VII. Radiation Effects

Two basic types of radiation damage

1. Displacement damage

Incident particles displace Si atoms from lattice sites

Roughly proportional to non-ionizing energy loss

However, details in energy deposition differ significantly between charged and neutral particles (e.g. neutrons and protons)

Example: GaAs is less sensitive than Si to displacement damage for neutrons, but much inferior for protons

Electrical effects Increased leakage current in detectors

Reduced carrier lifetime (signal loss due to trapping)

Reduced current gain in bipolar transistors

2. Ionization Damage

Energy deposition in insulating layers (e.g. SiO_2) forms electron-hole pairs, some of which are trapped. leading to charge buildup.

Electrical effects Increased surface leakage in detectors

Shifts in operating points of MOS transistors.

Radiation in LHC Tracking Detector

Particle rate from collisions at L= 10^{34} cm^{-2}s^{-1}

$$n' \approx 2 \cdot 10^{9} / r_{\perp}^{2}$$

At $r_{\perp}$= 30 cm

$$n' \approx 2 \cdot 10^{6} \text{ s}^{-1}\text{cm}^{-2}$$

Fluence after 1 year of operation (10^{7} s)

$$\Phi \approx 2 \cdot 10^{13} \text{ cm}^{-2}$$

Mostly minimum ionizing charged particles

Ionizing dose   0.7 Mrad

Innermost semiconductor tracking detectors at $r_{\perp}$= 10 cm

$\Rightarrow$ 10 x radiation

In addition:

Albedo neutrons from calorimeter

$\Rightarrow$ 10^{12} to 10^{13} neutron equivalent per year (1 MeV equiv.)

Challenges at sLHC

10-fold luminosity + doubled crossing time (25 $\rightarrow$ 50 ns)

Increased radiation damage

Increased multiplicity per crossing (~200 tracks)

$\Rightarrow$ Pattern Recognition

Preliminary Criteria for Detector Lifetime (ATLAS):

Design for 3000 fb^{-1} integrated luminosity

Include 2-fold safety factor

Fluences (ATLAS, 1 MeV neutron equivalent)

Pixel system :	r= 5 cm	$\Phi \approx 10^{16}$ cm^{-2}
	r= 13 cm	$\Phi \approx 3 \cdot 10^{15}$ cm^{-2}
Strips:	r= 38 cm	$\Phi \approx 7 \cdot 10^{14}$ cm^{-2}
	r= 70 cm	$\Phi \approx 4 \cdot 10^{14}$ cm^{-2}

Ionizing Dose: 1 Mrad $\triangleq 3 \cdot 10^{13}$ cm^{-2} $\Rightarrow$ Dose $\approx$ 10 – 300 Mrad

1. Displacement Damage

Incident particle capable of imparting 20 eV to Si atom can dislodge it from its lattice site

$\Rightarrow$ defect clusters

1 MeV neutron transfers ~ 60 - 70 keV to Si atom

Recoil Si displaces about 10^3 atoms in ~ 0.1 μm diameter

Relative displacement damage for various particles and energies

Particle	**proton**	**proton**	**neutron**	**electron**	**electron**
Energy	1 GeV	50 MeV	1 Mev	1 MeV	1 GeV
Relative Damage	1	2	2	0.01	0.1

Photons require >250 keV to produce displacement damage in Si (momentum conservation)

X-rays don't produce displacement damage.

^{60}Co γ rays cause displacement damage via Compton electrons.

Displacement damage has 3 important effects

- Formation of mid-gap states, which facilitate the transition of electrons from the valence to the conduction band.

  In depletion regions ⇒ generation current
  (increase in the current of
  reverse-biased pn-diodes)

  In forward biased junctions or non-depleted regions

  ⇒ recombination, i.e. charge loss.

- States close to the band edges facilitate trapping,
  where charge is captured and released after a certain time.

- A change in field characteristics

  Additional electron traps leading to fixed charge

Increase in Leakage Current

The increase in reverse bias current due to bulk damage is

$$\Delta I_r = \alpha \; \Phi$$

per unit volume, where Φ is the particle fluence and α the damage coefficient:

$$\alpha \approx 3 \cdot 10^{-17} \text{ A/cm}$$

for minimum ionizing protons and pions after long-term annealing and

$$\alpha \approx 2 \cdot 10^{-17} \text{ A/cm}$$

for 1 MeV neutrons.

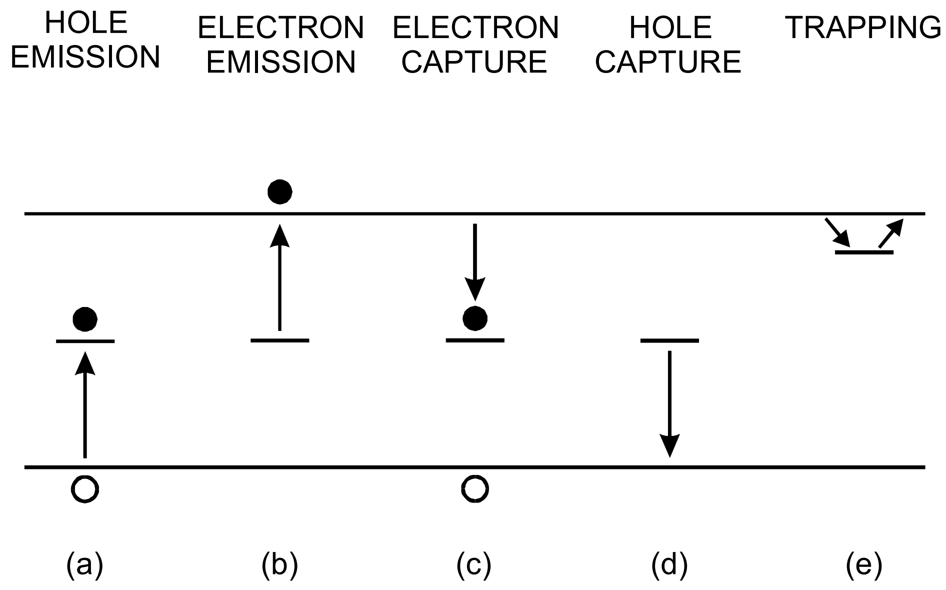
The reverse bias current depends strongly on temperature

$$\frac{I_R(T_2)}{I_R(T_1)} = \left(\frac{T_2}{T_1}\right)^2 \exp\left[-\frac{E}{2k}\left(\frac{T_1 - T_2}{T_1 T_2}\right)\right]$$

where E = 1.2 eV, so rather modest cooling can reduce the current substantially.

~ 6-fold current reduction in cooling from room temperature to 0°C

Emission and capture processes



a) Hole emission

Electron promoted from valence band to defect state

b) Electron emission

Electron transition from defect state to conduction band

a) + b) $\Rightarrow$ Additional charge carriers in conduction band "generation current"

c) Electron capture

Electron captured from conduction band

d) Hole capture

Electron transition to valence band

c) + d) $\Rightarrow$ Charge carriers removed from conduction band – "recombination"

e) Trapping: Charge captured and released after some time

Electronic effects of displacement damage

Generation Current

Increase in reverse bias current of detector diodes
(dark current)

$\Rightarrow$ Increased shot noise

Recombination

Charge loss during carrier transport

$\Rightarrow$ Signal loss in detectors

$\Rightarrow$ Decreased current gain in bipolar transistors

Buildup of fixed charge

$\Rightarrow$ Increased bias voltage required for full charge collection

Signal Yields at High Damage Levels

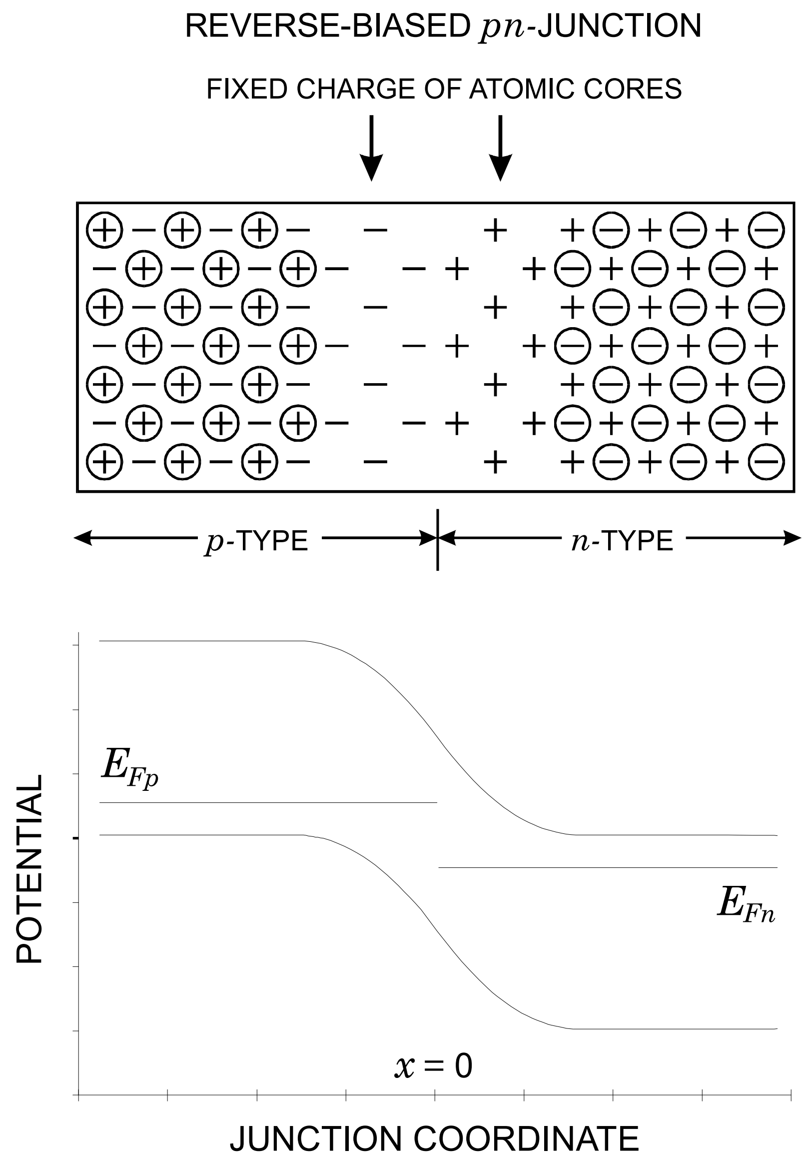
Currently the primary limit to sensor lifetime is buildup of space charge.

Pre-radiation:

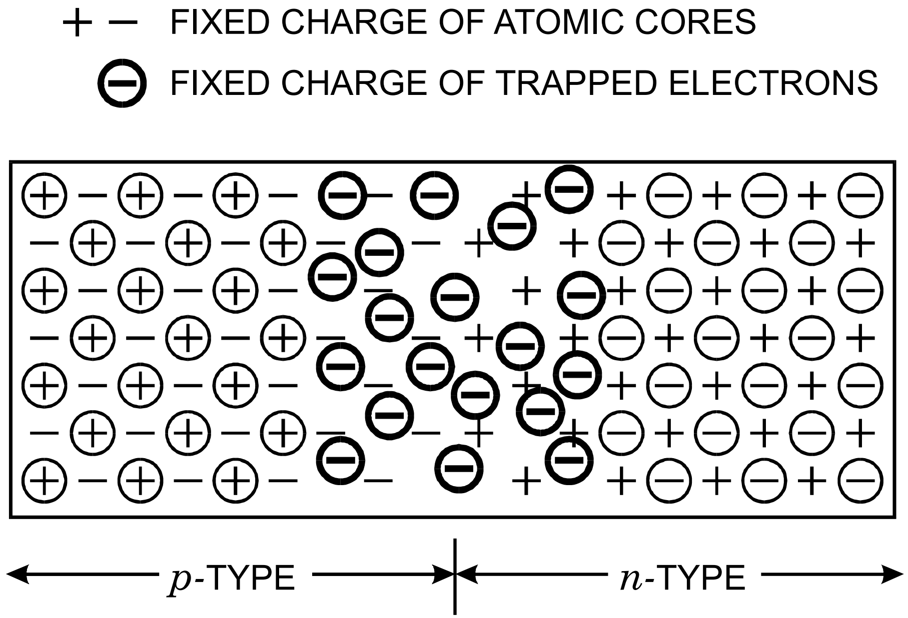
Bias voltage is required to sweep free carriers from the sensitive region,

i.e. remove free carriers introduced from dopant atoms,

leaving a **positive space charge** in n-type silicon.



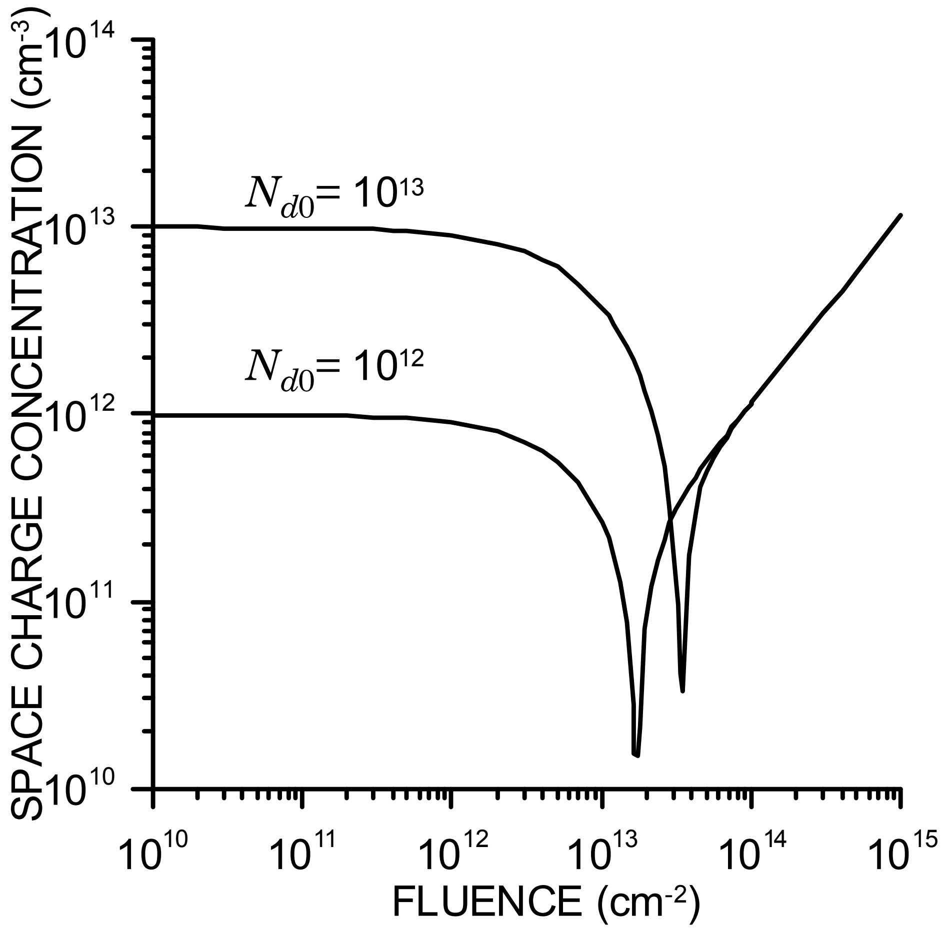
Displacement damage forms acceptor-like states that fill with electrons yielding a **negative space charge**.



At fluences $\Phi > 10^{14}$ cm^{-2} the negative space charge dominates.
(erroneously commonly called "type inversion")

Additional bias voltage is required to compensate for the field built up by the negative space charge.

The required bias voltage drops initially with fluence, until the positive and negative space charge balance and very little voltage is required to collect all signal charge.



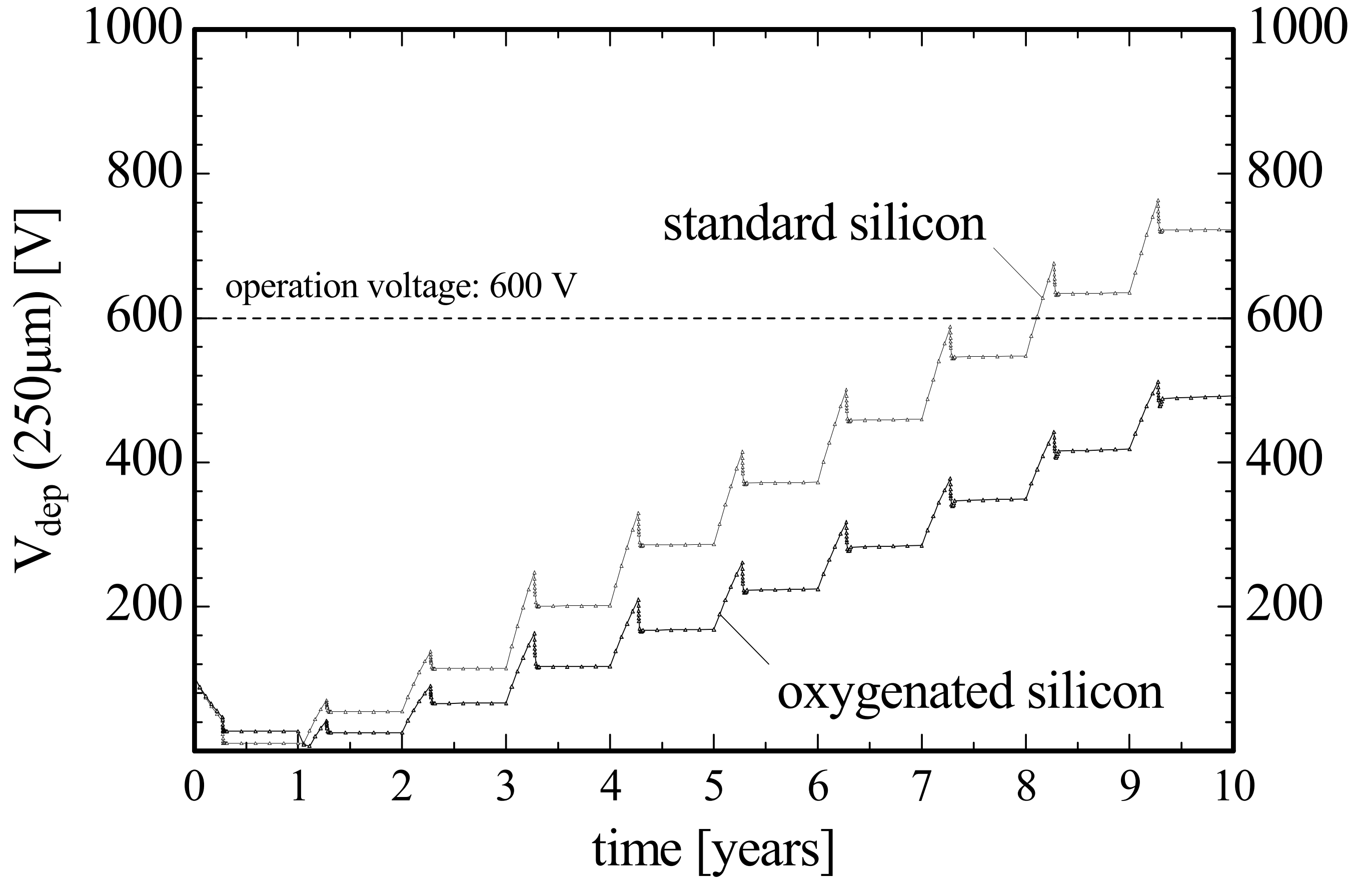
At larger fluences the negative space charge dominates, and the required operating voltage increases ($V \propto N$).

The safe limit on operating voltage ultimately limits the detector lifetime.

Strip detectors specifically designed for high voltages have been extensively operated at bias voltages >500V.

Dynamics of damage lead to complex formation and charging becomes strongly temperature dependent!

Jumps in operating voltage due to warm-up during maintenance.



(Renate Wunstorf, RD48)

At fluences $\Phi > 10^{15}$ cm^{-2} charge trapping becomes critical.

Carrier lifetime: $\tau \approx \dfrac{K}{\Phi}$, where $K \approx 2 \cdot 10^{6}$ s/cm^2

For $\Phi = 10^{15}$ the carrier lifetime $\tau \approx$ 2 ns.

For $\Phi = 10^{16}$ the carrier lifetime $\tau \approx$ 0.2 ns.

For comparison, typ. collection time for 300 μm thickness $t_c \approx$ 20 ns

At saturation velocity $v = 10^{7}$ cm/s,
a lifetime of $\tau \approx$ 0.2 ns corresponds to a drift length of 20 μm.

This is much smaller than the sensitive thickness of current pixel or strip detectors at LHC.

Charge Transport in the Presence of Trapping

Given a lifetime τ, a packet of charge Q_0 will decay with time: $Q(t) = Q_0 e^{-t/\tau}$

In an electric field the charge will drift. The time required to traverse a distance x is

$$t = \frac{x}{v} = \frac{x}{\mu E},$$

after which the remaining charge is

$$Q(x) = Q_0 e^{-x/\mu E\tau} \equiv Q_0 e^{-x/L}.$$

Since the drift length $L \equiv \mu\tau E$ is proportional to the mobility-lifetime product, $\mu\tau$ is often used as a figure of merit.

Assume a detector with a simple parallel-plate geometry. For a charge traversing the increment dx of the detector thickness d, the induced signal charge is

$$dQ_s = Q(x)\frac{dx}{d},$$

so the total induced charge

$$Q_s = \frac{1}{d}\int_0^d Q(x)dx = \frac{1}{d}\int_0^d Q_0 e^{-x/L} dx$$

$$Q_s = Q_0 \; \frac{L}{d} \; \left(1 - e^{-d/L} \right)$$

The magnitude of the recovered signal depends on the drift length relative to the width of the sensor's sensitive region.

$$d \gg L: \qquad \frac{Q_s}{Q_0} \approx \frac{L}{d}$$

$$d = 3L: \qquad \frac{Q_s}{Q_0} = 0.95$$

In high quality silicon detectors: $\tau \approx$ 10 ms

$\mu_e =$ 1350 V/cm·s^2

$E =$ 10^4 V/cm $\Rightarrow$ $L \approx$ 10^4 cm

In amorphous silicon $L \approx$ 10 μm (short lifetime, low mobility).

In diamond, however, $L \approx$ 100 – 200 μm (despite high mobility).

In CdZnTe at 1 kV/cm, $L \approx$ 3 cm for electrons, 0.1 cm for holes

Carrier lifetime also important for efficiency of solar cells!

These results only apply to single-electrode detector geometries where the electrode size is large compared to the sensitive thickness.

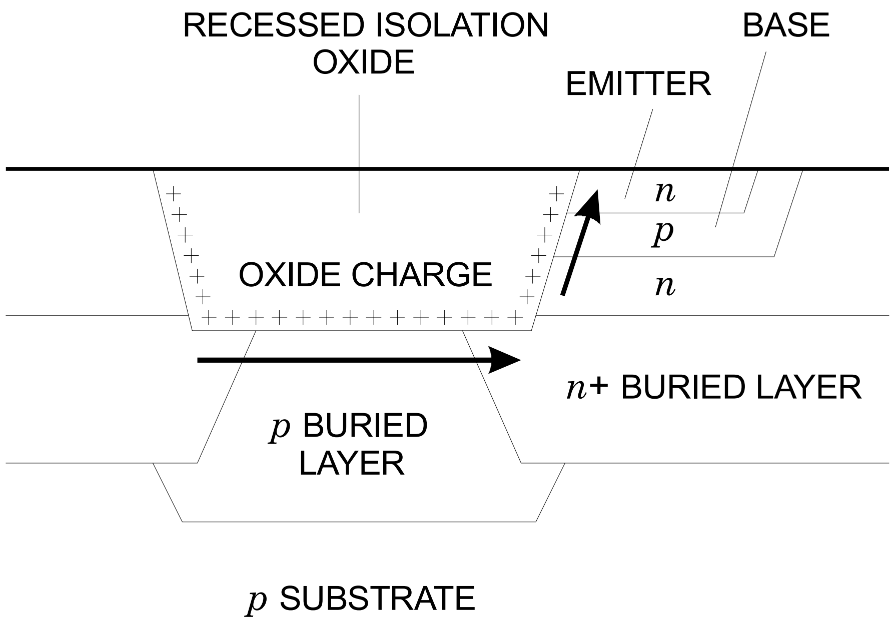
Radiation Damage in Bipolar Resistors

Bipolar transistors limited by degradation in DC gain $\beta_{DC} = I_C / I_B$

$$\frac{1}{\beta_{DC}} = \frac{1}{\beta_0} + K\Phi$$

BJT Optimum noise: $Q_n^2 \approx 4kT \frac{C_d}{\sqrt{\beta_{DC}}}$ (C_d = detector capacitance)

Current gain often degraded by radiation effects in isolation structures:

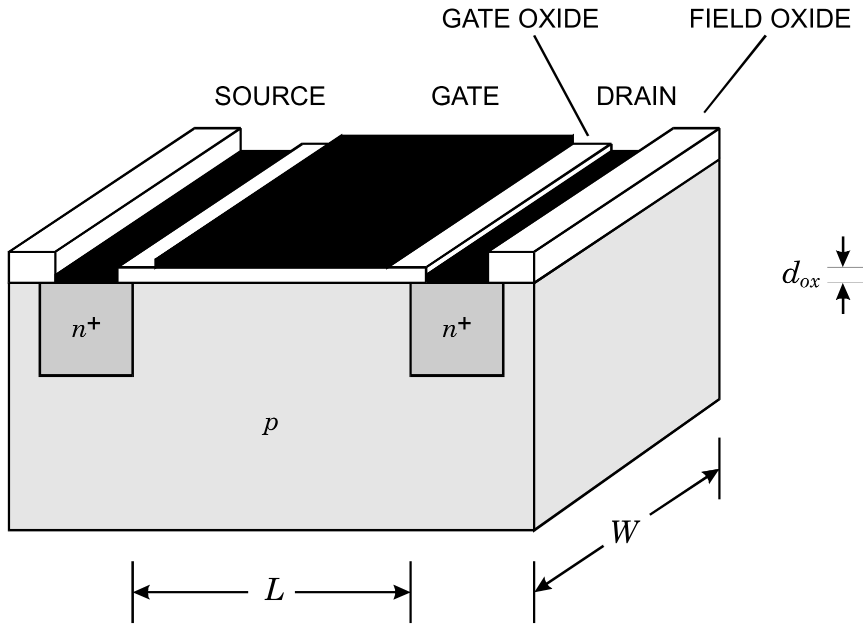


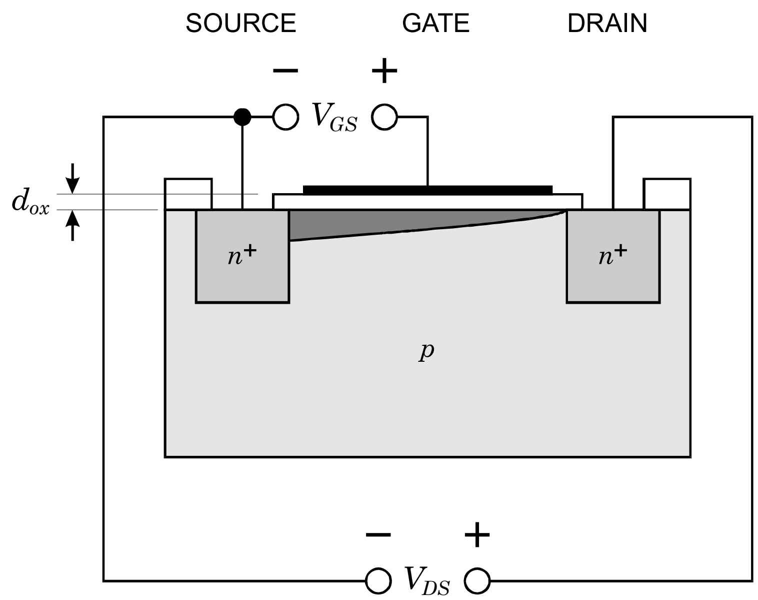
2. Ionization Damage

Energy deposition in insulating layers (e.g. SiO_2) forms electron-hole pairs, some of which are trapped. leading to charge buildup.

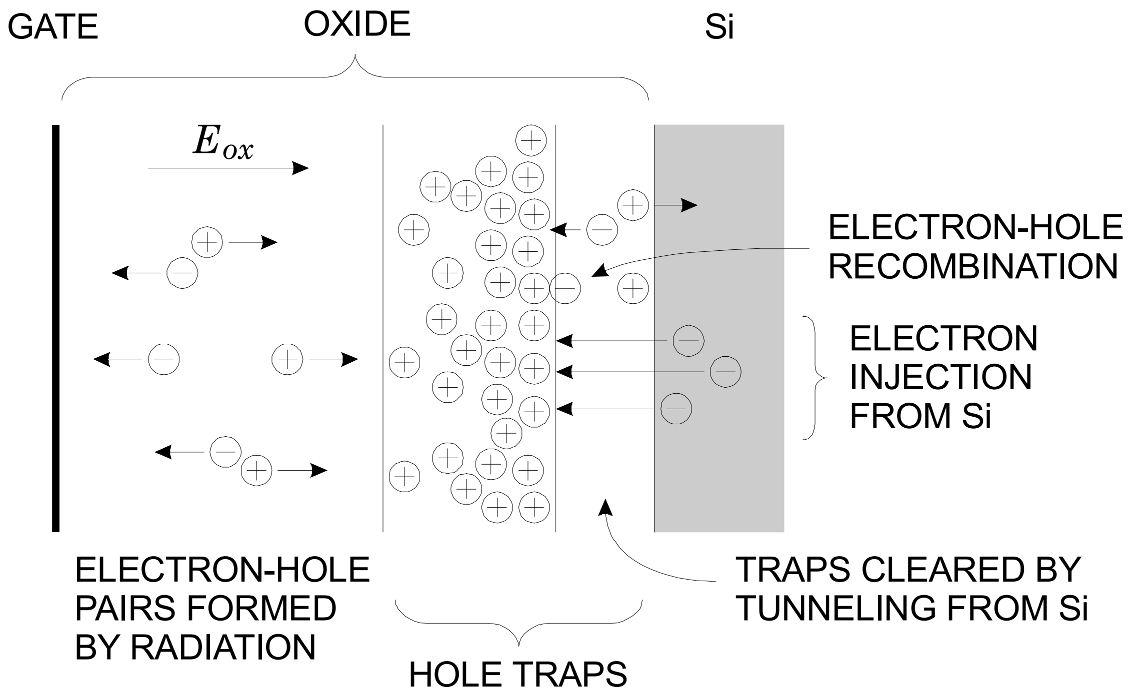
Electrical effects: Increased surface leakage in detectors and shifts in operating points of MOS transistors.

Principle of MOS transistor





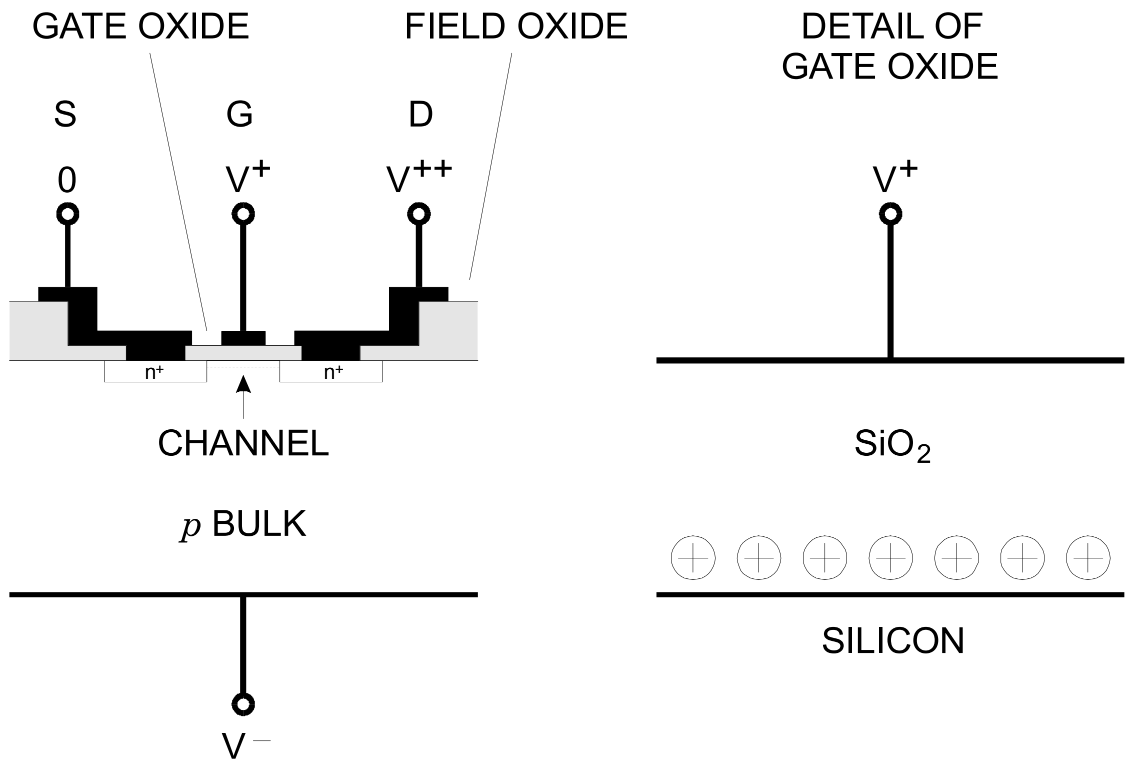
Processes in gate oxide under ionizing radiation
(charged particles, x-rays, gammas)



adapted from Boesch et al. IEEE Trans. Nucl. Sci (1986) 1191

Note: Photons with E<250 keV do not cause displacement damage directly.
Indirectly via Compton electrons, but much less than n or p.

Critical effects in MOS integrated circuits



Trapped holes at the Si – oxide interface change the voltage required at the gate to set the operating point.

Charge buildup in the surface oxide reduces isolation between adjacent devices.

Dose units

- Displacement damage depends on particle type and energy, so it must be characterized by fluence, particle type and energy.

  For example, for the LHC upgrade we are targeting fluences of protons, pions, and neutrons equivalent to 10^{16} cm^{-2} for neutrons of 1 MeV.

- Ionization damage depends on the ionizing energy loss, so the charge buildup depend only on the deposited energy, independent of particle type (x-rays, gamma, protons, ...)

  Radiation dose is expressed in rad (100 erg/g) or gray (1 J/kg = 100 rad).

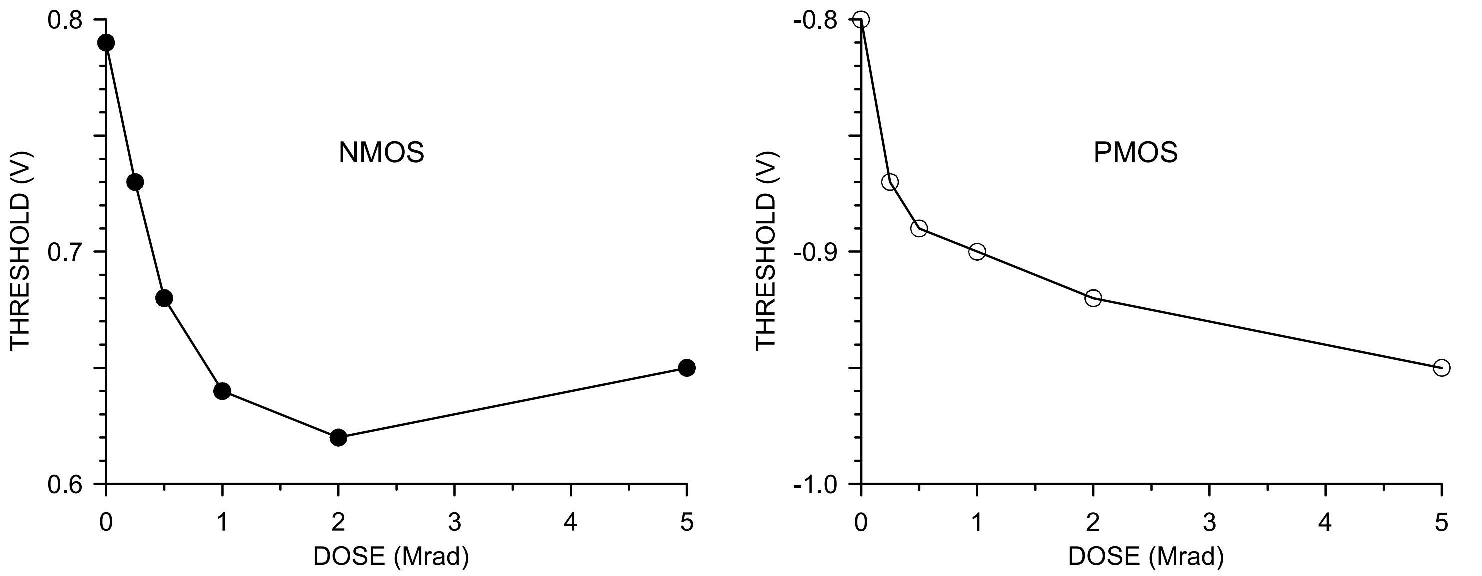
MOS transistors are well characterized by doses in Mrad.

Bipolar transistors are primarily susceptible to displacement damage, with ionization damage affecting device isolation and low-dose rate current gain, so both fluence and ionizing dose must be specified.

In the past (up to ~20 years ago)

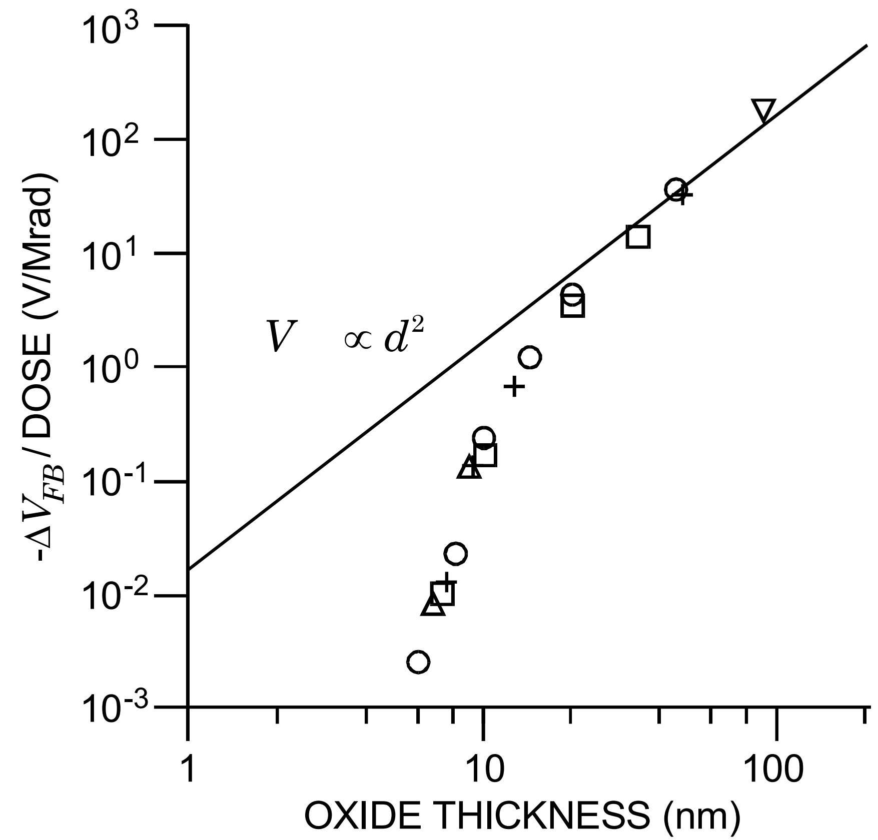
- commercial CMOS devices were limited to 10s of krad
- special radiation-hard CMOS processes to about 5 Mrad.

Typical threshold shifts for a 1.2 μm radiation-hardened process:



Submicron processes require thin gate oxides, which allow sufficient electron tunneling rates to neutralize the trapped hole charge.

Threshold shift vs. oxide thickness



Saks et al., IEEE Trans Nucl. Sci. NS-31 (1984) 1249

Complete pixel modules using thin oxide CMOS have been irradiated to 100 Mrad (proton $\Phi > 3 \cdot 10^{15}$ cm^{-2}) with no loss in functionality.

Ionization effects in devices determined by

- interface trapped charge
- oxide trapped charge
- mobility of trapped charge
- time and field dependence of charge states

Strongly dependent on

- rate of irradiation
- applied voltages and variation in time

  devices must be tested under voltage
- time variation of the radiation
- temperature

Radiation hardness limited primarily by sensor:

Charge trapping in the sensor $\Rightarrow$ reduced signal

To maintain S/N we can

a) reduce electronic noise

$\Rightarrow$ increased power (front-end power $\propto (S/N)^2$)

and/or

b) reduce sensor capacitance

pixels (material, power, cost)

reduce strip length

$\Rightarrow$ more readout ICs per unit area

Additional important concerns: low-mass power distribution, cooling

Gains in electronic noise vs. power are limited.

Alternatives?

Assume reduced signal charge S_{rad} / S_0 due to trapping:

Under optimum scaling to maintain signal-to-noise ratio,

input transistor power (≈ preamp power) scales with $(S_0 / S_{rad})^2$.

see Spieler, *Semiconductor Detector Systems*, Ch. 6

Best to scale strip length by S_{rad} / S_0.

Increases number of readout ICs by S_0 / S_{rad}

Increases power by S_0 / S_{rad}

Power services already major contribution to tracker material.

Radiation resistant design is a combination of

device properties,

layout, and

circuit design.

Circuit example:

Maintaining electronic levels depends on stabilizing the operating current in the input transistor.

Setting operating points by voltage bias introduces radiation dependence, as threshold shifts also shift the voltage required for a given device current.

Controlling the device current directly maintains operating point independently of threshold shifts.

Shifts in operating points or device matching can be corrected by trim DACs that allow external (digital) adjustment.

Example: SVX front-end amplifier

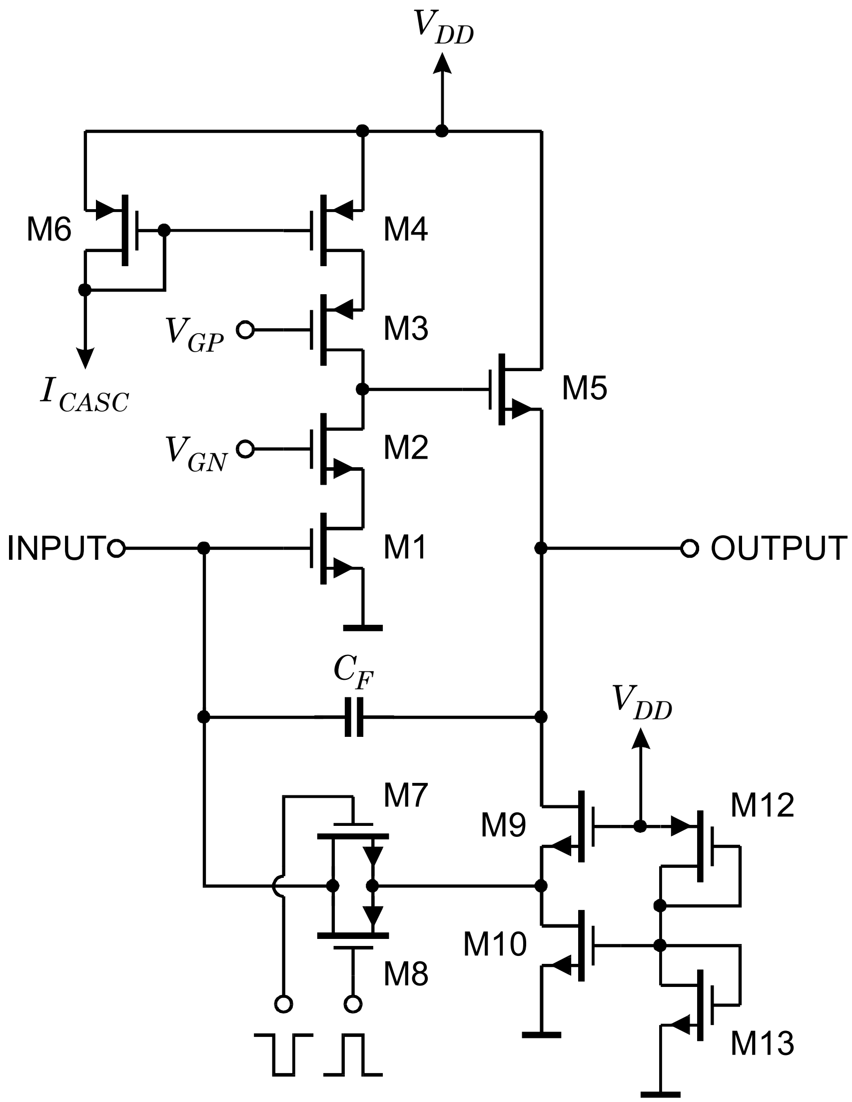
1st version developed in the 1980s in 3 μm CMOS.

Current controlled directly by the current mirror M6

In radiation tests SVX chip failed because of digital circuit malfunction (switching depends on threshold).

Analog front-end continued to function.

Many current designs still suffer from using voltage biasing (the conventional recipe).



Conclusions

The high signal-to-noise ratio obtainable with low-capacitance pixel structures extends detector lifetime.

The higher mobility of electrons makes them less sensitive to carrier lifetime than holes, so detector configurations that emphasize the electron contribution to the charge signal are advantageous, *e.g.*, n+ strips or pixels on a p- or n-substrate.

The occupancy of the defect charge states is strongly temperature dependent;

Competing processes can increase or decrease the required operating voltage.

It is critical to choose the operating temperature judiciously
(−10 to 0°C in typical collider detectors) and limit warm-up periods during maintenance.

Materials engineering, *e.g.*, introducing oxygen interstitials, can improve certain aspects and is under investigation.

At high fluences diamond is an alternative, since it operates as an insulator rather than a reverse-biased diode. Detector thicknesses are limited.

Currently, the lifetime of detector systems is still limited by the detectors.

In the electronics use of standard “deep submicron” CMOS fabrication processes with appropriately designed circuitry has increased the radiation resistance to fluences > 10^{15} cm^{-2} of minimum ionizing protons or pions.

Summary

- Mainstream commercial deep-submicron CMOS inherently
  provides high radiation resistance suitable for many applications.
  Complementary to specialized rad-hard processes.

  Highly developed commercial processes provide

  complete simulation tools

  economical fabrication

- Radiation-resistant circuitry depends on

  device properties

  layout

  circuit design

  Radiation resistance is the result of system design!

- Proposed work builds on international efforts at the scale of >$\$10^8$
  and more than a decade of R&D