# Radiation-hard detectors for very high luminosity colliders

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On behalf of the RD50 Collaboration
(http://rd50.web.cern.ch/rd50/)

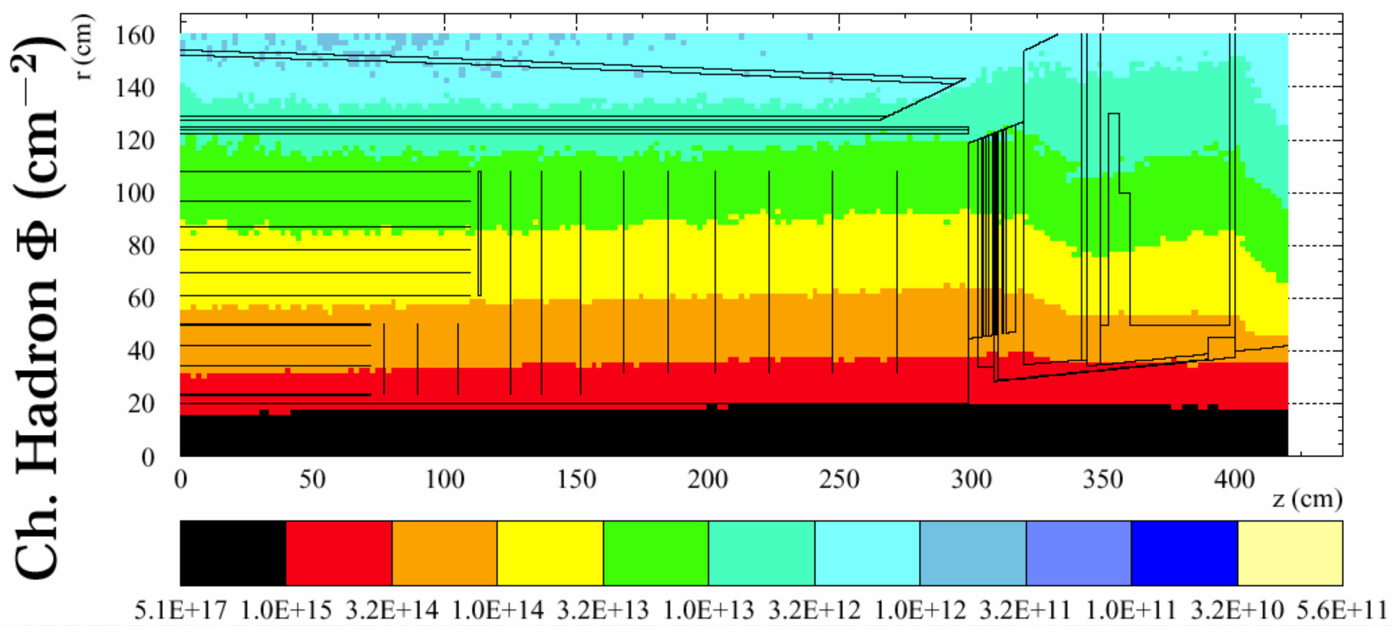
# Outline

- Motivations: the LHC upgrade
- The RD50 Collaboration
- Radiation effects in silicon detectors
- Leakage current density increase
- Oxygen and effective doping concentrations
- Czochralski and Magnetic Czochralski silicon
- Thin detectors: thinned and epitaxial
- 3-D, Semi 3-D and Stripixel detectors
- p-type substrate
- CCE simulations for pixel detectors
- CCE in SiC and GaN
- Summary

# LHC upgrade: from LHC to Super-LHC

(M. Hutinen: ″Radiation issues for S-LHC″, S-LHC Electronics Workshop, 26/2/04, CERN
O. Bruning: ″Accelerator upgrades for S-LHC″, S-LHC Electronics Workshop, 26/2/04, CERN)

| | LHC | | S-LHC |
|---|---|---|---|
| Proton Energy: | 7 TeV | => | 15 TeV |
| Collision rate: | 40 MHz | => | 80 MHz |
| Peak luminosity: | $10^{34}\ \mathrm{cm^{-2}\times s^{-1}}$ | => | $10^{35}\ \mathrm{cm^{-2}\times s^{-1}}$ |
| Integrated luminosity: | $500\ \mathrm{fb^{-1}}$ | => | $2500\ \mathrm{fb^{-1}}$ |



# Approach for tracker upgrade

| Radial distances of the actual CMS tracker | | | Expected S-LHC fluence for fast hadrons | Expected S-LHC dose |
|---|---|---|---|---|
| Pixel: | **4 cm** | => | **$1.6 \times 10^{16}$ cm$^{-2}$** | 420 Mrad |
| | **11 cm** | => | **$2.3 \times 10^{15}$ cm$^{-2}$** | 94 Mrad |
| Microstrip: | **22 cm** | => | **$8 \times 10^{14}$ cm$^{-2}$** | 35 Mrad |
| | **115 cm** | => | **$1 \times 10^{14}$ cm$^{-2}$** | 9 Mrad |

The current detector technologies can operate up to $\approx 10^{15}$ cm$^{-2}$!

| Region | Approach for the tracker upgrade |
|---|---|
| **R< 20 cm** | => R&D required |
| **20 cm<R<60 cm** | => Improving pixel technology |
| **R> 60 cm** | => Improving microstrip technology |

(see talk by R. Horisberger on CMS upgrade for S-LHC, yesterday)

# The RD50 Collaboration

## RD50: Development of Radiation Hard Semiconductor Devices for High Luminosity Colliders

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 bunch crossing);
- Low mass (reducing multiple scattering close to interaction point);
- 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

## I) Increase of the leakage current:

*Increase of the shot noise:* $F(\omega)=qI/\pi$

*Decrease of the S/N ratio*

*Increase of power dissipation:* $P=V\times I$

*Increase of voltage drop on bias resistors:* $\Delta V=R\times I$

## II) Variation of the depletion voltage ($V_{dep}$):

$V_{dep}>V_{breakdown}$: *the detector cannot operate fully depleted*

*Decrease of the charge collection efficiency*

*Decrease of the S/N ratio*

## III) Charge trapping:

*Decrease of trapping time constant and mean free path*

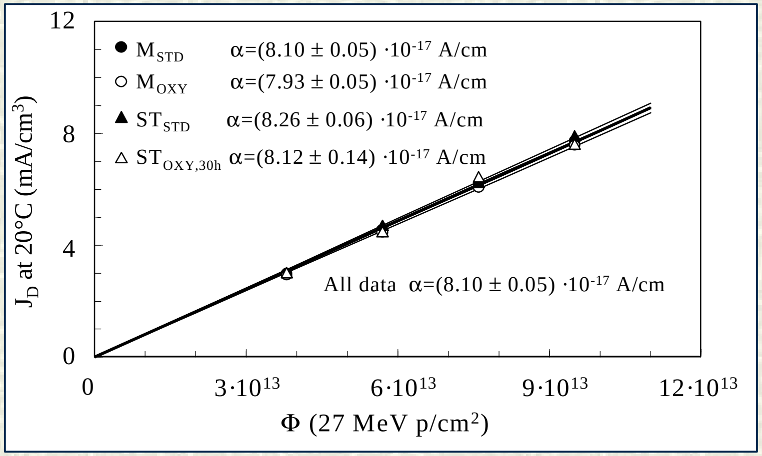
*Decrease of the charge collection efficiency*

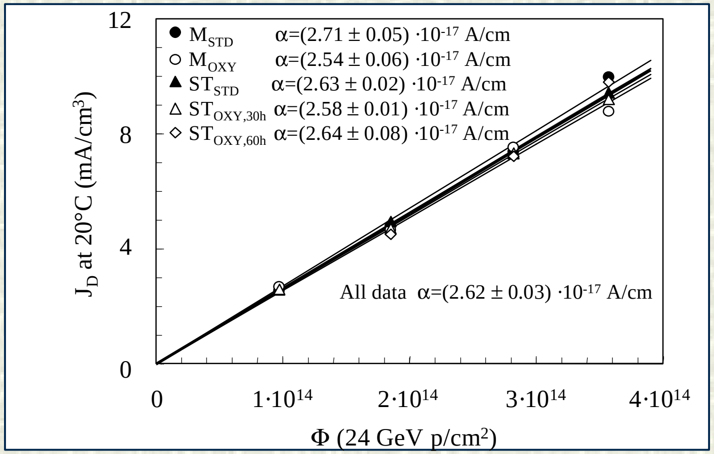
*Decrease of the S/N ratio*

# Leakage current density increase

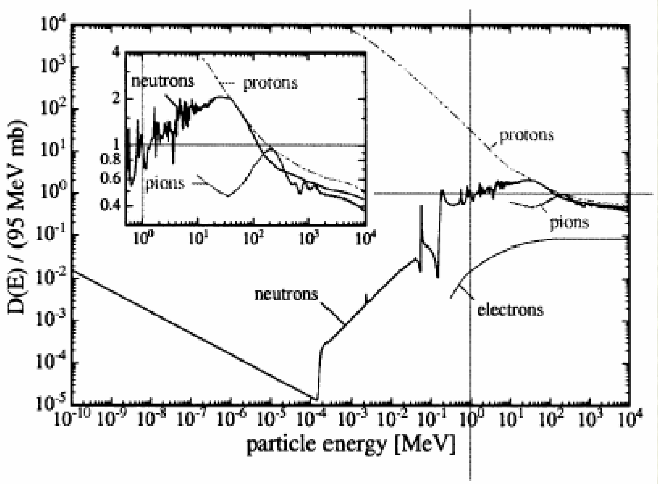
- The leakage current density (**J**) linearly increases with the particle fluence (F):

**J**=a ´ F





- The a parameter scales with the Non Ionizing Energy Loss (NIEL) of the impinging radiation.

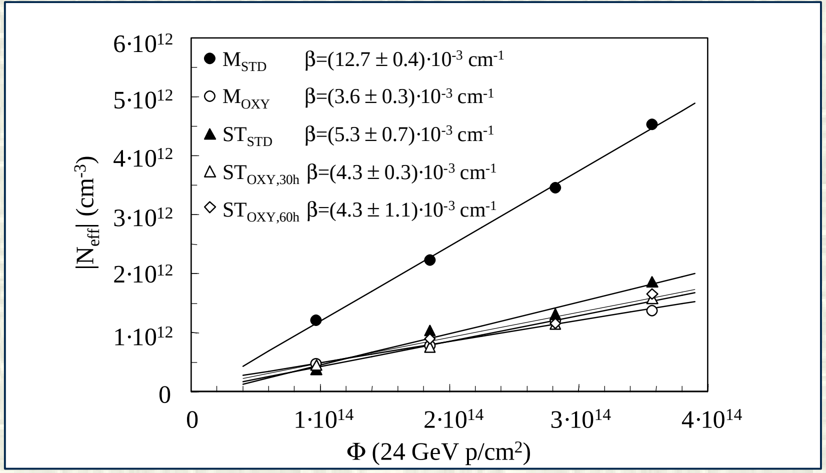


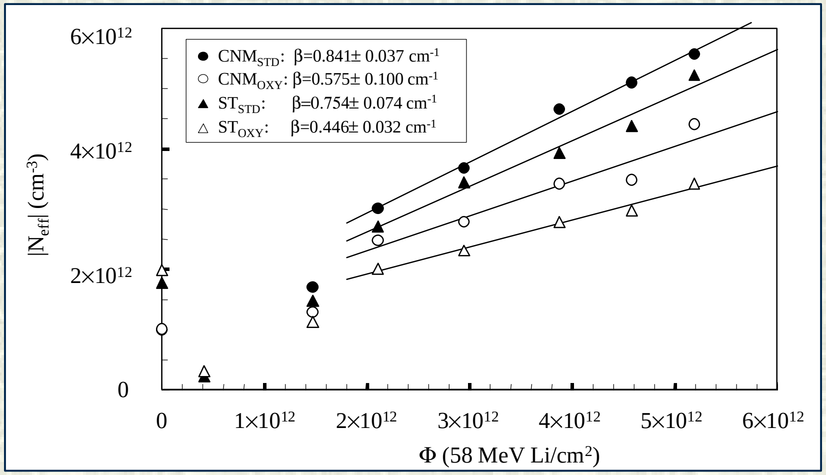
- Possible approach for limiting the leakage current density (**J**): only by decreasing the operating temperature (**T**).
  (J scales by a factor ≈2 every 7.5 K).

$$J(T_R) = J(T)\left(\frac{T_R}{T}\right)^2 \exp\left(-\frac{E}{2k_B}\left[\frac{1}{T_R}-\frac{1}{T}\right]\right)$$

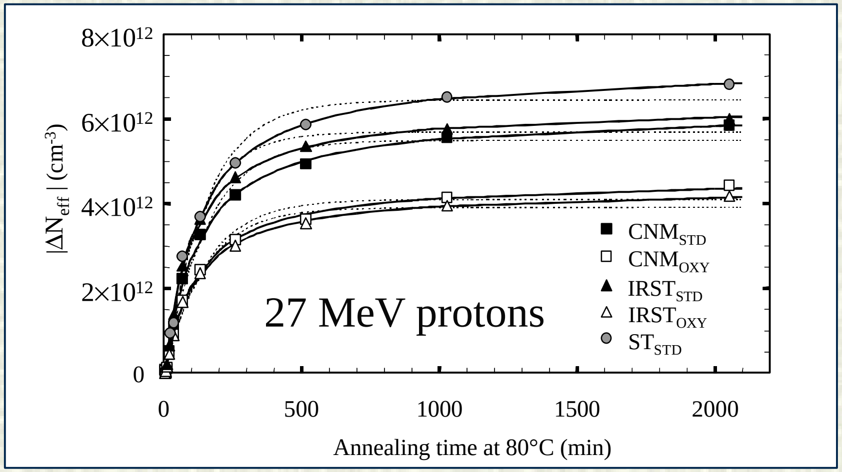
# Oxygen and effective doping concentration ($N_{eff}$)

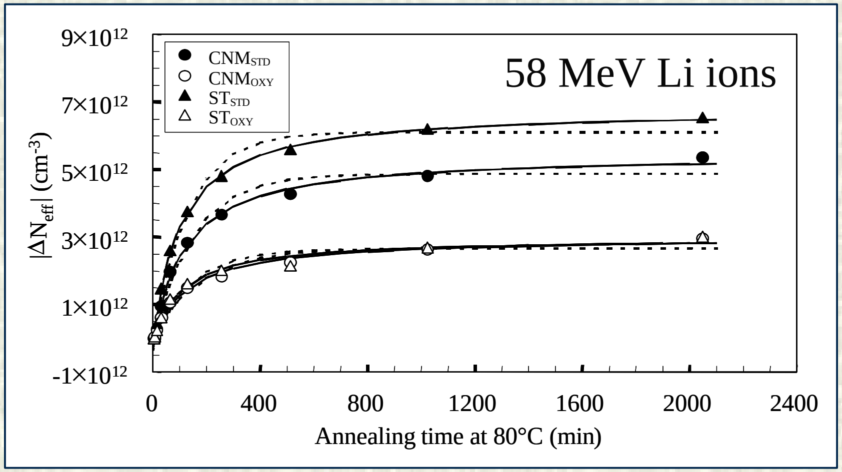
1. In n-type silicon, radiation induced donor removal and deep acceptor generation causes the Space Charge Sign Inversion (SCSI) effect : the effective doping concentration ($N_{eff}$), which is initially positive becomes negative.
After SCSI the $|N_{eff}| \propto V_{dep}$ increase is mitigated for charged hadrons and ions (not for neutrons) in Diffusion Oxygenated Float Zone (DOFZ) silicon, where $[O] > 10^{17}$ cm$^{-3}$ in the substrate.





2. After ≈20 days at RT since irradiation, $|N_{eff}| \propto V_{dep}$ reaches a minimum and starts to increase up to saturation (reverse annealing).
The reverse annealing amplitude is decreased for charged hadrons and ions (not for neutrons) in DOFZ Si, where $[O] > 10^{17}$ cm$^{-3}$.

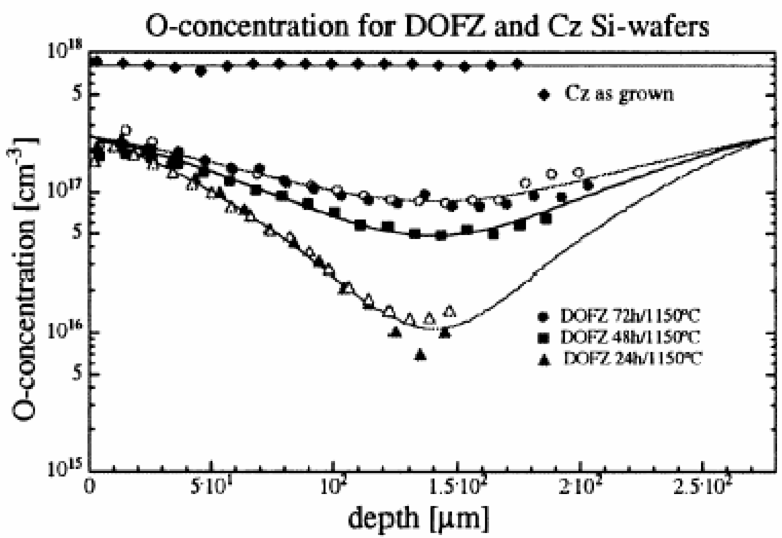




# Czochralski (CZ) and Magnetic Czochralski (MCZ) silicon

**Advantages:**

1. **Intrinsic higher oxygen concentration** in CZ ($[O]\approx 8\text{-}10\times10^{17}$ $cm^{-3}$) and MCZ ($[O]\approx 4\text{-}10\times10^{17}$ $cm^{-3}$) than Float Zone (FZ, $[O]<4\times10^{16}$ $cm^{-3}$) or Diffusion Oxygenated FZ (DOFZ, $[O]\approx 1\text{-}4\times10^{17} cm^{-3}$) Si.
2. No extra process needed for substrate oxygenation.
3. High resistivity (≈1-2 kΩ×cm) p- or n-type CZ and MCZ wafers **commercially available**.
4. CZ and MCZ wafers have **higher diameters** (300 mm) than FZ and DOFZ (150 mm).

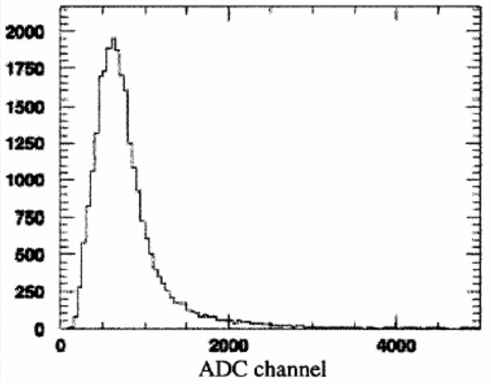


Attention has to be considered for avoiding **thermal donor activation** ($V_{dep}$ increase) during processing steps at 450 °C for n-type CZ and MCZ.

**Test beam results:**

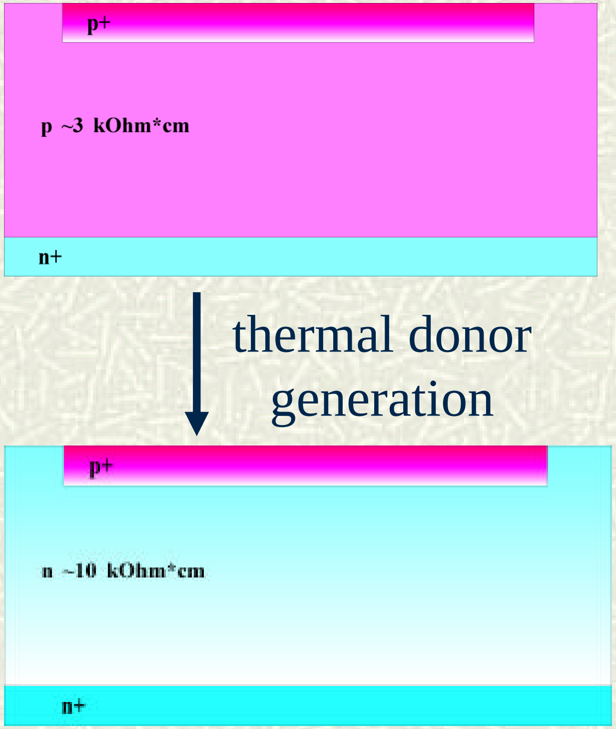
MCZ microstrip detector prototype (AC coupled, with 1024 strips, 6 cm long, w=10 µm, p=50 µm) has been tested by 225 GeV muon beam at CERN with AV1 chips (resolution 10 µm and S/N=10).

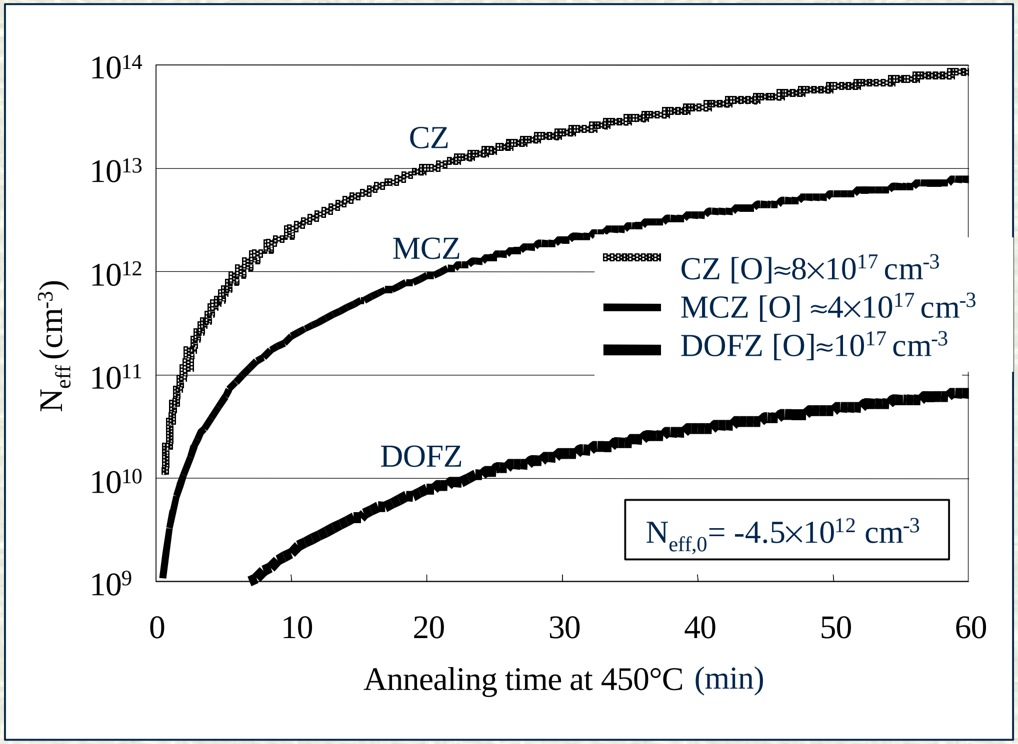
(E. Tuominen et al., Nuclear Physics B, Proc. Suppl. 125 (2003) 175)



# Magnetic Czochralski (MCZ) silicon: thermal donor generation

$[O] \approx 4\times10^{17}$ cm$^{-3}$ in MCZ silicon is suitable to take advantage of thermal donor generation at 450 °C for processing n-type detectors starting from p-type MCZ substrates.





$$N_{TD} = \left(\frac{a}{b}\right)\left(C_{io}\right)^{\chi}\frac{1}{\left|N_d - N_A\right|^2}\left(1 - e^{-b\times D_i\times C_{io}\times t}\right)$$

$N_{DT}$ is the thermal donor density;
a and b are experimental parameters.
**$C_{io}$** is the concentration of interstitial oxygen in silicon;
$\chi$ is a constant ($2<\chi<3$);
$|N_d-N_A|$ is the free carrier concentration;
$D_i$ is the diffusion constant of interstitial oxygen;
t is the time at a given temperature;

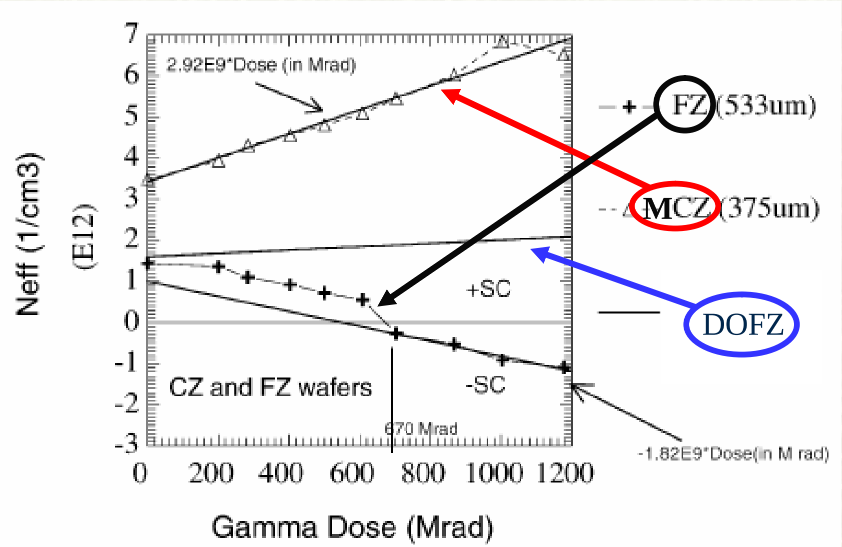
(J. Harkonen et al., 4th RD50 Workshop, http://rd50.web.cern.ch/rd50/4th-workshop/)

# Magnetic Czochralski (MCZ) silicon: radiation hardness

(Z. Li et al., IEEE TNS 51 (2004) 1901)

**$^{60}$Co g-ray irradiation**

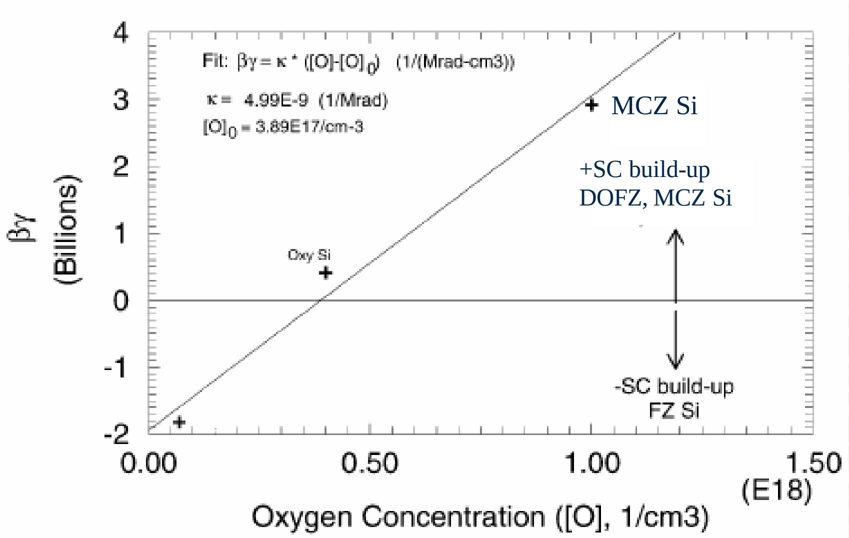
1. SCSI for **FZ** Si,
   $N_{eff}<0$ due to deep acceptor generation.
2. No SCSI for **MCZ** and **DOFZ** Si,
   $N_{eff}$ increases due to thermal donor activation.



**Model for space charge build up in g-irradiated Si**

1. $N_{eff}$ linearly increases with radiation Dose
   $N_{eff}= N_{eff,0}+b_g([O])\times Dose$

2. $b_g$ linearly depends on the substrate oxygen concentration
   $b_g=m\times[O]+q$ with $m=4.99\times10^{-9}$ $Mrad^{-1}$
   $q=1.94\times10^{9}$ $Mrad^{-1}\times cm^{-3}$

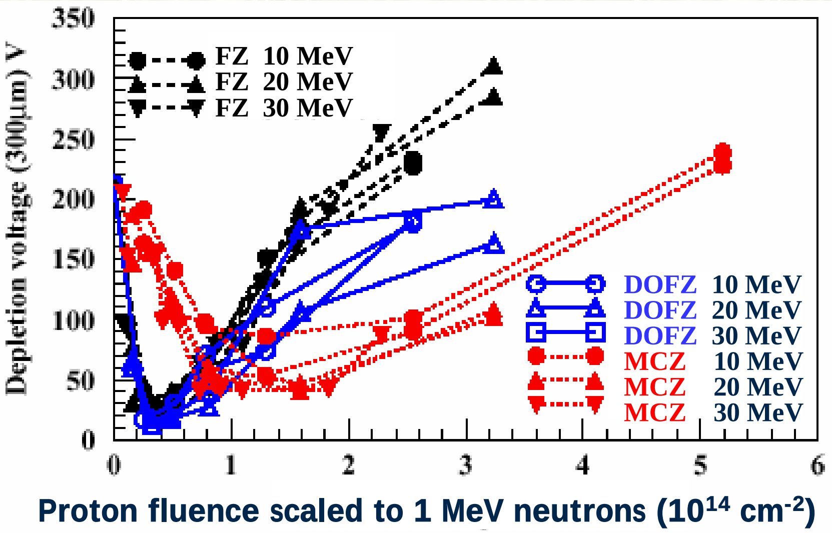


# Magnetic Czochralski (MCZ) silicon: radiation hardness

(J. Harkonen et al., NIM A 518 (2004) 346; Z. Li et al., IEEE TNS 51 (2004) 1901)

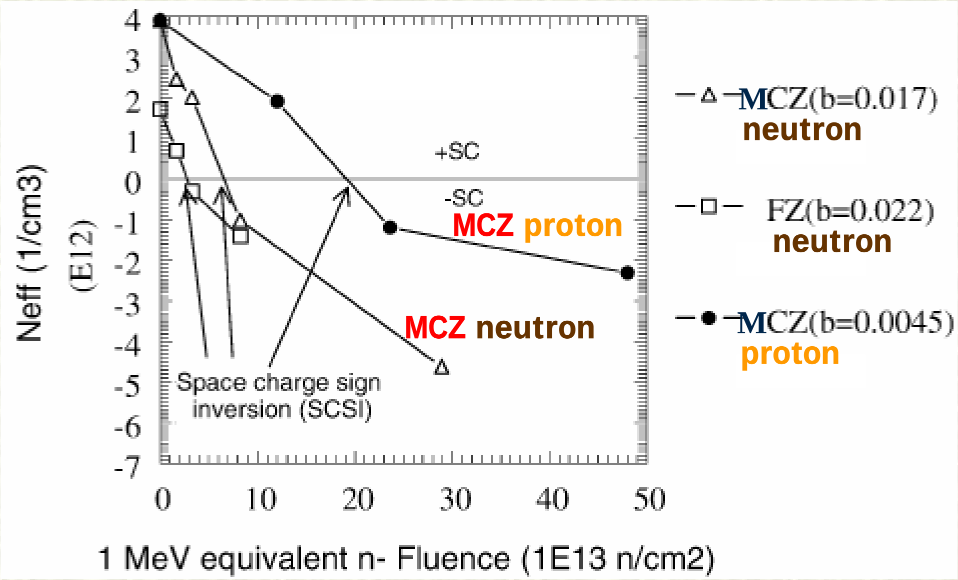
## Low energy proton irradiation

1. SCSI occurs in **FZ, DOFZ** and **MCZ** Si.
2. **MCZ** detectors present a lower $\mathbf{V_{dep}}$ variation rate after SCSI than **FZ** and **DOFZ** devices.
3. Oxygen mitigates deep acceptor formation during proton irradiation.



## **Proton** (**p**) and **neutron** (**n**) irradiations

The positive effect of high [O] on $|N_{eff}| \propto V_{dep}$ is strongly reduced when detectors are irradiated by neutrons.



# Positive effect of substrate oxygen: microscopic

## General microscopic considerations

1) formation of vacancy (V) related defects such as: VO (neutral at RT) or VO+V=$V_2O$ and $V_2$ related defects (deep acceptors) are competitive processes: VO is enhanced by ″high″ [O]:

a. g-**rays**: point defects (i.e., interstitial I and vacancies V)
   in DOFZ, MCZ and CZ, [O]>>[V]: VO enhanced, $V_2O$ and/or $V_2$ related defects suppressed

b. **Neutrons**: clusters (i.e., high defect density regions)
   in DOFZ, MCZ and CZ, [O]<<[V]: $V_2O$ and/or $V_2$ related defects present;

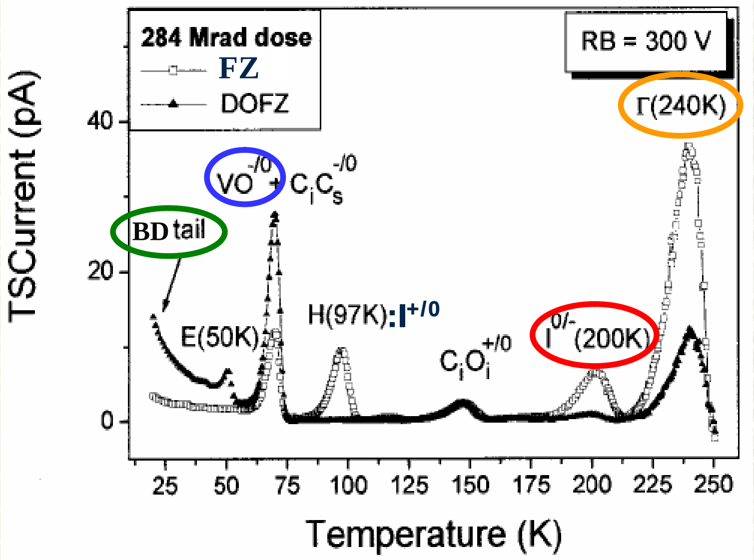
c. **Protons**: point defects and clusters: intermediate condition.

2) Thermal donor activation during irradiation is characteristic for high [O].

## $^{60}$Co g-ray irradiation of FZ and DOFZ silicon

| | I defect | Γ defect | BD center | VO |
|---|---|---|---|---|
| **Type** | Deep Acceptor | Deep Acceptor | Shallow Donor | Acceptor (neutral at RT) |
| **Energy level** | $E_C$-054 eV | $E_V$+0.68 eV | $E_C$-0225 eV | $E_C$-0.17 eV |
| **Effect on $N_{eff}$** | Yes (85% in FZ) | Yes (10% in FZ) | Yes (Compensates Γ and I in DOFZ) | Yes, indirectly: VO is neutral at RT, but VO is a competitive process with $V_2O$ or $V_2$ related defects and VO is enhanced by high [O]. |
| **Effect on $I_{leak}$** | Yes | Yes | No | No |
| **FZ silicon** | Present | Present | Absent | Present |
| **DOFZ silicon** | Reduced | Reduced | Enhanced with [O] | Enhanced with [O] |
| **Dose depencence** | Quadratic→ Second order defect | Linear | Over linear | --------- |
| **Microscopic** | *VO+V=$V_2O$?* | ------- | *TDD2?* | VO |

(I. Pintilie et al., NIM A 514 (2003) 18)

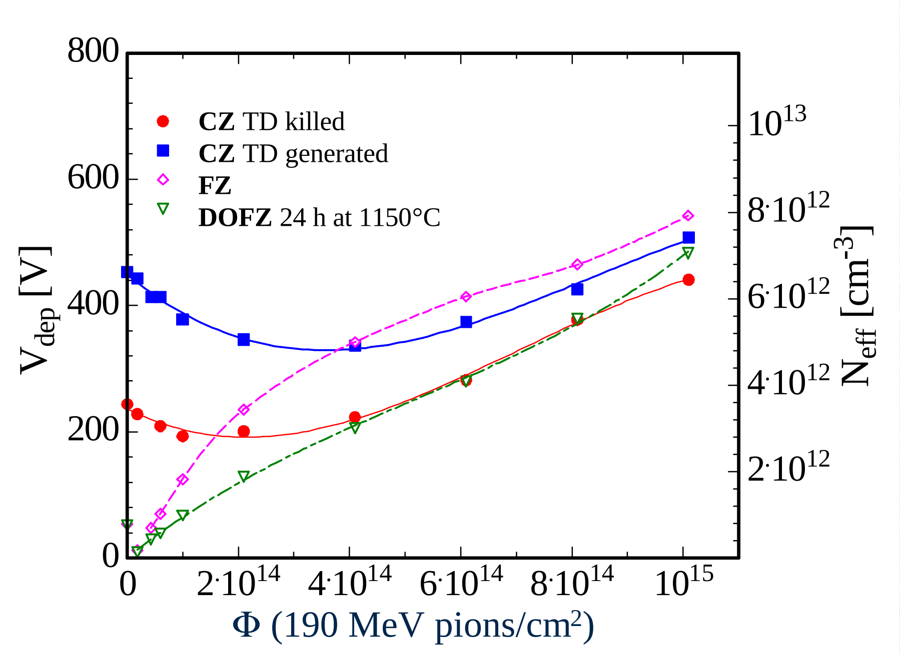


*E. V. Monakhov et al. in Phys. Rev. B 68 233203 (2003), investigating the $V_2$ isothermal annealing at 250 °C by DLTS, proposed that the X center ($E_C$-0.47 eV), whose density linear depends on [O], observed after that $V_2$ has been annealed out, is $V_2$+O=$V_2O$.*

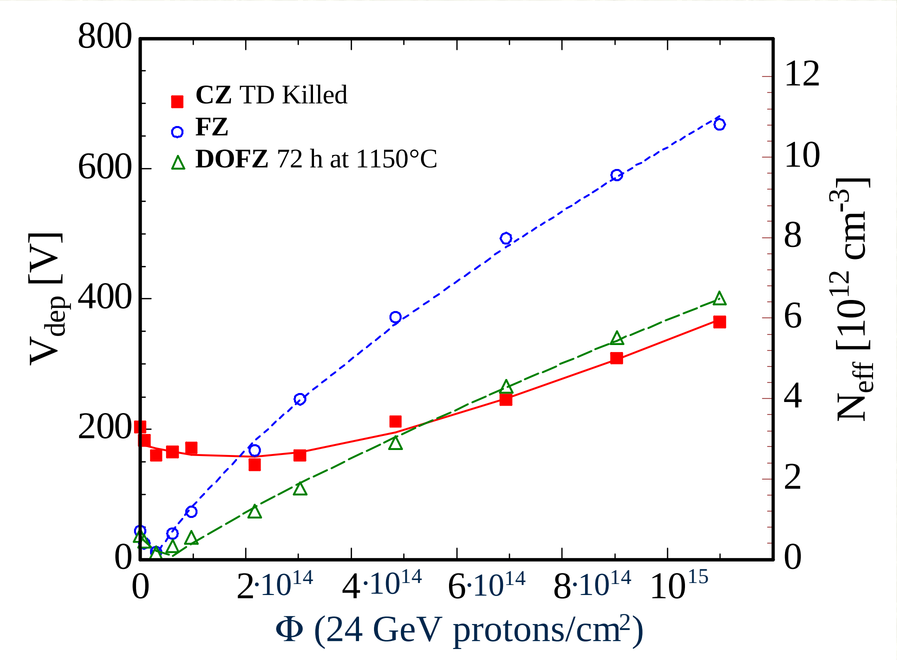
# Czochralski (CZ) silicon: radiation hardness

(E. Fretwurst et al., 3rd RD50 Workshop, http://rd50.web.cern.ch/rd50/3rd-workshop/)

190 MeV pions



24 GeV protons



1) SCSI in **FZ** and **DOFZ** after high energy pion or proton irradiation:
the linear $V_{dep}$ increase for **FZ** and **DOFZ** at high fluences is due to predominant acceptor generation (low [O]).

2) No SCSI in **CZ** after high energy pion or proton irradiation:
the linear $V_{dep}$ increase for **CZ** at high fluences is due to predominant donor generation (high ([O]).

3) The linear $V_{dep}$ increase rate at high fluences is lower for **CZ** than for **FZ** and **DOFZ**.

# Thin detectors

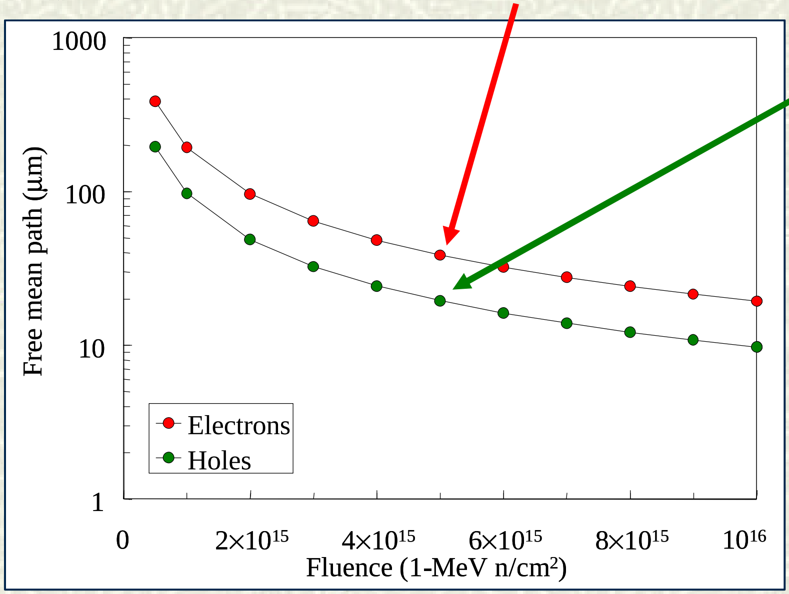
## Why thin detectors?

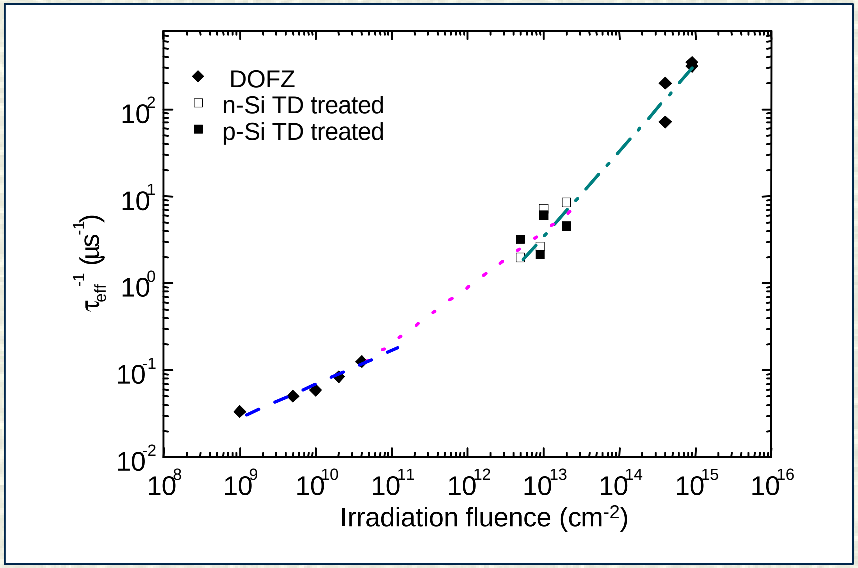
1. Smaller leakage current: $I_{leak} \propto W$
2. Smaller depletion voltage: $V_{dep} = qW^2 N_{eff}/2\varepsilon \propto W^2$
3. At S-LHC fluences, charge collection for planar detectors is limited by carrier mean free path, not by the W≈280-300 μm detector thickness

Example.

The trapping time constant (τ) rapidly decreases with fluence ($\Phi_{\text{1-MeV n}}$): $1/\tau_{e,h} = \beta_{e,h} \times \Phi_{\text{1-MeV n}}$ with $\beta_e = 5.7 \times 10^{-16}$ cm²/ns, $\beta_h = 7.7 \times 10^{-16}$ cm²/ns.

At **$F_{\text{1-MeV n}}$=5´10$^{15}$ cm$^{-2}$** the **carrier mean free path** (L=v×τ) even at the saturated carrier velocity ($v_{sat,e} = 1.1 \times 10^7$ cm/s, $v_{sat,h} = 7.5 \times 10^6$ cm/s) reduces to $L_e$=40 μm for electrons and $L_h$=20 μm for holes.



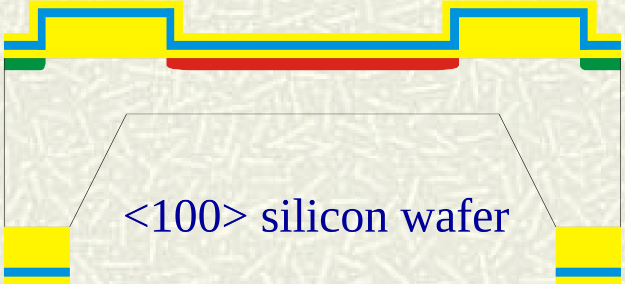


(J.Vaitkus et al., IWORID-6, July 2004, Glasgow)

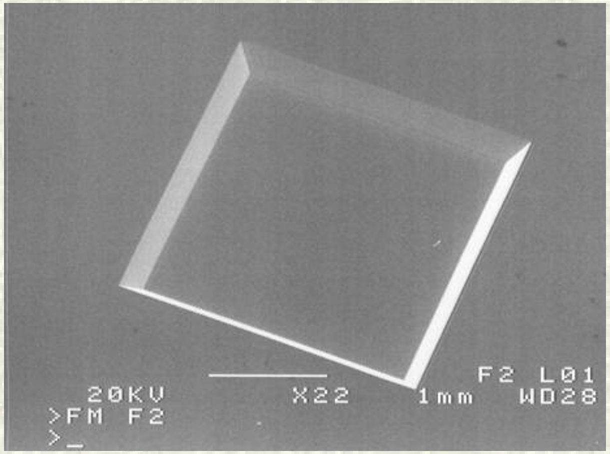
# Thin detectors: FZ thinned devices (W=50 μm)

## ITC-IRST, Trento

(E. Ronchin et al., NIM A 530 (2004) 134)



1. Tetra Methyl Ammonium Hydroxide (TMAH) etching from back.
2. Phosphorous deposition and diffusion from back.
3. Metal deposition from back.

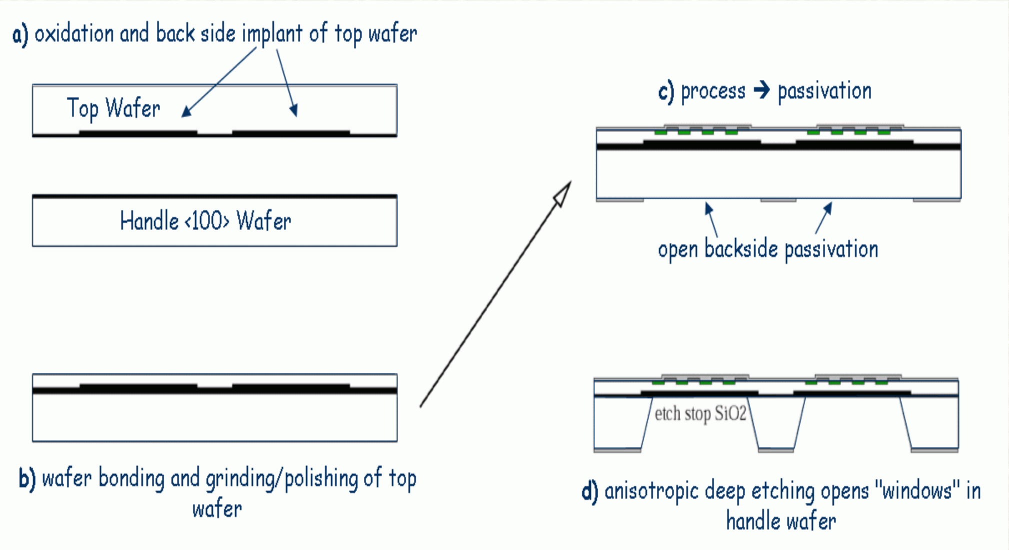


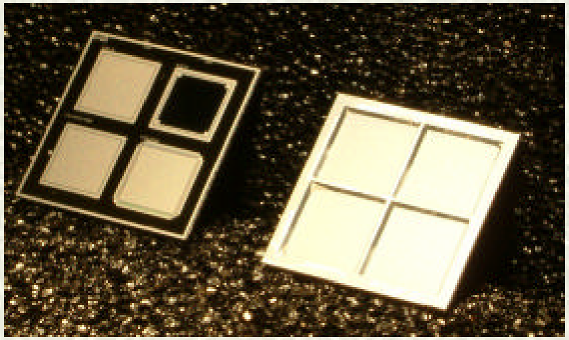
SEM: back view of a thinned device

Areas: 1 mm$^2$ - 20 mm$^2$ and I<1 nA/cm$^2$ at 20 V

## Semiconductor Detector Laboratory, MPI, Munich

(L. Andricek et al., 1$^{st}$ ECFA Workshop, Montpellier, November 2003)





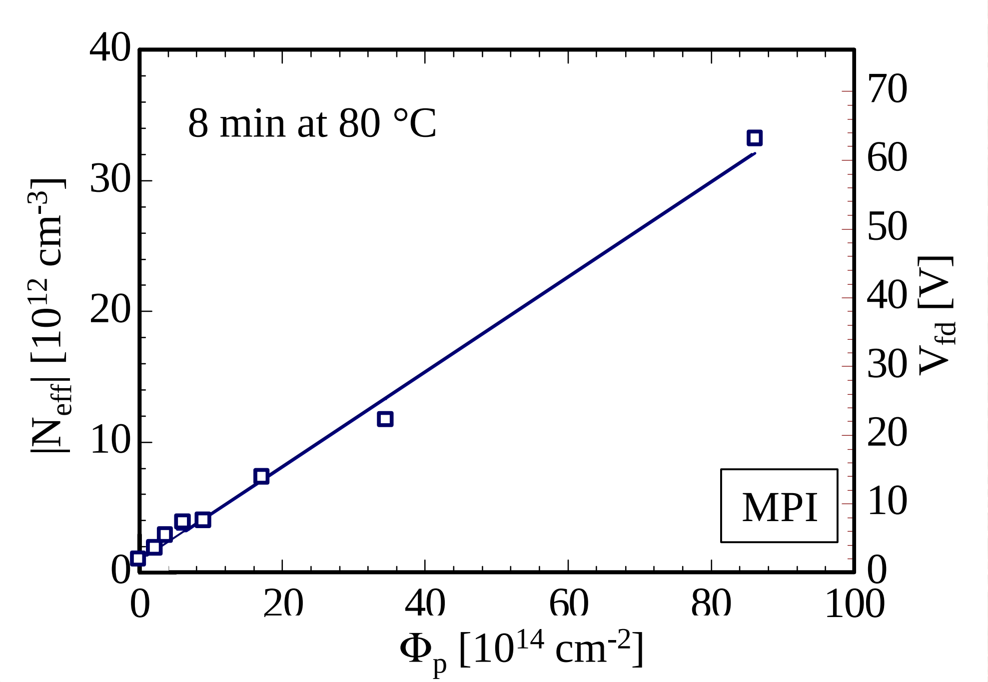
Photograph: front (left) and back (right) view of thinned devices

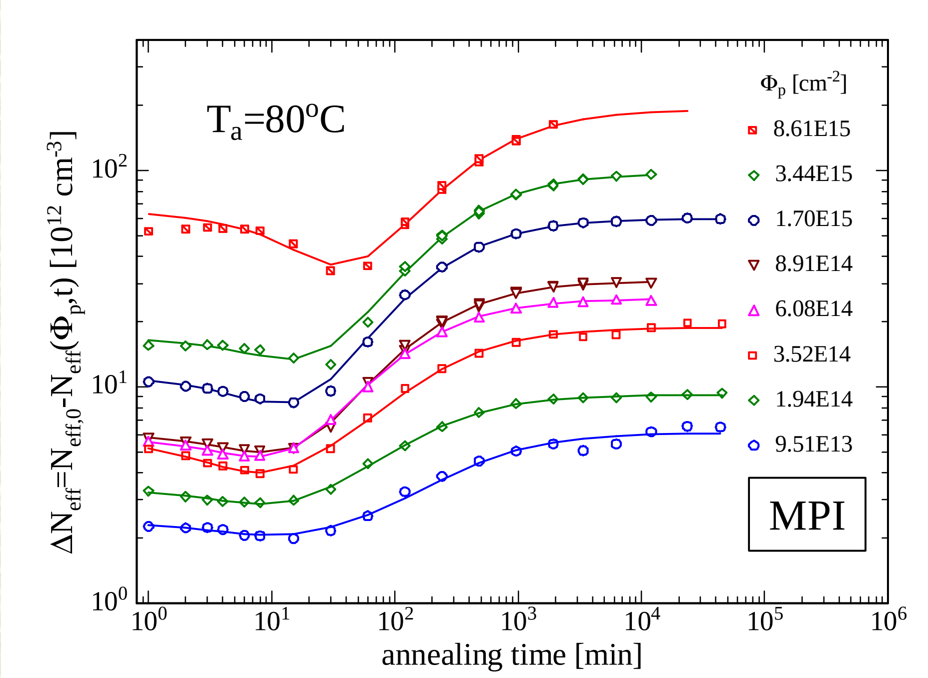
Area: 10 mm$^2$ and I<1 nA/cm$^2$ at 20 V

# MPI thinned devices (W=50 µm): radiation hardness

(E. Fretwurst et al., 4th RD50 Workshop, http://rd50.web.cern.ch/rd50/4th-workshop)

20 GeV proton irradiation: $\Phi_p=9.5\times10^{13}$-$8.6\times10^{15}$ cm$^{-2}$





**1. b =D|N$_{eff}$| /DF$_p$=3.6´10$^{-3}$ cm$^{-1}$ comparable with DOFZ.**

**2. V$_{dep}$»64 V for W=50 µm at F$_{max}$=8.6´10$^{15}$ cm$^{-2}$:**

**® V$_{dep}$»2300 V for W=300 µm at F$_{max}$=8.6´10$^{15}$ cm$^{-2}$;**

**® W<300 µm are required at S-LHC.**

**1. Stable damage component.**

**2. Short-term component (positive on V$_{dep}$).**

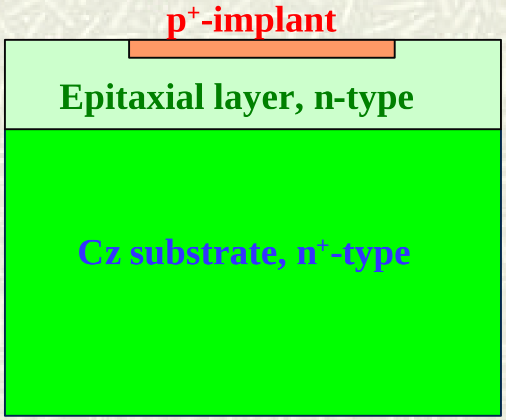
**3. Long term component: reverse annealing (negative on V$_{dep}$).**

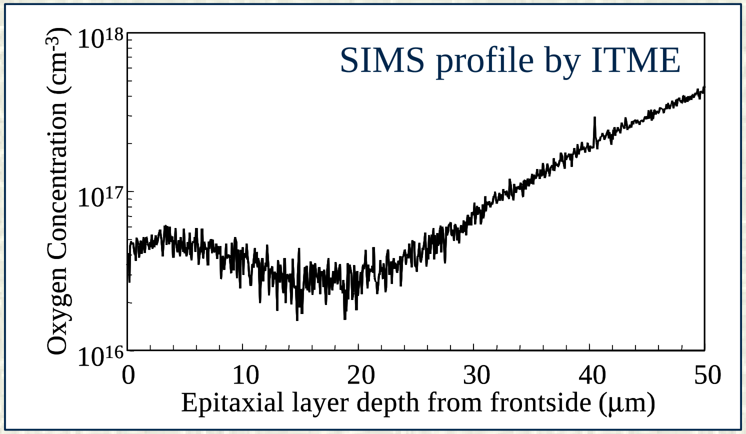
**4. SCSI reached before F$_{min}$= 9.5´10$^{13}$ p/cm².**

# Thin detectors: epitaxial layer (W=50 μm) on CZ substrate

(Hamburg Group, NIM A 515 (2003) 665)

1. Starting material: **low resistivity** (ρ<0.02 Ω·cm) **300 mm thick Czochralski** (CZ) **silicon substrate** doped by Sb donors.
2. A thin (**50 mm**) low resistivity (r=**50** Wx**cm**), **epitaxial silicon layer** doped by P donors has been grown by ITME (Warsaw, Poland) on the CZ substrate forming a simple n-$n^+$ structure.
3. $p^+$-n junction formed by **B implantation** on the epitaxial layer in a standard way using planar technology by CiS (Institute for Micro Sensors gGmbH, Erfurt, Germany) in order to obtain $p^+$-n-$n^+$ silicon detectors.
4. The detector active thickness is that of the epitaxial layer.





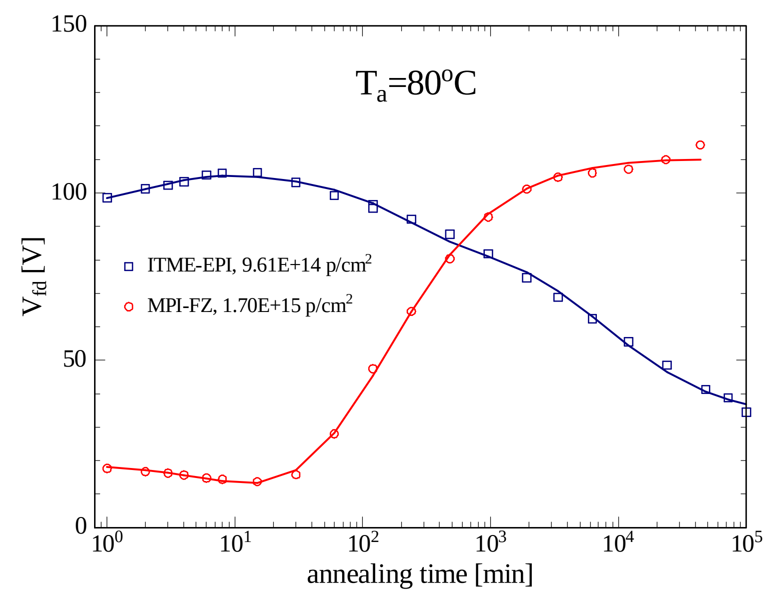
**Advantages**

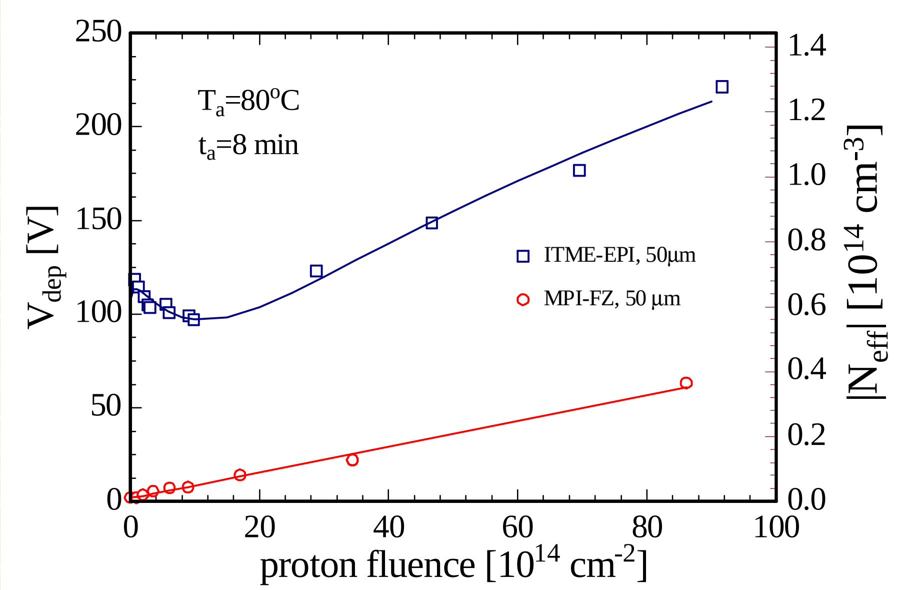
1. Thin detectors present moderate depletion voltages even if highly doped ($V_{dep,0}=qW^2N_{eff,0}/2\varepsilon$), with the advantage that the Space Charge Sign Inversion (SCSI) effect of the active layer, if present, is moved to higher fluences.
2. The CZ substrate is the backside $n^+$ ohmic contact, which is not depleted due to the high Sb doping level and acts also as a mechanical support for the thin epitaxial detector.
3. Due to the high oxygen concentration in the CZ substrate ([O]≈$10^{18}$ cm$^{-3}$), O diffuses into the epitaxial layer during the high temperature growth process improving the detector radiation hardness.

# Thin detector radiation hardness: epitaxial vs thinned

(E. Fretwurst et al., 4th RD50 Workshop, http://rd50.web.cern.ch/rd50/4th-workshop)

20-24 GeV proton irradiation





FZ thinned
(type inverted to p)

short term→ $V_{dep}$ decrease
long term → $V_{dep}$ increase
(predominant acceptor generation)

Epitaxial
(no type inverted)

short term→ $V_{dep}$ increase
long term → $V_{dep}$ decrease
(predominant acceptor generation)
**no $V_{dep}$ reverse annealing at RT!**

FZ thinned
(type inverted to p)

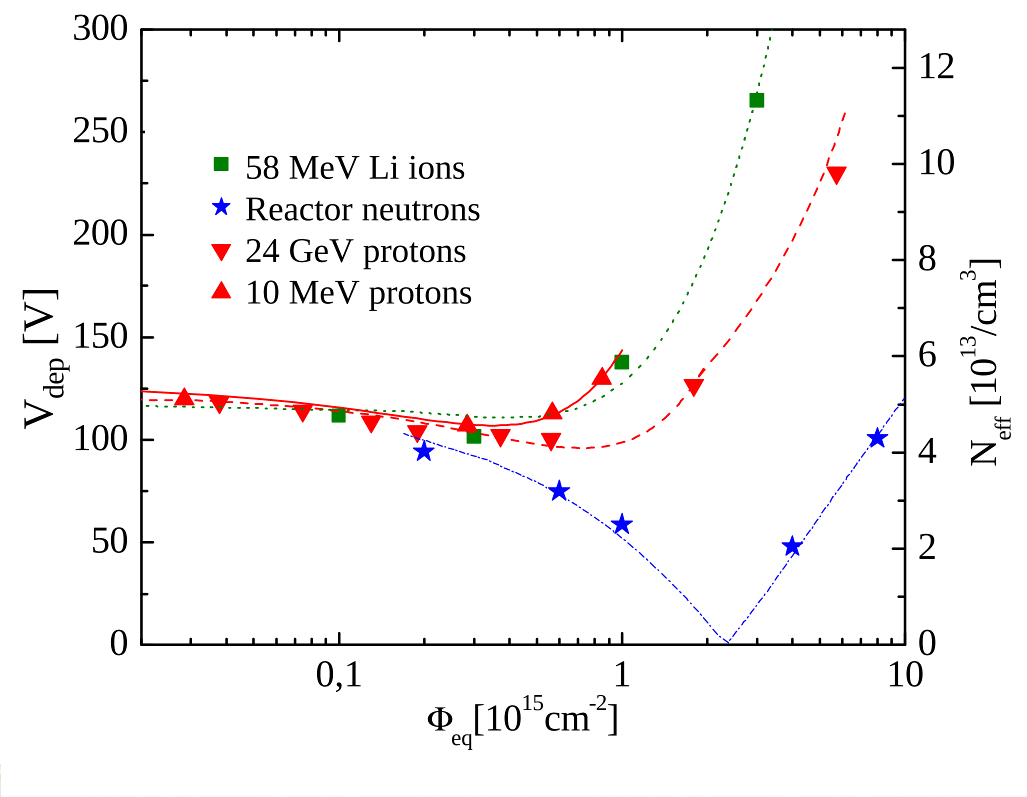
"low" [O]
predominant acceptor generation
during irradiation

Epitaxial
(no type inverted)

"high" [O]
predominant donor generation
during irradiation

# Thin detector radiation hardness: epitaxial

(G. Lindstrom et al., 3rd RD50 Workshop, http://rd50.web.cern.ch/rd50/3rd-workshop)



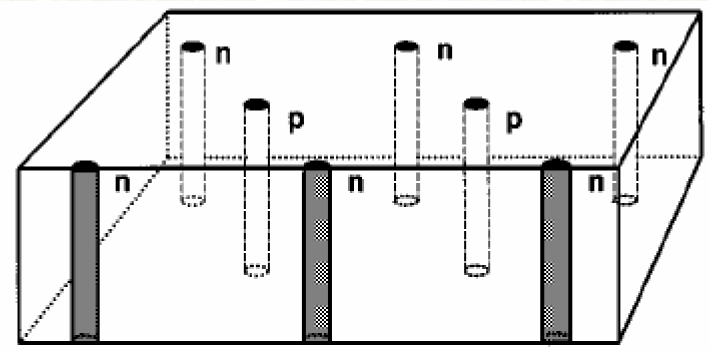
Epitaxial sensors can be type-inverted by neutrons
("low" [O] for cluster defects → predominant acceptor generation during irradiation)
but the high doping of the epitaxial layer moves the SCSI point to high fluences,
and **$V_{dep}$** is expected to be not higher than **125 V** at **$F_{eq}=10^{16}$ cm$^{-2}$**,
so confirming the **extreme radiation hardness** of this technology.

# 3-D 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.

-Important researches are now under investigation by a collaboration (not in RD50) within Brunel Univ., Hawaii Univ., Stanford Univ., and CERN (see talk by A. Kok, tomorrow).



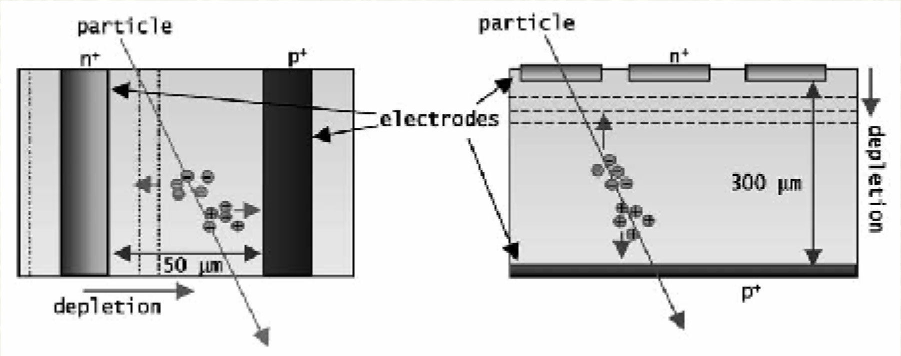
Picture taken from
C.J. Kenney et al., IEEE TNS 48 (2001) 189.

## Advantages:

-depletion thickness depends on $p^+$ and $n^+$ electrode distance, not on the substrate thickness;

-lower collection length than planar technology;

-lower charge collection time than planar technology.

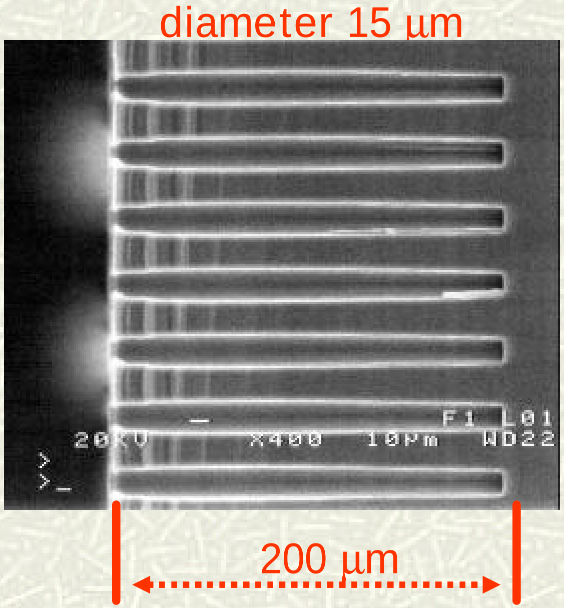


Picture taken from
C. Da Via et al., NIM A 509 (2003) 86.

# 3-D detectors: going on activity in RD50

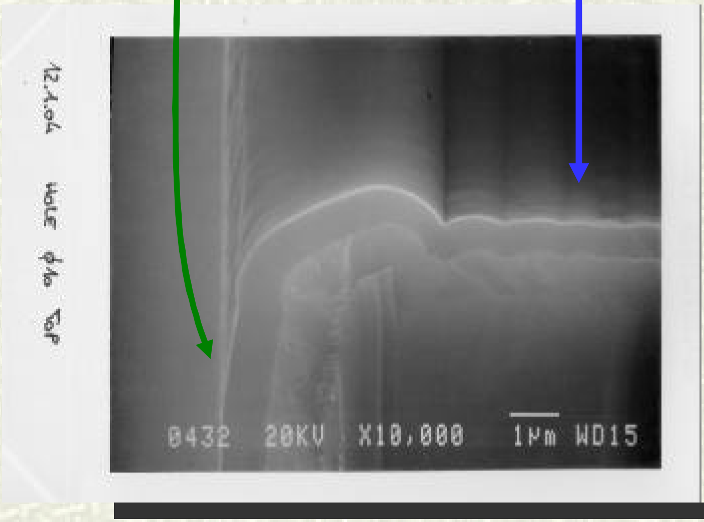
(M. Boscardin et al., 4th RD50 Workshop, http://rd50.web.cern.ch/rd50/4th-workshop)

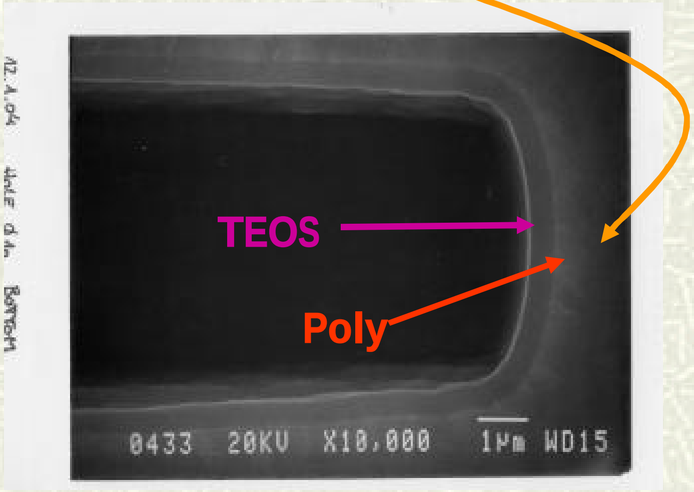
- Detector masks: Glasgow University
- Deep reaction ion etching: CNM, Barcelona
- Detector processing: ITC-IRST, Trento


diameter 15 µm

200 µm

| | Surface | Top | Botton |
|---|---|---|---|
| Poly | 1.05µm | 0.8µm | 0.7µm |
| TEOS | 0.96µm | 0.7µm | 0.6 µm |



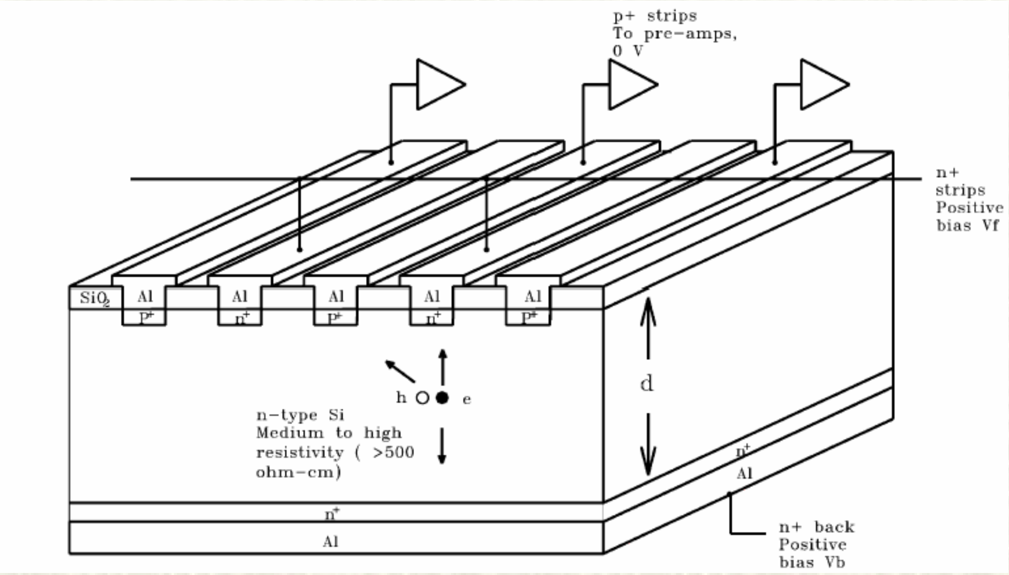


# Semi-3D detectors

(see talk by G. Kramberger, tomorrow)

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

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

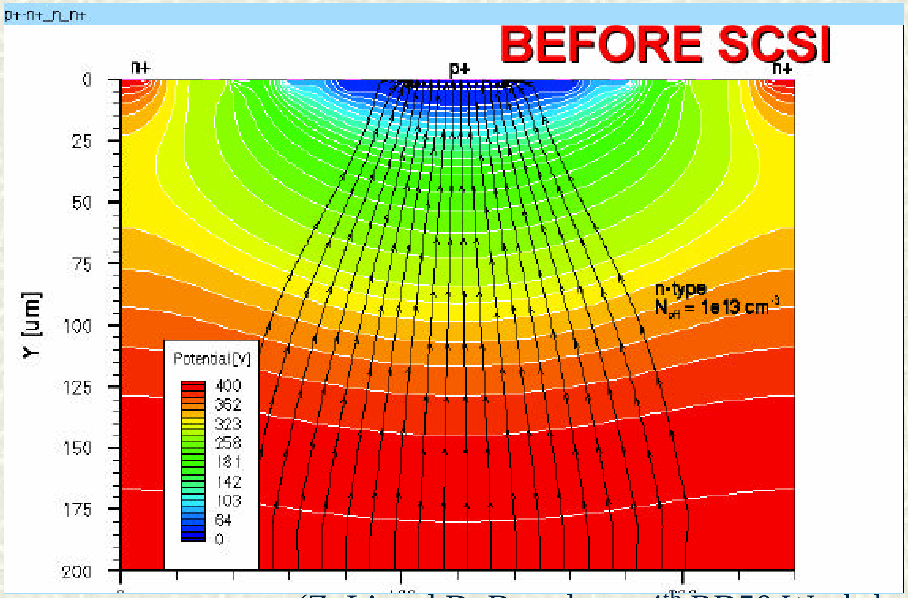


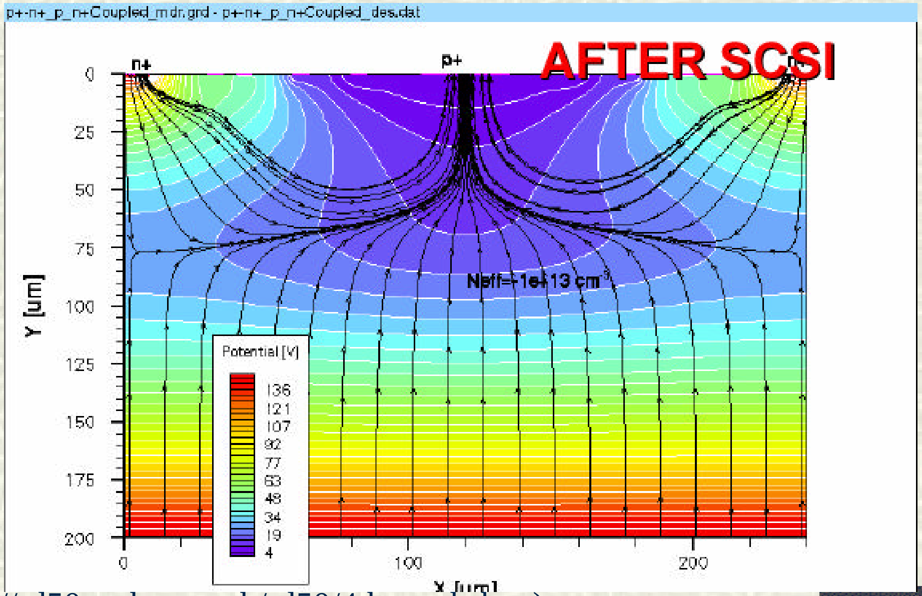
Advantages:

1. Single-side detector process.
2. After SCSI, the depletion occurs from both sides reducing the depletion voltage by factor 2.5.

Under investigation:

Complex electric field distribution before and after SCSI.





(Z. Li and D. Bortoletto, 4th RD50 Workshop, http://rd50.web.cern.ch/rd50/4th-workshop)

# Stripixel detectors

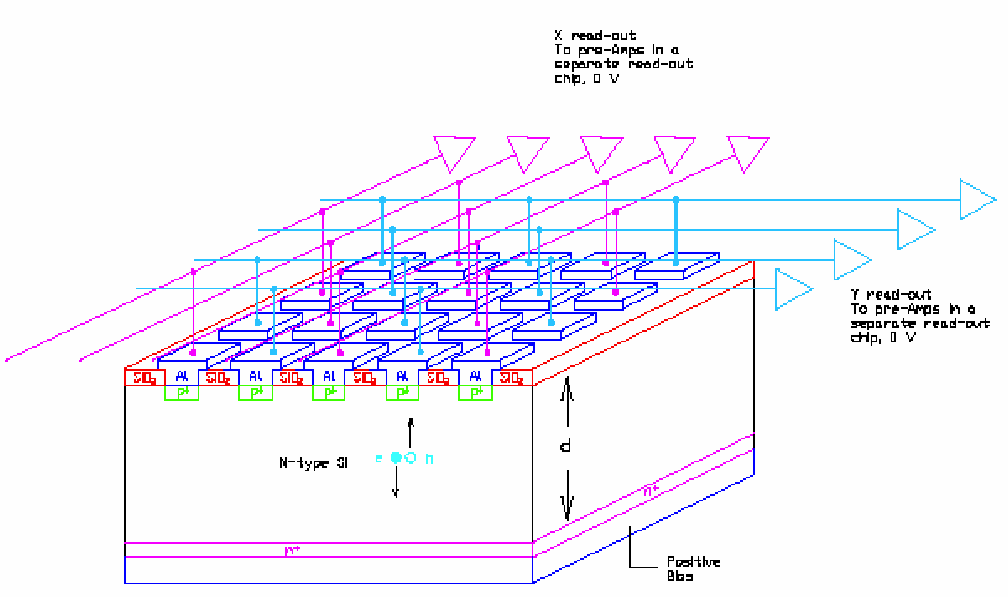
**Proposed by Z. Li** (NIM A 518 (2004) 738).

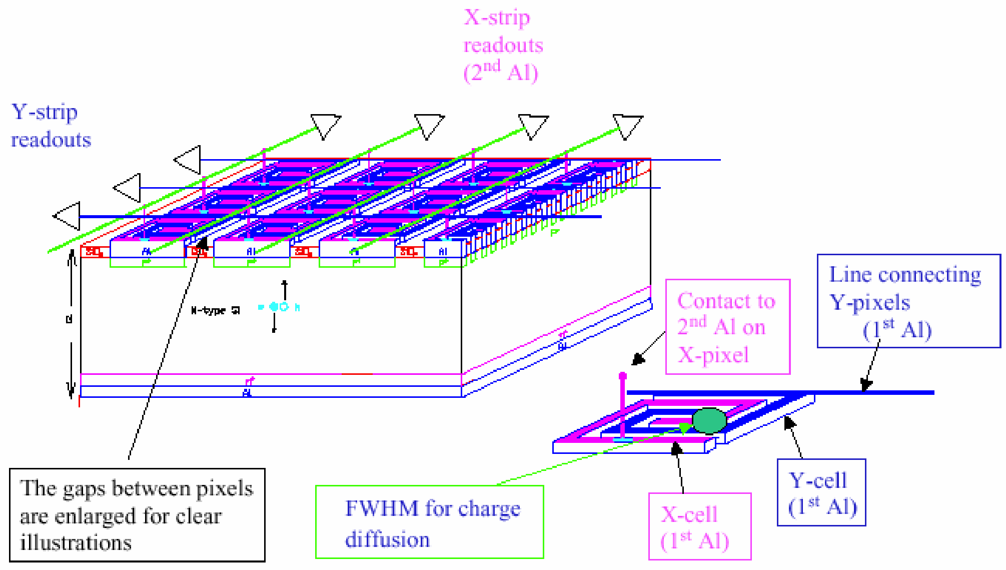
Pixel electrodes arranged in a projective X-Y readout.

Characteristics:

1. Projective readout of double-sided **strip** detectors minimizing the read-out channels;
2. Two-dimensional position resolution of **pixel** electrode geometry;
3. Single-side detector process with double metal technology;
4. Key parameter: standard deviation of the collected charge distribution: χ (≈10 µm).

| | |
|---|---|
| -Individual pixels alternatively connected to X- and Y- read-out. | -Each pixel is divided in two parts (X- and Y-cell). |
| -Charge must be collected at least by two pixels. | -Charge must be collected at least by one X- and by one Y-cell. |
| -Key condition: χ≥pitch | -Key condition: χ≥interleaved distance between X- and Y- cells |
| -Resolution can be better than pitch. | -If pitch>χ the resolution is fixed by the pitch. |



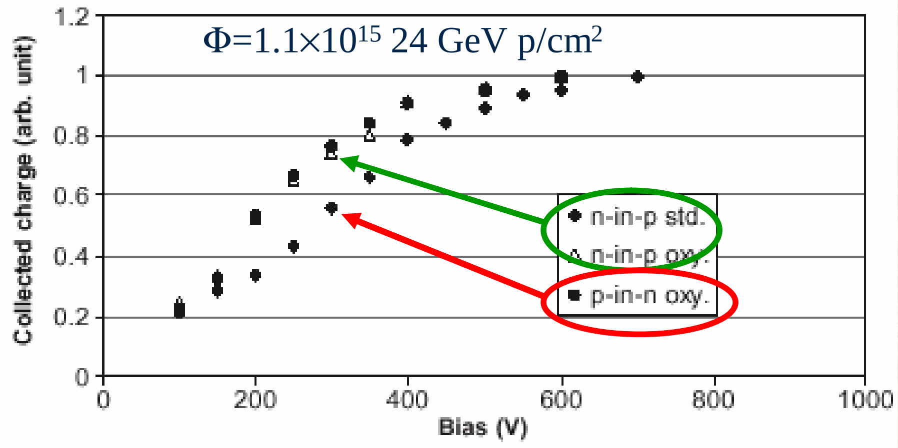


Alternative to macro-pixel detectors in the S-LHC upgrade between 15 cm and 60 cm?

# $n^+$-p detectors on DOFZ substrate

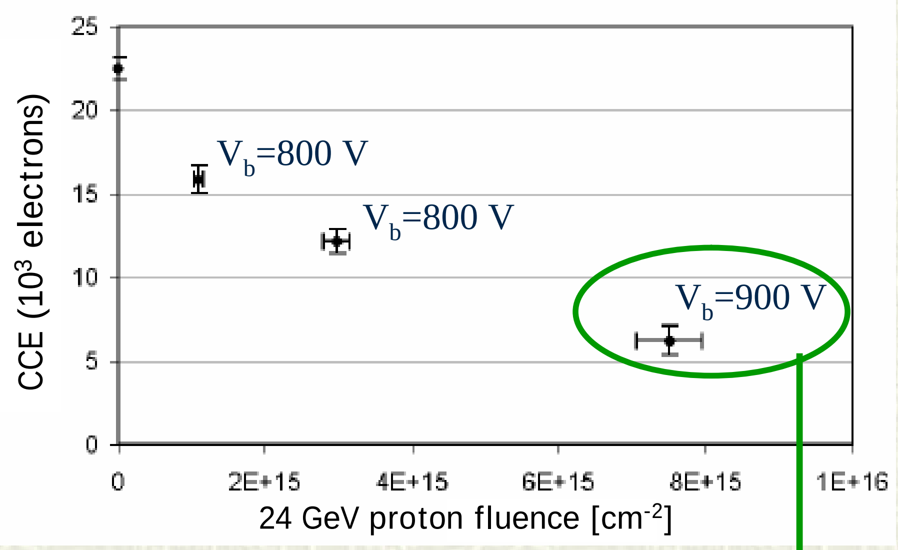
(G. Casse et al., NIM A 485 (2002) 153 and Proc. of the 10th VCI, Vienna, 16-21 Feb. 2004)

1. CCE(V) is improved if the read-out is at the high electric field contact: **$n^+$-p** detectors (no SCSI) **better than $p^+$-n** sensors after SCSI.
2. DOFZ p-type substrates are expected to be more radiation hard than FZ p-type Si.



## Miniature $n^+$-p microstrip detectors on DOFZ substrate

Area: 1× 1 $cm^2$
Thickness: 280 μm
Number of strips: 100
Read-out: SCT128 chip at 40 MHz
Source for CCE: $^{106}$Ru



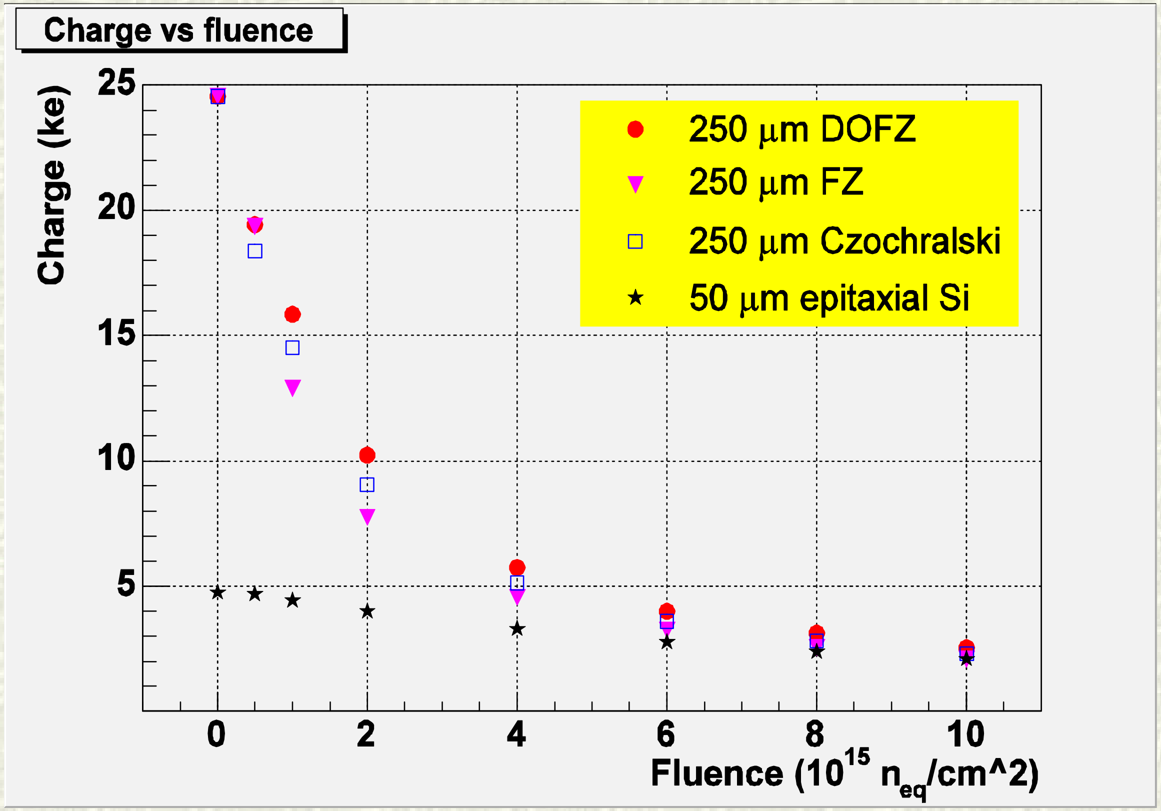
**Charge, collected** at 900 V bias after 7.5×$10^{15}$ 24-GeV p/$cm^2$ (5×$10^{15}$ 1-MeV equivalent neutrons/$cm^2$) for **DOFZ p-type detector**, is **6500 electrons** (corresponding to the charge deposited in a 90 μm thick un-irradiated silicon sensor).

# CCE simulations of pixel detectors

(T. Lari, Proc. of the 10th VCI, Vienna, 16-21 Feb. 2004)

Hypothesis:
1. Pixel dimensions: 70×70 $\mu m^2$ to cope with increased track density at SLHC.
2. T=-10 °C.
3. Read-out at the high electric field side:
   -n-side for FZ and DOFZ (type inverted);
   -p-side for Cz and Epitaxial (no type inverted).
4. $V_{bias}$: 600 V for FZ, DOFZ and CZ;
   150 V for Epitaxial.

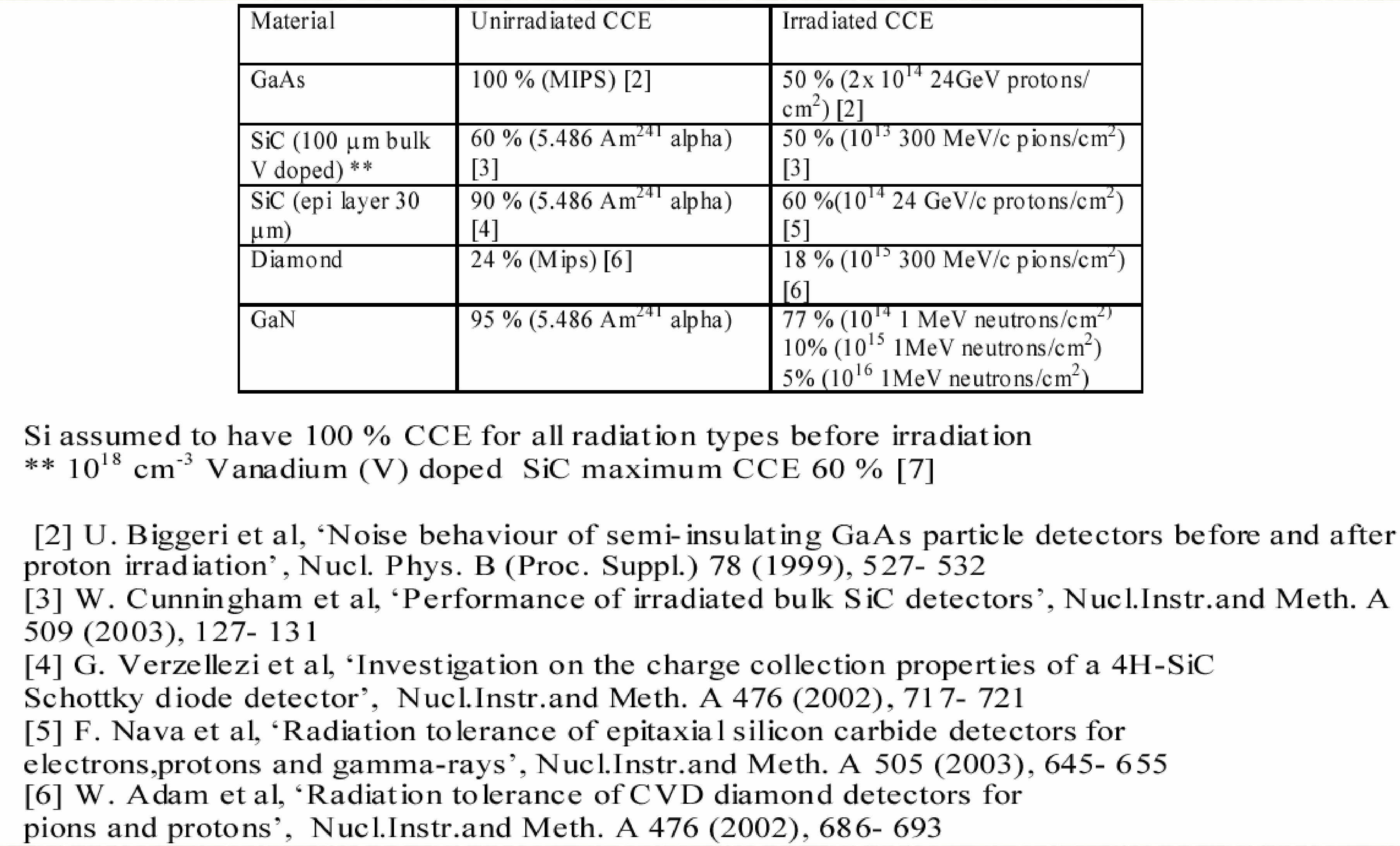
(see talks by T. Lari and G. Kramberger, tomorrow)



| **$10^{15}$ $n_{eq}/cm^{-2}$ fluence:** | • DOFZ better than FZ when the latter is no longer fully depleted at 600 V.<br>• DOFZ (n-side read-out) slightly better than CZ (p-side read-out).<br>• Epitaxial signal very low (because of thin sensor). |
|---|---|
| **$10^{16}$ $n_{eq}/cm^{-2}$ fluence:** | • All detectors are similar (trapping dominant). |

# CCE in SiC and GaN

(A. Blue et al., 4th RD50 Workshop, http://rd50.web.cern.ch/rd50/4th-workshop/)



| Material | Unirradiated CCE | Irradiated CCE |
|---|---|---|
| GaAs | 100 % (MIPS) [2] | 50 % (2x $10^{14}$ 24GeV protons/ cm$^2$) [2] |
| SiC (100 μm bulk V doped) ** | 60 % (5.486 Am$^{241}$ alpha) [3] | 50 % ($10^{13}$ 300 MeV/c pions/cm$^2$) [3] |
| SiC (epi layer 30 μm) | 90 % (5.486 Am$^{241}$ alpha) [4] | 60 %($10^{14}$ 24 GeV/c protons/cm$^2$) [5] |
| Diamond | 24 % (Mips) [6] | 18 % ($10^{15}$ 300 MeV/c pions/cm$^2$) [6] |
| GaN | 95 % (5.486 Am$^{241}$ alpha) | 77 % ($10^{14}$ 1 MeV neutrons/cm$^2$)<br>10% ($10^{15}$ 1MeV neutrons/cm$^2$)<br>5% ($10^{16}$ 1MeV neutrons/cm$^2$) |

Si assumed to have 100 % CCE for all radiation types before irradiation
** $10^{18}$ cm$^{-3}$ Vanadium (V) doped SiC maximum CCE 60 % [7]

[2] U. Biggeri et al, 'Noise behaviour of semi-insulating GaAs particle detectors before and after proton irradiation', Nucl. Phys. B (Proc. Suppl.) 78 (1999), 527- 532
[3] W. Cunningham et al, 'Performance of irradiated bulk SiC detectors', Nucl.Instr.and Meth. A 509 (2003), 127- 131
[4] G. Verzellezi et al, 'Investigation on the charge collection properties of a 4H-SiC Schottky diode detector', Nucl.Instr.and Meth. A 476 (2002), 717- 721
[5] F. Nava et al, 'Radiation tolerance of epitaxial silicon carbide detectors for electrons,protons and gamma-rays', Nucl.Instr.and Meth. A 505 (2003), 645- 655
[6] W. Adam et al, 'Radiation tolerance of CVD diamond detectors for pions and protons', Nucl.Instr.and Meth. A 476 (2002), 686- 693

# Summary

**General considerations:**

1. **Leakage current** can be limited only by **decreasing temperature** (×2 every  7.5 K);

2a. **Charge collection** at the S-LHC fluences (≥ 4-6×$10^{15}$ $cm^{-2}$) is **limited by carrier mean free path** and for planar technologies is less dependent on the detector thickness W.

2b. Benefits from **W decrease**: 1) **$I_{leak}$µW**; B) **$V_{dep}$µ$N_{eff}$´$W^2$**; C) **$N_{eff,0}$µ$V_{dep,0}$/$W^2$**

3. **High [O]** required for limiting $V_{dep}$ after irradiation thanks to **donor generation** (BD center) and **mitigation** of the **acceptor generation** (VO and $V_2O$ or $V_2$ related defects are competitive processes): interesting results for **MCZ** (no SCSI with γ-rays), **CZ** (no SCSI with high energy charge hadrons), and **Epitaxial on CZ** (no reverse annealing for high energy charge hadrons);

**Different technologies are under investigation in RD50:**

1. Experimental data on different technologies are fundamental inputs for **devices simulations** in order **to determine** the **W, [O]** and **$N_{eff,0}$** values **for** the **LHC upgrade**. W can be decreased accordingly to the maximum Φ and CCE required.
2. **CZ** and **MCZ** take advantage from higher [O] than FZ and DOFZ.
2. **Thinned devices** (50 µm) take advantage from $V_{dep}\propto W^2$, but small area sensors.
3. **Epitaxial** (50 µm) **on CZ** takes advantage from $V_{dep}\propto W^2$, high [O] and high $N_{eff,0}$ (SCSI postponed), large area sensors. Possible to increase the thickness to 100 µm to increase CCE.

**Different detector layouts are under investigation in RD50:**

1. **3-D** ($V_{dep}$ depends on the p-n electrode distance not on W), **Semi 3-D** ($V_{dep}$ lower by a factor 2.5, but complex electric field), **Stripixel** (Single-side detector process with double metal technology for two-dimensional read-out, alternative to macro-pixels).

More material on the RD50 WEB site:
http://rd50.web.cern.ch/rd50/