Recent Results on the Development of Ultra Radiation Hard Semiconductor Detectors for Very High Luminosity Colliders

Mara Bruzzi on behalf of the RD50 Collaboration

INFN, University of Florence, Italy

1. Motivations
2. The RD50 CERN Collaboration
3. Radiation effects in silicon detectors
4. Material Engineering
   - defect engineered Si
5. Planar devices with defect engineered Si
6. Device Engineering
   - Thin detectors: thinned and epitaxial
   - 3-D, Semi-3D and Stripixel detectors
7. Summary

1. Motivations

Large Scale Application of Si Detectors in LHC

Present working conditions:

$L \sim 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ in 10 years of LHC operation:

→ **$\phi \sim 10^{15}\ \mathrm{n/cm}^2$ for pixels**

$\phi \sim 10^{14}\ \mathrm{n/cm}^2$ for microstrips

LHC upgrade ("Super-LHC" … later than 2010)

$L \sim 10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ → **fluence up to $10^{16}\ \mathrm{cm}^{-2}$** ***after five years***

R&D needed for the development of a detector technology able to operate safely and efficiently in such an environment.

Anticipated Radiation Environment for Super LHC

Hadron fluence and radiation dose in different radial layers of the CMS tracker for an integrated luminosity of 2500fb^{-1} . (CERN-TH/2002-078)

Radius [cm]	Fluence of fast hadrons [cm^{-2}]	Dose [KGy]
4	1.6×10^{16}	4200
11	2.3×10^{15}	940
22	8.0×10^{14}	350
75	1.5×10^{14}	35
115	1.0×10^{14}	9.3

The tracker volume can be splitted into 3 radial regions:

1.	**R > 60cm**	**improved Si strip technology**
2.	**20cm < R < 60cm**	**improved hybrid pixel technology**
3.	**R < 20cm**	**new approaches and concepts required**

2. The RD50 CERN Collaboration

Development of Radiation Hard Semiconductor Devices for High Luminosity Colliders

- Collaboration formed in November 2001 - http://www.cern.ch/rd50
- Experiment approved as RD50 by CERN in June 2002
- 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").

- Presently 272 Members from 52 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, University of California Santa Cruz)

- **CMS groups in RD50:** Helsinki HIP, Karlsruhe University, Louvain University, INFN Bari-Florence-Perugia-Pisa, Purdue University, PSI-Villigen, Rutgers University..
- Several RD50 groups are within ATLAS, LHCb, ALICE, CDF and other experiments

Scientific strategies

- **Material Engineering**
  - **Defect and Material Characterisation**
  - **Defect Engineering of silicon**
  - **New detector materials (SiC, GaN ..)**

- **Device Engineering**

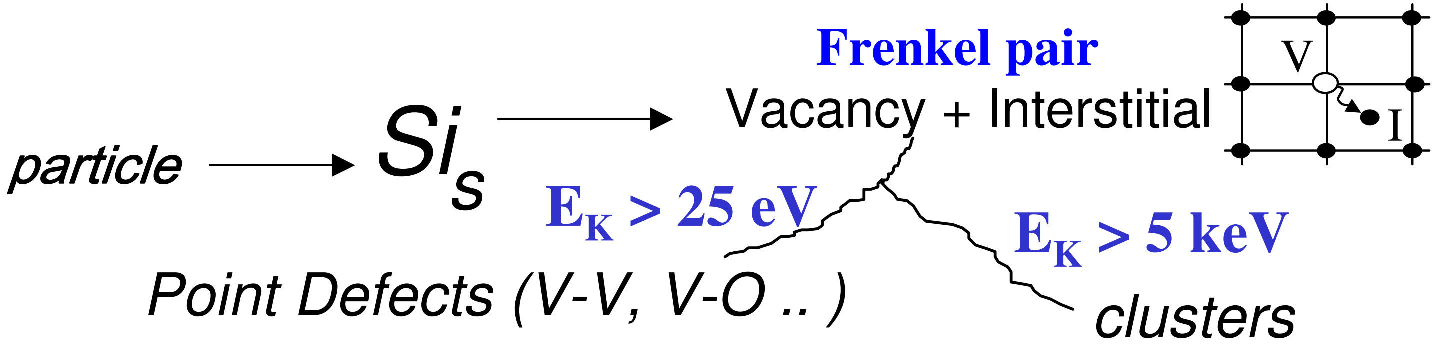
- Improvement of present planar detector structures (3D detectors, thin detectors, semi3-D, stripixel detectors,…)

- Tests of LHC-like detector systems produced with radiation-hard technology

- Variation of the operational conditions

3. Radiation effects in silicon detectors

Radiation Induced Microscopic Damage in Si



particle → Si_s →

Frenkel pair

Vacancy + Interstitial

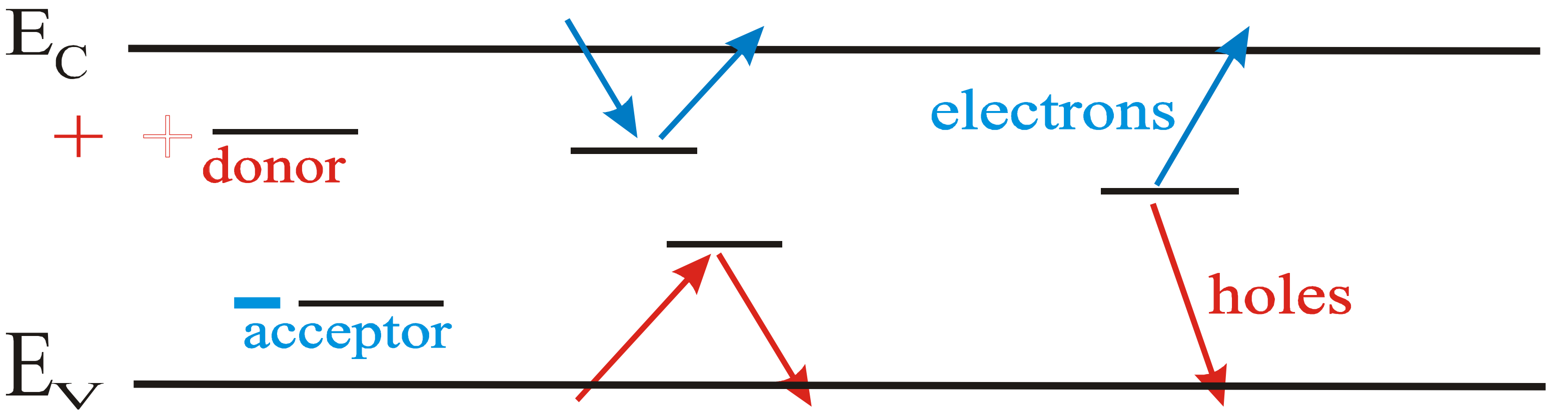
$E_K > 25$ eV

$E_K > 5$ keV

Point Defects (V-V, V-O ..)

clusters

Influence of defects on the material and device properties



charged defects

⇒ N_{eff} , V_{dep}

e.g. donors in upper and acceptors in lower half of band gap

Trapping (e and h)

⇒ **CCE**

shallow defects do not contribute at room temperature due to fast detrapping

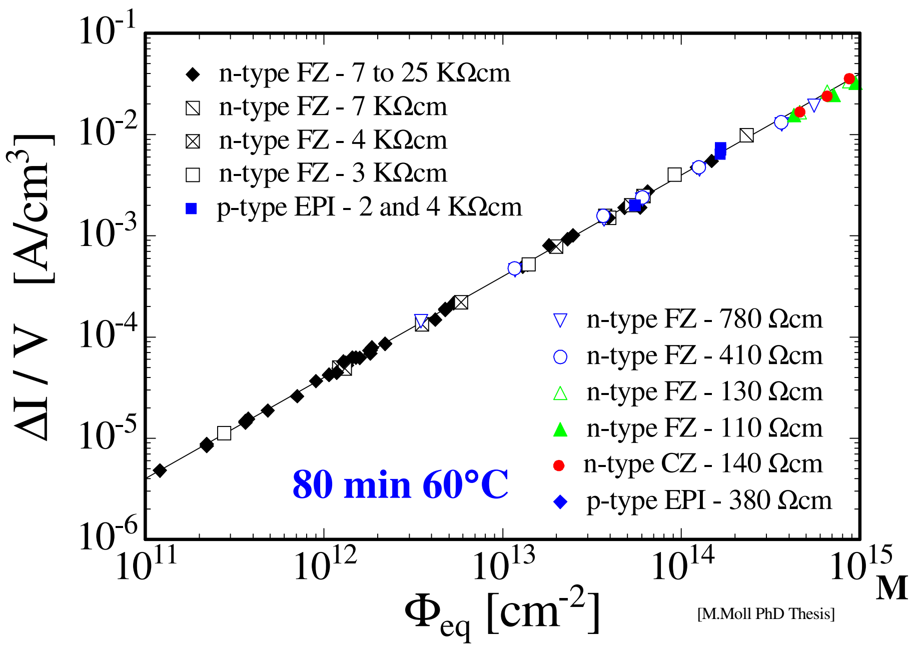
generation

⇒ **leakage current**

Levels close to midgap most effective

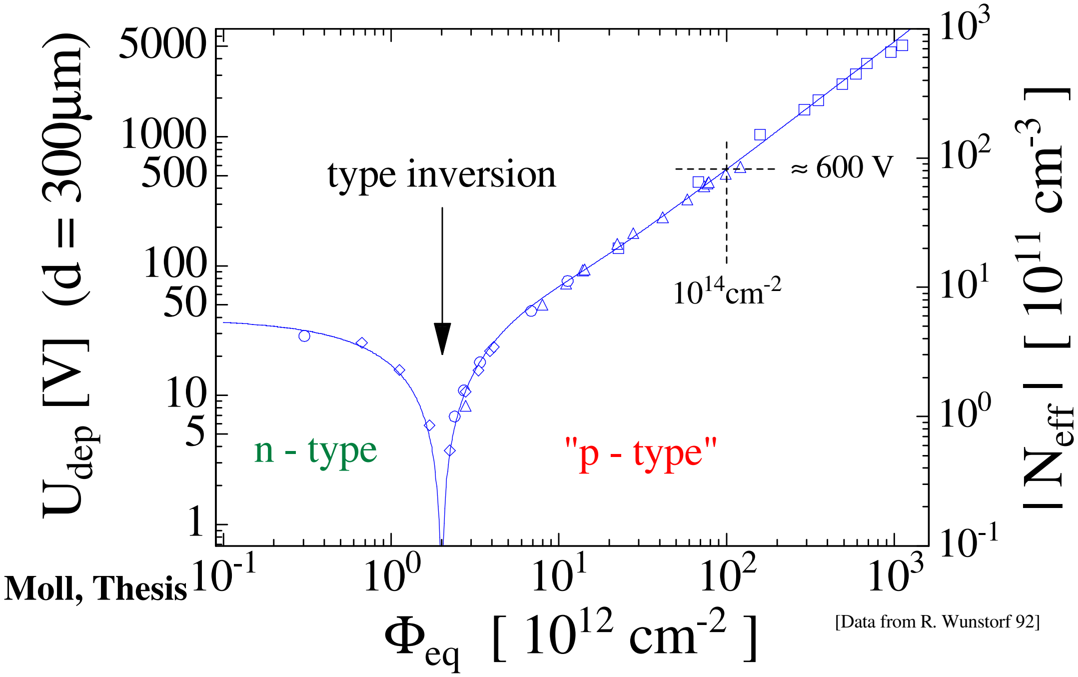
Macroscopic Radiation Damage in Si

Leakage Current



M. Moll, Thesis

Full Depletion Voltage



- **Damage parameter α (slope)**

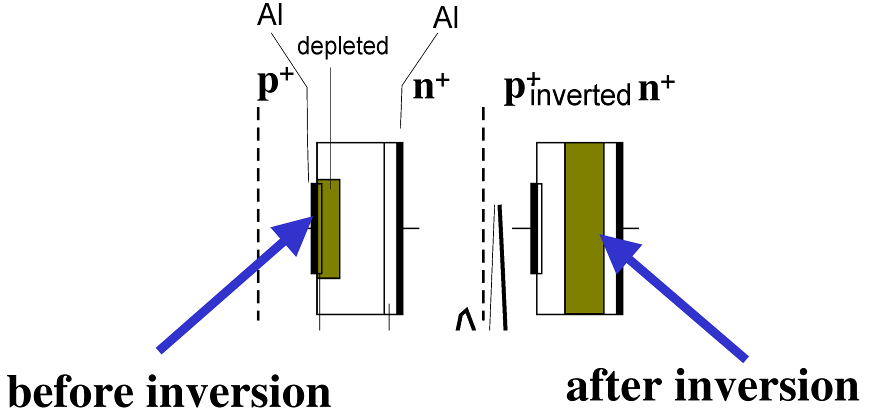
$$\boxed{\alpha = \frac{\Delta I}{V \cdot \Phi_{eq}}}$$

- **α independent of Φ_{eq} and impurities**

⇨ used for fluence calibration (NIEL-Hypothesis)

Type inversion:

SCSI – Space Charge Sign Inversion



V_{dep} and N_{eff} depends on storage time and temperature

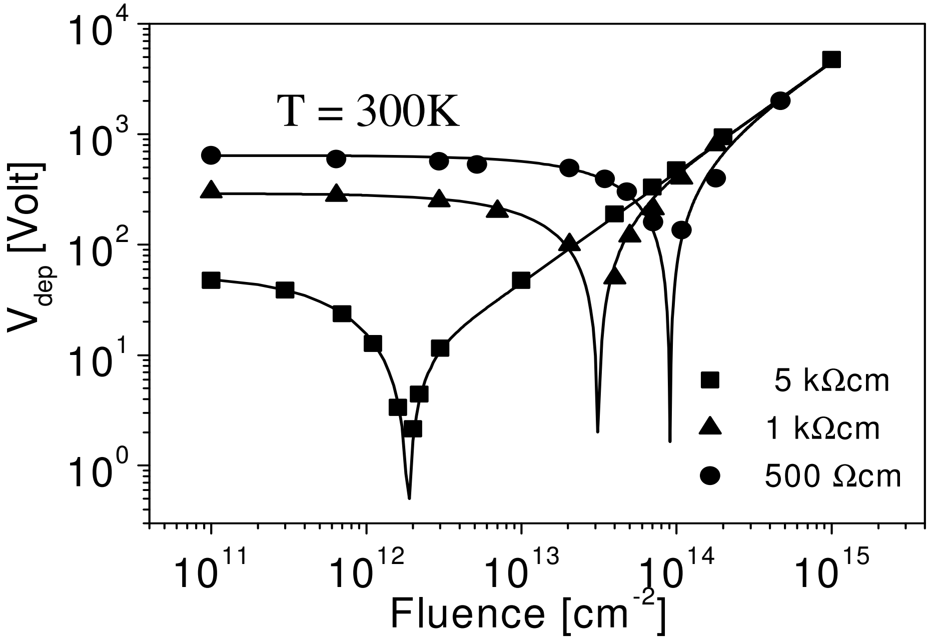
Stable Damage

$$\Delta N_{eff} = N_{C0}(1-e^{-c\cdot\phi}) + [g_c + g_a e^{-\frac{t}{\tau_a(T)}} + g_y(1-e^{-\frac{t}{\tau_y(T)}})]\phi$$

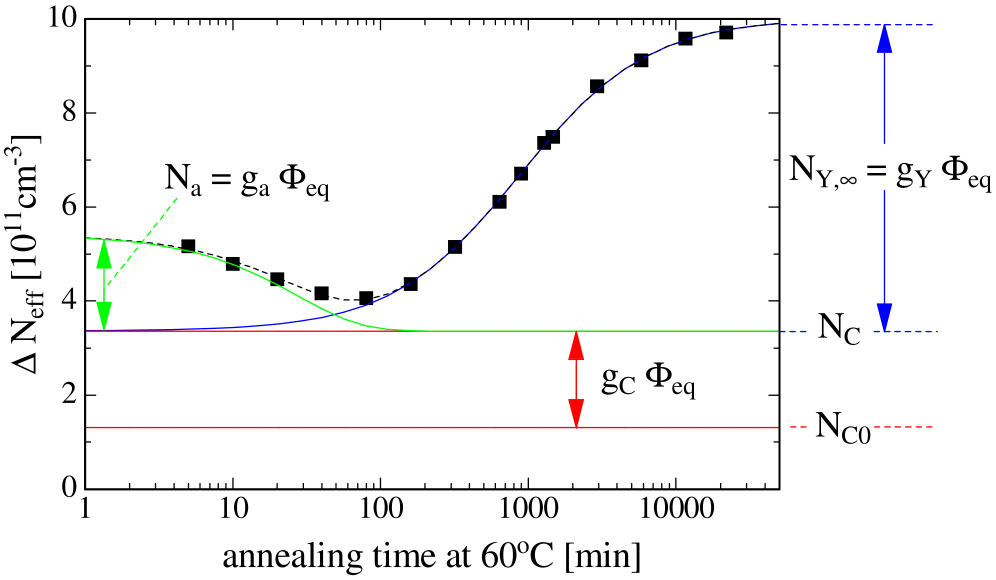
Beneficial Annealing

Reverse Annealing

ShallowDonor Removal



M. Bruzzi, Trans. Nucl. Sci. (2000)



G.Lindstroem et al, NIMA 426 (1999)

- **Short term:** “Beneficial annealing”
- **Long term:** “Reverse annealing”
  time constant : **~ 500 years (-10°C)**
  ~ 500 days (20°C)
  ~ 21 hours (60°C)

Charge Collection Efficiency

Limited by:

- **Partial depletion due to high V_{dep}**
- **Trapping at deep levels**
- **Type inversion (SCSI)**

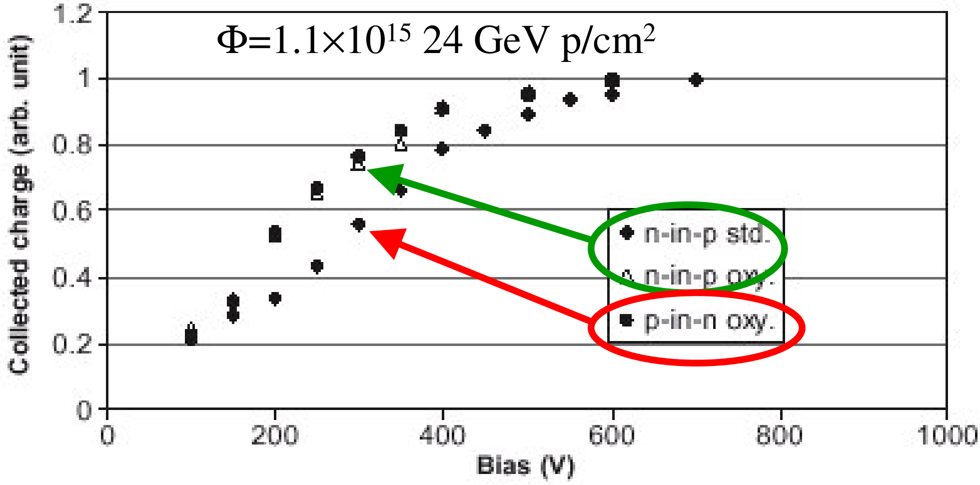
Collected Charge:

$$Q = Q_o \cdot \varepsilon_{dep} \cdot \varepsilon_{trap}$$

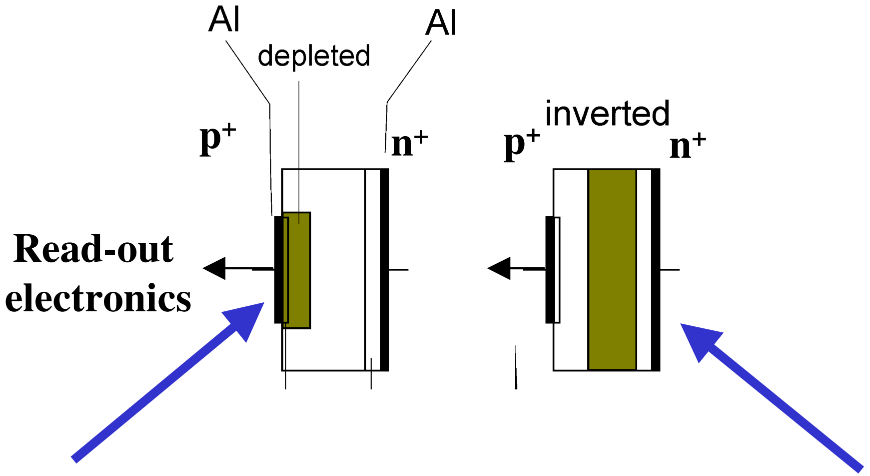
$$\varepsilon_{dep} = \frac{d}{W} \qquad \varepsilon_{trap} = e^{-\frac{\tau_c}{\tau_t}}$$

W: total thickness
d: Active thickness
τ_c : Collection time
τ_t : Trapping time

(G. Casse et al., NIM A 485 (2002) 153



CCE(V) improved if electronic read-out is closest to high electric field: **n^+-p** detectors (no SCSI) **better than p^+-n** sensors after SCSI.



before inversion

after inversion
neglecting double junction

4. Material Engineering

Defect Engineering of Silicon

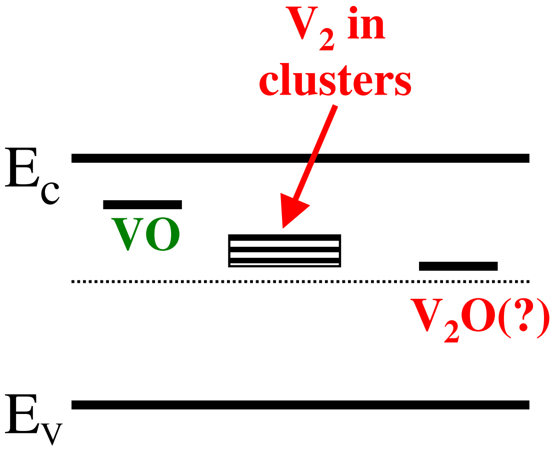
Influence the defect kinetics by incorporation of impurities or defects: Oxygen

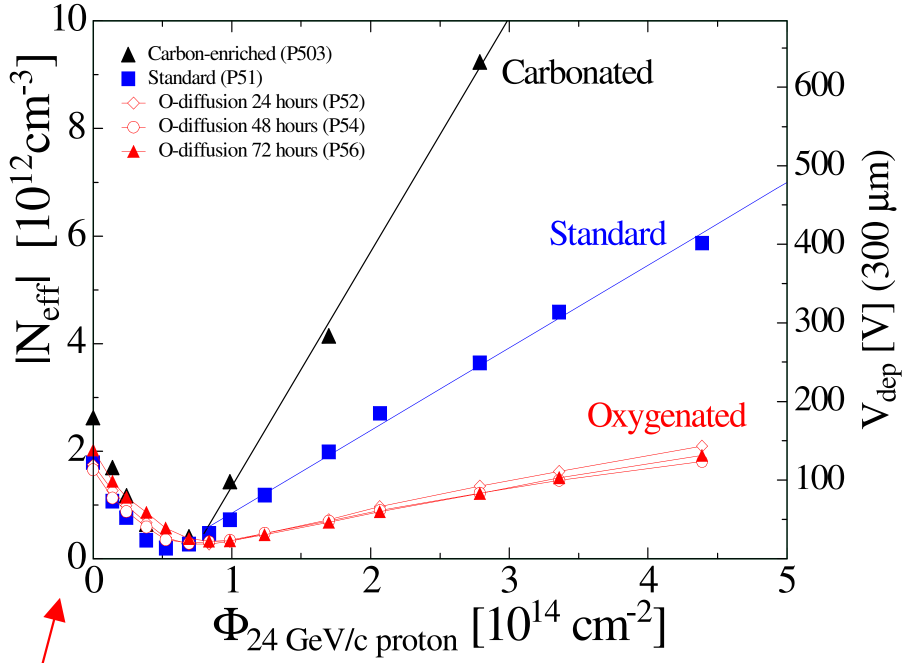
Initial idea: **Incorporate Oxygen to getter radiation-induced vacancies**
⇒ **prevent formation of Di-vacancy (V_2) related deep acceptor levels**

- Higher oxygen content ⇒ less negative space charge

One possible mechanism: V_2O is a deep acceptor

$$V \begin{cases} \xrightarrow{} O \longrightarrow VO & \text{(not harmful at RT)} \\ \xrightarrow{} VO \longrightarrow V_2O & \text{(negative space charge)} \end{cases}$$





DOFZ (Diffusion Oxygenated Float Zone Silicon) RD48 NIM A465 (2001) 60

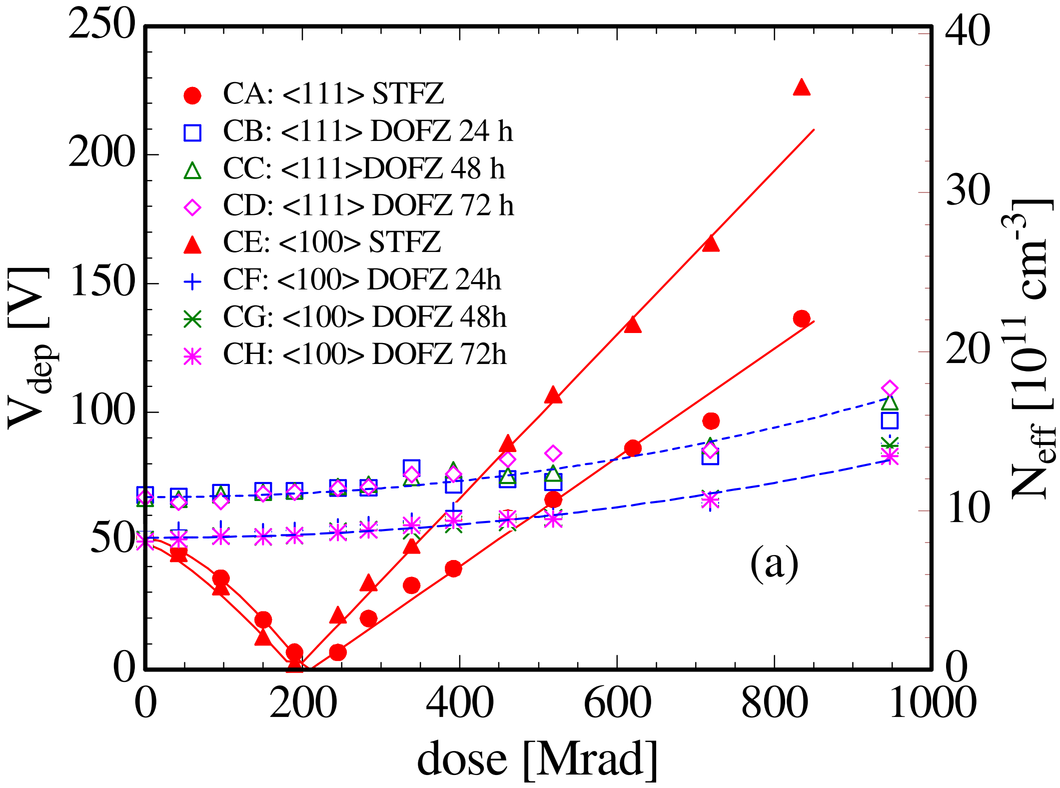
Different kind of Si materials investigated by RD50

Material	Symbol	ρ Ω cm	$[O_i]$ cm^{-3}
Standard n-and ptype FZ	STNFZ	$1\text{-}7 \cdot 10^3$	$< 5\ 10^{16}$
Diffusion Oxygenated FZ p and ntype	DOFZ	$1\text{-}7 \cdot 10^3$	$\sim 1\text{-}2\ 10^{17}$
Epi-layer 50 μm on CZ n-type ITME	EPI	50-100	substrate: $1 \cdot 10^{18}$
Czochralski Sumitomo, Japan n-type	CZ	$1.2 \cdot 10^3$	$\sim 8\text{-}9\ 10^{17}$
Magnetic Czochralski Okmetic Finland n-type and p-type	MCZ	$1.2 \cdot 10^3$	$\sim 5\text{-}9\ 10^{17}$

Czochralski Si

- Very high Oxygen content 10^{17}-10^{18}cm^{-3} **(Grown in SiO_2 crucible)**
- High resistivity (>1KΩcm) available only recently **(MCZ & CZ technology)**
- CZ wafers cheaper than FZ **(RF-IC industry got interested)**

DOFZ Si: Spectacular Improvement of γ-irradiation tolerance



Deep **Levels** responsible for macroscopic changes after γ-irradiation have been identified*:

I–defect: acceptor level at E_C-0.54eV
(approx. 85% of damage in standard FZ)
→ A candidate for the V_2O defect

Bistable shallow thermal donor also important in oxygen enriched Si

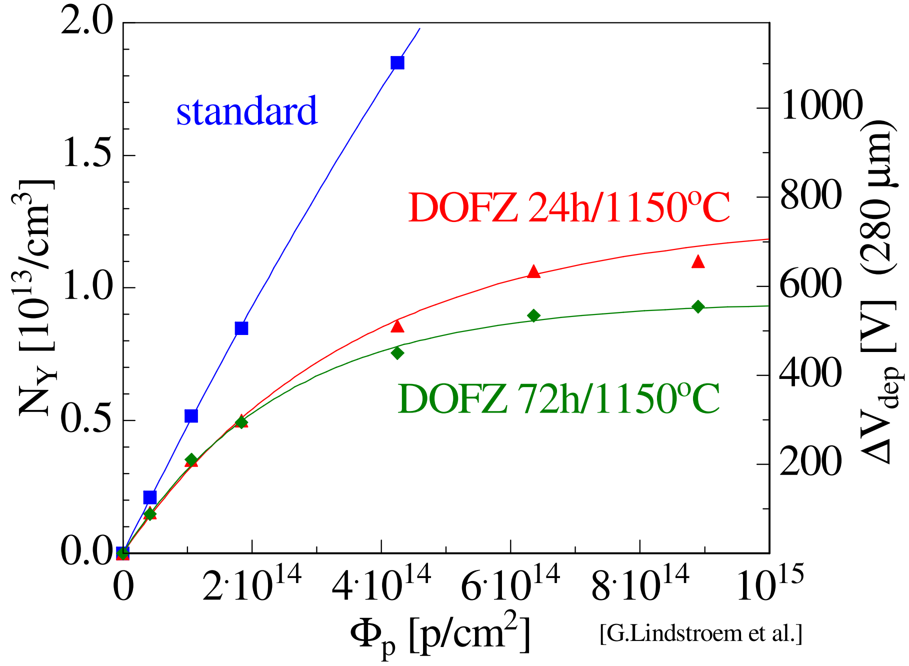
***I.Pintilie et al., App PhysLett,82, 2169, (2003)**

[E.Fretwurst et al. 1st RD50 Workshop]
See also:
- Z.Li et al. [NIMA461(2001)126]
- Z.Li et al. [1st RD50 Workshop]

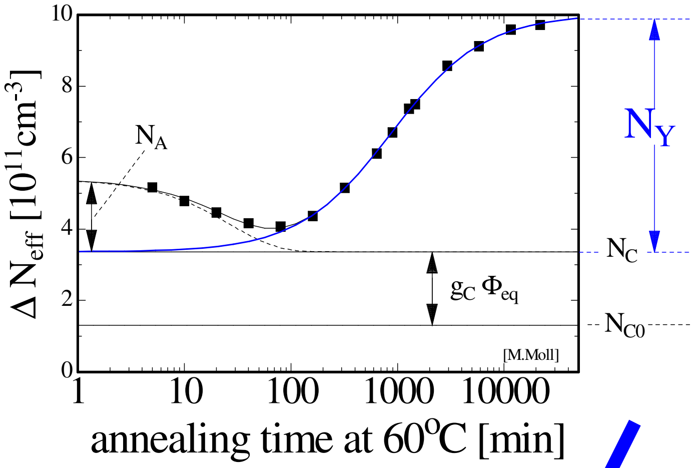
- No type inversion for oxygen enriched silicon!
- Slight increase of positive space charge
- Leakage increase not linear and depending on oxygen concentration

DOFZ Si Reverse annealing: saturation of amplitude and time constant linearly increasing with fluence

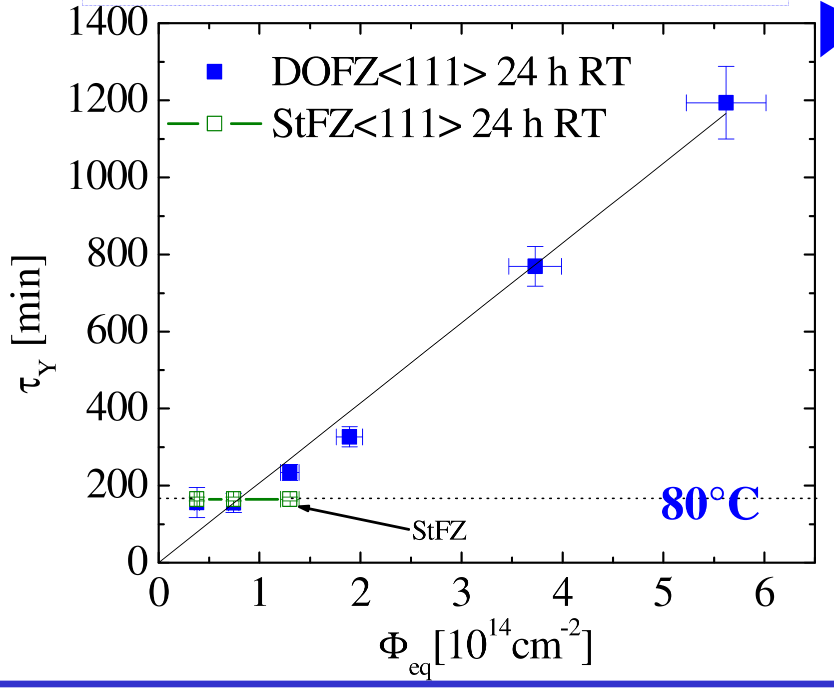
Data From G.Lindstrom et al.



Saturation of amplitude



delayed reverse annealing



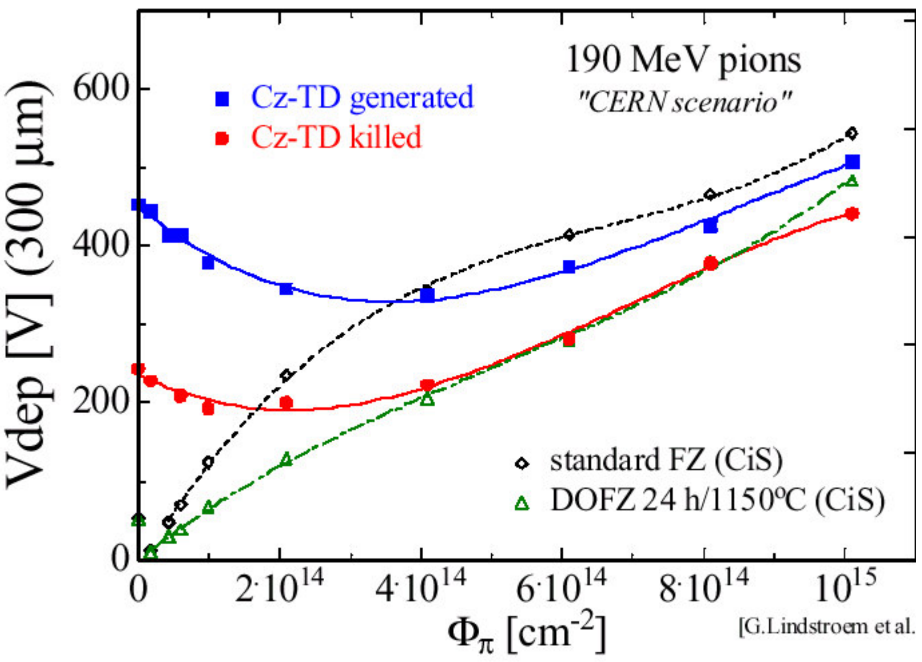
- Saturation of reverse annealing

  (24 GeV/c p - only little effect after neutron irradiation observed !)
- No big difference between

  24h and 72h oxidation at 1150ºC
- time constant depending on fluence

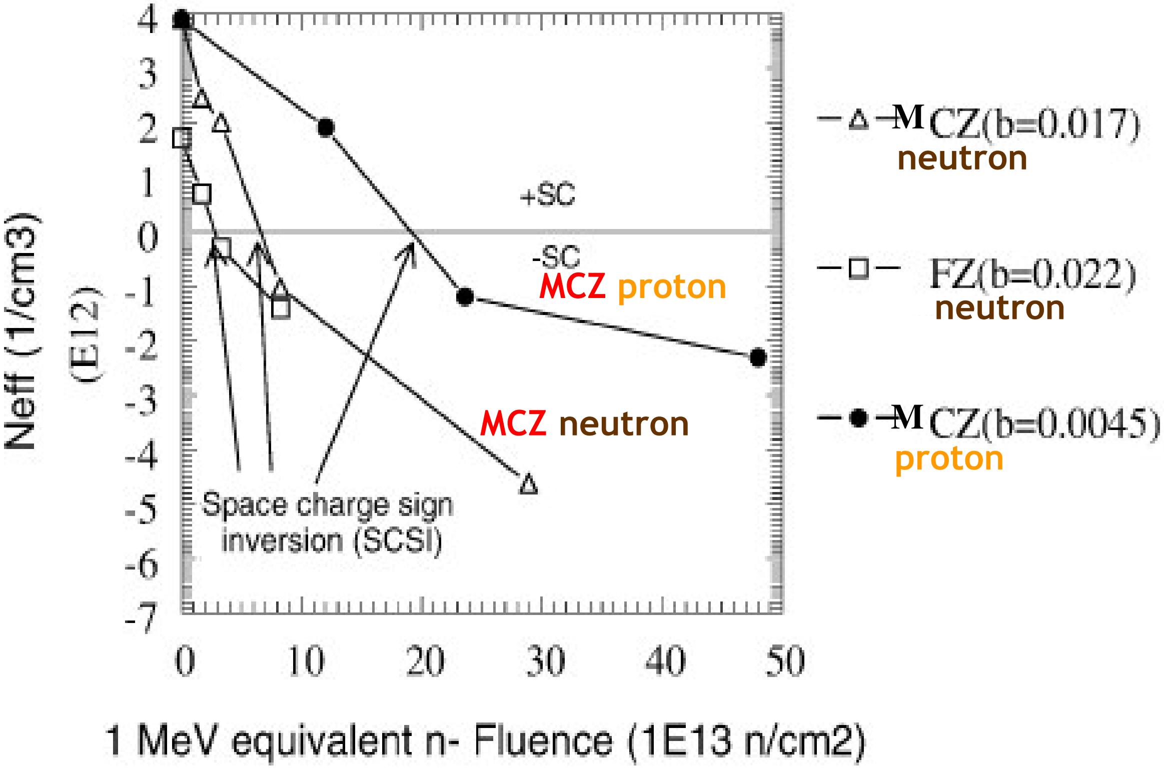
Czochralski Si

190 MeV π irradiation Villigen Cz from Sumitomo Sitix, Japan



Data From G.Lindstrom et al.

MCZ Okmetic after 24GeV/c p and neutron irradiation



Data From Z. Li et al. IEEE TNS

- ♦ **No or delayed type inversion (SCSI)**
- ♦ **Leakage current and charge trapping comparable to FZ silicon**

5. Planar devices with defect engineered Si

Activities in progress in RD50 on microstrip/pixel detectors

Miniature microstrip detectors have been produced or are under process with FZ, DOFZ, MCZ, epitaxial n-type and p-type Si by:

- CNM Barcelona & Liverpool
- IRST-Trento & italian groups (INFN)
- Helsinki HIP
- Common RD50 process under way

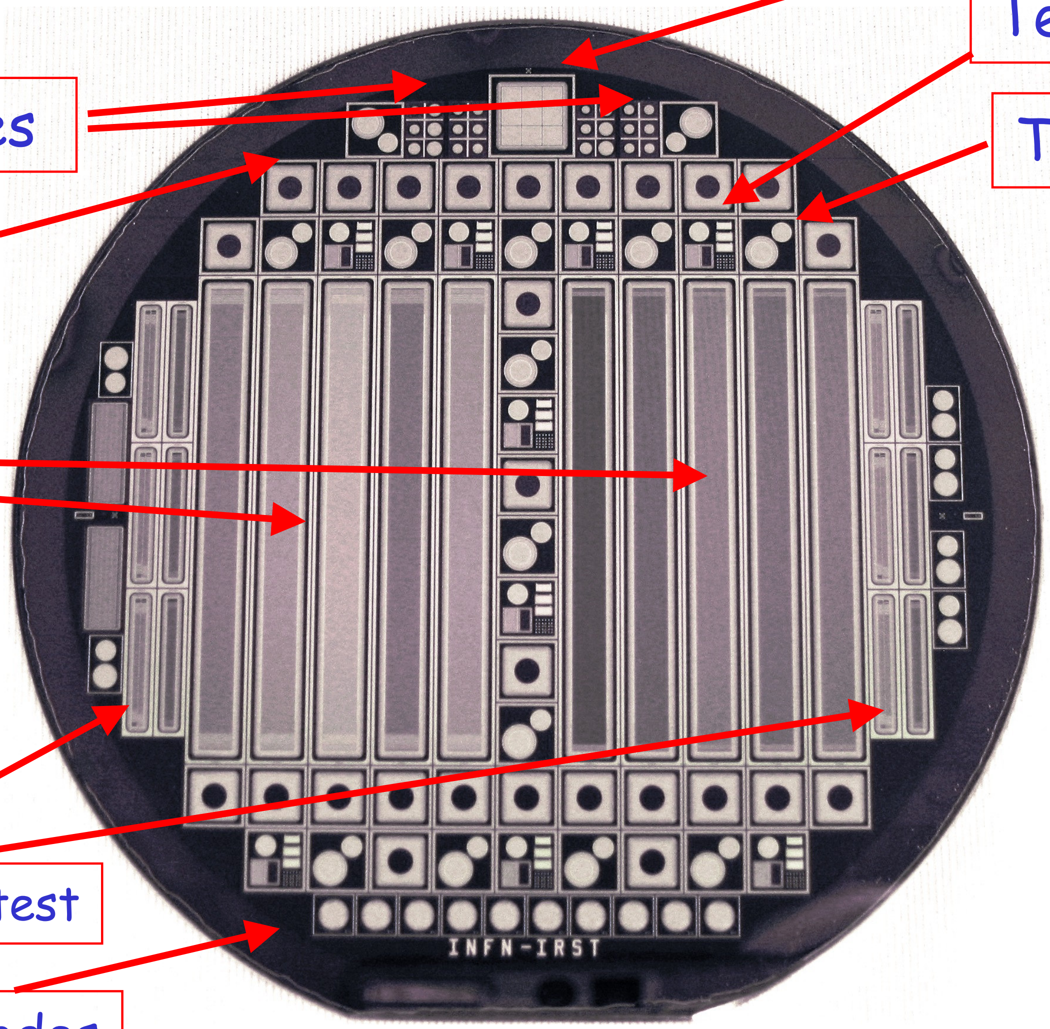
Pixels are currently in process:

- MCz, FZ, DOFZ n-type Si with Sintef using CMS/FPix masks (Purdue)
- MCz n-type Si with pixel and strips at BNL (Purdue, Rochester, BNL)
- CMOS Active Pixel Detectors (Perugia)

DOFZ and MCZ, CZ, EPI microstrip detectors and other rad-hard test structures - Italy

Italian network (INFN SMART project funded by CSN5): Pisa, Firenze, Bari, Perugia, Padova, Trieste, produced by ITC-IRST Trento

(See M. Boscardin et al. @ RD50 Workshop May 2004, CERN)



Pad detector

Test2

Test1

Edge structures

Square MG-diodes

Microstrip detectors

Inter strip Capacitance test

Round MG-diodes

SMART RUN, INFN-IRST

4” Si wafers

Materials:

(Fz,MCz,Cz,EPI)

n- and p-type

Process:

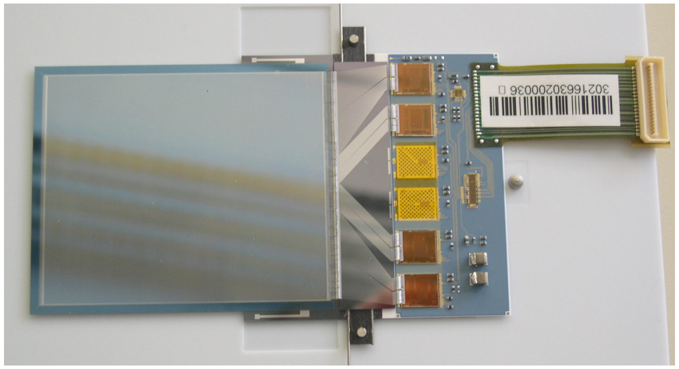
Standard

Low T steps

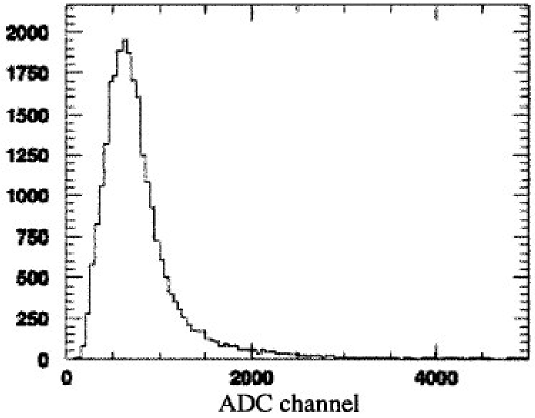
T.D.Killing

MCZ Si microstrip detectors - Helsinki

A 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

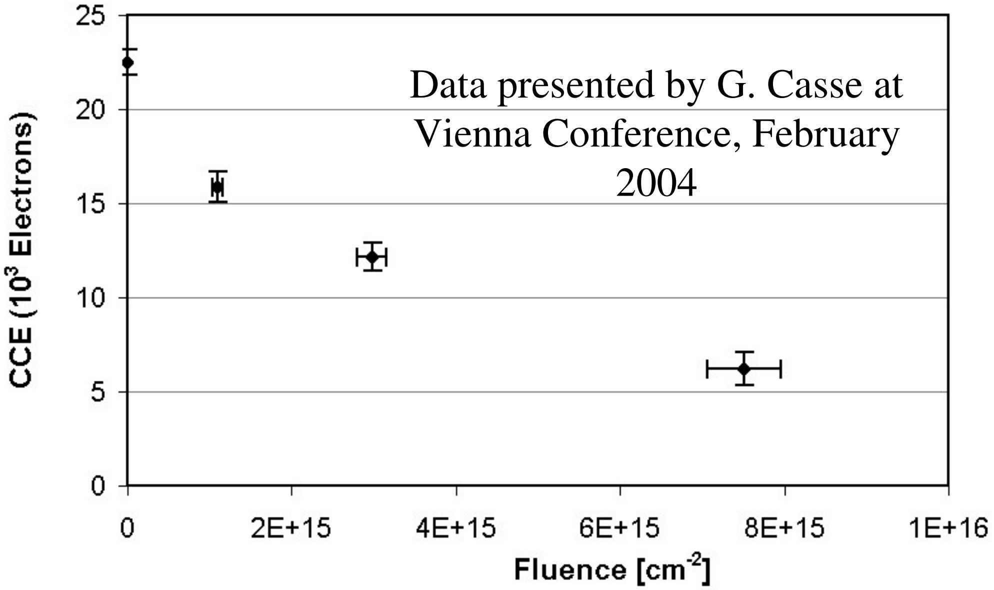


(E. Tuominen et al., Nuclear Physics B, Proc. Suppl. 125 (2003) 175)



n-on-p microstrip detectors – Liverpool & CNM Barcelona

- **Material: standard p-type and oxygenated (DOFZ) p-type**
- **Detectors:miniature n-in-p microstrip (280µm thick).**
- **Electronics: SCT128A LHC speed (40MHz) chip.**
- **Irradiation: 24GeV p up to 7.5 10^{15} cm^{-2}**
- **At highest fluence collected charge is Q~6500e at V_{bias}=900V. Corresponds to: ccd~90µm**



Data presented by G. Casse at Vienna Conference, February 2004

6. Device Engineering

Thin Si detectors

At S-LHC fluences, Charge collection limited by reduced carrier lifetimes τ, due to trapping, carrier mean free path is less than the active thickness

- **Benefits:**

1. Smaller leakage current: $I_{leak} \propto W$
2. Smaller depletion voltage $V_{dep} = qW^2 N_{eff}/2\varepsilon \propto W^2$ and Space Charge Sign Inversion (SCSI) moved to higher fluences.

- **Drawbacks**:
  - Lower mip signal in low fluence range, need low noise read-out

Group	β_e [10^{-16}cm²ns^{-1}]	β_h	particle / energy	max Φ_{eq} [cm-²]	T [°C]
Ljubljana	4.1	6	reactor n	10^{17}	-10
	5.7	7.7	π		-10
	5.6	7.7	24 GeV/c p		-10
Hamburg	4.7	5.7	24 GeV/c p	$6 \cdot 10^{14}$	+20
Dortmund	5.1	5	24 GeV/c p	10^{15}	0

$1/\tau_{e,h} = \beta_{e,h} \cdot \Phi_{eq}[\mathrm{cm}^{-2}] \rightarrow \tau \sim 1/\Phi$ $\tau \sim 0.2\ \mathrm{ns}$ for $\Phi = 10^{16}\ \mathrm{cm}^{-2}$

No significant material difference FZ, DOFZ, MCZ

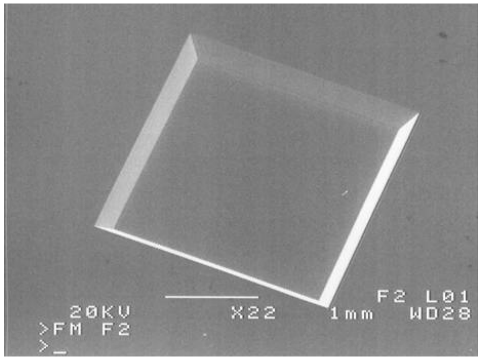
Thinned devices (W=50-100-50-200µm)

ITC-IRST, Trento

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

1. TMAH etching from back.
2. Phosphorous deposition and diffusion from back.
3. Metal deposition from back.

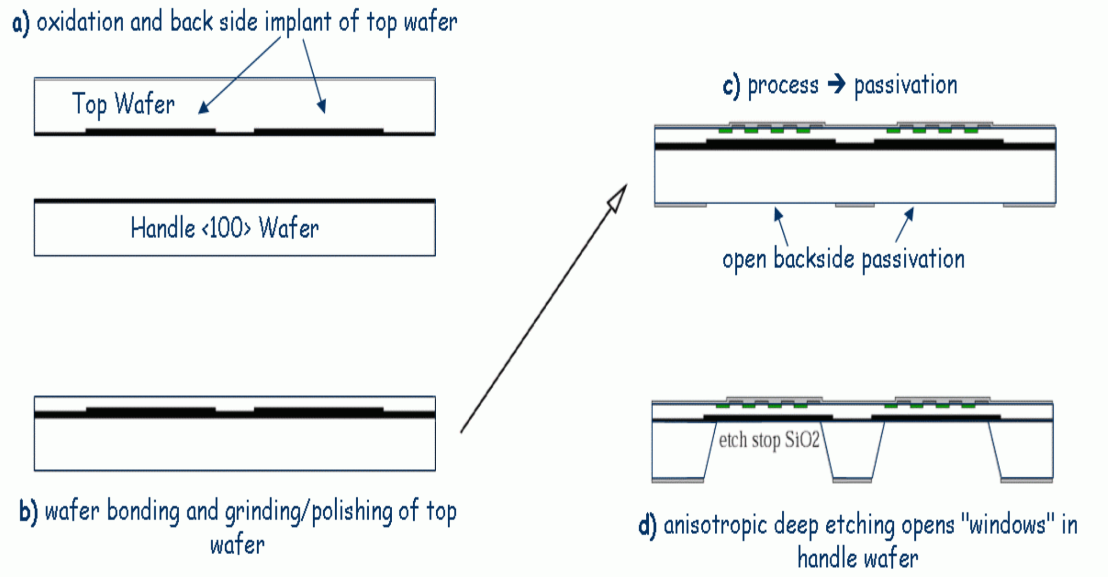
Areas: 1 mm^2 - 20 mm^2 and I<1 nA/cm^2 at 20 V
Thickness: 50-100µm



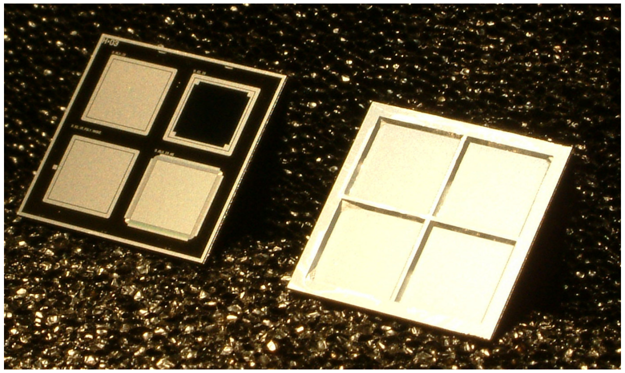
SEM: back view of a thinned device

Semiconductor Detector Laboratory, MPI, Munich

(L. Andricek et al., 1st ECFA Workshop, Montpellier, November 2003)



Area: 10 mm^2 and I<1 nA/cm^2 at 20 V
Thickness: 50µm



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

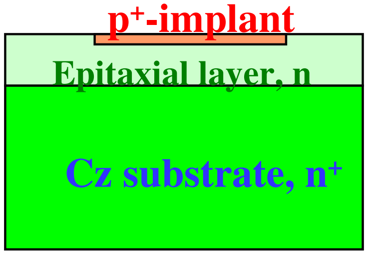
More: Purdue is currently processing thin segmented detectors with Micron (150-200 µm)

Epitaxial Si detectors

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

1. Substrate **low ρ** (<0.02 Ω·cm) **300 µm thick n-type Cz** Si Sb-doped.
2. Thin (**25-50-75 µm**) low ρ **(50 Ω·cm)**, P-doped **Si epilayer** grown by ITME (Warsaw)
3. p^+-n by **B implant** on epilayer by CiS (Erfurt).

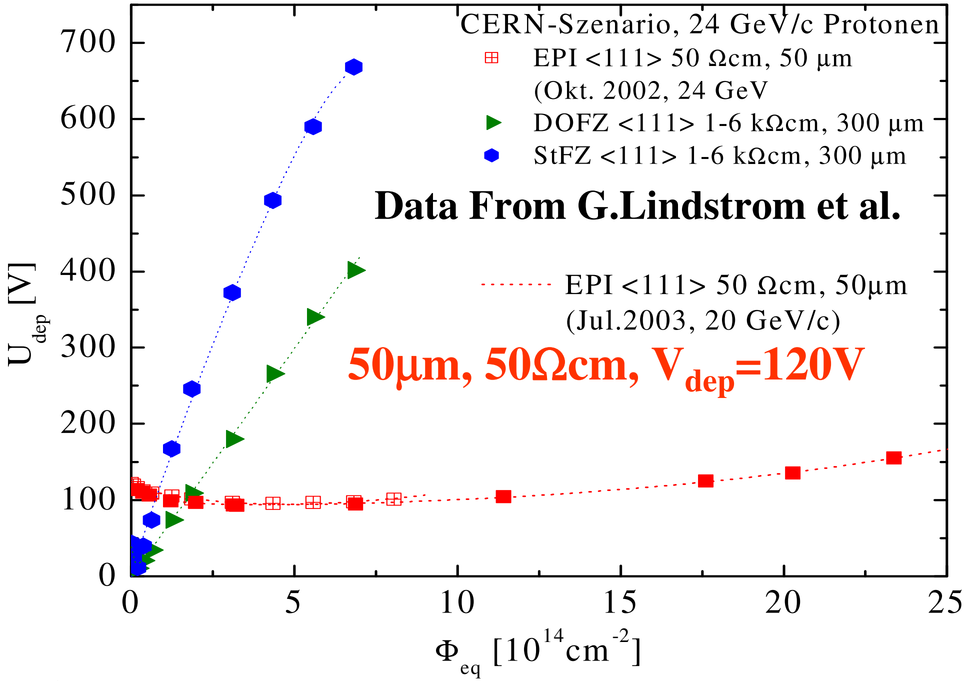
Detector max active thickness equals the epitaxial layer thickness.



p^+-implant

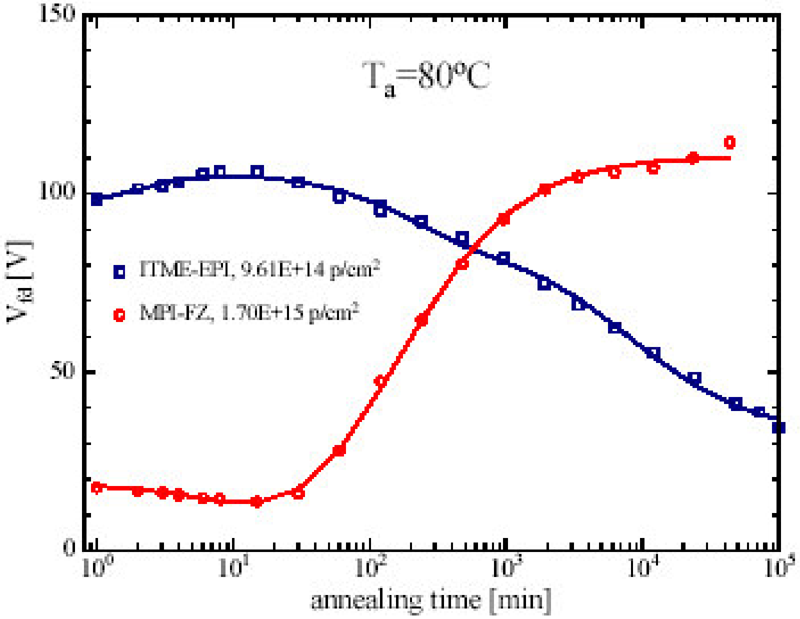
Epitaxial layer, n

Cz substrate, n^+



Data From G.Lindstrom et al.

50µm, 50Ωcm, V_{dep}=120V



E. Fretwurst et al., 4th RD50 Workshop, 4-7 May 2004

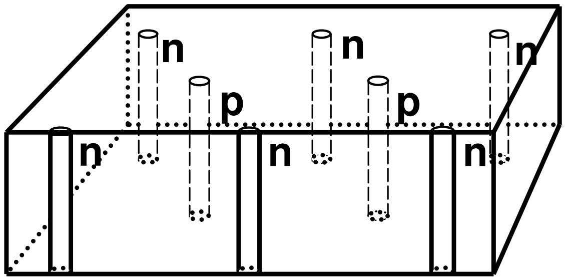
Advantages

1. 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.
2. Due to the high oxygen concentration in the CZ substrate ($[O] \approx 10^{18}$ cm^{-3}), **O diffuses into the epitaxial layer** during the high temperature growth process **improving the detector radiation hardness**.
3. Different annealing behaviour in epitaxial Si → No need of low temperature in maintenance operation of SLHC

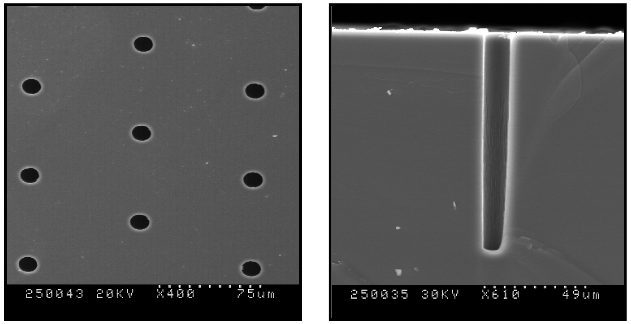
3D detectors

First proposed by Sherwood Parker

Present size up to ~1cm^2

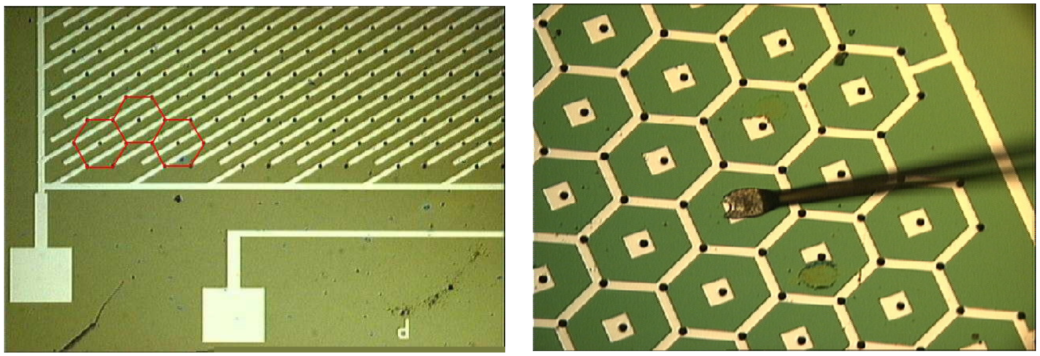


- Electrodes:
  - **narrow columns along detector thickness-“3D”**
  - **diameter:** 10µm **distance:** 50 - 100µm
- Lateral depletion:
  - **lower depletion voltage needed**
  - **thicker detectors possible**
  - **fast signal**
- Hole processing :
  - **Dry etching, Laser drilling, Photo Electro Chemical**
  - **Present aspect ratio (RD50) 13:1, Target: 30:1**
- Electrode material
  - **Doped Polysilicon**



SEM and photos by Glasgow group

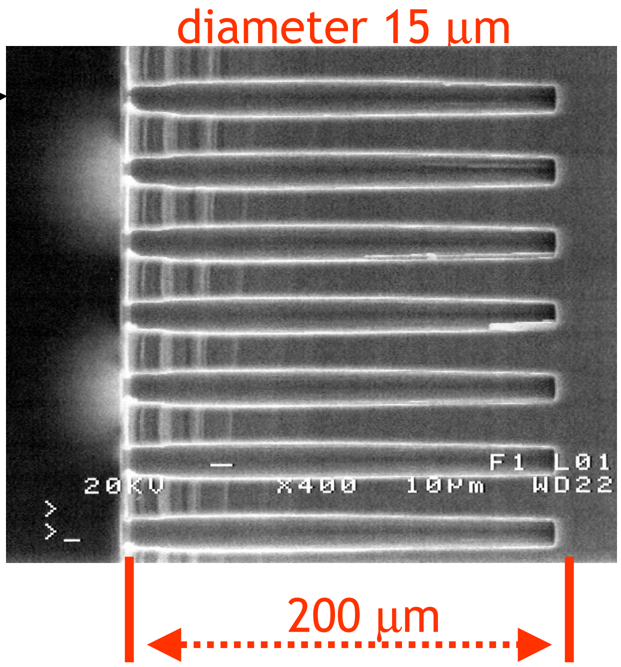
3D hexagonal geometry connected in strip and pixel configurations



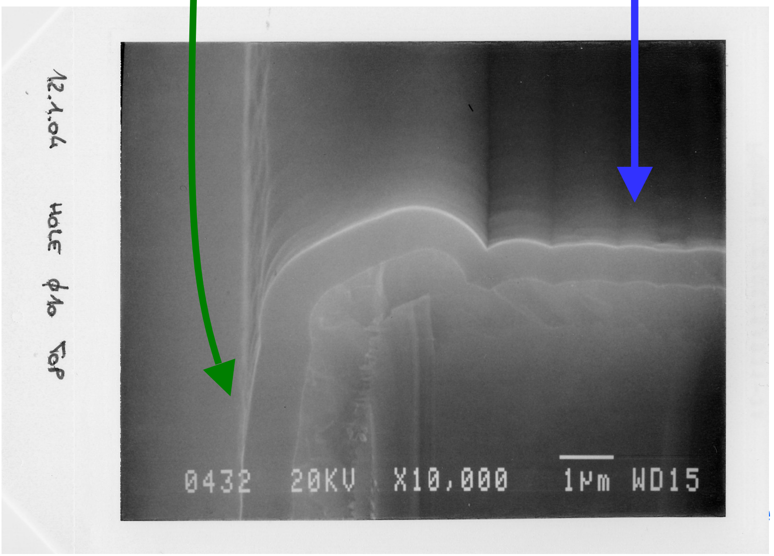
3-D detectors in RD50

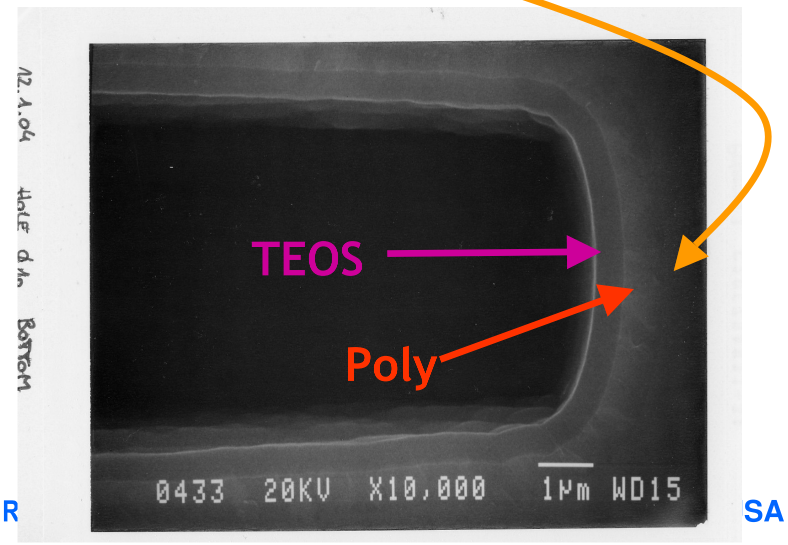
(M. Boscardin et al., 4th RD50 Workshop, http://rd50.web.cern.ch/rd50/4th-workshop)

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



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



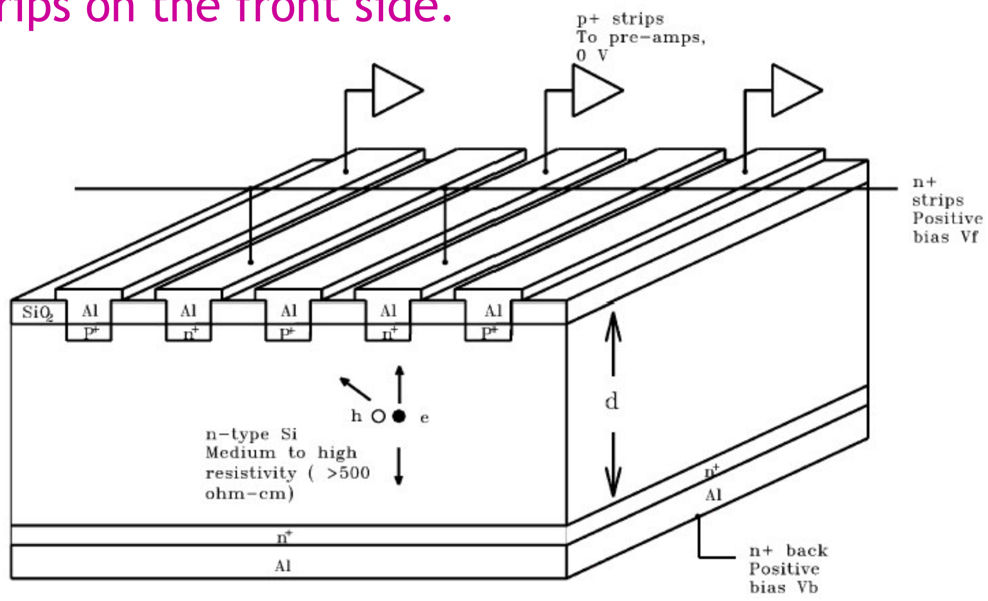


Semi-3D detectors

Proposed by Z. Li, BNL Instr. Div. (NIM A 478 (2002) 303).

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

Activity of BNL & US Groups

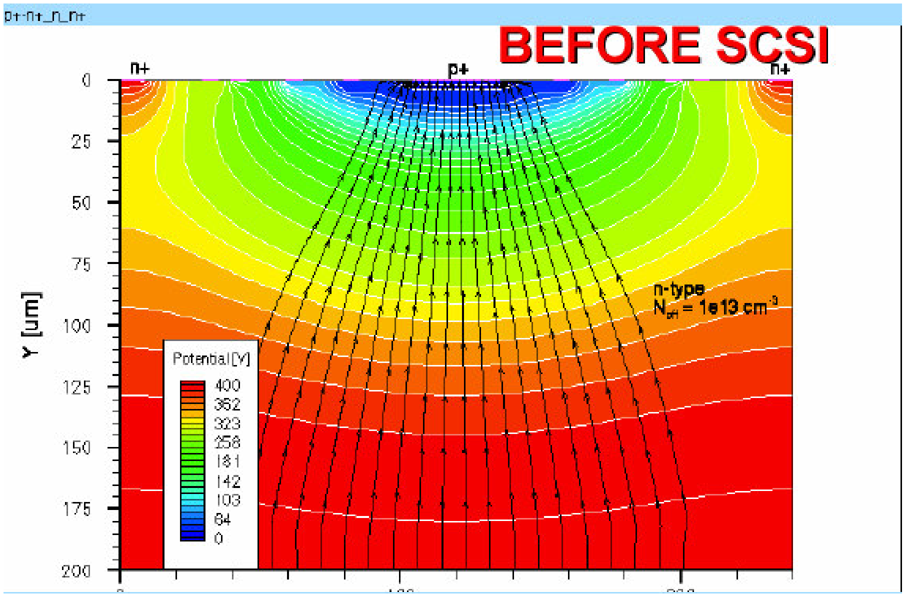


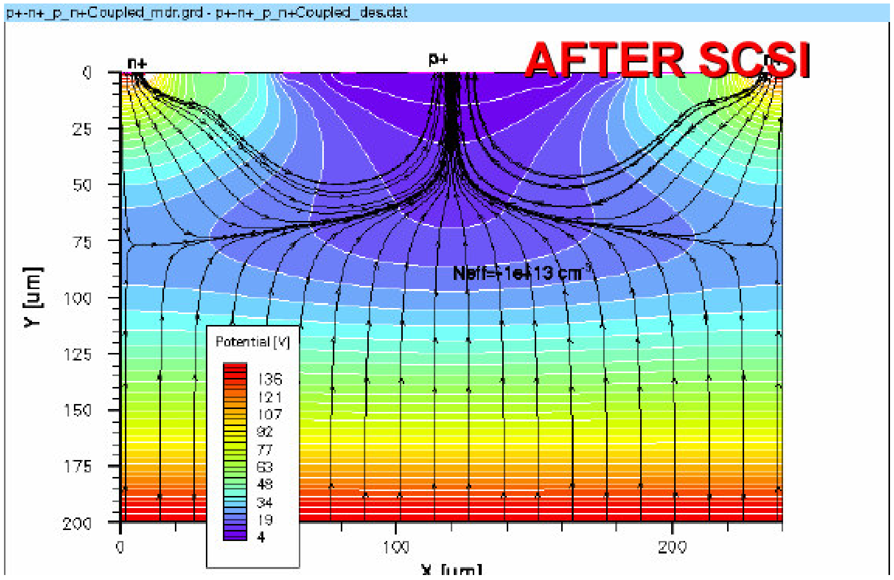
Advantages:

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

Under investigation:

Electric field distribution before and after SCSI





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

Proposed by Z. Li,BNL Instr. Div. (NIM A 518 (2004) 738).

Stripixel detectors

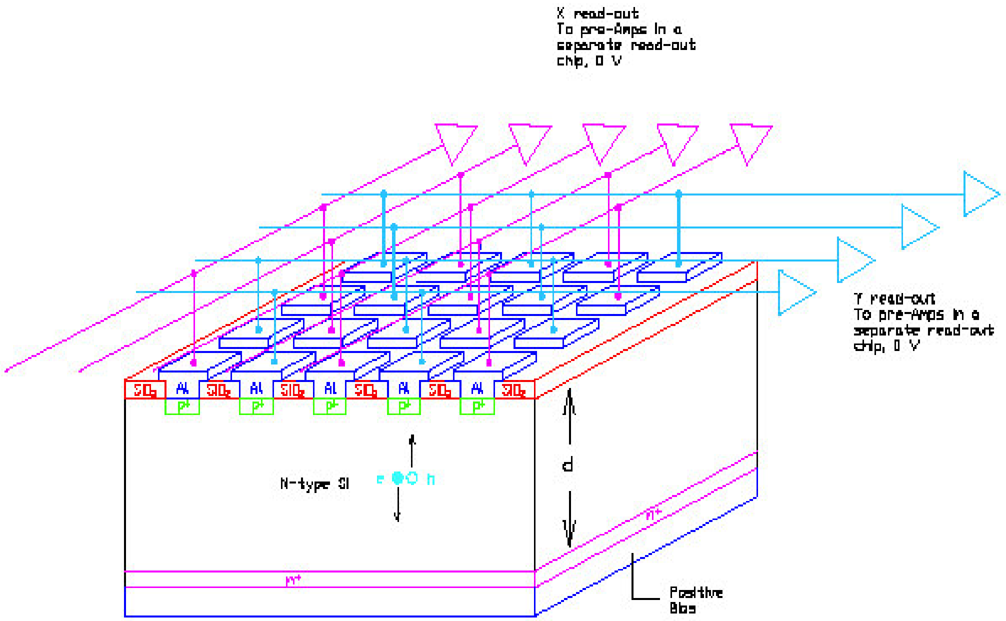
Pixel electrodes arranged in a projective X-Y readout.

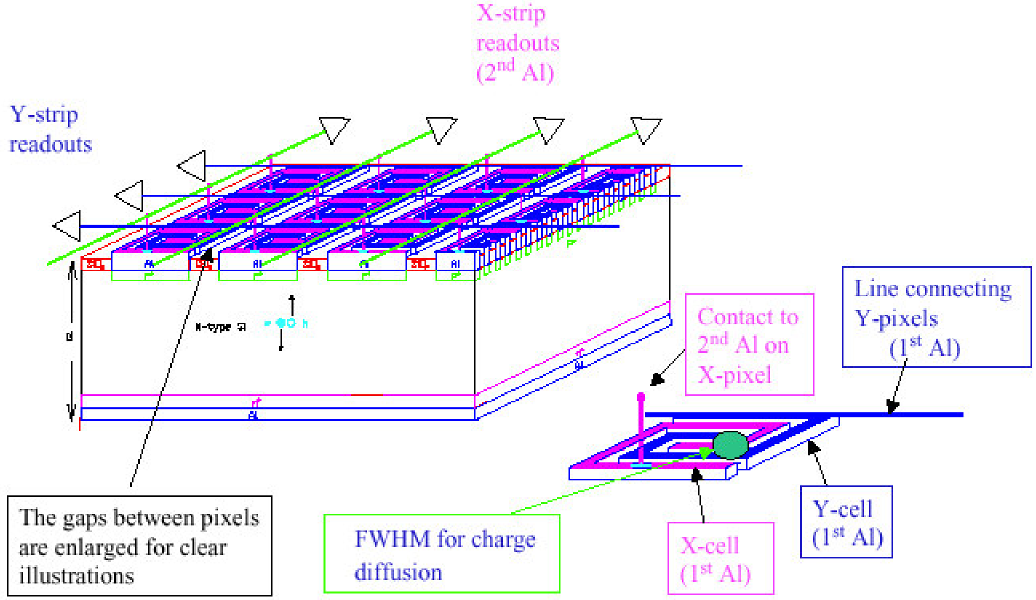
Advantages:

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)
5. Alternative to macro-pixel detectors in the SLHC upgrade between 15 cm and 60 cm?

-Individual pixels alternatively connected to X- & 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- & Y-cell).
-Charge must be collected at least by 1 X- & 1 Y-cells.
-Key: $\chi \geq$interleaved distance between X- & Y- cells
-If pitch>χ the resolution is fixed by the pitch.





7. Summary

- Radiation hard materials for tracker detectors at SuperLHC are under study by the CERN RD50 collaboration.
- At the fluence of 10^{16}cm^{-2} (Innermost layer of a SLHC detector) the active thickness of any silicon material is significantly reduced due to trapping. The two most promising options so far are:

  Thin detectors : drawback: radiation hard electronics for low signals needed
  3D detectors: drawback: technology has to be optimized

- At fluences up to 10^{15}cm^{-2} (Outer layers of a SLHC detector) the change of the depletion voltage and the large area to be covered by detectors is the major problem. CZ detectors could be a cost-effective radiation hard solution

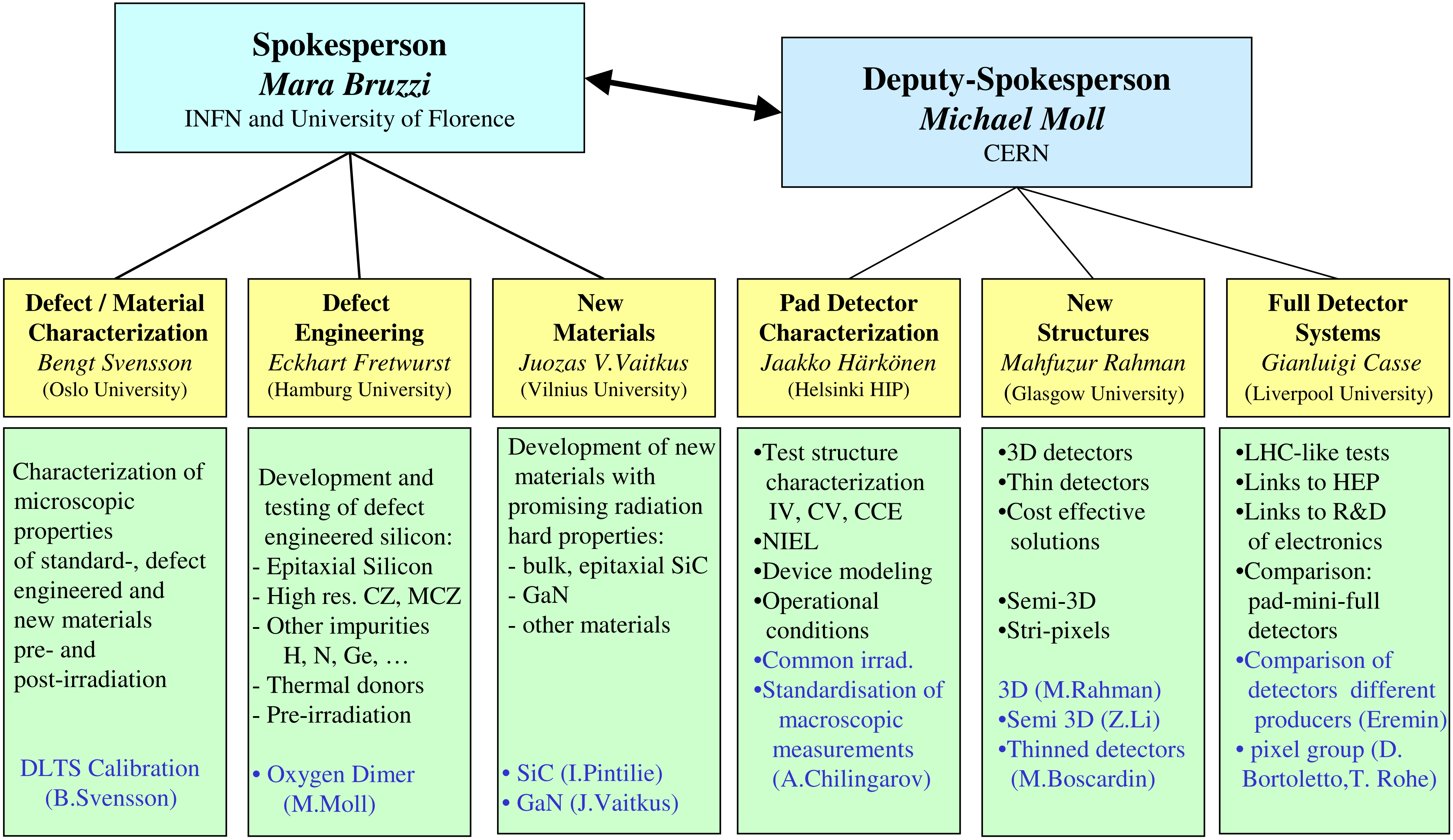
- Miniature microstrip and pixel detectors made with defect engineered Si have been fabricated by RD50 or are in process. First studies after irradiation with LHC-like electronics are encouraging: CCE on microstrip n-in-p oxygenated detector irradiated up to 7×10^{15} [24GeVp/cm^2] is > 6500e.

- New Materials like SiC,GaN are under investigation. More radiation studies needed.

RD50 web-site: http://www.cern.ch/rd50

Scientific Organization of RD50

Development of Radiation Hard Semiconductor Devices for High Luminosity Colliders



Spokesperson
Mara Bruzzi
INFN and University of Florence

Deputy-Spokesperson
Michael Moll
CERN

Defect / Material Characterization
Bengt Svensson
(Oslo University)

Characterization of microscopic properties of standard-, defect engineered and new materials pre- and post-irradiation

DLTS Calibration (B.Svensson)

Defect Engineering
Eckhart Fretwurst
(Hamburg University)

Development and testing of defect engineered silicon:
- Epitaxial Silicon
- High res. CZ, MCZ
- Other impurities H, N, Ge, …
- Thermal donors
- Pre-irradiation

- Oxygen Dimer (M.Moll)

New Materials
Juozas V.Vaitkus
(Vilnius University)

Development of new materials with promising radiation hard properties:
- bulk, epitaxial SiC
- GaN
- other materials

- SiC (I.Pintilie)
- GaN (J.Vaitkus)

Pad Detector Characterization
Jaakko Härkönen
(Helsinki HIP)

- Test structure characterization IV, CV, CCE
- NIEL
- Device modeling
- Operational conditions
- Common irrad.
- Standardisation of macroscopic measurements (A.Chilingarov)

New Structures
Mahfuzur Rahman
(Glasgow University)

- 3D detectors
- Thin detectors
- Cost effective solutions

- Semi-3D
- Stri-pixels

3D (M.Rahman)
- Semi 3D (Z.Li)
- Thinned detectors (M.Boscardin)

Full Detector Systems
Gianluigi Casse
(Liverpool University)

- LHC-like tests
- Links to HEP
- Links to R&D of electronics
- Comparison: pad-mini-full detectors
- Comparison of detectors different producers (Eremin)
- pixel group (D. Bortoletto,T. Rohe)

RD50 Primary Damage and secondary defect formation

- **Two basic defects**

I - Silicon Interstitial V - Vacancy

- **Primary defect generation**

I, I_2 higher order I (?)
⇒ I -CLUSTER (?) ⟸
V, V_2, higher order V (?) Damage?!
⇒ V -CLUSTER (?) ⟸

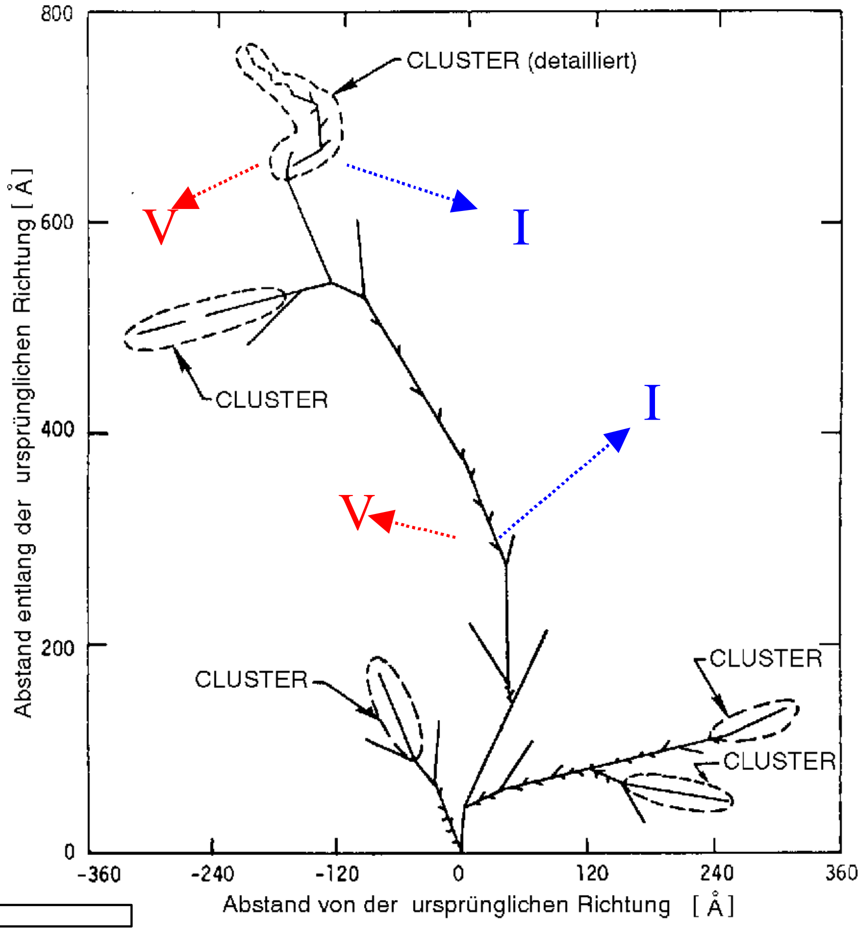
- **Secondary defect generation**

Main impurities in silicon: Carbon (C_s)
Oxygen (O_i)

$I+C_s \rightarrow C_i \Rightarrow C_i+C_s \rightarrow C_iC_s$
$C_i+O_i \rightarrow C_iO_i$
$C_i+P_s \rightarrow C_iP_s$

$V+V \rightarrow V_2$ $V+V_2 \rightarrow V_3$
$V+O_i \rightarrow VO \Rightarrow V+VO \rightarrow \underline{V_2O}$ ⟸
$V+P_s \rightarrow VP_s$

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



Damage?! ("V_2O-model")

B. New materials studied by RD50: SiC, GaN, …

SiC E_g = 3.3eV, (CC mips = 55e/µm) ; GaN E_g = 3.39eV

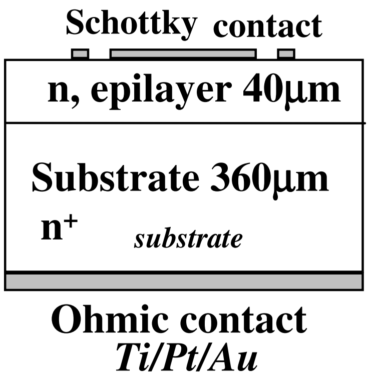
→ Low Leakage current even after very high fluences, radiation hardness under test

- **Semi-Insulating SiC**

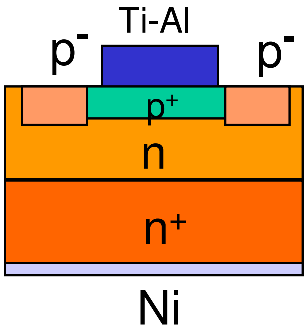
  - CCE 60% in as-grown CREE vanadium compensated, ~55% after irradiation with 10^{13}cm^{-2} 300 MeV/c π
  - Vanadium-free semi-insulating material from Okmetic: ~100% CCE in unirradiated material

- **Epitaxial SiC**

  - 6 new 2” wafers d~50µm, $N_{eff} \geq 5 \cdot 10^{13}$cm^{-3} produced by IKZ, Berlin
  - Common RD50 test structures produced and irradiated. Tests in progress
  - 100% CCE in unirradiated material

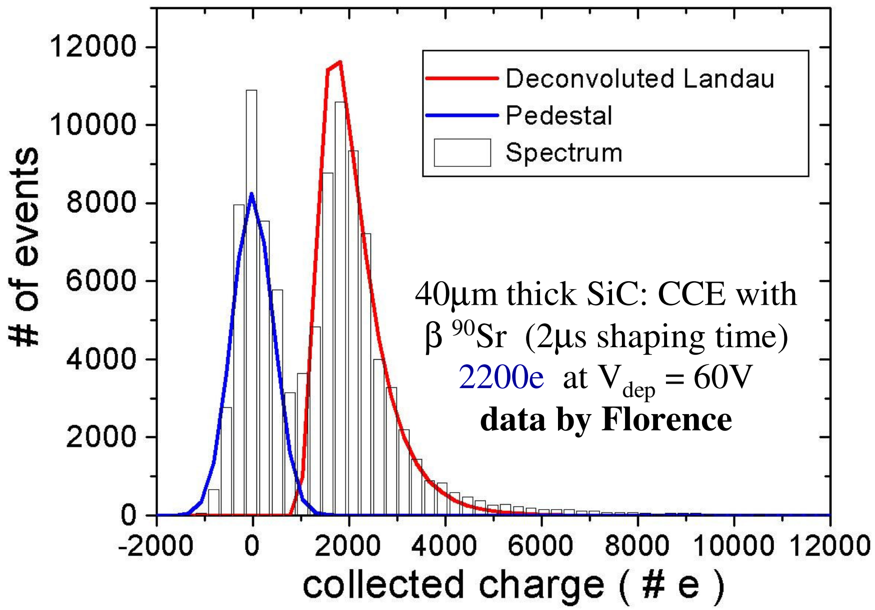


Modena&Alenia Systems, Italy



Perugia&IMM Bologna,Italy

Epilayer SiC from IKZ, Berlin
Substrate SiC from Okmetic or CREE



F. Nava et al., IEEE Trans. Nucl. Sci, (2004)

RADIATION FACILITIES within RD50

- **24 GeV/c protons, PS-CERN**
  up to 10^{16} cm^{-2}
- **TRIGA reactor neutrons, Ljubljana**
  up to 1x10^{16} cm^{-2}
- **26 MeV protons, Karlsruhe**
  1E14/cm2 on 10x10 cm^2 in 10 minutes
- **10-50 MeV protons, Jyvaskyla +Helsinki**
  up to 3x10^{14} cm^{-2}
- **^{60}Co dose, BNL, USA**
  up to 1.5GRad
- **58 MeV Li ions, Legnaro/ Padova**
- **900 MeV electrons, Trieste**
- **15MeV electrons, Oslo**