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Determining Intrinsic Electron Emission Yields of High Resistivity Ceramic Materials

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April 7, 2016
Intrinsic Yield

What is it and why do you care?
Intrinsic Yields

What is it and why do you care?

…the holy grail of spacecraft charging…

…Well, not actually a grail, but rather more like a largish cup not entirely devoid of knowledge and rather useful in understanding the flight of an African swallow….
What do you need to know about the materials properties?

Measured Materials Properties Used in Spacecraft Charging Codes

**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.

Charging codes such as NASCAP-2K or SPENVIS and NUMIT2 or DICTAT.

NASCAP-2k requires 19 Materials Parameters:

<table>
<thead>
<tr>
<th>NASCAP Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>[1] Relative dielectric constant; $\varepsilon_r$</td>
<td>$2.77 \pm 0.1$</td>
</tr>
<tr>
<td>[2] Dielectric film thickness; $d$</td>
<td>$2.5 \mu$m</td>
</tr>
<tr>
<td>[3] Bulk conductivity; $\sigma_o$</td>
<td>$(1.020.5) \cdot 10^8 \text{ ohm}^{-1} \cdot \text{m}^{-1}$</td>
</tr>
<tr>
<td>[4] Effective mean atomic number $&lt;Z_{\text{eff}}&gt;$</td>
<td>$20.6 \pm 0.5$</td>
</tr>
<tr>
<td>[5] Maximum SE yield for electron impact; $\delta_{\text{max}}$</td>
<td>$1.10 \pm 0.01$</td>
</tr>
<tr>
<td>[6] Primary electron energy for $\delta_{\text{max}}$; $E_{\text{max}}$</td>
<td>$(0.17 \pm 0.01) \text{ keV}$</td>
</tr>
<tr>
<td>[7] First coefficient for bi-exponential range law, $b_1$</td>
<td>$1 \text{ Å}$</td>
</tr>
<tr>
<td>[8] First power for bi-exponential range law, $n_1$</td>
<td>$1.70 \pm 0.01$</td>
</tr>
<tr>
<td>[9] Second coefficient for bi-exponential range law, $b_2$</td>
<td>$0.32 \pm 0.02 \text{ Å}$</td>
</tr>
<tr>
<td>[10] Second power for bi-exponential range law, $n_2$</td>
<td>$0.47 \pm 0.01$</td>
</tr>
<tr>
<td>[11] SE yield due to proton impact $\delta^{\text{H}}$ $(1\text{keV})$</td>
<td>$0.647 \pm 0.001$</td>
</tr>
<tr>
<td>[12] Incident proton energy for $\delta_{\text{max}}^{\text{H}}$; $E_{\text{max}}^{\text{H}}$</td>
<td>$(1000 \pm 250) \text{ keV}$</td>
</tr>
<tr>
<td>[13] Photoelectron yield, normally incident sunlight, $\sigma_{\text{pho}}$</td>
<td>$(4.88 \pm 0.1) \cdot 10^{-5} \text{ A} \cdot \text{m}^{-2}$</td>
</tr>
<tr>
<td>[14] Surface resistivity; $\rho_s$</td>
<td>$2 \cdot 10^{12} \text{ ohms}^{-1} \cdot \text{m}^{-1}$</td>
</tr>
<tr>
<td>[15] Maximum potential before discharge to space; $V_{\text{max}}$</td>
<td>$10000 \text{ V}$</td>
</tr>
<tr>
<td>[16] Maximum surface potential difference before dielectric breakdown discharge; $V_{\text{punch}}$</td>
<td>$850 \text{ V}$</td>
</tr>
<tr>
<td>[17] Coefficient of radiation-induced conductivity, $\sigma_r/k$</td>
<td>$2 \cdot 10^{15} \text{ ohms}^{-1} \cdot \text{m}$</td>
</tr>
<tr>
<td>[18] Power of radiation-induced conductivity, $\sigma_r$; $\Delta$</td>
<td>$1$</td>
</tr>
<tr>
<td>[19] Density; $\rho$</td>
<td>$(1.434 \pm 0.02) \cdot 10^3 \text{ kg} \cdot \text{m}^{-3}$</td>
</tr>
</tbody>
</table>
Electron Yields Determine Charge Accumulation

Electron yields characterize a material’s response to incident charged particles.

\[ \text{Yield} = \frac{e_{\text{out}}^-}{e_{\text{in}}^-} \]

Can be \(0<\sigma>>1\)

Leading to + or - charging

- Depends on material
- Incident electron energy
- Temperature
- Charge
  - Grounded conductors replenish net emitted charge in <ps
  - Yields of insulators change as charge accumulates in sample.
  - Intrinsic yield is the zero charge yield
Total, BSE, SE yields of Au with Continuous Beam

Back Scattered Electron Yield (BSE)
- Electrons from beam
- Includes elastically scattered e-
- By convention, >50 eV

Secondary Electron Yield
- Electrons originating from the material
- By convention, <50 eV

Total Electron Yield
- Sum of SE and BSE
Absolute Electron Emission Calibration: Round Robin Tests of Au and Graphite

Introduction

Accurate determination of the absolute electron yields of conducting and insulating materials is essential for models of spacecraft charging and related processes involving charge accumulation and emission due to electron beam and plasma interactions. Measurements of absolute properties require careful attention to calibration, experimental methods, and uncertainties.

This study presents a round robin comparison of these absolute yield measurements performed in four international laboratories. The primary objectives were to determine the consistency and uncertainties of such tests, and to investigate the effects of the similarities and differences of the diverse facilities. Apparatus using various low-fluence pulsed electron beam sources and methods to minimize charge accumulation have been developed and employed at these facilities.

Measurements were made for identical samples with reproducible sample preparation of three standard materials:

- The elemental conductor Au (25 μm thick foil of 99.99% purity)
- The elemental semiconductor HOPG (99.9% purity oriented graphite powder)
- The polymeric insulation polyimide (e.g. Acton Arlon™)

Total electron yields (TEY) of Au and HOPG are reported here.

Absolute electron yield measurements for various materials are necessary to determine absolute charging levels and hence to predict possible electrostatic breakdown and injection of charges into plasma. They have direct application to spacecraft charging, high voltage direct current (HVDC) power and transmission lines, ion thrusters, plasma deposition, multipactor, semiconductor metal-oxide interfaces, and nanoelectronics.

Descriptions of Facilities and Methods

CSIC SEY Facility

The CSIC SEY Facility of the Surface Engineering for Space and Terrestrial (SEST) Group at the University of Madrid (Spain) was used for the measurements. The facility includes a high-fluence electron beam source, a precision voltage measurement system, and a detection system.

LaSEINE TEEY Facility

The Laboratory of Nanotechnology for Water Treatment at the University of Lyon (France) was used for the measurements. The facility includes a high-fluence electron beam source, a precision voltage measurement system, and a detection system.

USU SEEM Facility

The Utah State University Space Physics and Astronomy Group (USU) has developed an electron beam source for use in electron emission measurements. The source is capable of producing a high-fluence electron beam with a variable energy range.

Measurements capabilities include:

- Wide energy range (1-100 keV)
- High fluence capabilities (up to 10^15 e^-/cm^2)
- Precision voltage measurement system
- Detection system

Onera DEESSE Facility

The Onera DEESSE Facility in France was used for the measurements. The facility includes a high-flux electron beam source, a precision voltage measurement system, and a detection system.

Round Robin Tests Results

Measurements were made of the absolute total electron yields at normal incidence over the full range of incident energies accessible with each group's instrumentation (a full range of 1 to 100 keV). Figures show linear plots with low energy detail insets (LEDS) and log-log plots of scaled yields (n/ν) versus scaled energy E/ν.

Summary

Summary of results:

- High correlation among the different facilities
- Good agreement between the different facilities
- Agreement with previous measurements

Topics of future round robin analysis:

- Additional facilities and measurements
- Comparison with other techniques
Low Fluence Methods for Insulator Yields

Hemispherical Grid Retarding Field Analyzer

- Pulsed low current electron source
  - 5 µs at 5 nA → ~10^6 e^-/pulse
  - 2.0*10^4 e^-/mm^2

- UV and Low Energy Electrons to discharge material after each pulse.

- Without discharge the yield would change from pulse to pulse due to electrons being reattracted to the charged sample surface.

Fully enclosed detector provides highly accurate absolute yields on insulators.
1% on conductors and ~5% on insulators.
Return current due to biasing leads to **Modified Yields**

(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

Depresses yield

**Negative Charging**

$E_0 > E_2$ with $\sigma < 1$

Shift emission spectra right

Enhances yield

To know the absolute surface potential one must know the absolute yield starting with no imbedded charge, i.e., **THE ABSOLUTE INTRINSIC YIELD**
Charge Distribution for Surface Potential Under Electron Bombardment (DDLM)

Dynamic Double Layer Model

Charge distribution is more complex:
- DDLM near surface
- Charge transport in RIC region
- Sample bias adds more complex charges and fields

\[
V_s = \frac{Q_o (\sigma - 1)d}{\varepsilon_o \varepsilon_r A_o} - \frac{\sigma Q_o \lambda_{SE} + Q_o R}{2 \varepsilon_o \varepsilon_r A_o}
\]

Data for Increasing Resistivity Samples

Gold Low-Yield Very Low Resistivity

Cr Coated Mylar High-Yield Low-Resistivity

Kapton Low-Yield High-Resistivity

CP1 Low-Yield Low-Resistivity
(Left) Yield Curve in Transition—Pulsed total yield of anodized Al tends toward unity as sample charges.

(Right) Yield Curve in Equilibrium—Pulsed total yield curve of RTV-silicone. Yield fluctuates around unity: charged steady-state.
Yield Decay Curve for Kapton

Incident pulses:
5 µs, ~25 nA, ~10 mm², ~13 fC/mm²-pulse, ~1·10⁶ e⁻/mm²-pulse

62% change over 50 pulses.
Decay Curve for Al₂O₃

Allow charge to build up

Intrinsic (uncharged) yield is given when $Q \rightarrow 0$
To proceed we need a model for $V_s(Q_i)$.

**Modeling the SE Escape Energy**

**Ratio of Charged To Uncharged SE Yield**

as a function of Surface Potential:

$$\frac{\delta_i(E_o, Q_i)}{\delta_o(E_o)} = \frac{\int_{0}^{50\text{ eV}} \frac{dN(E; E_o)}{dE} dE}{\int_{0}^{50\text{ eV}} \frac{dN(E; E_o)}{dE} dE}$$
Surface Voltage Relates to “Intrinsic” Yield Model

Combining all the pieces

\[
\frac{\delta_t(E_o, Q_t)}{\delta_o(E_o)} = \frac{\int_{0}^{50 \text{eV}} dN(E; E_o) dE}{\varepsilon V_s(Q_i)} \int_{0}^{50 \text{eV}} dN(E; E_o) dE
\]

Physics based model for yield SE recapture as a function of incident fluence

Analytic solution for secondary electron yield as surface potential changes in response to incident charge.

\[
\delta(eV_s) = (\sigma_o(E_o) - 1) \cdot \left( 1 - \frac{\lambda_{se}}{2 \cdot d} \right) \cdot \left( \frac{h(e_s)}{h(50 \text{eV})} - 1 \right) - \left[ \eta_o \cdot \left( 1 - \frac{\lambda_{se}}{2 \cdot d} \right) - \left( 1 + \frac{R}{2 \cdot d} \right) \right]
\]

DDLM model for surface potential

Decay curve data

Depth profile for net positive charging

Physics based model for yield SE recapture as a function of incident fluence
"Constructing" a Low-Fluence Yield Curve

Measured Yield Decay Curves at:
- $E_0 = 250$ eV
- $E_0 = 100$ eV
- $E_0 = 300$ eV
- $E_0 = 400$ eV
- $E_0 = 500$ eV

Constructed Yield Curves at Charge Density of:
- $\sim 4$ pC/mm$^2$
- $\sim 1$ pC/mm$^2$
- $\sim 0.4$ pC/mm$^2$
- $\sim 3$ fC/mm$^2$
Predicted Yield Curves at Various Surface Potentials

- Measured Yield
- Analytic Prediction as $Q \to 0$
- Analytic Prediction as $V_s = 0, 2, 5, 10, 20$ V
- Notice Predicted Duel-Peak
Enhanced Low Fluence Methods for Insulator Yields

Hemispherical Grid Retarding Field Analyzer
Electron Emission Detector

- Charge neutralization with low energy (~5 eV) e- and UV
- 10 eV to 30 keV incident electrons
- Precision absolute yield
  - ~1-2% accuracy with conductors
  - ~2-5% accuracy with insulators
- Fully enclosed HGRFA for emission electron energy discrimination.
- Measures all currents
- In situ absolute calibration
- In situ surface voltage probe
  - Multiple sample stage
  - ~100 K < T < 400 K
  - Reduced S/N
**Enhanced Low Fluence Methods for Insulator Yields**

- Faster pulsed electron beam
- Fast Low-Current Measurement
- Monitoring 6 detector element currents, separately biased
- Electron yields calculated from integrated current traces

\[
\sigma = 1 - \frac{\int_{\text{pulse}} [I_S + I_{St} + I_{IG} + I_{BG} + I_{DT}] dt}{\int_{\text{pulse}} [I_C + I_S + I_{St} + I_{IG} + I_{BG} + I_{DT}] dt}
\]
Initial Total Yields Curves of BN Near $E_1$

This is not impressive!!!
Improved Total Yields Curves of BN

Comparison of Linear Fits

Comparison of Semilog Fits

Intrinsic Yields
• Determine yield with pointwise method evaluated at each (or at least just a few) points of current traces.

• Current analysis should show yield changes in one pulse. (~1% of total pulse charge)
  • ~30 ns, ~5 nA, ~0.1 cm²,
  • ~160 fC/cm²-pulse,
  • ~2·10³ e⁻/cm²-pulse

• Initial Au data should show no charging effects and recover Au conductive yields

• Finally hope to see the zero charge plateau of the intrinsic yield...that holy grail!!!
USU Materials Physics Group

USU MPG Webpage