Radiation Tolerant Tracking Detectors for the sLHC

Mara Bruzzi

Florence University, INFN and SCIPP

Outline of the talk

- Motivations
- Radiation damage in FZ Si high resistivity detectors
- Defect engineering of silicon
- P-type detectors
- The SMART Italian project for the upgrade of superLHC
- Results on MCz Si n- and p-type
- Future trends

Large Scale Application of Si Detectors in LHC

Present working conditions:

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

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

$\phi \sim 10^{14}$ 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	$1.6x10^{16}$	4200
11	$2.3x10^{15}$	940
22	$8.0x10^{14}$	350
75	$1.5x10^{14}$	35
115	$1.0x10^{14}$	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 required** → **3D detectors**

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").

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

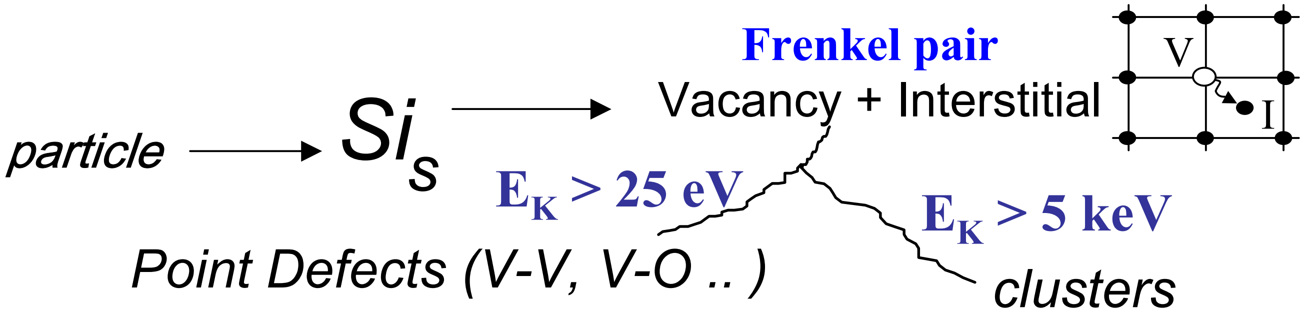
Defect / Material Characterization	Defect Engineering	New Materials	Pad Detector Characterization	New Structures	Full Detector Systems
Bengt Svensson (Oslo University)	*Eckhart Fretwurst* (Hamburg University)	*Juozas V.Vaitkus* (Vilnius University)	*Jaakko Härkönen* (Helsinki HIP)	*Mahfuzur Rahman* (Glasgow University)	*Gianluigi Casse* (Liverpool University)
Characterization of microscopic properties of standard-, defect engineered and new materials pre- and post-irradiation	Development and testing of defect engineered silicon: - Epitaxial Silicon - High res. CZ, MCZ - Other impurities H, N, Ge, … - Thermal donors - Pre-irradiation	Development of new materials with promising radiation hard properties: - bulk, epitaxial SiC - GaN - other materials	•Test structure characterization IV, CV, CCE •NIEL •Device modeling •Operational conditions	•3D detectors •Thin detectors •Cost effective solutions	•LHC-like tests •Links to HEP •Links to R&D of electronics •Comparison: pad-mini-full detectors
DLTS Calibration (B.Svensson)	• Oxygen Dimer (M.Moll)	• SiC (I.Pintilie) • GaN (J.Vaitkus)	•Common irrad. •Standardisation of macroscopic measurements (A.Chilingarov)	•3D (M.Rahman) •Semi 3D (Z.Li) •Thinned detectors (M.Boscardin)	•Comparison of detectors different producers (Eremin) • pixel group (D. Bortoletto,T. Rohe)

Selecting radiation- hard tracker detectors for SuperLHC

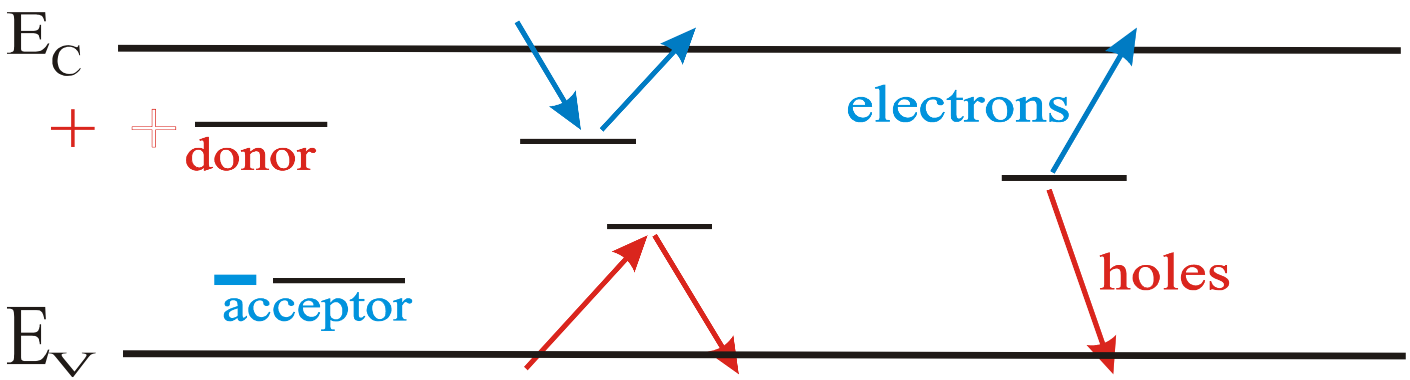
Main Selection Parameters → **Main Operative Characteristics** → **Main Material Characteristics**

- **High CCE** → Negligible trapping effects; High E field close r-o elect.
  - Negligible trapping effects → High crystalline quality & negligible rad-induced deep traps
  - High E field close r-o elect. → No type inversion
- **Low noise** → Low leakage current; Low dielectric constant
  - Low leakage current → big bandgap (but: higher e-h creation energy)
- **Low power** → Low leakage current; Low full depletion voltage
  - Low full depletion voltage → Thin thickness (but: higher capacitance); High resistivity
- **High speed** → High mobility & saturation field
- **Cost-effective** → Commercially available in large scale

Radiation Induced Microscopic Damage in Silicon



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

Vacancy amount and distribution depends on particle kind and energy

^{60}Co-gammas
- Compton Electrons with max. $E_\gamma \approx$1 MeV (<u>no cluster production</u>)

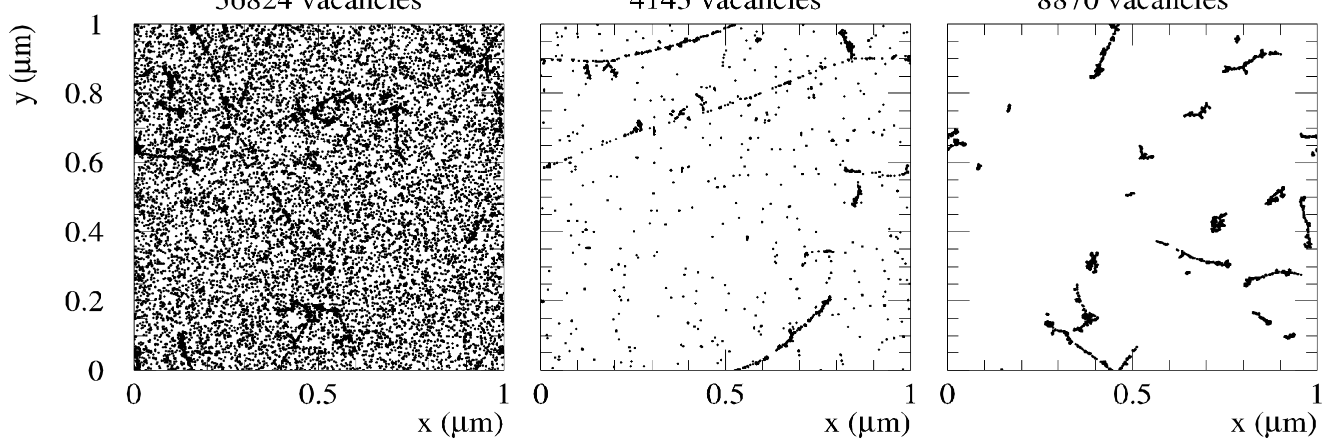
Electrons
- E_e > 255 keV for displacement
- E_e > 8 MeV for cluster

Neutrons (elastic scattering)
- E_n > 185 eV for displacement
- E_n > 35 keV for cluster

Only point defects ⟷ point defects & clusters ⟷ Mainly clusters

Initial distribution of vacancies in (1μm)^3 after 10^{14} particles/cm^2

10 MeV protons — 36824 vacancies | **24 GeV/c protons** — 4145 vacancies | **1 MeV neutrons** — 8870 vacancies



[Mika Huhtinen NIMA 491(2002) 194]

Primary Damage and secondary defect formation

- **Two basic defects**

  I - Silicon Interstitial V - Vacancy

- **Primary defect generation**

  I, I_2 higher order I (?)

  $\Rightarrow$ **I** -CLUSTER **(?)** $\Longleftarrow$

  V, V_2, higher order V (?) **Damage?!**

  $\Rightarrow$ V -CLUSTER **(?)** $\Longleftarrow$

- **Secondary defect generation**

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

$I + C_s \rightarrow C_i \Rightarrow C_i + C_s \rightarrow C_i C_S$

$C_i + O_i \rightarrow C_i O_i$

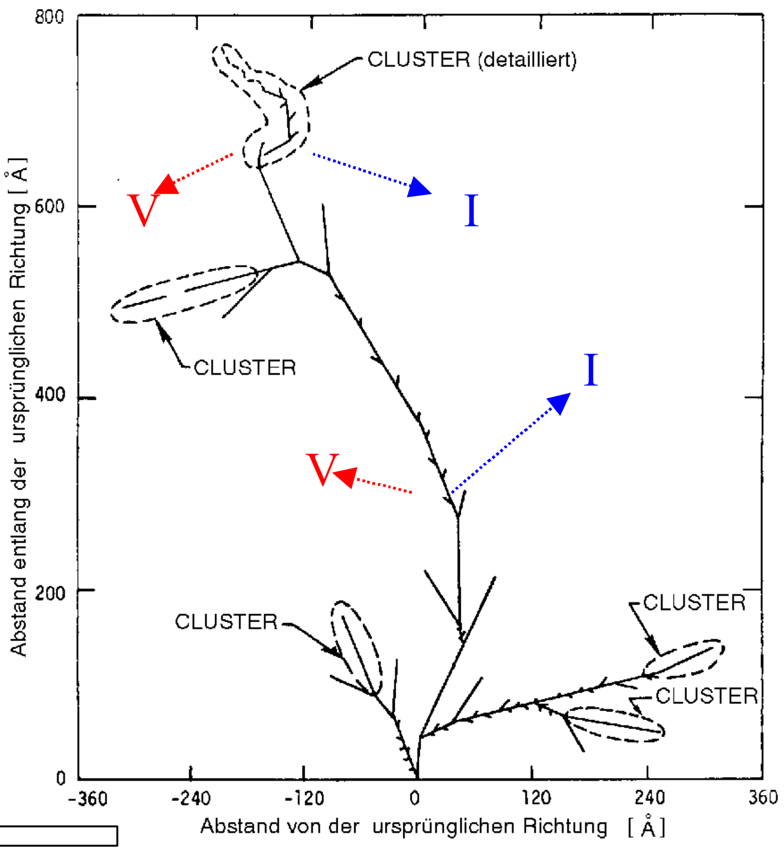
$C_i + P_s \rightarrow C_i P_S$

$V + V \rightarrow V_2$ $V + V_2 \rightarrow V_3$

$V + O_i \rightarrow VO \Rightarrow V + VO \rightarrow \underline{V_2O}$ $\Longleftarrow$

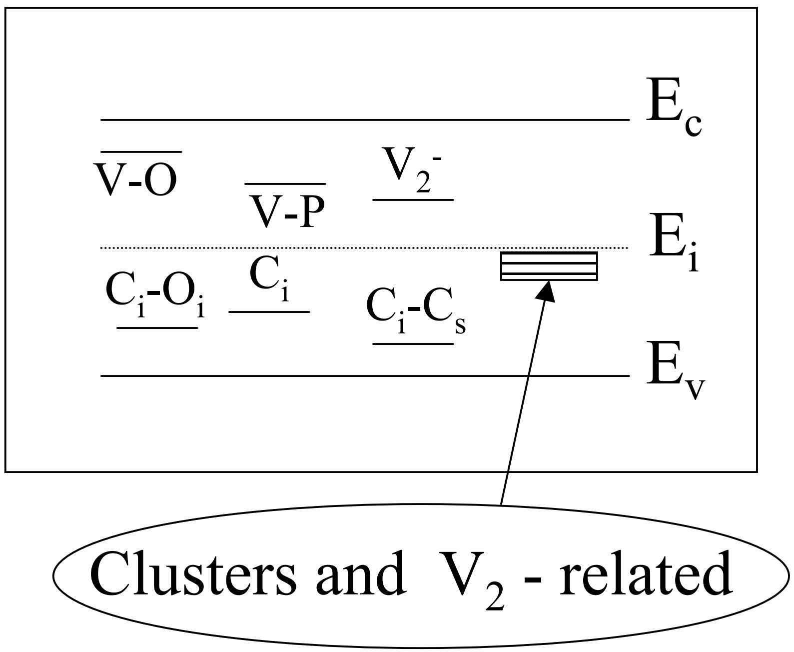
$V + P_s \rightarrow VP_s$

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



Damage?! ("V_2O-model")

Main Defects in Irradiated Silicon

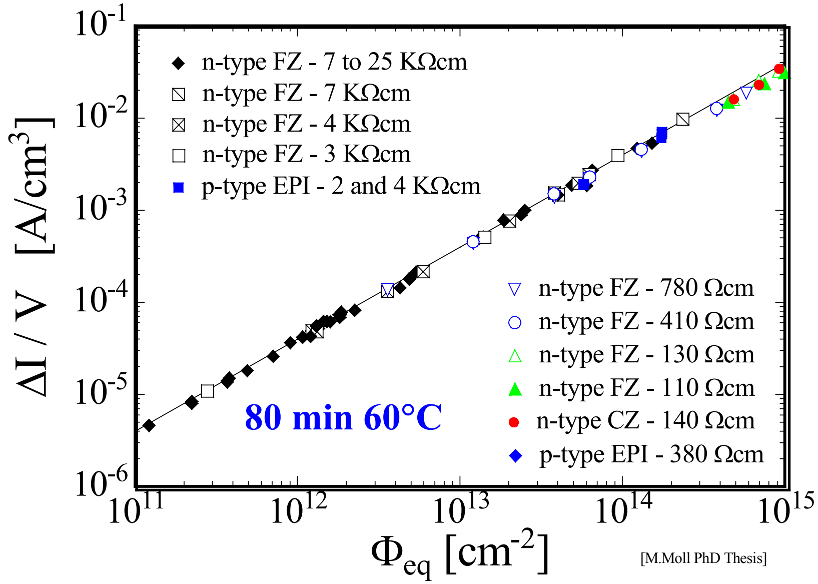


M. Bruzzi IEEE TNS, 2001

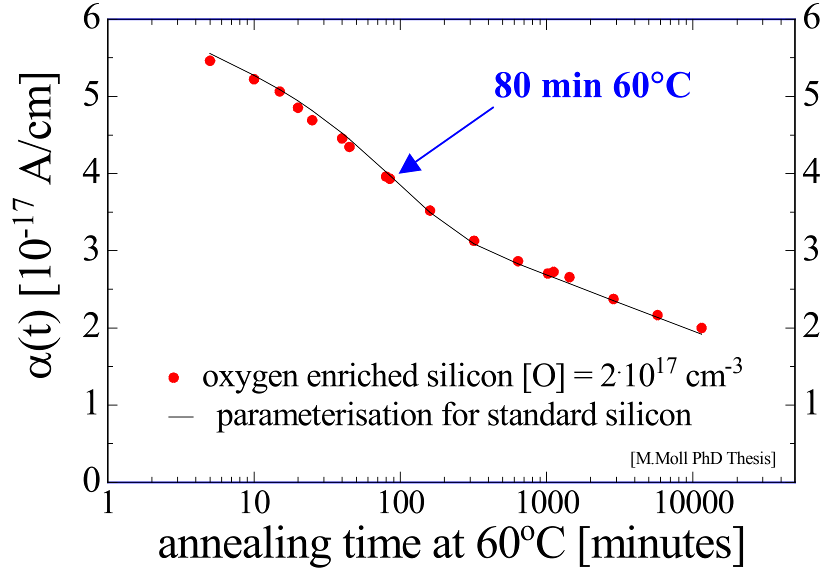
Defect Identity	Trap parameters			Annealing parameters	
	method	E_t [eV]	$\sigma_{n,p}$[cm^2]	$E_{ann.}$ [eV]	$T_{ann.}$ °C
V-O_i	DLTS	$E_c-0.17$	1.0×10^{-14}	2.1	350
C_iC_s	DLTS	$E_v+0.17$ $E_v+0.17$	1.4×10^{-14}	1.7	225 250
V_2^+	EPR	$E_v+0.25$ $E_v+0.21$	2×10^{-16}	1.3	300
$V_2^=$	DLTS TSC	$E_c-0.25$ $E_c-0.23$	$4\times10^{-16}\,e^{-.017/KT}$ 2×10^{-16}	1.3	300
C_i	DLTS	$E_v+0.3$ $E_v+0.33$	9×10^{-14}	0.74	50
C_iO_i	EPR PL DLTS TCT	$E_v+0.38$ $E_v+0.36$	2.5×10^{-15} 1.2×10^{-15}		400
V_2^-	EPR PL DLTS	$E_c-0.4$ $E_c-0.4$ $E_c-0.41$	2×10^{-15}	1.3	300
P-V	EPR HE DLTS	$E_c-0.4$ $E_c-0.46$	3.7×10^{15}	0.94-1.2	150
Si_i	DLTS	$E_c-0.49$	6.6×10^{-16}		
No assessed identity	TSC TCT DLTS/TCT	$E_c-0.48$ $E_c-0.52$ $E_v+0.48$ $E_v+0.51$	4×10^{-15} 5.5×10^{15} 1×10^{-14}		

Leakage Current

Hadron irradiation



Annealing



- **Damage parameter α (slope)**

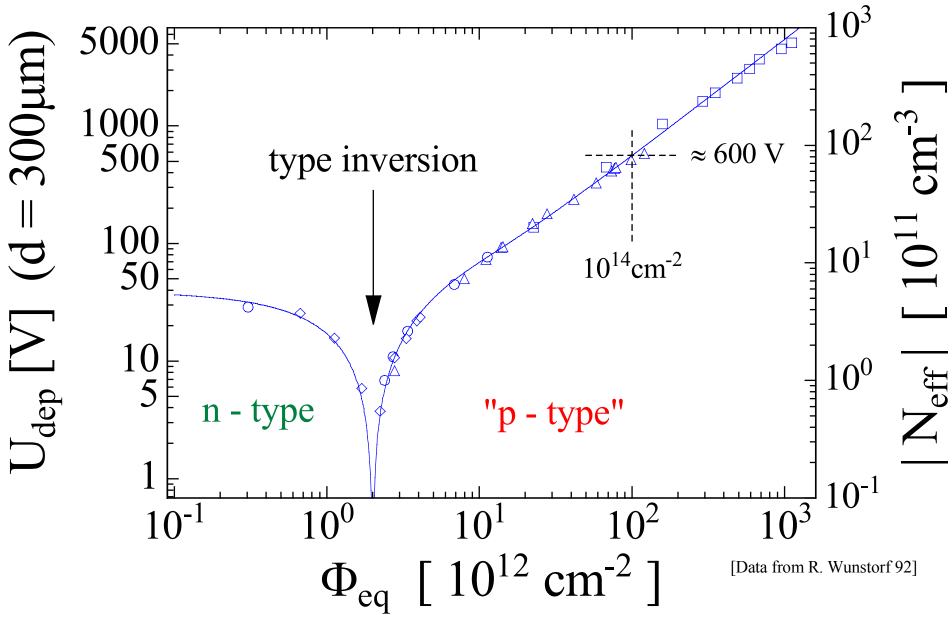
$$\alpha = \frac{\Delta I}{V \cdot \Phi_{eq}}$$

M. Moll, Thesis, 1999

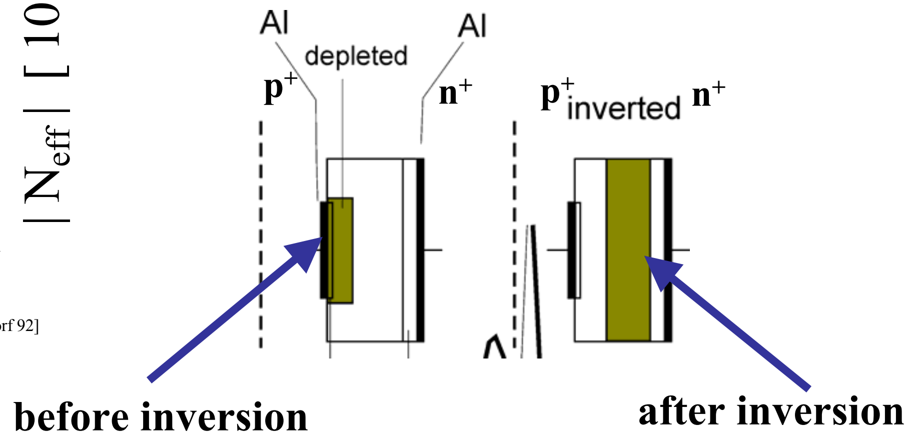
- **α independent of Φ_{eq} and impurities**
  ⇨ **used for fluence calibration (NIEL-Hypothesis)**

- **Oxygen enriched and standard silicon show same annealing**
- **Same curve after proton and neutron irradiation**

Depletion Voltage and Effective Space Charge Concentration



- **Type inversion:**
  SCSI – Space Charge Sign Inversion



after inversion and annealing saturation

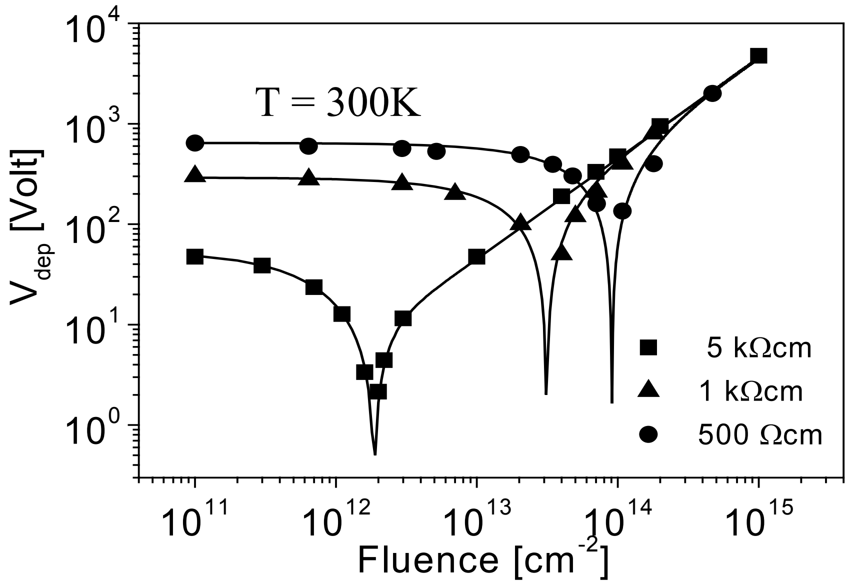
$$N_{eff} \sim \beta \cdot \phi$$

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

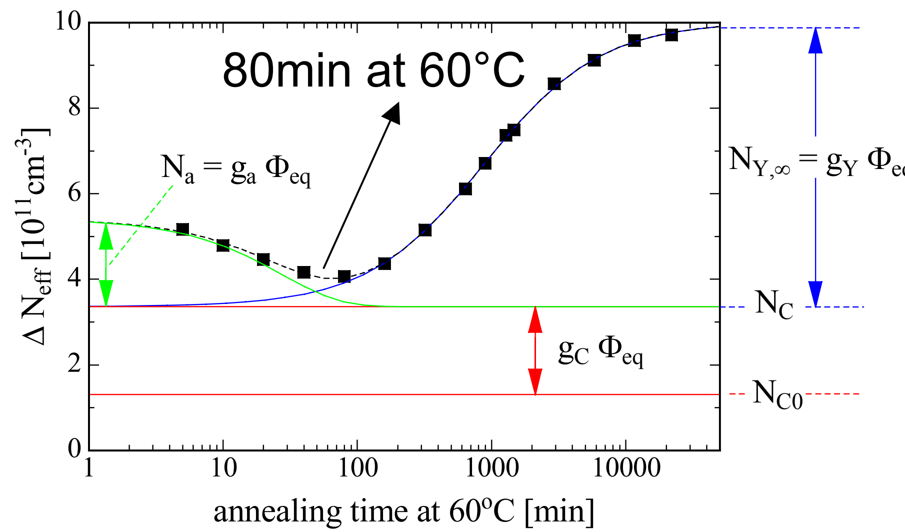
Stable Damage

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

ShallowDonor Removal **Beneficial Annealing** **Reverse Annealing**



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)
  30min (80°C)

Charge Collection Efficiency

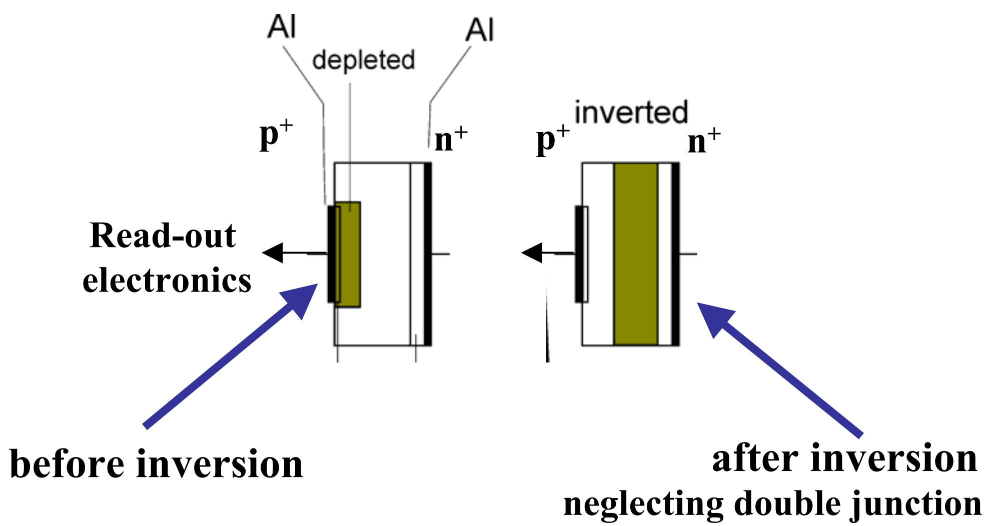
Limited by:

- **Partial depletion**
- **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



Main limitation at high fluence due to electron and hole trapping

Trapping times measured with Transient Current Technique (TCT) within RD50 with different n-type Si materials.

$$1/\tau_{e,h} = \beta_{e,h} \cdot \Phi_{eq} [cm^{-2}]$$

Group	β_e	β_h	particle	max Φ_{eq}	T
	$[10^{-16} cm^2 ns^{-1}]$		/ energy	$[cm^{-2}]$	[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

extrapolation to the high fluences :

$\rightarrow$ $\tau_t \sim 1/\Phi$ $\tau_t \sim$ **0.2 ns for** $\Phi = 10^{16}$ **cm**$^{-2}$

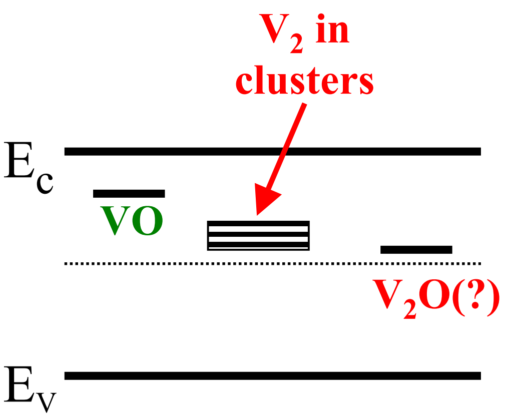
Defect Engineering of Silicon

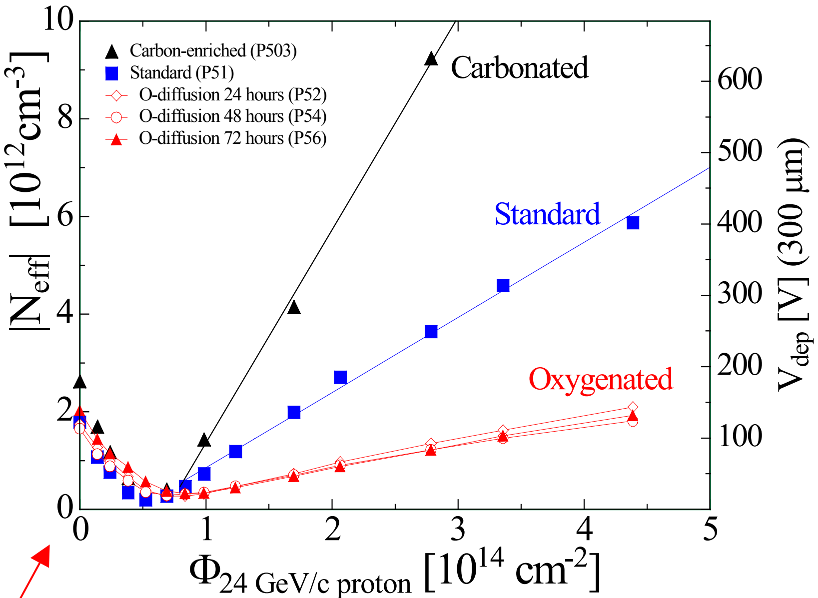
Influence the defect kinetics by incorporation of impurities or defects: Oxygen

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)

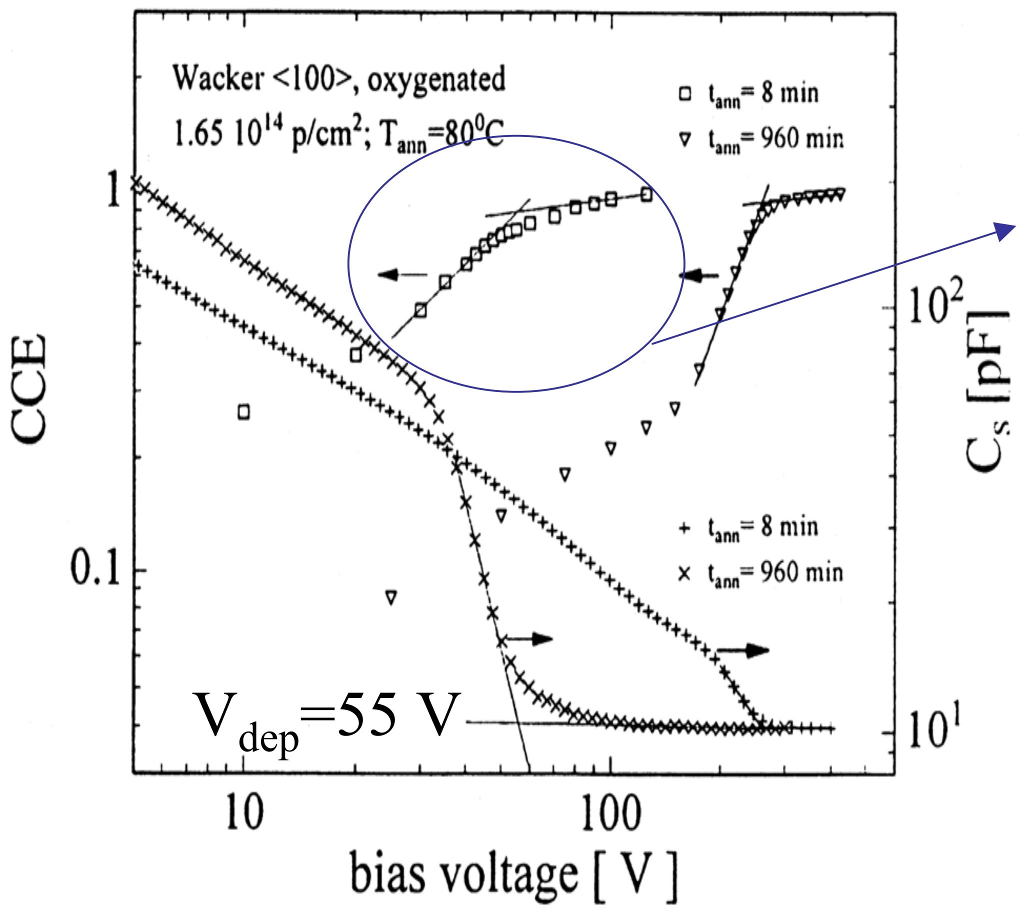


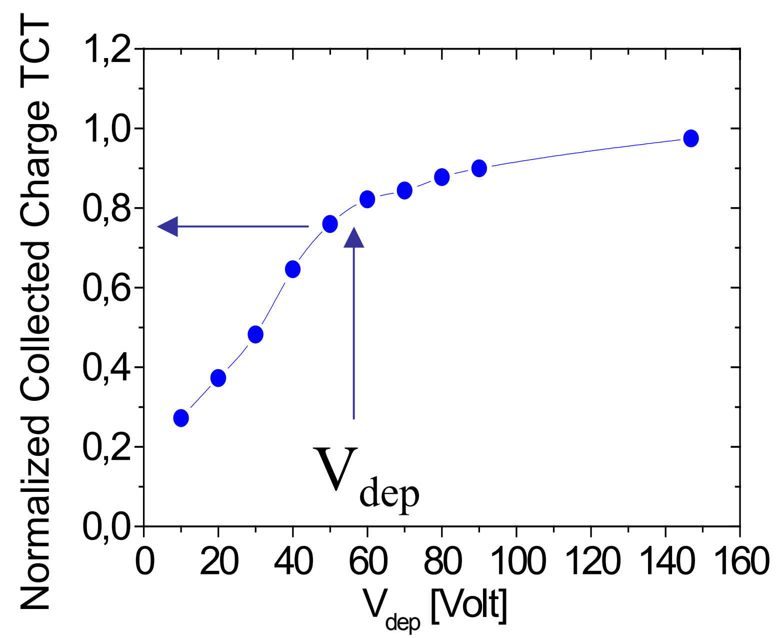


DOFZ (Diffusion Oxygenated Float Zone Silicon) RD48 NIM A465 (2001) 60

Problem with n-type DOFZ Silicon

V_{dep} determined by CV analysis <u>does not correspond</u> to the maximum CCE



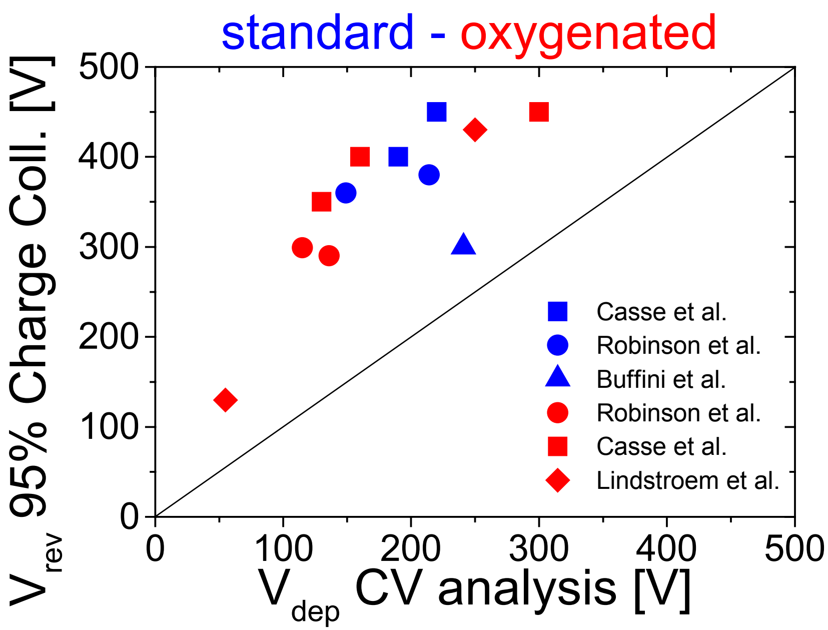


To maximise CCE it is necessary to overdeplete the detector up to :

$V_{rev} \sim 2\ V_{dep}$

G. Lindstroem et al. ROSE Coll. NIM A 466 (2001) 308-326

Discrepancy between CCE and CV analysis observed in diodes and microstrip detectors, ATLAS and CMS, DOFZ and Standard FZ

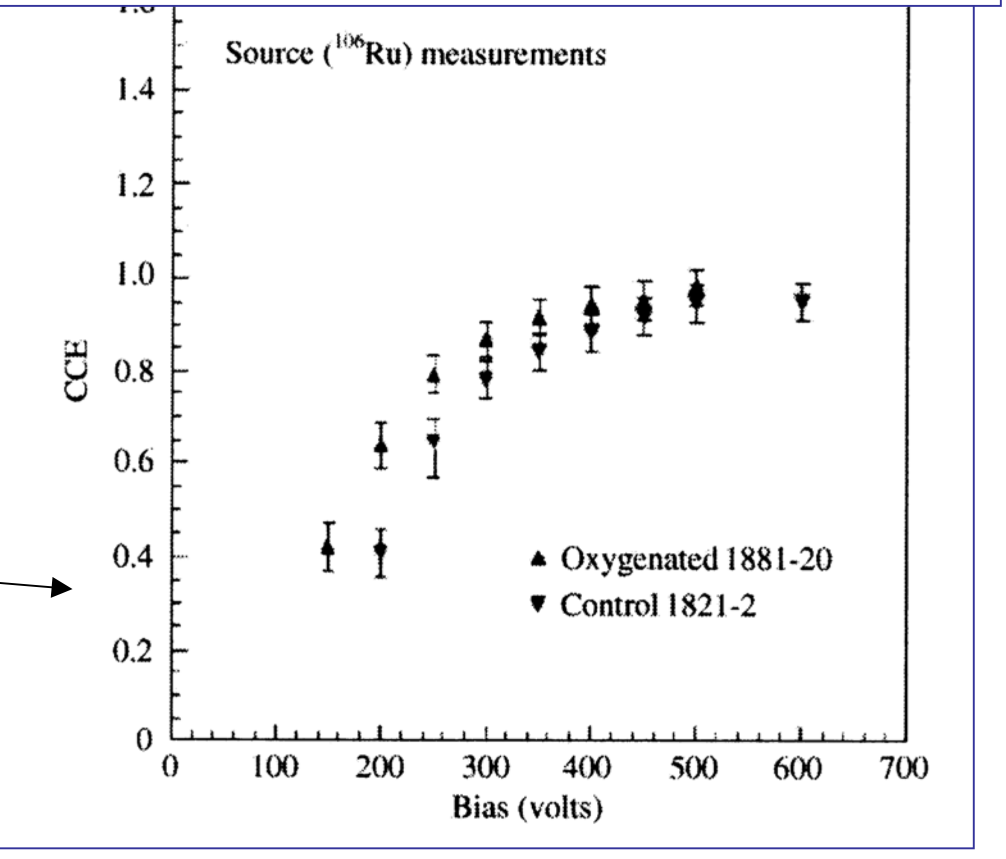


	Author	radiation	Exp.	material
●	Robinson et al., NIM A 461 (2001)	3×10^{14} 24GeV p/cm^2	ATLAS	Oxygen. + standard
■	Casse et al., NIM A 466 (2001)	$3\text{-}4 \times 10^{14}$ 24GeV p/cm^2	ATLAS	Oxygen. + standard
♦	Lindström et al., NIM A 466 (2001)	1.65×10^{14} 24GeV p/cm^2	ROSE	Oxygen. <100>
▲	Buffini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

The beneficial effect of oxygen in proton irradiated silicon microstrip almost disappear in CCE measurements

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

ATLAS microstrip CCE analysis after irradiation with 3×10^{14} p/cm^2

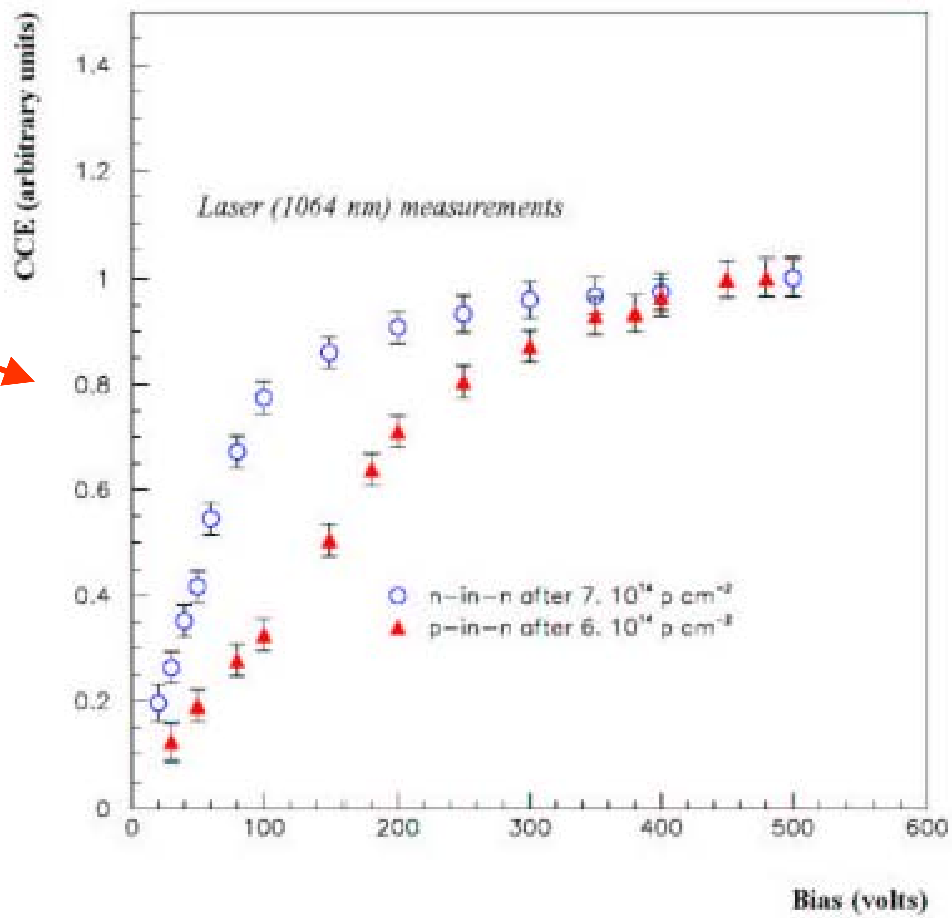


Deterioration of the charge collection efficiency

G. Casse, 1st RD50 Workshop, 2-4 Oct. 2002

n-side read-out after irradiation.

1060nm laser CCE(*V*) for the highest dose regions of an n-in-n (7.10^{14}p/cm^2) and p-in-n (6.10^{14}p/cm^2) irradiated LHC-b full-size prototype detector.



Different kind of oxygen enriched Si materials investigated by RD50

Material	Symbol	ρ Ω cm	$[O_i]$ cm^{-3}
Standard n-and p-type FZ	STNFZ	$1\text{-}7 \cdot 10^3$	$< 5\ 10^{16}$
Diffusion Oxygenated FZ p and 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 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)

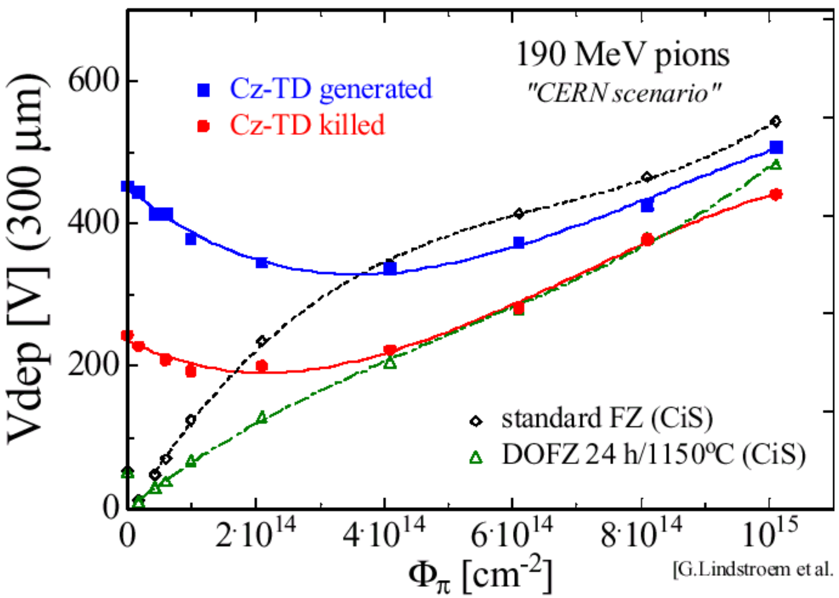
- High resistivity (>1KΩcm) available only recently (MCZ & CZ technology)

CZ wafers cheaper than FZ

- Starting with a p-type substrate offers the advantages of single-sided processing while keeping n^+-side read-out

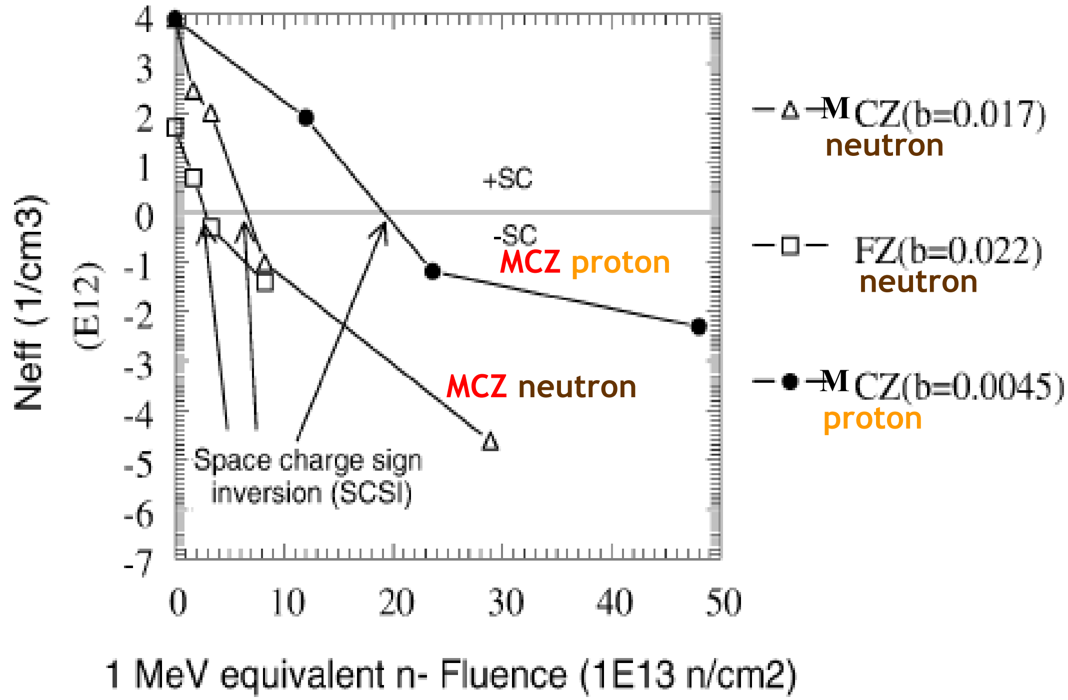
Czochralski Si

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



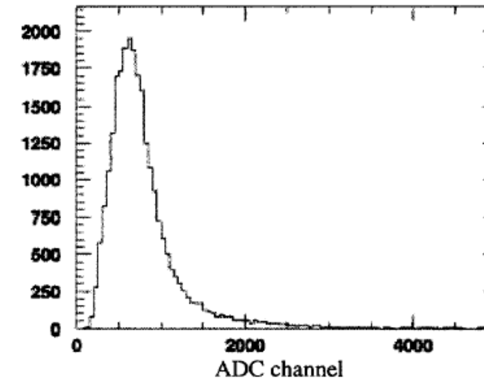
Data From Z. Li et al. IEEE TNS

- **No or delayed Space Charge Sign Inversion**
- **Leakage current and charge trapping comparable to FZ silicon**

MCZ n-type Si microstrip detectors - Helsinki

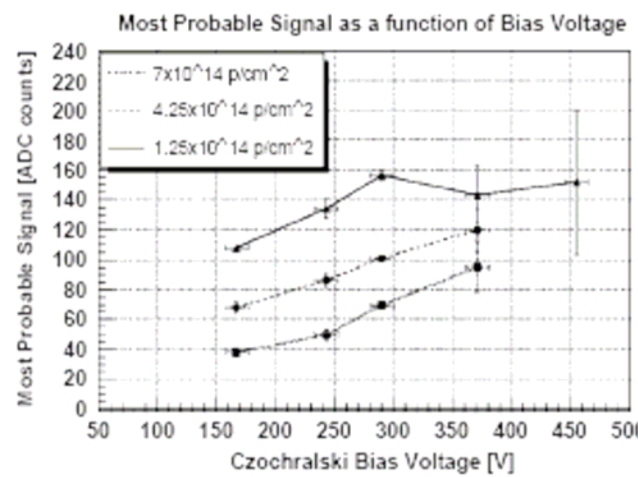
A MCZ microstrip detector prototype (AC coupled, with 1024 strips, 6 cm long, w=10 µm, p=50 µm) has been tested by 225 GeV muon beam at CERN with AV1 chips

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



First test beam with a full-size czochralski microstrip detector equipped with LHC speed electronics (SCTA) at CERN by the Glasgow group with a MCZ Si detector produced by Helsinki.

Unirradiated sensor S/N > 23:1
significant CCE after irradiation levels of up to $7x10^{14}$ 24 GeV p/cm^2.



C. Parkes NIM A, 2005

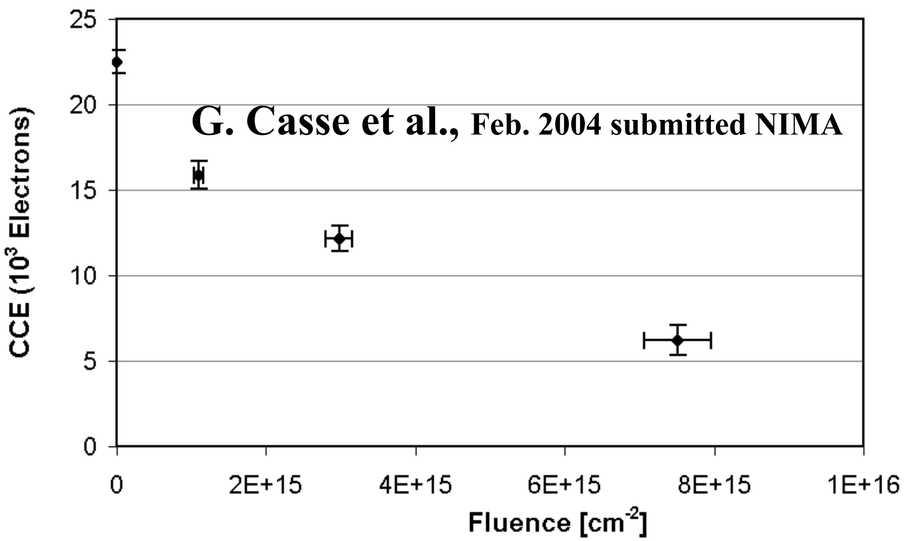
Early 2004: n-in-p microstrip detectors

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

- ❑ Miniature n-in-p microstrip detectors (280μm 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)

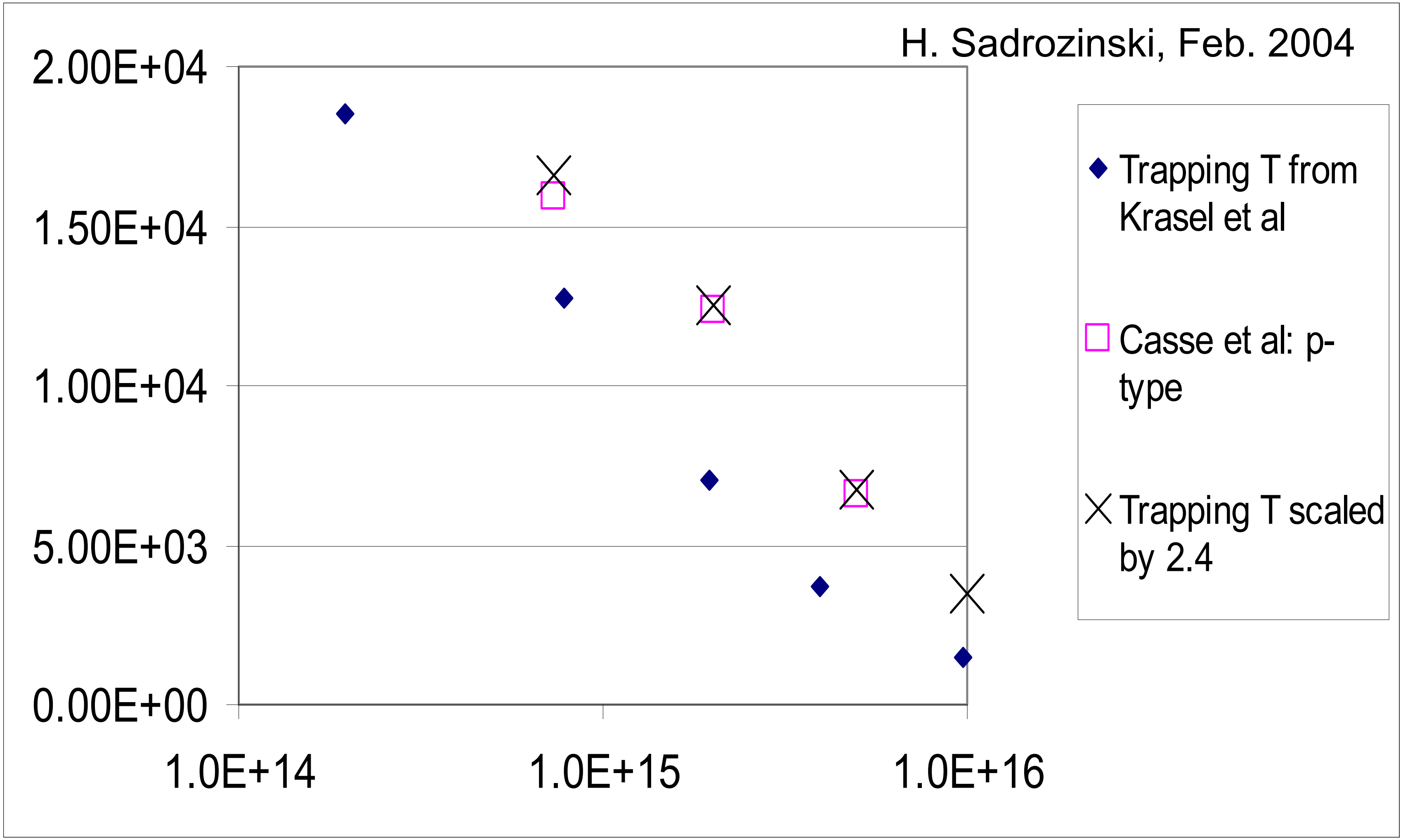
CCE ~ 60% after 3 10^{15} p cm^{-2} at 900V(standard p-type)

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



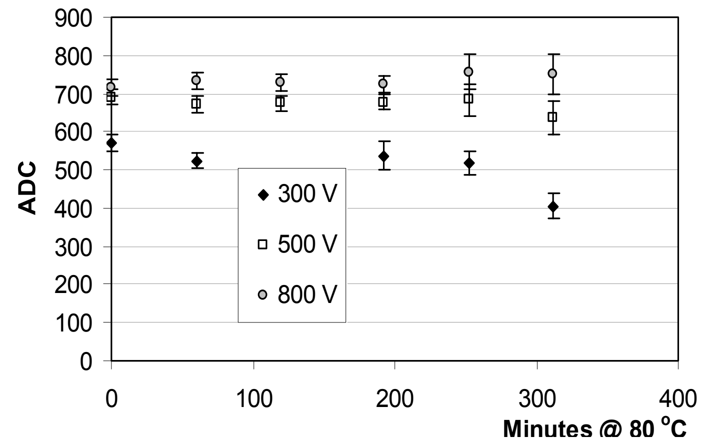
At the highest fluence Q~6500e at V_{bias}=900V. Corresponds to: ccd~90μm, trapping times 2.4 x larger than previously measured.

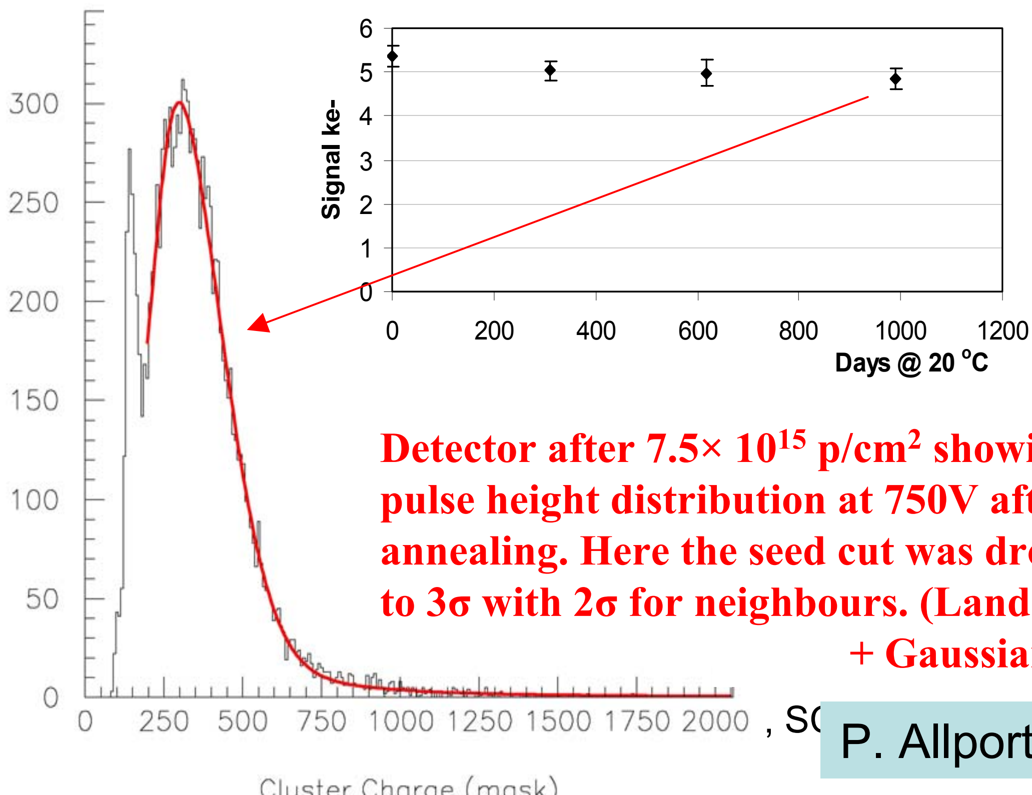
Collected Charge in P-type material: trapping underestimated by previous measurements

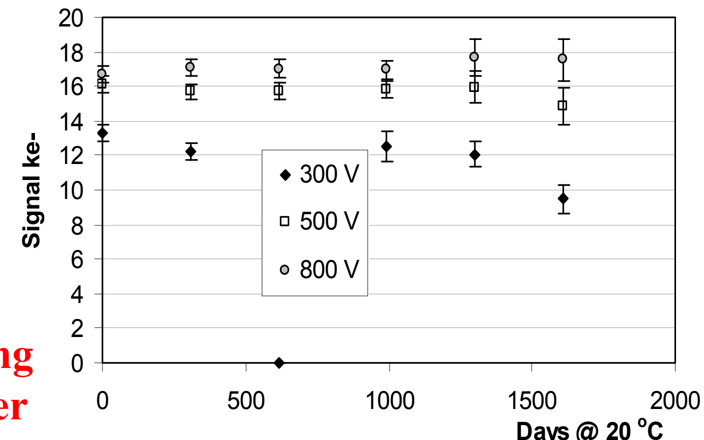


Recent n-in-p Results

Important to check that no unpleasant surprises during annealing.
Minutes at 80°C converted to days at 20°C using acceleration factor of 7430 (M. Moll).





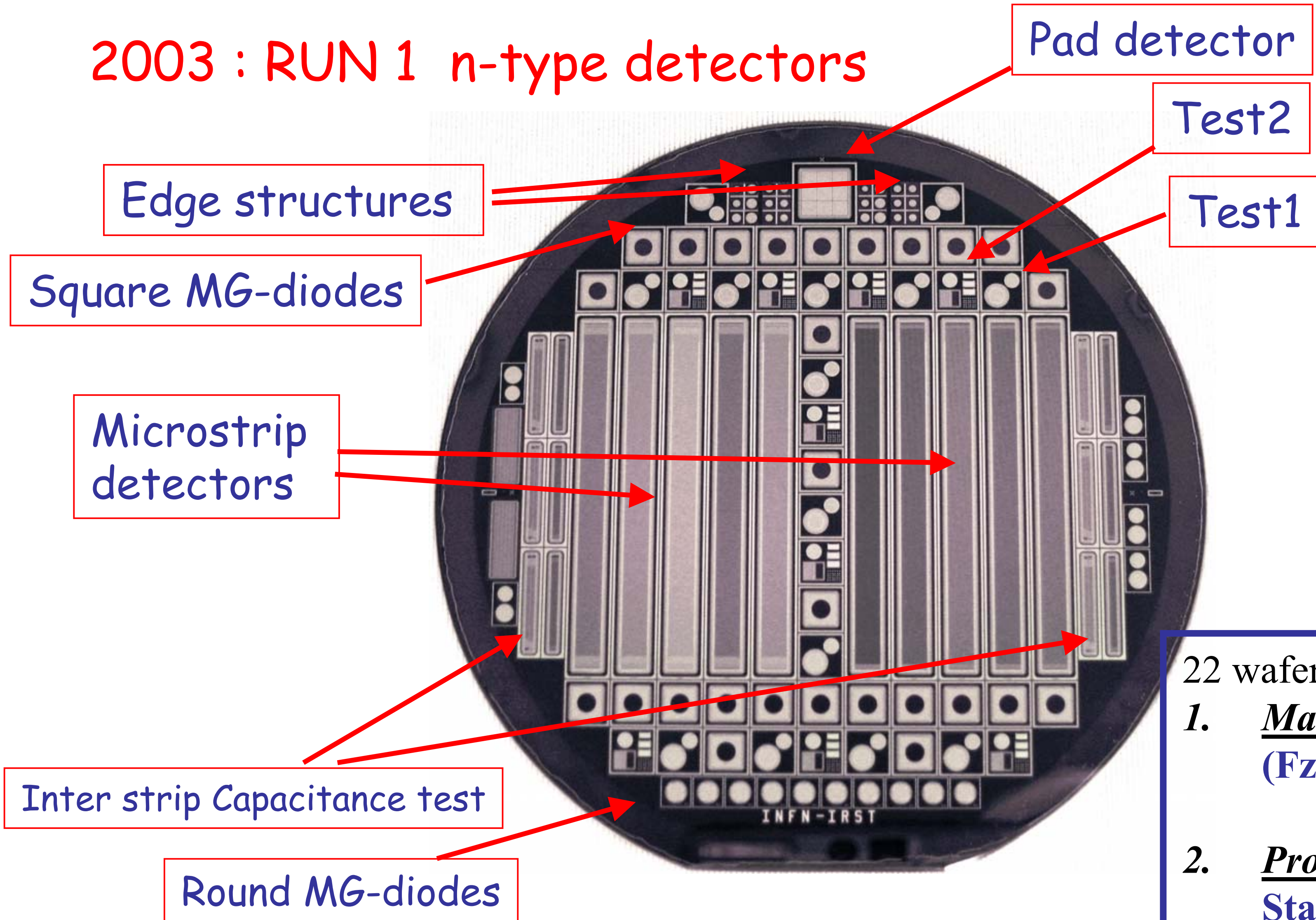


Detector after 7.5× 10^{15} p/cm^2 showing pulse height distribution at 750V after annealing. Here the seed cut was dropped to 3σ with 2σ for neighbours. (Landau + Gaussian fit)

Detector with 1.1× 10^{15} p/cm^2

An italian network within RD50: SMART

2003 : RUN 1 n-type detectors

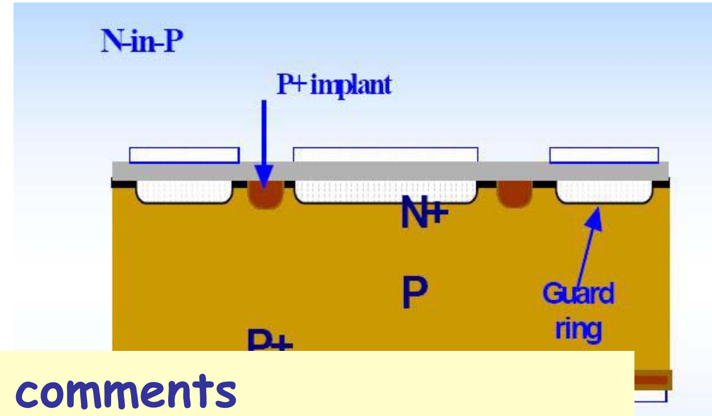


22 wafer Split in:

1. ***Materials***: **(Fz,MCz,Cz,EPI)**
2. ***Process***: **Standard** **Low T steps** **T.D.K.**

Summer 2004 : n+/p Process

- 2 p-spray **doses**
- 2-5 10^{12} cm^{-2}



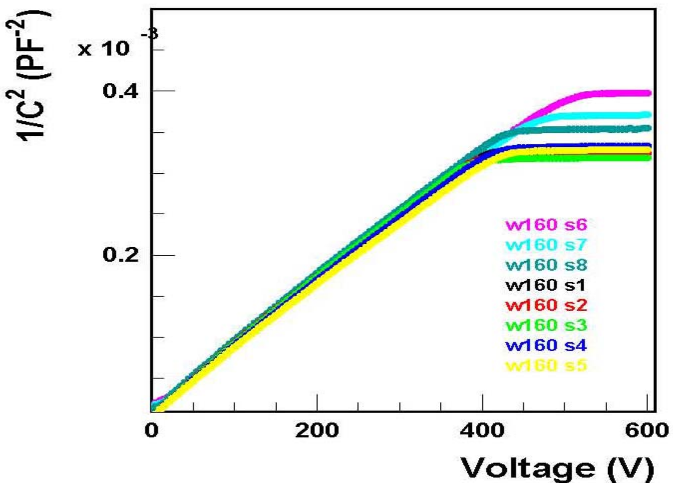
wafer #	**sub-type**	**comments**
6 wafers	**Fz <100> p-type >5kΩcm**	**525um**
7 wafers	**Fz <100> p-type >500Ωcm**	**200um**
11 wafers	**MCz <100> p-type >1.8kΩcm**	**300um**
24 wafers		

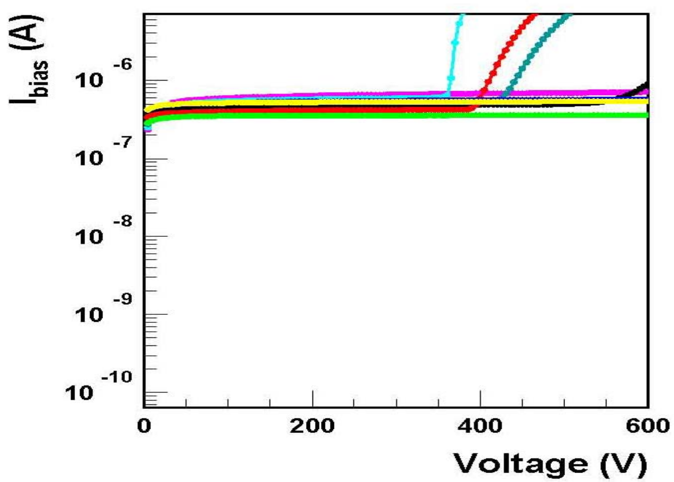
"Radiation hardness of high resistivity n- and p-type magnetic Czochralski silicon" for the studies on the pre- and post-irradiated materials performed on the diodes of these production runs.

	MCz Samples	Fz Samples
RUN I p-on-n	p-on-n **MCz** <100>, ρ>500 Ω cm ✓Standard: LTO, sintering @ 420C ✓no LTO, sintering @ 380C ✓no LTO, sintering @ 350C ✓no LTO, sintering @ 380C + TDK	p-on-n **Fz** <111>, ρ>6KΩ cm ✓Standard Process ✓sintering @ 380C
RUN II n-on-p	n-on-p **MCz** <100>, ρ>1.8 KΩ cm ✓No over-glass passivation ✓Low dose p-spray (3.0E12 cm^{-2}) ✓High dose p-spray(5.0E12 cm^{-2})	n-on-p **Fz** , 200 μm, ρ>5KΩ cm ✓Low dose p-spray (3.0E12 cm^{-2}) ✓High dose p-spray(5.0E12 cm^{-2})

Pre-irradiation Characterization

✓ **Good performances of the n-type detectors in terms of breakdown voltages and uniformity**



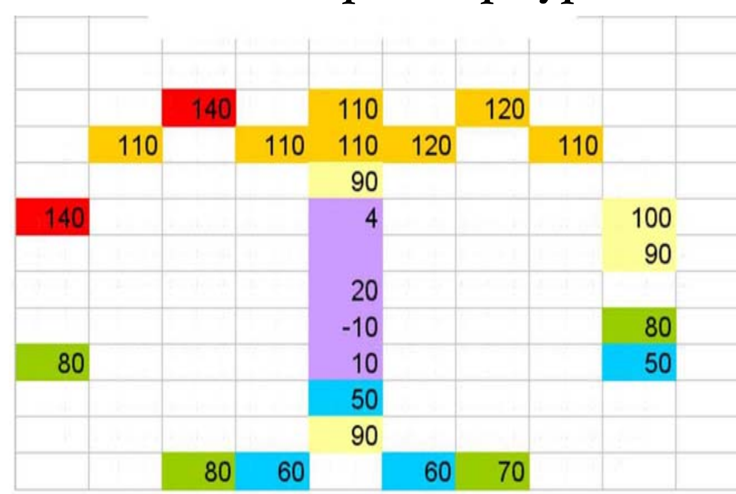


✓ **Problems for the p-type detectors:**

❖ low breakdown voltages for the 100 μm pitch detectors, probably due to the present implementation of the p-spray technique

❖ Disuniformity of the wafer resistivity, explained with a different oxygen concentration leading to a spread in the thermal donor activation.

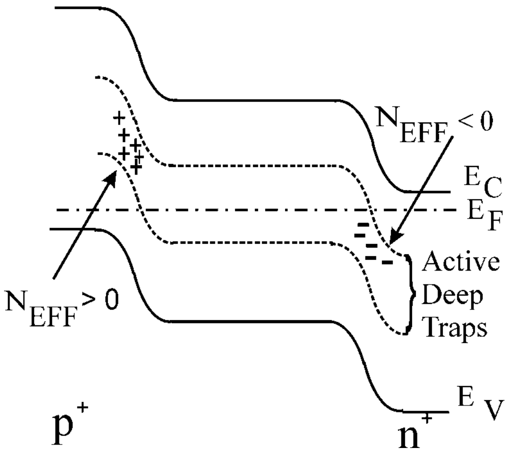
Map of the diodes Vdepl in a p-type MCz wafer



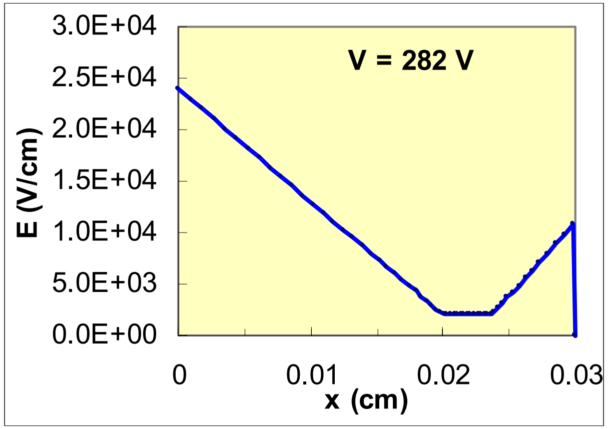
Measured in IRST

Electric field distribution in n-type MCz Si Detectors
SMART, Italy, measured at Ioffe on July 4-5, 2005

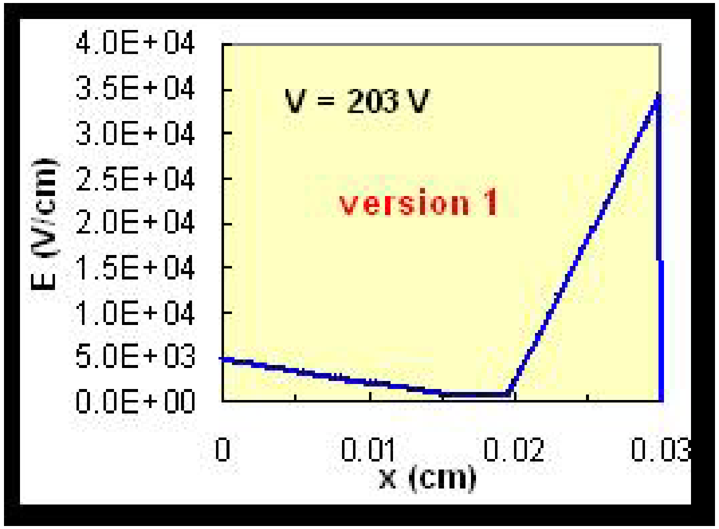
For very high fluences (of the order of 10^{14} n/cm^2) a depletion region can be observed on both sides of the device for STFZ p^+/n: this is still true for MCz Si n-type irradiated with neutons, not for those irradiated with protons



24 GeV protons,
F = 2e15 cm-2, CERN



neutrons, Fn = 5e14 cm-2,
Ljubljana

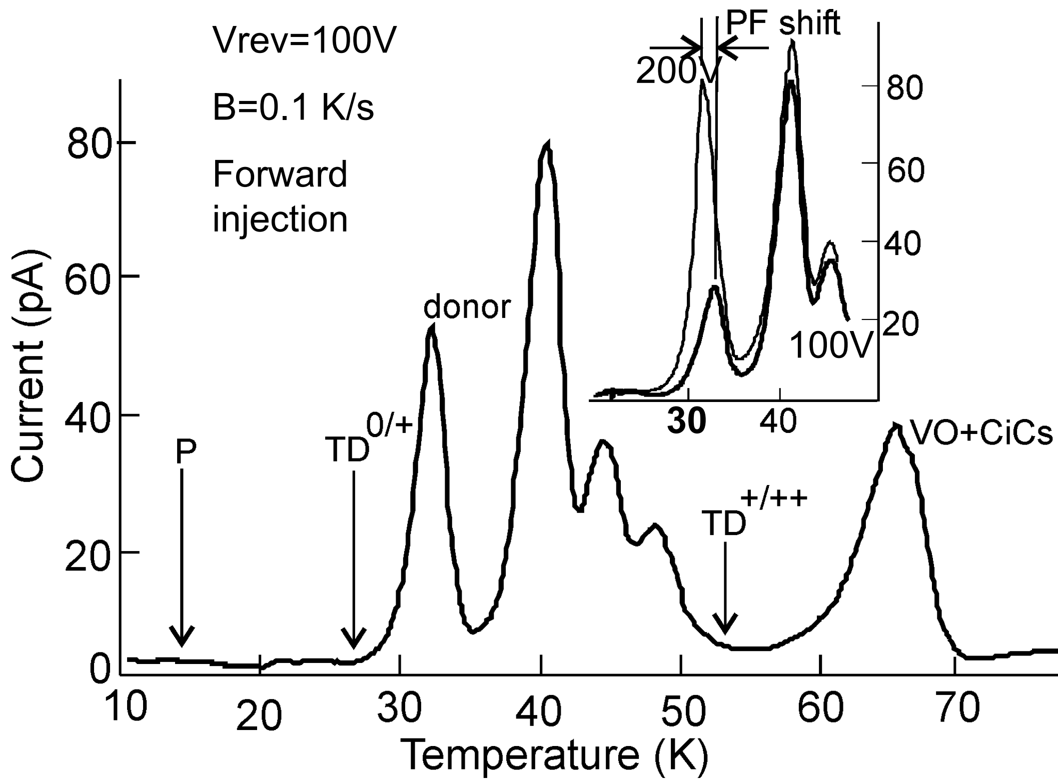


M. Scaringella et al. presented at Large Scale Applications and Radiation Hardness Florence, Oct. 2005

Possible microscopic explanation of the delayed SCSI or suppressed space charge sign inversion

1. EVIDENCE OF RADIATION INDUCED SHALLOW DONOR IN MCz

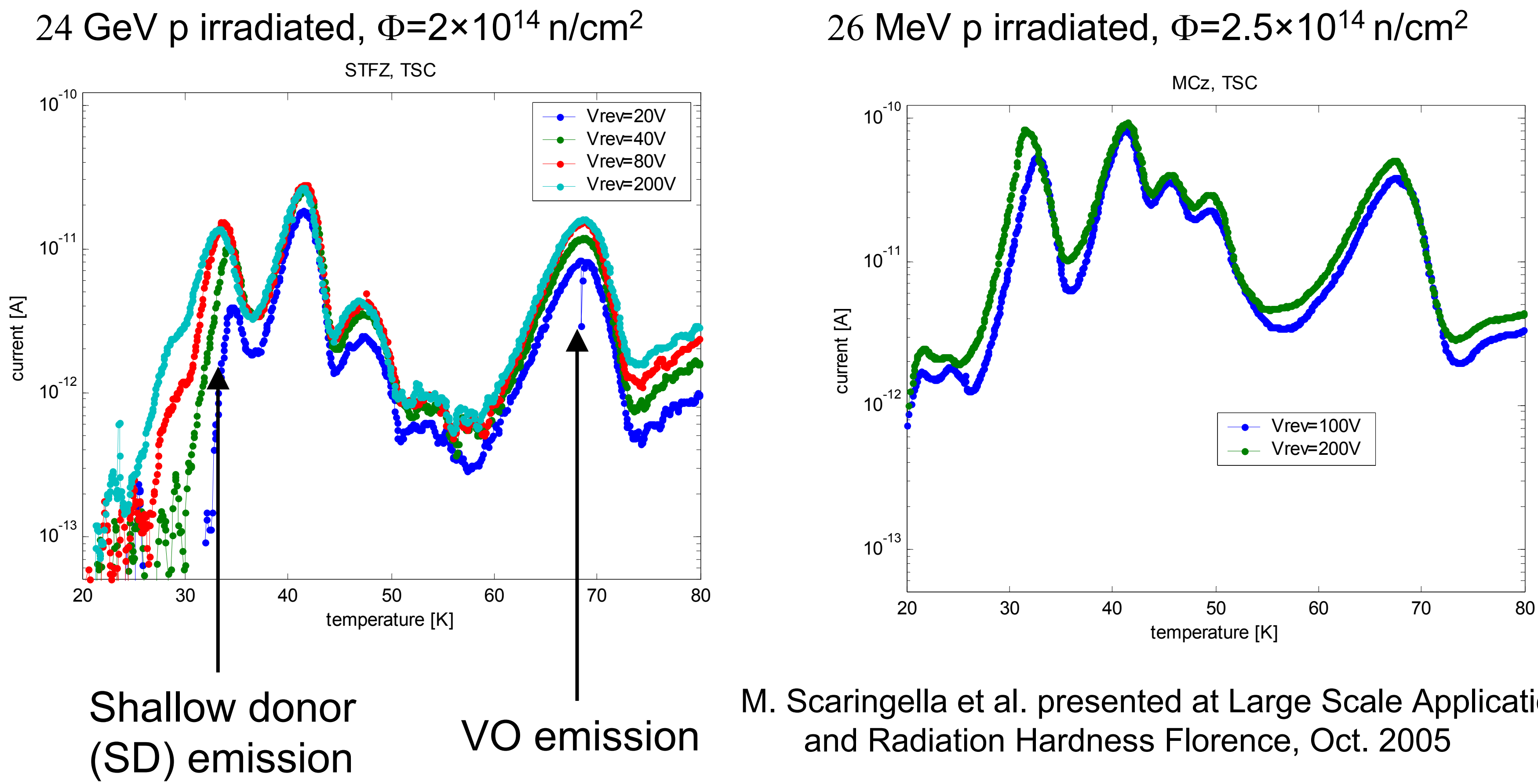
30 K peak (PF shift observed on peak at 30K, evidencing it is donor-like nature)



N type MCz Sample:
no LTO, sintering at 380°C
24GeV/c p up to $4x10^{14}p/cm^2$
Annealing: 1260min at 60°C
Full depletion at 93 V

M. Bruzzi et al. *Nucl. Instr. and Meth. A, in press*

2. Evidence of VO complex increase in MCz n-type (related to a decreased concentration of V_2 related defects at midgap

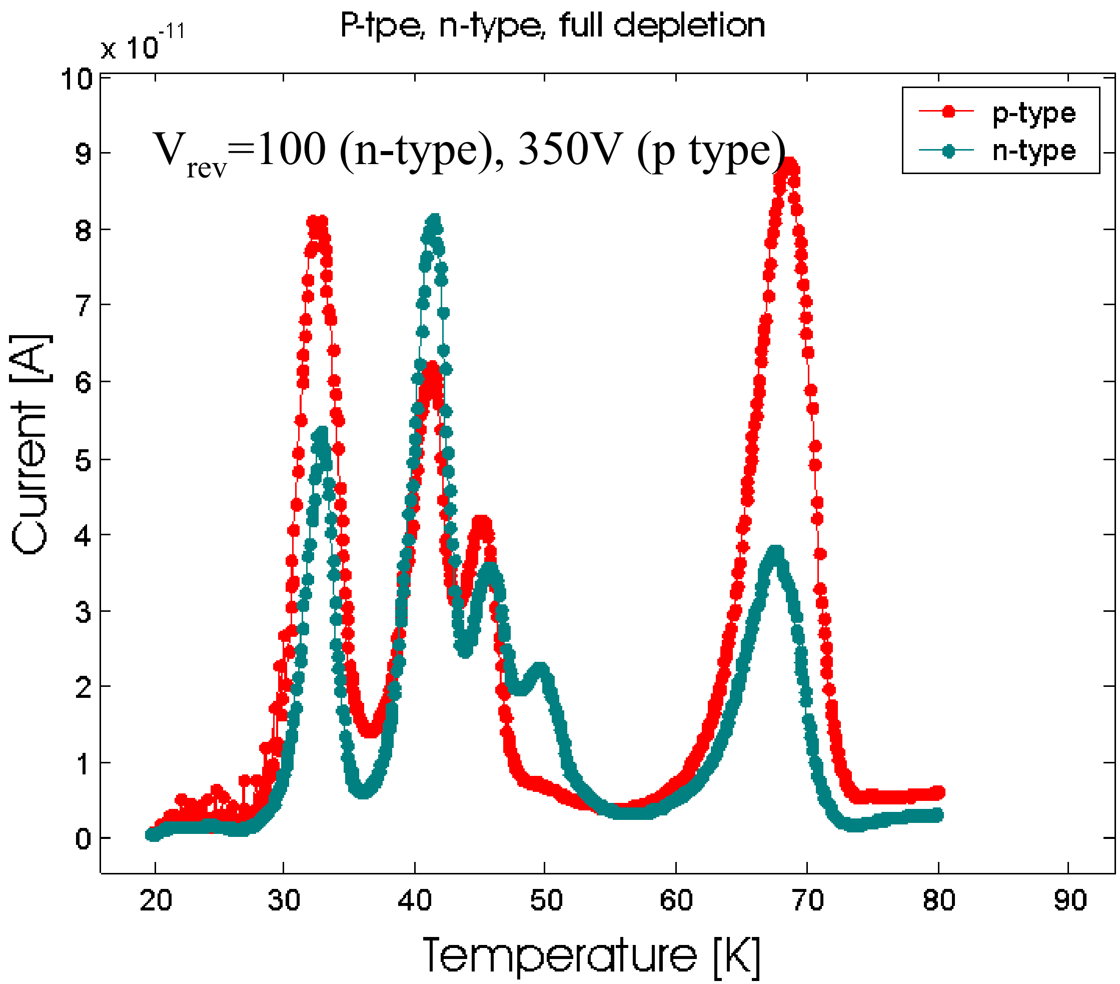


M. Scaringella et al. presented at Large Scale Applications and Radiation Hardness Florence, Oct. 2005

- Signal can be saturated for STFZ but not for MCz sample
- VO concentration is at least 3 times higher in MCz than in STFZ
- SD concentration is at least 5 times higher in MCz than in STFZ

Comparison p- and n-type MCZ after irradiation

n-on-p IRST
p-spray dose of $5x10^{12}cm^{-2}$
24GeV/c p up to $4x10^{14}p/cm^2$
annealing of 180min at 80°C
Full depletion voltage 337V.



The same shallow donor is obseved in p-type and n-type MCz Si

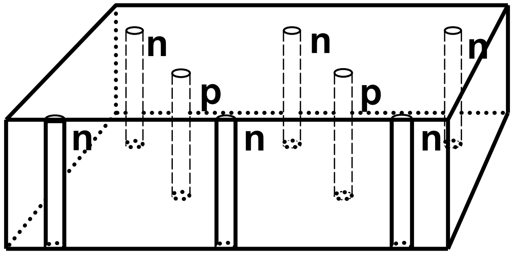
Bruzzi et al., Trento rd50 Workshop, Feb, 2004

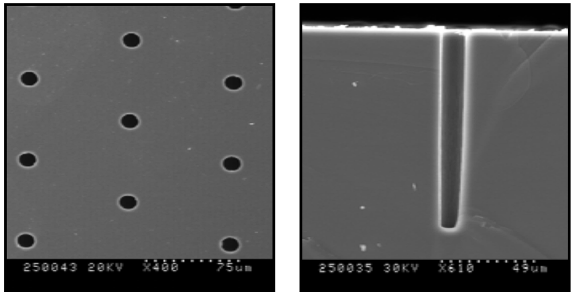
Further developments: 3D detectors

First 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**

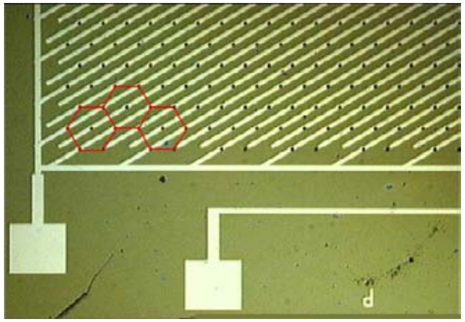
Present size up to ~1cm^2

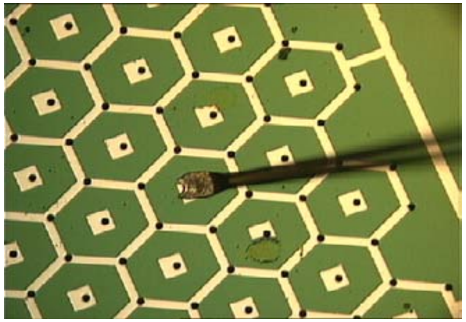




SEM and photos by Glasgow group

3D hexagonal geometry connected in strip and pixel configurations →





G. Dalla Betta, SCIPP talk, Sept. 2005

Conclusions

- Radiation hard materials for tracker detectors at SuperLHC are under study by the CERN RD50 collaboration. Fluence range to be covered with optimised S/N is in the range 10^{15}-$10^{16}cm^{-2}$. 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 . High resistivity MCz n-type and p-type FZ &MCz Si are most promising materials.

- Miniature microstrip and pixel detectors made with defect engineered Si n- and p-type have been fabricated by RD50 and are now under study.

- Quite encouragingly, **at higher fluences results seems better than first estrapolation made using parameters estimated at lower fluence**:

- **higher trapping times (p-FZ, p-DOFZ, first n-MCz SMART)**
- **delayed reverse annealing (MCz SMART)**
- **sublinear growth of the V_{dep} with fluence (p- MCz&FZ)**
- **delayed/supressed type inversion (p-MCZ&FZ, MCz n- protons)**