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Unified Density of States Based Model of Electron Transport and Emission of Spacecraft Materials

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A simplified approach to spacecraft charging modeling…

- Materials Properties
- Atomic Scale Models

- Spacecraft Potential Models
- Satellite Moving through Space
- Space Plasma Environment
Let us assume a spherical satellite....

Let us assume a planar cow....

Let us assume an instrumented, biased, I-V measuring planar cow....

Sequence of Models
The assumptions leading to the simplest model are:

1. A parallel plate geometry leads to a 1D model of electric transport.
2. The injected charge carriers are electrons from a bias electrode.
3. Injection occurs instantaneously at surface.

Surface voltage as a function of time,

\[ V_s(t) = \frac{J_0}{\varepsilon_0 \varepsilon_r} \left[ D \left( 1 - \frac{R(E_b)}{D} \right) \right] \]

Rear electrode current as a function of time,

\[ J_{\text{down}}(t) = J_0 \delta(t) \]

A displacement current

\[ \nabla \times \mathbf{H} = J_c + \frac{\partial}{\partial t} (\varepsilon_0 \varepsilon_r \mathbf{F}) \]
Finite injection, no dissipation

The assumptions leading to the simplest model are:

1. A *parallel plate geometry* leads to a 1D model of electric transport.
2. The injected charge carriers are *electrons from a bias electrode*.
3. Injection occurs *instantaneously at surface for finite time and space*.

Surface voltage as a function of time,

\[ V_s(t) = \frac{\bar{J}_o}{\varepsilon_0\varepsilon_r} \left[ D \left( 1 - \frac{R(E_b)}{D} \right) \right] x \text{??}

Rear electrode current as a function of time,

\[ J_{down}(t) = \bar{J}_o x \text{??}

A displacement current

\[ \nabla \times \vec{H} = J_c + \frac{\partial}{\partial t} (\varepsilon_0\varepsilon_r F) \]
Walden & Wintle considers general electrode injection current density as a function of applied electric field:

\[
I_{inj}(F) = \begin{cases} 
J_0(F) \cdot e^{f(F)} ; \text{exponential form} \\
\frac{J_0}{J_0} \cdot (F/F_o)^p ; \text{power law form}
\end{cases}
\]

\(J_0(F)\) and \(f(F)\) are arbitrary functions that vary slowly with \(F\) compared \(\exp[f(F)]\).

They assume \(0 \leq m \equiv \frac{1}{n} \leq 1\)

\[
\frac{dn_t}{dn} = \left[ \frac{J^c_{inj}}{J_0} \right]^{(1/m)-1} \quad \text{or} \quad J^c_{inj}(t) = \bar{J}_0[dn_t/dn]^{1-1/n} = \bar{J}_0[dn_t/dn]^{1-m} ;
\]

Total current density with displacement current density:

\[
I_{down}(t) = I^c_{down}(t) + I^{displacement} = \bar{J}_0 \left\{ \left( 1 + t/\tau_Q \right)^{-m} - \left( \frac{D-\frac{1}{2}R(E_b)}{D} \right) \cdot \left( 1 + t/\tau_Q \right)^{-1} \right\}
\]

\[
\tau_Q = \frac{\epsilon_0 \epsilon_r D m}{\bar{J}_0 [D-\frac{1}{2}R(E_b)] \left[ \frac{\partial f(F)}{\partial F} \right]^{-1}} \bigg|_{F=F(t=0)} = \frac{\epsilon_0 \epsilon_r D (t-\tau_Q)}{\bar{J}_0 [D-\frac{1}{2}R(E_b)] \left[ \frac{\partial F}{\partial t} \right]}
\]

\(\tau_Q\) is characteristic onset time for the injection current density, not to be confused with a decay time.
Surface voltage as a function of time,

\[ V_s(t) = \frac{\bar{J}_o}{\varepsilon_0 \varepsilon_r} \left[ D \left( 1 - \frac{R(E_b)}{D} \right) \right] x ? ? ? \]

Rear electrode current as a function of time,

\[ J_{down}(t) = \bar{J}_o x ? ? ? \]

A displacement current

\[ \bar{\nabla} \times \bar{H} = J_c + \frac{\partial}{\partial t} (\varepsilon_0 \varepsilon_r F) \]
The assumptions leading to the simplest model for this are:

1. A *parallel plate geometry* leads to a 1D model of electric transport.
2. The incident (or injected) charge carriers are *electron*.
3. The magnitude of the injected current density is approximated as the *time-averaged incident beam current* density,
   \[
   \bar{J}_0 \equiv \frac{\int_0^{t_{\text{dep}}} J_{\text{inj}}(t) \, dt}{\int_0^{t_{\text{dep}}} dt} \approx J_0 \left[ \frac{t_{\text{on}}}{t_{\text{on}} + t_{\text{off}}} \right]
   \]
4. *All charge is initially deposited at single penetration depth*, \( R \)
   \[
   \Sigma(z, t) = \int_0^t J_{\text{inj}}(t') \, dt' \delta[z - R]
   \]
5. *Charge deposited in the region 0<x<R quickly redistributes to a uniform volume charge distribution*
   \[
   \int_0^t \frac{J_{\text{inj}}(t')}{q_e R (E_b - q_e V_s(t'))} \Theta[z - R(E_b - q_e V_s(t'))] \, dt'
   \]
6. *There is no electron emission*; that is, the total electron yield \( Y = 0 \).
7. *There is no charge dissipation*. The dielectric acts as a perfect charge integrator.
Electron Beam Injection

What is different about electron beam deposition?

- Electron emission modifies current and voltage
- Extra current term for emitted charged particles
- Energy dependent emission
- Reattraction of secondary electrons to positive surface
- Different injection barrier in RIC region
- RIC
Electron Beam Injection and Electron Yield

Charge dependant electron yields are the key:

A simple model for surface voltage (or time) dependence of the yield for negative charging for $E_b > E_2$, based on a charging capacitor was proposed by Thomson:

$$\left[ 1 - Y(t; E_b + q_e V_s) \right] = \left[ 1 - Y(E_b + q_e V_s) \right] e^{-\left( Q(t) / \tau_Q \right)}$$

for $0 \geq q_e V_s(t) \geq (E_2 - E_b)$

$\tau_Q$ is a decay constant for the exponential approach of the yield to unity, as charge $Q(t)$ is accumulated with elapsed time and $E_2$ is the crossover energy.

Expression that describes the re-attraction of SE’s to the surface of a positively charged sample:

$$\sigma(E_o; V_s) = \frac{k}{6 E_o} \left[ h(eV_s; \chi) - h(50eV; \chi) \right] + 1,$$

where

$$h(\alpha; \chi) = \frac{3 \alpha + \chi}{(\alpha + \chi)^3},$$

$k$ is a material dependant proportionality constant, $\chi$ is the insulator electron affinity, and $\alpha$ is an arbitrary energy at which $h$ is evaluated.
Surface voltage as a function of time,
\[ V_s(t) = V_{\text{inj}}^d(t) \left( \frac{t}{\tau_o} \right) \]
(no dissipation) \hspace{1cm} (4.13)

with
\[
V_{\text{inj}}^d(t) = \begin{cases} 
  \left( 1 - \frac{R(E_b)}{D} \right) 
  & \text{(no emission)} \\
  \left( 1 - \frac{E_{2} - E_{b}}{D} \right) 
  & \text{(static emission)} \\
  \left( 1 - Y[E_{b} - q_{e}V_{s}(t')] \right) 
  & \text{(dynamic emission)} \\
  \left\{ \frac{1}{t} \int_{0}^{t} \left( 1 - Y[E_{b} - q_{e}V_{s}(t')] \right) dt' \right\} 
  & \text{(general emission)} 
\end{cases}
\]

Total current density with displacement current density:
\[
J_{\text{down}}(t) = J_{\text{down}}^{c}(t) + J_{\text{down}}^{\text{displacement}} = \frac{J_0}{\sigma_o} \left( 1 + \frac{t}{\tau_Q} \right)^{-m} - \left( \frac{D - \frac{1}{2}R(E_b)}{D} \right) \cdot \left( 1 + \frac{t}{\tau_Q} \right)^{-1}
\]
Electron Beam Injection and Emission, with dissipation

Surface voltage as a function of time,

\[ V_s(t) = \frac{I_o}{\varepsilon_o\varepsilon_r} \left[ D \left(1 - \frac{R(E_b)}{D}\right)\right] x \]

Rear electrode current as a function of time,

\[ J_{down}(t) = I_o x \]

A displacement current

\[ \vec{\nabla} \times \vec{H} = J_c + \frac{\partial}{\partial t} (\varepsilon_o\varepsilon_r F) \]
Electric field

(b) Double charge layer

\[ Z_{\text{ext}} \]

\[ Z = Z_{\text{ext}} \]

\[ \Delta V = \frac{\Sigma d}{\varepsilon_0 \varepsilon_r} \]

\[ E = \frac{\Sigma}{\varepsilon_0 \varepsilon_r} \]

\[ \Delta V = \frac{\Sigma L}{\varepsilon_0 \varepsilon_r} \]

\[ \frac{F_{\text{ext}}}{(z, t)} = \begin{cases} 0 & ; z \leq z_{\text{ext}} \\ \frac{V_{\text{ext}}}{z_d(t) - z_{\text{ext}}} & ; 0 < z < z_{\text{ext}} \\ \frac{V_{\text{bias}}(t) - \frac{\Sigma d(t)}{D}}{z_d(t) - z_{\text{ext}}} - \frac{V_{\text{ext}}}{z_d(t) - z_{\text{ext}}} & ; 0 \leq z < z_d(t) \\ \frac{V_{\text{bias}}(t) + \frac{\Sigma d(t)}{D}}{z_d(t) - z_{\text{ext}}} & ; z_d(t) \leq z \leq D \\ 0 & ; z > D \end{cases} \]

\[ F_{\text{up}}(z, t) = \begin{cases} V_{\text{bias}}(t) + V_{\text{ext}} & ; z \leq z_{\text{ext}} \\ V_{\text{bias}}(t) + V_{\text{ext}} - \frac{V_{\text{ext}} + \frac{\Sigma d(t)}{D}}{z_d(t) - z_{\text{ext}}} & ; 0 < z < z_{\text{ext}} \\ V_{\text{bias}}(t) + V_{\text{ext}} \left[ \frac{D}{z_d(t) - z_{\text{ext}}} + \frac{\Sigma d(t)}{D} \right] & ; z = 0 \\ V_{\text{bias}}(t) + V_{\text{ext}} \left[ \frac{(D - z)}{D} \right] & ; 0 \leq z < z_d(t) \\ V_{\text{bias}}(t) + V_{\text{ext}} \left[ \frac{(D - z)}{D} \right] - \frac{\Sigma d(t)}{D} - (D - z_d(t)) & ; z_d(t) \leq z \leq D \\ 0 & ; z > D \end{cases} \]

\[ F_{\text{down}}(z, t) = \begin{cases} V_{\text{bias}}(t) + V_{\text{ext}} & ; z \leq z_{\text{ext}} \\ V_{\text{bias}}(t) + V_{\text{ext}} - \frac{V_{\text{ext}} + \frac{\Sigma d(t)}{D}}{z_d(t) - z_{\text{ext}}} & ; 0 < z < z_{\text{ext}} \\ V_{\text{bias}}(t) + V_{\text{ext}} \left[ \frac{D}{z_d(t) - z_{\text{ext}}} + \frac{\Sigma d(t)}{D} \right] & ; z = 0 \\ V_{\text{bias}}(t) + V_{\text{ext}} \left[ \frac{(D - z)}{D} \right] & ; 0 \leq z < z_d(t) \\ V_{\text{bias}}(t) + V_{\text{ext}} \left[ \frac{(D - z)}{D} \right] - \frac{\Sigma d(t)}{D} - (D - z_d(t)) & ; z_d(t) \leq z \leq D \\ 0 & ; z > D \end{cases} \]

\[ V(z, t) = \begin{cases} V_{\text{bias}}(t) + V_{\text{ext}} & ; z \leq z_{\text{ext}} \\ V_{\text{bias}}(t) + V_{\text{ext}} - \frac{V_{\text{ext}} + \frac{\Sigma d(t)}{D}}{z_d(t) - z_{\text{ext}}} & ; 0 < z < z_{\text{ext}} \\ V_{\text{bias}}(t) + V_{\text{ext}} \left[ \frac{D}{z_d(t) - z_{\text{ext}}} + \frac{\Sigma d(t)}{D} \right] & ; z = 0 \\ V_{\text{bias}}(t) + V_{\text{ext}} \left[ \frac{(D - z)}{D} \right] & ; 0 \leq z < z_d(t) \\ V_{\text{bias}}(t) + V_{\text{ext}} \left[ \frac{(D - z)}{D} \right] - \frac{\Sigma d(t)}{D} - (D - z_d(t)) & ; z_d(t) \leq z \leq D \\ 0 & ; z > D \end{cases} \]
General form of conductivity in HDIM with explicit time dependence

\[
\sigma(t) = \sigma_{DC} \left[ 1 + \frac{\sigma_{AC}(v)}{\sigma_{DC}} + \frac{\sigma_{pol}}{\sigma_{DC}} \frac{t^{-1}}{\tau_{pol}} + \frac{\sigma_{diffusion}}{\sigma_{DC}} \right] + \frac{\sigma_{dispersive}}{\sigma_{DC}} t^{(1-\alpha)} + \frac{\sigma_{transit}}{\sigma_{DC}} t^{-(1+\alpha)} + \frac{\sigma_{RIC}}{\sigma_{DC}} \left( 1 - e^{-t_{RIC}/(t-t_{on})} \right) \left( 1 + \left( t - t_{off} \right)/\tau_{RIC}^{2} \right)^{-1}
\]

- **Dark Current** \( \sigma_{DC} \equiv q_e n_e \mu_e \) **dark current or drift conduction**—very long time scale equilibrium conductivity.
- **AC Conduction** \( \sigma_{AC}(v) \equiv \sum_i \left( (\varepsilon_r (v) - \varepsilon_r^0) \varepsilon_o \frac{1}{1+(v/v_i)^2} \right) \) frequency-dependent **AC conduction**—dielectric response to a periodic applied electric field.
- **Polarization** \( \sigma_{pol}(t) \equiv \left( \varepsilon_r^\infty - \varepsilon_r^0 \right) \varepsilon_o / \tau_{pol} \) long time exponentially decaying conduction due to **polarization**.
- **Diffusion** \( \sigma_{diffusion}(t) \equiv \sigma_{diffusion}^0 \cdot t^{-1} \) diffusion-like conductivity from gradient of space charge spatial distribution.
- **Dispersive** \( \sigma_{dispersive}(t) \equiv \begin{cases} \sigma_{dispersive}^0 \cdot t^{-(1-\alpha)} & \text{for } t < \tau_{transit} \\ \sigma_{transit}(t) \equiv \sigma_{transit}^0 \cdot t^{-(1+\alpha)} & \text{for } t > \tau_{transit} \end{cases} \) broadening of spatial distribution of space charge through coupling with energy distribution of trap states.
- **RIC** \( \sigma_{RIC}(t; \dot{D}, \tau_{RIC}^1, \tau_{RIC}^2) \equiv \sigma_{RIC}^0(\dot{D}(t)) \left( 1 - e^{-\tau_{RIC}^1/(t-t_{on})} \right) \left( 1 + \left( t - t_{off} \right)/\tau_{RIC}^2 \right)^{-1} \) radiation induced conductivity term resulting from energy deposition within the material.

Refer to (Wintle, 1983), (Dennison et al., 2009), and (Sim, 2012)
Conductivity in HDIM

Dark Current

Polarization

Diffusion

Dispersive/Transit

RIC

Current

Pre-Transit

Post-Transit

$t_0 = 0.$
Details of the HDIM conductivity mechanisms follow from descriptions of the spatial and energetic distributions of the trap density of state in the band gap of the HDIM. Theses model predict the time, $T$, $Q$, $F$, dose and dose rate dependence of the mechanisms and relate them to transition probabilities.

General form of conductivity in HDIM with explicit time dependence:

\[ N_{ex} = \dot{D} \rho / \varepsilon_0 \varepsilon_r \]

(a) Excitation by thermal or external source:  
\[ \alpha_{et}(\varepsilon) n_e(t) [N_t(\varepsilon) - n_t(\varepsilon, t)] \]

(b) Trapping
\[ \alpha_{et}(\varepsilon) n_e(t) [n_e(t) + n_t(\varepsilon, t)] \]

(c) De-trapping due to thermal excitation
\[ \int_{\varepsilon_C}^{\varepsilon_F} \alpha_{te}(\varepsilon) N_c n_t(\varepsilon, t) d\varepsilon f(\varepsilon) \]

(d) Recombination
\[ \alpha_{tr}(\varepsilon) n_e(t) n_h(t) P_{tr}(\varepsilon) \]

(e) Low temperatures

(f) Mid band recombination
SVP Charging and Discharging

- Uses pulsed non-penetrating electron beam injection with no bias electrode injection.
- Fits to exclude AC, polarization, transit and RIC conduction.

\[ \sigma(t) = \sigma_o \left\{ 1 + \left( \frac{\sigma_o^{\text{diffusion}}}{\sigma_o} \right) t^{-1} + \left( \frac{\sigma_o^{\text{dispersive}}}{\sigma_o} \right) t^{(1-\alpha)} \right\} \]

**Charging**

\[
V_s(t) = V_o \exp \left( \frac{-t \sigma(t)}{\epsilon_o \epsilon_r} \right) \\
\approx V_o \left[ 1 - \left( \frac{\sigma_0}{\epsilon_o \epsilon_r} t \right) \right] \left\{ 1 + \left( \frac{\sigma_o^{\text{diffusion}}}{\sigma_o} \right) t^{-1} + \left( \frac{\sigma_o^{\text{dispersive}}}{\sigma_o} \right) t^{(1-\alpha)} \right\}
\]

**Discharge**

\[ V(t) = V_o e^{-t \sigma(t)/\epsilon_o \epsilon_r} \]
Constant Voltage Chamber configurations inject a continuous charge via a biased surface electrode with no electron beam injection.
Electrostatic Discharge

Chamber configurations is the same as the constant voltage conductivity chamber, but with high field effects. It inject a continuous charge via a biased surface electrode with no electron beam injection.
RIC and RIC Region

RIC chamber uses a combination of charge injected by a biased surface electrode with simultaneous injection by a pulsed penetrating electron.

Top view of samples on window

RIC Chamber

Sample stack cross section
Electron Emission

Electron emission uses incident (charged, energetic) electrons injected with a pulsed or continuous electron beam and measures conducted electrons, emitted electrons and stored charge.
Photoyield and Cathodoluminescence

Photoyield is a variant of electron emission with incident (uncharged, energetic) photons and emitted and conducted electrons.

Cathodoluminescence is a variant of electron emission with incident (charged, energetic) electrons, conducted electrons, and emitted photons.
Conclusions

What this Microscopic Model buys us:

- Theoretical smorgasbord approach to a variety of test methods
- Model ties various methods and allows cross checks of materials properties
- Away to understand dependences of t, Q, F, T, dose, dose rate
- Direct ties to density of defect state models to understand basic physics and relate properties to microscopic structure

For Spacecraft Charging:

- Satellites are not cows...Complex satellites require:
  - Complex materials configurations
  - More power
  - Smaller, more sensitive devices
  - More demanding environments
- But...
  - Numerous groups are acquiring materials data
  - Basic physics (or at least semi-emperical) models allow limited data to be leveraged to model similar materials under extended conditions
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