The Internal Charge Evolution of Multilayered Materials Undergoing Mono-Energetic Electron Bombardment

Gregory Wilson
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THE INTERNAL CHARGE EVOLUTION OF MULTILAYERED MATERIALS
UNDERGOING MONO-ENERGETIC ELECTRON BOMBARDMENT

by

Gregory Wilson

A dissertation submitted in partial fulfillment
of the requirements for the degree

of

DOCTOR OF PHILOSOPHY

in

Physics

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2021
ABSTRACT

*The Internal Charge Evolution of Multilayered Materials Undergoing Mono-Energetic Electron Bombardment*

by

Gregory Wilson, Doctorate of Philosophy

Utah State University, 2021

Major Professor: Dr. JR Dennison
Department: Physics

This study presents the development of several models to predict the time evolution of the internal charge distribution of multilayer materials using known material properties and indirect measurement of the net surface potential and electrode currents. The first step in the process is to understand several important material properties related to electron interactions with the material. These include the electron penetration depth, secondary electron emission, charge transport and electrostatic discharge. By using energy dependent models of these properties, multilayer models can be developed. Using these models of properties, the net surface potential and the measurement of electrode currents can be used to extrapolate information about the internal charge distribution. A description of the Material Physics Group’s instrumentation is given along with specific instrumentation configurations unique to the given tests. Calibration and the use of the Surface Voltage Probe constructed by Joshua Hodges, parameterization of the STAIB electron gun and the measurement of the electrode currents are discussed in detail.

The theory for secondary electron yield for multilayer conductive materials is outlined for two scenarios, one with a high-density surface material and low-density substrate and another with a low-density surface material and high-density substrate. The results of the simulation show that the backscatter yield difference between the two materials affects the yield when electrons are able to backscatter from the substrate and interact with the surface layer on their traversal back out of the material. Otherwise, the surface layer material properties determine the yield, even for very thin surface layers.
The theory of multilayer charging for a multilayer dielectric is outlined for four configurations defined as surface layer deposition with grounded conductive layer, surface deposition with ungrounded conductive layer, conductive layer deposition with grounded conductive layer and conductive layer deposition with ungrounded conductive layer. The results for these tests are then outlined along with the fits given by the predictive models. The results of the tests show that knowledge of the energy-dependent electronic properties of the material, the energy of the incident electrons, and the geometry of the system are all vital to predict the outcome of the given scenario. It is shown that for multilayer materials with an ungrounded conductive layer, electrostatic discharge occurs after the material charges past the breakdown limits of the material. These results can help to design, construct, and model already deployed spacecraft to mitigate and prevent detrimental spacecraft charging effects.
The charging of multilayer materials as related to the charging of spacecraft is one of the primary concerns related to activities in the space environment. To understand how multilayer materials undergoing electron bombardment charge, an in-depth study of energy-dependent material properties must be undertaken. These properties include the electron penetration depth, secondary electron emission, charge transport and electrostatic discharge. By using energy dependent models of these properties, along with the geometry of the system, multilayer models can be developed to predict the time evolution of the internal charge distribution. Using these models, the net surface potential and the measurement of electrode currents can be used to extrapolate information about the internal charge distribution.

The Utah State University Materials Physics Group, with the funding of NASA James Webb Space Telescope project, performed several tests to understand the charging of multilayer dielectrics in various configurations. By using the Surface Voltage Probe to measure the net surface potential, along with measured electrode currents, the internal charge distribution can be inferred by using the developed theory for multilayer materials.

Because each scenario requires a unique analysis, the theory of multilayer charging for a multilayer dielectric is outlined for four configurations defined as (i) surface layer deposition with grounded conductive layer, (ii) surface deposition with ungrounded conductive layer, (iii) conductive layer deposition with grounded conductive layer, and (iv) conductive layer deposition with ungrounded conductive layer. The results for these tests are outlined along with the fits given by the predictive models. The results of the tests show that knowledge of the energy-dependent electronic properties of the material, the energy of the incident electrons and the geometry of the system are all vital to predict the outcome of the given scenario. It is shown that for multilayer materials with an ungrounded conductive layer, electrostatic discharge occurs after the
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Gregory Wilson
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LIST OF SYMBOLS

\( A \) = area of electrode (2.78)

\( A_b \) = incident area of beam (2.80)

\( b_{IMFP} \) = constant multiplier in IMFP power law approximation (2.15)

\( b_R \) = constant multiplier in high energy range power law approximation (2.16)

\( B_1 \) = fitting constant associated with the range in the FPL secondary electron yield model (2.44)

\( B_{1\text{max}} \) = fitting constant associated with the range in the FRPL secondary electron yield model (2.50)

\( B_2 \) = fitting constant associated with the IMFP in the FPL secondary electron yield model (2.44)

\( B_{2\text{max}} \) = fitting constant associated with the IMFP in the FRPL secondary electron yield model (2.51)

\( c \) = speed of light in a vacuum (2.17)

\( C \) = sample capacitance (2.96)

\( C_n \) = variable definition involving \( n \) in the SEY model (2.56)

\( C_{mn} \) = variable definition involving \( n \) and \( m \) in the SEY model (2.59)

\( C_{SE} \) = constant multiplier in the FPL secondary electron yield model (2.44)

\( C_{\text{max}} \) = constant multiplier in the RFPL secondary electron yield model (2.49)

\( C_{nm\gamma} \) = variable definition involving \( n, m, \) and \( \gamma_{\text{max}} \) (2.67).

\( C_{ML} \) = constant for the multilayer contribution in the multilayer secondary electron yield model (2.74)

\( d \) = material thickness (2.73)

\( d_{\text{Layer1}} \) = thickness of first layer in multilayer range approximation (2.27)

\( d_{\text{Layer2}} \) = thickness of second layer in multilayer range approximation (2.28)

\( d_{\text{Sample}} \) = thickness of full sample (4.6)

\( d_{\text{SiO}_2} \) = thickness of \( \text{SiO}_2 \) layer (4.1)

\( dz \) = infinitesimal length parameter (2.30)

\( \dot{D} \) = dose rate (2.75)

\( \dot{E} \) = mean energy lost per collision which is associated with the mean ionization energy (2.2)

\( E_b \) = electron beam energy (2.1)
\( E_{\text{gap}} \) = band gap energy (2.2)  
\( E_{\text{HI}}, E_{\text{LO}} \) = energies used to determine \( n_B \) from the Bethe Joy formula (2.21)  
\( E_{\text{HL}} \) = HOMO-LUMO gap (2.26)  
\( E_{\text{Layer2}} \) = electron energy upon entering second layer in multilayer range approximation (2.27)  
\( E_{\text{Layer3}} \) = electron energy upon entering third layer in multilayer range approximation (2.28)  
\( E_{\text{max}} \) = incident energy at maximum total yield (2.48)  
\( E_{\text{ML}} \) = transition energy in multilayer yield (2.74)  
\( E_{p}^{\text{eff}} \) = effective plasmon energy (2.2)  
\( E_{p} \) = plasmon energy (page 9)  
\( E_{\text{SE}} \) = average energy of potential SE in the material (2.40)  
\( f_{i} \) = number of elements associated with average atomic mass calculation (2.18)  
\( F \) = electric field (page 43)  
\( h \) = reduced Planck’s constant (2.2)  
\( J \) = bulk current in the material (page 43)  
\( \eta(E) \) = Heaviside step function (2.35)  
\( J_{b} \) = incident beam current (2.76)  
\( J_{b} \) = pulsed square wave beam current (2.84)  
\( J_{\text{disp}} \) = displacement current (2.95)  
\( J_{\text{electrode}} \) = electrode current (2.95)  
\( J_{\text{inj}} \) = total injected current into the material (2.93)  
\( J_{\text{total}} \) = total current into and out of the material (2.93)  
\( J_{\text{trans}} \) = total current transported out of the material (2.93)  
\( k \) = fixed empirical constant in the Bethe-Joy formula (2.19)  
\( k_{\text{PE}} \) = peak emission materials constant in energy spectrum of secondary electrons (2.85)  
\( k_{\text{RIC}} \) = material dependent RIC fitting parameter (2.75)  
\( l \) = material thickness associated with total resistance (page 46)  
\( l_{1} \) = material thickness of first layer associated with resistance (2.78)
\( l_2 \) = material thickness of second layer associated with resistance (2.78)

\( m \) = fitting parameter in the SEY equal to \( n_{IFMP} \) (2.43)

\( m_e \) = electron mass (2.2)

\( M_A \) = atomic weight (2.20)

\( \overline{M}_A \) = mean atomic weight by formula (2.3)

\( n \) = fitting parameter in the SEY equal to \( n_R \) (2.43)

\( n_0 \) = empirically found power exponent in predictive \( N_v^{pre} \) formula (2.24)

\( n_1 \) = \( Z_A \) weighting factor in predictive \( N_v^{pre} \) formula (2.25)

\( n_e \) = number of excited electrons generated within a material (2.29)

\( n_{IFMP} \) = IMFP power law exponent (2.15)

\( n_{ML} \) = power law fitting parameter in multilayer electron yield model (2.74)

\( n_R \) = range power law exponent (2.16)

\( N_0 \) = empirically found multiplicative factor in predictive \( N_v^{pre} \) formula (2.24)

\( N_1 \) = empirically found multiplicative factor in corrected predictive \( N_v^{pre} \) formula (2.25)

\( N_A \) = Avogadro’s number (2.3)

\( N_{emit} \) = number of emitted secondary electrons (2.88)

\( N_{offset} \) = empirically found constant in predictive \( N_v^{pre} \) formula (2.24)

\( N_{reat} \) = number of reattracted secondary electrons (2.87)

\( N_{sec} \) = total number of secondary electrons (2.87)

\( N_v \) = single fitting parameter defined as the effective number of valence electrons per atom (2.4)

\( N_v^{eff} \) = numerically determined value for \( N_v \) (2.3)

\( N_v^{pre} \) = predicted value of \( N_v \) (2.24)

\( P_{col} \) = probability of collision (2.9)

\( P_{EscIC} \) = join probability distribution of SE escape and an inelastic collision occurred (2.36)

\( P_{ES|IC} \) = probability distribution of SE escape given an inelastic collision occurred (2.34)

\( P_{IC} \) = probability distribution of an inelastic collision (2.32)

\( P_{Layer1} \) = power in first layer of multilayer deposited power model (2.81)
\( P_{\text{Layer}_2} \) = power in second layer of multilayer deposited power model (2.82)

\( P_{\text{Layer}_3} \) = power in third layer of multilayer deposited power model (2.83)

\( P_{SE} \) = probability distribution of secondary generation (2.29)

\( q_e \) = charge on an electron (2.2)

\( Q_{\text{col}} \) = charge collected on collector in HGRFA TEY calculation (page 70)

\( Q_{\text{grid}} \) = charge collected on grid in HGRFA TEY calculation (page 70)

\( Q_{\text{inc}} \) = total incident charge in HGRFA TEY calculation (page 70)

\( Q_{\text{sample}} \) = charge collected on sample in HGRFA TEY calculation (page 70)

\( Q_{\text{stage}} \) = charge collected on stage in HGRFA TEY calculation (page 70)

\( r \) = correlation factor (page 22)

\( R \) = composite electron range approximation (2.23)

\( R_1 \) = resistance approximation of first layer of multilayer material (2.78)

\( R_2 \) = resistance approximation of second layer of multilayer material (2.78)

\( R_{\text{CSDA}} \) = continuous slow down approximation range (2.1)

\( R_{\text{CSDA,CLA}} \) = continuous slow down approximation range using constant loss approximation (2.8)

\( R_{\text{Hi}} \) = high energy electron range approximation (2.14)

\( R_{\text{Layer}_1} \) = range approximation in first layer in multilayer range approximation (2.27)

\( R_{\text{Layer}_2} \) = range approximation in second layer in multilayer range approximation (2.28)

\( R_{\text{Layer}_3} \) = range approximation in third layer in multilayer range approximation (page 28)

\( R_{\text{LOW}} \) = low energy electron range approximation (2.7)

\( R_{\text{Mid}} \) = mid energy electron range approximation (2.12)

\( R_{SE} \) = range of secondary electrons (4.9)

\( R_{\text{tot}} \) = total resistance approximation of multilayer material (2.78)

\( S \) = stopping power (2.1)

\( S_{\text{CLA}} \) = stopping power using the continuous slowing down approximation (2.8)

\( I_{\text{on}} \) = time beam is on (2.84)

\( t_{\text{dep}} \) = total time of beam cycle (2.84)
\( V_{\text{corrected}} \) = surface voltage probe corrected sample reference voltage (3.2)

\( V_{\text{CSR}} \) = surface voltage probe non-charged corrected sample reference voltage (3.1)

\( V_{\text{GroundBefore}} \) = surface voltage probe ground before sample voltage measurement (3.1)

\( V_{\text{GroundAfter}} \) = surface voltage probe ground after sample voltage measurement (3.1)

\( V_{\text{Reference}} \) = surface voltage probe non-corrected sample reference voltage (3.1)

\( V_s \) = surface voltage (2.87)

\( V_{SE} \) = charging constant (2.92)

\( W_k \) = Lambert W function (2.55)

\( Y \) = time dependent secondary electron yield (2.89)

\( Y_0 \) = intrinsic secondary electron yield (2.89)

\( z \) = distance variable (2.32)

\( Z_A \) = atomic number (2.18)

\( \bar{Z}_A \) = number weighted mean atomic number (2.17)

\( \beta, \gamma, C, D, U \) = variables used in the TPP-2M formula (2.6)

\( \chi \) = insulator electron affinity or band gap plus sample bias for conductor (2.86)

\( \tilde{\chi} \) = reduced Chi-squared value (page 18)

\( \delta \) = secondary electron yield (2.37)

\( \delta_{\text{ERPL}} \) = extended reduced power law model for the secondary electron yield (2.61)

\( \delta_{\text{FRPL}} \) = full reduced power law model for the secondary electron yield (2.62)

\( \delta_{\text{RPL}} \) = reduced power law model for the secondary electron yield (2.60)

\( \delta_{\text{max}} \) = secondary electron yield at \( E_b = E_{\text{max}} \) (2.52)

\( \delta_{\text{ML}} \) = multilayer secondary electron yield model (2.74)

\( \delta_{\text{tot}} \) = two-layer secondary electron yield model with constant contamination layer growth (2.72)

\( \varepsilon_0 \) = permittivity of free space (2.2)

\( \varepsilon_r \) = relative dielectric constant (2.96)

\( \gamma_{1D} \) = one-dimensional geometric factor in secondary electron probability distribution (2.34)

\( \gamma_{3D} \) = three-dimensional geometric factor in secondary electron probability distribution (page 33)
\( \gamma_D \) = geometric factor in secondary electron probability distribution (page 33)

\( \gamma_{max} \) = ratio of \( B_1 \) to \( B_2 \) in FRPL model (2.63)

\( \lambda \) = inelastic mean free path at \( \bar{E} \) (2.4)

\( \lambda_{IMFP} \) = inelastic mean free path (2.4)

\( \lambda_{max} \) = related to \( E_{max} \) and the inelastic mean free path of electrons at \( E_{max} \) (2.64)

\( \lambda_{SE} \) = inelastic mean free path of secondary electrons (2.34)

\( \Phi \) = material work function (2.35)

\( \rho_1 \) = material resistivity of first layer (2.77)

\( \rho_2 \) = material resistivity of second layer (2.77)

\( \rho_m \) = material density (2.3)

\( \rho_{tot} \) = total material resistivity (2.77)

\( \sigma \) = electrical conductivity (page 43)

\( \sigma_1 \) = electrical conductivity of first layer (2.77)

\( \sigma_2 \) = electrical conductivity of second layer (2.77)

\( \sigma_{DC} \) = dark current conductivity (page 44)

\( \sigma_{down} \) = conductivity of the sample (2.93)

\( \sigma_{RIC} \) = radiation induced conductivity (2.75)

\( \sigma_{tot} \) = total conductivity of series approximation of multilayer materials (2.77)

\( \Sigma_{SB} \) = probability of overcoming surface barrier (2.34)

\( \Sigma_{SB}^{1D} \) = probability of overcoming the surface barrier in the 1D approximation (2.35)

\( \Sigma_{SE} \) = probability of electron excitation in secondary electron probability distribution (2.36)

\( \tau_{RIC} \) = RIC rise (turn on) time constant used in experiments (4.9)

\( \tau_{RIC}^1 \) = RIC rise time constant (page 55)

\( \tau_{RIC}^2 \) = RIC persistence constant (page 55)

\( \Delta_G \) = time constant for the growth rate of a contamination layer (2.72)

\( \Delta_{RIC} \) = material dependent RIC fitting parameter (2.75)
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>BSE</td>
<td>Backscatter Electrons</td>
</tr>
<tr>
<td>CCD</td>
<td>Charge-coupled device</td>
</tr>
<tr>
<td>CSDA</td>
<td>Continuous Slow Down Approximation</td>
</tr>
<tr>
<td>DAQ</td>
<td>Data acquisition</td>
</tr>
<tr>
<td>EFP</td>
<td>Electrostatic Field Probe</td>
</tr>
<tr>
<td>EFTP</td>
<td>Electrostatic Field Transfer Probe</td>
</tr>
<tr>
<td>ERPL</td>
<td>Extended reduced power law model</td>
</tr>
<tr>
<td>ESTAR</td>
<td>NIST database for inelastic mean free paths</td>
</tr>
<tr>
<td>FRPL</td>
<td>Full reduced power law model</td>
</tr>
<tr>
<td>FWHM</td>
<td>Full Width at Half Maximum</td>
</tr>
<tr>
<td>HGRFA</td>
<td>Hemispherical Retarding Grid Field Analyzer</td>
</tr>
<tr>
<td>IR</td>
<td>Infrared</td>
</tr>
<tr>
<td>IMFP</td>
<td>Inelastic Mean Free Path</td>
</tr>
<tr>
<td>LDPE</td>
<td>Low Density Polyethylene</td>
</tr>
<tr>
<td>MPG</td>
<td>Materials Physics Group</td>
</tr>
<tr>
<td>NIR</td>
<td>Near infrared</td>
</tr>
<tr>
<td>PEEK</td>
<td>Polyetheretherketone</td>
</tr>
<tr>
<td>RIC</td>
<td>Radiation Induced Conductivity</td>
</tr>
<tr>
<td>RPL</td>
<td>Reduced power law model</td>
</tr>
<tr>
<td>SE</td>
<td>Secondary Electrons</td>
</tr>
<tr>
<td>SLR</td>
<td>Single-lens reflex</td>
</tr>
<tr>
<td>SVP</td>
<td>Surface Voltage Probe</td>
</tr>
<tr>
<td>UV</td>
<td>Ultraviolet</td>
</tr>
<tr>
<td>UHV</td>
<td>Ultrahigh Vacuum</td>
</tr>
<tr>
<td>USU</td>
<td>Utah State University</td>
</tr>
<tr>
<td>VI</td>
<td>Virtual instrument</td>
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</tbody>
</table>
CHAPTER 1
INTRODUCTION

The focus of this thesis is the charging of multilayer materials undergoing electron beam bombardment with analysis based on secondary emission measurements as well as electrode currents and the net surface potential. This research follows work conducted by the Utah State University (USU) Materials Physics Group (MPG) to study the charging effects of optical mirrors in the space environment undergoing electron bombardment as well as a set of experiments to develop and validate theory for secondary electron emission for conductive multilayer materials. Other studies, such as electron induced photoluminescence, electrostatic discharge, and electron transport, have also been conducted and are reported in other presentations and publications done by the USU Materials Physics Group.

1.1 Multilayered Dielectrics in Spacecraft

Multilayered materials are used extensively in spacecraft construction. They are used, for example, in optical lenses, mirrors, and solar blankets. An example of a multilayer mirror geometry makeup is shown in Fig. 1.1. Contamination also creates surface layers on structures, components, and materials. Solar panels are an example of a mission critical component which can be affected by contamination leading to reduced efficiency as well as possible electrostatic discharges. Many of these components that incorporate multilayer

![Multilayered Dielectrics](image)

FIG. 1.1. A simple example of a very simple layer stack that consist of MgF2, Ta2O5 and Al2O3 with common thicknesses that are on the order of the wavelength of light. Many optics can have hundreds of layers with a resulting total thickness of around 10 um.
materials are mission critical components, especially optical components. This makes understanding the processes that can affect their durability and function essential.

1.2 Spacecraft Charging

Because of the possible catastrophic effects of the space environment (Hastings and Garrett, 1996), it is imperative that spacecraft charging and charge mitigation is understood. Even though the space environment is a complex problem, spacecraft charging can be broken down into the fundamental interactions between electrons and the effected materials. By understanding how charges bombard, move through and exit a material, research models can be developed to predict the behavior of complex systems. The first step in this processes is the independent characterization of each of these individual material properties (Dekany et al., 2012; Hoffmann and Dennison, 2012; Sim et al., 2012; Wilson and Dennison, 2012). This work has been a large focus of USU’s Material Physics Group over the last twenty-five years and has created a groundwork whereby the interplay between these processes that define the time evolution of the charge distribution can now be constructed (Dennison, 2012).

Using these properties accurate models can be developed to understand the charge build up, decay and electrostatic discharge of single layer materials. By using energy dependent models, multilayer scenarios can then be modeled to gain a better understanding of the internal charge evolution of multilayer materials.

1.3 Research Objectives

We begin, in Chapter 2, with a discussion of the background and theory of the individual material properties—the electron range, the electron yield, the material conductivity, and the power deposited—for a single layer material. We then extend the theory to multilayer materials and set up several multilayer models based on this framework. A discussion of the experimental setup, procedures and sample preparation is then conducted in Chapter 3 followed by an analysis of the results of the secondary electron emission experiments and the multilayer charging experiments in regard to the internal charge distribution in Chapter 4. This research outlines a process by which many multilayer layer charging scenarios can be understood and modeled using the measurable properties of the individual materials as well as the makeup of the multilayer material.
CHAPTER 2

THEORY AND BACKGROUND OF CHARGING PROCESSES

This chapter describes the theory of single layer dielectric charging, as well as multilayer charging with a focus on dielectrics. We first begin with a discussion of single layer charging and the physical processes which govern the charging and then describe how multiple layers affect each process. The main processes that will be described are: the range, the total electron yield, the conductivity including radiation induced conductivity, as well as a link to power deposition.

2.1 Space Environment

The space environment consists of a soup of energetic particles that interact with spacecraft and spacecraft materials. Each spacecraft orbit has its own set of primary physical components which makes the problem of spacecraft charging analysis very dependent upon the specific orbit. For example, Low Earth Orbit (LEO) has cold, dense, ionospheric plasma, dense supersonic neutral atmosphere, and orbital debris while; by contrast, Geosynchronous orbit (GEO) has a high energy plasmasheet, substorm plasma, UV radiation and solar flares (Hastings and Garrett, 1996). These environmental properties are also dynamic and can change the material properties of the surface creating a dynamic time-changing problem (Dennison, 2014). For this research, the focus is on energetic electrons that can be found in most orbits such as GEO, L2 (which is the orbit that the JWST will be located at), as well as interplanetary missions such as those to Europa.

Because energetic electrons exist throughout space and range from a few eV to hundreds of MeV, their effects are wide ranging and potentially catastrophic. Figure 2.1 shows typical differential fluxes versus energy for several different environments. From this graph it is clear that many environments have relatively constant fluxes from 10eV to 10 keV at which point the flux begins to decrease but there are still significant numbers of electrons with energies up to 1 MeV. Because of the wide range of energies, electrons will both interact with the surface as well as deep within the materials. For highly insulating materials, this can lead to deep dielectric charging as well as surface effects that can lead to electrostatic breakdown if charge is not able to dissipate in time. To understand the overall effect of electrons on space materials and components, an
understanding of each phenomenon is important, especially with multilayer materials. The phenomena that drive spacecraft charging that will be studied in this work include electron range, secondary electron emission, electron conduction and dose effects.

2.2 Electron Range

As an energetic electron traverses through a material, it undergoes inelastic and elastic collisions with the materials atoms. It continues to lose energy through these collisions and other energy loss mechanisms until it loses all of its kinetic energy and comes to rest with in the material. The electron range is a common way to parameterize the distance the electron travels through the material before it comes to a rest. The extrapolated range and the penetration depth are also valid descriptions of this traversal; however, while all three of these parameterizations are similar, they have distinct differences that must be carefully considered when choosing which one to use.

FIG. 2.1. Typical differential fluxes for electrons versus energy for several different environments.
The range is often employed in spacecraft charging calculations to predict the charge distribution of deposited electrons in materials, to determine shielding requirements, and to model secondary and backscattered electron emission. It is therefore important for spacecraft charging models to have a realistic, reasonably accurate, and efficient expression to predict the approximate range of electrons with energies commonly encountered in space plasma fluxes, from \( \sim 10 \) eV to \( \sim 10 \) MeV. This expression must also be readily implemented for a wide array of conducting, semiconducting and insulating spacecraft materials with a minimal number of fitting parameters for research and development purposes.

The USU Material Physics Group has developed a piecewise expression to approximate the electron range over an energy span of \( \sim 10 \) eV to \( \sim 10 \) MeV with a single fitting parameter, \( N_e \), for a wide range of materials (Wilson and Dennison, 2012). This approximation has been compared to the NIST ESTAR database with errors \(<20\%\) over the entire energy span with errors generally much less (Wilson et al., 2019). A predictive formula has also been developed to predict \( N_e \) using only readily available material parameters such as the material density and mean atomic number. This tool has been made publicly available via an HTML/Javascript webpage which also includes a downloadable Excel worksheet (Wilson et al., 2018).

2.2.1 Range, Extrapolated Range, and Penetration Depth

The most common ways to parameterize the traversal distance of electrons through a material are the range, extrapolated range, and penetration depth (Science, 1964). While each parameterization attempts to quantify the distance an energetic electron travels through a material, each one is distinct with its own strengths and weaknesses.

The electron range is defined as the maximum distance an electron can travel through a material before coming to rest. This can also be described as the path length of the electron. One of the key features of this parameterization is that it ignores elastic collisions which deflect the electron but do not decrease its energy, and thus, its total path length. This definition is valuable in defining shielding requirements for energetic electrons since it defines the minimum thickness of shielding required to stop all electrons. For higher energy electrons, \( >1 \) keV, the range is a reasonably accurate definition of the depth from the surface an electron normally incident upon the surface will penetrate due to the dominance of inelastic over elastic collisions.
Because of this dominance, the stopping power, defined as the retarding force acting on an electron due to its interacting with the material, is largely proportional to the ionization energy losses per unit length. This is known as electronic stopping, which also includes collisions which produce excitations within an atom. For much lower energies, especially at energies below the lowest excitation energy, collisions with the nuclei dominate, where energy loss is due to vibration or phonon production. For extremely high energies where relativistic effects are present, radiative stopping due to Bremsstrahlung contributes significantly resulting in nuclear stopping. The total stopping power is sum of these three mechanisms.

Because of the probabilistic nature of collisions and, at higher energies, the number of collisions is large, the total stopping power is taken as the average stopping power over a unit path length which removes fluctuations in the energy loss. This makes the total stopping power a continuous function along every point of the electrons path dependent only on the energy of the electron and material parameters. This does not mean however, that the stopping power is constant, only that it is continuous.

The range can be approximated using this stopping power by assuming that the electron energy loses energy continuously along its path as a result of the total stopping power. This approximation is known as the Continuous Slowing Down Approximation (CSDA) and is used to calculate the CSDA Range given by the integral of the reciprocal of the total stopping power (Ashley et al., 1978),

\[
R_{\text{CSDA}}(E_b) = \int_0^{E_b} \frac{dE}{S(E)}
\]

where \(E_b\) is the beam energy and \(S(E)\) is the energy dependent stopping power. The lower limit on the integral is generally taken as some small energy around 10 eV, since the electric stopping power at these small energies approaches 0 which causes the range to go to infinity. This approximation is used in the NIST ESTAR database; however, only values above 10 keV are tabulated there (Berger et al., 2017).

Because the range is the maximum distance an electron can travel, measuring it directly can be difficult due to very low count rates when using transmission techniques. To overcome this difficulty, the extrapolated range, which is defined as the point where the line tangent to the steepest point on a transmission versus thickness graph intersects the thickness axis (Tabata et al., 2002). Because this value is less than the range at energies where transmission count rates are much higher, it is possible to measure it in the laboratory. The extrapolated range is largely used to compare laboratory results with theory and to parametrize materials.
One key component that the extrapolated range demonstrates is the concept of range straggling, which is the fluctuation of the path length due to the probabilistic nature of collisions, both in frequency and the amount of energy lost. One thing to be careful of, however, is that range straggling should not be confused with the difference between the range and the penetration depth.

The electron penetration depth is the distance measured from the surface of the material to the point at which the electron comes to rest which is also known as the track-end penetration depth (Lazurik et al., 1998). This differs slightly from the maximum penetration depth which is the distance measured from the surface to the maximum distance an electron can penetrate which is also equal to the electron range. Because lateral scatter can cause electrons to deviate their trajectory, the maximum penetration depth or range is almost always greater than the track-end penetration length. The difference between the penetration depth and the range is shown in Fig. 2.2 where Monte-Carlo simulations of electron penetration are shown (Maletz et al., 2005). This figure clearly shows the effect of scattering on the penetration depth of individual electrons as well as the maximum penetration depth of all electrons from a given simulation which results in the value of the electron range.

FIG. 2.2. Monte Carlo simulations of electron Penetration with the Range indicated (Maletz et al., 2005).
Because the penetration depth ignores the path length and simply relies on the depth from the surface, it is highly susceptible to elastic collisions. The difference in the range and the penetration depth is especially apparent at low energies where elastic collisions dominate. This results in the penetration depth dropping significantly while the range actually increases due to the increase of the inelastic mean free path of electrons at low energies.

In order to quantify this parameter it is common to use the average maximum penetration depth of electrons (Lazurik et al., 1998). This parameter is useful because it can be readily related to transmission experiments similar to the extrapolated range. As a general rule, the average maximum penetration depth is lower than the extrapolated range, which are both less than the range (Lazurik et al., 1998).

Because of its wide use in spacecraft charging and its extendibility to other parameterizations, USU’s MPG chose to develop an extended model of the electron range for use over the applicable energy ranges and for a numerous assortment of materials.

2.2.2 Electron Range Approximation

In order to develop an approximation to the range, the model was broken in three parts corresponding to three energy ranges. The low energy range covers energies <10 eV to ~50 eV, the mid-energy range covers the range between ~50 eV to 1 keV, and the high energy range from 1 keV to >10 MeV.

2.2.3 Low Energy Range

Range calculations for electrons generally extend only down to a few tens of keV in energy ranges where there are many collisions. Below these energies, corrections to the CSDA range have been made in an attempt to extend calculations down to a few tens of eV. All of these approximations rely on integrating the total stopping power which results in the range monotonically decreasing. This approximation however, does not agree with low energy attenuation (Rundgren, 1999; Fitting et al., 2001; Offi et al., 2008; Offi et al., 2010) and transmission (Kanter, 1970; Ueno et al., 1986; Drouhin et al., 1995) experiments which show an increase in current for decreasing incident energies below ~50 eV. If the range decreased at these energies, one would expect attenuation and transmissions experiments to also show this reduction.

At these energies below ~50 eV, electron-electron interactions remain as the dominating energy loss mechanism (Kanter, 1970) with the distance between collisions determined by the inelastic mean free path
In order to approximate the range at these energies, it is assumed that the electron has only enough energy to undergo a single collision at this IMFP, thereby linking the range and the IMFP. Similar approximations have been done to link the IMFP with the attenuation path (Chen et al., 1992); however, the attenuation path still must take elastic collisions into account.

For the low energy approximation for the range, the energy lost in a single collision is assumed to be a distribution with a mean value $E_6$, the mean energy loss per collision. This energy distribution relies on the density of states of excitable electrons with the material. In order to use this distribution to get an accurate approximation of the IMFP, it requires the use of complicated models that take into account the collisional cross sections of electron-electron collisions with the various core and valence electrons in the material (Valentin et al., 2012; Emfietzoglou et al., 2017).

Because of the complicated nature of IMFP values at these low energies in the past a “universal curve” has been used as an approximation for the IMFP and the attenuation length (Seah, 1979). The model presented here does not attempt to accurately predict the IMFP for these low energies, but it does offer trend lines more robust than the simple universal curve while still maintaining a single fitting parameter. Figure 2.3 shows IMFP data for numerous materials (Brundle, 1974) along with the preliminary theory developed by Penn (Penn, 1976) and the current range model for Au as presented here (Wilson et al., 2018). While not exact, the universal curve still manages to fit numerous materials from varying material parameters.

In order to make this approximation, an extension of the TPP-2M (Tanuma et al., 1997) equation was developed. Because the TPP-2M equation is only valid for energies $>\sim 50$ eV, the IMFP is set equal to the TPP-2M equation at the mean energy loss, $\bar{E}$, and then extended to lower energies. To calculate, $\bar{E}$, a geometrical average of the band gap and the effective plasmon energy is used multiplied by an empirical factor of 2.8. This gives,

$$\bar{E} = 2.8 \left( \left( E_p^{\text{eff}} \right)^2 + \left( E_{\text{gap}} \right)^2 \right)^{1/2}$$

where $E_{\text{gap}}$ is the band gap energy and $E_p^{\text{eff}}$ is the effective plasmon energy where the plasmon energy is defined as $E_p = \hbar n_p q_e^2 / m_e \epsilon_0^{1/2}$ where $n_p$ is the conduction electron density. The effective plasmon
energy for an arbitrary atomic or molecular material is defined in analogy with the bulk free-electron plasma
energy for conductors as

\[ E_p^{\text{eff}} = \hbar \left( \frac{N_V^\text{eff} N_A \rho_m q_e^2}{M_A m_e \varepsilon_0} \right)^{1/2} \]  

(2.3)

where \( q_e \) is the electron charge, \( m_e \) is the mass of an electron, \( \varepsilon_0 \) is the permittivity of free space, and \( N_V^\text{eff} \) is a fitting parameter loosely related to the number of valance electrons per atom or molecule (Tanuma et al., 2005a). The inelastic mean free path at this mean energy is then given by

\[ \bar{\lambda}(N_v) = \lambda_{\text{IMFP}}(E, N_v) \]  

(2.4)

where \( \lambda_{\text{IMFP}} \) is given by the TPP-2M equation as

\[ \lambda_{\text{IMFP}}(E_b, N_v) = E_b E_p^{-2} \left[ \beta \ln(y E_b) - C E_b^{-1} + D E_b^{-2} \right]^{-1} \]  

(2.5)

using the energy-independent TPP-2M expressions for

FIG. 2.3. Universal curve of electron inelastic mean free path. The experimental data is given by Brundle (1974) and the theoretical model given by Penn (Penn, 1976). An approximation for the electron range for Au using the model presented here is also presented.
\[ \beta \equiv -0.1 + 0.34 \frac{E}{E^*} + 0.069 \rho_m^{0.1} \]

\[ \gamma \equiv 0.191 \rho_m^{-1/2} \]

\[ C \equiv 1.97 - 0.91 U \]

\[ D \equiv 53.4 - 20.8 U \]

\[ U \equiv \frac{N_e \rho_m}{\mu_A} \]

with energies \( U, E_m, E_p, \) and \( E_{\text{gap}} \) in eV and mass density \( \rho_m \) in g-cm\(^3\). Lower energy loss mechanisms (e.g., surface plasmons with energies \( \sim 1/\sqrt{2} \) that of bulk plasmons, low energy inter-band transitions, intra-band transitions, or phonon interactions) are not explicitly included in this model but are absorbed into \( \tilde{E} \) (Kittel, 1966; Pines, 1999; Schreiber and Glavatskikh, 2004) for energies \( E < \tilde{E} \lesssim 50 \) eV due to a decrease in the scattering rates for inelastic collisions which increases the range for low energy electrons (Fitting et al., 2004). The IMFP and the range are closely tied at these levels. For very low energies where only a single collision occurs before all of the electrons energy is lost, the IMFP and the attenuation length would be identical if elastic collisions did not occur which is also equal to the 1D mean escape depth (Jablonski and Powell, 1999; Fitting et al., 2004). Thus, since the electron range neglects elastic-electron scattering, it is synonymous to the IMFP at these low energies. Because the TPP-2M equation is not valid at energies below \( \sim 50 \) eV, a low energy approximation is made. This approximation is made based on the probability of having a collision as well as having enough energy to undergo an inelastic collision. Thus, using this low energy approximation of the IMFP for \( E_b < \tilde{E} \), the low energy range becomes,

\[ R_{\text{LOW}}(E_b, N_e^{\text{eff}}) = \left[ \frac{E_b}{\tilde{E}} \right] \tilde{\lambda}(N_e^{\text{eff}}) \left( \frac{1 - \exp[-1]}{1 - \exp[-E_b/\tilde{E}]} \right)^2. \]  

This function can be seen in Fig. 2.3 for Au below \( \tilde{E} = 70 \) eV.

2.2.4 Mid-Energy Range

Above \( \tilde{E} \), the range diverges from the IMFP due to the possibility of having multiple collisions. To approximate the mid-energy range, the constant loss approximation (CLA) for the stopping power is used. The stopping power is a complicated function with several energy dependent contributions. An approximation of the stopping power was first developed by Bethe in 1930 (Bethe, 1930). Since that time,
numerous corrections and modifications have been made to give a better approximation, extend its applicability to more materials, and extend it to lower energies (Joy and Luo, 1989; Tanuma et al., 2005b; Nguyen-Truong, 2015). In the CLA approximation the stopping power is constant, meaning that the energy loss rate is set to a constant value equal to the average energy lost per collision divided by the distance traveled giving \( \frac{dE}{dz} = S_{CLA}(E_b) \) which is a function of the incident energy, \( E_b \), and not its instantaneous energy \( E \).

Using the CSDA and CLA, if we integrate the inverse of this constant stopping power, we get the relation,

\[
R_{CSDA,CLA}(E_b) = - \int_0^{E_b} \frac{dE}{S_{CLA}(E_b)} = - \frac{E_b}{S_{CLA}(E_b)}.
\]

As long as the stopping power is independent of \( E \), we can choose any reasonable form and this approximation remains valid. Because the stopping power is defined by the unit energy loss per unit distance, we can approximate the stopping power as the mean energy loss per inelastic mean free path. Given that the probability of low energy electrons to have a collision with mean energy loss \( E_6 \) is given by and the probability to travel a distance equal to the mean free path is given by

\[
P_{col}(E_b) = \left( 1 - e^{-\frac{E_b}{\bar{E}}} \right) \quad (2.9)
\]

and the probability to travel a distance equal to the mean free path is given by

\[
P_{col}(\lambda_{IMFP}) = \left( 1 - e^{-\frac{\lambda_{IMFP}}{\bar{E}}} \right) = (1 - e^{-1}). \quad (2.10)
\]

Using these probabilities, an approximation of the stopping power can be given by,

\[
S_{CLA}(E_b, N_v^{eff}) = \frac{dE}{dz} \frac{P_{col}(E_b)}{P_{col}(\lambda_{IMFP})} = - \frac{\bar{E} \left( 1 - e^{-\frac{E_b}{\bar{E}}} \right)}{\lambda_{IMFP}(E_b, N_v^{eff})(1 - e^{-1})} \quad (2.11)
\]

Substituting Eq. 2.11 into Eq. 2.8 gives for the mid-energy range,

\[
R_{Mid}(E_b, N_v^{eff}) = \frac{E_b}{\bar{E}} \frac{\lambda_{IMFP}(E_b, N_v^{eff})}{(1 - e^{-\frac{E_b}{\bar{E}}})} \quad (2.12)
\]

The addition of the collisional probability acts to decrease the stopping power for a given beam energy. This correction to the CLA allows the stopping power to more closely resemble values for the stopping power in
this energy range as found in the literature (Tung et al., 1979; Nguyen-Truong, 2015) without adding any more fitting parameters.

The graph in Fig. 2.1 shows the mid-energy range for $E_b > E = 70 \text{ eV}$. The change from the low energy range to the mid-energy range is seamless with the range diverging from the IMFP above $\bar{E}$ due to multiple mean free paths in the range versus a single mean free path in the IMFP.

### 2.2.5 High Energy Range

Once the energy passes 1 keV, it is estimated that the electron will undergo approximately 15 collisions, given that $(1 \text{ keV})/\bar{E} \approx 14$ for Au. At this point, we are able to approximate the stopping power as,

$$S_{CLA}(E_b, N_v) = -\frac{\bar{E}}{\lambda_{IMFP}(E_b, N_v)}$$  \hspace{1cm} (2.13)

This gives for the CSDA range,

$$R_{HI}(E_b, N_v) = \frac{E_b}{\bar{E}} \lambda_{IMFP}(E_b, N_v).$$  \hspace{1cm} (2.14)

If we approximate the IMFP with a power law as,

$$\lambda_{IMFP}(E_b) = b_{IMFP} E_b^{n_{IMFP}}$$  \hspace{1cm} (2.15)

this gives for the high energy range,

$$R_{HI}(E_b) = b_R E_b^{n_R}$$  \hspace{1cm} (2.16)

where $b_R \equiv b_{IMFP}/\bar{E}$ and $n_R = 1 + n_{IMFP}$. For energies above ~0.5 MeV however, Bremsstrahlung begins to contribute significantly to the stopping power as seen in Fig. 2.4. To account for this, a first order relativistic like correction is added to the power law to give,

$$R_{HI}(E_b, N_v) = b_R E_b^{n_R-1} \left(1 + \frac{Z_{\text{eff}}^{0.39} E_b}{3 N_v m_e c^2}\right)^{-2}$$  \hspace{1cm} (2.17)

where $E_b$ is the incident beam energy, $c$ is the speed of light and $Z_{\text{eff}}$ is the number-weighted mean atomic number defined as
\[ Z_A = \frac{\sum_i (f_i Z_{Ai})}{\sum_i (f_i)} \]  

(2.18)

where \( f_i \) is the number of each type of element. Figure 2.4 shows the fit to tabulated data for Au from the ESTAR database, using both non-relativistic and relativistic power law expressions. Above 10 MeV, the first order relativistic correction for Eq. 2.17 is no longer sufficient and does not adequately reproduce the Bremsstrahlung effect. A closer approximation to the more complete relativistic Bethe formula is needed above 10 MeV.

The parameter \( n_R \) is determined by matching the slope of Eq. 2.17 with the slope of the range derived from the Bethe-Joy formula (Joy and Luo, 1989) given by

\[ R_{Bj}(E_b) = \left[ \frac{(4\pi e_0)^2 \bar{M}_A}{2\pi q_e^4 Z_A \rho_m} \right] E_b^2 \left[ \ln \left( \frac{\pi}{2} \left[ \frac{E_b/N_v}{E} + k \right] \right) \right]^{-1} \]  

(2.19)

where \( N_v \) is set equal \( N_v^{eff} \), \( \rho_m \) is the density, \( k = 0.8 \), and \( \bar{M}_A \) is the mean atomic weight by formula, given by

FIG. 2.4. Comparison between the standard power law and the relativistic power law for Au. The relativistic power law allows approximations for energies up to 10 MeV with percent errors ~20\%.
\[ M_A \equiv \sum_i (f_i M_{A_i})/\sum_i (f_i). \]  

(2.20)

This gives for the power law slope,

\[ \ln \left[ \frac{\ln \left( \frac{E_{HI}}{N_{v_{eff}} E} + k \right)}{\ln \left( \frac{E_{LO}}{N_{v_{eff}} E} + k \right)} \right] \]

\[ n_R(N_{v_{eff}}) \equiv \frac{\ln \left( \frac{E_{HI}}{N_{v_{eff}} E} + k \right)}{\ln \left( \frac{E_{LO}}{E_{HI}} \right)} + 2 \]  

(2.21)

where \( E_{HI} = 20 \text{ keV} \) and \( E_{LO} = 1 \text{ keV} \). The scaling parameter \( b_R \) is then determined by fitting the high energy range in Eq. 2.17 and the mid-energy range defined by Eq. 2.12 at \( E_b = E_{LO} \) to give,

\[ b_R(N_{v_{eff}}) \equiv \frac{E_{LO}^{2-n_R} \lambda_{IMFP}(E_{LO}, N_{v_{eff}})}{E \left( 1 - \left( 1 + \left[ \frac{2^{0.39} E_b}{3N_{v_{eff}} m_e c^2} \right]^{-2} \right) \right)} \frac{1 - \exp[-1]}{1 - \exp \left[ -\frac{E_{LO}}{E} \right]}. \]  

(2.22)

### 2.2.6 Full Range Model

Because these three equations are set equal to each other at each of the boundaries at \( E_{LO} \) and \( E_{HI} \), they form one continuous piece-wise function given by,

\[ R(E_b; N_{v_{eff}}) = \begin{cases} \left( \frac{E_b}{E} \right) \lambda_{IMFP}(E, N_{v_{eff}}) \left( \frac{1 - \exp[-1]}{1 - \exp \left[ -\frac{E_b}{E} \right]} \right)^2 & ; E_b < E \\ \left( \frac{E}{E} \right) \lambda_{IMFP}(E_b, N_{v_{eff}}) \frac{1 - \exp[-1]}{1 - \exp \left[ -\frac{E_b}{E} \right]} & ; E \leq E_b \leq E_{LO} \\ b_R E_b^{n_R-1} \left( 1 - \left[ 1 + \left[ \frac{2^{0.39} E_b}{3N_{v_{eff}} m_e c^2} \right]^{-2} \right] \right) & ; E_b > E_{LO} \end{cases} \]  

(2.23)

This function has been compared to data found in the NIST ESTAR database where differences are less than \( \sim 20\% \); however, errors are generally much less with the errors largely due to an inadequate relativistic correction as shown in Fig. 2.5 with the percent differences shown in Fig. 2.6. Figure 2.7 shows comparison for Au of the results of Eq. 2.23 with the NIST ESTAR database at high energies and the NIST IMFP database at mid-range energies. Similar results for Al, Al\(_2\)O\(_3\) and polyimide are shown in Wilson (2012). Figure 2.8 shows the effect of different \( N_v \) values on the range. Higher \( N_v \) values lead to underestimating the range whereas lower values overestimate the range.
FIG. 2.5. Comparison of the ESTAR range and IMFP with the full range model using the empirically found $N_{\text{eff}}$, and the predicted $N_{\text{pre}}$.

FIG. 2.6. Percent differences from the graph in Fig. 2.5.
FIG. 2.7. Comparison between several range approximations and the data from the ESTAR database for Au (Pines, 1999). The IMFP data for Au are also plotted along with the TPP-2M IMFP formula for $\lambda_{\text{IMFP}}(E)$ (Technology, 2010b).

FIG. 2.8. Graphs showing the variation of the range expression for Au, as a function of the single fitting parameter $N_v$. For graphs (a) through (d), $N_v = 1, 5, 12$ (best fit) and 20, respectively.
2.2.7 Empirical $N^\text{eff}_\nu$

Empirical values of $N^\text{eff}_\nu$ were derived from fits to range and inelastic mean free path (IMFP) values as a function of incident electron energy from two NIST databases. Tabulated values of the electron ranges at high energies using the CSDA can be found in the NIST ESTAR database spanning incident energies from $E_{\text{th}}$≈20 keV to ≈1 GeV. IMFP data are found in the IMFP database spanning incident energies from ≈500 eV to ≈2 keV. Original fits to ~20 materials using the range function have now been extended to include almost all of the 249 diverse materials found in the NIST databases; the materials now fit are categorized as (74 conductors, 17 semiconductors, 74 insulators), (156 solids, 7 liquids, 2 gases) and (92 elements, 47 compounds, 21 polymers, 5 composites).

To assess the accuracy of the range model, comparisons can be made several ways between the NIST database range values and range values predicted using the empirical $N^\text{eff}_\nu$ values derived from fits to the NIST databases. The agreement between range values compared in this way were found in almost all cases to give good fits, with differences typically less (often much less) than ±20% over full 10 eV <$E<$10 MeV spans.

Another way to quantify the agreement between range values from the NIST databases and those the predictive range formula using $N^\text{eff}_\nu$ values is to calculate the reduced chi-squared values, $\chi^2$, over the full ~500 eV to 10 MeV spans of NIST data. A plot of $\chi^2$ versus $N^\text{eff}_\nu$ for all the materials fitted is shown in Fig. 2.9. The mean $\chi^2$ is ~6·10^{-7}, indicative of very good fits. However, the standard deviation of the $\chi^2$ of ~2·10^{-6}, approximately 3X the mean $\chi^2$, suggests there is a wide range of $\chi^2$ values.

Indeed, plotting the $\chi^2$ values for all of the materials revealed that the greatest errors were from a small number of materials, which were in three main populations. The first category consists of materials with $N^\text{eff}_\nu$ ≤ 2 which followed a power law trend. The second category consists of elemental alkali (Li, Na, K, Rb, Cs, Fr; yellow diamonds in Fig. 2.9) and alkaline earth (Be, Mg, Ca, Sr, Ba, Ra; yellow squares) metals. The third category includes highly ionic alkali halide compounds (blue diamonds). When these three populations are removed, the mean $\chi^2$ is ~4·10^{-7}, with a standard deviation of ~1·10^{-6}. It is important to note, that while these three categories of materials are shown to have the greatest deviations, their $\chi^2$ values are...
still $\lesssim 1 \cdot 10^{-5}$. Even though Li has the greatest $\chi^2$, it still has reasonable agreement for the range when compared to NIST ESTAR range and IMFP data, with maximum errors still $\lesssim 40\%$.

In order to estimate the effect of variances in the fitting factor $N_v^{\text{eff}}$, variations of the composite fit were calculated with different $N_v^{\text{eff}}$. Comparisons of range versus energy for the ceramic insulator alumina (Al$_2$O$_3$)—with $N_v^{\text{eff}}$ set equal to 0.5, 2.8 (the calculated value from the fit), and 8.0, were performed while other materials parameters are held constant to the database range values as seen in Fig. 2.10. It was found that lower values of $N_v^{\text{eff}}$ overestimate the range, while higher values of $N_v^{\text{eff}}$ underestimate the range.

Based on the quality of the fits to the database values, the typical uncertainty in $N_v^{\text{eff}}$ is estimated to be
≤10%. Based on these results, even with significant variance in $N'_V$, we can expect to find values that are reasonably accurate for most applications.

To set limits on the effects of variations in $N'_V^{eff}$, we consider the physical ranges of $N'_V^{eff}$ (from 0.3 for ethane and 1.18 for Li to 15.2 for Ra) and $E_{gap}$ (zero for conductors to 10.8 eV for MgF$_2$ and 14.2 eV for LiF) as seen in Fig. 2.11. The band gap contribution to Eq. 2.2 is <10% for all conductors and semiconductors with $E_{gap} < 2.5$ eV and for all materials with $N'_V^{eff} > 8.3$. Only a few low-Z organic materials, including the alkanes and nyons, have low enough $N'_V^{eff} < 2.5$ and high enough $E_{gap} \geq [2.0 + 1.75N'_V^{eff}]$ for band gap contributions to $E' > 10$%; these can have as high as ~35% band gap contributions to $E'$ for the extreme case of ethane ($N'_V^{eff}=0.3$ and $E_{gap} \approx 7.5$ eV). Together this means that variations in $E_{gap}$ of <1 eV need not be considered, except for the case of a few highly insulating low-Z organic materials.
2.2.8 Predicting \( N^\text{pre}_v \)

In order to extend the usefulness of the approximate range model to materials where there is no range data available to empirically find the single fitting parameter \( N^\text{eff}_v \), a simple formula using material parameters was developed during this work to predict \( N^\text{pre}_v \):

\[
N^\text{pre}_v(Z_A) = N_o(\tilde{Z}_A^{\text{no}} + N_{\text{offset}})
\]  

(2.24)

This formula was found through extensive analysis of much more complex predictive formulas for \( N^\text{pre}_v \) involving products of power law terms for density, mean atomic number and weight, and band gap plus other properties including plasmon energy, conductivity, phase, and more. This general fit for \( N^\text{pre}_v \) was evaluated using general least squares fit analysis methods to simultaneously determine the best estimates for fitting parameters for each material property.

FIG. 2.11. Effect of \( N^\text{eff}_v \) on the mean energy lost per collision, \( \bar{E} \), and fractional change in \( \bar{E} \). Right axis solid lines are for \( \bar{E} \) and left axis dashed lines are for the fractional change. Curves are shown for \( E_{\text{gap}} \) equal to 0 eV (black), 5.4 eV (red), 7.8 eV (blue), and 14.2 eV (purple).
2.2.9 Effect of Atomic Number Correction

Remarkably, this predictive formula for effective number of valence electrons was a function of only the mean atomic number weighted by atomic fraction, $\bar{Z}_A$, which can be easily determined from the stoichiometric formula for compounds or from elemental fractions for composite materials as given by Eq. 2.18.

The fitting constants, $N_o$, $n_o$ and $N_{offset}$, were found through least squares fits to minimize the difference between $N_{V}^{pre}(\bar{Z}_A)$ and the empirical values for $N_{V}^{eff}$. Goodness of fit metrics of chi squared $\chi^2_{Nv}$ and linear correlation coefficient $r_{Nv}$ allowed quantification of the quality of these fits. The fitting parameters were then used to calculate values of $N_{V}^{pre}$, using the power law model. The $\chi^2_{red}$ vs $N_{V}^{pre}$ values are shown in Fig. 2.12.

To assess the ability to accurately predict $N_{V}^{eff}$, Fig. 2.13 plots the predicted $N_{V}^{pre}$ values against the empirical $N_{V}^{eff}$ values. Lines indicate ±10% (dashed red) and ±30% (purple dot-dashed) deviations from

![Graph showing reduced chi squared values, $\chi^2$, for comparisons of range values from the NIST databases to those predicted using the range approximation in this work.](image)
a one-to-one linear fit (solid red), which would be expected for an exact predictive model. It is apparent that while there is strong correlation ($r = 0.984$), there is substantial scatter of $\pm 15\%$ in the predictions from a perfect linear fit.

To refine Eq. 2.24, separate fits similar to Fig. 2.13 were made for materials subcategorized into grouping such as solids/liquids/gasses and conductors/semiconductors/insulators, with the hope that this categorization might reveal additional trends. Semiconductors showed excellent agreement. Insulators showed very good agreement, with a slight downward concavity. Although conductors showed good agreement, their values oscillated about the unity line, with amplitude increasing with increasing $N_v^{\text{eff}}$. Plots in Fig. 2.14(a) of the residuals ($N_v^{\text{pre}} - N_v^{\text{eff}}$) versus empirical $N_v^{\text{eff}}$ values also exhibited these patterns.

The observed patterns were very reminiscent of the deviations from linearity seen in plots of density versus atomic number for the elements. The oscillations in the density for conductors (and similar trends in

![FIG. 2.13. Comparison of predicted $N_v^{\text{pre}}$ values to empirical $N_v^{\text{eff}}$ values. Predicted $N_v^{\text{pre}}$ values versus empirical $N_v^{\text{eff}}$ values. The red and purple dashed lines represent 10% and 30% deviations, respectively, from an exact one-to-one linear fit (solid red).](image-url)
atomic radius and ionization energy) are well understood in terms of how many free electrons there are in the outermost shell and specifically the electron overlap in the d and f orbitals of transition and rare earth/actinide elements due to metallic interactions between atoms.

Therefore, a simple corrective term was added to the predictive formula dependent on the mean atomic number \( ar{Z}_A \) rather than elemental atomic number, so as to extend the correction to non-elemental materials. Using the residuals from a linear fit of \( \rho_m \) versus \( ar{Z}_A \), a scaled correction factor was added to giving:

\[
N_v^{pre}(\bar{Z}_A, \rho_m) = N_0 \left( \bar{Z}_A^{n_0} + N_{offset} \right) - N_1 (\rho_m - n_1 \bar{Z}_A)
\] (2.25)

![Graph](image)

**FIG. 2.14.** \( N_v^{pre} \) residuals versus empirical \( N_{eff} \) values. Uncorrected values are shown in (a) and corrected values in (b).
where \( N_1 \) is a scaling factor. The parameter \( n_1 \) was determined solely from \( \rho_m \) and \( \bar{Z}_A \) values, independent of range data, as the slope of a linear fit of \( \rho_m \) versus \( \bar{Z}_A \). The fitting constants, \( N_1, N_o, n_o \) and \( N_{offset} \), were found through least squares fits to minimize the difference between \( N_v^{pre}(\bar{Z}_A, \rho_m) \) and the empirical values for \( N_v^{eff} \). Separate values for the five fitting parameters, \( N_0, N_1, n_0, n_1, \) and \( N_{offset} \), were found for all materials and for materials separated by category. Values for these fitting constants for all materials and for materials separated by category are listed in Table 2.1.

To assess the ability to accurately predict \( N_v^{eff} \), Fig. 2.14(b) plots the residuals \( (N_v^{pre} - N_v^{eff}) \) against the empirical \( N_v^{eff} \) values. It is evident that the density correction term reduced almost all deviations to below 10%, with a much-improved correlation coefficient of \( r = 0.998 \).

To further assess the validity of the predictive formula for \( N_v^{pre} \) with density correction, comparisons are made of residuals calculated with both empirical \( N_v^{eff} \) and predicted \( N_v^{pre} \) (found in Table 2.2). The benefits of this correction for metals are clearly visible. The change in the \( N_v^{pre} \) for conductors can reduce residuals from as high as 50% to <5% as seen for Au. Li, an alkali metal, is once again an outlier similar to the other alkali and alkaline metals as shown in Fig. 2.14(b). However, while Li has the greatest \( \chi^2 = 3 \times 10^{-5} \), it still exhibits good agreement with data and is nearly identical when using \( N_v^{eff} \) versus \( N_v^{pre} \).

Non-metals and compounds do not see as large an improvement from the density corrections, since the correction is based on metallic bonding between atoms; however, they also do not exhibit large changes in range residuals and \( N_v^{pre} \) still remains within ~10% of \( N_v^{eff} \).

### 2.2.10 Estimation of Energy Gaps

In order to perform range calculations, a value for the electron band gap is needed for each material. However, the band gap is a more difficult parameter to determine than the stoichiometry or \( \rho_m \); this is

<table>
<thead>
<tr>
<th>Materials</th>
<th>( N_0 )</th>
<th>( n_o )</th>
<th>( N_{offset} )</th>
<th>( N_1 )</th>
<th>( n_1 )</th>
<th>( \chi^2_{Nv} )</th>
<th>( r_{Nv} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Materials</td>
<td>6.910</td>
<td>0.240</td>
<td>7.373</td>
<td>0.202</td>
<td>0.144</td>
<td>1.492</td>
<td>0.988</td>
</tr>
<tr>
<td>Insulators</td>
<td>8.625</td>
<td>0.212</td>
<td>13.83</td>
<td>0.188</td>
<td>0.144</td>
<td>0.861</td>
<td>0.986</td>
</tr>
<tr>
<td>Conductors</td>
<td>7.361</td>
<td>0.236</td>
<td>8.200</td>
<td>0.207</td>
<td>0.144</td>
<td>0.251</td>
<td>0.948</td>
</tr>
<tr>
<td>Semiconductors</td>
<td>5.202</td>
<td>0.289</td>
<td>5.176</td>
<td>0.268</td>
<td>0.144</td>
<td>0.109</td>
<td>0.997</td>
</tr>
</tbody>
</table>
especially true for some insulators, liquids and gases, and compounds, polymers and composites. Band gaps for conductors and conductive alloys can be set to zero, with $E$ determined by the effective plasmon energy, $E_p^{\text{eff}}$. Band gaps for many semiconductors and some insulators are readily available in the tabulated database (Wilson et al., 2018) but others are difficult to obtain.

Figure 2.15 shows the results of a study of the effect of changing the band gap on the predicted range. For a large band gap insulator Al$_2$O$_3$ ($E_{\text{gap}}=8.5$ eV), even ±30\% (±2.6 eV) variations in band gap energy change $N_V^{\text{eff}} \lesssim 10\%$ and $\chi^2 \lesssim 15\%$. Similar results for variations in band gap energies were found for many other materials, including Al, Sr, Au, Ac, and polyimide (Starley et al., 2016). It is important to notice that the relationship between $N_V^{\text{eff}}$ and $\chi^2$ is not linear outside of small changes in $E_{\text{gap}}$ where $|\text{Percent Change in } E_{\text{gap}}| \lesssim 20\%$.

Given the insensitivity to variations in band gap energies, other methods can be used to adequately estimate the appropriate energy gap for use with the predictive range formula. Optical absorption and reflection spectroscopy, photoemission spectroscopy, and thermal activation energies in electrical conductivity are common experimental methods to determine energy gaps (Costner et al., 2009). For some materials with band gaps in the visible range or lower, $E_{\text{gap}}$ might be estimated sufficiently well based solely of the color of the material. For example, Kapton will have a yellow/orange cutoff energy in the range of 2.1 eV, close the actual value of 2.32 eV.

As an example, optical absorption edges measured with VUV absorbance spectroscopy—which were correlated closely with the ionization energy in the study—were measured for a series of linear and

<table>
<thead>
<tr>
<th>Material</th>
<th>$N_v^{\text{eff}}$</th>
<th>$N_v^{\text{pre}}$</th>
<th>$\chi^2$</th>
<th>$\chi^2$</th>
<th>% change in $N_v$</th>
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</thead>
<tbody>
<tr>
<td>Au</td>
<td>10.814</td>
<td>5.8 x 10^{-8}</td>
<td>10.798</td>
<td>5.8 x 10^{-8}</td>
<td>-0.2</td>
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<td>Si</td>
<td>5.493</td>
<td>1.2 x 10^{-7}</td>
<td>5.607</td>
<td>2.2 x 10^{-7}</td>
<td>2.1</td>
</tr>
<tr>
<td>Al</td>
<td>5.195</td>
<td>7.4 x 10^{-8}</td>
<td>5.273</td>
<td>1.2 x 10^{-7}</td>
<td>1.5</td>
</tr>
<tr>
<td>SiO$_2$</td>
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<td>6.1 x 10^{-8}</td>
<td>4.472</td>
<td>5.6 x 10^{-7}</td>
<td>-5.2</td>
</tr>
<tr>
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<td>9.8 x 10^{-7}</td>
<td>-8.7</td>
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<tr>
<td>Li</td>
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<td>1.1 x 10^{-5}</td>
<td>1.608</td>
<td>3.2 x 10^{-5}</td>
<td>36.4</td>
</tr>
</tbody>
</table>
cyclic alkane molecules (Ueno, 2012). These energy gaps were then used to calculate the range for these materials, most of which lacked data in the NIST databases.

For other materials—including gases, liquids, and highly disordered solids—for which band gap is not a well-defined concept, the highest occupied molecular orbital-to-lowest unoccupied molecular orbital (HOMO-LUMO) gap, $E_{\text{HL}}$, can provide a reasonable surrogate for the band gap in solids (Ueno, 2012). We propose a potential connection to the range for $\bar{E}$ by adding $E_{\text{HL}}$ to the geometric mean of the effective plasmon energy and the band gap energy as

$$\bar{E} = 2.8 \left( \left( E_p^{\text{eff}} \right)^2 + \left( E_{\text{gap}} \right)^2 + (E_{\text{HL}})^2 \right)^{1/2}. \quad (2.26)$$

There are many calculations of the $E_{\text{HL}}$ (often referred to as the Kohn-Sham band gap) in the literature, many of which are calculated using density function theory (Ueno, 2012). Alternately, $E_{\text{HL}}$ for reasonably complex molecular or polymeric materials and compounds can be calculated using available quantum chemistry computational packages such as Gaussian (Frisch et al., 2004).

FIG. 2.15. Effect of band gap on the predicted range for alumina Al$_2$O$_3$. The fractional change in the band gap ($E_{\text{gap}}$=8.5 eV) versus the fractional change in $N_{\text{eff}}$ ($\bullet$) and the fractional change in fitting error ($\ast$,$\circ$).
Estimates of the appropriate energy gaps for composite materials and complex biological materials listed in the NIST databases (e.g., brain tissue and cortical bone tissue) are obviously much more difficult and ill-defined. For these materials, fits to NIST database values have been used to empirically determine $N_v^{eff}$, which in turn can lead to estimates of an effective energy gap. Values for 15 materials are shown in Table 2.3.

2.2.11 Range in Multilayer Dielectrics

Knowing the range of electrons becomes especially critical when dealing with multilayer materials, where the incident energy will determine where and in what layer charge and energy are deposited. Since the electron range is dependent on the incident beam energy, for subsequent layers, the beam energy must be scaled to account for the energy lost in any proceeding layers. To scale the energy, we can assume a constant energy loss as is done in the CLA. Thus, the energy can be calculated for the second layer by subtracting out the energy of the first layer which can be found by taking subtracting out the ratio of the thickness of the first layer to the total calculated range for an electron passing through the first layer assuming infinite thickness. The energy is thus calculated as,

$$E_{Layer2}(E_b) = E_b \left(1 - \frac{d_{Layer1}}{R_{Layer1}(E_b)}\right); \ d_{layer1} < R_{Layer1}$$

where $E_{Layer2}$ is the energy of electron entering the second layer, $d_{Layer1}$ is the thickness of the first layer and $R_{Layer1}(E_b)$ is the range in the first layer as a function of the beam energy. The range for the second layer is then given by $R_{Layer2}(E_{Layer2})$. For a third layer we can once again scale the energy and calculate the range. Thus, the incident electron energy for the third layer is given by

$$E_{Layer3}(E_b) = E_{Layer2} \left(1 - \frac{d_{Layer2}}{R_{Layer2}(E_{Layer2})}\right); \ d_{layer2} < R_{Layer2}$$

where $E_{Layer3}$ is the energy of electron entering the third layer, $d_{Layer2}$ is the thickness of the second layer and the electron range is given by $R_{Layer3}(E_{Layer3})$. A comparison of Ag in three different layer configurations is given in Fig. 2.16. A range graph for the separate layers in a multilayer material consisting of 120 nm if SiO$_2$, 220 nm of Ag and a 1 cm thick SiO$_2$ substrate is shown in Fig. 2.17.
TABLE 2.3. Material data for PEEK, normal and partially deuterated polyimide, PMMA, and tin-rich ITO where $E_{\text{gap}}$ is the band gap. The table also includes pentane, hexane, heptane, octane and decane where $E_{\text{HL}}$, the HOMO/LUMO gap, is used. Different structures can lead to different densities as shown by the various forms of boron nitride. Aluminum nitride is also included.

<table>
<thead>
<tr>
<th>Material</th>
<th>Formula</th>
<th>$Z_A$</th>
<th>$\rho_M$ (g/cm$^3$)</th>
<th>$\bar{\rho}_M$ (amu)</th>
<th>$N_V^{\text{eff}}$</th>
<th>$E_{\text{gap}}$</th>
<th>$E_{\text{HL}}$ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PEEK</td>
<td>$C_{21}H_{18}O_3$</td>
<td>4.00</td>
<td>1.32</td>
<td>7.58</td>
<td>1.09</td>
<td>3.1</td>
<td></td>
</tr>
<tr>
<td>PI (Kapton)</td>
<td>$C_{22}H_{10}N_2O_5$</td>
<td>5.01</td>
<td>1.42</td>
<td>9.77</td>
<td>1.51</td>
<td>2.32</td>
<td></td>
</tr>
<tr>
<td>Deuterated PI</td>
<td>$C_{22}H_{10}D_2N_2O_5$</td>
<td>5.03</td>
<td>1.42</td>
<td>9.93</td>
<td>1.09</td>
<td>2.32</td>
<td></td>
</tr>
<tr>
<td>PMMA (Lucite)</td>
<td>$C_6H_8O_2$</td>
<td>3.82</td>
<td>1.19</td>
<td>7.15</td>
<td>0.96</td>
<td>3.7</td>
<td></td>
</tr>
<tr>
<td>Tin-Rich ITO</td>
<td>$(In_2O_3)<em>{0.904}(SnO_2)</em>{0.096}$</td>
<td>24.17</td>
<td>6.80</td>
<td>55.02</td>
<td>1.09</td>
<td>4.11</td>
<td></td>
</tr>
<tr>
<td>Pentane</td>
<td>$C_5H_{12}$</td>
<td>2.47</td>
<td>0.63</td>
<td>4.24</td>
<td>0.33</td>
<td>7.18</td>
<td></td>
</tr>
<tr>
<td>Hexane</td>
<td>$C_6H_{14}$</td>
<td>2.50</td>
<td>0.66</td>
<td>4.31</td>
<td>0.34</td>
<td>7.14</td>
<td></td>
</tr>
<tr>
<td>Heptane</td>
<td>$C_7H_{16}$</td>
<td>2.52</td>
<td>0.68</td>
<td>4.36</td>
<td>0.36</td>
<td>7.09</td>
<td></td>
</tr>
<tr>
<td>Octane</td>
<td>$C_8H_{18}$</td>
<td>2.54</td>
<td>0.70</td>
<td>4.40</td>
<td>0.36</td>
<td>7.06</td>
<td></td>
</tr>
<tr>
<td>Decane</td>
<td>$C_{10}H_{22}$</td>
<td>2.56</td>
<td>0.73</td>
<td>4.45</td>
<td>0.38</td>
<td>7.05</td>
<td></td>
</tr>
<tr>
<td>Boron Nitride (Cubic)</td>
<td>BN</td>
<td>6</td>
<td>3.45</td>
<td>12.41</td>
<td>1.64</td>
<td>6.2</td>
<td></td>
</tr>
<tr>
<td>Boron Nitride (Hexagonal)</td>
<td>BN</td>
<td>6</td>
<td>2.1</td>
<td>12.41</td>
<td>1.80</td>
<td>5.2</td>
<td></td>
</tr>
<tr>
<td>Boron Nitride (Wurtzite)</td>
<td>BN</td>
<td>6</td>
<td>3.49</td>
<td>12.41</td>
<td>1.64</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Boron Nitride (Amorphous)</td>
<td>BN</td>
<td>6</td>
<td>2.28</td>
<td>12.41</td>
<td>1.77</td>
<td>5.05</td>
<td></td>
</tr>
<tr>
<td>Aluminum Nitride (Wurtzite)</td>
<td>AlN</td>
<td>10</td>
<td>3.26</td>
<td>20.50</td>
<td>2.78</td>
<td>6.02</td>
<td></td>
</tr>
</tbody>
</table>
FIG. 2.16. Estimated range for three layers of Ag. The flat regions are when the beam penetrates that layer.

FIG. 2.17. Estimated range for a multilayer dielectric with 120 nm of SiO$_2$, 220 nm of Ag and a 6250 µm SiO$_2$ substrate. The flat regions are due to the beam penetrating that layer.
2.3 Electron Yield

The total electron yield, defined as the ratio of emitted to incident flux, is fundamental in understanding the charging of materials (Hoffmann, 2010). The emitted electrons are further defined by their origin, where backscattered electrons originate from the beam and secondary electrons originate from within the material. The secondary electrons can again be further broken down into their source of production, either from excitations due to electrons from the incident beam (SE₁), or from excitations due to backscattered electrons which are exiting the material in a near surface region after being backscattered by an elastic collision (SE₂). These several distinctions are shown in Fig. 2.18.

While some of these distinctions are often ignored in order to simplify measurements or calculations, certain situations require that these distinctions remain intact. For the multilayer yields, these distinctions are especially important, largely due to the enhancement of the yield from backscattered electrons.

2.3.1 Probability of Secondary Electron Excitation

As considered in the earlier discussion on the range, when incident energetic electrons impinge on a sample, they impart kinetic energy to the sample. This energy transfer is characterized by the stopping power of the material which can approximate the number of excited electrons generated in the material in a distance $dz$ by

$$n_e(z, E) = -\frac{1}{E} S(E) P_{SE}(E, z)$$

(2.29)

where $E$ is the mean ionization energy required to generate potential secondaries and $P_{SE}(E, z)$ is the probability distribution of a secondary being generated at a depth $z$. As in the range discussion, the stopping power can be approximated as a constant ratio, the constant loss approximation (CLA). In Section 2.2 the range was broken it up into several energy regimes. For the yield, however, the CLA approximation over the entire path length is used given by,

$$S_{CLA}(E_b) = -\frac{dE}{dz} = -\frac{E_b}{\bar{r}(E_b)}$$

(2.30)

This gives an approximation for the number of potential secondaries within $dz$.\"
The probability of a secondary being generated includes two probability distributions: the first is the probability that the incident electron will travel a distance \( z \) within the material before undergoing an inelastic collision and the second is the probability that this inelastic collision will excite a secondary electron that then exits the material. Thus, the intersection of these two distributions is given by

\[
P_{SE}(E, z) = P_{E\text{inel}}(E_b, z) = P_{IC}(E_b, z)P_{E\text{el}}(z)
\]  

where

\[
n_e(z, E) = \frac{1}{E_R(E_b)} P_{SE}(E, z). \tag{2.31}
\]
where $P_{IC}(z)$, the probability to travel a distance $z$, and $P_{ES|IC}(z)$ is the probability of electron excitation and escape. The probability that an incident electron of energy $E_b$ travels a distance $z$ before having a collision is given in terms of the IMFP at $E_b$, $\lambda_{IMFP}(E_b)$ by

$$ P_{IC}(E_b, z) = e^{-\frac{z}{\lambda_{IMFP}(E_b)}}. \quad (2.33) $$

For energies above the mean ionization energy, $E_b > \bar{E}$, the probability that at least one electron is excited can be approximated as a constant, $\Sigma_{SE}$. To better approximate the yield at lower energies, a more accurate approximation is needed, such as an energy-dependent probability distribution function related to the Fermi-Dirac distribution. See for example the classic text by Pines (Pines, 1999) or the NIST Electron Inelastic-Mean-Free-Path database (Tanuma et al., 1993) along with other IMFP references cited in this dissertation (Tanuma et al., 2005a; 2005b, 1997; Rundgren, 1999; Jablonski and Powell, 1999; Ashley et al., 1978; Chen et al., 1992; Emfientzoglou et al., 2017; Kanter, 1970).

Once an electron is excited from an atom, there is a finite probability that the electron will traverse through the material and reach the surface. If the electron has enough energy to exceed the work function of the surface, then the electron can be emitted as a secondary electron. Taking the geometry into account gives an expression for the probability of escape given that an inelastic collision has already occurred as,

$$ P_{ES|IC}(z) = \gamma_D \cdot \Sigma_{SB} \cdot e^{-\frac{z}{\lambda_{SB}}} \cdot \cos(\theta) \quad (2.34) $$

where $\Sigma_{SB}$ is the probability of overcoming the surface barrier, $\lambda_{SE}$ is the mean free path of secondary electrons, $\gamma_D$ is a unitless factor that accounts for the geometry of the excitation, and $\theta$ is the internal trajectory angle of the potential secondary electron relative to the surface normal. In the 1D scattering case at normal incidence, the electron is either going toward or away from the surface giving $\theta = 0$ and $\gamma_D \rightarrow \gamma_{1D} = 1/2$, since trajectory toward and away from the surface are equally likely (Lundgreen and Dennison, 2020). A 3D model for isotropic emission from a 2D surface by normally incident electrons finds a geometry factor of $\gamma_D \rightarrow \gamma_{3D} \approx 1/3$ with $\gamma_{3D}/\gamma_{2D} \approx 2/3$ (Christensen, 2017; Lundgreen et al., 2021). As expected, allowing SEs to travel in non-normal directions results in a decrease in probability of reaching the surface with a concomitant decrease in $\delta_{max}$ and $E_{max}$ but no substantial change in the reduced yield curves (i.e., no substantial change in $n$ and $m$).
The effects of surface geometry on $\Sigma_{SB}$ are discussed by Nickels (Nickels, et al., 2000). For the simplest 1D model with normal incidence, $\Sigma_{SB}$ is unity above internal electron energies at the surface above the work function $\Phi$ and zero below

$$\Sigma_{SB}^{1D}(E) = H(E - \Phi)$$ (2.35)

where $H(E)$ is a Heaviside step function. A more common model sets $\Sigma_{SB}$ equal to a constant between zero and unity, independent of $E$. Nickles evaluated $\Sigma_{SB}^{1D}(E)$ for isotropic SE emission from the source of the SE generation, which results in a Lambertian (cosine) angular distribution of a SE from a 2D surface and leads to a modest reduction in $\Sigma_{SB}$ for unbiased surfaces (Nickels, 2000) and a more complex behavior for positively and negatively based surfaces (Christensen, 2017). These results are consistent with a voltage-dependent barrier potential model reminiscent of the standard Fresnel equations for optical transmission of light with a complex index of refraction; this was developed by Oliphant and Dennison (2006) using the standard SE emission energy spectrum model (Chung and Everhart, 1974) as extended by Chung (1975). $\Sigma_{SB}$ can also be used to model changes in SEY due to surface roughness and contamination (Lundgreen and Dennison, 2020).

The combined probability of an incident electron traveling a distance $z$, that a SE is generated, and that the SE traverses the material and escapes the surface is given by,

$$P_{ESMC}(E_b, z) = \gamma D \cdot \Sigma_{SB} \cdot \Sigma_{SE} \cdot e^{-z} \cdot e^{-\frac{z}{\lambda_{IMFP}(E_b)}}$$ (2.36)

where $\Sigma_{SE}$ is the probability of electron excitation. Combining these probabilities together and assuming the 1D case allows us to integrate from 0 to $R(E_b)$ giving,

$$\delta (E_b) = \frac{\Sigma_{SE} \Sigma_{SB}}{\gamma_{1D} E} \cdot \frac{E_b}{R(E_b)} \int_{0}^{R(E_b)} \frac{e^{-z} \cdot e^{-\frac{z}{\lambda_{IMFP}(E_b)}}}{\lambda_{IMFP}(E_b) + \lambda_{SE}} dz$$ (2.37)

$$\delta (E_b) = \frac{\Sigma_{SE} \Sigma_{SB}}{\gamma_{1D} E} \cdot \frac{E_b}{R(E_b)} \left[ \lambda_{IMFP}(E_b) \frac{\lambda_{SE}}{\lambda_{IMFP}(E_b) + \lambda_{SE}} \right]$$ (2.38)

$$\delta (E_b) = \frac{\Sigma_{SE} \Sigma_{SB}}{\gamma_{1D} E} \cdot \frac{E_b \lambda_{SE}}{R(E_b) \lambda_{IMFP}(E_b) + \lambda_{SE}} \left[ 1 - e^{-\frac{R(E_b)}{\lambda_{SE}} \left( \frac{\lambda_{SE}}{\lambda_{IMFP}(E_b)} + 1 \right)} \right]$$ (2.39)
\[
\frac{\sum SE \sum SB E_b}{\gamma_{1D} E \cdot R(E_b)} \frac{\lambda_{SE}}{R(E_b)} \left(1 - e^{-\frac{R(E_b)}{\lambda_{IMFP}(E_b)}}\right)
\]

(2.40)

where \(\frac{\lambda_{IMFP}(E_b)}{\lambda_{IMFP}(E_b) + \lambda_{SE}} \approx 1\) for \(\lambda_{IMFP}(E_b) \gg \lambda_{SE}\). Equivalently, Eq. (2.40) is valid for the limit \(E_b > \bar{E} > E_{SE}\), where the average energy of potential SE inside the material \(E_{SE}\) is almost as < 10eV.

2.3.2 Power Law Yield Model

In order to develop an approximate solution for the yield, the inelastic mean free path and the range both need to be approximated. Because the energies being considered are in the range from ~10 eV to >10 keV, the extension of the IMFP directly to the range is not adequate. Two different approaches can be taken to accommodate these energy ranges. The first approach is to include the full IMFP and range model with a correction to account for elastic scattering, which acts to reduce the range especially for lower energies. The second approach is to use two different power laws for the range and the IMFP which allows this correction to be accomplished in the fitting parameters used for the two power laws. Using the second approach, the values found for the power laws should be close to those found in the range model; however, there will be some discrepancy to account for the elastic correction mentioned. We propose two power laws,

\[ R(E) = b_R E^n_R, \quad (2.41) \]

\[ \lambda_{IMFP}(E) = b_{IMFP} E^{n_{IMFP}}. \quad (2.42) \]

It is important to note that the \(n_R\) in Eq. 2.41 is identical to the \(n_R\) in Eq. 2.16. Similarly, \(n_{IMFP}\) in Eq. 2.42 is identical to \(n_{IMFP}\) in 2.15. However, the approximation that \(n_R = n_IMFP + 1\) suggested in Section 2.2.5 is no longer valid as this section for yield models now includes energies covering low, mid and high energies where the approximation made in Section 2.2.5 is only valid for high energies. In order to conform to previous work done by the USU MPG, a change of variable will be used where \(n = n_R\), and \(m = n_{IMFP}\). It is, however, important to remember the origination of these parameters.

Inserting the power laws from Eq. 2.41 and 2.42 into the full yield expression from Eq. 2.39 or the approximate yield expression from Eq. 2.40 gives the full power law (FPL) model.
\[
\delta(E_b) = C_{SE} E_b^{1-n} \left( 1 - e^{-b_{IMFP} E_b^{n-m}} \right)
\]

where the constants can be grouped to give the simplified form,

\[
\delta(E_b) = C_{SE} E_b^{1-n} \left( 1 - e^{-b_1 E_b^{n-m}} \right),
\]

\[
C_{SE} \equiv \frac{\Sigma_{SE} \lambda_{SE} \lambda_{SE}'}{Y_{1D} b_R E} \left( \frac{b_{IMFP} E_b^m}{b_{IMFP} E_b^m + \lambda_{SE}} \right) = \frac{\Sigma_{SE} \lambda_{SE} \lambda_{SE}'}{Y_{1D} B_1 E} \left( \frac{E_b^m}{E_b^m + B_2/B_1} \right) \approx \frac{\Sigma_{SE} \lambda_{SE} \lambda_{SE}'}{Y_{1D} B_1 E}
\]

\[
B_1 \equiv \frac{b_R}{\lambda_{SE}},
\]

\[
B_2 \equiv \frac{b_R}{b_{IMFP}}
\]

where \(B_1/B_2 = b_{IMFP}/\lambda_{SE}\). Another form that this equation can take can be found by first defining the yield as a function relative to the energy at the maximum yield as,

\[
\delta \left( \frac{E_b}{E_{max}} \right) = C_{SE} \left( \frac{E_b}{E_{max}} \right)^{1-n} \left( 1 - e^{-b_1 E_b^{n-m}} \right),
\]

\[
c_{max} \equiv C_{SE} (E_{max})^{n-1},
\]

\[
B_{1_{max}} \equiv B_1 E_{max}^n,
\]

\[
B_{2_{max}} \equiv B_2 E_{max}^{n-m}.
\]

The yield at \(E_b = E_{max}\) is then given by

\[
\delta_{max} = c_{max} (1 - e^{-B_{1_{max}} - B_{2_{max}}} = c_{max} \left( 1 - e^{-B_{1_{max}} - B_{2_{max}} - B_{2_{max}}} \right).
\]

To determine \(B_{1_{max}}\) and \(B_{2_{max}}\) we can take the derivative of Eq. 2.44 and evaluate it at \(E_b = E_{max}\) where the slope of the yield is 0. This gives,

\[
-(1 - n)(e^{B_{1_{max}} + B_{2_{max}}} - 1) = nB_{1_{max}} + (n - m)B_{2_{max}}.
\]

If we set \(B_2 \gg B_1\) (or equivalently \(\lambda_{SE} \gg b_{IMFP} = \lambda_{IMFP} E^{-m}\)) then this equation becomes
$B_{1\text{max}} = -\frac{1-n}{n}(e^{B_{1\text{max}}}-1) = -C_n(e^{B_{2\text{max}}}-1)$  

(2.54)

where solutions are given in terms of the Lambert W function, $W_k(x)$ as,

$$B_{1\text{max}} = -W_{-1}\left(\frac{1-n}{n}e^\frac{1-n}{n} + \frac{1-n}{n}\right)$$

(2.55)

$$= -W_{-1}(C_ne^{cn}) + C_n,$$

(2.56)

If we instead set $B_1 \gg B_2$ (or equivalently $\lambda_{SE} \ll B_{\text{IMFP}} = \lambda_{\text{IMFP}}(E)E^{-m}$) these equations become

$$B_{2\text{max}} = -\frac{1-n}{n-m}(e^{B_{2\text{max}}}-1) = -C_{nm}(e^{B_{2\text{max}}}-1)$$  

(2.57)

$$B_{2\text{max}} = -W_{-1}\left(\frac{1-n}{n-m}e^{\frac{1-n}{n-m}} + \frac{1-n}{n-m}\right)$$

(2.58)

$$= -W_{-1}(C_{nm}e^{cn}) + C_{nm},$$

(2.59)

These two scenarios give for the reduced yield,

$$\frac{\delta_1(E_b)}{\delta_{1\text{max}}} = \frac{1}{(1-e^{-B_{1\text{max}}})}\left(\frac{E_b}{E_{\text{max}}}\right)^{1-n}\left(1-e^{-B_{1\text{max}}(\frac{E_b}{E_{\text{max}}})^n}\right)$$

(2.60)

$$\frac{\delta_2(E_b)}{\delta_{2\text{max}}} = \frac{1}{(1-e^{-B_{2\text{max}}})}\left(\frac{E_b}{E_{\text{max}}}\right)^{1-n}\left(1-e^{-B_{2\text{max}}(\frac{E_b}{E_{\text{max}}})^{-m}}\right)$$

(2.61)

These two equations define the reduced yield for the reduced power law (RPL) model and the extended reduced power law (ERPL) model previously developed by USU’s MPG. We can infer the reduced form for the full reduced power law (FRPL) model from the form of these equations as given by Eq. 2.5, however, we cannot deduce the coefficients of the FRPL using those in the ERPL and RPL.

$$\frac{\delta_c(E_b)}{\delta_{\text{max}}} = \frac{1}{1-e^{-B_{1\text{max}}-B_{2\text{max}}}}\left(\frac{E_b}{E_{\text{max}}}\right)^{1-n}\left(1-e^{-B_{1\text{max}}(\frac{E_b}{E_{\text{max}}})^n-B_{2\text{max}}(\frac{E_b}{E_{\text{max}}})^{-m}}\right)$$

(2.62)

$$= \left[1-e^{-B_{2\text{max}}(1+\frac{B_{1\text{max}}}{B_{2\text{max}}})}\right]^{-1}\left(\frac{E_b}{E_{\text{max}}}\right)^{1-n}\left(1-e^{-B_{2\text{max}}(\frac{E_b}{E_{\text{max}}})^{-m}}(1+\frac{B_{1\text{max}}}{B_{2\text{max}}})\right)$$
The reason why direct correlation between the coefficients does not work is due to the coupling between \( B_{1,4,5,6} \) and \( B_{7,5,6} \). In order to demonstrate the differences between these solutions, HOPG yield was fit with both the RPL, ERPL and FRPL. The FRPL model is then plotted substituting in \( B_{1,4,5,6} \) and \( B_{7,5,6} \) from the fits as shown in Fig. 2.19 with the parameters shown in Table 2.4.

From these fits, it is clear that while the high energy portion of the FRPL model fits nicely with the data, as do the other two models, the low energy yield drastically overshoots. This shows that by simply substituting in the parameters it is essentially summing the two fits. If instead the FRPL model is fit to the data and then the RPL and the ERPL models are plotted using the fitting parameters from the FRPL model then the two latter models undershoot the data, acting more like contributions to the yield and not as the full model as shown in Fig. 2.20.

Therefore, in order to find a solution to the FRPL model, a relationship between \( B_{1,4,5,6} \) and \( B_{7,5,6} \) must be defined. Taking the ratio of Eq 2.50 and Eq 2.51 yields:

\[
\frac{B_{1,4,5,6}}{B_{2,5,6}} = \frac{B_1 E_{\text{max}}^n}{B_2 E_{\text{max}}^{n-m}} = \frac{B_1}{B_2} E_{\text{max}}^m \equiv \gamma_{\text{max}} E_{\text{max}}^m \tag{2.63}
\]

\[
\gamma_{\text{max}} = \frac{B_1}{B_2} = \frac{b_{\text{IMFP}}}{\lambda_{\text{SE}}} = \frac{\lambda_{\text{IMFP}}(E_{\text{max}})}{\lambda_{\text{SE}}} E_{\text{max}}^{-m} \equiv \frac{\lambda_{\text{max}}}{\lambda_{\text{SE}}} \tag{2.64}
\]

from the definitions of \( B_1 \) and \( B_2 \) and evaluated at \( E_{\text{max}} \) to define \( \lambda_{\text{max}} = \lambda_{\text{IMFP}}(E_{\text{max}}) E_{\text{max}}^{-m} \). Inserting Eq. 2.63 into Eq. 2.53 gives

\[
-(1 - n)(e^{B_{2,5,6} \gamma_{\text{max}} E_{\text{max}}^{m+1}} - 1) = n B_{2,5,6} \gamma_{\text{max}} E_{\text{max}}^m + (n - m) B_{2,5,6} \tag{2.65}
\]
FIG. 2.19. HOPG yield with a fit using the dual variable \( n, m \) model. The variable \( n \) and the variable \( n, m \) models are then plotted using the fitting parameters from this fit.

FIG. 2.20. HOPG yield with fits from the reduced variable \( n \), and the reduced variable \( n,m \) models. The dual variable \( n,m \) model is then plotted using the fitting parameters from these fits.
Rearranging the equation so that it fits the form of a Lambert W function yields

\[ C_{\text{nm}} e^{C_{\text{nm}}} = e^{-B_{2\text{max}}(\gamma_{\text{max}}E_{\text{max}}^m + 1) + C_{\text{nm}}} \] (2.66)

\[ C_{\text{nm}} \equiv \frac{1 - n}{n} \left( \frac{1 + \gamma_{\text{max}}E_{\text{max}}^m}{1 - \frac{m}{n} + \gamma_{\text{max}}E_{\text{max}}^m} \right) \] (2.67)

With solutions along the -1 branch giving

\[ W_{-1}(C_{\text{nm}} e^{C_{\text{nm}}}) = -B_{2\text{max}}(\gamma_{\text{max}}E_{\text{max}}^m + 1) + C_{\text{nm}} \] (2.68)

which gives

\[ B_{2\text{max}} = \frac{1}{\gamma_{\text{max}}E_{\text{max}}^m + 1} \left[ C_{\text{nm}} - W_{-1}(C_{\text{nm}} e^{C_{\text{nm}}}) \right] \] (2.69)

and

\[ B_{1\text{max}} = B_{2\text{max}} \gamma_{\text{max}} E_{\text{max}}^m. \] (2.70)

In order to stay within the \( W_{-1} \) branch it requires that \( n > 1 \) and \( m < n \). Replacing \( B_{1\text{max}} \) in Eq. 2.62 in favor of \( \gamma_{\text{max}} \) gives,

\[ \frac{\delta_r(E_b)}{\delta_{\text{max}}} = \left[ 1 - e^{-B_{2\text{max}}(1 + \gamma_{\text{max}}E_{\text{max}}^m)} \right]^{-1} \left( \frac{E_b}{E_{\text{max}}} \right)^{1-n} \left( 1 \right) \]

\[ -e^{-B_{2\text{max}}(\frac{E_b}{E_{\text{max}}})^{n-m}(1 + \gamma_{\text{max}}E_{\text{max}}^m e^{m E_b})} \] (2.71)

The largest change in the fitting parameters between the ERPL and RFPL models, as shown in Table 1, is the value of \( m \). The ERPL model has a significantly lower \( m \) value than the RFPL model. However, because we have a physical tie to the value of \( m \), as the power law exponent to a power law fit of the IMFP, we can compare these \( m \) values to other IMFP data.

The resulting power laws from the FRPL is shown in Fig. 2.21. As seen in the figure, the power law for \( m=0.866 \) fits the data for the majority of the graph while the power law with \( m=0.60 \) fits only the lower energy data. This comparison allows approximations for both models by fitting the IMFP at different energy ranges. This figure also shows the power law fit for the energy range which matches up extremely well using
the n value found in all three models. From the figures presented, the most accurate prediction of the yield results from fitting the electron range and the IMFP over the full energy range and then using those values in the FRPL model.

2.3.3 Secondary Electron Yield of Multilayer Dielectrics

The secondary electron yield (SEY) of multilayer materials is largely determined by three key factors, the secondary yield of the surface material, the range of the excited secondary electrons in the material and the backscatter coefficients of each material.

This is seen in the approximation for the total electron yield for contamination layers proposed by Davies, Dennison and Chang (Davies and Dennison, 1997; Chang et al., 2000) where the time evolution of the total electron yield for a bulk layer and a surface contamination layer for a given incident electron energy is given by

\[
\delta_{tot}(t) = \delta_R e^{-\Delta \sigma t} + \delta_S (1 - e^{-\Delta \sigma t})
\] (2.72)

FIG. 2.21. Power law fits to the Range and IMFP formulas for HOPG.
where \( \delta_R \) is the SEY of the bulk material, \( \delta_S \) is the SEY of the surface material and \( \Delta \) is the time constant for the growth rate of the contamination layer. Thus, given that the contamination layer thickness grows at a rate of \( d = \Delta \cdot t \), the conversion from time dependence to depth dependence can be made by substituting \( d \) for \( \gamma \cdot t \). Because of the dependence on the electron range, this approximation will not take effect until the range of the beam is greater than the thickness of the top layer.

Once the beam can penetrate the top layer, the range of the secondary electrons must also be greater than the thickness of the top layer for them to traverse the top layer and escape. Since secondary electrons have energies \(< 50\) eV and are typically peaked at 2-5 eV, this value, \( R_{\text{max}}(E_{SE}) \), can be considered a constant and approximated as the maximum of the range of the secondaries. Thus, our equation becomes

\[
\delta_{\text{tot}}(E_B, d) = \begin{cases} 
\delta_S & ; \ R_{\text{max}}(E_{SE}) < d \\
\delta_S & ; \ R(E_B) < d \\
\delta_R(E_B) e^{-d} + \delta_S(E_B)(1 - e^{-d}) & ; \ \text{otherwise}
\end{cases}
\] (2.73)

For SiO\(_2\), looking at a graph for the range as seen in Fig. 3.20, any top layer that is thicker than \(~30\) nm is thicker than the maximum range of secondary electrons and therefore, the range is driven by the surface layer. For any layer that is thinner than \(~30\) nm, any electron beam that is \(< 900\) eV is non-penetrating, and thus the yield will also be driven by the surface layer.

This approximation can be improved on by taking into account the secondary electrons produced by backscattered electrons which can have a significant impact on the number of emitted secondary electrons (Thomas and Pattinson, 1970). To distinguish between the different types of produced secondaries, secondaries produced from the primary beam are notated as SE\(_1\), and secondaries produced from backscattered electrons are notated as SE\(_2\). Because of the nature of secondary electron emission and its dependence on surface potential, surface roughness, and attenuation length, the secondaries produced in the first few nanometers of the material will almost entirely drive secondary emission. Because of this, the effects of multilayer materials on the yield is driven by an increase or decrease in secondaries produced by backscattered electrons which produce SE\(_2\) as they traverse the surface layer after backscatter (Thomas and Pattinson, 1970).

Therefore, the secondary yield can only be affected by underlying layers when the energy of the primary electrons is sufficient to penetrate the surface layer nearly twice over, once to penetrate to the
underlying layer, backscatter, then travel back to within $R_{\text{max}}(E_{SE})$ of the surface where $SE_2$ can escape. This can be modeled by modifying the yield with an energy dependent step function which accounts for the change in secondary yield due to these backscattered electrons. Using Eq. 2.16, this gives,

$$\delta_{ML}(E_b, E_{\text{layer}}) = \left[ \frac{C_{SE}}{1 + e^{E_b - E_{ML} / E_b}} E_b^{1-n} + \frac{C_{ML}}{1 + e^{E_{ML} - E_b / E_{ML}}} E_b^{1-n_{ML}} \right] \left[ 1 - e^{-B_1 E_b^{-n} - B_2 E_b^{-n-m}} \right]$$  (2.74)

where $n, m, B_1, B_2$ and $C_{SE}$ are the fitting parameters for the surface layer and $C_{ML}$ and $n_{ML}$ are the fitting parameters for the combined multilayer system which includes $SE_2$ driven by backscattered electrons from the underlying layers and $E_{ML}$ is the energy required for the incident electrons to have a range twice that of the surface layer. It is important to note here that the terms in the second bracket do not include a contribution from the multilayer system, this is because this term only modifies the low energy yield where $E_b \ll E_{ML}$.

2.4 Material Conductivity

The conductivity of a material is a key factor in spacecraft charging. It determines how easily embedded charge can move through the material. Because insulators have low conductivity, they have the ability to acquire large, localized charges, which can exceed the strengths of the material (Andersen and Dennison, 2013). Because conductivity is also temperature dependent, it is important to know the conditions that the material will be subjected to. Radiation induced conductivity also plays a large role in the charging process as discussed below (Gillespie, 2013).

2.4.1 Dark Conductivity

The conductivity of a material determines how easily a deposited charge layer can move through the material in response to an electric field, $J(t) = \sigma(t) F(t)$; each term can be time-dependent. These electric fields, $F$, are produced by the embedded charge layers, the depletion layer, and the conductive planes in the material as modeled in Fig. 2.22. The measured currents will have two terms, a particle current conductivity proportional to the conductivity and a displacement current due to the change in the electric field due to charge accumulation.

For conditions considered here, we assume the conductivity has only two terms, the equilibrium (dark current) conductivity and radiation induced conductivity (RIC); we neglect contributions for polarization, diffusion and dispersion based on arguments related to the time dependence of these
contributions compared with our experimental times (Dennison and Sim, 2012; Hodges et al., 2012).

For low electron fluxes the conductivity, \( \sigma(t) \), is a static conductivity that approaches the equilibrium (dark current) conductivity of the material, \( \sigma_{DC} \); that is, \( \sigma_{RIC} \ll \sigma_{DC} \). For fused silica the equilibrium conductivity at room temperature is \( \sigma_{DC} = 1.5 \cdot 10^{-19} \text{ (}\Omega\text{-cm)}^{-1} \) (Culler and Rexford, 1965; Dennison et al., 2014).

2.4.2 Radiation Induced Conductivity

Radiation Induced Conductivity (RIC) is the enhanced conductivity that results from the energy deposited in the irradiated volume. For low fluxes RIC can be neglected. For high fluxes, however, RIC must be considered in regions where the incident beam penetrates. RIC is a function of the dose rate, \( \dot{D} \), which is the power deposited by incident radiation per unit mass (Dennison et al., 2009):

\[
\sigma_{RIC}(D) = k_{RIC} D^{\Delta_{RIC}}.
\] (2.75)

The dose rate in a homogeneous material is inversely proportional to the volume in which radiation energy is deposited under the linear energy transfer (LET) approximation; this volume is approximately equal to the beam cross sectional area times the range \( R \) (Roth et al., 2009). Therefore,

\[
\dot{D}(E_b) \equiv \frac{\partial D}{\partial t} \approx \frac{E_b J_b}{\rho_m R(E_b) q_e}.
\] (2.76)
where $J_b$ is the incident beam current density and $\rho_m$ is the mass density. The dose rates for disordered SiO$_2$ and Ag as a function of incident energy are shown in Fig. 2.23. RIC is expressed in terms of the dose rate as a power law with $\frac{1}{2} < \Delta_{RIC} < 1$ (Dennison et al., 2009). Figure 2.24 shows the RIC for SiO$_2$ as a function of incident energy for values of $\Delta_{RIC}$ spanning the expected range. For low $T$, $\Delta_{RIC} \to 1$ and for most materials $\Delta_{RIC}$ remains near unity for acceptable temperature ranges.

Notice that both $\dot{D}$ and $\sigma_{RIC}$ exhibit energy dependent maxima as a consequence of the minimum in the range expression. For fused silica $\Delta_{RIC} \approx 1$ and $k_{RIC} \approx 1.7 \cdot 10^{-16}$ (Ω·cm-rad/s)$^{-1}$ at room temperature (Culler and Rexford, 1965). For the multilayer charging tests, $\sigma_{RIC}$ is approximately $1 \cdot 10^{-10}$ (Ω·cm)$^{-1}$ at $J_b = 20$ nA/cm$^2$ and $1 \cdot 10^{-12}$ (Ω·cm)$^{-1}$ at $J_b = 2$ nA/cm$^2$, respectively. Because these conductivity values are relatively high, the charged bodies will reach equilibrium in the RIC region on smaller time scales than can be measured in the multilayer measurements described in Section 3.3.

FIG. 2.23. The dose rate as a function of energy in the LET approximation for Ag and disordered SiO$_2$. Notice the maximum in the dose rate at ~100 eV due to the minimum in the range.
2.4.1 Material Conductivity in Multilayer Dielectric

The conductivity of multilayered materials is dependent upon the individual layer conductivity as well as the layer configuration. For a material consisting of two materials as shown in Fig. 2.25, the total conductivity and resistivity of the material is given by

\[
\frac{1}{\sigma_{\text{tot}}} = \frac{1}{\sigma_1} + \frac{1}{\sigma_2} = \rho_1 + \rho_2 = \rho_{\text{tot}}
\]

(2.77)

where \(\sigma_{1,2}\) are the conductivities and \(\rho_{1,2}\) are the resistivities of the first and second layer respectively with the total resistance given by

\[
R_{\text{tot}} = R_1 + R_2 = \frac{\rho_1 l_1 + \rho_2 l_2}{A}
\]

(2.78)

where \(l_{1,2}\) is the thickness of layer 1 and 2 respectively and \(A\) is the cross sectional area. Since the charge layers are often not at the surface, such as an embedded charge from an electron beam, then the length \(l\) becomes \(l - R(E_b)\) for a delta layer charge layer deposited at a depth equal to the beam range. Thus, for an embedded charge layer in the top layer at a distance \(R(E_b)\) the extrinsic total resistance is given by
In many cases a conductive layer is placed in between two dielectrics. In this scenario, if there exists an ungrounded conductive layer between the two layers, the conductive layer acts as a direct connection between the two layers like a wire in a two resistor series circuit and makes no change to the total resistance. It may however, change the depth at which the electron beam penetrates.

2.5 Radiation Dose

The amount of power deposited in the material is proportional to the dose rate. To calculate the deposited power Eq. 2.76 is simply multiplied by the amount of material radiated. For a non-penetrating beam the deposited power is linearly proportional to the beam energy. Once the beam penetrates, the power deposited is proportional to the beam energy times the ratio of the thickness of the material to the electron range. Thus the deposited power is calculated by

\[
R_{tot} = \frac{\rho_1(l_1 - R(E_b)) + \rho_2 l_2}{A}
\]  (2.79)

FIG. 2.25. The total conductivity of a dual layer material is given by Eq. 2.77. The total resistance is dependent upon the layer thickness, as well as the depth at which the charge layer is deposited.
\[ P(E_b) = \begin{cases} \frac{E_b J_b A_b}{q_e} & ; R(E_b) < d \\ \frac{E_b J_b A_b}{q_e} \frac{d}{R(E_b)} & ; R(E_b) > d \end{cases} \]

where \( E_b \) is the beam energy, \( J_b \) is the beam current, \( A_b \) is the beam area, \( q_e \) is the charge of an electron, \( d \) is the thickness and \( R(E_b) \) is the energy dependent electron range. The approximated deposited power for 120 nm layer of SiO\(_2\) with \( J_b = 10 \) na/cm\(^2\) and \( A_b = 4.9 \) cm\(^2\) is shown in Fig. 2.26. Notice the linear behavior up until \(-2000\) eV, at which point, there is a reversal and the deposited power becomes inversely proportional to the range.

To calculate the deposited power for multiple layers we multiply Eq. 2.80 by the amount of material radiated and, for subsequent layers, replace \( E_b \) with the energy at which the electrons enter that particular layer as is done for the multilayer range calculations. Thus, the deposited power for the first three layers can be calculated as the following using the LET approximation.

For the first layer, the equation is the same as the power deposited for a single layer given by

\[ P_{Layer1}(E_b) = \begin{cases} \frac{E_b J_b A_b}{q_e} & ; R_{Layer1}(E_b) < d_{Layer1} \\ \frac{E_b J_b A_b}{q_e} \frac{d_{Layer1}}{R_{Layer1}(E_b)} & ; R_{Layer1}(E_b) > d_{Layer1} \end{cases} \]

where \( d_{Layer1} \) is the thickness of the first layer and \( R_{Layer1}(E_b) \) is the range in the first layer as a function of the beam energy. For the second layer, the energy must be scaled as the energy at which the electrons enter the second layer as is done in the range. Thus, using the scaled energy in the second layer, the deposited power is given by

\[ P_{Layer2}(E_{Layer2}) = \begin{cases} 0 & ; R_{Layer1}(E_{Layer1}) < d_{Layer1} \\ \frac{E_{Layer2} J_b A_b}{q_e} & ; R_{Layer2}(E_{Layer2}) < d_{Layer2} \\ \frac{E_{Layer2} J_b A_b}{q_e} \frac{d_{Layer2}}{R_{Layer2}(E_{Layer2})} & ; R_{Layer2}(E_{Layer2}) > d_{Layer2} \end{cases} \]

where \( E_{Layer2} \) is the energy of electron entering the second layer, \( d_{Layer2} \) is the thickness of the second layer and \( R_{Layer2}(E_{Layer2}) \) is the range in the second layer as a function of \( E_{Layer2} \). Finally, for the third layer, using the scaled energy for the incident electron in the third layer becomes
where once again $E_{Layer3}$ is the energy of the electrons entering the third layer, $d_{Layer3}$ is the thickness of the third layer and $R_{Layer3}(E_{Layer3})$ is the range in the third layer as a function of $E_{Layer3}$. Subsequent layers can be similarly calculated. Figure 2.26 shows the deposited power for our multilayered samples as a function of incident energy with 120 nm of SiO$_2$, 220 nm of Ag and a 6250 µm SiO$_2$ substrate with $J_b = 10$ nA/cm$^2$ and $A_b = 4.9$ cm$^2$.

2.6 Charging Models

Because there are numerous multilayer configurations it is useful to group them into two different scenarios which drives the physics of the system. These two scenarios include net negative surface potentials and net positive surface potentials. The surface potential will drive the processes that occur near the surface.
as well as thin surface layers. Because there can be much more complicated internal charging scenarios for multiple layer materials, such situations would need to be studied on a case by case basis. For the set of research in this dissertation, the two scenarios outlined below will be sufficient.

2.6.1 Net Negative Surface Potentials

When the total yield is less than unity, meaning that more electrons are injected into the material than are emitted from the surface, charging is negative. When this occurs, a small positive surface layer is created due to the deficit of electrons emitted near the surface while a larger deep negative layer is created in the material which produces an overall net negative surface potential as shown in Fig. 2.27.

2.6.2 Net Positive Surface Potentials

When the total yield exceeds unity, meaning more electrons are emitted than are injected, the material’s surface becomes positively charged due to a deficit of electrons. When this occurs a positive charge layer is created near the surface due the deficit of electrons caused by secondary electron emission as shown in Fig. 2.28.

2.6.3 Limiting Behaviors

As the net surface potential reaches a potential of a few volts positive, some secondary electrons are re-attracted to the surface or prevented from escaping which then can recombine with electron holes. This re-attraction effectively creates an upper limit on the net surface potential in the positive net surface potential

![Diagram](image.png)

FIG. 2.27 Net negative surface potentials occur with electron yields less than 1 when more electrons are injected than are emitted from the material. The red plus signs indicate electron holes and the blue circles represent electrons. The big negative signs represent the negative surface potential.
charging regime where the number of emitted electrons equals the number of injected electrons as shown in Fig. 2.29.

2.6.4 Internal Charge Evolution

The internal charge evolution is driven by the charge in versus charge out, where the charge in is dependent on the incident electron flux and energy and the net surface potential and the charge out is dependent on secondary electron yield and conduction. Because conduction is dependent on the electric field as well as the net surface potential, a time dependent model of the electric field must be used. To do this, the electric field is expressed using the double layer dynamic model (DLDM) from which the electric potential is calculated. There are then several corrections added to account for the time changing electron yield, charge movement through the material and change in the shape of the charge distribution.

FIG. 2.28 Diagram showing net positive limiting regime due to secondary electron reattraction. The arrows indicate reattraction of secondary electrons which establish a limit on the net surface potential to about 10 eV at which point almost all secondaries are reattracted.
The time rate of change in the electric field and the geometry of the system is then used to calculate the time rate of change of the net surface potential. Extending Walden’s work (Walden, 1972) with electrode injection currents to beam injection currents, the net surface potential as a function of time can then be calculated. For a detailed explanation of this model and process see (Hodges, 2012).

We begin with a list of assumptions that must be made in order to make the following calculations. These assumptions are the following:

1. A parallel plate geometry with a dielectric material above a grounded electrode, where the lateral extent of the layers is much larger than the thickness so edge effects and fringing fields can be neglected. This leads to a 1D model of electric transport.

2. The incident (or injected) charge carriers are electrons, with charge per electron \( q_e < 0 \). All charge transport mechanisms considered are only for electron transport. More complex models, not addressed here, allow for mobile recombination sites (holes) and for ionic conduction.

3. Beam charge injected as nonpenetrating radiation with charge and energy deposited in a depth range \( 0 < R < D \) with no biased electrode. The layer in which the charge is deposited is dependent upon the incident electron energy as contained in the range. The layer in which the electrons penetrate will be assumed under the specific experimental configuration.

4. The incident beam current, \( J_b \), is considered constant with all of the beam charge being trapped. Secondary electron emission will be considered separately and will act to modify this incoming current. This corresponds to an exponent of 1 in Walden’s Eq. 6 (Walden, 1972). The incident current is then either calculated as a pulsed square wave described as

\[
J_b(t) = \begin{cases} 
J_b & \text{if Beam On} \\
0 & \text{if Beam off}
\end{cases}
\]  

(2.84)

or attenuated to account for the duty cycle of the beam giving \( \overline{J_b} = J_b \frac{t_{on}}{t_{dep}} \) where \( t_{on} \) is the pulse time of the beam and \( t_{dep} \) is the total time for a complete cycle.

5. The time dependence of the yield for the positive scenarios is due to the reattraction of secondary electrons as the net surface potential becomes positive. As shown by Hoffmann, the energy spectrum of secondary electrons as shown in Fig. 2.30(a) is given by
where \( k_{PE} \) is a materials constant that defines the energy peak emission, \( E_b \) is the incident beam energy and \( \chi \) is the insulator electron affinity or band gap energy plus sample bias for a conductor. The number of electrons below a given energy can be found by integrating Eq. 2.85 giving

\[
N = \int_{0}^{E} \frac{k_{PE} E'}{E_b (E' + \chi)^3} dE' = \frac{k_{PE} E^2(E + 3\chi)}{6E_b \chi^2(E + \chi)^3}
\]  

For a given surface potential \( V_s(t) \), the fraction of electrons reattracted to the surface can be given by the number of electrons with energy below \( V_s(t)q_e \). Thus, the fraction of secondary electrons reattracted to the surface is given by

\[
\frac{N_{reat}}{N_{sec}} = \frac{(V_s(t)q_e)^2(V_s(t)q_e + 3\chi)}{(V_s(t)q_e + \chi)^3}
\]

and the fraction of secondary electrons which are emitted and contribute to the yield is then given by

\[
\frac{N_{emit}}{N_{sec}} = 1 - \frac{(V_s(t)q_e)^2(V_s(t)q_e + 3\chi)}{(V_s(t)q_e + \chi)^3} = \frac{\chi^2[3V_s(t)q_e + \chi]}{[V_s(t)q_e + \chi]^3}
\]

Thus, the time-dependent yield can be expressed as

**FIG. 2.30.** (a) Model of the secondary electron energy spectrum [after Hoffmann, 2010]. (b) 1-Y as a function of the net surface potential with an initial yield of 1.8.
\[ Y(E_b, t) = Y_0(E_b) \frac{x^2[3V_s(t)q_e + \chi]}{[V_s(t)q_e + \chi]^3} \]  

(2.89)

and \(1 - Y(E_b, t)\), as shown in Fig. 2.30(b), as

\[ 1 - Y(E_b, t) = 1 - Y_0(E_b) \frac{x^2[3V_s(t)q_e + \chi]}{[V_s(t)q_e + \chi]^3}. \]

(2.90)

6. For the negative scenario, the time rate of change of the yield is due to the retardation of the beam due to the net surface potential. This leads to the yield as a function of beam energy minus the surface potential times the charge of an electron

\[ 1 - Y(E_b; t) = 1 - Y(E_b - V_s(t)q_e). \]

(2.91)

As shown by Hodges (2012), this can be approximated by the following,

\[ 1 - Y(E_b; t) = (1 - Y_0)e^{-\frac{V_s(t)}{V_{SE}}} \]

(2.92)

where \(V_{SE}\) is a charging constant.

It is also hypothesized that RIC allows negative charges to migrate to the surface which increases the probability of an electron being able to be ejected from the surface as a secondary electron. This increase of the yield may explain the charging behavior in Section 4.2.4.

7. The conductivity has several assumptions based upon the experimental setup.

a. The polarization term, \(\sigma_{pol}(t)\), can be neglected. For most polymeric insulators (including LDPE and Kapton HN\textsuperscript{TM}), the polarization time constant, \(\tau_{pol}<10\) s, is shorter than the time before the first surface voltage measurement for experiments considered here (typically \(\gtrsim 100\) s). Higher frequency ac conductivity is also neglected in all cases for the pulsed injection.

b. The measurements described in this thesis do not extend to times greater than the transit time, \(\tau_{transit}\), which is the time for charge to move through the entire volume of the sample. Hence, the transition from \(\sigma_{dispersive}\) to \(\sigma_{transit}\) can typically be neglected, except as specifically noted. Since the experiments typically run for durations \(t_{max}<\tau_{transit}\), the conductivity does not reach equilibrium at \(\sigma_{dc}\), but rather approaches quasi-equilibrium at \(\sigma_{0} > \sigma_{dc}\).
c. Time-averaged RIC during charging is approximately \( \langle \sigma_{RIC}(t; \mathcal{D}, \tau_{RIC}^1, \tau_{RIC}^2) \rangle_t = \sigma_{RIC}^0(\mathcal{D}) \) (Gillespie, 2013). The beam pulse and repetition rates used are such that lower \( \sigma_{RIC}(t) \) due to the rise time governed by \( \tau_{RIC}^1 \) is approximately compensated for by the persistent RIC governed by \( \tau_{RIC}^2 \) after the beam is turned off. This leads to a redistribution of charge above the penetration depth giving a uniform distribution from \( R(E_b) \) to the surface with the center of charge located at \( R(E_b)/2 \). Charge movement below \( R(E_b) \) is unaffected. The 5 keV scenarios produce a beam which penetrates to the silver electrode causing RIC to govern the conductivity of the top layer. This allows electrons from the grounded silver electrode to travel to the surface and recombine with the charge depletion layer caused by the emission of secondaries. More details of this situation are discussed in Sections 4.2.3 and 4.2.4.

8. The total current, \( J_{total}(t) = q_e \frac{d\rho(t)}{dt} = \frac{d\rho(t)}{dt} \), is then given by the summation of all the currents into and out of the material where \( q_e < 0 \) is the charge of an electron. These currents included the injected current which consists of the incident beam current, the secondary electron emission, and the charge transport current which accounts for the charges moving through the material towards the grounded backplane. The total current thus takes the form for positive charging

\[
J_{total}(t) = J_{inf}(t) + J_{trans}(t) = \int_0^b \left[ 1 - V_s(E_b) - \frac{1}{2} Y_0(E_b) \frac{3V_s(t)\rho_e + \chi}{[V_s(t)\rho_e + \chi]^3} \right] - \frac{\sigma_{down} V_s(t) A}{(d-R(E_b))} \tag{2.93}
\]

where \( \sigma_{down} \) is the conductivity of the sample, \( A \) is the area of the sample, \( d \) is the distance from the surface to the grounded plane (material thickness) and \( R(E_b) \) is the range of the incident electron beam.

Similarly, for the negative charging scenarios the injected current becomes

\[
J_{total}(t) = \int_0^b (1 - V_s(t) - \frac{1}{2} Y_0(E_b)) e^{-\frac{V_s(t)}{\sqrt{2}e}} + \frac{\sigma_{down} V_s(t) A}{(d-R(E_b))} \tag{2.94}
\]

While Walden’s work uses current dependent on the electric field, the time dependence of the injection current can be fully contained in the time dependence of the surface potential \( V_s(t) \). We can thus extend Walden’s work with electrode injection currents to beam injection currents by extending his equations to use the net surface potential instead of the electric field (Walden, 1972)

9. The electrode current is computed by assuming a capacitor model with a displacement current in parallel with a resistor with conductance \( \sigma_{down} \). Thus the electrode current takes the form
\[ J_{\text{electrode}}(t) = J_{\text{disp}}(t) + J_{\text{trans}}(t). \]  

The displacement current arises due to the time rate of change in the electric field which can be related to the time rate of change of the net surface potential given by

\[ J_{\text{disp}}(t) = \varepsilon_0 \varepsilon_r A \frac{\partial F(t)}{\partial t} = C \frac{\partial V(t)}{\partial t} = \frac{\varepsilon_0 \varepsilon_r A}{(d - R(E_b))} \frac{\partial V(t)}{\partial t} \]

where \( C \) is the capacitance of the system. Thus, the displacement current is due to charge that develops on the metal insulator interface in response to electric fields created by charge deposited in the insulator from an incident beam that acts to cancel out the electric fields within the conductor. Because the deposited charge migrates through the material which in turn changes the electric fields in the material, the displacement current changes with respect to the change in the electric field which can be related to the net surface potential, hence Eq. 2.96.
CHAPTER 3
EXPERIMENTAL DETAILS

The purpose of this chapter is to describe space environment simulations, experimental instrumentation, multilayer samples, and the analysis of the multilayer charging data. At the end the chapter is the experimental test matrix with the applicable experimental conditions.

3.1 Laboratory Simulations of the Space Environment

In order to create and validate models with which the effect of the space environment on dielectrics can be predicted, ground-based testing must be employed. The USU Materials Physics Group has designed and constructed several ultrahigh vacuum (UHV) \((10^{-7} \text{ to } 10^{-9} \text{ torr})\) systems in which spacecraft simulations can be conducted involving electrostatic breakdown, material conductivity and resistivity, electron induced cathodoluminescence, radiation induced conductivity, and electron beam charging. Using these systems, we can effectively simulate numerous space-like scenarios and employ numerous procedures and apparatus to measure the respective needed quantities to validate proposed models as well as determine sample characteristics.

Because the space environment is diverse and dependent upon location and time, it is important to determine which space environment is valid for the specific application. Since our studies are dependent upon electron energies and fluxes, it is important to have a model by which one can predict these values. Once the average electron energies and fluxes are known, different space weather scenarios can be simulated in a ground-based facility. For the experiments considered here, the target space environment was the L2 environment, which is appropriate for many missions most notably for the James Webb Space Telescope (JWST). Figure 3.1 shows the electron flux versus the electron energy for the L2 environment. It is clear from this graph that the L2 environment is dominated by electron energies \(\leq 30\) keV. These electrons are responsible for most surface charging effects (Frominckx and Sojka, 1992; Hastings and Garrett, 1996). Even though fluxes of higher energy electrons are reduced by more than four orders of magnitude, they are largely responsible for significant effects such as deep dielectric charging, single event interrupts, and
radiation damage (Holmes-Siedle and Adams, 2002). The experiments presented here focus on energies $\lesssim 30$ keV, although many of the models and processes could be extended to higher energies.

Two other factors that need to be precisely controlled are the vacuum pressure and the temperature. The vacuum of space is typically $<10^{-7}$ Pa, but can be $>10^{-3}$ Pa in local space environments due to outgassing or mass ejection. Pressure variations have significant impact on contamination rates, susceptibility to arcing, and thermal transport. Temperature has far more drastic variations which can range from 20 K to 350 K depending on which side of the spacecraft is being illuminated by the Sun and whether or not solar shielding is being used (Hastings and Garrett, 1996; Donegan et al., 2010). It is therefore important to take these variables into consideration for the models as well as the testing apparatus when running ground-based simulations.

![FIG. 3.1. Integrated flux density vs Energy for the electron flux in the L2 environment. The left light blue region describes electrons with energies which are deposited in 0.1 to 0.2 um Ag coating. The red region describes charge deposited in 0.03 to 0.05 um SiOx coating. The right green region describes charge deposited in 0.03 to 0.05 um SiOx coating.](image)
3.2 Multilayer Yield Measurements

Because the secondary electron yield drives the charging processes for surface charging, several experiments were performed to characterize the yield for several multilayer materials. The data were then fit using the models from Section 2.3.3. Because the effects of multilayers are only seen for thin surface layers, two sets of dual-layer materials were prepared with a thin surface layer on a thick substrate. In order to ensure that no charging was occurring so as to study the fundamental processes, two conductive materials were chosen, gold, and carbon. The first sample set consisted of thin layers of free-standing graphitic amorphous carbon films (Stoner, 2018) adhered to smooth, high-purity gold foil substrates. The second sample set consisted of various thickness of Au, sputter deposited on atomically smooth highly ordered pyrolytic graphite (HOPG) substrates. Diagrams of these two sample configurations are shown in Fig. 3.2.

3.2.1 Instrumentation

In order to measure the secondary electron yield, a hemispherical grid retarding field analyzer (HGRFA) was employed in USU MPG’s Electron Emission Test (EET) chamber in the Space Environment Effects Materials (SEEM) facility. This chamber consists of a vacuum chamber with working pressures of \( \sim 1 \times 10^{-7} \) to \( 5 \times 10^{-9} \) Torr, two electron guns to give a total energy range of 20 eV to 30,000 eV, an ion gun, heaters and cryostat refrigerator, a carousel sample holder and various sensors. The electron guns include a low-current Staib Instruments (Model EK-5-S) electron gun with an energy range of 20 eV to 5 keV and a high energy Kimball (Model EGPS-21B) electron gun with an energy range of 5 keV to 30 keV. Both of

![Diagram of sample configurations](image)

FIG. 3.2. Simple diagrams of the two material sample sets. The first sample set consisted of thin layers of amorphous carbon films adhered to thick gold substrates. The second sample set consisted of thin layers of gold sputter coated on thick highly ordered pyrolytic graphite substrates.
these electron guns were used in the multilayer yield experiments in order to fulfill the energy requirements. The yield was measured using the HGRFA for both energy ranges and the results were combined during analysis.

The HGRFA consists of several hemispherical wire mesh grids along with a carbon coated aluminum hemisphere as shown in Fig. 3.3. Incident electrons enter through the drift tube (T) and hit the sample (J). Secondary and backscattered electron currents are measured by the Collector (Q), as well as the Bias and Inner Grid (R,S). The two nearly concentric wire grid hemispheres (S,R) allow the energy of the emitted electrons to be measured by biasing the Bias grid to the discriminating energy. All electrons with energies less than the bias will be deflected back to the inner grid (S) and the stage (U). The inner grid is held at zero potential to ensure incident electrons are not deflected by the bias grid and the collector is held at +50 V relative to the bias grid to ensure that any secondaries generated at the collector are reattributed to the collector. These different biases increase the accuracy of the device and also allow the energy discrimination of the emitted electrons which is vital for secondary and backscattered measurements. The full details of the HGRFA, its operation, and use is described by Christensen (2017).

FIG. 3.3. Hemispherical-grid retarding-field analyzer.
3.2.2 Sample Preparation

In order to prepare the two sets of material samples, careful consideration to repeatability and uniformity was considered. Because of the high sensitivity of the electron yield to surface roughness, contamination, surface layer thickness, annealing, etc., this section will describe in detail the sample preparation for the two sets of samples.

3.2.2.1 Carbon Foils on Au Substrates

To make the Au substrates, 4N, 250 µm (0.01”) thick Au foil was punched out using a 10 mm diameter punch as shown in Fig. 3.4. The Au samples were then put in a beaker of acetone and put in an ultrasonic cleaner for 20 minutes. Once finished, they were removed with tweezers and immediately rinsed off with methanol and then immediately dried using a fast stream of dry nitrogen gas. Because the hole punch adds concavity to the foil samples, they were mounted with the concave side facing out on 10 mm diameter copper slugs (used in the carousel sample blocks) as shown in Fig. 3.5. The reason for the concave side facing up is due to the convex side tended to have scratch marks due to the ultrasonic cleaner but the concave side remained largely scratch free.

The next step is coating each Au substrate with carbon foil. The carbon foils were purchased from ACF Metals (Stoner, 2018) with thicknesses ranging from 0.1 µg/cm² to 50 µg/cm² as shown in Fig. 3.6.

FIG. 3.4. Punched Au foil using a 10 mm punch.
These foils come on microscope slides in order to aid in their application. To begin with their application to the Au foils mounted on the copper slugs a pan of distilled water was heated to 30 C° as shown in Fig. 3.7. One of the important aspects of this setup is the large open area so that the Au samples could be slowly lowered into one end of the water while the carbon foil floated undisturbed on the other end. In order to apply the carbon foils, however, the carbon foil needs to be cut and floated on the water.

To cut the carbon foils, the glass slides were taped down using double sided tape as shown in Fig. 3.8. For the very thin carbon foils, they were very difficult to see which makes it imperative that care was taken when following these steps. First, a metal ruler was firmly mounted above the glass slide to act as a...
glide that could be moved to different positions. It is important that this ruler does not touch the top of the slide or it could damage the carbon foil. Next, several cuts were made across the carbon foil using a razer blade and the metal ruler guide. Four were made around the perimeter and then several within the perimeter to make squares just slightly larger than the Au samples.

Next, the cut carbon foils were floated on the distilled water by carefully and slowly lowering the cover glass into the water at a 45° angle. It was important to float the samples at one end of the water so that
the samples can be lowered into the other end. Once the Au samples were gently lowered into the other end, without letting go of them, they were slowly moved under one of the carbon foils. It can be difficult to see the very thin foils so a light at an angle was helpful to see them.

The Au samples were then slowly lifted at a slight angle to coat the sample. If they are at too much of an angle the foil will move out of the way as the water moves across the Au sample; if there is not enough angle then the carbon foil can get water deposits stuck underneath it. If things are not going correctly, the Au sample can be slowly lowered back down into the water and then the process repeated.

Once the samples were coated, they were placed in a storage container and then placed into a dry nitrogen environment overnight. The following morning, they were completely dry and were directly mounted into the sample carousel and placed into the vacuum chamber. The total time that the clean Au was exposed to oxygen was only on the order of an hour. Several samples were also placed on thin microscope slides as practice as well as to perform transmission experiments to confirm their thicknesses.

3.2.2.2 Au Deposition on HOPG Substrate

The second set of samples were HOPG substrates adhered to Cu slugs with Au deposited on top. These samples were created by cutting small squares of HOPG about 1 mm thick and mounting them to 10 mm diameter Cu slugs using double sided Cu tape.

These samples were then coated with Au using an EMS-150 ES high vacuum sputter coating system with high purity Au targets in USU’s Microscopy Core Facility. This system is shown in Fig. 3.9. Several different thicknesses were made by adjusting the time of deposition.

Once the samples were coated, they were placed in a clean container and kept in a dry nitrogen environment until they were ready to be mounted on the sample carousel and placed in the chamber.

3.2.3 Experimental Procedures

In order to determine the effects of surface layer thickness on the yield, the total, secondary, and backscattered yield were measured for each sample using the HGRFA in the MPG SEEM test chamber shown in Fig. 3.10. Two different electron guns were used to obtain both high energy and low energy yield. The first step in the experimental procedure was the mounting of the samples on the rotatable sample carousel which has a capacity of nine samples. It also has a ~5 mm diameter Faraday cup to measure the incident flux.
This was useful to check that the electron gun was working along with the current measurement system. The carousel was then placed inside the chamber according to the carousel mounting procedures.

Once the chamber was pumped down and the electron gun turned on and blanked, the desired sample is aligned. For the STAIB gun, the sample can be aligned by using the light of the electron gun (if the gun is not deflected, which was done for experiments outlined in later sections). For the HEED gun, the sample was aligned by using lasers aligned to the electron gun and the adjacent port windows.

In order to measure the currents coming off the HGRFA and the sample, the currents from the collector, bias grid, and inner grid and stage are first amplified using fast response picoammeters that use optically isolated operational amplifiers (Thomson et al., 2003). The sample must be connected to one of these picoammeters by connecting the corresponding BNC from the yellow patch panel to the corresponding sample picoammeter. For the sets of testing in this research, the gain setting was set to 200 as shown in Fig. 3.11. These amplified currents are then measured using a Tektronix TDS 2014 Oscilloscope. This is a 4 channel, 100 MHz, 1 GS/s oscilloscope, used to measure the sample (white), collector (yellow), inner
grid+stage (green), and outer grid (red) currents where the colors represent the tape on the cables entering into the pico-ammeters as shown in Fig. 3.11.

It was also important that the inner grid and the stage signal currents were combined before they entered the picoameters. This was done at the breakdown box shown in Fig. 3.12(a). It was important that the proper scale setting was used on the oscilloscope to ensure maximum resolution while ensuring that measurements do not go off-scale. Because of this, it was important to take several triggers at several different energies to get the scaling correct before taking a series of yield measurements.

The biasing of the Outer Grid was done differently than it was in the past in order to fully ground the Outer Grid when the backscatter yield was not being used. This was done to reduce noise that was present with power supplies that were being used when doing secondary electron energy spectra measurements. For
these sets of experiments, the power supply was a 50 V battery power supply used to minimize the high frequency noise in the bias voltage. To switch between the biasing power supply and ground, a dual pole relay circuit was built, using two TTL signals from the DAQ card to control the switching as shown in Fig. 3.12(c). This was done to assure that the battery power supply was never directly grounded. A 487 Ω current limiting resistor was placed in series with the power supply in the chance that a user error occurs, and the batteries are directly shorted to ground.

In order to control these TTL signals, as well as the control to the STAIB electron gun, a LabView program was developed which automates the process. This program, with its front panel shown in Fig. 3.13, has the ability to manually or automatically take secondary yield data. To make pulse yield measurements, first ensure that the STAIB gun is on and properly warmed up and all settings are set to zero. Using the folder button to the right of the Yield Data Folder, select the folder where the data will be saved.
When measurements begin, two new folders in the selected directory are created named “TEY” (total electron yield) and “BSEY” (backscatter electron yield). Next, the “Project Name” and “Sample Name” text boxes are filled in. These are used to name the created the data files. The Flooding dropdown box determines if flooding will be used or not. The flood duration is set using the “Flood Duration” number box. Click the “Yield Data” drop down box to select to take total yield data, backscattered data, or both. Finally, the number of pulses per energy is set using the “Number of Pulses” check box. Currently, the “Grid Bias (V)” number box does not do anything. How pulse yield measurements are taken depend on whether automatic or manual operation is selected.

When the Operation latch is set to Automatic, pressing the “Take Pulse Data” Start button, automatically selects the first row in the “Beam Configuration” table. Then, if the computer control button is off, it will be turned on at this time. It does not matter if this is on before pressing Start or not, operation will be the same. The oscilloscope will initialize and then measurements will begin. After the measurements for
When the Operation Latch is set to manual, pressing the “Take Pulse Data” Start button, the program turns on Computer Control if it is not yet on. This sets the STAIB gun to the gun operation setting values of the boxes without changing them (ignoring the Beam Configuration table). The program will then take pulse yield measurements for one energy. When collection at this single energy is completed, the program goes back into standby mode, leaving the gun at the current settings and leaving the Computer Control on.

### 3.2.4 Analysis Methods

In order to analyze the data, the total yield and the backscattered yield data were imported into the Yield Tools procedure built by Justin Christensen in IGOR. The data were then loaded into IGOR for plotting.
The specific settings used in Christensen's Yield Tool for the analysis outlined in this section are as follows:

1. The incident charge is calculated as $Q_{inc} = Q_{sample} + Q_{coll} + Q_{grid} + Q_{stage}$
2. For TEY, the emitted charge is calculated as $Q_{emit} = Q_{coll} + Q_{grid} + Q_{stage}$
3. For BSEY the emitted charge is calculated as $Q_{emit} = Q_{coll}$
4. Once the secondary yield, backscatter and total yield are calculated, they are then loaded into another IGOR document for the curve fitting and analysis.

3.3 Multilayer Dielectric Charging Measurements

For our investigation, pulsed charging experiments were conducted using multilayered dielectric materials of an SiO$_2$-based optical coating, a conductive middle layer and an SiO$_2$ substrate in order to predict space weather effects on thin film multilayer dielectrics. In order to distinguish the effects of multiple layers, tests were made with the conductive layer both grounded and ungrounded for two beam energies which either penetrated into the top layer or penetrated into the conductive layer. To ensure that the experiments could be extended to space like environments they were conducted in the main USU electron emission ultrahigh vacuum test chamber (Chang et al., 1998), modified for observations of low intensity UV/VIS/NIR glow over a broad range of sample temperatures (Dekany et al., 2012; Evans et al., 2012). The following sections outline the sample, sample preparation, and the experimental procedure.

3.3.1 Instrumentation

To simulate the space environment the needed equipment includes an electron gun to simulate electron fluxes, an ultrahigh vacuum chamber to simulate the vacuum of space, and an apparatus to control the sample temperature. To understand the electron interaction and the temperature dependence of the materials the needed equipment includes; fast picoammeters to measure charge movement through the sample as well as image charges in response to changing electric fields, surface voltage probe to measure the net surface potential, optical equipment to look at resulting arcs and other optical events, and temperature probes to measure the sample temperature.

While the USU MPG has several ultrahigh vacuum systems as well as the remaining needed equipment to perform multilayer charging experiments, several modifications and upgrades were needed in
order to successfully fulfill the requirements of the tests. These upgrades as explained below include: light shielding for the electron gun to remove stray light from the electron gun’s filament, calibration of the electron gun with a 1” beam diameter target, modification of the sample block holders to accommodate multilayer materials, sample voltage probe modifications to increase sample viewing angle, upgrading the LabView interfacing for the surface voltage probe (SVP) to perform real-time drift correction, and calibration and IGOR scripting to graph and analyze the acquired data.

This consists of a UHV chamber with a controllable vacuum (<10^{-10} to 10^{-3} Torr), two electron sources—a low energy source (STAIB, Model NEK-050-SP) and a high energy source (Kimball, Model EGPS-21B), a sample carousel for sample mounting which is also equipped with a Faraday cup as well as several apparatus for characterization measurements. This allows for diverse space environments to be simulated and for precise measurements to be made in real-time. Much of the system is automated by LabView programs which are interfaced with the various instruments. The key instrumentation used for these sets of measurements is the HGRFA (Hoffmann and Dennison, 2010; Christensen, 2017).

The system used for these studies as shown in Fig. 3.14 is similar to that discussed in Section 3.2.1, with several modifications required for these sets of measurements. The first of these modifications was the reconfiguration of the electron source to reduce stray light produced by the filament. In order to see arc signatures on and near the samples with the video imaging devices, the light in the chamber needed to be

![Fig. 3.14](image-url)
reduced. The light coming from the hot tungsten electron gun filament as well as the resulting light on the sample is shown in Fig. 3.15. In order to reduce this light, the electron gun was angled to the side and an aperture was made and mounted in the chamber.

The electron beam was then deflected using the gun’s built in deflection controls. The aperture has a main body, as shown in Fig. 3.16(b), with a large aperture and a removable faceplate, as show in Fig. 3.16(a), to reduce the aperture as well as add linear translation perpendicular to the beam. Both the main body and the faceplate were then coated in Aquadag™, a colloidal graphite coating, to reduce reflection. The assembled aperture was then mounted inside the chamber on the same port as the electron gun as shown in Fig. 3.16(d) with set screws that press against the port walls.

To angle the electron gun so that the light cone from the filament would be blocked was done by an adjustable angled adapter as shown in Fig. 3.17 which could be deflected up to ~5°. The electron gun was limited, however, by how far it could be angled due to the tip of the gun hitting the inside of the chamber wall; this gave ~3.4° deflection as shown in Fig. 3.18. The electron gun also had limitations on how far it could bend the electron beam; thus, the optimal angle of deflection had to be calculated in order to fully aperture the light beam but still have enough control to fully deflect the beam as shown in Fig. 3.18. The port was then extended which allowed the light beam to be fully blocked while still being able to deflect the electron beam through the aperture.

FIG. 3.15. Light from the electron gun needed to be redirected off the sample via an adjustable angle adapter. (a) The light coming out of the tip of the electron gun produced by the filament. (b) The resulting light projected onto the sample from the filament of the electron gun.
The second modification that needed to be made was to the sample blocks. Initially the sample blocks were designed to hold a ½” diameter sample with a single electrode at the back of the sample. The new samples were 1” in diameter as shown and needed to have the option of connecting to the back of the sample as well as a conductive middle layer. To accomplish this, 1” diameter Cu pedestals were made, and the samples were connected to the Cu pedestals with Cu double-sided conductive adhesive tape as shown in Fig. 3.19(a). New sample blocks were then made with a 1” diameter opening for the sample which then held the Cu pedestals with insulating standoffs as shown in Fig. 3.19(b,c,d) so that the Cu pedestal was electrically isolated in order to measure the current on the back of the sample. Adjustable spring-loaded screws on the bottom of the sample block then allow an electrical connection to the Cu pedestal. One of the screws was then backed off slightly so that it was electrically isolated from the Cu pedestal and a wire was used to attach

![Images of sample blocks and Cu pedestals](image-url)

FIG. 3.16. Light aperture coated with Aquadag to reduce light from the electron gun filament from reaching the sample side of the chamber. (a) shows the removable aperture covers which can be linearly translated on the main body aperture. (b) is the main aperture body which mounts inside the chamber. (c) shows the main body aperture with the adjustable aperture. (d) shows the full assembled aperture mounted inside the chamber as viewed from the outside.
the screw to the conductive middle layer of the sample as shown in Fig. 3.19(c). This allowed two leads to be connected to the back of the sample and a second electrode where applicable. The sample block was then mounted onto the sample carousel and electrical connections were made as explained by Hoffmann (Hoffmann, 2010). Attachment of a liquid nitrogen reservoir allowed for sample cooling.

To monitor the temperature, thermocouples were connected to a multiplexor which was then routed to a GPIB based DAQ interface controlled by a LabView™ program. This allowed the continuous measurement of the temperature block, the chamber, and the room temperature. During these tests, imaging instruments were also used to help detect arcing events. Two cameras and two fiber optic spectrometers were used to monitor low light intensity and rapid flashes associated with arcs. Though not the focus of this dissertation, detailed studies of the optical signatures of cathodeluminescence and arcing were conducted; these results are reported elsewhere (Dekany et al., 2012; Evans et al., 2012).

3.3.1.1 Characterization of Electron Sources

The samples were subjected to short pulses ($t_{on}=15$ s) of electron bombardment using a low energy electron gun [Staib, EK-5-S1], that delivers a well-characterized, low-flux pulsed beam (typically ~50 pA/cm$^2$ to 1 μA/cm$^2$) over an energy range of 20 eV to 5 keV. Beam fluxes were monitored with a Faraday cup with beam current densities of 20±1 nA/cm$^2$ at 200 eV and 2.7±1 nA/cm$^2$ at 5 keV with an exposed

FIG. 3.17. The STAIB electron gun mounted on the chamber with the axial translator. (a) The axial translator which allowed the gun to be tilted up to 5 degrees from the perpendicular but the chamber had a limitation on how much the gun could be tilted before it hit the chamber wall as shown in (b).
sample area of 4.9±0.2 cm². Two energies were used for these experiments, one which embedded charge in the first layer and one which embedded charge in the second layer.

Given that the thickness of the first SiO₂ layer was approximately 0.120 µm, the first beam energy chosen was 200 eV since the range is approximately 0.003 µm for a 200 eV beam in SiO₂ as shown in Fig. 3.20. The second beam energy chosen was 5000 eV in order to fully penetrate the SiO₂ layer and embed into the middle conductive layer. An incident 5000 eV electron will lose ~3700 eV in the SiO₂ layer, which leaves ~1300 eV to embed ~0.124 µm into the Ag layer as shown by the range of Ag in Fig. 3.21. The deposited power for our sample configuration and a 1 nA/cm² beam is shown in Fig. 3.22. Notice that no power is deposited in the Ag conducting layer until a beam energy of ~2200 eV is reached, which is the point at which electrons fully penetrate the top layer.

FIG. 3.18 CAD drawing of the STAIB electron gun mounted on the chamber with the axial translator. (a) Top down horizontal cut of the chamber showing the light path vs the electron path. (b) The geometry of the projected light beam versus the electron beam.
Using these energies, electron gun settings needed to be found in order to produce a 1" diameter spot. Since the electron gun was made for a small (~1 mm) collimated beam, settings from previous experiments could not be used (see Hoffmann, 2010). To determine the largest beam size available, a series of beam profiles were taken using a Faraday cup which was mounted on a Cu pedestal on the sample block. Using an automated LabVIEW™ routine in the IESD LabVIEW™ program, the Faraday Cup was vertically translated across the beam as data were acquired using the GPIB interfacing and a data acquisition (DAQ) card (National Instruments, Model BNC2110) under LabVIEW™ control.

Using this method, beam profiles were taken at various focus settings as seen in Fig. 3.23. Data from these plots were then plotted as seen in Fig. 3.24 to help determine the optimal focus setting for a given beam energy to produce the largest beam spot diameter at full width half max (FWHM) to fully illuminate the
FIG. 3.20. Electron range approximation for SiO$_2$ (Wilson and Dennison, 2012). The penetration depth for 200 eV electrons is ~0.003 µm with yield of ~4 and ~0.12 µm for 2200 eV electrons with yield of ~0.9.

FIG. 3.21. Electron range approximation for Ag (Wilson and Dennison, 2012). For 5000 eV electrons ~3700 eV is lost in 0.12 µm insulating cover layers, thus ~1300 eV electrons embed ~0.124 µm into the Ag layer.
sample with as much uniformity as possible. The defocused electron beam produced a beam profile at the sample with about ±30% uniformity over an ~3 cm diameter beam spot. The resulting focus settings chosen were 0.3 for a 200 eV beam and 0.96 for a 5 keV beam as shown in Fig. 3.24.

3.3.1.2 Surface Voltage Measurements

To measure the net surface potential, a high impedance, non-contact electrostatic voltage probe was employed. The surface voltage probe (SVP), built by Hodges (Hodges, 2012), allows the net surface potential to be measured between beam pulses with a range from ~1 V to ~10 kV and a resolution of ≤1.5 V. The SVP utilizes Fredrickson’s idea that a floating transfer probe can induce a surface voltage on an external witness plate that is proportional to the sample’s surface voltage, and can be easily measured with standard noncontact electrostatic field probes outside of the vacuum chamber (Fredrickson, 1979). The USU

FIG. 3.22. Deposited energy in a multilayer sample of ~0.120 µm of SiO₂, ~0.220 µm of Ag and a 6250 µm SiO₂ substrate. Notice that no energy is deposited in Ag layer until a beam energy of 2200 eV is reached.
FIG. 3.23. Electron beam profiles for the various beam energies. (a) 200 eV beam (b) 5 keV beam and chosen profiles with included tertiary and stage currents for 200 eV beam (c) and 5 keV beam (d).

FIG. 3.24. Electron beam focus settings vs beam energy to predict focus settings for higher beam energies.
MPG has developed an instrument that has a gold-plated neutral electrode, which can be moved in front of a charged sample. This internal electrode is electrically connected via a thin wire to a witness plate externally mounted to the vacuum chamber. The two electrodes and wire are highly electrically isolated so that charge neutrality can be maintained for extended periods of time.

As the internal electrode is moved in front of a charged sample, charge will polarize within the isolated plates and connecting wire as diagramed in Fig. 3.25. The charge will migrate through the probe to the internal electrode and equalize the electric field caused by the sample charge by developing an equal magnitude charge density on the internal electrode. Assuming the probe is perfectly isolated from ground, an opposite polarity charge with equal magnitude net charge of that on the internal electrode will develop on the external plate. Thus, the charge density on the external witness plate is directly proportional to that of the internal plate and the sample. This external witness plate is then measured with an electrostatic field transfer probe (EFTP) to determine the sample’s charge density.

Originally, the SVP was used in conjunction with the hemispherical grid analyzer as shown in Fig. 3.26(a). For the set of experiments reported here, imaging of the sample was required, thus, modifications to the SVP were needed in order to view the sample as seen in Fig. 3.26(b). To make the modification, an

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**FIG. 3.25.** Schematic of charge distribution for the EFTP assembly. Shown are the sample, charge transfer probe, and EFP. (Hodges, 2012)
aluminum cylinder was added to the SVP as shown in Fig. 3.26(c). The entire front side was then coated with Aquadag™ in order to reduce reflections and glare from stray light and sample glow as shown in Fig. 3.26(d).

To determine the calibration factor to convert the EFTP voltage to the sample surface, a Cu slug was placed into the sample position and raised to a known potential using a constant dc voltage source and the EFTP voltage is read. The Cu potential was then plotted against the EFTP voltage and a slope was calculated. This slope then gave the conversion factor from the read EFTP voltage to the net surface potential of the sample. This process, originally outlined by Hodges (Hodges, 2012) was automated using LabView. This allows the calibration factor to be determined quickly and efficiently. An example calibration run is shown in Fig. 3.27. Since this correction factor changes slightly over time it is important to find a correction factor at least once before a set of runs.
Once the calibration factor is known, measurements can be taken. To take a surface voltage measurement, the process consists of several steps. The first step of the measurement process is grounding the SVP over a grounded surface to ensure there is no excess charge on the two electrodes and connecting wire and to ensure a valid ground reference voltage. Once the SVP has been grounded, it is then ungrounded, and an initial ground reference voltage is taken over the grounded surface. This measurement is done by taking a set number of measurements, usually 5, and then calculating the average and standard deviation. The SVP is then moved over the sample and another reference voltage is taken by taking another set of data points, usually 20, and then taking their average and standard deviation. The SVP is moved back off the sample and over a grounded surface to take another ground reference voltage by once again taking a set of measurements, usually 5, then calculating their average and standard deviation. The SVP is then grounded and ungrounded again to remove drift and other charging artifacts which occur over long periods of time and reduce the accuracy of the measurements. A diagram of this process is shown in Fig. 3.28. The initial non-charged corrected sample reference voltage, \( V_{CSR} \), is then calculated by subtracting the mean of the ground reference voltages, acquired before and after the sample measurement, from the sample reference voltage or

\[
V_{CSR} = \text{mean}(V_{reference_{1-20}}) - \frac{\text{mean}(V_{GroundBefore_{1.5}}) + \text{mean}(V_{GroundAfter_{1.5}})}{2}
\]  

(3.1)

This process is then repeated, but with the electron gun turned on during the initial grounding phase of the cycle to irradiate the sample. The corrected sample voltage is then calculated by subtracting the mean
of the grounded reference voltages, before and after, from the sample voltage and then subtracting the non-charged sample reference. Thus

$$V_{\text{corrected}} = \left[ \text{mean}(V_{\text{probe}_{1:20}}) - \frac{\text{mean}(V_{\text{groundBefore}_{1:5}}) + \text{mean}(V_{\text{groundAfter}_{1:5}})}{2} \right] - V_{\text{CSR}} \quad (3.2)$$

This process is very similar to that developed by Hodges, with the addition of the subtraction of the $V_{\text{CSR}}$ term instead of just subtracting the first data point. The time between the pulses was limited to $t_{\text{off}} \approx 84$ s by the time required to take a surface voltage measurement. A LabView™ program was made to automate this process which takes into consideration the calibration factor as well as the corrections that need to be made due to drift as explained above. For detailed information about the SVP see (Hodges, 2012; Hodges et al., 2012).

### 3.3.1.3 Electrode Current Measurements

Electrode currents were measured during the entirety of the run from a copper electrode on the back of the mirror to ground and between the conductive layer and ground when the conductive layer was grounded. Measurements were taken using fast sensitive picoammeters with <0.2 pA resolution (Thomson et al., 2003) and recorded using GPIB interfacing and a DAQ card under LabView™ control similar to the beam profile measurement process using the LabView™ program IESBD_DC Profiler. A screenshot of this program is shown in Fig. 3.29.
Currents can either be caused by charges moving through the material to the conductive electrodes or by image charges forming on the electrodes in response to moving charges within the material known as a displacement current. Analysis of these currents and how to separate them are described in Section 3.4.2.

3.3.2 Sample Preparation

Samples (2.5 cm diameter) were prepared with thin film (≈120 nm thick) disordered SiO$_2$ (fused silica) deposited on ≈220 nm thick highly reflective, optically smooth metal (mostly Ag) layers on a 2.7 mm thick fused quartz substrate. A representative model of the sample structure is shown in Fig. 3.30. The samples were imaged, both with front lighting as in Fig. 3.31(a) and back lighting as in Fig. 3.31(b).

As seen from the back lit images, there were small defects in the conductive layers which enabled light to shine through. A closer inspection of the light spots suggested that they were diffraction limited and only on the order of ≈5 µm or less as shown in Fig. 3.32. The samples were then optically cleaned and underwent a ≈12 hr vacuum bakeout at ≈390 K and ≈1·10$^{-3}$ Pa to eliminate adsorbed water and volatile contaminate. During the bakeout, the sample was grounded to eliminate initial embedded charge. Separate samples were used for each test due to long charge dissipation times.
The samples were mounted on Cu pedestals on a multi-sample carousel and were placed in the EET ultrahigh vacuum chamber (base pressure $<1 \cdot 10^{-6}$ Pa) for >24 hrs in order to allow outgassing before measurements were made. The sample carousel was thermally anchored to (but electrically isolated from) a cryogen reservoir. In combination with resistive heaters and liquid N$_2$ cryogen, the samples were maintained over a range of temperatures from $\sim$150 K to $\sim$400 K with a long-term stability of $\pm$3 K. Measurements reported here were made at 298 K (and at 135 K as noted).

FIG. 3.30. Layering diagram of the sample with layer material and thickness.

FIG. 3.31. Optical images of the samples. (a) Front of the sample showing the beveled edge. (b) Backlit image where the holes are small holes in the silver layer on the order of $\sim$600 nm.
Fused silica is a highly resistive insulator as shown in Fig. 3.33. One aspect that also needed to be considered and which plays a big role is spacecraft charging is the temperature dependence of the resistivity. Fig. 3.34 shows the exponential like quality of the resistivity versus the temperature. The samples being tested will operate in space applications on JWST at temperatures around 30 K. At these temperatures, the insulators become near perfect charge integrators meaning that once charge is embedded, the timescales at which charge is able to move is far beyond the one hour timescale of our experiments (indeed often beyond

<table>
<thead>
<tr>
<th>Material</th>
<th>Quartz</th>
<th>Fused Silica</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>2.65</td>
<td>2.2</td>
</tr>
<tr>
<td>Melting point (°C)</td>
<td>1830</td>
<td>1830</td>
</tr>
<tr>
<td>Permittivity (ε')*</td>
<td>3.8-5.4</td>
<td>3.8</td>
</tr>
<tr>
<td>Tan (δ x 10⁴) *</td>
<td>3</td>
<td>---</td>
</tr>
<tr>
<td>Loss factor (ε'') *</td>
<td>0.0015</td>
<td>---</td>
</tr>
<tr>
<td>Dielectric field strength (MV/m) †</td>
<td>15.0-25.0</td>
<td>15.0-40.0</td>
</tr>
<tr>
<td>Resistivity (Ω-m)</td>
<td>$10^{12}$-$10^{16}$</td>
<td>$&gt;10^{18}$</td>
</tr>
</tbody>
</table>

*Dielectric properties at 1 MHz and 25 °C
† Page estimates breakdown at 180 MV/m.

FIG. 3.33. SiOₓ thin films can have substantially different electrical properties from SiO₂ materials. Since nature of doping and disordered of JWST films is not known, these properties are not well known.
the 1-3 decades intended lifetime of JWST). With this experimental setup, however, the lowest achievable temperatures with liquid nitrogen cryogens were \(~120\) K. At these temperatures, the resistivity is still large enough that bulk charge movement can be neglected.

To test the surface as well as the volumetric resistivity of our samples, Cu electrodes were placed on the surface of the sample as shown in Fig. 3.35. This allowed the resistivity to be measured across the surface as in Fig. 3.35(a), or through the volume as in Fig. 3.35(b). Results are shown in Fig. 3.36.

FIG. 3.34. Fit to the measured resistivity versus temperature data for bulk fused silica. The solid curves are based on Arrhenius fits to the valid range of temperature data. The dashed curves are extrapolations of the curves to higher and lower temperatures, down to the operating temperature of the JWST at 30 K.

FIG. 3.35. Copper tape was placed on the surface of the mirror and leads were attached to run resistivity tests. (a) Surface measurements. (b) Volume measurements.
The electron yield for bulk fused silica was also measured in order to determine surface charging and is seen to be highly dependent upon incident energy and incident charge as shown in Fig. 3.37. An energy

<table>
<thead>
<tr>
<th>Volume Resistivity (ohm-cm)</th>
<th>Absolute Uncertainty (ohm-cm)</th>
<th>Relative Uncertainty (%)</th>
<th>Surface Resistivity (ohm-sq)</th>
<th>Absolute Uncertainty (ohm-sq)</th>
<th>Relative Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>856108 SWFPANA #1</td>
<td>1.03E+11</td>
<td>± 2.40E+09</td>
<td>± 2.336</td>
<td>2.49E+11</td>
<td>± 4.63E+10</td>
</tr>
<tr>
<td>856108 SWFPANA #2</td>
<td>2.75E+10</td>
<td>± 8.30E+08</td>
<td>± 3.021</td>
<td>2.65E+11</td>
<td>± 3.38E+10</td>
</tr>
<tr>
<td>856208 POM #3</td>
<td>9.96E+10</td>
<td>± 5.05E+09</td>
<td>± 5.071</td>
<td>2.53E+11</td>
<td>± 4.28E+10</td>
</tr>
<tr>
<td>856208 POM #4</td>
<td>1.14E+11</td>
<td>± 1.62E+10</td>
<td>± 14.192</td>
<td>2.60E+11</td>
<td>± 3.24E+10</td>
</tr>
</tbody>
</table>

FIG. 3.36. Measured resistivity of the mirrors through their volume and across their surface. POM 3 and POM 4 mirrors were both used in these experiments and are representative of all samples used in these experiments.

FIG. 3.37. Total electron yield for fused silica. (a) Yield as a function of incident energy for fused silica. Dark green points show the measured total yield, including charging effects. Green curve shows the total yield determined for negligible charging (Hoffmann and Dennison, 2012). (b) Total yield of fused silica as a function of charge in the pulse used to determine the yield (Thomson, 2004; Hoffmann, 2010; Wilson and Dennison, 2012).
of 200 eV gives an electron yield >1 at ~1.1 while a 5 keV electron beam gives yields <1 at ~0.8.

3.3.3 Measurement Procedure

The samples were first prepared as explained in Section 3.3.1, imaged, and then mounted in the sample blocks. The samples were then mounted on the sample carousel and installed in the chamber. Continuity checks were then performed to validate all electrode connections. The SVP was also checked to make sure it was in proper working order. At this point all ports on the chamber were closed and the pump down process began. The electron gun filament was then warmed up and the SVP correction factor was found using the automated process explained above and in (Hodges, 2012). The Xybion video camera was then set up and the sample alignment was marked so that each sample was in the same position. The SVP was then moved over the sample to reduce unwanted charging during the electron beam characterizations.

The electron beam was then characterized, and the temperature monitoring started. A variety of visible and UV light sources were used for neutralization of negatively charged surfaces through the photoelectric effect. Often, samples were heated to ~50 °C overnight to increase conductivity and dissipate charge after a day of electron emission measurements. The samples were then either brought back to room temperature or cooled to 135 K depending on the experiment parameters. Increasing the sample temperature up to 100 °C was also used for dissipation of deep buried charge by thermally increasing the sample conductivity. The clocks on each computer were also set to synchronize the timing between the various instruments.

Immediately before each run the beam current was verified using the Faraday cup and was then internally blanked. The sample was then placed in front of the blanked beam and aligned using the Xybion camera. Each computer was then initialized, and output files names were set. The run was then started and followed the automated LabView™ routine.

Total time for each experimental run was on the order of 1 hr or until equilibrium was reached or electrostatic breakdown was observed. To confirm that near-equilibrium was achieved, a few tests on the order of a few hours were also conducted. At the end of each run, the beam was blanked, files were saved and the process of setting up another run was begun. After all the runs had taken place, the vacuum was
brought back up to atmospheric pressure and the samples were removed and post images were taken of each sample.

Four experiments are considered where each experiment differ in terms of the incident energy, flux, and temperature which produces dramatically different results for the different cases. Two experiments used low incident energy (200 eV) and two consider high incident energy (5000 eV). Two experiments had an ungrounded conducting layer and two had a grounded conducting layer. To interpret the experiments, three physical phenomena must be considered—the electron range, electron yield, and the electron transport (conductivity) of the material—and how they are affected by the experimental conditions.

3.3.4 Analysis

It is often impossible or unpractical to measure the internal charge distribution inside a dielectric directly, thus experimentally measurable quantities which can be related to the internal charge distribution are used. For the experiments discussed here, the measurable quantities are: temperature, incident beam energy, incident beam flux, electrode currents and net surface potential. The temperature, incident beam energy and incident beam flux are all experimentally controlled while the electrode currents and the net surface potential must be experimentally measured.

Once these measurements are made, they can be used in models which then predict the charge accumulation and dissipation in the material. These models use the energy dependent range to determine electron depth, and the temperature dependent conductivity of the material to determine charge dissipation. Using the geometry of the material, simple models can be constructed which roughly predict the distribution of the charges which then can predict the net surface potential. Thus, by measuring the net surface potential and the electrode currents the internal charge distribution can quickly validate the models.

To analyze the data that comes from LabView™ from each computer, it was first imported into IGOR using a fixed routine which synchronized timing between the separate instruments and plotted relevant graphs. The IGOR™ routine also applied offsets and calibration coefficients to the several instruments depending on the needed data processing. Table 3.1 shows the several detectors and the applied corrections from both the LabView™ routines as well as the IGOR™ routine. After the needed corrections are applied, further analysis as described in Chapter 4 can be applied.
TABLE 3.1. Data corrections in LabView™ and IGOR™ for each of the instruments used

<table>
<thead>
<tr>
<th>Instrument</th>
<th>LabView Corrections</th>
<th>IGOR corrections</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrometer</td>
<td>Voltage Offset applied at beginning of each run to zero the electrometer.</td>
<td>Timing Correction</td>
</tr>
<tr>
<td>Surface Voltage Probe</td>
<td>Calibration factor correction applied at beginning of each run. Offset calculated and applied at beginning of each run. Drift correction applied after every measurement.</td>
<td>None</td>
</tr>
<tr>
<td>Temperature</td>
<td>Calibration Factor</td>
<td>NA</td>
</tr>
</tbody>
</table>
CHAPTER 4
RESULTS AND ANALYSIS

This section describes the experimental results and the analysis from the four scenarios outlined in Section 2.6 using the theory developed in Chapter 2 and the analysis procedure described by Hodges (Hodges, 2012) to model the net surface potential and electrode currents. It begins with a summary of the results, then an outline for the specific analysis for each scenario, and then a presentation of the results for the corresponding scenarios.

4.1 Multilayer Yield Results

The multilayer yield results can be split into two sections, the carbon on gold and the gold on carbon. The difference between these two scenarios is largely determined by their backscatter yields where the gold has a high backscatter yield, and the carbon has a low backscatter yield. Higher backscatter yields are expected for high atomic materials such as Au (Z=79) rather than C (Z=6) (Reimer, 2000). The secondary yield measurements show either an increase or a decrease in the secondary yield near the energy that the beam can penetrate the surface layer twice (see Section 2.3.3). For the C-Au samples the secondary yield increases while with the Au-HOPG samples the secondary yield decreases. This change is attributed to the change in SE2 which is higher for Au than C. As seen from the results below, this clearly differentiates the multilayer structure as well as the thickness of the surface layer.

4.1.1 Carbon on Gold

The carbon on gold scenario involves a low-density, low-yield, low-backscatter material on top of a high-density, high-yield, high-backscatter material. According to the theory, this should result in a material that behaves like carbon at lower energies with an increase in yield for energies greater than twice the range of the carbon surface layer. The compiled results for the secondary electron yield for the carbon on gold experiments are shown in Fig. 4.1. As seen in Fig. 4.1, even for 0.5 nm thick carbon coatings, the secondary yield at low energies matches that of the thick carbon results. This shows that surface coatings, even a few atoms thick, can drive the secondary electron emission process for low energies. For incident electron energies with ranges greater than twice the surface layer thickness, there is a jump in the secondary electron yield due to an increase in backscattered electrons and thus SE2. It is important to note that the 0.5 nm and 1
nm secondary yields do not see this change in the yield until ~750 eV. This is likely due to the difference between the range and the mean penetration depth as well as the uncertainty in the thickness of the carbon films. The second feature of the secondary yield that changes is the slope at high energies. With increasing thickness of carbon, there is a decrease in the slope after the contribution of SE$_2$ electrons from the Au backscattered electrons.

A second set of data that further solidifies the theory based on SE$_2$ electrons is the backscattered yield for C on Au as shown in Fig. 4.2. The backscatter yield of the multilayer samples increases up to the Au backscatter yield just after the range of twice of the thickness of the surface layer. This shows that the underlying Au substrate contributes significantly to the backscattered yield as soon as electrons have enough energy to penetrate the surface layer, backscatter off of the gold, and traverse the surface layer once more to exit the sample. As they exit the surface the second time, they act to increase the secondary electron yield through SE$_2$ emission. It is interesting to note that the backscatter yield follows the carbon yield until it increases to the full Au backscatter yield. Since SE$_1$ emission remains largely the same for the various thickness, it is SE$_2$ emission that drive the differences in the yield for various thicknesses. Since SE$_2$ is driven

![Graph showing secondary electron yields versus incident electron energy for different thicknesses of carbon on gold.](image)

**FIG. 4.1.** Secondary electron yields versus incident electron energy for the carbon on gold experiments with the range of electrons for twice the thickness of the surface layer indicated on the x axis.
by backscattered electrons, as the backscattered yield of the multilayer samples approach the backscattered yield of Au, then SE\textsuperscript{2} emission of the multilayer materials will all approach a similar value.

4.1.2 Gold on HOPG

The gold on HOPG scenario involves a high-density, high-yield, high-backscatter material on top of a low-density, low-yield, low-backscatter material. According to the theory, this should result in a material that behaves like gold at lower energies with a decrease in yield for energies greater than twice the range of the gold surface layer. The compiled results for the Au on HOPG experiments is shown in Fig. 4.3. From these experiments, it is also clear that even 1 nm of Au causes the low energy yield to follow that of Au and not of HOPG. For higher energies, due to the low backscatter of HOPG, the yield decreases, and the slope increases to a value similar to that of HOPG. The change in the yield appears to be more subtle than the C on Au scenario except for the very thick Au surface layers. Even those samples, however, are still more gradual and result in more of a slope change than a sharp drop in the yield.

This effect is clearly seen in the backscatter yield shown in Fig. 4.4, where the backscatter yield gradually decreases after incident electron energies result in a range where a significant number of electrons penetrate the surface layer. A summary of all of the fitting parameters for these sets of experiments is found in Table 4.1. These results show the general trends as described above for the two different scenarios of Au on HOPG and C on Au.
FIG. 4.3 Secondary electron yields versus incident electron energy for the gold on HOPG experiments with the range of electrons for twice the thickness of the surface layer indicated on the x axis.

FIG. 4.4. Backscatter electron yields versus incident electron energy for the carbon on gold experiments with the range of electrons for twice the thickness of the surface layer indicated on the x axis.
TABLE 4.1. Parameters and fit parameters for multilayer yield tests.

<table>
<thead>
<tr>
<th>Material</th>
<th>$C_{SE}$</th>
<th>$n_1$</th>
<th>$m$</th>
<th>$B_1$</th>
<th>$B_2$</th>
<th>$E_{Layer}$</th>
<th>$C_{ML}$</th>
<th>$n_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 nm C on Au</td>
<td>125.12</td>
<td>1.711</td>
<td>1.428</td>
<td>1.71E-5</td>
<td>8.946E-3</td>
<td>879</td>
<td>39.40</td>
<td>1.498</td>
</tr>
<tr>
<td>1 nm C on Au</td>
<td>433.82</td>
<td>1.922</td>
<td>1.455</td>
<td>3.91E-6</td>
<td>3.01E-3</td>
<td>753</td>
<td>24.46</td>
<td>1.443</td>
</tr>
<tr>
<td>10 nm C on Au</td>
<td>216.16</td>
<td>1.808</td>
<td>1.442</td>
<td>8.22E-6</td>
<td>5.54E-3</td>
<td>1473</td>
<td>11.39</td>
<td>1.365</td>
</tr>
<tr>
<td>100 nm C on Au</td>
<td>284.76</td>
<td>1.826</td>
<td>1.528</td>
<td>9.07E-6</td>
<td>5.48E-3</td>
<td>4792</td>
<td>9.32</td>
<td>1.347</td>
</tr>
<tr>
<td>500 nm C on Au</td>
<td>130.50</td>
<td>1.741</td>
<td>1.380</td>
<td>1.70E-5</td>
<td>7.00E-3</td>
<td>10347</td>
<td>0.56</td>
<td>1.078</td>
</tr>
<tr>
<td>HOPG</td>
<td>98.945</td>
<td>1.714</td>
<td>1.122</td>
<td>1.18E-5</td>
<td>4.30E-3</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1 nm Au on HOPG</td>
<td>23.92</td>
<td>1.456</td>
<td>1.484</td>
<td>6.67E-5</td>
<td>2.73E-2</td>
<td>876</td>
<td>131.48</td>
<td>1.712</td>
</tr>
<tr>
<td>5 nm Au on HOPG</td>
<td>35.53</td>
<td>1.476</td>
<td>1.406</td>
<td>2.78E-5</td>
<td>2.68E-2</td>
<td>2026</td>
<td>174.06</td>
<td>1.712</td>
</tr>
<tr>
<td>10 nm Au on HOPG</td>
<td>41.28</td>
<td>1.486</td>
<td>1.452</td>
<td>1.88E-5</td>
<td>2.61E-2</td>
<td>2346</td>
<td>197.90</td>
<td>1.710</td>
</tr>
<tr>
<td>50 nm Au on HOPG</td>
<td>20.41</td>
<td>1.369</td>
<td>1.270</td>
<td>3.58E-5</td>
<td>2.73E-2</td>
<td>4900</td>
<td>360.98</td>
<td>1.761</td>
</tr>
<tr>
<td>100 nm Au on HOPG</td>
<td>15.07</td>
<td>1.326</td>
<td>1.077</td>
<td>4.60E-5</td>
<td>1.45E-2</td>
<td>5211</td>
<td>1030.60</td>
<td>1.846</td>
</tr>
<tr>
<td>Au</td>
<td>40.86</td>
<td>1.470</td>
<td>1.015</td>
<td>1.24E-5</td>
<td>6.41E-3</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
4.2 Multilayer Charge Evolution Results

While the experiments have several experimental parameters, they can be categorized into four basic charging scenarios: surface deposition – grounded, surface deposition – ungrounded, conductive layer deposition – grounded, and conductive layer – ungrounded. Each of these scenarios has several similarities and differences that can be extended to numerous situations. Three of these scenarios, surface deposition – grounded and ungrounded and conductive layer deposition grounded, exhibited a self-limiting positive net surface potential while the conductive layer deposition ungrounded led to high negative net surface potentials and electrostatic breakdown. Each scenario is defined by the depth that the incident electrons penetrate, as well as the total electron yield and the material geometry and configuration.

4.2.1 Surface Deposition – Grounded

As seen in the model described in Section 2.6.4, this scenario has an ungrounded top surface and a grounded plane located at the silver electrode. At the energies used here, the electron range is ~3 nm, which only penetrates the top surface. Because the difference between the penetration depth and the grounded electrode is large, our charge transit time is much larger than our experiment time. Thus, the instantaneous change in charge accumulated in the upper insulating layer is given by

\[
\frac{dQ(t)}{dt} = J_{\text{total}}(t) = \int_0^1 \left[ 1 - Y_0(E_b) \frac{x^2 [3V_s(t)q_e + \chi]}{[V_s(t)q_e + \chi]^3} \right] - \frac{\sigma_{\text{down}} |V_s(t)| A}{(d_{SiO_2} - R/2)} .
\]  (4.1)

This produces two dynamic double layers, one from the embedded charge (nominally at the range \( R(E_b) \)), and a second from the charge deficit layer produced by the emission of secondaries. As shown by Walden (1972), if we assume all of the injected charge is trapped then the instantaneous electric fields produced in the regions between the charge layers and the grounded plane can be expressed as

\[
\frac{dF(z,t)}{dt} = \begin{cases} 0 & z < 0 \\ 0 & 0 < z < R_{SE} \\ \frac{J_bY_0(E_b)}{\varepsilon_0 \varepsilon_r A} \frac{x^2 [3V_s(t)q_e + \chi]}{[V_s(t)q_e + \chi]^3} - \frac{\sigma_{\text{down}} |V_s(t)| A}{\varepsilon_0 \varepsilon_r A} & R_{SE} < z < R \\ - \frac{J_bY_0(E_b)}{\varepsilon_0 \varepsilon_r A} \frac{x^2 [3V_s(t)q_e + \chi]}{[V_s(t)q_e + \chi]^3} \frac{\sigma_{\text{down}} |V_s(t)| A}{\varepsilon_0 \varepsilon_r (d_{SiO_2} - R/2)} & R < z < d_{SiO_2} \\ 0 & d_{SiO_2} < z \end{cases}
\]  (4.2)

Extending this to the instantaneous surface potential yields,
\[
\frac{dV_s(t)}{dt} = \frac{J_b}{\varepsilon_0 \varepsilon_R A} \left( d_{SiO_2} - \frac{R}{2} \right) - \frac{J_b V_0(E_b) \chi^2 \left[ 3V_s(t)q_e + \chi \right]}{V_s(t)q_e + \chi} \left( d_{SiO_2} - R_{SE} \right) - \frac{\sigma_{down} |V_s(t)|}{\varepsilon_0 \varepsilon_R} \tag{4.3}
\]

Because the difference between \(d_{SiO_2} - R/2\) and \(d_{SiO_2} - R_{SE}\) is only \(\sim 1.2\%\), we can approximate the instantaneous surface potential as

\[
\frac{dV_s(t)}{dt} = \frac{J_b}{A} \left[ 1 - Y_0(E_b) \frac{\chi^2 \left[ 3V_s(t)q_e + \chi \right]}{V_s(t)q_e + \chi} \right] \left( d_{SiO_2} - \frac{R}{2} \right) - \frac{\sigma_{down} |V_s(t)|}{\varepsilon_0 \varepsilon_R} \tag{4.4}
\]

with the current on the electrode given by

\[
J_{\text{electrode}} = J_b \left[ 1 - Y_0(E_b) \frac{\chi^2 \left[ 3V_s(t)q_e + \chi \right]}{V_s(t)q_e + \chi} \right] - \frac{\sigma_{down} |V_s(t)| A}{(d_{SiO_2} - \frac{R}{2})} \tag{4.5}
\]

To solve the differential equation for the surface potential analytically produces several complications due to the time dependence of the injected charge due to the time varying yield, thus numerical methods were employed to give a solution for \(V_s(t)\).

![Surface potential versus time for the 200 eV grounded scenario](image)

FIG. 4.5. Surface potential versus time for the 200 eV grounded scenario
For a 200 eV electron beam with a grounded conductive layer, we expect to see a small self-limiting positive net surface potential with the only current on the silver electrode being that of a displacement current due to image charges. The net surface potential versus time is shown in Fig. 4.5 and the silver electrode current versus time is shown in Fig. 4.6. To model the net surface potential and the electrode current the equations outlined above were used using two different methods. The first method consisted of applying a constant current scaled according to the beam on/off time. This model is shown in Fig. 4.5 labeled as $V_s$ Theory and in Fig. 4.6 as Silver Electrode Theory with parameters shown in Table 4. The second method considered a pulsed square wave beam which mimicked the original pulsed beam. This resulted in a net surface potential which followed the continuous scaled current model but showed the effects of the pulsed beam as shown in Fig. 4.5 labeled as $V_s$ Pulsed Theory. The silver electrode current for the beam pulsed beam theory differs more drastically from the continuous scaled current model while more closely resembling the silver electrode current data as seen in Fig. 4.6. This is more clearly seen in Fig. 4.7 where data and the two models for the silver electrode current are compared in a zoomed in view.

To see how the silver electrode current data compares to the model, the net surface potential was calculated using the measured current in Fig. 4.6. This calculated net surface potential is seen in Fig. 4.5.
labeled as $V_s$. Extrapolated from Current. This compares closely to both models used but does seem to be slightly higher than the measured net surface potential. While the values of the incident current and the yield for the test parameters versus the fit parameters compare closely, there appears to be a large discrepancy between the values of the bulk conductivity, $\sigma_{\text{down}}$. Fitting parameters for the fits are shown in Table 4.2.

This is probably due to a combination of RIC as well as other charge movement mechanisms possibly due to material damage or other lower resistance charge paths.

### 4.2.2 Surface Deposition – Ungrounded

Again, using a 200 eV monoenergetic electron beam, the electron range will be approximately 3 nm. For this configuration however, the grounded plane will be the back electrode since the silver layer will be ungrounded. This gives for the electric field,

![Graph](image)

**FIG. 4.7.** Silver electrode vs time as the current approach’s equilibrium. (a) Zoomed in view showing the overall decay. (b) A zoomed in view of the graph showing the equilibrium pulse shapes.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Test Parameters</th>
<th>Fit Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J_0$ (A)</td>
<td>$-9.43 \times 10^{-8}$</td>
<td>$-1.55 \times 10^{-7}$</td>
</tr>
<tr>
<td>$\sigma_{\text{down}}$ (ohm$^{-1}$ m$^{-1}$)</td>
<td>$3.0 \times 10^{-17}$</td>
<td>$1.10 \times 10^{-14}$</td>
</tr>
<tr>
<td>$Y_0$</td>
<td>$\sim 1.1$</td>
<td>$1.3$</td>
</tr>
<tr>
<td>$\chi$ (eV)</td>
<td>NA</td>
<td>$11$</td>
</tr>
<tr>
<td>$d$ (m)</td>
<td>$1.2 \times 10^{-7}$</td>
<td>$9.0 \times 10^{-8}$</td>
</tr>
</tbody>
</table>
\[
\frac{d\mathbf{F}(z, t)}{dt} = \begin{cases}
0 & z < 0 \\
-\frac{J_b Y_0(E_b) X^2 [3V_s(t)q_e + \chi]}{[V_s(t)q_e + \chi]^3} & 0 < z < R_s \\
-\frac{\sigma_{\text{down}} |V_s(t)|}{\varepsilon_0 \varepsilon_r A} & R_s < z < R \\
0 & d_{\text{sample}} < z
\end{cases}
\]

(4.6)

and, using the same processes as earlier for Eq. 4.3, the instantaneous net surface potential is given as,

\[
\frac{dV_s(t)}{dt} = \frac{J_b}{A \left[ 1 - Y_0(E_b) \frac{X^2 [3V_s(t)q_e + \chi]}{[V_s(t)q_e + \chi]^3} \right]} \left( \frac{d_{\text{sample}} - R}{2} \right) - \frac{\sigma_{\text{down}} |V_s(t)|}{\varepsilon_0 \varepsilon_r} \]

(4.7)

with the current on the electrode given by

\[
J_{\text{electrode}} = J_b \left[ 1 - Y_0(E_b) \frac{X^2 [3V_s(t)q_e + \chi]}{[V_s(t)q_e + \chi]^3} \right] - \frac{\sigma_{\text{down}} |V_s(t)| A}{(d_{\text{sample}} - R/2)}
\]

(4.8)

Again, because of the time dependence in the surface potential it is often not possible to find an analytical solution to the surface potential. Numerical methods were again used to find a solution with fitting parameters shown in Table 4.3. In theory, the 200 eV ungrounded scenario is very similar to the grounded case save the distance to the grounded plane which effectively changes the capacitance of the system. The data however, seems to imply that there are other mechanisms involved, including electrostatic breakdown and a change in the capacitance of the system. As we see from Fig. 4.8 the material charges much slower than the grounded scenario with an equilibrium of \(~10\) V which is slightly greater than the grounded scenario. This seems to be due to the change in capacitance of the system due to the change in distance of the charge layer to the grounded plane.

There is a discrepancy between the measured distance and the distance used in theory as shown in Table 4.3 likely due to the difference in the range and average penetration depth along with the ungrounded
TABLE 4.3. Parameters and fit parameters for 200 eV ungrounded scenario.

<table>
<thead>
<tr>
<th></th>
<th>$J_b$ (A)</th>
<th>$\sigma_{\text{down}}$ (ohm$^{-1}$ m$^{-1}$)</th>
<th>$Y_0$</th>
<th>$\chi$ (eV)</th>
<th>$d$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Parameters</td>
<td>-9.43 x 10$^{-8}$</td>
<td>3.0 x 10$^{-17}$</td>
<td>~1.1</td>
<td>NA</td>
<td>6.25 x 10$^{-3}$</td>
</tr>
<tr>
<td>Fit Parameters</td>
<td>-1.4 x 10$^{-8}$</td>
<td>3.0 x 10$^{-15}$</td>
<td>1.3</td>
<td>25</td>
<td>2.55 x 10$^{-7}$</td>
</tr>
</tbody>
</table>

Ag layer and its distance to the mounting assembly as well as the difference in the conductivity. Looking at the net surface potential there is good agreement between the measured potential and the theory as well as the potential extrapolated from the current up to about 2000 s. At this point, the extrapolated potential takes a deviation upward which is likely due to electrostatic breakdown; this is evident in Fig. 4.9 where the measured electrode current becomes erratic.

Even though the net surface potential is only 10 V positive the internal charge density can be extremely high since there is no fast charge dissipation mechanism for the ungrounded scenario. This change in the capacitance and potentially the resistivity of the system as seen in the erratic behavior of the measured

FIG. 4.8. Surface potential versus time for the 200 eV ungrounded scenario.
current possibly explains the difference between the measured current and the theoretical current. Similar to the grounded case we also see a higher value for the conductance of the sample which again is possibly due to material breakdown or other leakage paths. This also could lead to the discrepancy in the shape of the current pulses as shown in Fig. 4.10.

4.2.3 Conductive Layer Deposition – Grounded

For a 5000 eV monoenergetic electron beam the electron range in disordered SiO₂ is ~560 nm. At this depth, the electrons penetrate through the surface dielectric and into the conductive layer. This removes
the current term in the surface potential but adds another current term to the electrode current. Thus, our instantaneous electric field can be expressed as

$$\frac{d\vec{F}(z,t)}{dt} = \begin{cases} \frac{j_b Y_0(E_b) X^2 [3 V_e(t) q_e + \chi]}{\epsilon_0 \epsilon_r A} & \text{if } 0 < z < 0 \\ - \frac{\sigma_{\text{down}} |V_e(t)|}{\epsilon_0 \epsilon_r} - \frac{\sigma_{\text{RIC}} |V_s(t)|}{\epsilon_0 \epsilon_r} (1 - e^{-t/\tau_{\text{RIC}}}) & \text{if } R_{SE} < z < d_{\text{SiO}_2} \\ 0 & \text{if } d_{\text{SiO}_2} < z \end{cases}$$

(4.9)

where the extra term is due to charges moving from the grounded plane to recombine with the charge deficit layer. A third term could be added which would take into account the recombination after the charge transit time. The data suggests that this occurs around 4000 s or 620 s of beam on time. Also, because the beam penetrates the entire top layer RIC must also be taken into account using the time constant, $\tau_{\text{RIC}}$. The instantaneous net surface potential is then given by

$$\frac{dV_s(t)}{dt} = \frac{j_b}{A} \left[ -\frac{Y_0(E_b) X^2 [3 V_e(t) q_e + \chi]}{[V_e(t) q_e + \chi]^3} \right] \left( \frac{d_{\text{SiO}_2} - R_{SE}/2}{\epsilon_0 \epsilon_r} - \frac{\sigma_{\text{down}} |V_s(t)|}{\epsilon_0 \epsilon_r} - \frac{\sigma_{\text{RIC}} |V_s(t)|}{\epsilon_0 \epsilon_r} (1 - e^{-t/\tau_{\text{RIC}}}) \right).$$

(4.10)

The current on the grounded electrode will then consist of the beam current incident on the electrode current plus the induced image current due to the positive charge layer created by secondary emission. Thus the electrode current becomes,

$$j_{\text{electrode}} = j_b \left[ 1 - \frac{Y_0(E_b) X^2 [3 V_e(t) q_e + \chi]}{[V_e(t) q_e + \chi]^3} \right] - \frac{\sigma_{\text{dark}} |V_s(t)| A}{(d_{\text{sample}} - R/2)} - \frac{\sigma_{\text{RIC}} |V_s(t)| A}{(d_{\text{sample}} - R/2)} \left( 1 - e^{-t/\tau_{\text{RIC}}} \right).$$

(4.11)

For the 5 keV grounded scenario the net surface potential is governed by the charge layer created by the deficit of electrons near the surface which creates a self-governed positive net surface potential as shown in Fig. 4.11. Parameters are defined in Table 4.4. The current of beam electrons is approximated to be
fully captured within the silver layer. This approximation is possibly the cause of the difference in the measured current versus the theoretical current shown in Fig. 4.12.

By assuming that the entire beam current is captured in the silver layer, the silver electrode current becomes more negative than what is actually measured. The current pulse shapes of the measured current versus the measured current still have very similar profiles as shown in Fig. 4.13. With the values used, RIC begins to dominate the conductivity of the material around 2000 s with a value of 1.43 x 10^4 for $\tau_{RIC}$, however, RIC generally has a turn on time around 10 minutes which likely explains the discrepancy between the fit and measured data. It is likely that there are other conduction mechanisms, such as electric breakdown, that is altering the charge migration in the material.

TABLE 4.4. Parameters and fit parameters for 5 keV grounded scenario.

<table>
<thead>
<tr>
<th>Test Parameters</th>
<th>$J_B$ (A)</th>
<th>$\sigma_{down}$ (ohm$^{-1}$ m$^{-1}$)</th>
<th>$\sigma_{RIC}$ (ohm$^{-1}$ m$^{-1}$)</th>
<th>Y</th>
<th>$\chi$ (eV)</th>
<th>d (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.03 x 10$^{-9}$</td>
<td>3.0 x 10$^{-17}$</td>
<td>1.0 x 10$^{-10}$</td>
<td>$\sim$0.8</td>
<td>NA</td>
<td>1.2 x 10$^{-7}$</td>
<td></td>
</tr>
<tr>
<td>1.10 x 10$^{-8}$</td>
<td>1.0 x 10$^{-14}$</td>
<td>4.0 x 10$^{-14}$</td>
<td>0.8</td>
<td>20</td>
<td>9.0 x 10$^{-8}$</td>
<td></td>
</tr>
</tbody>
</table>

FIG. 4.11. Surface potential versus time for the 5 keV grounded scenario.
4.2.4 Conductive Layer Deposition – Ungrounded

For a 5 keV electron beam with an ungrounded conductive layer, we expect significantly different behavior than seen for the surface voltage with a grounded conductive layer. The high energy incident electrons deposit negative charge in the conductive layer. Because the conductive layer is ungrounded there will be no fast charge dissipation mechanism. Because there is no limiting behavior from re-attraction of secondary electrons, we should see a high net negative potential. Because of the low conductivity, the charge cannot dissipate through the dielectric substrate to the grounded rear electrode faster than charge is being

FIG. 4.12. Silver electrode versus time for the 5 keV grounded scenario.

FIG. 4.13. Silver electrode current vs time. (a) A zoomed in view showing the overall trend. (b) A further zoomed in view showing the pulse shapes.
deposited by the beam, thus the potential will become more and more negative until the produced electric fields exceed the limits of the material or produce fields strong enough to produce arcing from the exposed surface of the conductive layer to the surrounding grounded sample holder ~2 mm away.

The initial current shown in Fig. 4.15 and voltage behavior shown in Fig. 4.14 are indeed markedly different, rising very rapidly to negative voltages beyond -100 V with the first pulse, followed by a short duration reversal for the next three beam pulses. Similar retrograde charging behavior has been reported for FEP, LDPE, and other polymers (Molinié et al., 2012; Gross et al., 1981); this has been attributed to (i) trapping/recombination on an increasing trapped charge in regions where RIC becomes active over a finite time and space charge accumulation (Molinié et al., 2012; Gross et al., 1981) or (ii) defect generation due to beam aging above 100 kGy (Khatipov, 2001) (our pulses generate only ~5 kGy, so this may not be pertinent for this early effect). Inspecting the separate pulses of Fig. 4.16 we see that there is an obvious change in the beam profile possibly due to the change in RIC and other charging behaviors.

After the fourth pulse, the surface voltage again shows a linear increase, but now at a charging rate of ~2.4 V/pulse. The linear charging at the lower rate continues until the sample reaches -170 V, at which point electric field across the ~1 mm film-to-sample holder gap (with a reasonable field enhancement of ~25 due the aspect ratio and surface roughness) exceeding the breakdown field strength 4 MV/m measured for a

![Graph](image_url)

**FIG. 4.14.** Surface potential versus time for the 5 keV ungrounded scenario.
A ~60 nm thin film of disordered SiO$_2$ (Anders, 2008). At $t_{\text{arc}} \approx 3987$ s an electrostatic discharge occurred from the conductive layer to the sample holder, as observed in the imaging instruments and the electrometer. In the six subsequent pulses after $t_{\text{arc}}$, the rear electrode current continued to increase to ~50% above the incident beam current as the surface voltage rapidly decreased to near zero potential. Increasing numbers of arcs became apparent in the pulses after $t_{\text{arc}}$, to the point at which currents were quite erratic. This is consistent with excess charge leaking from increasing areas of the thin film as successive regions of the thin film experience breakdown, as seen in the discharge study (Andersen et al., 2012).

FIG. 4.15. Silver electrode versus time for the 5 keV ungrounded scenario.
FIG. 4.16. Zoomed in views of the silver electrode current vs time. (a) A zoomed in view showing the overall trend (b) A zoomed in view showing the irregular pulse shapes.
CHAPTER 5

SUMMARY AND CONCLUSIONS

Because multilayered materials are used extensively in spacecraft design it is important to apply these methods to proposed designs to ensure that the expected space environment does not create scenarios which exceed the limitations of the materials. By applying advisable design configurations early on, time, money and equipment can be saved even before modeling and construction have begun. It also allows current spacecraft configurations to be characterized to understand if a given space environment is unsafe so that that safety procedures can be employed to minimize damage to critical components. This type of multilayer charging analysis is especially important for novel materials such as those found in space suits and solar blankets, exposed dielectrics where contamination is likely such is the case with solar panels, and sensitive instrumentation like optical assemblies where the effects of charging and dielectric breakdown can result in degradation and potential failure of the instrument.

In order to perform this analysis, it is important to understand the several phenomena that drive spacecraft charging as they relate to bulk material as well as more complicated multilayer configurations. One of the areas where such knowledge is lacking is multilayer electron yield, especially for very thin surface layers. Therefore, a set of experiments and analysis were performed to create multilayer yield models capable of describing the electron yield of multilayer materials. Another set of analysis was performed on multilayer materials with a thicker surface layer to demonstrate and model the several charging scenarios that develop from common configurations and how indirect measurements can assist in the prediction and detection of dielectric breakdown. This set of analysis showed the effects of the individual charging phenomena on the internal charge distribution and the resulting charging effects.

5.1 Multilayer Electron Yield Results

The difference between the two yield scenarios is due to the difference in how the backscatter yield changes according to the surface and substrate layers. For the carbon on gold, the backscatter yield sees a drastic increase since the backscatter yield of gold is significantly greater than that of carbon. For the gold on HOPG, the backscatter yield decreases once electrons penetrate the gold, but because the backscatter yield of HOPG is lower, it does not directly affect the change of the backscatter yield, but instead the yield
decreases due to the probability of a backscatter occurring before it penetrates the gold layer decreases for higher energies. This causes the change to be more gradual versus the reflective wall-like transition of the carbon on gold.

Another way to compare the results to one another is to compare the fitting parameters of the fits in Fig. 4.1 and Fig. 4.3 as shown in Table 4.1. From these parameters, the high energy slope, $n$, is fairly consistent across the surface layer thicknesses and matches that of the bulk material of the surface layer. For all the C on Au data, the average value of $n = 1.79$ with standard deviation $SD = 0.08$. For all the Au on C data, the average value of $n = 1.43$ with standard deviation $SD = 0.07$. The m values, the low energy slope, appears to be mostly consistent with a slight decrease from thin to thick surface layers. For all the C on Au data, the average value of $m = 1.4$ with standard deviation $SD = 0.1$ and for all the Au on C data the average value of $m = 1.3$ with standard deviation $SD = 0.2$. Another way to compare the multilayer results is with the values of $n_{ML}$, the high energy slope for the substrate, which are fairly consistent across the layers but gradually increase as the thickness increases for the Au on C data and gradually decreases as the thickness increases for the C on Au data.

The results of the experiments both confirm the effects of the surface layer dominating low energy yields and backscattered electrons dominating the effects of the substrate. Because of the short range of secondary electrons, as well as the material dependent properties of the surface such as the work function, even very thin surface layers, drastically change the secondary electron yield to match that of surface material. Because backscattered electrons contribute significantly to secondary electrons generated at the surface they are a dominate part of multilayer yield. Their effect is likely increased due to the spread in energies of backscattered electrons which can lose energy before reaching the surface resulting in shorter IMFP values which increases the probability of a collision near the surface. By comparing the secondary and backscattered yield of materials, electron yield trends of multilayer configurations can be predicted.

5.2 Multilayer Charging

Through observation of the net surface potential and the currents from the rear electrode and the conducting plane (when grounded), we have been able create a model to infer the internal charge distribution in multilayered samples. The results showed that the four scenarios of ungrounded dielectric surface
deposition, grounded dielectric surface deposition, ungrounded conductive layer deposition and grounded conductive layer deposition led to two net surface potential charging regimes, small positive charging and high negative charging. This allows prediction of electric fields in the multilayer material and the likelihood of electrostatic breakdown (which was observed in several runs). While the net surface potential showed the charge equilibrium reached after a given pulse, the electrometer data showed the time evolution of the charges as they reached equilibrium. This gave information about displacement currents, charging of internal floating conductors, and signs of arcing.

Clearly the combination of high-resolution surface voltage and electrode current measurements coupled with an accurate model of the evolving charge distribution provide valuable tools to understand both laboratory tests and actual spacecraft charging and arcing events. Using this information design considerations and construction guidelines can be implemented to help minimize scenarios where spacecraft charging might become an issue.

There were several limiting behaviors which governed the charging and net surface potential of the several configurations. The main limiting behavior that was exhibited was the reattraction of secondary electrons which limited the net surface potential for the positive charging scenarios. This reattraction is governed by the energy of the emitted secondaries as well as the value of the net surface potential. While this limits the net surface potential, it does not limit the individual charge layers, thus there can still be high electric fields within the material which can cause electrostatic breakdown as seen in the 5 keV ungrounded scenario. The other limiting behavior was due to the conductivity of the material. While this did not have much effect in these experiments it does create a limit on the amount of charge a material will hold.

While the net surface potential is a good indicator of external fields, it does not accurately predict the possibility of an internal electrostatic breakdown. In both of the ungrounded scenarios we saw evidence of electrostatic breakdown while in the grounded scenarios there was no similar evidence. In the 5 keV grounded scenario, breakdown occurred after ~4200 s and with a net surface potential of 163 V. If we assume all of the injected charge is trapped in the silver layer which was about -1.2 x 10^{-5} C this would create an electric field ~7.15 x 10^8 N/C. This would produce a surface potential of ~-182 V. The charge depletion layer with a secondary electron yield of 0.9 would leave a charge depletion layer of about 1.2 x 10^{-6} C creating an electric field of ~1.43 x 10^9 N/C with a surface potential of ~+18 V. Thus, the net surface potential is ~164
V which corresponds closely to the net surface potential measured by the SVP. While this overly simplifies the model and does not include charge movement it does give an estimate of the internal electric fields at which breakdown occurred. By using more advance models and accurate materials characteristics, breakdown scenarios can be constructed to understand the limits of material configurations.

5.3 Future Work

For multilayer yields, the analysis performed in this dissertation focused solely on conductive materials. For thin insulating materials, this problem becomes more complicated due to the effects of charging. This makes it difficult to measure the intrinsic yield since the changing surface potential modifies the electron yield as was seen during the multilayer charging tests. Further, non-homogenous materials provide another scenario where the combination of different materials is not adequately explained by a linear combination of the two.

The study of the internal charge distribution of materials has been largely successful; however, most of the theories describe monoenergetic fluxes whereas most actual electron space plasma fluxes have broad continuous energy distributions with significant fluxes from $10^1$ eV to $10^7$ eV (Hastings and Garrett, 1996). Due to current experimental limitations, it has generally been assumed in the spacecraft community that the charge evolution of a material undergoing bombardment from a broad energy spectrum electron flux can be approximated by the linear superposition of several mono-energetic tests.

While this assumption has been generally accepted, no systematic studies have been conducted to compare monoenergetic and broad energy spectrum tests, largely due to the complication and cost of producing broad energy spectrum electron fluxes. Currently the two main methods used to produce broad energy spectrum fluxes are: (i) the use of a radioactive source such as Sr$^{90}$ or Co$^{60}$ and (ii), complex systems of high energy beams with moderating foils as used in the “SIRENE” facility built by the European Space Agency (Dirassen et al., 2003) and others (Dennison et al., 2007). This topic was identified as a key area of current interest at the 2010 International Spacecraft Charging Conference where non-static charging models used to understand a first order relationship between monoenergetic and non-monoenergetic tests with respect to the internal charge evolution of insulators were described as one of the four critical “New Frontiers” in spacecraft charging (Ferguson, 2010).
To extend this model to multiple incident electron energies, the assumption that incident fluxes at various fluxes add linearly predicts that the equilibrium becomes

\[ V_s = \sum_i J_{bi} \frac{[1 - Y(E_{bi})]}{\sigma_{dc}} R(E_{bi}) \frac{[D - R(E_{bi})]}{D} \]  

(5.1)

for a discrete set of \( i \) incident current beams at energies \( E_{bi} \). Given a continuous energy dependent incident current distribution \( \int_b(E_b) \), this becomes

\[ V_s = \int \frac{\int_b(E_b)[1 - Y(E_b)]}{\sigma_{dc}} R(E_b) \frac{[D - R(E_b)]}{D} dE_b \]  

(5.2)

Because electron beams can have non-linear effects such as radiation induced conductivity, a linear supposition of mono-energetic tests is not sufficient to fully characterize the charging of materials, especially multi-layer materials. Therefore, non-linear effects will need to be investigated and incorporated into the models to fully characterize and predict the internal charge evolution for broad spectrum electron beams.
REFERENCES


APPENDICES
APPENDIX A
HGRFA REDESIGN

The USU’s MPG has previously developed instrumentation which enables the characterization and measurement of materials undergoing energetic electron bombardment. This instrumentation consists of an ultrahigh vacuum chamber equipped with electron guns, a sample carousel, temperature controllers, electrical feedthroughs, a surface voltage probe (SVP), a hemispherical grid retarding field analyzer (HGRFA) and other various instrumentation. This chamber is equipped to simulate diverse space environments from $10^{-10}$ to $10^{-3}$ Torr and electron fluxes with energies from 10 to 30,000 eV.

The HGRFA and the SVP are the primary instruments used in the studies outlined in Section II and are the focus of design improvements in Section V. The HGRFA is a detector used to measure electron emission from insulators and conductors undergoing electron bombardment. It can also be used for stimulated emission studies. It was originally developed by Nickles (2002) and Thomson (2004) and then further improved by Hoffmann (2010) and Christensen (2017). Improvements outlined in this section were necessary to facilitate future work on single layer and multilayer insulators.

The HGRFA fully encloses one of eleven samples that can be positioned in front on a charged particle source via rotation of the sample carousel. An aperture on the front of the instrument allows an incoming electron or ion beam to bombard the sample. An enclosing hemisphere allows the capture of all emitted electrons with a retarding-field analyzer grid system for emitted-electron energy discrimination. The current instrument was originally calibrated giving yield accuracies with systematic errors < 5%. It was then further improved by Christensen, wherein he reduced electrical noise, reduced sample charging, improved charge neutralization and improved analysis methods (Christensen, 2017).

The SVP, originally built and validated by Hodges (2012), is used to measure the net surface potential of charged insulators. It uses a capacitive technique employing two electrically connected Au plates, one inside the chamber and one outside the chamber. By measuring the potential on the outside plate using an electrostatic field probe and moving the inside plate over the sample, the net surface potential of the sample can be calculated given the system is properly calibrated. This system was originally purposed to work in
conjunction with the HGFRA; however, due to equipment failure and other complications this was never fully realized.

A.1 Design Improvements

In order to capture higher fidelity yield measurements for single layer and multilayer materials, several instrument upgrades were performed. The center rod alignment was the only upgrade made and incorporated before the capture of the data in this work, however, several of the upgrades were completed but not yet incorporated. While all of these upgrades were completed, most of them were not incorporated into the chamber in time for the data acquisition in this work. The incorporation of these final upgrades into the main chamber will be necessary for high fidelity yield measurements on multilayer insulators and will be a focus of future student. The original plan was to modify the existing HGFRA; however, after consideration it was concluded that this was not feasible, nor would it achieve the necessary requirements. Because of this, a new re-design of the HGFRA was completed which incorporated the necessary upgrades. The design changes can be grouped into several categories which include; Surface Voltage Probe, Electrically Isolated Rings Design, Front Instrument Plate, Hemispheres, Wiring, and Center Rod Alignment.

A.1.1 Surface Voltage Probe

The primary reason for the re-design of the HGRFA was to incorporate the SVP with the HGRFA. The original complications arose due to the inability to repair the damaged stepper motor. The replacement motor was not only larger than the original, but it also had a different form factor. To overcome this, two solutions were designed as shown in Fig. A.1(a) and (b). The first solution uses a set of miter gears which allows the motor to be mounted sideways and the second uses a precision gearing system with a miniature chain. The second method allows the motor to be positioned on the top of the device allowing greater flexibility in motor choice.

Incorporating the SVP with the HGRFA facilitates several capabilities. The first capability includes the ability to measure the charge deposited in multilayer materials. This is done by first measuring the current coming into the sample and the current leaving the sample, either by electron emission or by conductance, as well as any image currents. The net surface potential is then measured, which together with the measured currents, can help determine in which layers the charge was deposited.
The second application deals with the charging of insulators during secondary electron emission studies. As the secondary electron emission of insulators are being measured, they can charge positively or negatively. For low energy electron beams this becomes increasingly important since the charging of the sample not only changes the electron landing energy but it also creates an electric field within the HGRFA. In order to negate this, the stage and the inner grid can be biased to match the potential of the sample; however, to do this, the potential must first be known. By making repeated measurements of the sample using the SVP during measurements, the bias required can be continually updated as the sample charges. By using this method the true intrinsic yield of highly insulating materials can be extracted.

Other applications that require both the HGRFA and the SVP include charge buildup effects on cathodoluminescence, charge buildup effects on arcing, as well as charge accumulation and decay for highly insulated materials undergoing electron bombardment. All of these measurements require that both the HGRFA and the SVP are working in conjunction with one another.

A.1.2 Electrically Isolated Rings Design

In order to increase the reliability of the instrument and to ease assembly and disassembly, the grids were re-designed to attach to electrically isolated rings, which connect to form the back plate of the device as shown in Fig. A.1(c,d). The exploded view of the HGRFA with the grids and collector attached to the isolated rings is shown in Fig. A.1(d). This design not only makes the device more reliable and easier to assemble and disassemble, it also isolates the outer shielding from the stage and creates the possibility to have modular sample plates for various mounting configurations.

The reliability of the design comes from the ability to mount the hemispherical grids, as well as the collector, directly to their respective rings. This allows each grid to be independently assembled and disassembled allowing each grid to be removed and repaired without disassembling the entire instrument. This also allows the electrical connections to be made to each ring independently which makes wiring more versatile and robust.
Another feature that this design offers is the ability to isolate the sample plate, which electrically connects to the stage as shown in Fig. A.2, with the outer shielding and beam aperture. This enables the current from the stage to be used to help determine the total emitted current from the sample, since the stage is part of the enclosing hemisphere.

This modular ring design also allows for the design of different sample plates for different mounting configurations. This includes the mounting to a separate thermally controlled sample stage with temperatures ranging from 40 K to 293 K (Dekany et al., 2013). It also includes the ability to attach it in a horizontal configuration which would allow loose dust and powders to be measured.

The rings are then shielded with a copper backplate as shown in Figs. A.2 and A.3(b), which reduces noise and protects the rings and wiring from other conductors. The rectangle cutout allows for the sample carousel to fit flush against the sample plate, as shown in Fig. A.2.

FIG. A.1. HGRFA CAD design. (a) Miter gear drive design for the SVP motor mount. (b) Chain drive design for the SVP motor mount. (c) Collapsed view of the HGRFA to show isolated rings with attached hemispheres. (d) Exploded view of the HGRFA to show isolated rings with attached hemispheres.
A.1.3 Front Instrument Plate

The original front instrument panel had several modifications to it; however, these caused several issues. One of the greatest issues is that the instrument ports do not have a clear view of the sample due to...
the drift tube. This creates shadows on the sample from the UV light source as well as the electron flood gun. In order to rectify this issue, the new front instrument panel will have the instrument ports placed at large angles from the drift tube, so that they have a clear view of the sample. This will also reduce the number of emitted electrons that escape through the opening in the collector since emission falls off as a function of $\cos(\theta)$ or faster (Hoffmann, 2010).

The new design, as shown in Fig. A.3(a), will also enable the entire front instrument panel to be easily removed and replaced if necessary. This allows the instrument to be modified without needing to redesign the entire outer-shielding.

A.1.4 Hemispheres

When the original instrument was being designed there was no cost effective way to manufacture custom hemispheres to be used as grid mandrels. Because of this, compromises were made wherein already manufactured hemispheres were purchased. These hemispheres, however, were slightly aspherical. Because the grids are formed by laying wire mesh over one of these hemispheres, any asphericity was also transferred to the grids. Because of this, the electric fields between the biased grid and the inner grid and the biased grid and the collector were not purely radial. The non-radial components of the electric field limits the resolution of the energy spectrum measurements of the secondary electrons.

In order to rectify this issue, custom hemispheres will be made to ensure that the grids and collector are spherical. This allows the exact size of the grids and collector to be chosen, whereas before they were not. How the collector attaches to the collector ring has also been improved. The hemisphere will have counter-bored holes allowing the screw to enter in from the outside of the hemisphere and screw into the baseplate as shown in Fig. A.4(a). The current HGRFA design requires that the hemisphere itself be tapped. Because of the wall thickness of the hemisphere and due to it being constructed using aluminum, the threads have become stripped several times requiring them to be re-drilled and re-tapped. This has caused the screws to bulge the aluminum of the outer-wall, creating an unreliable mounting, as shown in Fig. A.4(b).
A.1.5 Wiring

The current wiring of the HGRFA, as shown in Fig. A.5(a), consists of different iterations of improvements which have been applied to the instrument over several years. Because of this, the wiring is unreliable, un-shielded, and is difficult to disconnect and connect each time the HGRFA must be removed.

FIG. A.4. (a) Current wiring of HGRFA consists of several iterations of modifications. (b) The wiring from the front panel will run down the wire guide and be held in place by the wire harness. The wiring coming from the insulated rings will come straight down from behind the copper backplate and be held in place by the wire harness.

FIG. A.5. Fix for shielding mounting on HGRFA. (a) Cross section view of the HGRFA outer shielding and outer shielding ring. With this design the outer shield hemisphere will be protected from bulging and stripping in contrast (b) the current HGFRA outer shielding which shows the bulging of the aluminum caused by re-tapping stripped threads.
for repairs or improvements. This has led to electrical noise, loss of measurements, shorts between grids, disconnected leads, and shorts to ground.

The new design corrects this by shielding and routing the wiring from the front beam plate, as shown in Fig. A.3, to the wire harness as shown in Fig. A.3(a) and Fig. A.5(b). The wiring for the grids connects directly to the isolated rings and is then routed down to the wiring harness, as shown in Fig. A.5(b). At the wiring harness a ceramic quick connector allows the easy and quick removal of the HGRFA without needing to change or adjust wiring on the instrument while still maintaining a secure connection that will not disconnect or short.

A.1.6 Center Rod Alignment

Another issue with the current instrumentation deals with the ability to center the electron beam on the sample. To get an accurate profile of the beam, so that the current and spot size are known, the profile has to be measured by a Faraday cup (FC). Because the FC is mounted within one of the sample slots, this requires a measurement to first be made with the FC, then the sample carousel is rotated over the desired sample. If the axis of rotation is not aligned with the axis of the chamber, then the sample can be shifted relative to the beam. This changes both the beam current, as well as the beam profile that is hitting the sample. Because the sample carousel is held by a three-axis rod that acts like a pendulum, if the weight on the rod is not balanced then the entire sample carousel can shift. This becomes problematic with use of the HGFRA, since it creates an uneven weight distribution relative to the rod.

In order to fix this problem, a flange with a 5.1 mm diameter rod affixed, is to be mounted on the bottom of the carousel mounting plate. As the carousel moves up and down the rod will be able to slide in and out of a conical hole. This conical hole, or center rod catch, will then be centered in the chamber by the use of springs, as shown in Fig. A.6. This will help align the rod with the chamber axis without requiring that the rod be fixed vertically.

Designing and building a new HGRFA, using what USU’s MPG has learned from over a decade of measurements, will increase reliability, reduce noise, ease assembly and disassembly, and open up new measurement possibilities. This instrument will allow needed research to be conducted for dynamic secondary electron emission tests, charge storage tests, cathodoluminescence tests, as well as a host of others.
The design itself has taken into consideration everything learned from the current instrument as well as future needs as discussed by Christensen (2017). The new instrument will also allow new improvements to be designed and easily added due to its modular design. The measurements and science that will come from this device will not only help understanding of spacecraft charging, but it will further the ability to accurately measure, model and predict the effects of the space environment on novel materials.

A.2 Assembly

This section will detail the assembly of the HGRFA including the assembly of the grids. To begin, make sure that all pieces have been properly cleaned. Before assembly begins, the collector and sample plate aperture need to be painted with Aquadag. Next, the grids need to be made and assembled as detailed in Section 6.2.1. The Collector then needs to have wire mesh added to the optical ports outlined in Section 6.2.3. After this point, the main assembly can begin.
A.2.1 Grid Assembly

To assemble the inner and outer grid, you will need three pieces per grid. For the outer grid this includes the Outer Grid Ring, the Out Grid and the Outer Grid Hemisphere as shown in Fig. A.7 along with the wire mesh. To begin, in order for the wire mesh to be sandwiched snuggly, you need to cover the two sandwiching faces with copper tape as shown in Fig. A.8. Next, lay down the Outer Grid Ring as shown in Fig. A.7(a) with the outermost edge facing down and insert the Outer Grid Hemisphere into the center as shown in Fig. A.7(c).

Lay the wire mesh over the hemisphere and then place the retaining ring as shown in Fig. A.9(a). Press the ring down with a significant amount of force and then pull up on the wire mesh around the outside against the retaining ring in order to make a bend in the mesh all the way around the retaining ring. This bend will be used as a guide to cut out the ring. You can also use a marker if necessary.

Remove the retaining ring and the wire mesh and cut around the marked guide. Then, replace the wire mesh, making sure that there is no wire that extends out past the ledge on the Outer Grid as shown in the final assembly in Fig. A.9(b). To attach the wires, hold the retaining ring down on the ring and flip the entire assembly over, keeping the hemisphere inside of the wire mesh. Next, screw in the #0-80 ¼ flat head screws. If there is wire mesh in the screw hole, use a pick or other small tool to move and shift it out of the way. Once all the screws are snug, then tighten them the rest of the way down.

Turn it back over and place it on a flat surface and press the assembly down on the hemisphere to give the wire a final stretch. Finally, inspect your work to make sure the wire is tightly secured all the way.

FIG. A.7. Needed parts to assemble a grid. (a) Outer Grid Ring. (b) Outer Grid. (c) Outer Grid Hemisphere inside the Outer Grid and Outer Grid Ring.
around the retaining ring. In order to protect the grids, leave them over the hemisphere while the other grid is assembled. The other grid is constructed using the same method.

A.2.2 Drift Tube Hole Construction

To construct the holes for the drift tubes, begin by punching out four copper tape discs using an 11mm punch. Also, cut out four 0.001” thick tantalum discs using the same 11mm punch. Next, turn the tantalum discs into rings by using a 5/16” hole punch as seen in Fig. A.11. Next, place a single disk of copper tape (as made earlier) over each ring. Mark on the grid where the rings need to be placed. This can be done by marking the center of the hemisphere and then placing one of the copper disc + tantalum ring pieces over the mark with tantalum showing.

FIG. A.8. Outer Grid Ring and Outer Grid covered with copper tape.

FIG. A.9. Wire mesh assembly. (a) Wire mesh sandwiched on Outer Grid Ring. (b) Final Grid Assembly.
Next, place the grid back over the hemisphere, keeping the tantalum ring centered. Next, place another tantalum ring + copper disc on the top, with the tantalum ring facing down, making the sticky side of the copper tape discs connecting in the middle of the ring so that it then holds it in place. You should be able to then remove the grid assembly from the hemisphere and the rings should remain held in place by the covering copper discs. Mount this sideways as shown in Fig. A.10(a) so that you can spot weld it.

Using the spot welder with the external leads, spot weld the tantalum rings together by pressing firmly against the copper discs, making sure that the discs are between the leads of the spot welder. Go around the ring until it is decently welded. Be careful not to use too much power and not to miss the disc or you may melt and cut the wire mesh. At this point, heat up the copper tape discs with a heat gun or with the spot welder on the continuous setting to melt the glue and remove the copper discs. Once removed, finish spot welding the tantalum rings. Once it is securely welded, use methanol or acetone to remove the remaining glue residue. This should look like Fig. A.10(b).

Next, place the grid back over the hemisphere and use a razor blade to cut out the wire mesh on the inside of the ring. Repeat this process for the hole for the angled drift tube. Once done with both rings, this
should look like Fig. A.12. You may need to use a razor blade to cut off some of the tantalum rings where they intersect. You can make this modification as you test the fit during assembly.

A.2.3 Collector Mesh

The collector needs several wire grids placed within the non-drift tube ports in order to keep as uniform electric field as possible. This can be done before or after the collector is painted with Aquadag. To begin, punch out several copper tape discs using a 7/32” punch. Stick one of these discs to a small section of wire about the size of a nickel as shown in Fig. A.13(a). Next, prepare several rings using 0.01” stainless steel plate as shown in Fig. A.13(b). Next, put the ring inside of the collector and use a 3/16” punch to form the ring to ensure that it is cylindrical and uniform as shown in Fig. A.13(c).

Remove the molded retaining ring, place the wire over the collector hole (on the outside), aligning the copper disc over the hole and then insert the retaining ring over the wire and force it and the wire into the

FIG. A.12. Fully completed grid with drift tube holes.
hole making the wire mesh flush with the inside wall of the collector. On the top, spot weld the extra wire to the stainless steel retaining ring. Cut off the rest of the wire. When completed, the top should look like Fig. A.14(a) and (b) and the bottom like Fig. A.14(c).

A.2.4 Main Assembly

The main assembly is quite straightforward. The first step is to place the Aquadagged stage plate on the sample plate with a layer of Kapton Insulation between the two to electrically isolate the stage plate and the sample plate as shown in Fig. A.15(a). The next step involves connecting the collector to the collector ring as shown in Fig. A.15(b). Finally, connect the outer shield to the outer shield ring as shown in Fig. A.15(c). Use the appropriate screws for each connection. The next step is to assemble the rings into the outer shielding.

FIG. A.13 Collector mesh inserts construction. (a) Wire mesh with copper disc. (b) Retaining rings. (c) Molding the rings to ensure they are uniform and fit the holes.

FIG. A.14 Finished assembly of collector mesh inserts. (a) Top of collector with inserted and spot welded grids. (b) Wire grid on inside of collector. (c) Inside of collector with grids after it has been coated with Aquadag.
To begin, place three alumina spacers over the three 0-80 tapped holes and put a alumina tube in each spacer. Place the collector ring inside the outer shielding so that the three alumina tubes go into the three holes in the collector ring. Make sure that the collector is facing the correct direction. To know which way is up, find the little notch on the outer shielding ring. On the collector, the second drift tube hole should be on the bottom. See Fig. A.16(a) for alignment. Next, place another alumina spacer on the tube that is now sticking through the collector ring, place an 0-80 washer and then an 0-80 screw. Do this for all three holes. Once that is done repeat as shown in Fig. A.16(b) until you have all of the rings placed as shown in Fig. A.16(c). You can then attach the front beam plate, and the cable guides.

A.2.5 Surface Voltage Probe and Motor Mount

To mount the surface voltage probe you first must attach the SVP axle mount to the SVP as shown in Fig. A.17(a). This is done by first threading the wires through a washer. The washer is used as spacing so
that it does not come into contact with the stage plate as shown in Fig. A.17(b). The retaining washer also needs to have a groove milled out of the back so as to allow the wires to come through without pinching them against the bearing. Next, attach the axle mount with the cut out on the big part of the axle on the top so that the cables can route through it when you insert it into the bearing on the sample stage ring. You will notice in Fig. A.17(b) that the two screws that mount the SVP axle mount to the SVP are not in the original design. These were added in to accommodate the axle. A new redesign will need to keep this in mind. The next step is to route the cable through the bearing and then insert the SVP axle into the bearing as shown in Fig. A.17(c). Finally, place the retaining spacer on the axle on the front side as shown in Fig. A.17(c).

Now, the next few steps depend on if you are mounting the SVP motor on the top of the Outer Shield or if you are mounting it on the back of the copper back plate. If you are mounting it on the back of the copper back plate you need to make a shim for the gear to fit on the axle as shown in Fig. A.18(a) and (b). Next, you need to add in a 4-40 tapped hole to the miter gears if they do not already have one as shown in Fig. A.18(c).

FIG. A.17. SVP mounting on the HGRFA. (a) SVP axle mount attached to SVP. (b) SVP mounted on sample stage ring. (c) Front side on stage ring with mounted SVP.

FIG. A.18. (a) SVP Axle with shim for Miter Gear. (b) SVP axle with shim and miter gear. (c) Miter gear drilled out to fit SVP Motor.
Third, the miter gear that will mount to the motor needs to be drilled out to accommodate the motor shaft. Use a #12 drill as shown in Fig. A.18(c). If you are mounting the SVP motor on the top of the Outer Shield, you only need to attach the small gear and chain as shown in Fig. A.19(a).

To mount the motor, you first need to prepare the SVP potentiometer. First, get three male connectors and cut off the end that the wires would go in. These then need to be attached to the SVP using UHV compatible conductive epoxy. Be careful not to get conductive epoxy between the leads. If you do, you need to wipe it off thoroughly before you cure the epoxy. When curing the epoxy on the potentiometer, make sure that you use a heat sink to pull heat from the potentiometer so that it does not get too hot. The Epoxy needs to cure above 110 °C but the potentiometer cannot get above 120 °C. By using a heat sink you can achieve both. When curing, try to achieve a temperature of around 140 °C. The setup is shown in Fig. A.19(b) and the final product in Fig. A.19(c). Another part that needs to be epoxied is the brush motor mount as shown in Fig. A.19(d). Take note of the insulator on the inside of the brush motor mount.

The next step is to mount the SVP Motor along with the potentiometer, motor brush mount and the corresponding gear. To mount the motor, first place the motor into the motor mount. Next, double sticky tape the potentiometer onto the back metal washer. Make sure that the contacts do not touch the back metal washer. You may need to grind one side of the washer to give a little bit of tolerance.

Next, place the potentiometer and metal washer onto the motor with the metal washer toward the motor as shown in Fig. A.20. Next, put some Kapton sticky tape on the retaining nut and tighten it down against the potentiometer. Next, place the motor brush mount onto axle and push it down until the brush just touches

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**FIG. A.19.** SVP potentiometer construction. (a) SVP mounted with the motor mounted on the top of the Outer Shield. (b) Curing configuration for SVP Potentiometer. (c) Cured SVP Potentiometer with leads. (d) Mounted potentiometer brush.
The potentiometer and tighten the set screws. Next place the gear onto the axle of the motor and tighten the set screw. shows a diagram of the motor mount assembly.

A.2.6 Flood Gun Assembly

To assemble the flood gun you first need to spot weld a grid onto two of the washers as shown in Fig. A.21(a). Next, you want to spot weld some wire onto those two washers plus an extra blank washer. It is easiest to use some chromel or alumel wire for this since it spot-welds easily. Next, you want to use a small amount of super glue to attach the ruby spheres to the washers as shown in Fig. A.21(a) and (b) and then glue them into a stack as shown in Fig. A.21(b). Make sure that the wires all stick out the same way. You also need to weld a washer onto the top of the can as shown in Fig. A.21(b). The final assembled main body is shown in Fig. A.21(c).
FIG. A.21. Electron flood gun construction. (a) Pieces of the Electron Flood Gun. (b) View of the lens stack separated by ruby spheres, the can and the back cab. (c) Assembled flood gun.
APPENDIX B

ONLINE ELECTRON RANGE TOOL

Two different range computation tools have been developed to make the database more readily available and to extend its applicability. The first tool is a Microsoft Excel worksheet and the second is an HTML/JavaScript webpage hosted by Utah State University’s Materials Physics Group at http://mpg.physics.usu.edu/range/ (Wilson and Dennison, 2012).

B.1 Microsoft Excel Worksheet

The Microsoft Excel worksheet as shown in Fig. B.1 is a multipage worksheet which calculates the electron range and IMFP for 246 materials using a database of materials properties and values of $N_{\text{eff}}$ determined from fits to the NIST databases (Technology, 2010a; Wilson and Dennison, 2012). The worksheet also allows 10 user input custom materials for which $N_{\text{pre}}$ is determined by user input materials information. The calculated range data are presented in both tabular and graphical format as shown in Fig. B.1.

![Table](image)

**FIG. B.1.** Left side of the Graphs and Data tab. This includes a drop-down list of three different materials, check boxes to include each data set in the output, energy range settings, and a tabular list of the data.
The worksheet is organized into several tabs including the *Information*, *Graphs and Data*, *Custom Material*, *Material Data*, *Range Calculation*, and *IMFP Calculation* tabs. All user-customizable fields are denoted with an orange fill, as shown in Fig. B.1. Cells without orange fill should not be changed without a clear understanding of inner workings of the worksheet.

The *Information* tab acts as a front end to the worksheet with links to information on how to use the worksheet, the theoretical basis for the model and its development, and supporting references for this and related range models.

The *Graphs and Data* tab (Fig. B.2) is the main worksheet where user interaction occurs. This tab includes three drop-down lists where three different materials can be selected. Below each drop-down list is a check box which turns the data export for each material on or off. The material properties are then displayed in a table to the right. The range data are presented in two formats which can be copied and pasted into other

<table>
<thead>
<tr>
<th>Material</th>
<th>Formula</th>
<th>$Z_A$</th>
<th>$\rho_m$ (g/cm$^3$)</th>
<th>$\overline{\mu}_A$ (amu)</th>
<th>$N_v^{\text{eff}}$</th>
<th>$E_{\text{gap}}$ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gold</td>
<td>Au</td>
<td>79</td>
<td>19.32</td>
<td>196.97</td>
<td>7.684</td>
<td>0</td>
</tr>
<tr>
<td>Silicon Glass</td>
<td>SiO$_2$</td>
<td>9.98</td>
<td>2.32</td>
<td>19.99</td>
<td>2.793</td>
<td>9.5</td>
</tr>
<tr>
<td>Aluminium</td>
<td>Al</td>
<td>13</td>
<td>2.7</td>
<td>26.98</td>
<td>3.254</td>
<td>0</td>
</tr>
</tbody>
</table>

FIG. B.2. Right side of the *Graphs and Data* tab. This includes lists of the material properties of the selected materials, as well as a customizable graph of the data.
applications for further use by the user: (i) a tabular format and (ii) a graphical format (When pasting the graph into another Microsoft program, use the Picture option).

Any formatting properties of the graph can be readily changed according to user preferences using Excel options. The energy range for calculations and plotting can also be customized by editing the values in cells B8 and D8, which will automatically adjust the graph axes to fit the data. The Log Energy checkbox in cell E8, automatically changes the graph between a Log-Log plot and a Linear-Linear plot and changes the spacing of the 200 energy values calculated from linear to logarithmic.

The Custom Material tab (Fig. B.3) is used to input custom material properties and determine the number-weighted Mean Atomic, \( \bar{Z} \), and Average Atomic Weight, \( \bar{M} \), for up to 10 custom materials. \( \bar{Z} \) and \( \bar{M} \) are calculated for a custom material by entering the number of atoms of each element (rows 6 to 108) from the material’s chemical formula. For example, in column D of, sodium chloride (NaCl) is entered as a custom material, with the name in cell D1, the chemical formula in cell D2, the mass density in cell D3, the band gap in cell D4, and 1 in cells D16 and D22 for Na and Cl respectively. Cells D119 and D120 list the calculated values of 14 for \( \bar{Z} \) and 29.22 for \( \bar{M} \). Calculations and plots for custom material can then be selected from one of the three drop-down boxes in the Graphs and Data tab. Note, the custom materials are found at the bottom of the list and not in alphabetical order. Values for the relative number of atoms for a material can also be entered as percentages; see an example for tin-rich indium-tin oxide (ITO) in column G. Specific isotopes of elements (rows 109-115 for deuterium (D), tritium (T), He\(^3\), C\(^{13}\), C\(^{14}\), N\(^{15}\), O\(^{18}\) and rows 116 to 117 for two isotopes) with user-defined atomic numbers and atomic weights can also be selected for custom materials; see an example for partially deuterated polyimide \([C_{22}H_{53}N_{22}O_{5}]_n\) in column E.

The Material Data tab includes a table which lists all of the 246 materials for which \( N_{\text{eff}} \) has been determined from fits to the NIST databases, along with the required material properties and parameters for the model. At the bottom of the material list is a set of 10 rows for custom materials carried over from the Custom Material tab along with their material properties, fitting constants, and model parameters.

The Range Calculation tab calculates the range for all materials listed in the Material Data tab (246 NIST materials and 10 custom materials) for the energies specified in column B using the parameters found in the Material Data tab. The energies specified in column B are determined by the \( E_{\text{min}} \) and \( E_{\text{max}} \) values and the Log Energy checkbox found on the Graphs and Data tab.
The IMFP Calculation tab lists the calculated IMFP data values from the TPP-2M equation, as described in (Tanum et al., 2005a; Wilson and Dennison, 2012), for all materials listed in the Material Data tab. The energies used in the calculation are pulled from the Range Calculation tab.

FIG. B.3. The Custom Material tab in the Excel worksheet. Examples are shown for sodium chloride, PEEK, partially deuterated LDPE, and tin-rich ITO.
B.2 HTML/JavaScript Webpage

The HTML/JavaScript webpage, shown in Fig. B.4, is an online tool which calculates the electron range for 246 NIST materials as well as any number of custom materials. The webpage consists of two different pages, the Supporting Documents and the Electron Range Approximation Tool page.

The Supporting Documents page is nearly identical to the Information Page of the Excel worksheet. It lists the current version of the Range Tool and the date it was updated, as well as the current supporting documents and references.

The Electron Range Approximation Tool page consists of several different parts that allows users to select the data to output and several input boxes for user control.

To begin using the tool, a user selects the desired material by clicking the Material drop-down box as shown in Fig. B.4. Next, click the Add Material button to the right of the drop-down box to add the material to the Material Table and the graph. To add multiple materials, simply select another material from the drop-down box and click the Add Material button again. This can be done for any number of materials.

The Material Table shown in Fig. B.5 shows the currently graphed materials, along with their key material parameters. The Legend column of the Material Table allows users to customize the color of the trace of a specific material. The Remove Material buttons allows users to either remove a specific material by clicking the corresponding Remove button or remove all materials by clicking the Remove All button in the header row.

After one or more materials are added to the table and graph, the desired energy range can be customized by changing the Energy Min (eV), Energy Max (eV), and Energy Steps buttons. You can also select whether the energy steps are linearly or logarithmically spaced by checking or unchecking the Log (E) checkbox. The range of energies that are applicable for this model is ~10 eV to ~10^7 eV. If you select energies outside of this range, the input box will be outlined and red and a warning will popup. The number of energy steps can also be configured, but should generally be less than 10^5 points or the webpage may become
FIG. B.4. The HTML/JavaScript webpage. At the top of the page is the Material drop-down box. Just to the right of the drop-down box is the Add Material button. Just below those is the Material Table. Below those are the Energy Input Boxes and below these are the Data Export buttons. The Graph, rendered by an HTML Canvas using D3.js, takes up the rest of the webpage.
unstable. The vertical range axis of the graph can also be changed between linear and logarithmic by unchecking or checking the Log (R) checkbox.

After selecting the desired materials to graph, the data can be output in several formats using the three export buttons located directly above the graph. The Material Table Export method exports the Material Table as a tab-delimited text file. The Export Graph method exports the graph as a .png image file. The Export Data method exports the range data as a tab-delimited text file that can be imported into Microsoft Excel or other analysis or graphing programs compatible with tab-delimited text files.

To input a custom material with the HTML/JavaScript online tool, first select Custom in the Material drop-down box found at the top of the material list. A set of input boxes will appear (Fig. B.5) to input the required material properties. The Material Name and Formula are entered as text, whereas the other inputs are numeric.

Material $\bar{Z}_A$ and Material $\bar{M}_A$ can both be automatically calculated by clicking the Calculate button to the right of Material $\bar{Z}_A$. This opens a popup window, as shown in Fig. B.6. To use this calculator, click on the cell in the periodic table corresponding to an element or isotope listed in the chemical formula and enter the number (or fraction) of atoms for the given element; repeat this for all the elements/isotopes in the material formula. To remove an element from the calculation, simply click on the element and enter 0. When all elements/isotopes are entered, click on the Ok button at the bottom right of the popup. Scroll down or maximize the popup window if you cannot see the Ok button or some elements are not visible in the popup window. Alternately, you can click the gray area outside the popup to close the calculator and enter the values manually.

To have the HTML/JavaScript online tool automatically calculate $N_{\text{pre}}$ using the predicted method, enter 0 in the input box for $N_c$. Once all the custom material properties have been entered, click on the Add Material button to insert it into the list for analysis and graphing. You can repeat the procedure to add additional custom materials.
FIG. B.5. The custom material input boxes. $\bar{Z}_A$ and $\bar{M}_A$ can be calculated by clicking the Calculate button which opens a popup window where the chemical formula can be entered, as shown in FIG. B.6. The Material Table which includes the material name, chemical formula, atomic number, atomic mass, effective number of valence electrons, and band gap. The table also includes the Legend, which allows you to change the line color in the graph and a column with buttons to remove the material from the table and graph.
FIG. B.6. The color-coded periodic table for $\bar{Z}_A$ and $\bar{M}_A$ calculation of custom materials. Note additional isotopes in gray cells in the top row of the table.
EDUCATION:


2016 – MS Physics; Montana State University, Bozeman, Montana

2011 – BS Physics; Utah State University, Logan, Utah

2011 – BS Mathematics; Utah State University, Logan, Utah

2005 – Associates of Science; Dixie State College, St. George, Utah

EXPERIENCE:

2019-Pres. – Senior Scientist - Electro Magnetic Applications, Int. Lakewood, CO

Specialize in space environment effects on materials and spacecraft as well as electromagnetic effects of lightning and other high current/high voltage phenomenon. Perform testing and simulation of electromagnetic effects on materials, aircraft, and spacecraft.

2018-2019 – Senior Engineer - National Technical Systems, Pittsfield, MA

Perform lightning effect simulations using COMSOL and several data analysis tools. Developed several JavaScript methods to automate geometry creation and other simulation processes. Teach lightning effects on aircraft courses with an emphasis on simulation and modeling.

2016-2019 – Graduate Research Assistant - Utah State University, Logan, UT

Expanded electron range models, redesigned and constructed secondary yield and surface voltage instrumentation, designed and constructed small form factor electron flood gun, designed and created a program to visually detect radiation induced arcing events, developed instrumentation and computer interfacing for two material characterization test chambers.

2013-2016 – Graduate Research/Teaching Assistant - Montana State University, Bozeman, MT

Developed and tested embedded RF antennas in 3D printed structures. Taught undergraduate beginning
physics lab courses.

2013 – AFRL Summer Internship – AFRL, Albuquerque, NM

Worked on data acquisition system for RIC measurements. Developed low energy electron flux sensor.

Worked on instrumentation for energetic electron radiation measurements. Developed magnetic field control system for low energy electron flood gun.

2010-2013 – Undergraduate/Graduate Research Assistant - Utah State University, Logan, UT

Worked on electron range modeling, cathodoluminescence, surface voltage charging and measurement and effects of energetic electron bombardment.

FUNDING:

USU Utah NASA Space Grant Consortium Fellowship (UNSGC), ($30,000, August 2016 to July 2018) [for Gregory Wilson with JR Dennison].


USU Undergraduate Research and Creative Opportunities (URCO), "Degradation Effects of Ionizing Radiation on Commercially Available Spacecraft Components," ($2,350, June 2016 to December 2016) [for Alex Souvall with Gregory Wilson and J.R. Dennison].

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ORGANIZATIONS:

Memberships: American Physical Society, Institute for Electrical and Electronics Engineers, and Sigma Pi Sigma.

REFEREED PUBLICATIONS:


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Anne Starley, Gregory Wilson, Lisa Phillipps and JR Dennison, “Predictive Formula for Electron Penetration Depth of Diverse Materials over Large Energy Ranges,” *Proceedings of the 14th Spacecraft Charging Technology Conference*, Space Research and Technology Centre of the European Space Agency (ESA/ESTEC), (Noordwijk, Netherlands, April 4-8, 2016), 2 pp.


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SENIOR THESES AND PROJECTS:


