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Computational Models for Electrical Breakdown in Solids

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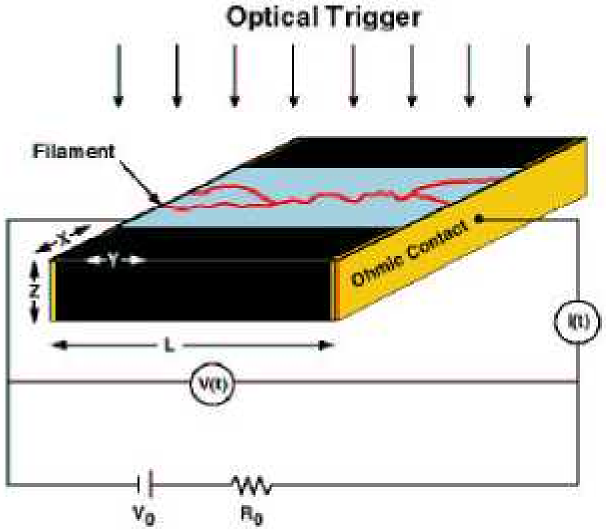
Electrical Breakdown in Solids



Objectives:

Develop methods for predicting optically-triggered electrical breakdown of PCSS devices (controlled breakdown) and undesired breakdown in other high-voltage devices

NW Applications:

Fireset triggers and neutron generators

Approach:

Develop full-physics continuum simulation capability for electrical breakdown based on microscopic physics

Include effects of radiation, defects and contacts

Develop predictive simulation capability of breakdown physics for ASC software

Team Members:

H. P. Hjalmarson (PI, 1435), K. E. Kambour (1739) and R. P. Joshi (Old Dominion)

Collaborators:

F. J. Zutavern (15333), A. Marr (15333) and R. J. Hoekstra (1433)

PCSS: Photoconductive Semiconductors Switch

Electrical Breakdown in Solids
Intent & Applicability

Technical Impact

- Physics-based understanding of electrical breakdown in solids

Sandia Mission

- PCSS devices for sprytron triggers
- Solid insulator breakdown for weapons components
- GaN anti-fuzes for MOS devices
- Energy storage devices
- New high-voltage applications

External Connections

- Guided S. Kang Ph.D thesis at Texas Tech University
- Guided K. Kambour Ph.D thesis at Texas Tech University
- Working with R. Joshi at Old Dominion University

External Community Linkage

I. Lock-on discovery paper

G. M. Loubriel, M. W. O'Malley and F. J. Zutavern, "Toward pulsed power uses for photoconductive semiconductor switches: Closing switches", Proc. 6th IEEE Pulsed Power Conf., Arlington, VA, p. 145, 1987.

II. Selected development papers

F. J. Zutavern, G. M. Loubriel, H. P. Hjalmarson, A. G. Baca, T. A. Plut, R. R. Gallegos, W. D. Helgeson and M. W. O'Malley, "High Gain GaAs Photoconductive Semiconductor Switches (PCSS): Device Lifetime, High Current Testing, Optical Pulse Generators", Proc. SPIE 2343, 1994.

G. M. Loubriel, F. J. Zutavern, A. Mar, H. P. Hjalmarson, A. G. Baca, M. W. O'Malley, W. D. Helgeson, R. A. Falk and D. J. Brown, "Longevity of Optically Activated, High Gain GaAs Photoconductive Semiconductor Switches", IEEE Tran. on Plasma Sci. 26, p. 1393, 1998.

A. Mar, G. M. Loubriel, F. J. Zutavern, M. W. O'Malley, W. D. Helgeson, D. J. Brown, H. P. Hjalmarson, A. G. Baca, R. L. Thornton and R. D. Donaldson, "Doped contacts for high-longevity optically activated, high-gain GaAs photoconductive semiconductor switches", IEEE Tran. Plasma Sci. 28, p. 1507, 2000.

III. Selected theory papers

H. P. Hjalmarson, F. J. Zutavern, G. M. Loubriel, M. T. Buttram, A. G. Baca and L. A. Romero, "A Thermal Ionization Model for the Sustaining Phase of Lock-on in GaAs", Proc. SPIE 1873, p. 117 1993.

H. P. Hjalmarson, G. M. Loubriel, F. J. Zutavern, D. R. Wake, S. Kang, K. Kambour and C. W. Myles, "A collective impact ionization theory of lock-on", Proceedings of the 12th Pulsed Power Conference, p. 299, 1999.

K. Kambour, C. W. Myles and H. P. Hjalmarson, "Steady-state properties of lock-on current filaments in GaAs", IEEE Tran. Plasma Sci. 28, p. 1497, 2000.

K. Kambour, H. P. Hjalmarson and C. W. Myles, "A collective theory of lock-on in photoconductive semiconductor switches, IEEE Pulsed Power Conference Proceedings, 2003.

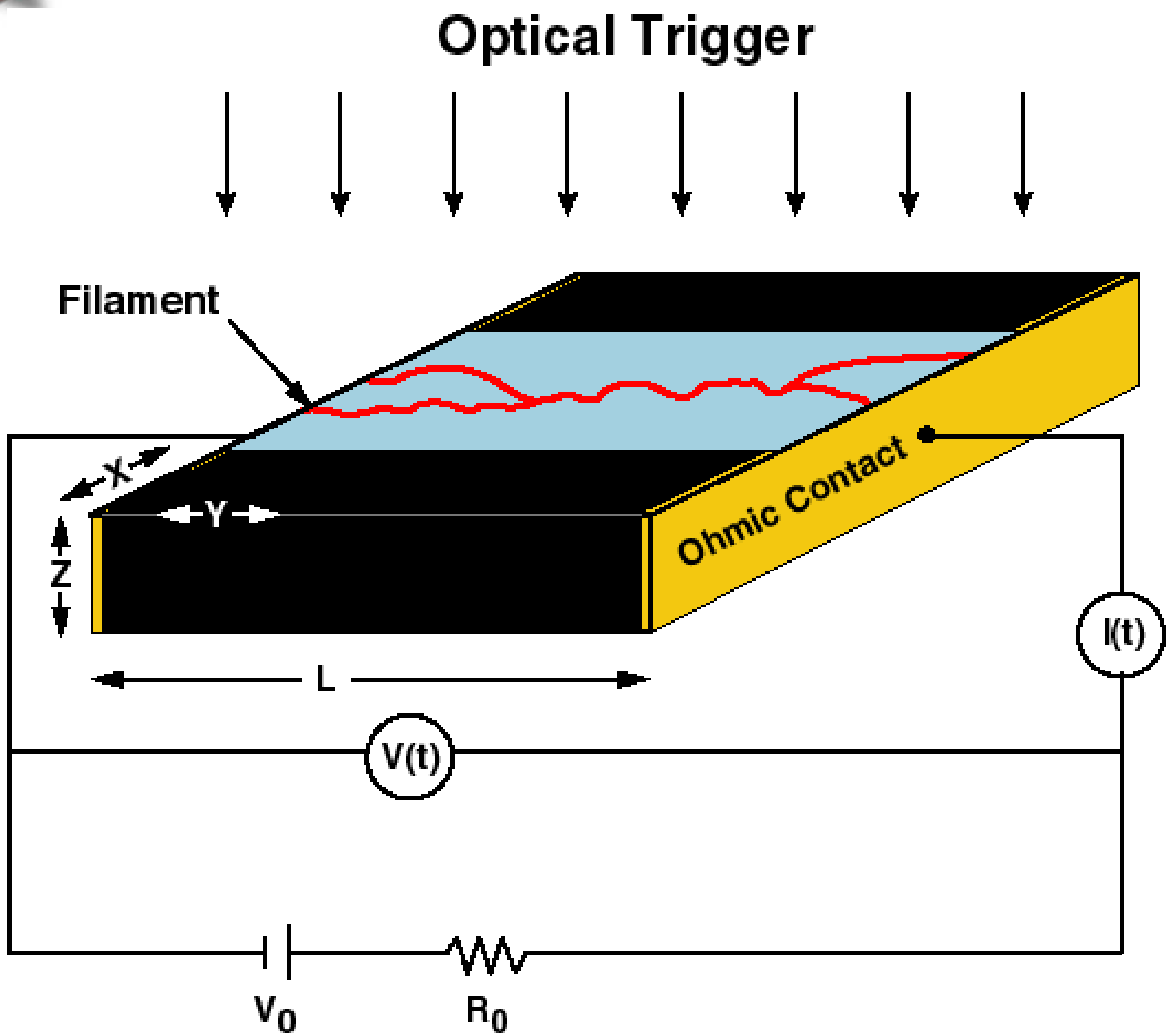
K. Kambour, H. P. Hjalmarson, F. J. Zutavern, A. Mar, C. W. Myles and R. P. Joshi, Simulation of current filaments in photoconductive semiconductor switches, IEEE Pulsed Power Conference Proceedings, 2005.

K. Kambour, H. P. Hjalmarson and C. W. Myles, Theory of Electrical Breakdown in Solid Insulators, in preparation.

Also two patents and numerous presentations

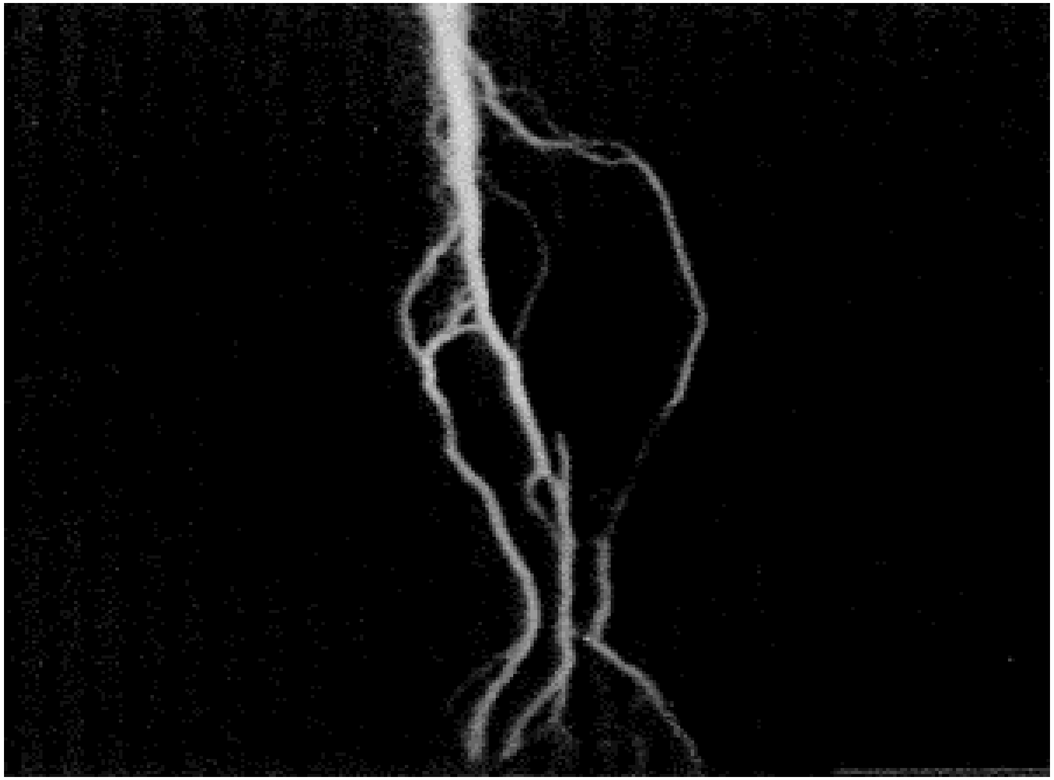
Outline

- Photoconductive Semiconductor Switches (PCSS's)
- Lock-on
- Collective Impact Ionization Theory
- Monte Carlo Calculations
- Continuum Calculations
- Conclusions



Optical Trigger
Filament
X
Y
Z
L
Ohmic Contact
I(t)
V(t)
V_0
R_0

Current Filaments



Lock-On

Characterized by a persistent or 'locked-on' electric field (~5 kV/cm) after laser turn off.

Accompanied by the formation of current filaments visible in the infrared.

The lock-on field is much lower than the bulk breakdown field for GaAs.

Approach: Physics-Based

Intrinsic Breakdown

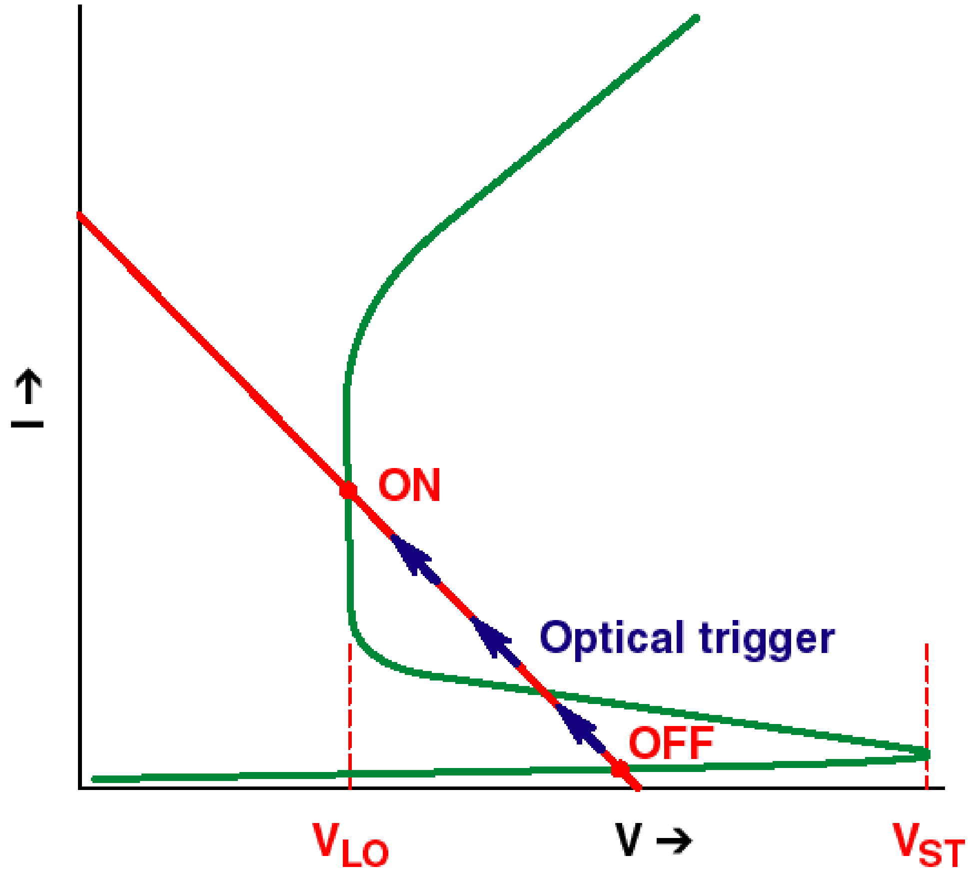
- Seek multiple steady state solutions
- Breakdown causes defects and damage
- Consistent with gas breakdown
- Consistent with 10^7 switch cycles of PCSS devices

Extrinsic Breakdown

- Associated with defects and damage
- Very difficult to develop a physics-based theory because each problem is a special case

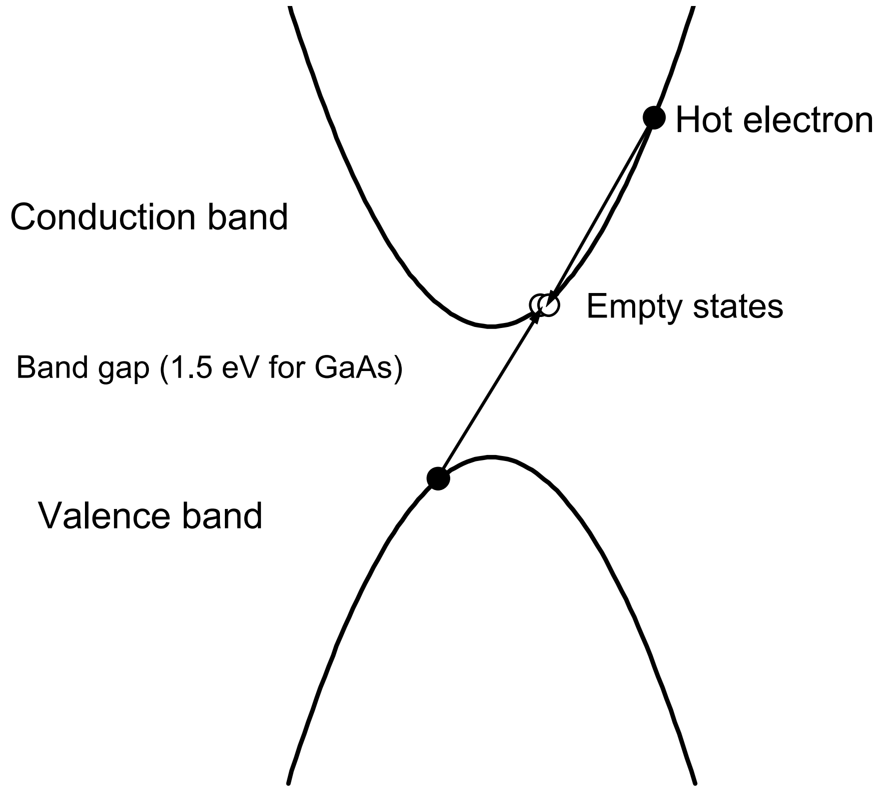
We assume intrinsic breakdown in order to construct a general physics-based theory

Guiding Principle: a Bistable Switch



Seek a microscopic model that gives an S-like IV characteristic

Impact Ionization



Energy & momentum restrict the allowed transitions

An electron heated by the electric field generates another electron and a hole

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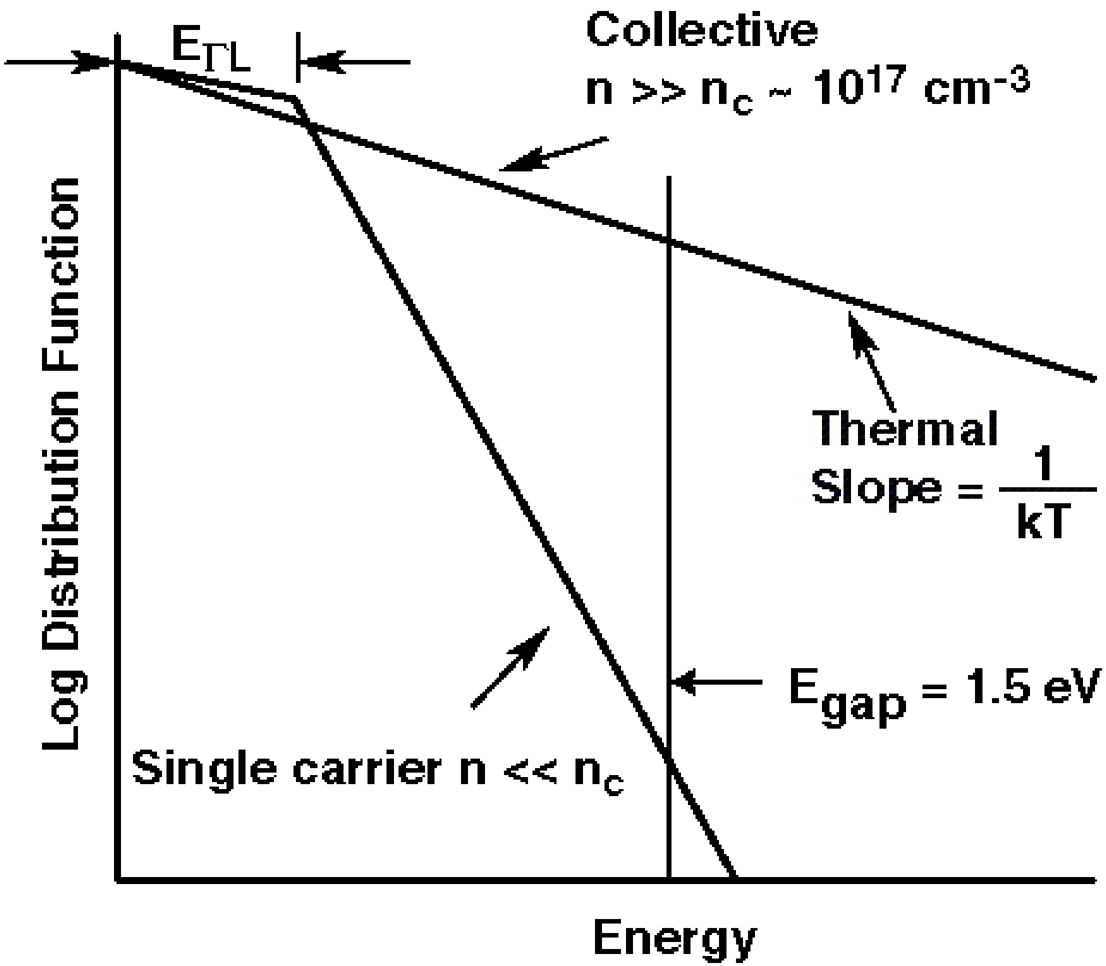
Carrier Distribution Function



The tail of the distribution function generates electrons and holes by impact ionization

Collective Impact Ionization Theory

Explains highly conductive filaments sustained by a lock-on field lower than the breakdown field.

Inside (high carrier density): the carrier-carrier scattering increases the efficiency of impact ionization for the hot carriers.

Outside (low carrier density): the electric field is too low to create carriers by impact ionization.

Monte Carlo Calculations

Carrier density n depends on distribution function f and rates r:

$$\frac{dn}{dt} = \int f_{k1i}(r_{ii} - r_{Auger} - r_{defects})d^3k$$

Microscopic calculations: Determine the steady-state carrier distribution function f

•Perform Ensemble Monte Carlo (EMC) calculations (paricle-based transport calculations)

•Use a Maxwellian approximation to the distribution function

Continuum calculations: Use a breakdown model in continuum transport simulations

•Include hot carriers, optical phenomena, electric contacts and defects

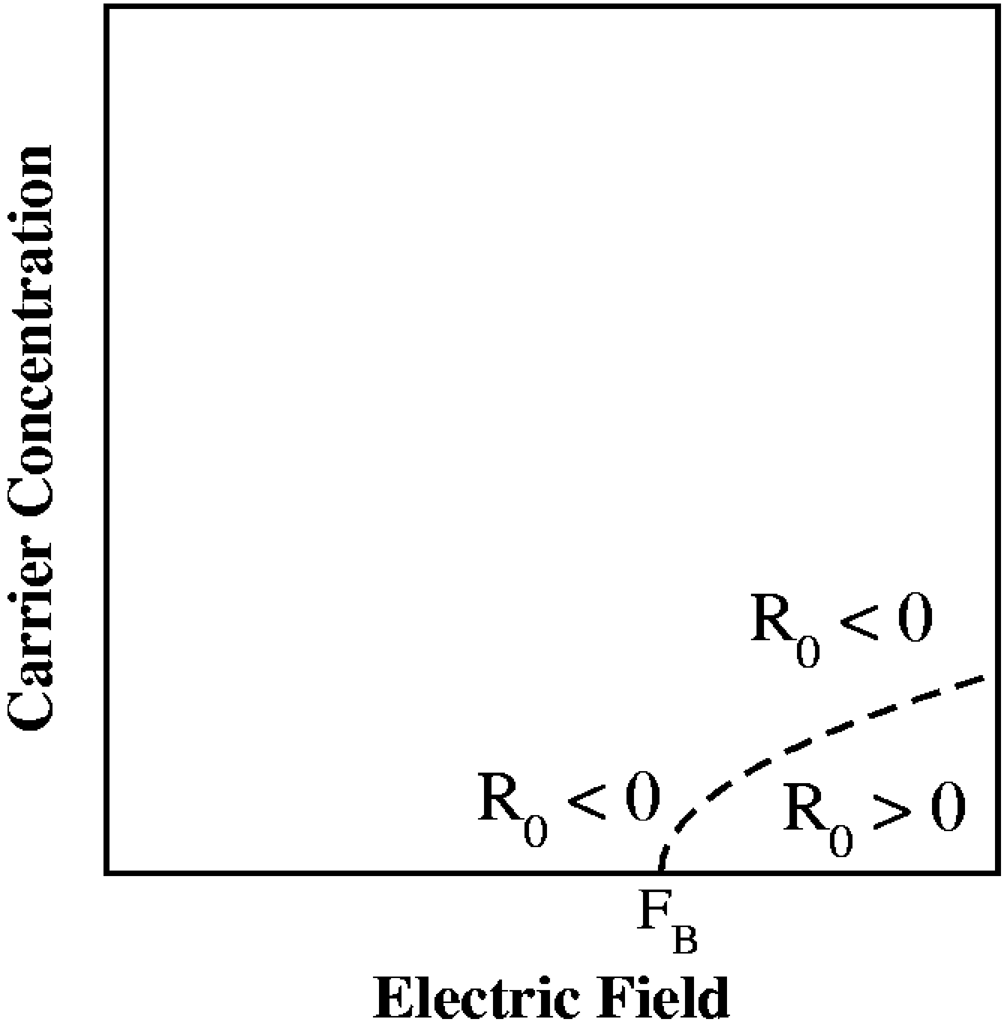
Evolution to a Steady State Solution (no carrier-carrier scattering)

$$\frac{dn}{dt} = R_0(F,n)n = 0$$

$$R_0(F,n) = C_{ii}(F) - C_{Auger}n^2 - C_{defects} = 0$$

$$n(F) = \sqrt{\frac{C_{ii}(F) - C_{defects}}{C_{Auger}}}$$

Steady State Solution
(no carrier-carrier scattering)



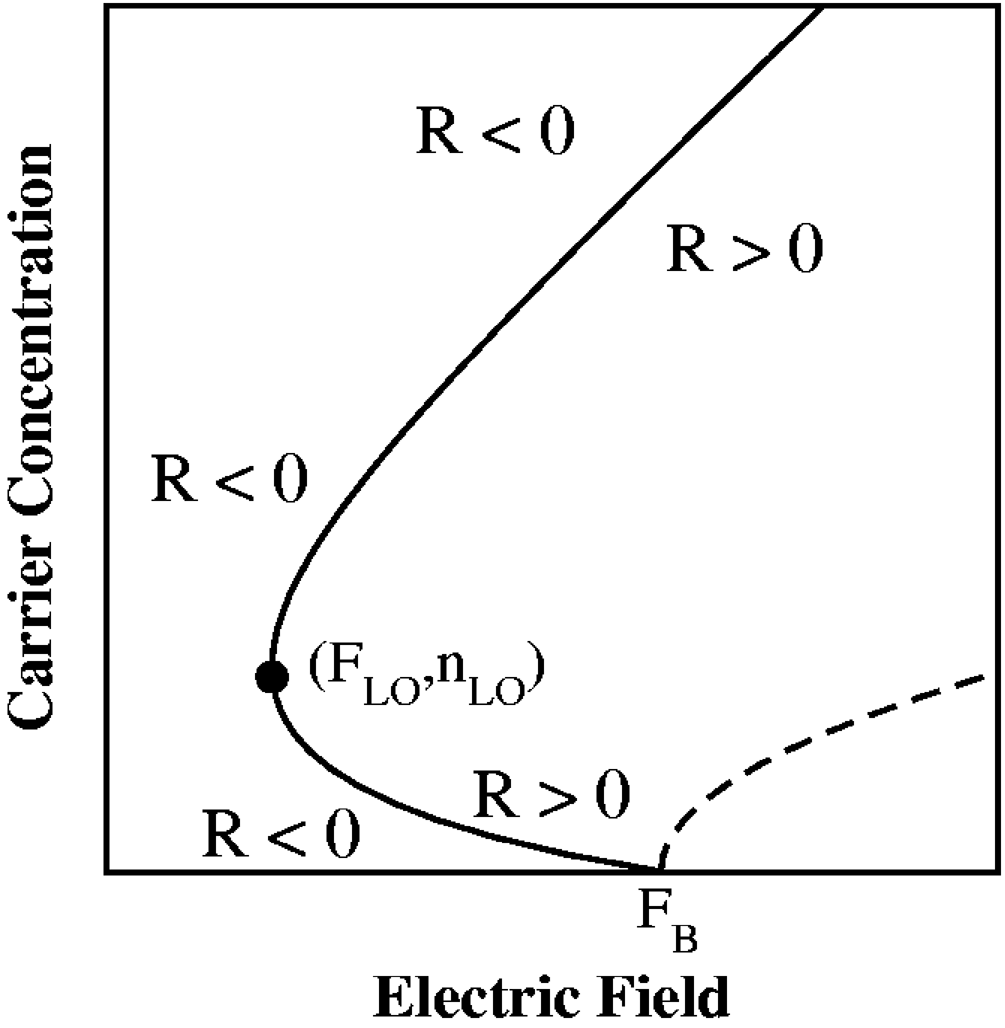
Evolution to Steady State Solutions (carrier-carrier scattering included)

$$\frac{dn}{dt} = R(F,n)n = 0$$

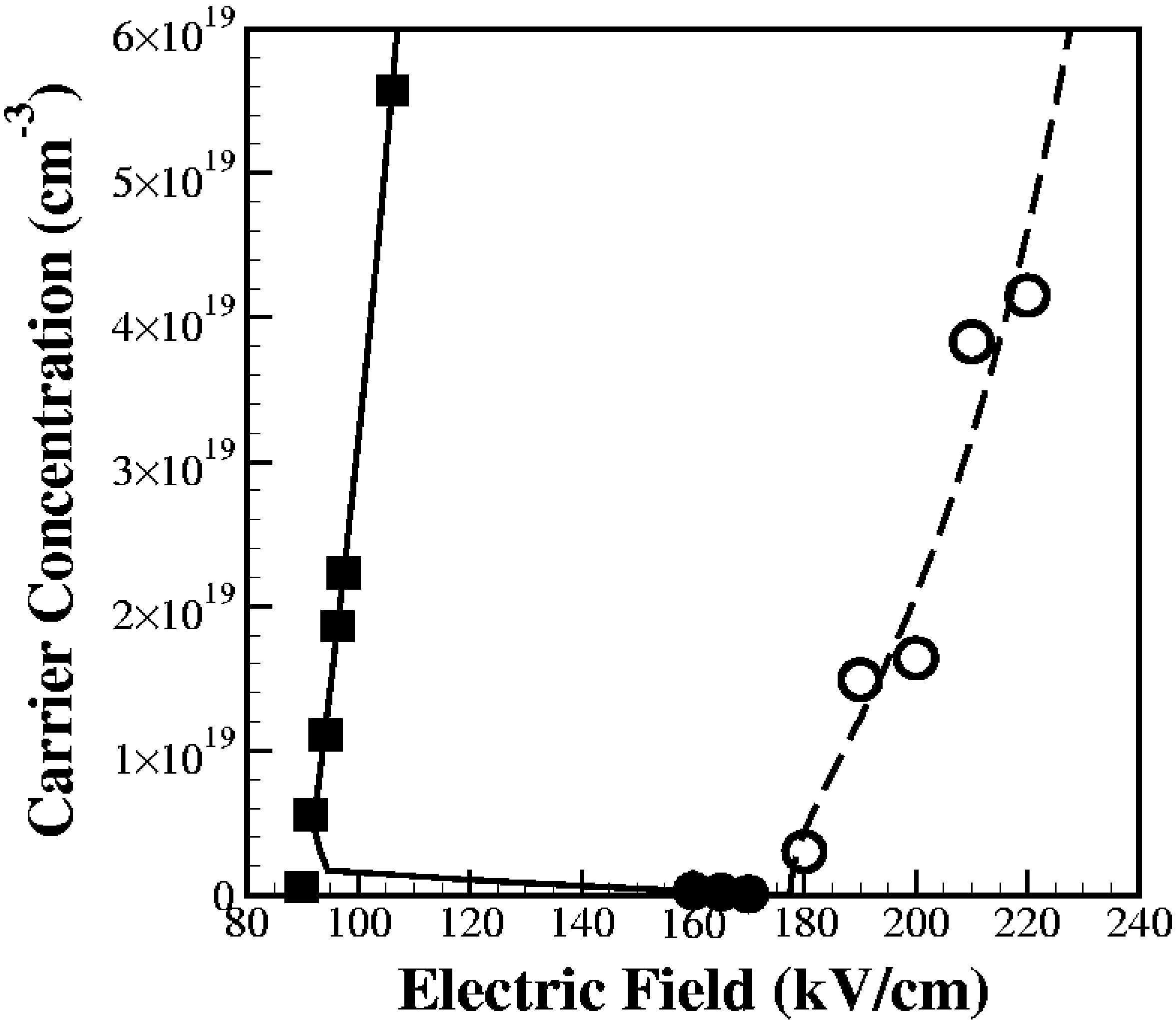
$$R_0(F,n) = C_{ii}(F,n) - C_{Auger}n^2 - C_{defects} = 0$$

$$\approx C_{ii0}(F) + C_{ii1}(F)n - C_{Auger}n^2 - C_{defects}$$

Steady State Solutions (carrier-carrier scattering included)

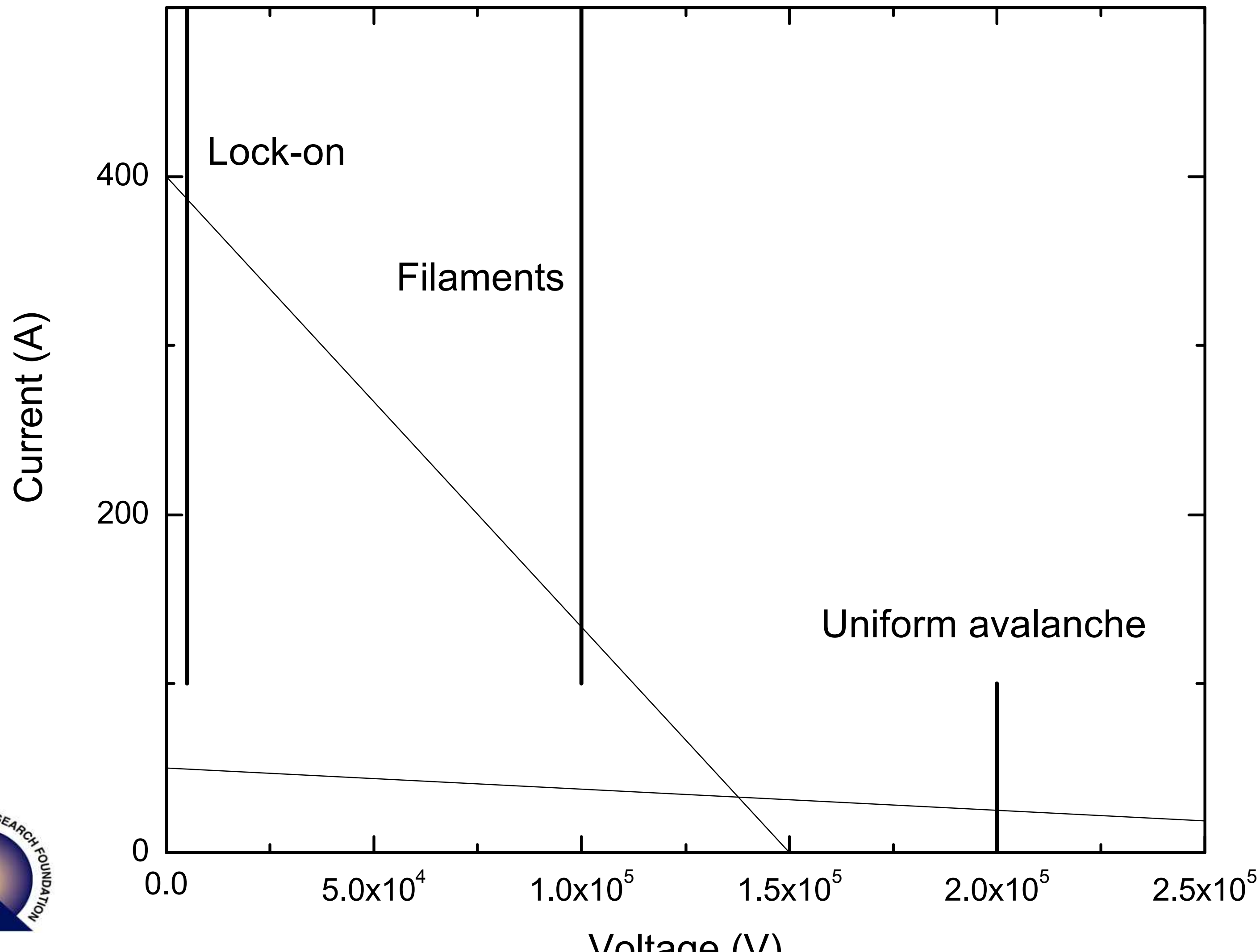


EMC Simulations for GaAs

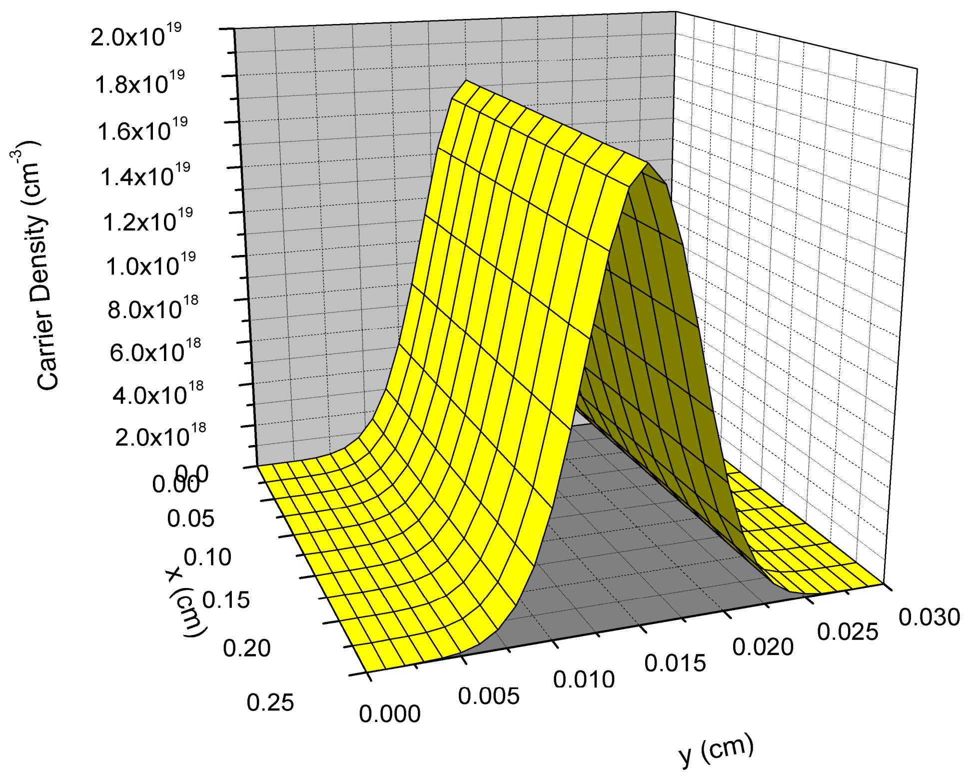


Qualitative Physics of Electrical Breakdown

Two types of steady state solutions: Uniform and filamentary



Filament Carrier Density



Linkage to Experiments

- Filaments
  - Early simulations predicted filaments; later observed using infrared imaging
- Load line
  - Electrical data is consistent with the postulated load line
- Fast rise time
  - CIIT predicts sub-nanosecond rise time
- Neutron irradiation
  - CIIT explains why neutron irradiation defects increase the LO field
- Electrical contacts
  - Theory insights helped develop improved contacts (one patent)
  - CIIT explains how self-triggering depends on polarity
- Fast filament propagation
  - CITT simulations show very fast filament propagation
- Lock-on voltage
  - The LO voltage does not agree with the CITT predictions
  - A new microscopic mechanism is being developed

Experiments have been stimulated by the theory

Conclusions

Collective Impact ionization Theory (CIIT) predicts that lock-on will occur in GaAs at a field much less than the intrinsic breakdown field in GaAs, in qualitative agreement with experiment.

CIIT also predicts that the lock-on current will flow in stable current filaments in agreement with experiment.

CIIT also produces stable uniform avalanche solutions consistent with other experiments

Future Work

Finish the PCSS problem

- Improve the continuum theory to agree with the observed lock-on field
- Improve PCSS longevity by focusing on electrical contact degradation
- Examine radiation effects

Apply these physics ideas to other mission problems

- Weapons insulation
- Improved radiation detectors

Extra Slides

Continuum Calculations

Continuity equations for electrons $n(r,t)$, holes $p(r,t)$, and intrinsic $n_i(r,t)$ carrier densities :

$$\partial n / \partial t = g + B(n_i^2 - np)(n + p) + A(n_i^2 - np) + 1/q\nabla \mathbf{J}_n$$
$$\partial p / \partial t = g + B(n_i^2 - np)(n + p) + A(n_i^2 - np) + 1/q\nabla \mathbf{J}_n$$

Current equations for electron and hole currents :

$$\mathbf{J}_\mathrm{n} = -qn\mathbf{v}_n(\mathbf{E}) + D_n\nabla n$$
$$\mathbf{J}_\mathrm{p} = -qp\mathbf{v}_p(\mathbf{E}) + D_p\nabla p$$

Poisson's equation for the electric field :

$$\nabla \mathbf{E} = -\frac{\mathrm{q}}{\varepsilon}(p - n)$$

Load line equation for the switch voltage $V(t)$ in terms of a power supply voltage V_0 and resistance R_0 :

$$\partial \mathrm{V(t)}/\partial \mathrm{t} = \mathrm{V}_0 + V(t) + R_0 I(t)$$

Total carrier current :

$$I(t) = \frac{1}{L}\int (\mathrm{J}_\mathrm{n}(r,t) + J_p(r,t))dr$$

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