Development of radiation tolerant silicon detectors for the SLHC

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http://www.cern.ch/rd50

The RD50 CERN Collaboration

Development of Radiation Hard Semiconductor Devices for High Luminosity Colliders

http://rd50.web.cern.ch/rd50/

- **Collaboration formed in November 2001**
- **Experiment approved as RD50 by CERN in June 2002**
- **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)

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Main Objective

- Development of ultra-radiation hard semiconductor detectors for the luminosity upgrade of the LHC to 10^{35} $cm^{-2}s^{-1}$ (“Super-LHC”)

Challenges

- Radiation hardness up to 10^{16} cm^{-2} required
- Fast signal collection (10 ns bunch crossing)
- Low mass (reducing multiple scattering close to interaction point)
- Cost effectiveness

RD50 Scientific Strategies

Material Engineering

- **Defect and Material Characterisation**
- **Defect engineering of silicon**
  - DOFZ
  - MCz and Cz
  - Pre irradiated
  - Epi silicon
- **New detector materials**
  - SiC,…

Device Engineering

- **Improvement of present planar detector structures**
  - p-on-n
  - thin detectors
- **New detector**
  - 3D detectors (semi 3D, STC-3D …)
  - stripxel
- **cost effective detectors**
- **Tests of LHC-like detector systems produced with radiation-hard technology**

Silicon Material

	Symbol	$\rho(\Omega cm)$	$[O_i]$ (cm^{-3})
Standard n-or p-type FZ	StFZ	$1–7\times10^3$	$< 5\times10^{16}$
Diffusion oxygenated FZ, n-or p-type	DOFZ	$1–7\times10^3$	$\sim 1–2\times10^{17}$
Czochralski Sumitomo, Japan	Cz	$\sim 1\times10^3$	$\sim 8\text{-}9\times10^{17}$
Magnetic Czochralski Okmetic, Finnland	MCz	$\sim 1\times10^3$	$\sim 4\text{-}9\times10^{17}$
Epitaxial layers on Cz-substrates, ITME	EPI	50 -150	1×10^{17}

Cz silicon

- Cz wafers cheaper than FZ

EPI silicon

- Recently available various thickness p and n-type

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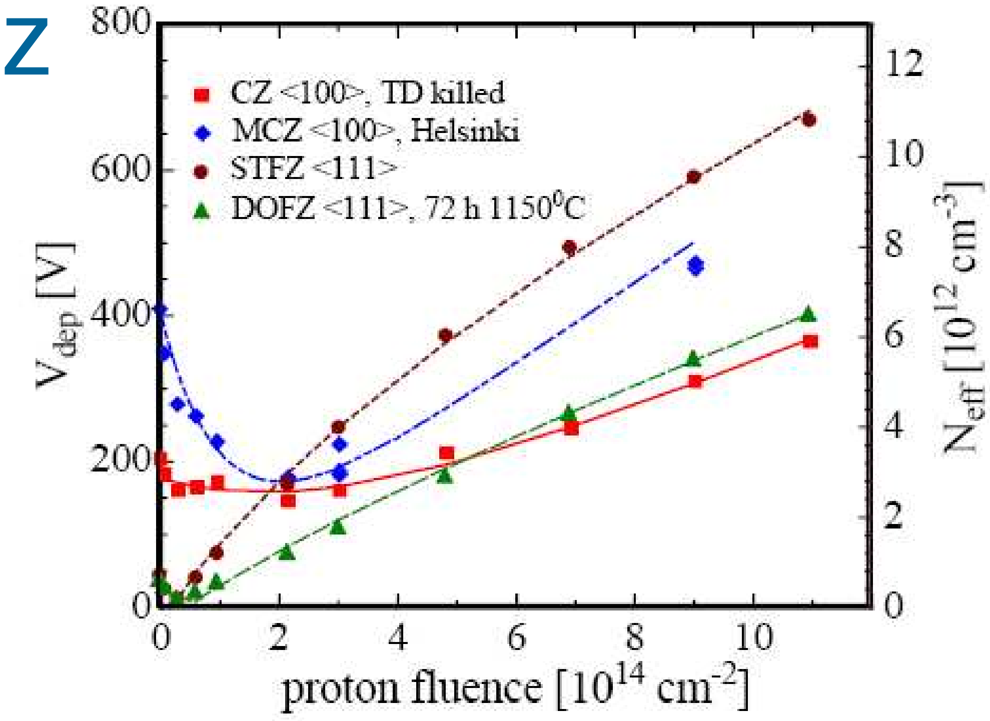
FZ, DOFZ, Cz, MCz



24 GeV/c proton irradiation

Standard FZ silicon

- type inversion at ~ 2x10^{13} p/cm^2
- strong N_{eff} increase at high fluence

Oxygenated FZ (DOFZ)

- type inversion at ~ 2x10^{13} p/cm^2
- reduced N_{eff} increase at high fluence

Cz silicon and MCz silicon

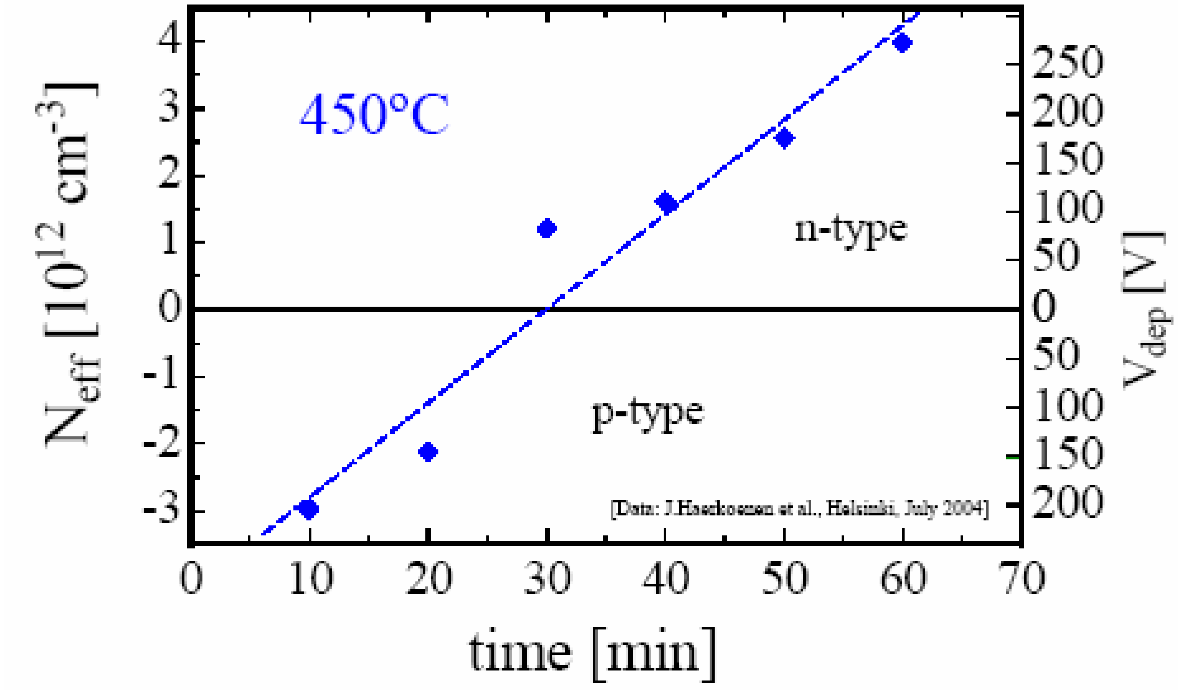
- no type inversion for charged hadron irradiation in the overall fluence range
  ⇒ donor generation overcompensates acceptor generation in high fluence range

Common to all materials:

- same reverse current increase
- same increase of trapping (electrons and holes) within ~ 20%

MCz Silicon from p- to n-type

- **Thermal Donor generation due to heat treatment at 450ºC**
- **Effective doping concentration (V_{dep}) can be tailored**



starting with p-type material and converting it to n-type

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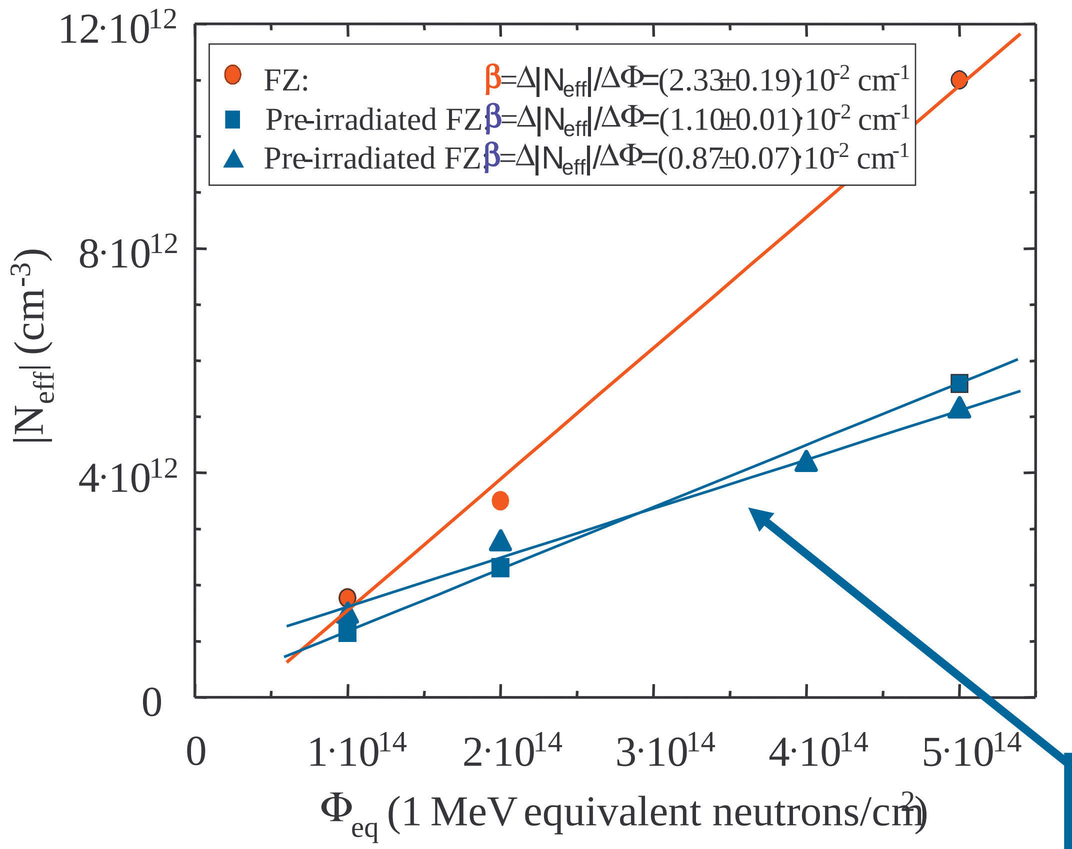
Pre-irradiated silicon

P. G. Litovchenko et al., 10th European Symposium on Semiconductor Detectors Wildbad Kreuth,, 12-16 June 2005



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

Pre-irradiation = 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 T~ 850 ºC (2 hours)

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

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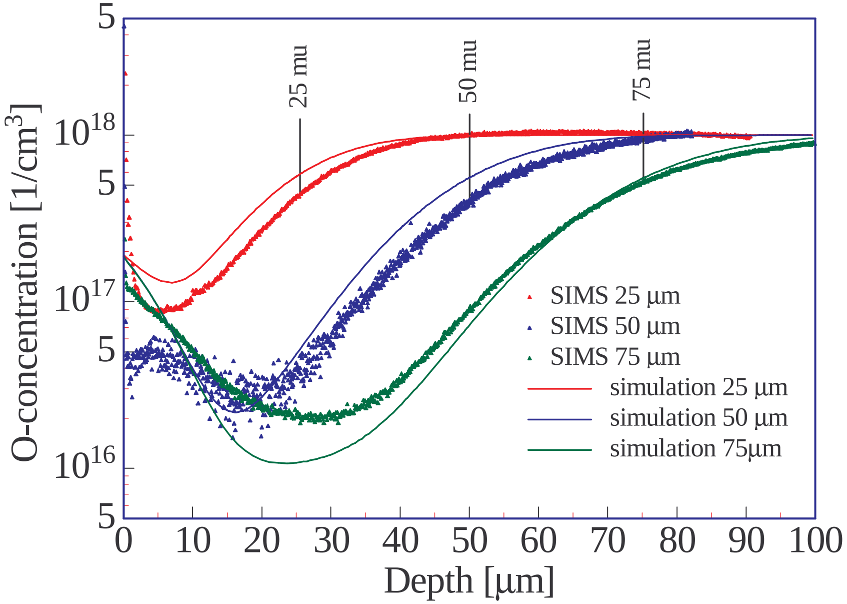
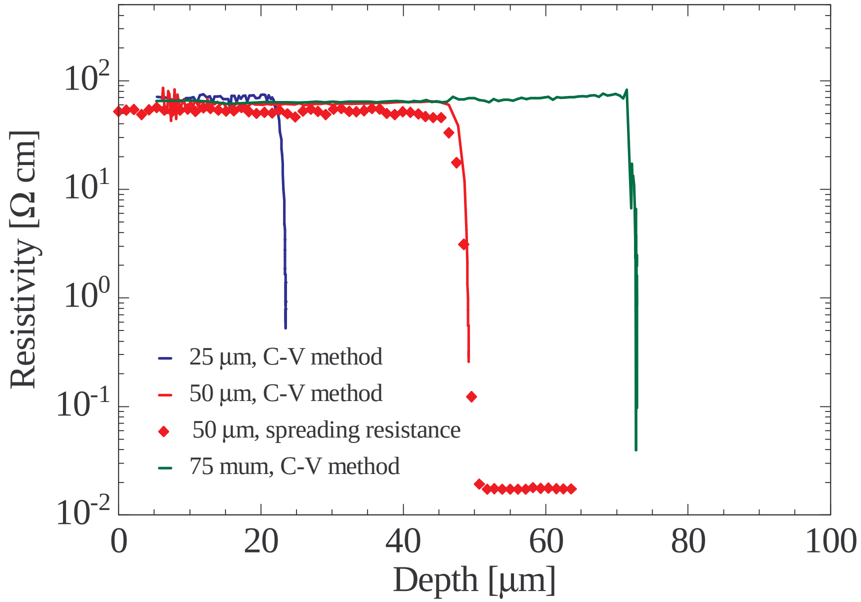
Epi silicon: material characterization

G. Lindström, 10th European Symposium on Semiconductor Detectors, Wildbad Kreuth,12-16 June 2005





Ø **Oxygen depth profiles**

SIMS-measurements after diode processing

O diffusion from substrate into epi-layer

(SIMS-measurements: A. Barcz/ITME, Simulations: L. Long/CiS)

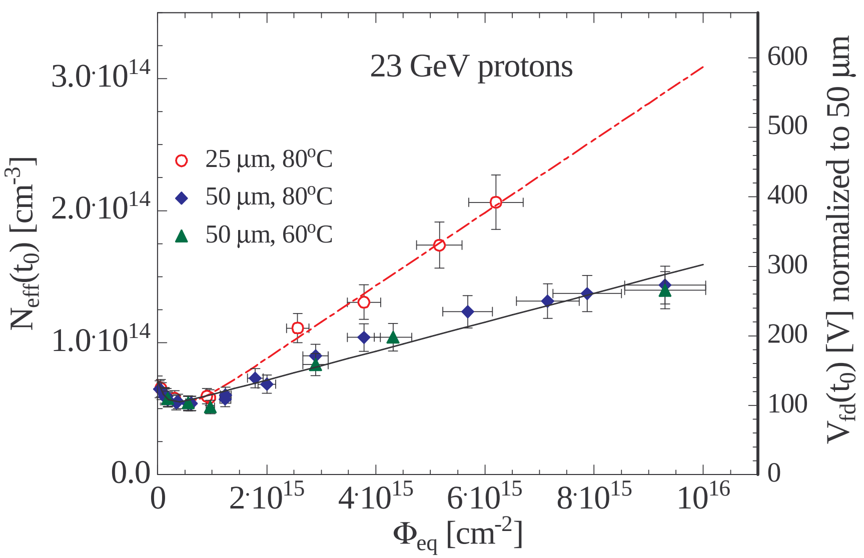
Ø **Resistivity profiles**

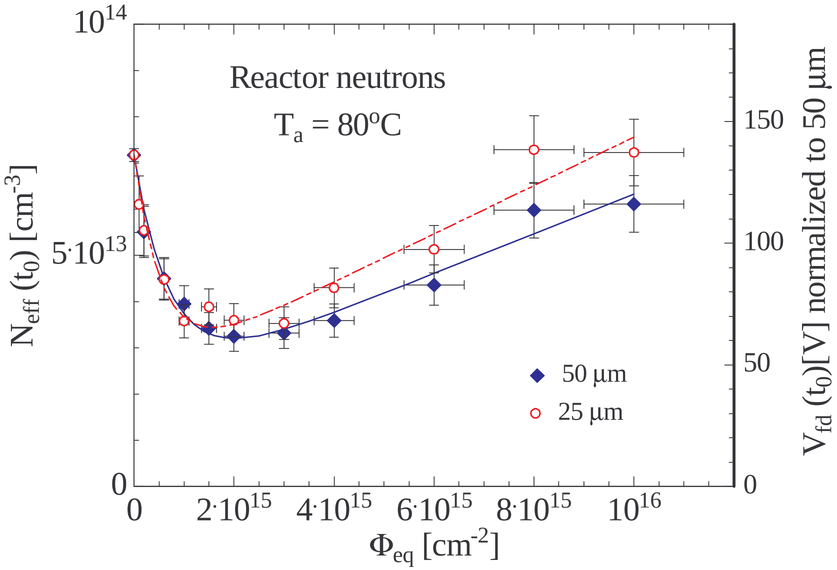
Excellent homogeneity in epi-layers

(SR-measurements: E. Nossarzewska, ITME)

Epi silicon: proton and neutron irradiated

G. Lindström, 10th European Symposium on Semiconductor Detectors, Wildbad Kreuth,12-16 June 2005





No space charge sign inversion after proton and neutron irradiation
Introduction of shallow donors overcompensates creation of acceptors

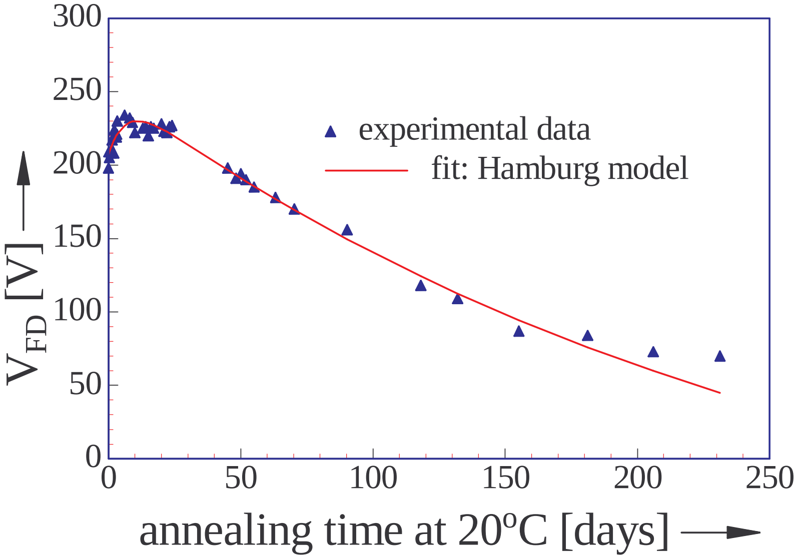
Ø Protons: Stronger increase for 25 µm compared to 50 µm
à higher [O] and possibly [O2] in 25 µm (see SIMS profiles)

Ø Neutrons: Similar effect but not nearly as pronounced
most probably due to less generation of shallow donors
and as strong influence of acceptors

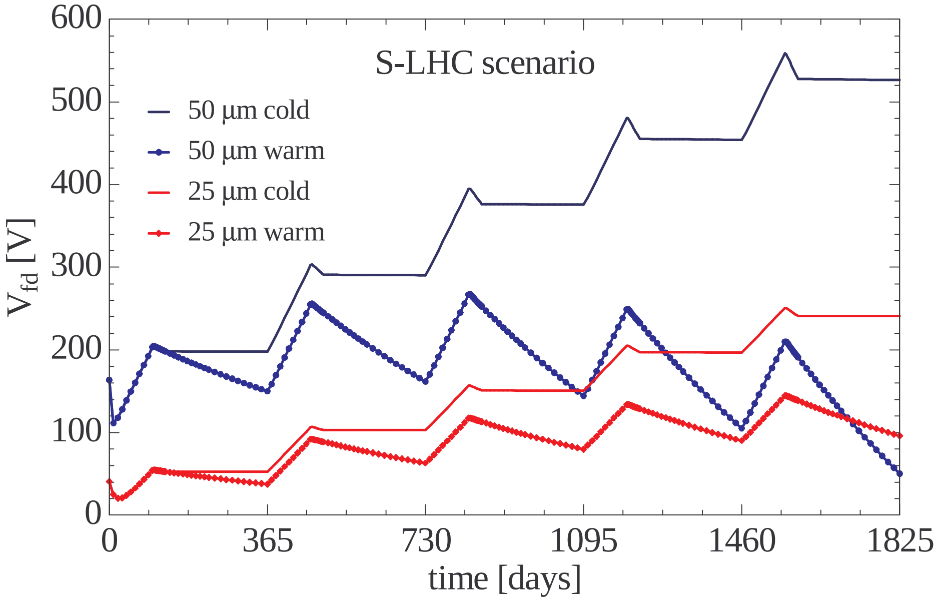
Epi silicon: S-LHC scenario

G. Lindström, 10th European Symposium on Semiconductor Detectors, Wildbad Kreuth,12-16 June 2005

Example: EPI 50 µm, Φp = 1.01·10^{16} cm^{-2}



20℃ annealing results can be fitted with Hamburg model



Ø RT storage during beam off periods extremely beneficial

Ø Damage during operation at -7℃ compensated by 100 d RT annealing

Ø Depletion voltage for full SLHC period less than 300 V

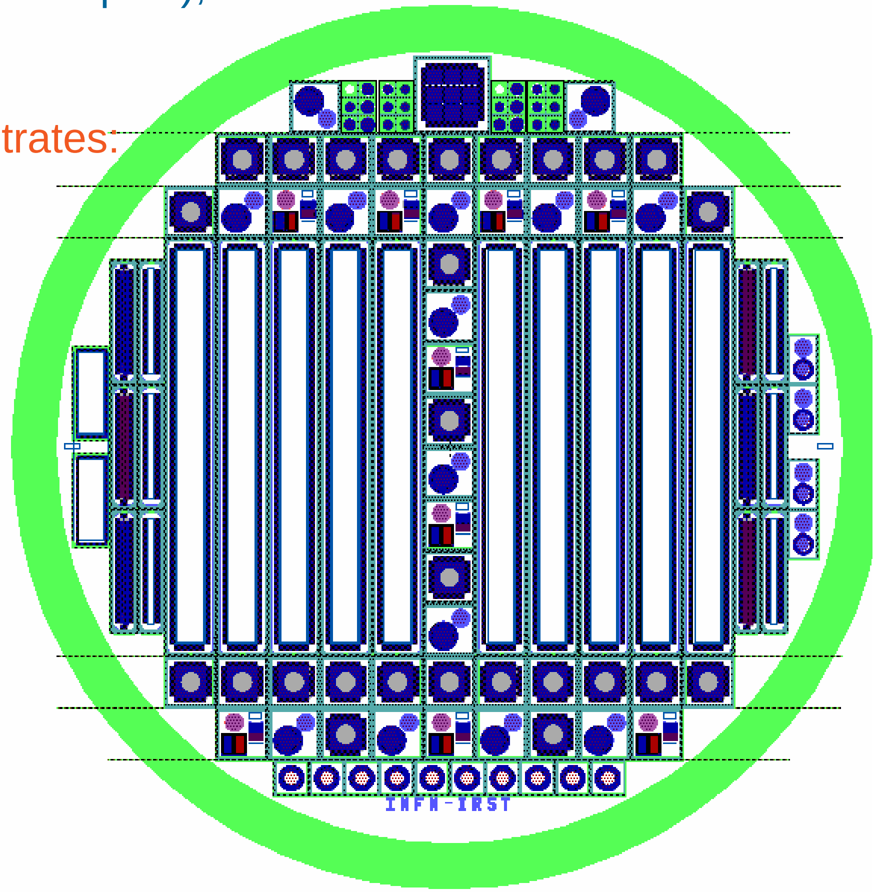
SMART - Italian RD50 group

Layout

10 mini-strip (0.6x4.7cm^2, 50 and 100 μm pitch, AC coupled),
37 pad diodes and various test structures

Wafers processed by IRST, Trento on silicon substrates:

Fz	n-type 6 kΩ-cm <111> p-type >5000Ωcm <100> 200μm
MCz	n-type >500Ω-cm <100> p-type >1.8kΩcm <100>
Cz	n-type >900Ω-cm <100>
Epi	n-type ~50Ω-cm <100> (50 μm)



See following presentations by

Monica Scaringella (Firenze)
and
Valeria Radicci (Bari)

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n-on-p detector

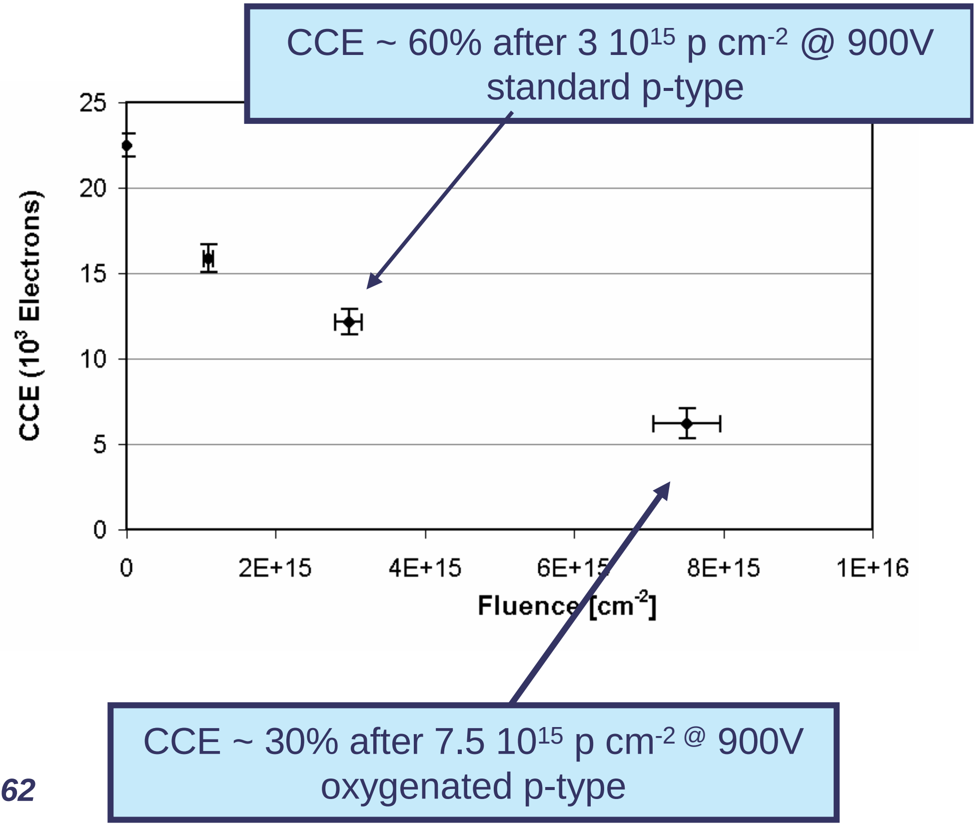
Ø no type inversion,
Ø high electric field stays on structured side,
Ø collection of electrons

q Miniature n-in-p microstrip detectors (280mm thick)

q Detectors read-out with a SCT128A LHC speed (40MHz) chip

q Material: standard p-type and oxygenated (DOFZ) p-type

q Irradiation 24GeV protons



CCE ~ 60% after 3 10^{15} p cm^{-2} @ 900V standard p-type

CCE ~ 30% after 7.5 10^{15} p cm^{-2} @ 900V oxygenated p-type

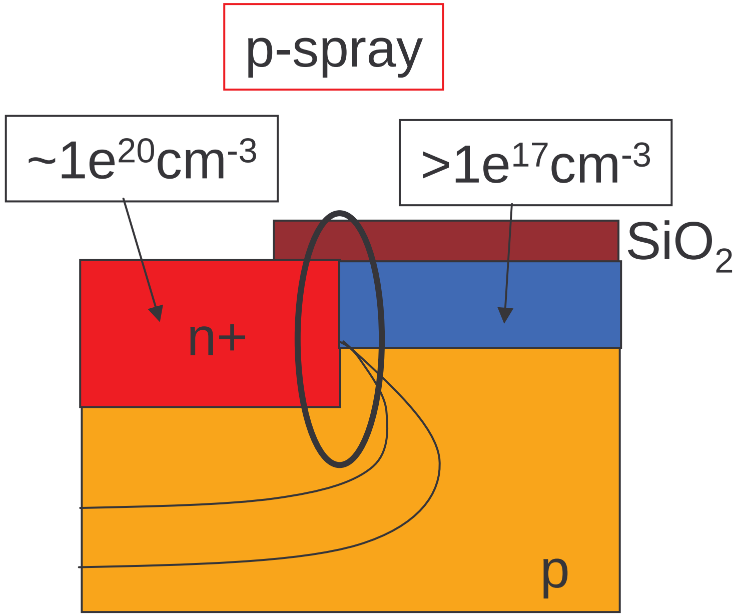
G. Casse et al., NIM A518 (2004) 340 and NIM A535 (2004) 362

n-on-p detector technology

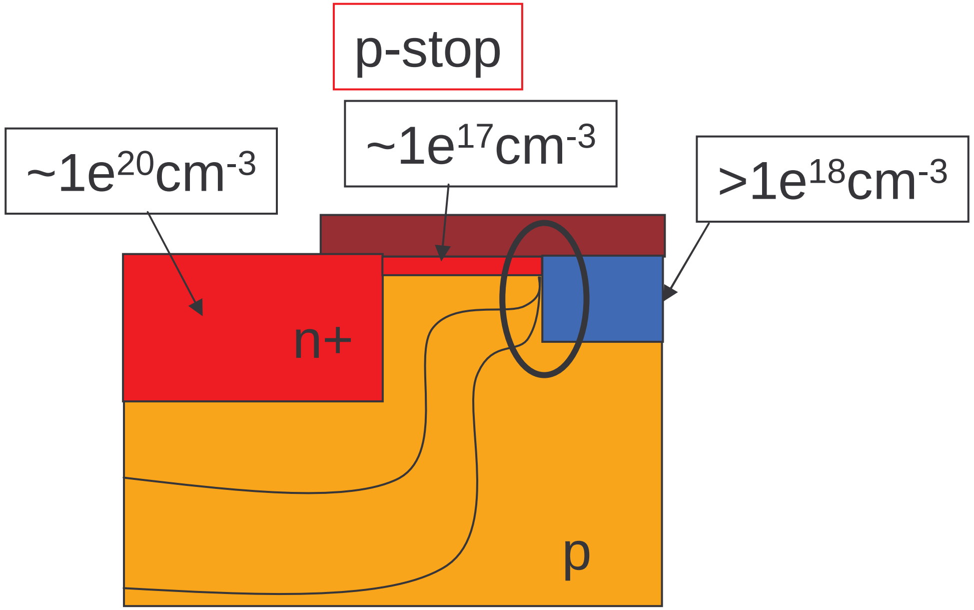
C. Piemonte el al, 5th RD50 workshop 2004

n-on-p detector requires an isolation implant between n+ structures

- p-stop
- p-spray *(should be implanted with a slightly lower dose),*
- moderated p-spray *(“combination” between p-stop and p-spray)*



better after irradiation



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Thin Detector

G. Kramberger, Simulation of signal in irradiated silicon detectors for SLHCVertex 2004, Sep., 2004

Why thin detectors?

W is the thickness of the detector active layer

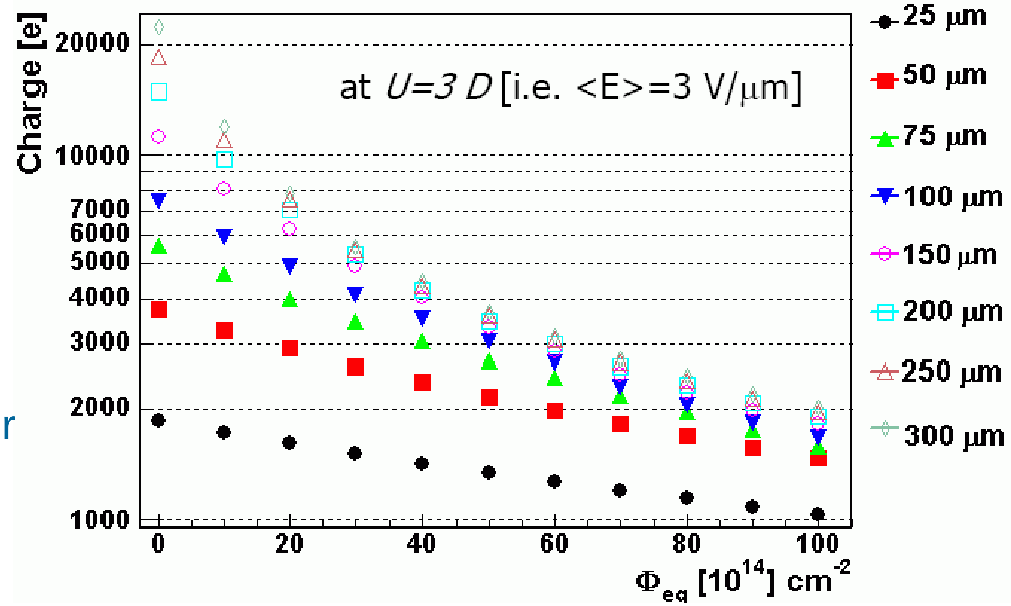
- Smaller leakage current: $I_{leak} \propto W$
- Smaller depletion voltage: $V_{dep} \propto W^2$
- At Super-LHC fluences, charge collection is limited by charge trapping, i.e. by reduced carrier mean free path, not by detector thickness

Advantage

- can be fully depleted
- less material in the vertex region

Drawback

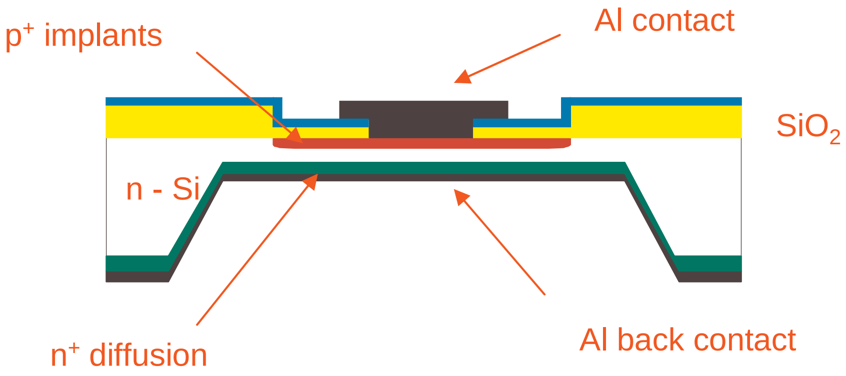
- capacitance to the back-plane is larger
- much more difficult to handle
- worse performance in initial period



Thin Detector: technology

Silicon Etch ITC-irst Trento Italy

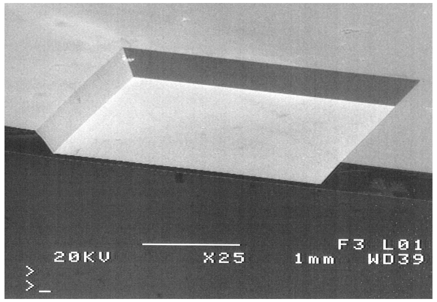
- technology based on local silicon thinning
- wet anisotropic silicon etchant TMAH



S.. Ronchin et al., NIM A530 (2004) 134

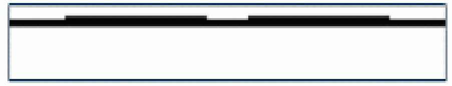
Irradiated with Li-ion at 1 x 10^{13} Li/cm^2

- the 50 µm V_{dep} does not exceed 6 V
- for 300 µm thick sensors V_{dep}=230 V

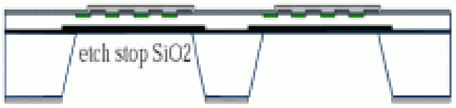


Wafer bonding
MPI Munich Germany

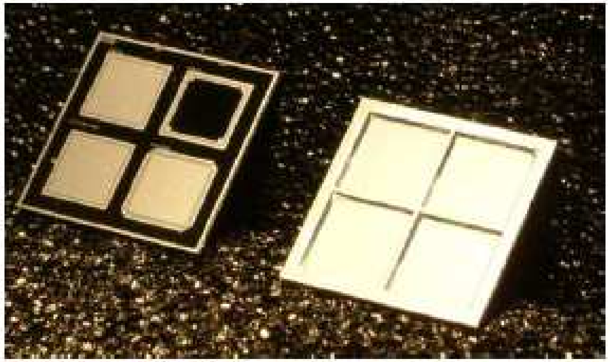
L. Andricek et al.,
TNS 51 (2004) 1117



b) wafer bonding and grinding/polishing of top wafer



d) anisotropic deep etching opens "windows" in handle wafer



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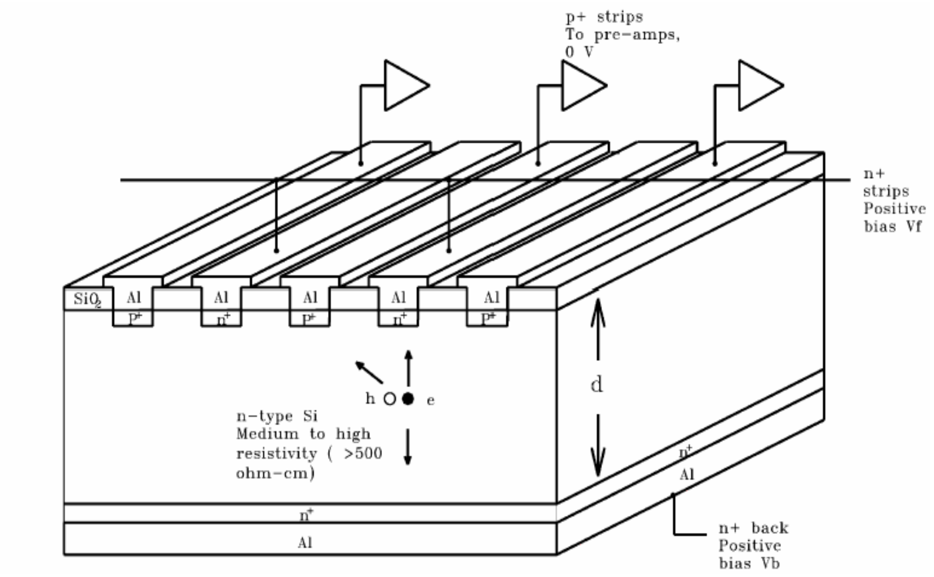
Semi-3D

Z. Li NIM A478 (2002) 303

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



Advantages:

- Single-side detector process.
- After $N_{eff}<0$, the depletion occurs from both sides reducing the depletion voltage.

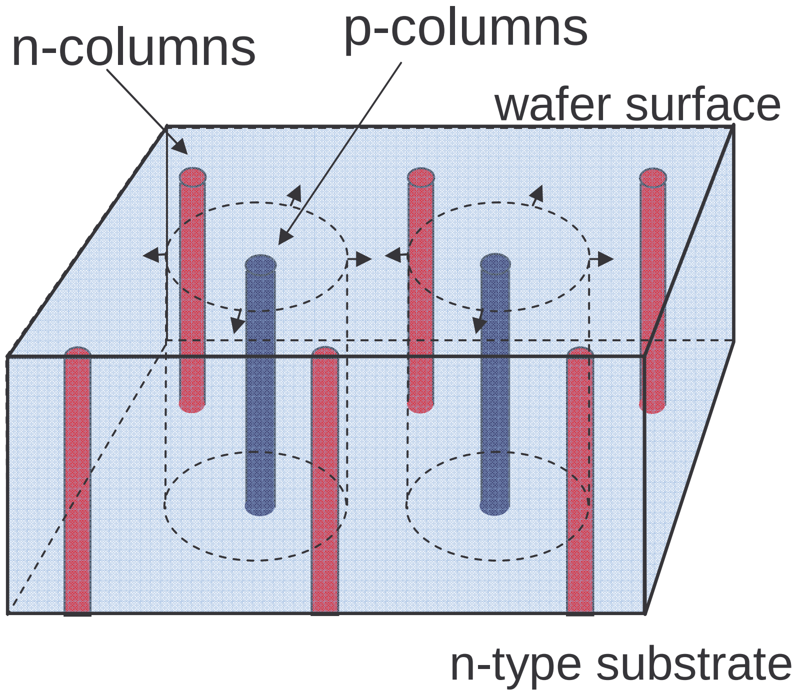
Under investigation

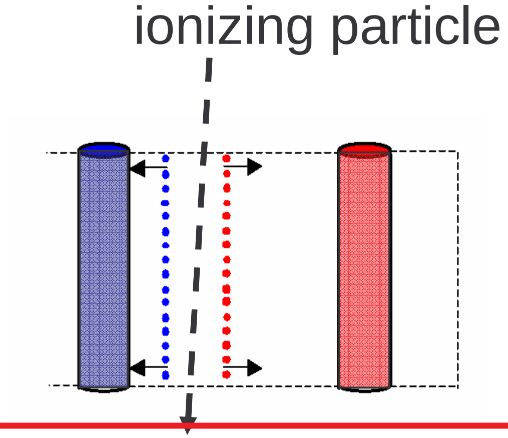
- Complex electric field distribution before and after SCSI.

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

3D detectors: concept

S.I. Parker, C.J. Kenney, J. Segal, Nucl. Instr. Meth. Phys. Res. A 395 (1997) 328





Short distance between electrodes:

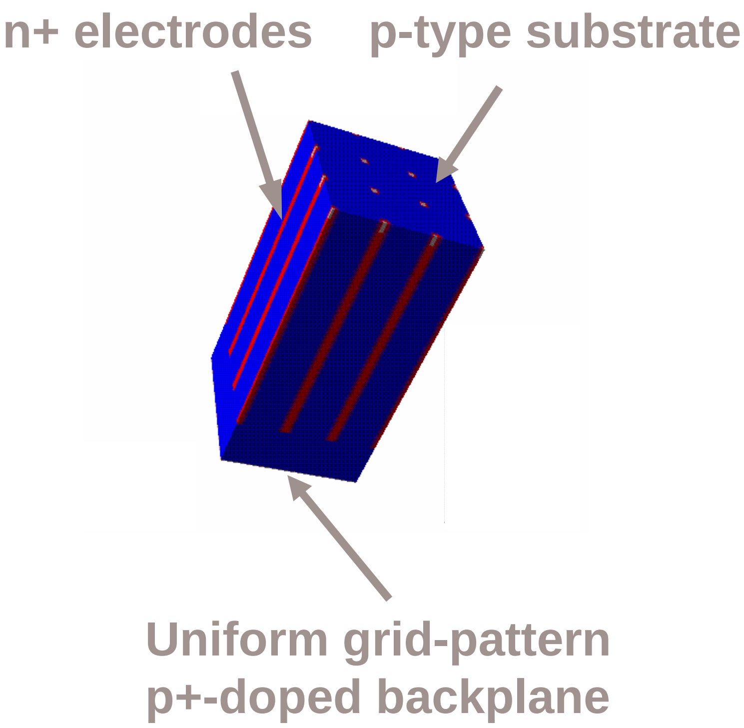
- low full depletion voltage
- short collection distance

➡ more radiation tolerant than planar detectors!!

DRAWBACK: Fabrication process rather long and not standard => mass production of 3D devices very critical and very expensive.

3D-stc detectors proposed at ITC-irst

C. Piemonte, et al. NIM A 541 (2005) 441



Single-Type-Column

- Etching and column doping performed only once
- Holes not etched all trough the wafer
  - bulk contact is provided by a backside uniform p$^+$ implant (single side process)
- No hole filling

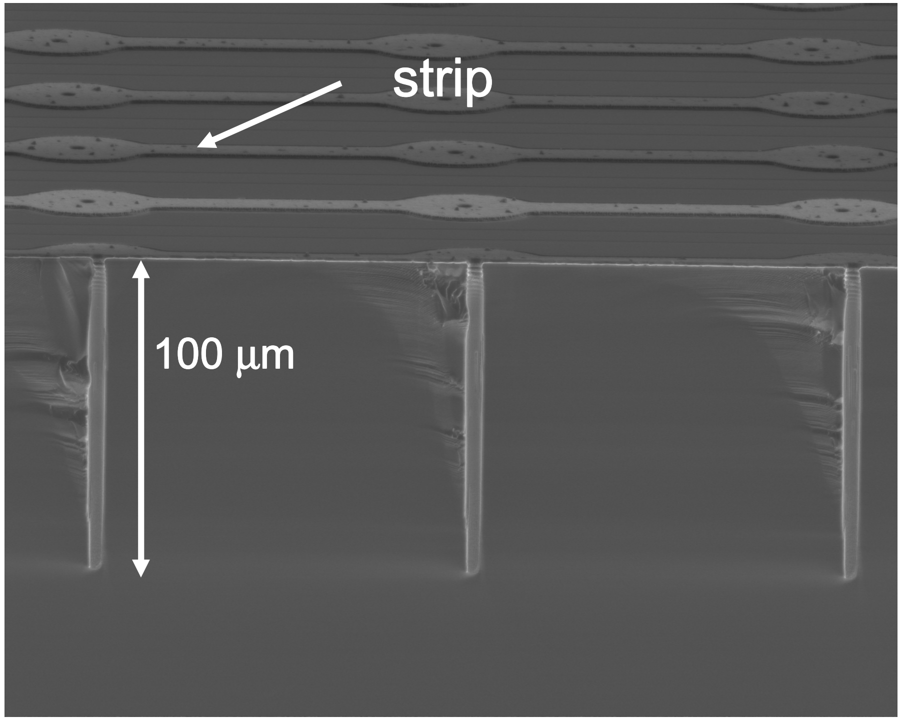
⬇

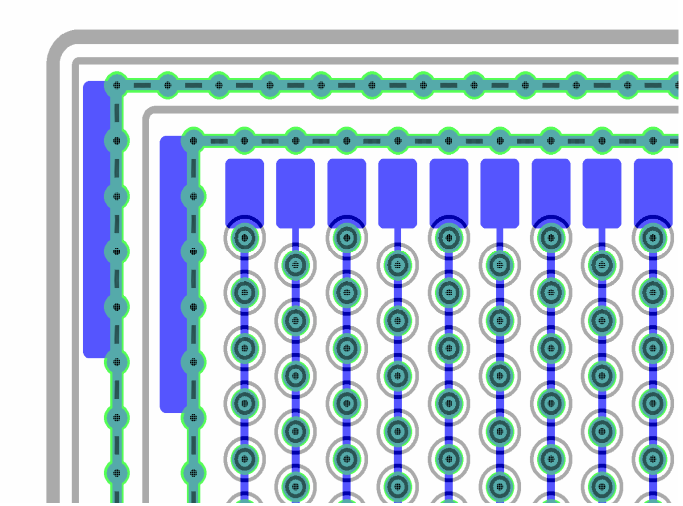
Process simplification

3D-stc detectors proposed at ITC-irst

3D - stc layout

- AC and DC coupling
- Inter-columns pitch 80-100 μm
- Two different p-stop layouts and p-spray
- Holes Ø 6 or 10 μm





average current per column < 1pA

See following presentation by

Alberto Pozza (Trento)

SUMMARY

Outer layers of a SLHC detector main problem:

 ¤ the change of the depletion voltage

 ¤ the large area to be covered by detectors

n CZ and MCZ silicon detectors could be a cost-effective radiation hard solution (no type inversion, use p-in-n technology)

n oxygenated p-type silicon microstrip detectors show very encouraging results

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.

n TMAH-Thinned devices (50-100 µm) take advantage from Vdep$\propto$W2, but small area sensors are available.

n epitaxial up to 150 µm ; high [O], large area sensors, RT annealing

 ¤ drawback: radiation hard electronics for low signals needed

n 3D detectors drawback: technology has to be optimized

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