Semiconductor materials and detectors for future very high luminosity colliders

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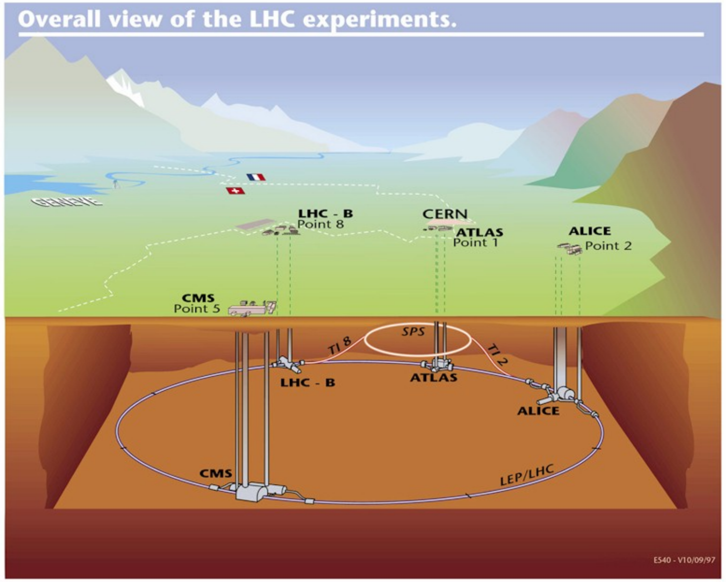
On behalf of the CERN RD50 Collaboration
(http://rd50.web.cern.ch/rd50/)

Outline

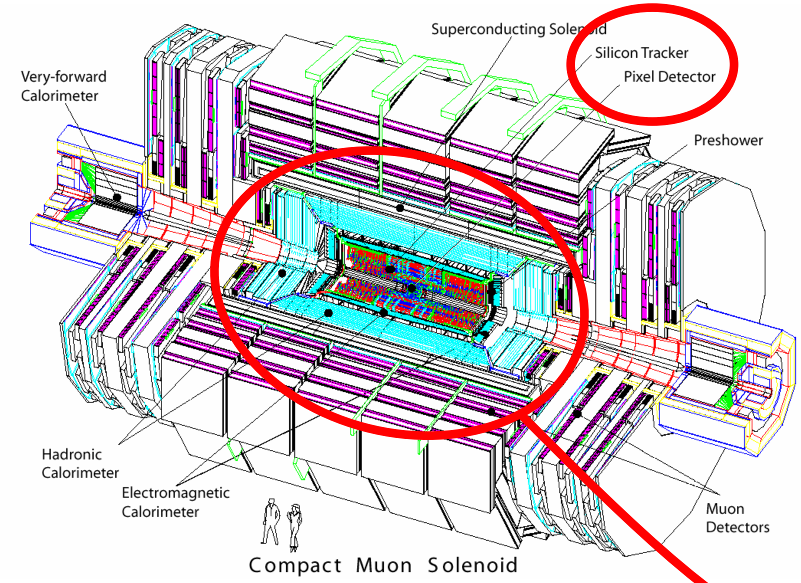
- Motivations: the LHC upgrade
- The CERN RD50 Collaboration
- Improving the silicon detector radiation hardness:
    - -Oxygen in the silicon substrate
    - -Thin detectors: TMAH-thinned and epitaxial
    - -Pre-irradiated silicon
- New detector structures: 3D-STC and Semi-3D
- Summary

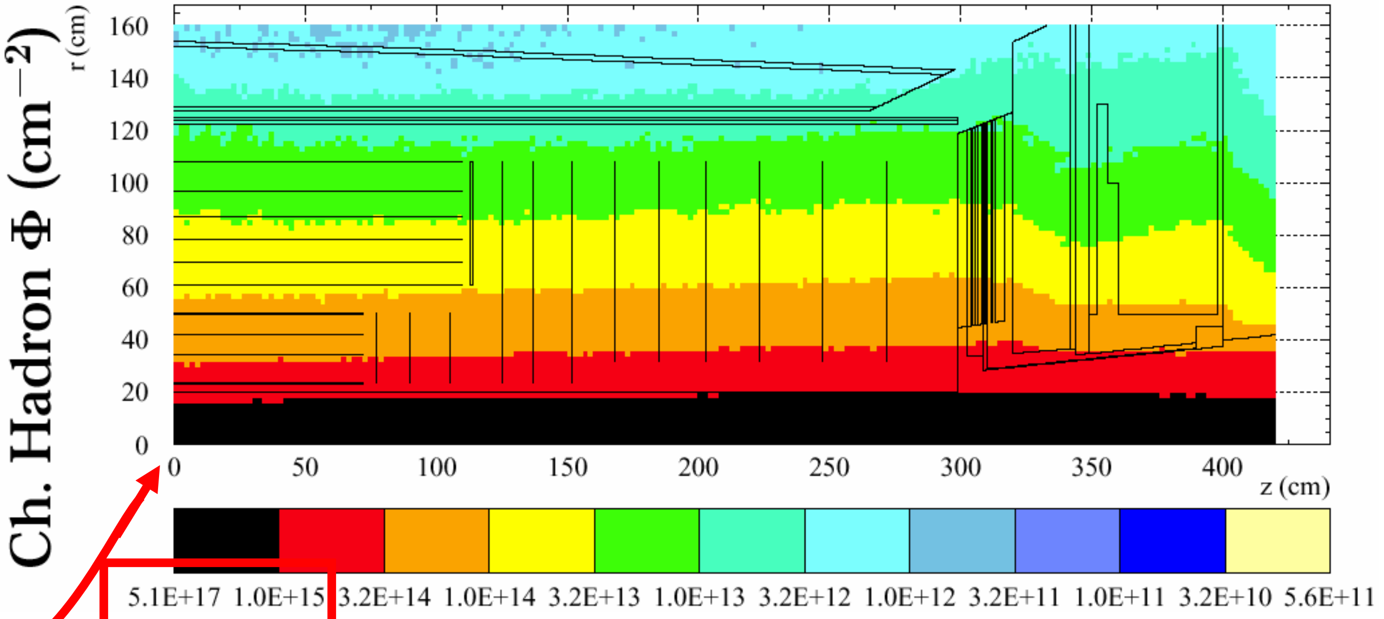
The upgrade of the Large Hadron Collider (LHC) at CERN



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

	LHC (2007)		Super-LHC (2015)
Proton Energy:	7 TeV	=>	15 TeV
Collision rate:	40 MHz	=>	80 MHz
Peak luminosity:	$10^{34}\ \mathrm{cm}^{-2}\times\mathrm{s}^{-1}$	=>	$10^{35}\ \mathrm{cm}^{-2}\times\mathrm{s}^{-1}$
Integrated luminosity:	$500\ \mathrm{fb}^{-1}$	=>	$2500\ \mathrm{fb}^{-1}$





The CERN RD50 Collaboration

1. **Formed in November 2001**
2. **Approved 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} (Super-LHC).

Challenges:

- **Radiation hardness of semiconductor detectors up to fast hadron fluences of 10^{16} cm^{-2};**
- **Fast signal collection (10 ns bunch crossing);**
- **Low mass (reducing multiple scattering close to interaction point);**
- **Cost effectiveness.**

Presently 254 Members from 54 Institutes

Belgium (Louvain), Belarussia (Minsk), Canada (Montreal), Czech Republic (Prague (2x)), Finland (Helsinki, Lappeenranta) , Germany (Berlin, Dortmund, Erfurt, Friburg, Hamburg, Karlsruhe), Israel (Tel Aviv), Italy (Bari, Bologna, Florence, Milano, Padova, Perugia, Pisa, Trento, Trieste, Turin), Lithuania (Vilnius), Poland (Warsaw (2x)), Norway (Oslo (2x)), Romania (Bucharest (2x)), Russia (Moscow, St.Petersburg), Slovenia (Ljubljana), Spain (Barcelona, Valencia), Switzerland (CERN, PSI), Ukraine (Kiev), United Kingdom (Exeter, Glasgow, Lancaster, Liverpool, Sheffield, Guilford), USA (Albuquerque, BNL, Fermilab, Purdue, Rochester, Rutgers, Santa Cruz, Syracuse)

Radiation effects in silicon detectors

I) Increase of the leakage current:

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

Decrease of S/N ratio

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

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

Leakage current decreases by a factor ≈2 every 7.5 K

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

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

Decrease of charge collection efficiency

Decrease of S/N ratio

III) Increase of the charge trapping:

Decrease of trapping time constant and mean free path

Decrease of charge collection efficiency

Decrease of S/N ratio

Oxygen in the silicon substrate

Silicon type	Acronym	Characteristics	[O] (cm^{-3})
Float Zone	**FZ**	**Standard**	**≈$4 \cdot 10^{16}$**
Diffusion Oxygenated Float Zone	**DOFZ**	**FZ + O diffusion for 24-48 h at 1100-1200 °C from SiO_2 layers**	**≈$1 \cdot 10^{17}$**
Magnetic Czochralski	**MCZ**	**CZ + Magnetic field during crystal growth to improve homogeneity**	**≈$5 \cdot 10^{17}$**
Czochralski	**CZ**	**Standard**	**≈$8 \cdot 10^{17}$**

1. Why **Oxygen (O)** is important in n-type silicon?

   V are **radiation induced vacancies**:

   a) **O** absent: **$V + V = V_2$** (**deep acceptor**) => **V_{dep} variation**

   b) **O** present: **$V + O = VO$** (**neutral at RT**) => **Mitigation of V_{dep} variation**

   c) **O** finished: **$V + V = V_2$** (**deep acceptor**)
   $V + VO = V_2O$ (**deep acceptor**) } =>**V_{dep} variation**

2. Irradiation with

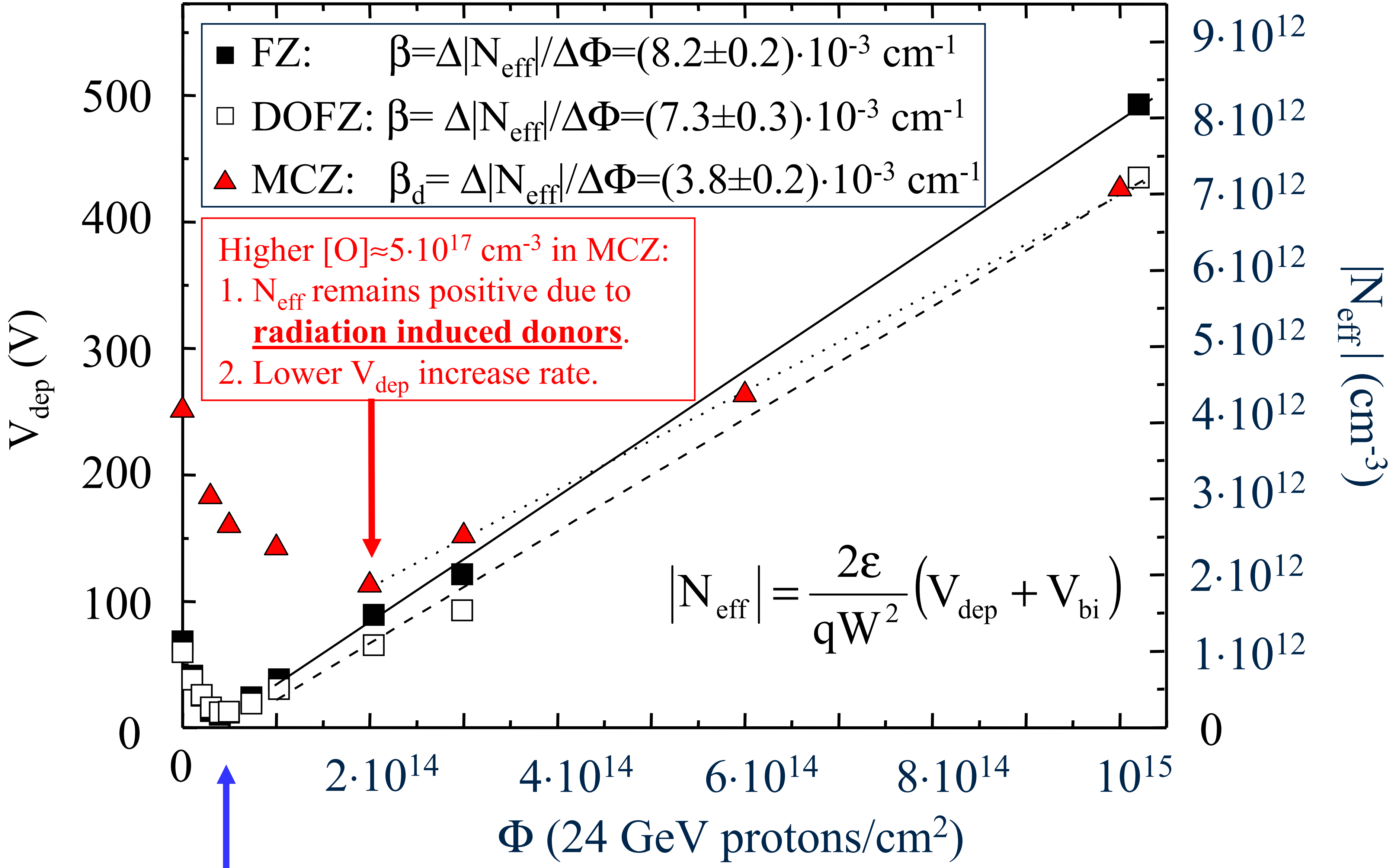
   a) **γ-rays:** point defects → [**O**]>>[**V**] in DOFZ, MCZ, CZ →**Mitigation of V_{dep} variation**

   b) **Neutrons**: clusters → [**O**]<<[**V**] in DOFZ, MCZ, CZ →**No mitigation of V_{dep} variation**

   c) **Protons**: point defects and clusters → **intermediate condition between γ-rays and neutrons**

3. High [**O**] => **Donor activation** during irradiation

Example: FZ, DOFZ and MCZ Silicon



■ FZ: $\beta=\Delta|N_{eff}|/\Delta\Phi=(8.2\pm0.2)\cdot10^{-3}$ cm^{-1}

□ DOFZ: $\beta=\Delta|N_{eff}|/\Delta\Phi=(7.3\pm0.3)\cdot10^{-3}$ cm^{-1}

▲ MCZ: $\beta_d=\Delta|N_{eff}|/\Delta\Phi=(3.8\pm0.2)\cdot10^{-3}$ cm^{-1}

Higher [O]≈$5\cdot10^{17}$ cm^{-3} in MCZ:

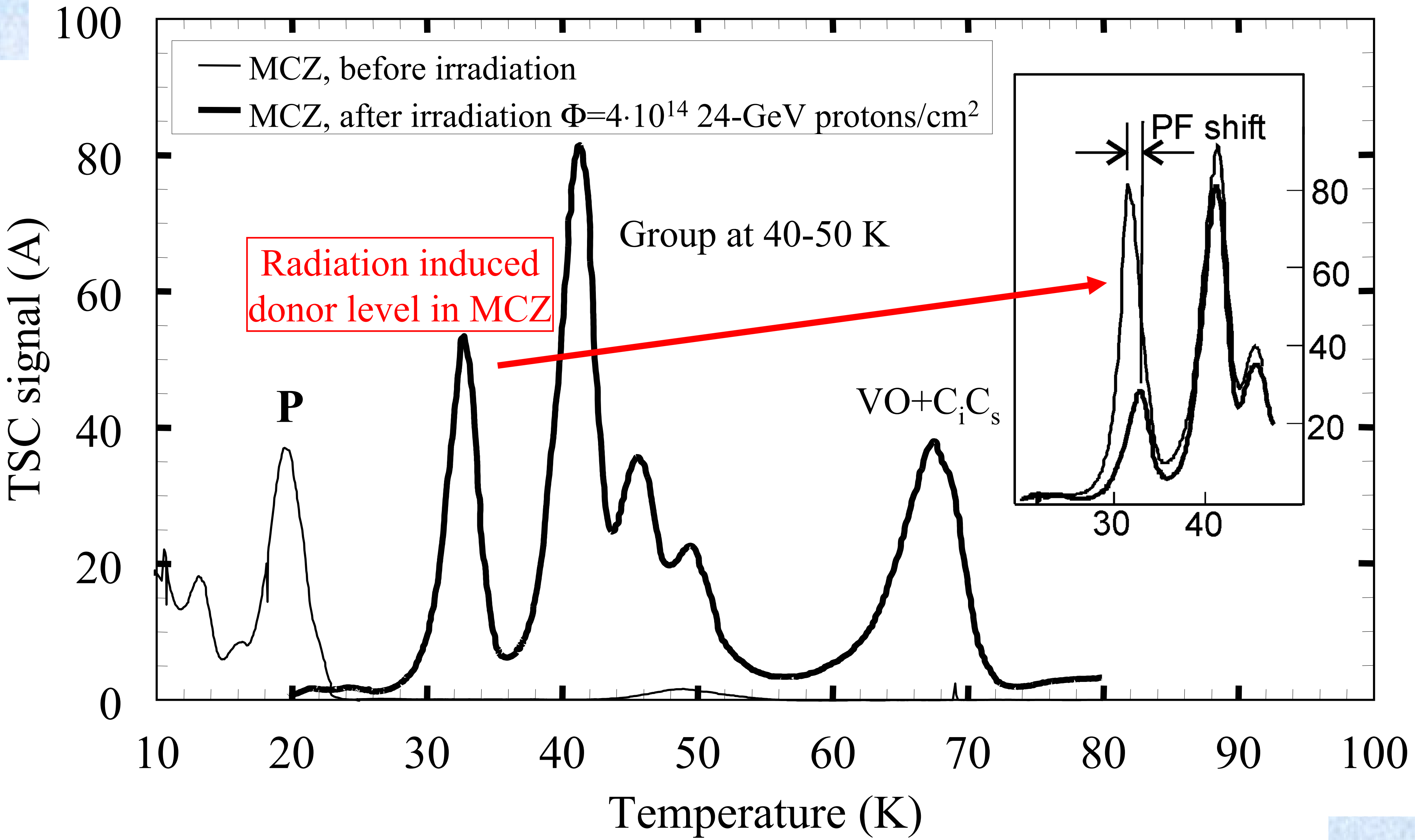
1. N_{eff} remains positive due to **radiation induced donors**.
2. Lower V_{dep} increase rate.

$$|N_{eff}| = \frac{2\varepsilon}{qW^2}\left(V_{dep} + V_{bi}\right)$$

1. V_{dep} decreases to 0 and then increases due to **radiation induced deep acceptors**: $N_{eff}<0$.
2. Lower V_{dep} increase rate for DOFZ with higher [O]≈$4\cdot10^{17}$ cm^{-3} than FZ.

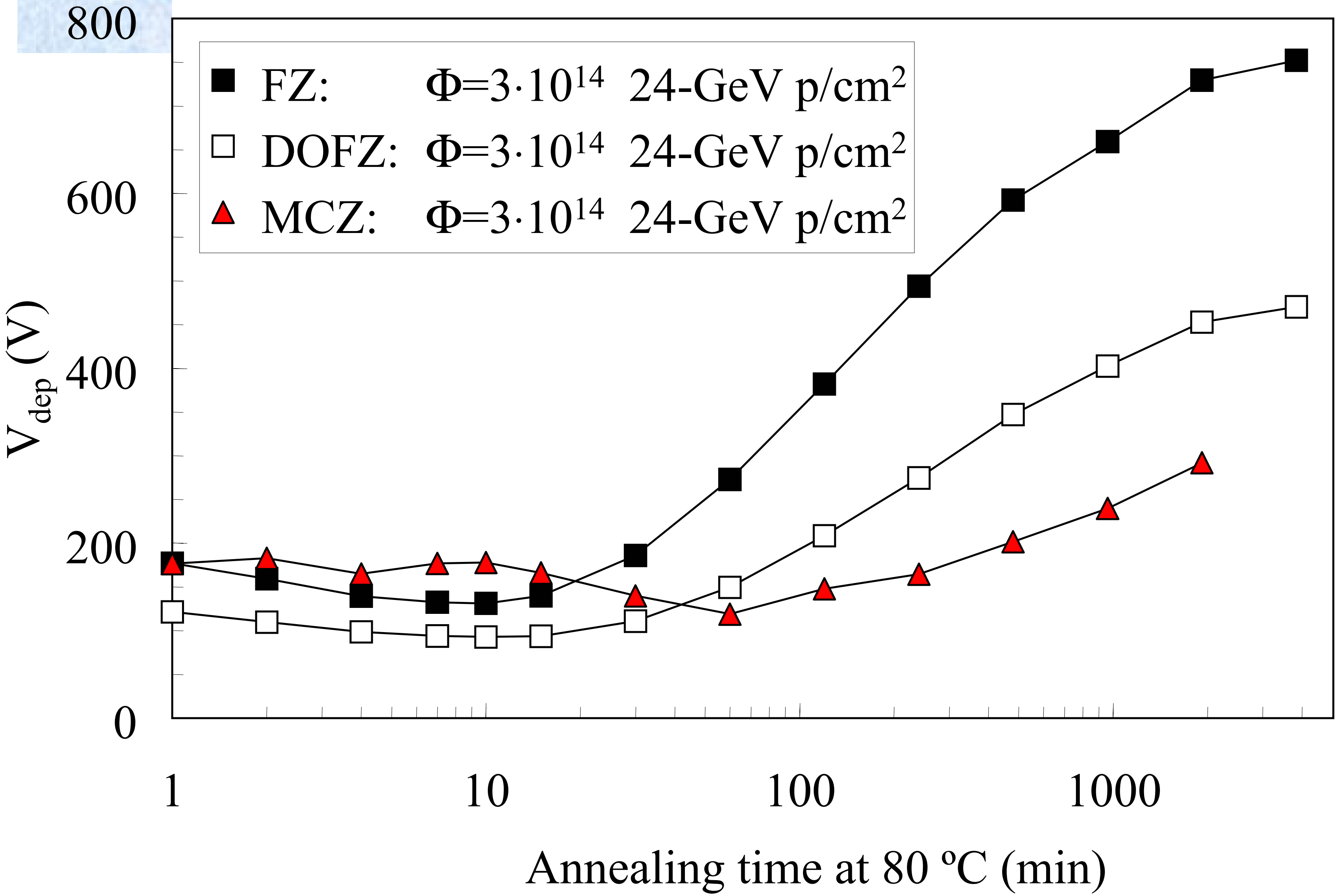
Observation of radiation induced donors in MCZ

D. Menichelli et al., "Shallow donors in MCz-Si n- and p-type detectors at different process temperature, irradiation and thermal treatments," presented at the 6th RD50 Workshop (Helsinki, Finland), 2-4 June 2005. On line available: http://rd50.web.cern.ch/rd50/.



Oxygen improves the V_{dep} long-term performace

M. Lozano et al., "Comparison of radiation hardness of p-in-n, n-in-n and n-in-p silicon pad detectors on FZ, DOFZ and MCZ Si," presented at the 5th RD50 Workshop (Geneve, Switzeland), 14-16 October 2004. On line available: http://rd50.web.cern.ch/rd50/.



V_{dep} increase called "reverse annealing" due to deep acceptor generation: $V+V=V_2$. $[O]\approx4\cdot10^{16}$ cm^{-3}

... lower for DOFZ: $V+O=VO$ due to higher $[O]\approx10^{17}$ cm^{-3}

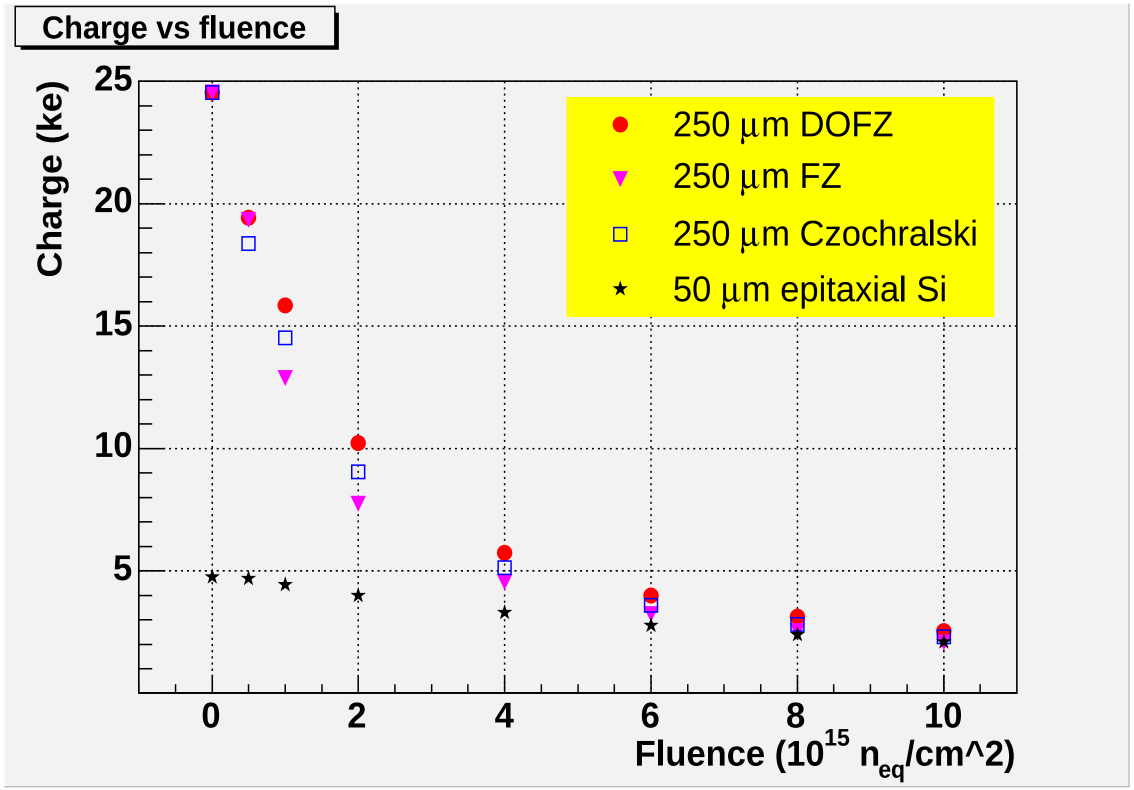
$[O]\approx5\cdot10^{17}$ cm^{-3} in MCZ improves the long-term performance

Thin detectors

Why thin detectors?

W is the thickness of the detector active layer.

1. Smaller leakage current: $I_{leak} \propto W$
2. Smaller depletion voltage: $V_{dep} \propto W^2$
3. At Super-LHC fluences, charge collection is limited by charge trapping, i.e. by reduced carrier mean free path, not by W≈280-300 μm detector thickness



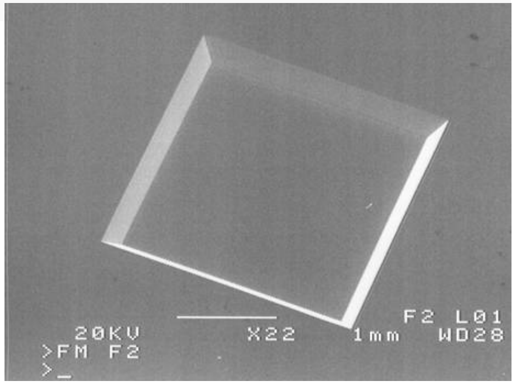
T. Lari, "Detailed simulation of pixel sensors", presented at the Vertex Conference (Menaggio, Italy), 13-18 September 2004.

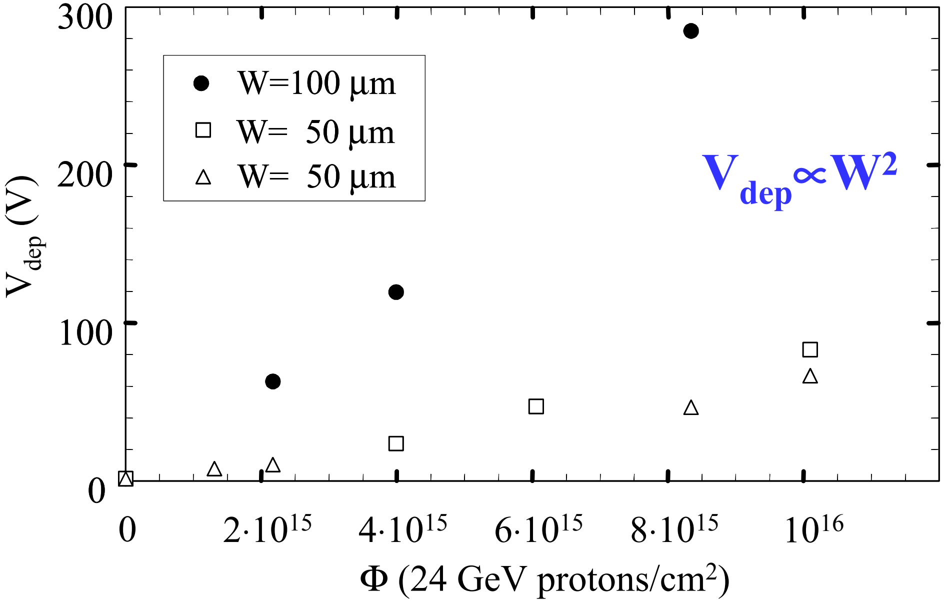
Thin detectors

TMAH-Thinned devices

(E. Ronchin et al., NIM A530 (2004) 134 and
L. Andricek et al., TNS 51 (2004) 1117)

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

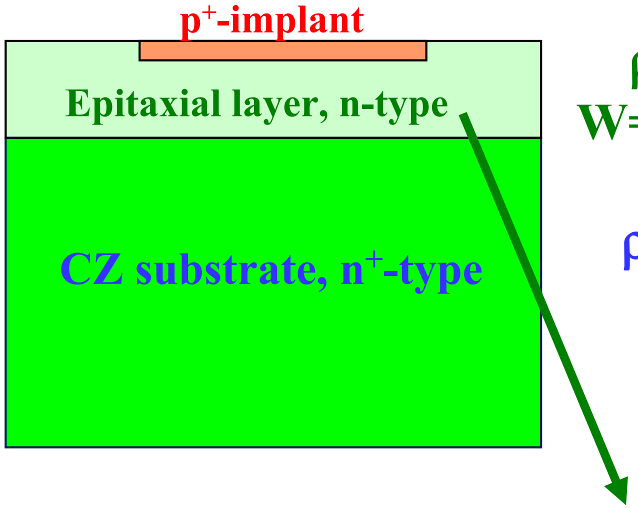




$V_{dep} \propto W^2$

Thin epitaxial layer on CZ substrate

(Hamburg Group, NIM A515 (2003) 665)



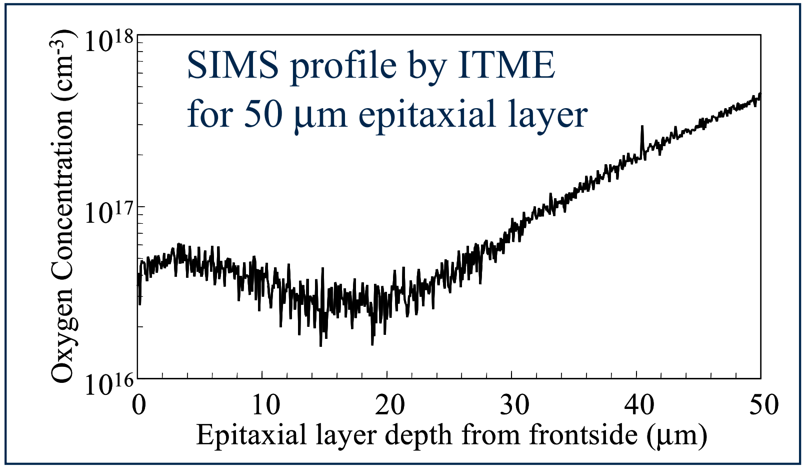
p^+-implant

Epitaxial layer, n-type

CZ substrate, n^+-type

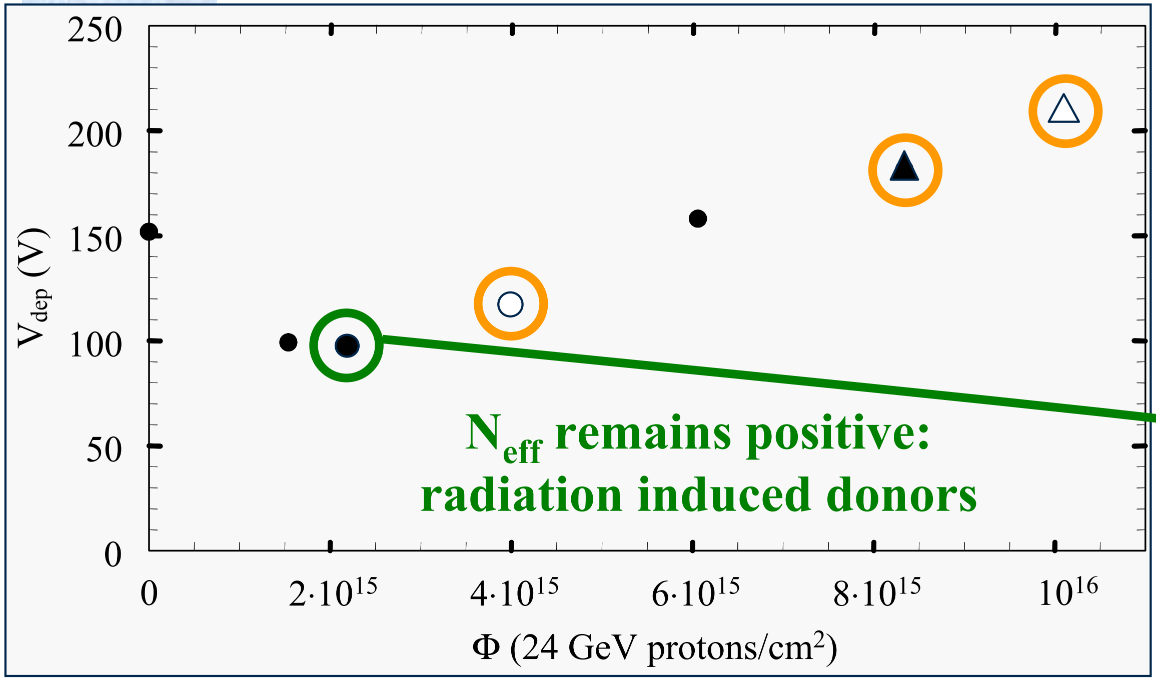
ρ=50 Ω·cm,
W=25, 50,75 μm

ρ=0.02 Ω·cm,
D=300 μm

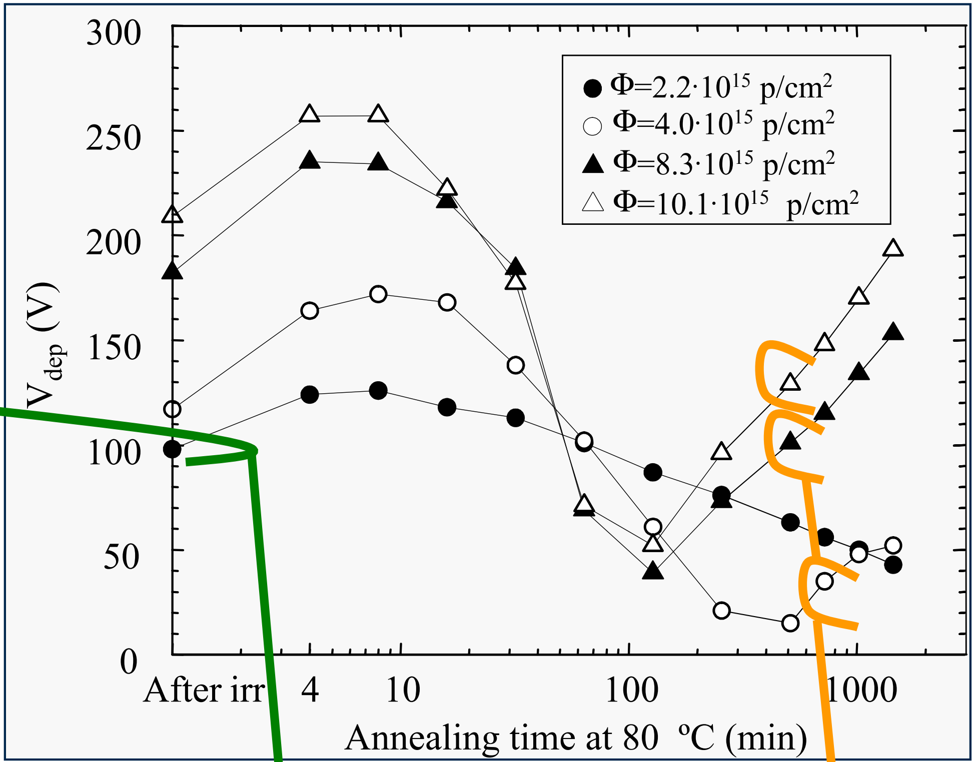


SIMS profile by ITME
for 50 μm epitaxial layer

Thin epitaxial layer on CZ substrate

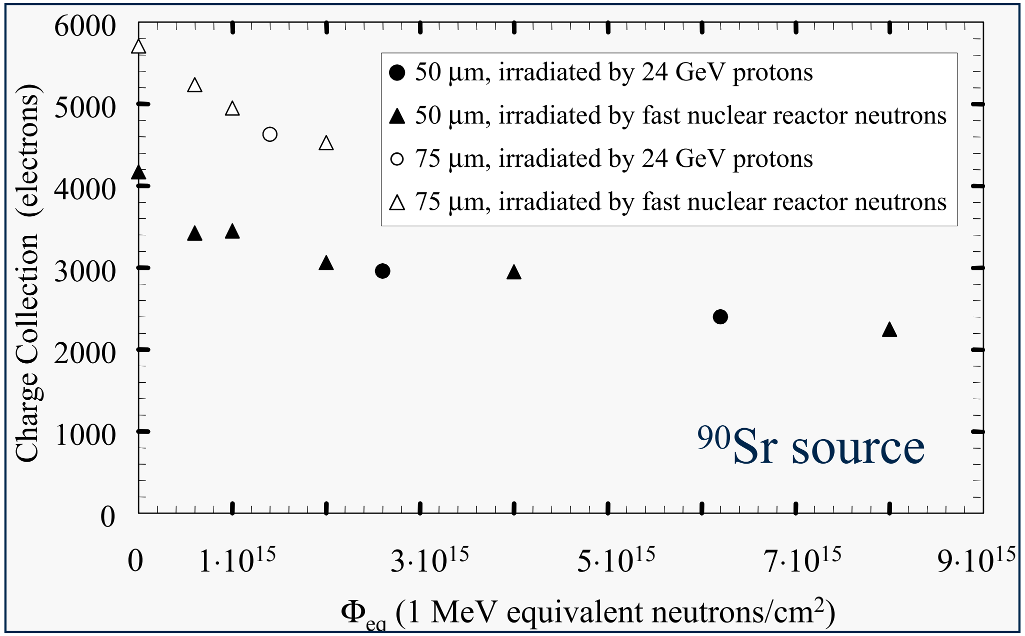


N_{eff} remains positive: radiation induced donors



V_{dep}↑,↓:
N_{eff} remains positive

V_{dep}↑,↓,↑ :
N_{eff} becomes negative due to deep acceptor generation



G. Kramberger et al., "Charge collection properties of heavily irradiated epitaxial silicon detectors," presented at RESMDD 2004 Conference (Florence, Italy), 10-13 October 2004

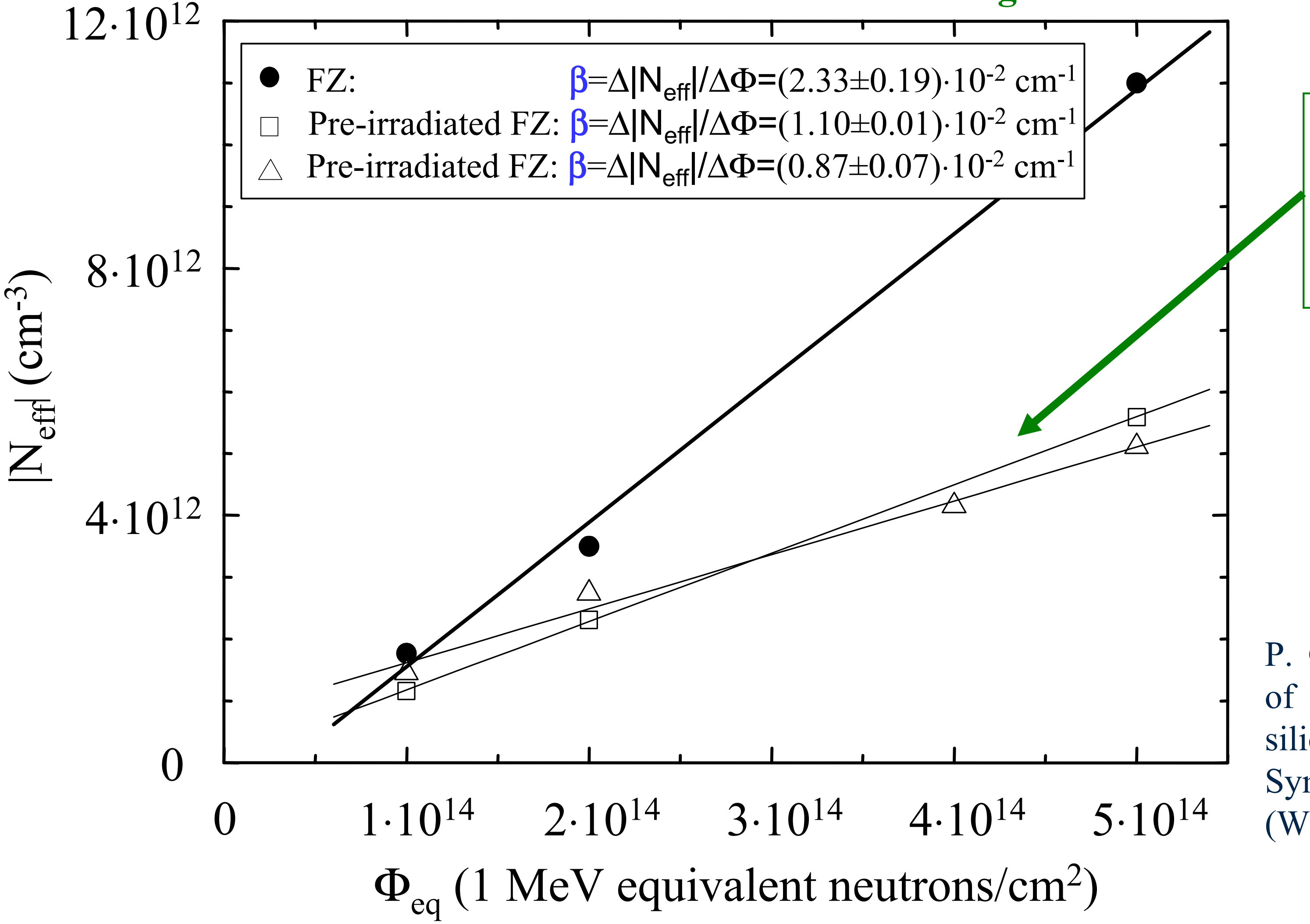
Pre-irradiated silicon

Substrate: FZ, n-type, 300 µm thick, ρ= 3-4 kΩ·cm

Pre-irradiation: Idea. Formation of sinks for primary radiation defects. These sinks are complexes of radiation induced defects with neutral impurities, such as C and O, always present in silicon

How to produce these sinks? Irradiation by fast nuclear reactor neutrons up to ≈10^{16} n/cm^2

Annealing with RT≤T≤ 850 ºC (2 hours)



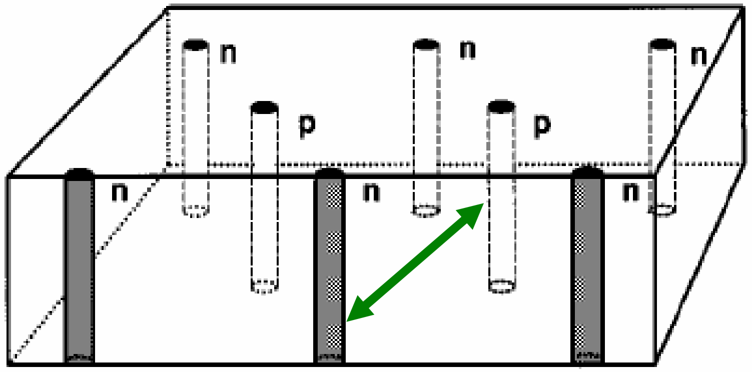
Lower $|N_{eff}|$ increase rate
for pre-irradiated devices
after neutron irradiation
(never observed for oxygenated Si)

P. G. Litovchenko et al., "Radiation hardness of silicon detectors based on pre-irradiated silicon," presented at the 10th European Symposium on Semiconductor Detectors (Wildbad Kreuth, Germany), 12-16 June 2005

New detector structures: 3D-Single Type Column

-3D detector were proposed by S.I. Parker, C.J. Kenney and J. Segal (NIM A 395 (1997) 328).

-Called 3D because, in contrast to silicon planar technology,
have three dimensional (3D) p and n electrodes penetrating the silicon substrate.



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

Advantages:

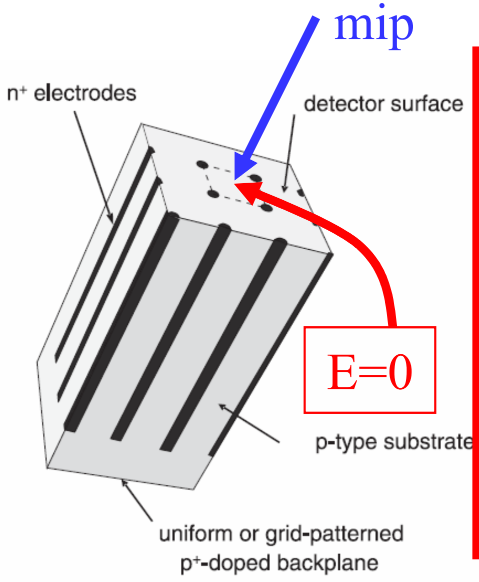
-depletion thickness depends on p^+ and n^+ electrode distance, not on the substrate thickness;

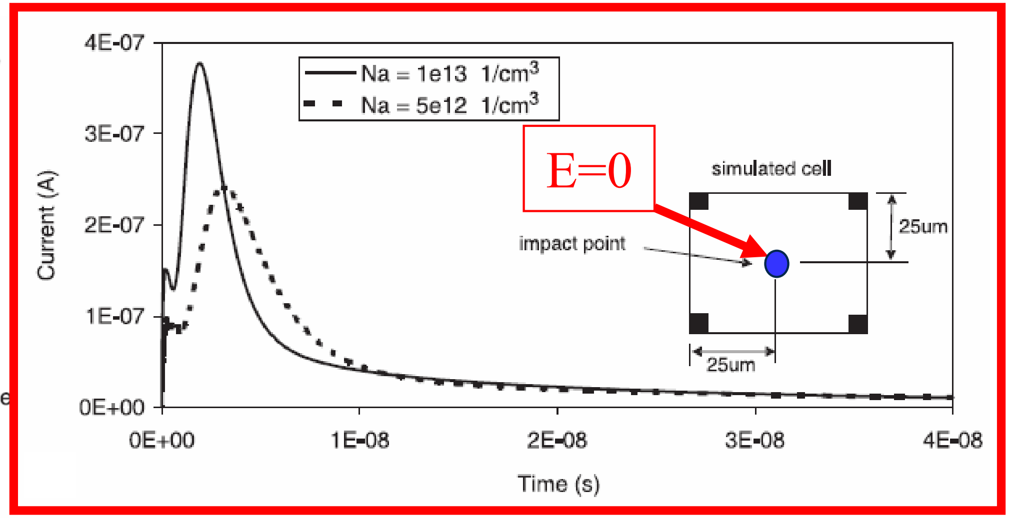
-lower collection length and time than planar technology.

-3D-Single Type Column (3D-STC) detectors are a simplified version of 3D sensors under investigation by the RD50 Collaboration

-Have three dimensional (3D) n electrodes penetrating the p-type silicon substrate.

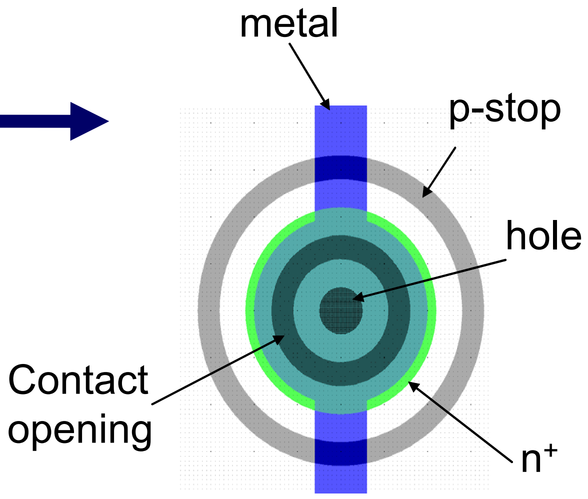
(C. Piemonte et al., NIM A541 (2005) 441)



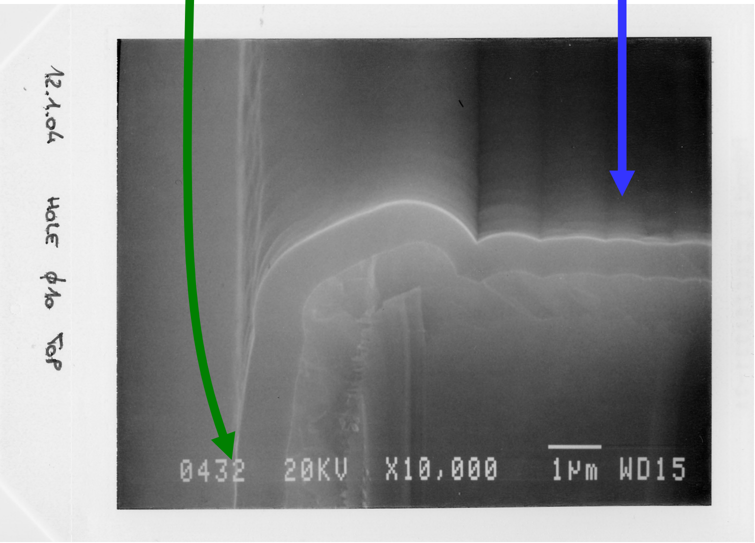


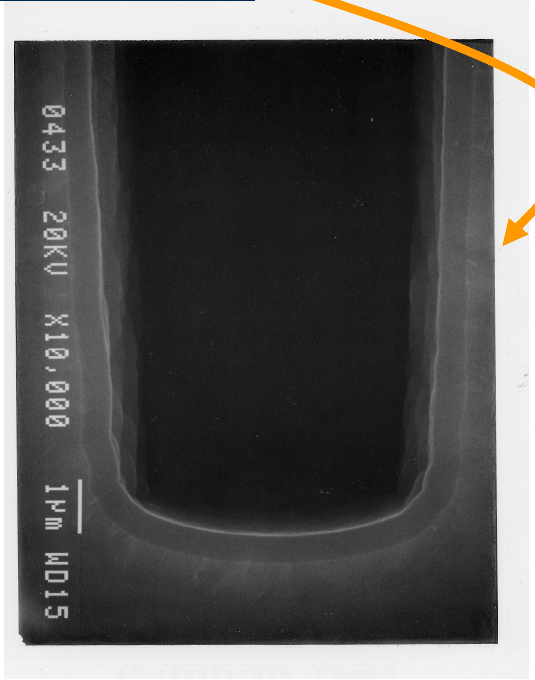
New detector structures: 3D-Single Type Column

- Detector masks: ITC-irst, (Italy)
- Deep reaction ion etching: CNM (Spain)
- Detector processing: ITC-irst (Itay)

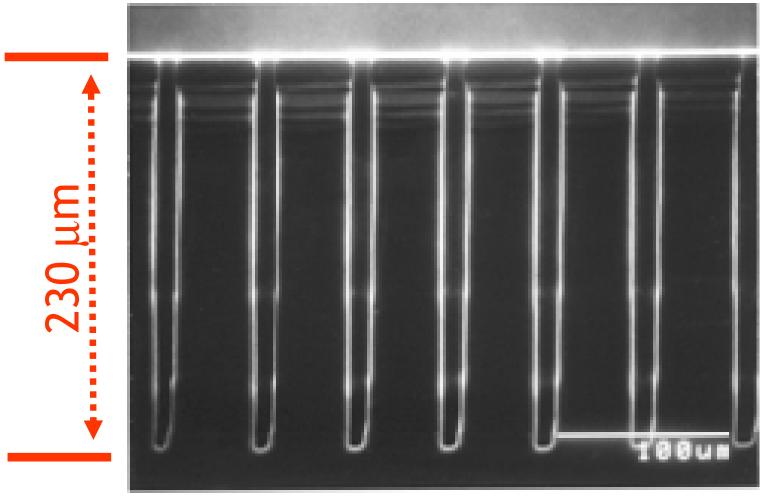


	Surface	Top	Botton
Poly	1.05µm	0.8µm	0.7µm
TEOS	0.96µm	0.7µm	0.6 µm





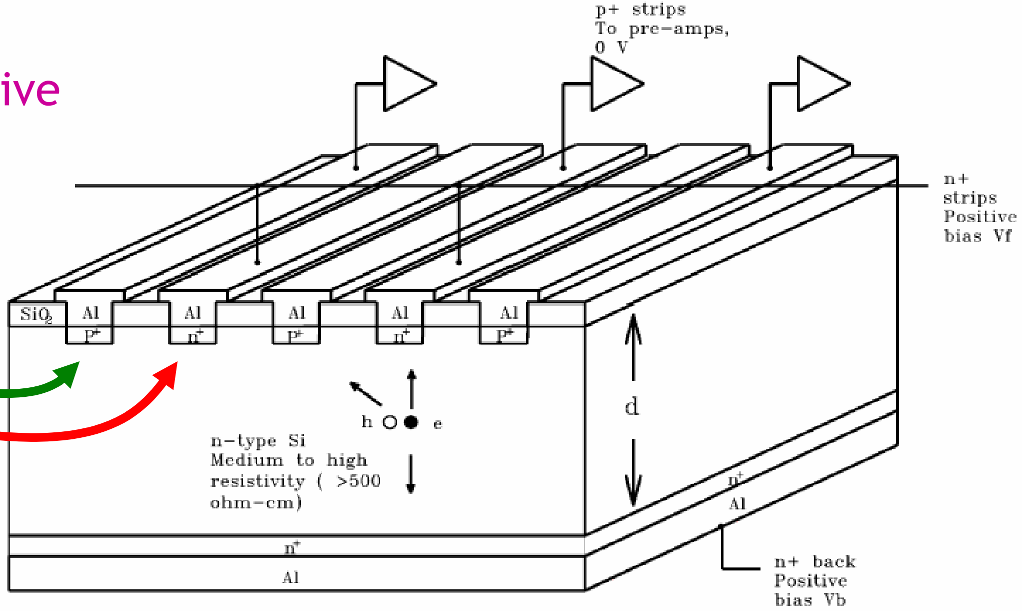
Hole diameter 10 µm



New detector structures: Semi-3D

Proposed by Z. Li (NIM A478 (2002) 303).

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

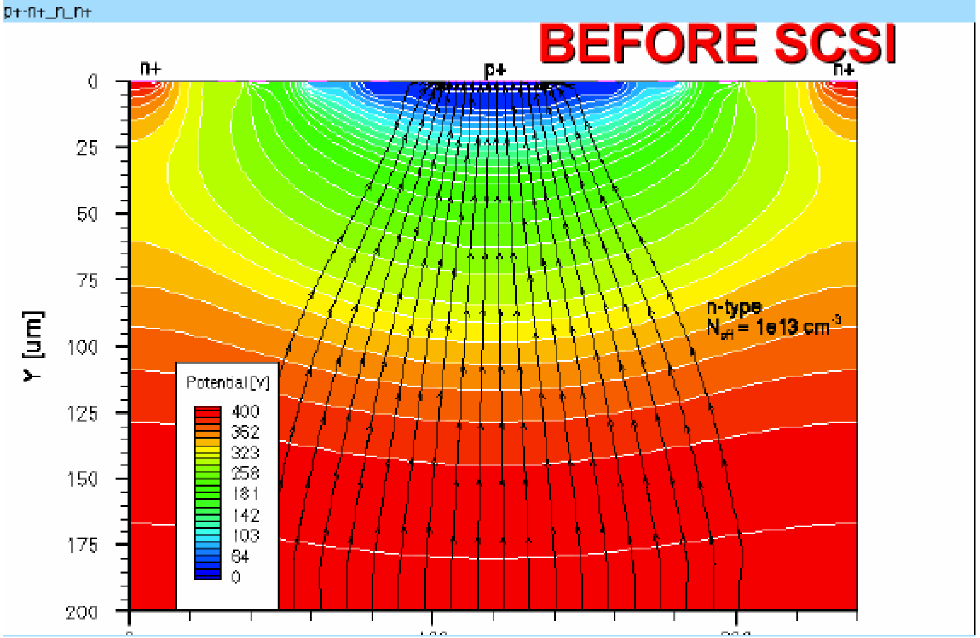


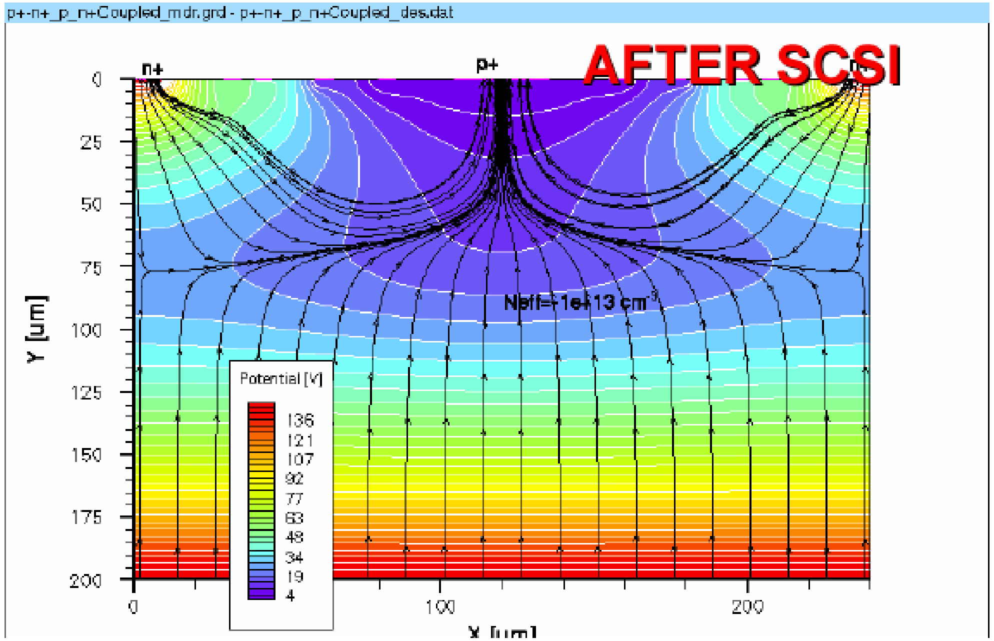
Advantages:

1. Single-side detector process.
2. After $N_{eff}<0$, 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)

Summary

General considerations:

1. **Charge collection** at Super-LHC fluences ($\geq 4\text{-}6\times10^{15}$ cm^{-2}) is **limited by carrier mean free path** and for planar technologies is less dependent on detector thickness W.
2. Benefits from **W decrease**: 1) $\mathbf{I_{leak}\propto W}$; B) $\mathbf{V_{dep}\propto W^2}$.
3. **High [O]** required for limiting V_{dep} increase after irradiation thanks to **donor generation** and **mitigation** of **deep acceptor creation**.

Different technologies are under investigation in the CERN RD50 Collaboration:

1. **CZ** and **MCZ** silicon take advantage from higher [O] than FZ and DOFZ.
2. **TMAH-Thinned devices** (50-100 μm) take advantage from $V_{dep}\propto W^2$, but small area sensors are available.
3. **Thin** (25, 50, 75 μm) **epitaxial layer on CZ substrate** takes advantage from $V_{dep}\propto W^2$ and high [O]. Large area sensors. Possible to increase the thickness to 100-150 μm to increase the charge collection.
4. **Pre-irradiated silicon**: V_{dep} increase mitigated after neutron irradiation (never observed for oxygenated silicon).
5. **P-type substrate devices** (see the paper).

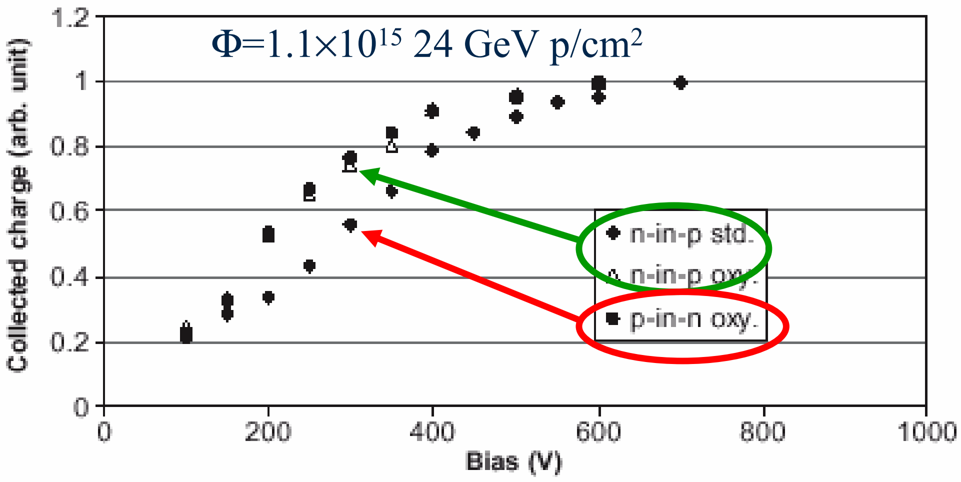
Different detector layouts are under investigation beyond pixel and microstrip:

1. **3D-STC** (3D detector with Single Type Column), **Semi-3D** (V_{dep} lower by a factor 2.5, but complex electric field after SCSI), **3D** and **Stripixel** (see the paper).

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

P-type substrate detectors

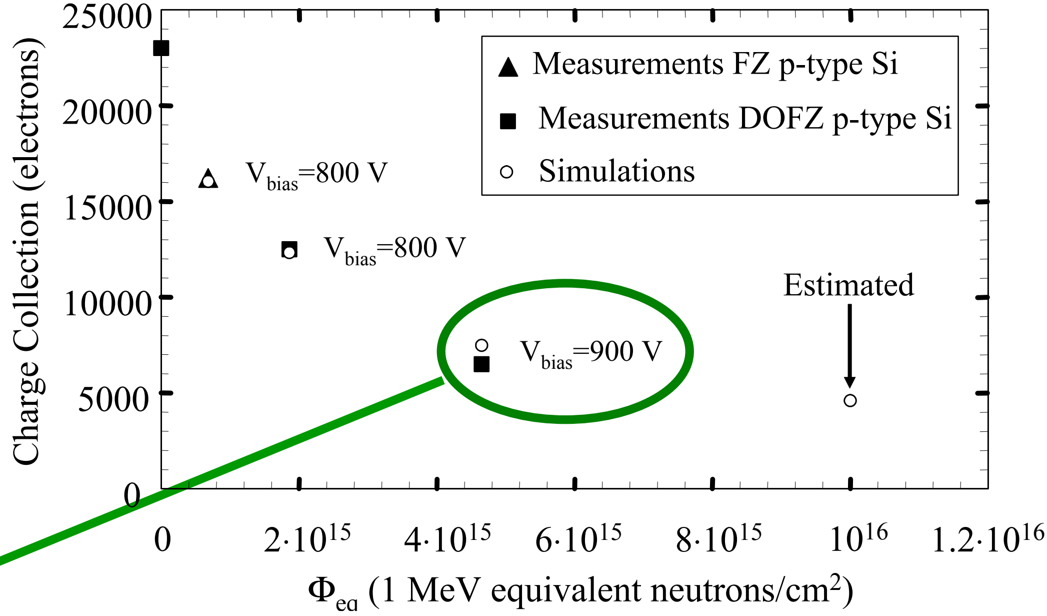
(G. Casse et al., NIM A518 (2004) 340 and NIM A535 (2004) 362)



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
Simulations ("3 level model", M .Petasecca et al., NIM A546 (2005) 291) in agreement with measurements.



Charge, collected at 900 V bias after 7.5×10^{15} 24-GeV p/cm^2 (5.3×10^{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).

Stripixel detectors

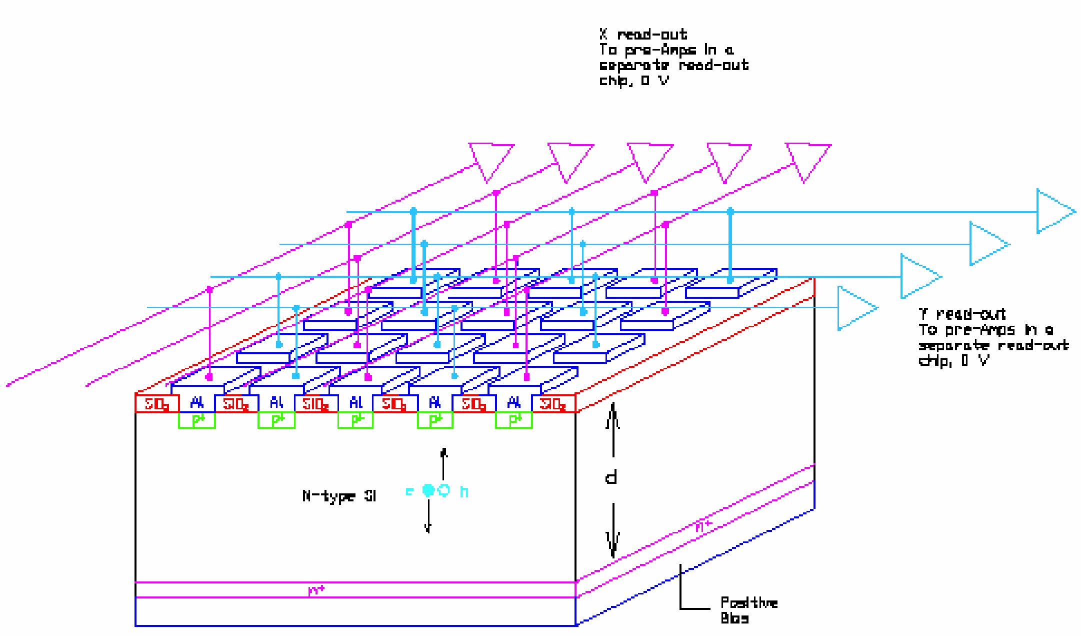
Proposed by Z. Li (NIM A 518 (2004) 738).

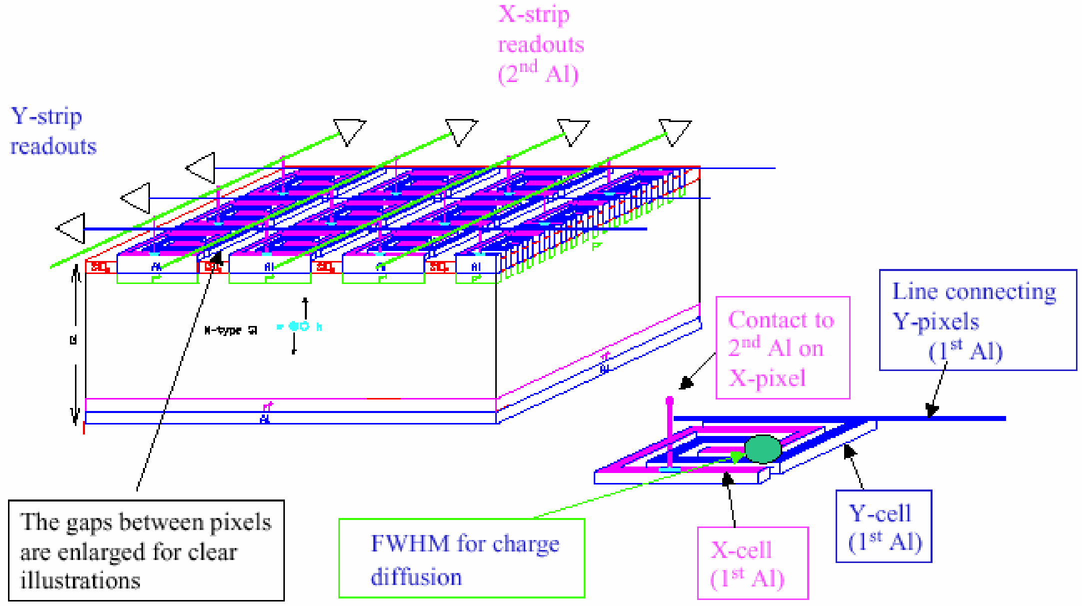
Pixel electrodes arranged in a projective X-Y readout.

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 ($\approx$10 μm).

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





Alternative to macro-pixel detectors in the Super-LHC upgrade between 15 cm and 60 cm.

Approach for silicon tracker upgrade

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

The current detector technologies can operate up to $\approx10^{15}$ 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