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Materials at the Atomic Scale: A Key to Exploring the Vast Reaches of Space

JR Dennison
Utah State University

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Materials at the Atomic Scale: A Key to Exploring the Vast Reaches of Space

J.R. Dennison

Materials Physics Group
Physics Department, Utah State University

Jet Propulsion Laboratory
August 3, 2015
To paraphrase Douglas Adams, “Space is [harsh]. You just won’t believe how vastly, hugely, mind-bogglingly [harsh] it is.”

Interactions with this harsh space environment can modify materials and cause unforeseen and detrimental effects to spacecraft.
Primary Motivation For Our Research—Spacecraft Charging

NASA’s concern for spacecraft charging is caused by plasma environment electron, ion, and photon-induced currents. Charging can cause performance degradation or complete failure.

Majority of all spacecraft failures and anomalies due to the space environment result from plasma-induced charging

- Single event interrupts of electronics
- Arching
- Sputtering
- Enhanced contamination
- Shifts in spacecraft potentials
- Current losses
What do you need to know about the materials properties?

**Charge Accumulation**
- Electron yields
- Ion yields
- Photoyields

**Charge Transport**
- Conductivity
- RIC
- Dielectric Constant
- ESD

As functions of materials species, flux, and energy.

Dynamics of the space environment and satellite motion lead to dynamic spacecraft charging.

- Solar Flares
- Rotational eclipse

Complex dynamic interplay between space environment, satellite motion, and materials properties.
A Puzzle from Solar Probe Plus: Temperature and Dose Effects

**Wide Temperature Range**

<100 K to >1800 K

**Wide Dose Rate Range**

Five orders of magnitude variation!

**Wide Orbital Range**

Earth to Jupiter Flyby
Solar Flyby to 4 $R_s$
Integration with Spacecraft Charging Models

SEE Handbook or NASCAP predicts on-orbit spacecraft charging in GEO and LEO environments.

Materials Research

NASCAP Upgrades

Typical SEE Handbook Simulation
Spacecraft Interactions with Space Plasma Environment

Spacecraft adopt potentials in response to interaction with the plasma environment.

- **Incident fluxes and electron emission govern amount of charge accumulation**

- **Resistivity governs:**
  - Where charge will accumulate
  - How charge will redistribute across spacecraft
  - Time scale for charge transport and dissipation

- **Conservation of charge implies:**

  \[ Q_{net} = \{Q_{Incident} - Q_{Emitted}\} \]
Charge Balance Equation

In terms of particle properties

\[ Q_{\text{net}} = \{Q_{\text{Incident}} - Q_{\text{Emitted}}\} \]

\[ = \left\{ -q_e N_e + q_{\text{Ion}} N_{\text{Ion}} + q_{\text{Ph}} N_{\text{Ph}} \right\} - (-q_e) \cdot \left[ N_e' + N_{\text{Ion}}' + N_{\text{Ph}}' \right] \cdot A \cdot \Delta t \]

In terms of electron yields

\[ 0 = \left[ \delta + \eta - 1 \right] \cdot N_e + \left( 1 + \sigma_{\text{Ion}} \right) \cdot N_{\text{Ion}} + \sigma_{\text{Ph}} \cdot N_{\text{Ph}} \]

- \( \sigma_e \equiv \delta + \eta \), Electron-induced electron yields
- \( \sigma_{\text{Ion}} \), Ion-induced electron yields
- \( \sigma_{\text{Ph}} \), Photon-induced electron yields

➢ Assumes no ions emitted, \( q_{\text{Ion}} = q_e \), and \( q_{\text{Ph}} = 0 \)
Extension to Flux Energy Distributions

For energy independent flux densities

\[ 0 = \left[ \delta + \eta - 1 \right] \cdot N_e + \left( 1 + \sigma_{Ion} \right) \cdot N_{Ion} + \sigma_{Ph} \cdot N_{Ph} \]

Weighting for energy dependent flux densities (#/m²-s-eV)

\[ \int N_e(E_e) \cdot dE_e = \int \left[ \delta(E_e) + \eta(E_e) \right] \cdot N_e(E_e) \cdot dE_e + \left\{ \int \left[ 1 + \sigma_{Ion}(E_i) \right] \cdot N_{Ion}(E_i) \cdot dE_i + \int \sigma_{Ph}(E_{Ph}) \cdot N_{Ph}(E_{Ph}) \cdot dE_{Ph} \right\} \]

- Determines net charge
- Separates environment and materials effects (mostly)
- Positive charging terms ranked in importance:
  - Ion effect usually small
  - Photon effect often dominates in sunlight
  - In eclipse, driven by \( \delta + \eta \)
Causes of Threshold Charging
Changes in Space Plasma Environment

Electron Critical Temperature

\[
\int N_e(E_e) \cdot dE_e = \int \left[ \delta(E_e) + \eta(E_e) \right] \cdot N_e(E_e) \cdot dE_e + \left\{ \int [1 + \sigma_{ion}(E_i)] \cdot N_{ion}(E_i) \cdot dE_i + \int \sigma_p(E_p) \cdot N_p(E_p) \cdot dE_p \right\}
\]

Model Electron Flux Density as Maxwellian Distribution:

\[ N_e(E_e) = N_e(E_e; T_e, n_e) \]

Solve charge balance equation for critical temperature, \( T^* \), at which charge fluxes balance and sample potential = 0 eV

Verified in theory and on spacecraft by Olsen, Laframboise and Lai

Lai & Della-Rose, 2001
Causes of Threshold Charging
Changes in Space Plasma Environment
Relative Electron Flux Density

\[ 1 = \langle \delta + \eta \rangle + \left( \frac{N_{Tot}^{Ion}}{N_e^{Tot}} \right) \cdot \langle 1 + \sigma_{Ion}(E_{Ion}) \rangle + \left( \frac{N_{Tot}^{Ph}}{N_e^{Tot}} \right) \cdot \langle \sigma_{Ph}(E_{Ph}) \rangle \]

Model Electron Flux Density as proportional to plasma density:

\[ N_e(E_e) = n_e \cdot N_e(E_e; T_e) \]

If ion and photon contributions are negligible, no critical plasma density

Only if electron contribution alone leads to negative charging, there can be transition to positive charging as ion or photon contribution increases

Verified by Olsen and Lai

Lai & Tautz, 2006
Causes of Threshold Charging
Changes in Environment/Spacecraft Interface
Satellite Orbit and Satellite Geometry

\[ \int N_e(E_e) \cdot dE_e = \int [\delta(E_e) + \eta(E_e)] \cdot N_e(E_e) \cdot dE_e + \left\{ \int [1 + \sigma_{Ion}(E_i)] \cdot N_{Ion}(E_i) \cdot dE_i + \int \sigma_{Ph}(E_{Ph}) \cdot N_{Ph}(E_{Ph}) \cdot dE_{Ph} \right\} \]

Obviously, changes in orbit can lead to changes in fluxes
- Eclipse by Earth
- Radiation belts
- Magnetotail aberation

Adjacent surfaces can affect fluxes
- Shadowing
- Reflection
- Differential charging

Fluxes and yields coupled through charge accumulation

Lai & Tautz, 2006
Causes of Threshold Charging  
Changes in Environment/Spacecraft Interface  

**Satellite Orientation**

\[
\int N_e(E_e) \cdot dE_e = \int [\delta(E_e) + \eta(E_e)] \cdot N_e(E_e) \cdot dE_e + \left\{ \int [1 + \sigma_{Ion}(E_i)] \cdot N_{Ion}(E_i) \cdot dE_i + \int \sigma_{Ph}(E_{Ph}) \cdot N_{Ph}(E_{Ph}) \cdot dE_{Ph} \right\}
\]

Consider satellite orientation relative to directional fluxes

- Sunlight
- Solar wind
- Trapped particle fluxes

Effective cross section acts as dot product

Penetration depth effect
- Valid for incident particles \( \lambda_{mfp} > \) emitted electron \( \lambda_{mfp} \)
  - e.g., SE and photon
- Not valid for BSE or low energy ions
  - (Reflectivity dealt with below)

\[
\langle \sigma_P \rangle = \frac{1}{N_{Tot}} \int [N_P(E_P) \cos(\varphi)] \left\{ \frac{\sigma^n(E_P)}{\cos(\varphi)} \right\} dE_P
\]

Effective Surface Area

Lai & Tautz, 2006
Causes of Threshold Charging

Materials Parameters

Change of Materials

\[
N_e(E_e) \cdot dE_e = \int \left[ \delta(E_e) + \eta(E_e) \right] \cdot N_e(E_e) \cdot dE_e
\]

\[+ \left\{ \int [1 + \sigma_{ion}(E_i)] \cdot N_{ion}(E_i) \cdot dE_i + \int \sigma_{ph}(E_{ph}) \cdot N_{ph}(E_{ph}) \cdot dE_{ph} \right\}
\]

Causes of Threshold Charging

Materials Parameters

Change of Materials

Measured Materials Properties Used in Spacecraft Charging Codes

19 Materials Parameters used in NASCAP-2k:

- Electron-induced SE and BSE emission
- Ion-induced electron emission
- Photoyield
- Resistivity
- Radiation-induced conductivity

NASCAP Parameter | Value
--- | ---
[1] Relative dielectric constant; \( \varepsilon_r \) | 2.77 ± 0.1
[2] Dielectric film thickness; \( d \) | 2.5 μm
[3] Bulk conductivity; \( \sigma_o \) | \((1.0 \pm 0.5) \cdot 10^{-19}\) ohm\(^{-1}\)·m\(^{-1}\)
[4] Effective mean atomic number <\( Z_{eff} >\) | 20.6 ± 0.5
[5] Maximum SE yield for electron impact; \( \delta_{max} \) | 1.10 ± 0.01
[6] Primary electron energy for \( \delta_{max} \); \( E_{max} \) | (0.17 ± 0.01) keV
[7] First coefficient for bi-exponential range law, \( b_1 \) | 1 Å
[8] First power for bi-exponential range law, \( n_1 \) | 1.70 ± 0.01
[9] Second coefficient for bi-exponential range law, \( b_2 \) | 0.32 ± 0.02 Å
[10] Second power for bi-exponential range law, \( n_2 \) | 0.47 ± 0.01
[11] SE yield due to proton impact \( \delta^H (1 \text{keV}) \) | 0.647 ± 0.001
[12] Incident proton energy for \( \delta_{max}^H \); \( E_{max}^H \) | (1000 ± 250) keV
[13] Photoelectron yield, normally incident sunlight, \( \sigma_{pho} \) | \((4.88 \pm 0.1) \cdot 10^{-5}\) A·m\(^{-2}\)
[14] Surface resistivity; \( \rho_s \) | 2.10\(^{10}\) ohms-square
[15] Maximum potential before discharge to space; \( V_{max} \) | 10000 V
[16] Maximum surface potential difference before dielectric breakdown discharge; \( V_{punch} \) | 850 V
[17] Coefficient of radiation-induced conductivity, \( \sigma_r \); \( k \) | 2.·10\(^{-15}\) ohms\(^{-1}\)·m\(^{-1}\)
[18] Power of radiation-induced conductivity, \( \sigma_r \); \( \Delta \) | \(1.434 \pm 0.02\)·10\(^{-3}\) kg·m\(^{-3}\)
[19] Density; \( \rho \) | \((1.434 \pm 0.02) \cdot 10^3\) kg·m\(^{-3}\)
Electron Terms

\[ \int N_e(E_e) \cdot dE_e = \int \left[ \delta(E_e) + \eta(E_e) \right] \cdot N_e(E_e) \cdot dE_e \]

\[ + \left\{ \int [1 + \sigma_{ion}(E_i)] \cdot N_{ion}(E_i) \cdot dE_i + \int \sigma_{ph}(E_{ph}) \cdot N_{ph}(E_{ph}) \cdot dE_{ph} \right\} \]

- \( E_1 \) and \( E_2 \) where curves cross when ion and photon terms neglected
- Areas between curves determine \( Q_{net} \)
- Can contribute positive or negative net charge

Electron Yield Curve

Electron Flux Density and Weighted Flux

- Standard Day 9/4/97
- Purvis Worst Case
- AT-6 Extreme
Return current due to biasing leads to Threshold Charging

(a) Normal emission

V_{bias} = 0
V_{bias} < 0
V_{bias} > 0

(b) Non-normal emission

V_{bias} = 0
V_{bias} < 0
V_{bias} > 0

Positive Charging
E_1 < E_0 < E_2 with \sigma > 1
Shifts emission spectra left

Negative Charging
E_0 > E_2 with \sigma < 1
Shifts emission spectra right
Photon Term

\[
\int N_e(E_e) \cdot dE_e = \int \left[ \delta(E_e) + \eta(E_e) \right] \cdot N_e(E_e) \cdot dE_e \\
+ \left\{ \int [1 + \sigma_{I_{ion}}(E_i)] \cdot N_{I_{ion}}(E_i) \cdot dE_i + \int \sigma_{P_{ph}}(E_{ph}) \cdot N_{P_{ph}}(E_{ph}) \cdot dE_{ph} \right\}
\]

- Photon magnitude usually large
- “Turned off” in eclipse
- Always contributes positive charge
Ion Term

\[
\int N_e(E_e) \cdot dE_e = \int \left[ \delta(E_e) + \eta(E_e) \right] \cdot N_e(E_e) \cdot dE_e + \left\{ \int \left[ 1 + \sigma_{\text{Ion}}(E_i) \right] \cdot N_{\text{Ion}}(E_i) \cdot dE_i + \int \sigma_{\Phi}(E_{\Phi}) \cdot N_{\Phi}(E_{\Phi}) \cdot dE_{\Phi} \right\}
\]

- Ion magnitude usually small
- Always contributes positive charge

Ion Yield Curve

Ion Flux Density and Weighted Flux

Au

Standard Day
9/4/97

Purvis
Worst Case

AT-6
Extreme
Miscalibration or systematic errors of materials measurements can lead to errors

- Absolute yield calibration changes $\delta_{\text{max}}$ & $\sigma_{\text{max}}$
- Instrument miscalibration of offset potentials of sources, sample and detector can shift $E$ axis and effect $E_{\text{max}}$, $E_1$ and $E_2$
- Study of “critical values” for $\delta_{\text{max}}$, $E_{\text{max}}$, $n$, $Z_{\text{eff}}$, $T_e$, and $n_e$ (Chang & Dennison, 2000)
Causes of Threshold Charging

Materials Parameters

Contamination and Layered Materials

\[
\int N_e(E_e) \cdot dE_e = \int [\delta(E_e) + \eta(E_e)] \cdot N_e(E_e) \cdot dE_e + \left\{ \int [1 + \sigma_{\text{Ion}}(E_i)] \cdot N_{\text{Ion}}(E_i) \cdot dE_i \right\} + \int \sigma_{\text{Ph}}(E_{\text{Ph}}) \cdot N_{\text{Ph}}(E_{\text{Ph}}) \cdot dE_{\text{Ph}}
\]

Dramatic changes in charging potential result from modest contamination in this ground-based study.

SE yield changes by \(\sim\) factor of 2 for C contamination of Au and Al/Al\(_2\)O\(_3\)

Full scale contamination on this graph is about 2-3 monolayers of carbon on Au.

A “critical contamination” observed for NASCAP Interactive Spacecraft Charging Handbook studies of “flat panel test”

Layered materials thinner than \(\lambda_{\text{mfp}}\) behave similar to contamination

Chang & Dennison, 2000
Causes of Threshold Charging
Materials Parameters
Charge Accumulation

\[
\int N_e(E_e) \cdot dE_e = \int [\delta(E_e) + \eta(E_e)] \cdot N_e(E_e) \cdot dE_e \\
+ \left\{ \int [1 + \sigma_{Ion}(E_i)] \cdot N_{Ion}(E_i) \cdot dE_i \right\} + \int \sigma_{Ph}(E_{Ph}) \cdot N_{Ph}(E_{Ph}) \cdot dE_{Ph} \right\}
\]

- Accumulated charge affects all phases of yield mechanisms
  - SE production
  - SE transport
  - SE emission

- Accumulated charge also affects incident fluxes and return currents
Causes of Threshold Charging

Materials Parameters
Charge Accumulation

\[
\int N_e(E_e) \cdot dE_e = \int [\delta(E_e) + \eta(E_e)] \cdot N_e(E_e) \cdot dE_e \\
+ \left\{ \int [1 + \sigma_{Ion}(E_i)] \cdot N_{Ion}(E_i) \cdot dE_i \\
+ \int \sigma_{Ph}(E_{Ph}) \cdot N_{Ph}(E_{Ph}) \cdot dE_{Ph} \right\}
\]

• As charge accumulates in yield decay curves, yield decreases toward unity

• Can generate pseudoyield curves for low energy fluences

• Lowest fluence yield produced positive equilibrium potential

• Higher fluence yield curves produced negative equilibrium potential
Causes of Threshold Charging

Materials Parameters
Optical Absorptivity

\[
\int N_e(E_e) \cdot dE_e = \int \left[ \delta(E_e) + \eta(E_e) \right] \cdot N_e(E_e) \cdot dE_e \\
+ \left\{ \int \left[ 1 + \sigma_{I_on}(E_i) \cdot N_{I_on}(E_i) \cdot dE_i + \int \sigma_{p_h}(E_{p_h}) \cdot N_{p_h}(E_{p_h}) \cdot dE_{p_h} \right] \right\}
\]

- Only absorbed photons deposit energy into the material and can thus create SE.

- Typical absorptivity has another cos term

- Both reflectivity and transmission can affect absorbtivity.

\[
\langle \sigma_{p_h} \rangle_e = \frac{1}{N_e^{Tot}} \int \left[ N_{p_h}(E_{p_h}) \cos(\varphi) \right] \left\{ \frac{\sigma_{p_h}^n(E_{p_h})}{\cos(\varphi)} \right\} \left[ 1 - R_n(E_{p_h}) - T_n(E_{p_h}) \cos(\varphi) \right] dE_{p_h}
\]

Effective Surface Area  Penetration Depth Effect  Absorptivity

Also see Lai & Tautz, 2006
Causes of Threshold Charging
Materials Parameters

Materials Properties Parameterization

\[ N_e(E_e) \cdot dE_e = \int [\delta(E_e) + \eta(E_e)] \cdot N_e(E_e) \cdot dE_e \]

\[ + \left\{ \int [1 + \sigma_{Ion}(E_i)] \cdot N_{Ion}(E_i) \cdot dE_i \right\} + \int \sigma_{Ph}(E_{Ph}) \cdot N_{Ph}(E_{Ph}) \cdot dE_{Ph} \]

Poor parameterization of materials data can lead to errors

- SE Yield 3 to 5 parameter empirical fit poor, especially for insulators.
- BSE Yield fit is very poor single parameter empirical fit
- Ion Yield is very poor 2 parameter empirical fit focused at high energy
- Photoyield not even energy dependant

- No dependence on T, Q, E, history
- Cannot handle layers or contamination
Causes of Threshold Charging
Materials Parameters
Bandgap and Electron Yields

\[
\int N_e(E_e) \cdot dE_e = \int \left[ \delta(E_e) + \eta(E_e) \right] \cdot N_e(E_e) \cdot dE_e \\
+ \left\{ \int \left[ 1 + \sigma_{\text{ion}}(E_i) \right] \cdot N_{\text{ion}}(E_i) \cdot dE_i + \int \sigma_{\text{ph}}(E_{ph}) \cdot N_{ph}(E_{ph}) \cdot dE_{ph} \right\}
\]

Changes in Bandgap affect SE production and SE transport

- Changes in conduction band population
  - Thermal excitation
  - Photo excitation
  - Radiation excitation

- Changes in band structure
  - Thermal annealing
  - Radiation damage

- Grais and Bastawaros (2004) -- 21 semiconductors and insulators [top graph].

- Corbridge and Dennison (2004) -- changes in small bandgaps due to thermal annealing [bottom graph]
Complex dynamic interplay between space environment, satellite motion, and materials properties

USU Studies

Environment Conditions ↔ Materials Conditions ↔ Materials Properties ↔ Spacecraft Charging
Complex dynamic interplay between space environment, satellite motion, and materials properties

Consider 5 Cases of Dynamical Change in Materials:

- Contamination and Oxidation
- Surface Modification
- Radiation Effects (and t)
- Temperature Effects (and t)
- Radiation and Temperature Effects
Case I: Evolution of Contamination and Oxidation

“All spacecraft surfaces are eventually carbon…”
--C. Purvis

This led to lab studies by Davies, Kite, and Chang
Case I: Evolution of Contamination and Oxidation

Wake Side

- 13 Grounded Samples
- 12 Biased Samples: for 3 sets of 4 samples with low current biases for charge-enhanced contamination studies.
- 6 Concealed samples

Sample Holders

- Holder area 5 cm x 15 cm
- 9 mm diameter exposed sample area

Grounded Guard Plate

-5 VDC

Before & After
Kapton, HN

Before & After
Ag coated Mylar with micrometeoroid impact

Grounded Samples

Before & After
Black Kapton

+5 VDC

Before & After
Ag coated Mylar

-15 VDC
Case II: Surface Modification

Reflectivity changes with surface roughness

Successive stages of roughening of Cu

Absorption Coefficient from Diffuse Reflection

Reflectivity Change
Cases I and II: Reflectivity as a Feedback Mechanism

Reflectivity changes with surface roughness and contamination

- Reflect → Charging → Contamination
- Reflect → Emissivity → Temp → Contamination
- Charging → Reflectivity
- Radiation → Reflect → Emissivity → Temp → Contamination

See Lai & Tautz, 2006 & Dennison 2007

JWST Structure: Charging vs. Ablation

Before | Zoomed Images | After
See Lai & Tautz, 2006 & Dennison 2007
Case III: Radiation Effects

Large Dosage (>10^8 Rad)

Medium Dosage (>10^7 Rad)

Low Dose Rate (>10^0 Rad/s)

“...Earth is for Wimps…” H. Garrett

Examples: RBSP, MMS, JUNO, JGO/JEO

“...auroral fields may cause significant Radiation induced Conductivity (RIC) changes...” H. Garrett

Mechanical Modification of Electron Transport and Emission Properties Caused by bondbreaking and trap creation

Examples: RBSP, JUNO, JGO/JEO

Temperature dependent Radiation induced Conductivity (RIC) Total Yield (electronlike)}
Case IV: Temperature Effects

Strong T Dependence for Insulators

Charge Transport
- Conductivity
- RIC
- Dielectric Constant
- ESD

Examples:

IR and X-Ray Observatories
JWST, WISE, WMAP, Spitzer, Herscel, IRAS, MSX, ISO, COBE, Planck

**Outer Planetary Mission**
Galileo, Juno, JEO/JGO, Cassini, Pioneer, Voyager,

**Inner Planetary Mission**
SPM, Ulysses, Magellan, Mariner
Case IV: Temperature Effects

Strong T Dependence for Insulators

Charge Transport
- Conductivity
- RIC
- Dielectric Constant
- ESD

\[ k(T) \]

Temperature Dependence of Resistivity with Model Fits

\[ \sigma_{VRH} \sim \exp(T^{-\frac{1}{4}}) \]
\[ \sigma_{TAH} \sim \exp(T^{-1}) \]

Uniform Trap Density
\[ \Delta(T) \to 1 \]
\[ k(T) \to k_{RIC_0} \]

Exponential Trap Density
\[ \Delta(T) \to \frac{T_c}{T + T_c} \]
\[ k(T) \to k_{RIC_1} \left[ 2 \frac{m^*_e k_B T}{2\pi\hbar^2} \left( \frac{m^*_e m^*_h}{m_e m_h} \right)^{3/4} \right]^{T/T_c} \]

\[ \sigma_{RIC}(T, D) = k_{RIC}(T) \cdot D^{\Delta(T)} \]
Case V: Temperature and Dose Effects

**Wide Temperature Range**

$<$100 K to $>$1800 K

**Wide Dose Rate Range**

Five orders of magnitude variation!

**Wide Orbital Range**

Earth to Jupiter Flyby

Solar Flyby to 4 $R_S$
Case V: Temperature and Dose Effects

“We anticipate significant thermal and charging issues.”

J. Sample

Charging Study by Donegan, Sample, Dennison and Hoffmann
Case V: Temperature and Dose Effects

Wide Orbital Range
Earth to Jupiter Flyby
Solar Flyby to 4 $R_s$

Wide Temperature Range
<100 K to >1800 K

Wide Dose Rate Range
Five orders of magnitude variation!
Case V: Temperature and Dose Effects

Dark Conductivity

\[ \sigma_{DC}(T) = \sigma_o^{DC} e^{-E_o/k_B T} \]

RIC

\[ \sigma_{RIC}(T) = k_{RIC}(T) D \]

Dielectric Constant

\[ \varepsilon_r(T) = \varepsilon_{RT} + \Delta \varepsilon (T - 298 K) \]

Electrostatic Breakdown

\[ E_{ESD}(T) = E_{ESD}^{RT} e^{-\alpha_{ESD}(T-298K)} \]
Case V: Temperature and Dose Effects

A peak in charging at ~0.3 to 2 AU

“…Curiouser and curiouser…”

--Alice
Case V: Temperature and Dose Effects

A fascinating trade-off

- Charging increases from increased dose rate at closer orbits
- Charge dissipation from T-dependant conductivity increases faster at closer orbits

General Trends

Dose rate decreases as $\sim r^{-2}$

$T$ decreases as $\sim e^{-r}$

$\sigma_{DC}$ decreases as $\sim e^{-1/T}$

$\sigma_{RIC}$ decreases as $\sim e^{-1/T}$

and decreases as $\sim r^{-2}$
What do you need to know about the materials properties?

Charging codes such as NASCAP-2K, SPIS and NUMIT2, DICTAT require:

**Charge Accumulation**
- Electron yields
- Ion yields
- Photoyields
- Luminescence

**Charge Transport**
- Conductivity
- RIC
- Dielectric Constant
- ESD
- Range

ABSOLUTE values as functions of materials species, flux, fluence, and energy.

At 11th SCTC Ferguson identified four “New Frontiers in Spacecraft Charging”

Specifically, his first two frontiers were:

#1 Non-static Spacecraft Materials Properties
#2 Non-static Spacecraft Charging Models

Complex dynamic interplay between space environment, satellite motion, and materials properties

Changes in materials properties as a function of time, position, energy, and charge:

- Time (Aging), t
- Position (z)
  - Charge distributions, \( Q(z,t) \)
  - Surface voltage, \( \Delta V(xy,t) \)
- Energy
  - Temperature, \( k_B T \)
  - Deposited Energy (Dose), \( D \)
  - Power Deposition (Dose) Rate, \( \dot{D} \)
- Charge
  - Accumulated Charge, \( \Delta Q \) or \( \Delta V(Q, \Delta V,D,\dot{D},t) \)
  - Charge Profiles, \( Q(z,t) \)
  - Charge Rate (Current), \( \dot{Q} \)
  - Conductivity Profiles, \( \sigma(z,t,Q,\dot{Q},D,\dot{D}) \)
  - Electron emission (\( e^- I^+, \Gamma \))
  - Light emission
    - Cathodoluminescence \( I_t(t,xy,Q,D,\dot{D}) \)
    - Arcing \( I_t(t,xy,Q,D,\dot{D}), \dot{Q}_t(t,z,Q,D,\dot{D}) \)
Facilities & Capabilities

Sample Characterization & Preparation
- Bulk composition (AA, IPC).
- Surface contamination (AES, AES mapping ESD).
- Surface morphology (SEM, optical microscopy).

Conduction Related Properties:
- Bulk & surface conductivity.
- High resistivity testing.
- Capacitance, dielectric constant, charge decay monitoring, and electrostatic discharge.

Electron Induced Emission:
- Total, secondary and backscattered yield vs. incident energy and angle.
- Energy-, angle-resolved emission spectra.

Ion Induced Emission:
- Total electron and ion yield versus incident energy and angle.

Photon Induced Emission:
- Total electron yield vs photon energy.
- Energy-angle resolved photoelectron yield cross-sections.

- Two ultrahigh vacuum chambers for electron emission tests equipped with electron, ion, and photon sources, detectors, and surface analysis capabilities.
- Two high vacuum chambers for resistivity tests.
- Extensive space environment simulation capabilities.
A Path Forward for Dynamic Materials Issues

For dynamic materials issues in spacecraft charging:

- Synthesis of results from different studies and techniques
- Development of overarching theoretical models
  
These theoretical models allow extension of measurements made over limited ranges of environmental parameters to make predictions for broader ranges encountered in space.
A Materials Physics Approach to the Problem

Measurements with many methods...

Interrelated through a...

Complete set of dynamic transport equations

\[
J = q_e n_e(z,t) \mu_e F(z,t) + q_e D \frac{dn_{tot}(z,t)}{dz} \\
\frac{\partial}{\partial z} F(z,t) = q_e n_{tot} / \varepsilon_0 \varepsilon_r \\
\frac{\partial n_{tot}(z,t)}{\partial t} - \mu_e \frac{\partial}{\partial z} [n_e(z,t)F(z,t)] - q_e D \frac{\partial^2 n_e(z,t)}{\partial z^2} = N_{ex} - \\
\alpha_{er} n_e(z,t)n_{tot}(z,t) + \alpha_{et} n_e(t)[N_e(z) - n_e(z,t)] \\
\frac{dn_h(z,t)}{dt} = N_{ex} - \alpha_{er} n_e(z,t)n_h(z,t) \\
\frac{dn_e(z,z,\varepsilon,t)}{dt} = \alpha_{et} n_e(z,t)[N_e(z,\varepsilon) - n_e(z,\varepsilon,t)] - \\
\alpha_{te} N_e \exp \left[ -\frac{\varepsilon}{kT} \right] n_e(z,\varepsilon,t)
\]

…written in terms of spatial and energy distribution of electron trap states
Conclusions

• Satellites are not spherical cows…
  Complex satellites require:
  • Complex materials configurations
  • More power
  • Smaller, more sensitive devices
  • More demanding environments
  • More sophisticated modeling with dynamic materials properties

• There are numerous clear examples where accurate dynamic charging models require accurate dynamic materials properties

• It is not sufficient to use static (BOL or EOL) materials properties

• Environment/Materials Modification feedback mechanisms can cause a whole herd of new problems
A Truly Daunting Task....

To address:
• Myriad spacecraft materials
• New, evolving materials
• Many materials properties
• Wide range of environmental conditions
• Evolving materials properties
• Feedback, with changes in materials properties affecting changes of environment

Requires:
• Conscious awareness of dynamic nature of materials properties can be used with available modeling tools to foresee and mitigate many potential spacecraft charging problems
• For dynamic materials issues in spacecraft charging, as with most materials physics problems, synthesis of results from different studies and techniques, and development of overarching theoretical models allow extension of measurements made over limited ranges of environmental parameters to make predictions for broader ranges encountered in space.
• Solid State models based on defect DOS provide synergism between methods for more extensive and accurate materials properties.
Support & Collaborations

NASA SEE Program
JWST (GSFC/MSFC)
SPM (JHU/APL)
RBSP (JHU/APL)
Solar Sails (JPL)
AFRL
Boeing
Ball Aerospace
Orbital
USU Blood Fellowship
AFRL/NRC Fellowship
NASA Grad Res. Fellowships

USU Materials Physics Group

USU MPG Webpage
J. R. Dennison received the B.S. degree in physics from Appalachian State University, Boone, NC, in 1980, and the M.S. and Ph.D. degrees in physics from Virginia Tech, Blacksburg, in 1983 and 1985, respectively. He was a Research Associate with the University of Missouri—Columbia before moving to Utah State University (USU), Logan, in 1988. He is currently a Professor of physics at USU, where he leads the Materials Physics Group. He has worked in the area of electron scattering for his entire career and has focused on the electron emission and conductivity of materials related to spacecraft charging for the last two decades.
Decay time vs. resistivity base on simple capacitor model.

\[ \tau = \rho \varepsilon_r \varepsilon_0 \]

Range of Charge Storage Method

- 1 min \( \rightarrow \) \( \rho \varepsilon_o \approx 1 \times 10^{15} \ \Omega \text{-cm} \)
- 1 hr \( \rightarrow \) \( \rho \varepsilon_o \approx 4 \times 10^{16} \ \Omega \text{-cm} \)
- 1 day \( \rightarrow \) \( \rho \varepsilon_o \approx 1 \times 10^{18} \ \Omega \text{-cm} \)
- 1 yr \( \rightarrow \) \( \rho \varepsilon_o \approx 4 \times 10^{20} \ \Omega \text{-cm} \)
- 10 yr \( \rightarrow \) \( \rho \varepsilon_o \approx 4 \times 10^{21} \ \Omega \text{-cm} \)
- 500 yr \( \rightarrow \) \( \rho \varepsilon_o \approx 1 \times 10^{23} \ \Omega \text{-cm} \)
Resistivity and Dissipation of Charge

**Balance** \( V_{\text{in}} \) and \( V_{\text{out}} = V_{\text{drain}} + V_{\text{splash}} \)

\[
Q(t) = Q_0 + [Q_+(x) - Q_-(x)] + [I_{\text{in}} + (I_{\text{leak}} + I_{\text{emit}})] \cdot \frac{t}{A} + \text{other terms}
\]

- \( I_{\text{leak}} \) determined by charge transport (resistivity or conductivity)
- Resistivity of insulating materials determines:
  - Where charge will accumulate.
  - How charge will redistribute across the spacecraft to reach equilibrium.
  - Where & how much charge will recombine.
  - Time scale for charge transport and dissipation.
Orbit Time and Charge Decay Time

Treating thin film insulator as simple capacitor, charge decay time proportional to resistivity.

\[ \tau = \rho \varepsilon_r \varepsilon_0 \]

1 hr \( \rightarrow \) \( \rho \cdot \varepsilon_0 \sim 4 \cdot 10^{16} \text{ } \Omega\text{-cm} \)

1 day \( \rightarrow \) \( \rho \cdot \varepsilon_0 \sim 1 \cdot 10^{18} \text{ } \Omega\text{-cm} \)

1 yr \( \rightarrow \) \( \rho \cdot \varepsilon_0 \sim 4 \cdot 10^{20} \text{ } \Omega\text{-cm} \)

10 yr \( \rightarrow \) \( \rho \cdot \varepsilon_0 \sim 4 \cdot 10^{21} \text{ } \Omega\text{-cm} \)

Typical orbits from 1 to 24 hours.

Typical orbits from 1 to 24 hours.
Just a drop in the bucket...

Complete set of dynamic transport equations

\[ J = q_e n_e(z,t) \mu_e F(z,t) + q_e D \frac{dn_{tot}(z,t)}{dz} \]

\[ \frac{\partial}{\partial z} F(z,t) = q_e n_{tot}/\varepsilon_0 \varepsilon_r \]

\[ \frac{dn_{tot}(z,t)}{dt} - \mu_e \frac{\partial}{\partial z} [n_e(z,t)F(z,t)] - q_e D \frac{\partial^2 n_e(z,t)}{\partial z^2} = N_{ex} - \alpha_{er} n_e(z,t)n_{tot}(z,t) + \alpha_{et} n_e(t)[N_e(z) - n_t(z,t)] \]

\[ \frac{dn_h(z,t)}{dt} = N_{ex} - \alpha_{er} n_e(z,t)n_h(z,t) \]

\[ \frac{dn_t(z,e,t)}{dt} = \alpha_{et} n_e(z,t)[N_e(z,e) - n_t(z,e,t)] - \alpha_{te} N_e \exp\left[-\frac{e}{kT}\right] n_t(z,e,t) \]

A quantum mechanical model of the spatial and energy distribution of the electron states
Charge Storage Resistivity: Instruments

Experimental setup of the charge storage method
### Application to CRESS IDM Pulse Data

**CRRES IDM Pulse and Environmental Data**

A. Robb Frederickson & Donald H. Brautigam

- Characterize electron flux data
- Model charge profile from dose rate and stopping power
- Calculate internal electric field
- Model transport with measured resistivity
- Predict pulsing rate and amplitude with only environment data, materials parameters, and Maxwell equations !!!

<table>
<thead>
<tr>
<th>Dark Conductivity</th>
<th>Radiation-Induced Conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>typical = $5 \times 10^{-18}$ (Ω-m)$^{-1}$</td>
<td>typical = $0.3 \times 10^{-18}$ (Ω-m)$^{-1}$</td>
</tr>
<tr>
<td>improved $5 \times 10^{-19}$ (Ω-m)$^{-1}$</td>
<td>“improved” same as typical</td>
</tr>
<tr>
<td>best guess $1.7 \times 10^{-19}$ (Ω-m)$^{-1}$</td>
<td>best guess same as typical</td>
</tr>
</tbody>
</table>

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![Electric Field and Pulse Rate graphs](image)
USU Arc/Glow Test Configuration

Sample cooled with I-N$_2$ to 100-135 K. Chamber walls at ambient.
Case IV: Temperature Effects—JWST

**JWST**

**Very Low Temperature**
Virtually all insulators go to infinite resistance—perfect charge integrators

**Long Mission Lifetime (10-20 yr)**
No repairs
Very long integration times

**Large Sunshield**
Large areas
Constant eclipse with no photoemission

**Large Open Structure**
Large fluxes
Minimal shielding

**Variation in Flux**
Large solar activity variations
In and out of magnetotail

**Complex, Sensitive Hardware**
Large sensitive optics
Complex, cold electronics