Section V: Total Dose Effects

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Section 514

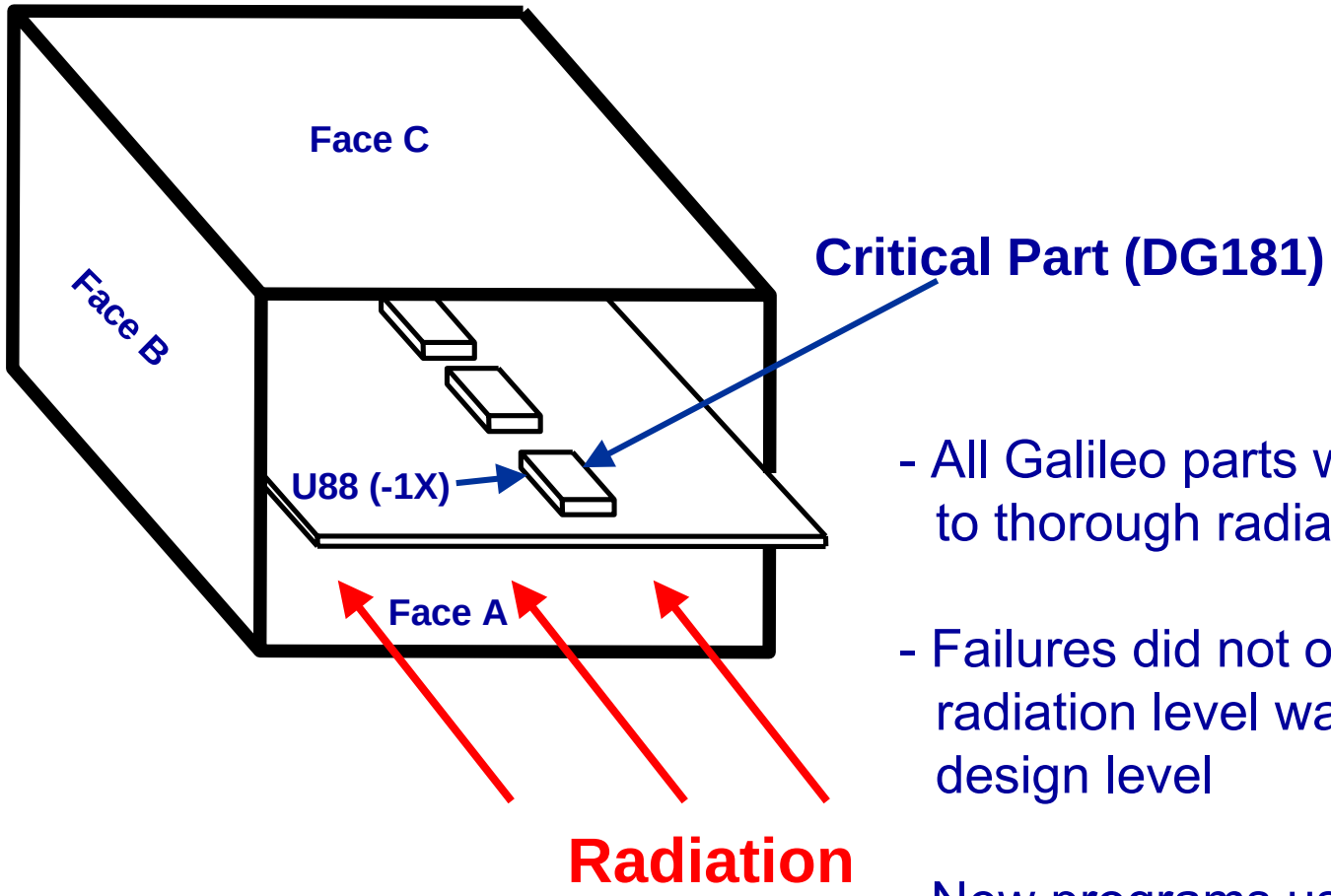
Space Radiation Effects

1) Single Event Effects (SEE)
   - Hard / Permanent
   - Soft / Recoverable

2) Total Ionizing Dose (TID)
   - Usually dominated by protons
   - Electrons are important for some planetary missions

3) Displacement Damage (DD)

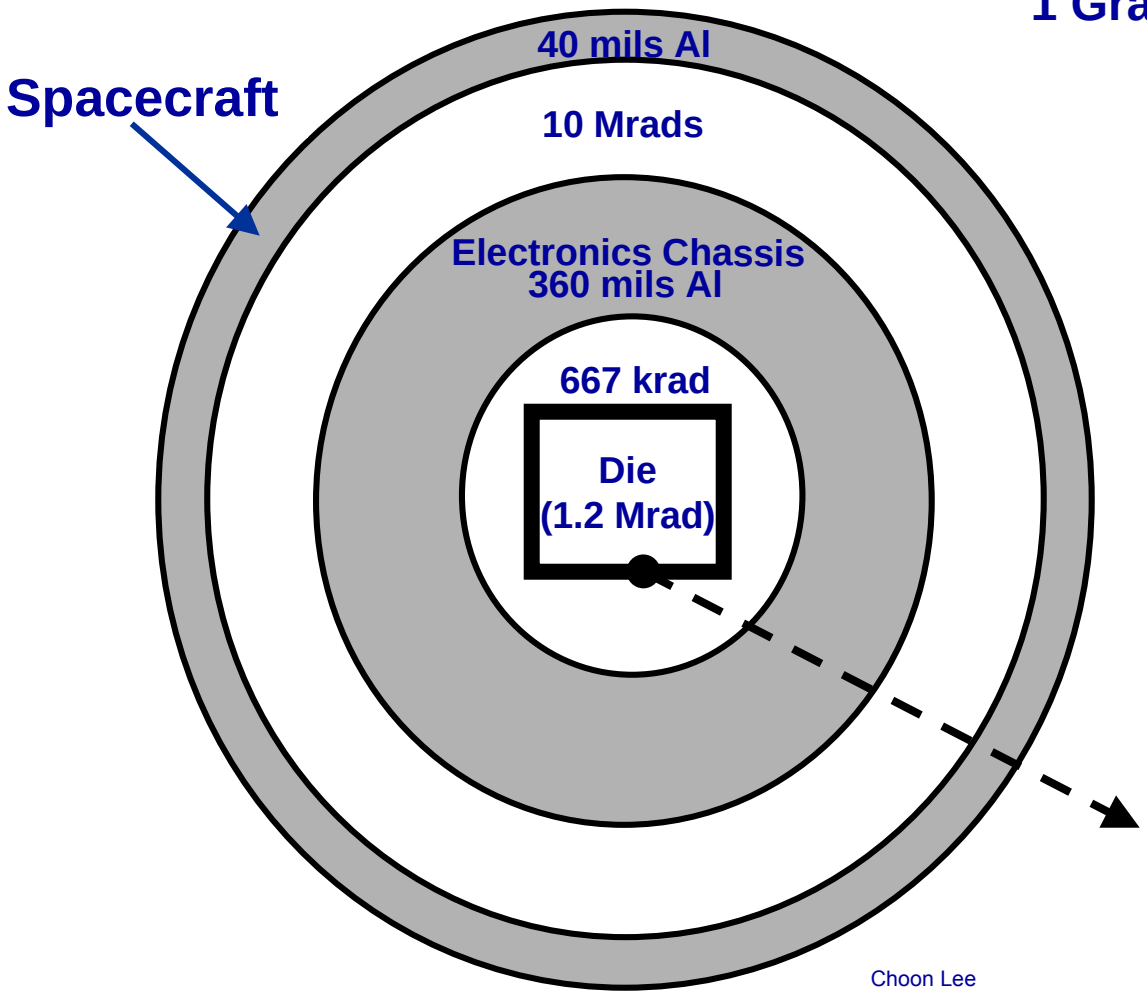
Galileo Total Dose Problem



- All Galileo parts were subjected to thorough radiation testing
- Failures did not occur until radiation level was close to design level
- New programs use less stringent design methods

X2000/Europa Shielding Analysis

1 Grad outside Spacecraft!

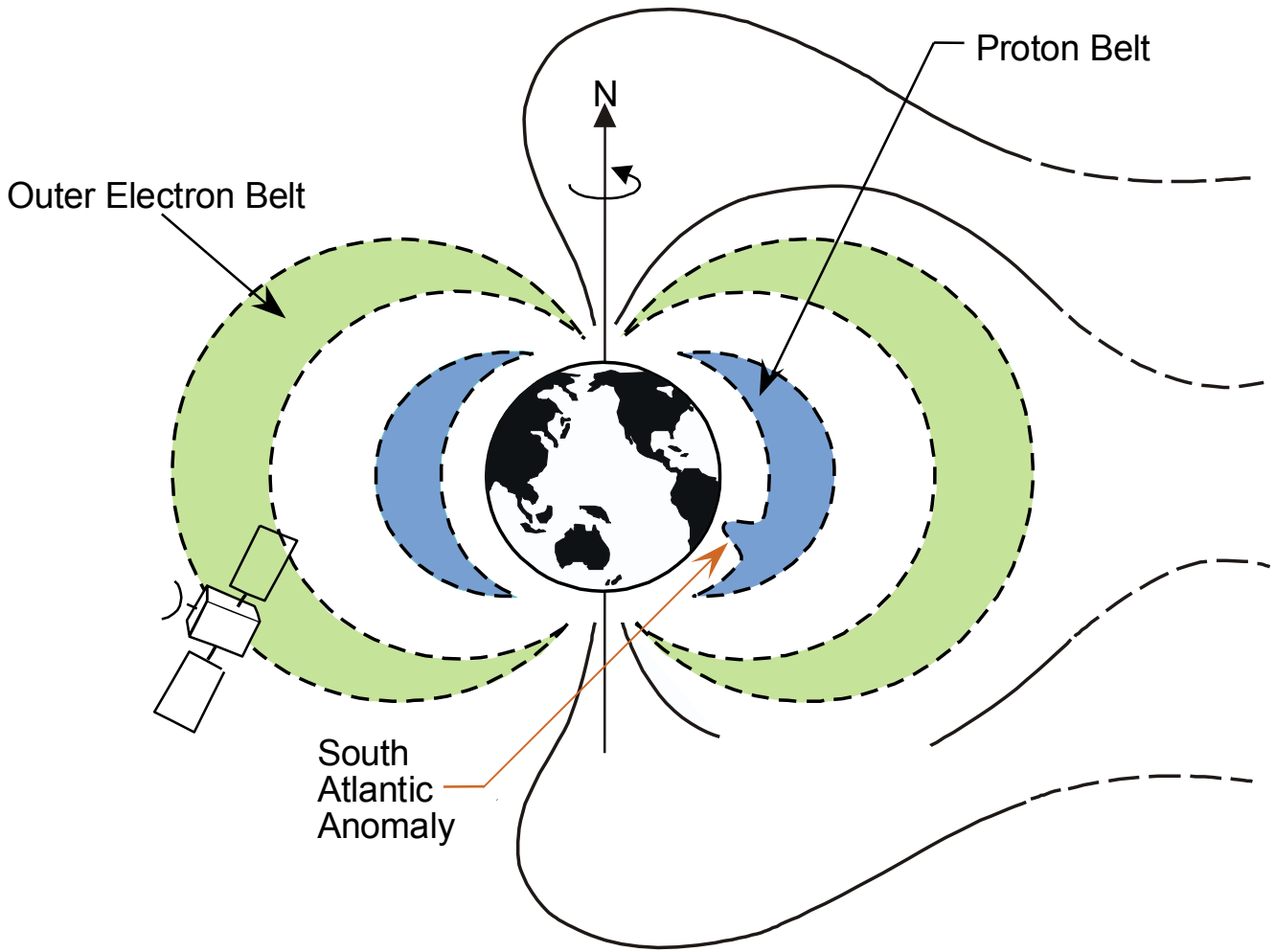


Additional 1.7 inches of Al shielding around the die provide 30 krad dose which allows use of 60 krad die with RDM of 2.0

Outline

- Radiation Environment Shielding
- Basic Mechanisms
- MOS
- Bipolar
- COTS
- Testing
- Warnings and Misconceptions
- Recommendations

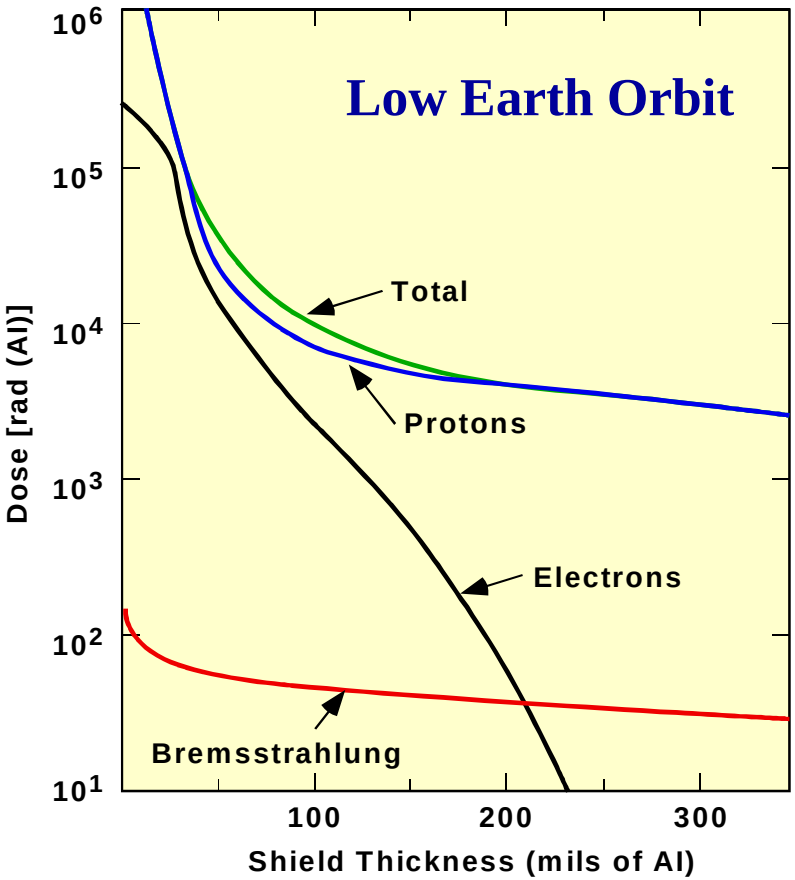
Near Earth TID Environment

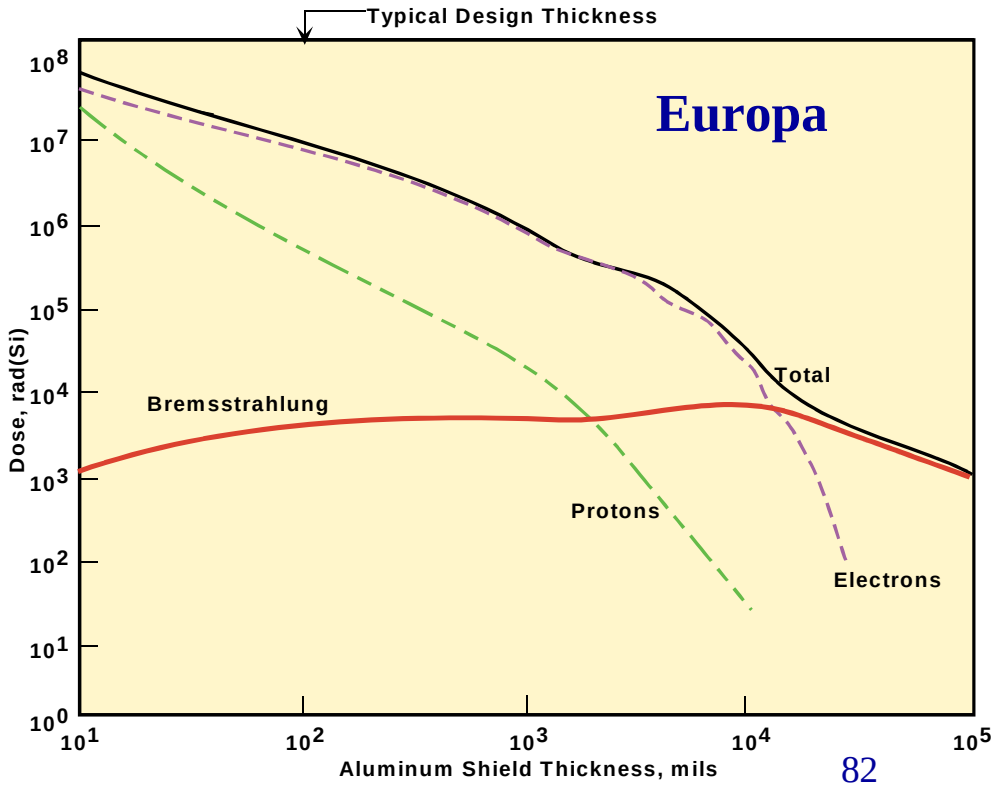


- Total accumulated dose depends on orbit altitude, orientation, and time.

TID Shielding

- Electrons more effectively shielded than protons
- Incremental shielding gives diminished returns



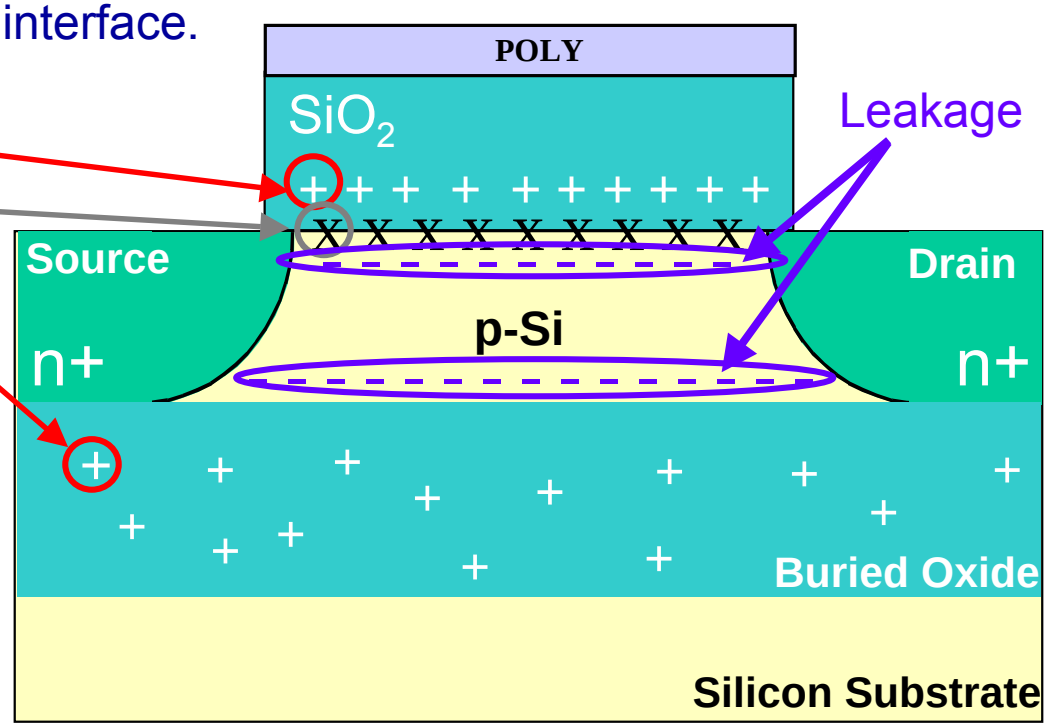


Total Dose Effects in MOS Devices

Charge trapping in SiO_2 and at Si/SiO_2 interface.

1. Oxide Trapping (N_{ot})
2. Interface Trapping (N_{it})

- Dominated by point defects



$$V_{th} = V_{th}' + \phi_{MS} - \frac{Q_F}{C_O} - \frac{Q_M \gamma_M}{C_O} - \frac{N_{it} \cdot e \cdot (2\phi_f)}{C_{ox}} - \frac{N_{ot} \cdot e}{C_{ox}}$$

Metal/Semi Work Function; Fixed Charge; Mobile Ions; Interface Traps; Oxide Traps

$$V_{th}' = 2\phi_F \pm (K_S/K_O)\ \chi_O \sqrt{\frac{4qN_B}{K_S\ \varepsilon_O}} \pm \phi_F$$

Basic Mechanisms

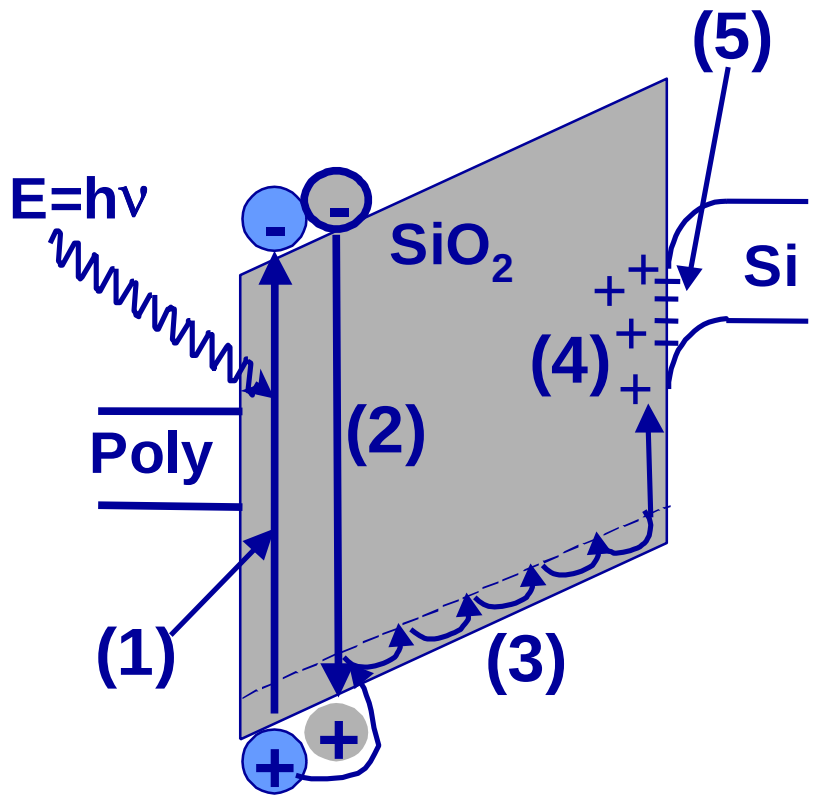
(1) Electron-Hole (e^-/h^+) Pair Generation
- ~17 eV / pair for SiO_2

(2) e^-/h^+ Pair Recombination / Yield
- Source
- Field

(3) Electron and Hole Transport
- e^- ~ psec
- h^+ ~ msec - sec

(4) Hole Trapping
- Precursor Density
- Cross section

(5) Interface Trap Formation
- Delayed buildup



DEVICE PARAMETER SHIFT

What Is a rad?

1 rad = 100 erg / gram

 # electron-hole pairs (SiO_2) ~ 8.1×10^{12} /cm^3 / rad

Energy Unit Conversion of rad

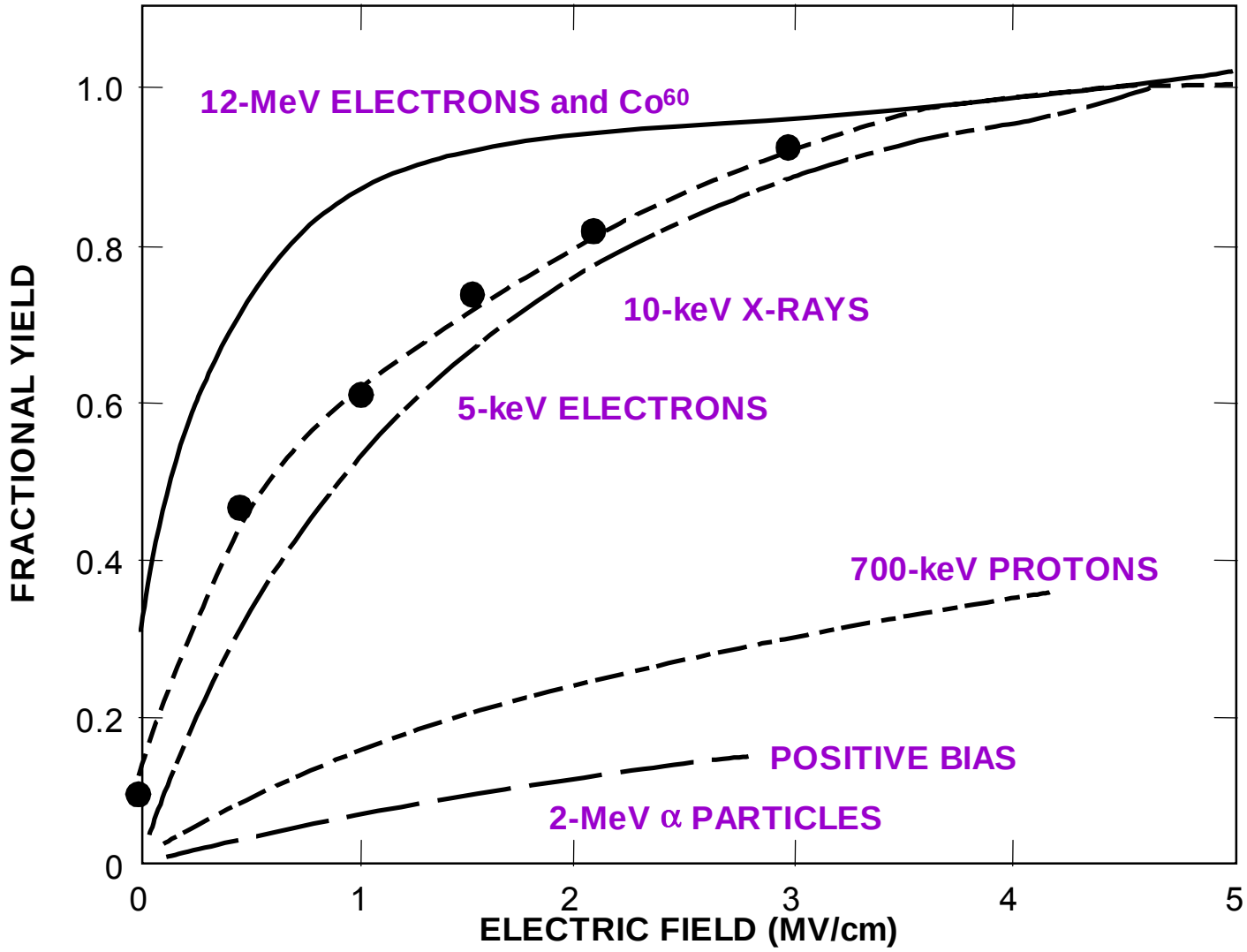
ρ_{SiO_2}

$$\frac{\#\ \text{pairs}}{\text{rad} \cdot \text{cm}^3} = \frac{\left[\left(\frac{100\ \text{ergs}}{\text{gram}} \right) \left(\frac{10^{-7}\ \text{J}}{\text{erg}} \right) \left(\frac{\text{eV}}{1.6 \times 10^{-19}\ \text{J}} \right) \right] \cdot (2.2\ \text{g / cm}^3)}{17 +/- 1\ \text{eV}}$$

(electron-hole pair creation energy in SiO_2)

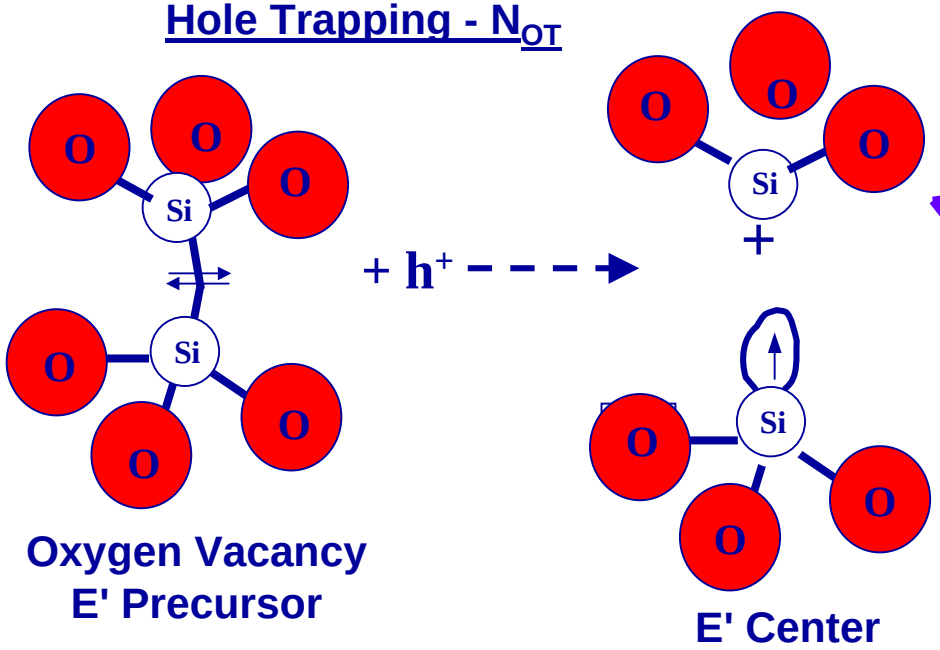
Recombination and Yield

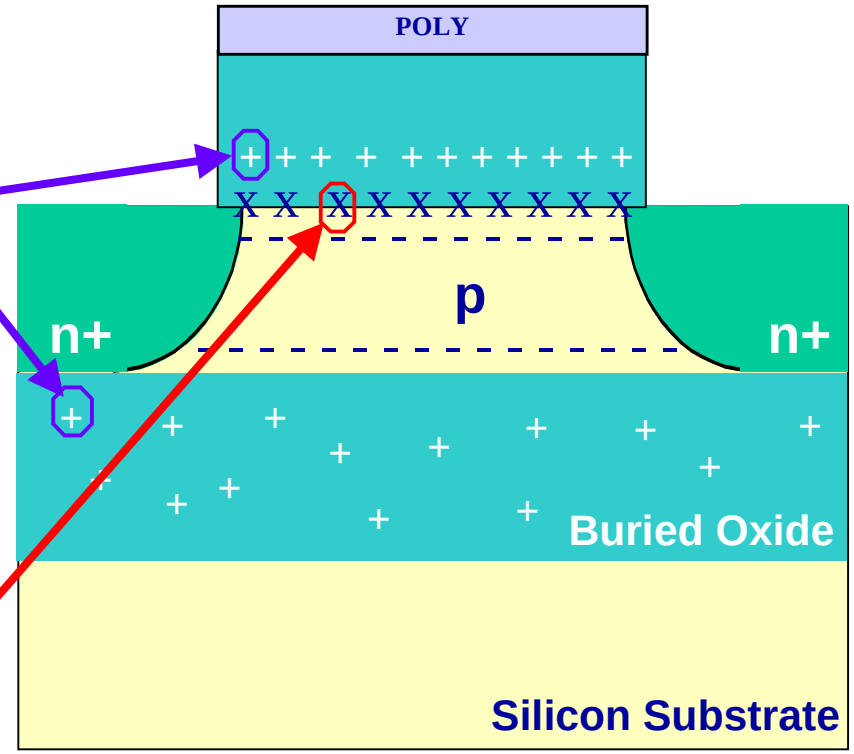
- Radiation source and oxide field dependent



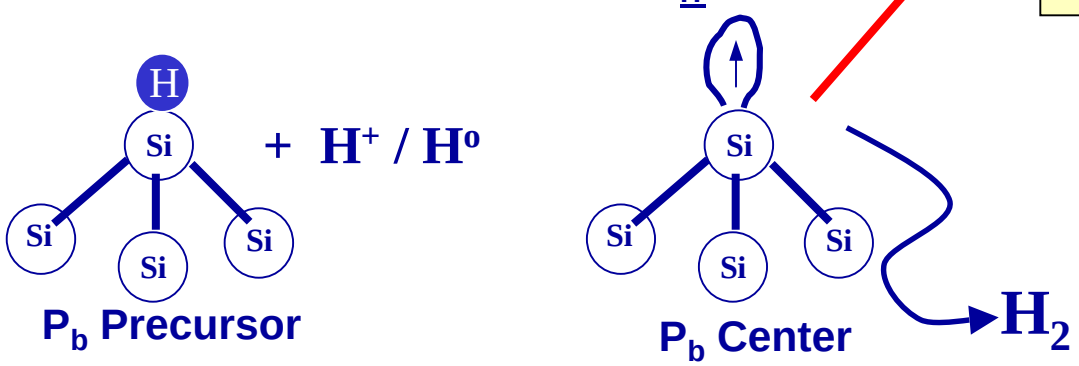
Total Dose Defects in MOS Devices

Hole Trapping - N_{OT}





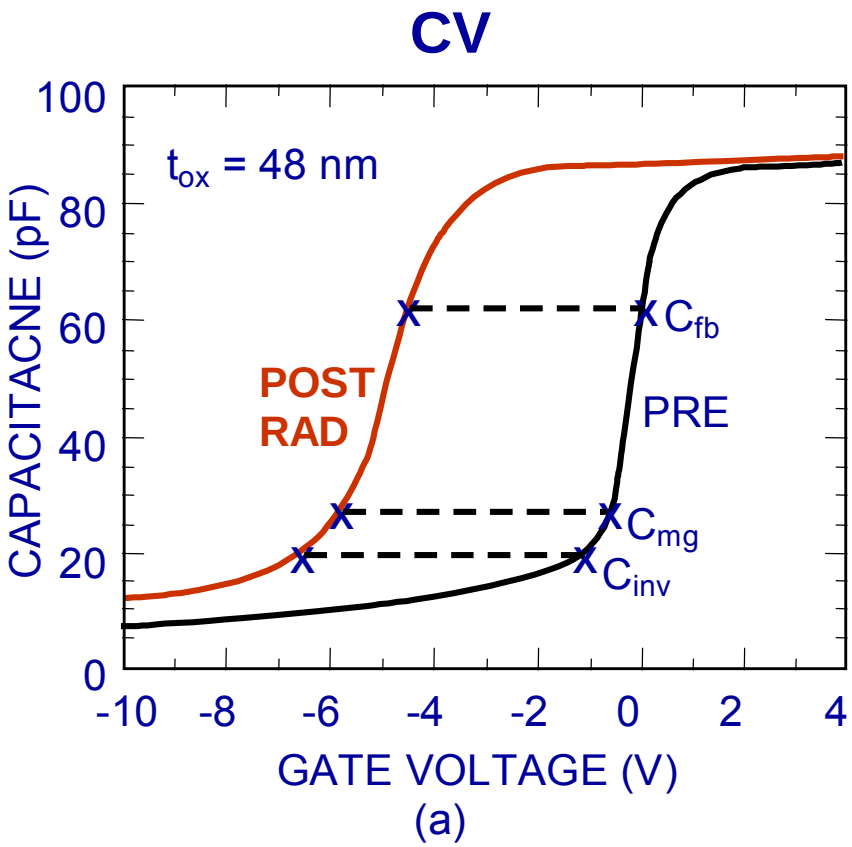
Interface Trap Formation - N_{IT}

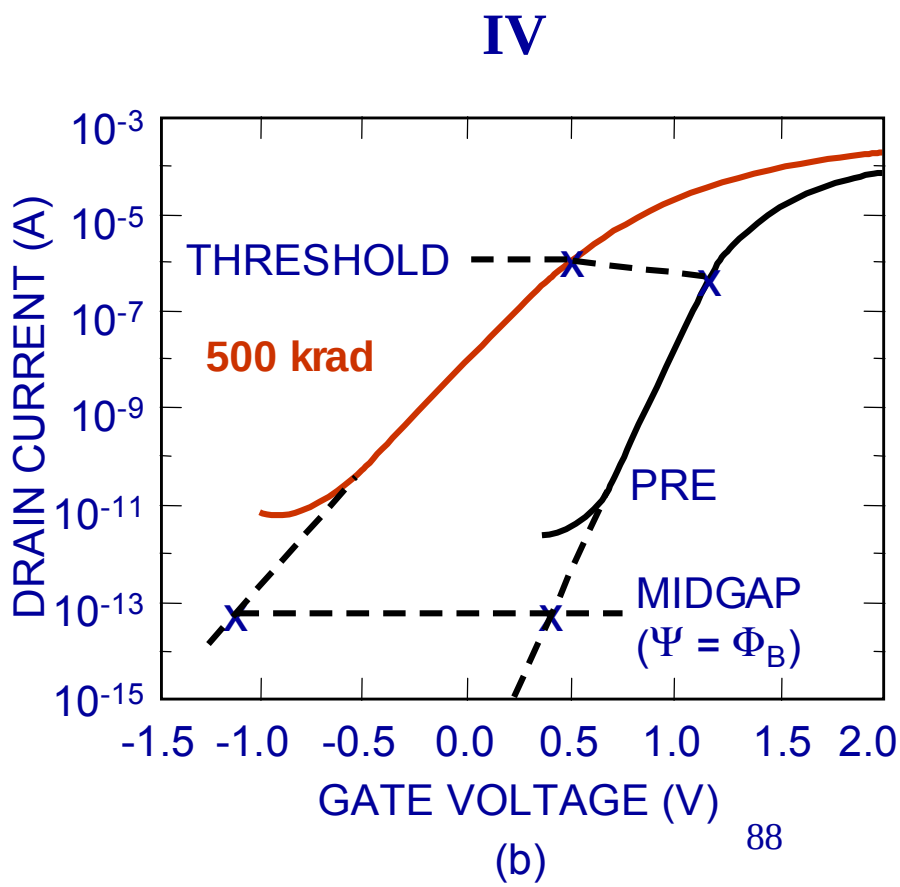


Radiation Damage Participants

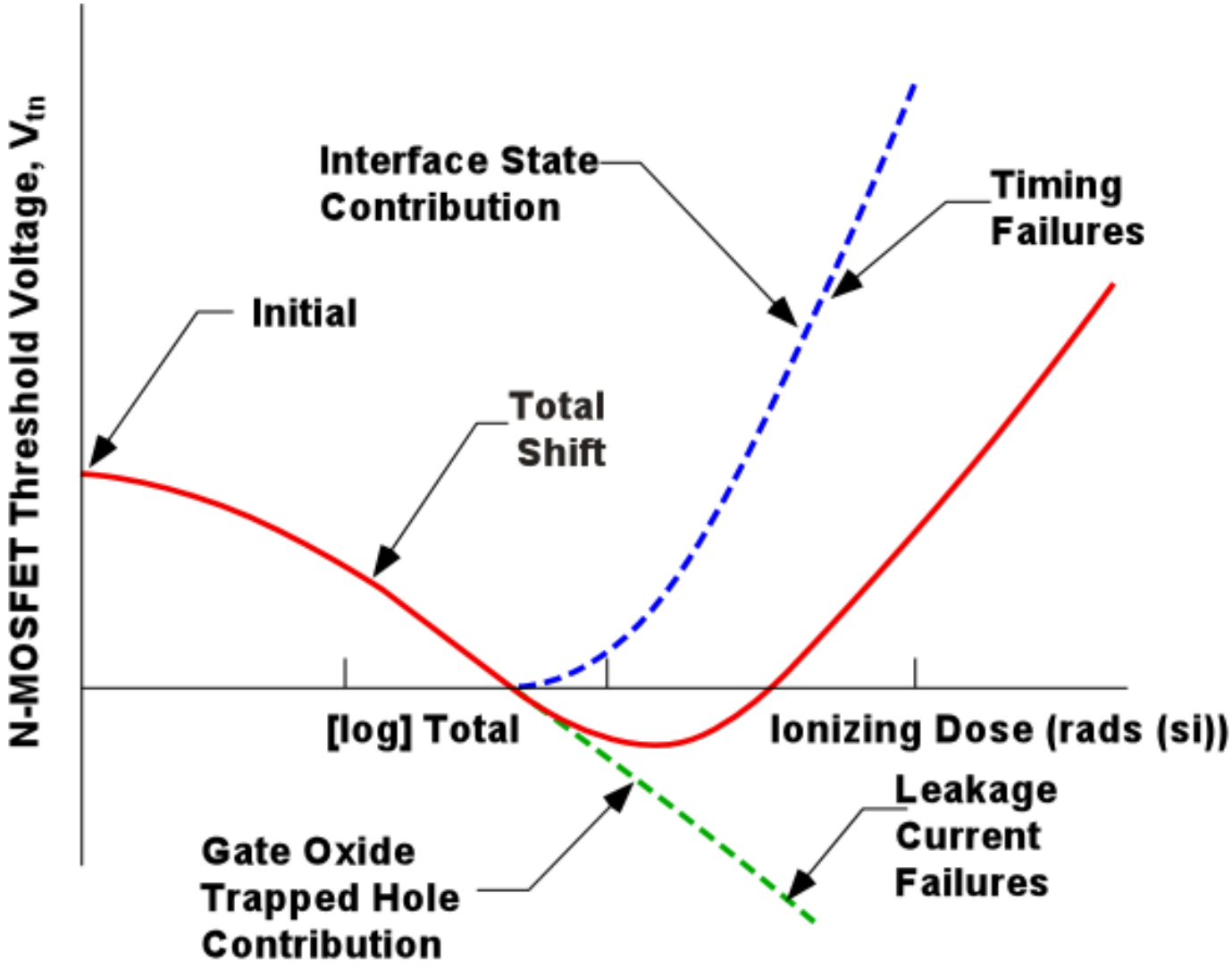
E', P_b, P_b H, E'H, H^+, H^0, H_2, h^+

Influence of Hole Traps and Interface Traps on CV and IV Curves





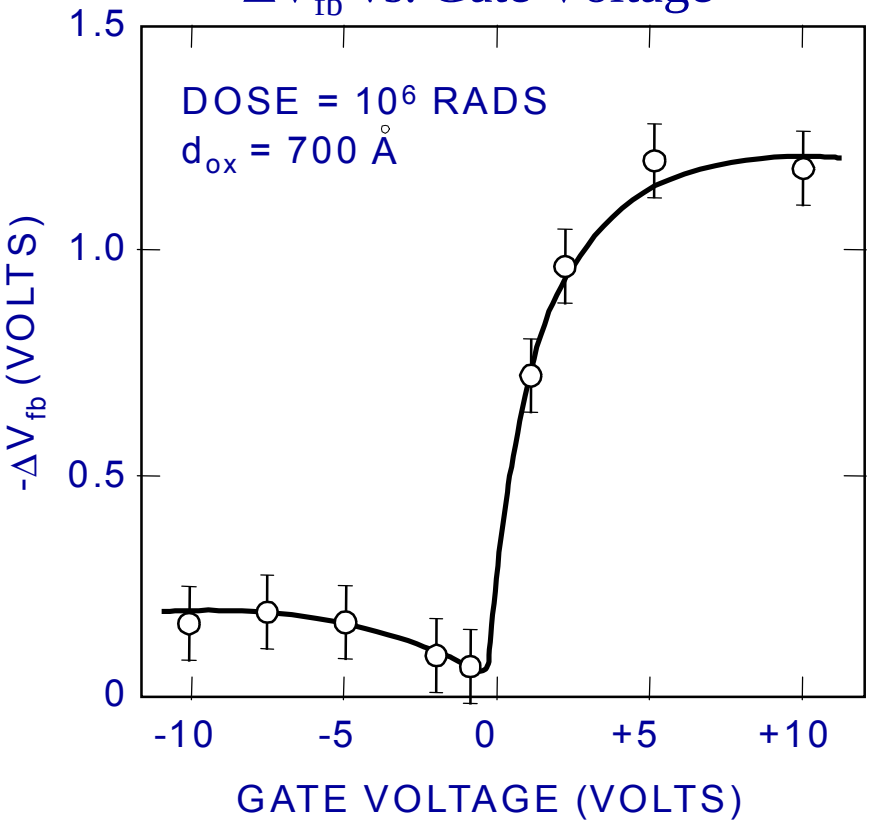
Influence of Interface and Oxide Trapped Charge



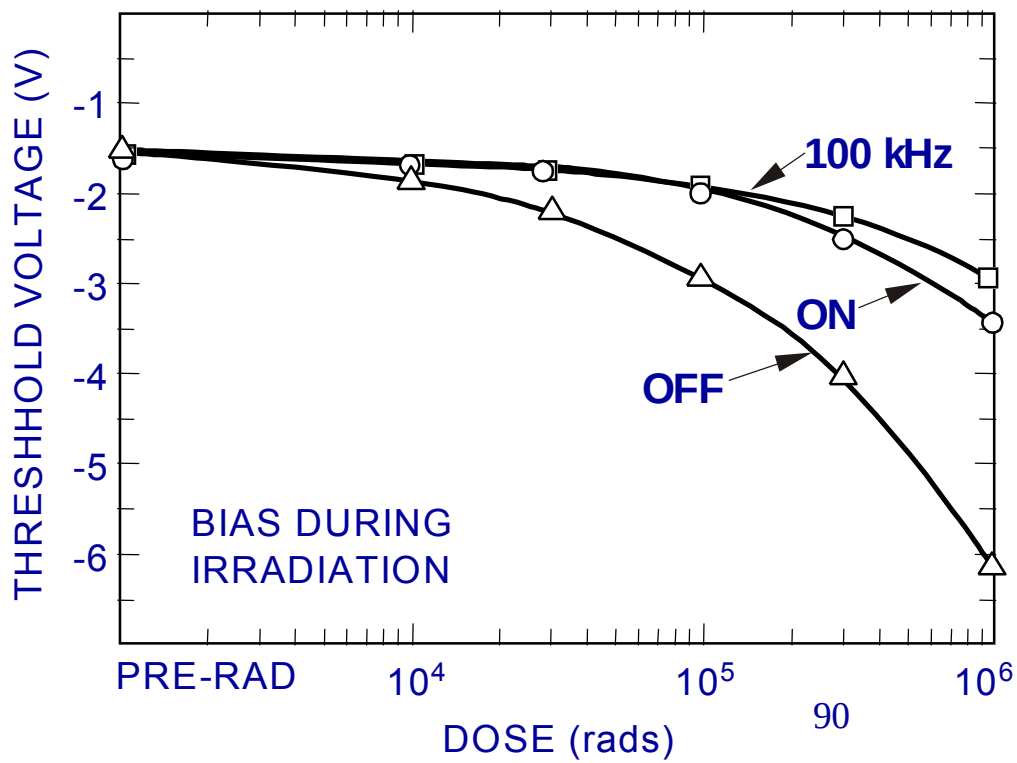
Effects of Bias

- **Bias has a strong influence on the radiation response**
- **Powering down a device can sometimes improve radiation response**
- **A powered device is not always worst case**

ΔV_{fb} vs. Gate Voltage

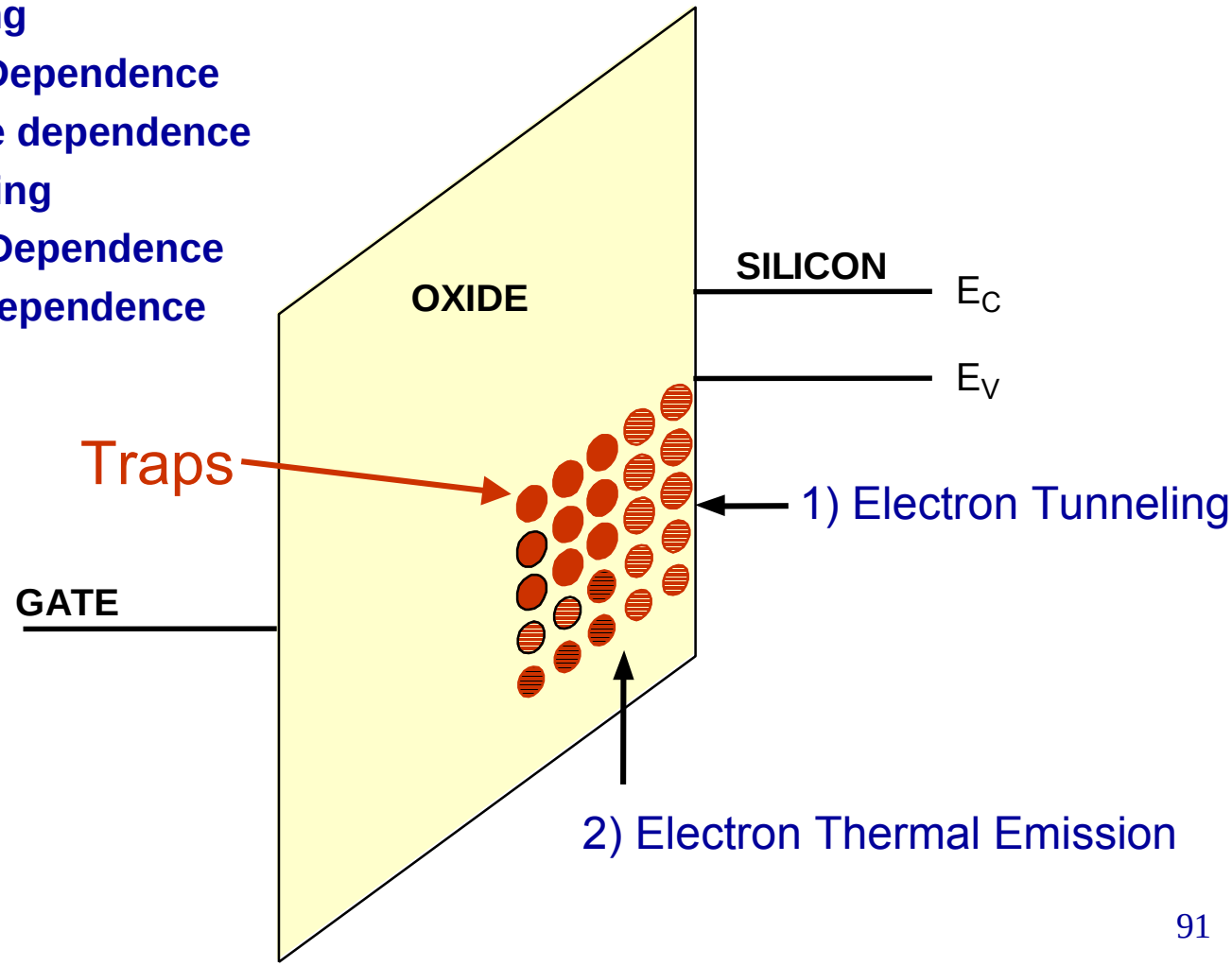


Dynamic vs. Static Bias



Annealing

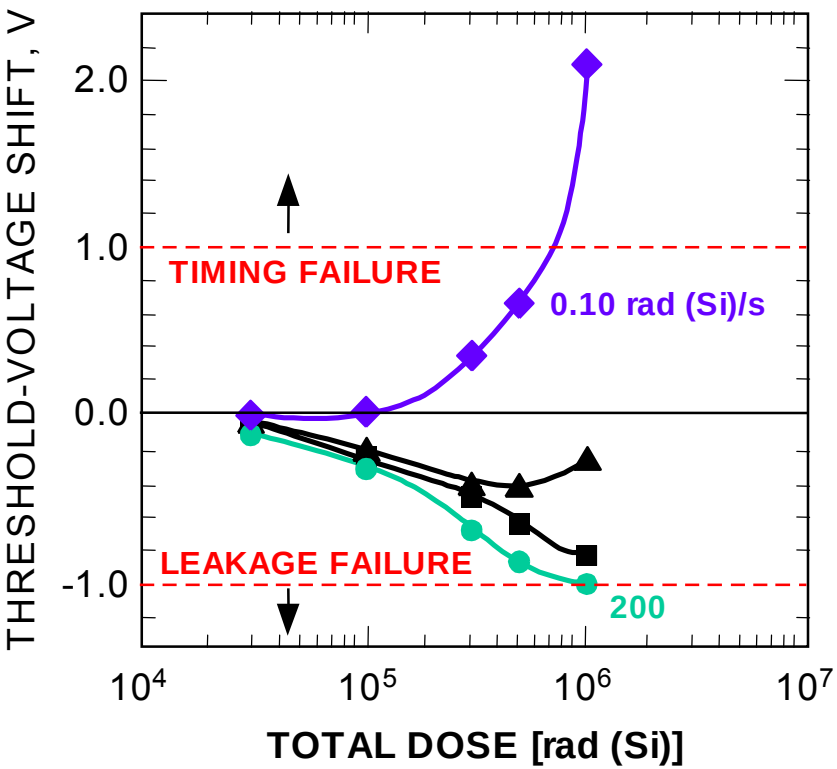
1) **Tunnel Annealing**
   - **Spatial Dependence**
   - **Log time dependence**
2) **Thermal Annealing**
   - **Energy Dependence**
   - **Temp. Dependence**



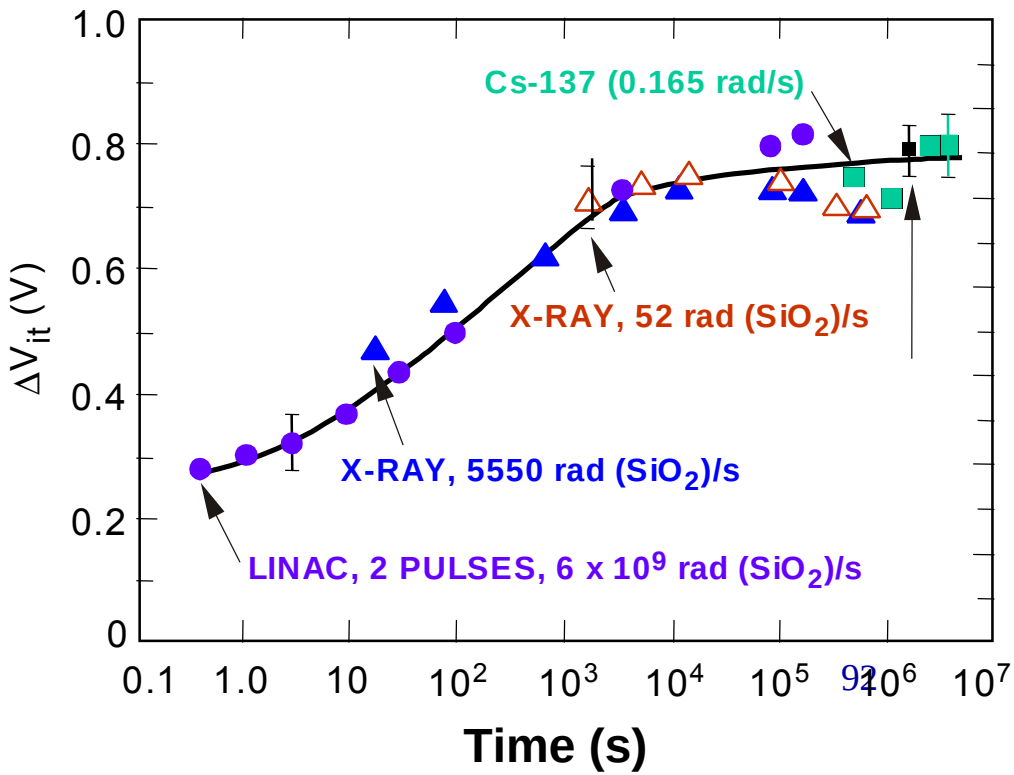
Dose Rate Effects

- Hole traps and interface traps build-up and anneal on different time scales.
- Irradiation at different dose rates can produce different failure mechanisms and total dose hardness.
- When time is considered, dose rate effects in CMOS disappear.

ΔV_{th} vs. Dose



ΔV_{it} vs. Time



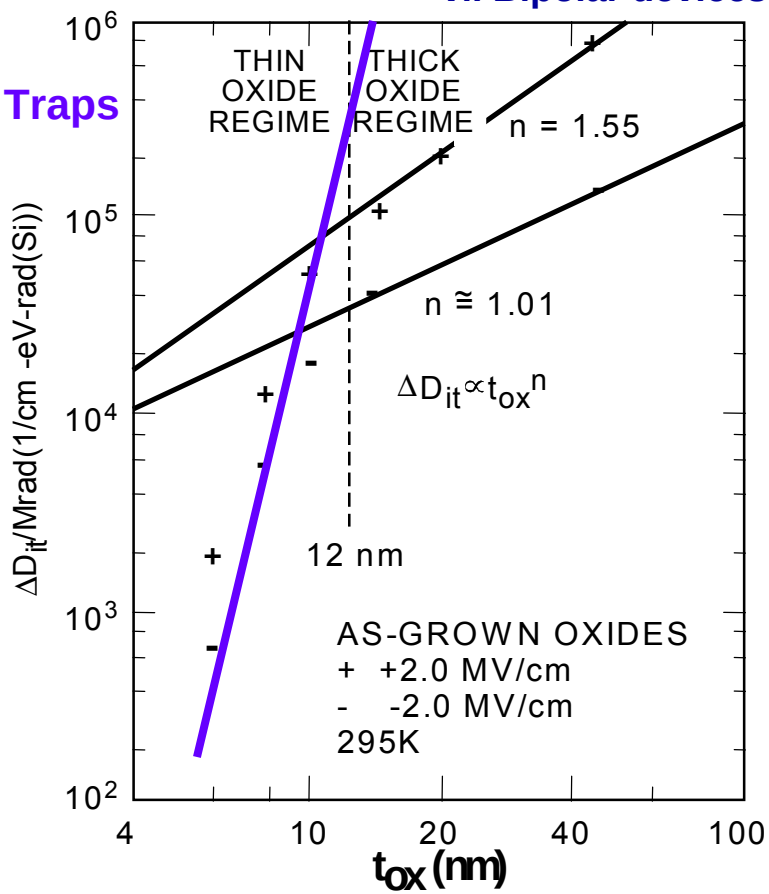
Oxide Thickness

Trapping drops off steeply in thin oxides but there are still problems:

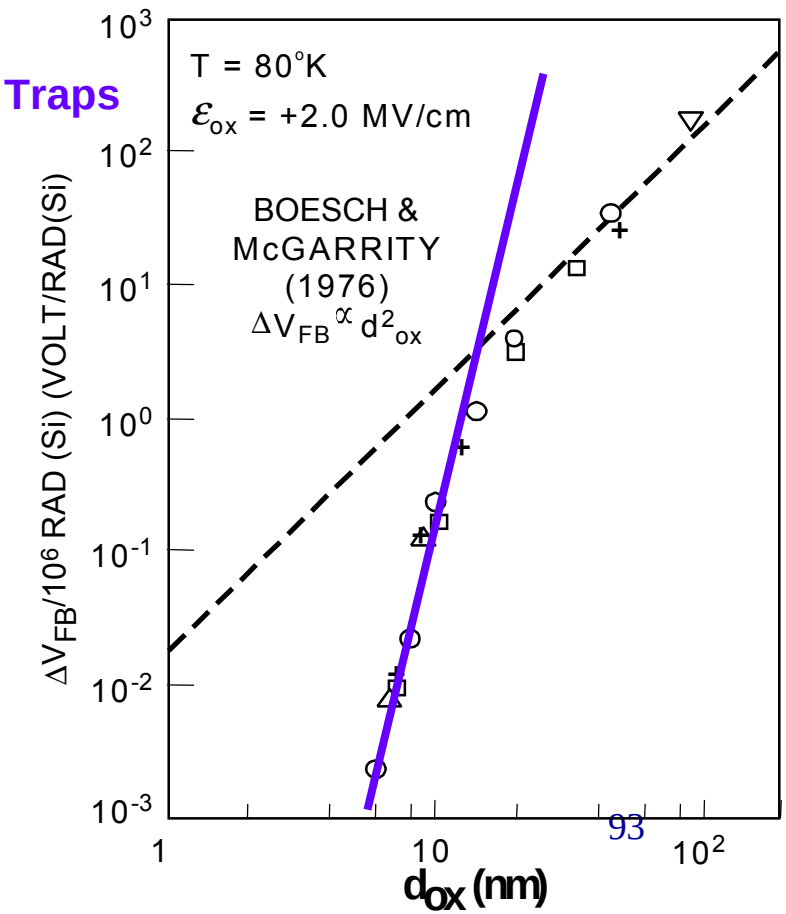
1) Radiation Induced Leakage Currents (RILC) in ultrathin oxides

2)Thick oxides:
- **i. Power MOSFETs**
- **ii. Field oxides**
- **iii. Silicon-on-insulator (SOI) buried oxides**
- **vi. Bipolar devices.**

Interface Traps

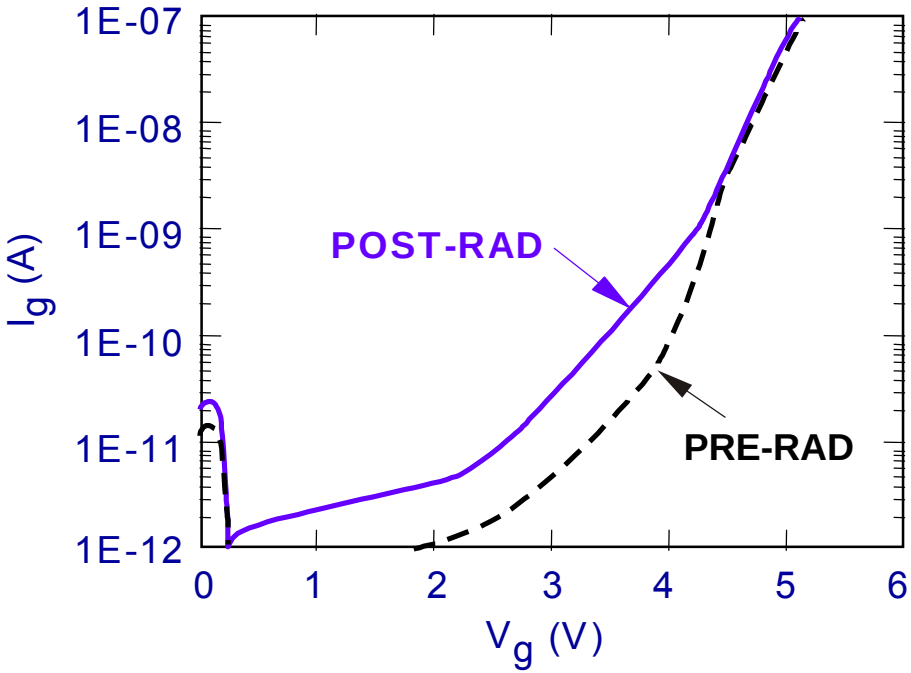


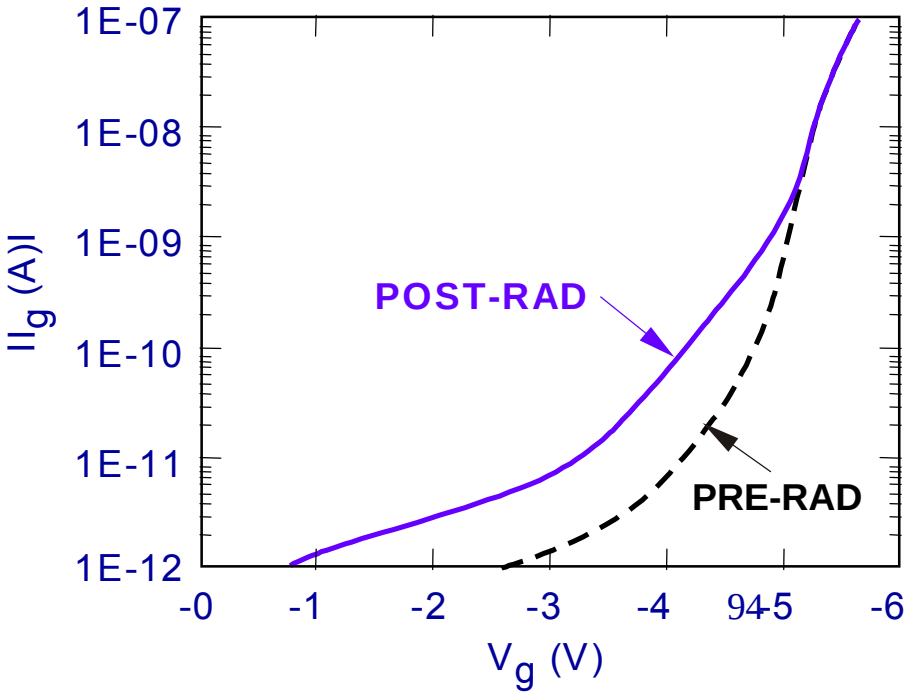
Hole Traps



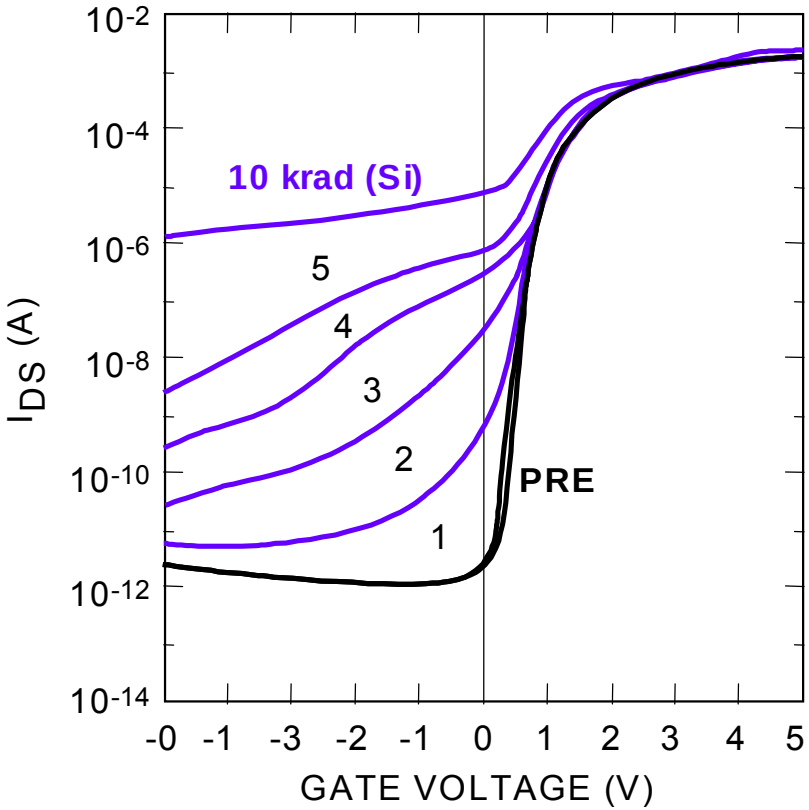
Radiation Induced Leakage Current (RILC)

- **Reported in thin oxides (<10 nm) at high doses (>1Mrad).**
- **Similar to stress induced leakage current (SILC).**
- **Thought to be due to trap assisted tunneling.**
- **Possible failure mechanism for flash memories.**

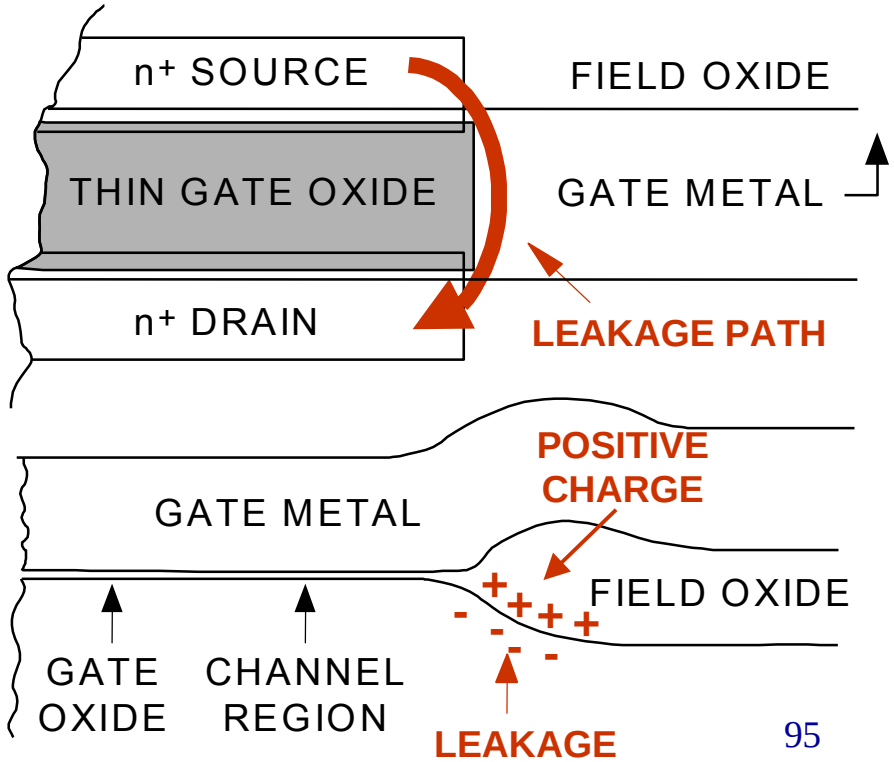




Field Oxide Leakage



- **Field oxides thick and poorly controlled.**
- **Dominant failure mechanism for commercial processes.**
- **Geometry is critical.**



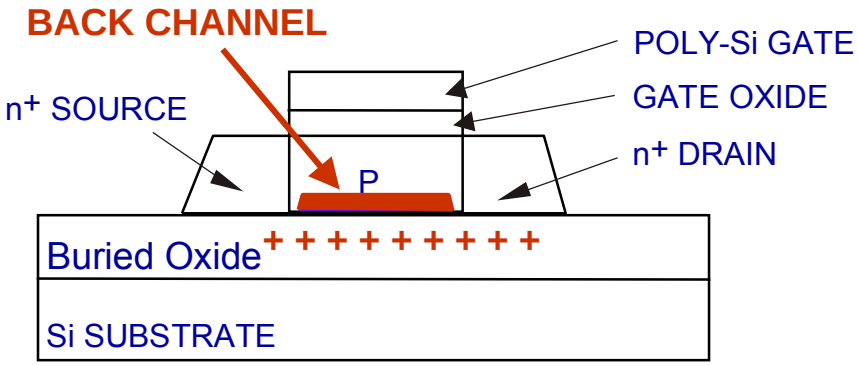
Silicon-on-Insulator (SOI)

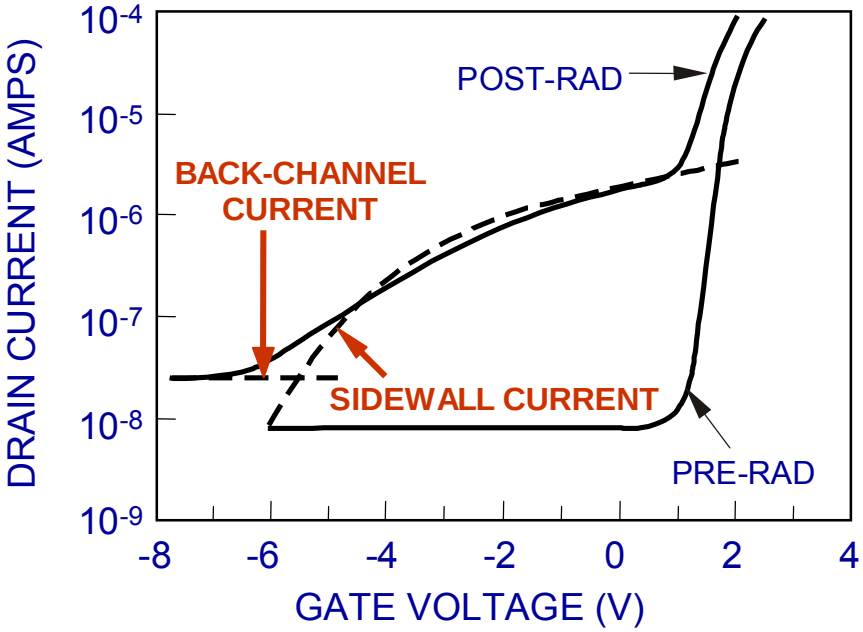
SOI Advantages:

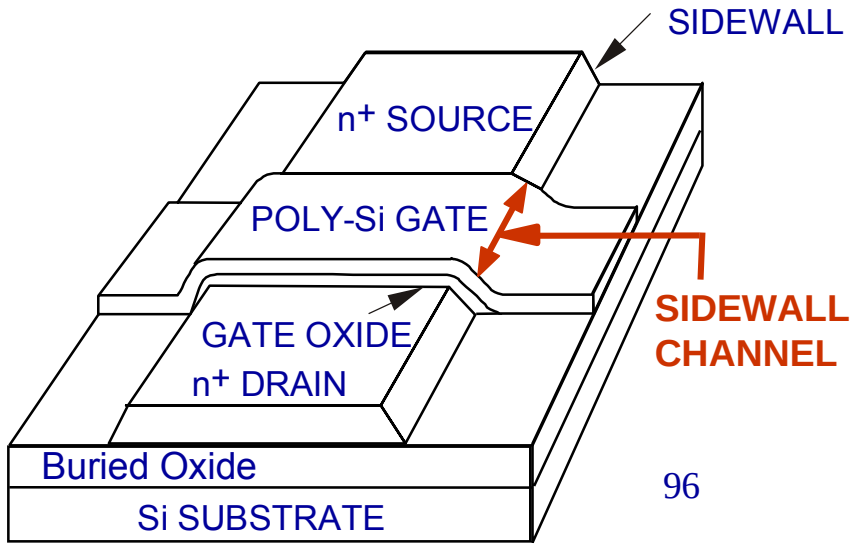
1. **Total Isolation**
2. **SEU Immune**
3. **High Speed**
4. **Low Power**
5. **Latchup Eliminated**

New SOI Total Dose Leakage Paths:

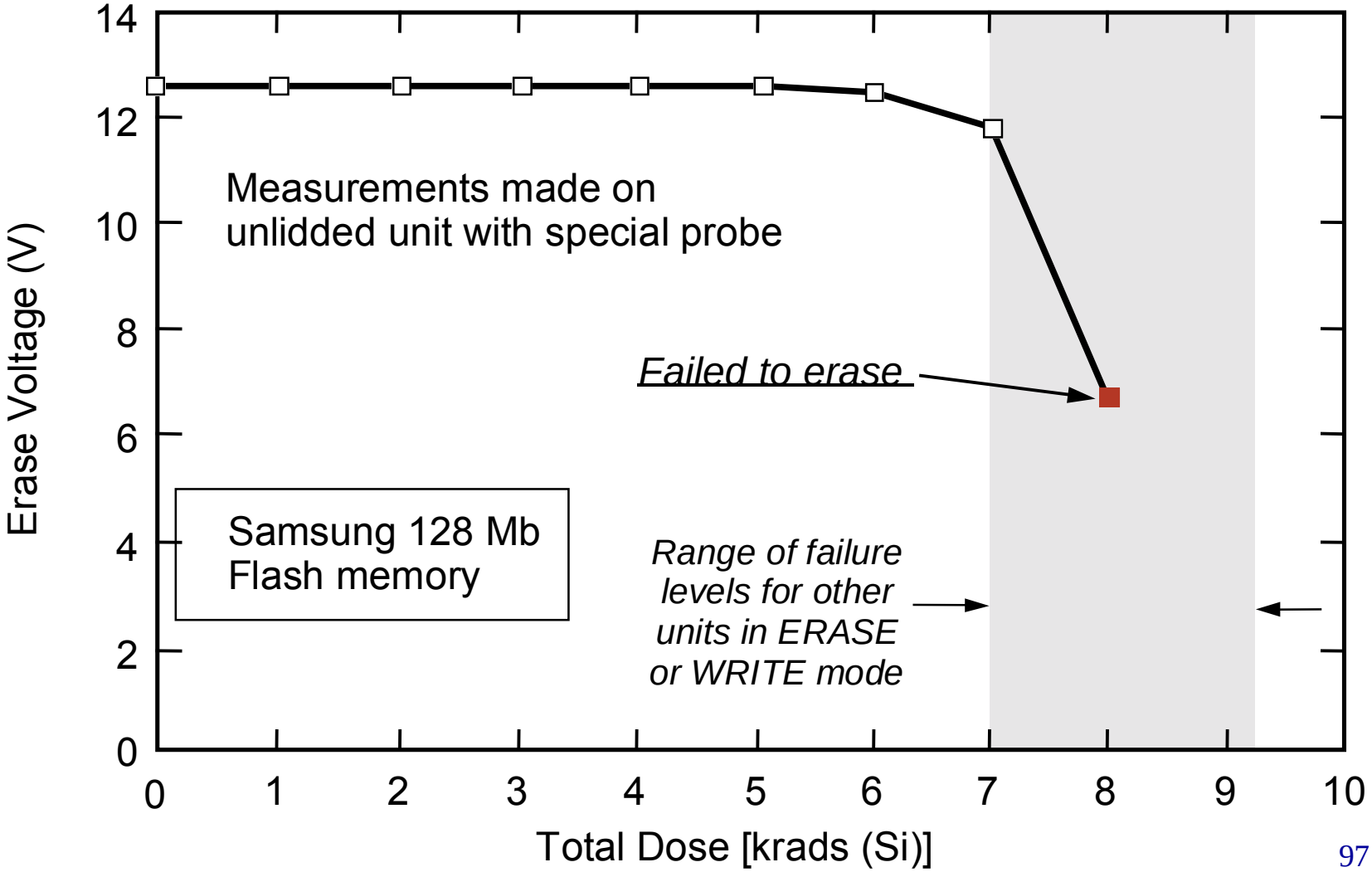
1. **Back Channel Leakage**
2. **Sidewall Leakage**





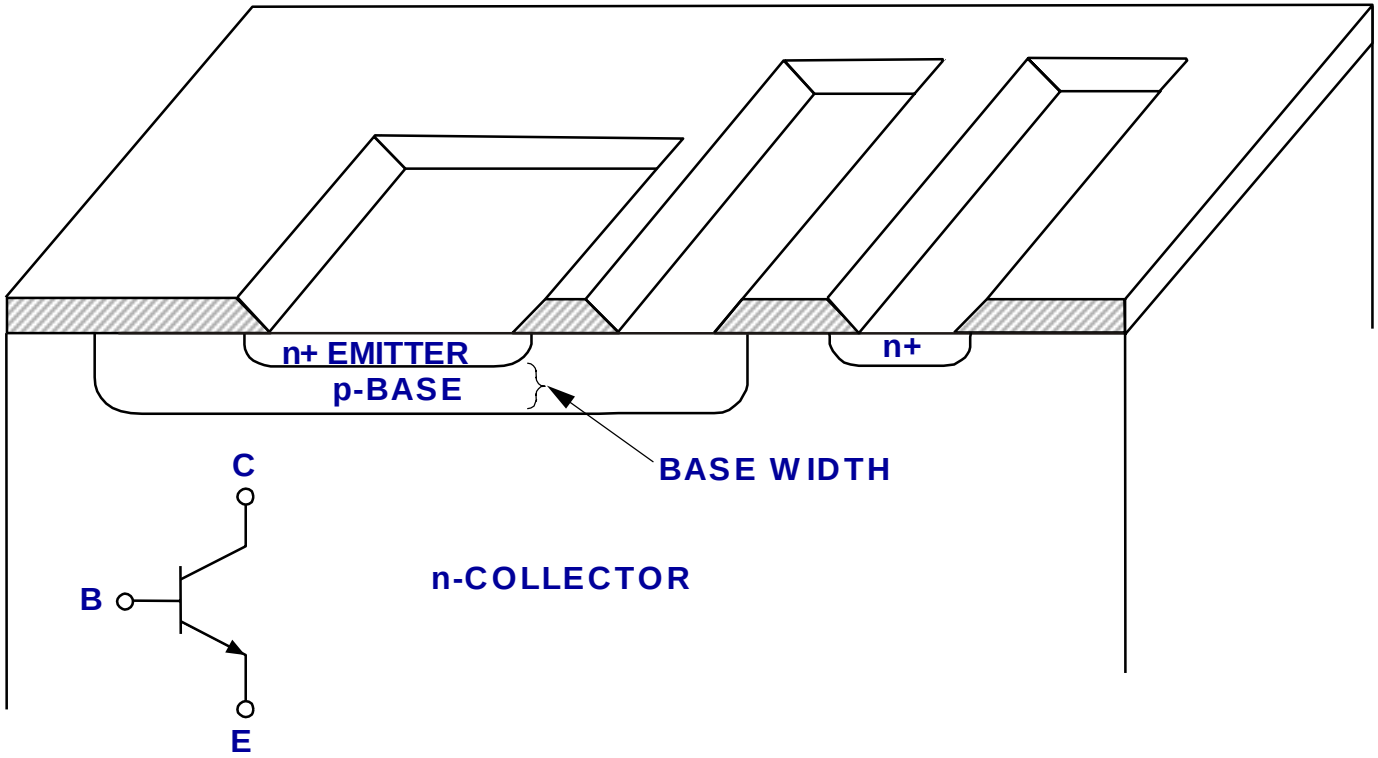


Flash Memories

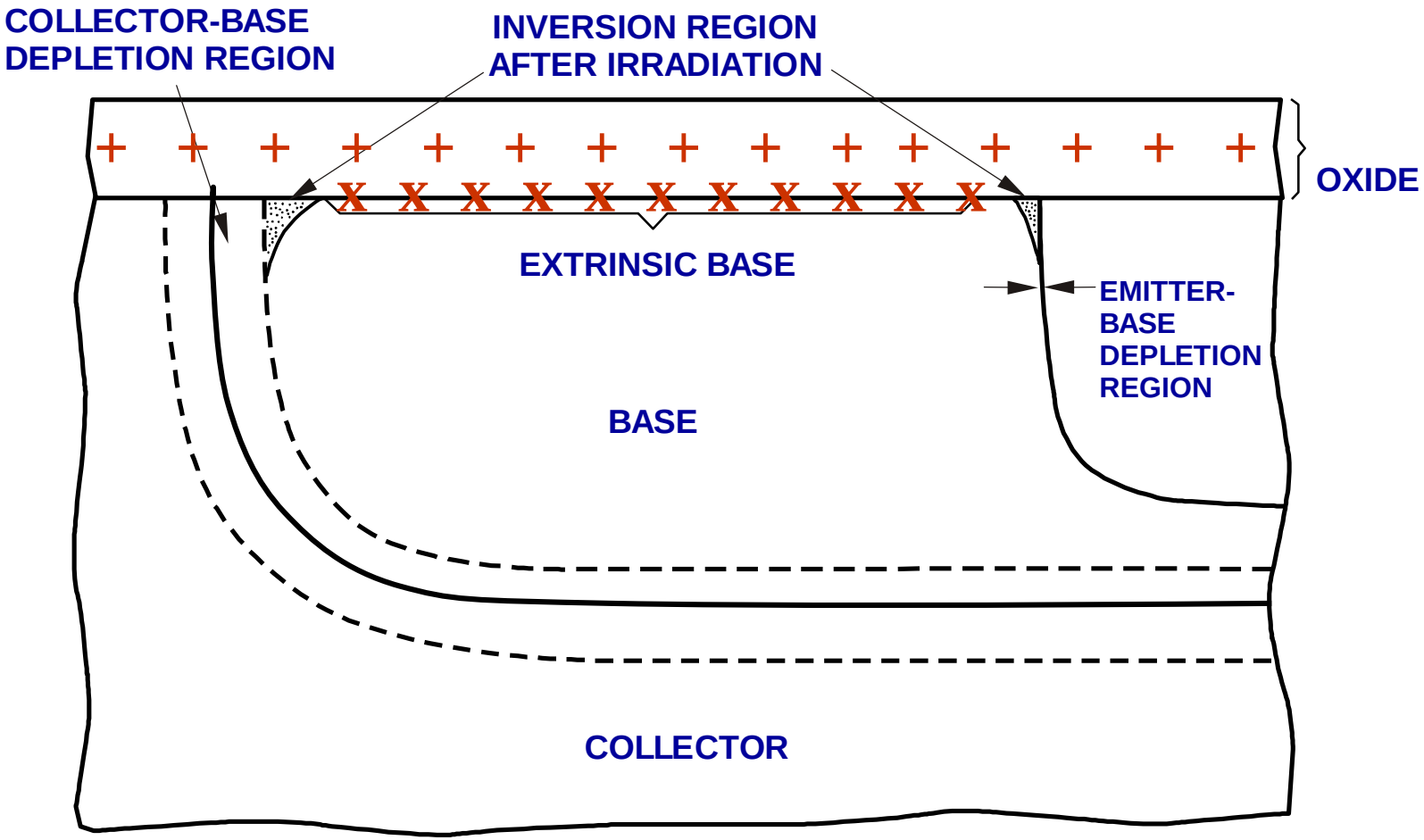


Linear BJT

Structure of a bipolar transistor

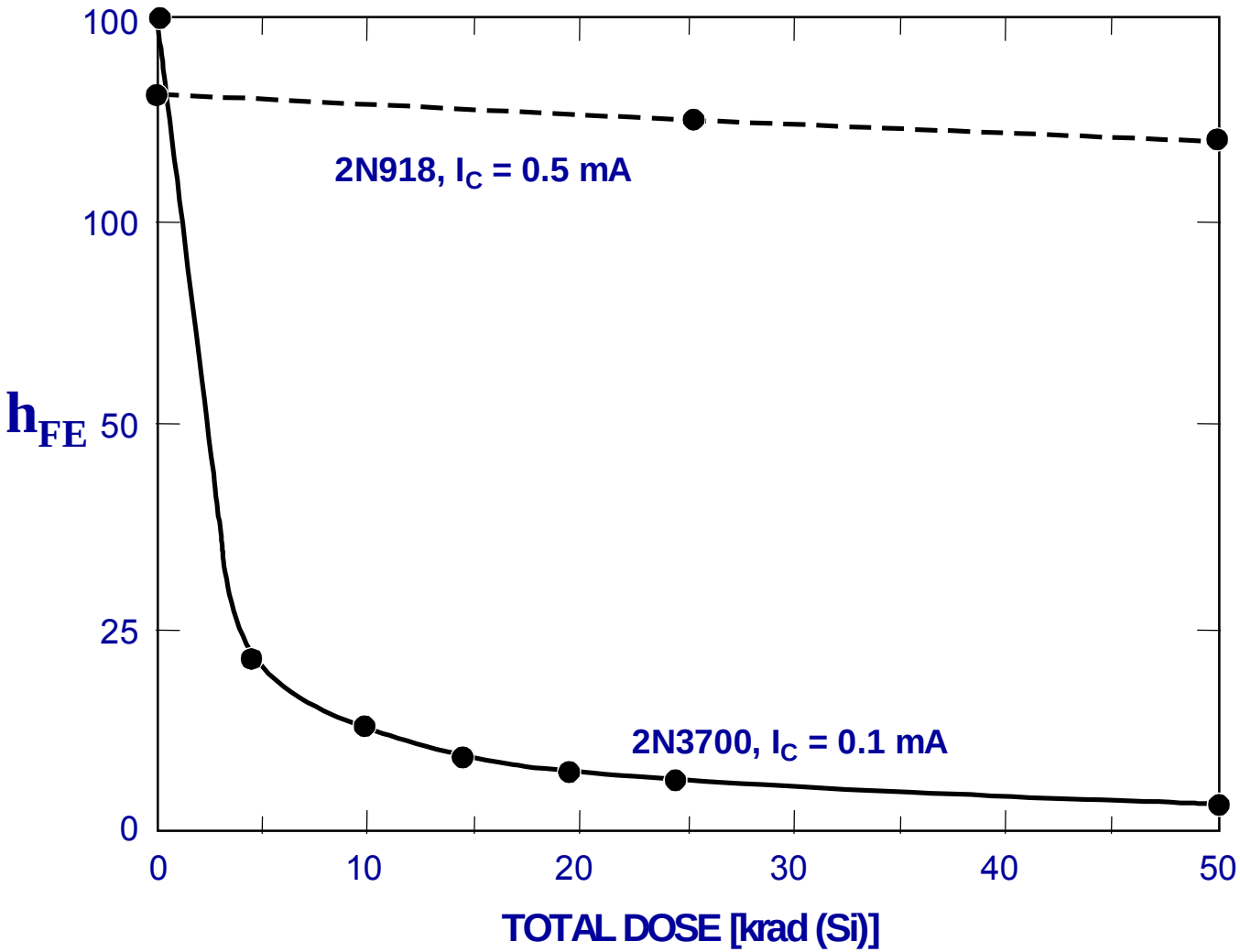


Bipolar Transistor: Gain Degradation

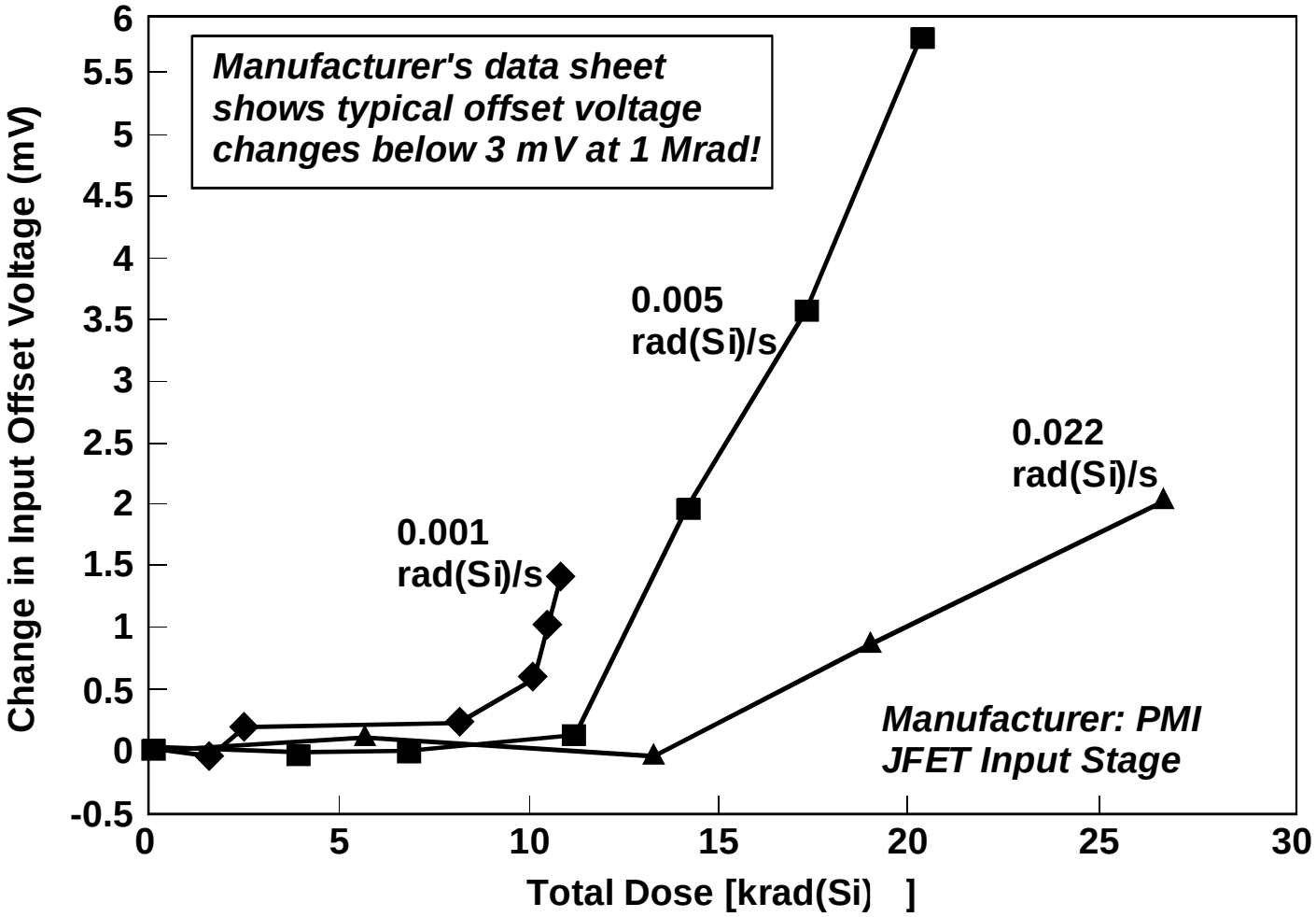


- Charge trapped at and near the interface above the base region can degrade gain and increase leakage.

Gain Degradation of Two Transistor Types Used on Cassini

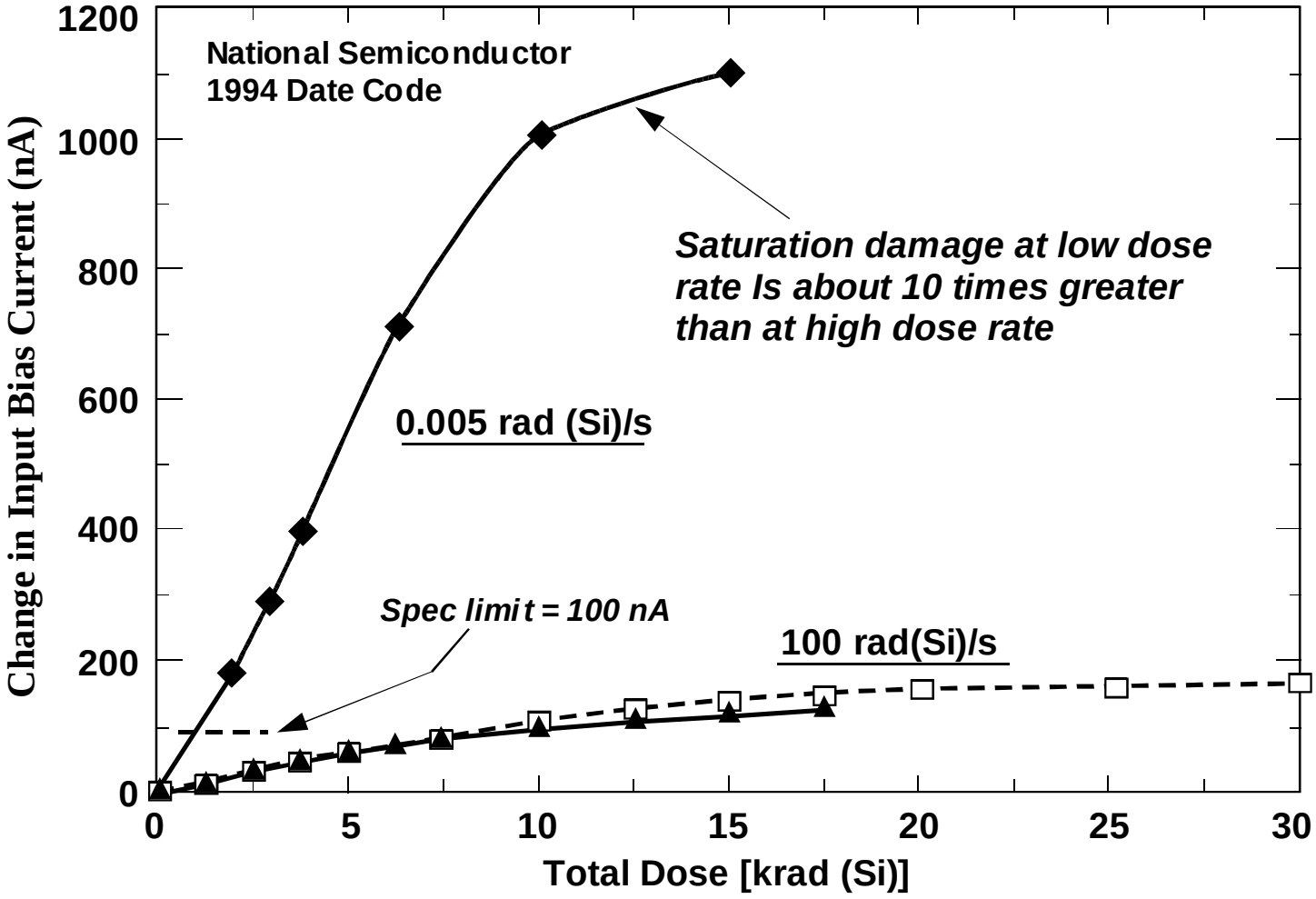


Extremely Low Dose Rate Sensitivity (ELDRS)

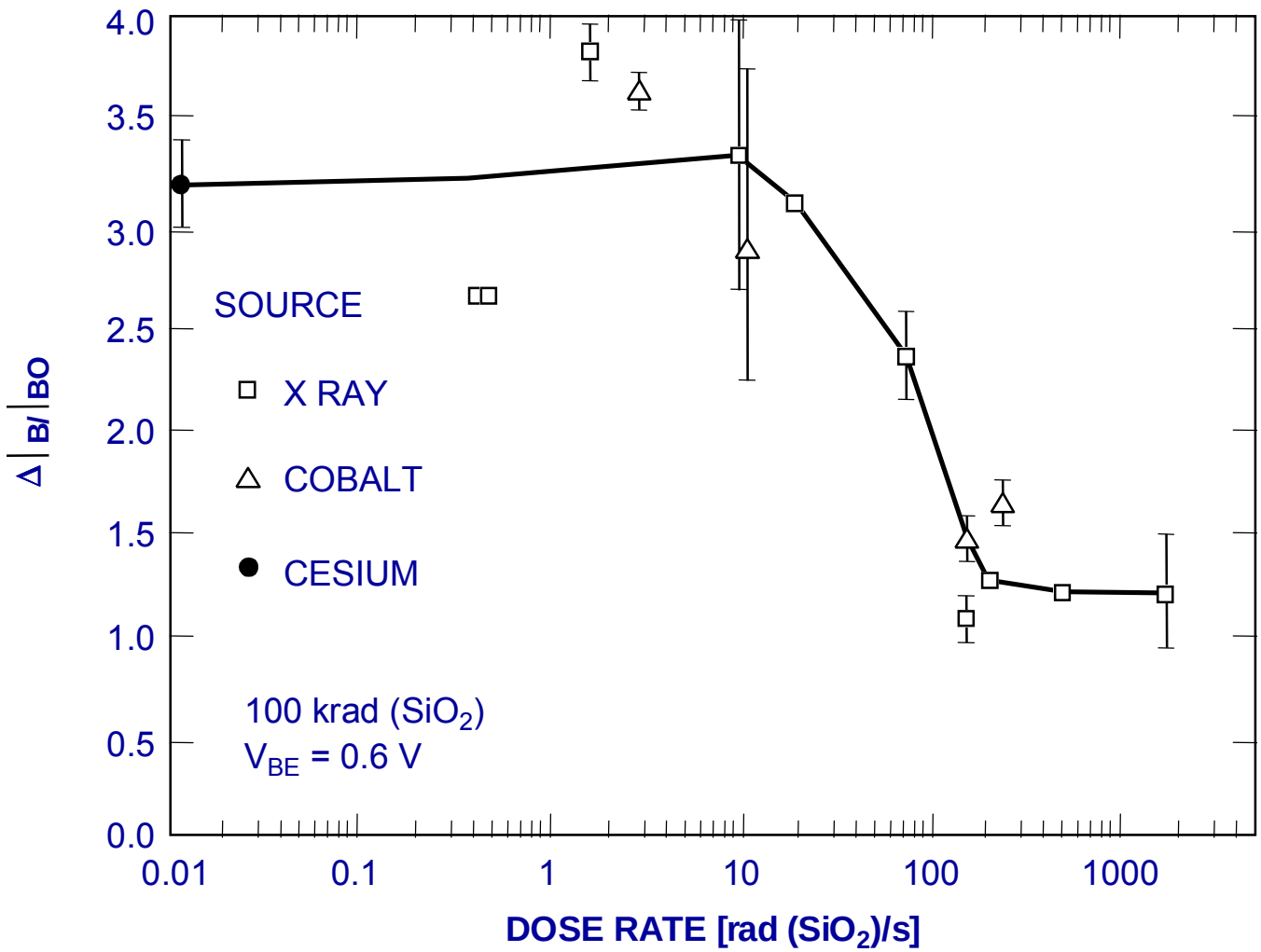


- Some bipolar device show extreme degradation at low dose rates.

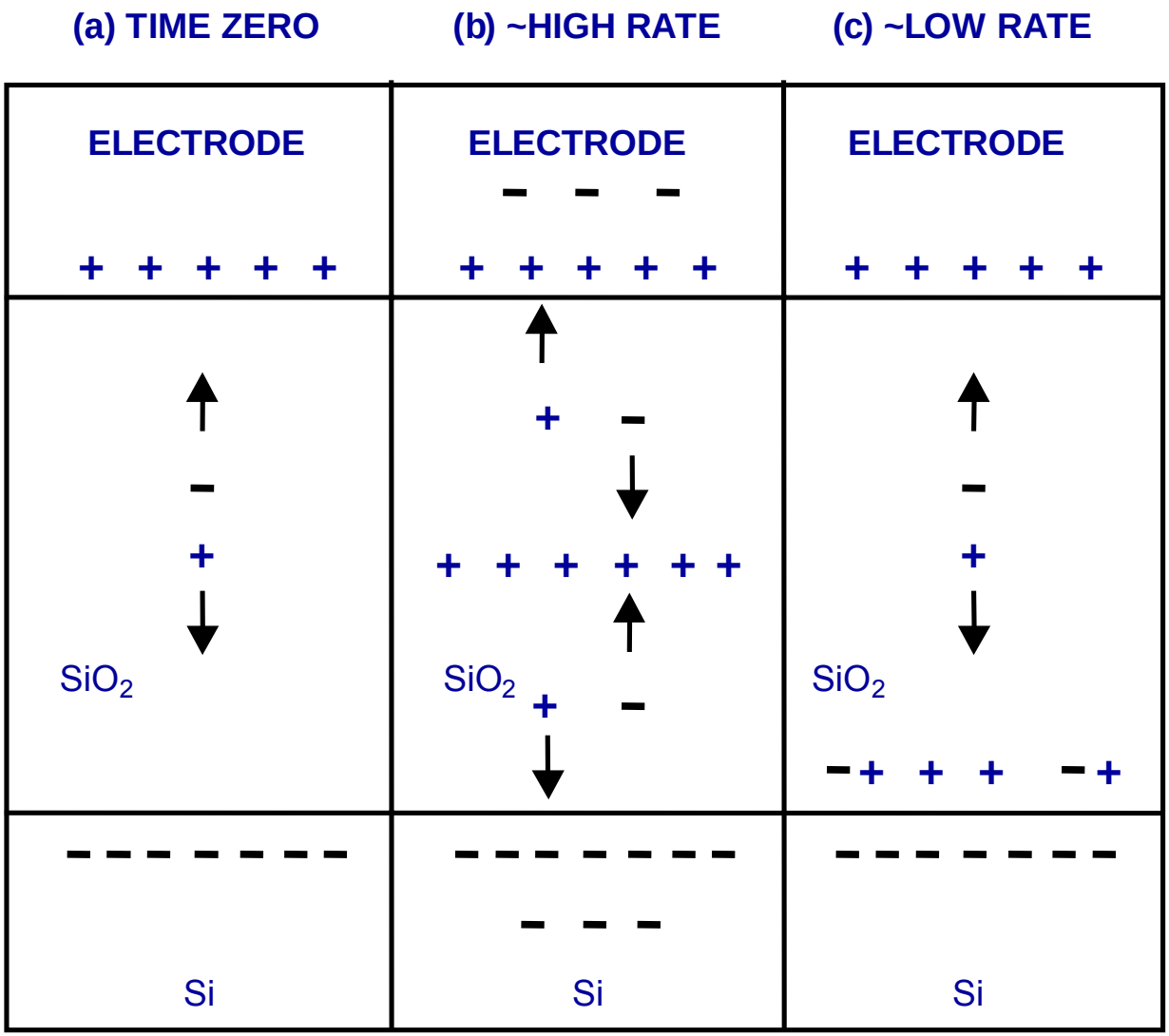
ELDRS: Effect of Dose Rate on I_b for LM111 Comparator



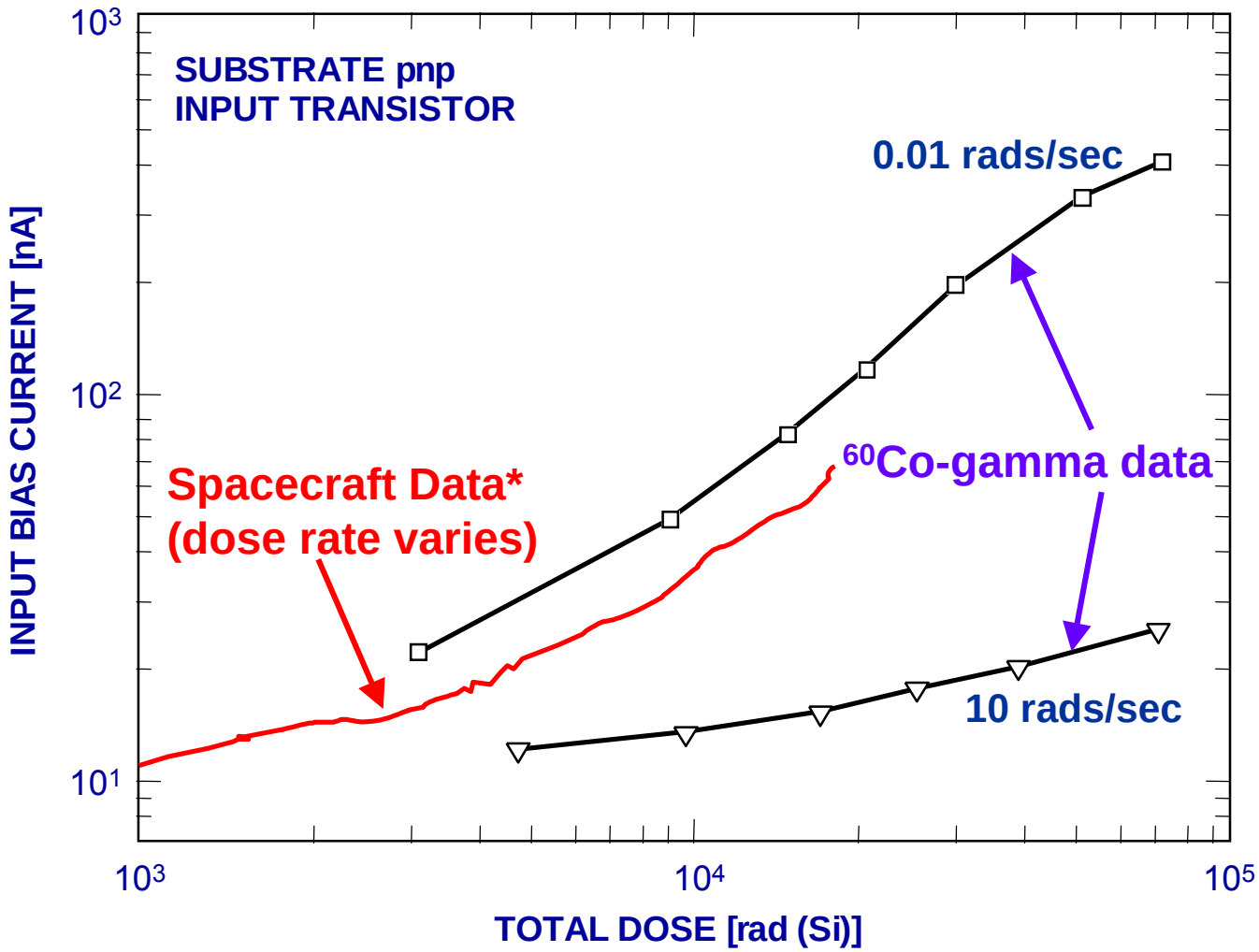
ELDRS


4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.01
0.1
1
10
100
1000
Δ|B/|BO
DOSE RATE [rad (SiO2)/s]
SOURCE
X RAY
COBALT
CESIUM
100 krad (SiO2)
VBE = 0.6 V

ELDRS Degradation Model - Space Charge Effects



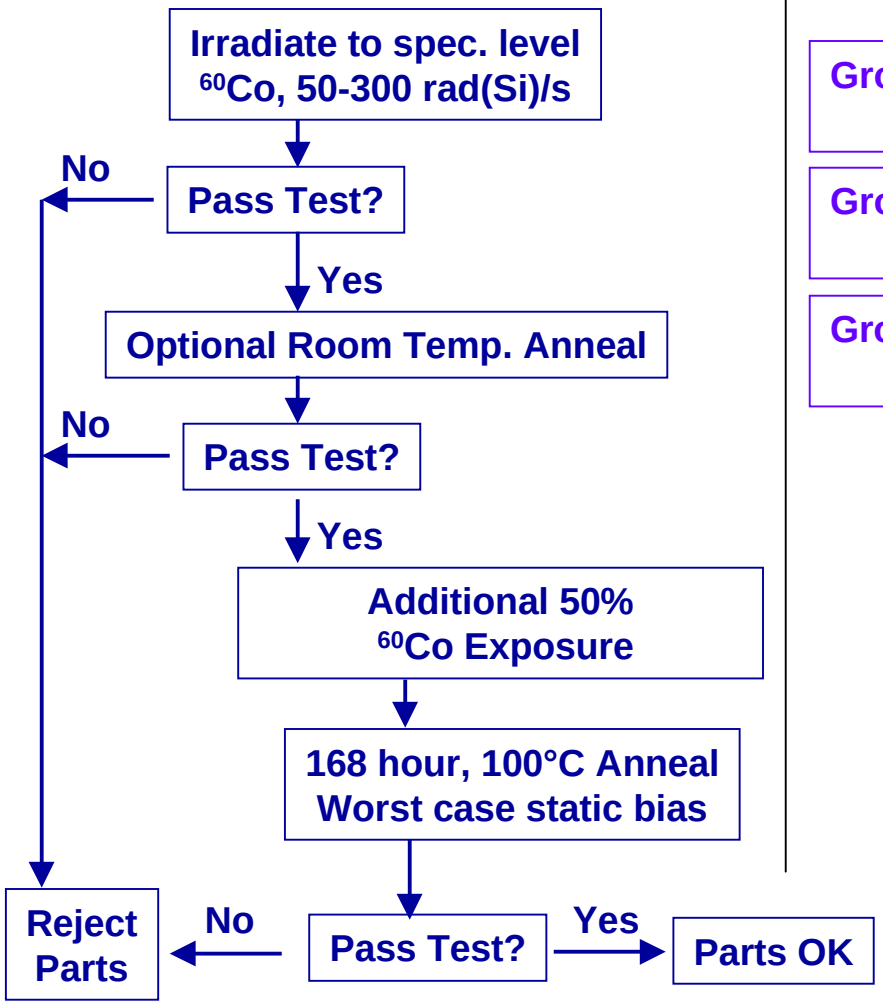
ELDRS in Space: LM124 Op-Amp



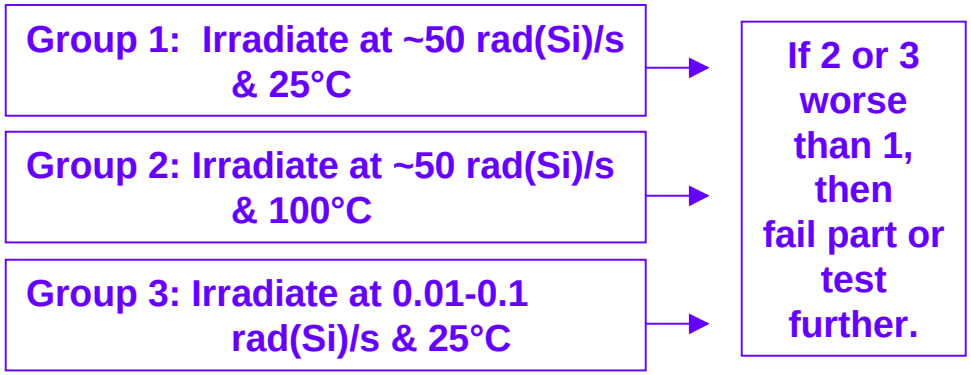
*Titus et al., IEEE Trans. Nucl. Sci. 46, 1608 (1999).

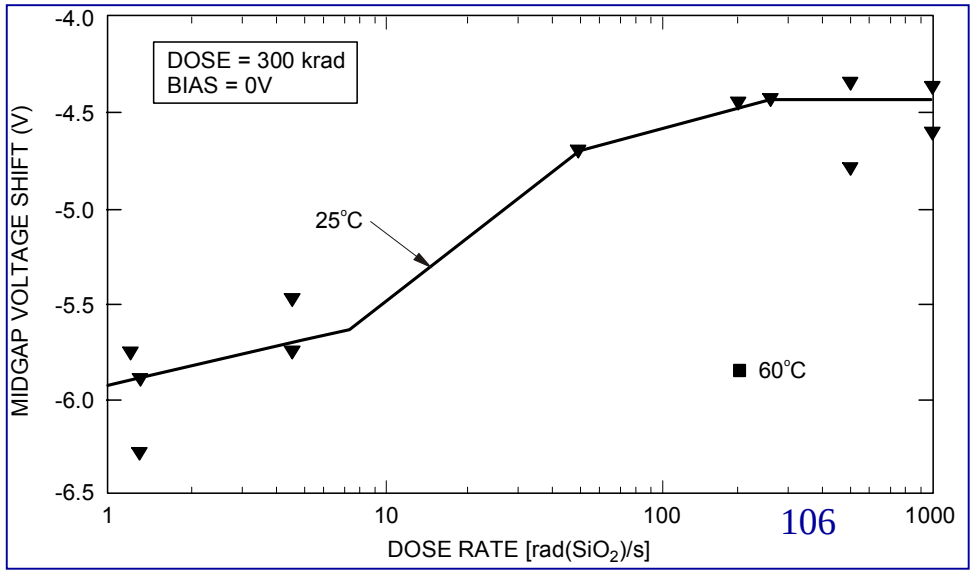
Testing

MOS Testing: MIL-STD 883D, 1019

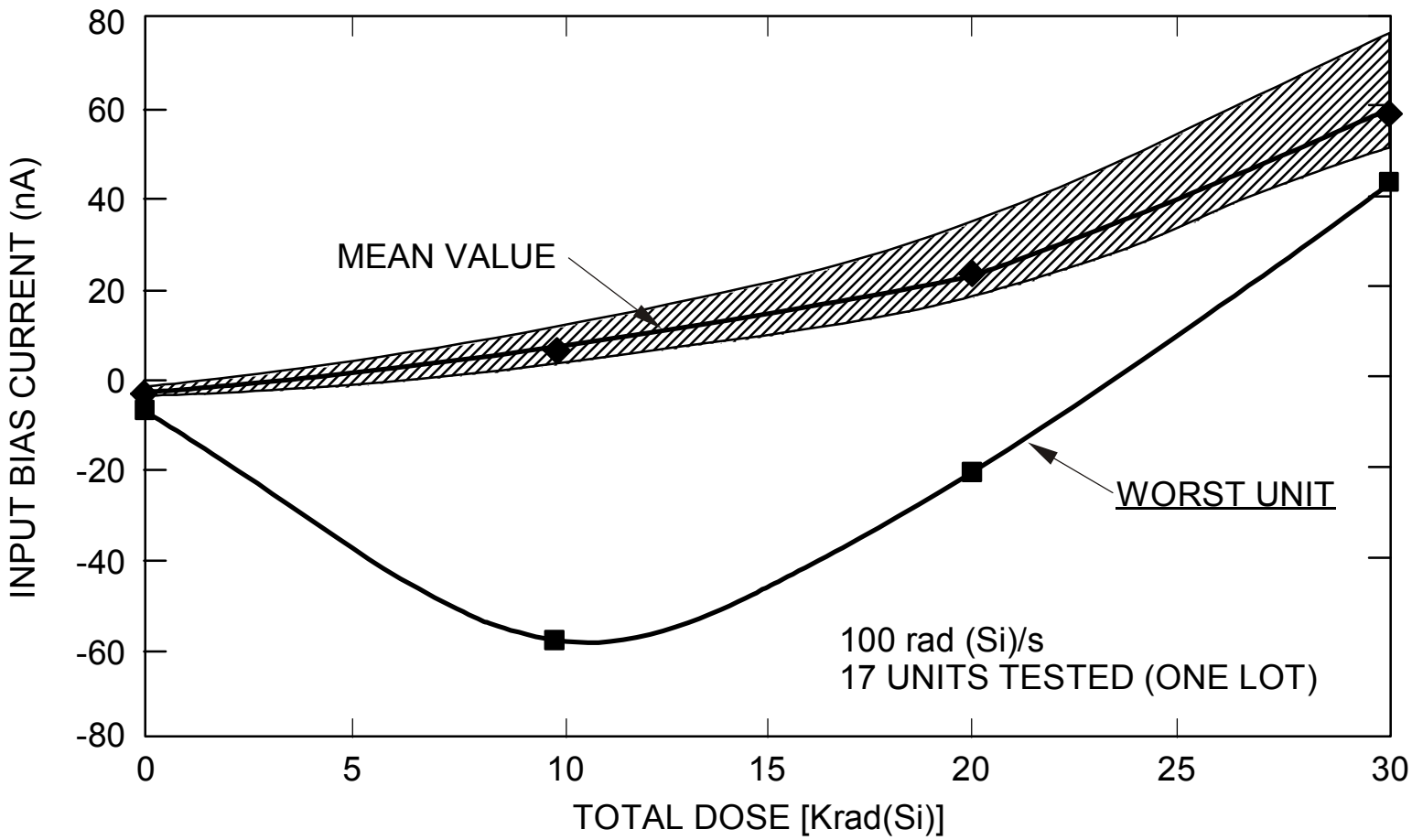


BiPolar/ELDR: ASTM F-1892 Pre-screen

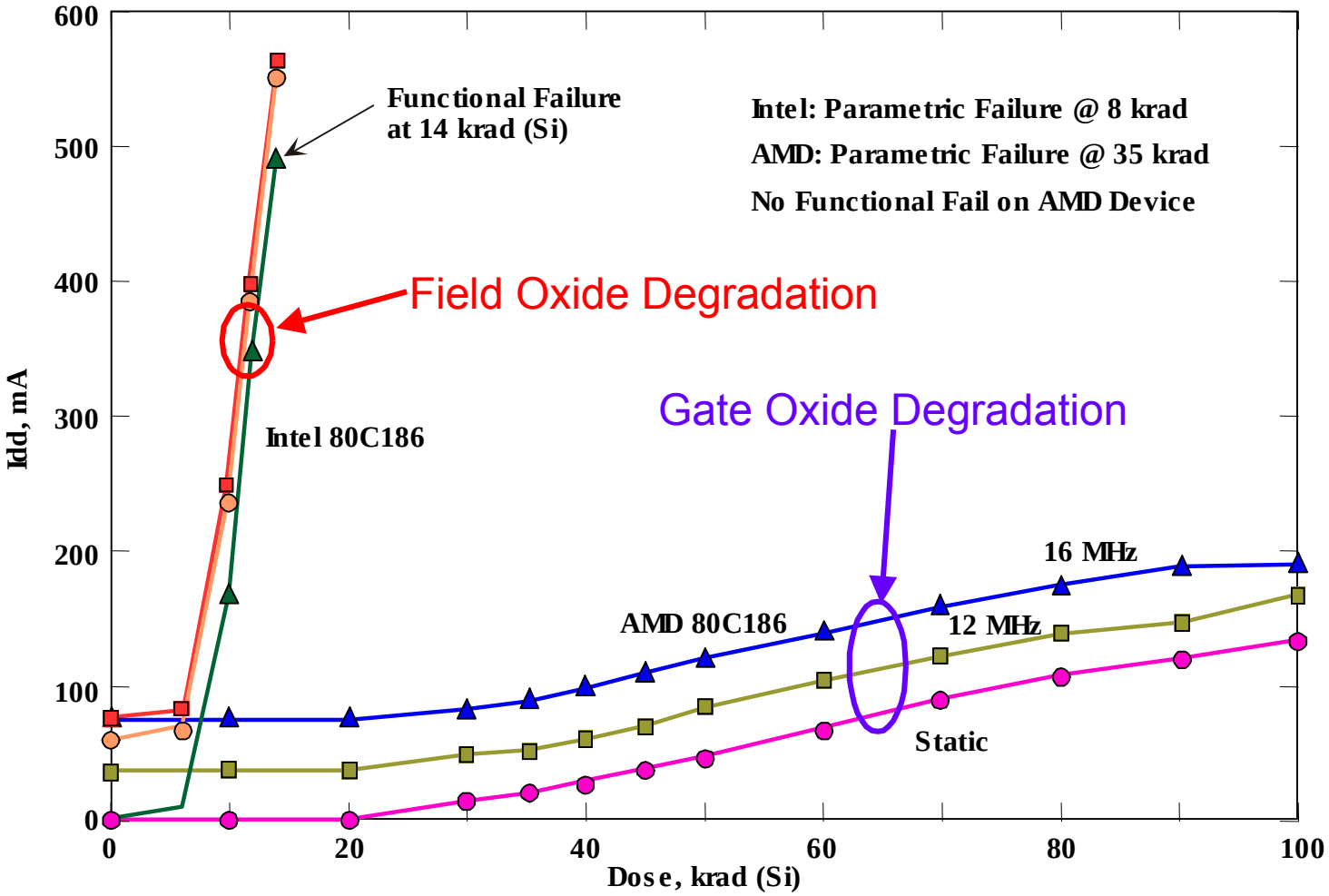




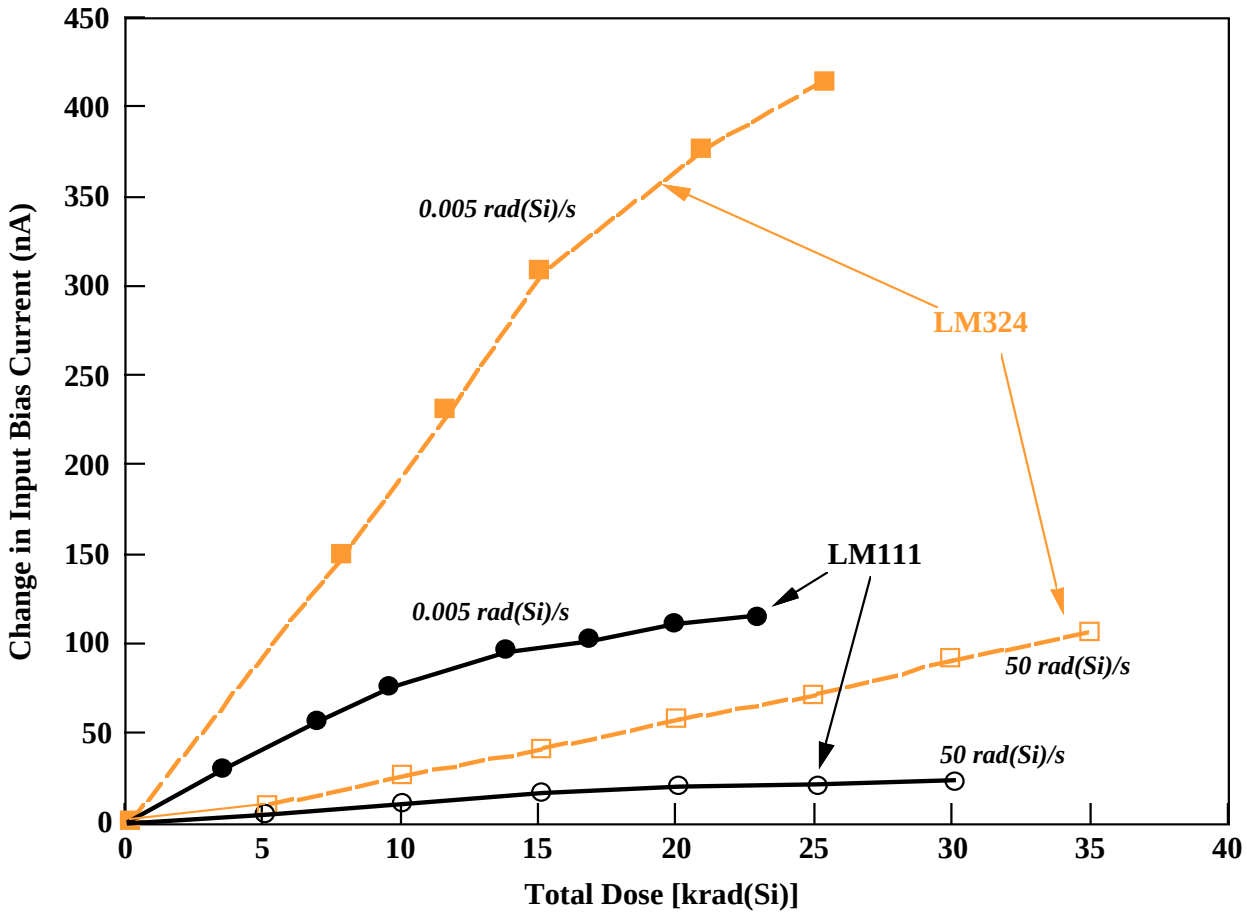
COTS Variability: OP27 Op-Amp



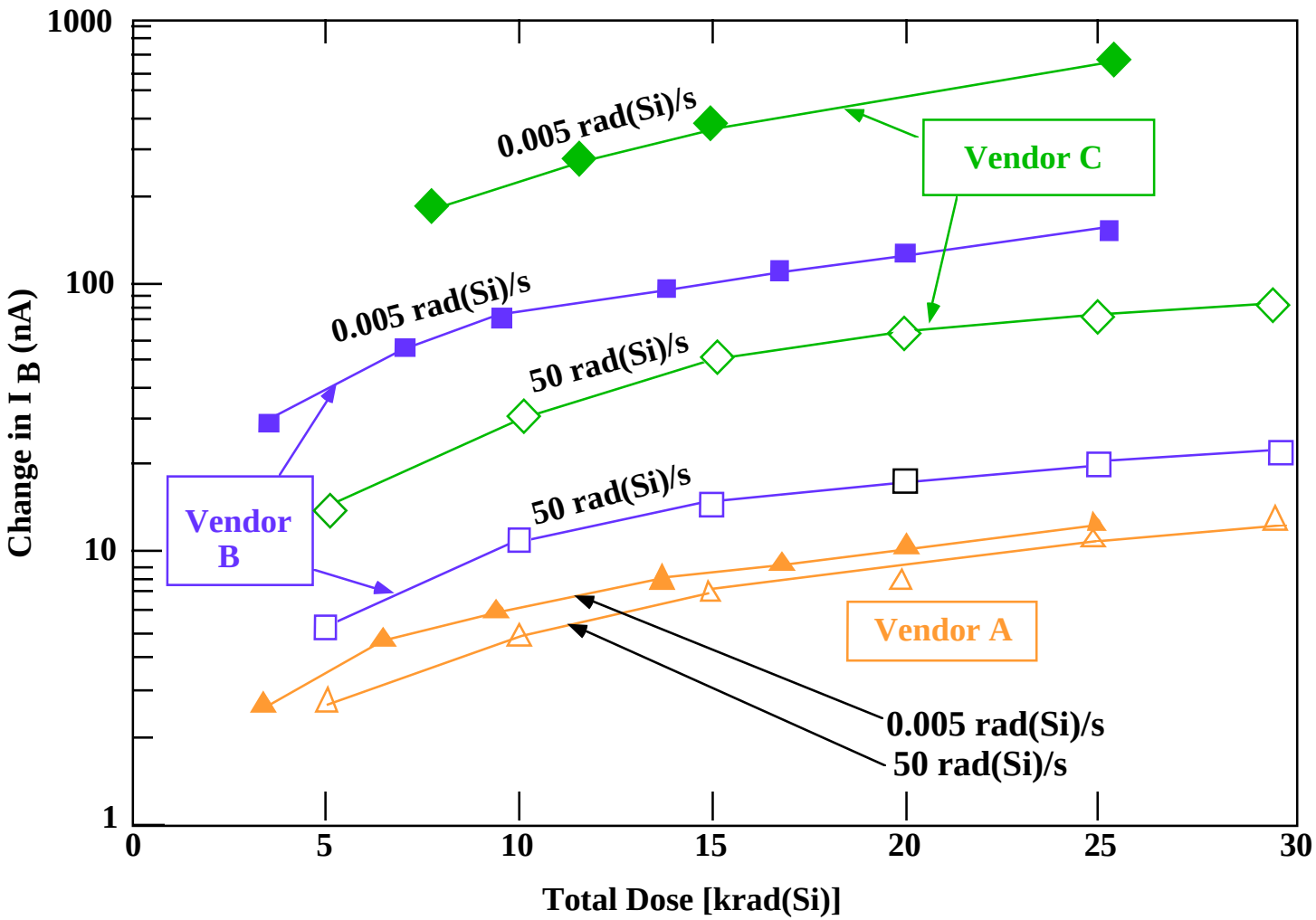
COTS: Same Part, Different Failure Mechanism



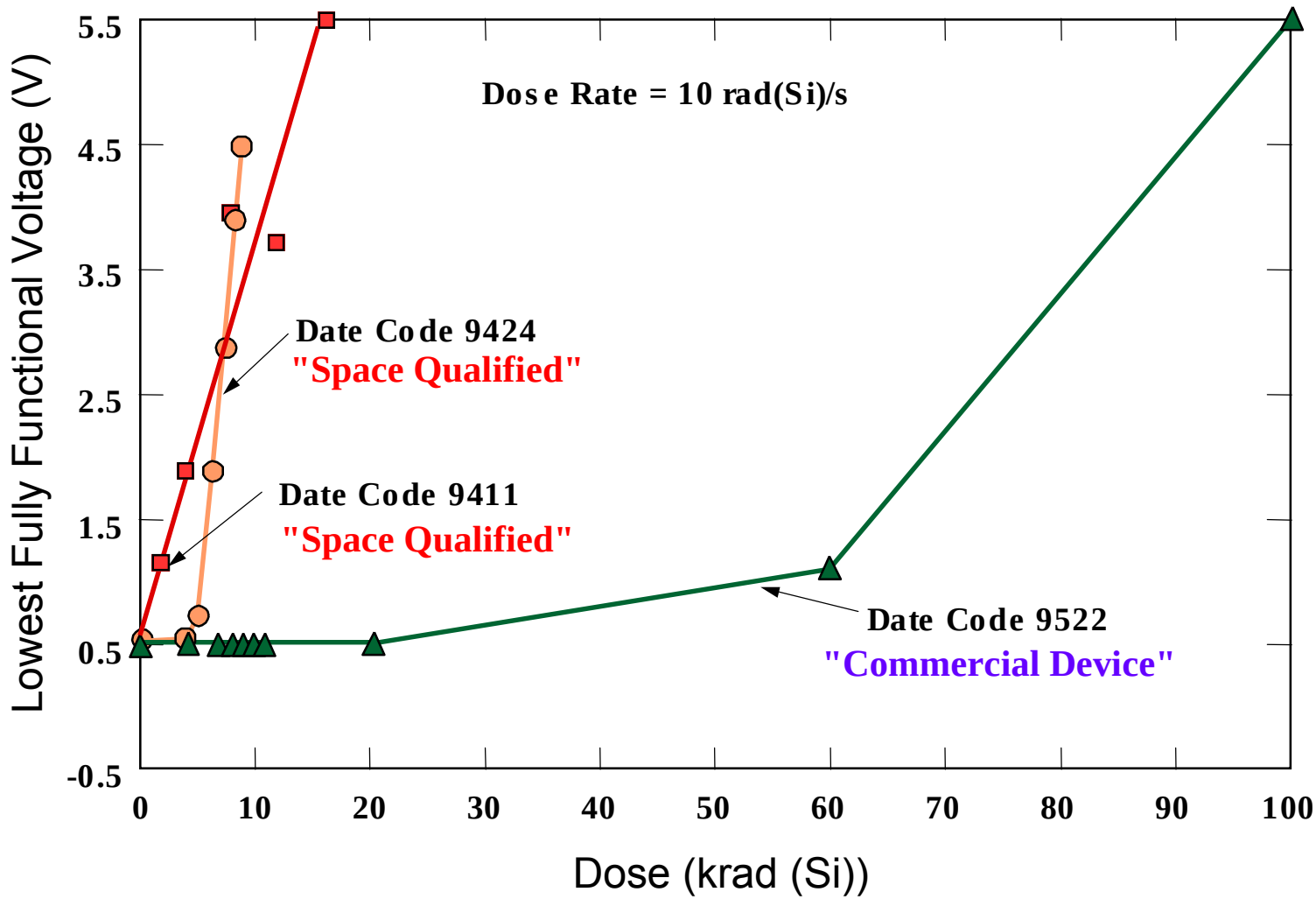
COTS / ELDRS Part Variation: Same Manufacturer



COTS / ELDRs: Manufacturer Variation



Warning: Space Qualified Isn't Always



Warnings / Common Misperceptions

- No bias does not mean that no damage will occur
  - Linear IC's can exhibit more damage when unbiased
  - Discrete transistor damage is about a factor of two lower when unbiased
  - CMOS bias effects are very complex
    - Generally some improvement when parts are unbiased
    - Needs to be checked on part-by-part basis

- Radiation data is not "generic"
  - Do not assume that data from one manufacturer applies to same part type from another manufacturer
  - Radiation response may change as manufacturing process evolves

- Characterization data must encompass use conditions
  - Example: linear IC data with +/- 15V power supplies cannot be used for 5/0 V applications
  - Total dose data bases are of limited value
  - Be aware of ELDRS

Recommendations

1. Get Radiation Testing office involved early

2. Consider using a part where radiation data already exists

3. When radiation testing is done, prepare course of action for parts that fail
   - Shielding
   - Redesign
   - Scheduling delay/cost factors

4. Lot acceptance testing is generally recommended (except for missions with very low levels)

5. Use extreme care when archival data is used

Conclusions

Total dose effects have not been a major factor in older missions
- Thorough radiation testing and parts control
- Conservative design specifications

Total dose effects will be more important for new systems
- Minimal radiation testing and parts control
- Less conservative design specifications
- New effects (particularly ELDRs)
- Subtle failure modes in complex parts

Sensitive Technologies
- Technologies with internal charge pumps (e.g., flash memories)
- High-precision linear integrated circuits
- Field oxide failures in advanced CMOS

Most Total dose problems are avoidable or preventable
- Total dose must be a design criteria

Typical Total Dose Failure Levels of Various Technologies

Technology	Failure Level [Krad(Si)]
Linear IC's	2 - 50
Mixed-signal IC's	2 - 30
Flash Memories	5 - 15
DRAMs	15 - 50
Microprocessors	15 - 70

Further Reading

1. Ma, T.P., and P.V. Dressendorfer, *Ionizing Radiation Effects in MOS Devices and Circuits*, (Wiley and Sons, New York, 1989).
2. P.V. Dressendorfer, “Basic Mechanisms for the New Millenium,” in 1998 *IEEE NSREC Short Course*, (IEEE, Piscataway, NJ, 1998).
3. All IEEE Nuclear and Space Radiation Effects Conference (NSREC) Proceedings (see December issues of IEEE Transactions on Nuclear Science, 1964-present).
4. All IEEE NSREC Radiation Effects Data Workshops (199x-present).
5. All IEEE NSREC Radiation Effects Short Courses (1980-present).
6. J. Bennedetto, “Economy-Class Ion-Defying ICs in Orbit,” IEEE SPECTRUM, March 1998, p. 36-41.
7. T. Oldham, *Ionizing Radiation Effects in MOS Oxides*, (World Scientific, River Edge, NJ, 1999).