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Evolution of Materials Properties and the Space Plasma Environment through Interactions and the Dynamics of Spacecraft Charging

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Evolution of Materials Properties and the Space Plasma Environment through Interactions and the Dynamics of Spacecraft Charging

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USU Materials Physics Group
A simplified approach to spacecraft charging modeling…

This results in a complex dynamic interplay between space environment, satellite motion, and materials properties.
The Space Environment

Dynamics of the space environment and satellite motion lead to dynamic spacecraft charging (min to decades)

- Solar Flares, CME, Solar Cycle
- Orbital eclipse, Rotational eclipse

Solar wind and Earth’s magneto-sphere structure.

Incident fluxes of:

- Electrons, e⁻
- Ions, I⁺
- Photons, γ
- Particles, m

Typical Space Electron Flux Spectra [Larsen].

Solar Electro-magnetic Spectrum.
What do you need to know about the materials properties?

**STATIC Charging codes** such as NASCAP-2K or SPENVIS and NUMIT2 or DICTAT require:

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

**Charge Transport**
- Conductivity
- RIC
- Permittivity
- Electrostatic breakdown
- Penetration range

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>[1] Relative dielectric constant; $\varepsilon_r$ (Input as 1 for conductors)</td>
<td>1, NA</td>
</tr>
<tr>
<td>[2] Dielectric film thickness; $d$</td>
<td>0 m, NA</td>
</tr>
<tr>
<td>[3] Bulk conductivity; $\sigma_o$ (Input as -1 for conductors)</td>
<td>-1; (4.26 ± 0.04) · 10^7 ohm^-1·m^-1</td>
</tr>
<tr>
<td>[4] Effective mean atomic number $&lt;Z_{\text{eff}}&gt;$</td>
<td>50.9 ± 0.5</td>
</tr>
<tr>
<td>[5] Maximum SE yield for electron impact; $\delta_{\text{max}}$</td>
<td>1.47 ± 0.01</td>
</tr>
<tr>
<td>[6] Primary electron energy for $\delta_{\text{max}}$; $E_{\text{max}}$</td>
<td>(0.569 ± 0.07) keV</td>
</tr>
<tr>
<td>[7] First coefficient for bi-exponential range law, $b_1$</td>
<td>1 Å, NA</td>
</tr>
<tr>
<td>[8] First power for bi-exponential range law, $n_1$</td>
<td>1.39 ± 0.02</td>
</tr>
<tr>
<td>[9] Second coefficient for bi-exponential range law, $b_2$</td>
<td>0 Å</td>
</tr>
<tr>
<td>[10] Second power for bi-exponential range law, $n_2$</td>
<td>0</td>
</tr>
<tr>
<td>[11] SE yield due to proton impact $\delta^H(1\text{keV})$</td>
<td>0.3364 ± 0.0003</td>
</tr>
<tr>
<td>[12] Incident proton energy for $\delta^H_{\text{max}}$; $E^H_{\text{max}}$</td>
<td>(1238 ± 30) keV</td>
</tr>
<tr>
<td>[13] Photoelectron yield, normally incident sunlight, $j_{\text{pho}}$</td>
<td>(3.64 ± 0.4) · 10^{-5} A·m^{-2}</td>
</tr>
<tr>
<td>[14] Surface resistivity; $\rho_s$ (Input as -1 for non-conductors)</td>
<td>-1 ohms·square^-1, NA</td>
</tr>
<tr>
<td>[15] Maximum potential before discharge to space; $V_{\text{max}}$</td>
<td>10000 V, NA</td>
</tr>
<tr>
<td>[16] Maximum surface potential difference before dielectric breakdown discharge; $V_{\text{punch}}$</td>
<td>2000 V, NA</td>
</tr>
<tr>
<td>[17] Coefficient of radiation-induced conductivity, $\sigma_r$; $k$</td>
<td>0 ohms^-1·m^-3, NA</td>
</tr>
<tr>
<td>[18] Power of radiation-induced conductivity, $\sigma_r$; $\Delta$</td>
<td>0, NA</td>
</tr>
</tbody>
</table>
Specific focus of our work is the change in materials properties as a function of time, position, energy, and charge:

- **Time (Aging),** $t$
- **Position (xy,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, $Q(xy,z,t)$
  - Charge Rate (Current), $\dot{Q}(xy,z,t)$
  - Conductivity Profiles, $\sigma(z,t,Q,\dot{Q},D,\dot{D})$
  - Electron emission ($e^- I^+, \Gamma$)
- **Light emission**
  - Cathodoluminescence $I_R(t,xy,Q,D,\dot{D})$
  - Arcing $I_R(t,xy,Q,D,\dot{D}), \dot{O}_R(t,xy,z,Q,D,\dot{D})$
Materials Physics Group Measurement Capabilities

- Electron Emission
- Ion Yield
- Photoyield
- Luminescence
- Conductivity
- Electrostatic Discharge
- Radiation Induced Cond.
- Radiation Damage

Dependence on: Time, Pressure, Temperature, Charge, E-field, Dose, Dose Rate
USU Experimental Capabilities

Absolute Yields

- SEE, BSE, emission spectra, (<20 eV to 30 keV)
- Angle resolved electron emission spectra
- Photoyield (~160 nm to 1200 nm)
- Ion yield (He, Ne, Ar, Kr, Xe; <100 eV to 5 keV)
- Cathodoluminescence (200 nm to 5000 nm)
- No-charge “Intrinsic” Yields
- T (<40 K to >400 K)

Other Capabilities

- Conductivity (<10^{-22} [ohm-cm]^{-1})
- Surface Charge (<1 V to >15 kV)
- ESD (low T, long duration)
- Radiation Induced Conductivity (RIC)
- Evolution of internal charge distributions (PEA)
- Multilayers, contamination, surface modification
- Radiation damage
- Modeling
- Sample Characterization
Instrumentation Overview

Sadly (for an experimentalist) there is no time for this!

(Perhaps you will ask a question)
Examples of Dynamical Change in Materials

I. Contamination and Oxidation
II. Reflectivity as a Feedback Mechanism
III. Radiation Effects (and t)
IV. Temperature Effects (and t)
V. Radiation and Temperature Effects
VI. Charge Accumulation Effects
VII. Multilayer/Nanocomposite Effects
Case I: Evolution of Contamination and Oxidation

Build up of C contamination on Au by long-duration, high current keV electron beam
Common to SEM work

Davies, Kite, and Chang

“All spacecraft surfaces are eventually carbon…”
--C. Purvis (lead for NASCAP)

Threshold differential charging at ~5 nm of contamination!!!

Approx. Contamination Thickness (nm)

Negative Potential (10-Veq) (in volts)

Contamination (Exposure Time in hours)
Case I: Evolution of Contamination and Oxidation

Before            After
Kapton
AO and UV degradation (AO fluence standard)

Before            After
Ag
AO degradation (AO fluence standard)

Before               After
Black Kapton
Surface modified by AO, UV

Before            After
Al coated PET

168 Sample with 18 mon exposure on ISS
Ram, wake and “layered” exposure to: AO, UV, vacuum, ΔT

Dennison, Evans and Prebola, IEEE-TPS 2012.
Case II: Reflectivity as a Feedback Mechanism

Reflectivity changes with surface contamination, oxidation and roughness:

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

Grounded Guard Plate

Radiation → Reflect → Emissivity → Temp → Contamination

4 samples held a constant potential to test charge enhanced contamination:

- +5 VDC
- -15 VDC

See Lai & Tautz, 2006 & Dennison, 2007

Radiation Damage (Color Change) of PET
Case III: Radiation Effects

Large Dosage (>10^8 Rad)

Medium Dosage (>10^6 Rad)

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

Examples: RBSP, MMS, JUNO, JGO/JEO
Examples: JWST, SPP, Comm Sats.

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

Radiation Induced Conductivity (RIC)
Temperature dependent trap filling and depletion

\( \sigma_{RIC}(T, D) = k_{RIC}(T) \cdot D^{\Delta(T)} \)

Examples: RBSP, JUNO, JGO/JEO

(Hoffmann & Sim)

(Gillespie & Sim)
Case IV: Temperature Effects

Strong T Dependence for Insulators

Charge Accumulation

- Electron Emission
- Charge Recombination

Charge Transport

- Conductivity
- RIC
- Permittivity
- Electrostatic Discharge

Examples:

IR and X-Ray Observatories
JWST, WISE, WMAP, Spitzer, Herschel, 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—A “Perfect Storm”

**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
Case IV: Temperature Effects in Charge Transport

Strong T Dependence for Insulators

Charge Transport

- Conductivity
- RIC

\[ \sigma_{RIC}(T, D) = k_{RIC}(T) \cdot D^{\Delta(T)} \]

**Exponential Trap Density**

\[ \Delta(T) \rightarrow \frac{T}{T + T_c} \]

\[ k(T) \rightarrow k_{RIC} \left[ \frac{2 \left( m_e^* k_B T \right)^{3/2}}{m_e^* m_n^*} \right]^{3/4} \]

**Uniform Trap Density**

\[ \Delta(T) \rightarrow 1 \]

\[ k(T) \rightarrow k_{RIC} \]

**Delta Function Trap Density**

\[ \Delta(T) \rightarrow 1 \]

\[ k(T) \rightarrow k_{RIC} T \]

---

**Graphs**

- LDPE
  - kRIC data
  - kRIC error
  - exponential fit
  - linear fit
  - mean kRIC

- PTFE
  - kRIC data
  - kRIC error
  - exponential fit
  - linear fit
  - mean kRIC

- SiO₂
  - kRIC data
  - kRIC error
  - exponential fit
  - linear fit
  - mean kRIC

---

**Diagrams**

- Temperature vs. Conductivity (Ln (Calculated Resistivity (Ohm-cm)) vs. Temperature (K))
- Exponential DOS vs. Temperature
- Uniform DOS vs. Temperature
- Delta Function DOS vs. Temperature
Case V: Temperature and Dose Effects

Solar Probe Mission
• Mission design by APL/GSFC
• Materials testing by Dennison and Hoffmann
• Evolutionary Charging Study by Donegan, Sample, Dennison & Hoffmann (See Donegann et al, JSR 2009)
• Revised mission design and new charging study (See Donegan 11th SCTC for update)

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**

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

Charging model using T and r dependant inputs at various orbits predict a peak in charging at ~0.3 to 2 AU
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 $\sim r^2$
Case VI: Charge Effects of Yields, Currents & Surface Voltage

Measure:

$J_{\text{in}}$, $J_{\text{emit}}$, $J_{\text{rear}}$

$V_{\text{bias}} = 0$, $V_{\text{bias}} < 0$, $V_{\text{bias}} > 0$

Electron Yields (electron/electron)

Incident Electron Energy (eV)

Electron Counts (arbitrary units)

Electron Energy (eV)

SE Spectral Data
Chung and Everhart Fit
Combining all the pieces

\[
\frac{\delta_i(E_o; Q_i)}{\delta_o(E_o)} = \frac{\int_{0}^{50 \text{ eV}} dN(E; E_o) \, dE}{eV_s(Q_i) \int_{0}^{50 \text{ eV}} dN(E; E_o) \, dE}
\]

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

\[
\delta(eV_s) = (\sigma_o(E_o) - 1) \cdot \left(1 - \frac{\lambda_{\text{se}}}{2 \cdot d}\right) \cdot \frac{h(\varepsilon_s)}{h(50 \text{ eV})} - 1 \\
- \frac{h(0)}{h(50 \text{ eV})} \cdot \left[ \eta_o \cdot \left(1 - \frac{\lambda_{\text{se}}}{2 \cdot d}\right) - \left(1 + \frac{R}{2 \cdot d}\right) \right]
\]

- Analytic solution for SE yield as \( V_s \) changes with \( J_{\text{in}} \)
- Walden/Wintle model modified for electron beam injection gives:
  - \( V_s \) in terms of \( J_{\text{in}} \)
  - \( J_{\text{rear}} \) in terms of \( J_{\text{in}} \)

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

\[
\sigma(E_o Q) = \eta(E_o) + \delta(E_o Q)
\]

Decay curve data

DDLM model for surface potential

Depth profile for net positive charging

Surface Voltage Relates to “Intrinsic” Yield Model
Case VII: Multilayer/Nanocomposite Effects

**Length Scale**
- Nanoscale structure of materials
- Electron penetration depth
- SE escape depth

**Time Scales**
- Deposition times
- Dissipation times
- Mission duration

C-fiber composite with thin ~1-10 µm resin surface layer

Black Kapton™ (C-loaded PI)

Thin ~100 nm disordered SiO2 dielectric coating on metallic reflector
Diversity of Emission Phenomena in Black Kapton

Ball Black Kapton
Runs 131 and 131A

<table>
<thead>
<tr>
<th>Phenomenon</th>
<th>Energy (keV)</th>
<th>Power Density (uW/cm²)</th>
<th>Current (nA/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>22 keV</td>
<td>110 or 4100</td>
<td>5 or 188</td>
<td></td>
</tr>
<tr>
<td>135 K</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Surface Glow
Relatively low intensity
Always present over full surface when e-beam on
May decay slowly with time

Edge Glow
Similar to Surface Glow, but present only at sample edge

"Flare"
2-20x glow intensity
Abrupt onset
2-10 min decay time

Arc
Relatively very high intensity
10-1000X glow intensity
Very rapid <1 us to 1 s

InGaAs Video Camera
(900 nm to 1700 nm)

CCD Video Camera
(400 nm to 900 nm)
For C-fiber/resin composite Surface Glow, Edge Glow, and Arcing Frequency are all found to increase with:

- increasing incident electron flux and energy
- decreasing T
Thickness Dependant Model for Luminescence

\[ I_y(J_b, E_b, T, \lambda) \propto \dot{D}(J_b, E_b) \left[ \frac{1}{\dot{D} + \dot{D}_{\text{sat}}} \left( \frac{\varepsilon_{\text{ST}}}{k_B T} \right) \right] \left\{ 1 - \mathcal{A}_f(\lambda) \left[ 1 + R_m(\lambda) \right] \right\} \]

where dose rate \( \dot{D} \) (absorbed power per unit mass) is given by

\[ \dot{D}(J_b, E_b) = \frac{E_b J_b [1 - \eta(E_b)]}{q_e \rho_m} \left[ \frac{1}{1/R(E_b)} \right] ; R(E_b) > L \]
Measured Cathodoluminescence Spectra for Fused Silica

Spectra vs T

Four peaks evident

Peak Intensity vs T

Red decreases with increasing T
Others increases with increasing T

Wavelength shift vs T

Red increases with increasing T
Purple decreases with increasing T
Model for Luminescence Intensity in Fused Silica

Spectra vs T

Peak Intensity vs T

Wavelength shift vs T

- Spectra vs T: Graph showing luminescence spectra for different temperatures.
- Peak Intensity vs T: Graph showing normalized peak intensity versus temperature.
- Wavelength shift vs T: Graph showing wavelength shift versus temperature.

**Diagram Descriptions:**

(a) Conduction Band: Diagram showing conduction band with energy levels and transitions.
(b) Conduction Band: Diagram showing conduction band with energy levels and transitions at different temperatures.
(c) Conduction Band: Diagram showing conduction band with energy levels and transitions at different temperatures.
(d) Conduction Band: Diagram showing conduction band with energy levels and transitions at different temperatures.

Energy Levels:
- $E_{CB}$: Conduction Band
- $E_{VT}$: Valence Band
- $E_{DG}$: Direct Gap
- $E_{IR}$: Indirect Band Gap
- $E_{DL}$: Defect Level
- $E_{VB}$: Fermi Level

Transitions:
- Intersystem Crossings
- Non-radiative processes or $e^- h^+$ recombination

Temperature Conditions:
- $T = 0$: Low Temperature
- Low T: Intermediate Temperature
- High T: High Temperature

Energy Levels and Transitions are depicted with arrows indicating energy transitions and interactions.
Conclusions

• Complex satellites require:
  • Complex materials configurations
  • More power
  • Smaller, more sensitive devices
  • More demanding environments

• 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 many new problems

• Understanding of the microscale structure and transport mechanisms are required to model dynamic materials properties for dynamic spacecraft charging models
End with a Bang
Instrumentation Overview
Extremely Low Conductivity

Constant Voltage Conductivity

- Time evolution of conductivity
- $<10^{-1}$ s to $>10^6$ s
- $\pm 200$ aA resolution
- $>5 \cdot 10^{22}$ $\Omega$-cm
- $\sim 100$ K $< T < 375$ K
Absolute Electron Yields

Hemispherical Grid Retarding Field Analyzer Electron Emission Detector

- **Works with incident:**
  - 20 eV to 30 keV electrons
  - ~100 eV to 5 keV ions
  - ~0.5 eV to 7 eV photons

- **Precision absolute yield**
  - ~1-2% accuracy with conductors
  - ~2-5% accuracy with insulators
  - measures all currents
  - in situ absolute calibration

- low energy e⁻ and UV charge neutralization
- **in situ** surface voltage probe
- **multiple sample stage**
- ~100 K < T < 400 K

Fig. 2. Hemispherical Grid Retarding Field Analyzer (HGRFA). (a) Photograph of sample stage and HGRFA detector (side view). (b) Cross section of HGRFA. (c) Photograph of sample stage showing sample and cooling reservoir. (d) Side view of the mounting of the stepper motor. (e) Isometric view of the HGRFA detailing the flood gun, optical ports, and wire harness.
Surface Voltage Probe

- Inside SEE HGRFA
- ~0.5 V to 15 kV range
- ±0.5 V resolution
- Arc scan
- ~7 s min scan time
Low Temperature Cryostat

Closed Cycle He Cryostat
- $35 \text{ K} < T < 350 \text{ K}$
- $\pm 0.5 \text{ K}$ for weeks
- Multiple sample configurations

Used with:
- Constant Voltage Cond.
- RIC
- SEE/BSE
- Cathodoluminescence
- Arcing
- Surface Voltage Probe

Radiation Sources
- A Electron Gun
- B Sample Pedestal
- C Sample
- D Sample Mount
- E Sample Mask Selection Gear
- F Interchangeable Sample Holder
- G In situ Faraday Cup

Sample Mount
- H Spring–Loaded Electrical Connections
- I Temperature Sensor
- J Radiation Shield

Analysis Components
- K UV/Vis/NIR Reflectivity Spectrometers
- L CCD Video Camera (400–900 nm)
- M InGaAs Video Camera (800–1200 nm)
- N InSb Video Camera (1000–5000 nm)
- O SLR CCD Camera (300–800 nm)
- P Fiber Optic Discrete Detectors
- Q Collection Optics

Instrumentation (Not Shown)
- Data Acquisition System
- Temperature Controller
- Electron Gun Controller
- Electrometer
- Oscilloscope

Chamber Components
- R Multilayer Thermal Insulation
- S Cryogen Vacuum Feedthrough
- T Electrical Vacuum Feedthrough
- U Sample Rotational Vacuum Feedthrough
- V Turbomolecular/Mech. Vacuum Pump
- W Ion Vacuum Pump
- X Ion/Convectron Gauges – Pressure
- Y Residual Gas Analyzer – Gas Species
Closed-System Helium Refrigerator Sample Stage Mounting

High Energy Electron Gun

Faraday Cup Z Translation Stage

USU Closed Cycle He Cryostat
Photon Emission Measurements

Sample cooled with l-N₂ to 100-135 K.

Chamber walls at ambient.

Luminescence/Arc/Flare Test Configuration
- Absolute spectral radiance
- ~200 nm to ~5000 nm
- 4 cameras (CCD, iiCCD, InGaAs, InSb)
- Discreet detectors filters
- 2 Spectrometers (~200 nm to ~1900 nm)
- e⁻ at ~1 pA/cm² to ~10uA/cm² & ~20 eV to 30 keV
- 35 K < T < 350 K
- Multiple sample configurations to ~10x10cm
• λ range: detectors (700-5500 nm), cameras (400-5000 nm), and spectrometers (200-1700 nm)

• Current range: (0.1 pA to 1 mA)

• Temporal range: <10^{-9} s to >10^4 s
Radiation Induced Conductivity

~4 MeV Pulsed Electrons
Electrostatic Breakdown

![Diagram of an electrostatic breakdown setup]

- **Vacuum Chamber**
- **Aluminum Cold Reservoir**
- **Sample Plate**
- **Test Sample**
- **Electrode**

![Graph showing electric field strength vs. current]

- **Current (µA)**
- **Electric Field Strength (MV/m)**

![Graph showing endurance time vs. electric field]

- **Endurance Time (s)**
- **Electric Field x10^6 (V/m)**

- **Critical Field**
- **Bond Breaking Field**
Just a drop in the bucket…

**Complete set of dynamic transport equations**

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

\[
\frac{\partial}{\partial z} F(z, t) = q_e n_{tot} / \epsilon_0 \epsilon_r
\]

\[
\frac{\partial n_{tot}(z, t)}{\partial t} - \mu_e \frac{\partial}{\partial z} [n_e(z, t) F(z, t)] - q_e D \frac{\partial^2 n_e(z, t)}{\partial z^2} = N_{ex} -
\]

\[
\alpha_{er} n_e(z, t) n_{tot}(z, t) + \alpha_{et} n_e(t) [N_e(z) - n_t(z, t)]
\]

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

\[
\frac{dn_e(z, \varepsilon, t)}{dt} = \alpha_{et} n_e(z, t) [N_e(z, \varepsilon) - n_t(z, \varepsilon, t)] - \]

\[
\alpha_{te} N_e \exp \left[ - \frac{\varepsilon}{kT} \right] n_t(z, \varepsilon, t)
\]

**A quantum mechanical model** of the spatial and energy distribution of the electron states