Scuola Nazionale SIRAD
Legnaro, 6/4/2005

# EFFETTI DA EVENTO SINGOLO (SEE): UN’INTRODUZIONE

**Alessandro Paccagnella**

paccag@dei.unipd.it

DIPARTIMENTO DI INGEGNERIA
DELL’INFORMAZIONE – Universitá di Padova
via Gradenigo 6B, 35131 Padova, ITALY

# OUTLINE

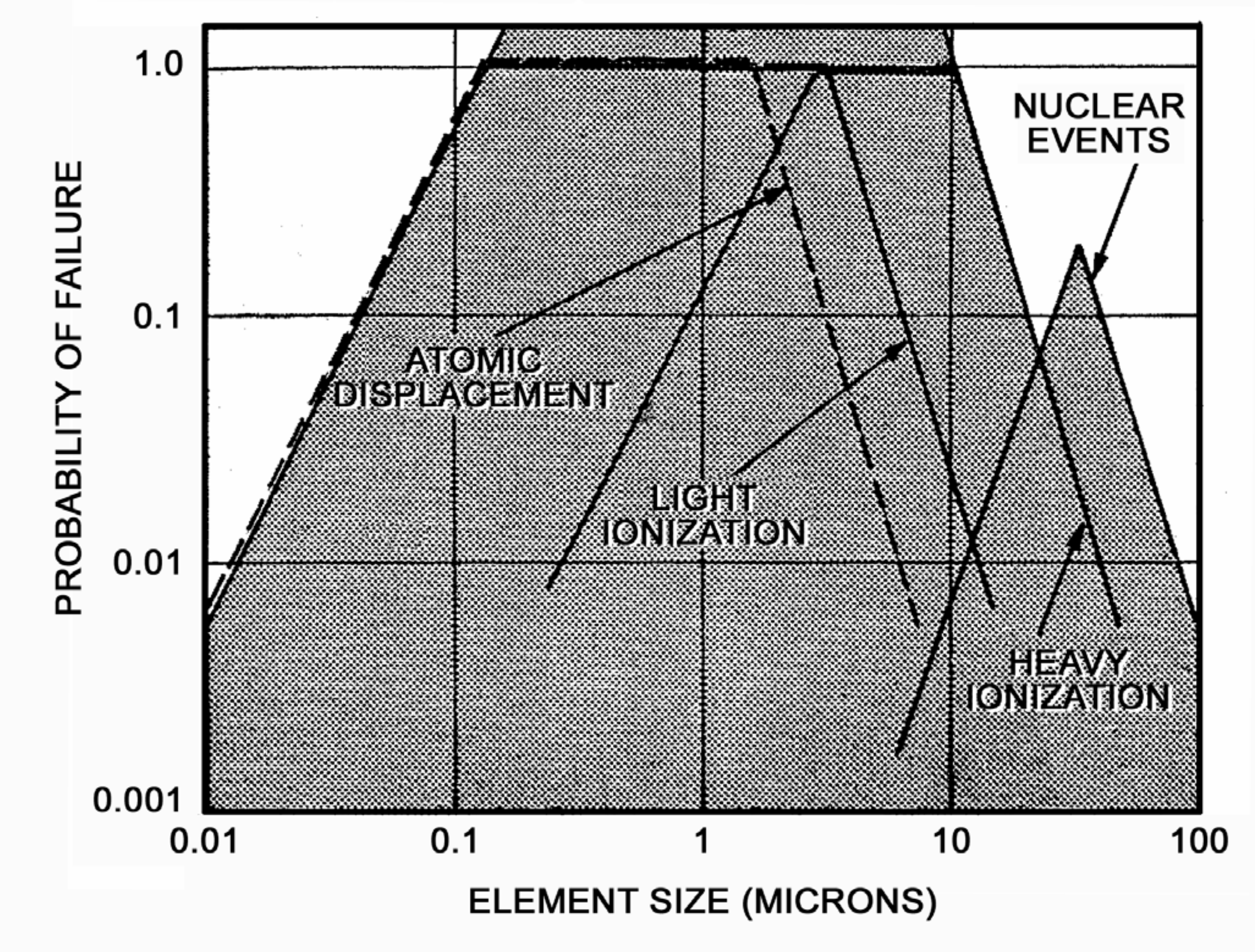
- Introduction
- Charge generation by an ionizing particle in Si and $SiO_2$
  - LET
  - Collection mechanisms
  - Recombination
  - Simulations
- Single Event Effects
  - Sources
  - Classification
  - Cross section
- Conclusions

# News reports

- **Single Event Effect (SEE)**: perturbation of the behavior of electronic (optoelectronic) devices, circuits and/or systems produced by a single ionizing particle

- *“SRAM soft errors cause hard network problems”*
  Anthony Cataldo 08/17/2001
- *“Soft errors a problem as SRAM geometries shrink”* Jeanne Graham 01/28/2002
- *“Strategy for reducing soft errors is needed”* Mark-Eric Jones, 8/27/ 2002

# Early warning of SEE's at sea level



*J.T. Wallmark and S.M. Marcus, Proc IRE, 1962*

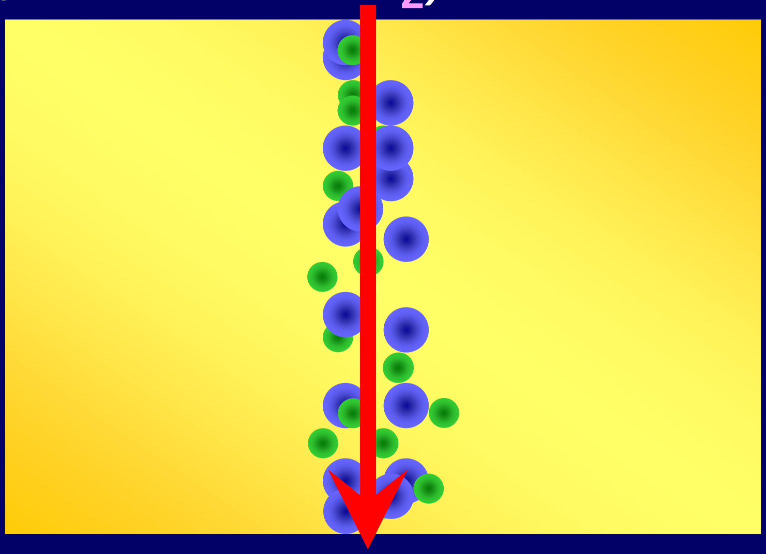
# Charge generation

- An ionizing particle generates a (dense) track of electron-hole pairs in semiconductors **(Silicon)** and dielectrics **($SiO_2$)**
- The number of generated carriers is proportional to the particle **Linear Energy Transfer (LET)** coefficient ($MeVcm^2/mg$), i.e., the energy loss/unit path length (Energy / e-h pair: **3.6 eV in Si**, **17 eV in $SiO_2$**)

Ion track

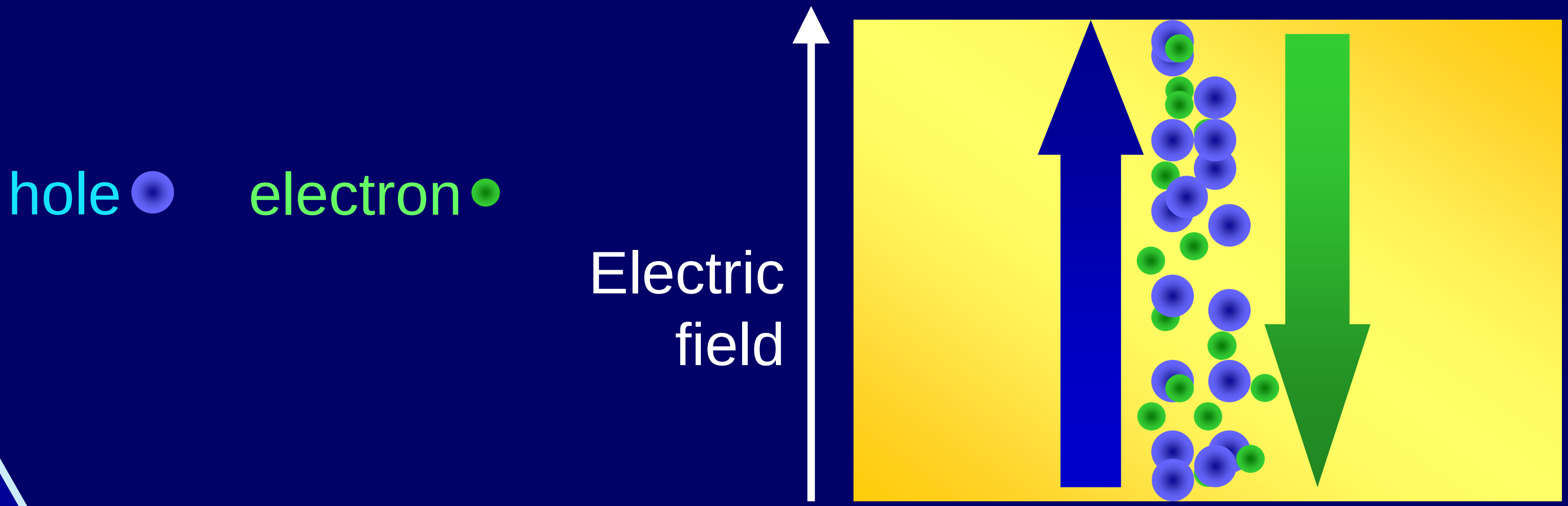
hole ●

electron ●

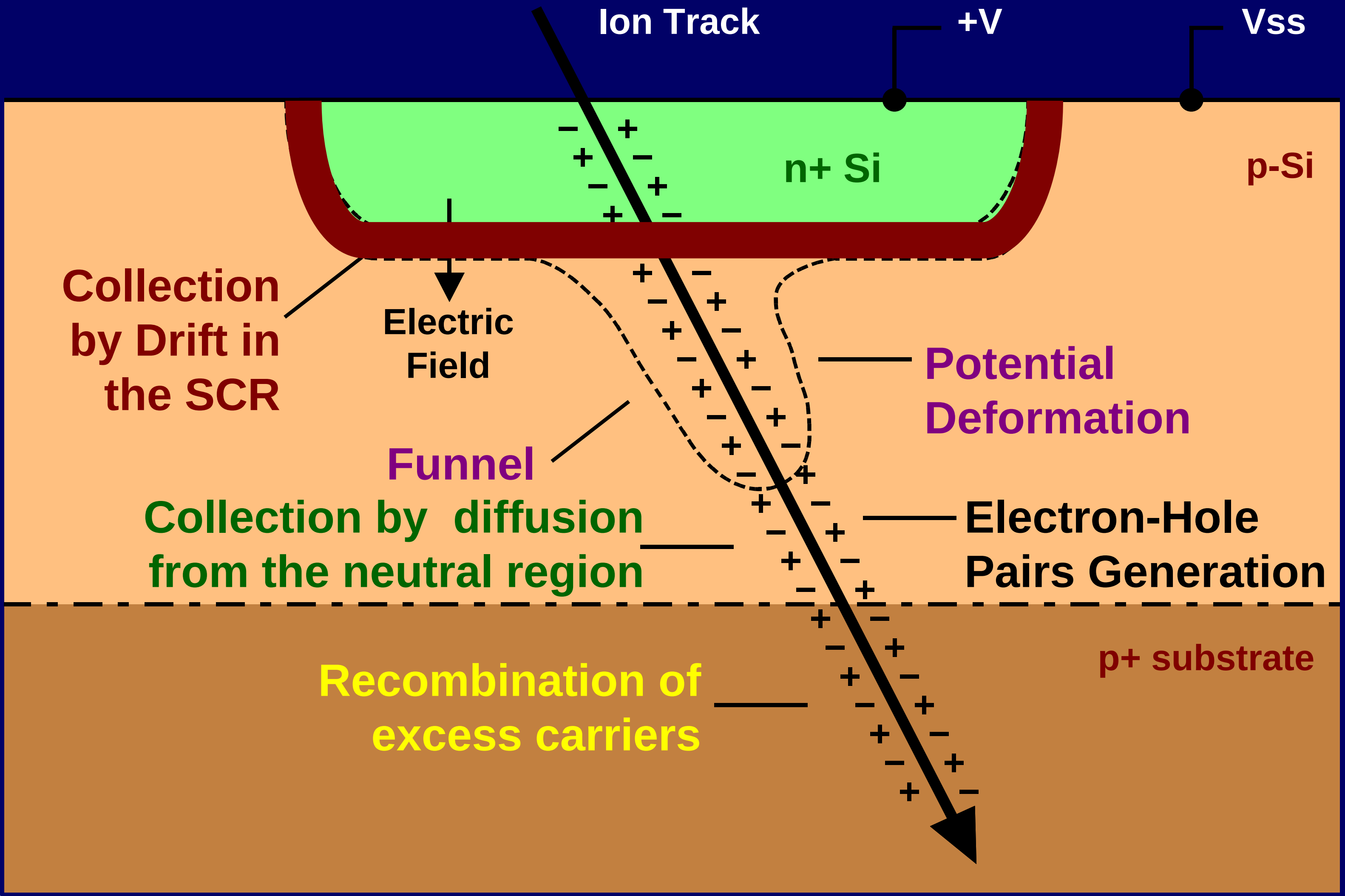


# Charge generation and collection

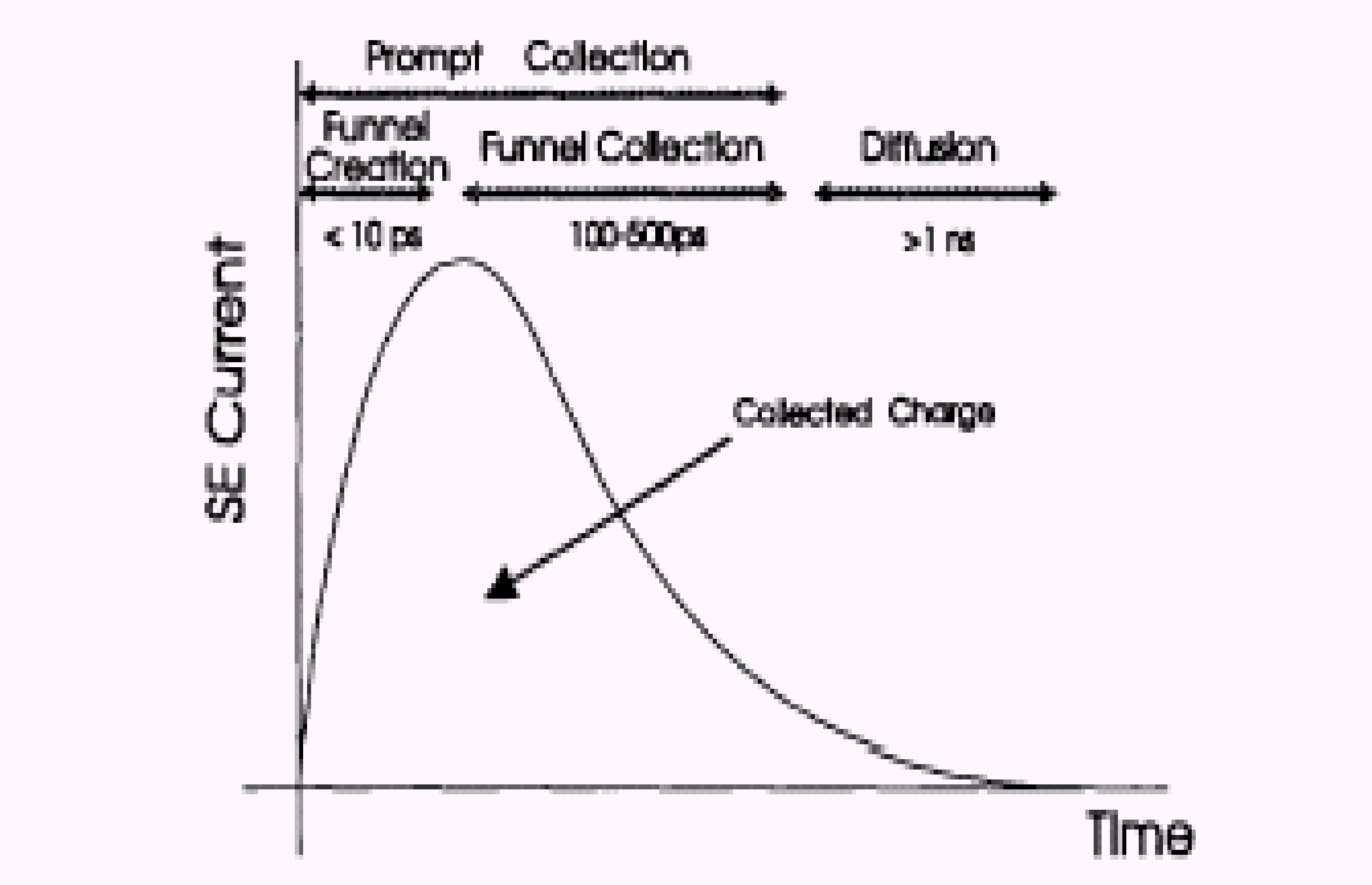
- Under an external electric field the two columns of carriers recombine and drift: many electrons and holes survive in Si, fewer in $SiO_2$
- Eventually, a net negative/positive charge can be collected at sensitive nodes



# Charge collection in a reverse biased p-n junction



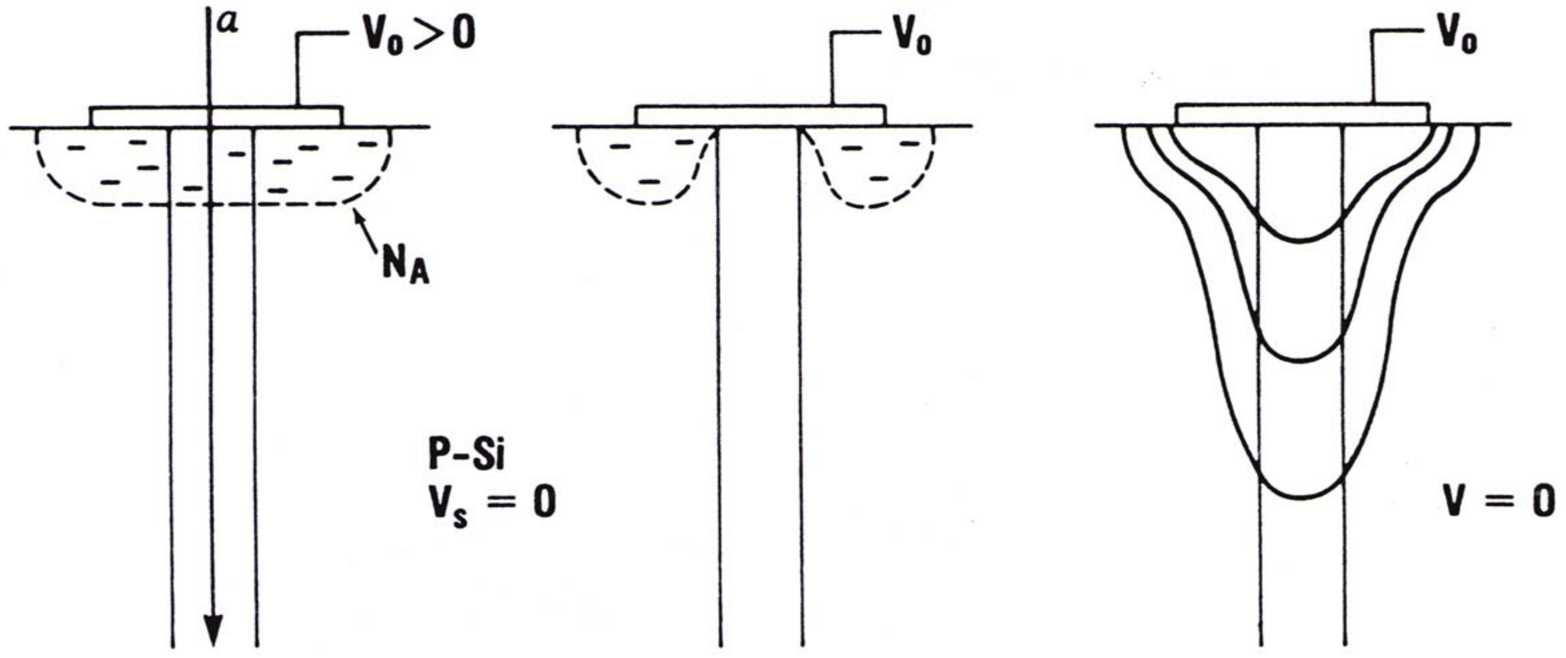
# Time evolution of charge collection



*T. Oldham, NSREC Short Course, 2003*

- The classical view: three stages of charge collection: **drift, funneling, diffusion**
- However, contacts are too small to sustain funneling in highly scaled CMOS…
- …and highly doped buried layers (retrograde wells) reduce charge diffusion

# Charge funneling mechanism



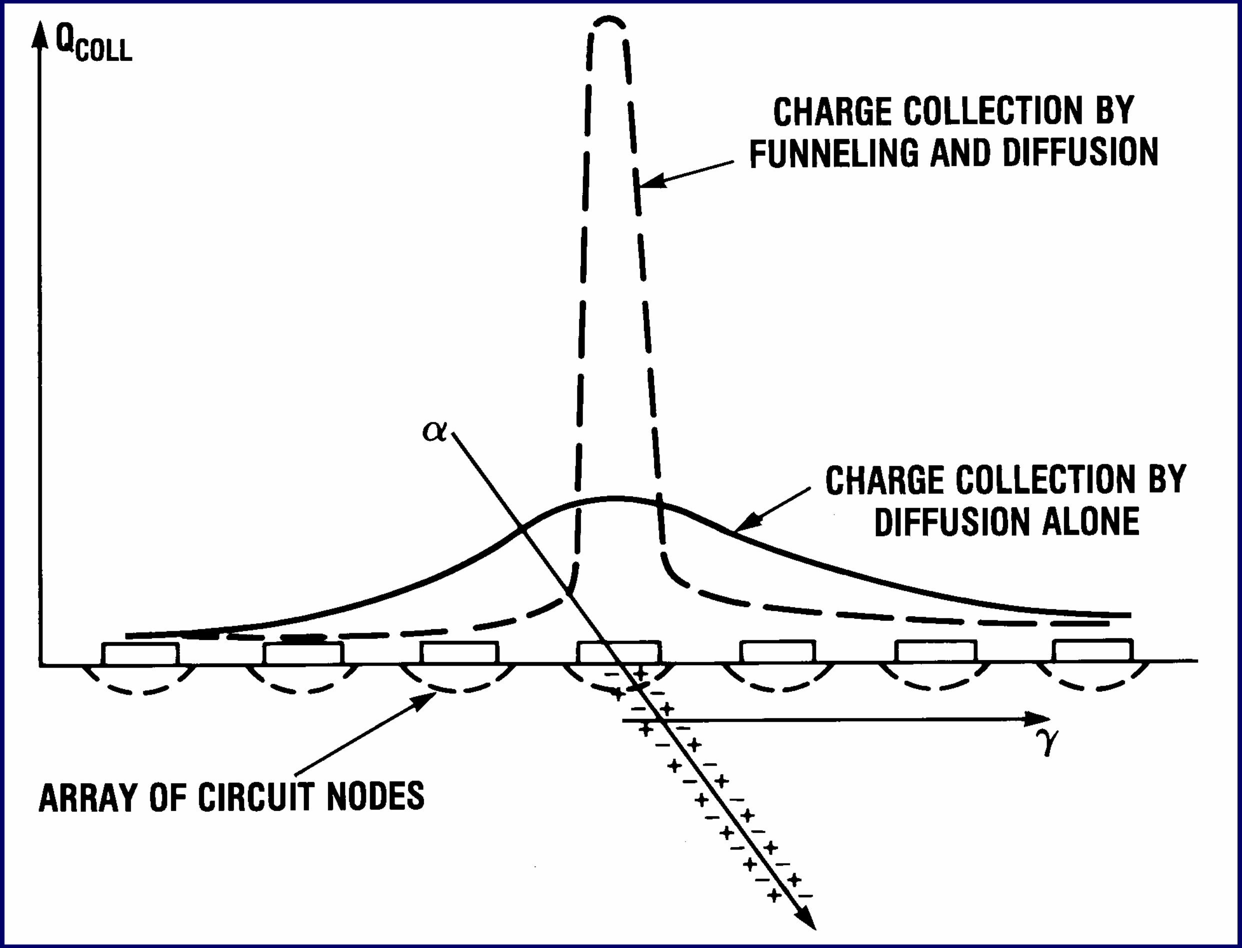
(a) a - PARTICLE STRIKE
($t = 0$)
$n = P >> N_A$

(b) JUNCTION DEPLETION
LAYER NEUTRALIZED
($t > 0$)

(c) EQUIPOTENTIAL LINES
EXTENDED DOWN
ALONG TRACK

*F.B. McLean and T.R. Oldham, IEEE-TNS29, 1982*

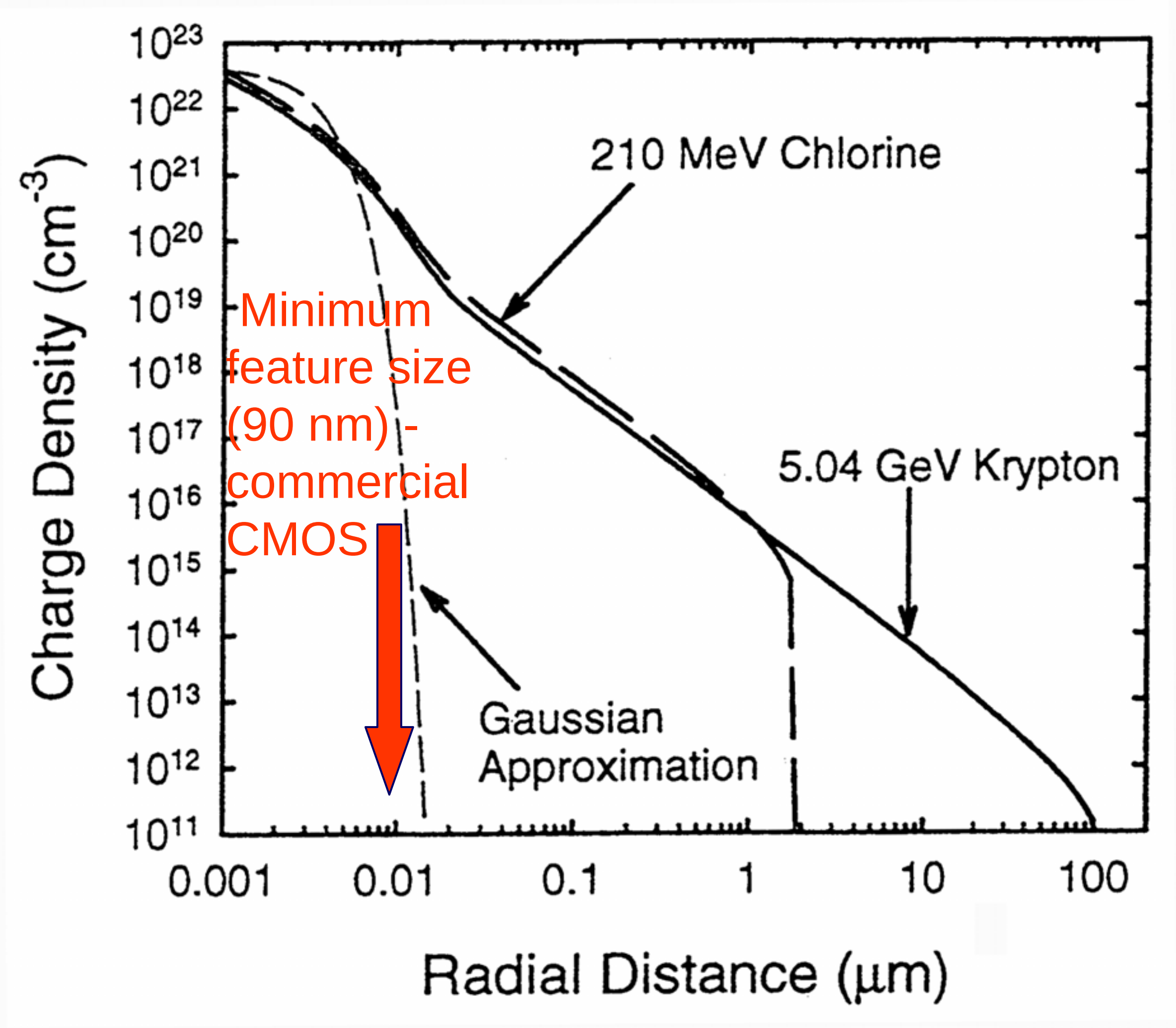
# Charge collection across circuits



- “Traditional” view of charge collection in Si circuits fabricated with relaxed CMOS technologies
- Only particles at low impact angles may affect different devices, if diffusion charge collection is excluded

*T. Oldham, NSREC Short Course, 2003*

# Calculated e-h track structure in Si

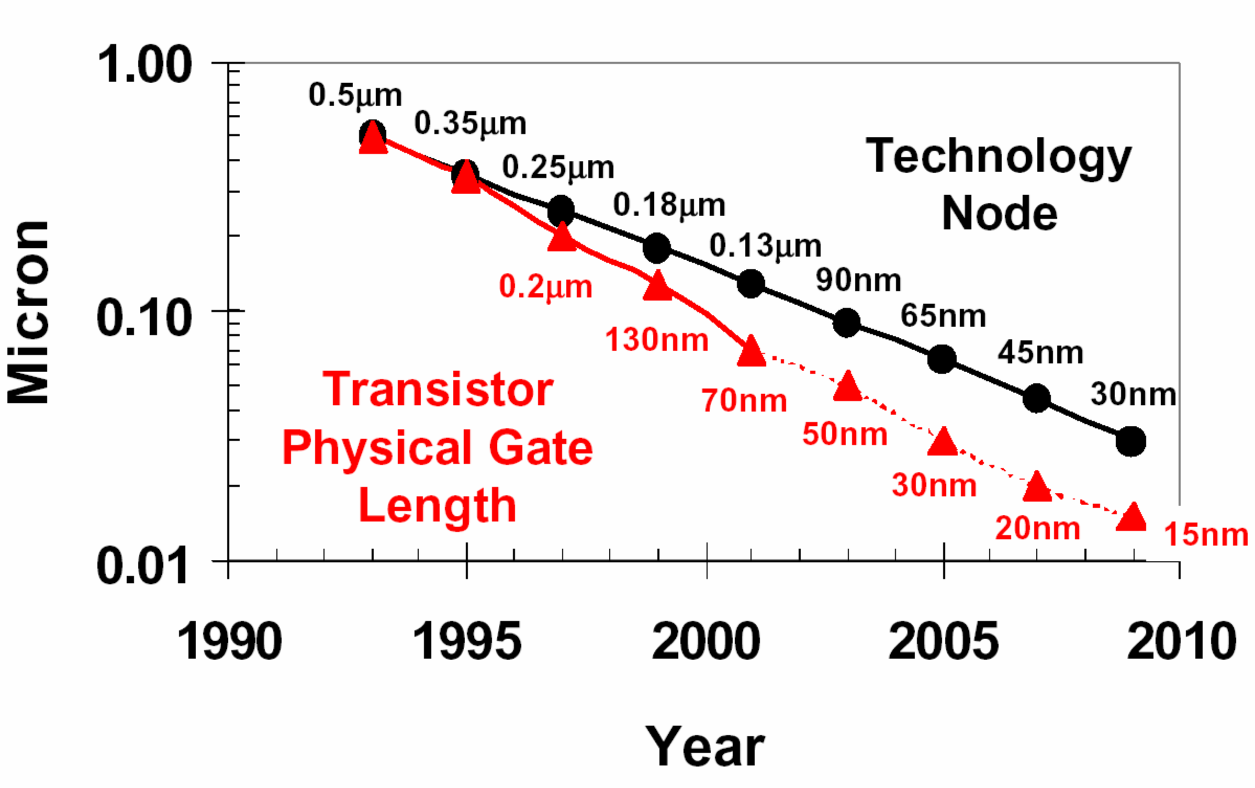


Minimum feature size (90 nm) - commercial CMOS

*P. Dodd, et al., IEEE-TNS45, 1998*

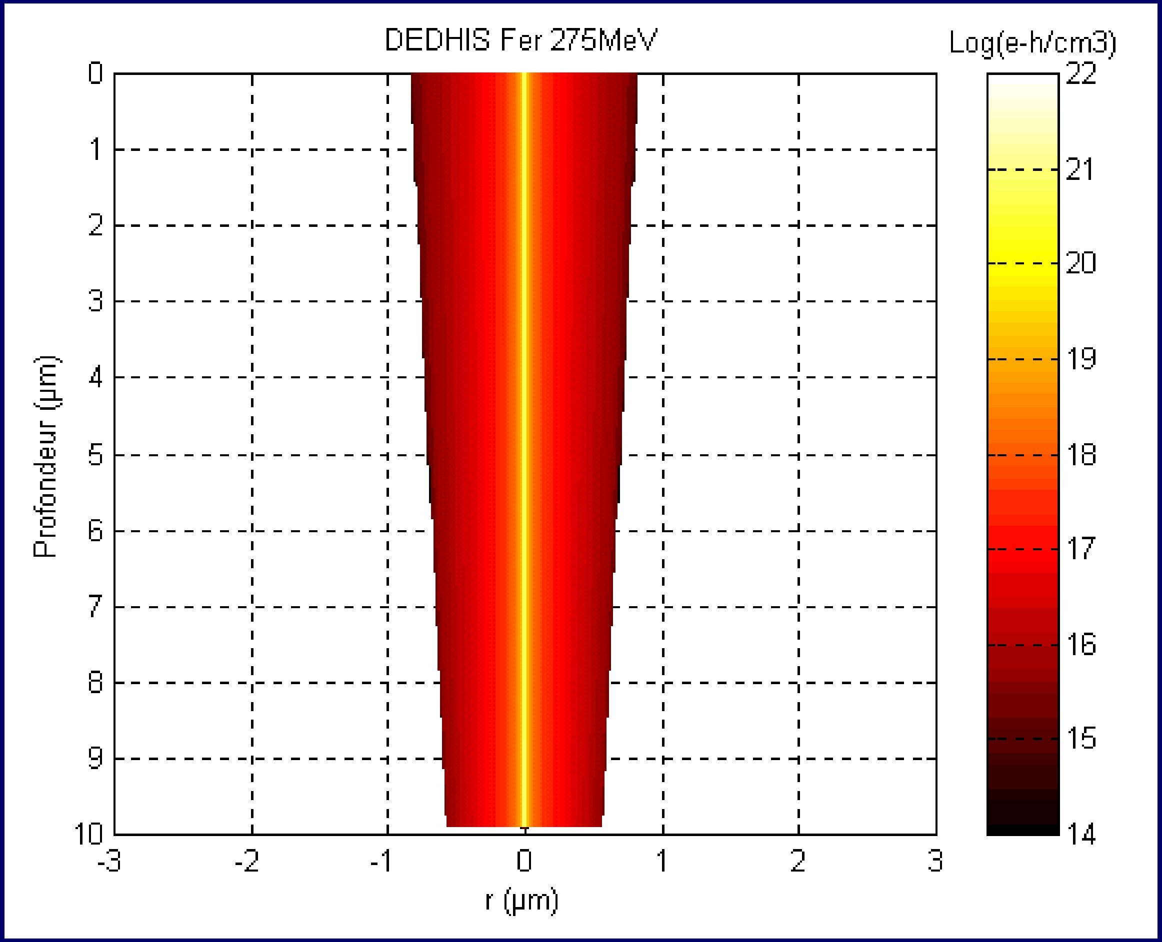
# Moore's Law

Moore's law is (self-)validated by reducing the device dimension over the years, by scaling down the minimum feature size of the CMOS technology node



*Source: INTEL*

# Simulated heavy ion e-h track in Si



Fe ions 275 MeV
LET=24 MeVcm$^2$/mg

LET metrics in Si:

1 MeVcm$^2$/mg

↓

6.4·10$^4$ e-h pairs/µm

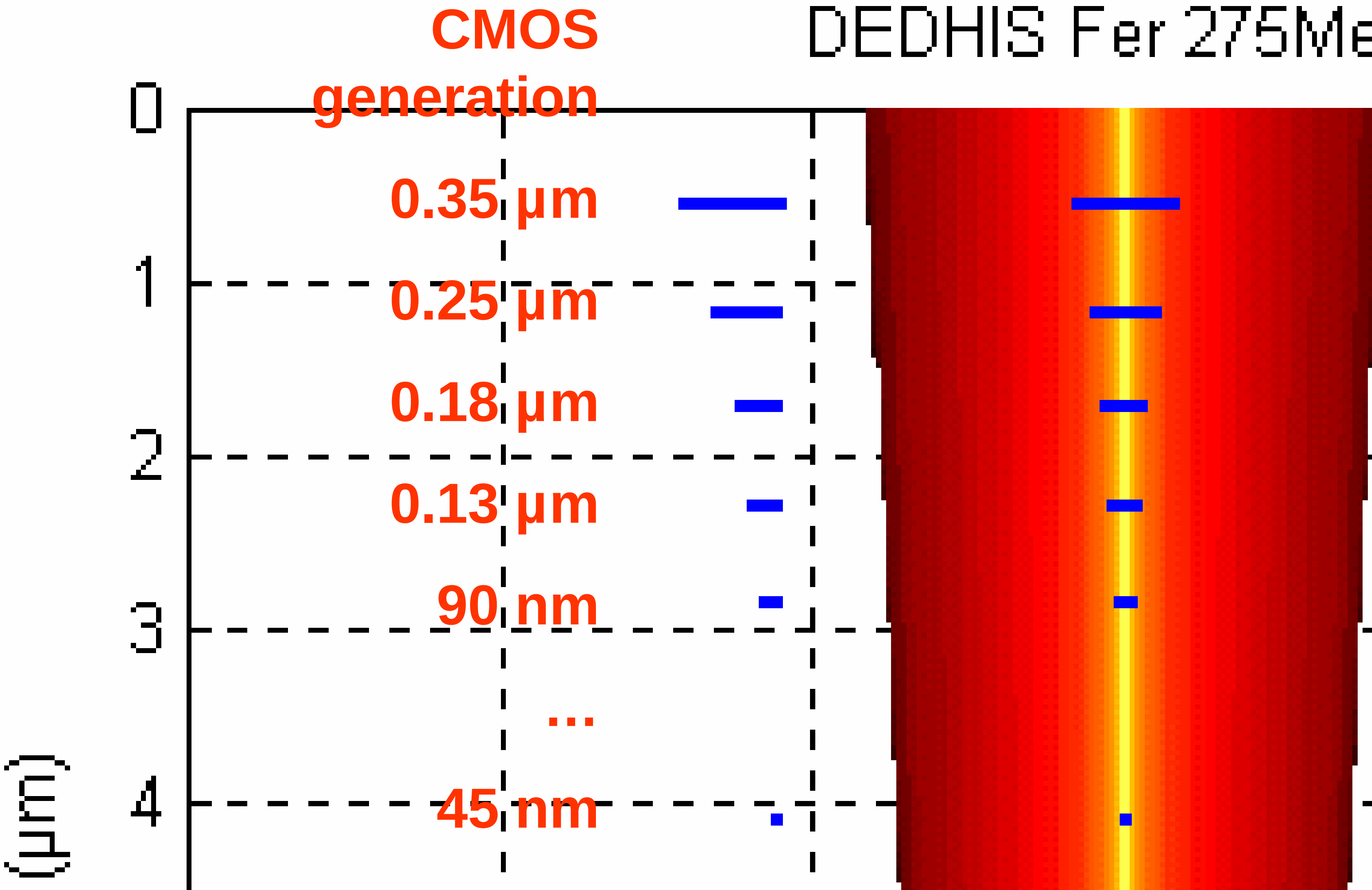
↓

10 fC/µm

Electron-Hole density (cm$^{-3}$)

*P. Foulliat, EWRHE 2004*

# Heavy ion e-h track in Si vs. CMOS minimum size



**CMOS generation**

**0.35 µm**

**0.25 µm**

**0.18 µm**

**0.13 µm**

**90 nm**

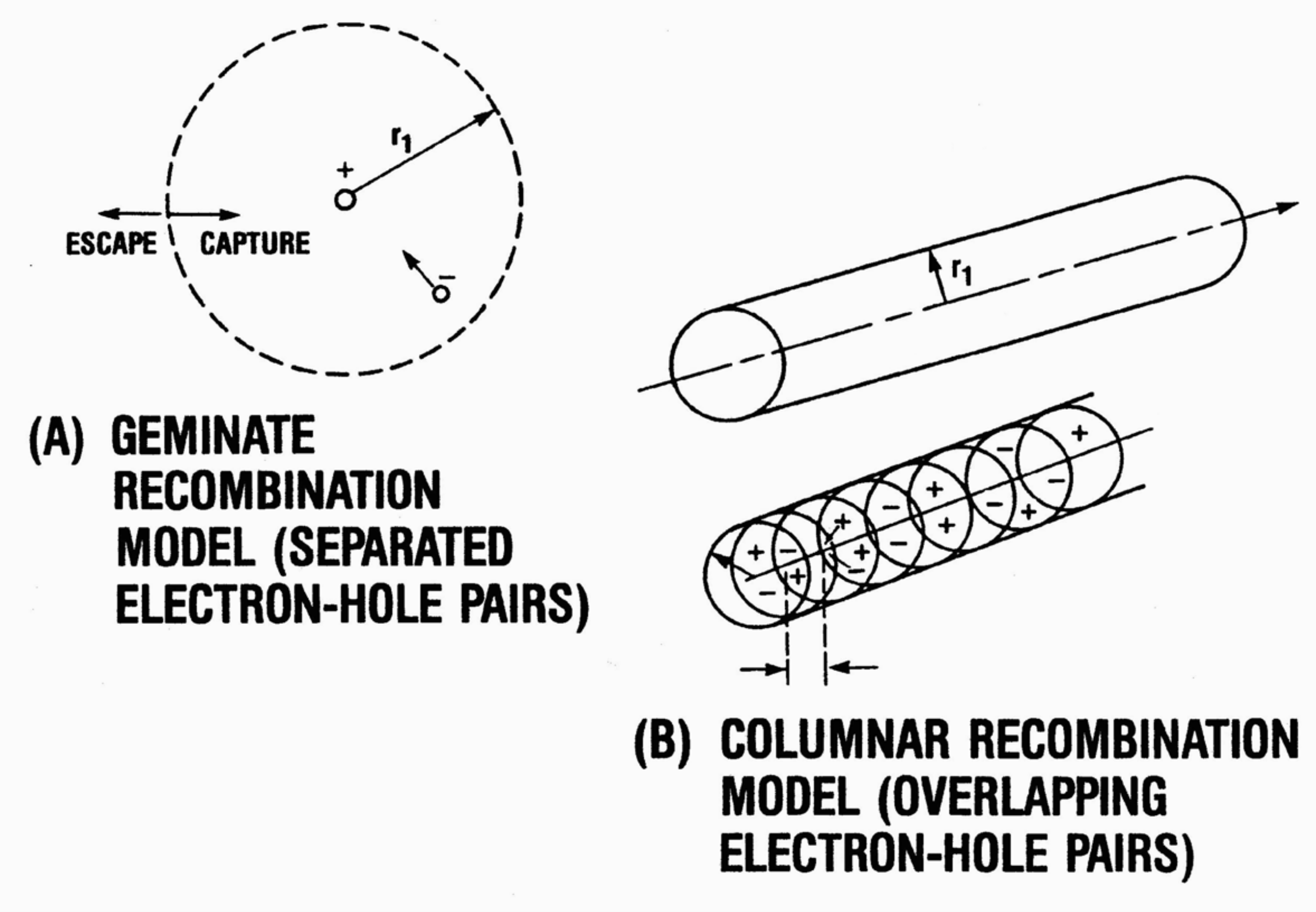
**…**

**45 nm**

# Ion e-h tracks in $SiO_2$

- Column radius smaller than in Si because of carrier energy loss due to optical phonons
- Gaussian distribution with b=3.5 nm usually assumed
- Fewer e-h pairs than in Si because of greater pair production energy (17 eV vs. 3.6 eV)
- Much greater recombination than in Si
- Detailed track structure calculations (similar to those presented for Si) not yet available
- Models available in literature developed in thick (>20 nm) oxides, not updated to current MOS gate oxides that are few nm's thick: for instance, $t_{ox}$=2.3 nm for the 0.13 µm CMOS technological node

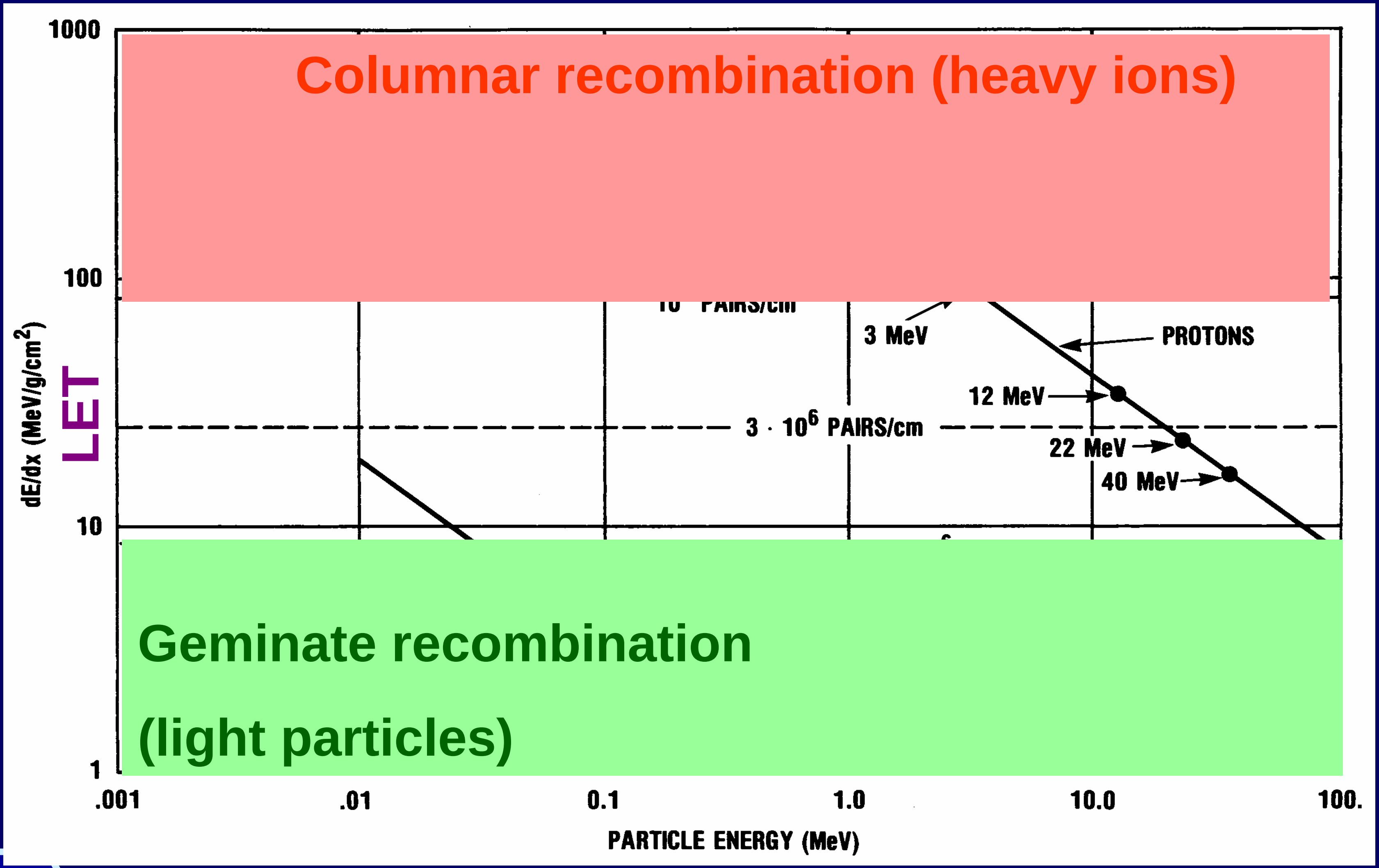
# Recombination models in $SiO_2$



**(A) GEMINATE RECOMBINATION MODEL (SEPARATED ELECTRON-HOLE PAIRS)**

**(B) COLUMNAR RECOMBINATION MODEL (OVERLAPPING ELECTRON-HOLE PAIRS)**

# LET in $SiO_2$ and recombination mechanisms



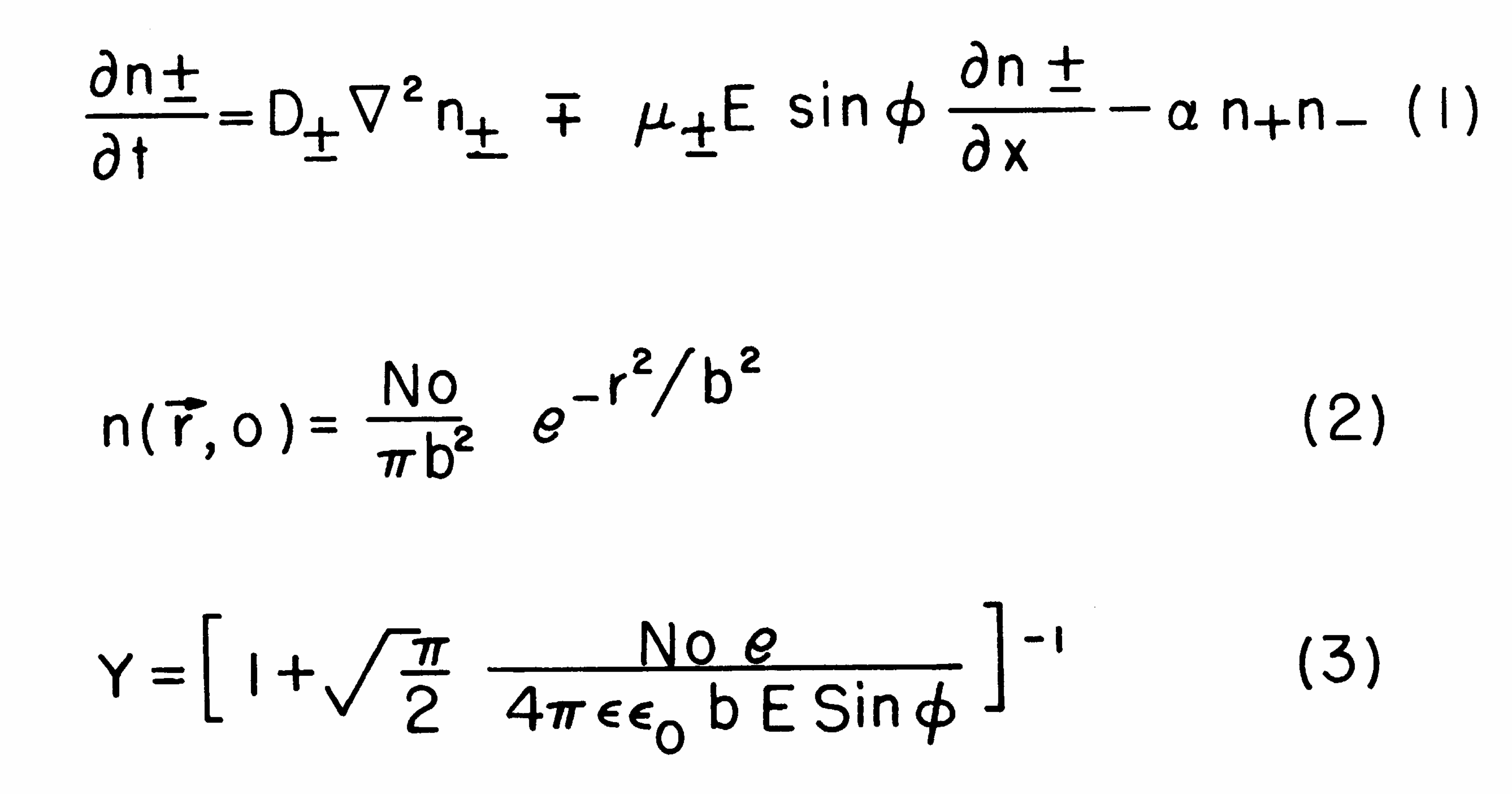
Columnar recombination (heavy ions)

Geminate recombination

(light particles)

*T. Oldham and J. McGarrity, IEEE-TNS30, 1983*

# Columnar recombination: a classical problem



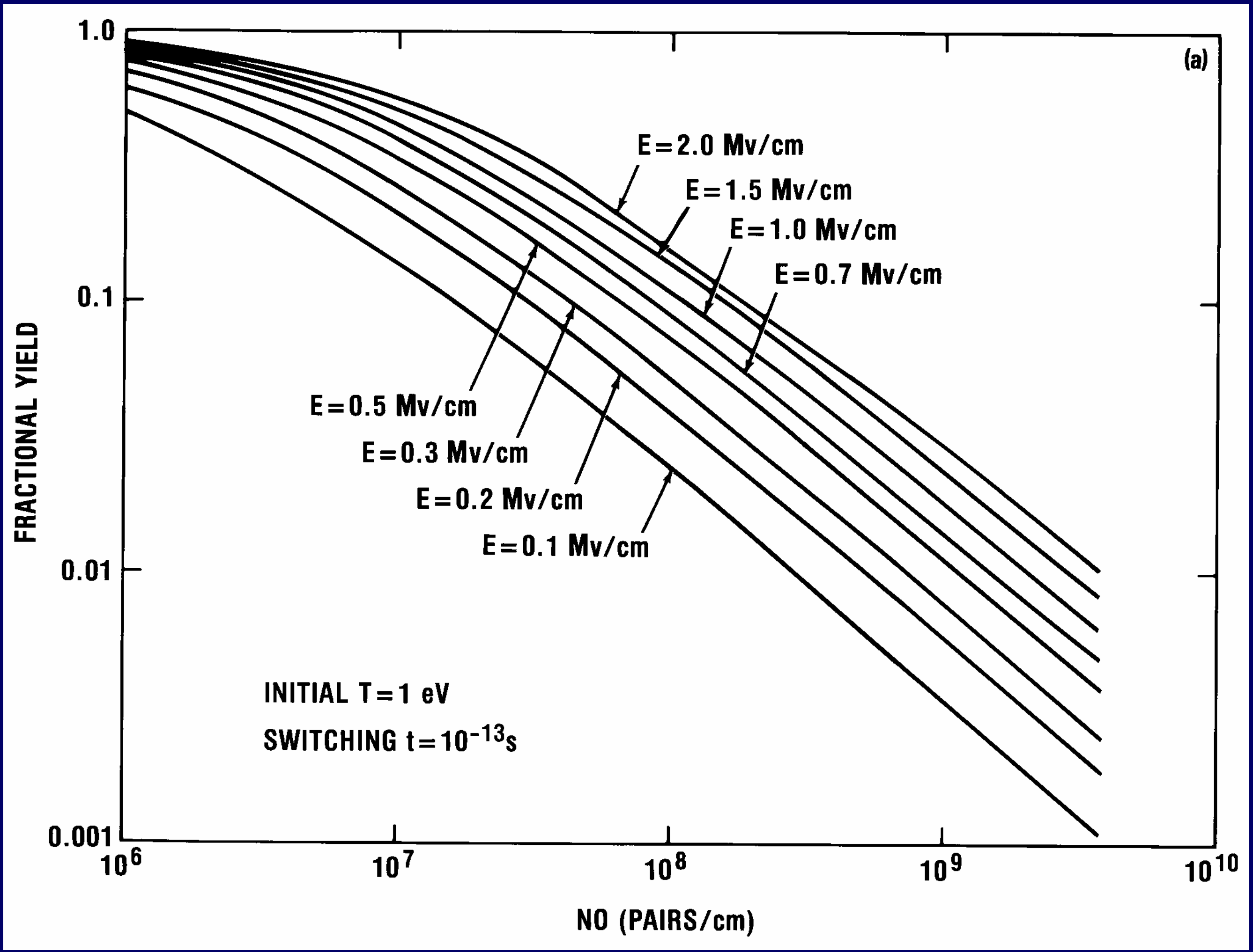
$$\frac{\partial n_\pm}{\partial t} = D_\pm \nabla^2 n_\pm \mp \mu_\pm E \sin\phi \frac{\partial n_\pm}{\partial x} - \alpha n_+ n_- \tag{1}$$

$$n(\vec{r},0) = \frac{N_0}{\pi b^2} e^{-r^2/b^2} \tag{2}$$

$$Y = \left[ 1 + \sqrt{\frac{\pi}{2}} \frac{N_0 e}{4\pi\epsilon\epsilon_0 b E \sin\phi} \right]^{-1} \tag{3}$$

*G. Jaffe, Ann. Phys., 1913*

# Calculated yield in thick oxides



- In $SiO_2$: 1MeVcm$^2$/mg

$1.3 \cdot 10^4$ e-h pairs/µm

- For heavy ions the percentage of carriers surviving recombination (**yield**) may be as low as 0.1%

*T. Oldham, J. Appl. Phys. 87, 1985*

# Charge transport in $SiO_2$

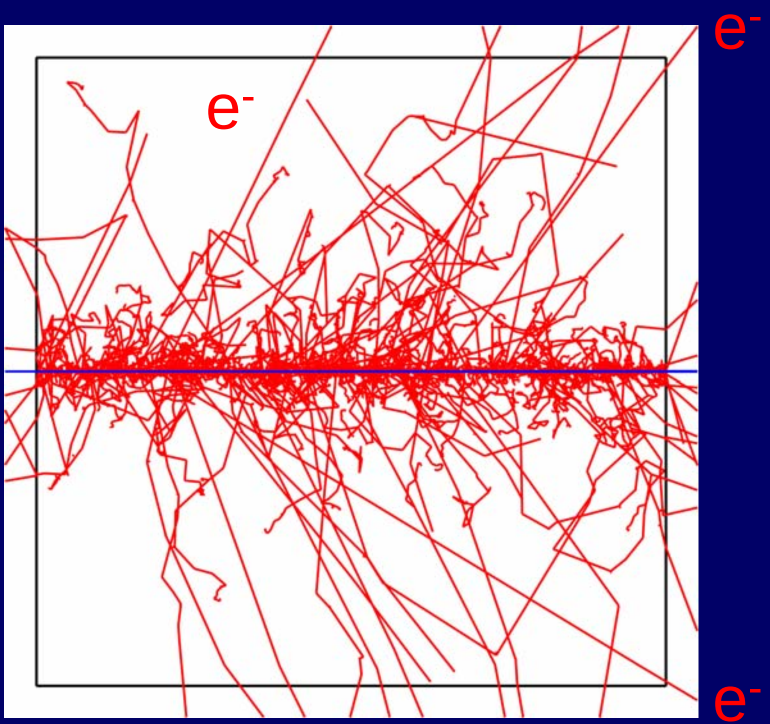
- In thick oxides (>20 nm), after the first generation-recombination phase the surviving electrons are rapidly swept out by an external electric field
- The remaining holes moves slowly in $SiO_2$ via hopping transport (*dispersive transport*) under the effect of an external electric field, eventually reaching the cathodic interface with Si where they can be trapped at local defects
- In thin gate oxides (few nm's) both electrons and holes may rapidly escape from the oxide in short time (ps)
- Charge transport in gate/field oxides is usually considered to be not effective in promoting SEE's, but things may change in CMOS technologies with thin dielectrics…

# Myth of the average event

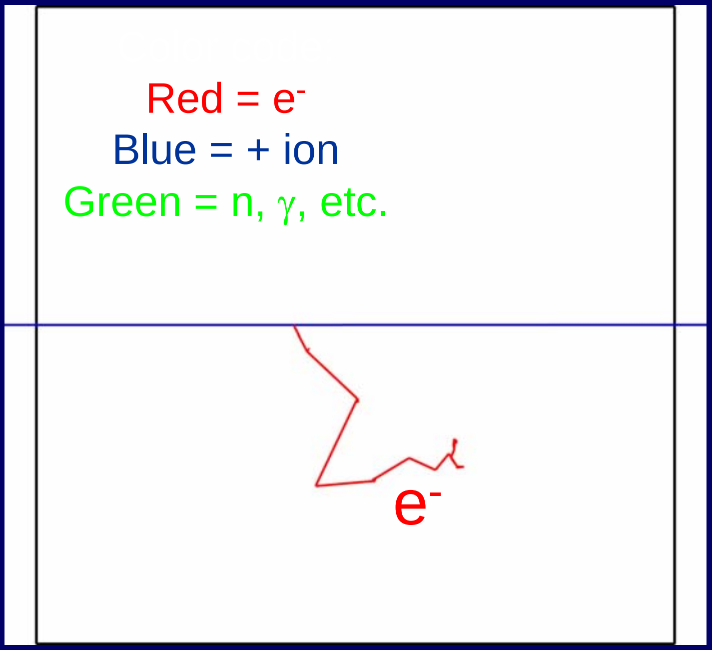
- Simulation of Single Event Effects may start from the analysis of the impact of a single particle on a single device, i.e., a MOSFET
- Deviating behaviors may occur (“*Myth of the average event*”)!

100 MeV p on Si

*R. Schrimpf, EWRHE 2004*



Average: Track with apparent radial structure, $\Delta E \approx 1$ keV

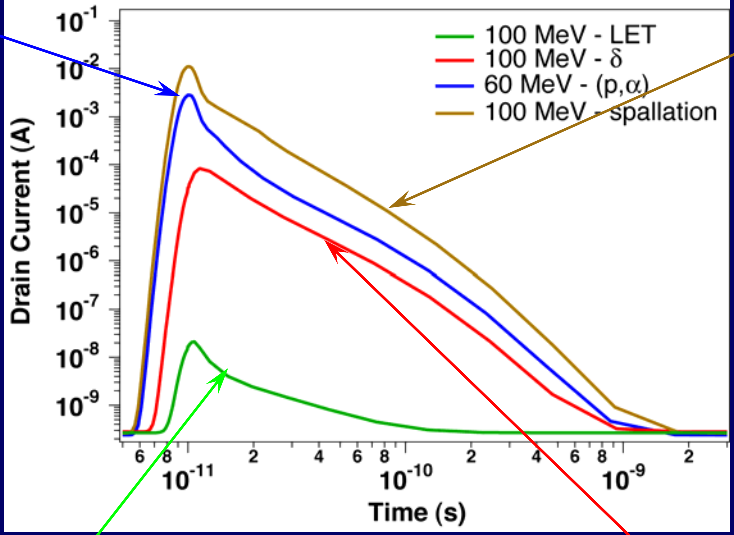


Single event: Proton + $\delta$-ray $\Delta E = 7.8$ keV

# Simulation of a MOSFET response

*R. Schrimpf,*
*EWRHE*
*2004*

(p,α)



Spallation

LET

δ

Drain current versus time for various events

# Current interests in SEE's

- Single event effects (SEE) on electronic devices are produced by a single ionizing particle, such as alpha's from radioactive decay or cosmic rays
- Historically, this problem has been faced by institutions coping with radiation harsh environments:

Space/defense/high energy physics/nuclear power/…
(NASA, ESA, Sandia, CERN, Fermilab, CEA,...)

↓

Avionic (Boeing, Lockheed, …)

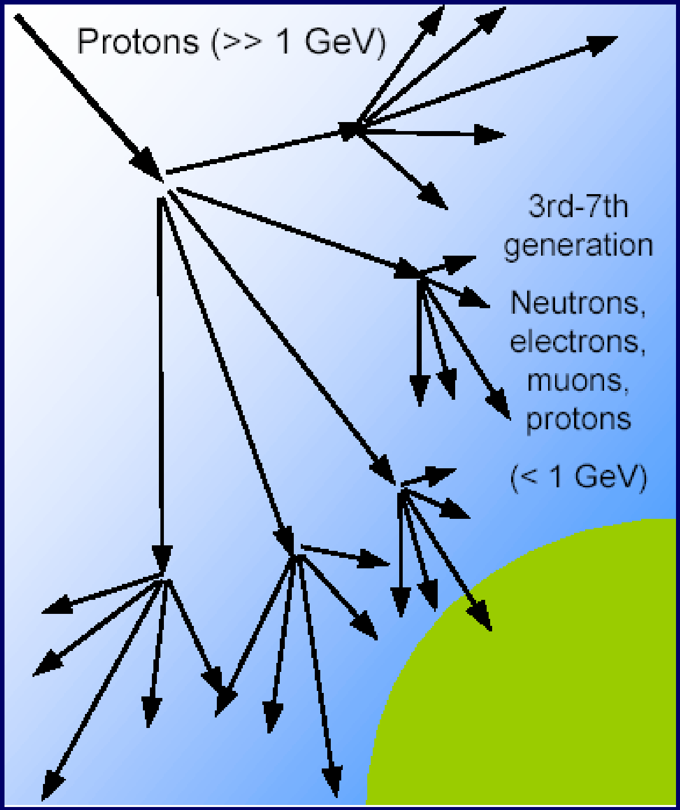
- More recently the SEE issue has been seriously investigated for its reliability implications even at sea level in everyday life by:
  - Semiconductor *companies*: IBM (since'80s), Intel, STMicroelectronics, TI, Infineon,…
  - Semiconductor IC *customers*: less prone to show their interest

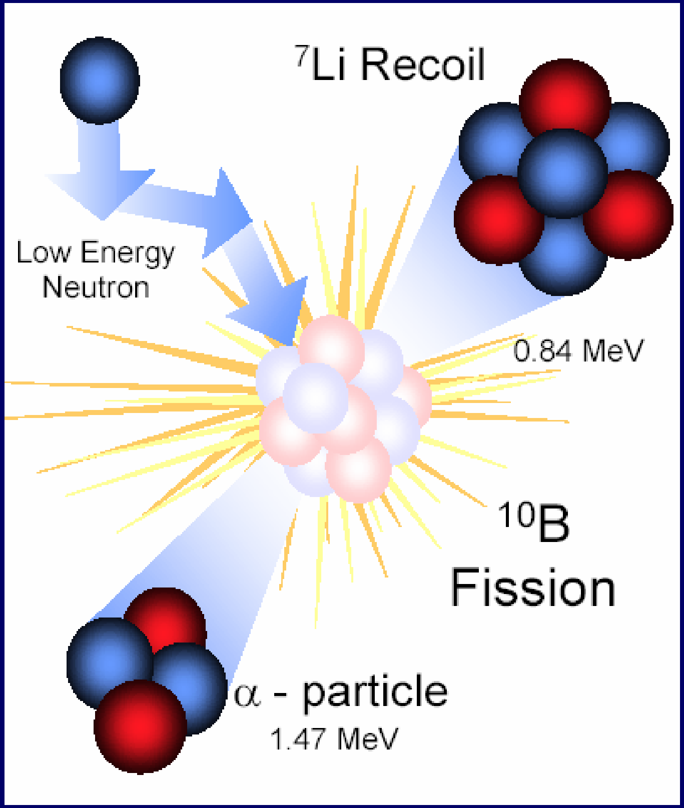
# Sources of Single Event Effects

- Space applications:
  - – High-energy heavy ions
    - Long range in Si, large LET, direct interaction
  - – High-energy protons (trapped, solar, cosmic)
    - Direct / Indirect interaction through nuclear reactions
- Terrestrial and avionic applications:
  - – High energy neutrons (cosmic ray byproducts)
    - Indirect interaction through nuclear reactions
  - – Low energy neutrons (thermal)
    - Indirect interaction via $^{10}B$ nuclear reaction
  - – Alpha particles from radioactive decay of contaminants in the chip/package/solder
    - Short range in Si, small LET, direct interaction

# Single Event Effects even at sea level

- High energy neutrons
- Low energy neutrons





# Alpha particle emission rates

| Material | Emission rate ($\alpha$/cm$^2$-hr) |
|---|---|
| Bare Si | 0.00020 |
| Plastic (epoxy) | 0.00080 |
| Ceramic lid A | 0.15 |
| Ceramic lid B | 3.10 |
| Ceramic DIP A | 0.02320 |
| Ceramic Dip B | 0.03230 |
| Ceramic Dip C | 0.02610 |
| Plastic DIP A | 0.00109 |
| Plastic DIP B | 0.00124 |

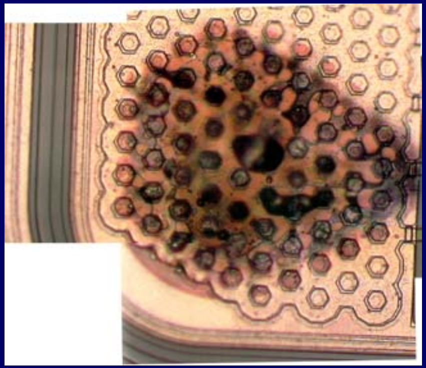
*L. Lantz, IEEE-TR45, 1996*

# Critical charge and threshold LET

- The ionizing particle generates electron-hole pairs along its track, producing in turn a transient current pulse in the circuit at random (unpredictable) instants
- If the charge collected by a sensitive node of the device/circuit is larger than the **critical charge** required to start an anomalous behavior, an ***effect*** may be seen affecting the electrical performance of the device/circuit:
  - Soft errors
  - Hard (destructive) errors
- The critical charge corresponds to a particular LET value, that is over a minimum **threshold LET** value required to start the SEE (but the incidence angle of the particle plays a fundamental role!)
- The severity of the effect on the device/circuit depends on:
  - pulse/charge intensity
  - type of effect
  - system criticality

# Classification of SEE's

- **Non-destructive (soft errors)**:
  - – Single Event Transient (SET)
  - – Single Event Upset (SEU)
    - Single Bit Upset (SBU)
    - Multiple Bit Upset (MBU)
  - – Single Event Functional Interruption (SEFI)
  - – Single Event Latchup (SEL or SELU)… *may be also destructive*
- **Destructive (hard errors)**:
  - – Single Event Burnout (SEB)
  - – Single Event Gate Rupture (SEGR)
  - – Stuck Bits



***Destructive event in a COTS 120V DC-DC Converter***

*K. LaBel, EWRHE 2004*

# SEE countermeasures

Single Event Effects in devices/circuits can be **mitigated** by using different strategies at different levels. For instance:

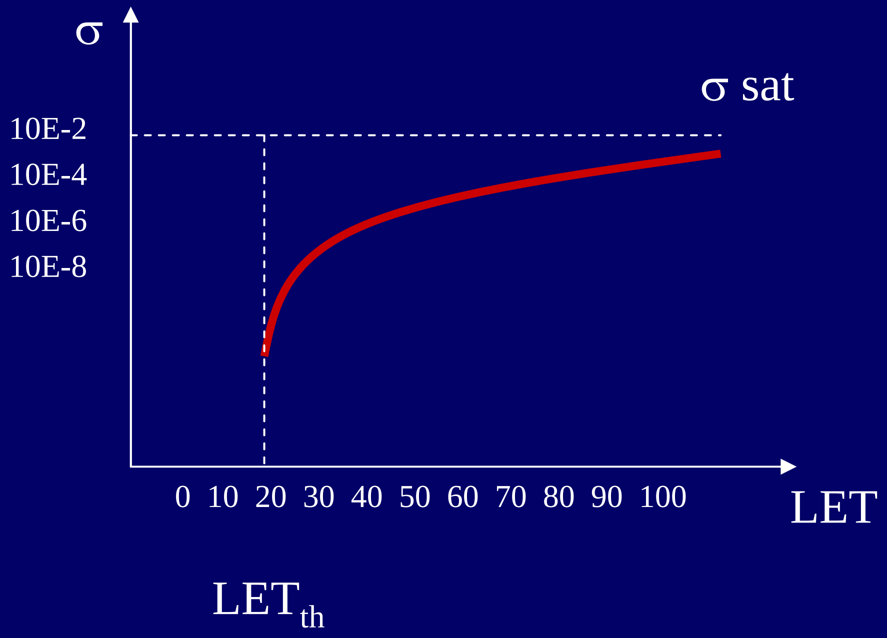
- **circuit level**, by using specific technologies or processes for fabrication (such as epi-CMOS, SOI, additional capacitors in SRAM, or rad-hardened electronic components)
- **design level**, by using *ad hoc* logic structures aiming to SEE immunity (such as SEE immune latches)
- **system level**, by modifying the software and/or the hardware (such as triple redundancy)

# SEE ground testing

- Accelerated tests are performed to evaluate the expected error / failure rate (FIT = 1 error / $10^9$ hours) of the device/system in the specific operating environment (Space, HEP, Avionic, …) by using:
  - Ion beams from accelerators
  - Neutron beams
  - Alpha sources
  - Laser testing
- The SEE sensitivity of each SEE type (SEU, SEL, SEB, …) in any particular device is evaluated by measuring the corresponding **cross section** vs **LET**:
  - **Cross section** : $\sigma$(**LET**) = # Events / particle fluence ($cm^2$)
- The error rates in operating condition is derived from cross sections and the features (nature of particles, corresponding fluxes, mission duration) of the actual environment
- Error rate = # errors / device day

# SEE cross section

- **$LET_{th}$** is the minimum (threshold) LET to cause the specific SEE
- The saturation cross section $\sigma_{sat}$ is approached at high LET values
- The $\sigma$(LET) curve is obtained by measuring the cross section at a few LET values and fitting data with a Weibull curve



| *Device Threshold* | *Environment to be Assessed* |
|---|---|
| LETth < 10 MeV*cm2/mg | Cosmic Ray, Trapped Protons, Solar Flare |
| LETth = 10-100 MeV*cm2/mg | Cosmic Ray |
| LETth > 100 MeV*cm2/mg | No analysis required |

*R. Velazco, EWRHE 2004*

# Conclusions

- Single event effects are produced by collecting the charge generated (usually in the semiconductor) by a single ionizing particle: charge > critical charge
- The e-h track may include more than one active device (e.g., MOSFET)
- Different SEE’s may occur depending on the device type, being either soft or hard in nature
- Each SEE for a specific device is characterized by its cross section and threshold LET
- SEE’s are expected not only in radiation harsh environments but also at sea level
- …more SEE fun to come in the next lecture!