Lecture 4

- Radiation damage
    - In sensors
    - In readout electronics

Literature

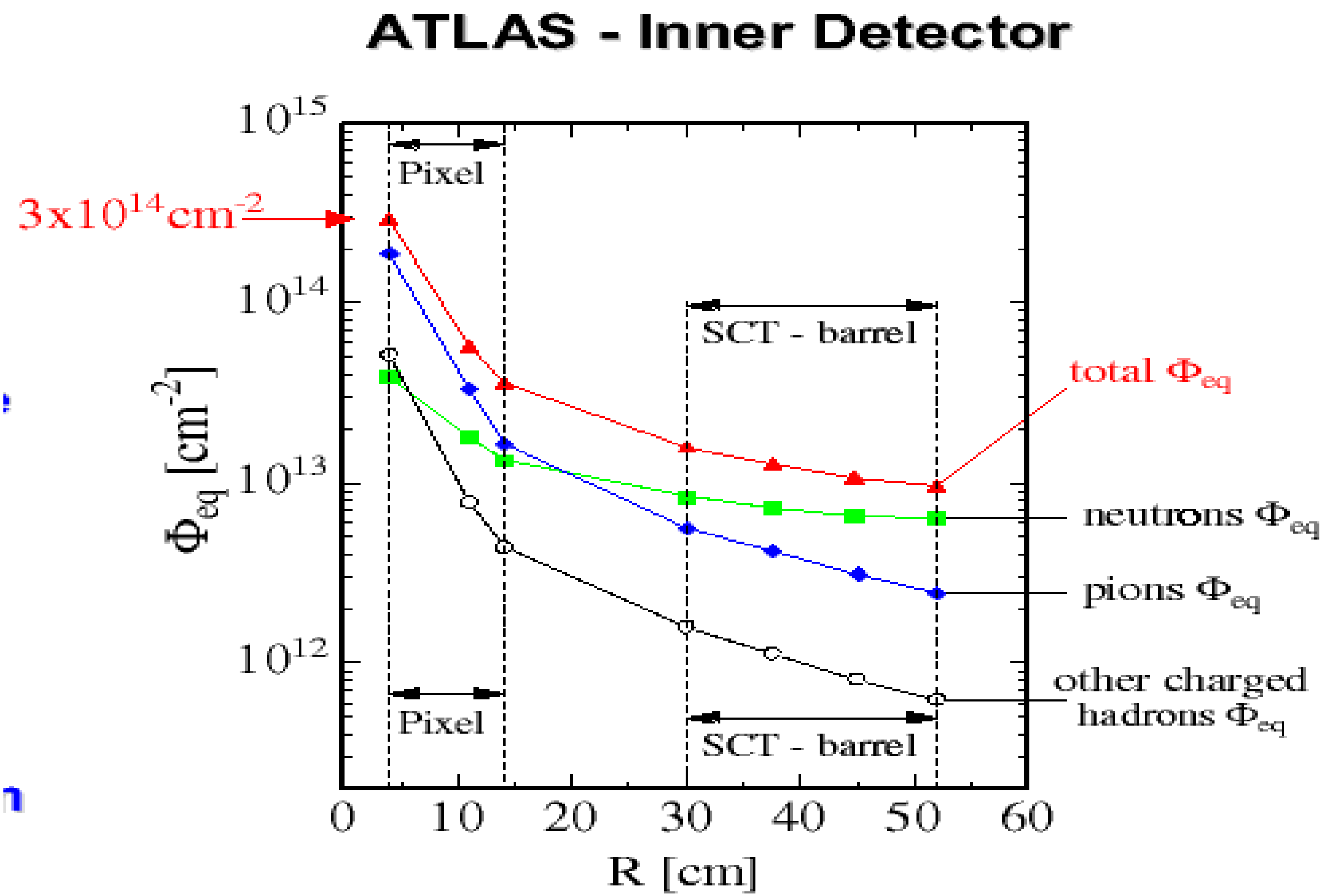
- Semiconductor Radiation Detectors, Gerhard Lutz, Springer-Verlag, 1999
- http://rd48.web.cern.ch/RD48 (ROSE)
- http://rd49.web.cern.ch/RD49 (RADTOL)

Radiation damage to semiconductors

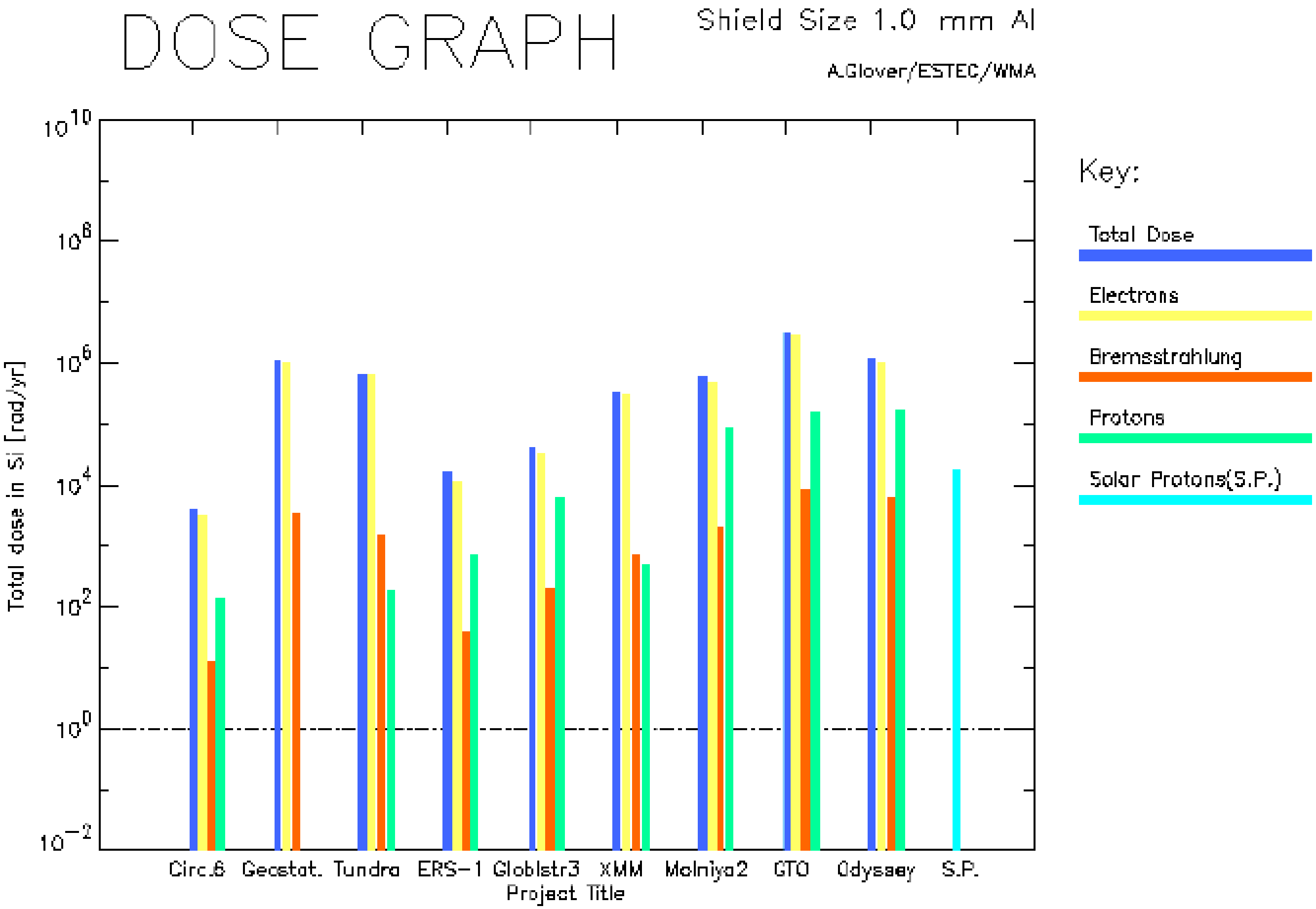
We want to detect ionising radiation with our detector but at the same time the radiation will damage our detector. The radiation induced damage is for most users small but for applications in high energy physics, space and in medicine the damage to the detector may be substantial degrading the performance. There are two kinds of radiation damage

- Bulk damage, which affects the the doping and structure of the sensor bulk.
- Surface damage, which affects the oxide and oxide interface in the sensor.

Expected dose in HEP



Expected dose in space



Solar events can produce peak flux (at earth) > 10^6 protons/cm^2/s (>10 MeV)
Yearly dose around 1 kGy (100 krad)

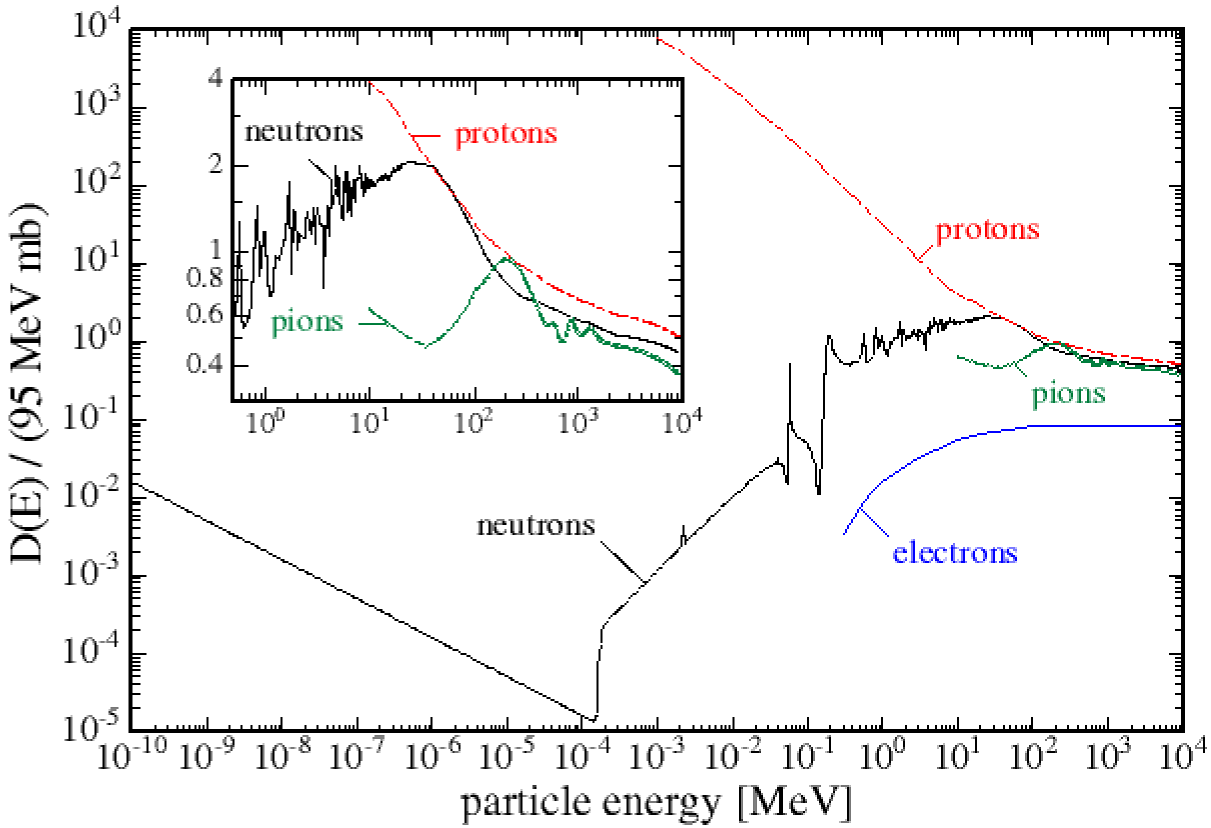
Bulk and surface damage

- Bulk damage is caused by charged and neutral heavy particle (heavier than electrons) destroying the structure of the semiconductor crystal. The damage is seen by:
    - ✔ Leakage Current increase
    - ✔ Depletion Voltage increase
    - ✔ Charge Collection decrease

- Surface damage is caused by photons and charge particles ionising the oxide leaving trapped charge in the oxide changing the Flat Band condition. The damage is seen by:
    - ✔ Increased capacitance to neighbour cells in a segmented sensor
    - ✔ Surface current
    - ✔ Impedance change to neighbour cells in a segmented sensor

Bulk Damage (1)

- The damage to the semiconductor bulk depend on the particle type
  →Non Ionising Energy Loss (NIEL)



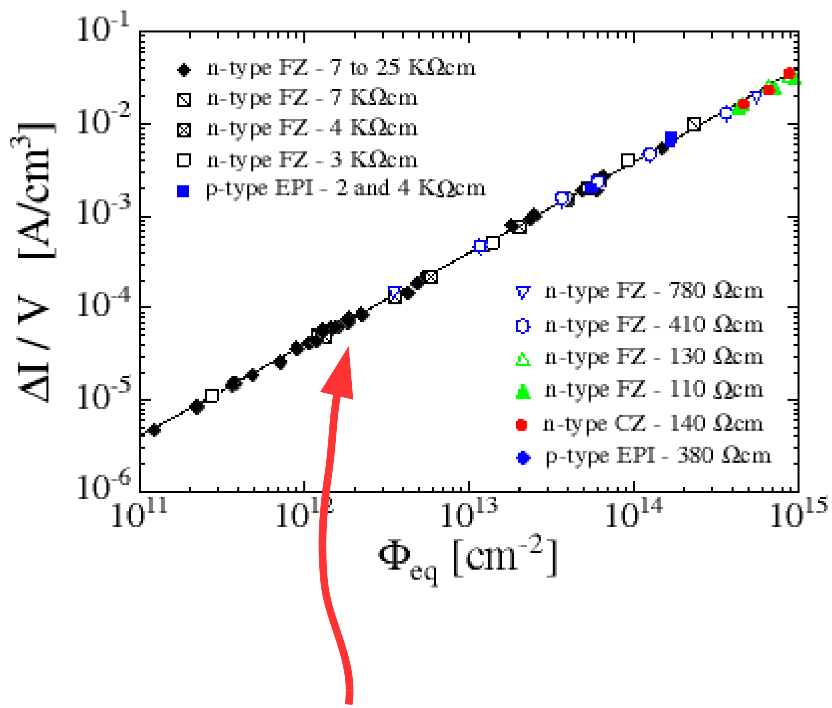
For Silicon:
100 MeVmb
= 2.14 keVcm^2/g

Bulk Damage (2)

- Since the bulk damage depend on the particle fluence (=integrated flux), particle type, particle energy we normalise the fluence parameter by using the NIEL curve to equal damage for 1 MeV neutrons

$$\Phi_{eq}$$

Damage parameter



α (silicon) = $3.99 \pm 0.03\ 10^{17}$ A/cm

- The increase of leakage current in damaged silicon is independent of
  - Initial doping concentration
  - type of material
  - crystal orientation

BUT

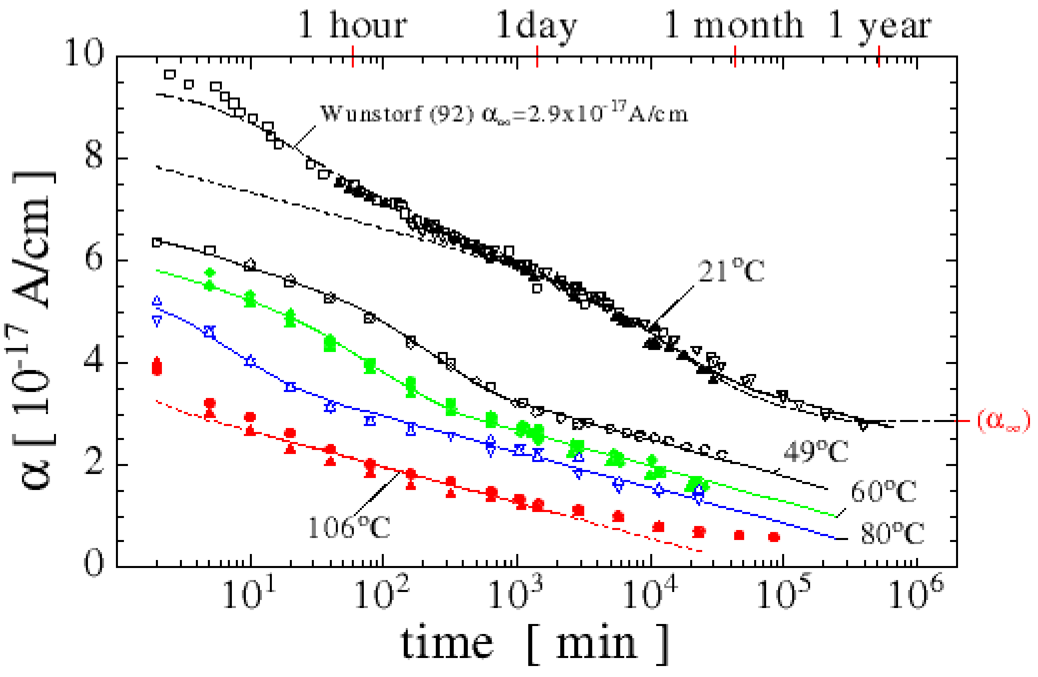
dependent of temperature

- Define damage parameter

$$\alpha = \frac{\Delta I}{V \Phi_{eq}}$$

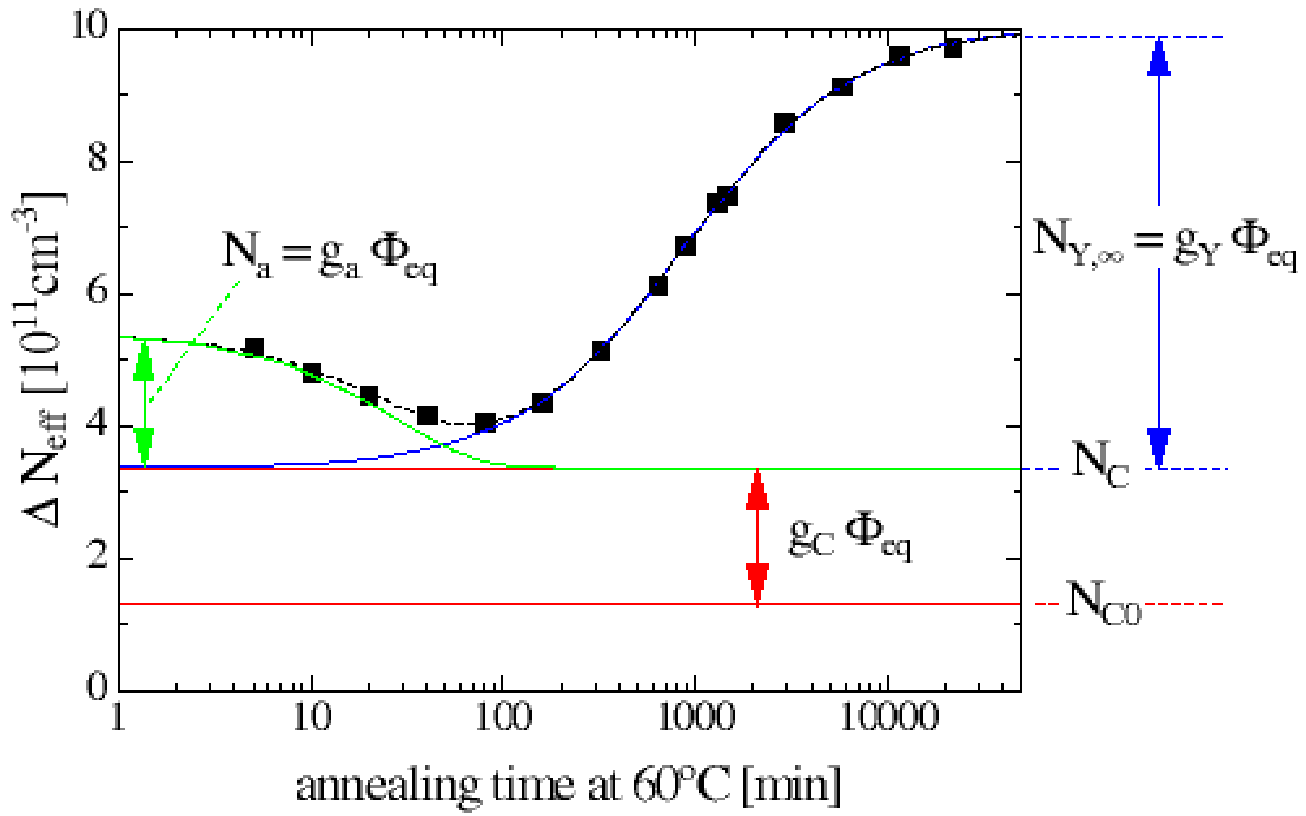
Annealing

- Some of the damage to the semiconductor by NIEL is repaired by annealing. The annealing depend on temperature and time.



Reverse annealing

- Unfortunately not all annealing is beneficial. The beneficial annealing is a fast process while the reverse annealing is a slow process. The reverse annealing is like the beneficial annealing temperature dependent.
- The damage parameter is defined by a observable, change in leakage current (ΔI). The increase in current is in fact caused by the change in the material doping, N_{eff}.



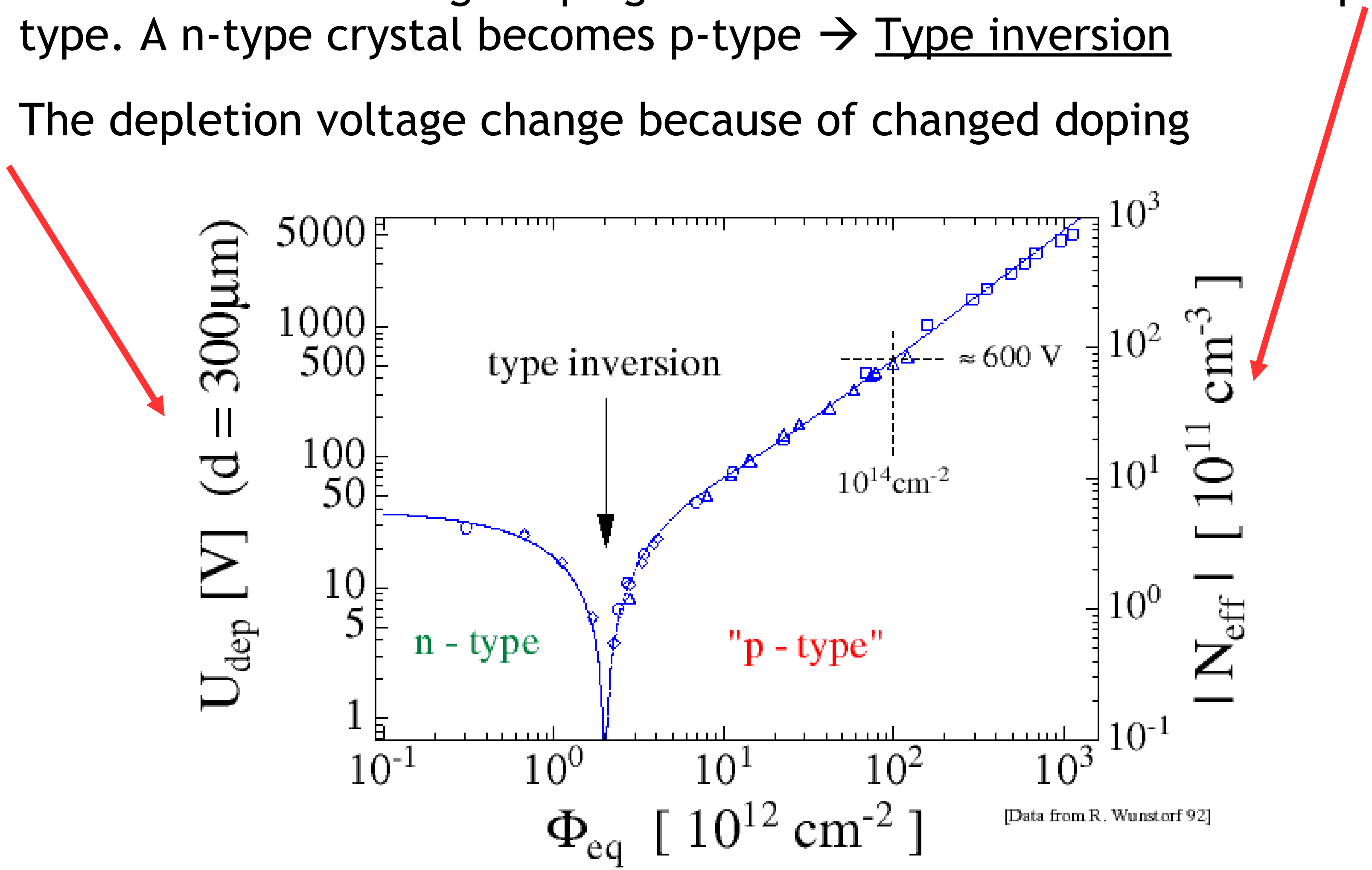
N_C =stable damage

N_A = beneficial annealing

N_Y = reverse annealing

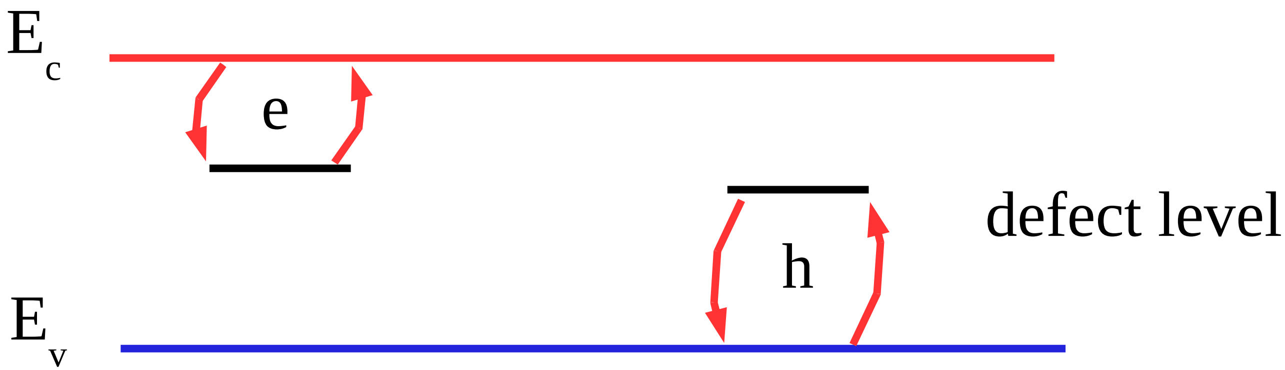
Type inversion

- The silicon bulk change doping concentration and become more p-type. A n-type crystal becomes p-type → <u>Type inversion</u>
- The depletion voltage change because of changed doping



Trapping

- The radiation damage create defects in the crystal lattice → new levels introduced into the energy gap where electrons/holes are trapped.
- Charge collection efficiency falls off at about 1% per 10^{13} n/cm (Φ_{eq})

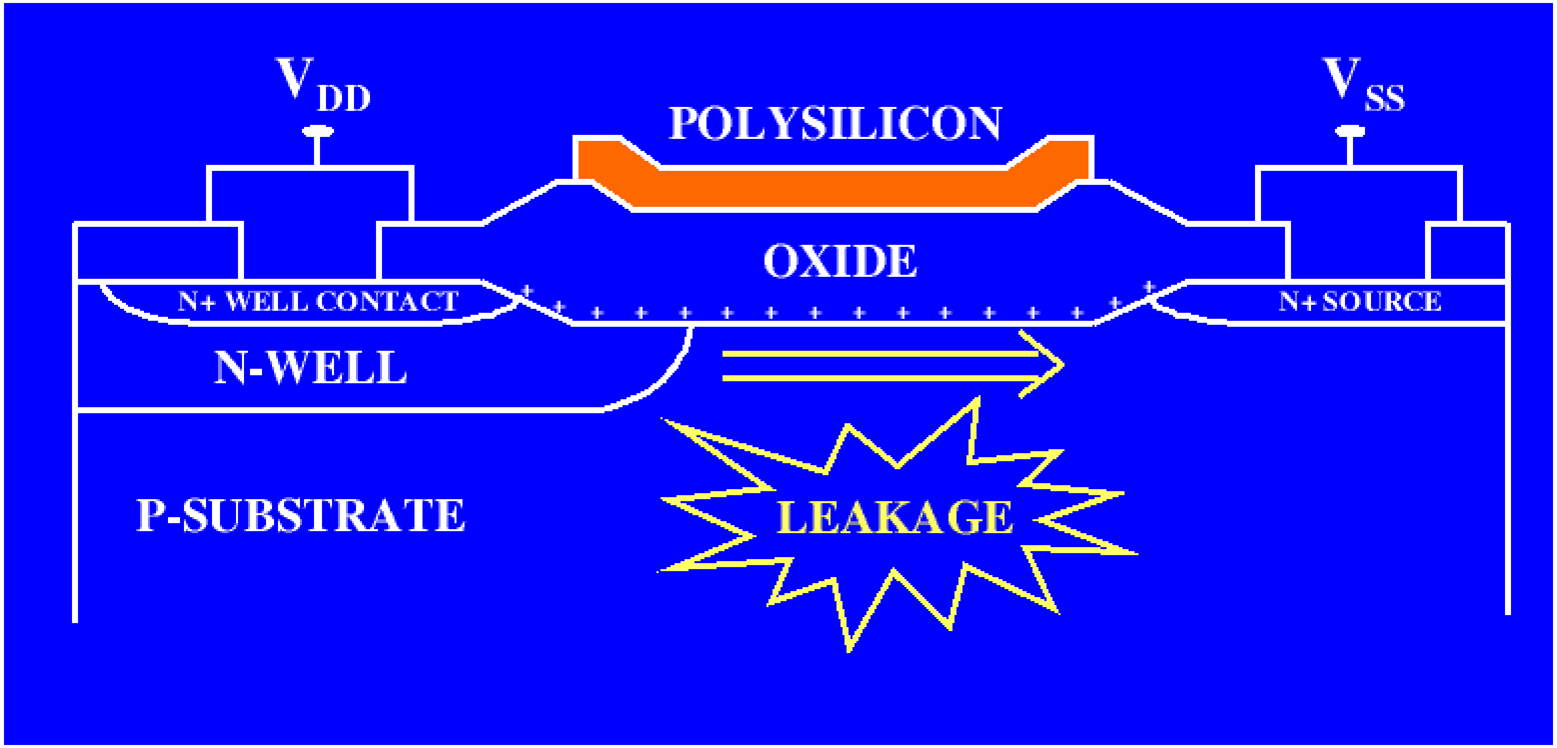


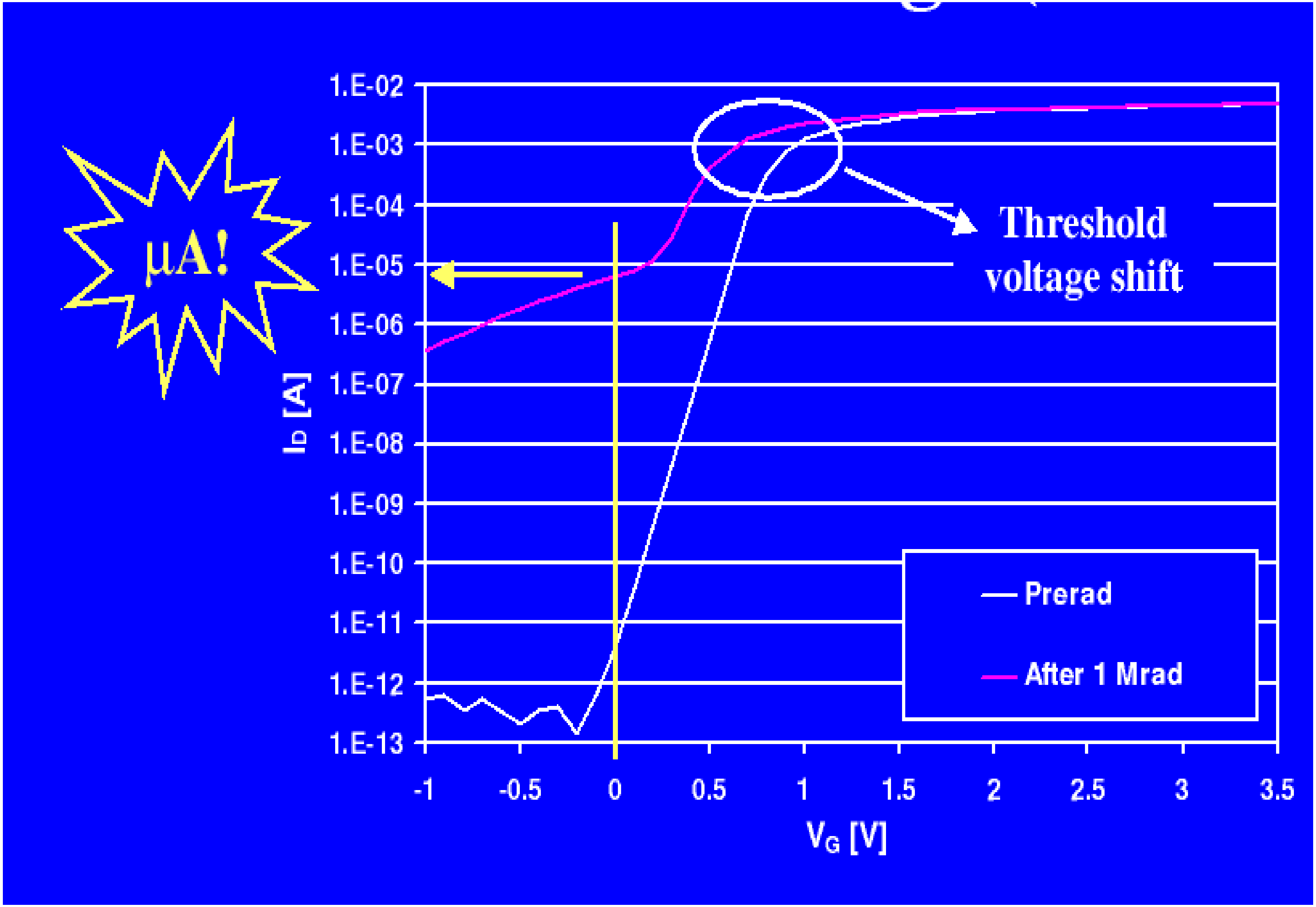
Surface damage

- Surface damage is changing the properties of the oxide layer and its interface with the crystal→ change in ε_r
- The effect saturates at 1-2 kGy (100-200 krad) increasing the capacitance by x2

Radiation damage in readout electronics

- Like the sensors the readout electronics is damaged by radiation giving
  - Threshold shift
  - Increased leakage
  - Single event Latch-up, Single event Upset

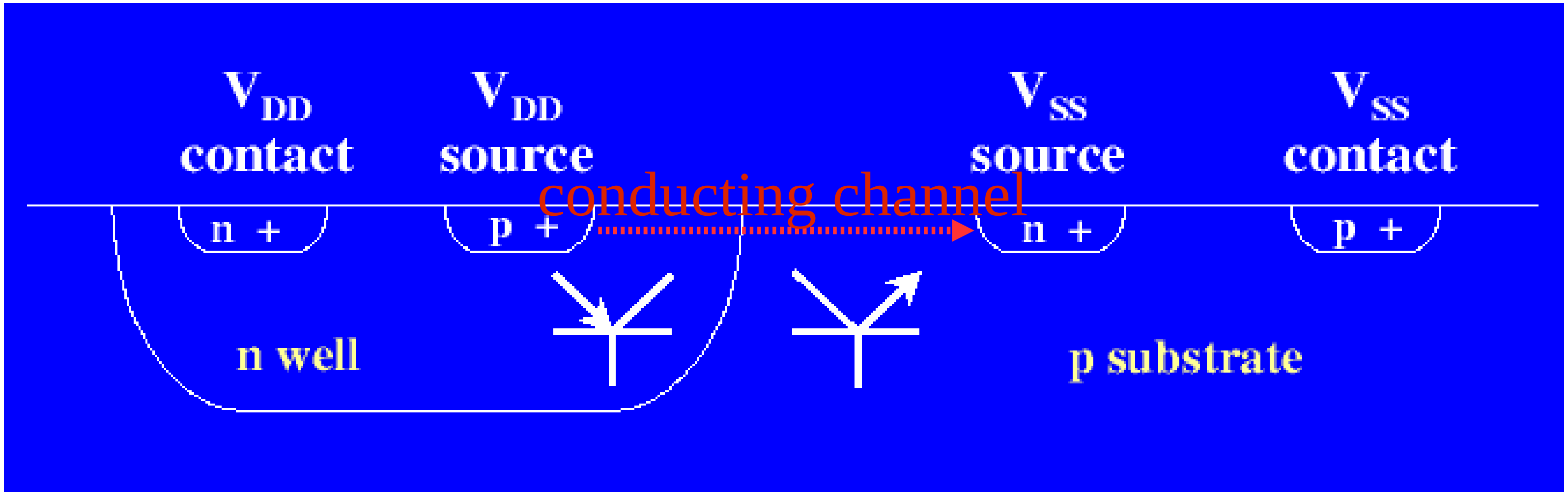




µA!
Threshold voltage shift
1.E-02
1.E-03
1.E-04
1.E-05
1.E-06
1.E-07
1.E-08
1.E-09
1.E-10
1.E-11
1.E-12
1.E-13
I_D [A]
-1
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
V_G [V]
Prerad
After 1 Mrad

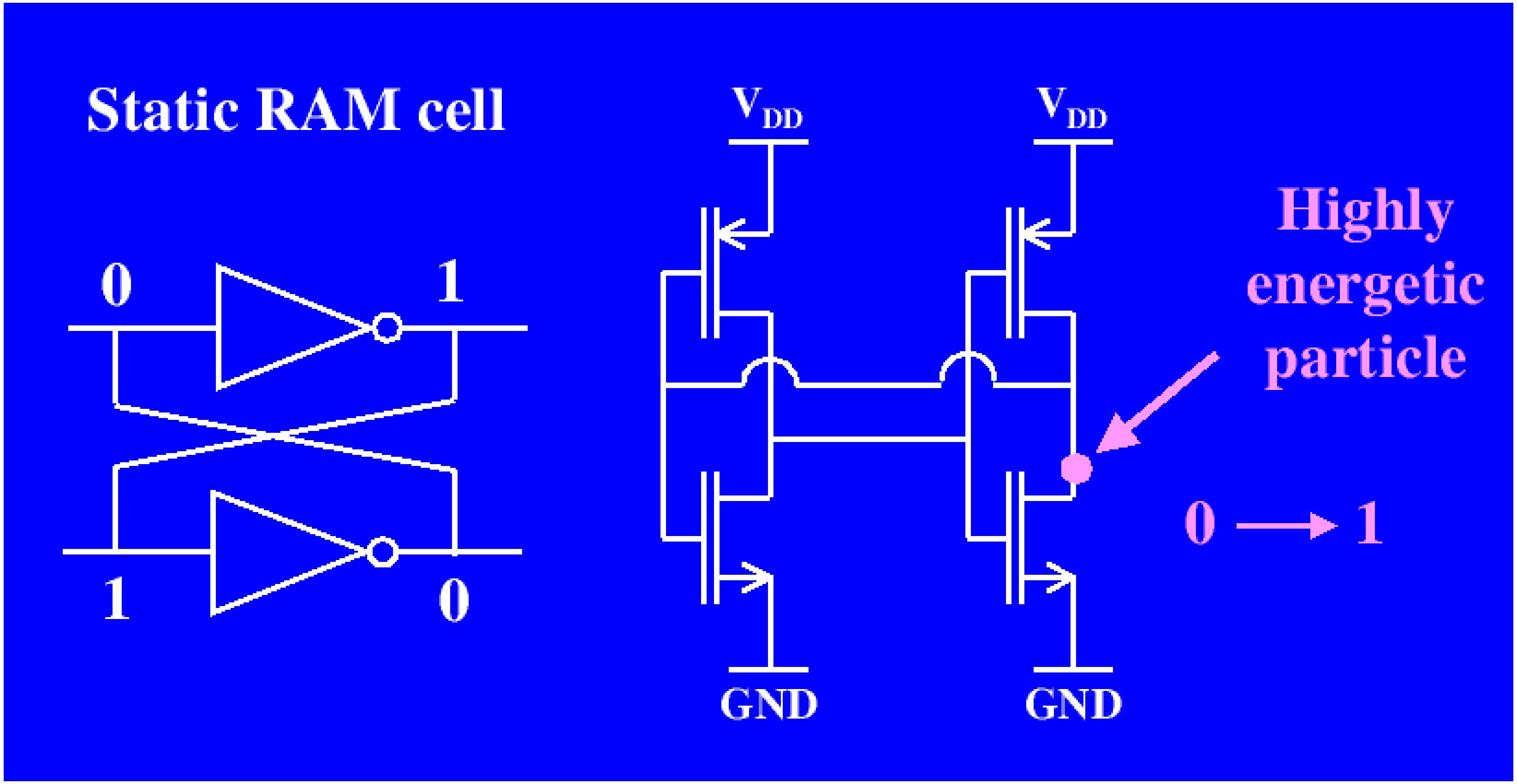
Latch-up

- Latch-up can be initiated by an ionising particle→ high current which may damage the electronics



Single Event Upset

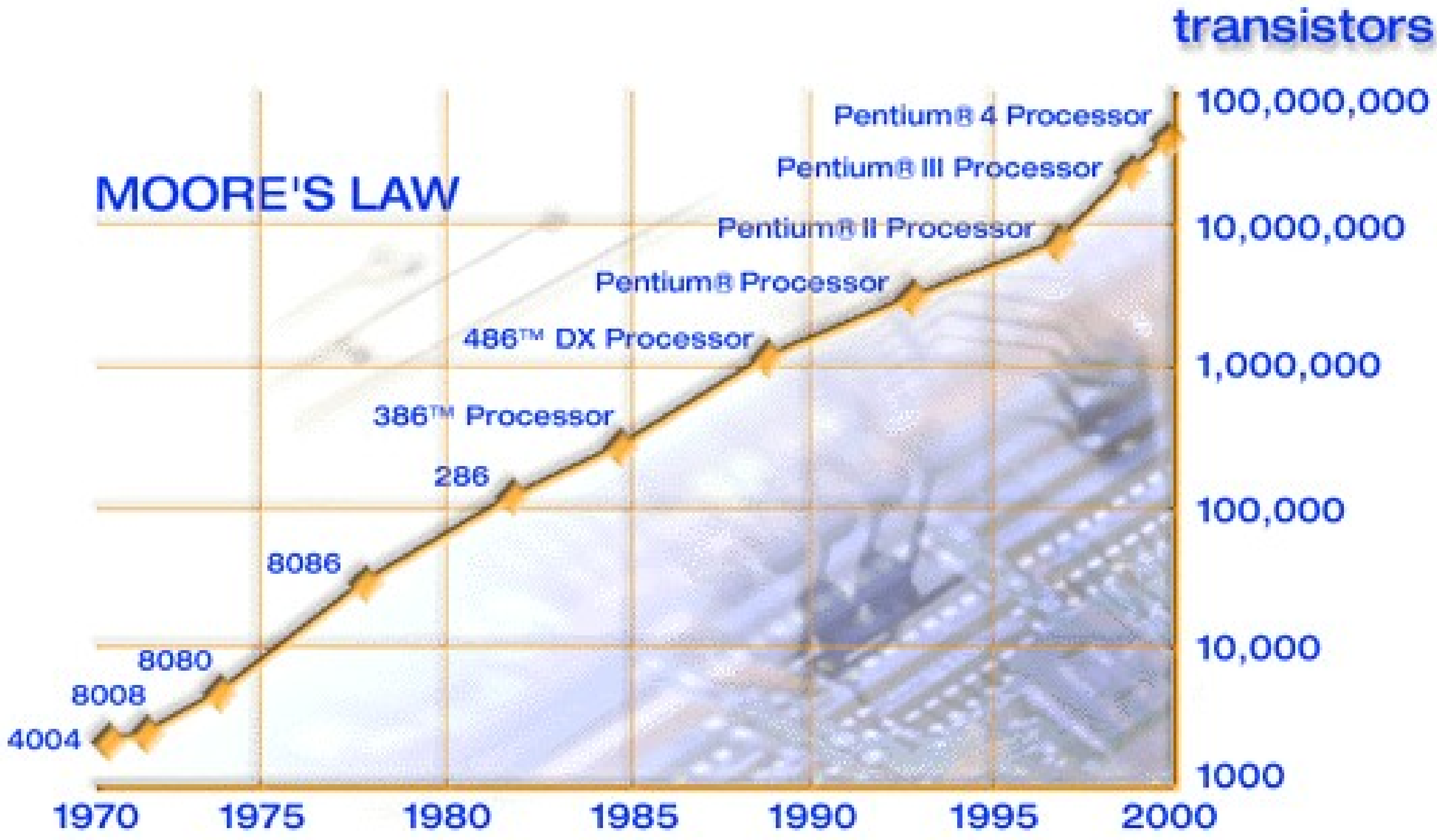
- A memory bit in a memory cell can be flipped by ionising radiation

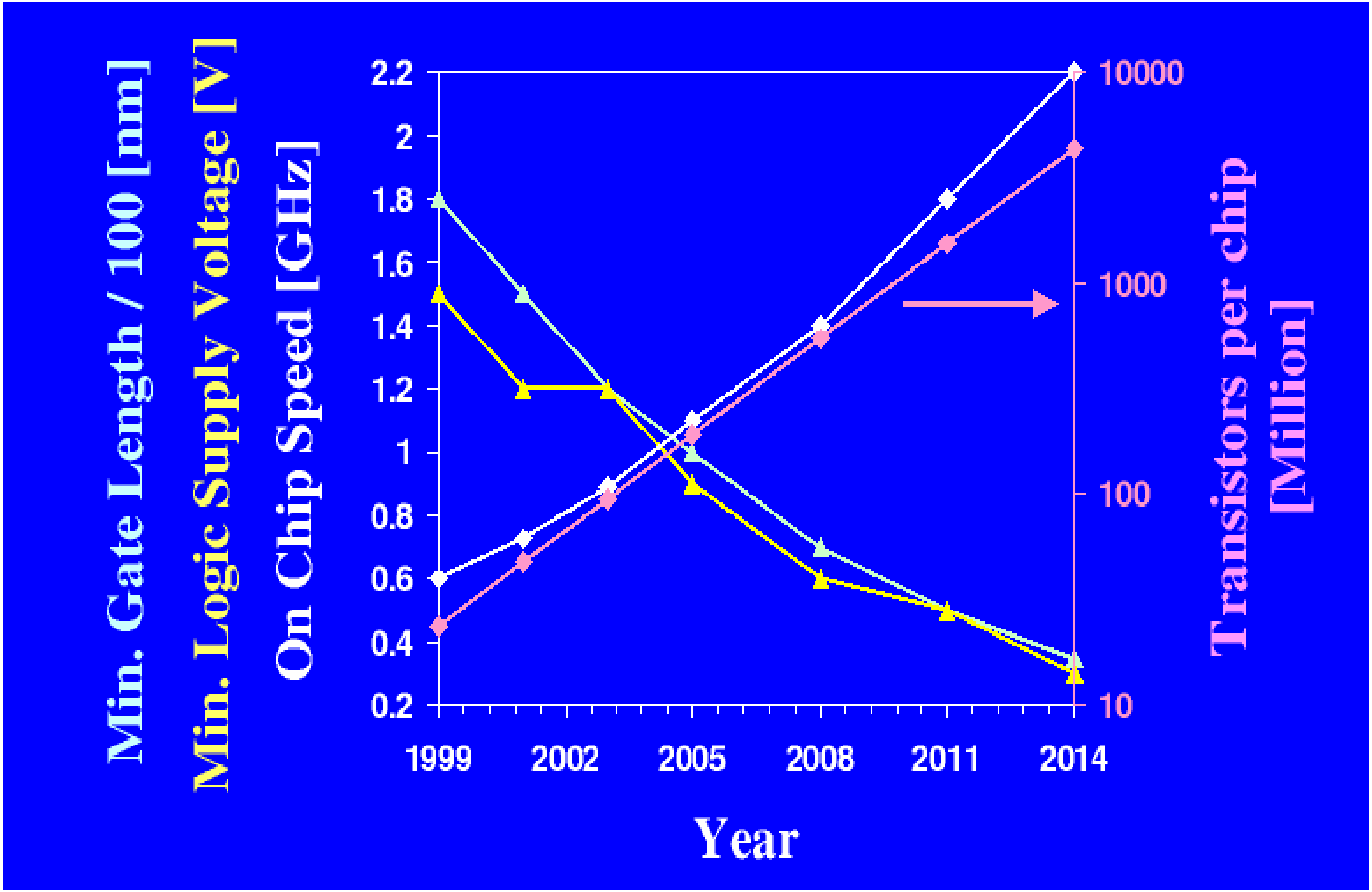


Rad-hard electronics

- To fight radiation damage to electronics special design rules and especially by radiation hardened fabrication processes. Most processes were developed under the "Cold War" for military usage and become available only after the end of the "Cold War". Unfortunately the science community did not possess a budget capable of matching the reduction in military funding.....end of the saga?

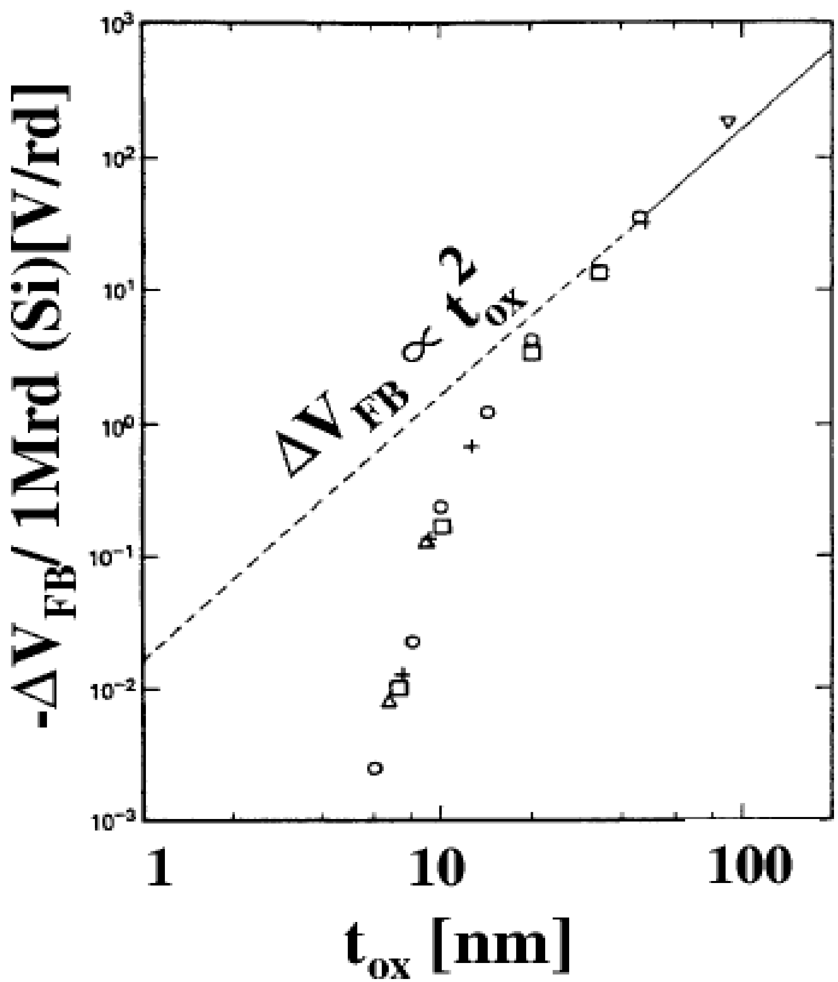
Moore's law and transistor size

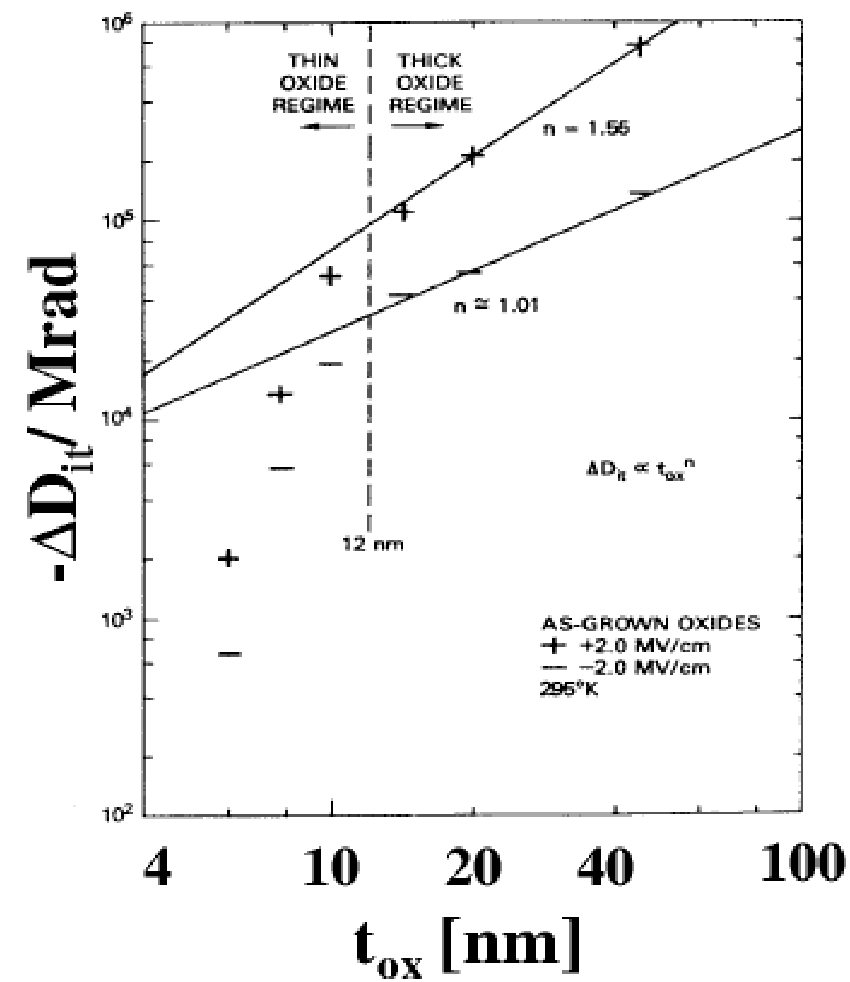




Min. Gate Length / 100 [nm]
Min. Logic Supply Voltage [V]
On Chip Speed [GHz]
Transistors per chip [Million]
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
10000
1000
100
10
1999
2002
2005
2008
2011
2014
Year

Dose scaling in electronics





N. S. Saks et al., ***IEEE TNS***, vol. 31, no. 6, Dec. 1984, and vol. 33, no. 6, Dec. 1986.

The Miracle

- The steep fall off in dose scaling with thin oxide thickness allow leading edge electronics to be used in radiation environments.

END LECTURE