Radiation Effects in Microelectronics and the Missing Model

Talk to Nuclear Science & Engineering and Global Nuclear Security Technology Divisions at ORNL

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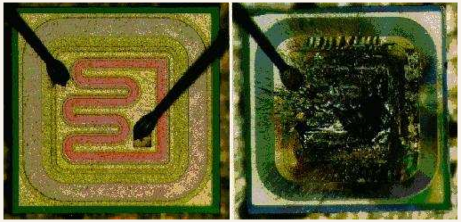
Video of damaged device



Why Microelectronics?

- **As sensors?**
  - Carefully designed devices are selective to energy and type of radiation
  - Many devices amplify interaction effects (sensitivity)
  - Disadvantage: not reuseable (sometimes) and most research aimed at *preventing* radiation effects
- **Industry interest**

W. E. Price, IEEE Trans. Nucl. Sci., Dec. 1965

Spacecraft	Cause of Failure
Explorer XIV	power supply
Explorer XV	transistor
UK-1	solar power system
TRAAC	solar cells
Transit IV B	solar cells
Telstar I[a]	transistor

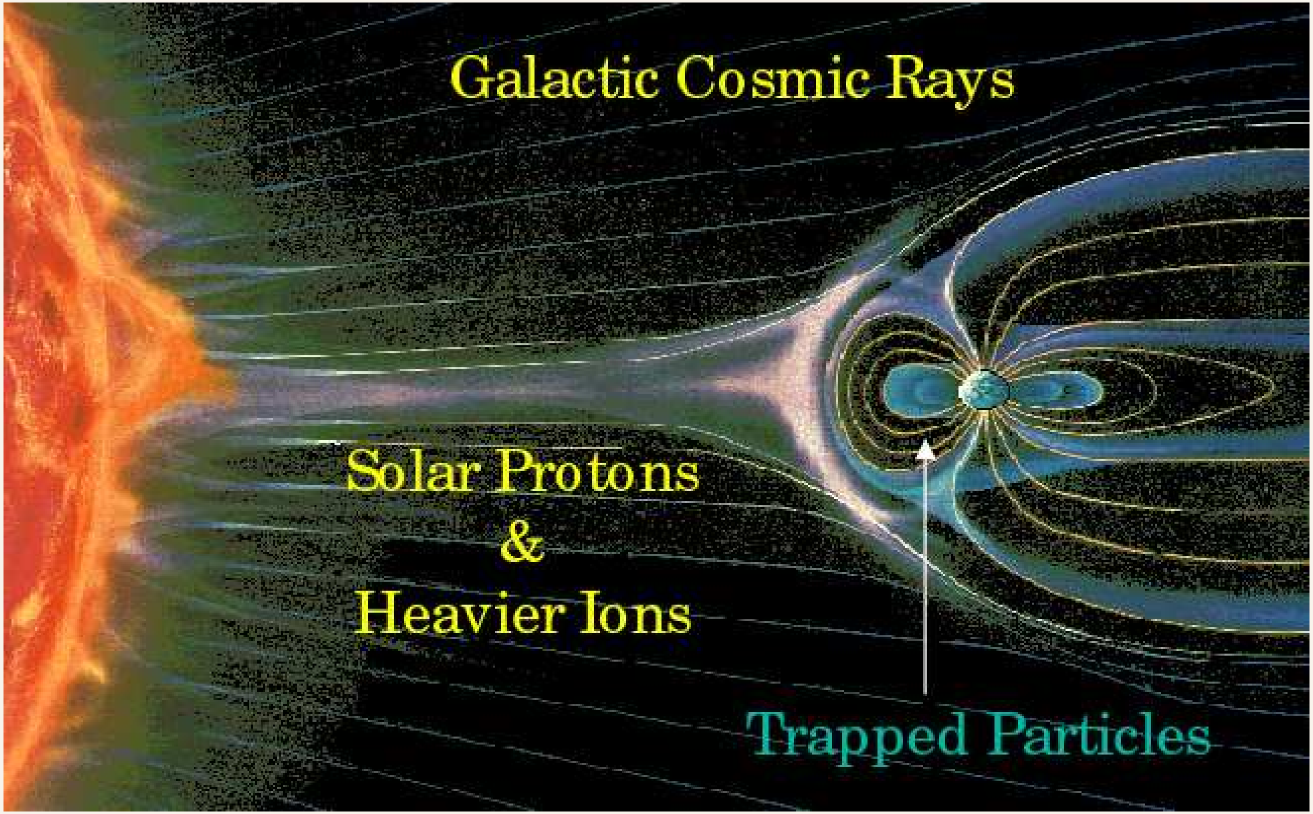
[a] failed Nov. 24, 1962; restored Jan. 3, 1963
Mayo et al., *Bell Syst. Tech. J.* 43, 1631 (1963)

Image on title slide courtesy of `http://www.netlink.co.uk/users/stereo/paper.html`

Outline

- Space radiation environment and effects
- Device modeling and behavior
  - Compact model of MOSFET burnout
  - Power diode burnout
  - Nanocrystal photoluminescence
- Model fidelity

Space Radiation



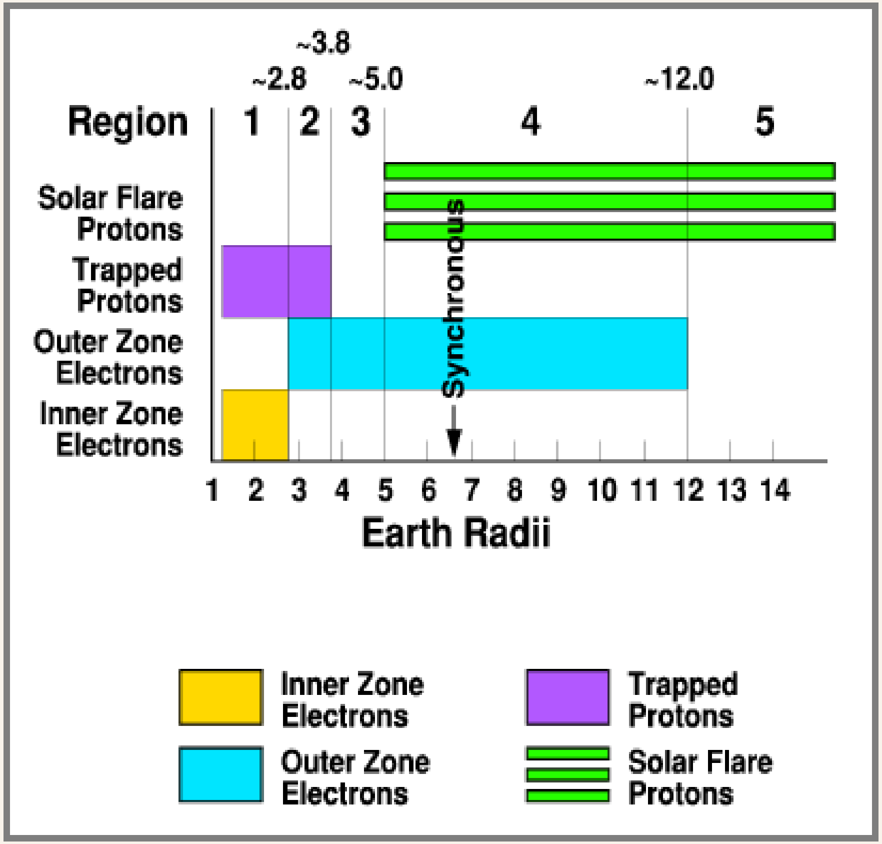
http://radhome.gsfc.nasa.gov/radhome/environ.htm

Particles

- **Trapped Protons** - AP8-MIN AP8-MAX - Solar Min: Higher; Solar Max: Lower - Geomagnetic Field; Solar Flares; Geomagnetic Storms
- **Trapped Electrons** - AE8-MIN AE8-MAX - Solar Min - Lower; Solar Max - Higher - Geomagnetic Field; Solar Flares; Geomagnetic Storms - LEO, GEO, HEO, Transfer Orbits
- **Galactic Cosmic Ray Ions** - CREME CHIME Badhwar & O'Neill - Solar Min - Higher; Solar Max - Lower - Ionization Level; Orbit Attenuation - LEO, GEO, HEO, Interplanetary
- **Solar Flare Protons** - KING JPL92 - During Solar Max Only - Distance from Sun; Outside 1 AU; Orbit Attenuation - Location of Flare on Sun - LEO, GEO, HEO, Interplanetary
- **Solar Flare Heavy Ions** - CREME; JPL92; CHIME - During Solar Max Only - Distance from Sun; Outside 1 AU; Orbit Attenuation - Location of Flare on Sun - LEO, GEO, HEO, Interplanetary

copied shamelessly from NASA's website

Earth's Radiation Belts

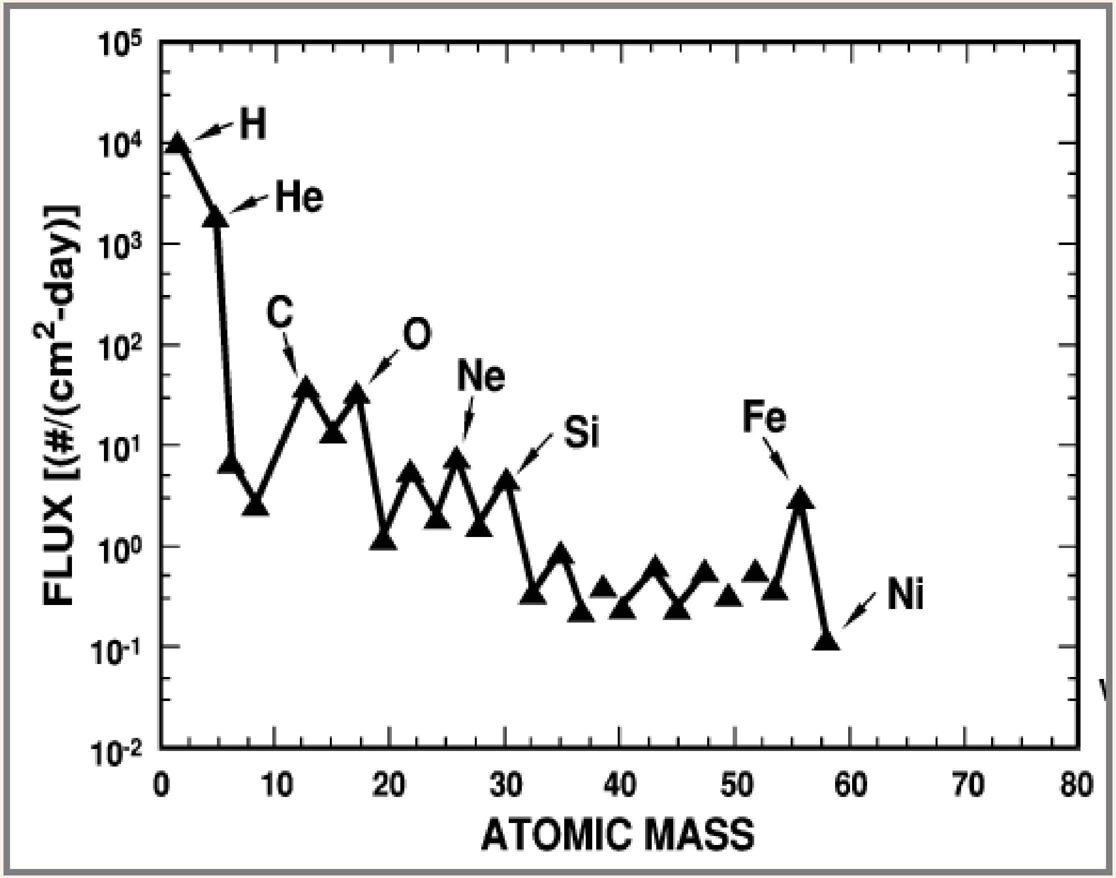


E. G. Stassinopoulos and J. P. Raymond, Proc. of the IEEE 76, 1423 (1988)

- 1 Earth radius is 6380 km
- geosynchronous orbit is at 35,800 km
- outer zone electrons have higher fluxes ($\sim 10\times$) and energies than inner zone electrons
- maximum energy of trapped electrons is 7 MeV

Galactic Cosmic Rays

Near Earth Observations



- 85% protons
- 14% alpha particles
- less than 1% heavy ions

P. Meyer, R. Ramaty, and W. R. Weber, Physics Today 27, 23 (1974)

Other Radiation Environments

- Military
  - higher dose rates
  - neutrons, x-ray/gamma & transient effects bigger concerns than for space
- High-energy particle accelerators
  - analogous to space environment
  - neutrons and “exotic” particles are also present
- Nuclear reactors
  - doses can be quite high (up to 10^8 rad(Si))
  - neutrons are very important
- Semiconductor processing (deep UV & x-rays)
  - plasma processing
  - advanced lithography
  - e-beam tools
- Terrestrial
  - primary concern is single event effects

Terrestrial Threats to Microelectronics

- **Alphas from decay of trace impurities**

  Uranium and Thorium (and daughters) produce ionizing alphas with energy in the range $4 - 8\,\mathrm{MeV}$. Impurities arise from wet etch processing materials, metalization eutectic solder, etc. Alphas travel up to $70\,\mu\mathrm{m}$ and generate more charge at lower energy.

- **Neutrons from Cosmic ray cascades**

  Less than 1% of heavy ions of galactic origin reach sea level. Complex cascades result in pions, muons, protons, electrons and neutrons. Neutrons are most likely to reach sea-level altitudes and dependent on altitude. Thermal neutrons create energetic Si recoils and fragments.

- **^{10}B + neutron reaction**

  The ^{10}B cross-section is orders of magnitude greater than other dopants and creates an alpha plus Li recoil. Triggered by $15\,\mathrm{eV}$ neutrons. Lithium generates $25\,\mathrm{fC}/\mu\mathrm{m}$ compared to alphas, which generates $16\,\mathrm{fC}/\mu\mathrm{m}$.

Basic Radiation Effects in Microelectronics

Overview

- Ionization effects
  - total dose damage
  - photocurrents
    - **single events**
    - transient
- Displacement damage
  - defects
  - device effects

Single Events

- Soft errors
  - Correctable by reprogramming the circuit into its correct logic state
  - If error rate is too high, it can cause system degradation and potentially mission failure
  - Arise when a heavy-ion or proton deposits sufficient energy to change the state of a circuit node
- Hard errors
  - Are created when a heavy ion deposits sufficient energy to cause permanent damage to a device
  - Error cannot be corrected by reprogramming
  - Types of hard errors include latchup, snapback, single-event burnout, and single-event gate rupture

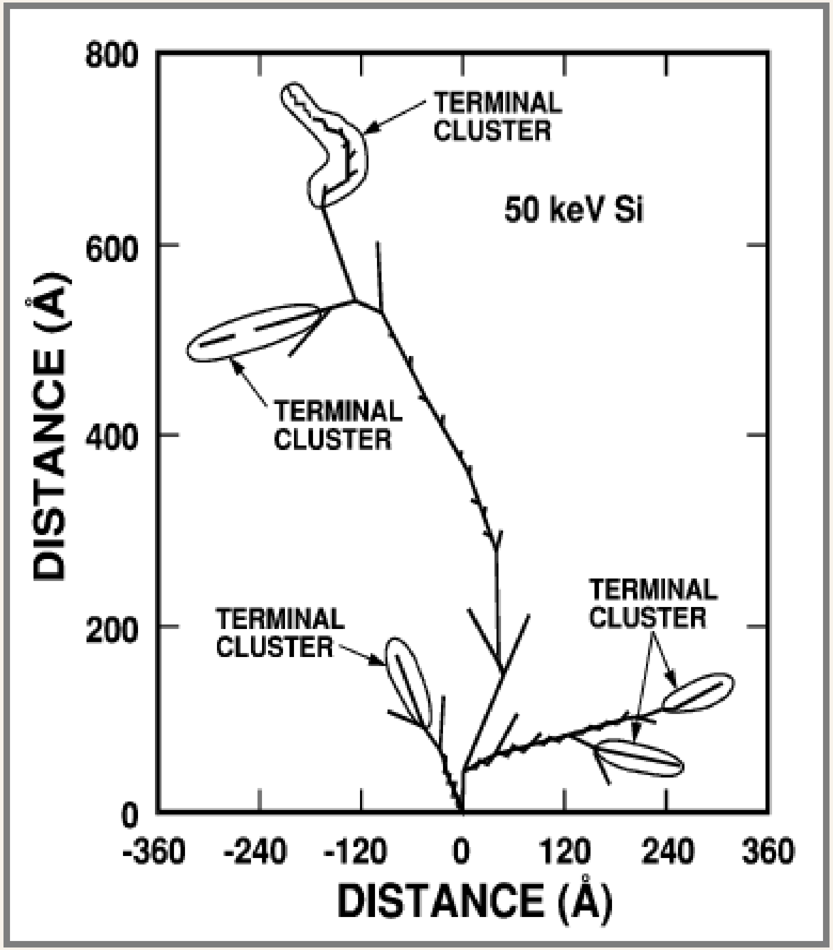
Single-Event Effects

- Ion loses energy in a material by excitation and ionization of atoms
- It creates a very high density electron-hole plasma along its path
- The amount of energy deposited by an ion is given by its mass-stopping power (SRIM) defined as the Linear Energy Transfer, $LET = dE/dx \div \rho$
- Protons for most circuits cannot deposit enough energy locally to directly cause single-event upsets however, there are exceptions (e.g., optocouplers)
- Usually, protons induce upsets by dislodging atoms from their lattice sites or through nuclear interactions with lattice atoms
- Resulting secondary particles may deposit sufficient energy to cause single-event upsets
- Total deposited charge

$$Q_I = \frac{1.6 \times 10^{-2} \cdot LET \cdot \rho}{E_p}$$

- Critical charge is highly device and circuit dependent
- Can be as low as 50 fC (equivalent to 3×10^5 electrons), or even less in modern highly scaled devices

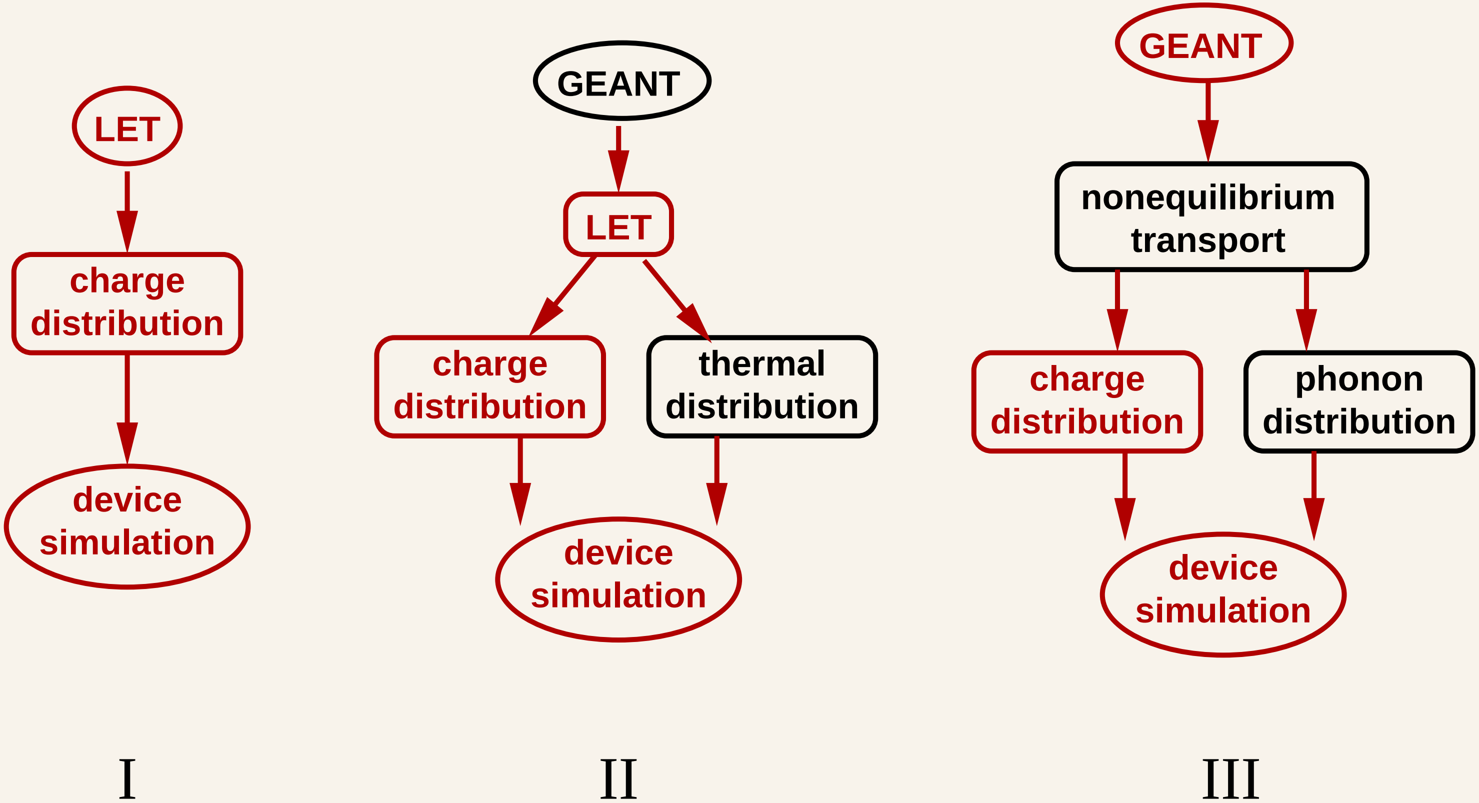
Displacement Damage (NIEL)



G. P. Summers, 1992 IEEE NSREC Short Course

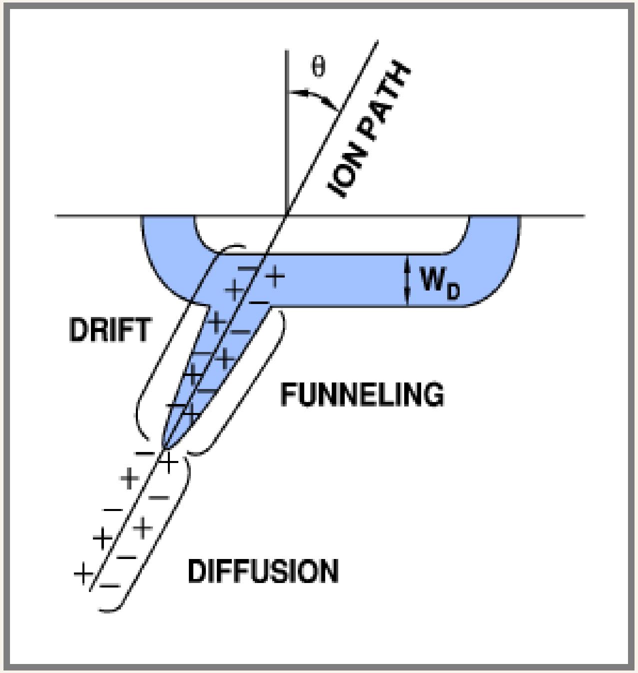
- Atoms are knocked free from lattice site producing interstitial atoms and vacancies
- Combination of interstitial atom and vacancy called a Frenkel pair
- About 90% of vacancy pairs recombine within one minute after irradiation

Models



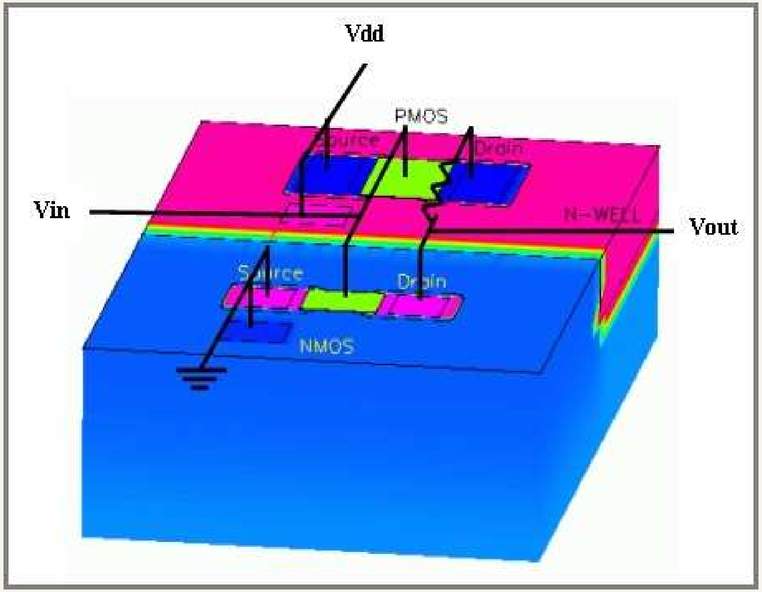
- Geant can track particles from TeV to keV
- Device simulators can handle tens of eV
- **What about thermalization processes?**

LET Device Modeling



- Charge deposition originates from **secondary ionization model** and LET.
- Funneling
- Inherent BJT

- Drift-diffusion to track the evolution and collection of charge
- Mixed-mode for system level performance
- Griding along ion track difficult
- Track radius is empirical



(S.V. Mahajan, Vanderbilt Thesis, 2003)

Secondary Ionization Model

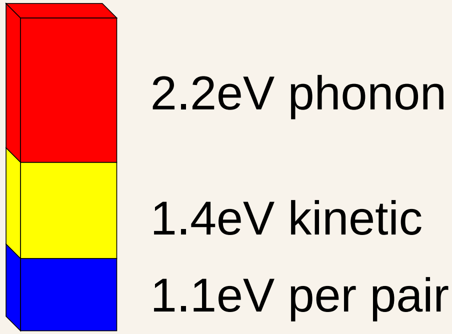
Assumptions (Shockley, 1961)

- band structure is ignored (no effective mass)
- scattering by high frequency phonons only
- fitting parameters are "averages" and constant

Parameters

- E_R – vibrational energy of *Raman* phonons
- E_i – threshold energy for e-h production
- L_R – mean free path between Raman modes
- L_i – mean free path between ionizations (also defined as $r = L_i/L_R$)

Ionization energy for silicon:



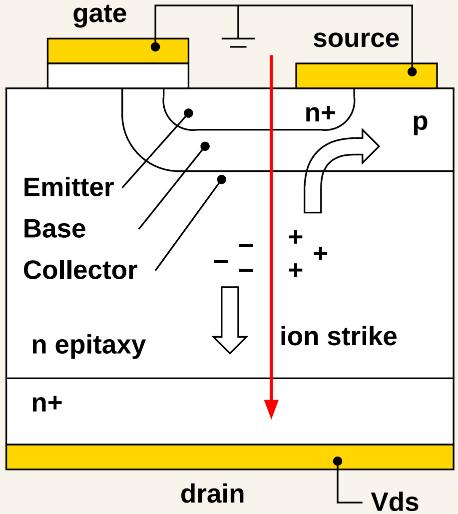
- Ionization probability: $P(E) = 1 - \exp[-(E - E_i)/rE_R]$
- Energetic particles will deposit energy in e-h pairs and phonons in a ratio dependent on the ionization probability.

$$E_{\text{pair}} = 2E_f + E_i + rE_R \approx 2.2E_i + rE_R$$

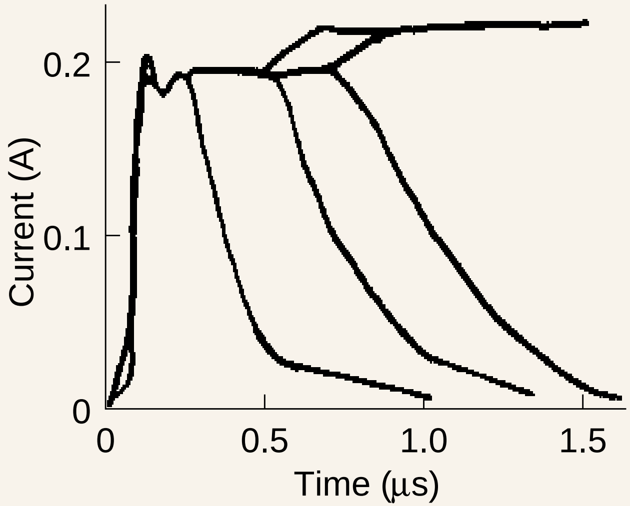
If $E_f \approx 0.6E_i$ (leftover energy that won't be used for ionization)

Compact model of MOSFET

Device Structure

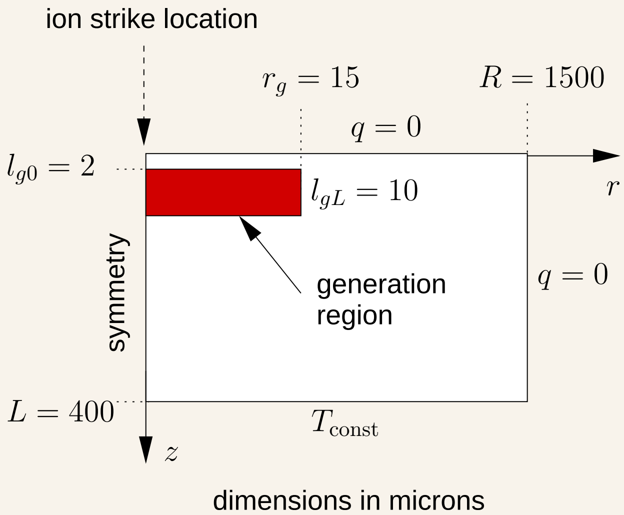


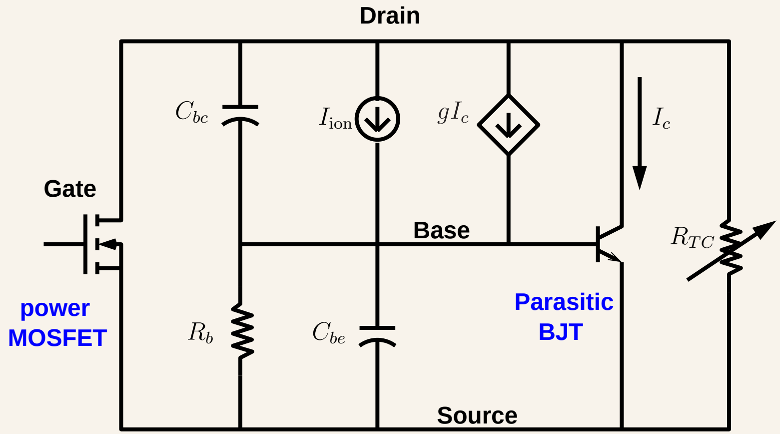
Heating (Johnson et al. 1996)



- LET (Linear Energy Transfer) creates ehps
- Parasitic BJT is turned on depending on LET
- *Without thermal modeling secondary rise and breakdown can NOT be predicted* (Walker, Microelectronics Reliability, 41(4), 2001, p.571)

SEB Model Circuit

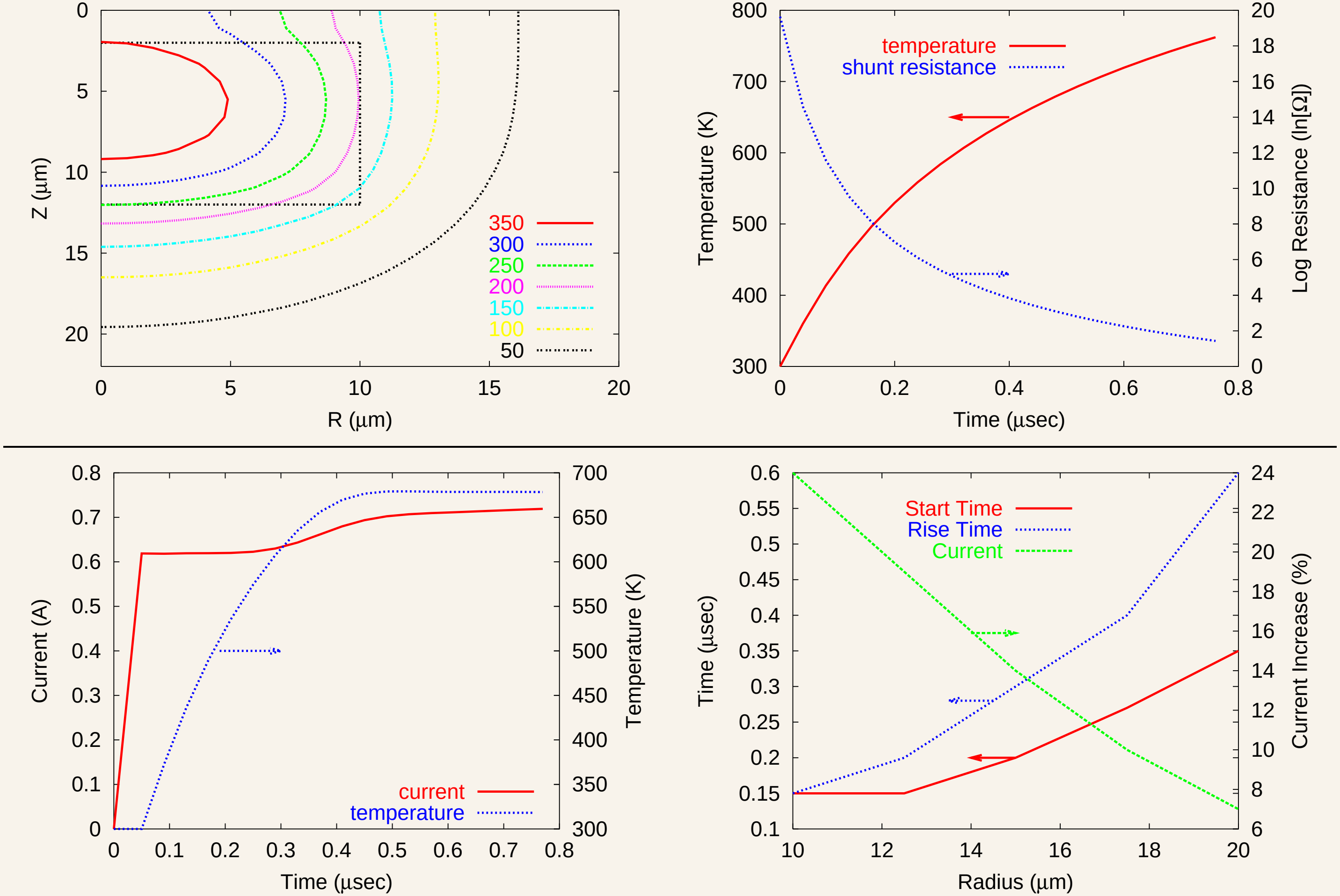




- Generation region corresponds to epitaxial layer
- Variable resistance is temperature dependent
- Electrical and thermal model are coupled through the variable resistance
- Thermal feedback allows burnout of device

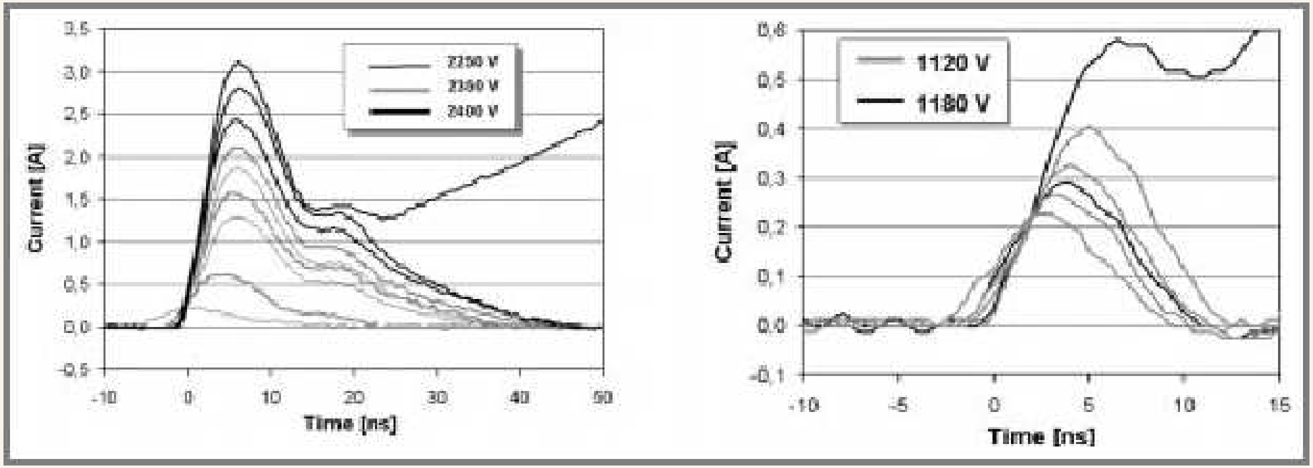
(Walker, Microelectronics Reliability, 41(4), 2001, p.571)

SEB Simulation Results

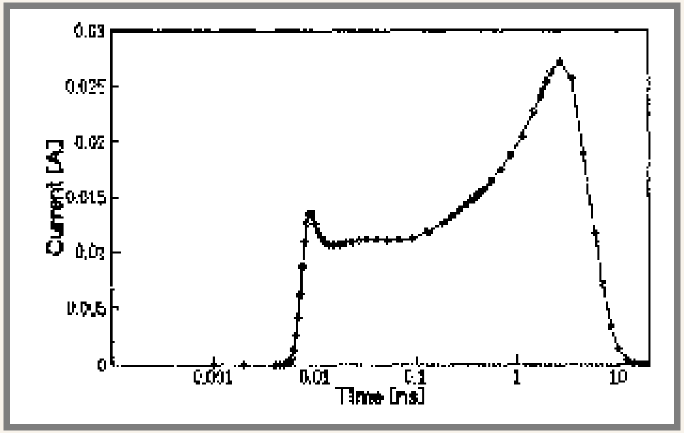


(Walker, Microelectronics Reliability, 41(4), 2001, p.571)

Observations of Diode Burnout



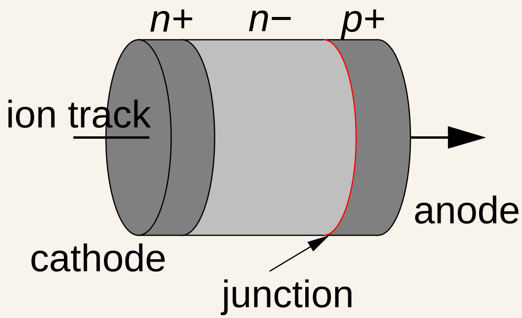
Soelkner, TNS, v. 47, no. 6, p. 2365.



Kabza, Intl Symp Pow Semi Dev & IC, 1994, p. 9

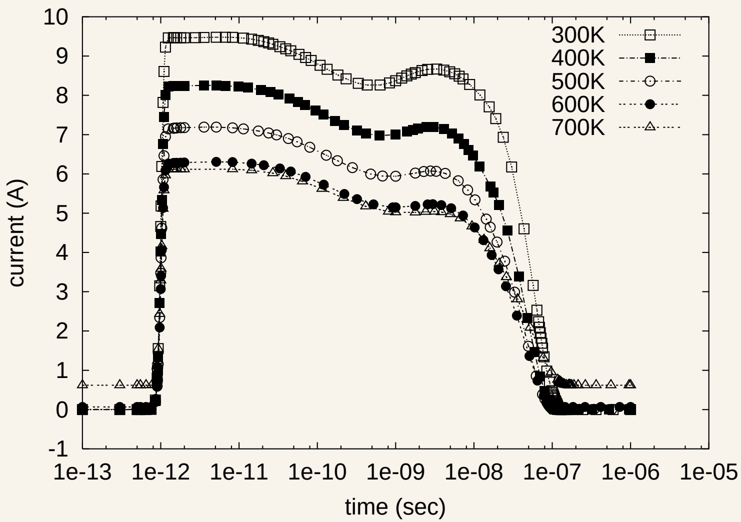
Model for Single-Event Burnout in Power Diode

Physical model



region	length (μm)	doping (cm^{-3})
$n+$	30	2×10^{19}
$n-$	420	2×10^{13}
$p+$	50	2×10^{19}

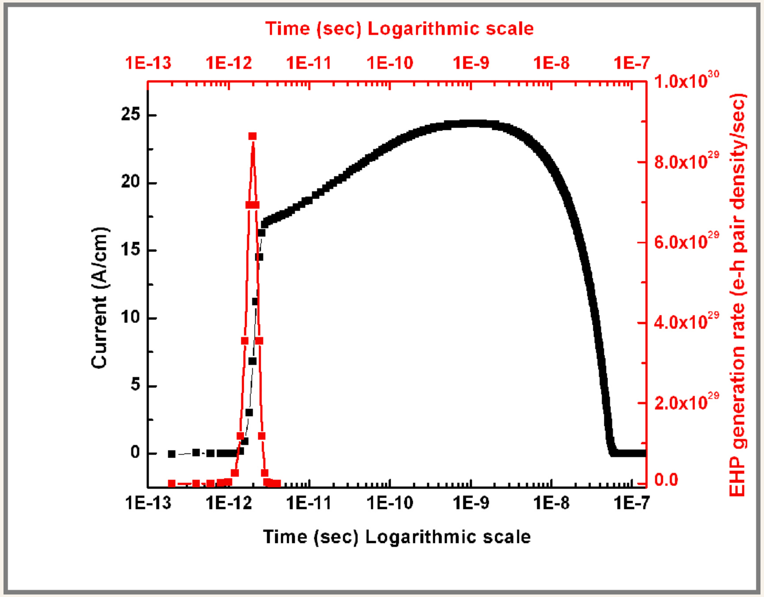
Without thermal effects



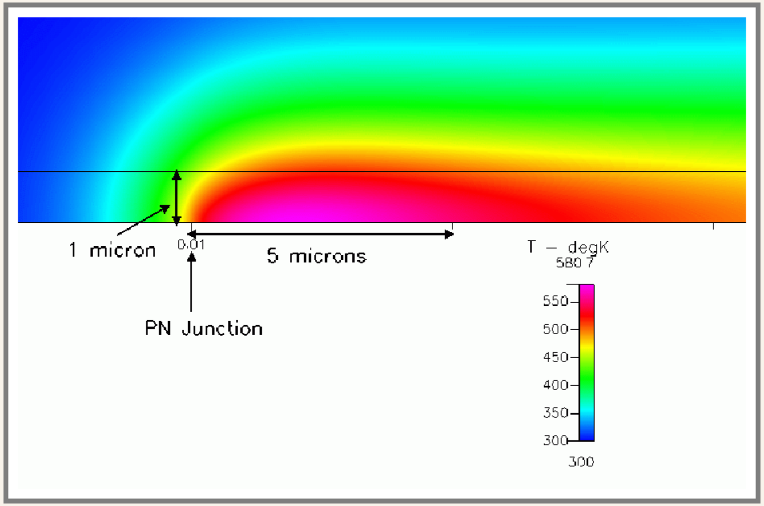
- Double hump feature matches previous results
- Second rise due to impact ionization
- For large temperatures, nominal current is non-negligible because of intrinsic carrier concentration

(A. Albadri, TNS, 52(6), 2005, p.2194)

Diode SEB Results



- Temperature at junction rises dramatically in short amount of time
- Impact ionization is a strong function of temperature
- Temperature feedback required for failure



- Initial rise in current is due to e-h pair generation
- Second rise is due to impact ionization and short across the device

(S.V. Mahajan, Vanderbilt Thesis, 2003)

Shockley works, so why not LET?

Shockley model $E_{\text{pair}} = 3.6\,\text{eV}$ assuming:

- $E_i \approx E_g = 1.12\,\text{eV}$
- $E_R = 0.063\,\text{eV}$ from dispersion relation
- $rE_R \approx 1.1\,\text{eV}$ from quantum yield experiments

McKay & McAfee (1953)	3.6 ± 0.3
Chynoweth & McKay (1957)	$2.5 - 3.0$
Vavilov (1959)	4.2 ± 0.6
Van Overstaeten & DeMan (1970) Woods, Johnson & Lampert (1973) Grant (1973)	3.6

But LET ...

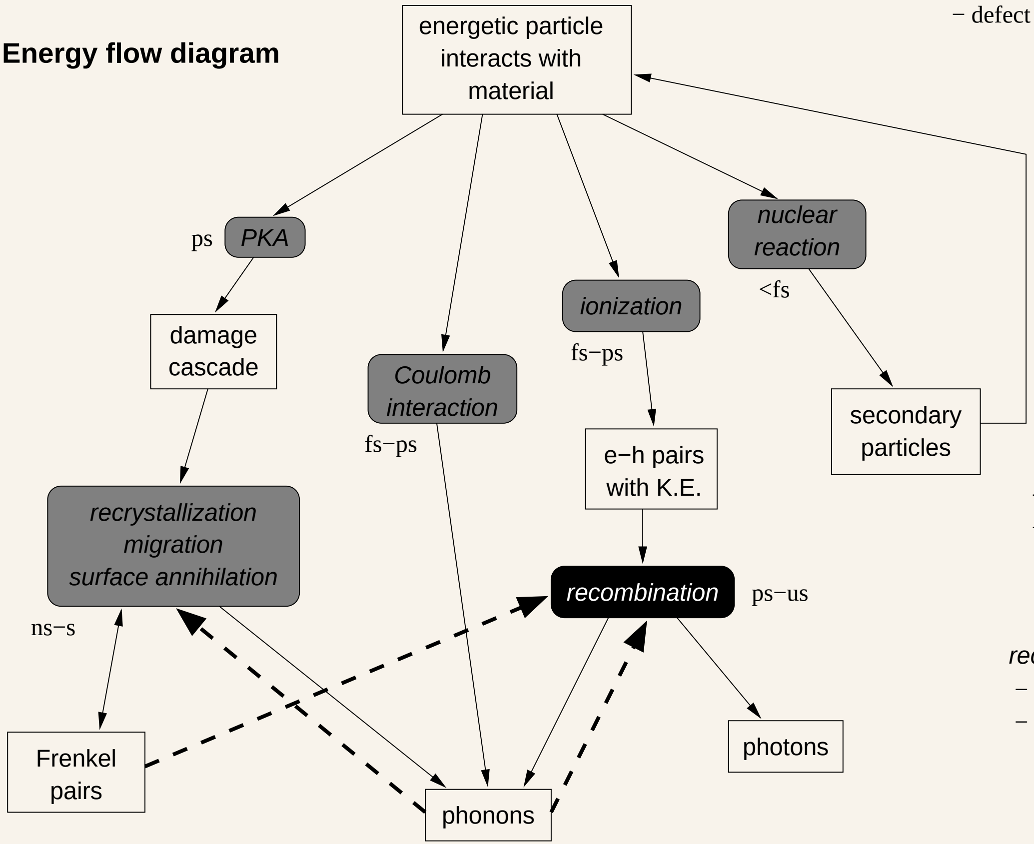
1. $3.6\,\text{eV}$ is an *average*
2. Does not consider non-equilibrium effects
3. Does not consider temperature dependence
4. Does not consider spatial distribution of charge and heat
5. Does not consider band structure explicitly

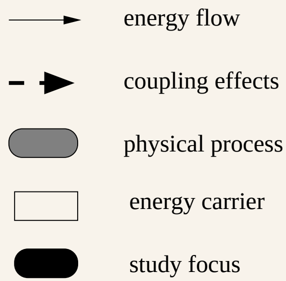
Radiation Interaction Map

Internal 1−page storyboard for radiation NIRT

Nano effects
- confined phonon dispersion and DOS
- surface state electron scattering (for recombination)
- defect migration

Energy flow diagram





PKA
- NIEL − general model to estimate damage
- MARLOWE − MD to calculate cascades

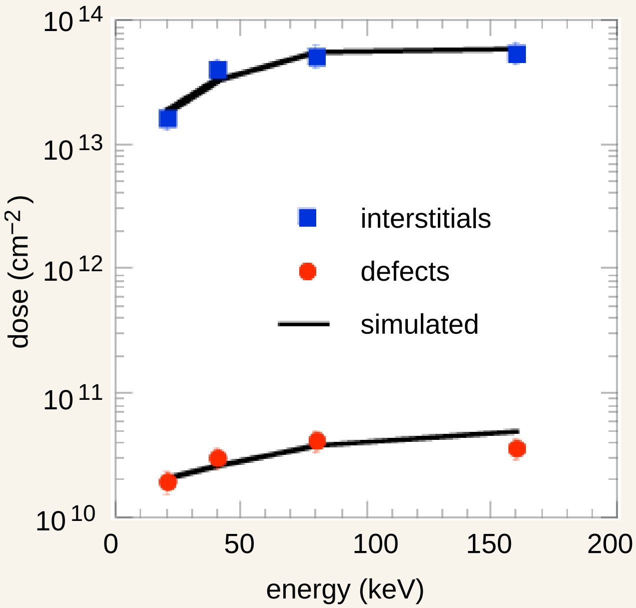
recrystallization
- MARLOWE ?
- classical MD

nuclear
- GEANT4

Coulomb / ionization
- LET − highly empirical, average (Shockley model)
- DFT − not really feasible here (outside scope)
- GEANT4 − MC−based mix of empirical and first principles

recombination
- many classical models
- **full−band MC (include surface state scattering, defects, confined phonons)**

Nanocrystal/Radiation interactions

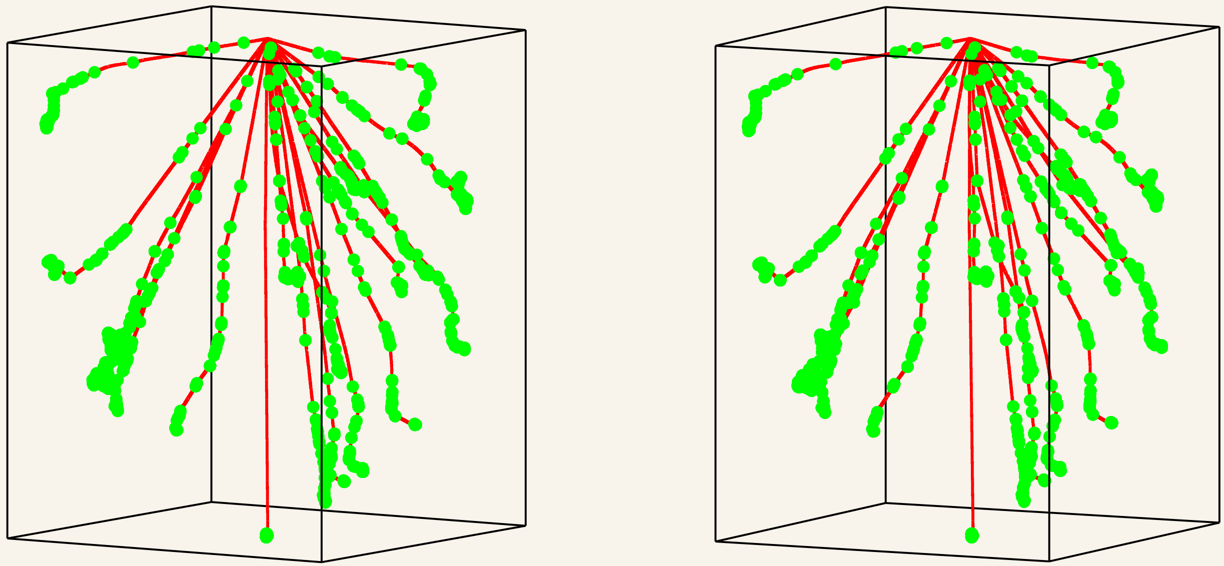


- Homogeneous nucleation
  - nucleation is a power of peak concentration
  - increase in energy lowers concentration
  - drop # defects, # interstitials
- Heterogeneous nucleation
  - SMIC's as sites
  - increase in number due to increase in damage

Energy dependence of damage accumulation under normalized conditions, showing that low energy (near surface) damage results in less damage than deeper in the bulk. Adapted from Saleh, APL, v. 77, n. 1, p. 112, 2000.

Marlowe results

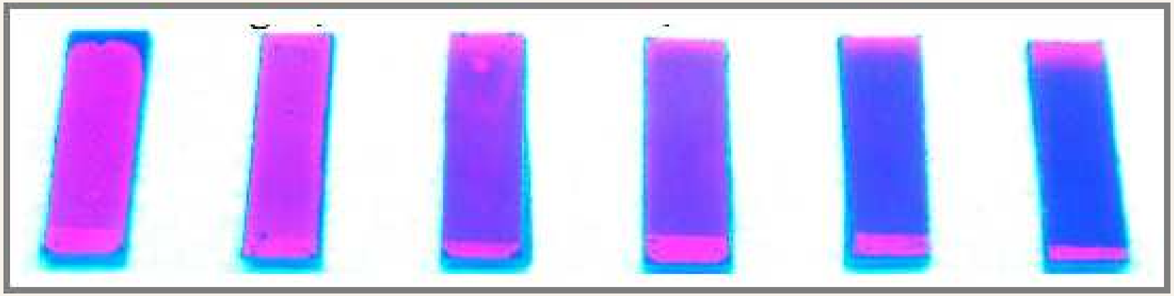
Proton irradiation of CdSe lattice



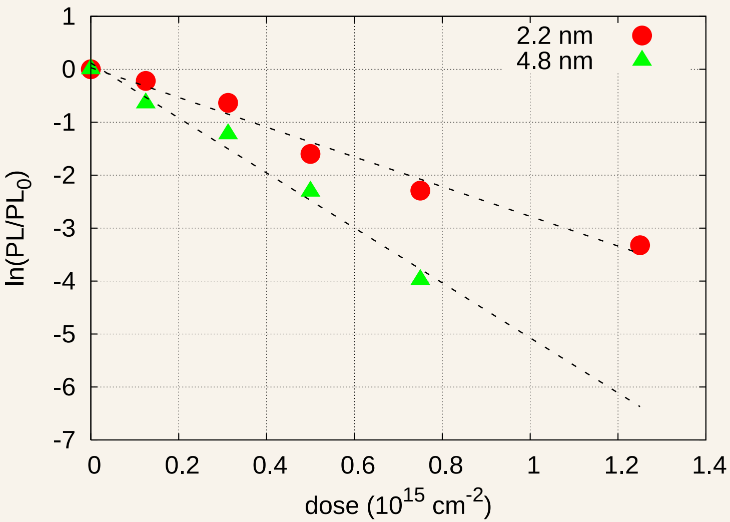
- 20 separate tracks in $1.2\,\mu\mathrm{m}$ cube, green points are recoils
- Damage is located at lower energy regions suggesting nanocrystals will be sensitive to energy range

Nanocrystal photoluminesence

CdSe nanocrystals



increasing dose rate ⟶



NC size (nm)	theoretical σ_{NC}	experimental σ_{NC}
4.8	1.14	5.19
2.2	0.11	2.58

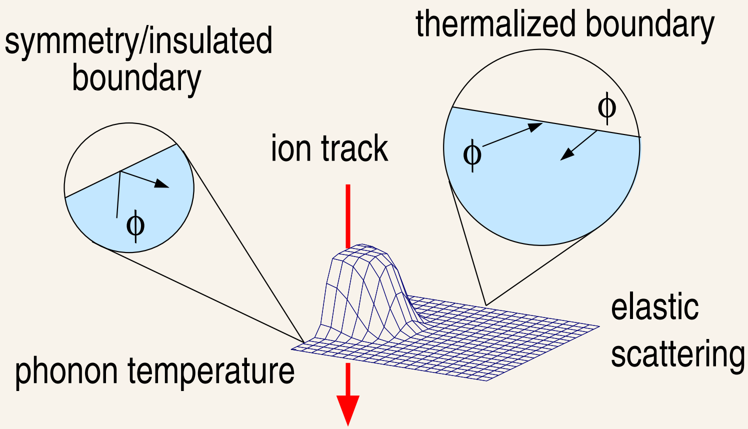
(R.C. Feldman, unpublished)

Non-equilibrium Phonon Transport

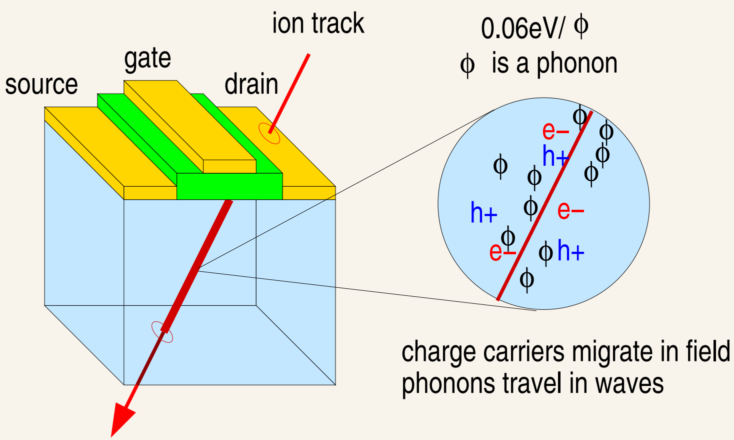
Phonon transport

number	$N = \sum_p \sum_{i=1}^{N_b} \langle n(\omega_i) \rangle D(\omega_i) \Delta\omega_i$
occupation	$\langle n \rangle = \left[\exp\left(\frac{\hbar\omega}{k_B T} \right) - 1 \right]^{-1}$
temperature	$\frac{E}{V} = \sum_p \sum_{i=1}^{N_b} \frac{\hbar\omega_i D(\omega_i)\Delta\omega_i}{\exp\left(\hbar\omega / k_B \tilde{T}\right) - 1}$

Phonon scattering



Phonon deposition



(Walker, TNS, 51(6), 2004, p.3318)

impurity

$$\tau_i^{-1} = \alpha\sigma\rho|\mathbf{V}_g|, \quad \mathbf{V}_g\text{:group velocity}$$

$$\sigma = \pi r^2 \left(\frac{\chi^4}{\chi^4 + 1} \right), \quad \chi = r|\mathbf{K}|$$

normal

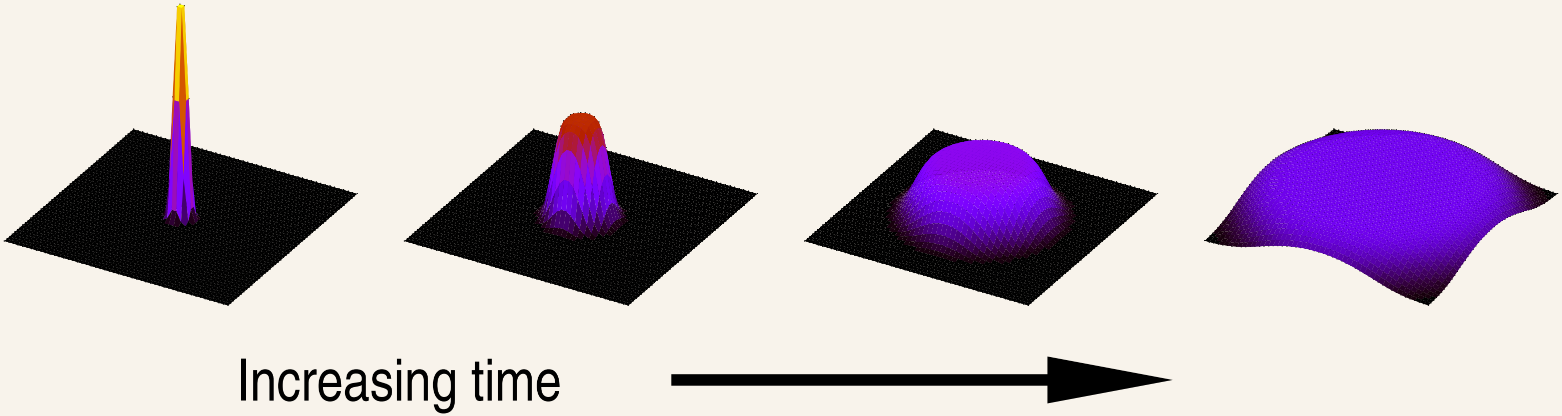
$$\tau_{NU}^{-1} = B_L \omega^2 T^3$$

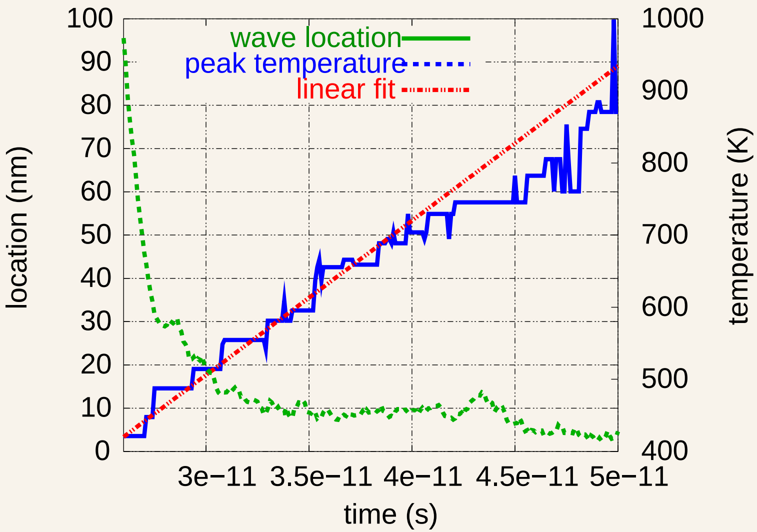
$$\tau_N^{-1} = B_{TN} \omega T^4$$

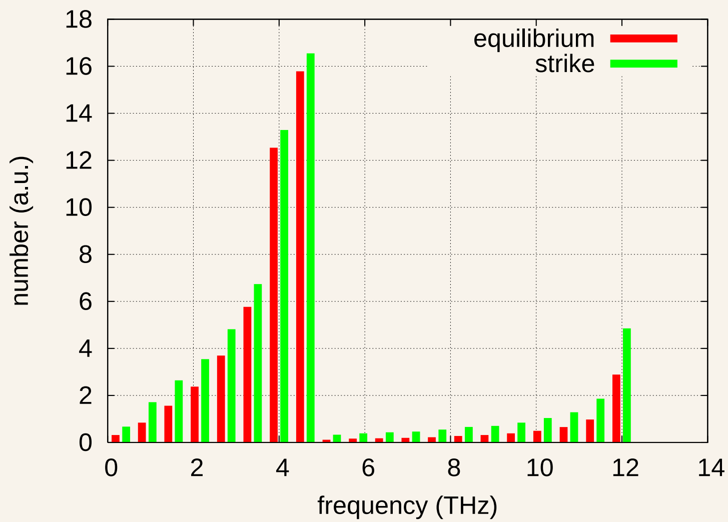
Umklapp

$$\tau_U^{-1} = \begin{cases} 0 & \omega < \omega_{1/2} \\ B_{TU}\omega^2 / \sinh\left(\frac{\hbar\omega}{k_B T}\right) & \omega > \omega_{1/2} \end{cases}$$

Radiation-Induced Phonons

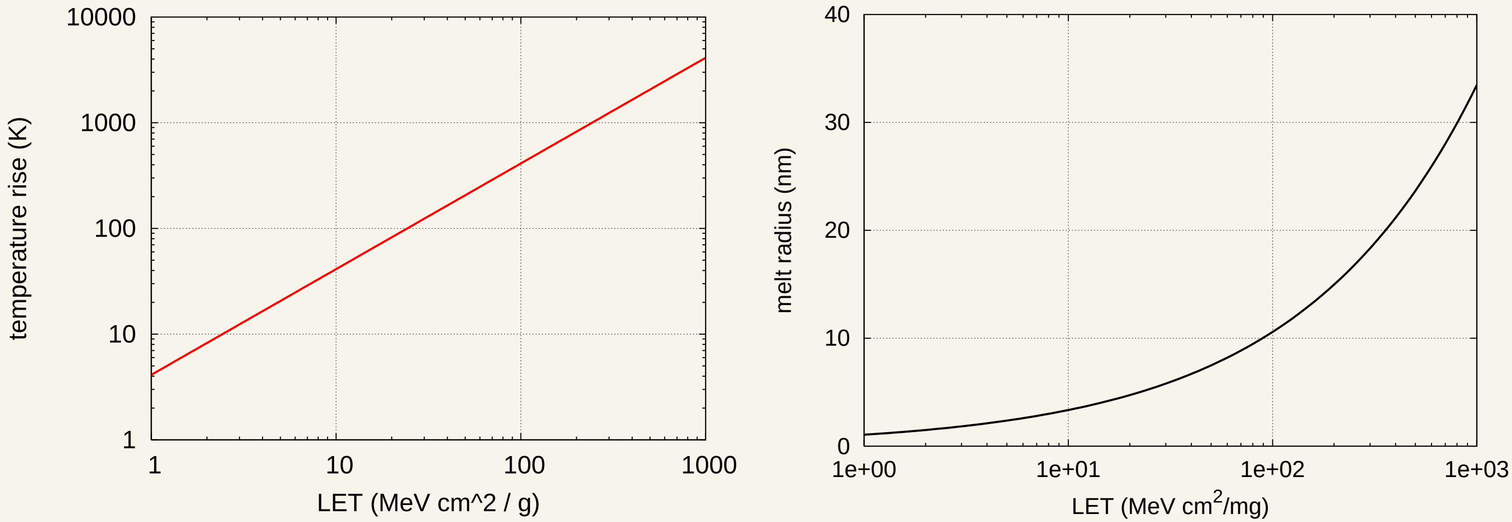






(Walker, TNS, 51(6), 2004, p.3318)

Radiation-Induced Thermal Failure?

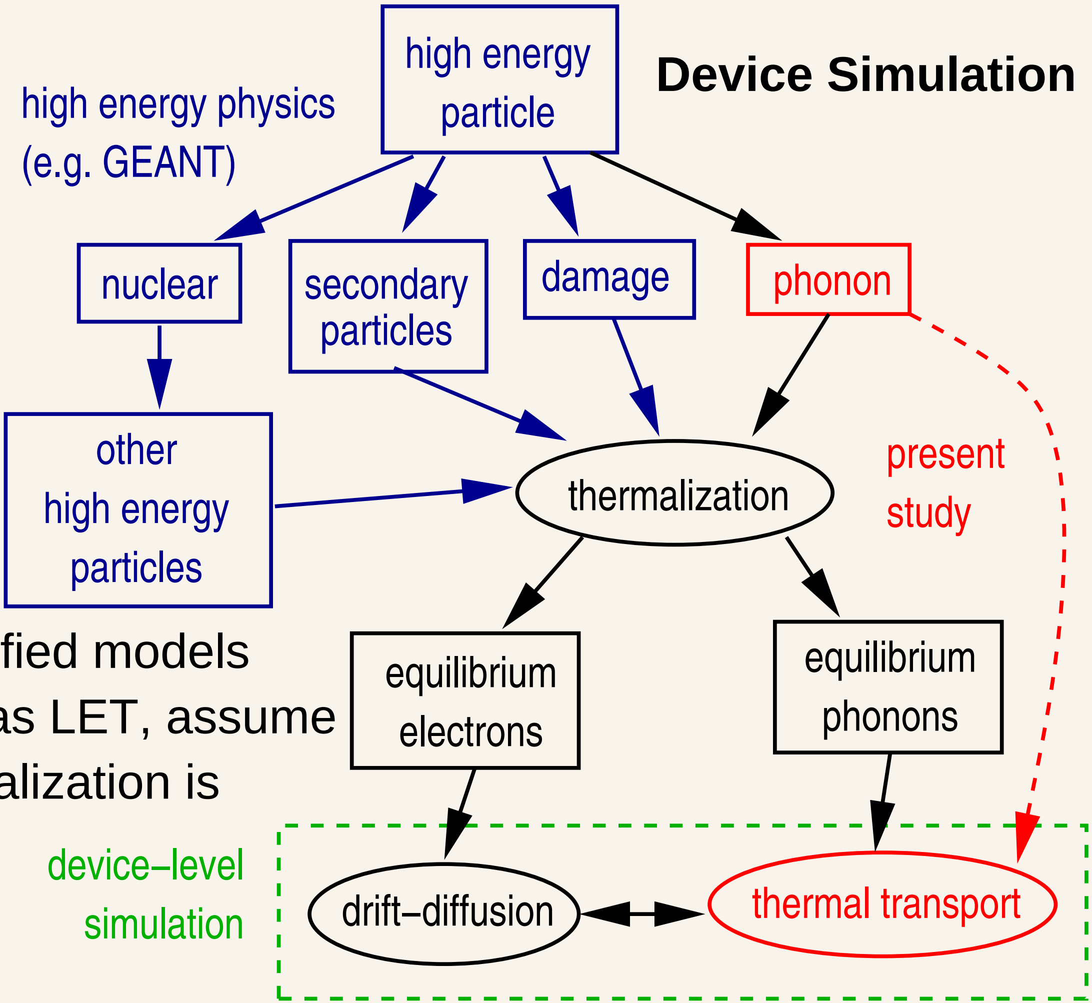


- How are phonons really generated?
- Melt radius is arguably a dubious parameter because temperature is an equilibrium quantity
- Highly scaled devices may fail due to thermal deposition of energy regardless of ionization

(Walker, TNS, 51(6), 2004, p.3318)

Thermal Energy Deposition Map

Device Simulation

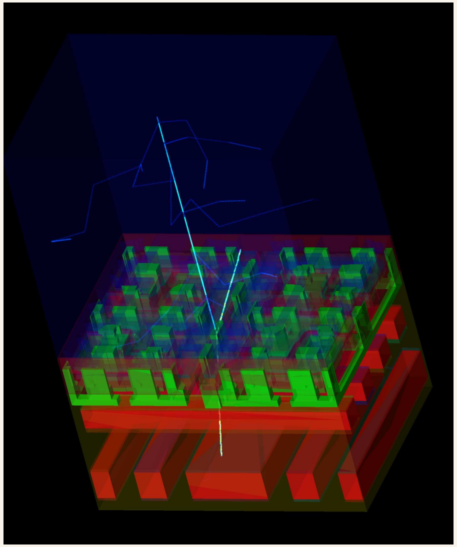


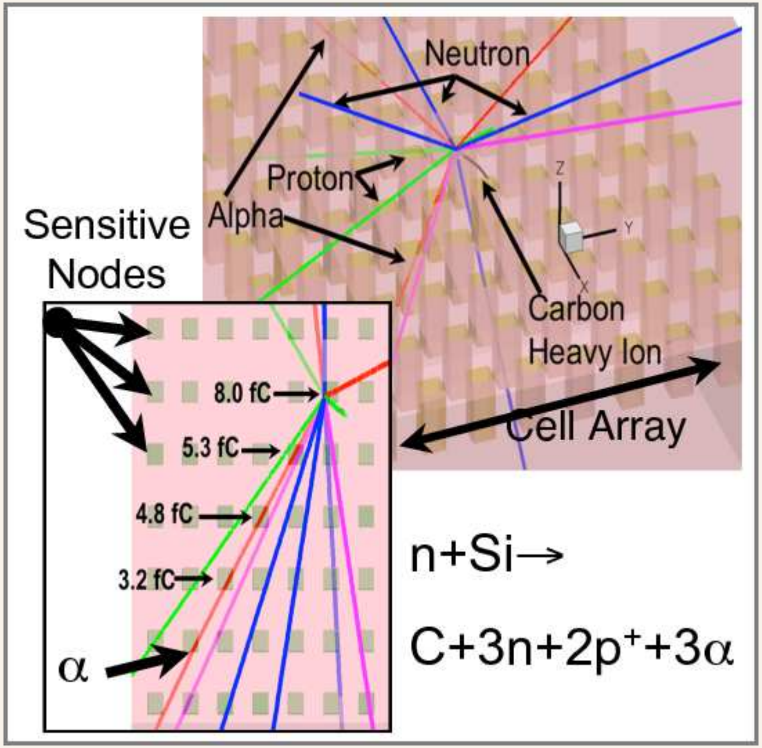
Simplified models such as LET, assume thermalization is trivial

(Walker, TNS, 51(6), 2004, p.3318)

MRED

Monte Carlo Radiation Energy Deposition

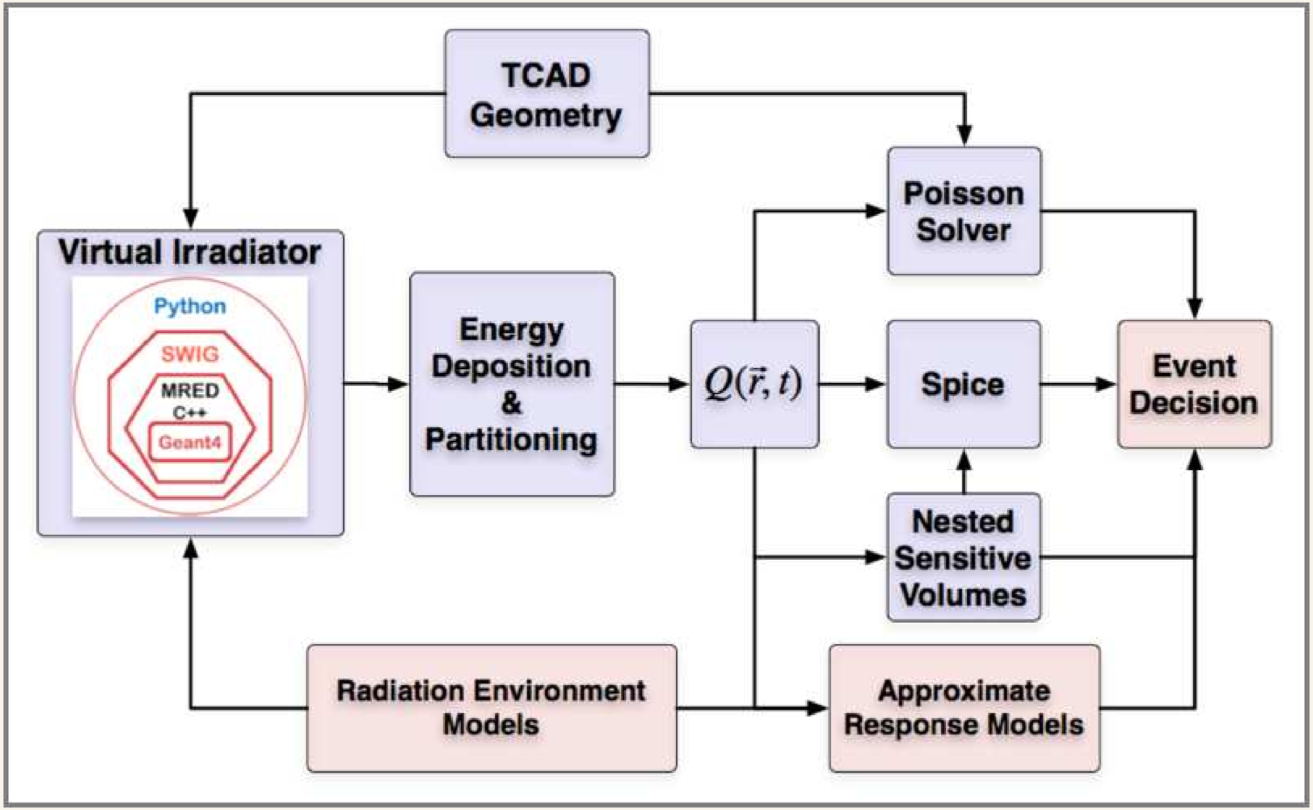




- Will identify “interesting” events
- Can collect statistics on device behavior as a function of radiation environment

(R.A. Weller, Radiation Effects and Reliability Group, Vanderbilt)

Model integration



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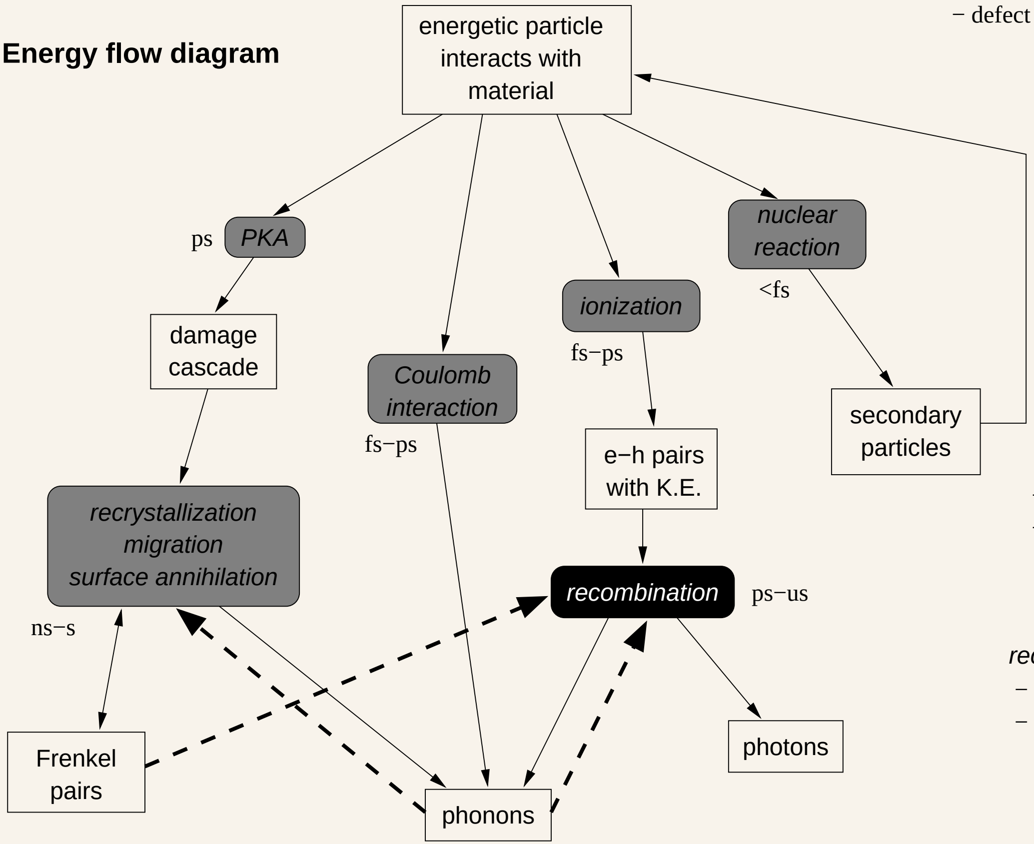

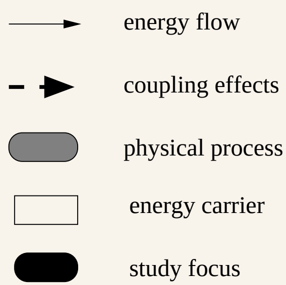

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− DFT − not really feasible here (outside scope)
− GEANT4 − MC−based mix of empirical and first principles

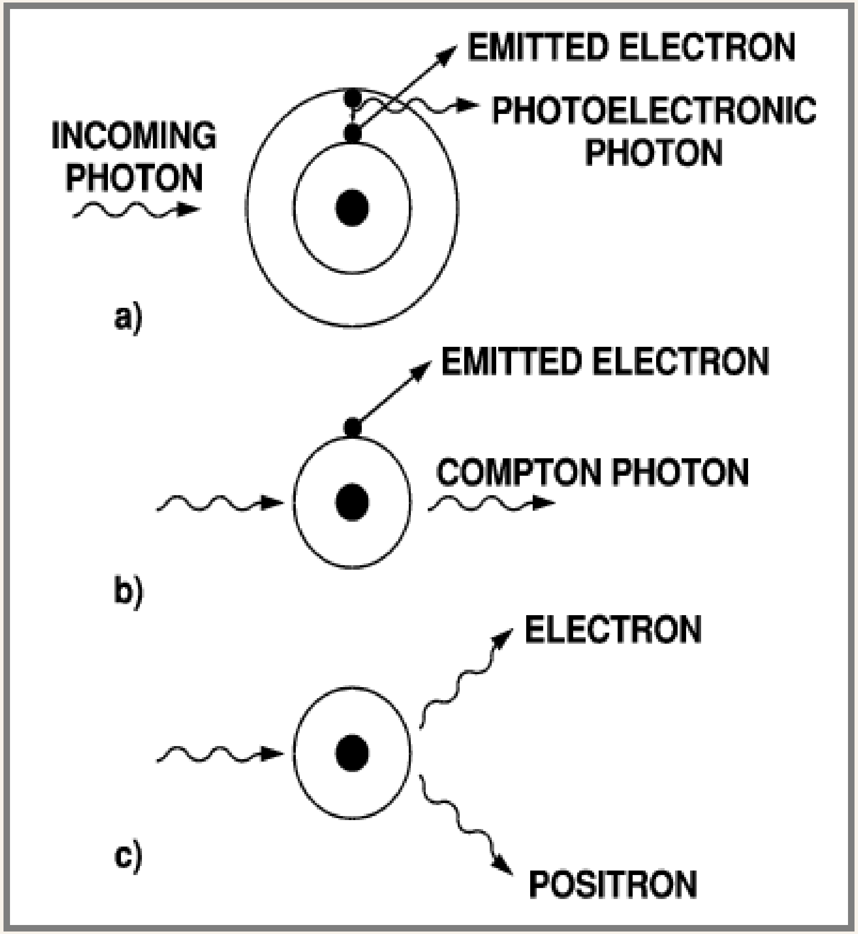
recombination
− many classical models
− full−band MC (include surface state scattering, defects, confined phonons)

Summary

- A great deal of research on *reducing* radiation effects in microelectronics can be leveraged for radiation detection.
- Better fidelity models are needed to capture physical interactions in scaled devices
- Nanomaterials and structures?
- 100eV to 10eV energy range represents a transition between models and physics that is not sufficiently captured

Extra Slides

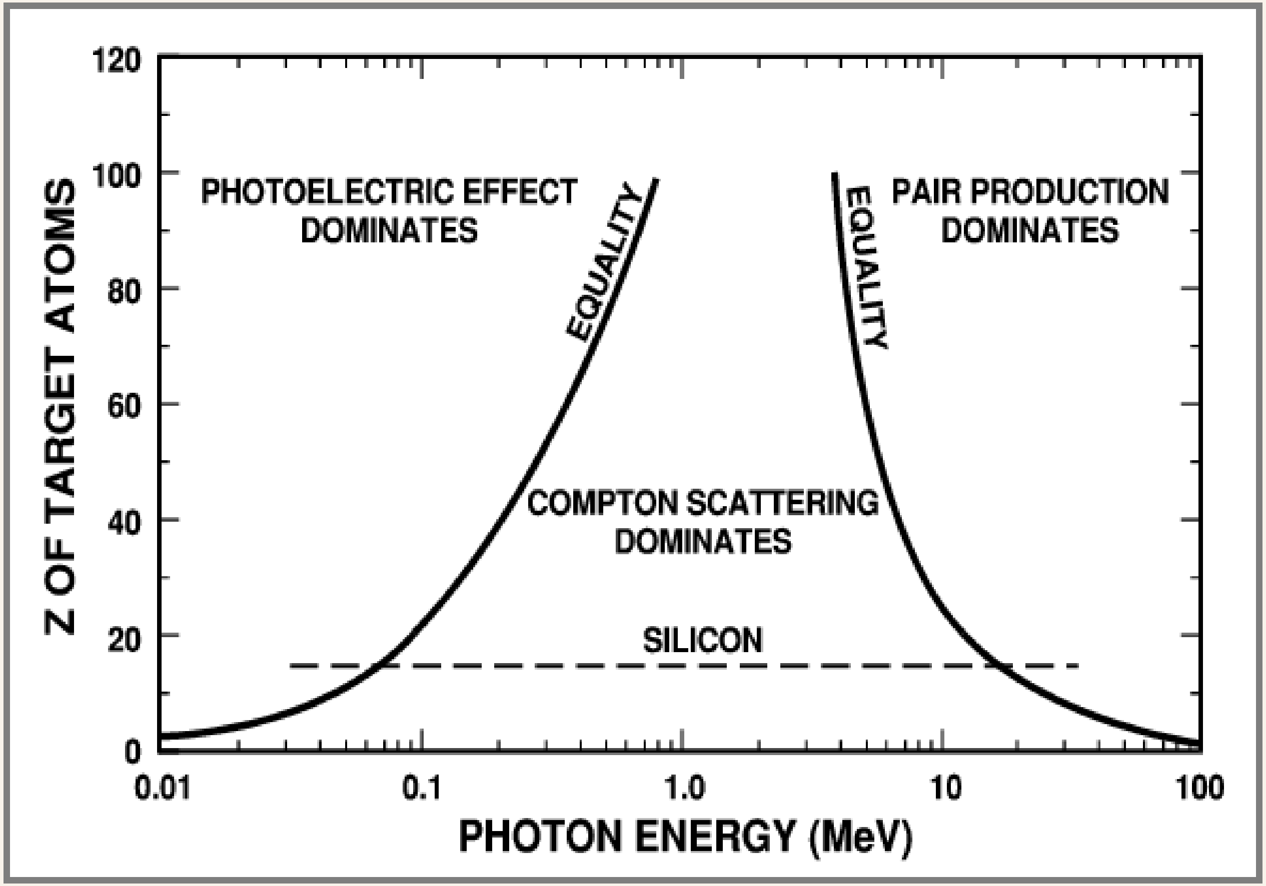
Interaction Processes



D.M. Fleetwood, Radiation Effects Short Course, Vanderbilt University, August, 2001

- Photons interact with materials through the a) photoelectric effect, b) Compton scattering, and c) pair production
- Ionization damage from high-energy photon, electrons and protons are qualitatively similar, but yields vary.

Photon Interactions

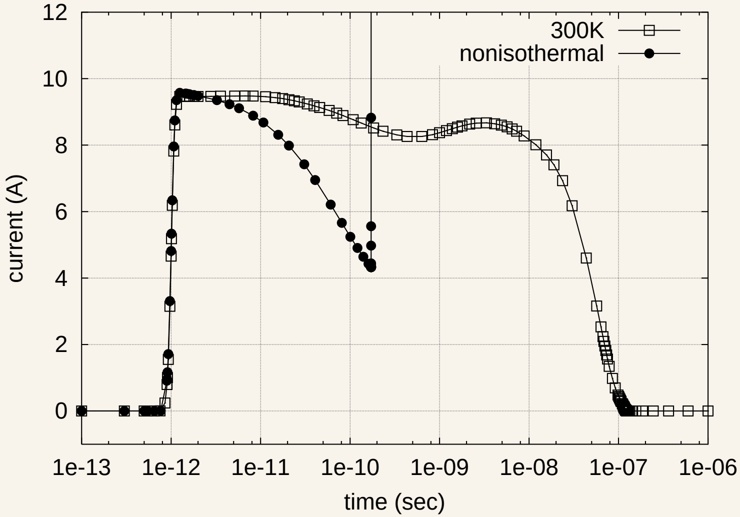


R. D. Evans, The Atomic Nucleus, McGraw-Hill, New York, 1955

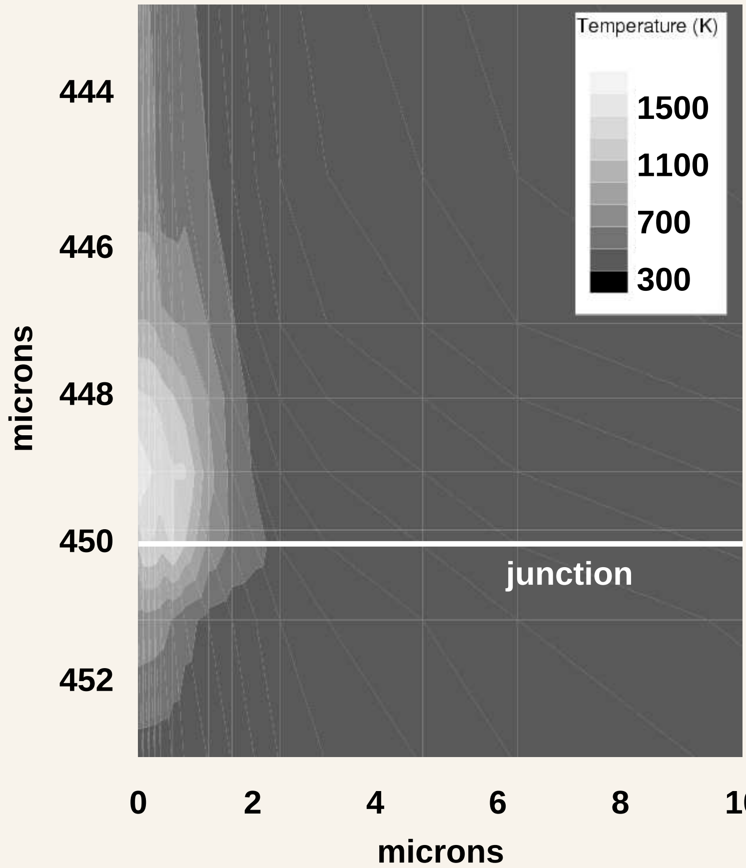
- 10 keV x-rays interact via the photoelectric effect
- Co-60 gamma rays (1.25 MeV) interact by Compton scattering
- but 10 keV x-ray to Co-60 correlation established

Diode SEB Simulation Results

Transient Response



Temperature at 1×10^{-10} sec



Radiation Products Map