Semiconductor detectors

An introduction to
semiconductor detector physics
as applied to particle physics

Contents

4 lectures – can’t cover much of a huge field

- Introduction
- Fundamentals of operation
- The micro-strip detector
- Radiation hardness issues

Lecture 4 – Radiation Damage

- Effects of radiation
  - Microscopic
  - Macroscopic
  - Annealing
- What can we do?
  - Detector Design
  - Material Engineering
  - Cold Operation
  - Thin detectors/Electrode Structure – 3-D device

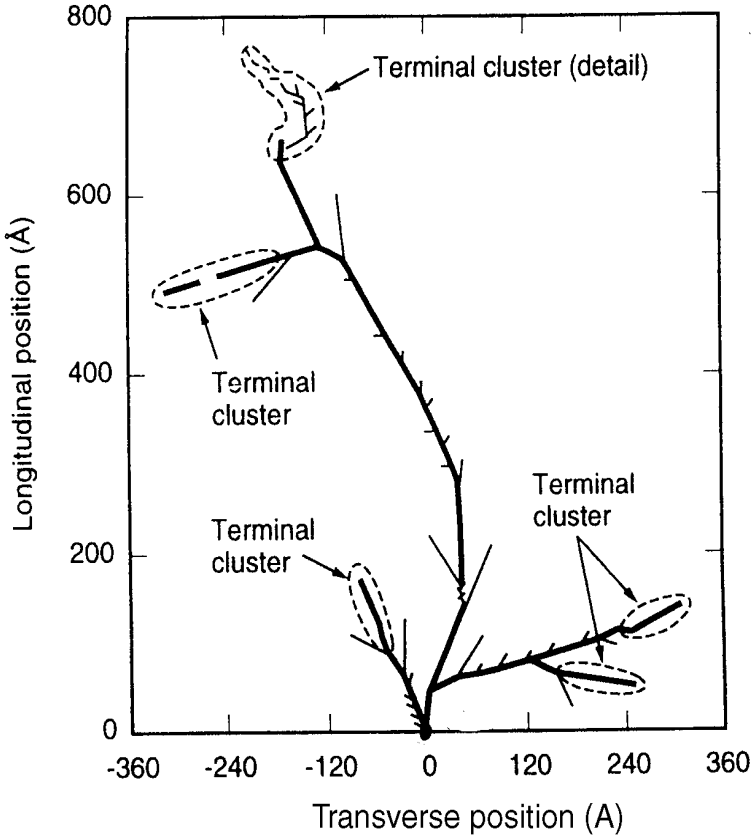
Effects of Radiation

- Long Term Ionisation Effects
  - Trapped charge (holes) in SiO_2
  - interface states at SiO_2 - Si interface
  - Can’t use CCD’s in high radiation environment
- Displacement Damage in the Si bulk
  - 4 stage process
  - Displacement of Silicon atoms from lattice
  - Formation of long lived point defects & clusters

Displacement Damage

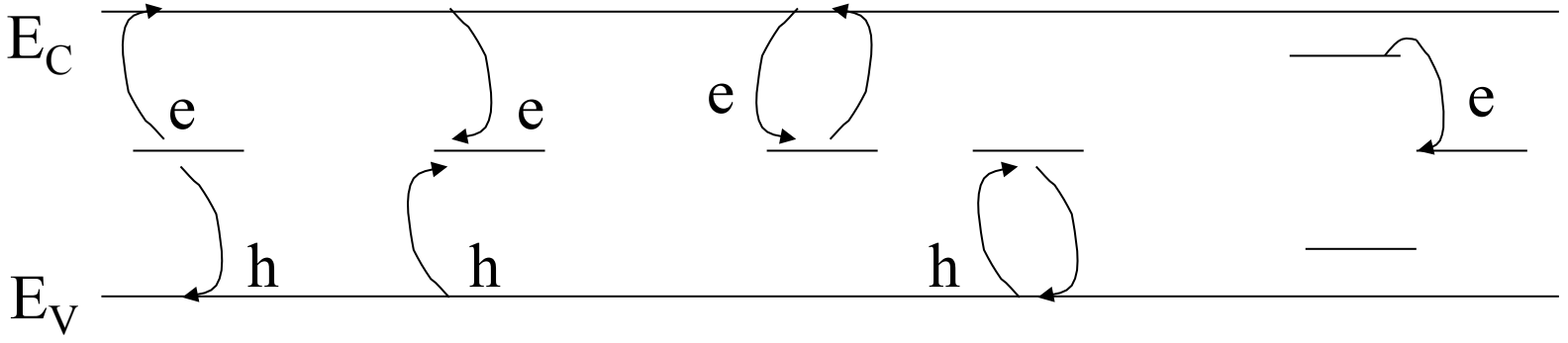
- Incoming particle undergoes collision with lattice
  - knocks out atom = Primary knock on atom
- PKA moves through the lattice
  - produces vacancy interstitial pairs (Frenkel Pair)
  - PKA slows, reduces mean distance between collisions
  - clusters formed
- Thermal motion ≈98% lattice defects anneal
  - defect/impurity reactions
- Stable defects influence device properties

PKA



- Clusters formed when energy of PKA< 5keV
- Strong mutual interactions in clusters
- Defects outside of cluster diffuse + form impurity related defects (VO, VV, VP)
- e & γ don't produce clusters

Effects of Defects

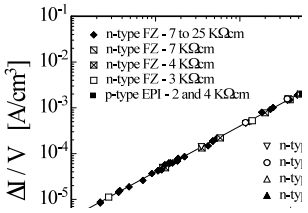


Leakage Current

Charge Collection

Effective Doping Density

Reverse Current

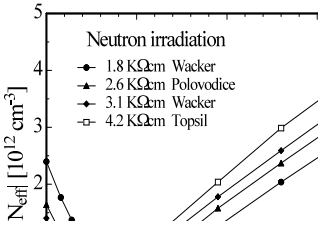


- I = $\alpha\Phi$Volume
- Material independent
  - linked to defect clusters
- Annealing material independent
- Scales with NIEL
- Temp dependence

$$I(T) \propto T^2 \exp\left(-\frac{E_g}{2kT}\right)$$

$\alpha = 3.99 \pm 0.03 \times 10^{-17}\text{Acm}^{-1}$
after 80minutes annealing at 60°C

Effective Doping Density

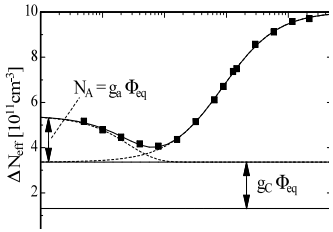


- Donor removal and acceptor generation
  - type inversion: n ⇒ p
  - depletion width grows from n^+ contact
- Increase in full depletion voltage
  - $V \propto N_{eff}$

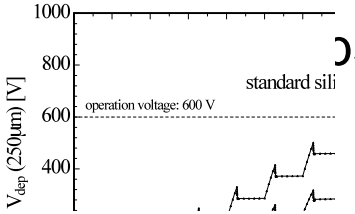
$$N_{eff}(\Phi) = N_{eff}(0)\exp(-c\Phi) - \beta\Phi$$

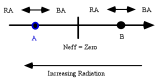
$\beta = 0.025\text{cm}^{-1}$ measured after beneficial anneal

Effective Doping Density



- Short-term beneficial annealing
- Long-term reverse annealing
  - temperature dependent
  - ɔs below -10°C





After type inversion

Before type inversion

Signal speed from a detector

- Duration of signal = carrier collection time
- Speed $\propto$ mobility & field
- Speed $\propto$ 1/device thickness
- PROBLEMS
  - Post irradiation mobility & lifetime reduced
    - $\mu\tau$ lower $\therefore$ longer signals and lower Q_s
  - Thick devices have longer signals

Signal with low lifetime material

- Lifetime, τ, packet of charge Q_0 decays

- In E field charge drifts $$Q(t) = Q_o e^{-t/\tau}$$
- Time required to drift distance x:

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

- Remaining charge:
  - Drift length, $L \propto \mu\tau$

  $\mu\tau$ is a figure of merit.

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

Induced charge

- Parallel plate detector:

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

$$L >> d: \quad \frac{Q_s}{Q_0} \approx \frac{L}{d}$$

- In high quality silicon detectors:
- $\tau \approx 10\text{ms}$, $\mu_e = 1350\text{cm}^2\text{V}^{-1}\text{s}^{-1}$, $E = 10^4\text{Vcm}^{-1}$

  $\Rightarrow L \approx 10^4\text{cm}$ ($d \sim 10^{-2}\text{cm}$)

  - Amorphous silicon, $L \approx 10\mu\text{m}$ (short lifetime, low mobility)
  - Diamond, $L \approx 100\text{-}200\mu\text{m}$ (despite high mobility)
  - CdZnTe, at 1kVcm-1, $L \approx 3\text{cm}$ for electrons, 0.1cm for holes

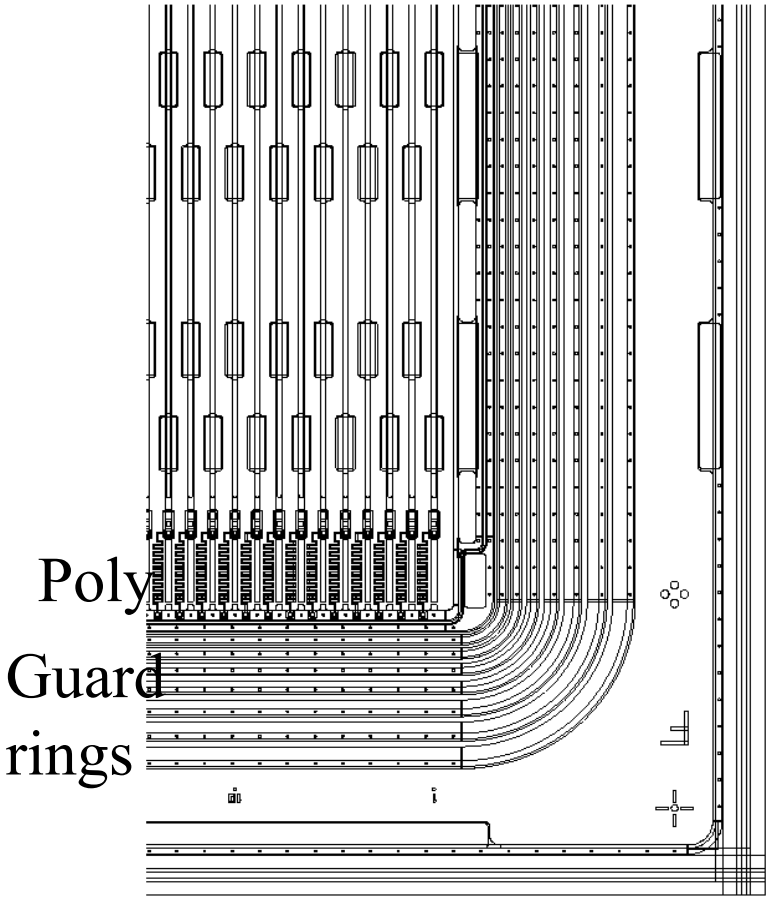
What can we do?

- Detector Design
- Material Engineering
- Cold Operation
- Electrode Structure – 3-D device

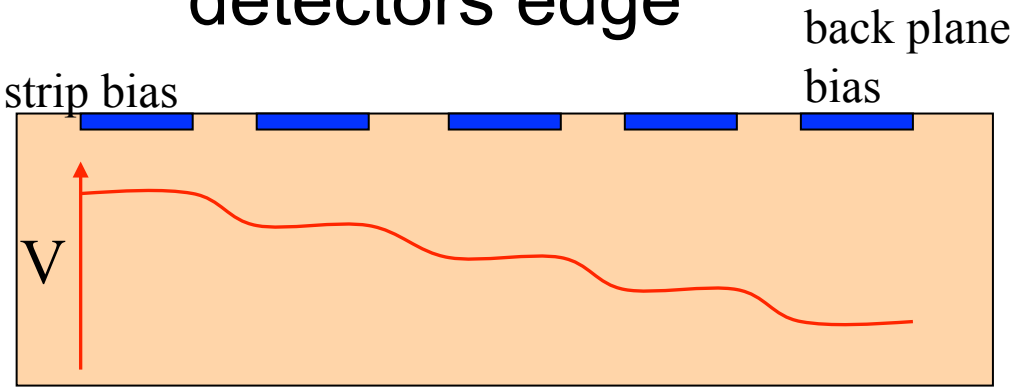
Detector Design

- n-type readout strips on n-type substrate
  - post type inversion ⇒ substrate p type ⇒ depletion now from strip side
  - high spatial resolution even if not fully depleted
- Single Sided
- Polysilicon resistors
- W<300μm thick ⇒ limit max depletion V
- Max strip length 12cm ⇒ lower cap. noise

Multiguard rings



- Enhance high voltage operation
- Smoothly decrease electric field at detectors edge

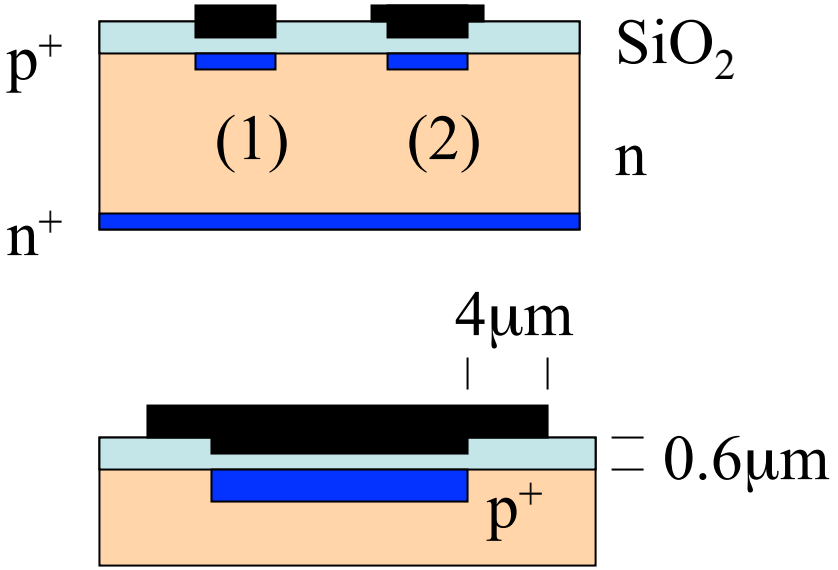


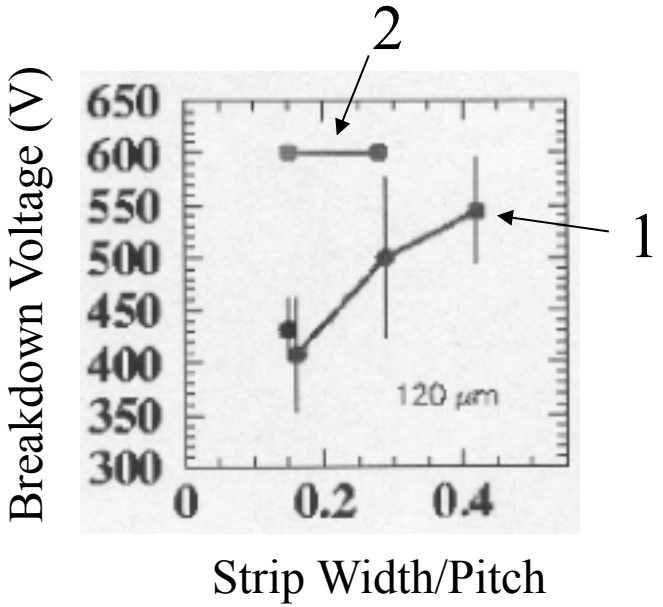
Substrate Choice

- Minimise interface states
- Substrate orientation <100> not <111>
  - Lower capacitive load
  - Independent of ionising radiation
- <100> has less dangling surface bonds

Metal Overhang

- Used to avoid breakdown performance deterioration after irradiation

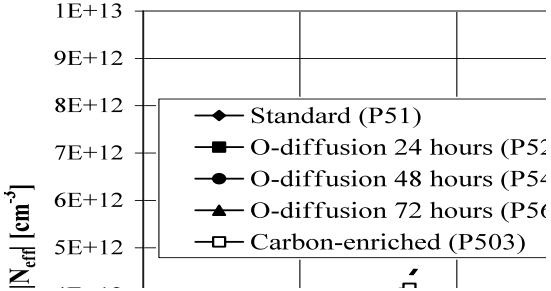




<111> after 4 x 10^{14} p/cm^2

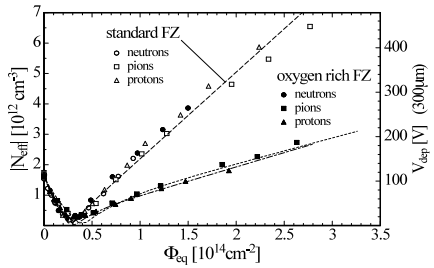
Material Engineering

- Do impurities influence characteristics?
- Leakage current independent of impurities
- N_{eff} depends upon $[O_2]$ and [C]



O_2 works for charged hadrons

- N_{eff} <u>un</u>affected by O_2 content for neutrons
- Believed that charge particle irradiation produces more isolated V and I



$V + O \Rightarrow VO$

$V + VO \Rightarrow V_2O$

$V_2O \Rightarrow$ reverse annealing

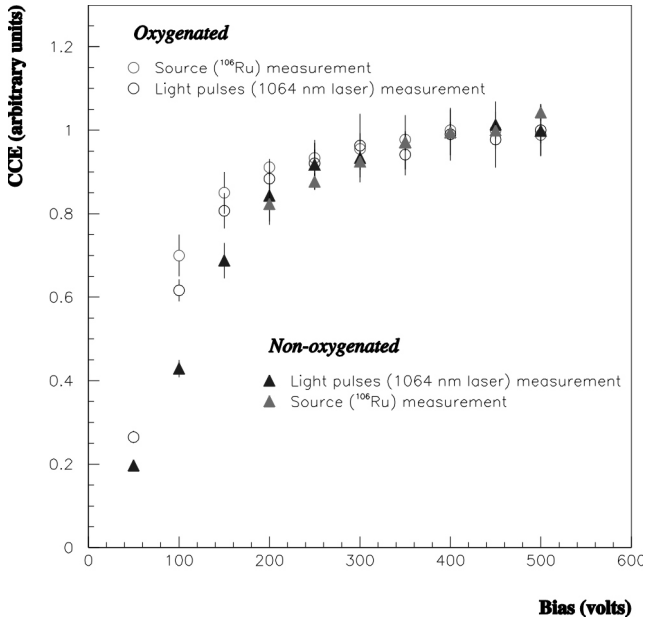
High [O] suppresses V_2O formation

Charge collection efficiency

- Oxygenated Si enhanced due to lower depletion voltage

CCI ~ 5% at 300V

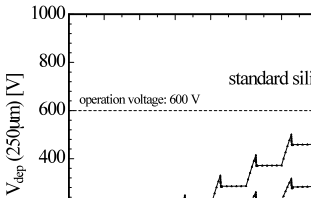
after 3×10^{14} p/cm^2



CCE of MICRON ATLAS prototype strip detectors irradiated with 3 10^{14} p/cm^2

ATLAS operation

Damage for ATLAS barrel layer 1

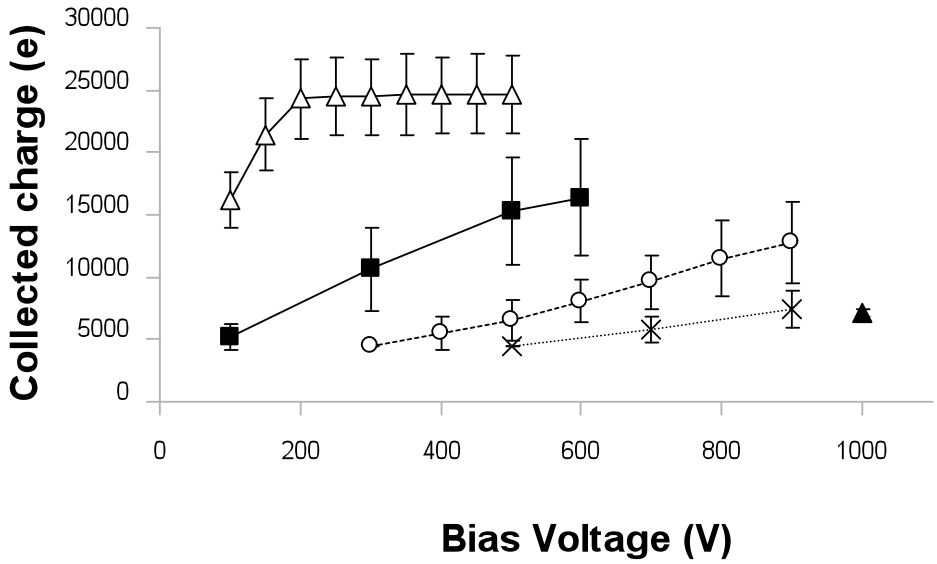


Use lower resistivity Si to increase lifetime in neutron field

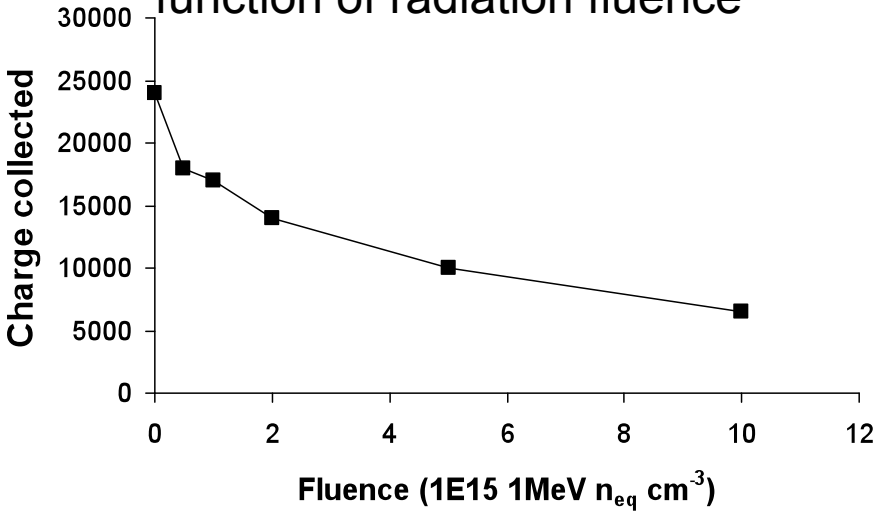
Use oxygenated Si to increase lifetime in charge hadron field

Charge collection loss at SLHC fluences

Collected charge as a function of bias voltage for different irradiation fluences



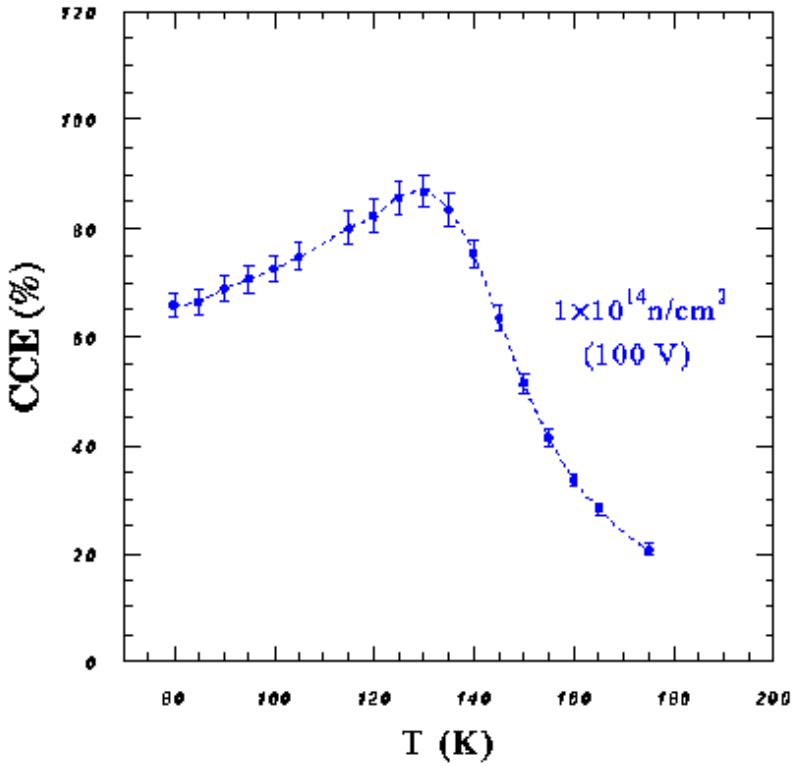
Collected charge at 1000V as a function of radiation fluence



Charge collected is more than expected from previous equations and fits to lifetime with fluence
The reason is explained due to avalanche multiplication under the strip implant at the very high electric fields in the detector

Cold Operation

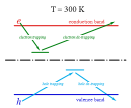
- Know as the "*Lazarus effect*"
- Recovery of heavily irradiated silicon detectors operated at cryogenic temps
  - observed for both diodes and microstrip detectors

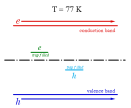


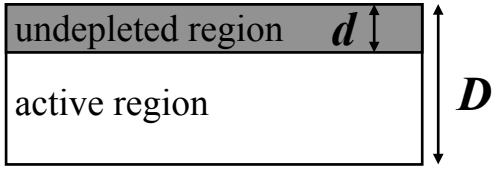
The Lazarus Effect

- For an undepleted heavily irradiated detector:

$$CCE \propto \left(\frac{d}{D}\right)^2 \exp\left(-\frac{t_{drift}}{\tau_{trap}}\right) \quad \text{where} \quad d^2 \propto \frac{1}{|N_{eff}|}$$





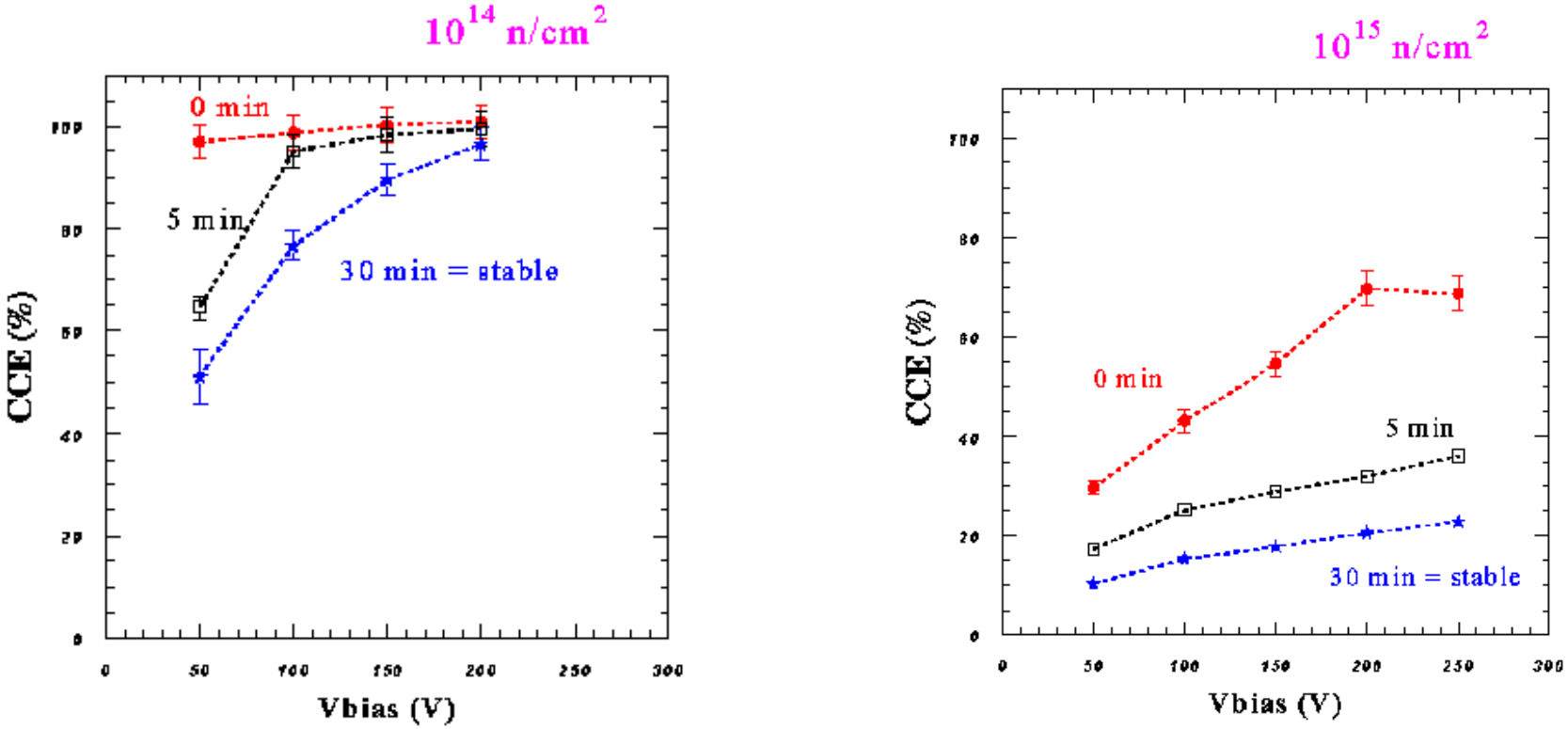


- Traps are filled ⇒ traps are neutralized

  N_{eff} compensation (confirmed by experiment)

B. Dezillie et al., IEEE Transactions on Nuclear Science, 46 (1999) 221

Reverse Bias



Measured at 130K - maximum CCE

CCE falls with time to a stable value

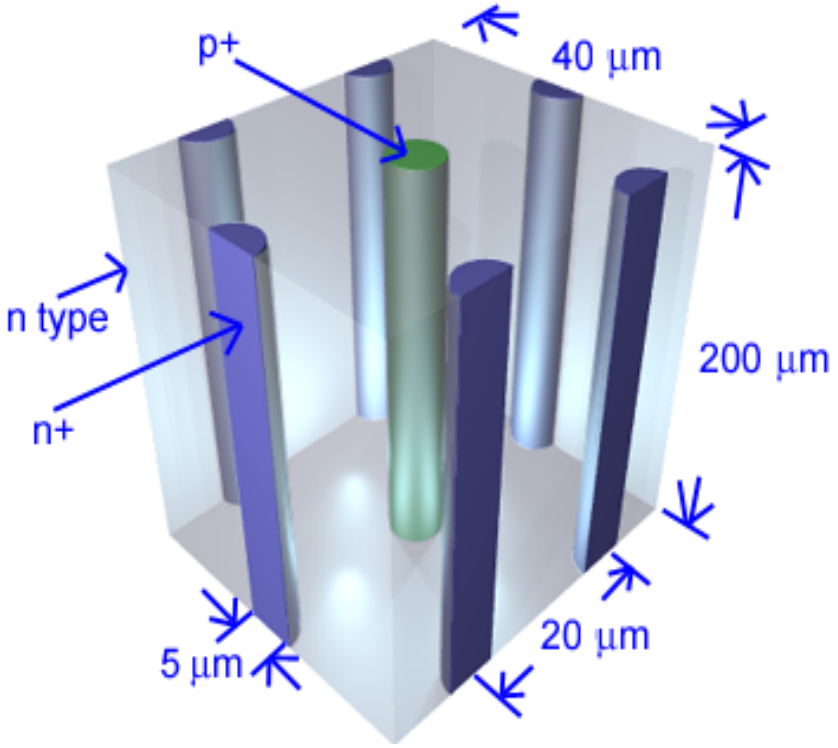
Cryogenic Results

- CCE recovery at cryogenic temperatures
  - CCE is max at T ~ 130 K for all samples
  - CCE decreases with time till it reaches a stable value
- Reverse Bias operation
  - MPV ~5'000 electrons for 300 μm thick standard silicon detectors irradiated with $2 \cdot 10^{14}$ n/cm^2 at 250 V reverse bias and T~77 K
  - very low noise
- Forward bias is possible at cryogenic temperatures
- No time degradation of CCE in operation with forward bias or in presence of short wavelength light
  - same conditions: MPV ~13'000 electrons

Electrode Structure

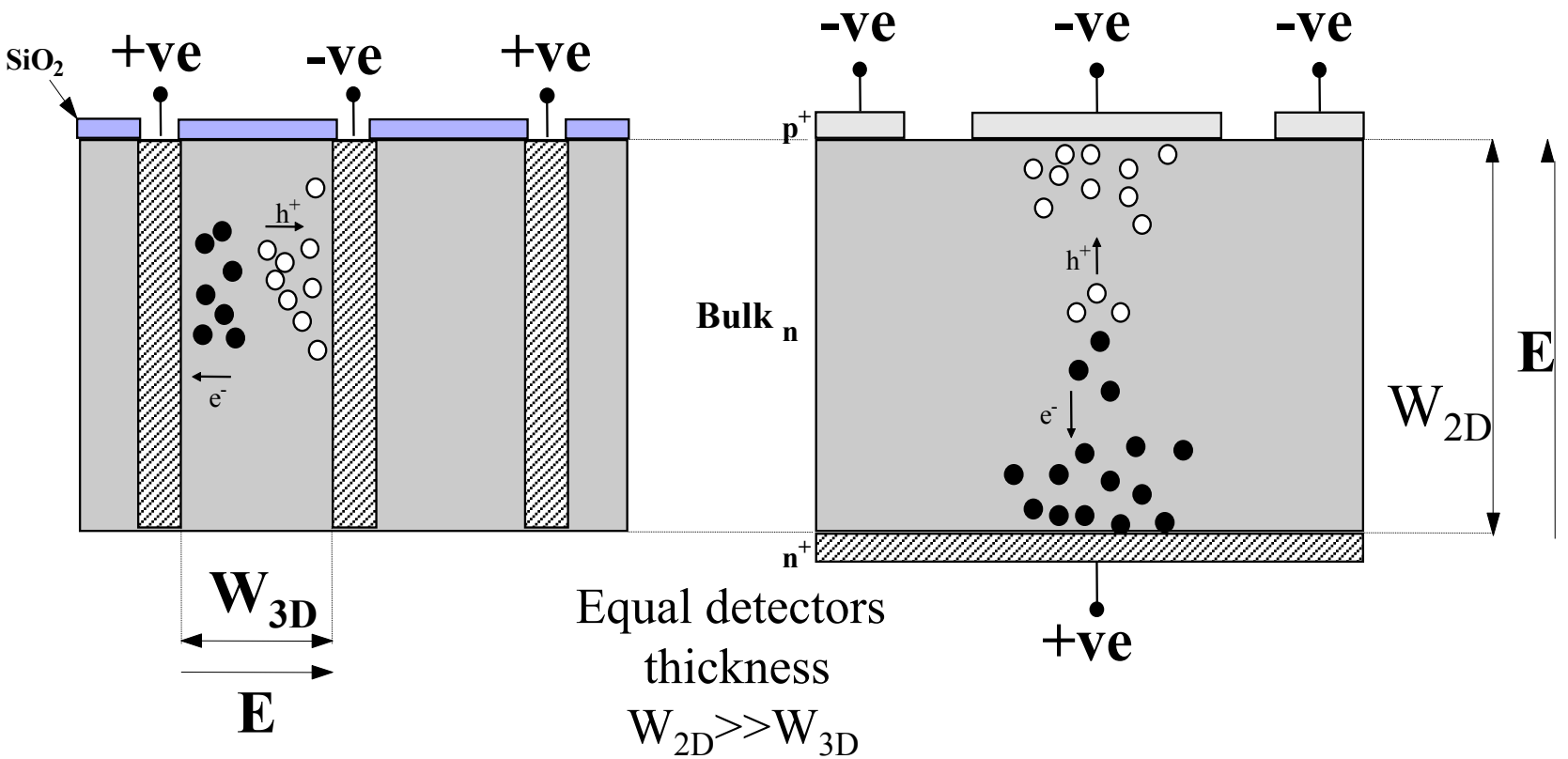
- Increasing fluence
  - Reducing carrier lifetime
  - Increasing N_{eff}
    - Higher bias voltage
    - Operation with detector under-depleted
- Reduce electrode separation
  - Thinner detector $\Rightarrow$ Reduced signal/noise ratio
  - Close packed electrodes through wafer

The 3-D device



- Co-axial detector
  - Arrayed together
- Micron scale
  - USE Latest MEM techniques
- Pixel device
  - Readout each p+ column
- Strip device
  - Connect columns together

Operation



Equal detectors thickness
$W_{2D} >> W_{3D}$

Carriers swept horizontally
Travers short distance between electrodes

Carriers drift total thickness of material

Proposed by S.Parker, Nucl. Instr. And Meth. ***A 395*** *pp. 328-343(1997).*

Advantages

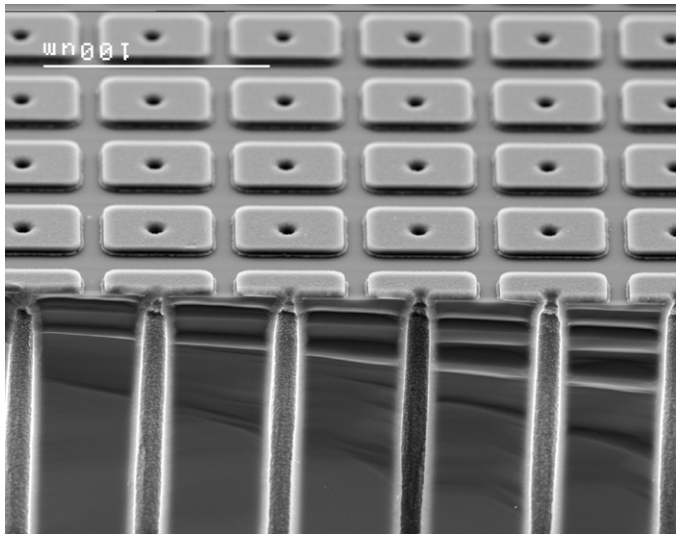
- If electrodes are close
  - Low full depletion bias
  - Low collection distances
  - Thickness NOT related to collection distance
  - No charge spreading
  - Fast charge sweep out

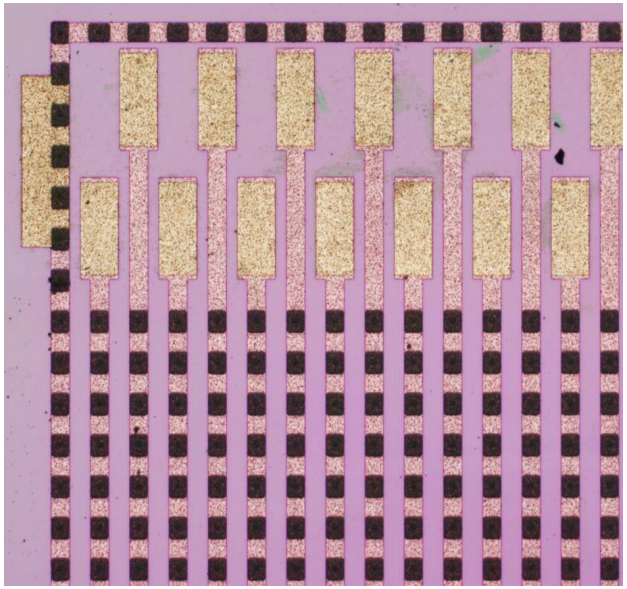
$$V_{fd} = \frac{qN_D W^2}{2\varepsilon}$$

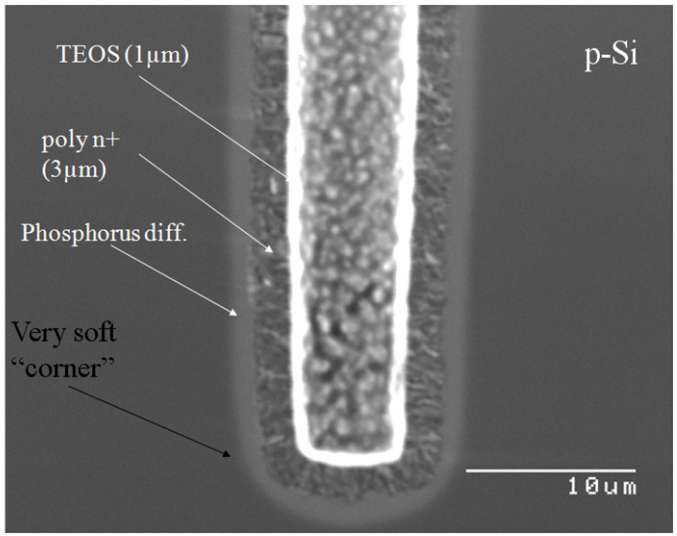
$$Q_s = Q_0 \frac{L}{d}\left(1 - e^{-d/L}\right)$$

A 3-D device

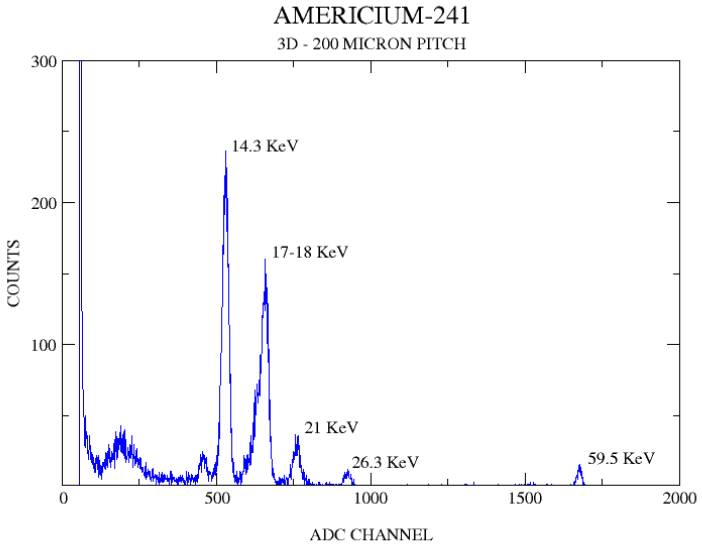
- Form an array of holes
- Fill them with doped poly-silicon
- Add contacts
  - Can make pixel or strip devices
- Bias up and collect charge

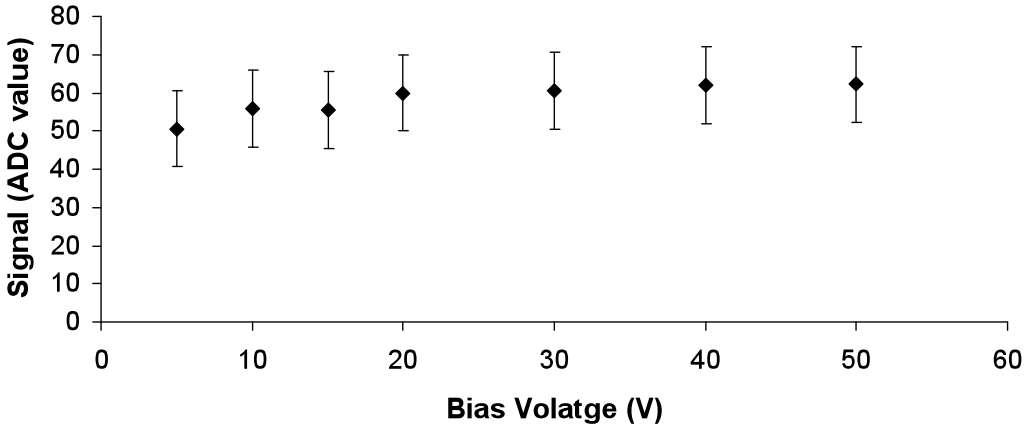






Real spectra

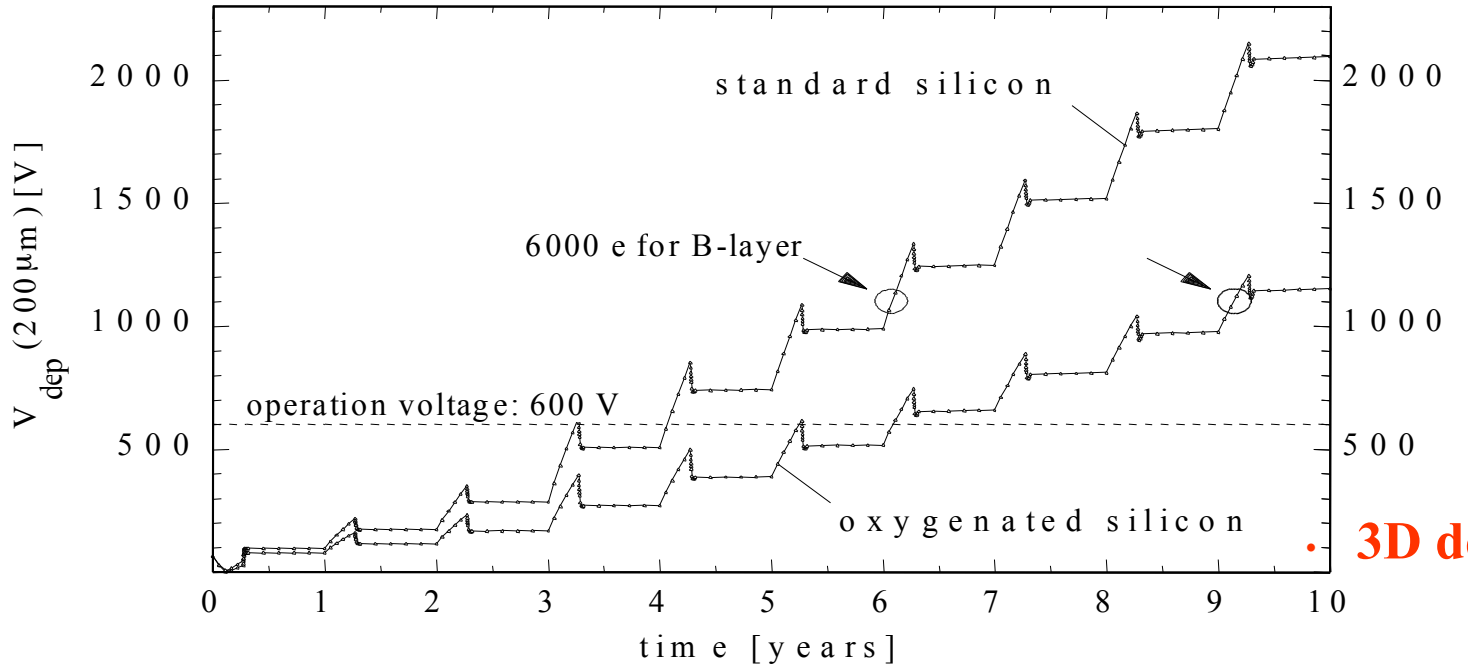




Very good energy resolution

At 20V
Plateau in Q collection
⇒Fully active

3-D V_{fd} in ATLAS



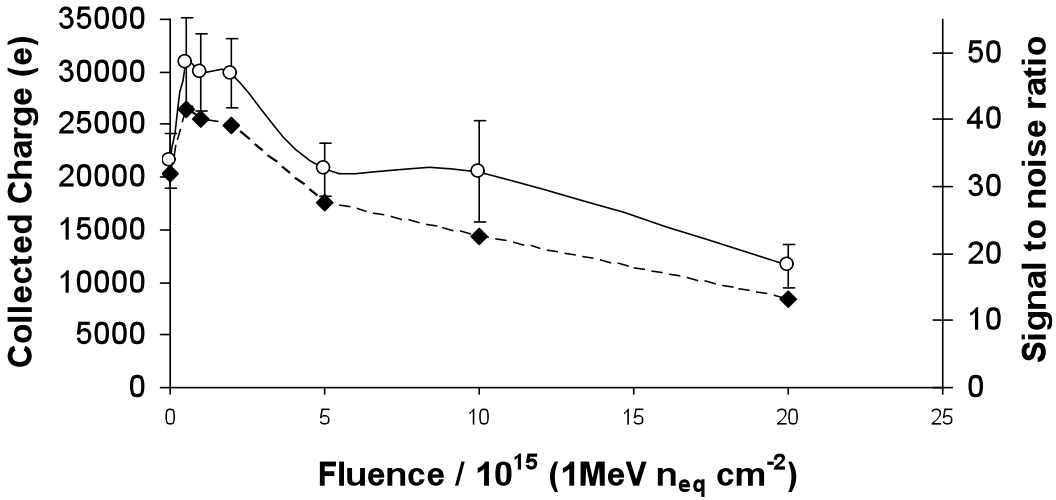
3D detector!

Damage projection for the ATLAS B-layer

(3rd RD48 STATUS REPORT CERN LHCC 2000-009, LEB Status Report/RD48, 31 December 1999).

3D charge collection

- Small electrode spacing
  - Increases charge collection due to lower drift distance
  - Reduces bias voltage
  - Increases fields and therefore enhances charge multiplication effects



The collected charge (solid line and open circles) and the signal to noise ratio (dashed line and solid diamonds) as a function of irradiation dose for the double side 3D detectors bias to their maximum sensible bias voltage (which was between 250V and 350V).

Summary

- Tackle reverse current
  - Cold operation, -20°C
  - Substrate orientation
  - Multiguard rings
- Overcome limited carrier lifetime and increasing effective doping density
  - Change material
  - Increase carrier lifetime
  - Reduce electrode spacing

Final Slide

- Why?
- Where?
- How?
- A major type
- A major worry