Radiation tolerant materials for semiconductor tracking detectors at SuperLHC

Mara Bruzzi

INFN, Dipartimento Energetica, University of Florence, Italy

- ✓Motivation to develop radiation harder detectors
- ✓Introduction to the RD50 collaboration
- ✓Radiation Damage
- ✓ Material Engineering
- ✓Summary

Large Scale Application of Si Detectors in High Energy Physics Experiments

LHC: Present working conditions:

$L \sim 10^{34}$ cm^{-2}s^{-1} within 10 years fast hadron fluence:

→

f ~ 10^{15} n/cm^{2} for pixels

f ~ 10^{14} n/cm^{2} for microstrips

LHC upgrade (“Super-LHC” … later than 2010)

$L \sim 10^{35}$ cm^{-2}s^{-1} → fluence up to 10^{16} 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

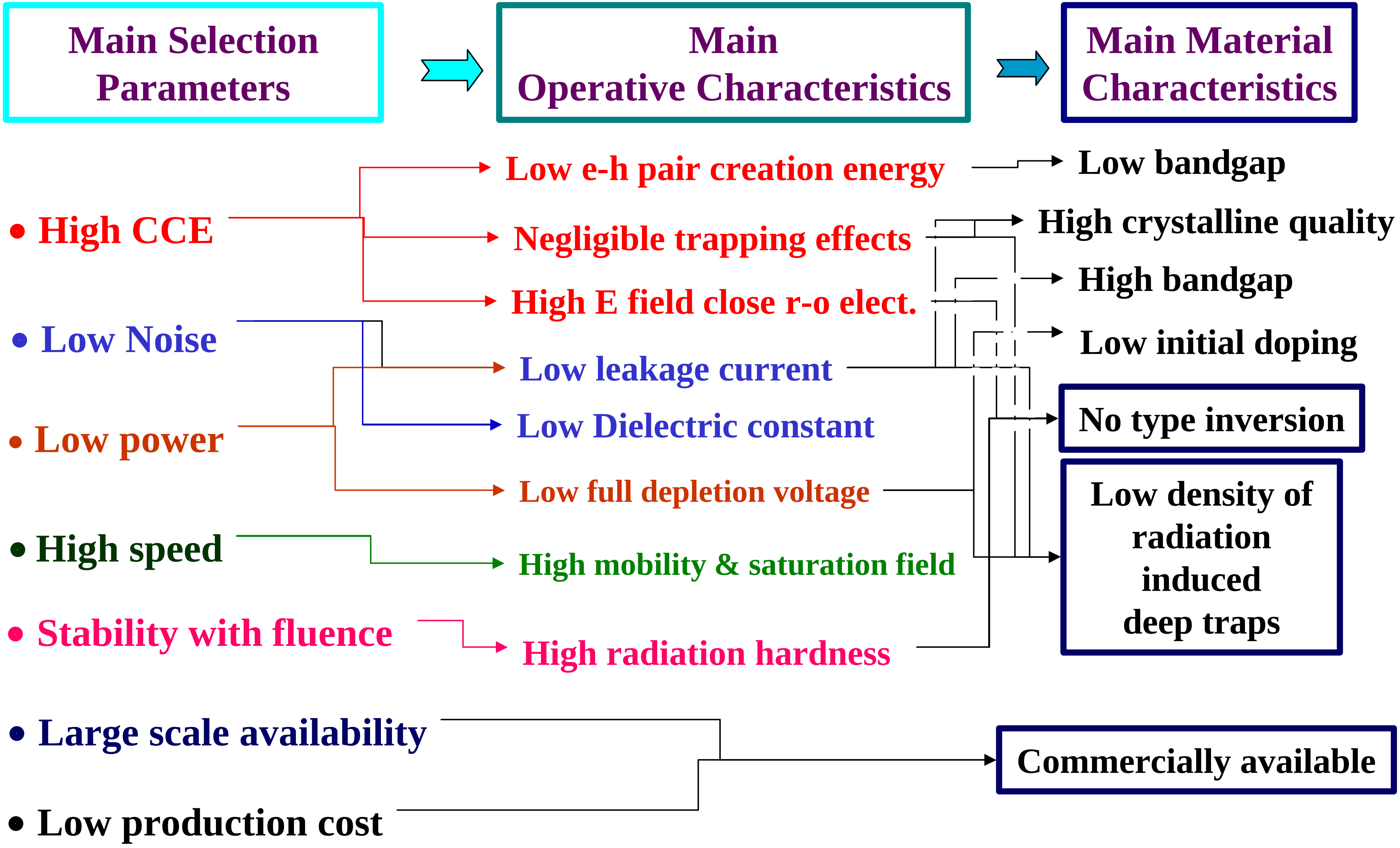
Hadron fluence and radiation dose in different radial layers of the CMS tracker for an integrated luminosity of 2500fb^{-1} . (CERN-TH/2002-078)

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

Proposal to split the tracker volume 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**

Selecting Radiation- Hard materials for tracker detectors at SuperLHC



Main Selection Parameters → **Main Operative Characteristics** → **Main Material Characteristics**

- High CCE
- Low Noise
- Low power
- High speed
- Stability with fluence
- Large scale availability
- Low production cost

Low e-h pair creation energy

Negligible trapping effects

High E field close r-o elect.

Low leakage current

Low Dielectric constant

Low full depletion voltage

High mobility & saturation field

High radiation hardness

Low bandgap

High crystalline quality

High bandgap

Low initial doping

No type inversion

Low density of radiation induced deep traps

Commercially available

Status of radiation-hard materials for tracking detectors at SLHC

Property	Si	Diamond	Diamond	4H SiC
Material Quality	Cz, FZ, epi	Polycrystalline	single crystal	epitaxial
E_g [eV]	1.12	5.5	5.5	3.3
$E_{breakdown}$ [V/cm]	$3\cdot10^5$	10^7	10^7	$2.2\cdot10^6$
m_e [cm^2/Vs]	1450	1800	>1800	800
m_h [cm^2/Vs]	450	1200	>1200	115
v_{sat} [cm/s]	$0.8\cdot10^7$	$2.2\cdot10^7$	$2.2\cdot10^7$	$2\cdot10^7$
Z	14	6	6	14/6
e_r	11.9	5.7	5.7	9.7
e-h energy [eV]	3.6	13	13	7.6
Density [g/cm3]	2.33	3.515	3.515	3.22
Displacem. [eV]	13-20	43	43	25
e-h/mm for mips	89	36	36	55
Max initial ccd [mm]	>500	280	550	40 (= thickness)
Max wafer f tested	6”	6”	6mm	2”
Producer	Several	Element-Six	Element-Six	Cree-Alenia, IKZ
Max f luence[cm^{-2}]	$7x10^{15}$ 24GeV p	$2x10^{15}$ n, p, p	Not reported	10^{16} in progress
CERN R&Ds	RD50, RD39	RD42	RD42	RD50

See H. Kagan Talk

See Kinoshita Talk

CERN R&Ds for LHC

- **RD-2 SITP (1990-1994)**
  Study of a Tracking/Preshower Detector for the LHC

- **RD-8 GAASWORKS (1991-1995)**
  Development of GaAs Detectors for Physics at the LHC

- **RD-19 PIXEL (1991-2000)**
  Development of Hybrid and Monolithic Silicon Micropattern Detectors

- **RD-20 Si TRACKER(1990-1994)**
  Development of High Resolution Si Strip Detectors for Experiments at High Luminosity LHC

- **RD39 SMSD (1994 – present)**
  Cryogenic Tracking Detectors ® **J. Harkonen talk, this session**

- **RD42 (1994 – present)** ® **H. Kagan talk, this session**
  Development of Diamond Tracking Detectors for High Luminosity Experiments at the LHC

- **RD48 ROSE (1996-2000)**
  Radiation Hardening of Silicon Detector

- **RD49 RADTOL (1997-2000)**
  Studying Radiation Tolerant ICs for LHC

- **RD50 (2002 -)**
  Development of Radiation Hard Semiconductor Devices for Very High Luminosity Colliders

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").

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**

- **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)

Scientific strategies

- **Material Engineering**

  - Defect and Material Characterisation

  - Defect engineering of silicon

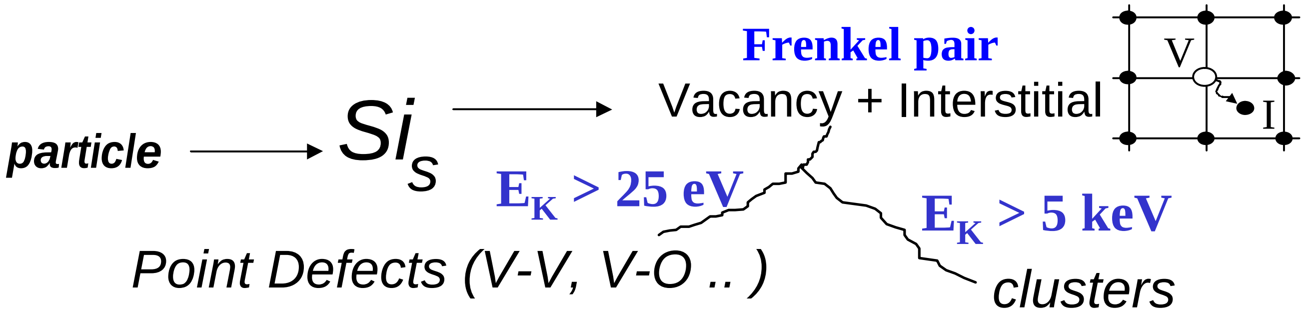
  - New detector materials (SiC, ..)

- **Device Engineering**

  - Improvement of present planar detector structures (3D detectors, thin detectors, cost effective detectors,…)

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

Radiation Induced Microscopic Damage in Silicon



particle → Si_s →

Frenkel pair

Vacancy + Interstitial

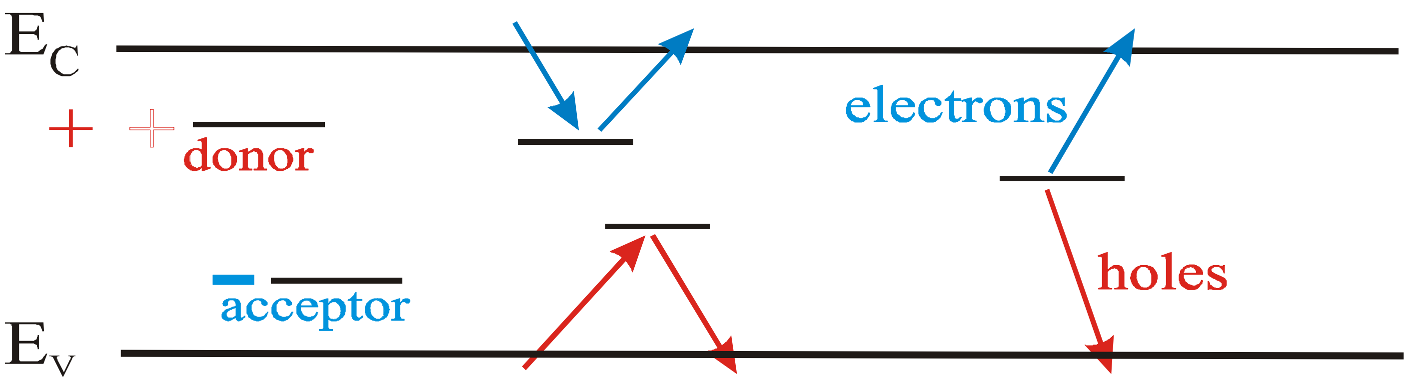
E_K > 25 eV

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

E_K > 5 keV

clusters

Influence of defects on the material and device properties



charged defects

Þ N_{eff} , V_{dep}

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

Trapping (e and h)

Þ CCE

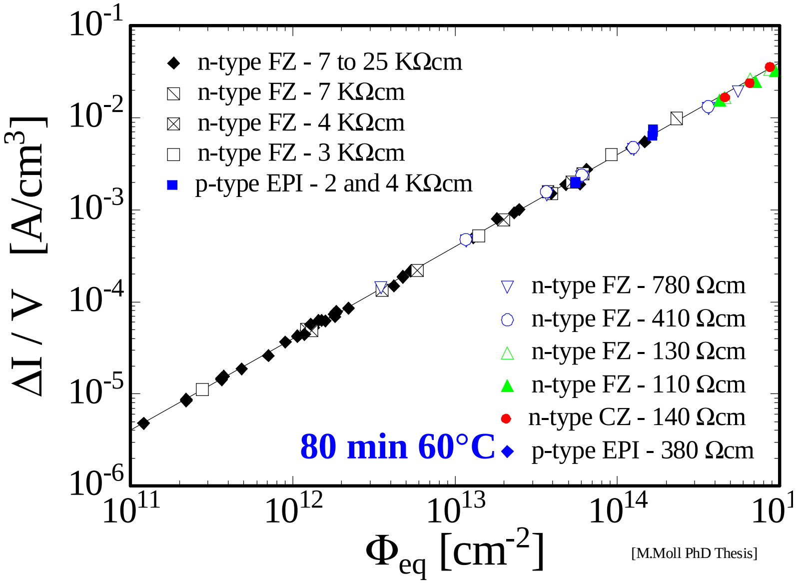
shallow defects do not contribute at room temperature due to fast detrapping

generation

Þ leakage current

Levels close to midgap most effective

Leakage Current



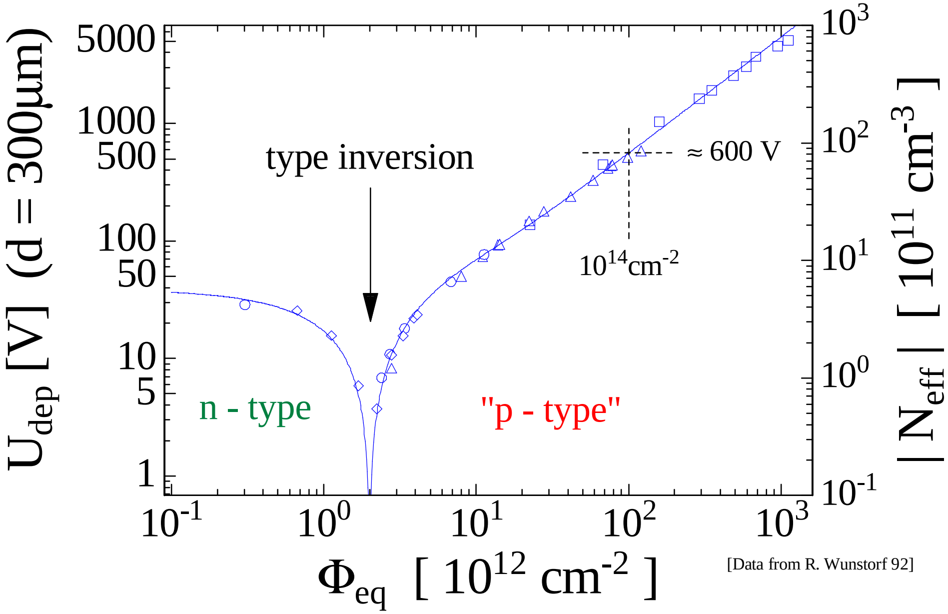
[M.Moll PhD Thesis]

- **Damage parameter** a **(slope)**

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

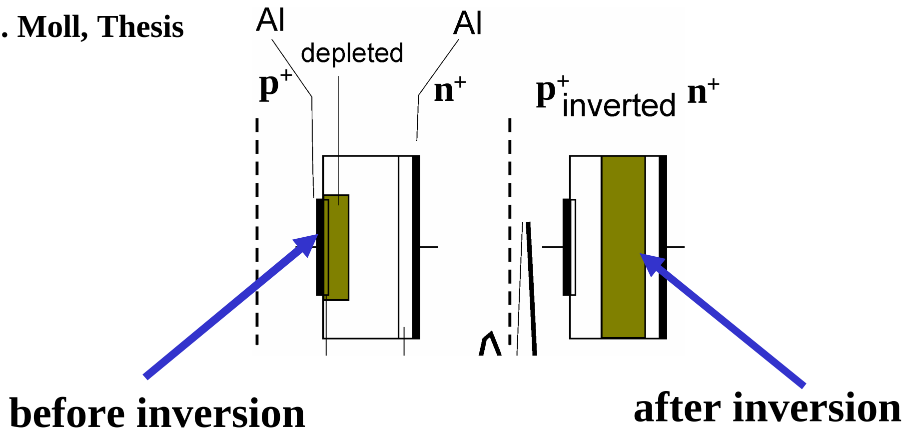
- a **independent of** F_{eq} **and material kind**

V_{dep}, N_{eff}



[Data from R. Wunstorf 92]

M. Moll, Thesis



Charge Collection Efficiency

Limited by:

- **Partial depletion**
- **Trapping at deep levels**
- **Type inversion**

Collected Charge: $\mathrm{Q} = \mathrm{Q}_o \cdot e_{\mathrm{dep}} \cdot e_{trap}$

$$e_{dep} = \frac{d}{W} \qquad e_{trap} = e^{-\frac{t_c}{t_t}}$$

W: total thickness

d: Active thickness

τ_c : Collection time

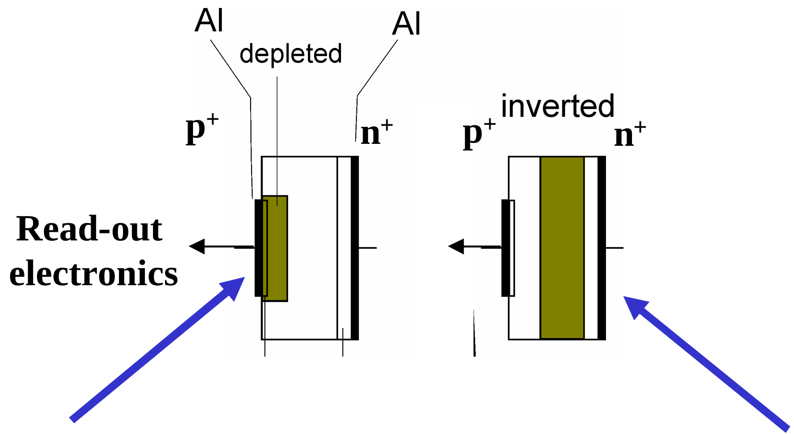
τ_t : Trapping time

Trapping time reduced by radiation:
Krasel et al. (RD50)
for e/h up to 10^{15} cm^{-2} n- Si:

$1/\ t_t = 5*(F/10^{16})\ \mathrm{ns}^{-1}$

$t_t \sim 1/\ F$

$t_t = 0.2\ \mathrm{ns}$ for $F = 10^{16}\ \mathrm{cm}^{-2}$



before inversion

after inversion
neglecting double junction

Defect Engineering of Silicon

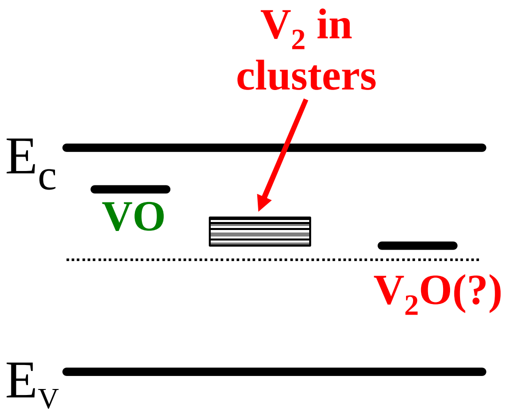
Influence the defect kinetics by incorporation of impurities or defects: Oxygen

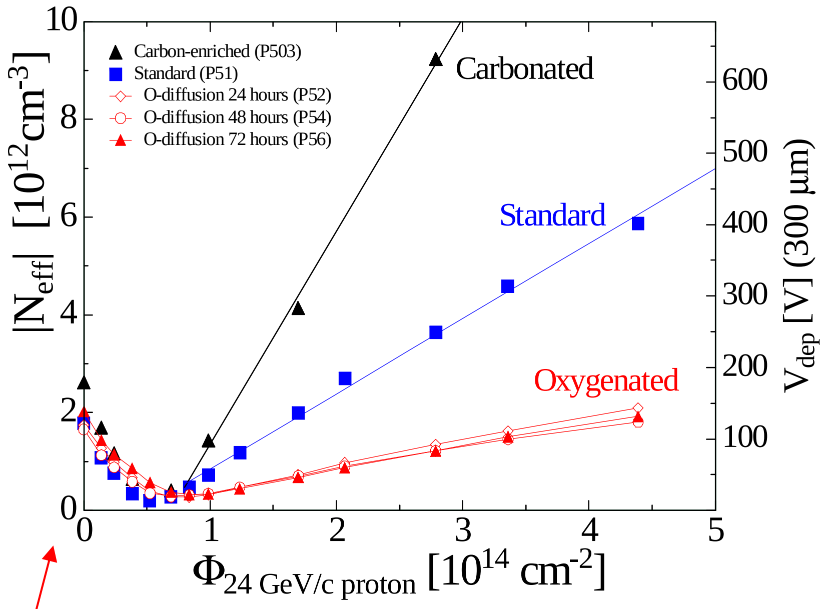
Initial idea: **Incorporate Oxygen to getter radiation-induced vacancies**
⇒ prevent formation of Di-vacancy (V_2) related deep acceptor levels

- Higher oxygen content ⇒ less negative space charge

One possible mechanism: V_2O is a deep acceptor

V → O → VO (not harmful at RT)
V → VO → V_2O (negative space charge)





DOFZ (Diffusion Oxygenated Float Zone Silicon) RD48 NIM A (1999)

Different kind of Si materials investigated by RD50

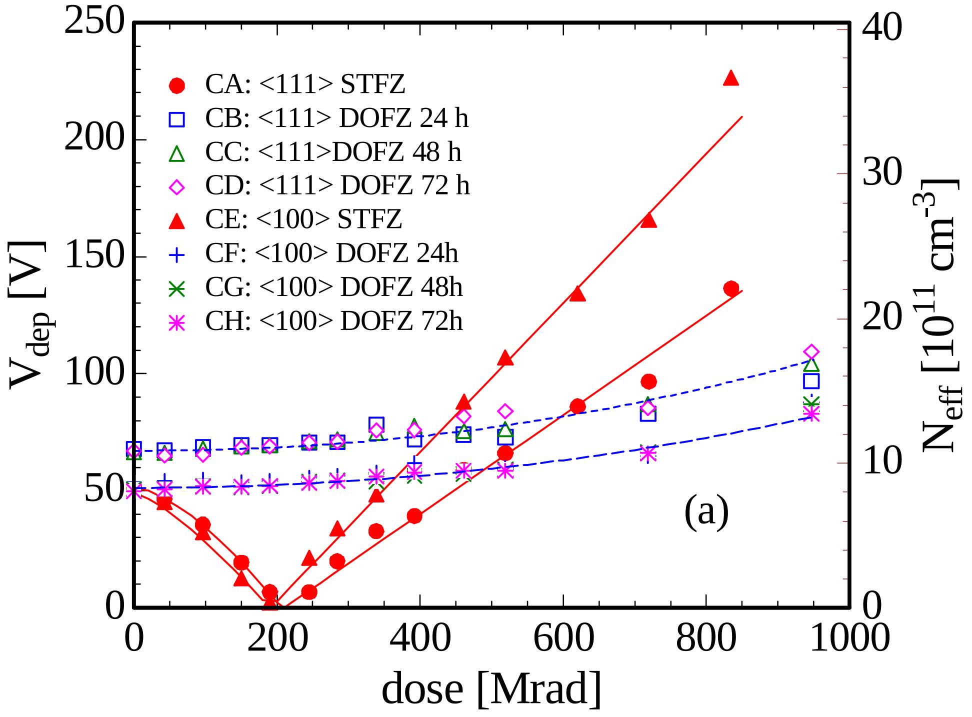
Material	**Symbol**	**r W cm**	**[O_i] cm^{-3}**
Standard n- or p-type FZ	**STNFZ**	**1-7 · 10^3**	**< 5 10^{16}**
Diffusion Oxygenated FZ p- or n-type	**DOFZ**	**1-7 · 10^3**	**~ 1-2 10^{17}**
Epi-layer 50 µm on CZ n-type ITME	**EPI**	**50-100**	**substrate: 1· 10^{18}**
Czochralski Sumitomo, Japan	**CZ**	**1.2 · 10^3**	**~ 8-9 10^{17}**
Magnetic Czochralski Okmetic Finland	**MCZ**	**1.2 · 10^3**	**~ 5-9 10^{17}**

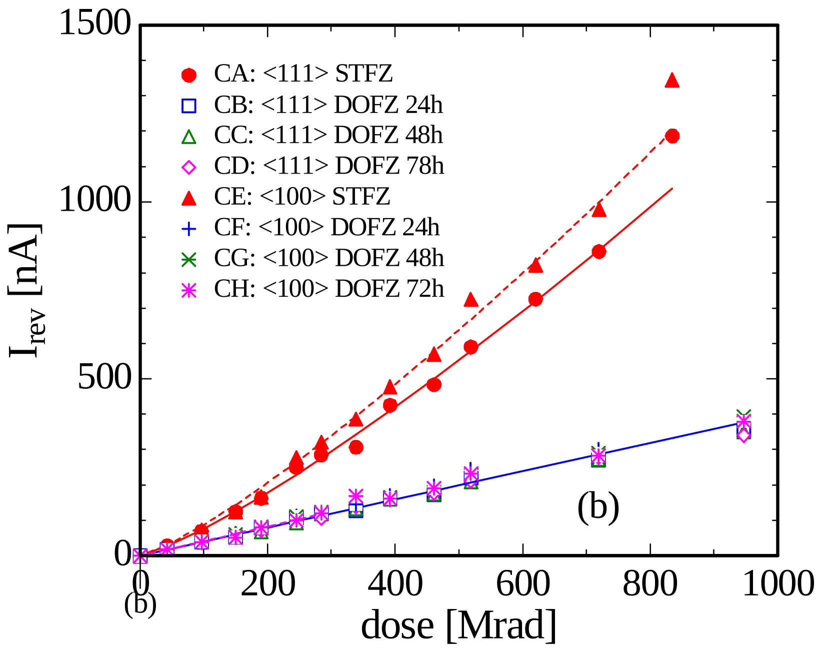
Czochralski Si

See also talk of J. Harkonen

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

DOFZ Si: Spectacular Improvement of γ-irradiation tolerance


Depletion Voltage


Leakage Current

- No type inversion for oxygen enriched silicon!
- Slight increase of positive space charge

  (due to Thermal Donor generation?)
- Leakage increase not linear and depending on oxygen concentration

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

Characterization of microscopic defects
- γ-irradiated silicon detectors -

•<u>For the first time</u> **macroscopic changes of the depletion voltage and leakage current can be explained by electrical properties of measured defects →** **Major breakthrough!**

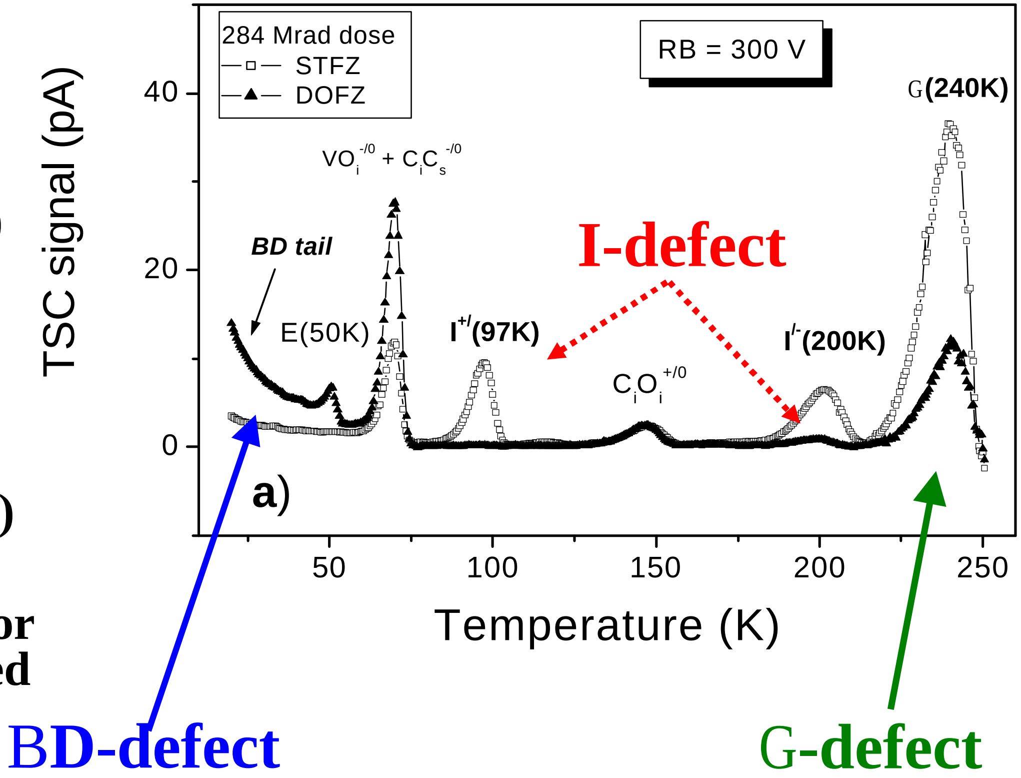
I.Pintilie et al., Applied Physics Letters,82, 2169, March 2003

Levels responsible for macroscopic changes after γ-irradiation:

- I–defect: **acceptor level at E_C-0.54eV (coming up for approx. 85% of damage)** <u>peculiarity</u>: **quadratic dose dependence**
  ⇒ **is this the V_2O defect ?**

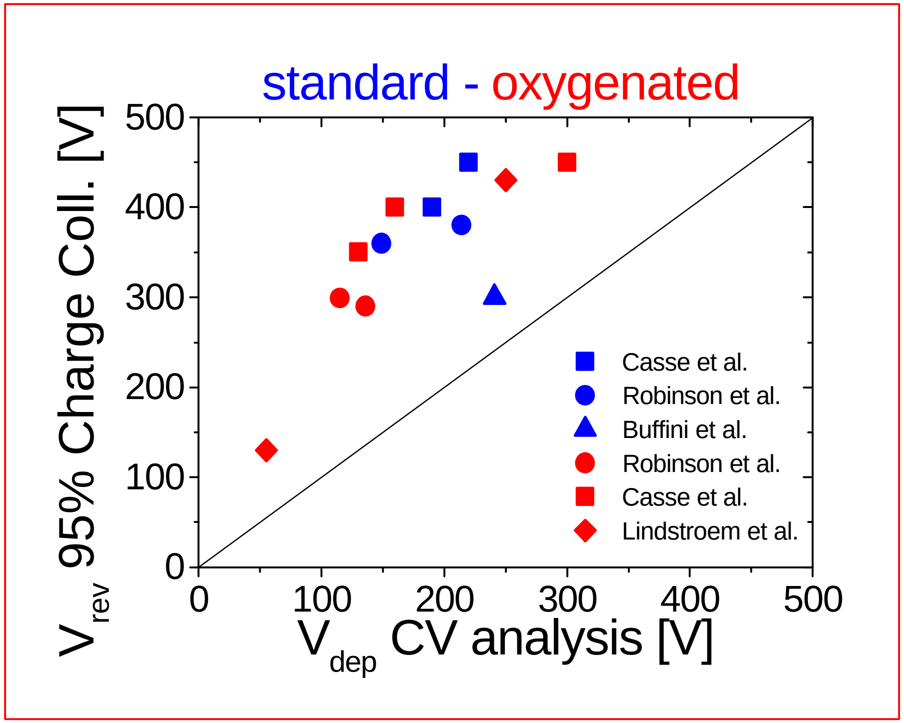
- Γ-defect: **acceptor level at E_V+0.68eV (coming up for approx. 10% of damage)**

- BD-defect: **bistable shallow thermal donor (important in oxygen enriched silicon)**



Discrepancy between CCE and CV analysis with p^+n devices

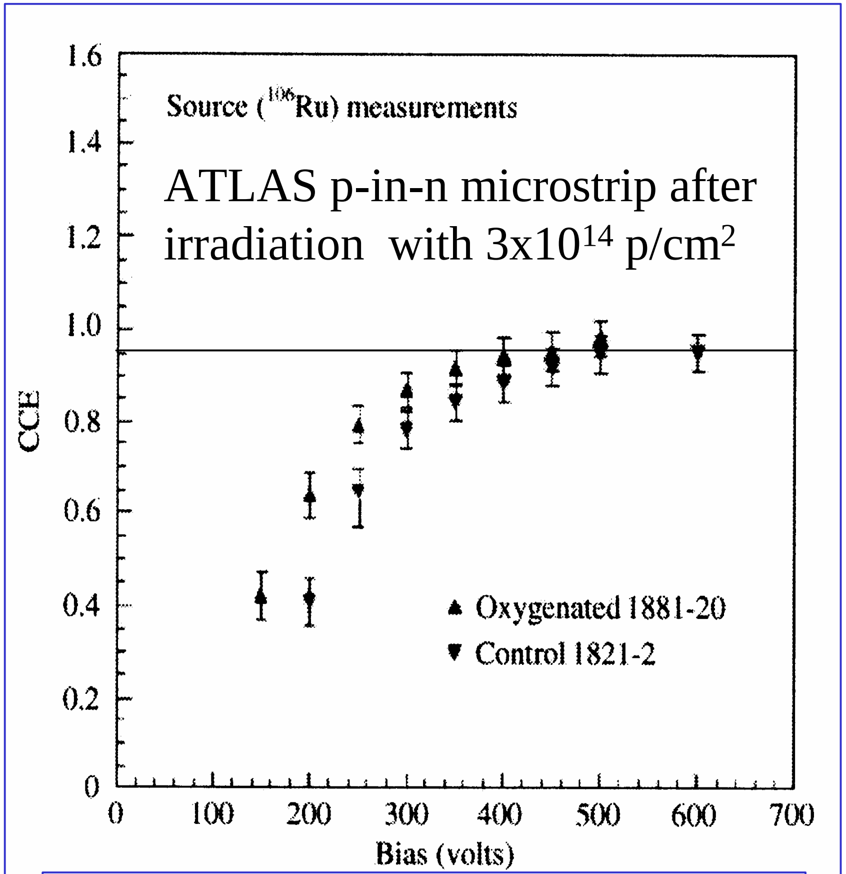
In segmented p^+n detectors read-out with LHC-like electronics above the CV-derived depletion voltage, the CCE continues to rise significantly with bias. **To maximise CCE overdepletion V_{CCE}~$2V_{dep}$ is needed both in n-type standard and oxygenated Si.**



	Author	radiation	Exp.	material
?	Robinson et al., NIM A 461 (2001)	3×10^{14} 24GeV p/cm^2	ATLAS	Oxygen. + standard
¦	Casse et al., NIM A 466 (2001)	$3\text{-}4 \times 10^{14}$ 24GeV p/cm^2	ATLAS	Oxygen. + standard
?	Lindström et al., NIM A 466 (2001)	1.65×10^{14} 24GeV p/cm^2	ROSE	Oxygen. <100>
?	Buffini et al., NIM A (2001) in press	1.1×10^{14} 1MeV n/cm^2	CMS	Standard <111>

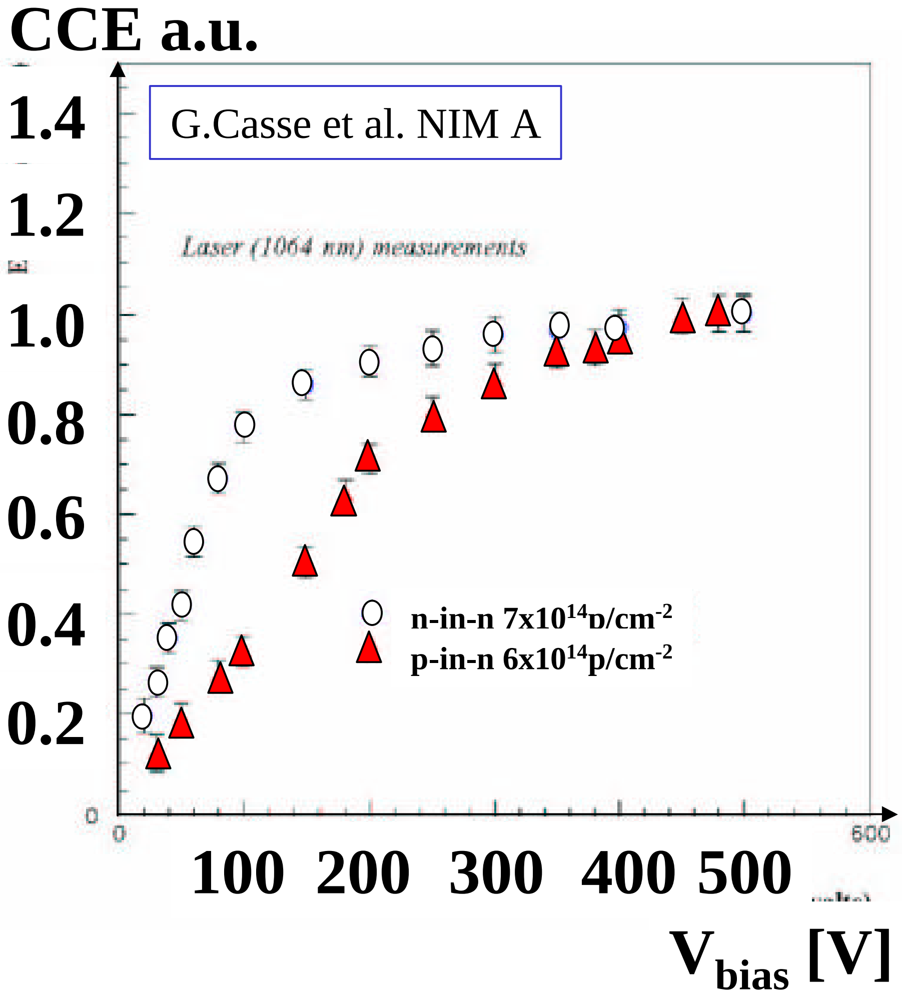
Same behavior for standard and oxygenated (DOFZ), <100> and <111>Si

The beneficial effect of oxygen in proton irradiated DOFZ p^+n Si microstrips almost disappear in CCE measurements due to type inversion. Better results achieved with n-in-n detectors.



ATLAS p-in-n microstrip after irradiation with 3×10^{14} p/cm^2

G.Casse et al. NIM A 466 (2001) 335-344



G.Casse et al. NIM A

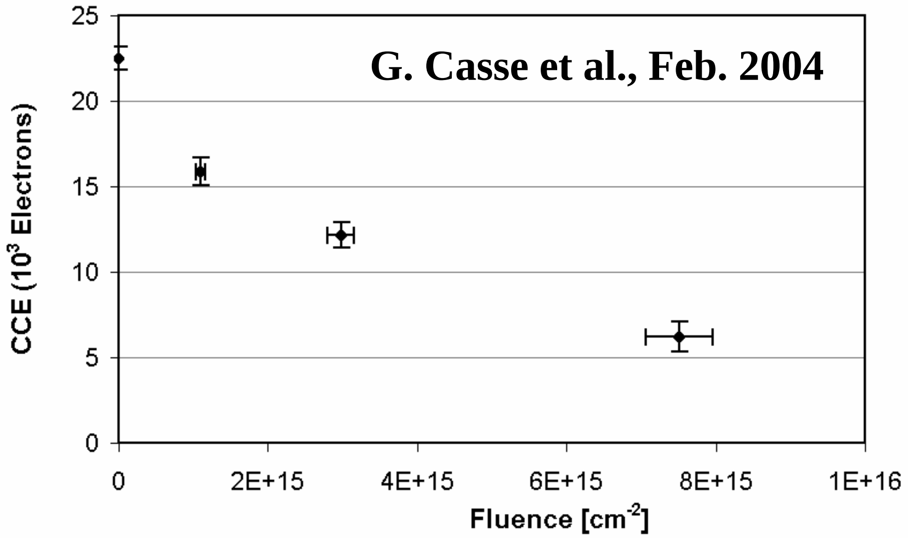
Recent results with n-in-p microstrip detectors

Liverpool & CNM-Barcelona within RD50
Data presented by G. Casse at Vienna Conference, February 2004

- **Miniature n-in-p microstrip detectors (280mm thick) produced by CNM-Barcelona using a mask-set designed by the University of Liverpool.**
- **Detectors read-out with a SCT128A LHC speed (40MHz) chip**
- **Material: standard p-type and oxygenated (DOFZ) p-type**
- **Irradiation: 24GeV protons up to 3 10^{15} p cm^{-2} (standard) and 7.5 10^{15} p cm^{-2} (oxygenated)**

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

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

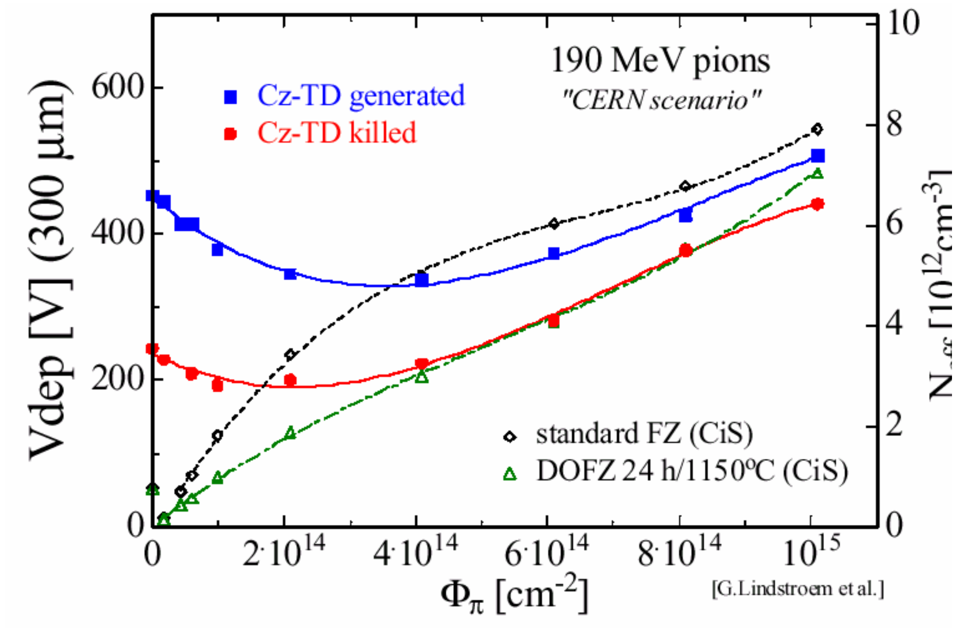


At the highest fluence Q~6500e at V_{bias}=900V corresponding to: ccd~90µm

n-type Czochralski Si

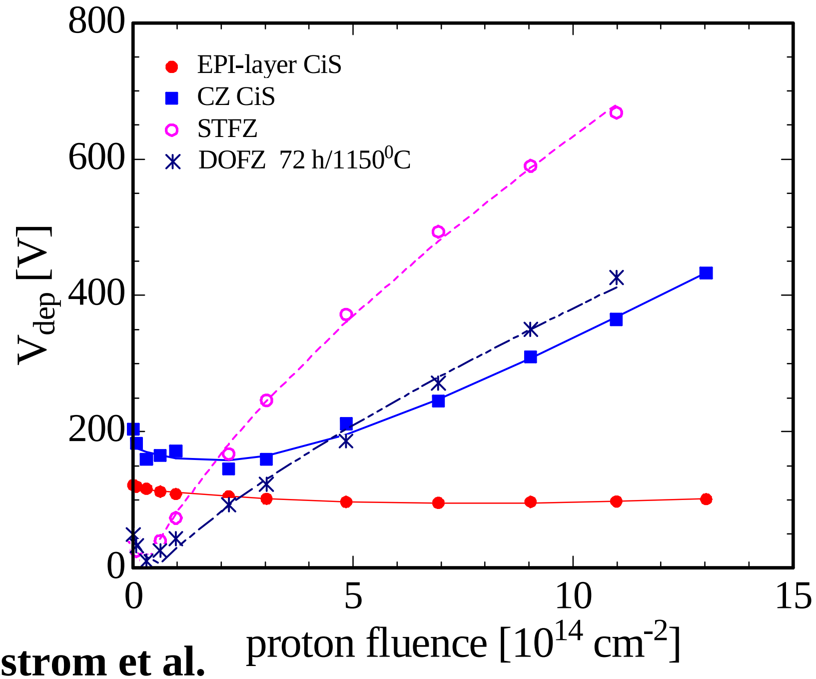
190 MeV p irradiation Villigen

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**
- **Charge collection efficiency under study**

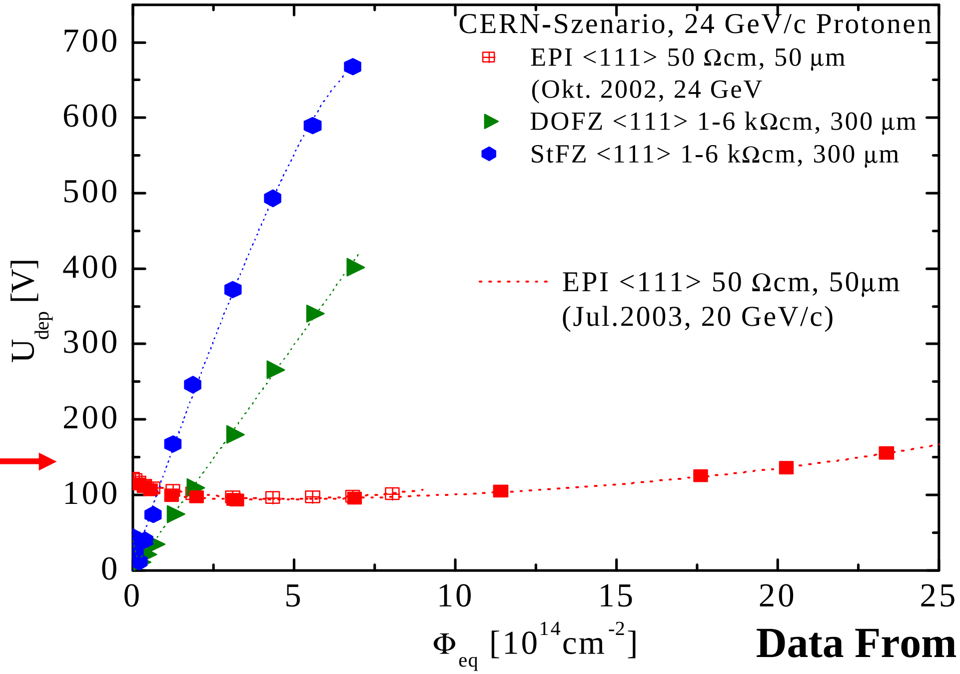
Epitaxial silicon

Motivation: **After 1 MeV neutron irradiation to 10^{15} cm^{-2}**
the effective drift length for e is ~150mm and for h ~50mm

Þ use thin detectors (50-100mm) from the beginning, with low resistivity Epitaxial Si

50mm, 50Wcm on CZ Si made by ITME (Warsaw)

120 V



160 V

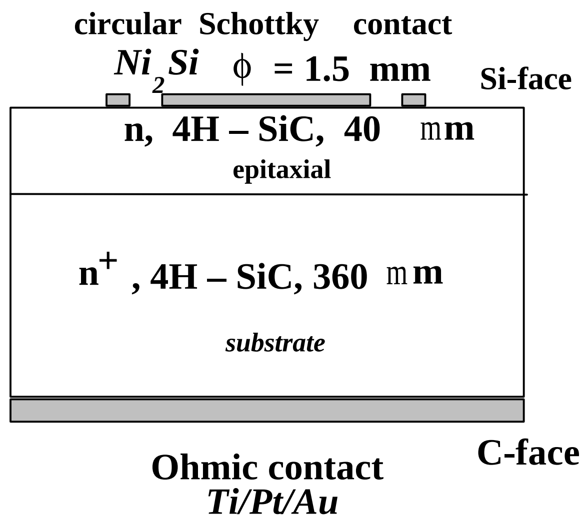
Data From G.Lindstrom et al.

- Leakage current almost identical to CZ, FZ, DOFZ detectors
- CCE with β-source under study

New Materials: Epitaxial SiC

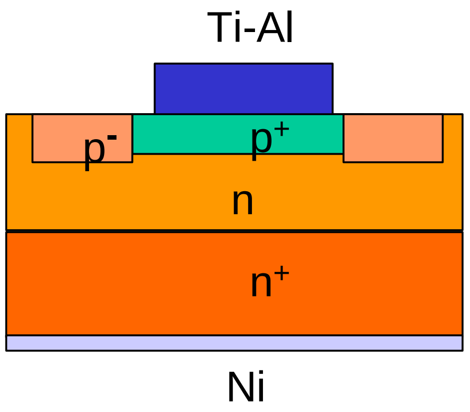
- **Semi-Insulating SiC**
  - – $\rho > 10^{11} \Omega$cm due to vanadium compensation
  - - CCE 60% in as-grown, ~55% after irradiation with 10^{13}cm^{-2} 300 MeV/c π
  - - Vanadium is responsible of incomplete charge collection
- **Epitaxial 4H-SiC**
  - - 6 new 2" wafers d~50μm, $N_{eff}=5\cdot10^{13}$cm^{-3} produced by CREE and IKZ, Berlin
  - - Common RD50 test structures produced and irradiated

Schottky Barrier detector



Modena&Alenia Systems, Italy

p^+n junction detector

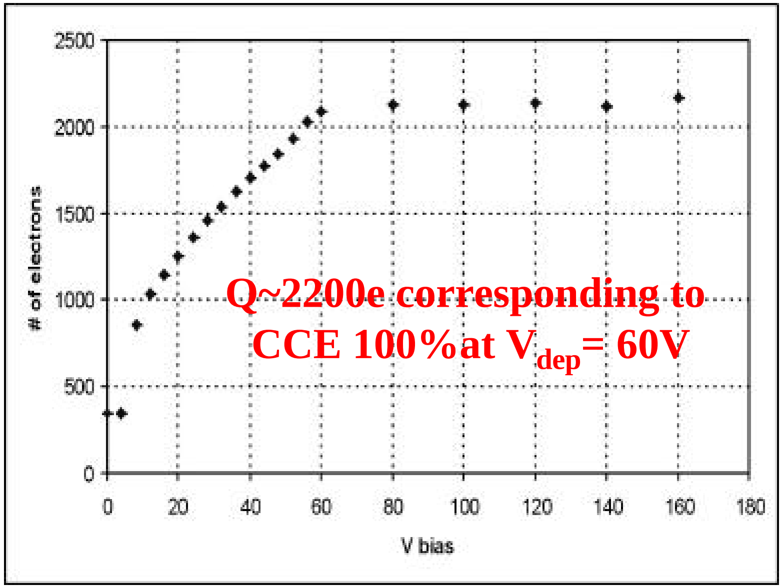


Perugia&IMM Bologna,Italy

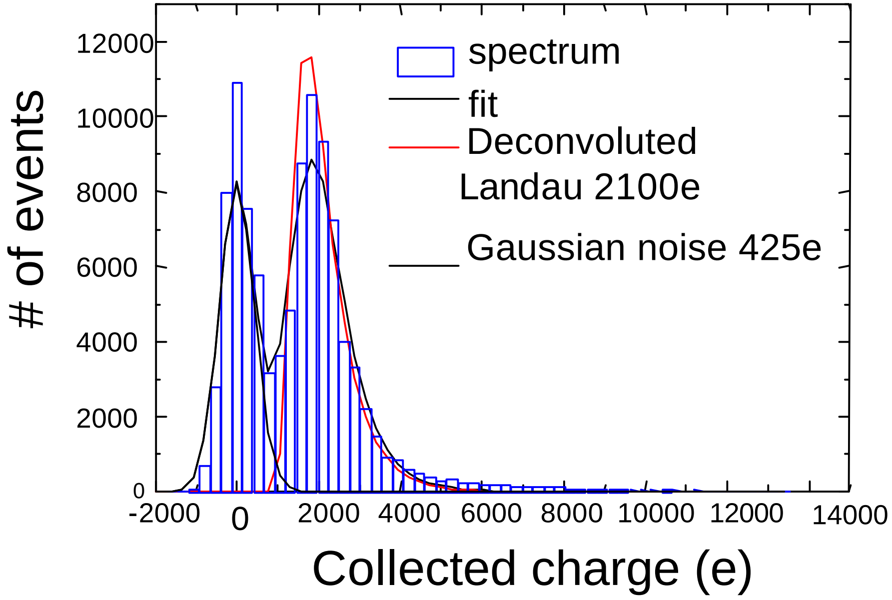
Epitaxial SiC Schottky Barriers

- **n epilayer N$_{eff}$ ~5´10^{13}cm^{-3} 40mm by IKZ Berlin on CREE substrate; Schottky contacts**
- **No priming / polarization effects observed**
- **Charge collection efficiency tested with as ^{241}Am and b ^{90}Sr**

100% before irradiation: 2200e with mips



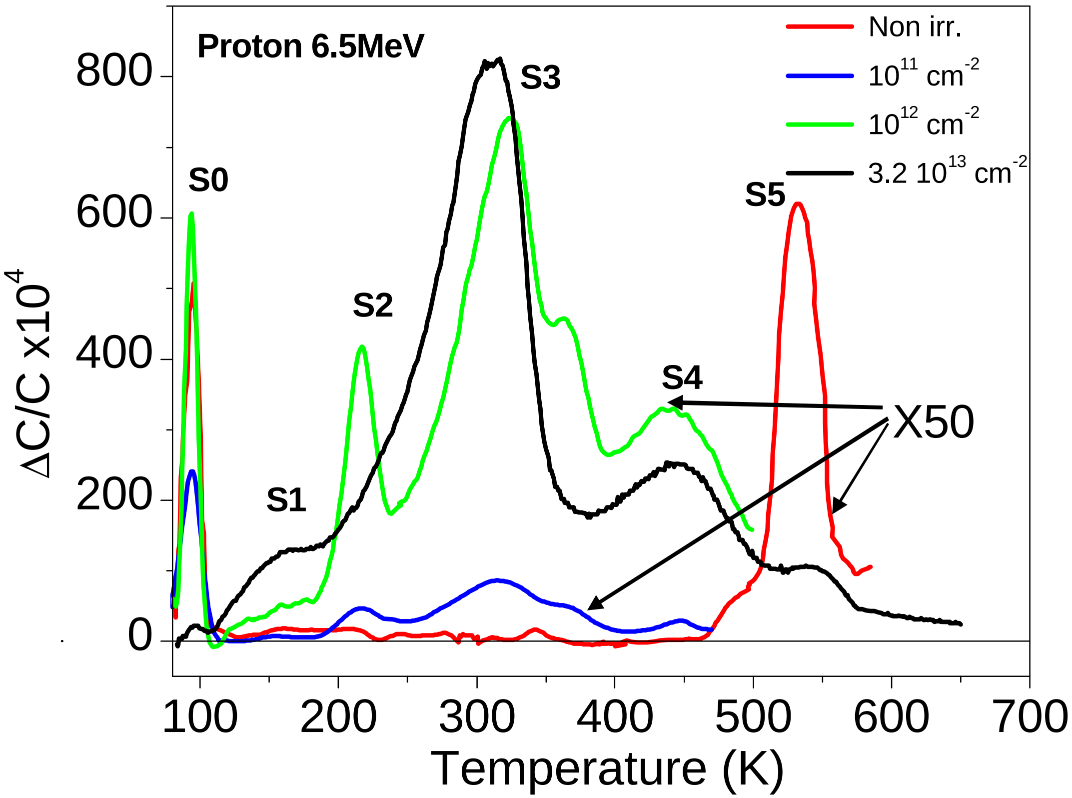
Q~2200e corresponding to CCE 100% at V$_{dep}$= 60V



Data from F. Nava, S. Sciortino, M. Bruzzi et al., IEEE Trans. Nucl. Sci, (2004)

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

- ♦ n epilayer 7mm
- ♦ N_{eff} ~7´10^{15}cm^{-3}
- ♦ Schottky Barriers Ti or Ni
- ♦ Ohmic contacts Ti/Ni/Ag
- ♦ Deep levels by C-DLTS
- ♦ 6.5MeV p up to 6.4x10^{13}cm^{-2}



Six traps detected after irradiation. High generation coefficients.

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

- ♦ E = 0.18 - 1.22eV
- ♦ s = 10^{-13}-10^{-18}cm^{-2}
- ♦ N_t = 10^{11} - 5x10^{14} cm^{-3}

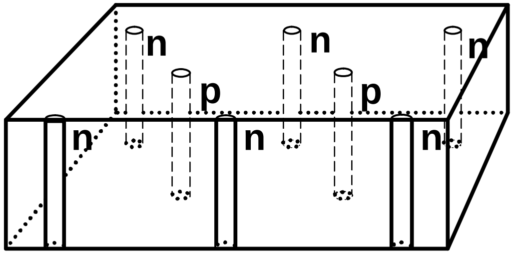
Devices irradiated up 10^{16} cm^{-2} 24GeV protons (CERN) and fast neutrons (Ljubljana). Measurements are in progress.

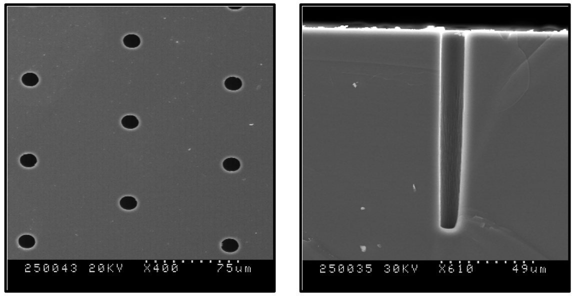
Device Engineering: 3D detectors

proposed by Sherwood Parker

- 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**

Present size
up to ~1cm^2





see S. Parker talk, June 17

Advantage: application possible with all radiation-hard materials.

Within RD50, IRST-Trento is developing 3D detectors, in collaboration with CNM Barcelona. **See M. Boscardin talk, June 17**

Summary

- **Possible radiation hard materials for tracker detectors at SuperLHC have been selected by CERN R&Ds as: Defect engineered Si, diamond (poly- and single-crystal) and epitaxial SiC.**

- **Si (RD50): At the fluence of 10^{16}cm^{-2} (Innermost layer of a SLHC detector) the active thickness of any material is significantly reduced due to trapping. Promising results of CCE on microstrip n-in-p detectors produced with oxygenated Si irradiated up to 7×10^{15} [24GeVp/cm^2] have been measured within RD50: 6500e corresponding to 90mm ccd. The effect of oxygen in CCE on CZ Si is still under study.**

- **SiC (RD50): 100% CCE over 40mm epilayer (2200e). Thicker epilayers needed (up to 100mm). Radiation hardness under study.**

- **Diamond polycrystalline (RD42)*: achieved 270mm ccd (mp signal: 8000e), deteriorates to 80% after 2×10^{15}cm^{-2} 24GeV p, need to extend measurements to 10^{16}cm^{-2}.**

- **Diamond single crystal (RD42)*: achieved 550mm CCE. Limited size of 6mm diameter, no radiation hardness study available in literature.**

***Data from RD42, NIMA Sept. 2003, more on H.Kagan talk**