Silicon Detectors - I

B.G. Svensson

University of Oslo, Department of Physics, Physical Electronics,
P.O. 1048 Blindern, N-0316 Oslo, *NORWAY*

and

University of Oslo, Centre for Materials Science and Nanotechnology
P.O. 1128 Blindern, N-0318 Oslo, *NORWAY*

UNIVERSITY OF OSLO
Department of Physics

SENTER FOR MATERIALVITENSKAP OG NANOTEKNOLOGI

Micro- and Nanotechnology Laboratory (MiNaLab), 5000 m^2, OSLO

(April-2004)


MiNa-lab


...inside

MiNa-lab (Oslo, Aug-2002)

UNIVERSITY
OF OSLO

Staff at MiNa

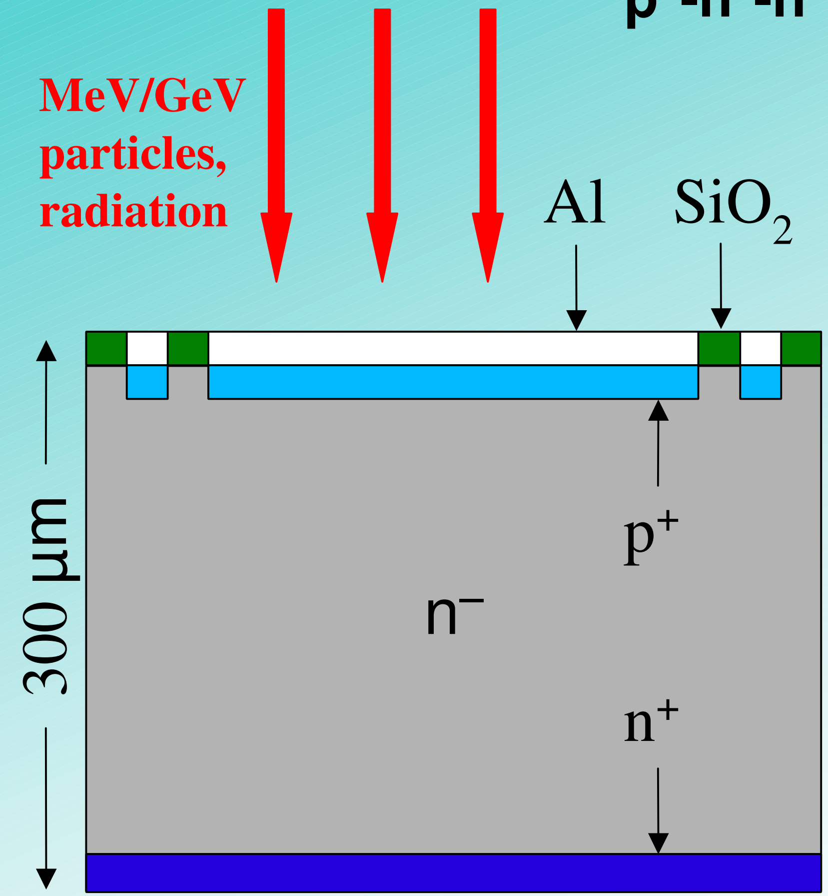
PhD students	Post-doctors/Researchers	'Permanent'
Giovanni Alfieri	Jens S. Christensen	Viktor Bobal, engineer
Marc Avice	Ulrike Grossner	Terje G. Finstad, prof
Jan H. Bleka	Philip Y.Y. Kan	Liv Furuberg, ass. prof (adj)
Thomas Moe Børseth	Eduoard V. Monakhov	A. B. Hanneborg, ass. prof (adj)
Ingelin Clausen	Leonid Murin	Andrej Yu. Kuznetsov, ass. prof
K-M. Johansen	Ioana Pintilie	Thomas Martinsen, engineer
Matthieu Lacolle	Alexander Ulyashin	Ola H. Sveen, ass. prof
Jeyanthinath Mayandi	*2 New Post-docs*	Bengt G. Svensson, prof
Mads Mikelsen		Aasmund Sudbø, prof (UNIK)
Ramon Schifano		David I. Wormald, eng. (30 %)
Lasse Vines		
2 New PhD students	**~6 MSc students, Visitors**	

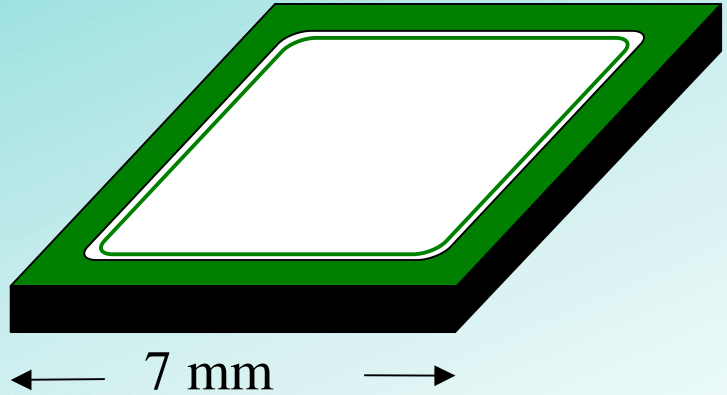
Outline

- Some fundamentals about materials, device physics and processing related to Si detectors
- Radiation tolerance of Si detectors, limiting factors
- Defect/impurity engineering of Si detectors
- New detector structures

‘Baby detector’

p^+-n^--n^+ Si detectors





$n^- \sim (2\text{-}5)\times10^{12}$ cm^{-3}

Cf $n_i \sim 1.5\times10^{10}$ cm^{-3} @ RT

p^+, n^+ by ion implantation

UNIVERSITY
OF OSLO
Department of Physics/Physical Electronics

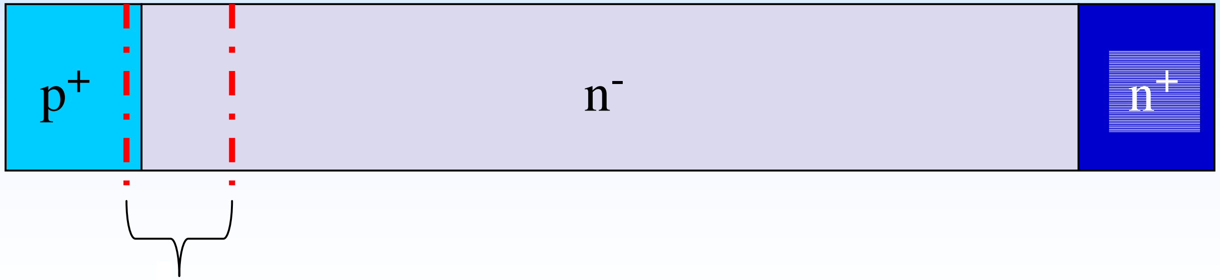
MeV ion accelerator at UiO/MiNa-lab

Ion implantation and RBS-analysis

National Electrostatics Corporation, 1 MV terminal voltage

Basic considerations

(zero bias)



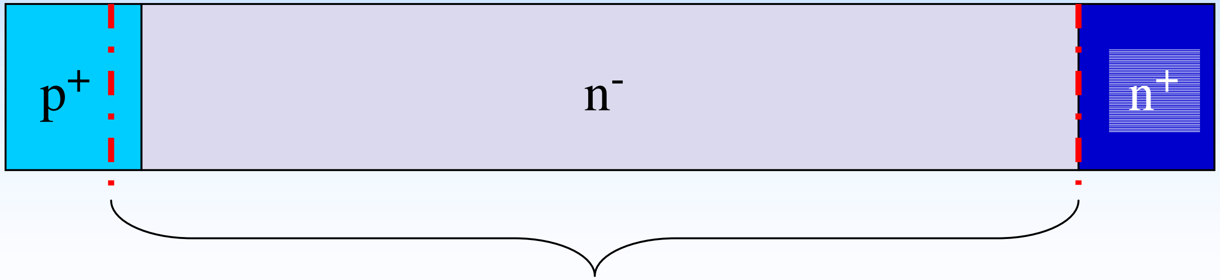
$W = \left(2\varepsilon V_0(N_a+N_d)/q(N_a+N_d)\right)^{1/2}$ - depletion region

$N_a >> N_d \longrightarrow W = \left(2\varepsilon V_0/(qN_d)\right)^{1/2} \approx 20\ \mu m$

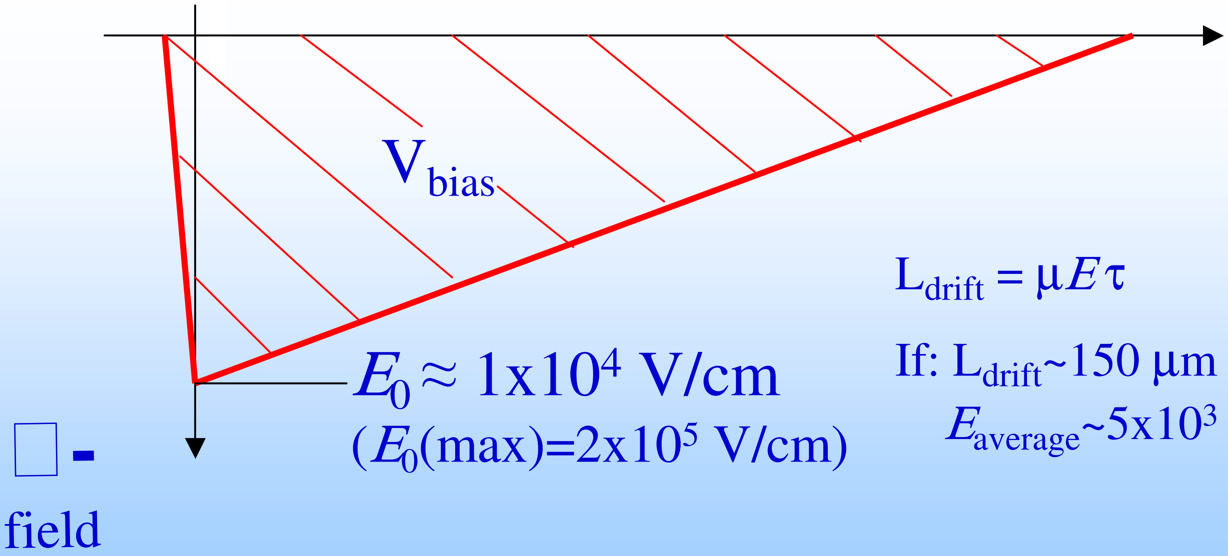
$L_D = \left(\varepsilon kT/q^2N_d\right)^{1/2} \approx 3\ \mu m$ - **Debye length** at RT

Basic considerations

(full (over) depletion)



$W \approx 300\ \mu m \Rightarrow V_{reverse\ bias} \approx 135\ V$



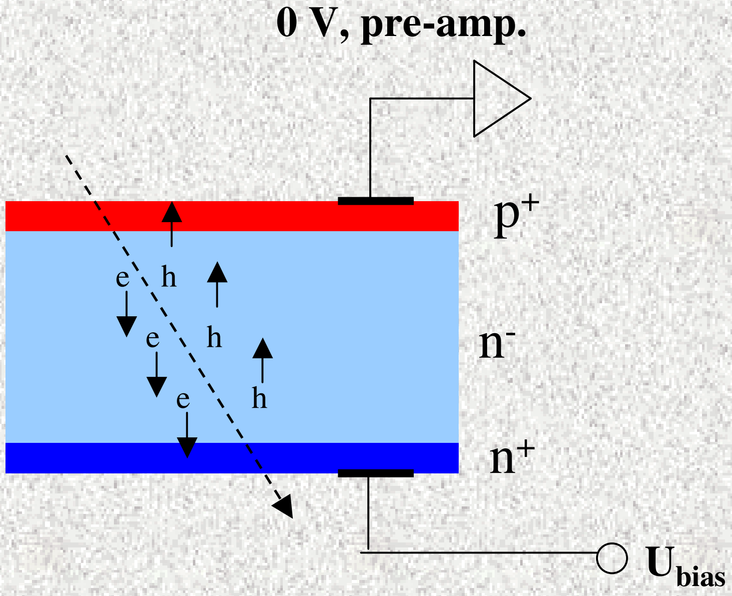
$L_{drift} = \mu E \tau$

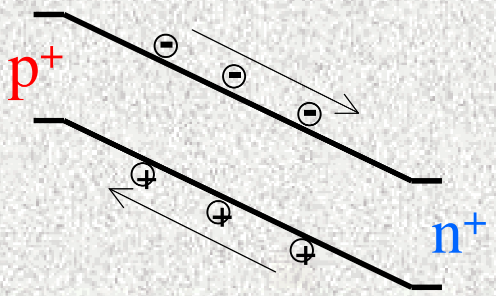
If: $L_{drift} \sim 150\ \mu m$

$E_{average} \sim 5x10^3$ V/cm

$\rightarrow \tau_{hole} \approx 6$ ns

Silicon particle detectors





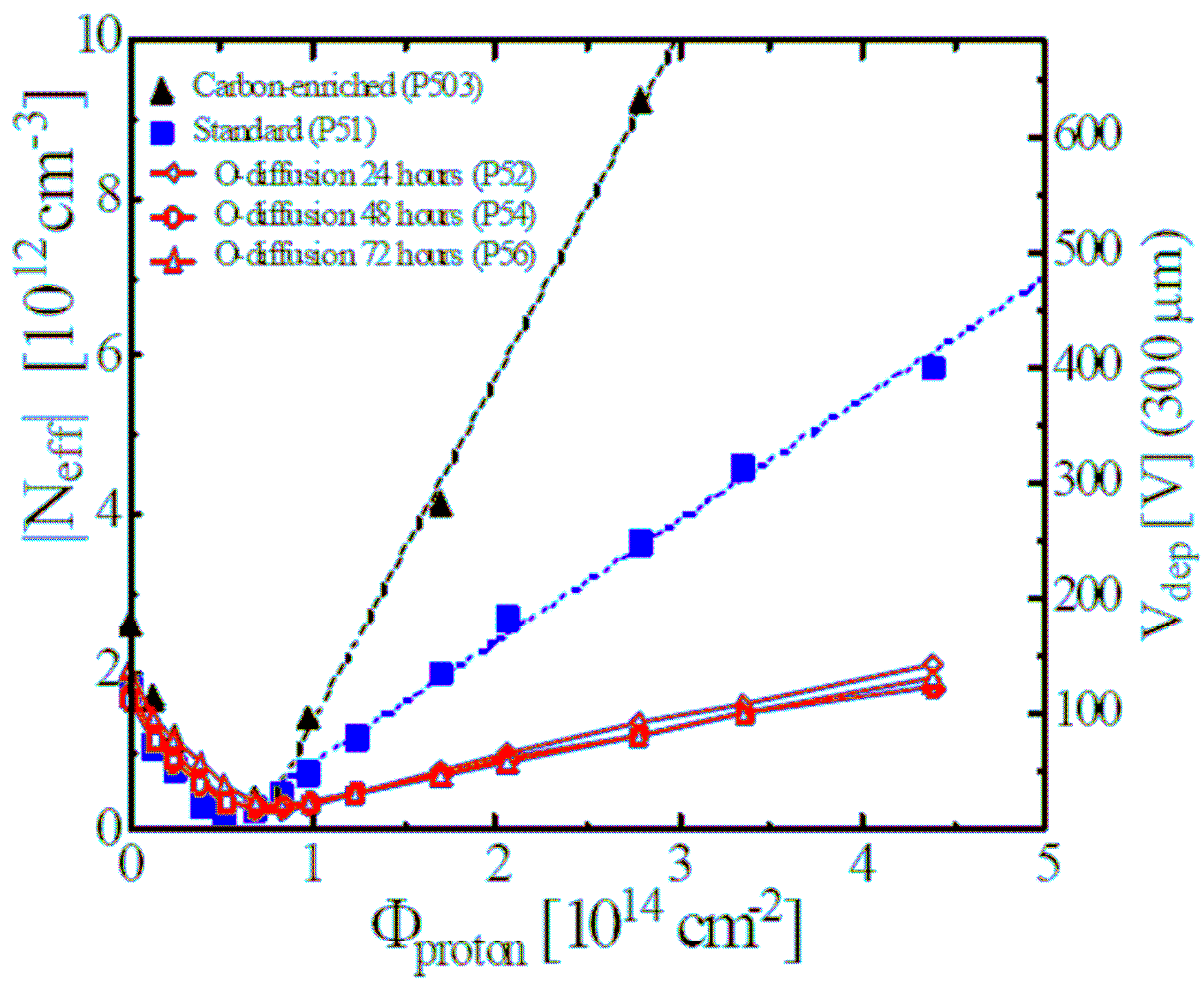
Advantages:

- high signal-to-noise ratio

- fast direct charge readout

- high spatial resolution

Impurity engineering of high-purity Si-detectors



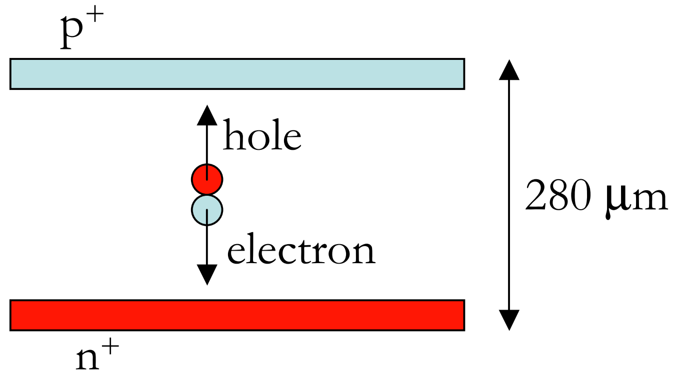
G.Lindström et al. (The RD48 Collaboration); "Developments for Radiation Hard Silicon Detectors by Defect Engineering - Results by the CERN RD48 (ROSE) Collaboration –"NIM A 465/1 (2001) 60-69.

Signal formation

$$Q=\int_{t=0}^{t} I dt = q\int_{t=0}^{t}\vec{v}\vec{E}_w dt = q\int_{\vec{r}_0}^{\vec{r}(t)}\vec{E}_w d\vec{r}$$

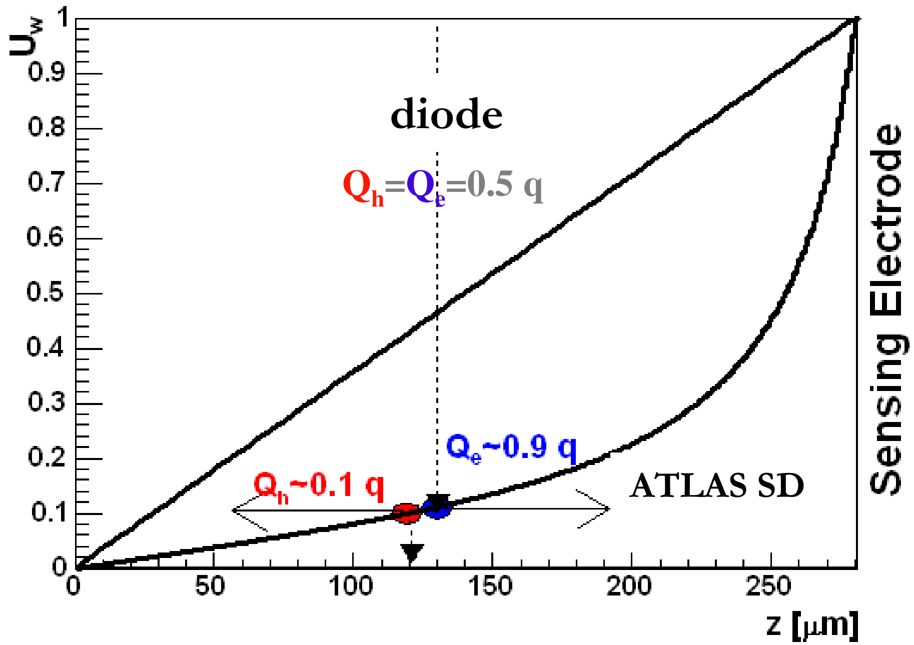
$$Q=q[U_w(\vec{r})-U_w(\vec{r}_0)]$$

$$Q_{e-h}=Q_e+Q_h$$



Contribution of drifting carriers to the total induced charge depends on ΔU_w!

Simple in diodes and complicated in segmented devices!
For track:
$Q_e/(Q_e+Q_h)=19\%$
in ATLAS strip detector

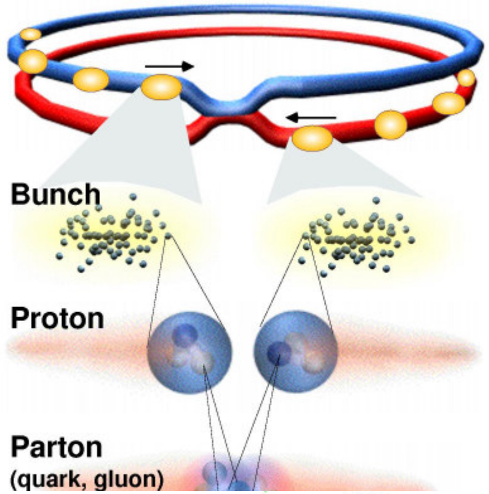


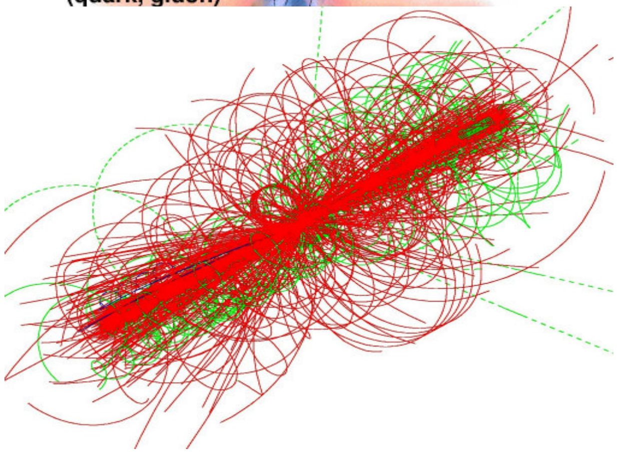
Outline

- Some fundamentals about materials, device physics and processing related to Si detectors
- **Radiation tolerance of Si detectors, challenges and limiting factors**
- Defect/impurity engineering of Si detectors
- New detector structures

Silicon Detectors: Favorite Choice for Particle Tracking

Example: Large Hadron Collider LHC, start 2007





LHC properties →

- **Proton-proton collider, 2 x 7 TeV**
  Luminosity: 10^{34}
- **Bunch crossing: every 25 nsec, Rate: 40 MHz**
  event rate: 10^9/sec (23 interactions per bunch crossing)
- **Annual operational period: 10^7 sec**
- **Expected total op. period: 10 years**

Experimental requests	Detector properties
Reliable detection of mips →	S/N ≈ 10
High event rate →	time + position resolution:
high track accuracy →	~10 ns and ~10 µm
Complex detector design →	low voltage operation in normal ambients
Intense radiation field during 10 years →	Radiation tolerance up to 10^{15} hadrons/cm²
Feasibility, e.g. 200 m² for CMS →	large scale availability known technology, low cost

! Silicon Detectors meet all Requirements !

G. Lindström et al.

Main motivations for R&D on Radiation Tolerant Detectors: Super - LHC

- **LHC upgrade**

  ⇨ **LHC (2007), L = 10^{34}cm^{-2}s^{-1}**

  10 years → **500 fb^{-1}** ϕ(r=4cm) ~ $3\cdot10^{15}$cm^{-2}

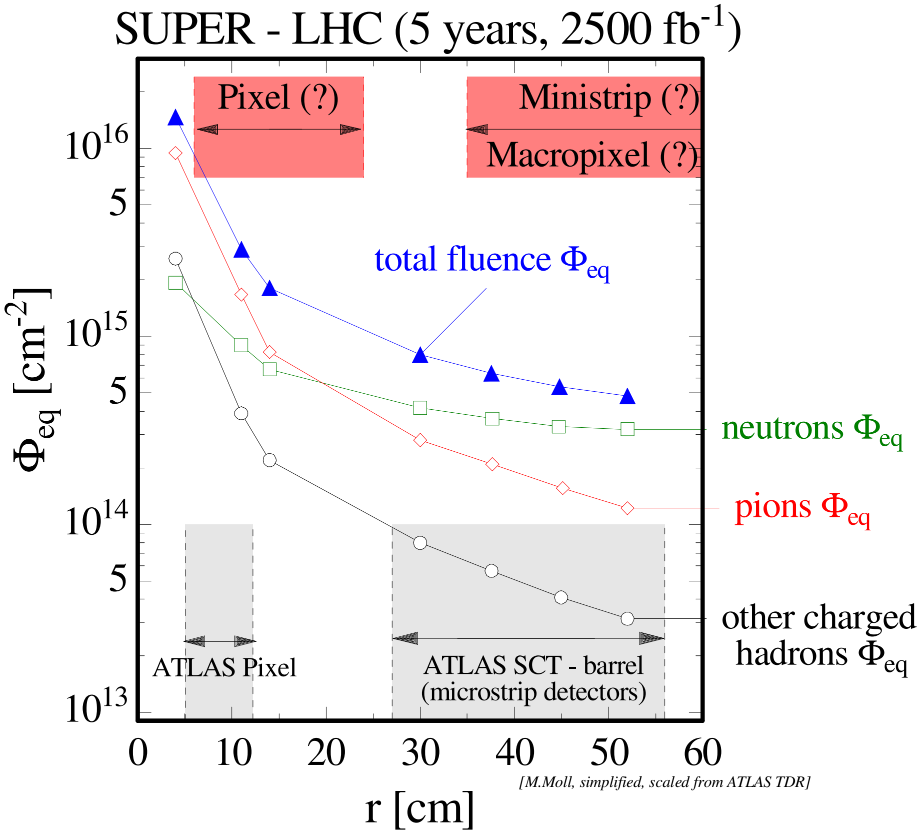
  CERN-RD48

  $\times$ **5**

  ⇨ **Super-LHC (2015 ?), L = 10^{35}cm^{-2}s^{-1}**

  5 years → **2500 fb^{-1}** ϕ(r=4cm) ~ $1.6\cdot10^{16}$cm^{-2}

  CERN-RD50



- **LHC (Replacement of components)**

  e.g. - LHCb Velo detectors (~2010)

  - ATLAS Pixel B-layer (~2012)

- Linear collider experiments (generic R&D)

  Deep understanding of radiation damage will be fruitful for linear collider experiments where high doses of e, γ will play a significant role.

G. Lindström et al.

Radiation Damage in Silicon Detectors

Two types of radiation damage in detector structures:

- **Bulk (Crystal) damage** due to **Non Ionizing Energy Loss (NIEL**

  - displacement damage, built up of crystal defects –

  I. Increase of **leakage current** (increase of shot noise, thermal runaway)

  II. Change of **effective doping concentration**
  (higher depletion voltage, under- depletion)

  III. Increase of **charge carrier trapping** (loss of charge)

- **Surface damage** due to **Ionizing Energy Loss (IEL)**

  - accumulation of charge in the oxide (SiO_2) and Si/SiO_2 interface –
  affects: interstrip capacitance (noise factor), breakdown behavior, …

! Signal/noise ratio = most important quantity !

G. Lindström et al.

Trapping and recombination of carriers

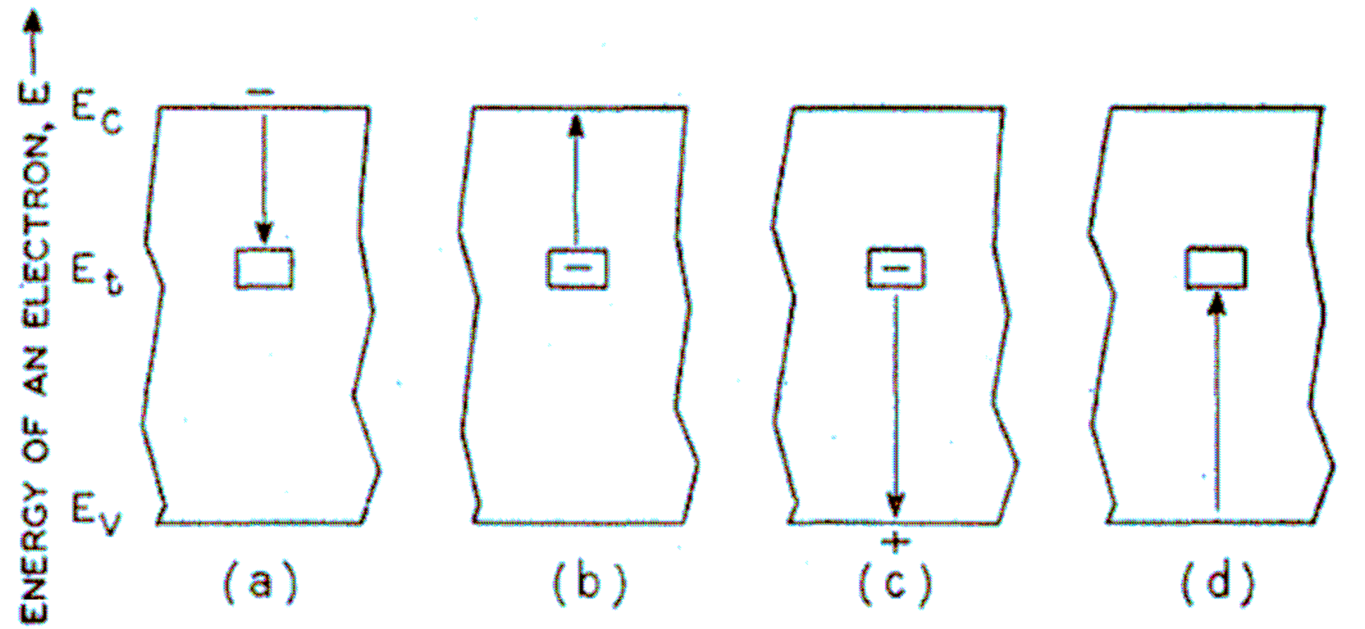
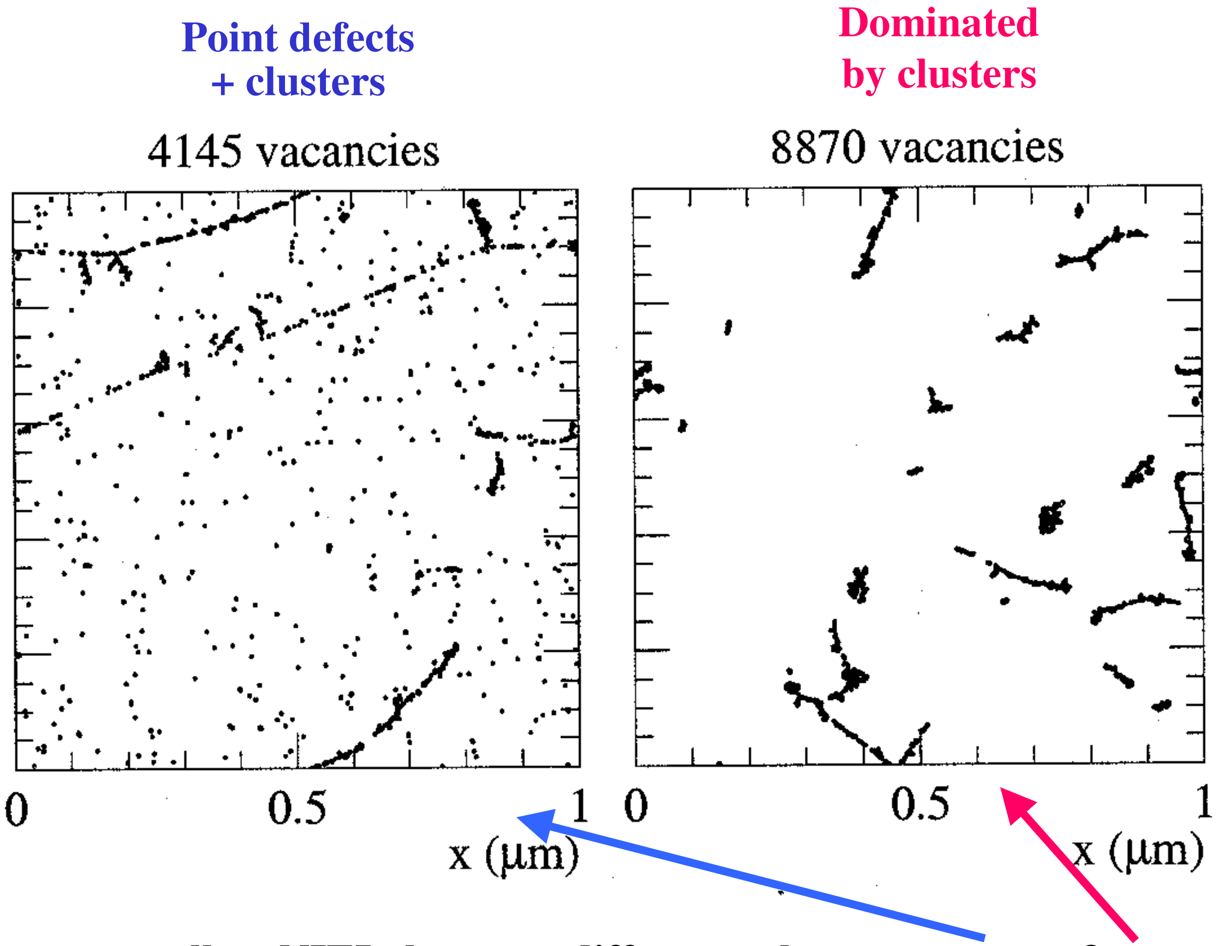


FIG. 1. The basic processes involved in recombination by trapping: (a) electron capture, (b) electron emission, (c) hole capture, (d) hole emission.

Schockley and Read, Phys. Rev. **87**, 835 (1952)

Deterioration of Detector Properties by displacement damage NIEL

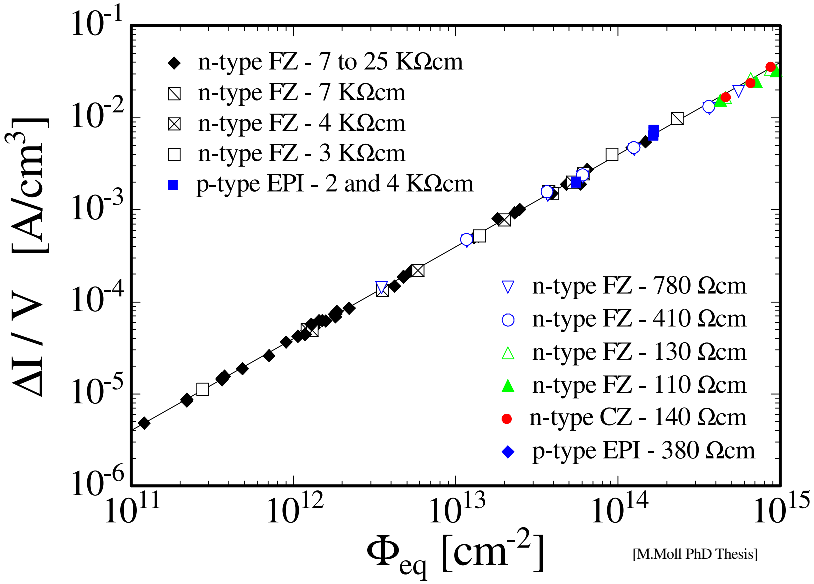


Damage effects generally ~ NIEL, however differences between proton & neutron damage important for defect generation in silicon bulk

Radiation Damage – Leakage current

Increase of Leakage Current

…. with particle fluence:



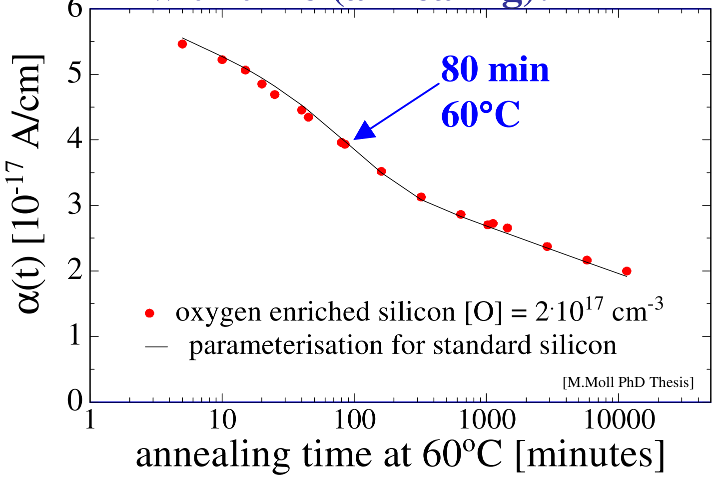
- **Damage parameter α (slope in figure)**

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

Leakage current per unit volume and particle fluence

- α is constant over several orders of fluence and independent of impurity concentration in Si
  ⇨ can be used for fluence measurement

with time (annealing):



- **Leakage current decreasing in time (depending on temperature)**
- **Strong temperature dependence:**

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

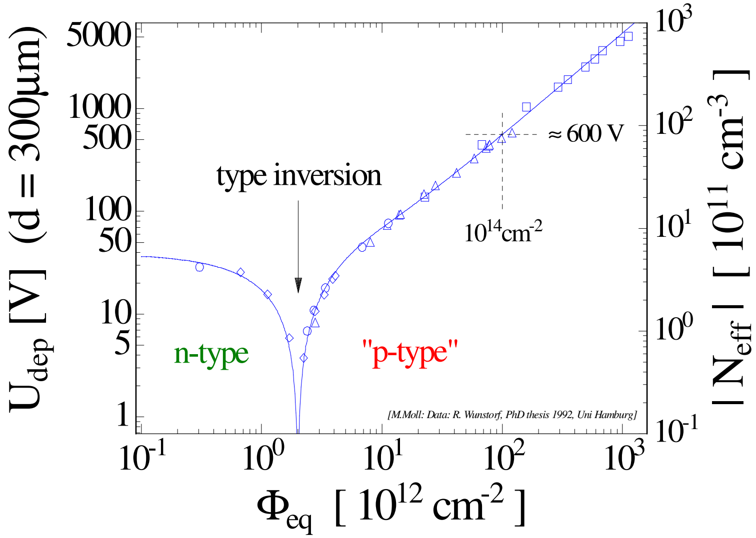
Consequence:
Cool detectors during operation!
Example: I(-10°C) ~1/16 I(20°C)

G. Lindström et al.

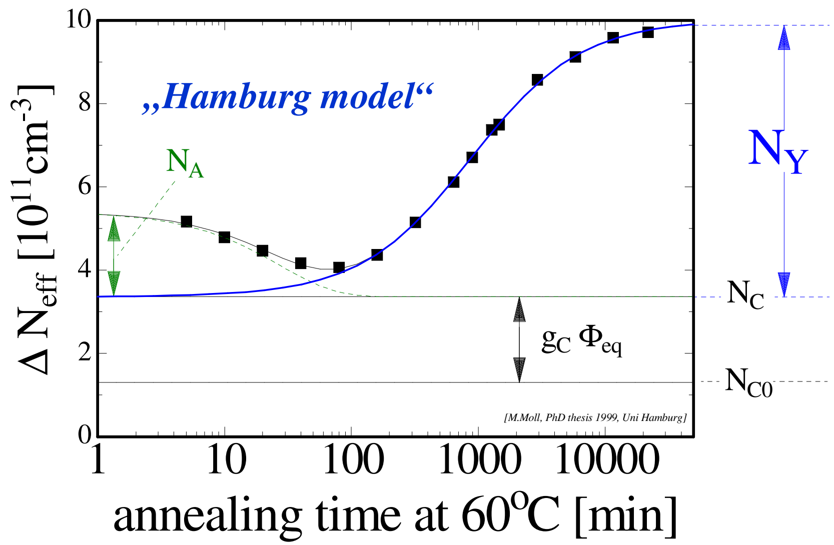
Radiation Damage – Effective doping concentration

Change of Depletion Voltage V_{dep} (N_{eff})

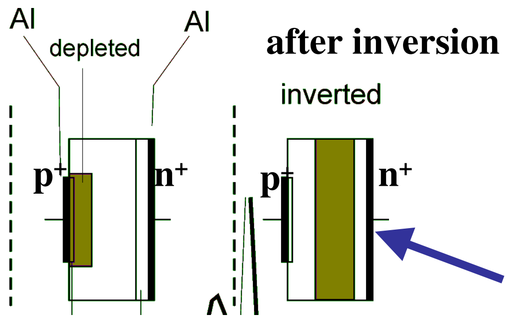
…. with particle fluence:



…. with time (annealing):



"**Type inversion**": N_{eff} changes from positive to negative (Space Charge Sign Inversion)



Short term: "**Beneficial annealing**"

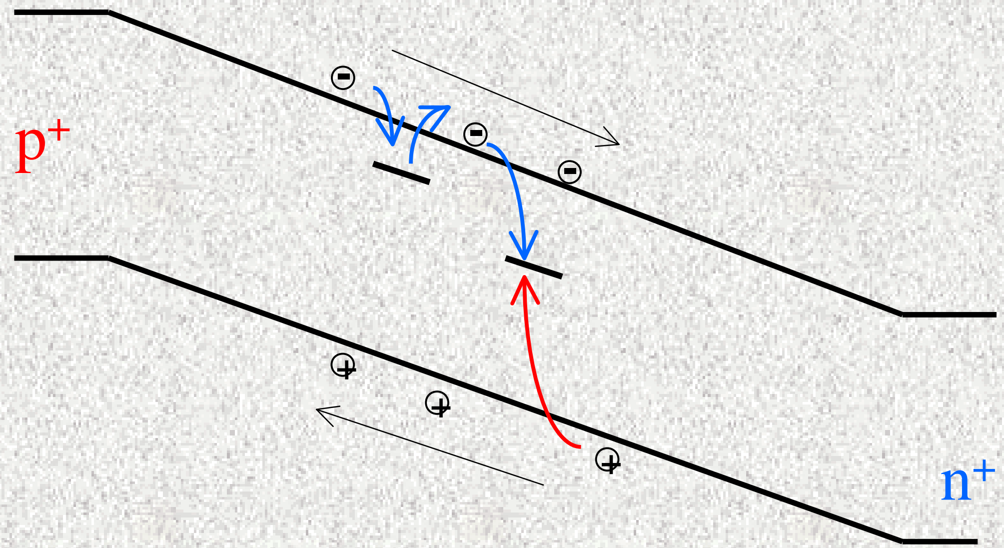
Long term: "**Reverse annealing**"

- time constant depends on temperature:
  - ~ 500 years (-10°C)
  - ~ 500 days (20°C)
  - ~ 21 hours (60°C)

Consequence: Cool Detectors even during beam off (250 d/y)
alternative: acceptor/donor compensation by defect enginrg.

G. Lindström et al.

Charge trapping & recombination



- *Increase of charge collection time*
- *Decrease of the charge collection efficiency*
- *Decrease of the S/N ratio*

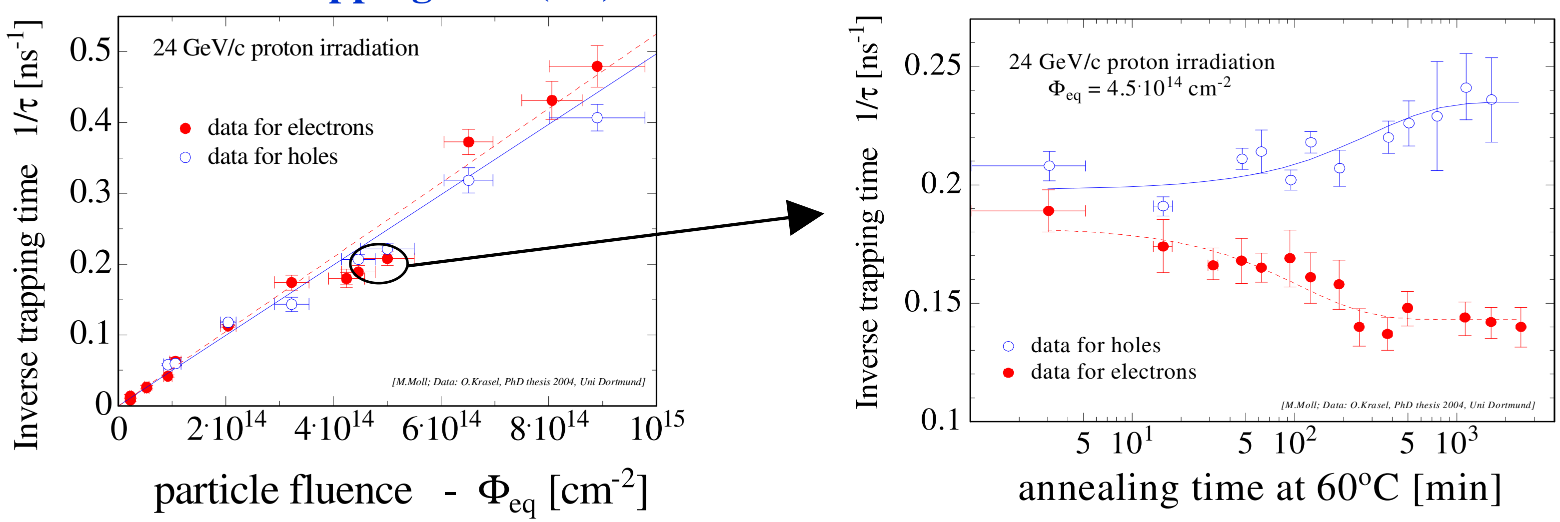
Radiation Damage – Charge carrier trapping

Deterioration of Charge Collection Efficiency (CCE) by trapping

Trapping is characterized by an effective trapping time τ_{eff} for electrons and holes:

$$Q_{e,h}(t) = Q_{0e,h} \exp\left(-\frac{1}{\tau_{eff\ e,h}} \cdot t \right) \qquad \text{where:} \qquad \frac{1}{\tau_{eff\ e,h}} \propto N_{defects}$$

Increase of inverse trapping time (1/τ) with fluence ….. and change with time (annealing):



Charge trapping leads to very small $\lambda_{e,h}$ at $\Phi_{eq} = 10^{16}/cm^2$

Consequence: Cooling does not help but: use thin detectors (~100µm) and p-type Si

UHH G. Lindström et al.

„Executive Summary“

- *Si-Detectors in the inner tracking area of future colliding beam experiments have to tolerate hadronic fluences up to $\Phi_{eq} = 10^{16}/cm^2$*
- *Deterioration of the detector performance is largely due to bulk damage caused by non ionizing energy loss (NIEL) of the particles*
- *Reverse current increase (most likely due to both point defects and clusters) is effectively reduced by cooling. Defect engineering so far not successful*
- *Change of depletion voltage is severe, also affected by type inversion and annealing effects. Modification by defect engineering is possible, for standard devices continuous cooling is essential (‚freezing‘ of annealing)*
- *Charge trapping is possibly the ultimate limitation for Si-detectors, responsible defects are unknown, cooling and annealing have minor effects*

Outline

- Some fundamentals about materials, device physics and processing related to Si detectors
- Radiation tolerance of Si detectors, challenges and limiting factors
- **Defect/impurity engineering of Si detectors**
- New detector structures

The RD50 Collaboration

RD50: Development of Radiation Hard Semiconductor Devices for High Luminosity Colliders (http://rd50.web.cern.ch/rd50/)

1. Formed in November 2001
2. Approved by CERN in June 2002

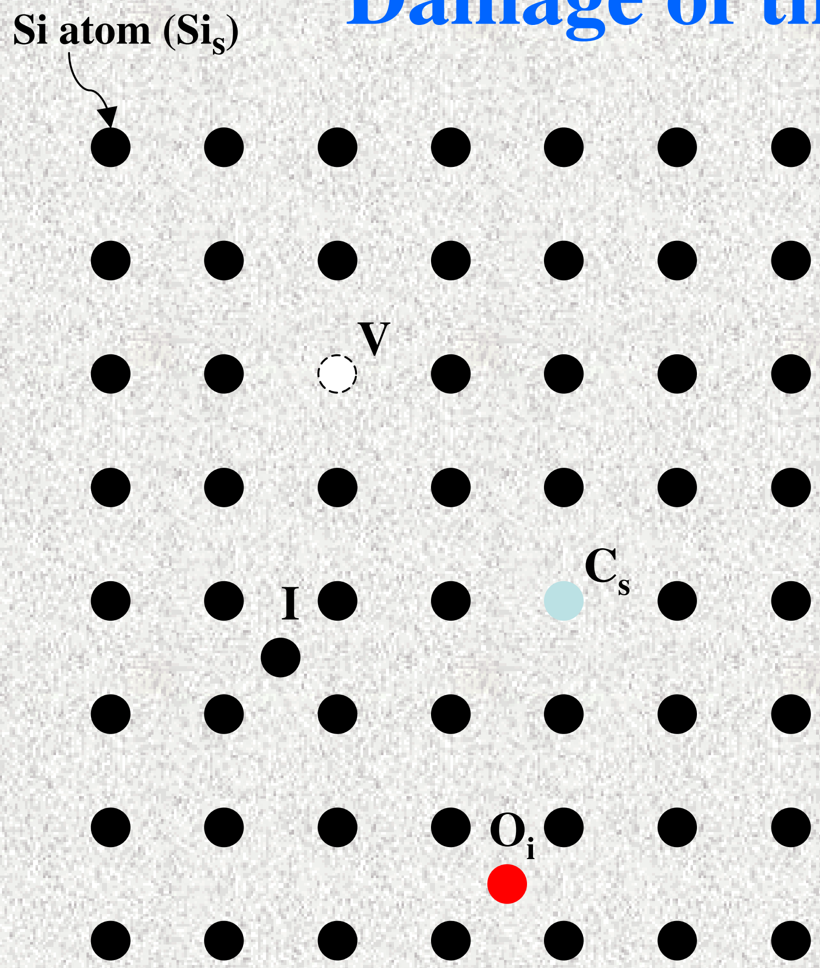
Main objective:
Development of ultra-radiation hard semiconductor detectors for the luminosity upgrade of LHC to 10^{35} $cm^{-2}s^{-1}$ (S-LHC)
Challenges:
- Radiation hardness up to fluences of 10^{16} cm^{-2} required;
- Fast signal collection (10 ns);
- Cost effectiveness.

Presently 280 Members from 55 Institutes

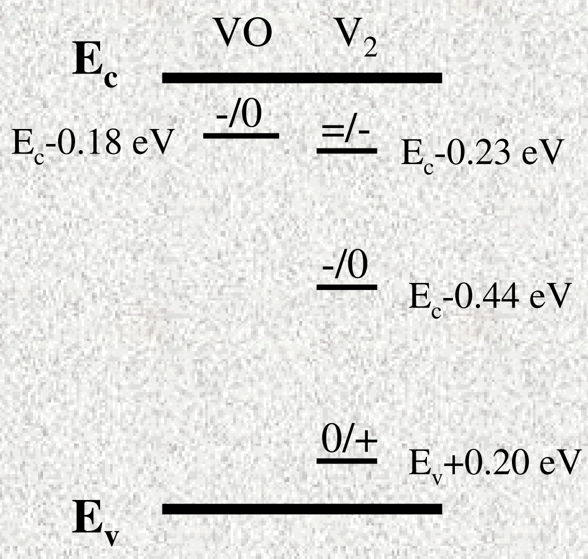
Belgium (Louvain), Canada (Montreal), Czech Republic (Prague (2x)), Finland (Helsinki (2x), Oulu), Germany (Berlin, Dortmund, Erfurt, Halle, Hamburg, Karlsruhe), Greece (Athens), Israel (Tel Aviv), Italy (Bari, Bologna, Florence, Milano, Modena, Padova, Perugia, Pisa, Trento, Trieste, Turin), Lithuania (Vilnius), Norway (Oslo (2x)), Poland (Warsaw), Romania (Bucharest (2x)), Russia (Moscow (2x), St.Petersburg), Slovenia (Ljubljana), Spain (Barcelona, Valencia), Sweden (Lund) Switzerland (CERN, PSI), Ukraine (Kiev), United Kingdom (Exeter, Glasgow, Lancaster, Liverpool, London, Sheffield, University of Surrey), USA (Fermilab, Purdue University, Rutgers University, Syracuse University, BNL, University of New Mexico)

Radiation effects in silicon detectors

Damage of the crystal lattice



Electronic levels of main electron traps in Si:



Main types of Si-detector materials used

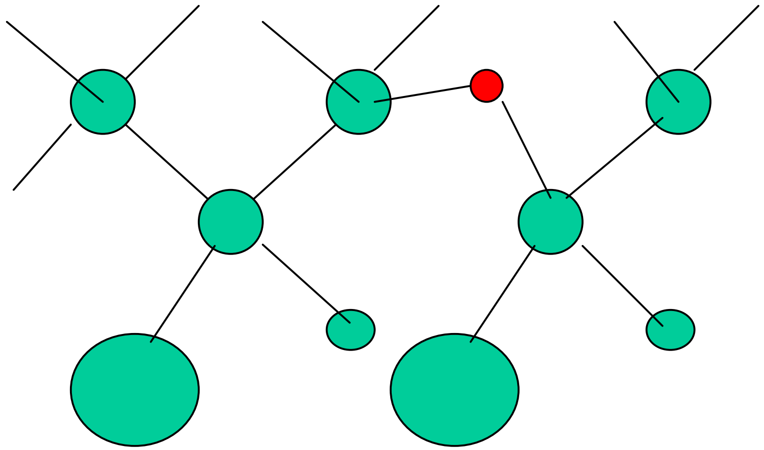
- *Float zone (Fz); low oxygen and carbon content, $[O_i]<5x10^{15}$ cm^{-3} and $[C_s]<5x10^{15}$ cm^{-3}*

- *Diffusion oxygenated Fz (DOFZ), $[O_i]$~$3x10^{17}$ cm^{-3} and $[C_s]<5x10^{15}$ cm^{-3}*

- *Magnetic Czochralski (MCz), $[O_i]$~$7x10^{17}$ cm^{-3} and $[C_s]<5x10^{15}$ cm^{-3}*

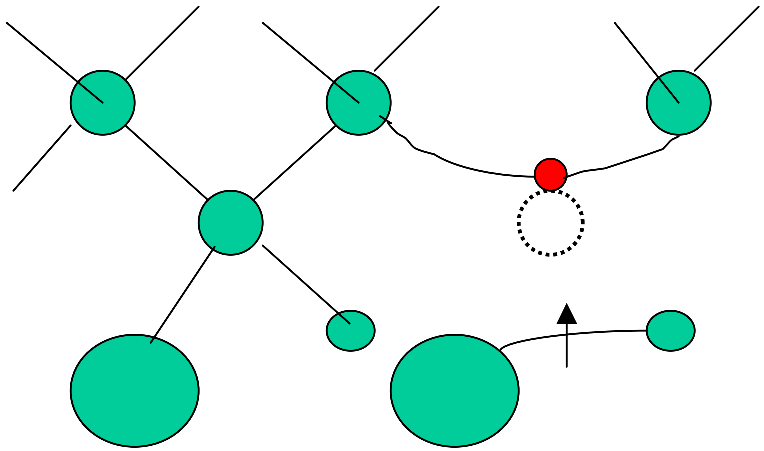
- *Epitaxial layers (Epi) on highly doped substrates, $[O_i]<5x10^{15}$ cm^{-3} and $[C_s]<5x10^{15}$ cm^{-3}*

Impurity engineering of high-purity Si

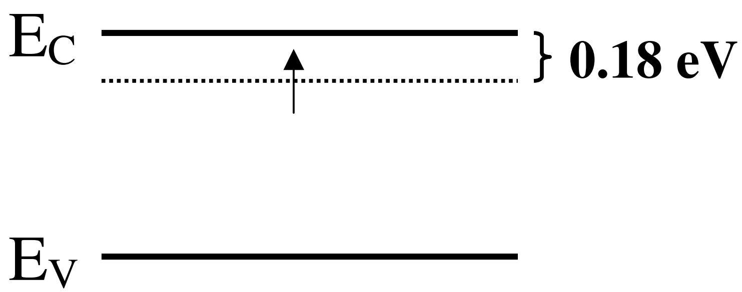


Silicon

Oxygen (O_i)
Interstitial configuration

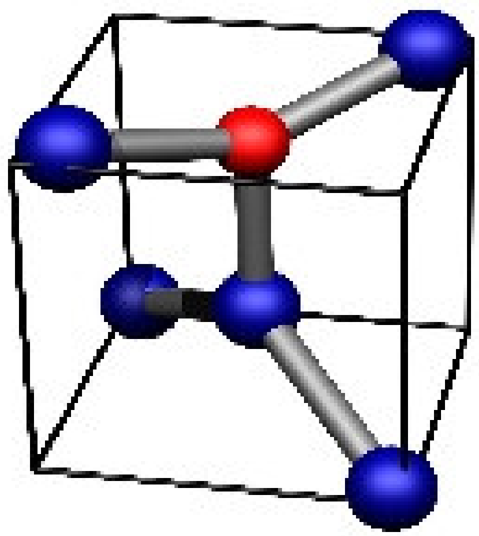


Vacancy oxygen (VO) center (0/-)

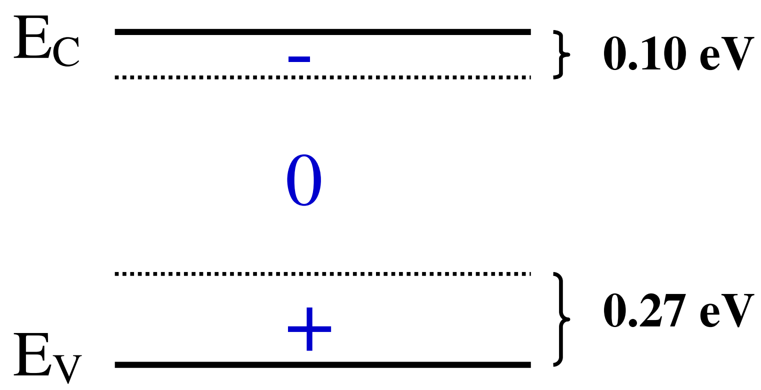


UNIVERSITY
OF OSLO

Interstitial carbon (C_i)



Three different charge states (-,0,+)

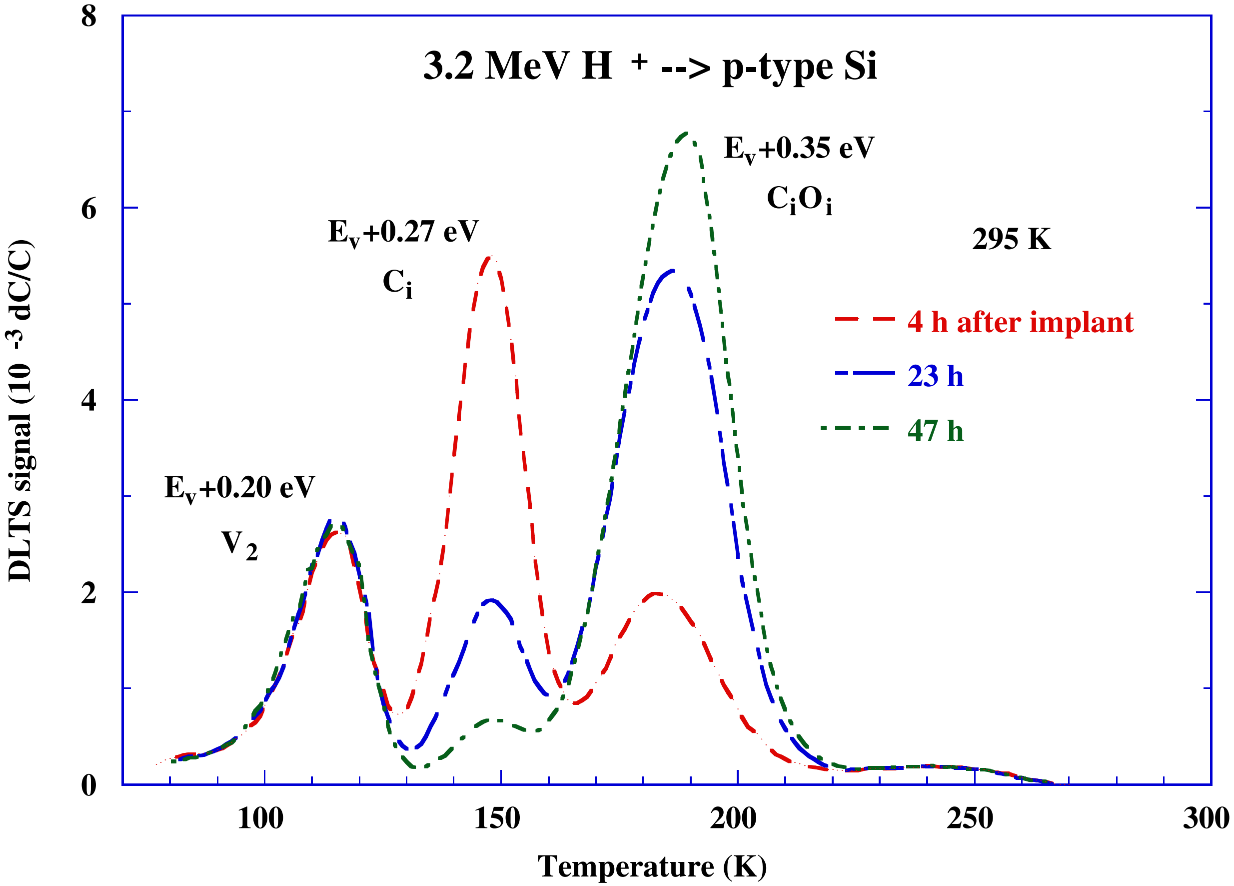


C_s has a strong impact on the overall defect generation via its role as I-trap; C_s + I → C_i

Carbon is of key importance in n^-/p^- detector layers, either directly or indirectly

G. Davies and R.C. Newman, ***Handbook of Semiconductors*****,** Eds T.S. Moss, S. Mahajan **(Elsevier, Amsterdam, 1994) ch. 21, p. 1557**

Evolution of C_i at RT; an illustration

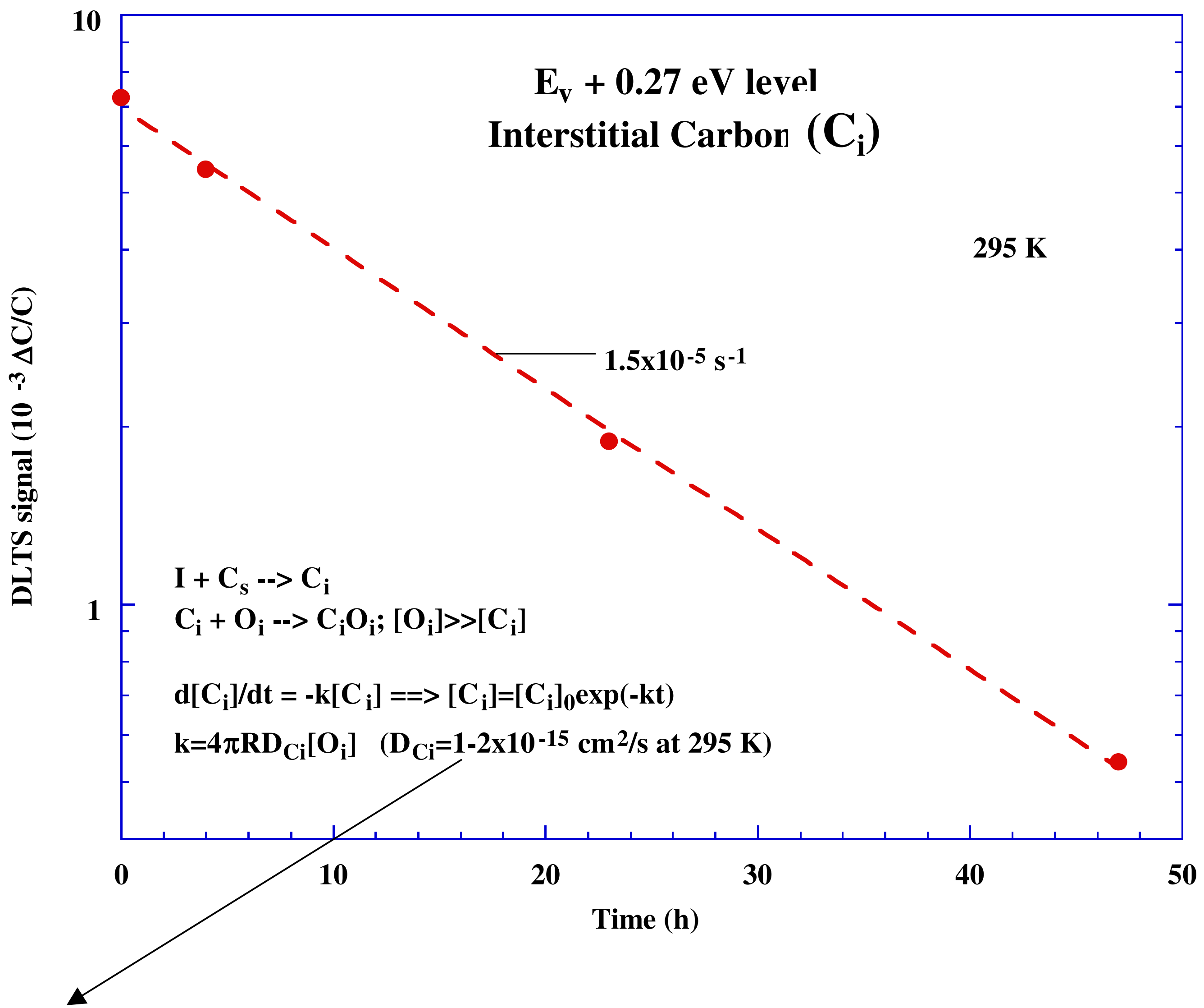


Fz (~15 Ωcm)

$[O_i]$~1.2x10^{16} cm^{-3}

$[C_s]$≤5x10^{15} cm^{-3}

Lalita et al., NIMB **120**, 27 (1996)

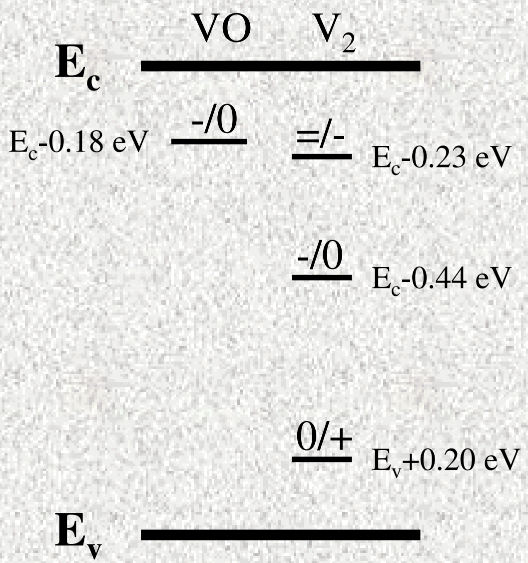


Cf value by Tipping, Newman, Semicond. Sci. Techn. **2**, 315 (1987)

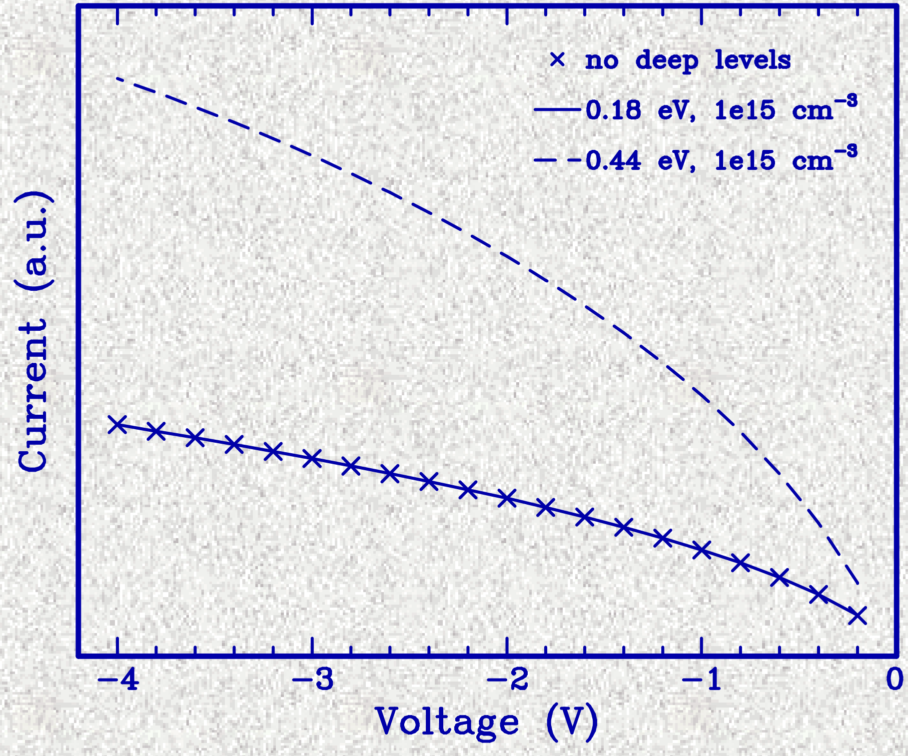
$D_{Ci} = 0.4\exp(-0.87(eV)/kT)\ cm^2/s$

Lalita et al., NIMB **120**, 27 (1996)

Purpose of defect engineering



$$V + O_i \rightarrow VO$$
$$V + V \rightarrow V_2$$



Leakage current as a function of the bias in silicon detector with different types of defects (SILVACO TCAD).

Monakhov et al., Sol. St. Phen. 82-84, 441 (2002)

Suppress formation of defects with levels close to mid-gap !!

Key defect reactions and why oxygenation

$V + I \rightarrow \emptyset$ *(only a few % survive)*

$I + C_s \rightarrow C_i$
$C_i + C_s \rightarrow C_sC_i$
$C_i + O_i \rightarrow C_iO_i$
……

$V + O_i \rightarrow VO$
$V + VO \rightarrow V_2O$
$V + V \rightarrow V_2$
$V + V_n \rightarrow V_n+1\ (n\geq 2)$

C_s traps ('immobolizes') I and suppresses self-annihilation ☹

O_i traps V and suppresses V-clustering ☺

(Standard interpretation of oxygenation effect….)

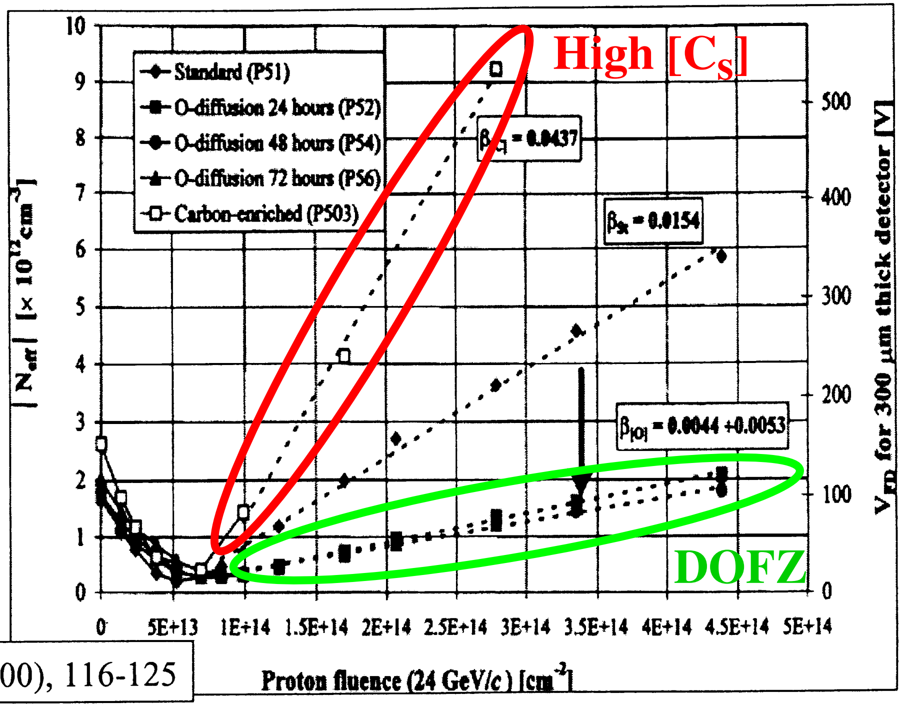
Impurity engineering of high-purity Si

DOFZ Si is significantly radiation harder than standard Si for
γ, π, p irradiations
Almost no effect for neutron irradiations

$$N_{eff} = \left| N_c(0) \cdot e^{-c\phi} - \beta \cdot \phi \right|$$

$\beta_{\text{standard Si}} \sim 3\ \beta_{\text{DOFZ}}$

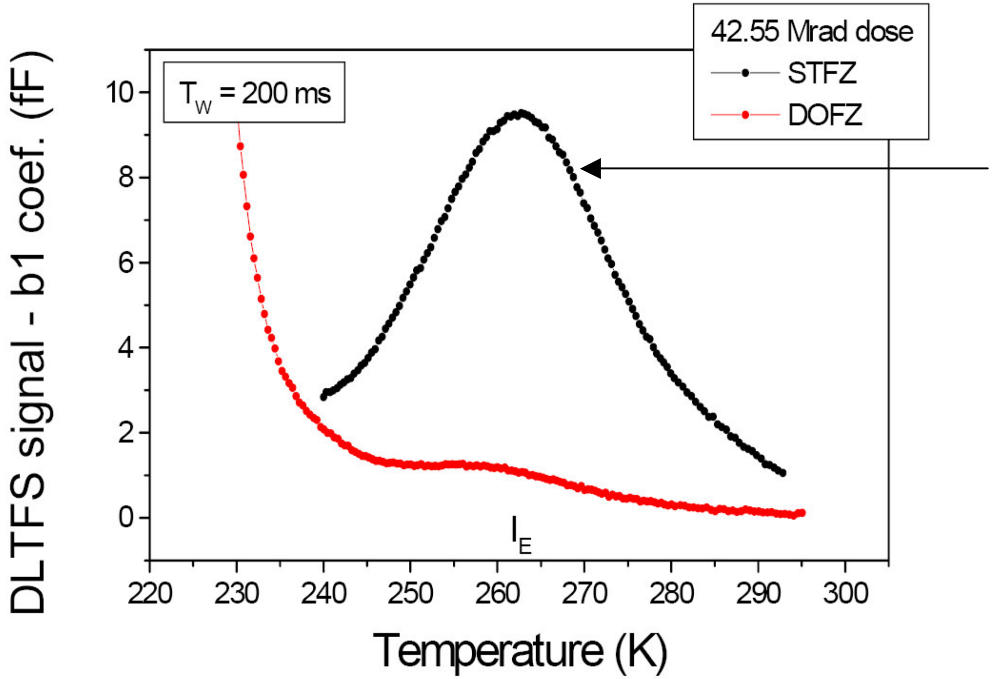
Reverse annealing significantly reduced



RD48, NIM A 447 (2000), 116-125

ATLAS-Pixel collaboration has now adopted DOFZ Si
CMS-Pixel is considering this option

γ-irradiated Si-detectors



I-center

E_c-0.545 eV

$\sigma_n = 1.7x10^{-15}$ cm^2

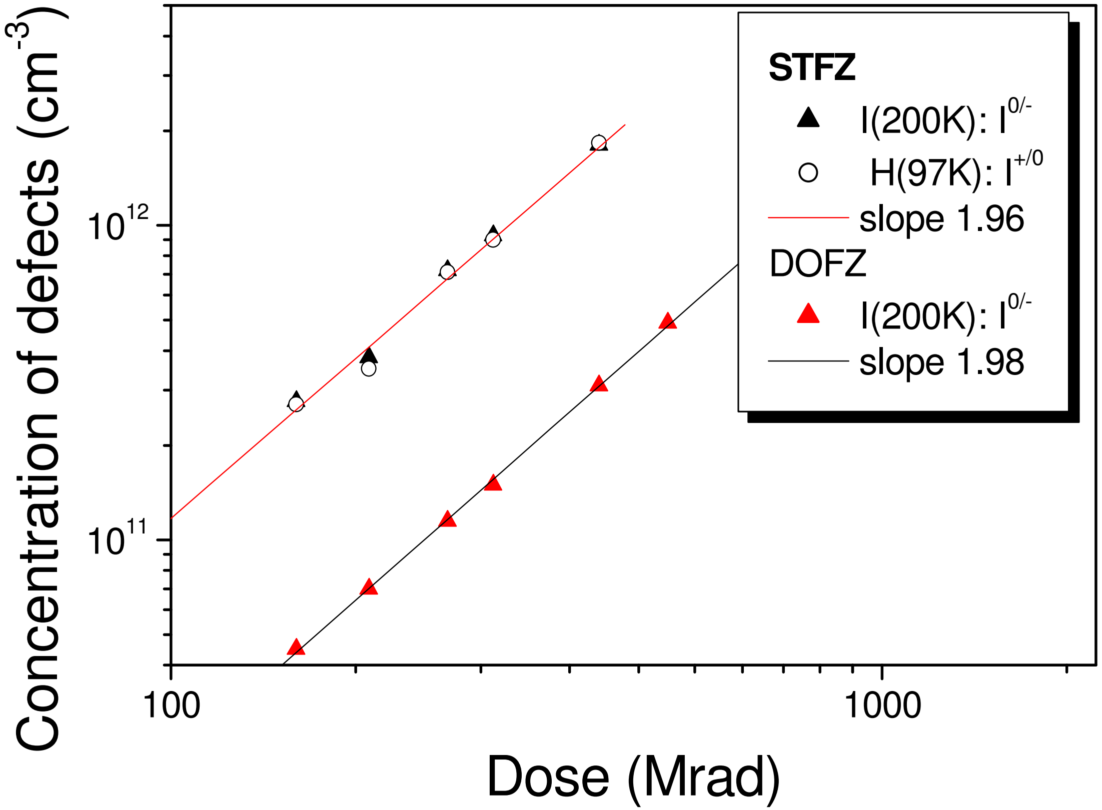
$\sigma_h = 9x10^{-14}$ cm^2

Key defect for space charge inversion,…

Identity of I??

I. Pintilie at al., Appl. Phys. Lett. **81**, 165 (2002)

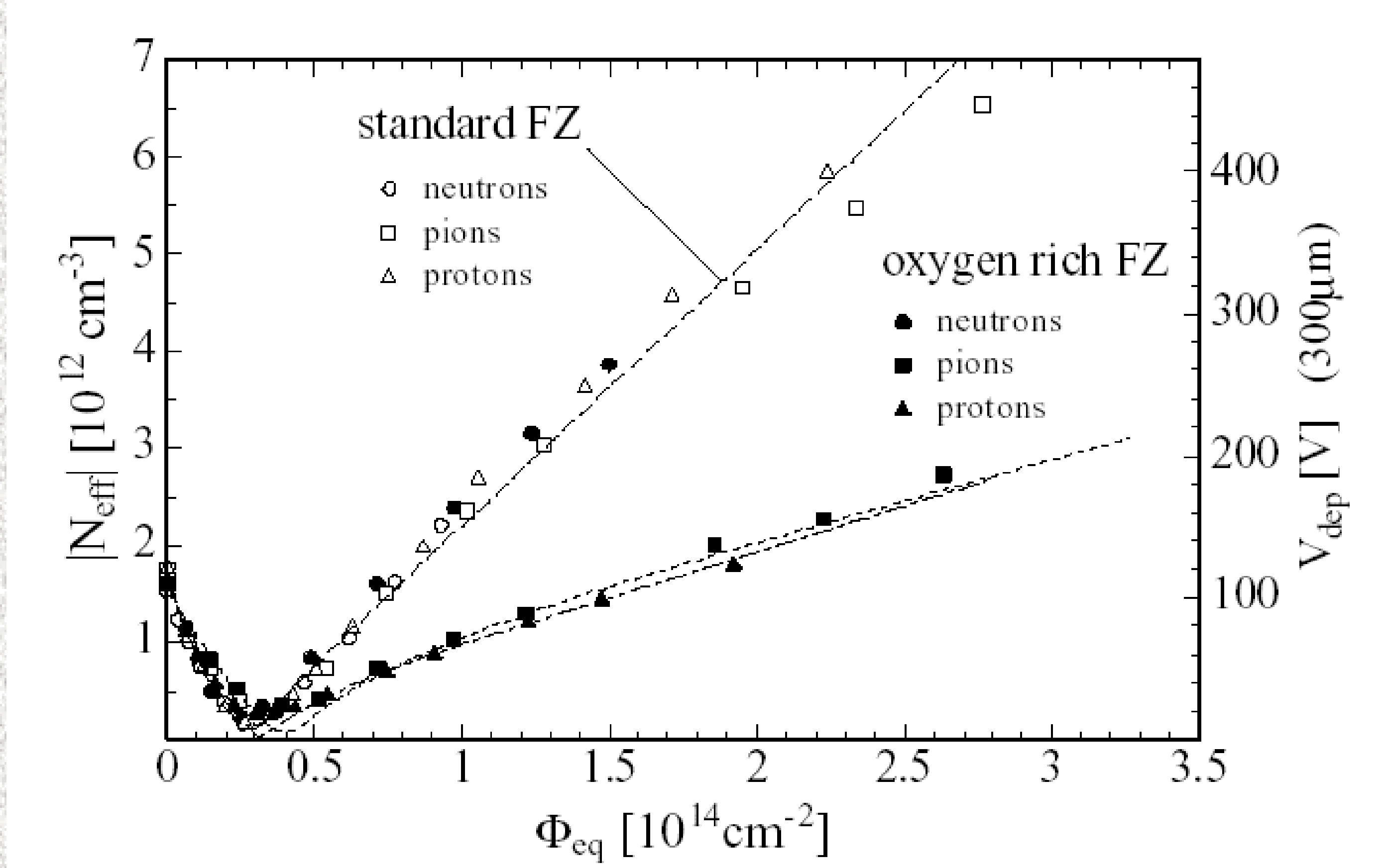
γ-irradiated Si-detectors



The I-center has a quadratic dose dependence → 'simple' cluster-type defect

I. Pintilie at al., Appl. Phys. Lett. **82**, 2169 (2003)

No radiation hardening for neutrons



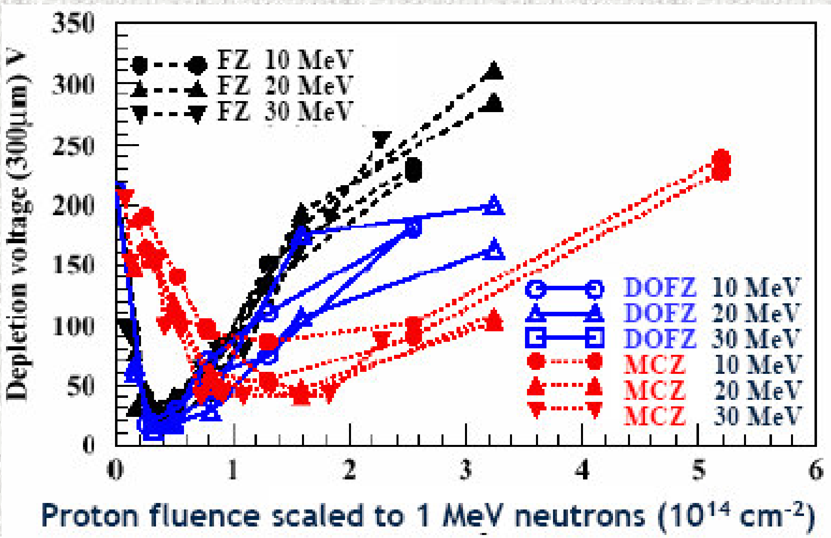
Oxygenation does not affect direct cluster formation!?

Improving Si radiation hardness

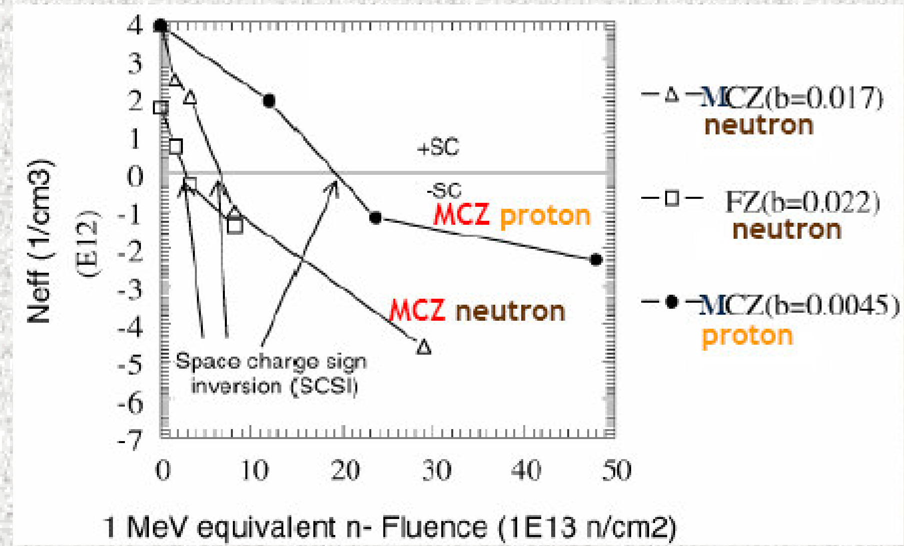
Magnetic Czochralski (MCZ) silicon

standar FZ-Si:	[O]~10^{16} cm^{-3}
oxygenated FZ-Si:	[O]~1-4x10^{17} cm^{-3}
MCZ-Si:	[O]~10^{18} cm^{-3}

Higher radiation tolerance...



...but the same 'neutron problem'.



Summary of defect/impurity engineering

- Oxygenation (shallow VO instead of deep levels)
- Decrease in carbon content (C effects vacancy-interstitial annihilation) → *argument for epi-detectors*
- Hydrogenation (H passivates dangling Si bonds)
- Formation of electrically inactive extended defects (sink for vacancies and interstitials)
- Engineering of ’direcly created’ clusters (neutron irradiation) is a challenge…

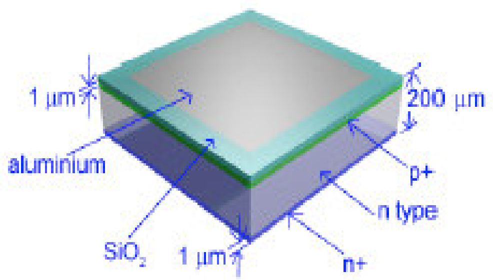
Outline

- Some fundamentals about materials, device physics and processing related to Si detectors
- Radiation tolerance of Si detectors, challenges and limiting factors
- Defect/impurity engineering of Si detectors
- **New detector structures**

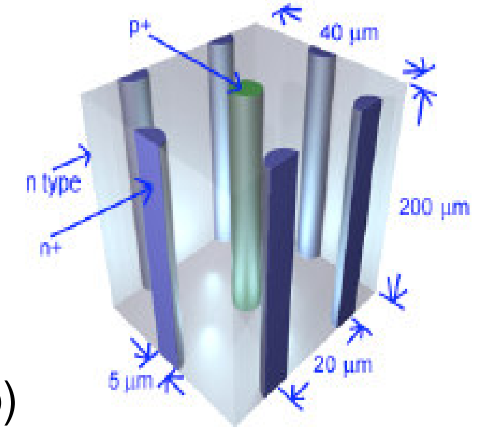
3D detectors

- Proposed by S.I. Parker, C.J. Kenney and J. Segal (NIM A 395 (1997) 328)
- Called 3-D because, in contrast to silicon planar technology, have three dimensional (3-D) electrodes penetrating the silicon substrate
- Presently, a joint effort exists between Brunel Univ., Hawaii Univ., Stanford Univ., SINTEF and UiO

Conventional (a) and 3D (b) detectors:



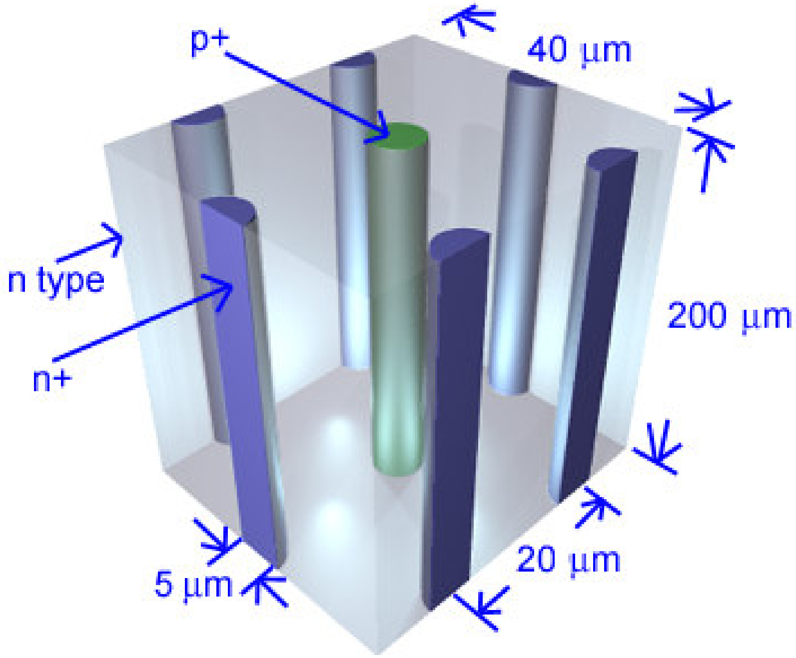
a)

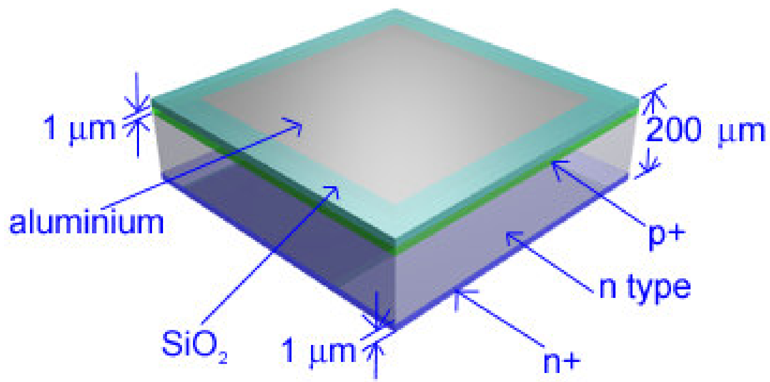


b)

depletion thickness depends on p+ and n+ electrode distance, not on the substrate thickness → (1) can operate at very low voltages or (2) can have a high doping for ultra-high radiation hardness, and (3) short distance for charge collection

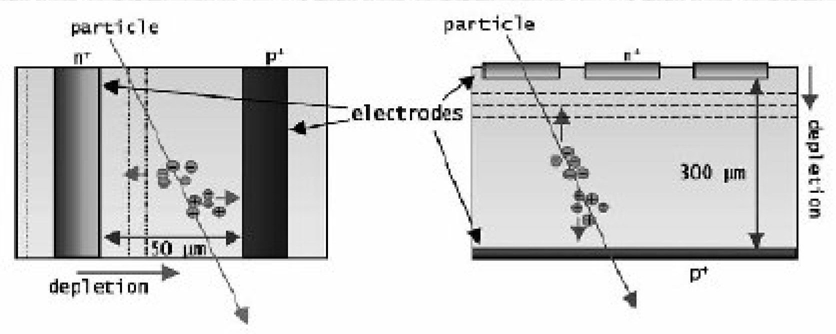
Schematics of 3D- and ordinary detector structures



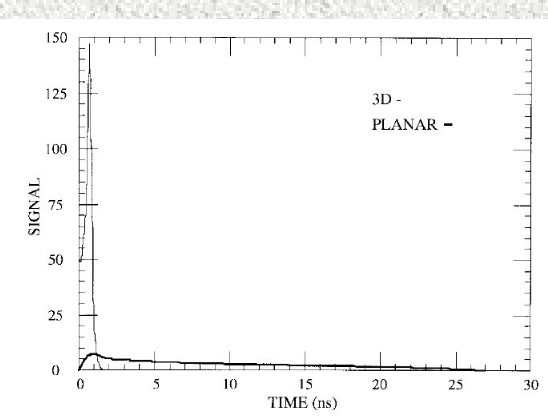


3D detectors

Charge collection in 3D detectors



- shorter collection length than planar technology
- shorter charge collection time than planar technology
- higher charge collection efficiency

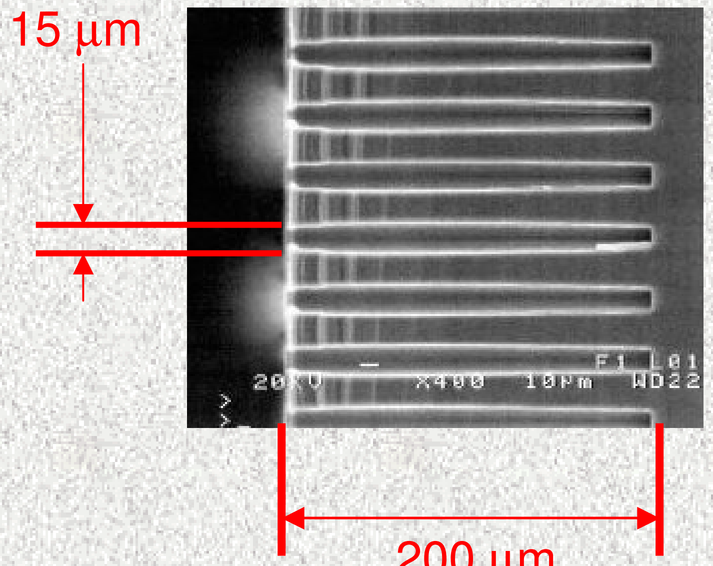


computer simulations of the charge collection dynamics for planar and 3D detectors

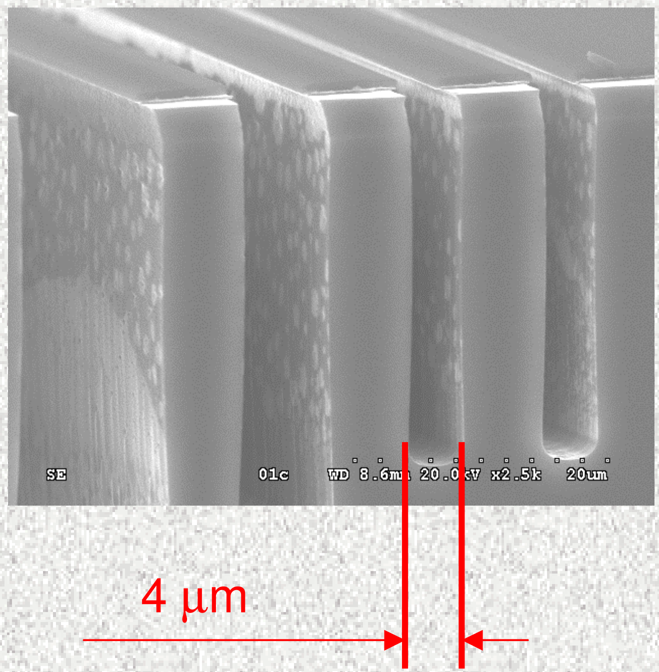
3D detectors

Real devices

a 3D detector structure:



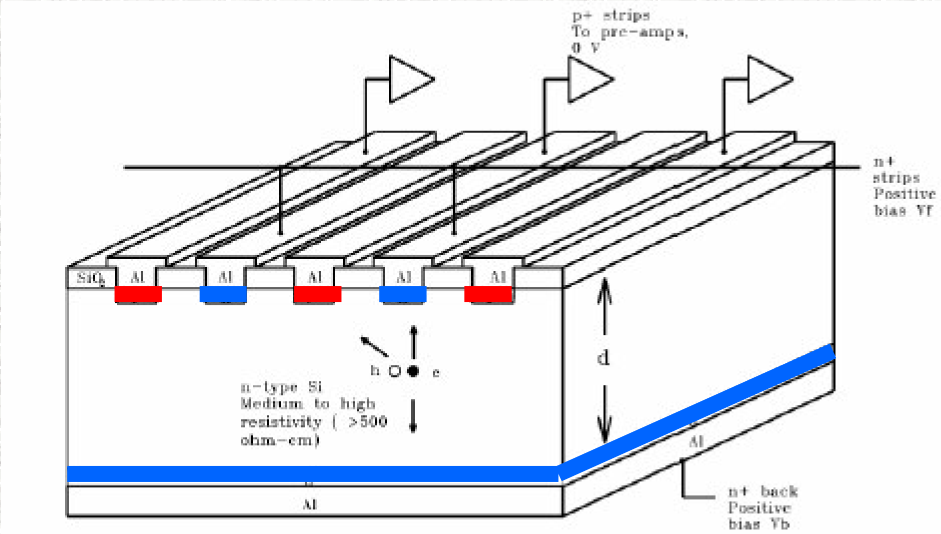
a 3D structure etched at SINTEF:

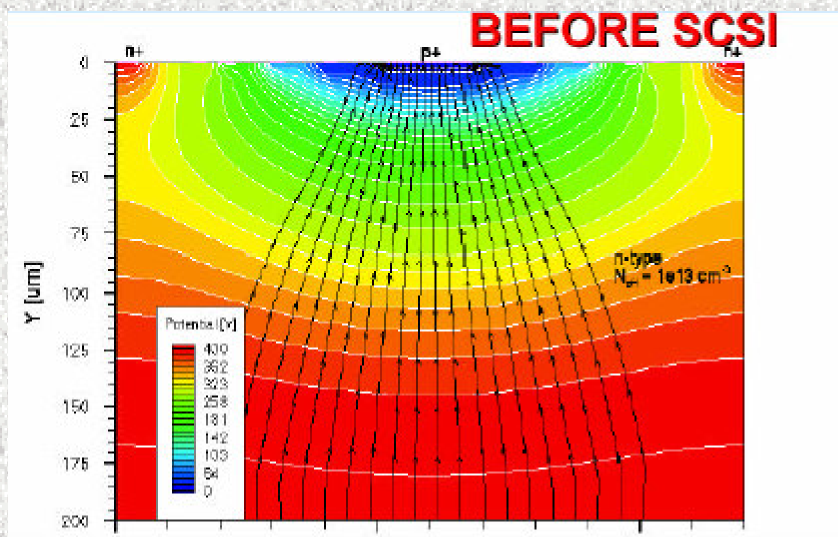


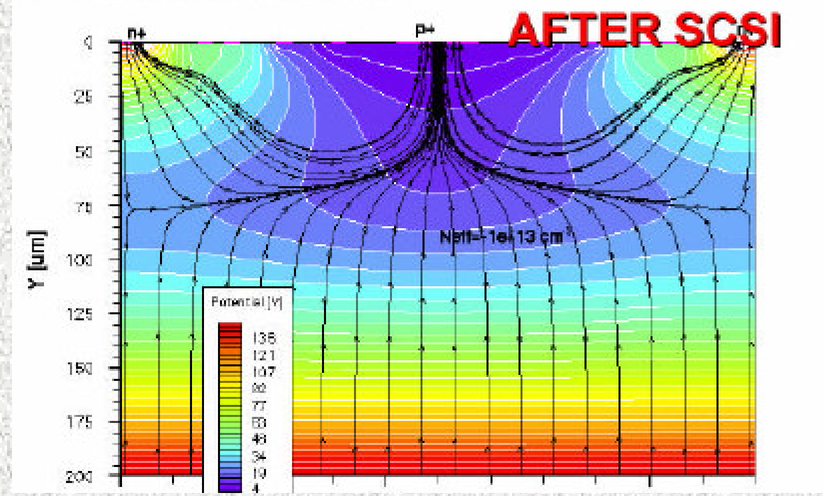
Semi-3D detectors

Proposed by Z. Li (NIM A 478 (2002) 303).

Single-side detectors with alternating p- and n- strips on the front side







After SCSI, the depletion occurs from both sides reducing the needed depletion voltage by factor 2.5

FINAL SUMMARY

- ✓ There is considerable activity and progress in improving radiation hardness of Si particle detectors, reaching 10^{16} cm^{-2} (1 MeV n eq.) is, indeed, a challenge

- ✓ Using the so-called defect/impurity engineering, the range of working fluences has been extended up to **>10^{15} cm^{-2}**

- ✓ The progress in semiconductor microtechnology allows design of detector structures with 'inherent' ultra-high radiation tolerance; development of a viable industrial ‘3D technology’ is in progress

Thin detectors

Advantages:

1. Smaller leakage current: $I_{leak} \propto W$

2. Smaller depletion voltage: $V_{dep} = qW^2 N_{eff}/2\varepsilon \propto W^2$

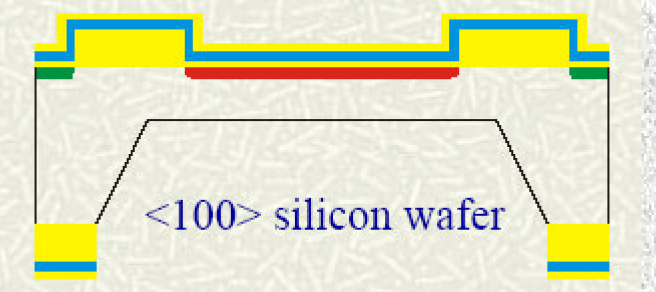
3. Lower probability for trapping and recombination ($\propto W$)

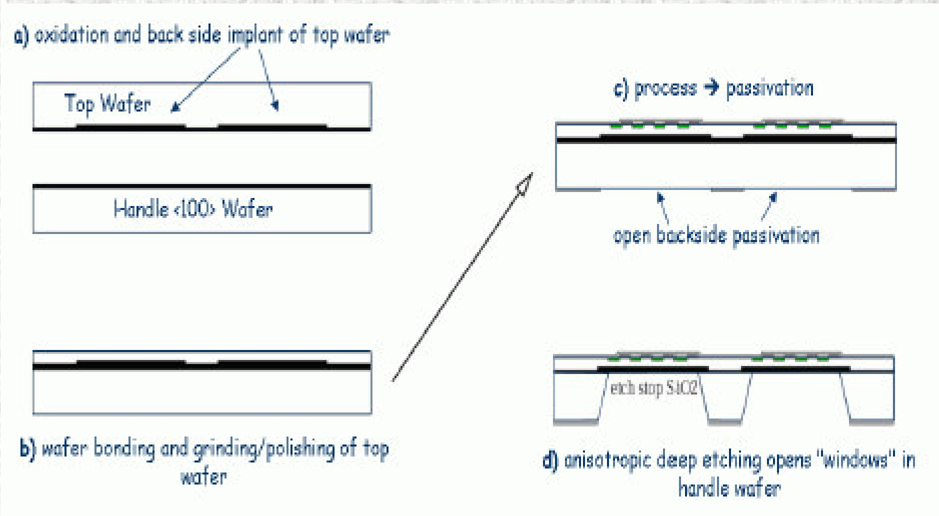
Disadvantage:

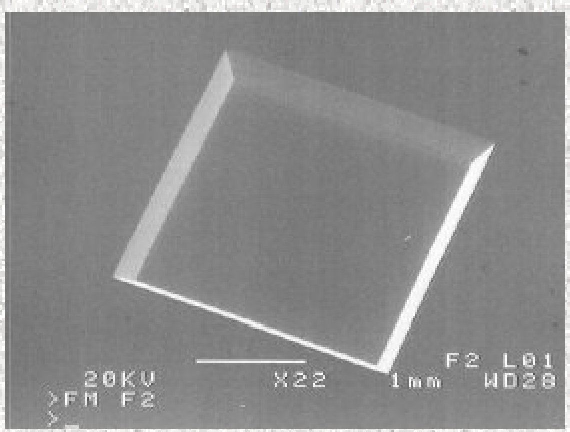
Smaller amount of carriers generated by a particle, i.e., smaller amplitude of the signal ($\propto W$)

Thin detectors

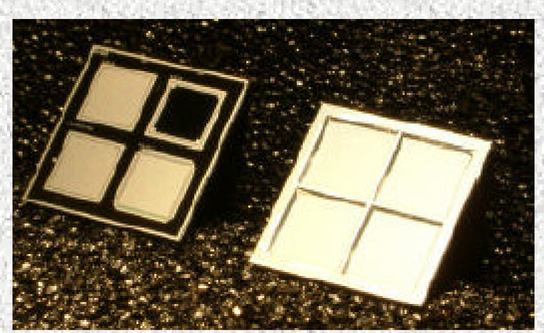
FZ thinned devices (W=50 mm)







SEM: back view of a thinned device
Area: 1 mm² - 20 mm² and
I<1 nA/cm² at 20 V

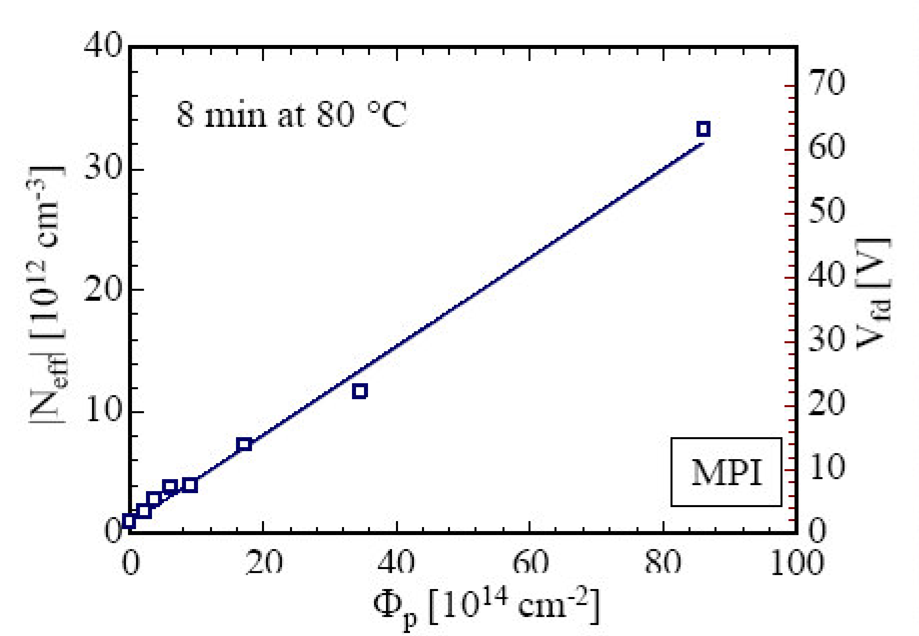


Front (left) and back (right) view of thinned devices
Area: 10 mm2 and I<1 nA/cm2 at 20 V

Thin detectors

FZ thinned devices (W=50 mm): Radiation hardness

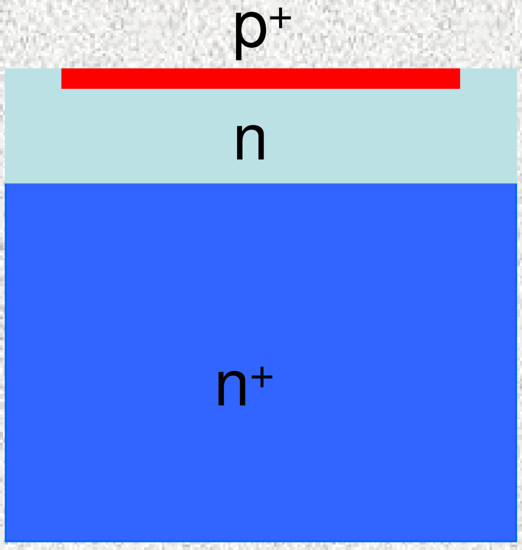
20 GeV proton irradiation: Φ_p=9.5x10^{13}-8.6x10^{15} cm^{-2}

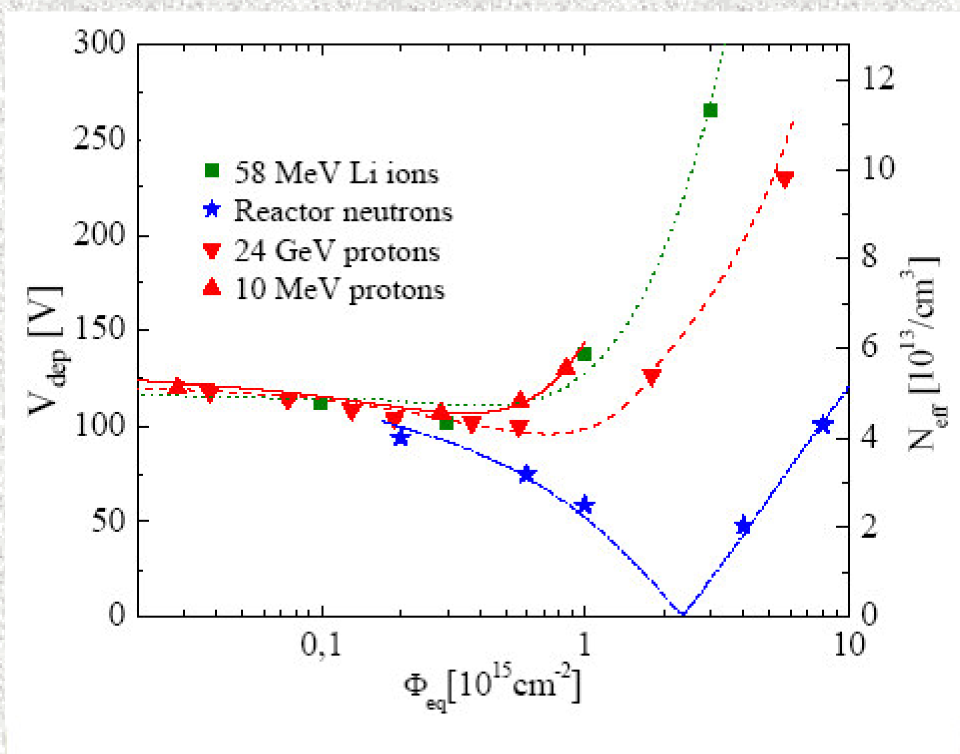


for W=300 µm at Φ=8.6x10^{15} cm^{-2}: V_{dep}~2300 V

Thin detectors

Epitaxially grown layer (W=50 μm)

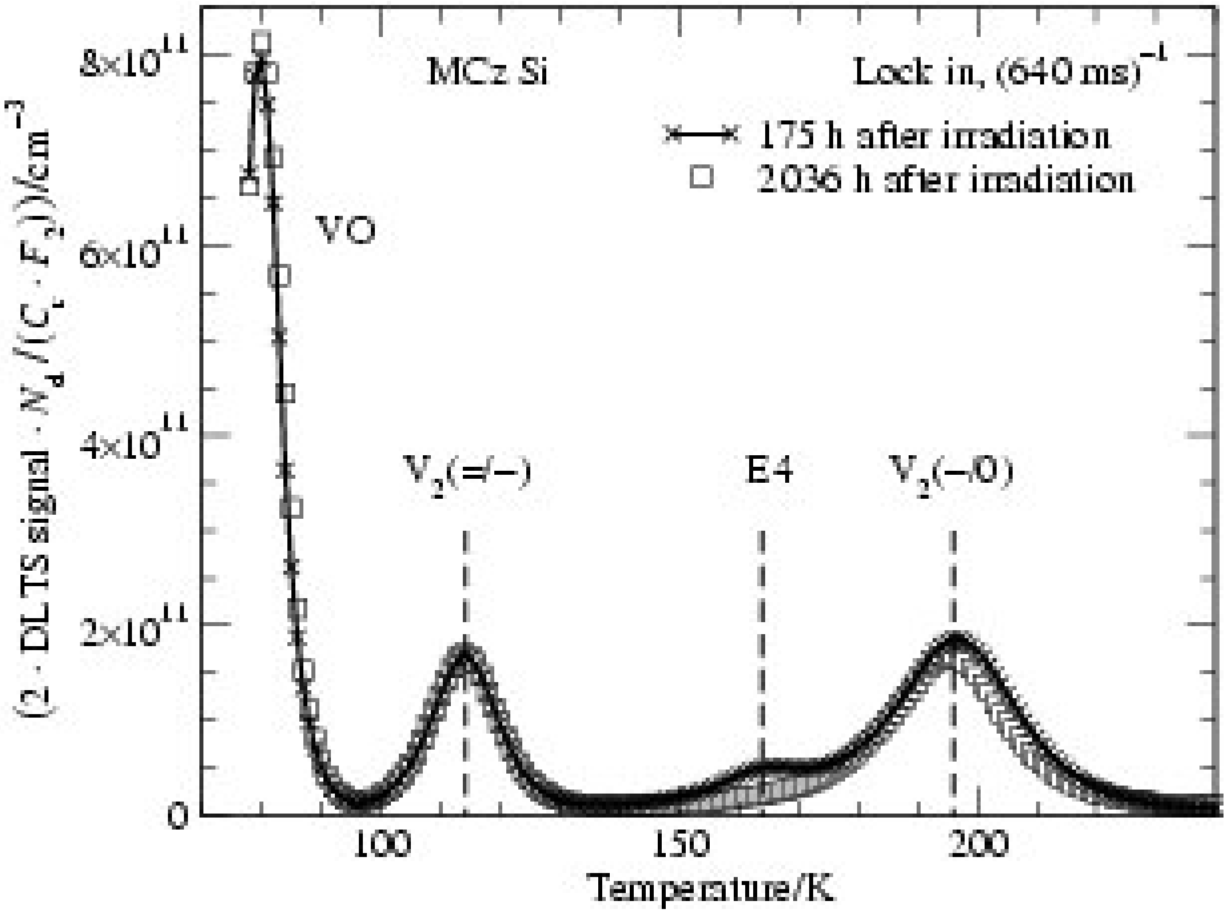




The smaller thickness of the detecting region (epi-layer) allows to increase the doping and still use relatively low bias ($W \propto \sqrt{V/N_d}$)
Higher doping shifts the SCSI point to higher fluences.

UNIVERSITY
OF OSLO

Typical DLTS-spectra



P⁺-n⁻-n⁺ MCz diode

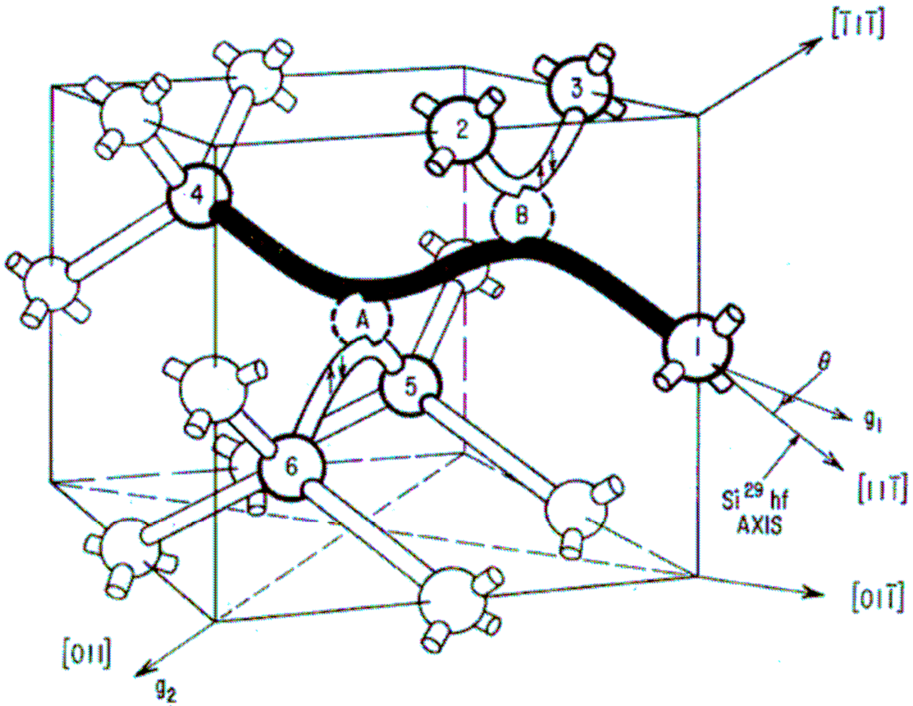
N_d~5x10^{12} cm^{-3}

6 MeV e$^-$, 5x10^{12} cm^{-2}

Bleka et al., ECS Trans, in press (2006)

UNIVERSITY
OF OSLO

The V_2-center



Four different charge states (=,-,0,+) with corresponding levels at E_c-0.23, E_c-0.43 and E_v+0.20 eV

The most prominent intrinsic defect stable at RT

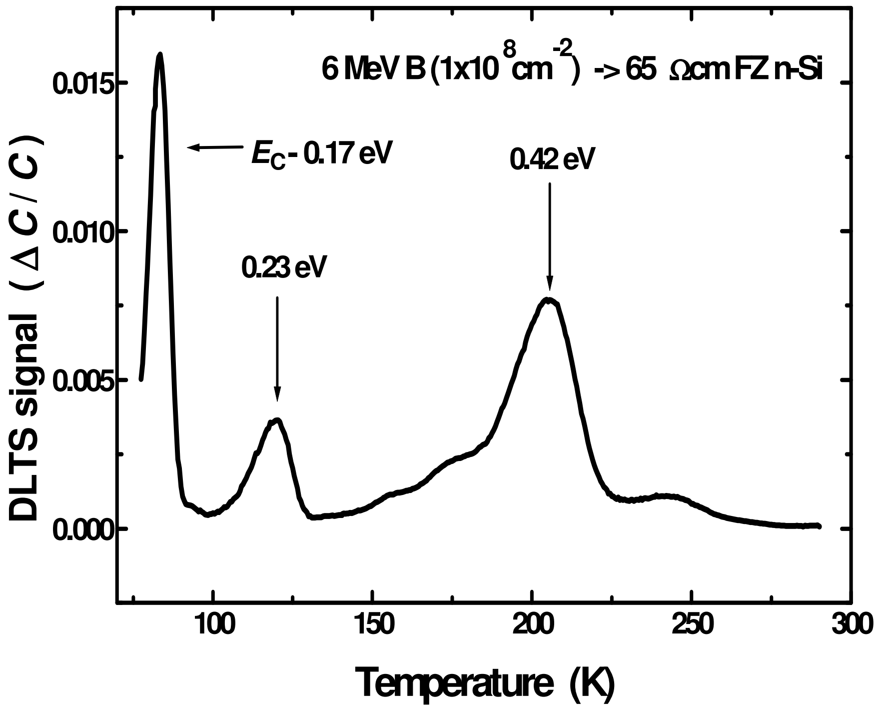
J.W. Corbett, G.D. Watkins, Phys. Rev. Lett. **7,** 314 (1961)

……

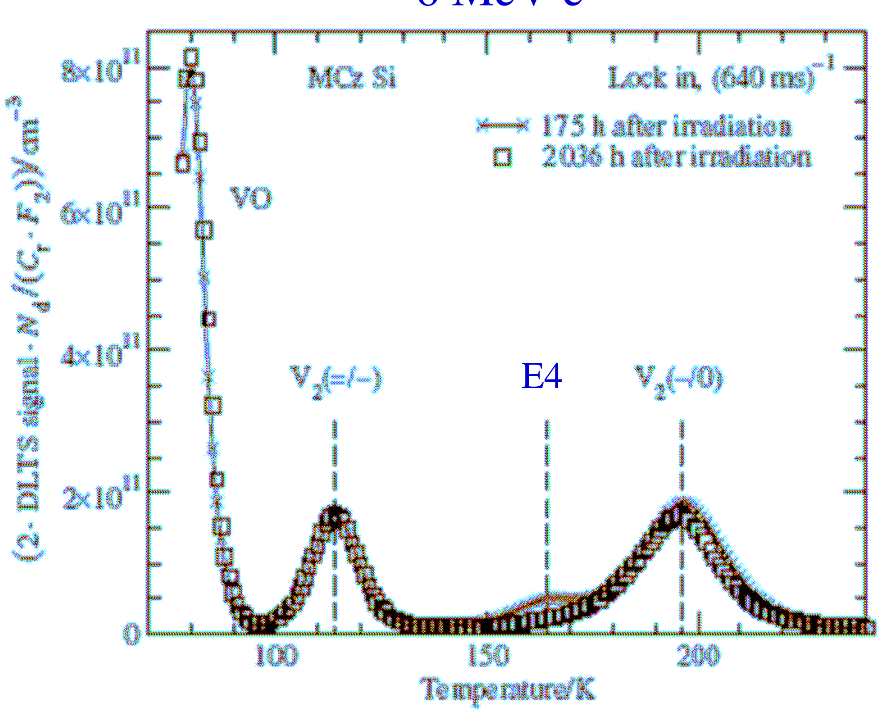
Presumably of key importance in n^-/p^- detector layers, either directly or indirectly

Generation of VO and V_2; *mass effect*

6 MeV ^{11}B

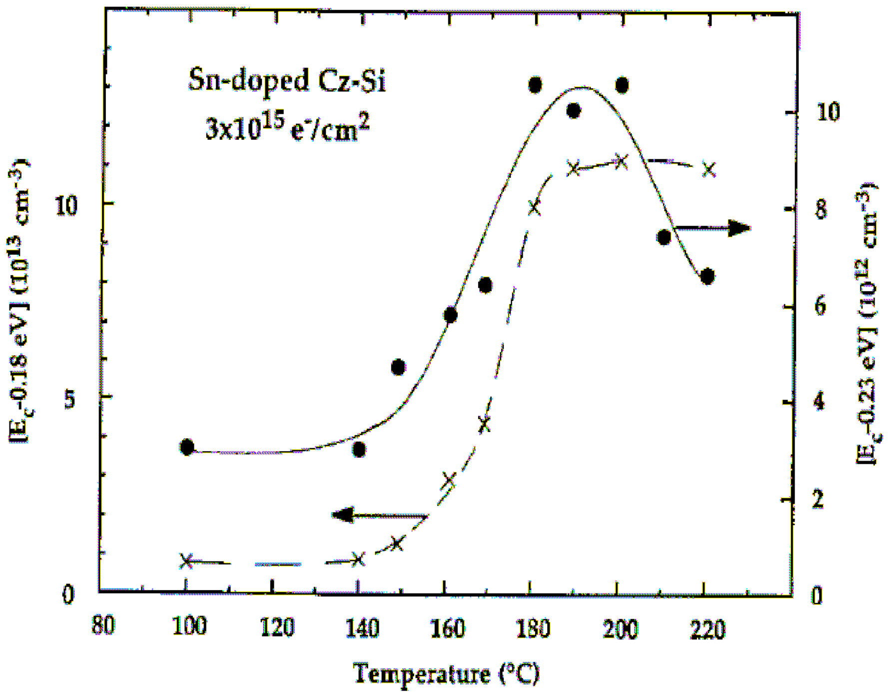


6 MeV e^-

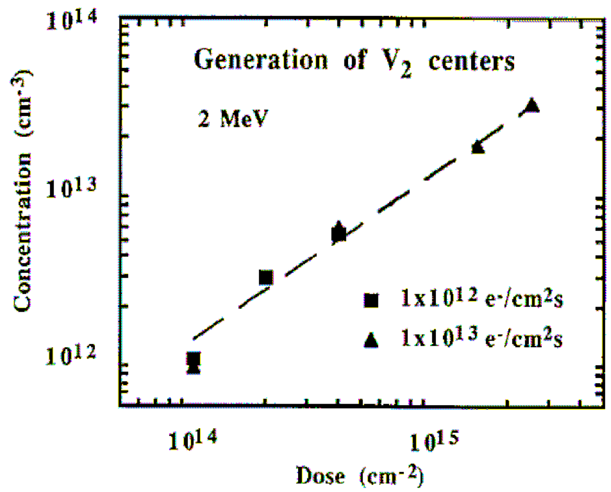


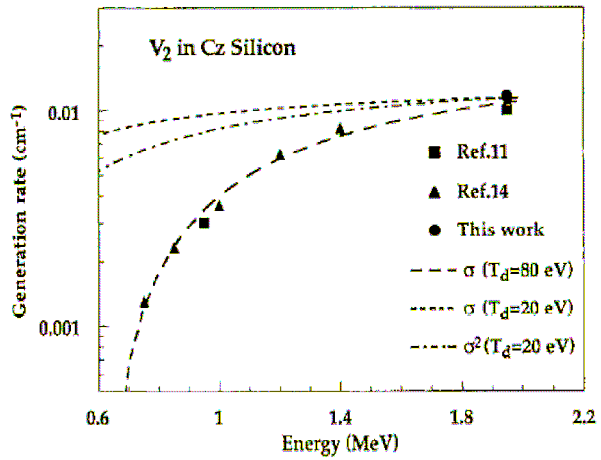
Importance of V_2 (and higher order clusters) increases with increasing elastic energy deposition (NIEL), e.g., neutral hadrons

Generation mechanism for V_2



Svensson, Lindström, J. Appl. Phys. **72**, 5616 (1992)

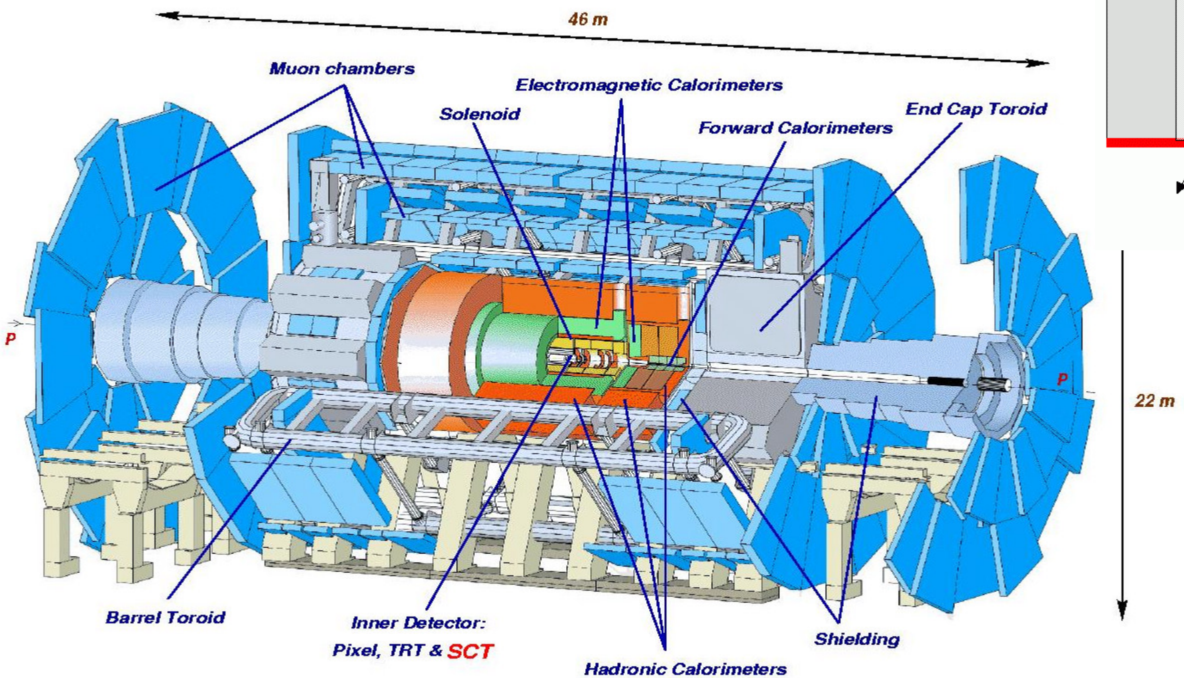




’Direct’ generation of V_2 prevails (pairing of V’s formed by different impinging electrons is negligible)!

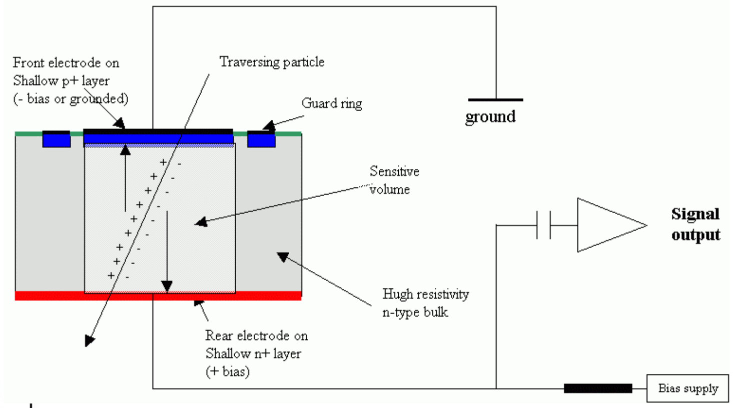
LHC ATLAS Detector – a Future HEP Experiment

Overall length: 46m, diameter: 22m,
total weight: 7000t, magnetic field: 2T
ATLAS collaboration: 1500 members

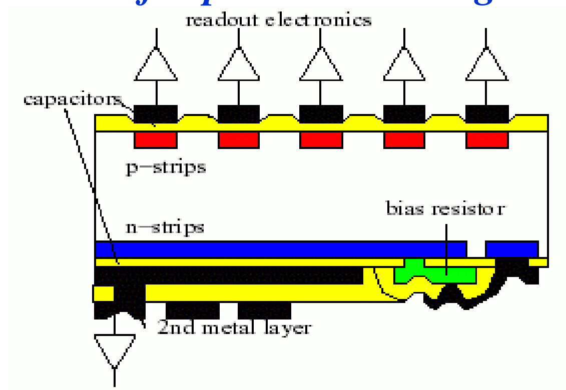


2nd general purpose experiment:
CMS, with all silicon tracker!

principle of a silicon detector:
solid state ionization chamber



micro-strip detector
for particle tracking



For innermost layers: pixel detectors

Acknowledgements

Financial support from

- the Norwegian Research Council (NFR – Strategic programs on micro/nanotechnology and materials science (NANO/FUNMAT))
- the Nordic Research Training Academy (NorFA)
- University of Oslo (Functional materials program)

is gratefully acknowledged.

Impurity engineering of high-purity Si

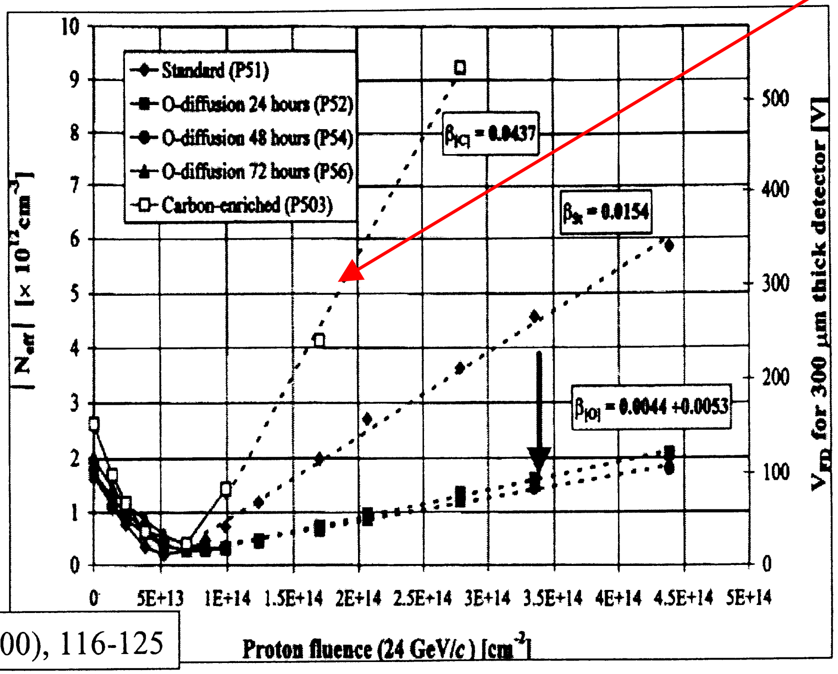
DOFZ Si is significantly radiation harder than standard Si for γ, π, p irradiations
Almost no effect for neutron irradiations

$$N_{eff} = \left| N_c(0) \cdot e^{-c\phi} - \beta \cdot \phi \right|$$

$$\beta_{\text{standard Si}} \sim 3\ \beta_{\text{DOFZ}}$$

Reverse annealing significantly reduced

The role of C_s may be indirect



RD48, NIM A 447 (2000), 116-125

ATLAS-Pixel collaboration has now adopted DOFZ Si
CMS-Pixel is considering this option