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Engineering Tool for Temperature, Electric Field and Dose Rate Dependence of Low Conductivity Spacecraft Materials

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Materials Physics Group
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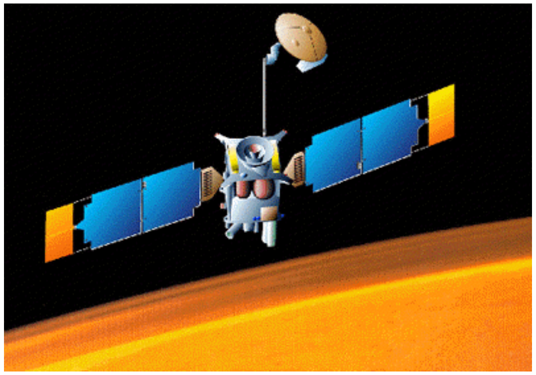
Study Support by NASA JWST Project



AIAA Aerospace Sciences Meeting
January, 2009

USU Materials Physics Group

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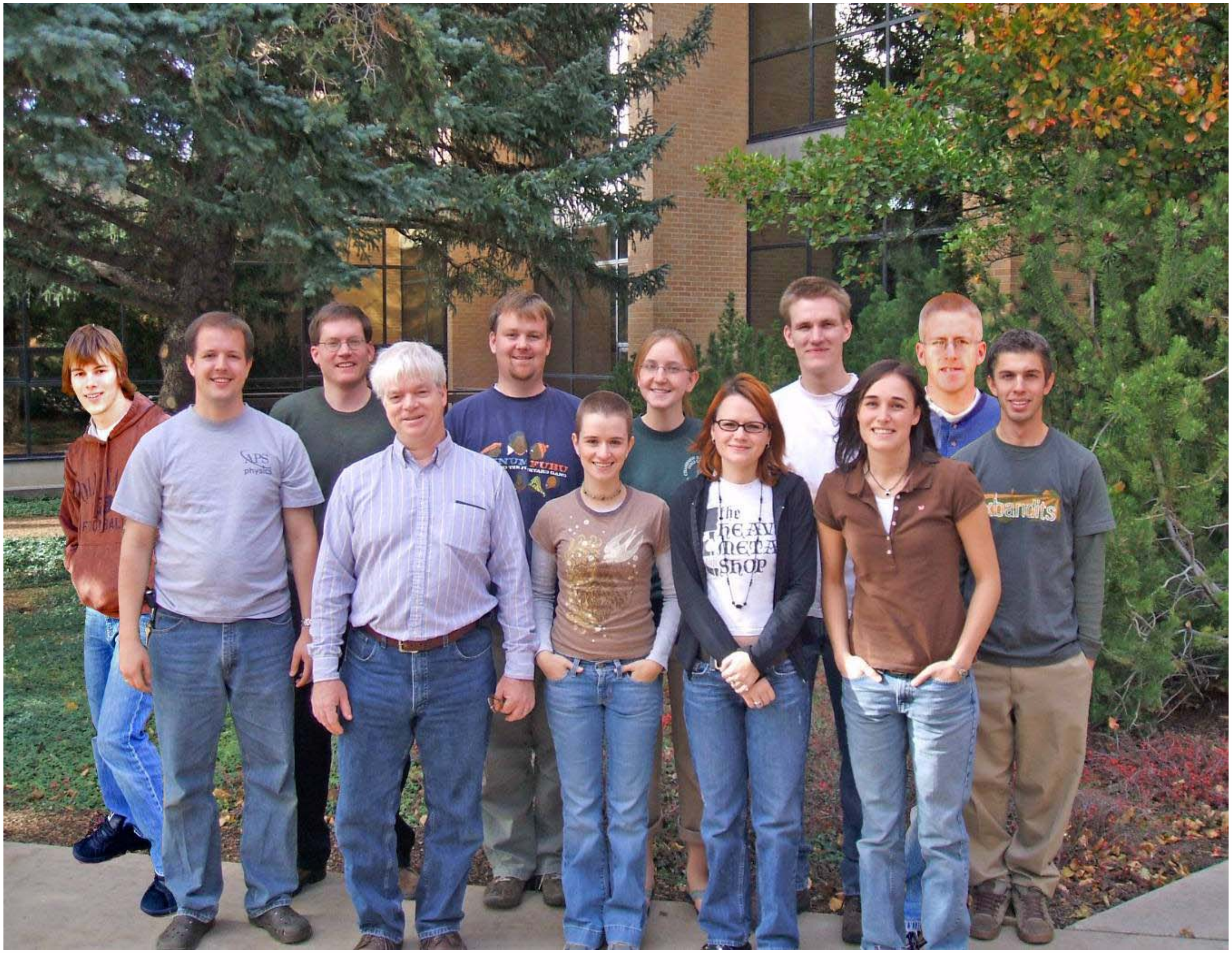
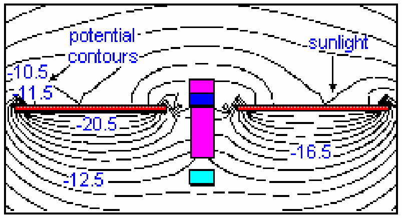
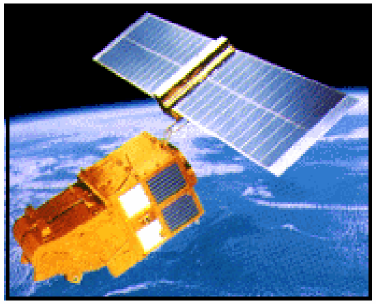


Surface Voltages Predicted by Spacecraft Charging Models





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

UtahState UNIVERSITY

Materials Research

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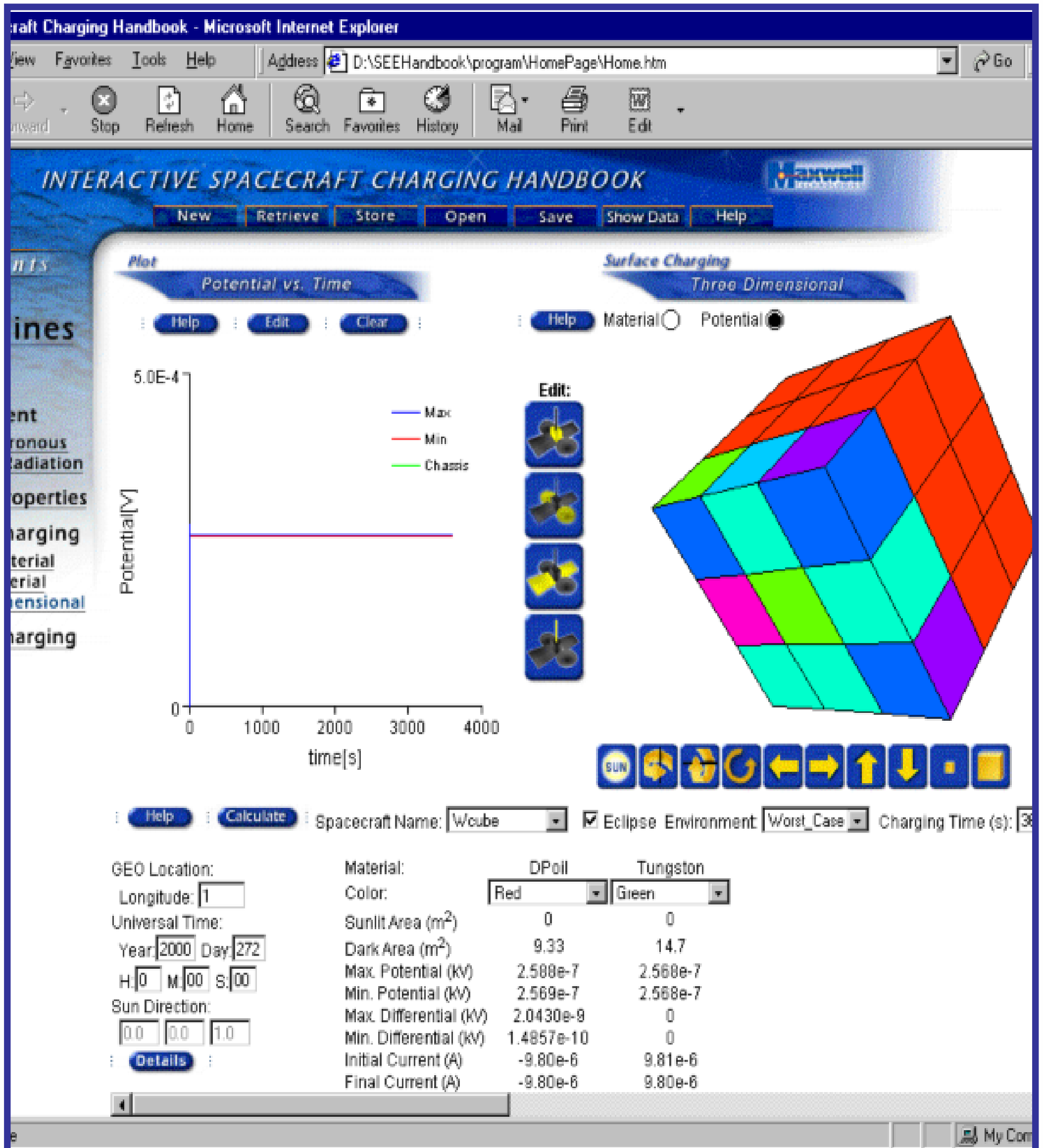
NASCAP Upgrades

NASCAP-2K



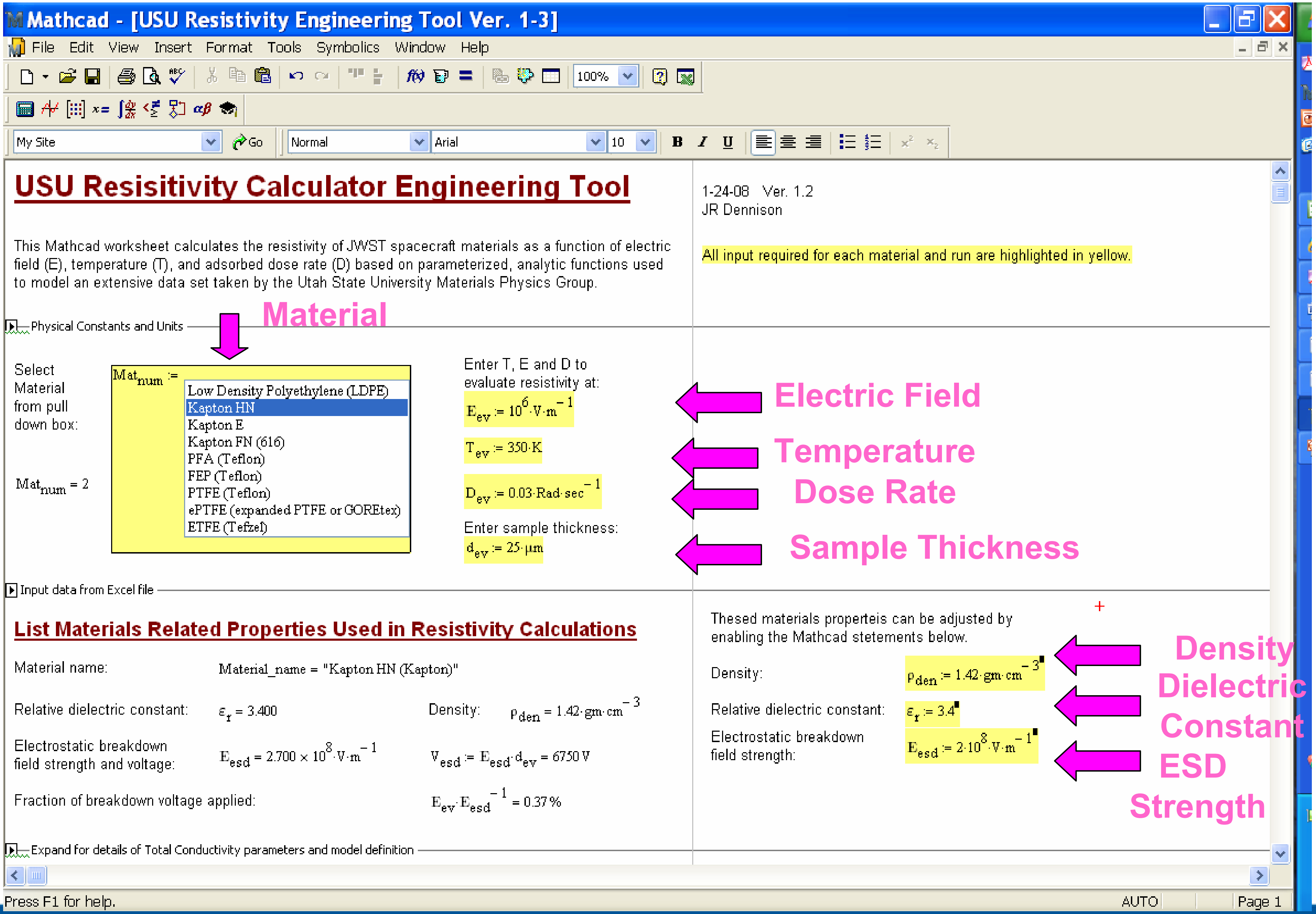
Spacecraft Name: Wcube ☑ Eclipse Environment: Worst_Case Charging Time (s):

GEO Location:
Longitude: 1
Universal Time:
Year: 2000 Day: 272
H: 0 M: 00 S: 00
Sun Direction:
0.0 0.0 1.0

Material:	DPoil	Tungston
Color:	Red	Green
Sunlit Area (m^2)	0	0
Dark Area (m^2)	9.33	14.7
Max. Potential (kV)	2.588e-7	2.568e-7
Min. Potential (kV)	2.569e-7	2.568e-7
Max. Differential (kV)	2.0430e-9	0
Min. Differential (kV)	1.4857e-10	0
Initial Current (A)	-9.80e-6	9.81e-6
Final Current (A)	-9.80e-6	9.80e-6

Typical SEE Handbook Simulation

USU Resistivity Engineering Tool Inputs



USU Resisitivity Calculator Engineering Tool

1-24-08 Ver. 1.2
JR Dennison

This Mathcad worksheet calculates the resistivity of JWST spacecraft materials as a function of electric field (E), temperature (T), and adsorbed dose rate (D) based on parameterized, analytic functions used to model an extensive data set taken by the Utah State University Materials Physics Group.

All input required for each material and run are highlighted in yellow.

Physical Constants and Units

Material

Select Material from pull down box:

$Mat_{num} :=$
- Low Density Polyethylene (LDPE)
- Kapton HN
- Kapton E
- Kapton FN (616)
- PFA (Teflon)
- FEP (Teflon)
- PTFE (Teflon)
- ePTFE (expanded PTFE or GOREtex)
- ETFE (Tefzel)

$Mat_{num} = 2$

Enter T, E and D to evaluate resistivity at:

$E_{ev} := 10^{6} \cdot V \cdot m^{-1}$

Electric Field

$T_{ev} := 350 \cdot K$

Temperature

$D_{ev} := 0.03 \cdot Rad \cdot sec^{-1}$

Dose Rate

Enter sample thickness:

$d_{ev} := 25 \cdot \mu m$

Sample Thickness

Input data from Excel file

List Materials Related Properties Used in Resistivity Calculations

Material name: Material_name = "Kapton HN (Kapton)"

Relative dielectric constant: $\varepsilon_r = 3.400$

Density: $\rho_{den} = 1.42 \cdot gm \cdot cm^{-3}$

Electrostatic breakdown field strength and voltage: $E_{esd} = 2.700 \times 10^{8} \cdot V \cdot m^{-1}$ $V_{esd} := E_{esd} \cdot d_{ev} = 6750\,V$

Fraction of breakdown voltage applied: $E_{ev} \cdot E_{esd}^{-1} = 0.37\,\%$

Thesed materials properteis can be adjusted by enabling the Mathcad stetements below.

Density: $\rho_{den} := 1.42 \cdot gm \cdot cm^{-3}$

Density

Relative dielectric constant: $\varepsilon_r := 3.4$

Dielectric Constant

Electrostatic breakdown field strength: $E_{esd} := 2 \cdot 10^{8} \cdot V \cdot m^{-1}$

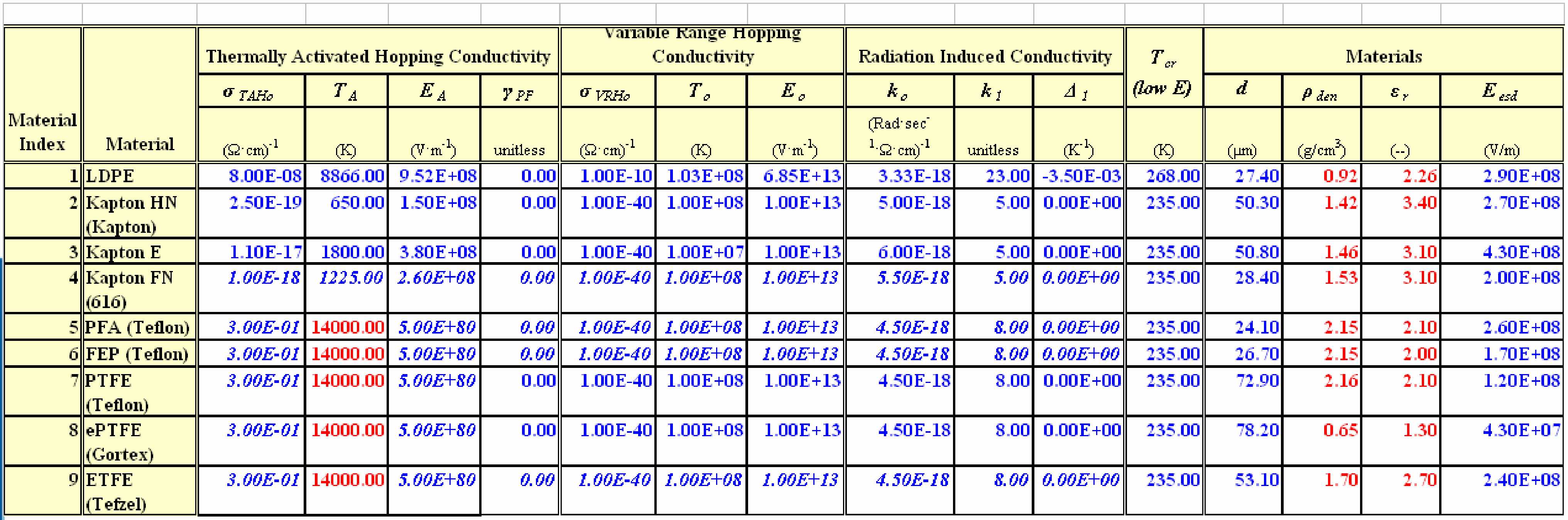
ESD Strength

Expand for details of Total Conductivity parameters and model definition

USU Resistivity Engineering Tool Inputs

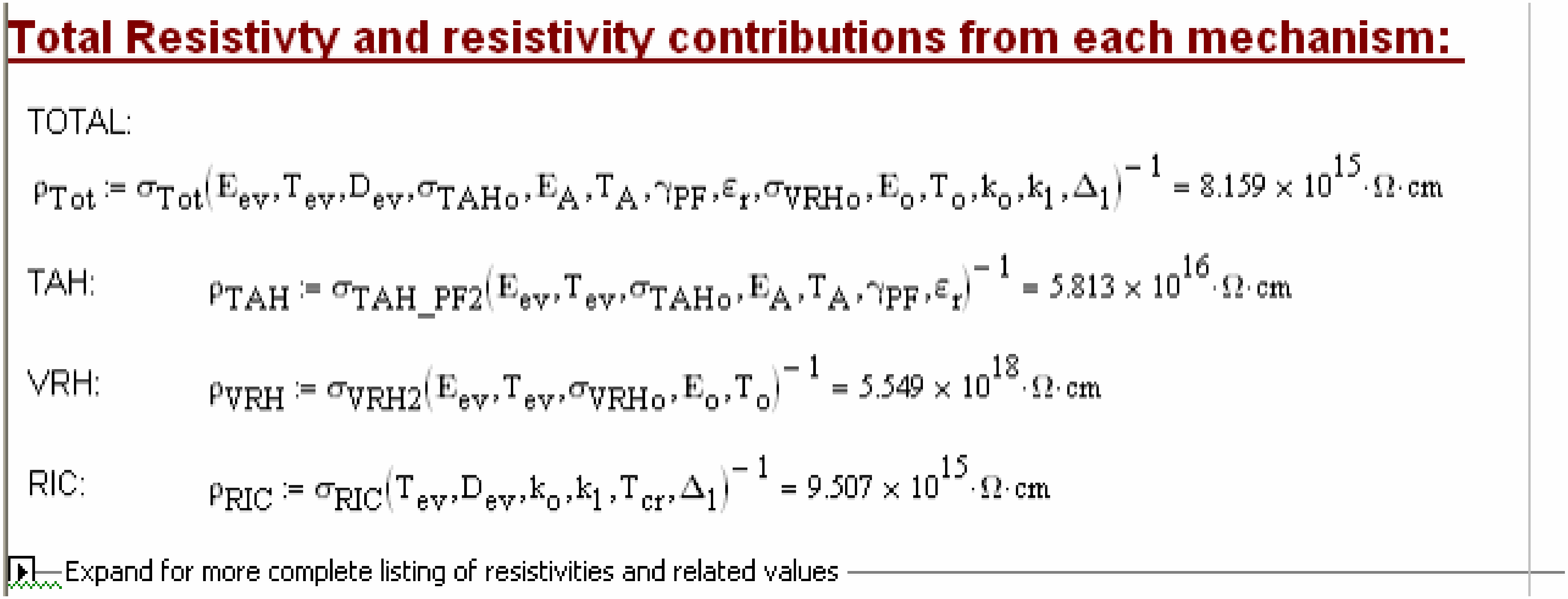
Resistivity Database Master Parameter List

Excel File



Material Index	Material	Thermally Activated Hopping Conductivity				Variable Range Hopping Conductivity			Radiation Induced Conductivity			T_{cr} (low E)	Materials			
		σ_{TAHo}	T_A	E_A	γ_{PF}	σ_{VRHo}	T_o	E_o	k_o	k_1	Δ_1		d	ρ_{den}	ε_r	E_{esd}
		$(\Omega \cdot cm)^{-1}$	(K)	$(V \cdot m^{-1})$	unitless	$(\Omega \cdot cm)^{-1}$	(K)	$(V \cdot m^{-1})$	$(Rad \cdot sec^{-1} \cdot \Omega \cdot cm)^{-1}$	unitless	(K^{-1})	(K)	(μm)	(g/cm^3)	(--)	(V/m)
1	LDPE	8.00E-08	8866.00	9.52E+08	0.00	1.00E-10	1.03E+08	6.85E+13	3.33E-18	23.00	-3.50E-03	268.00	27.40	0.92	2.26	2.90E+08
2	Kapton HN (Kapton)	2.50E-19	650.00	1.50E+08	0.00	1.00E-40	1.00E+08	1.00E+13	5.00E-18	5.00	0.00E+00	235.00	50.30	1.42	3.40	2.70E+08
3	Kapton E	1.10E-17	1800.00	3.80E+08	0.00	1.00E-40	1.00E+07	1.00E+13	6.00E-18	5.00	0.00E+00	235.00	50.80	1.46	3.10	4.30E+08
4	Kapton FN (616)	*1.00E-18*	*1225.00*	*2.60E+08*	*0.00*	*1.00E-40*	*1.00E+08*	*1.00E+13*	*5.50E-18*	*5.00*	*0.00E+00*	235.00	28.40	1.53	3.10	2.00E+08
5	PFA (Teflon)	*3.00E-01*	14000.00	*5.00E+80*	*0.00*	*1.00E-40*	*1.00E+08*	*1.00E+13*	*4.50E-18*	*8.00*	*0.00E+00*	235.00	24.10	2.15	2.10	2.60E+08
6	FEP (Teflon)	*3.00E-01*	14000.00	*5.00E+80*	*0.00*	*1.00E-40*	*1.00E+08*	*1.00E+13*	*4.50E-18*	*8.00*	*0.00E+00*	235.00	26.70	2.15	2.00	1.70E+08
7	PTFE (Teflon)	*3.00E-01*	14000.00	*5.00E+80*	0.00	1.00E-40	1.00E+08	1.00E+13	4.50E-18	8.00	0.00E+00	235.00	72.90	2.16	2.10	1.20E+08
8	ePTFE (Gortex)	*3.00E-01*	14000.00	*5.00E+80*	0.00	1.00E-40	1.00E+08	1.00E+13	4.50E-18	8.00	0.00E+00	235.00	78.20	0.65	1.30	4.30E+07
9	ETFE (Tefzel)	*3.00E-01*	14000.00	*5.00E+80*	*0.00*	*1.00E-40*	*1.00E+08*	*1.00E+13*	*4.50E-18*	*8.00*	*0.00E+00*	235.00	53.10	1.70	2.70	2.40E+08

USU Resistivity Engineering Tool Outputs



Total Resistivty and resistivity contributions from each mechanism:

TOTAL:

$$\rho_{Tot} := \sigma_{Tot}\left(E_{ev}, T_{ev}, D_{ev}, \sigma_{TAHo}, E_A, T_A, \gamma_{PF}, \varepsilon_r, \sigma_{VRHo}, E_o, T_o, k_o, k_1, \Delta_1\right)^{-1} = 8.159 \times 10^{15} \cdot \Omega \cdot cm$$

TAH: $$\rho_{TAH} := \sigma_{TAH\_PF2}\left(E_{ev}, T_{ev}, \sigma_{TAHo}, E_A, T_A, \gamma_{PF}, \varepsilon_r\right)^{-1} = 5.813 \times 10^{16} \cdot \Omega \cdot cm$$

VRH: $$\rho_{VRH} := \sigma_{VRH2}\left(E_{ev}, T_{ev}, \sigma_{VRHo}, E_o, T_o\right)^{-1} = 5.549 \times 10^{18} \cdot \Omega \cdot cm$$

RIC: $$\rho_{RIC} := \sigma_{RIC}\left(T_{ev}, D_{ev}, k_o, k_1, T_{cr}, \Delta_1\right)^{-1} = 9.507 \times 10^{15} \cdot \Omega \cdot cm$$

▸ Expand for more complete listing of resistivities and related values

Scope of USU Experimental Studies

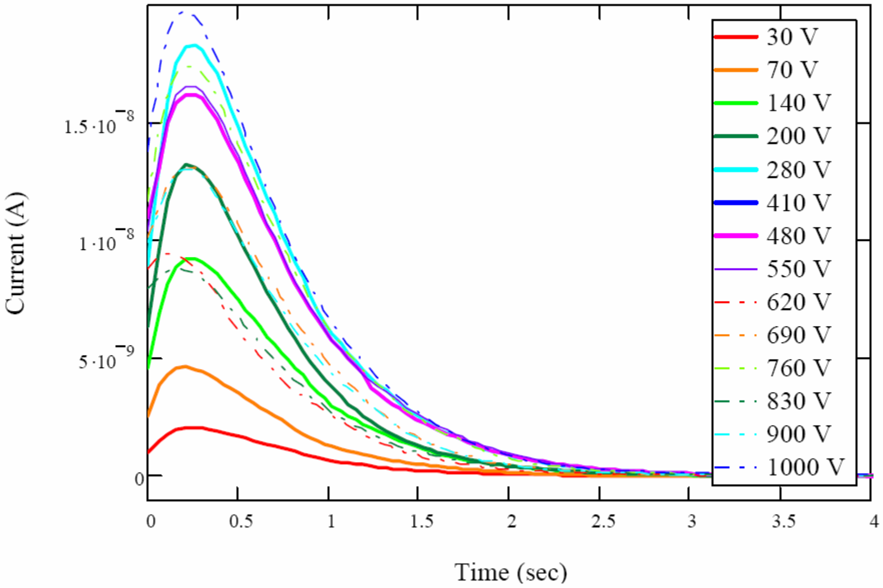
Determine the resistivity and related materials properties of critical JWST materials over the appropriate range of environmental conditions:

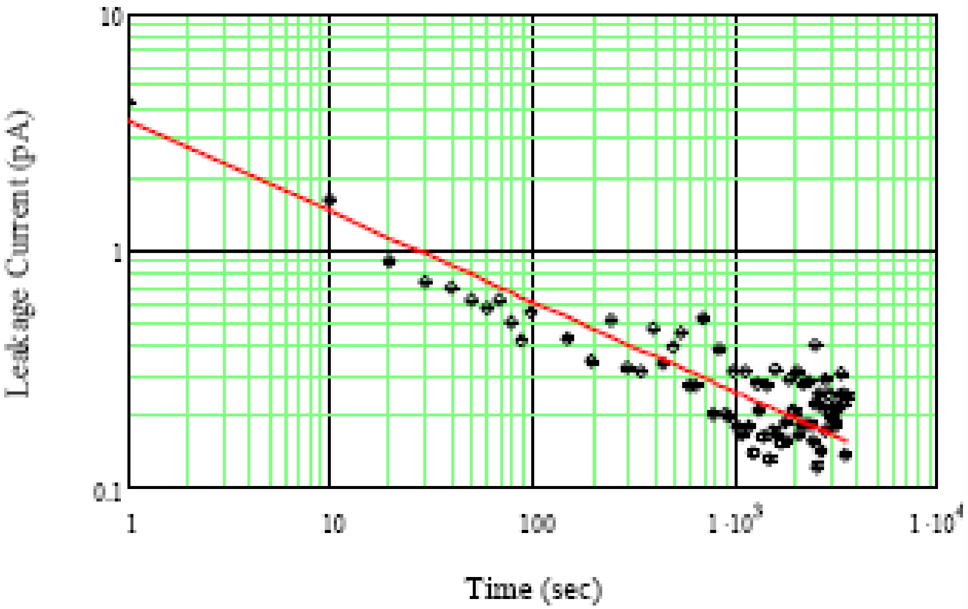
- **Temperature: ~100 K to 365 K**
- **Electric field: low to breakdown field (~3x10^8 V/m)**
- **Radiation dose: low dose to ~10 rad/sec**

Appropriate theory has been used to obtain parametric fits to the data and, where necessary, extend the data to experimentally inaccessible regions.

Validity and range of the theories were determined.

Transient Currents





Polarization

Space Charge Diffusion

$$\sigma_P(t) = \left[\varepsilon_o\left(\varepsilon_r^\infty - \varepsilon_r^o\right)\Big/\tau_P\right] e^{-t/\tau_P}$$

$$\sigma_{diff}(t) = \left(q_c\, D_o / E\right) {\partial p(t)}\Big/{\partial z}$$

Temporal changes in current as sample comes to equilibrium are not considered in this study.

Polarization Current (short term—10 s to a few hrs)
Diffusion Current (long term—10 min to a few days)

RIC Measurements

- Designed and built an entirely new test system
- Characterized instrumentation and methods
- Used standard model for RIC, augmented with T-dependent k and Δ

- Determined k and Δ for JWST materials over range of dose rates encountered by JWST
    - Measurements made from ~0.01 to ~10 rad/s

- Determined T dependence of k and Δ for JWST materials
    - Measurements made from ~105 K to ~335 K

Electrostatic Breakdown (ESD) Measurements

- Extensive room T measurements (5-20 per material)
- Limited studies completed at $T<T_{rm}$, down to ~140 K.
- Limited studies completed on endurance (ramp rate) testing

- Breakdown fields were mid-10^7 V/m to mid-10^8 V/m for all materials, except ePTFE.

- Typical results have 10% to 30% variation in V_{esd}.

- Typically measured results 10-25% higher than manufacturer's values. Attributed to slower ramp rate and dry samples.

- Found modest dependence on ramp rate.

Conductivity Mechanisms

Engineering tool considers three conductivity mechanisms.

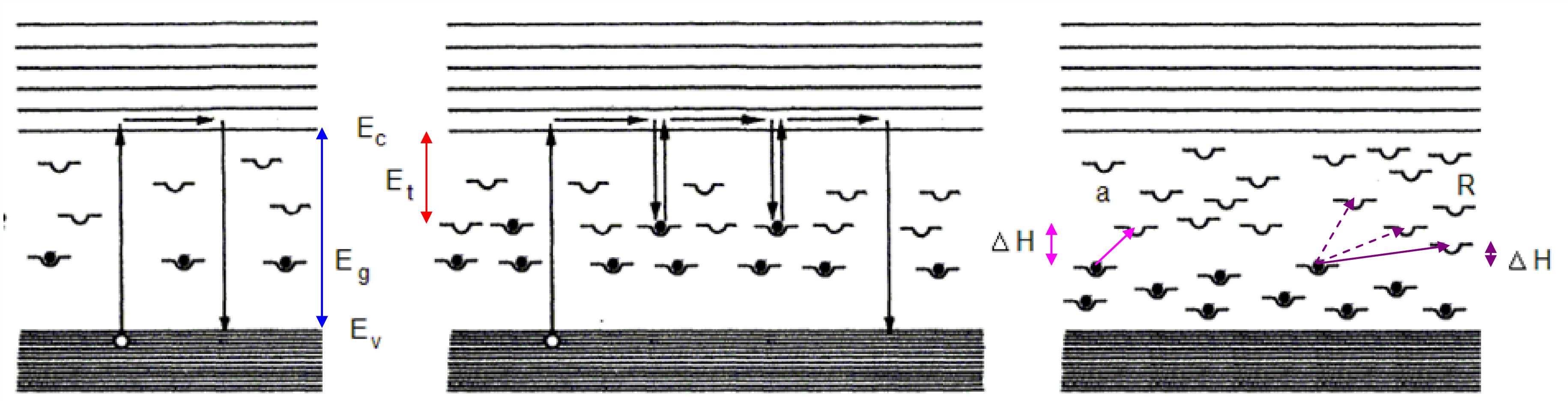
TAH and VRH depend on F and T

RIC depends on D and T

$$\sigma_{Total}(F,T,\dot{D}) = \sigma_{TAH}(F,T) + \sigma_{VRH}(F,T) + \sigma_{RIC}(\dot{D},T)$$

Conduction Models

Model: T and E Dependence of DC Conductivity



Intrinsic SC **RIC** **TAH** **VRH**

Thermally Activated Hopping Conductivity

TAH theory is based on thermally assisted quantum tunneling from adjacent trap sites of a single well depth and separation.

An E-field favors one direction of motion over another, leading to sinh behavior:

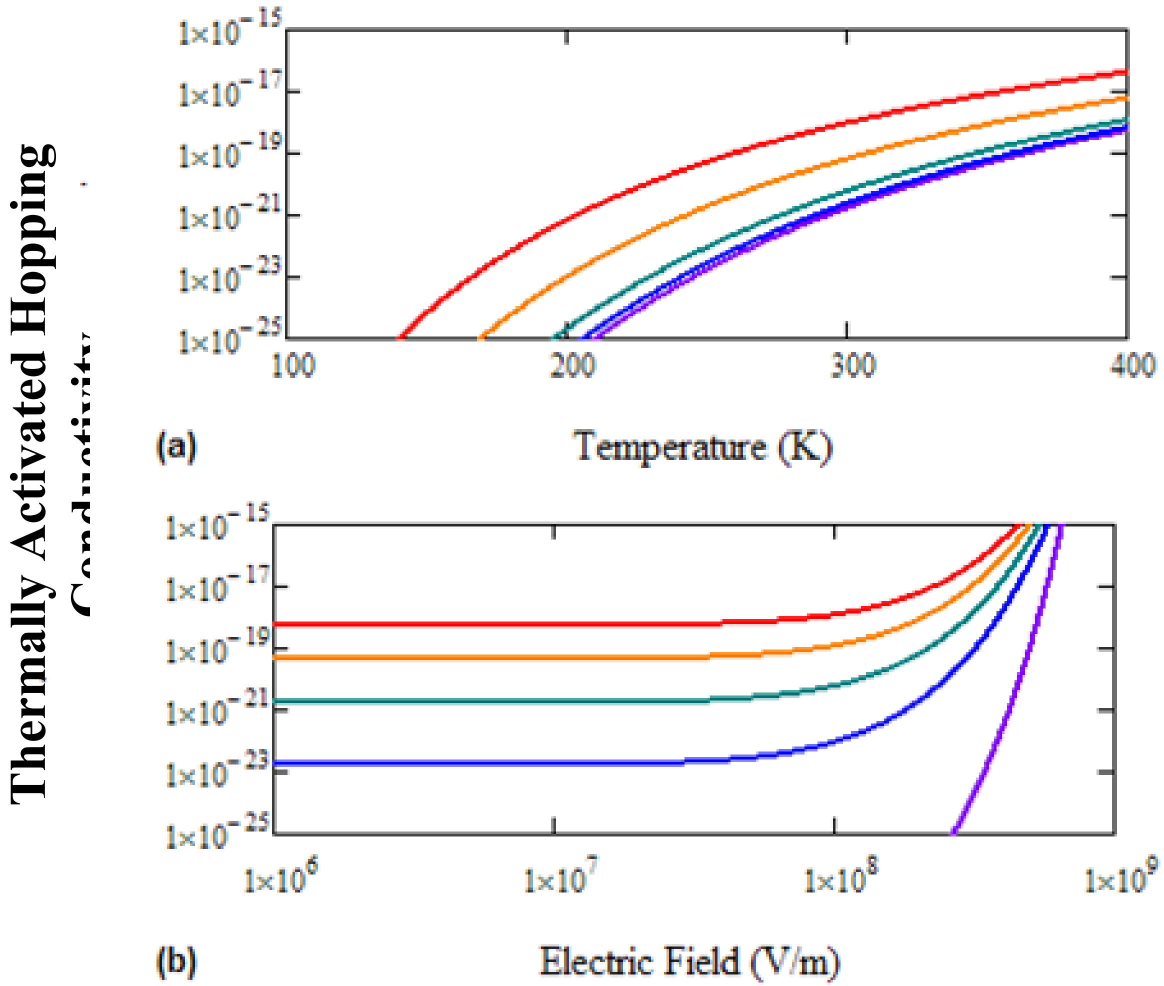
$$\sigma_{TAH}(F,T)=\left[\frac{2N(T)\nu_{TAH}\,a\,q_e}{F}\right]\exp\left[\frac{-\Delta H}{k_B T}\right]\sinh\left[\frac{a\,q_e\,F}{k_B T}\right]=\left\{\sigma_{TAHo}(T)\left({}^{T_A}\!/_{T}\right)Z_A(\beta_A)\exp\left({}^{-T_A}\!/_{T}\right)\right\}$$

$$\beta_A\equiv 4F\,T_A/3\,F_A\,T=q_e\,F\,a/k_B T \qquad \text{with} \qquad Z_A(\beta_A)\equiv {}^{1}\!/_{\beta_A}\,\sinh(\beta_A)$$

Reduced fitting parameters

$$\sigma_{TAHo}(T)\equiv 2\;N(T)\;\nu_{TAH}\;q_e^{\,2}\,a^2, \qquad T_A\equiv\Delta H/k_B \qquad \text{and} \qquad F_A\equiv 4\Delta H/3q_e\,a$$

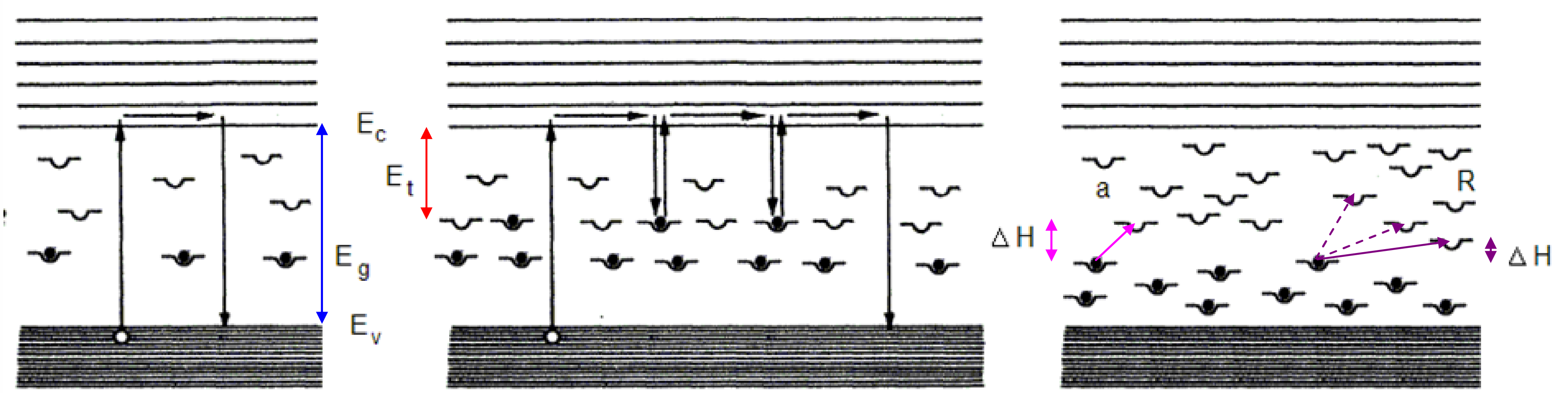
TAH Dependence on E and T



Temperature and electric field dependence of thermally activated hopping conductivity. (a) *Temperature dependence with electric fields of 1·107 V/m (purple), 5·107 V/m (blue), 1·108 V/m (green), 2·108 V/m (orange) and 3·108 V/m (red).* ***(b)*** *Electric field dependence with temperatures of 150 K (purple), 250 K (blue), 300 K (green), 350 K (orange) and 400 K (red). Curves are based on Eq. (2). To approximately match LDPE data we have set σTAHo=1.4·10-10 (Ω-cm)-1 and FA=9.5·108 V/m for TA=6626 K. FESD is ~3·108 V/m.*

Conduction Models

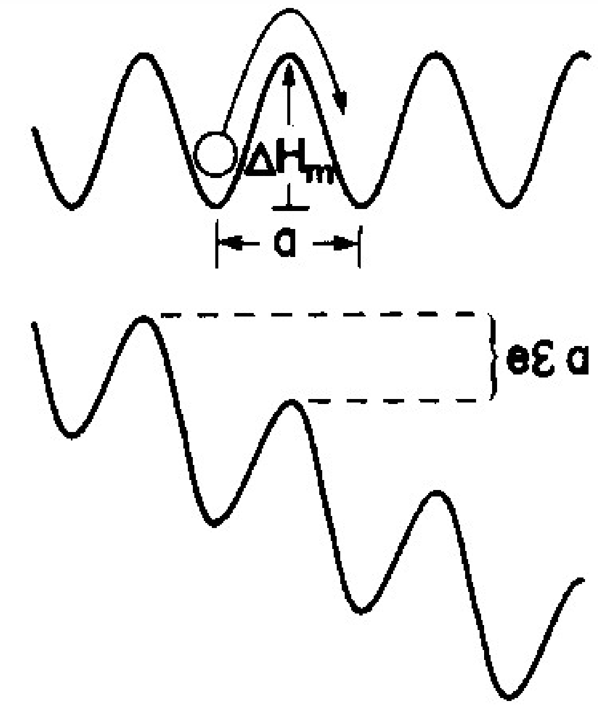
Model: T and E Dependence of DC Conductivity



TAH

Theory of Thermally Activated Hopping Conductivity

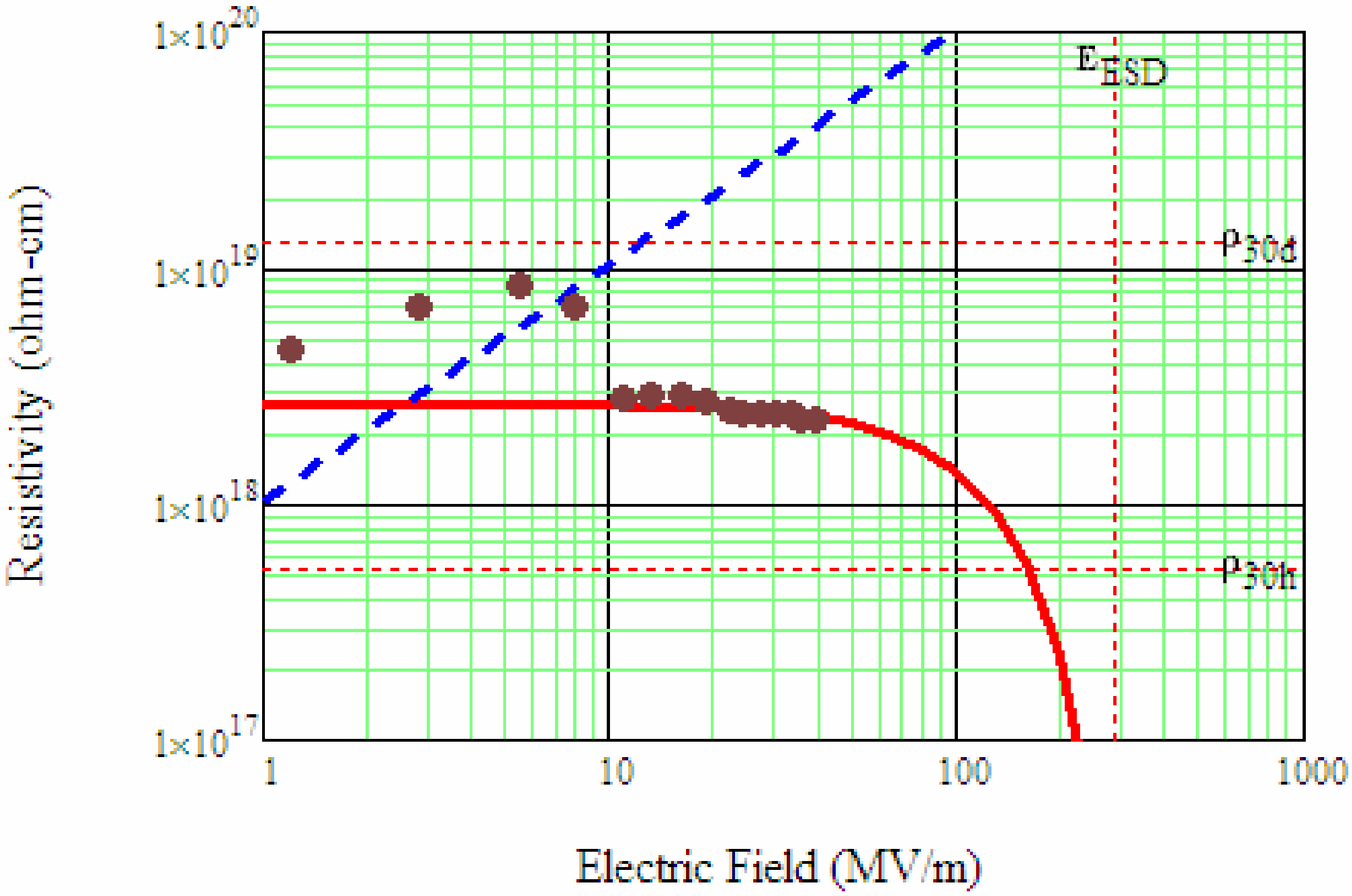
Theory of thermal assisted hoping conductivity provides a model for the temperature and electric field dependence of the conductivity of polymers:



$$\sigma_{TAH}(F,T) = \left[\frac{2N(T)\nu_{TAH}\,a\,q_e}{F}\right]\exp\left[\frac{-\Delta H}{k_B T}\right]\sinh\left[\frac{a\,q_e\,F}{k_B T}\right] = \left\{\sigma_{TAHo}(T)\left({}^{T_A}\!/_{T}\right) Z_A(\beta_A)\,\exp\left(-{}^{T_A}\!/_{T}\right)\right\}$$

$\sigma_{TAHo}(T) \equiv 2\,N(T)\,\nu_{TAH}\,q_e^{\;2}\,a^2,$ $\quad T_A \equiv \Delta H / k_B$ *and* $F_A \equiv 4\Delta H / 3q_e\,a$

E-field Dependence of TAH



Note divergence at E_{ESD}

Variable Range Hopping Conductivity

Variable range hopping model of Mott and Davis (as extended by Huges and Apsley for E-field dependence), allows hopping at a range of distances over a distribution of trap energy states:

Theory leads to "T ¼ " behavior

$$\sigma_{VRH}(F,T) = \left\{ \sigma_{VRHo}(T) \left({T_V}\big/{T} \right)^{1/4} Z_{V1}(\beta_V) \exp\left[\left({-T_V}\big/{T} \right)^{1/4} Z_{V2}(\beta_V) \right] \right\}$$

$$\beta_V \equiv 4F\,T_V \big/ 3F_V\,T = q_e\,F\,(2\alpha)^{-1} / k_B T$$

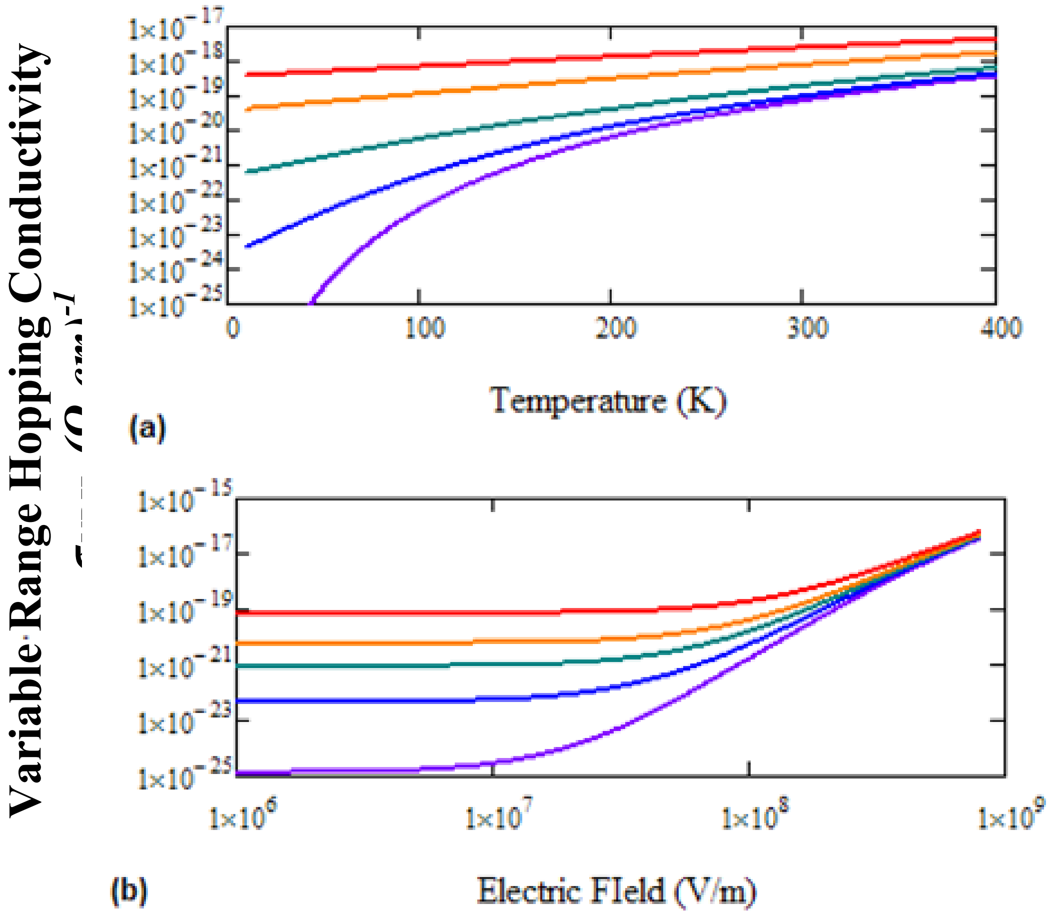
$$Z_{V1}(\beta_V) \equiv \left[2/Z_{Vo}(\beta_V)\right]^{1/4} \quad \text{and} \quad Z_{V2}(\beta_V) \equiv \left(\frac{-1}{2\beta_V}\right) \cdot \left[1 + \frac{Z_{Vo}(\beta_V)}{Z_{Vo}(\beta_V) - \frac{3}{2}\beta_V} \right] \cdot Z_{V1}(\beta) \cdot \left[\frac{\frac{3+\beta_V}{24\cdot(1+\beta_V)^3} - \frac{1}{8} - \frac{\beta_V}{3}}{\frac{2+\beta_V}{6\cdot(1+\beta_V)^2} + \frac{1}{3} + \frac{\beta_V}{2}} \right]$$

$$\textit{with} \quad Z_{Vo}(\beta_V) \equiv \frac{\left(1+{\beta_V}\big/{2}\right)}{(1+\beta_V)^2} + \left(1+\frac{3}{2}\beta_V\right)$$

Reduced fitting parameters

$$\textit{with} \quad \sigma_{VRHo}(T) = 2\,N_{E_F}\,\nu_{VRH}\,q_e^{\,2} \big/ (2\alpha)^2, \quad T_V \equiv 3(2\alpha)^3 / N_{E_F}\pi k_B \quad \textit{and} \quad F_V \equiv 4(2\alpha)^4 / N_{E_F}\pi q_e$$

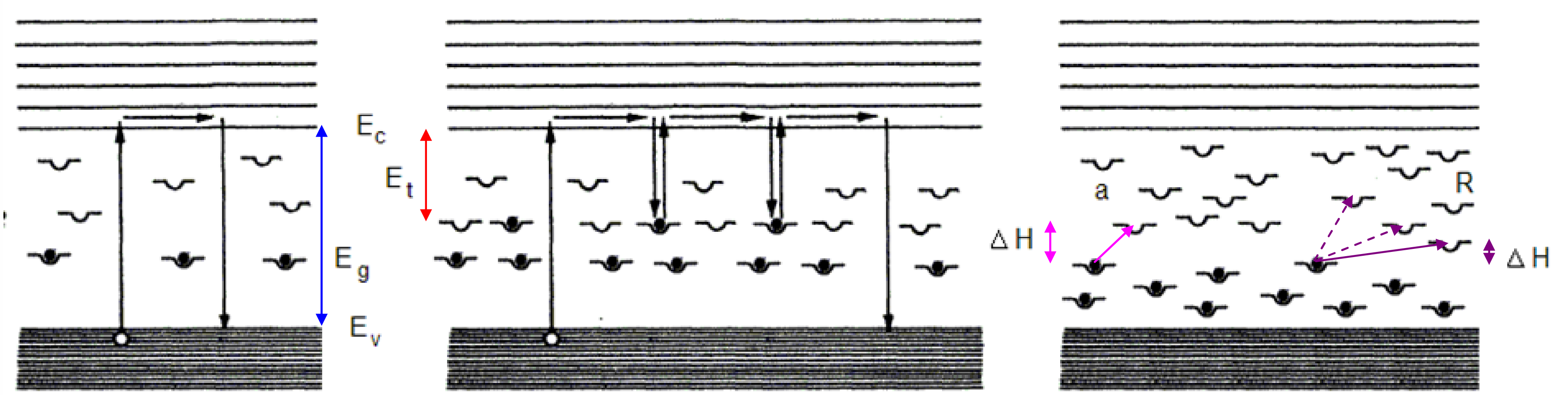
VRH Dependence on E and T



Temperature and electric field dependence of variable range hopping conductivity. (a) Temperature dependence with electric fields of 1·107 V/m (purple), 5·107 V/m (blue), 1·108 V/m (green), 2·108 V/m (orange) and 3·108 V/m (red). (b) Electric field dependence with temperatures of 50 K (purple), 100 K (blue), 150 K (green), 200 K (orange) and 300 K (red). Curves are based on Eq. (4). To approximately match LDPE data we have set σVRHo=1.0·10-10 (Ω-cm)-1 and FV=6.9·1013 V/m for TV=1.0·108 K.

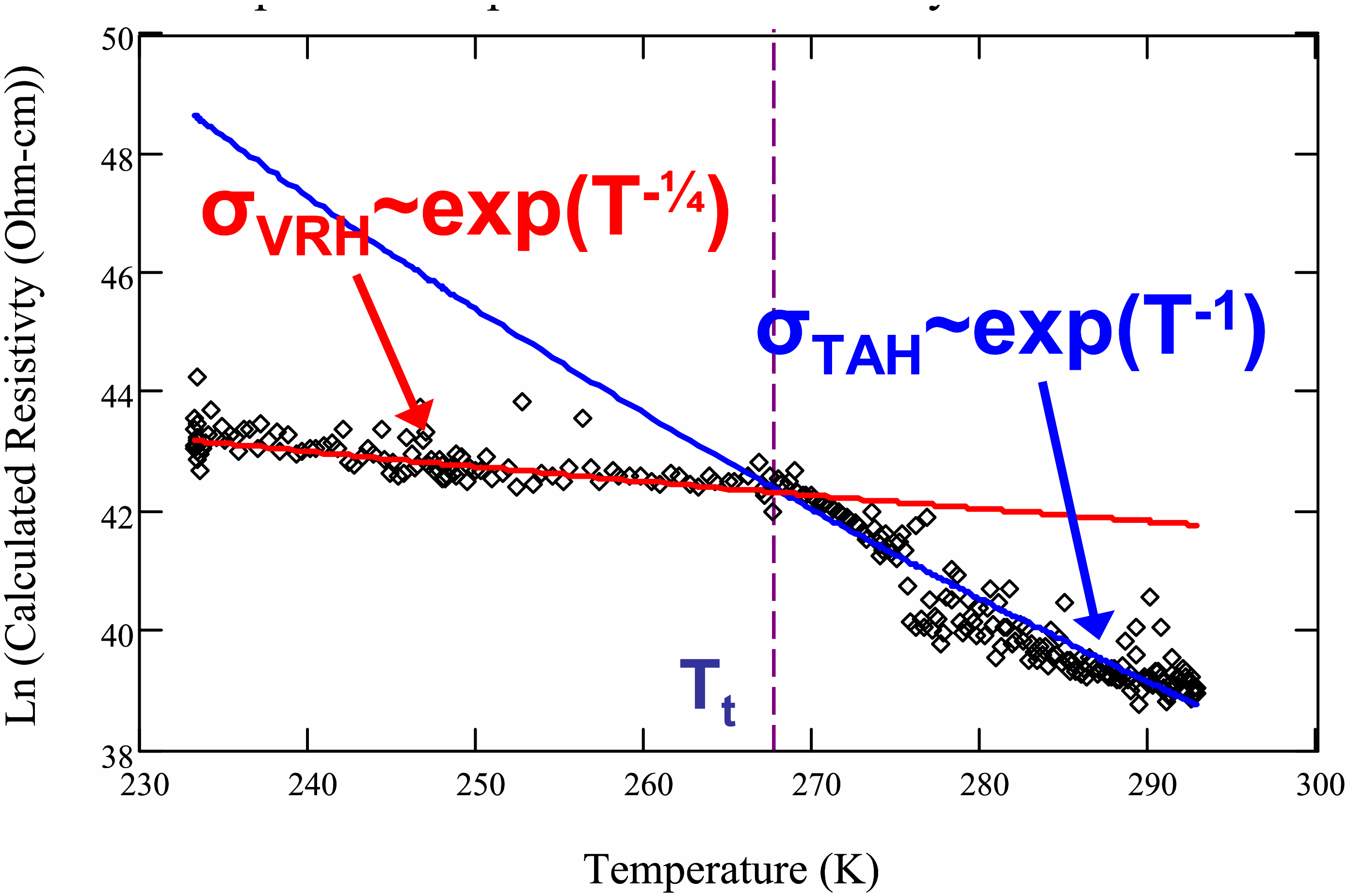
Conduction Models

Model: T and E Dependence of DC Conductivity



VRH

Temperature Dependence of TAH and VRH



Note change in slope for transistion from TAH to VRH.

This occurs near a beta structural phase transition.

Fit for RIC

Basic theory for RIC follows from the Rose, Fowler, Vaiserberg for radiation assisted thermal hopping from a distribution of multiple trap sites

The key power law relation has T dependant coefficients k_{RIC} and Δ

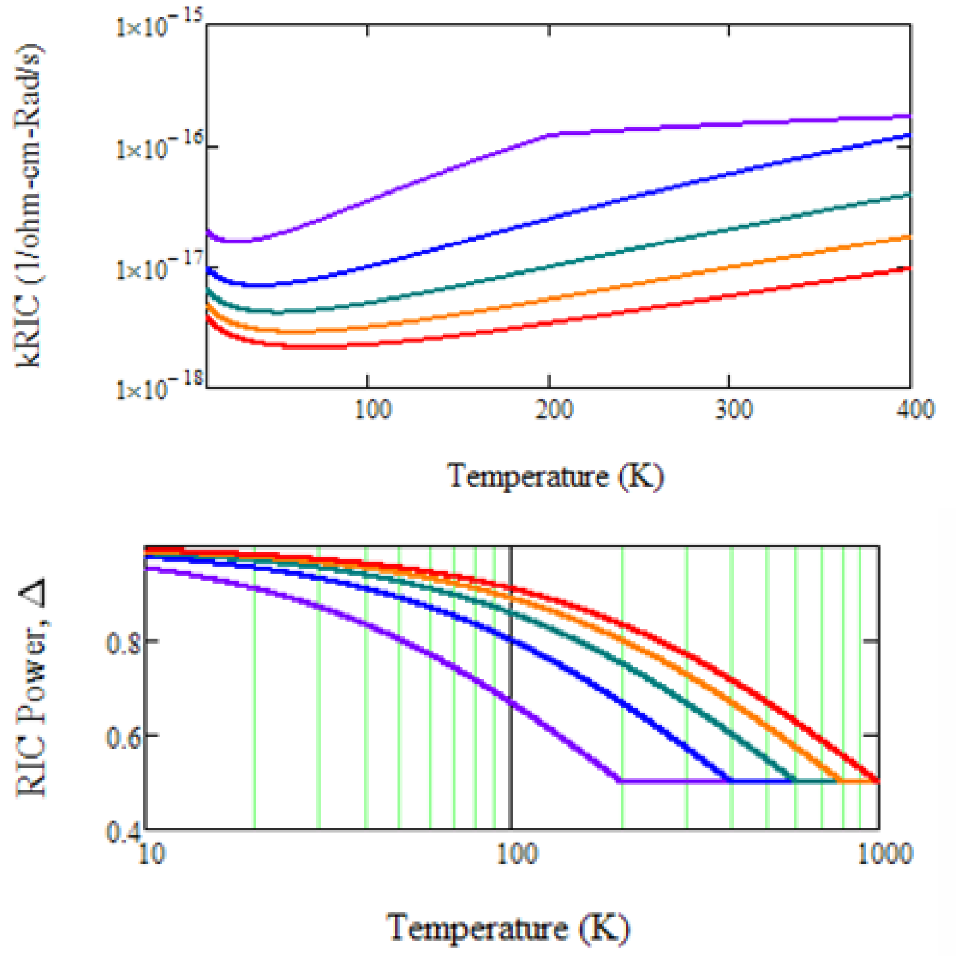
$$\sigma_{RIC}(\dot{D}) = k_{RIC}(T)\ \dot{D}^{\Delta(T)}$$

$$\Delta(T) = \left[1 + T/T_{RIC}\right]^{-1}$$

$$k_{RIC}(T) = q_e\mu_o\left[\left(\frac{\rho_m}{s\Sigma n_o T_{RIC}}\right)\left(\frac{m_e^*}{3k_B T}\right)^{1/2}\right]^{\Delta(T)}\left[2\left(\frac{\sqrt{m_e^* m_h^*}\,k_B T}{2\pi\hbar^2}\right)^{3/2}\right]^{1-\Delta(T)} = k_{RICo}\cdot k_{RIC1}{}^{\Delta(T/T_{RIC})}\left[T/T_{RIC}\right]^{3/2-2\cdot\Delta(T/T_{RIC})}$$

$$\textit{with}\quad k_{RICo} \equiv \left[\frac{q_e\mu_o}{\pi\sqrt{2\pi}\,\hbar^3}\left(m_e^* m_h^*\right)^{3/4}\left(k_B T_{RIC}\right)^{3/2}\right]\quad \textit{and}\quad k_{RIC1} \equiv \left[\left(\frac{\pi\sqrt{2\pi}\,\rho_m\,k_B\,\hbar^3}{\sqrt{3}\,s\Sigma n_o}\right)\left(\frac{\sqrt{m_e^*}}{\left(m_e^* m_h^*\right)^{3/4}}\right)\left(k_B T_{RIC}\right)^{-3}\right]$$

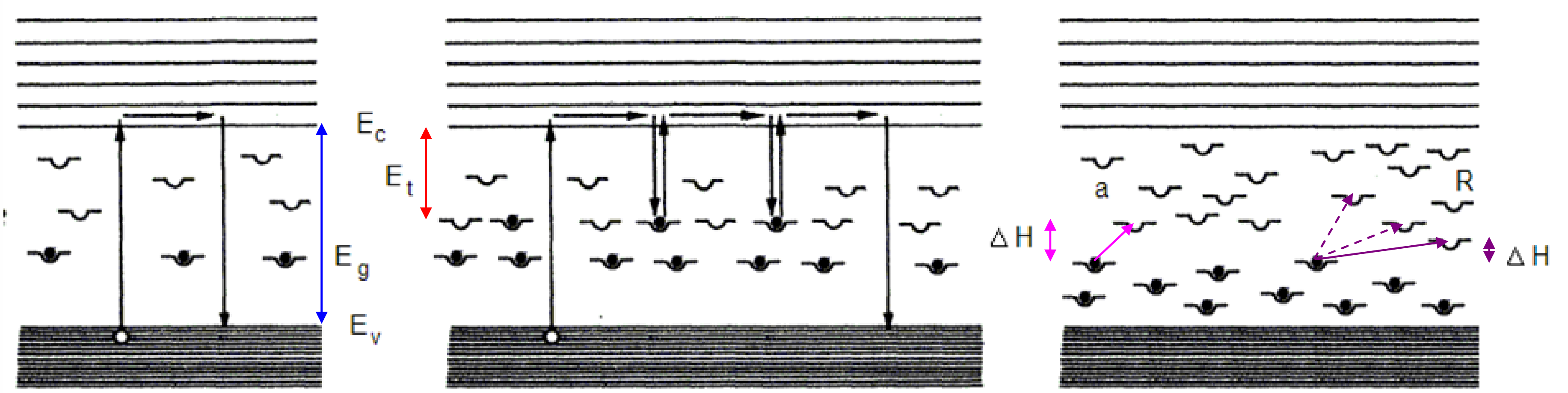
RIC Dependence on D and T



Temperature dependence of the RIC parameters. (a) Proportionality constant, kRIC, based on Eq. (8). (b) RIC power, Δ, based on Eq. (7). Values shown are for TRIC set to 200 K (purple), 400 K (blue), 600 K (green), 800 K (orange) and 1000 K (red). To approximately match LDPE data we have set kRICo=1.8·10-14 (Ω-cm-Rad/sec)-1 and kRIC1=4.6·10-5 for TRIC=600 K.

Conduction Models

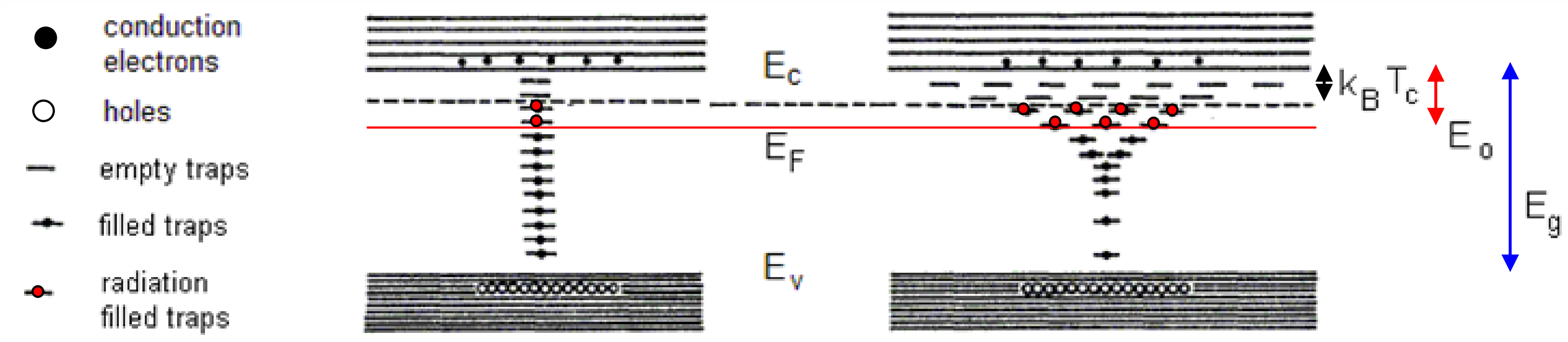
Model: T and E Dependence of DC Conductivity



RIC

What IS Radiation Induced Conductivity (RIC)

Theoretical Model: T and D Dependence of RIC



Uniform Trap Density

$$\Delta(T)\rightarrow 1$$

$$k(T)\rightarrow k_{RICo}$$

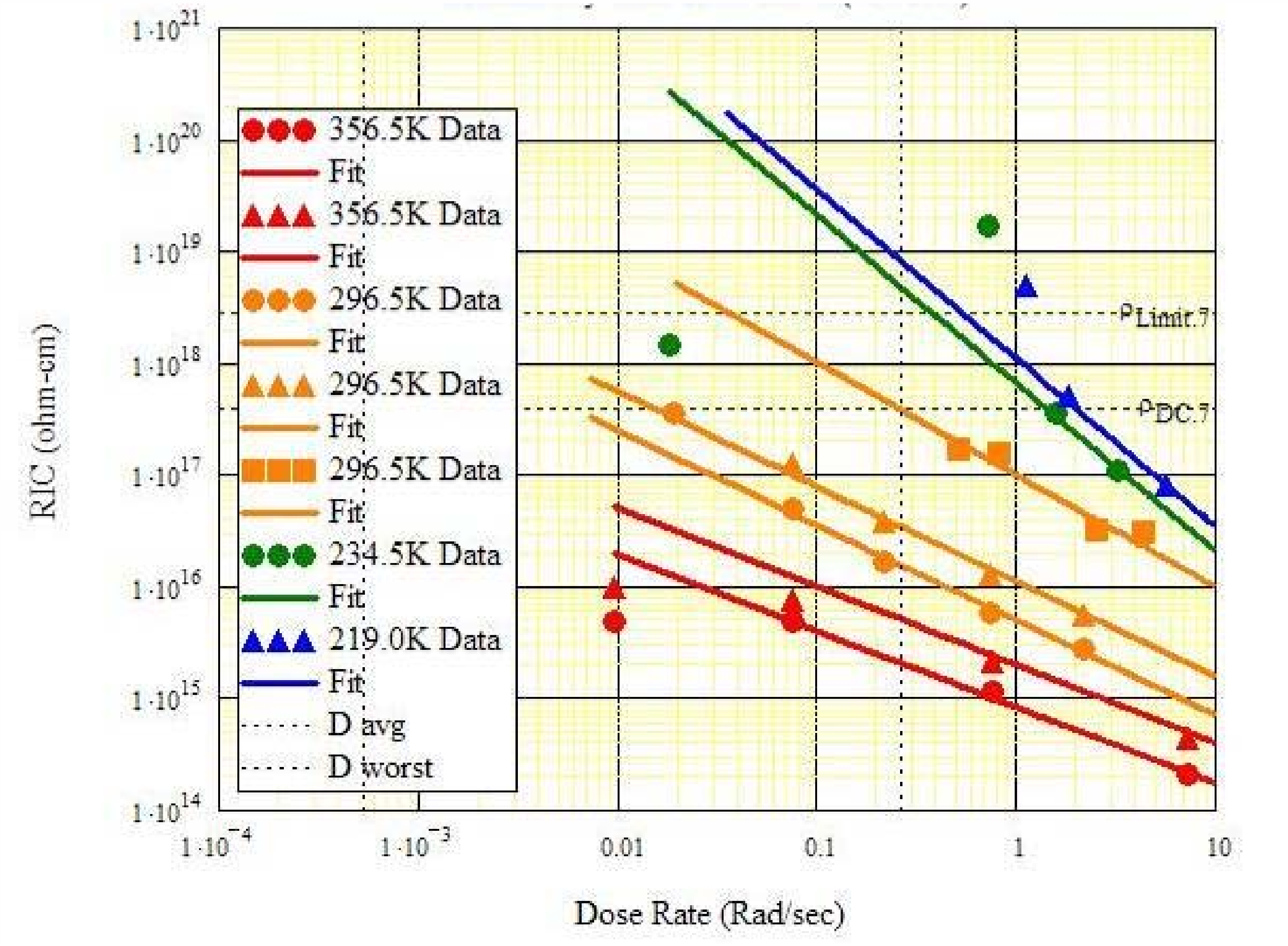
Exponential Trap Density

$$\Delta(T)\rightarrow {}^{T_c}\!\big/_{T+T_c}$$

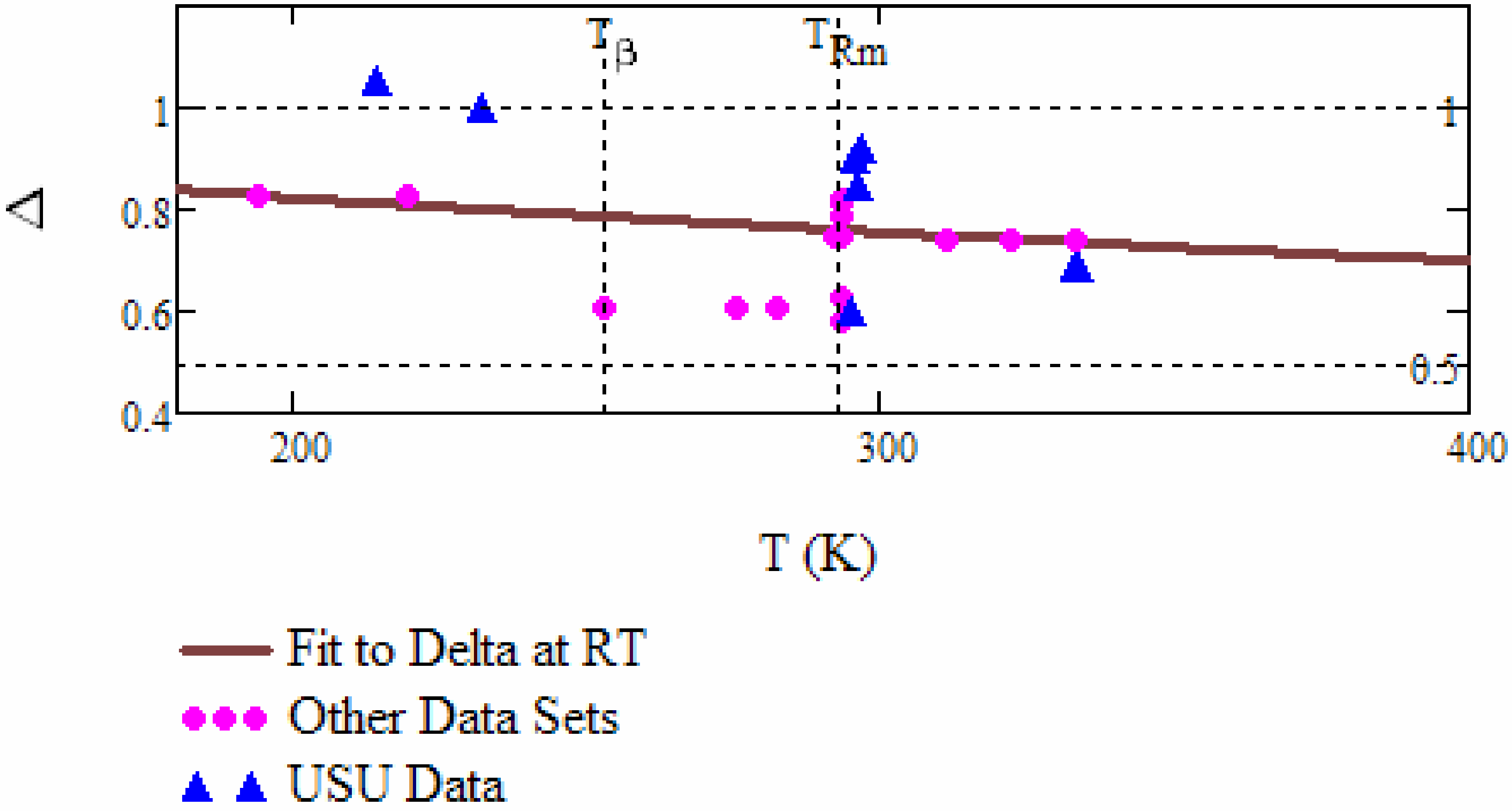
$$k(T)\rightarrow k_{RIC1}\left[2\left(\frac{m_e k_B T}{2\pi\hbar^2}\right)^{3/2}\left(\frac{m_e^* m_h^*}{m_e\, m_e}\right)^{3/4}\right]^{\frac{T}{T+T_c}}$$

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

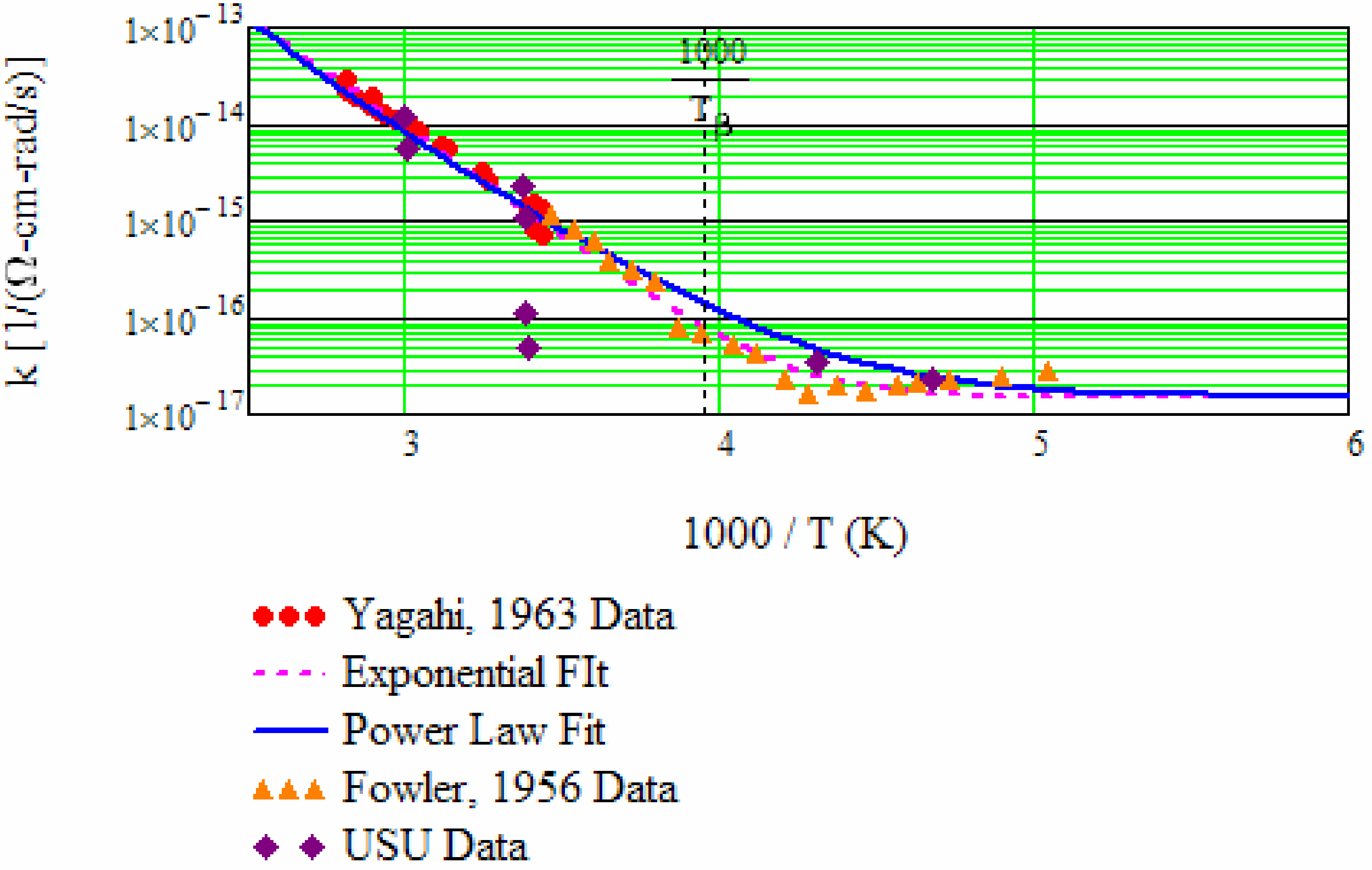
Comparison of RIC at Various T



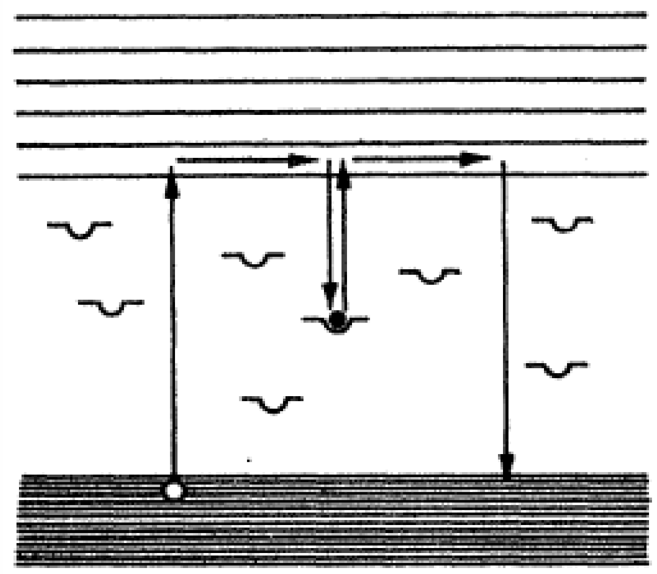
Comparison of RIC at Various T

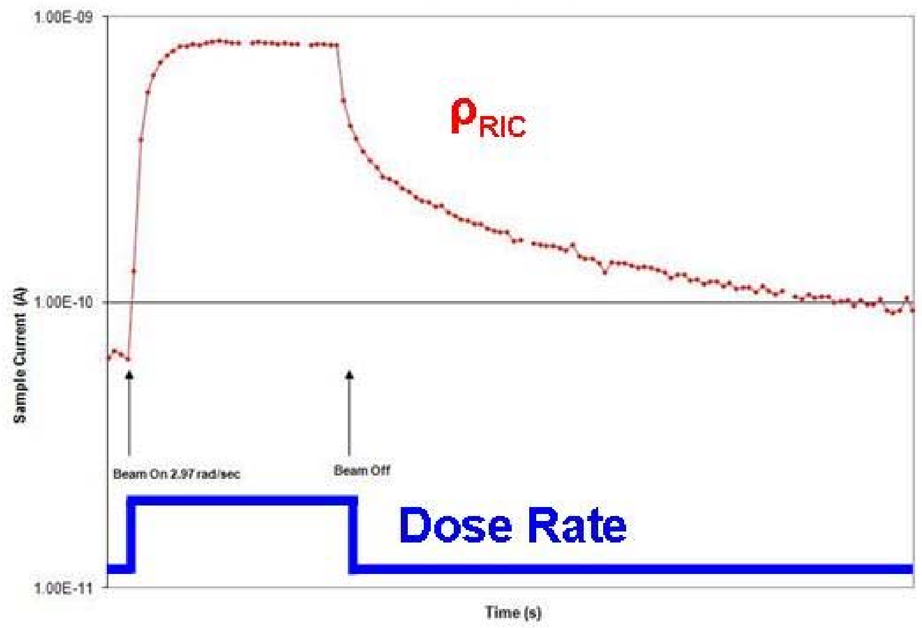


Comparison of RIC at Various T



Time Behavior of RIC





Dose Dependant RIC

$$\sigma_{RIC}(\dot{D}) = k_{RIC} \cdot \dot{D}^{\Delta}$$

Persistent RIC

$$\sigma_{RIC}(t) = \sigma_{RIC_o}\left(1 + t/\tau_{trap}\right)^{-1}$$

In real time, when the radiation is turned on, a finite period is required for the measured conductivity to approach the radiation induced conductivity.

Similarly, when the radiation is turned off, the measured conductivity also takes a finite amount of time to decay down to the material's initial conductivity.

Electrostatic Breakdown Theory

Based on the thermodynamic model for ESD

From an expression for bond disruption, from an expression for charge mobility similar to the TAH model, we get

$$1 = \left(\frac{k_B T}{h/t_{en}} \right) \exp\left[\frac{-\Delta G}{k_B T} \right] \sinh\left[\frac{q_e F_{ESD} \lambda}{k_B T} \right] = \left(\frac{k_B T}{h/t_{en}} \right) \left(\frac{\frac{3}{4} F_{ESD}}{F_{A'}} \right) \left[\frac{T_{A'}}{T} Z_{A'}(\beta_{A'}) \exp\left[\frac{-T_{A'}}{T} \right] \right]$$

Reduced fitting parameters

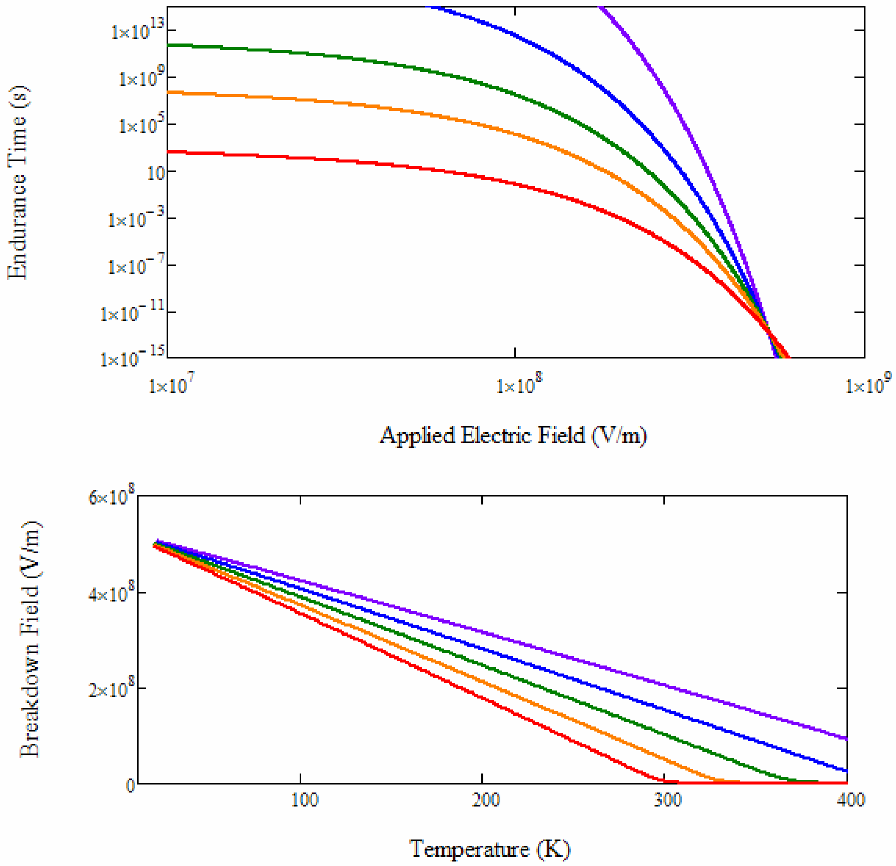
$$\textit{with} \qquad \beta_{A'} \equiv 4 F_{ESD} T_{A'} / 3 F_{A'} T = q_e F_{ESD} \lambda / k_B T$$

$$T_{A'} \equiv \Delta G / k_B \qquad \textit{and} \qquad F_{A'} \equiv \Delta G / \tfrac{3}{4} q_e \lambda \rightarrow \tfrac{3}{4} F_{ESD}$$

Finally, an expression for breakdown field strength in terms of endurance time and the fitting parameters:

$$F_{ESD} = \left[\frac{k_B T}{q_e \left(\frac{3}{4} \lambda \right)} \right] \csc h^{-1} \left[\left(\frac{h/t_{en}}{k_B T} \right) \exp\left(\frac{-\Delta G}{k_B T} \right) \right] = \left(\tfrac{3}{4} F_{A'} \frac{T}{T_{A'}} \right) \csc h^{-1} \left[\left(\frac{h/t_{en}}{k_B T} \right) \exp\left(\frac{-T_{A'}}{T} \right) \right]$$

ESD Dependence on Endurance Time



Temperature dependence of the electrostatic field breakdown strength. ***(a) Endurance, or time to breakdown, a function of applied electric field, based on Eq. (9). Curves shown are for temperature set to 150 K (purple), 200 K (blue), 250 K (green), 300 K (orange) and 400 K (red). (b) Breakdown field strength as a function of temperature, based on Eq. (10). Curves shown are endurance times set to 100 s (purple), 102 s (blue), 104 s or 2.8 hr (green), 106 s or 11.6 days (orange) and 108 s or 3.2 yr (red). To approximately match LDPE data, we have set FESD=9.5·108 V/m and ΔG'=1.22 eV.***

Representative Fitting Parameters for LDPE

Based on the best overall fits to the full data set, Using the equations above, we estimate the fitting parameters to be:

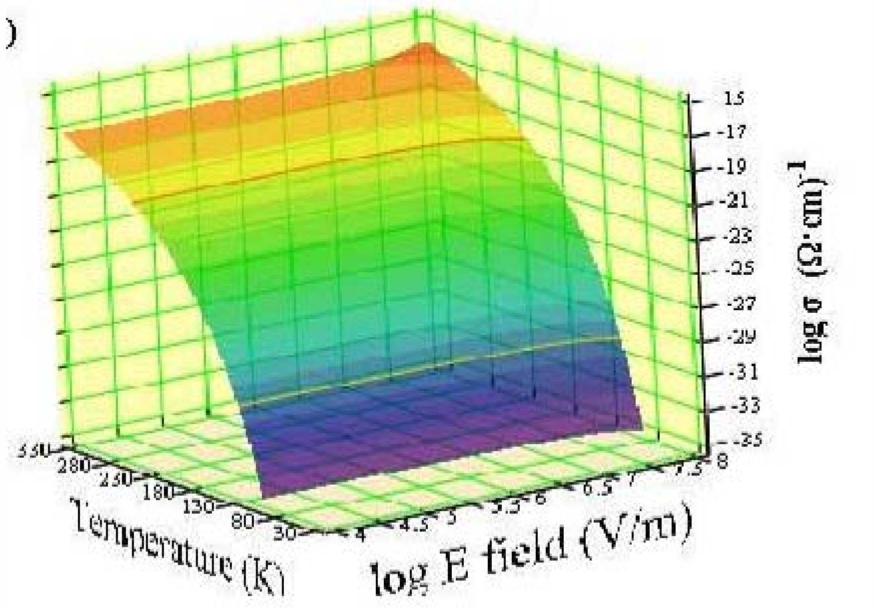
$\sigma_{TAHo} = 8.0\cdot10^{-8}$ $(\Omega\text{-cm})^{-1}$
$E_A = 9.5\cdot10^{8}$ V/m
$T_A = 8.9\cdot10^{3}$ K

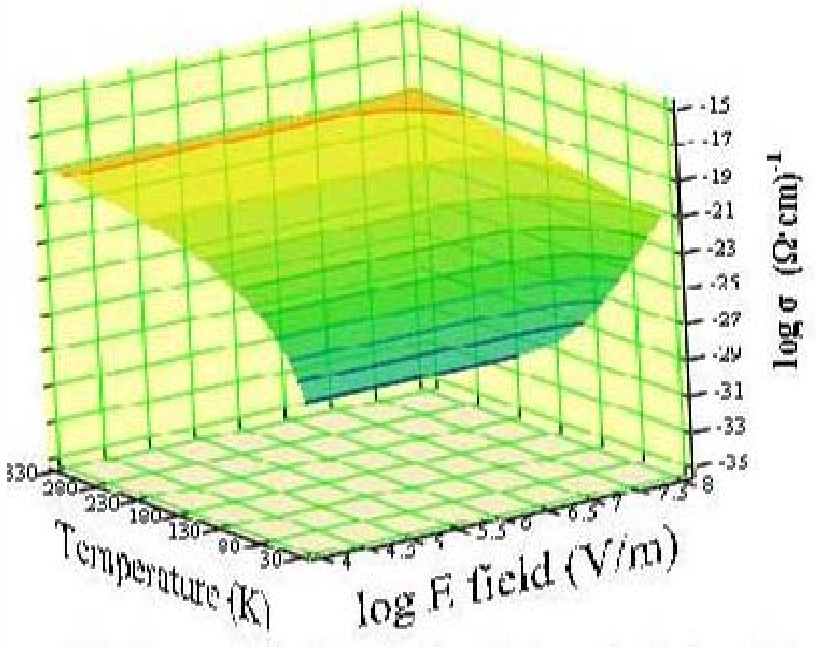
$k_{RICo}=1.8\cdot10^{-14}$ $(\Omega\text{-cm-Rad/sec})^{-1}$
$k_{RIC1}=4.6\cdot10^{-5}$
$T_{RIC}=600$ K

$\sigma_{VRHo} = 1.0\cdot10^{-10}$ $(\Omega\text{-cm})^{-1}$
$E_V = 6.9\cdot10^{13}$ V/m
$T_V = 1.0\cdot10^{8}$ K

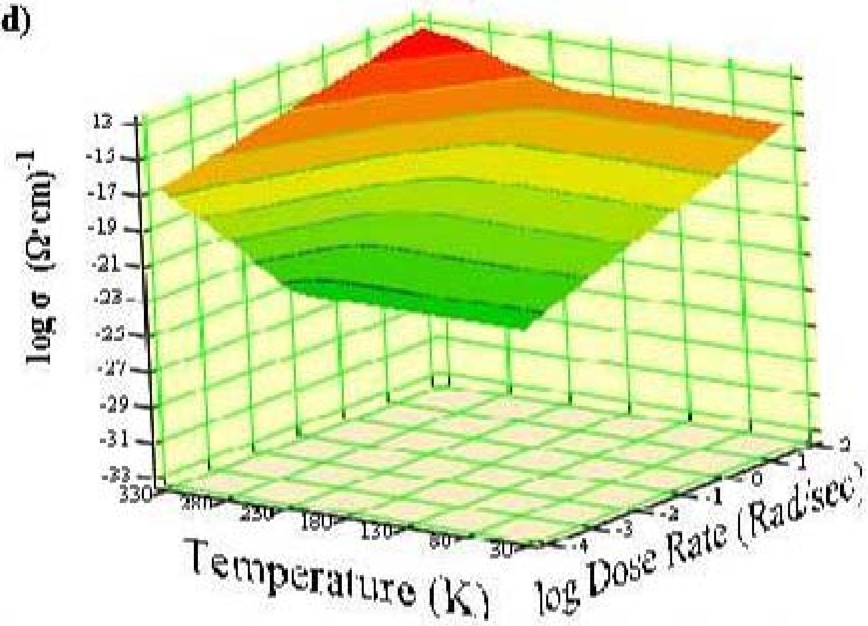
ΔG, of 1.2 eV

Individual Conductivity Components





(d)



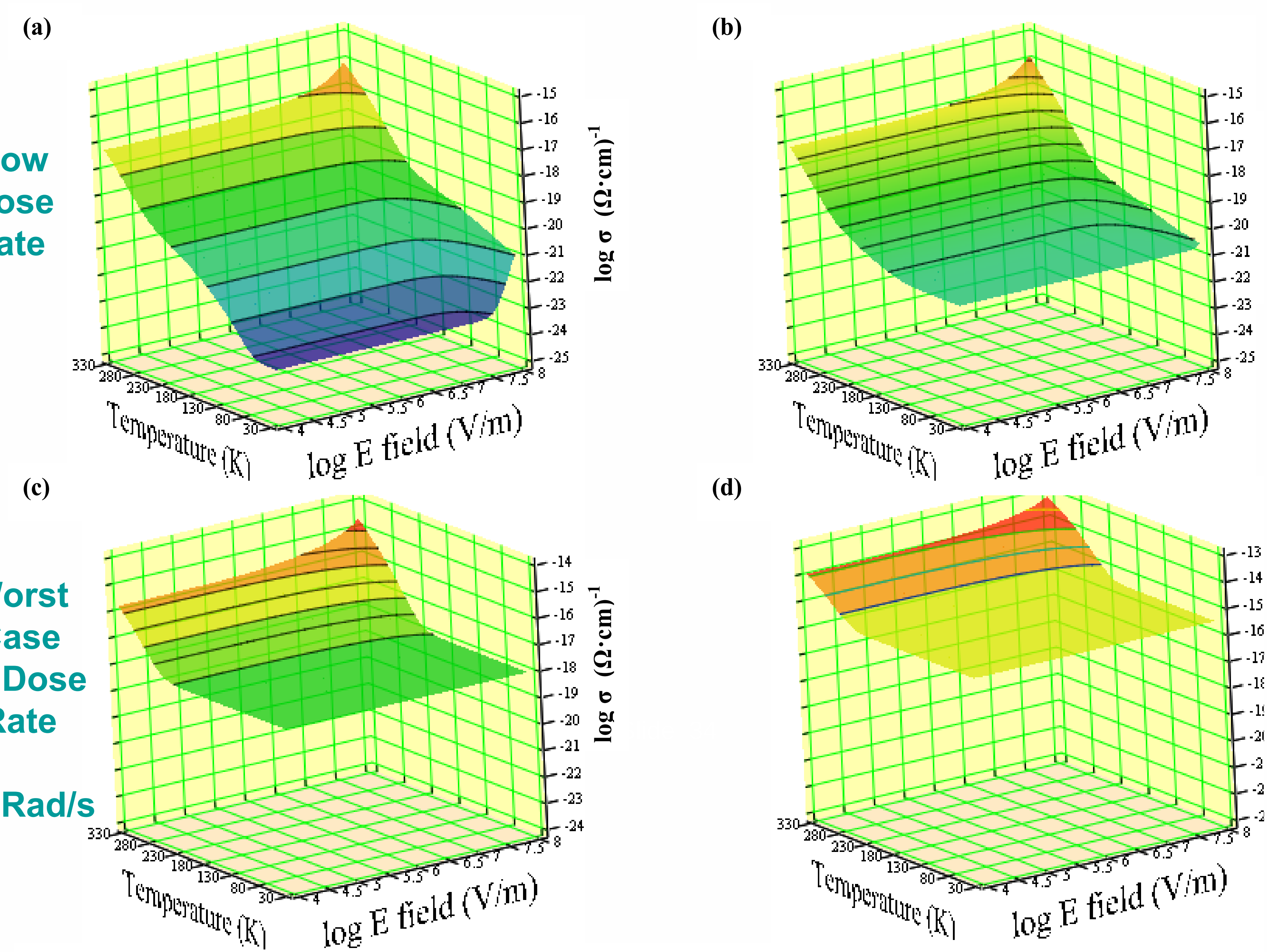
LDPE Data

TAH

VRH

RIC

Constant Voltage Resistivity Fits--LDPE



Low dose rate

Average L2 Dose Rate

5 mRad/s

Worst Case L2 Dose Rate

0.2 Rad/s

High Dos Rate

10 Rad/s

Figure . Total conductivity as a function of temperature and E-field for various absorbed dose rates. E-field and conductivity ax logarithmic. (a) Low absorbed dose rate of 10^{-6} Rad·sec^{-1}. (b) Approximate average L2 absorbed dose rate of $5.4·10^{-4}$ Rad·se Approximate worst case (storm) L2 absorbed dose rate of $2.7·10^{-1}$ Rad·sec^{-1}. (d) High absorbed dose rate of 10^{+2} Rad·sec^{-1}.

Summary

- Extensive Resistivity measurements made.
- Physics-based parameterized models determined from literature.
- New Engineering tool developed.
  - Tool capabilities are being updated.
  - Hopefully more materials will be added.
  - Looking for mechanism to distribute information.