Basic Mechanisms: Displacement Damage

LANL Radiation Effects Summer School

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Overview

- Displacement Damage
  - Consequences
  - Physical mechanisms
  - Electrical degradation
  - Modeling displacement damage
  - Current research

Consequences

Displacement damage (DD) creates defects in the semiconductor lattice, leading to long-term electrical degradation.

Electrical degradation includes

- Changes in carrier concentration
- Increased
  - leakage current or dark current
  - power consumption
  - channel on-resistance
  - noise
- Decreased
  - charge transfer efficiency
  - carrier lifetime
  - carrier mobility
  - gain

Hubble Space Telescope
Image: NASA, https://www.nasa.gov/mission_pages/hubble/spacecraft

Susceptible parts include

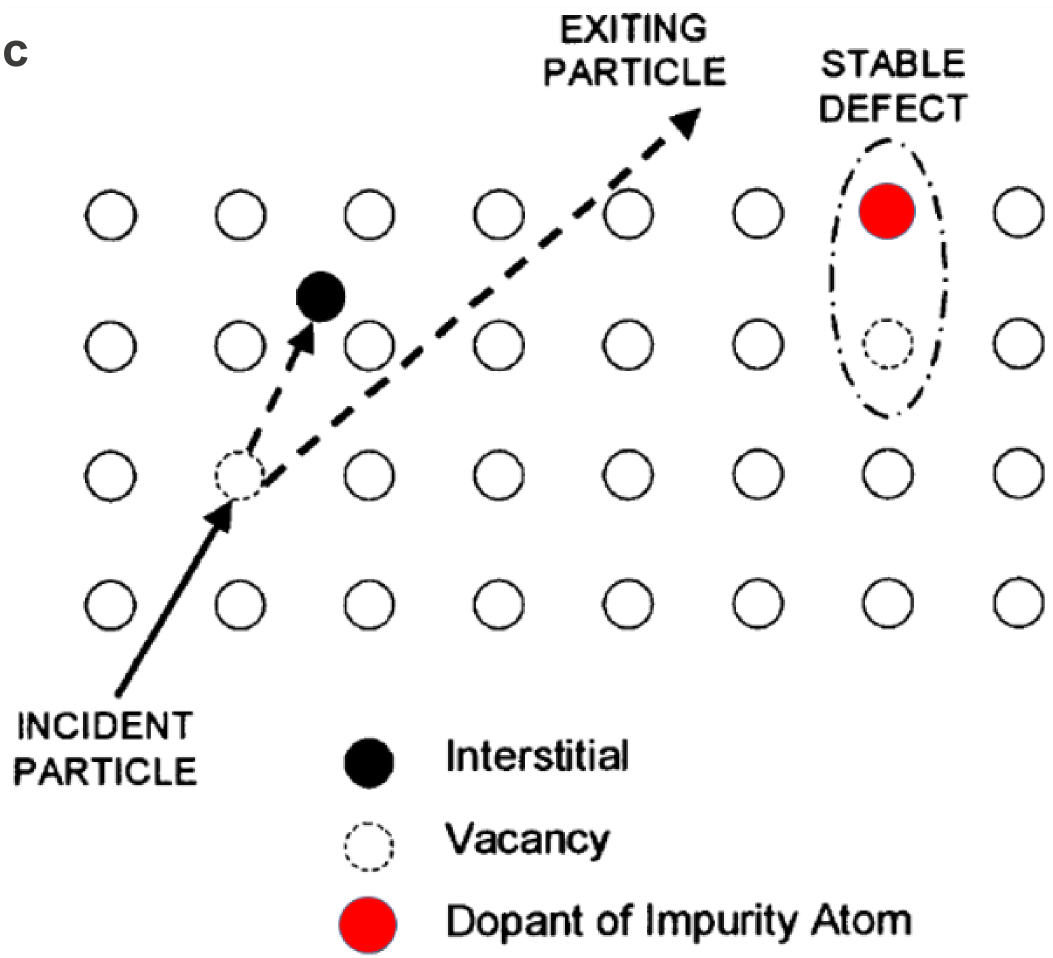
- Diodes
- BJTs
- Solar cells
- MOSFETs and power MOSFETs
- Pixels (CCD, APS, other sensor detectors)

Physical mechanisms: vacancies and interstitials

Particles that can cause atomic displacements:

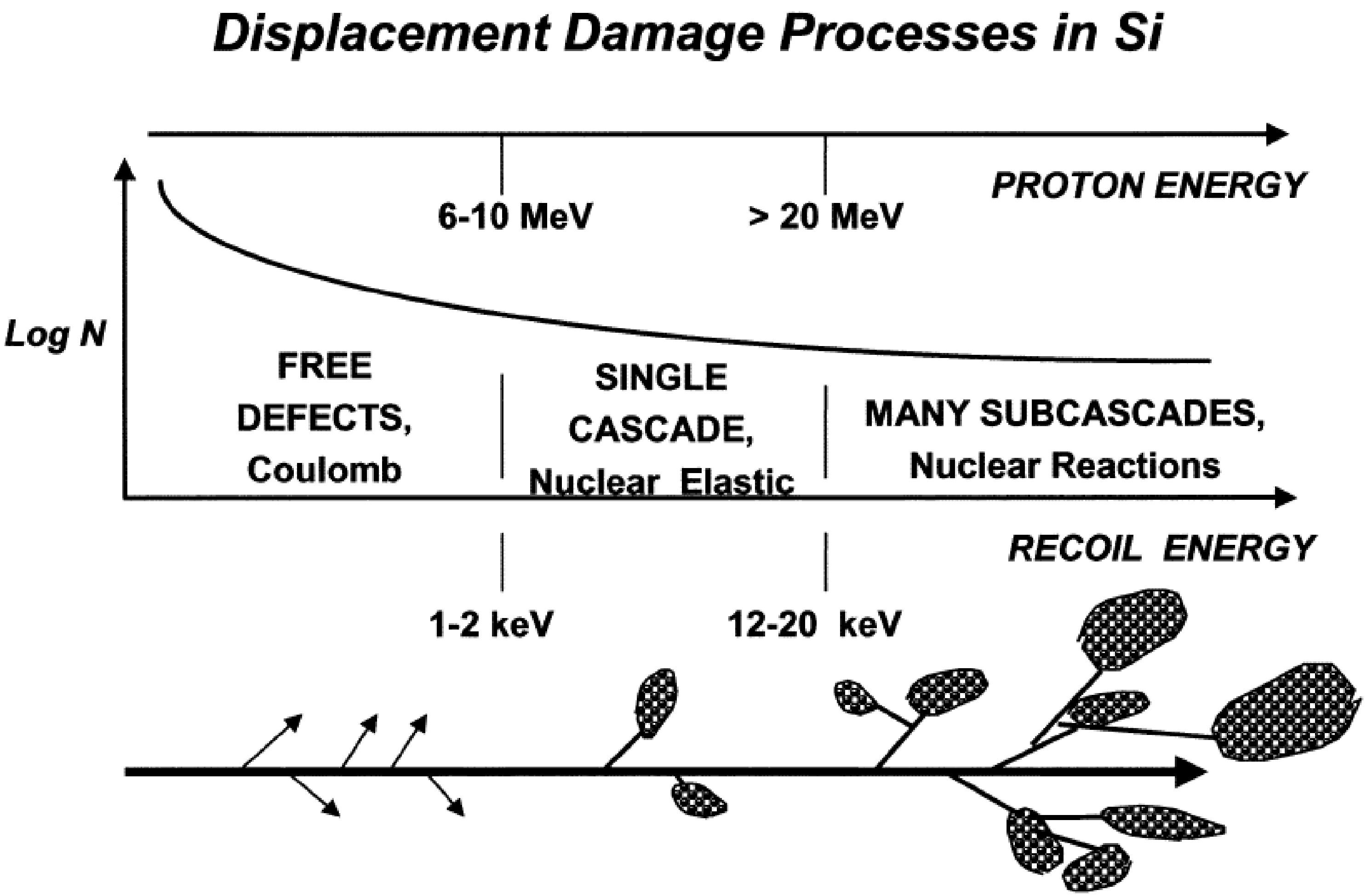
- Light and heavy ions
- Helium ions & α particles
- Protons and deuterons
- Neutrons
- Electrons
- Gamma rays
- Pions

How?
Compton scattering generates electrons that can displace atoms.



Incident radiation particle creating Frenkel pair (vacancy + interstitial atom)
After Marshall and Marshall, NSREC Short Course, Section IVB, 1999

Physical mechanisms: defect clusters



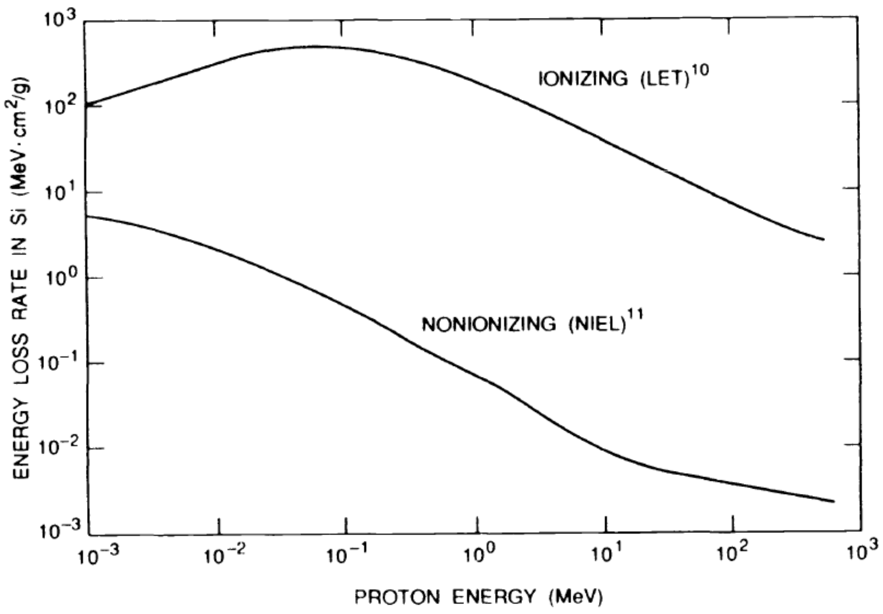
Frenkel pair production and defect cluster size vs. incident proton energy

After Srour, Marshall, and Marshall, *TNS* 50, 2003

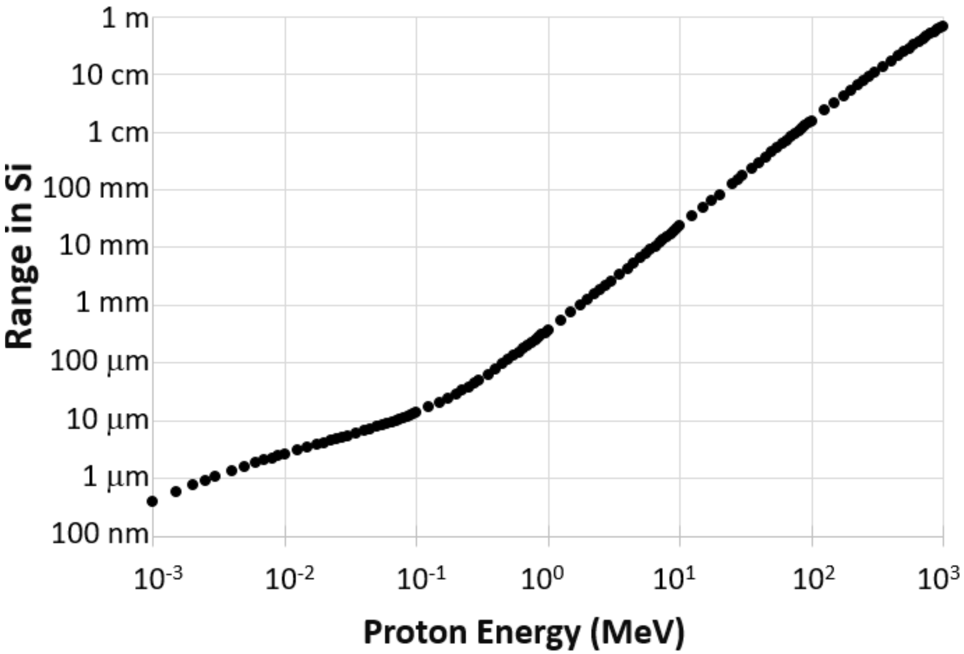
Physical mechanisms: ionizing vs. nonionizing energy loss

As charged particles travel through the semiconductor lattice, they lose energy through ionizing and nonionizing processes.

- Ionizing processes → single-event effects (SEE) and total ionizing dose (TID)
- Nonionizing processes → displacement damage



Rates at which protons lose ionizing and nonionizing energy in silicon
After Dale and Marshall, *SPIE 1447*, 1991

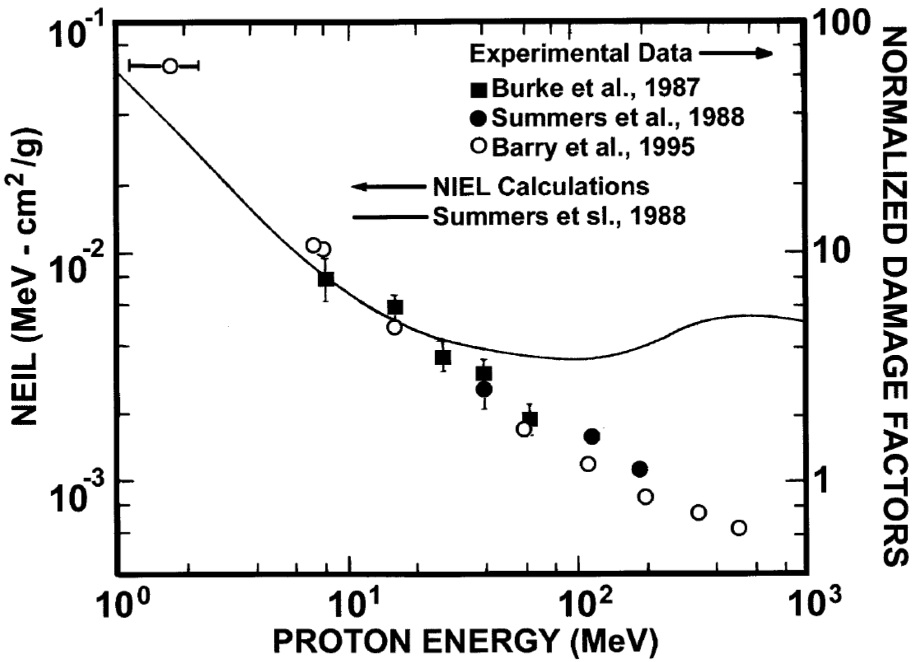


Protons in silicon: range vs energy
Range calculated as projected range (g/cm^2) divided by density of Si (g/cm^3). Projected range values from PSTAR in NIST Standard Reference Database 124

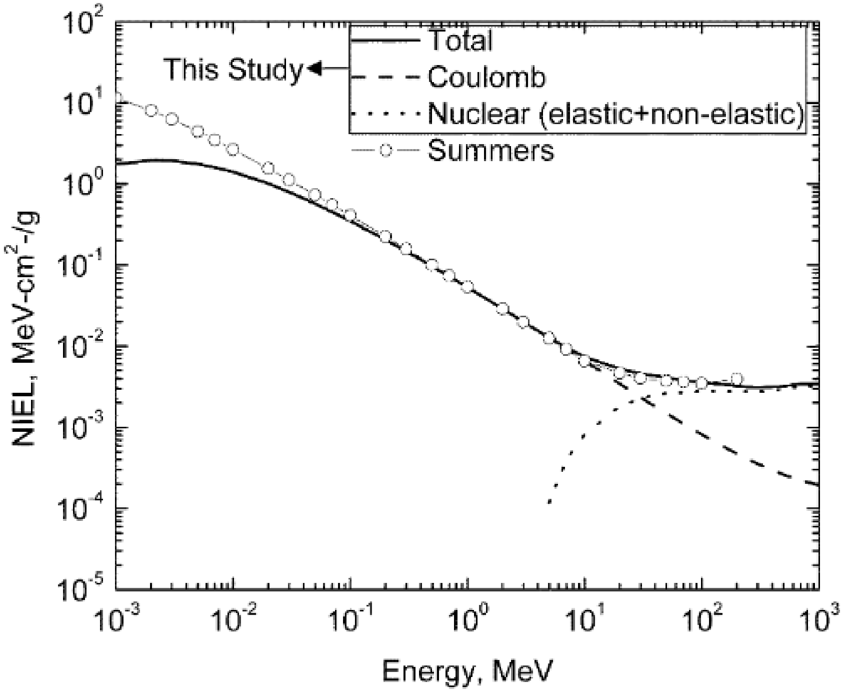
Physical mechanisms: nonionizing energy loss (NIEL)

"Nonionizing energy loss (NIEL) is a quantity that describes the rate of energy loss due to atomic displacements as a particle traverses a material."

- Jun et al., *TNS* 50 2003



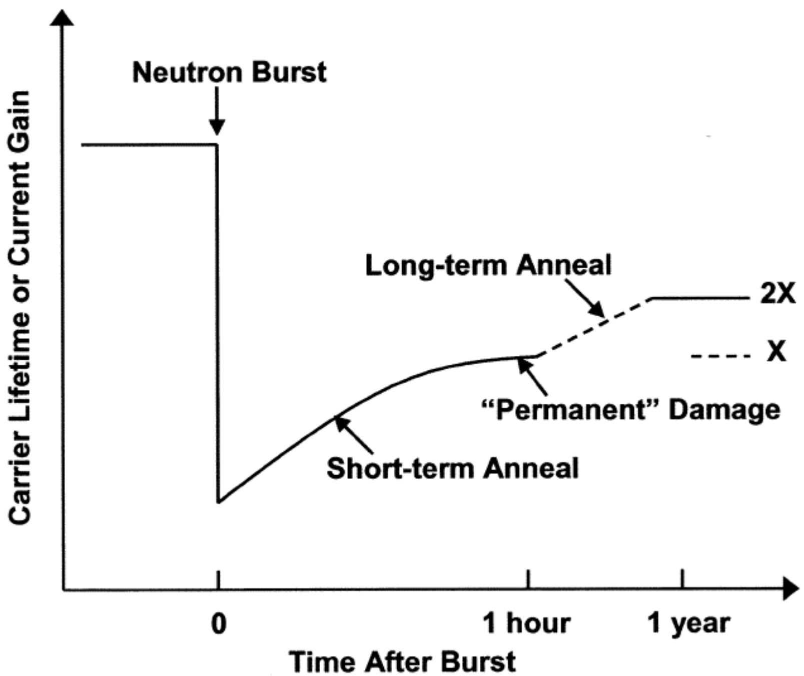
Early NIEL calculations vs measurements of proton-induced GaAs electrical degradation
After Srour, Marshall, and Marshall, *TNS* 50, 2003



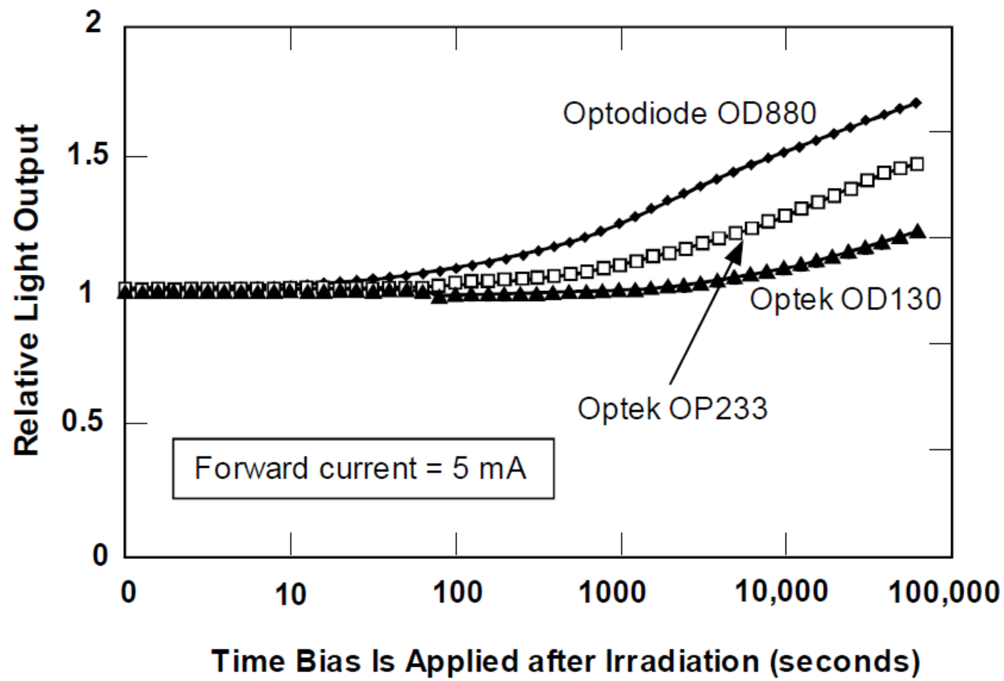
NIEL calculations for proton-irradiated GaAs incorporating screened, classical, and relativistic Coulomb scattering plus nuclear elastic and inelastic processes
After Jun et al., *TNS* 50, 2003

Physical mechanisms: annealing

Electrical degradation in some semiconductors (including Si) can partially recover through room temperature annealing. Other semiconductors (GaAs) can partially recover after thermal- or charge injection-induced annealing.



Recovery of carrier lifetime (or current gain) with annealing
After Srour, Marshall, and Marshall, *TNS* 50, 2003



Recovery of GaAs photodiodes with charge injection-induced annealing
After Johnston et al., *TNS 46*, 1999

Physical mechanisms: charge carriers, drift, & diffusion

Current is due to the movement of charge carriers – negatively charged electrons and positively charged holes – through drift and diffusion. Net current is zero at thermal equilibrium.

Diffusion: motion due to non-uniform charge carrier concentration
Drift: motion due to the presence of an electric field

Drift-diffusion equations for electrons and holes:

- Electron current density: $J_{nx} = q\mu_n n\mathcal{E}_x + qD_n \frac{dn}{dx}$
- Hole current density: $J_{px} = q\mu_p p\mathcal{E}_x + qD_p \frac{dp}{dx}$

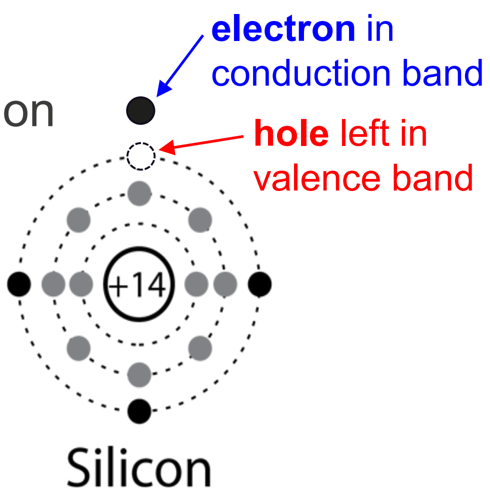
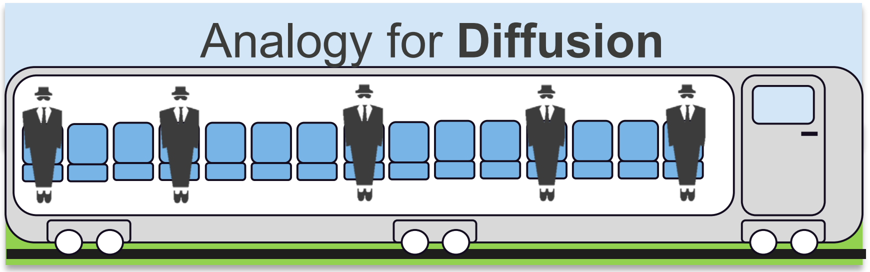
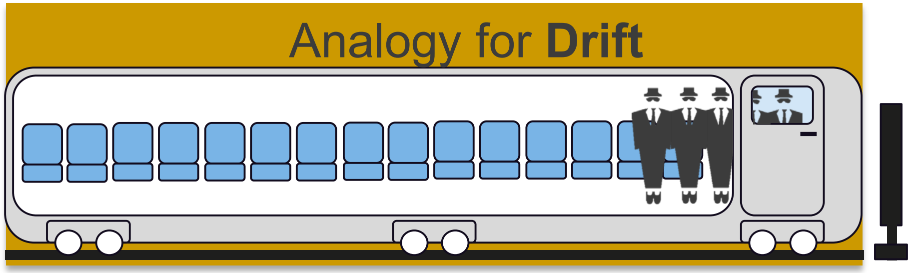


Image adapted from hyperphysics.phy-astr.gsu.edu



Train is moving: passengers spread out



Train station: passengers line up to exit

Physical mechanisms: carrier mobility and lifetime

Displacement damage decreases carrier mobility and increases resistivity.

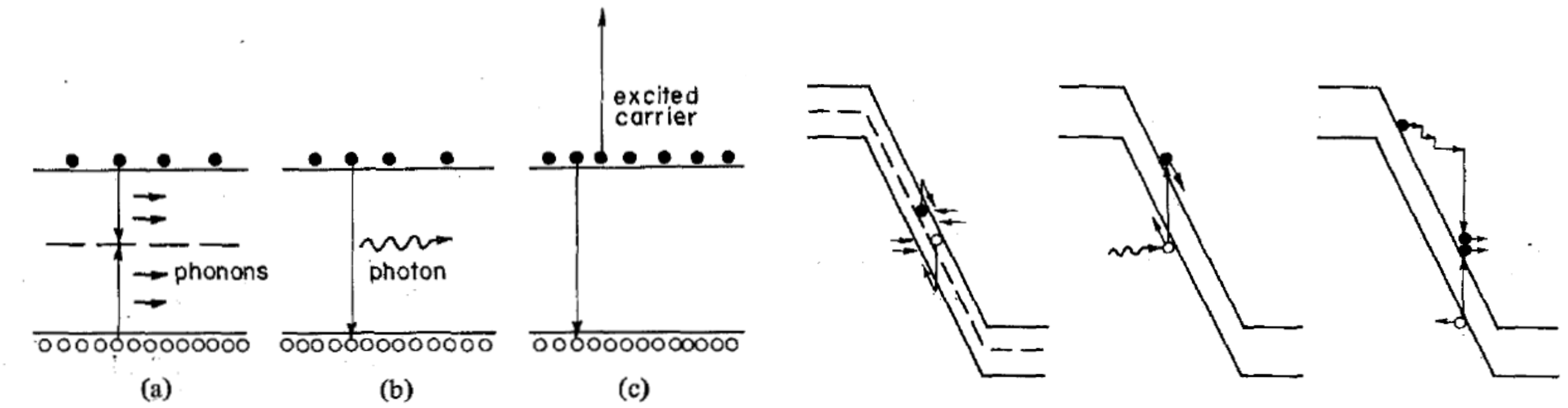
Electron mobility μ_n: $$\mu_n = \frac{q\tau_{cn}}{m_n^*}$$

Hole mobility μ_p: $$\mu_p = \frac{q\tau_{cp}}{m_p^*}$$

Carrier mobility is the relationship between electronic charge, mean time between scattering processes, and effective mass.

More defects → shorter scatter time

Resistivity ρ: $$\rho = \frac{1}{q\mu_n n + q\mu_p p}$$

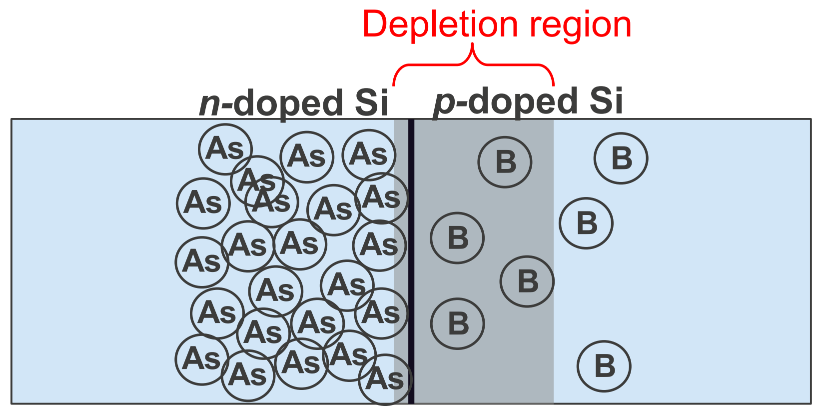


Recombination (left) and generation (right) processes in semiconductors: Shockley-Read-Hall recombination and generation, radiative recombination and e/h pair generation, and Auger recombination / avalanche generation. After Schroder, *TED* ED-29, 1982

Physical mechanisms: PN junctions

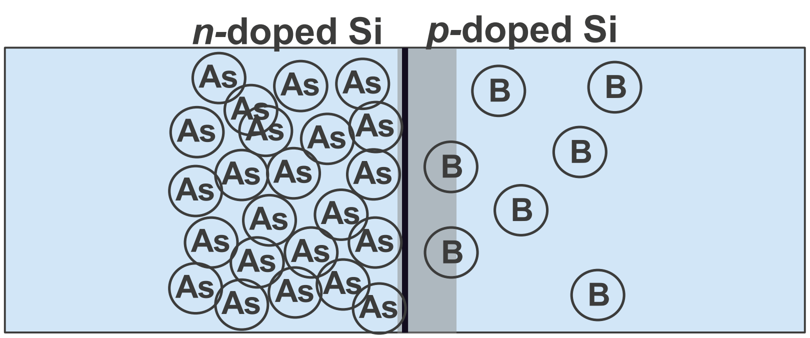
"intrinsically doped"

n_i = ~1 × 10^{10} atoms/cm^3



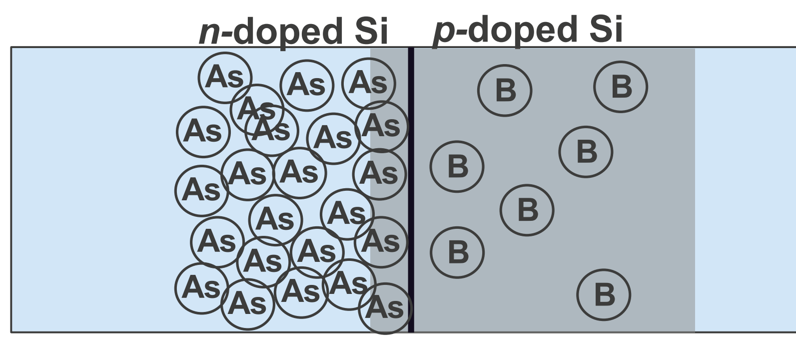
Unbiased (V_A = 0 V) *pn*-junction

n_i = 1 × 10^{10} atoms/cm^3
N_d = 1 × 10^{18} atoms/cm^3
N_a = 1 × 10^{16} atoms/cm^3



Forward biased (V_A = 0.7 V) *pn*-junction

n_i = 1 × 10^{10} atoms/cm^3
N_d = 1 × 10^{18} atoms/cm^3
N_a = 1 × 10^{16} atoms/cm^3



Reverse biased (V_A = -3 V) *pn*-junction

n_i = 1 × 10^{10} atoms/cm^3
N_d = 1 × 10^{18} atoms/cm^3
N_a = 1 × 10^{16} atoms/cm^3

Physical mechanisms: SRH recombination

Shockley-Read-Hall (SRH) recombination rate *U* describes the 4 ways that charge carriers (electrons and holes) interact with lattice defects:

1. Electron capture
2. Electron emission
3. Hole capture
4. Hole emission

$$U = \frac{(pn - n_i{}^2)}{\tau_{n0}\left[p + n_i e^{\left(\frac{E_i - E_t}{kT}\right)}\right] + \tau_{p0}\left[n + n_i e^{\left(\frac{E_t - E_i}{kT}\right)}\right]}$$

U = spontaneous recombination – spontaneous generation.

After Muller, Kamins, and Chan, 2003

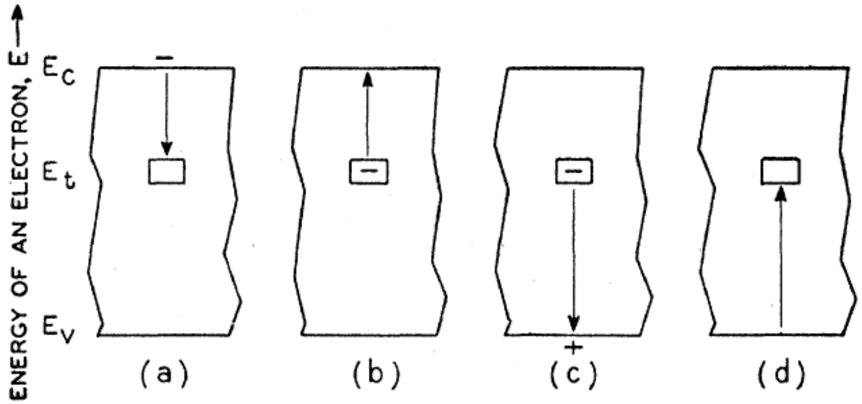
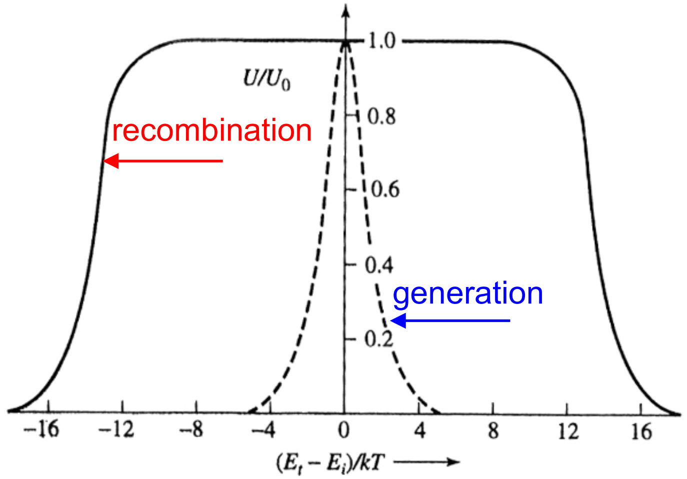


FIG. 1. The basic processes involved in recombination by trapping: (a) electron capture, (b) electron emission, (c) hole capture, (d) hole emission.

After Shockley and Read, *Phys. Rev.* 87, 1952

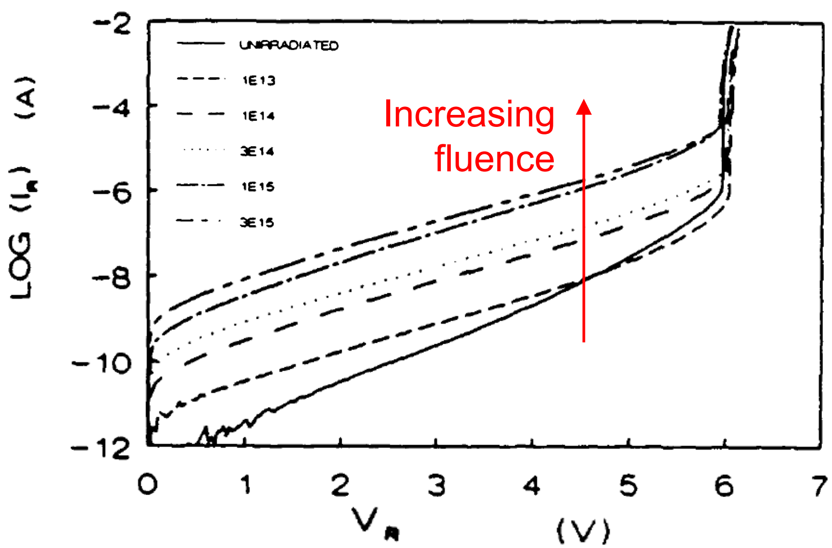


Recombination and generation vs energy level

After Muller, Kamins, and Chan, 2003

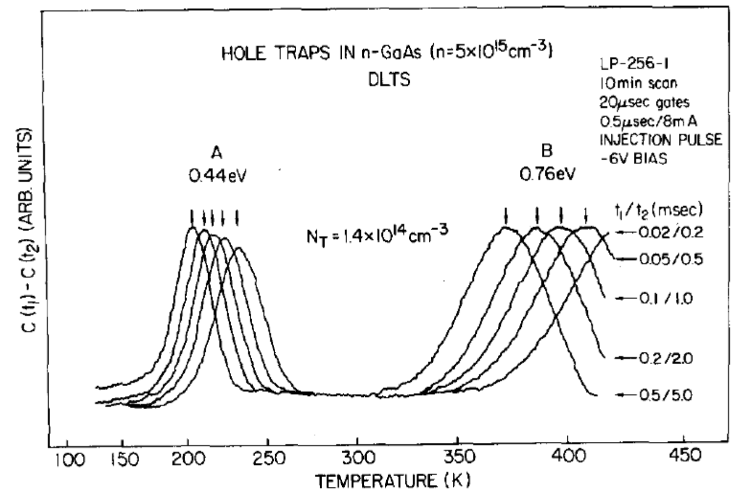
Electrical degradation: measuring damage

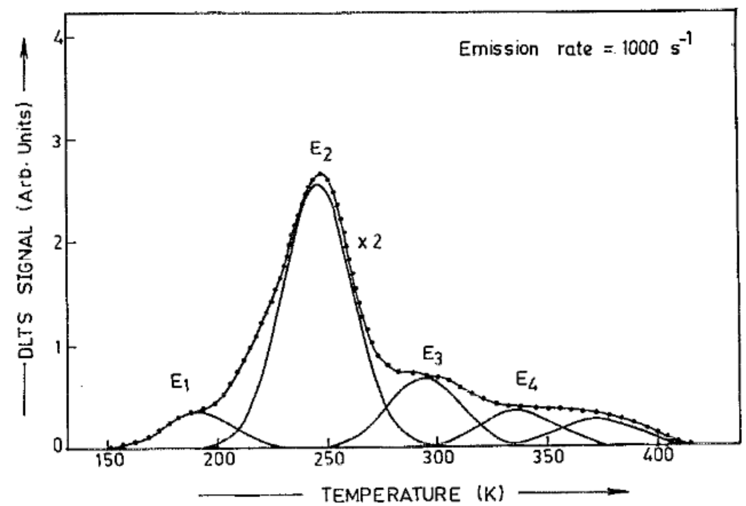
- IV curves
  - Changes in leakage / dark current
  - Changes in gain
- Deep level transient spectroscopy (DLTS) or deep level optical spectroscopy (DLOS)
  - Defect energy level
  - Defect concentration
  - Defect capture rates
- Photoconductive decay
  - Minority carrier lifetime



IV curves of neutron-irradiated diode

After Khanna, Pepper, and Stone, *Def. Res. Est. Ottawa*, 1992



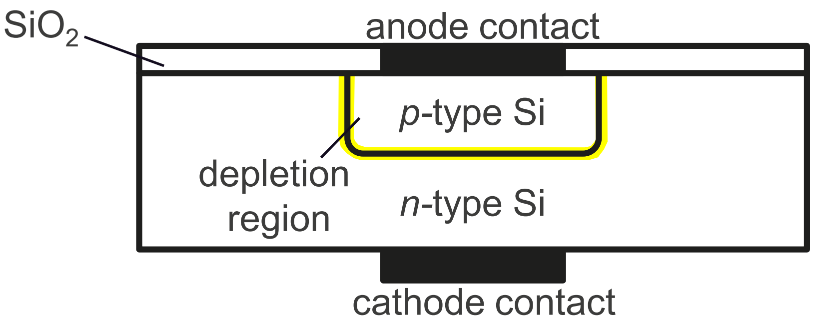


DLTS signals in GaAs (above) and *Si* (below)

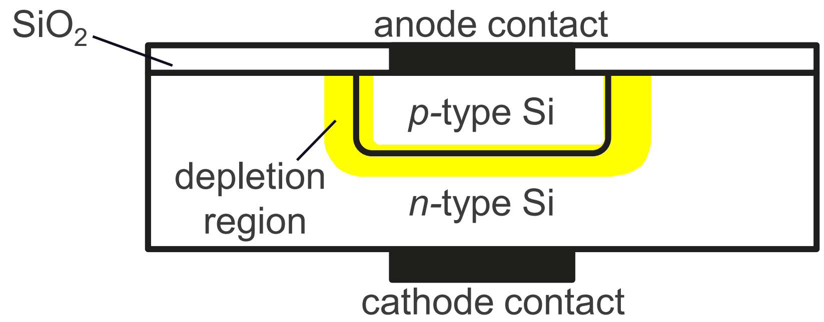
After Lang, *J. Appl. Phys.*45, 1974 and Chaudhari et al., *J. Appl. Phys.* 70, 1991

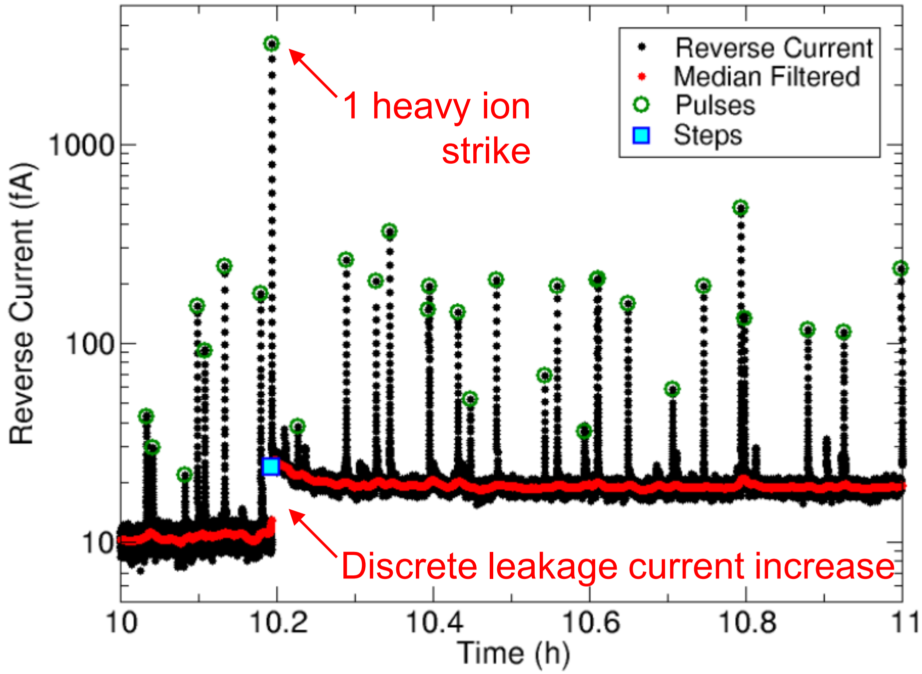
Electrical degradation: diodes

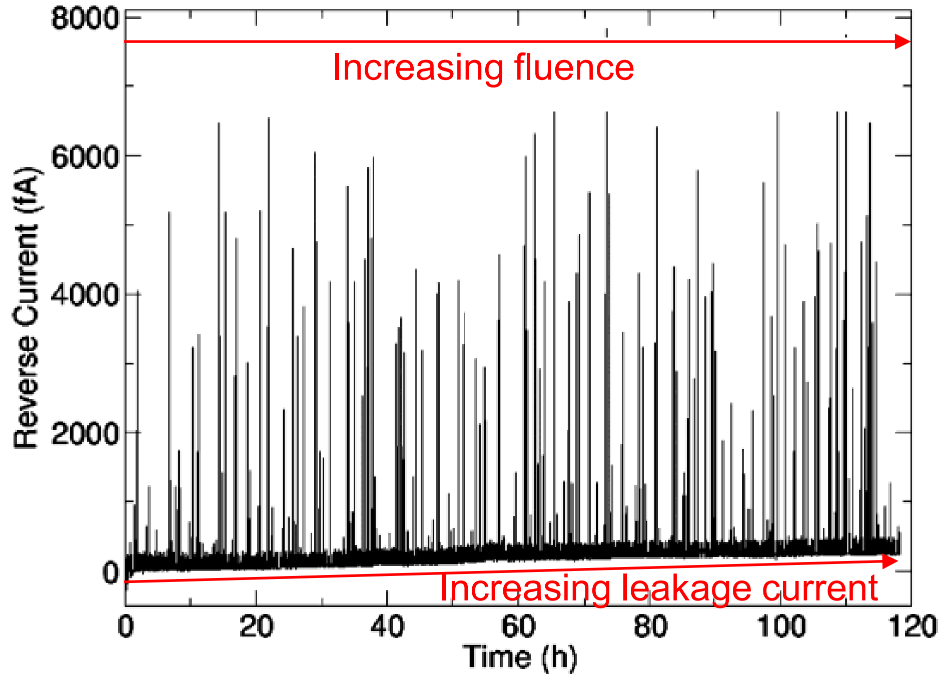
Forward-biased diode



Reverse-biased diode





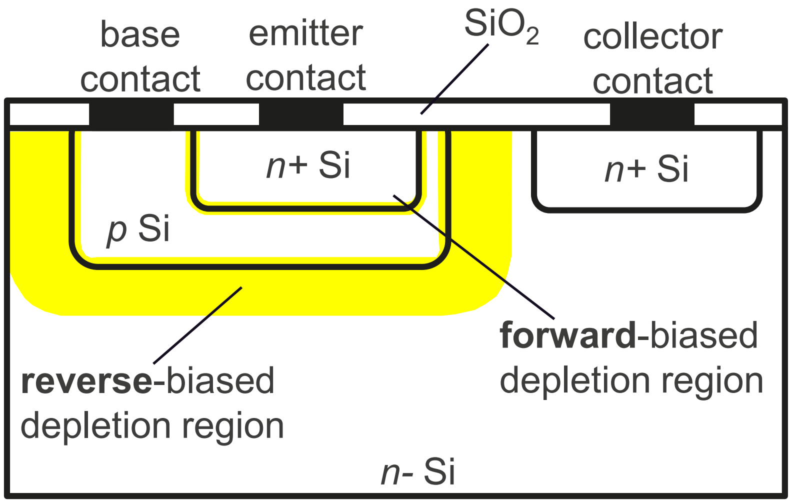


Discrete (left) and long-term (right) increases in leakage current measured in a ^{252}Cf-irradiated diode.

After Auden et al., *TNS* 59, 2012

Electrical degradation: BJTs

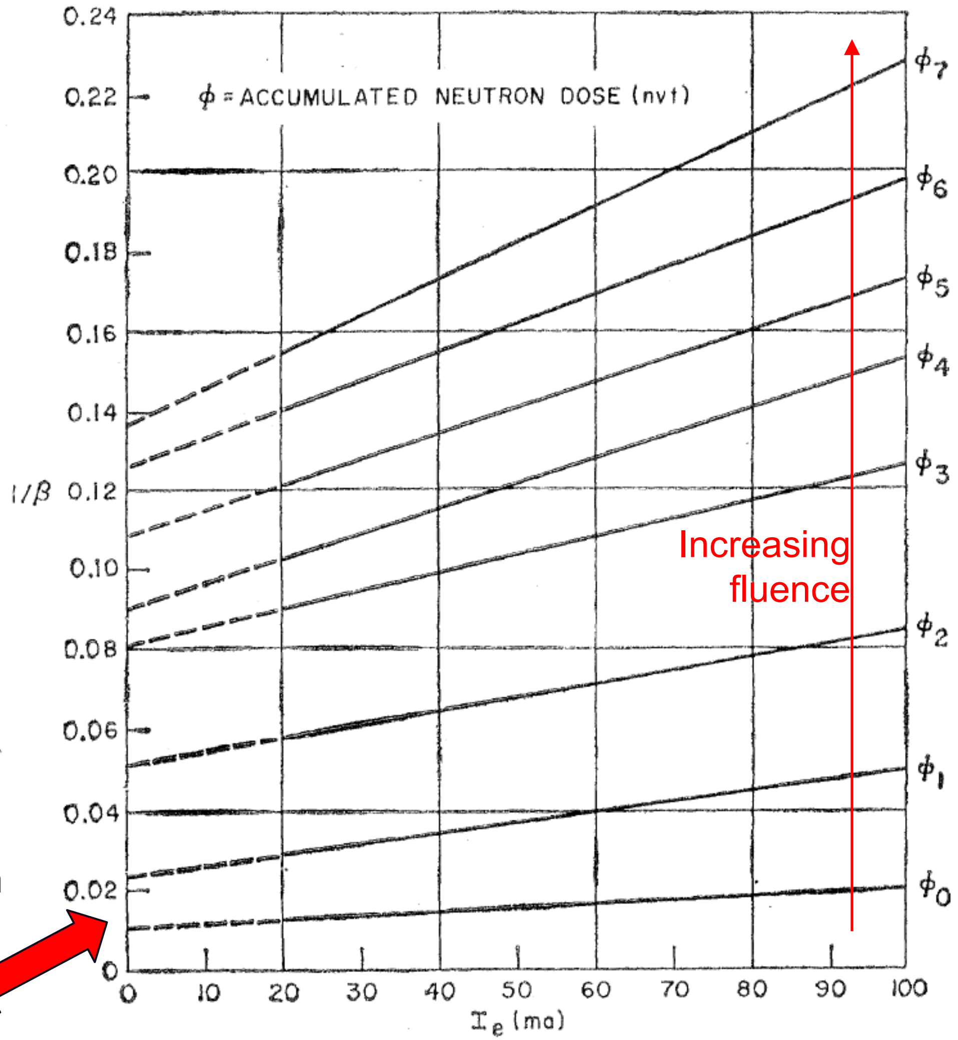
BJT in **active** bias



Gain: $\beta = \frac{I_C}{I_B} = \frac{\textit{collector current}}{\textit{base current}}$

Displacement damage increases recombination current in the *p*-type base and base-emitter depletion region, increasing base current and reducing gain.

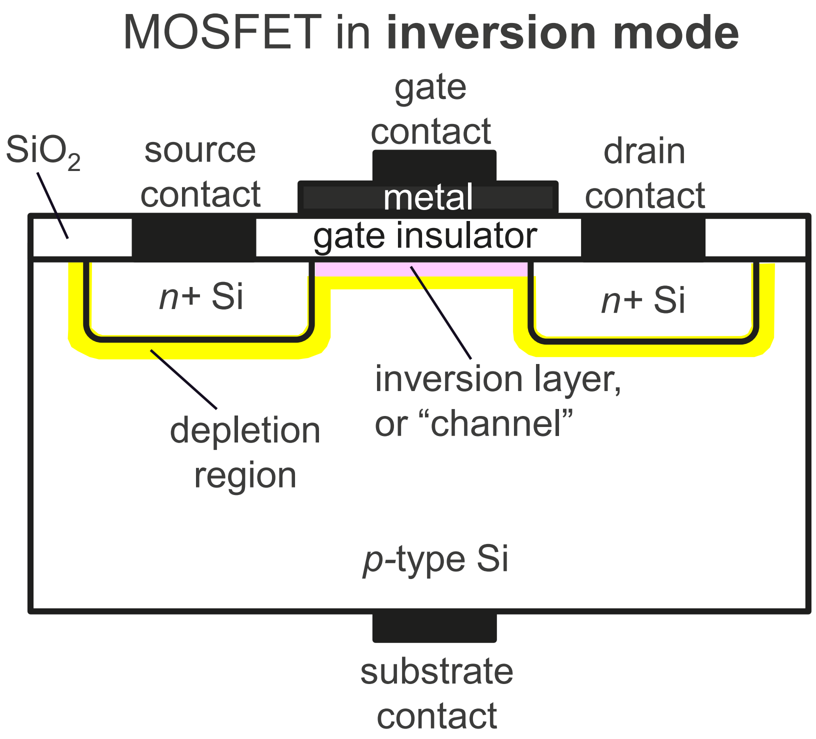
Note: the Messenger-Spratt equation came from this work. $$\frac{1}{\tau_0} = \frac{1}{\tau_i} + \frac{\phi}{K}$$



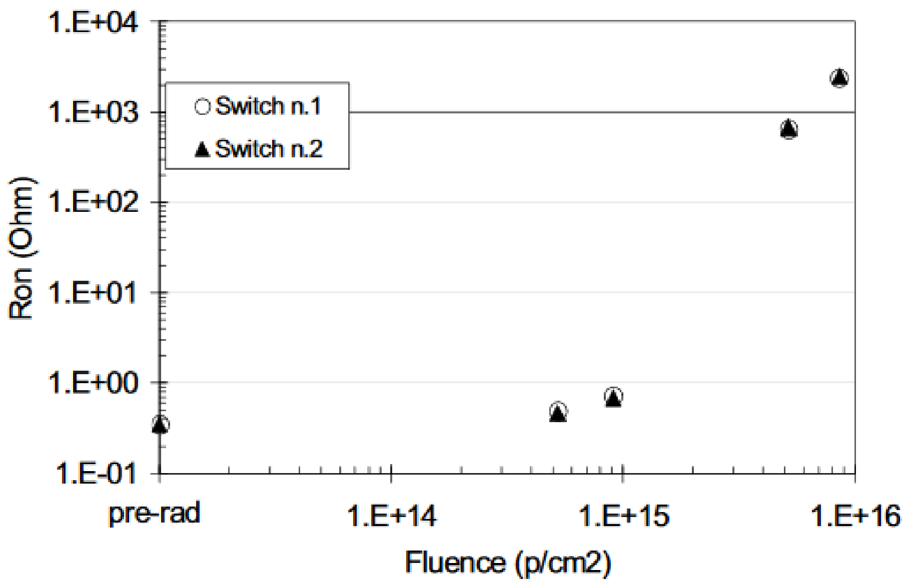
Decreasing gain in a neutron-irradiated germanium BJT

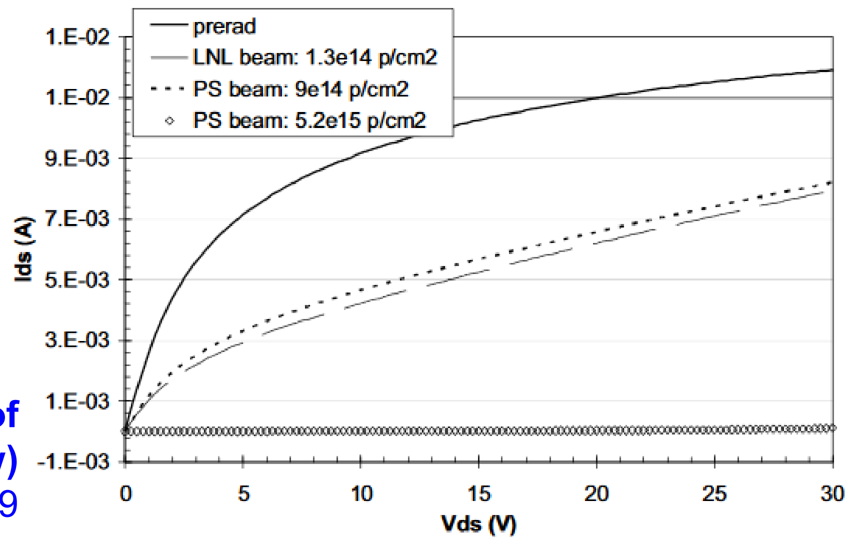
After Messenger and Spratt, *Proc. IRE, 1958*

Electrical degradation: MOSFETs



When applied gate voltage exceeds threshold voltage, an inversion layer appears under the gate, creating a channel that allows electrons to flow from source to drain.



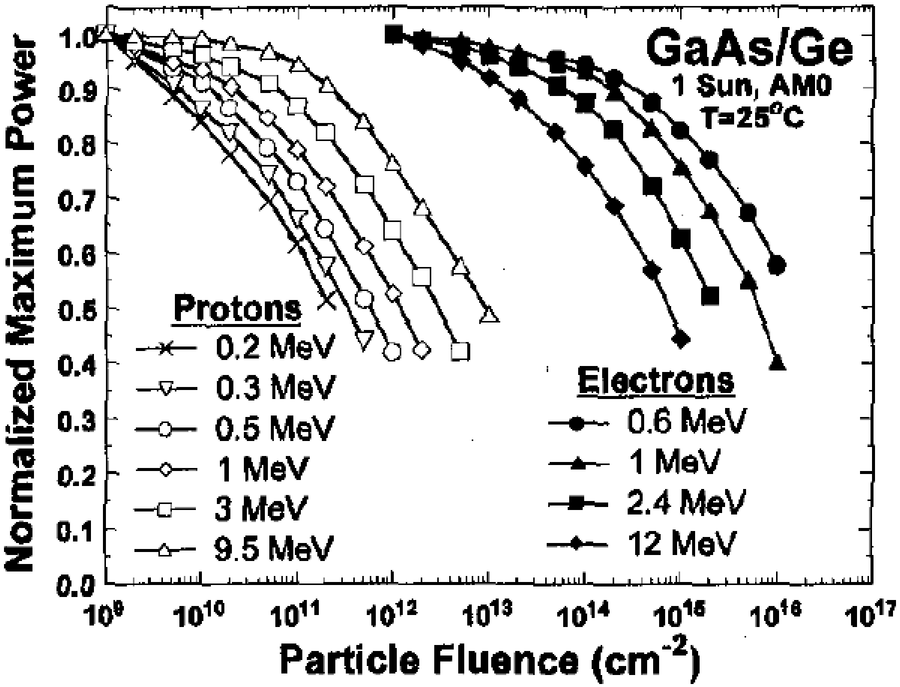


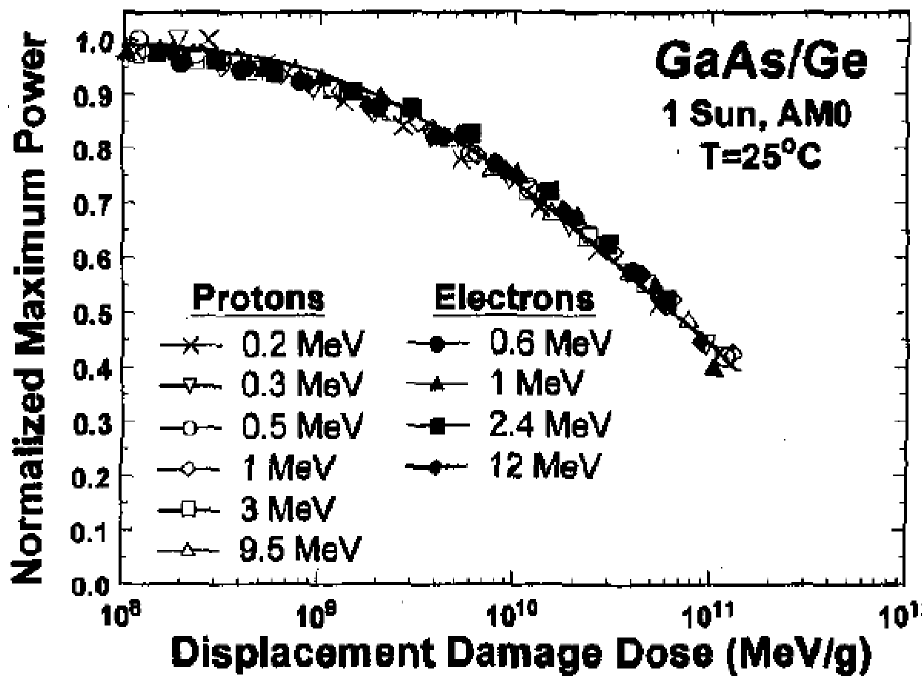
Proton-irradiated NMOS transistors: degradation of on-resistance (above) and output conductance (below)
After Faccio et al., RADECS 2009

Electrical degradation: solar cells

Solar cells convert visible light to current. Conversion efficiency degrades with increasing displacement damage.

Also: note that damage-induced electrical degradation differs for a given fluence of electrons or protons, but degradation is consistent for a given amount of displacement damage dose.



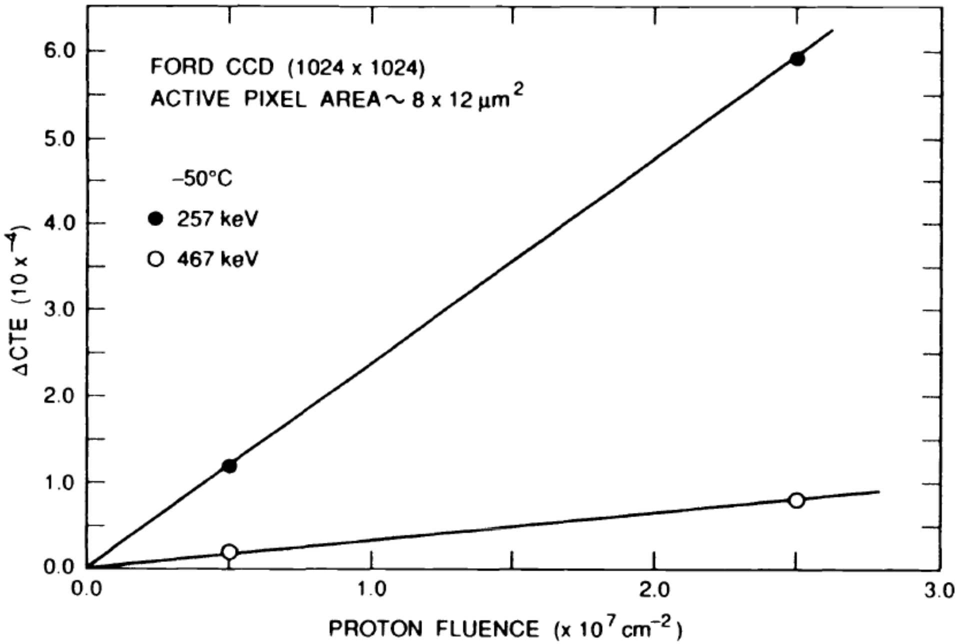


Solar cells irradiated with protons and electrons: maximum power degradation vs fluence (left) and displacement damage dose (right)

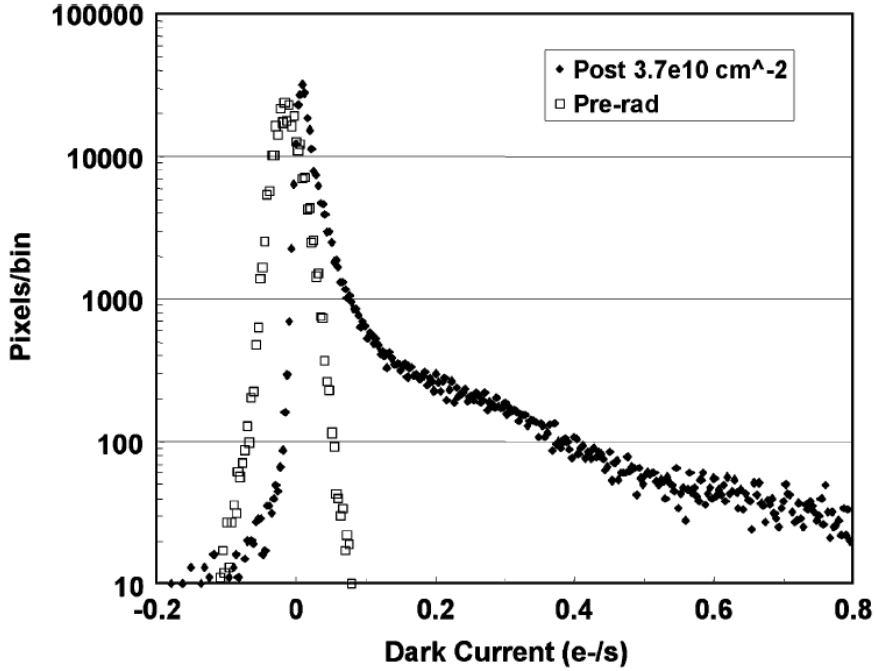
After Messenger et al., *TNS 46*, 1999

Electrical degradation: Pixels

Displacement damage causes degradation in sensor array pixel devices. Increased dark current can lead to hot pixels, increased noise, and increased power consumption.



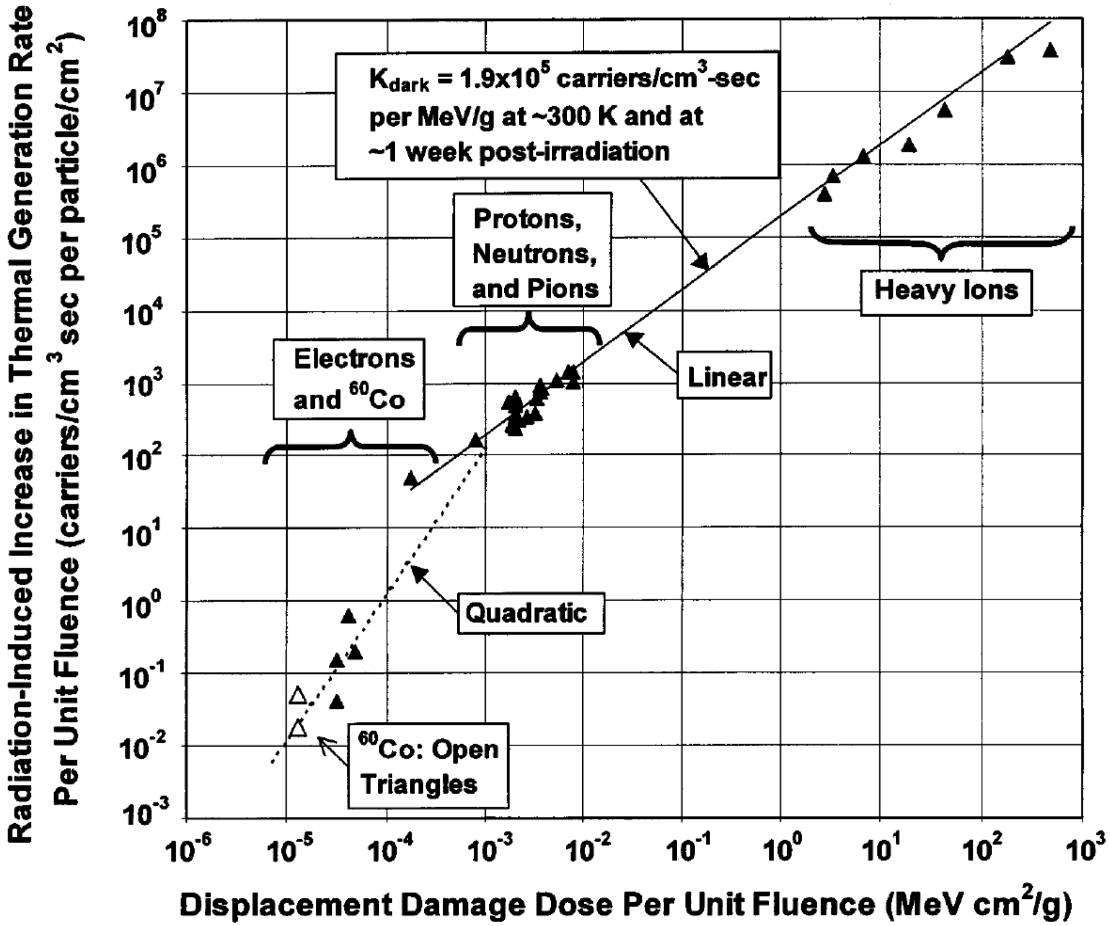
Proton-irradiated Si CCD: change in charge transfer efficiency (CTE)
After Dale and Marshall, *SPIE* 1447, 1991



Proton-irradiated HgCdTe detector array: histogram of dark current increase
After Marshall et al., *TNS* 54, 2007

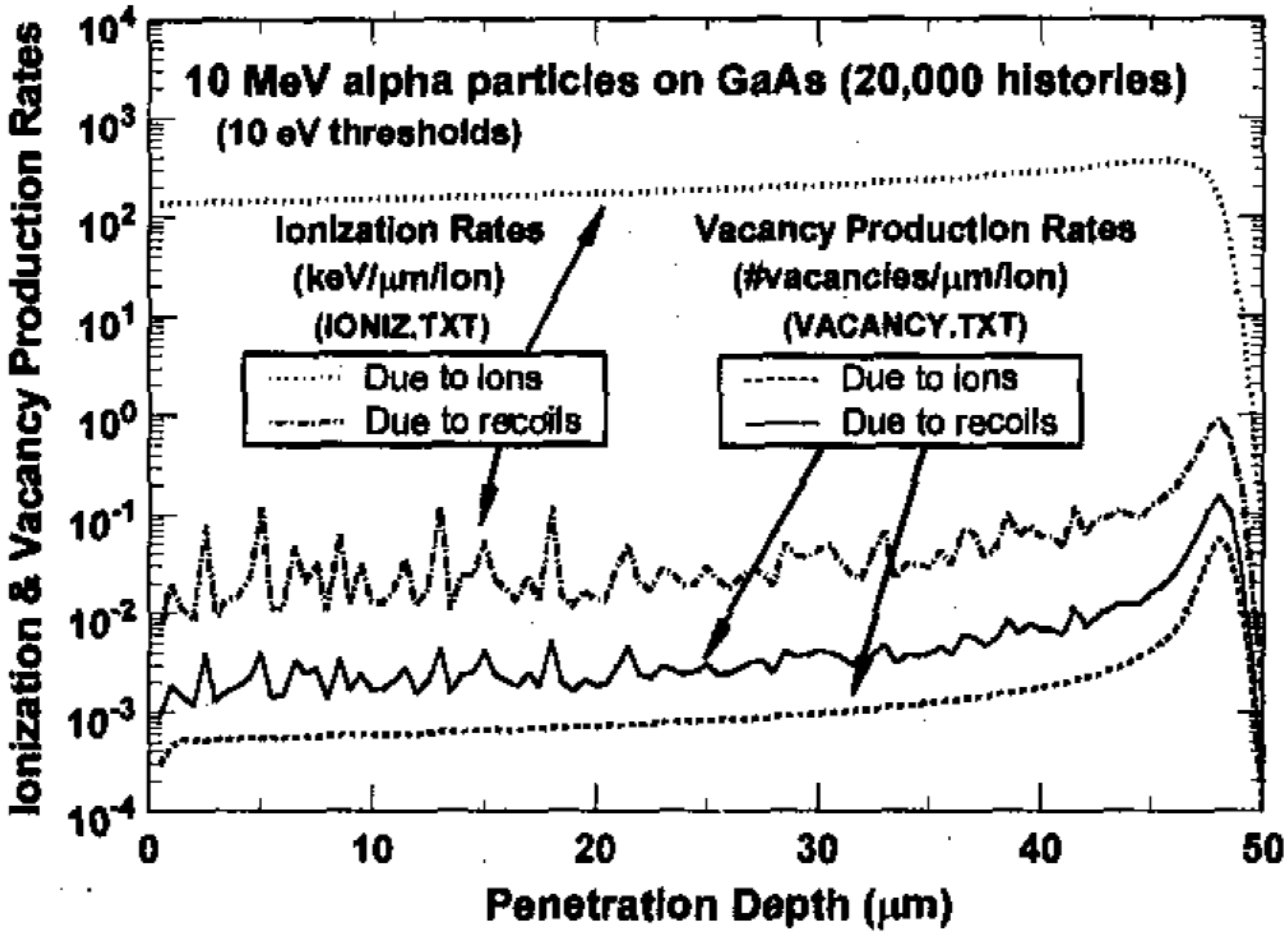
Modeling: universal damage factor K_{dark}

Universal damage factor K_{dark}: "increase in thermal generation rate per unit deposited displacement damage dose." - Srour & Lo, *TNS* 47, 2000



K_{dark} × NIEL vs NIEL, After Srour and Lo, *TNS* 47, 2000

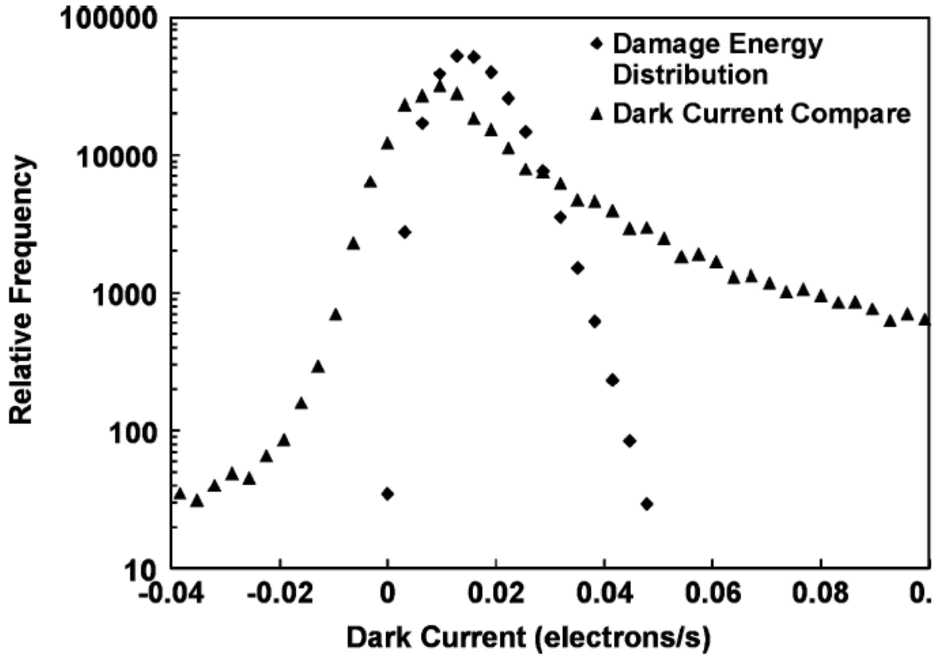
Modeling: SRIM



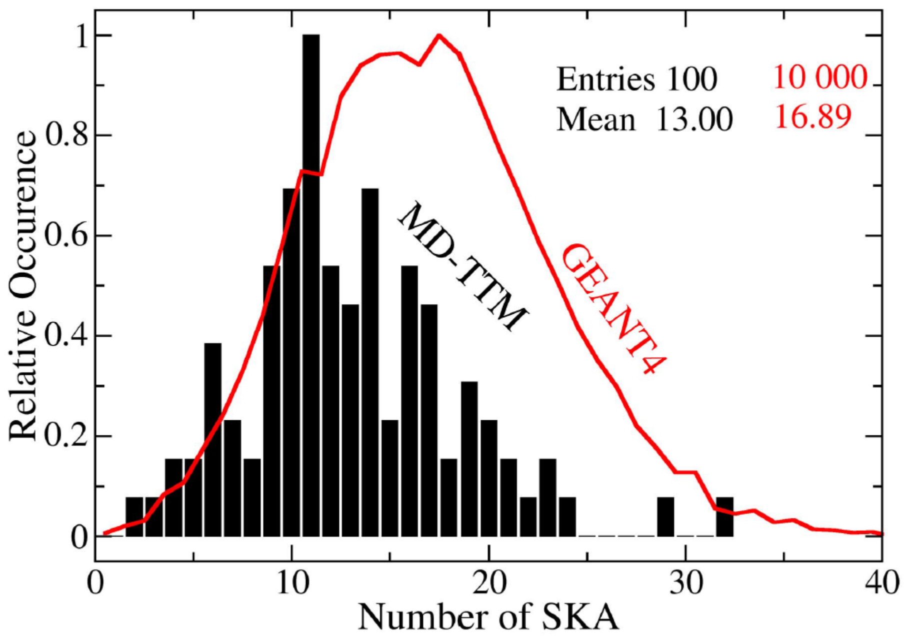
SRIM simulations of vacancies caused by incident ions and recoil ions vs. depth (ionization vs. depth also shown)
After Messenger et al., *TNS 46*, 1999

Modeling: Geant4 / MRED

Geant4 and MRED (a Geant4-based package) provide Monte Carlo simulations of nonionizing energy deposition using the binary collision approximation (BCA).



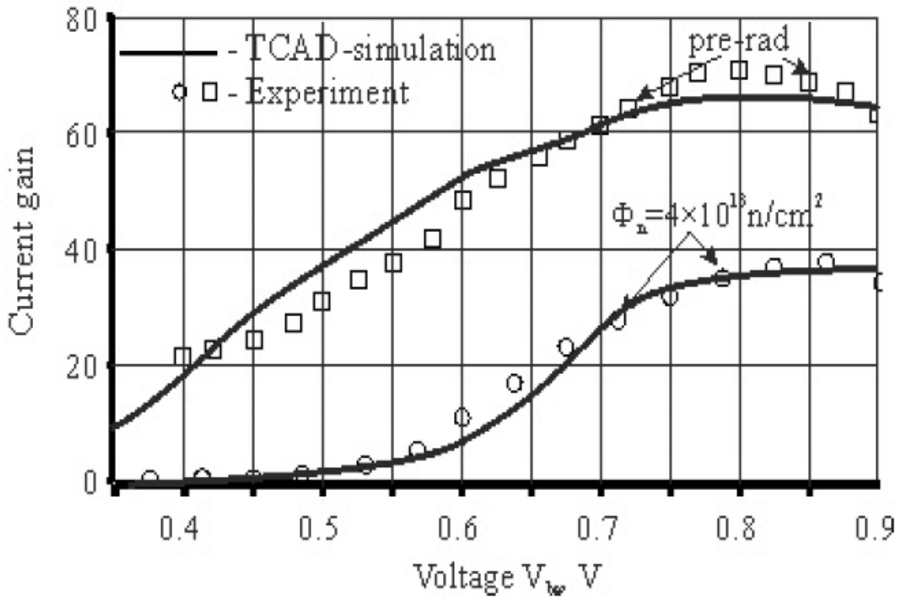
Histogram of dark current in pixels (measured, simulated with MRED)
After Marshall et al., *TNS* 54, 2007



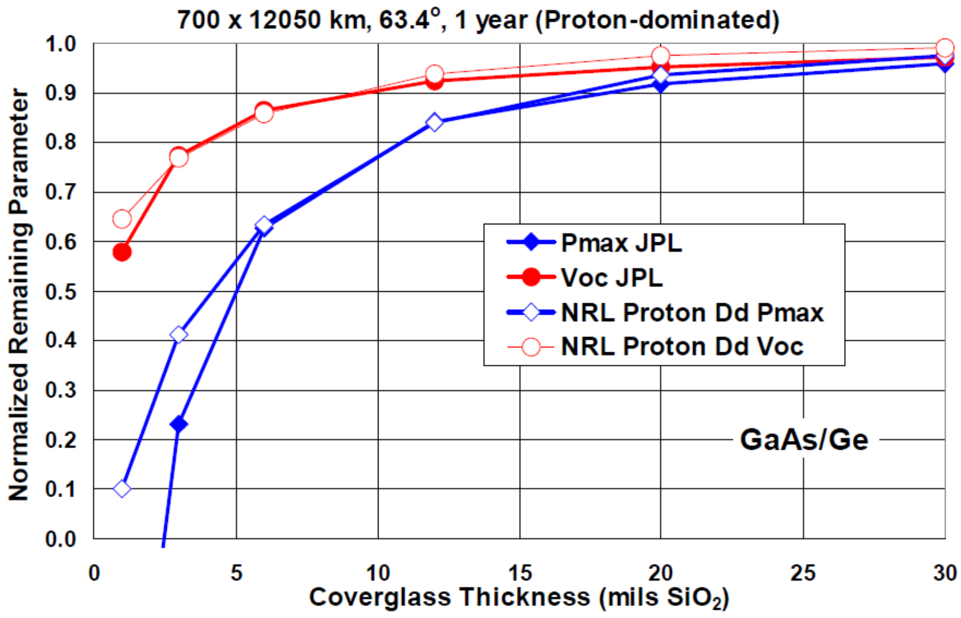
Histogram of secondary knock-on atoms (SKA) (simulated with MRED)
After Jay et al., *TNS* 64, 2017

Modeling: other tools

TCAD, SPENVIS's SCREAM code, and JPL's equivalent fluence method are modeling techniques that can incorporate the effects of displacement damage variables such as minority carrier lifetime and displacement damage dose.

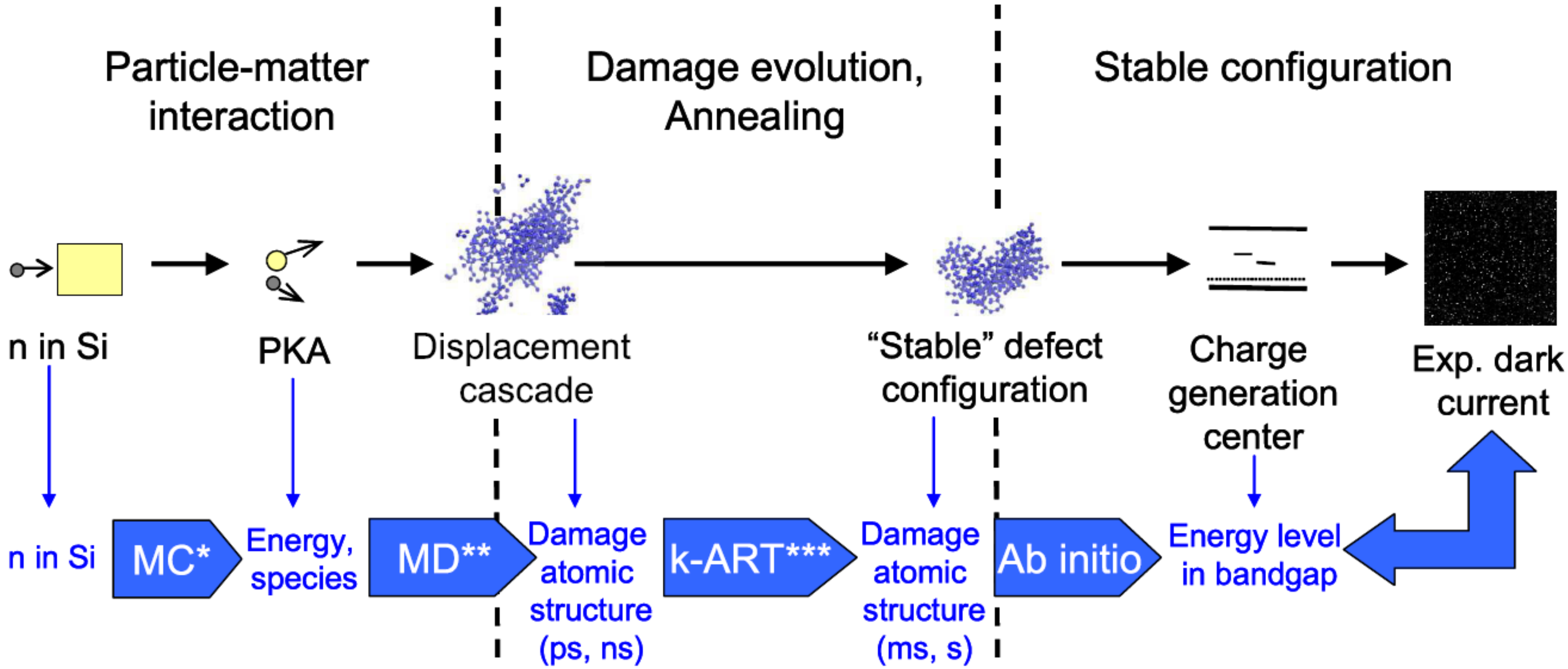


TCAD simulations and measurements of gain degradation in irradiated Si BJT
After Petrosyants, Kozhukhov, and Popov, *S&T* 227, 2018



Comparison of solar cell degradation calculated by JPL's equivalent fluence model and NRL SPENVIS team's SCREAM code
After Messenger et al., Photovoltaic Specialists 2010

Current research: Monte Carlo + molecular dynamics



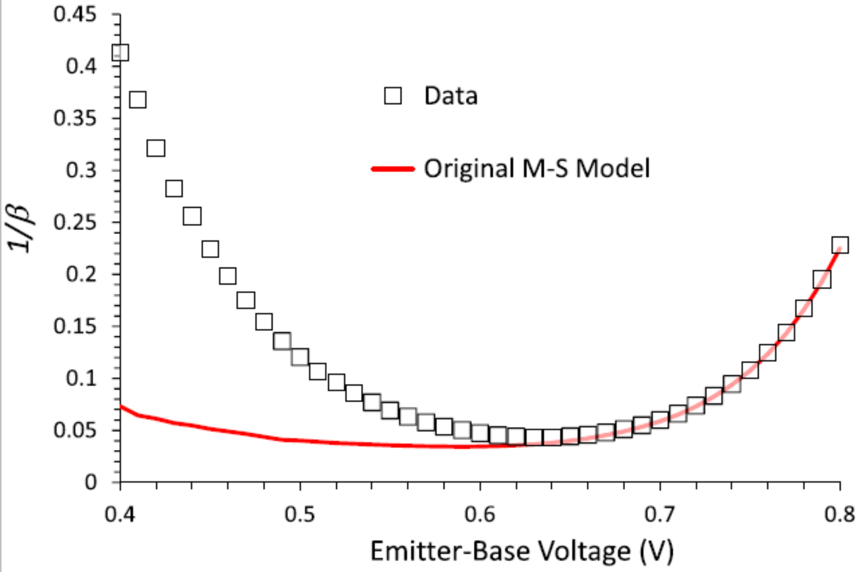
*MC = Monte Carlo (Binary Collision Approximation)
**MD = Molecular Dynamics
***k-ART = Kinetic Activation-Relaxation Technique

Simulation approach for modeling single particle displacement damage in silicon
After Raine et al., *TNS* 64, 2017

Current research: gain degradation in small BJTs

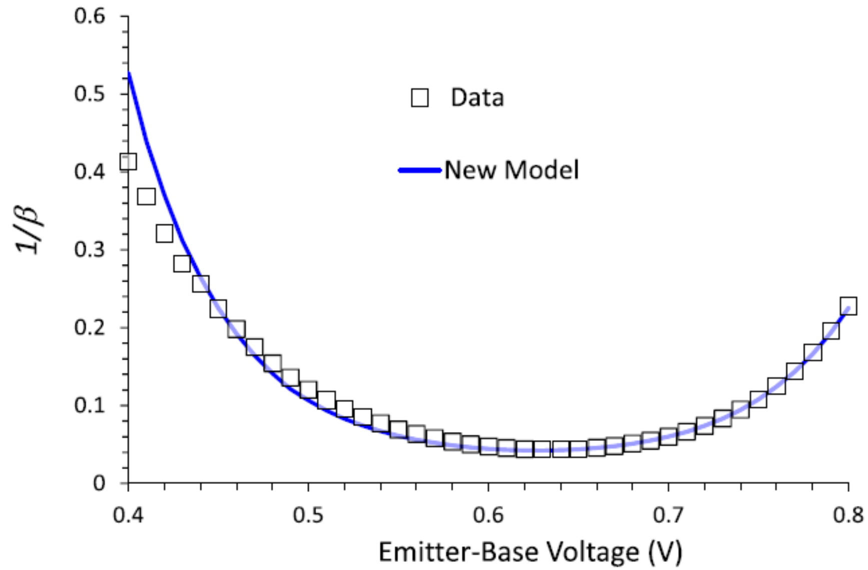
Degradation model only considers increase in base current

$$\frac{1}{\beta} = \frac{1}{\beta_0} + \frac{\Delta I_{B3}}{I_{C0}} = \frac{1}{\beta_0} + K_1' W_B^2 \Phi_p$$



Degradation model also considers base-emitter depletion region recombination

$$\frac{1}{\beta} == \frac{1}{\beta_0} + K_1' \left[W_B^2 + W_D W_B \frac{N_B}{n_i} \exp\left(-\frac{V_{EB}}{2V_T}\right)\right] \Phi_p$$



Measured BJT gain degradation vs original Messenger-Spratt equation (left) and modified Messenger-Spratt equation (right)

After Barnaby et al., *TNS* 64, 2017

Conclusions

- Displacement damage is a cumulative effect that degrades electrical performance through atomic displacements.
- Atomic displacements that result in stable defects reduce electron and hole mobility.
- Particles that result in atomic displacement include heavy and light ions, protons and deuterons, neutrons, electrons, gamma rays, and pions.
- Susceptible parts include diodes, BJTs, solar cells, pixels, and MOSFETs.
- Displacement damage can be estimated through NIEL calculations and modeling Frenkel pair generation. Work is on-going to link Monte Carlo simulations with molecular dynamics to quantify predicted electrical degradation from knowledge of incident particle energy and species.