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Development of Radiation Hard Sensors for Very High Luminosity Colliders

- CERN-RD50 project -

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On behalf of CERN RD50 Collaboration

Complete author list at http://www.cern.ch/rd50

LHC: $\mathscr{L} = 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ 10 years operation
fluence of fast hadrons : $\phi(R = 4\mathrm{cm}) \sim 3 \cdot 10^{15}\ \mathrm{cm}^{-2}$

Possible LHC upgrade ("Super-LHC"): $\mathscr{L} = 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
5 years operation

Anticipated Radiation Environment (CERN-TH/2002-078)

Radius (cm)	Fluence of fast hadrons [cm^{-2}]	Dose [kGy]
4	1.6×10^{16}	4200
22	8.0×10^{14}	350
115	1.0×10^{14}	9.3

Present semiconductor detector technology is not able to operate at such high fluences/doses

RD50 - Development of Radiation Hard Semiconductor Devices for High Luminosity Colliders

280 Members from 55 Institutes

Main Objective

Development of ultra-radiation hard semiconductor detectors, able to withstand fast hadron fluences and doses as expected for luminosity upgrade of the LHC to 10^{35} cm^{-2}s^{-1}.

47 European and Asian institutes (34 west, 11 east)
Belgium (Louvain), Czech Republic (Prague (2x)), Finland (Helsinki (2x), Oulu), Germany (Berlin, Dortmund, Erfurt, Halle, Hamburg, Karlsruhe), Greece (Athens), 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)

7 North-American institutes
Canada (Montreal), USA (Fermilab, Purdue University, Rutgers University, Syracuse University, BNL, University of New Mexico)

1 Middle East institute
Israel (Tel Aviv)

Detailed member list: http://cern.ch/rd50

RD50 - Scientific objectives and strategies

Three R&D strategies:

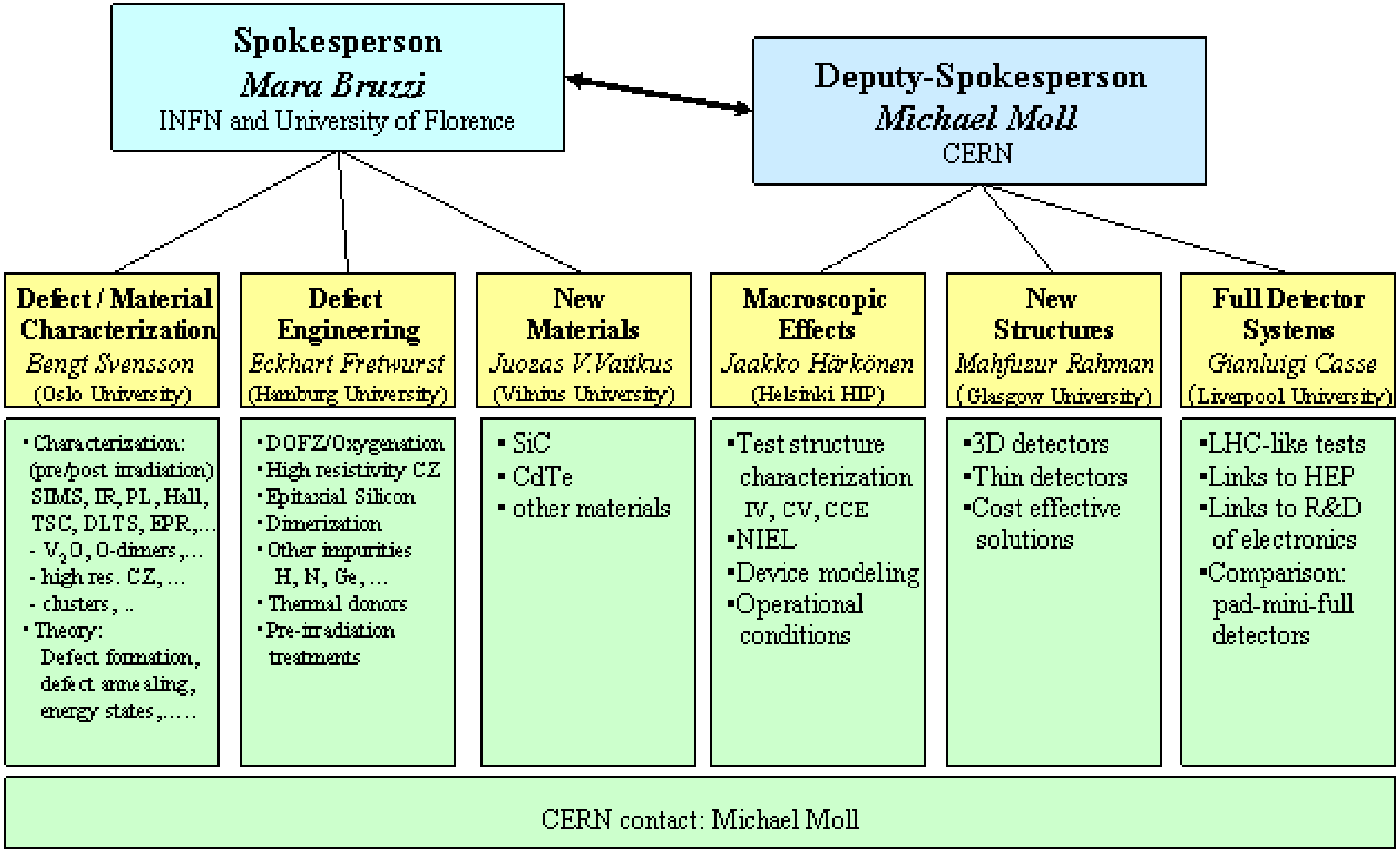
- Material engineering
  - Defect engineering of silicon (oxygenation, dimers, …)
  - New detector materials (SiC, …)
- Device engineering
  - Improvement of present planar detectors (3D detectors, thin detectors, cost effective detectors,…)
- Variation of detector operational conditions
  - Low temperature operation
  - Forward bias operation

RD50
Center of gravity

Further key tasks:

- Basic studies
- Defect modeling and device simulation

Scientific Organization of RD50



Spokesperson
Mara Bruzzi
INFN and University of Florence

Deputy-Spokesperson
Michael Moll
CERN

Defect / Material Characterization
Bengt Svensson
(Oslo University)

- Characterization: (pre/post irradiation) SIMS, IR, PL, Hall, TSC, DLTS, EPR,…
  - V_2O, O-dimers,…
  - high res. CZ, …
  - clusters, ..
- Theory: Defect formation, defect annealing, energy states,…..

Defect Engineering
Eckhart Fretwurst
(Hamburg University)

- DOFZ/Oxygenation
- High resistivity CZ
- Epitaxial Silicon
- Dimerization
- Other impurities H, N, Ge, …
- Thermal donors
- Pre-irradiation treatments

New Materials
Juozas V.Vaitkus
(Vilnius University)

- SiC
- CdTe
- other materials

Macroscopic Effects
Jaakko Härkönen
(Helsinki HIP)

- Test structure characterization IV, CV, CCE
- NIEL
- Device modeling
- Operational conditions

New Structures
Mahfuzur Rahman
(Glasgow University)

- 3D detectors
- Thin detectors
- Cost effective solutions

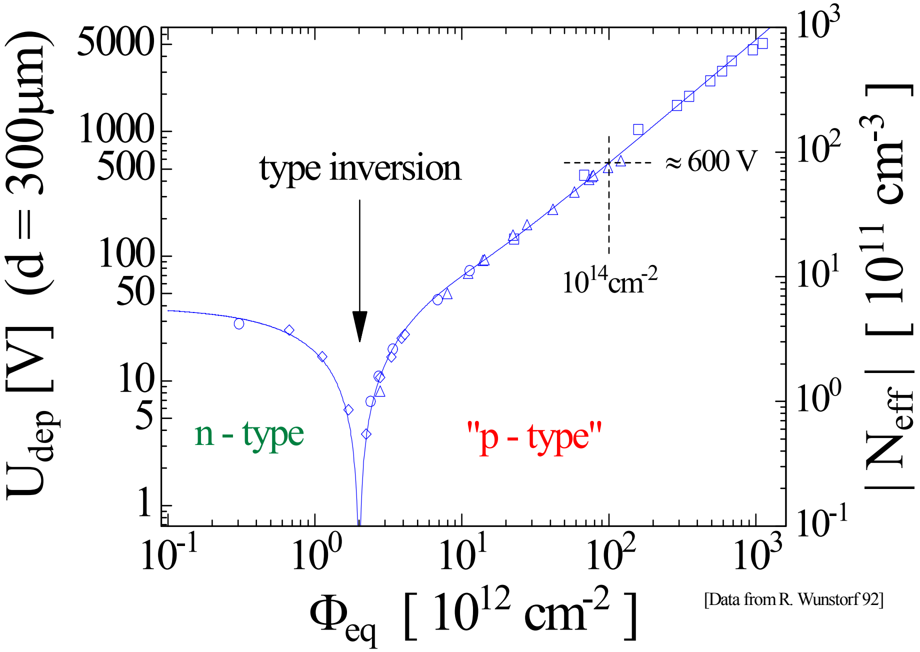
Full Detector Systems
Gianluigi Casse
(Liverpool University)

- LHC-like tests
- Links to HEP
- Links to R&D of electronics
- Comparison: pad-mini-full detectors

CERN contact: Michael Moll

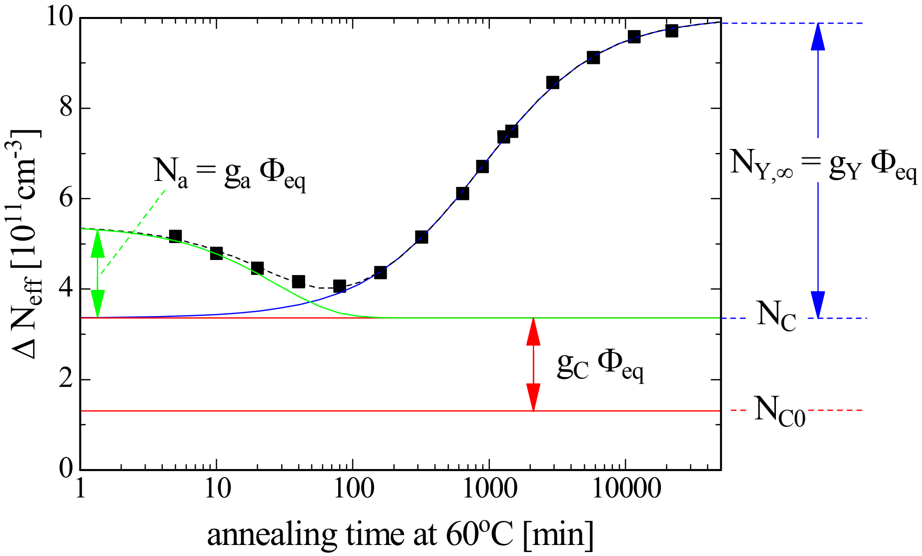
Macroscopic Radiation Damage

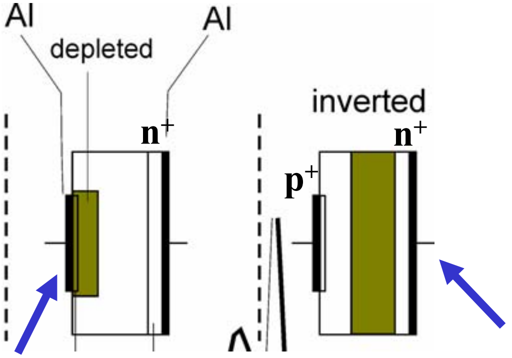
1. Change of V_{dep}, N_{eff} and annealing behavior



[Data from R. Wunstorf 92]

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





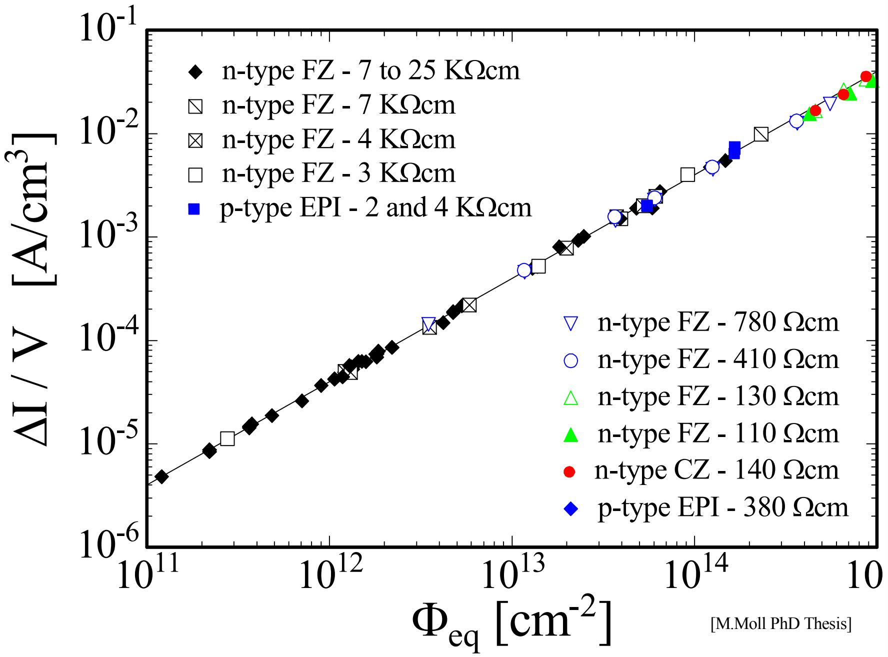
Before SCSI

After SCSI

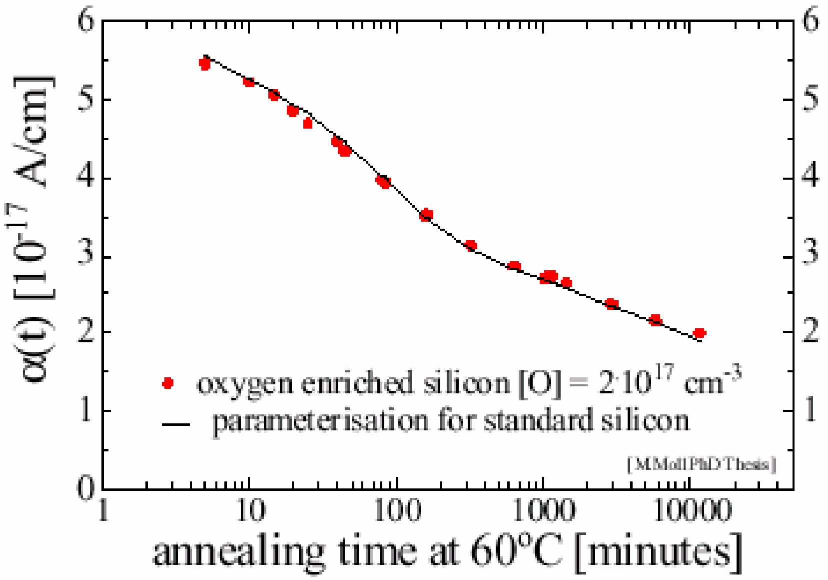
after inversion and annealing saturation

$$N_{eff} \sim \beta \cdot \phi$$

2. Increase of leakage current and annealing behaviour



[M.Moll PhD Thesis]



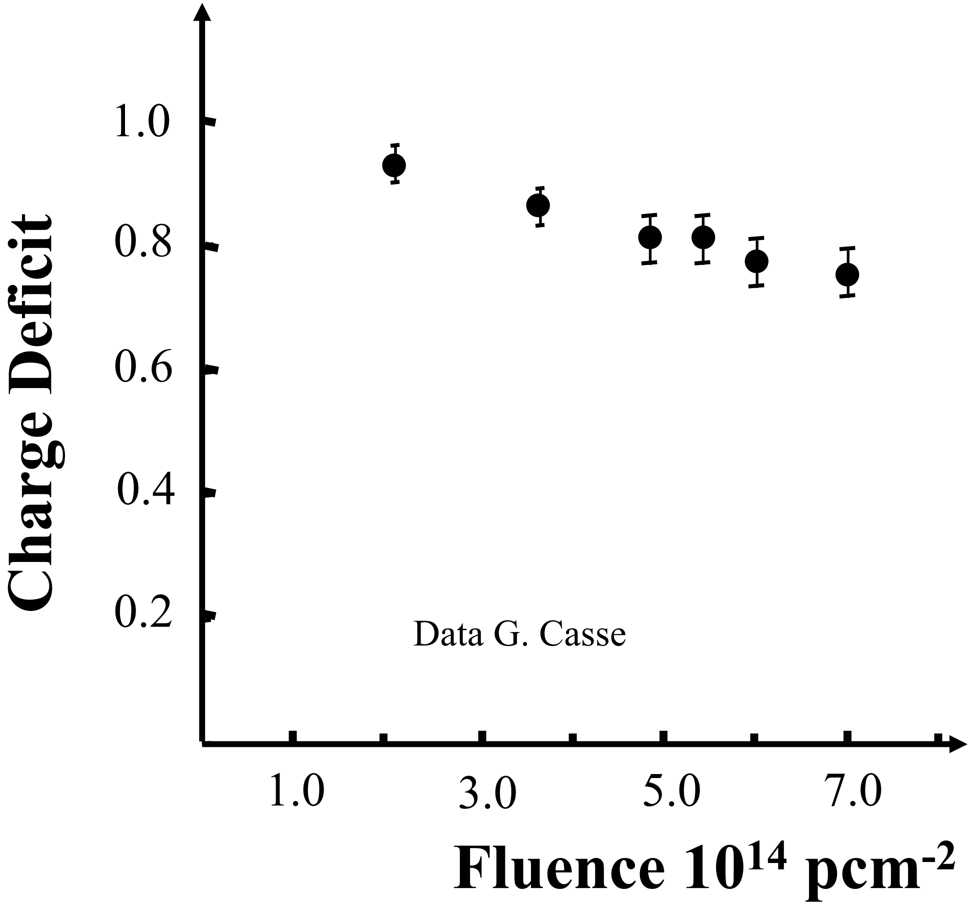
[M.Moll PhD Thesis]

$$\frac{I_{dep}}{Volume} = \alpha \cdot f \qquad \alpha = 3 \cdot 10^{-17}\, A/cm$$

3. Deterioration of the charge collection efficiency

- Trapping of generated e-h at defects
- Under-depletion due to high N_{eff}
- SCSI : keeping high electric field

on the read out side will significantly improve charge collection

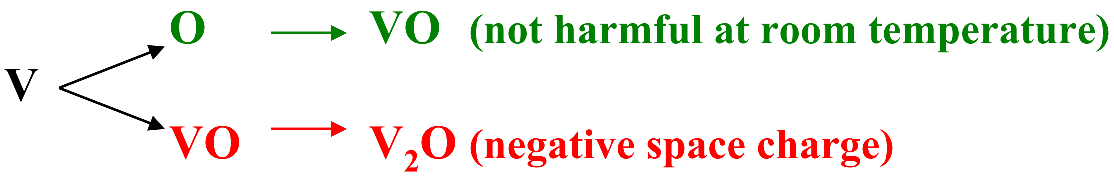


Signal (^{106}Ru ß–source) degradation as a function of fluence in a non-homogeneous irradiated detector (n-in-n).

Defect Engineering of Silicon

Impurities incorporation to prevent the formation of divacancy related defects

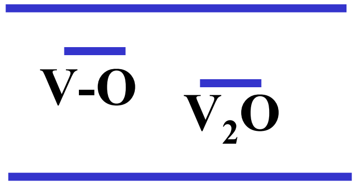
→ **Oxygen can getter vacancies reducing the formation of deeper levels as V_2O**

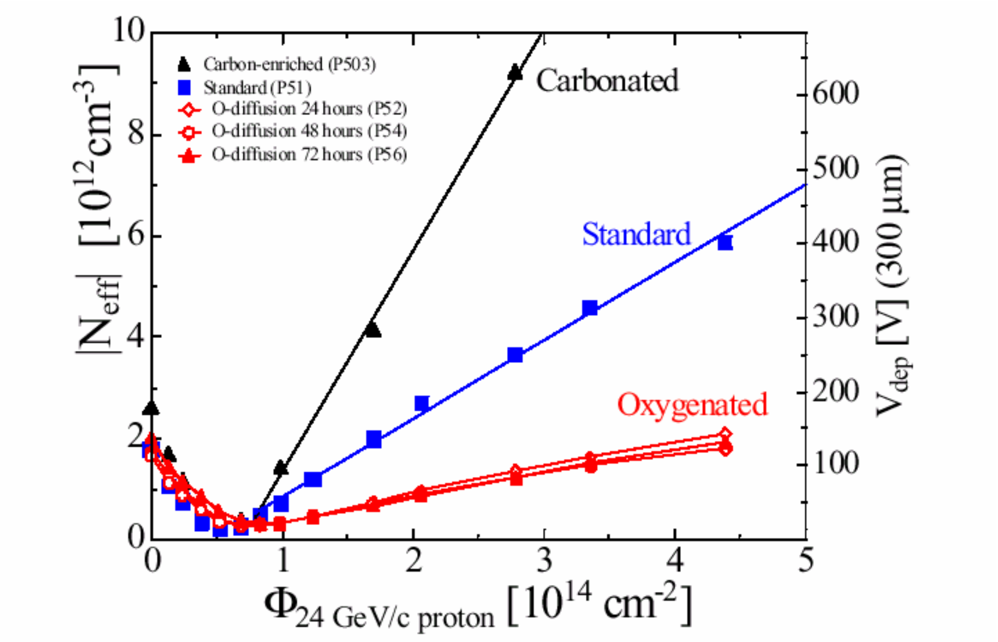


V

O → VO (not harmful at room temperature)

VO → V_2O (negative space charge)





[RD48-NIMA 465(2001) 60]

Benefit with gamma and 24GeV/c protons in terms of β. No benefit with neutrons.

Different kind of Si materials investigated by RD50

Material	Symbol	ρ Ω cm	$[O_i]$ cm^{-3}
Standard n- or p-type FZ	STNFZ	$1\text{-}7 \cdot 10^3$	$< 5\ 10^{16}$
Diffusion Oxygenated FZ p or n-type	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	CZ	$1.2 \cdot 10^3$	$\sim 8\text{-}9\ 10^{17}$
Magnetic Czochralski Okmetic Finland	MCZ	$1.2 \cdot 10^3$	$\sim 5\text{-}9\ 10^{17}$

- Microscopic study of radiation induced defects

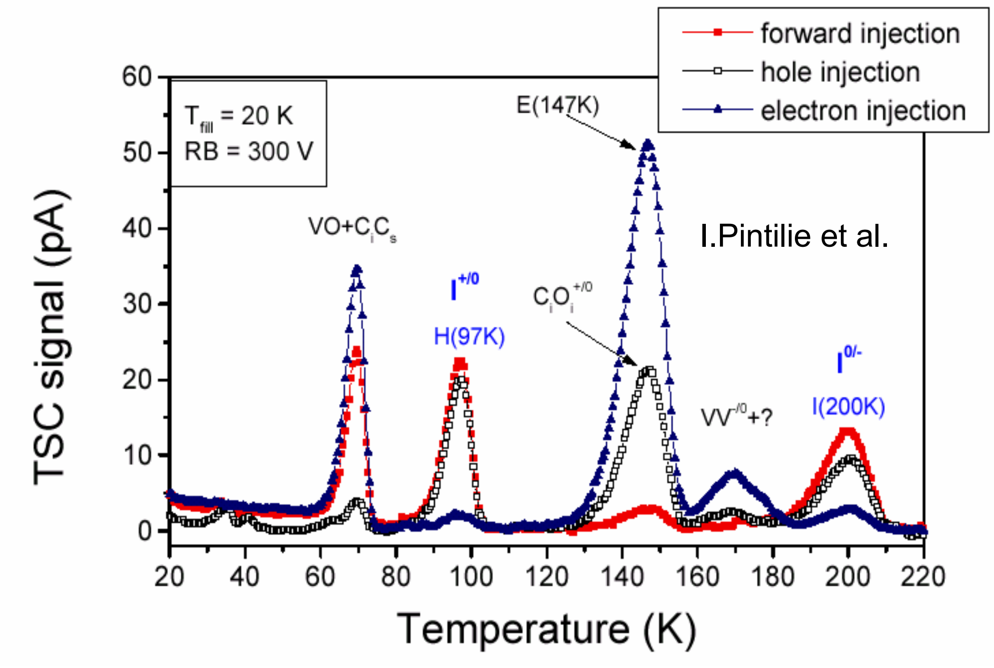
- Changes in the macroscopic parameters of single pad detectors

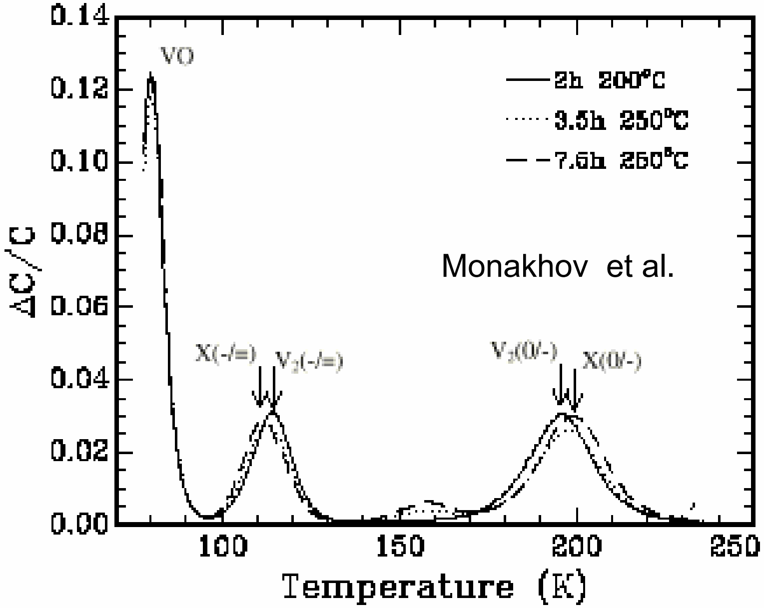
- Performance of segmented devices

Microscopic study of radiation induced defects

Interpretations for the V_2O energy level structure

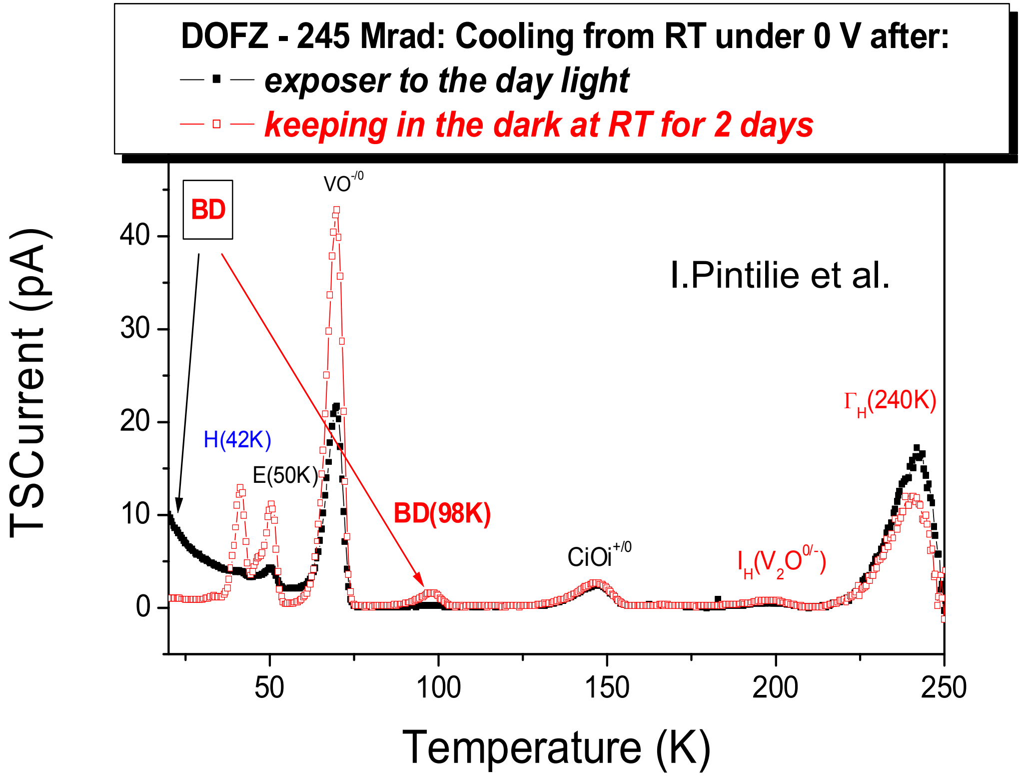
- **"I defect" Acceptor + Donor E_c- 0.545 eV + E_v+0.23 eV induced by irradiation**
  [I.Pintilie et al., APL 82 (13), 2169 (2003)]
- **"X-defect" Double-acceptor E_c-0.467eV + E_c-0.233eV irradiation + annealing of V_2**
  [E.Monakhov et al.,PRB 65(2002)233207]





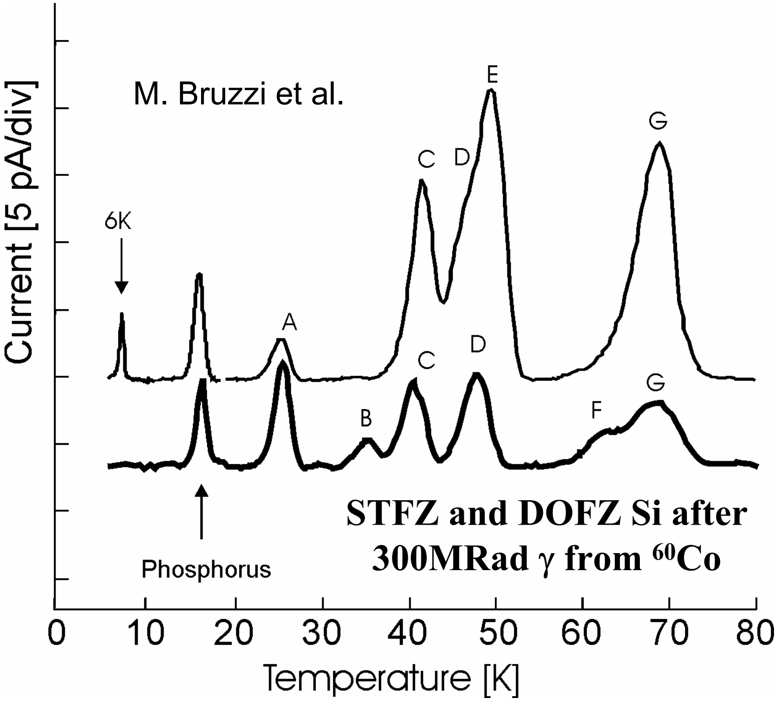
I defect responsible for type inversion in Standard FZ Si after ^{60}Co γ–irradiation and for increase of leakage current with dose. It appears in oxygen lean Si.

Presence of a bistable donor which overcompensate radiation induced deep acceptors



It has been proven that the beneficial effect of oxygen consists not only in suppression of deep acceptors but creation of donors as well !!

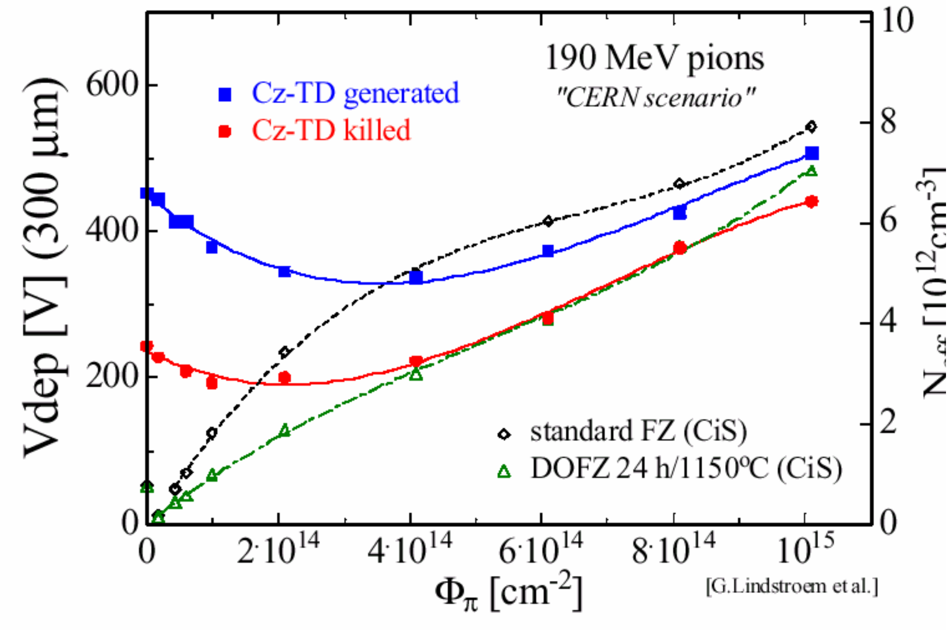
Study of the role of shallow donors in oxygen enriched material in progress in the low T range 4.2- 80K



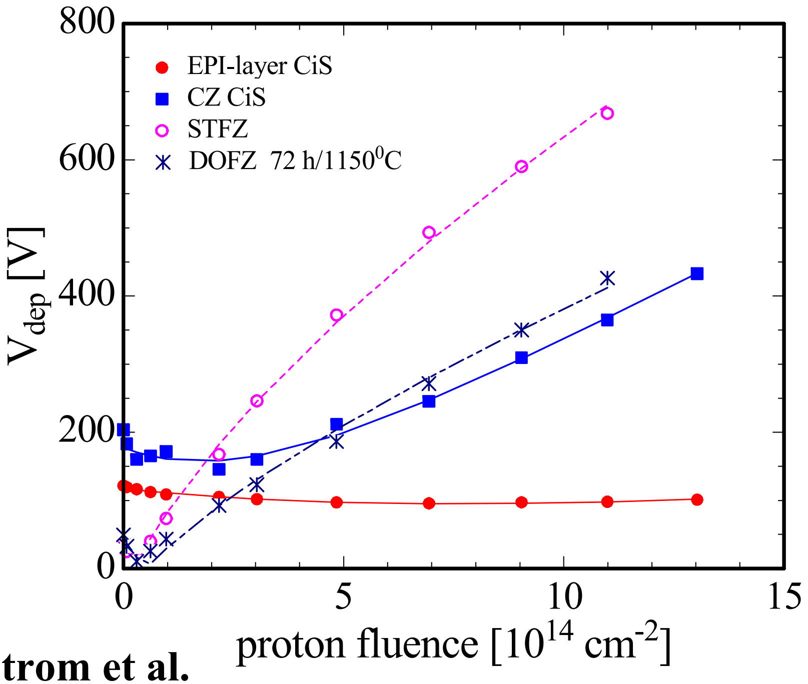
STFZ and DOFZ Si after 300MRad γ from ^{60}Co

Macroscopic Effects: recent results on Czochralski Si

190 MeV π irradiation Villigen
Cz from Sumitomo Sitix, Japan



24 GeV/c p irradiation CERN
Cz from Sumitomo Sitix, Japan



Data From G.Lindstrom et al.

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

10-30 MeV proton Jyväskylä, Finland
Magnetic Cz-Si Okmetic, Finland

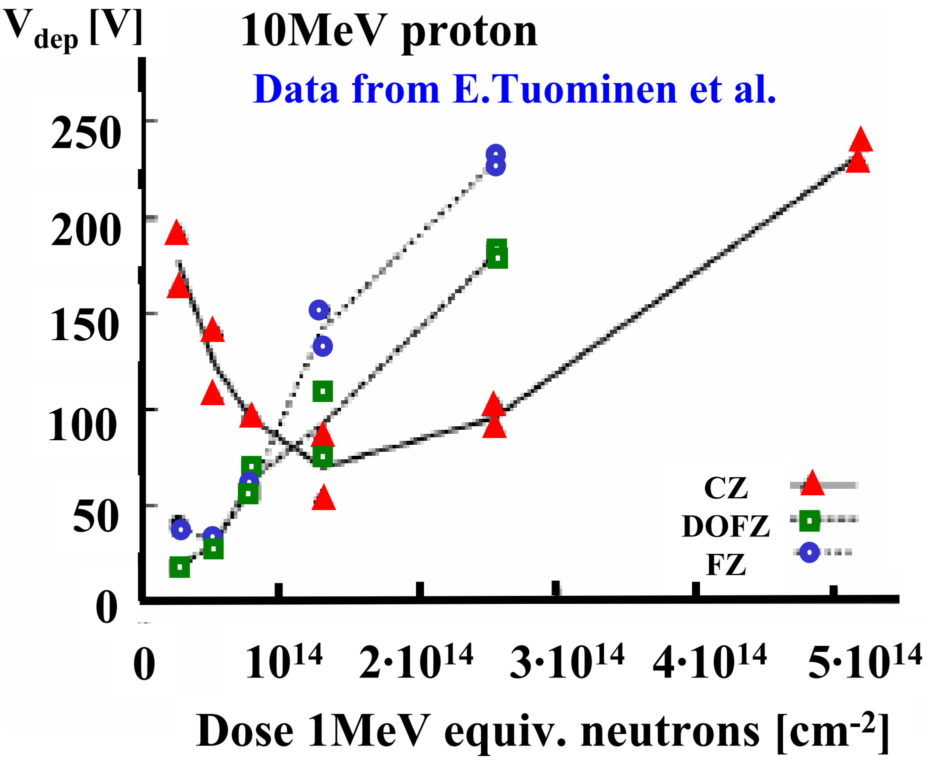
Improvement in V_{dep}, N_{eff}

Observed SCSI

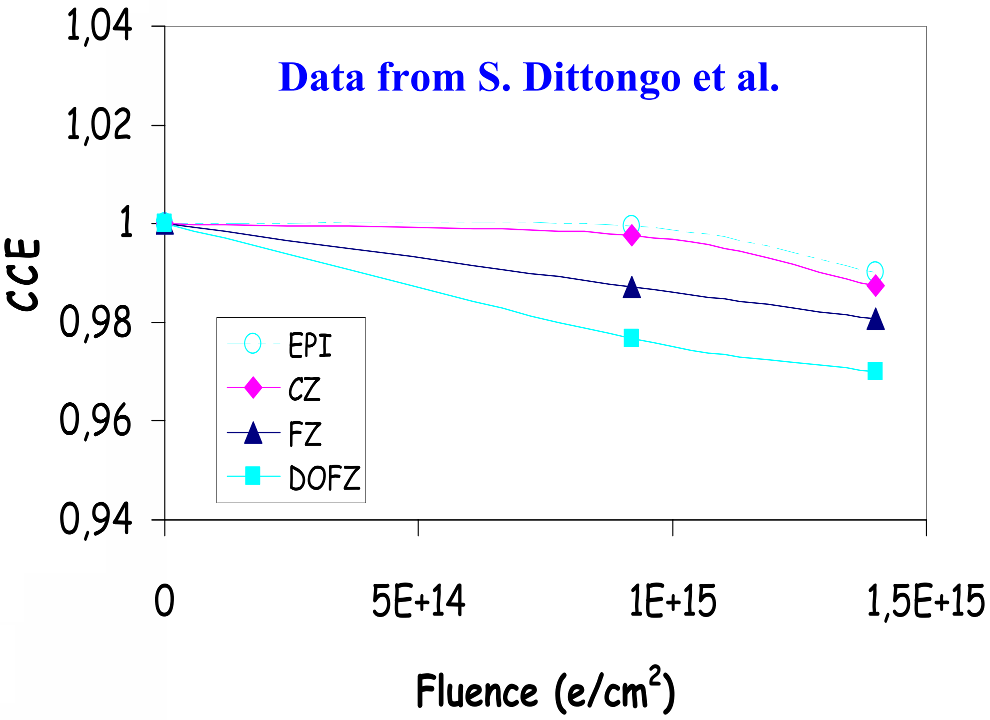
Reduction of reverse current ??

900 MeV electron Elettra (Trieste, Italy) CZ-Si Sumitomo Japan, EPI-ITME

Decrease of CCE observed only beyond 10^{15} ecm^{-2} for CZ and EPI



Data from E.Tuominen et al.



Data from S. Dittongo et al.

New Materials: Silicon Carbide and GaN

Property	Diamond	Si	4H- SiC	GaN
E_g [eV]	5.5	1.12	3.3	3.39
μ_e [cm^2/Vs]	1800	1450	800	1000
μ_h [cm^2/Vs]	1200	450	115	30
e-h pair creation [eV]	13	3.6	7.6-8.4	8.9
Displacement [eV]	43	13-20	25	≥15
Signal [e/μm]	36	89	51-55	~50
Density [g/cm^3]	3.515	2.329	3.22	6.15

♦ **Wide bandgap**

⇒ **lower leakage current than silicon**

♦ **Higher displacement threshold than silicon**

⇒ **radiation harder than silicon (?)**

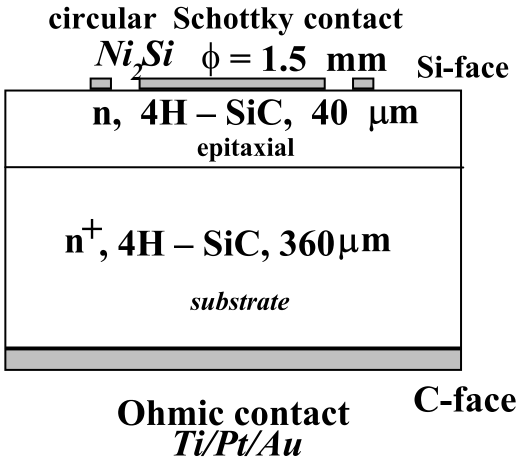
♦ **Signal:**

⇒ **more charge than diamond**

Common SiC RD50 test structures under way, coordinated by Hamburg, Glasgow, Tel Aviv.

Several research activities already in action.

Epitaxial SiC Schottky Barriers



circular Schottky contact

Ni_2Si $\phi = 1.5$ mm

Si-face

n, 4H – SiC, 40 μm

epitaxial

n^+, 4H – SiC, 360μm

substrate

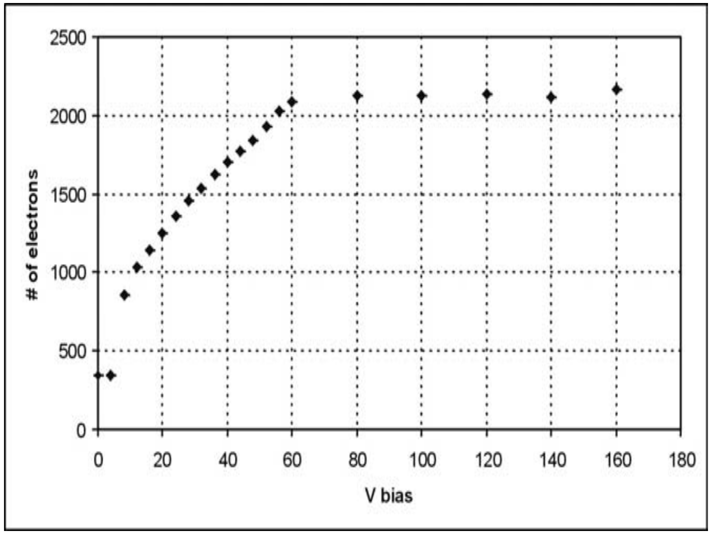
Ohmic contact

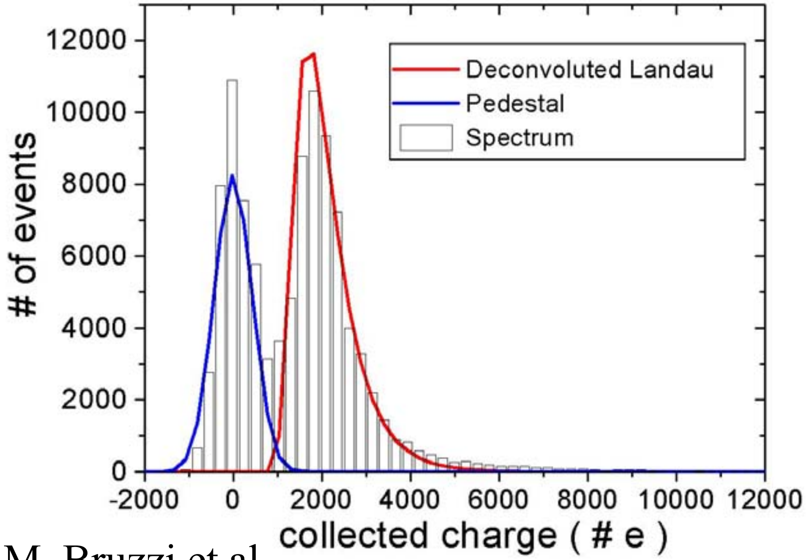
Ti/Pt/Au

C-face

- **n epilayer N_{eff} ~5×10^{13}cm^{-3} 40μm by IKZ Berlin on CREE substrate**
- **Schottky and Ohmic contacts produced by Alenia System**
- **Charge collection efficiency tested with αs ^{241}Am and β ^{90}Sr**
- **Irradiation tests with 24GeV proton in progress**

Q~2200e corresponding to CCE 100%at V_{dep}= 60V





Data from F. Nava, S. Sciortino, M. Bruzzi et al.

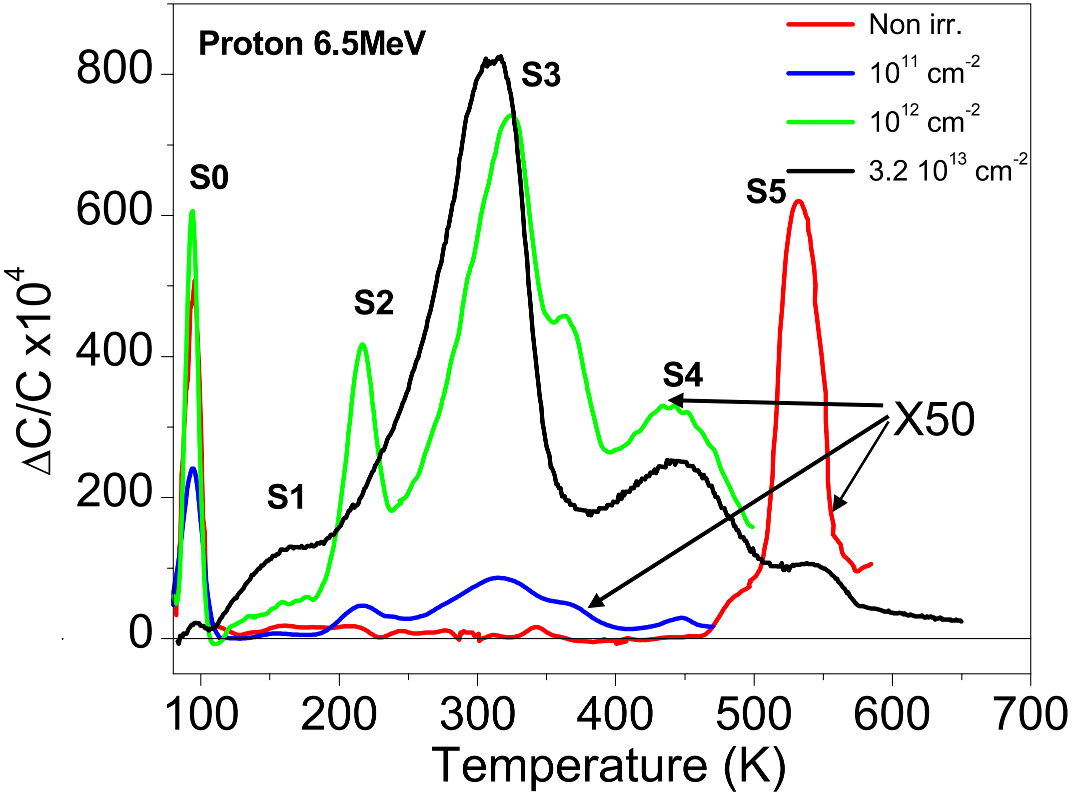
Proton-irradiation induced defects in epitaxial 4H-SiC Schottky Barriers

Research activity by the group of Bologna in collaboration with Torino

- **n epilayer 7µm**
- **N_{eff} ~$7\times10^{15}cm^{-3}$**
- **Schottky Barriers Ti or Ni**
- **Ohmic contacts Ti/Ni/Ag**
- **Deep levels by C-DLTS**
- **6.5MeV p up to $6.4\times10^{13}cm^{-2}$**

Six traps detected

- **E = 0.18 - 1.22eV**
- **$s = 10^{-13}-10^{-18}cm^{-2}$**
- **$N_t = 10^{11} - 5\times10^{14}$ cm^{-3}**



Data from A. Castaldini, A. Cavallini et al.

The creation of energy levels with N_t of the same order of magnitude of the doping density does not affect the charge transport in the detector. This probably due to the shallow energies of the traps.

2. SiC Triode Detector structures

Produced and tested at Ioffe Physico-Technical Institute, St. Petersburg, Russia

♦ **Development of radiation-hard triode (transistor) detector structures based on SiC layers. Triode detector to get amplification of a charge generated in the detector bulk and realize the gain of the detector signal compared to that in the diode structure.**

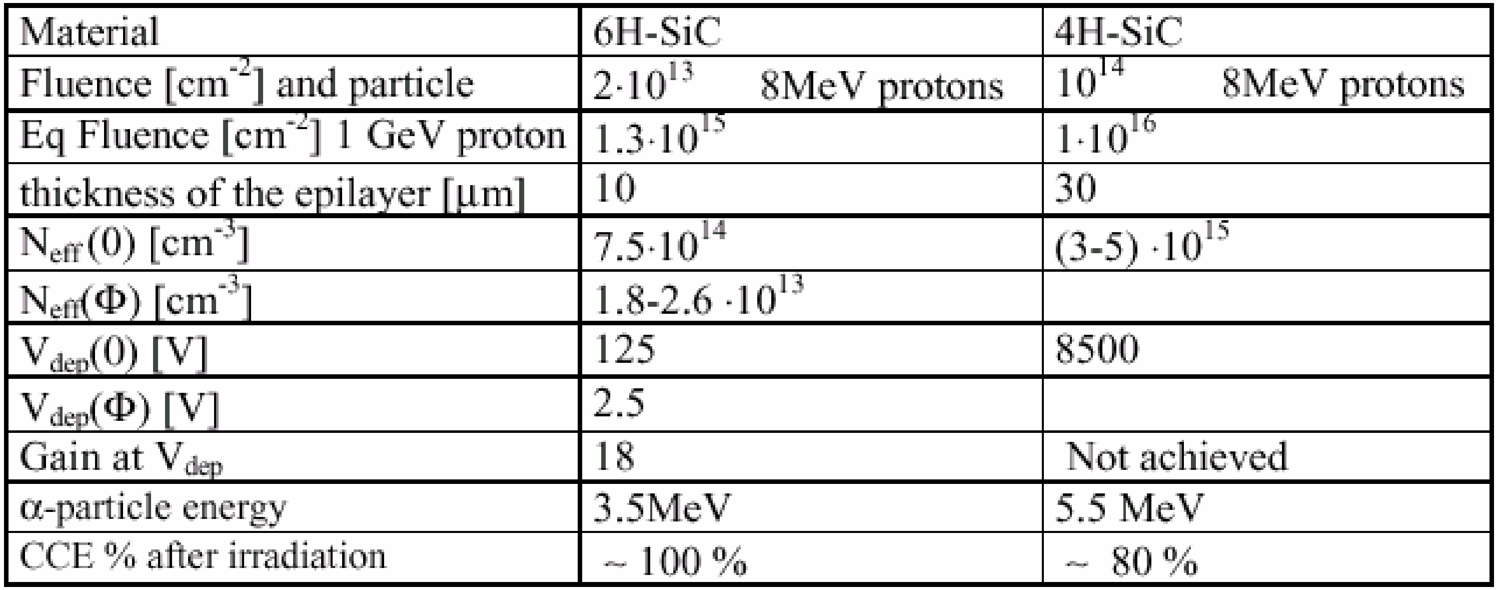
♦ **p-type epilayer SiC grown by sublimation epitaxy on n^+ SiC wafers:**
6H-SiC (processed at Ioffe Institute) 10µm
4H-SiC (processed in Linkoping University, Sweden) 30µm

Emitter: n^+ SiC wafer **Base: p^+ epi-layer** **Collector: Schottky barrier**

♦ **Irradiation at Ioffe Institute with 8 MeV protons up to 10^{13}-10^{14}cm^{-2}, corresponding to 10^{16}cm^{-2} 1GeV protons**

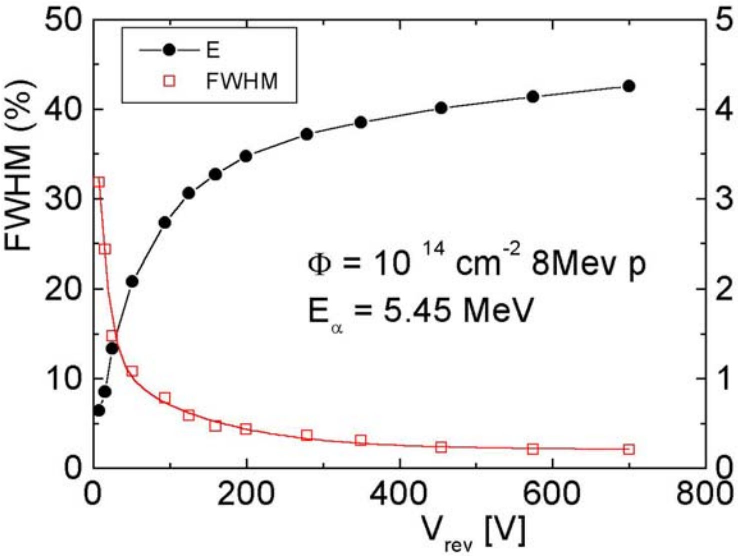
♦ **Charge collection efficiency investigated with α-particles E_α = 3.5 -5.45MeV**

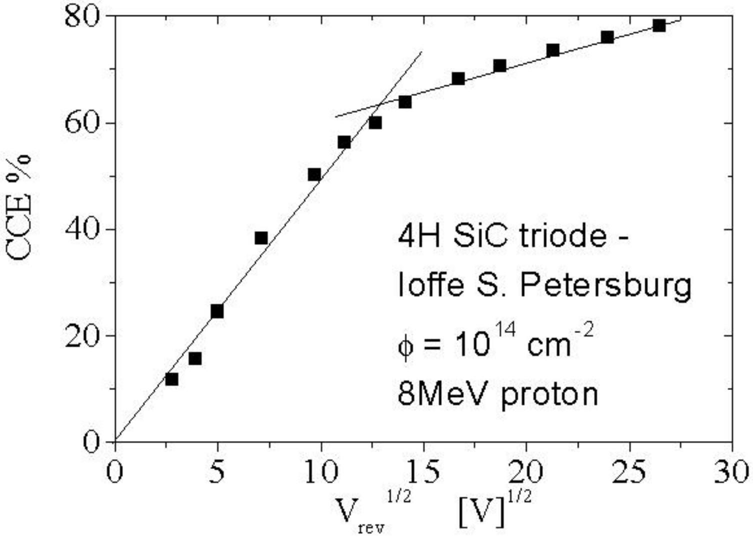
Results on Triode epitaxial SiC Detector after irradiation with 8 MeV p up to 10^{14}cm^{-2}



Material	6H-SiC	4H-SiC
Fluence [cm^{-2}] and particle	$2 \cdot 10^{13}$ 8MeV protons	10^{14} 8MeV protons
Eq Fluence [cm^{-2}] 1 GeV proton	$1.3 \cdot 10^{15}$	$1 \cdot 10^{16}$
thickness of the epilayer [μm]	10	30
$N_{eff}(0)$ [cm^{-3}]	$7.5 \cdot 10^{14}$	$(3\text{-}5) \cdot 10^{15}$
$N_{eff}(\Phi)$ [cm^{-3}]	$1.8\text{-}2.6 \cdot 10^{13}$	
$V_{dep}(0)$ [V]	125	8500
$V_{dep}(\Phi)$ [V]	2.5	
Gain at V_{dep}	18	Not achieved
α-particle energy	3.5MeV	5.5 MeV
CCE % after irradiation	~ 100 %	~ 80 %

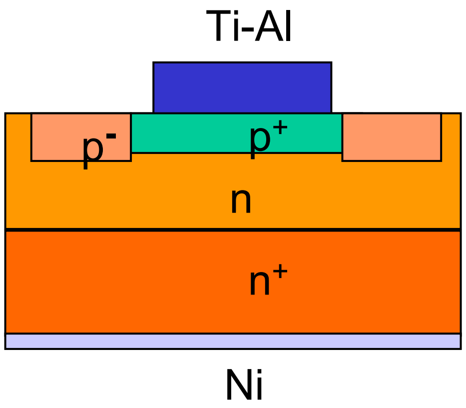
Data From E. Verbitskaya et al.

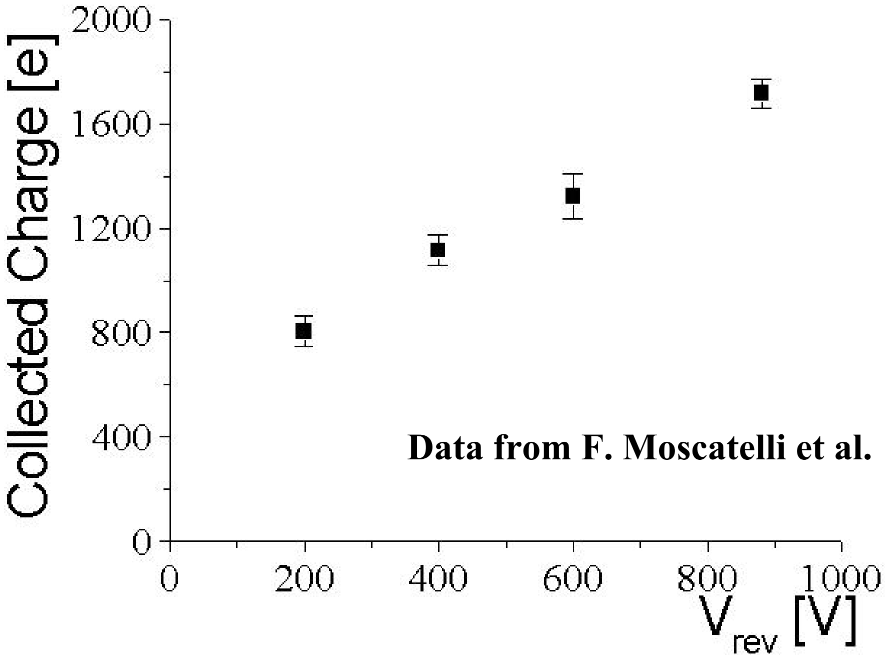




3. SiC p^+n junction detectors

Research activity of the Perugia group in collaboration with Florence, IMM-CNR Bologna and INSA-CEGELY, Lyon France





Data from F. Moscatelli et al.

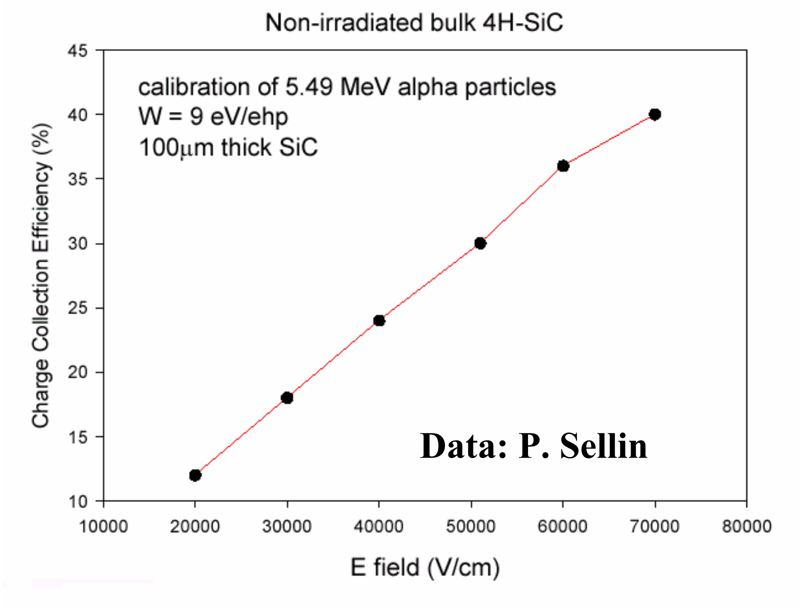
$W = 40\ \mu m$ $N_{eff} = 1.1 \cdot 10^{15} cm^{-3}$

$V_{dep} \sim 1600V$ Tested at Florence with β from ^{90}Sr

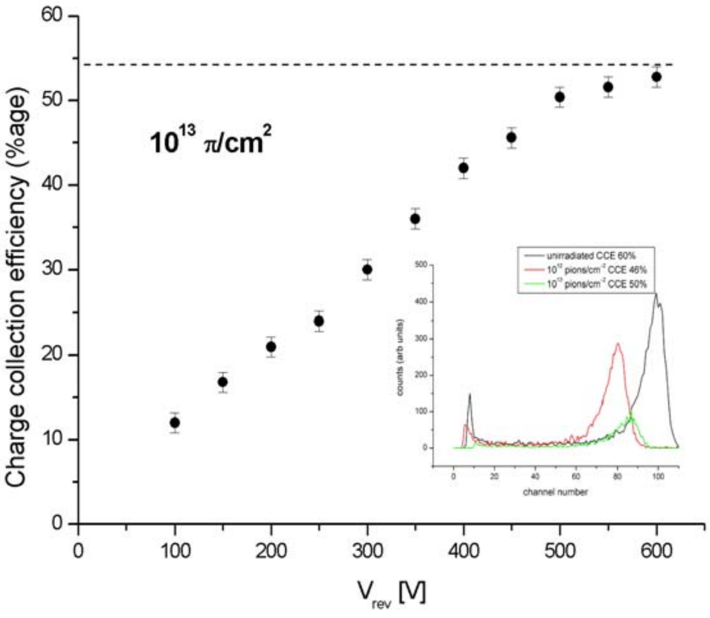
At 900V from C-V, depletion depth ~30μm, charge collected 1720e → CCE 100%

Semi-Insulating SiC detectors

Research activity of Glasgow, Surrey, Vilnius. Bulk SiC has incomplete charge collection (no e transport) and suffers for polarisation effects (traps e.g. Vanadium and micropipes)



Data: P. Sellin



Simulated CCE of bulk and epi devices up to fluences of 10^{16} cm^{-2} in talk N33-3 by Tina Quinn et al.

Data from M. Rahman et al.

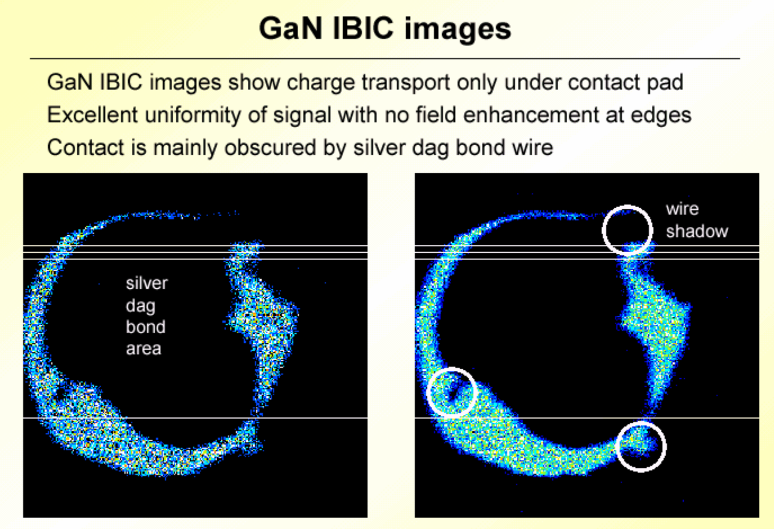
Semi-Insulating GaN detectors

Research activity of Vilnius, Glasgow, Surrey

- **SI-GaN epitaxial layer on n-type GaN substrate** (University of Tokushima Japan)
- **Au Schottky contacts 1.5 mm diameter**
- **Charge Collection tested with α-particles ^{241}Am by Glasgow, Surrey groups**
- **Irradiated by X rays 600MRad**
- **Irradiated by neutrons in Ljubljana up to 5x10^{14}cm^{-2}**

SI-GaN	**Energy**	**Fluence**	**CCE %**
Non-Irradiated			92
Irradiated by X-rays	10keV	600MRad	100
Irradiated by neutrons	100keV	5x10^{14}cm^{-2}	77

Future work: study thicker SI-GaN epilayers



GaN IBIC images

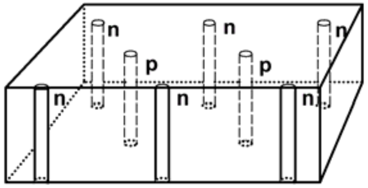
GaN IBIC images show charge transport only under contact pad
Excellent uniformity of signal with no field enhancement at edges
Contact is mainly obscured by silver dag bond wire

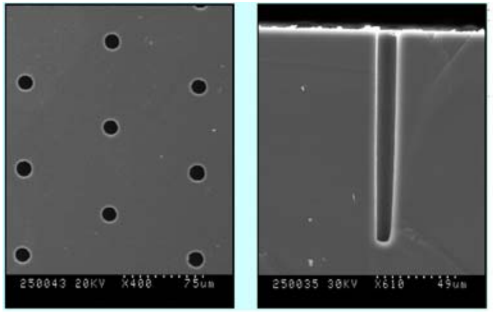
See P. Sellin and J. Vaitkus talks at 2nd RD50 workshop

www.cern.ch/rd50

Device Engineering: 3D and Semi3D detectors

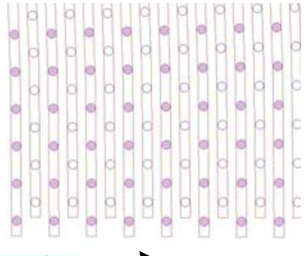
- Semi 3-d devices, proposed by Z. Li, BNL, made in collaboration with US groups
- 3-d devices, proposed by S. Parker.

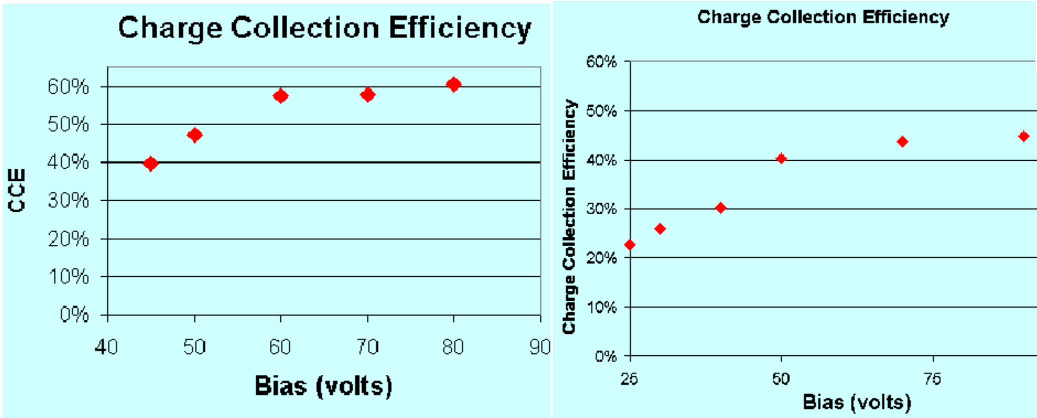




Holes processing: dry etching, Laser drilling, Photo electrochemical. Present aspect ratio (within RD50) 13:1, target > 30:1

Some result (α spectroscopy) before and after 10^{14} 300 MeV/c π cm^{-2}

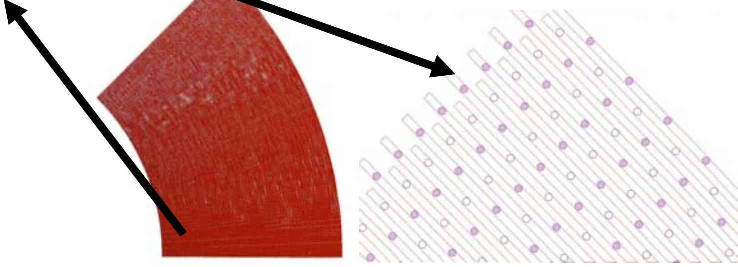




before

after

Data from P. Roy, 2nd RD50 workshop



3D design for Velo

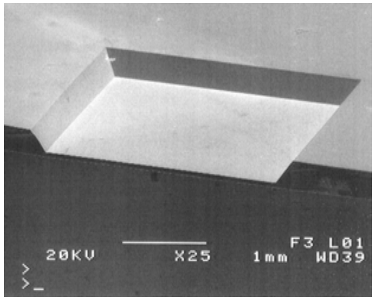
Very promising silicon devices for speed and radiation hardness.

Device engineering: Thin SiC detectors by micromachining

The active thickness of the device after heavy irradiation is limited by the effective drift lengths e: ~150μm, h:~50μm after 1MeV neutron irradiation at 10^{15}cm^{-2} (Kramberger et al.).

Thin Si detectors 50-100μm: low V_{dep}, limited leakage current
Two technical Approaches:

- **Thinning by micromachining: research activity of the IRST-Trento group in collaboration with the other italian groups.**



IRST-Trento: SEM of a silicon wafer thinned by TMAH

Cross section of a thinned silicon detector by IRST-Trento

Thickness [μm]	**Leakage Current [nA/cm^3]**	**V_{dep} [V]**
300	**80**	**12**
99	**30**	**~1**
57	**55**	**<1**

Ready to be irradiated.

- **Epitaxial Si detectors: wafers by ITME, processed by CiS, now irradiated up to 9.2410^{15} 24GeV p/cm^2 at CERN, measurements (Hamburg group) in progress.**

Talks of RD50 group members at IEEE 2003 NSS and RTSD

N4-5 Super radiation hard technologies: 3D and widegap detectors M.Rahman et al.

N20-6 Measurement of the Trapping Time constants in proto-irradiated, Si …. O. Krasel et al.

N20-4 Radiation damage in bipolar transistors caused by thermal neutrons, I. Mandic et al.

N26-17 Lithium Ion Irradiation effects on diodes manufactured on epitaxial Si, A.Candelori et al.

N26-20 Radiation damage tests of all-p type termination structures …. C. Piemonte et al.

N26-21 An enhanced device simulation of heavily irradiated silicon … F. Moscatelli et al.

N26-22 TSc analysis of gamma irradiated standard and oxygenated diodes … D. Menichelli et al.

N33-2 Radiation Hardness of high resistivity CZ Si detectors after gamma…. Z. li et al.

N33-3 Comparison of Bulk and Epitaxial 4H-SiC detectors T. Quinn et al.

N36-117 Single Neutron pixel detectors based on medipix-1 Device, I.Iakubek et al.

R15-2 On the physical processes induced by particle irradiation … by A.Cavallini et.

R18-4 Perfomance of Silicon Carbide Radiation Detectors, F. Nava et al.

Summary

RD50: Development of Ultra Radiation Hard semiconductor detectors for Super LHC. Promising results have been obtained:

♦ Radiation hardening by defect engineering: reduction of N_{eff} at high fluences of fast hadrons and gamma doses using oxygen enriched Si (DOFZ, Cz, MCz, epitaxial)

♦ SiC and GaN → good charge collection properties but thicker layers required to be competitive with Si

♦ 3-D detectors: promise of radiation hardness ($\sim 10^{14}$ p/cm^2), improvement of aspect ratio, electrodes in progress

♦ device engineering by thinning, edge-less detectors, semi-3d: projects running

♦ Irradiations at very high doses (10^{16}cm^{-2}) of single pad and segmented devices in progress