Recent Results on Radiation Hard Semiconductor Detectors for SuperLHC

Mara Bruzzi on behalf of the RD50-Collaboration

INFN Firenze, University of Florence, Italy

- Motivation
- Radiation Damage in Si detectors
- Strategies for radiation hardening of detectors
  - Material engineering
  - Device engineering
- Summary

Motivation

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

LHC: $L = 10^{34}\text{cm}^{-2}\text{s}^{-1}$ $\xrightarrow{\text{10 years}}$ **f(R=4cm)** ~ $3{\cdot}10^{15}\text{cm}^{-2}$
f(R=75cm) ~ $3{\cdot}10^{13}\text{cm}^{-2}$

⇨ Technology available ⇨ However, serious radiation damage!

´ 5

S-LHC: $L = 10^{35}\text{cm}^{-2}\text{s}^{-1}$ $\xrightarrow{\text{5 years}}$ **f(R=4cm)** ~ $1.6{\cdot}10^{16}\text{cm}^{-2}$

⇨ Technology not available ⇨Focused and coordinated R&D mandatory to develop radiation hard and cost-effective detectors

- **LHC experiments** (…starting 2007)

⇨ **Radiation hard technologies now adopted have not been completely characterized**: Oxygen-enriched Si in ATLAS/CMS pixels

⇨ **Replacement of components** e.g. for LHCb Velo at r < 4cm a replacement of detectors is foreseen after 3 years operation

- **Linear collider experiments**

Deep understanding of radiation damage will be fruitful for linear collider experiments where high doses of e, γ will play a significant role.

The CERN RD50 Collaboration

http://www.cern.ch/rd50

- **Collaboration formed in November 2001**
- **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** (Going from 25ns to 10 ns bunch crossing ?)
- **Low mass** (reducing multiple scattering close to interaction point)
- **Cost effectiveness** (big surfaces have to be covered with detectors!)

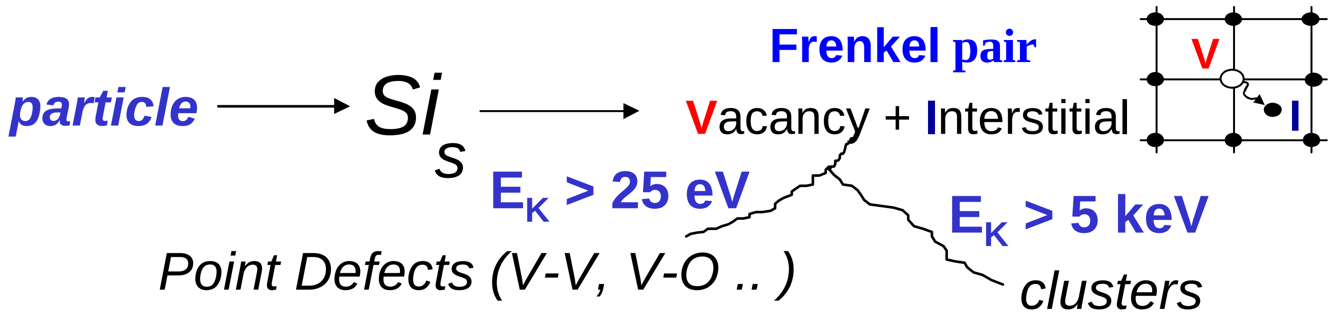
- **Presently 271 Members from 52 Institutes**

Belarus (Minsk), Belgium (Louvain), Canada (Montreal), Czech Republic (Prague (2x)), Finland (Helsinki, Lappeenranta), Germany (Berlin, Dortmund, Erfurt, Hamburg, Karlsruhe), Israel (Tel Aviv), Italy (Bari, Bologna, Florence, Milano, 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), Switzerland (CERN, PSI), Ukraine (Kiev), United Kingdom (Exeter, Glasgow, Lancaster, Liverpool, Sheffield, University of Surrey), USA (Fermilab, Purdue University, Rochester University, Rutgers University, SCIPP Santa Cruz, Syracuse University, BNL, University of New Mexico)

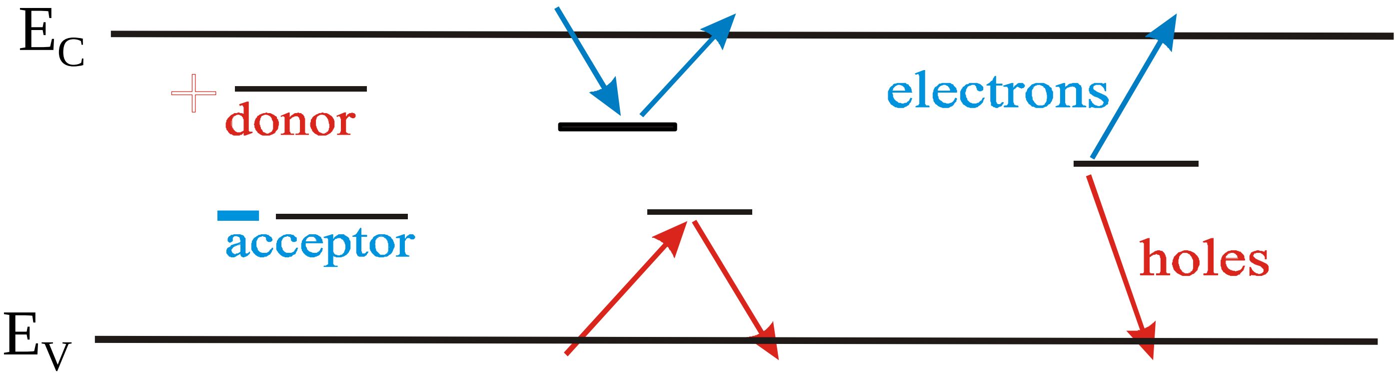
Radiation Hardening Strategies

- **Material Engineering**
  - **Defect and Material Characterization**
  - **Defect engineering of silicon**
  - **New detector materials (SiC, GaN, ...)**
- **Device Engineering**
  - **Improvement of present planar detector structures (thin detectors, 3D / semi-3D detectors, cost effective detectors,…)**
  - **Tests of LHC-like detector systems produced with radiation-hard technology**
- **Change of operational conditions (RD39)**
  - **Low temperature**
  - **Injection** ® **V. Eremin talk, this session**
  - **Forward bias**

Radiation induced defects and impact on device performance



Influence of defects on the material and device properties



charged defects
Þ **N_{eff} , V_{dep}**
e.g. donors in upper half of band gap and acceptors close to midgap

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

Defect Engineering of Silicon

Influence the defect kinetics by incorporation of impurities or defects:

- **Oxygen**

  getters radiation-induced vacancies: V + O ® VO (not harmful at RT)

  High oxygen content reduces formation of V_2, V_3, V_2O, V_2O_2,...;

  i.e. related deep acceptor levels ⇒ less negative space charge

- **Oxygen dimers**

  getters vacancies V: V + O_2 ® VO_2 (electrically not active)

  getters interstitials I: I + O_2 ® IO_2

  IO_2 acts as precursor for Thermal Donor (TD) formation

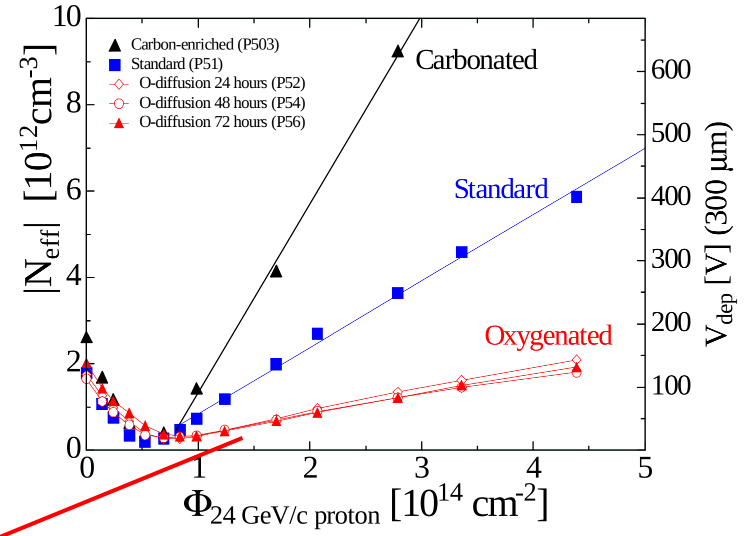
- **Multi-Oxygen complexes**

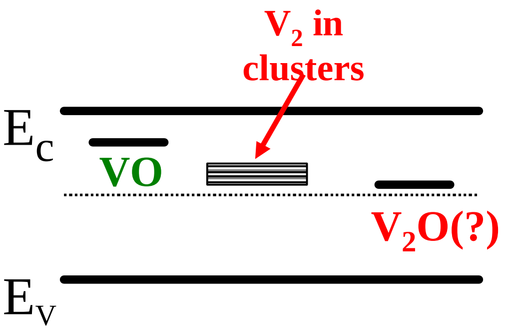
  formation, deactivation of TDs

  transformation of Cz-silicon from p- to n-type

- **Hydrogen**

  passivation of defects?, promotion of TD formation





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

Silicon Materials under Investigation by RD50

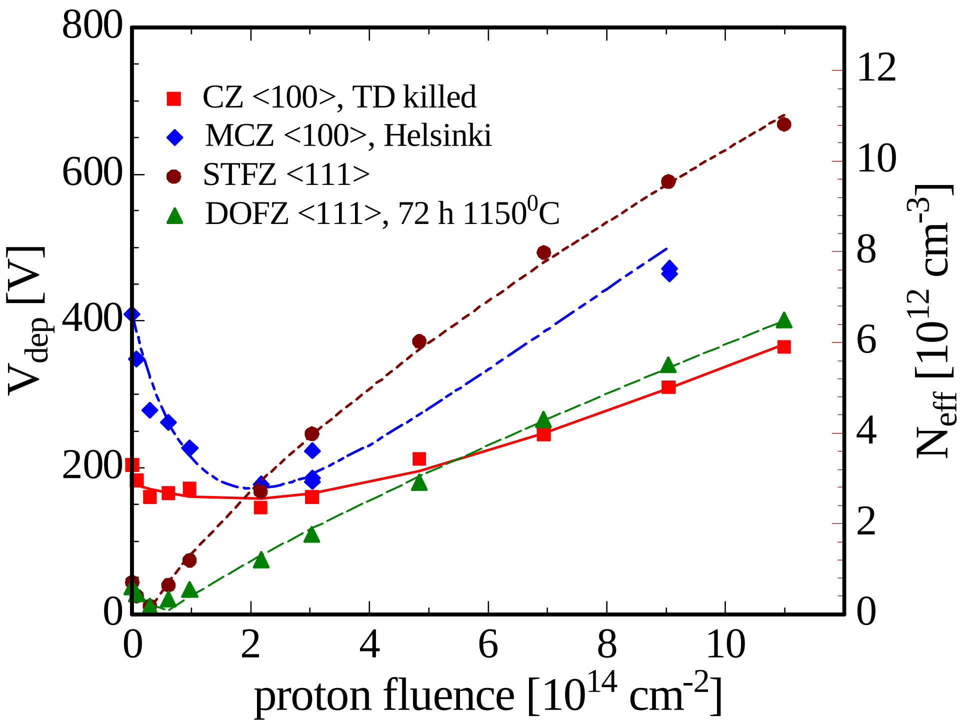
Material	Symbol	r (Wcm)	[O$_i$] (cm^{-3})
Standard n- or p-type FZ	StFZ	1–7´10^{3}	< 5´10^{16}
Diffusion oxygenated FZ, n- or p-type	DOFZ	1–7´10^{3}	~ 1–2´10^{17}
Czochralski Sumitomo, Japan	Cz	~ 1´10^{3}	~ 8-9´10^{17}
Magnetic Czochralski Okmetic, Finnland	MCz	~ 1´10^{3}	~ 4-9´10^{17}
Epitaxial layers on Cz-substrates, ITME	EPI	50 - 100	< 1´10^{17}

- **Cz-silicon:**
  high O_i and O_2 concentration, formation or deactivtion of TDs possible
  transformation of p- to n-type by TDs possible
- **EPI-silicon:**
  O_i concentration ~ 10^{17}, very inhomogenious
  O_2 concentration expected to be high due to out-diffusion from the Cz substrate
  thin layers Þ high doping (posphorous) possible

Standard FZ, DOFZ, Cz and MCz Silicon

CERN-scenario experiments

23 GeV protons



- **Standard FZ (STFZ)**
  type inversion at ~ 2´10^{13} p/cm^2
  strong N_{eff} increase at high fluence

- **Oxygenated FZ (DOFZ)**
  type inversion at ~ 2 ´10^{13} p/cm^2
  reduced N_{eff} increase at high fluence

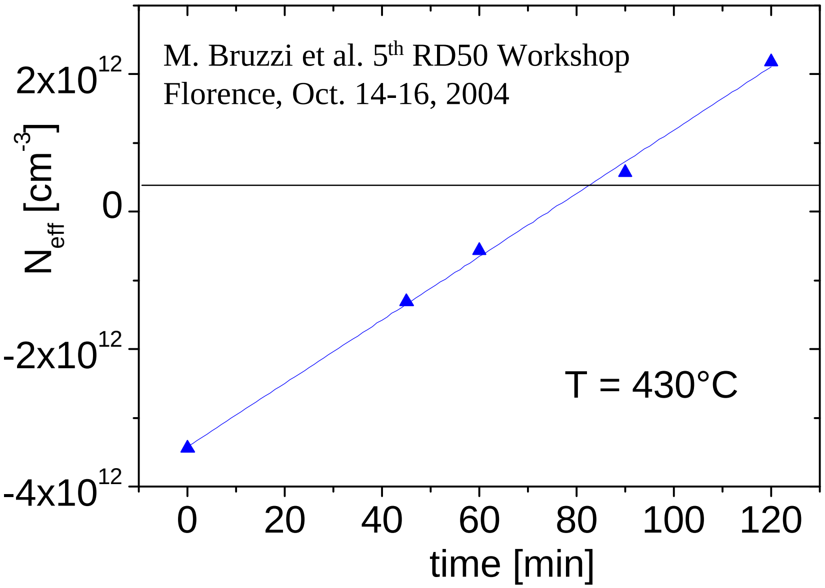
- **Cz and MCz**
  no type inversion in the overall fluence range, verified by TCT measurements (G. Kramberger, 4-th RD50 workshop)
  Þ donor generation > acceptor generation in high fluence range

- **Common to all materials:**
  same reverse current increase
  same increase of trapping (electrons and holes) within ~ 20%

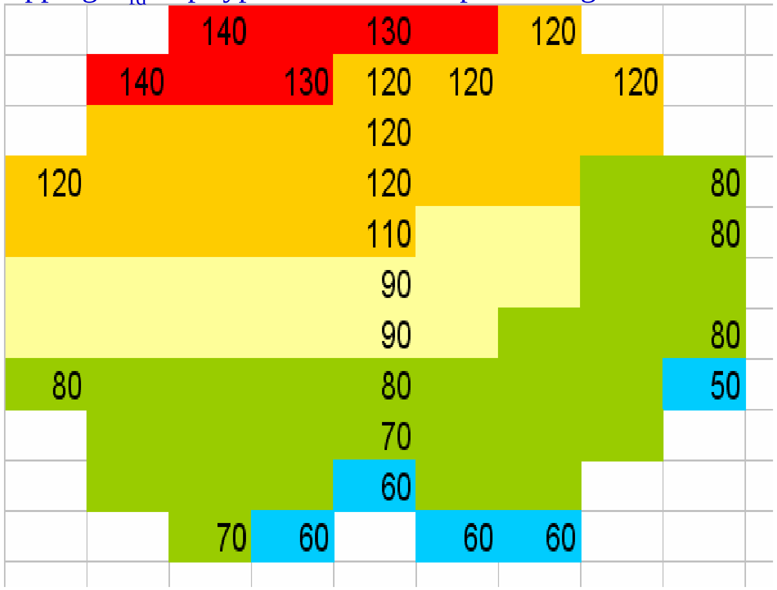
Thermal Donor activation in MCz Si

Effective doping concentration (depletion voltage) in MCz Si can be tailored by thermal treatment with T » 400-450°C which enhances Thermal Donor activation

starting with p-type, converting it to n-type


M. Bruzzi et al. 5th RD50 Workshop
Florence, Oct. 14-16, 2004

Mapping V_{fd} in p-type MCz Si after processing at IRST-Trento



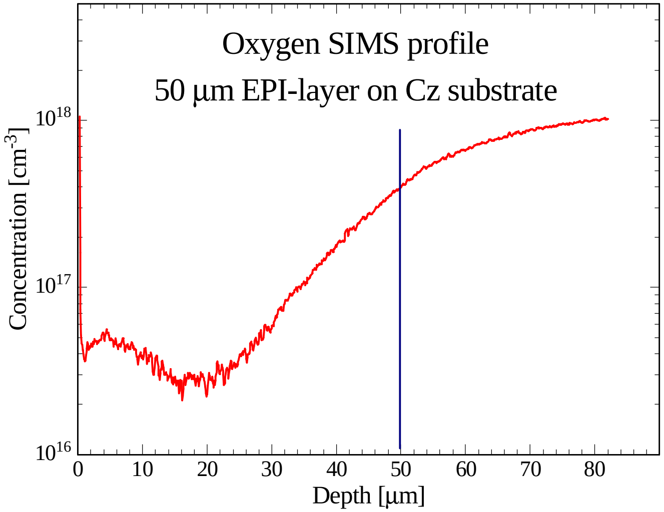
		140		130		120		
	140		130	120	120		120	
				120				
120				120				80
				110				80
				90				
				90				80
80				80				50
				70				
				60				
		70	60		60	60		

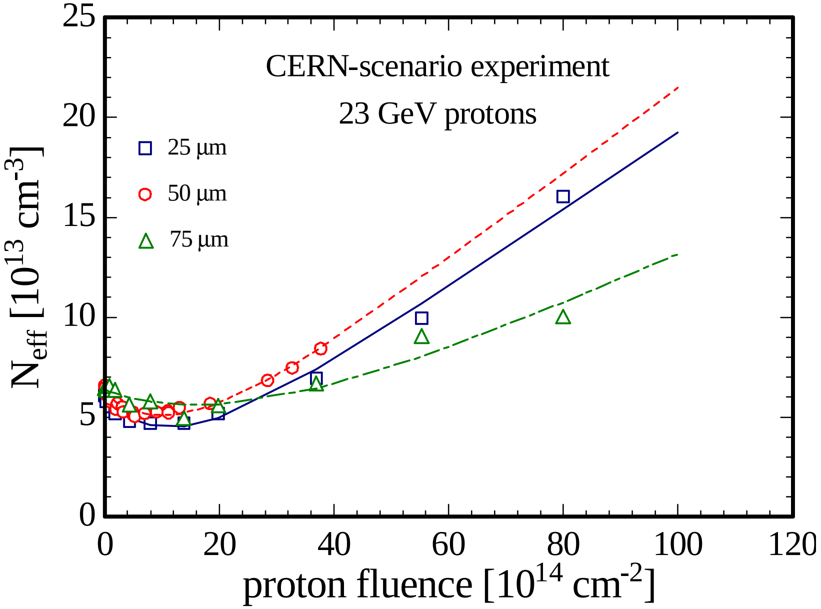
C. Piemonte et al. 5th RD50 Workshop.
Florence, Oct. 14-16, 2004

Spread in N_{eff} , V_{fd} due to the fluctuations in the concentration of native defects (O_i, H, ..) locally affecting the TDs generation rates → hidden parameters, difficult to control

See also J. Harkonen talk, this session

EPI Devices – 23 GeV Protons





Epitaxial silicon grown by ITME

Layer thickness: 25, 50, 75 mm

Resitivity: ~ 50 Wcm

Oxygen: [O] » 9´10^{16} cm^{-3}

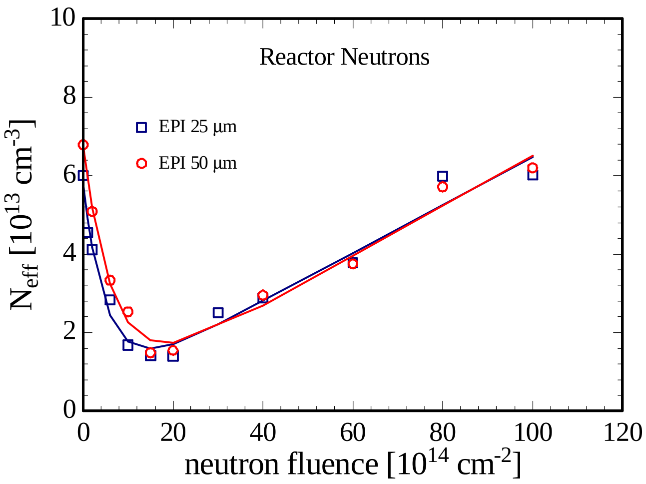
out-diffusion from Cz substrate into EPI-layer

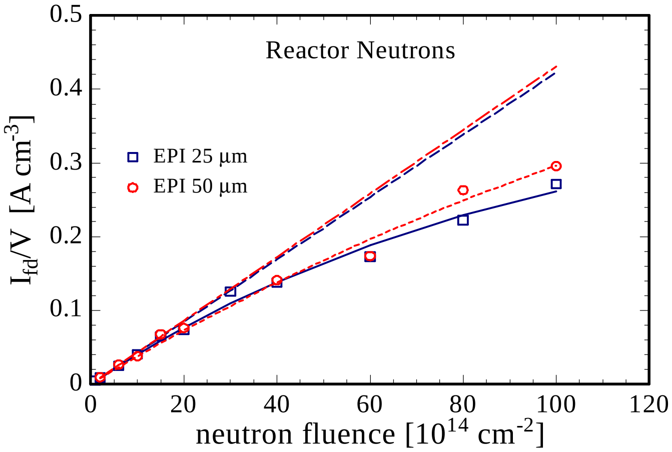
O-dimers: presence detected by the formation of the IO_2-defect

- **No type inversion in the full range up to ~ 10^{16} p/cm^2**
- **Development of N_{eff} nearly identical for 25 mm and 50 mm, lower increase for 75 mm has to be proven**
- **Proposed explanation: introduction of donors > generation of deep acceptors at high fluences**

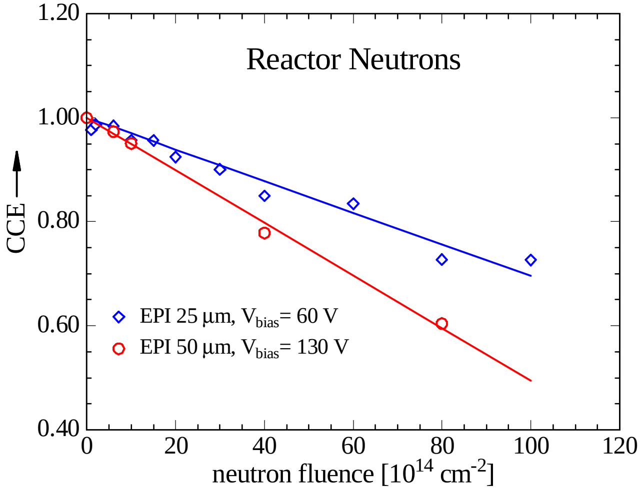
E. Fretwurst, Univ. Hamburg, RESMDD04, Florence, October 10.-13. 2004

EPI Devices – Reactor Neutrons





Irradiation:
TRIGA-reactor/Ljubljana
Measurements:
after irradiation
before annealing



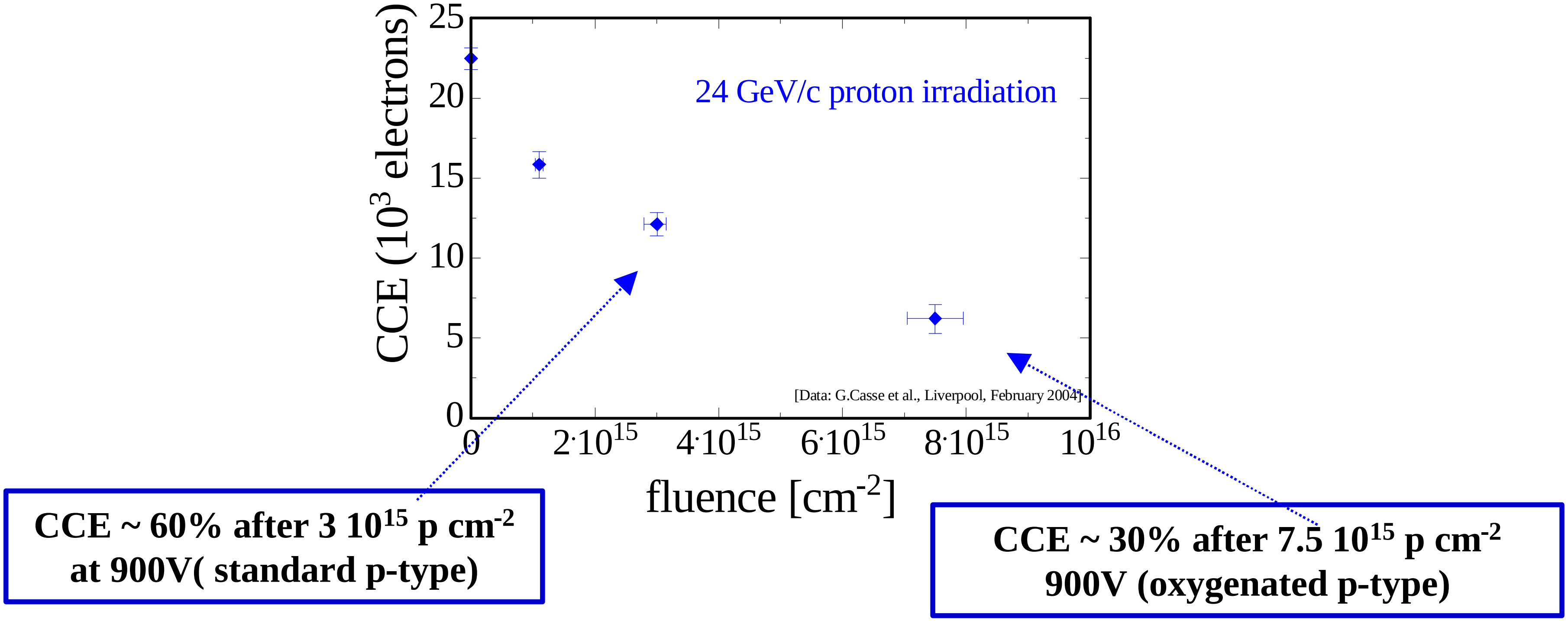
- **N_{eff} development:**
  Minimum between 1.5 - 2 ´ 10^{15} cm^{-2}
  N_{eff} at 10^{16} cm^{-2} » N_{eff} before irradiation
  Type inversion at ~ 2 ´ 10^{15} cm^{-2} , yes or no?
  First annealing studies indicate “no type inversion“
- **Reverse current increase:**
  saturation effect at high fluences
  straight lines indicate fits for low fluence range
  a = 4.3 ´ 10^{-17} A/cm
  reduction at 10^{16} cm^{-2} » 31-36% with respect to linear fit
- **Charge collection efficiency for 5.8 MeV a-particles:**
  25 mm: CCE(10^{16} cm^{-2}) » 70%
  50 mm: CCE(10^{16} cm^{-2}) » 50%

E. Fretwurst, Univ. Hamburg, RESMDD04, Florence, October 10.-13. 2004

Device Engineering: n-in-p Microstrip Detectors

- Miniature n-in-p microstrip detectors (280μm).
- Detectors read-out with LHC speed (40MHz) chip (SCT128A)
- Material: standard p-type and oxygenated (DOFZ) p-type

G. Casse et al., Vienna Conference, Feb. 2004



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

Device Engineering - Thin Detectors

Motivation for using thin detectors:

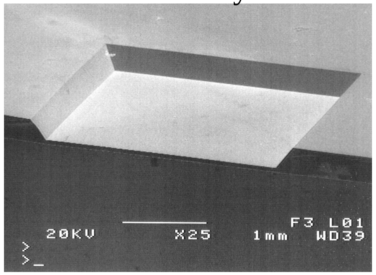
- Smaller leakage current: I_{leak} µ W, W sensitive detector thickness
- Smaller voltage for total depletion: V_{dep} µ W^2
- Charge collection at very high fluences is limited by carrier trapping
- **Drawback:** mip signal ~ 3500e-h pairs

ITC-IRST, Trento, Italy

Thinning by chemical attacks

Cross section of a thinned silicon detector

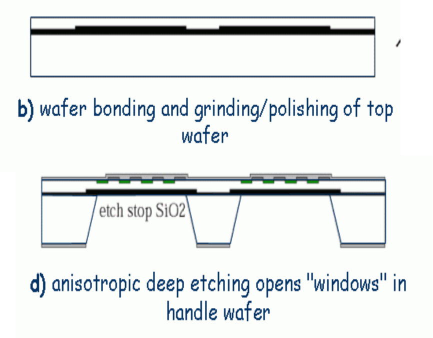
IRST: SEM of a Si wafer thinned by TMAH



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

MPI-Munich, Germany

Wafer bonding technology



b) wafer bonding and grinding/polishing of top wafer

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

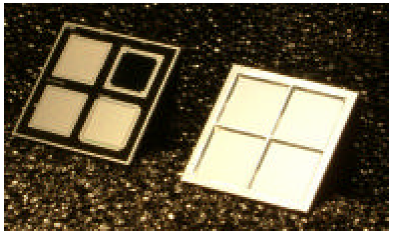
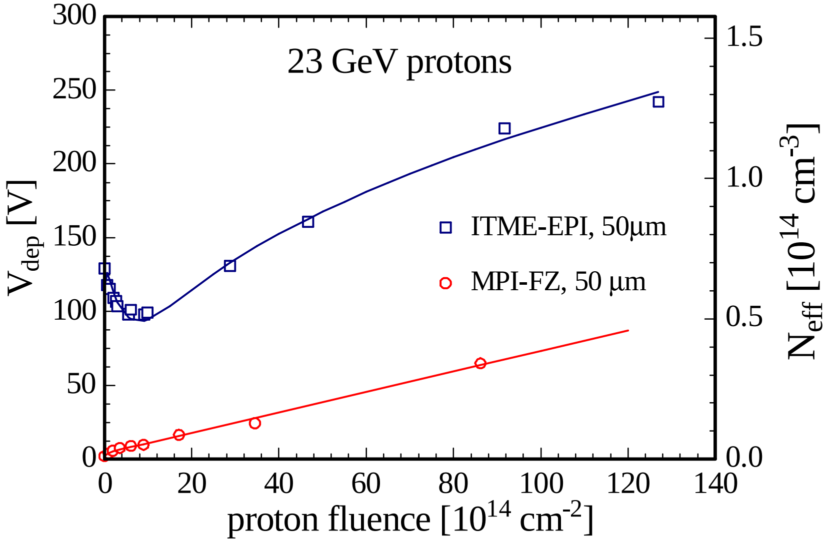


Photo:
front (left) and
back (right) view
of thinned devices

(L.Andricek, 1st ECFA Workshop, Montpellier, Nov. 2003)

MPI thin devices compared with epitaxial

E. Fretwurst, Univ. Hamburg, RESMDD04, Florence, October 10.-13. 2004



Effective introduction rates:

- **MPI chip:**
  b$_{eff}$ **= 0.0036 cm^{-1}**
  comparable with DOFZ-Si

- **EPI device:**
  b$_{eff}$ **= 0.0084 cm^{-1}**
  shallow donor creation

IRST thin devices after irradiation with Li^+ ions in Padova

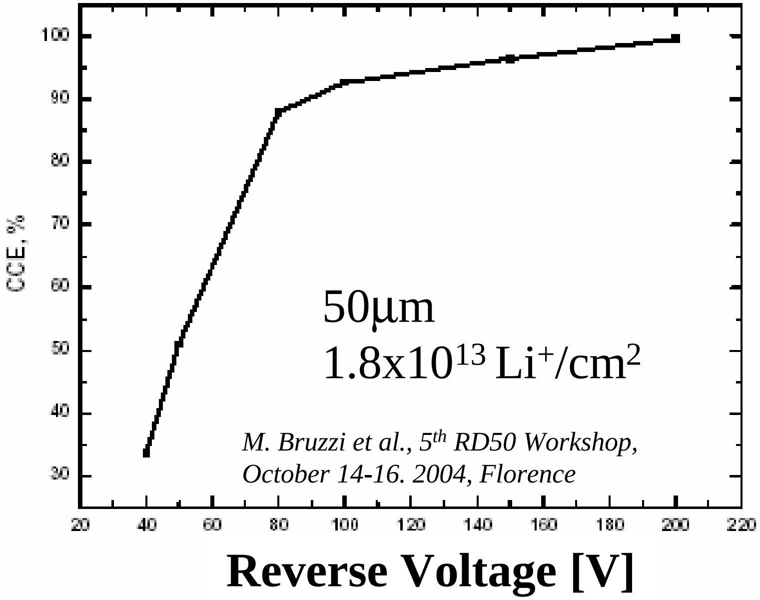
Up to $1.8\text{x}10^{13}$ Li/cm^2 → $8.1\text{x}10^{14}$ 1MeV n/cm^2

100% CCE measured with ^{90}Sr b **@ -20°C**

But need to overdeplete: $V_{CCE} >> V_{CV}$

V_{CCE} = 75V (50m**m)**

V_{CCE} = 230-300V (100m**m)**

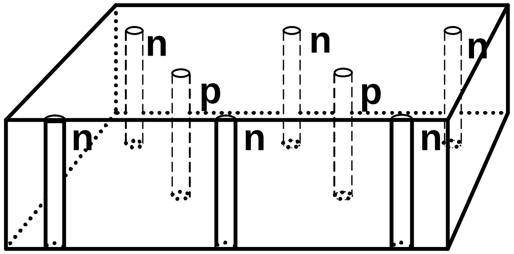


M. Bruzzi et al., 5th RD50 Workshop, October 14-16. 2004, Florence

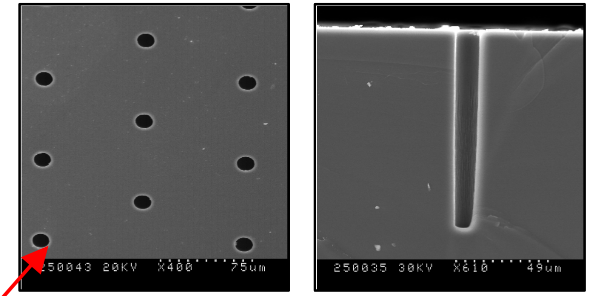
Device Engineering –3D Detectors

(*Introduced by S.I. Parker et al., NIMA 395 (1997) 328*)

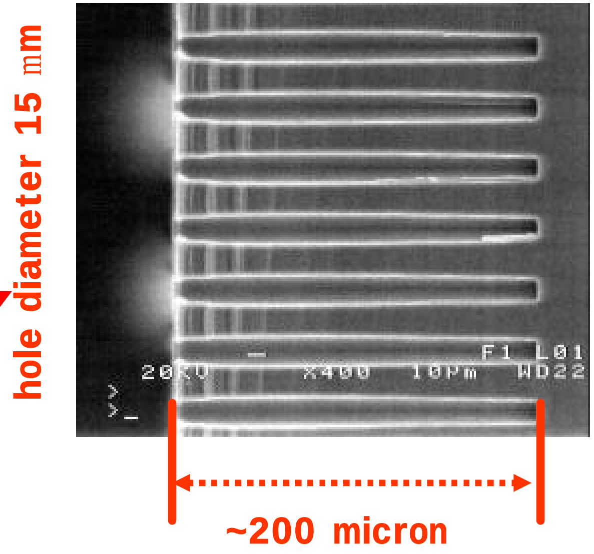
- **Electrodes:**
  - narrow columns along detector thickness-“3D”
  - diameter: 10µm distance: 50 - 100µm
- **Lateral depletion:**
  - lower depletion voltage needed
  - thicker detectors possible
  - fast signal



- **Hole processing :**
  - Dry etching, Laser drilling, Photo Electro Chemical
  - Present aspect ratio (RD50) 13:1, Target: 30:1
- **Electrode material:**
  - Doped Polysilicon (Si)
  - Schottky (GaAs)



Glasgow University



3D detector developments within RD50:

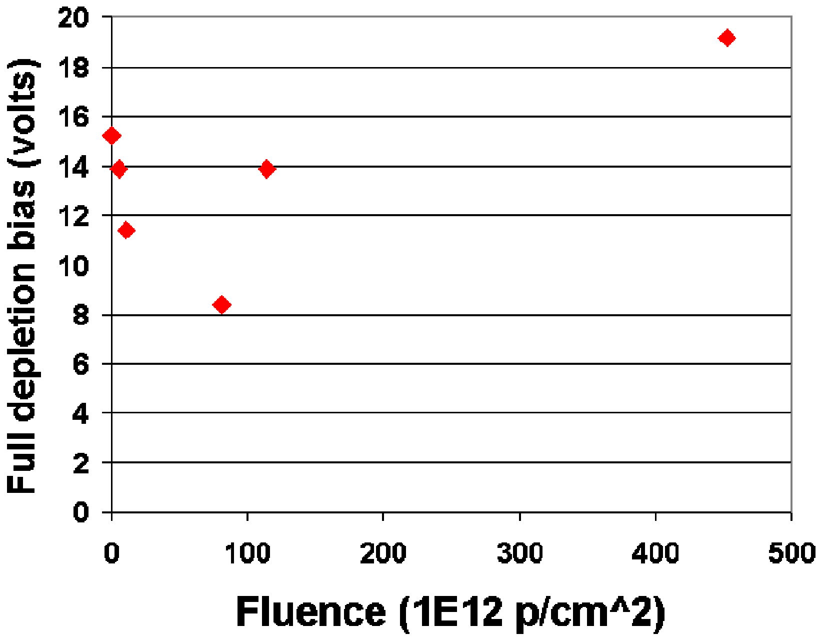
1) Glasgow University – Schottky contacts
2) IRST-Trento and CNM Barcelona (since 2003)

CNM: Hole etching (DRIE); IRST: all further processing
diffused contacts or doped polysilicon deposition

(see C. Piemonte IRST, this conference)

Proton irradiation of 3D detectors produced at Glasgow

- High res n-type silicon, 85μm pitch, close-packed hexagonal pixels
- Irradiation with 24 GeV/c protons at CERN
- 7 fluences from 5 x 10^{12} to 4.5 x 10^{14} p /cm^2



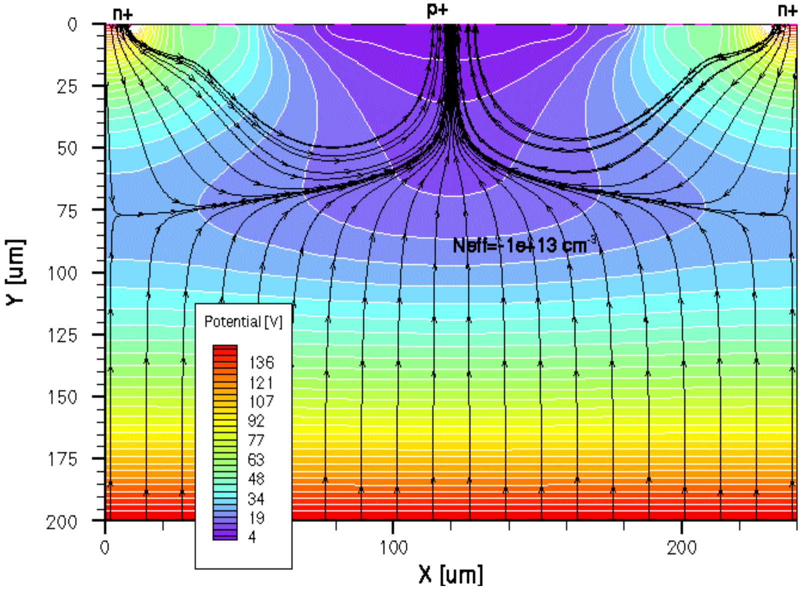
For 4.5 x 10^{14} p/cm^2
Depletion voltage = 19V
Type inversion observed

Device Engineering –Semi-3D Detectors

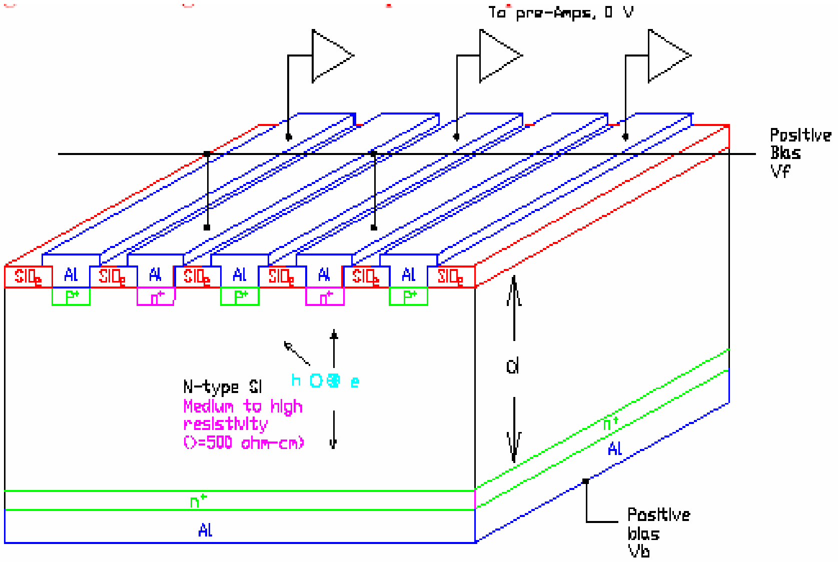
Semi 3-D devices proposed by Z. Li, BNL.

- **Planar technology easier to process than 3D sensors**
- **Single-sided processing**
- **Large reduction in detector full depletion voltage after type inversion**
- **Processing of first prototype completed**

n^+(150V) **p^+(0 V)** **n^+(150V)**



n^+(150V)



Z. Li et al. NIMA478, (2002), 303-310

Simulation of electric profile in semi 3D after irradiation to $5x10^{14}$ n/cm^2.

Summary

- **Different materials and new device concepts for tracking detectors in SLHC-experiments are under study by the CERN-RD50 collaboration.**

- **In different tracking areas different detector concepts and materials have to be optimized:**
  Outer layers exposed up to 10^{15} hadrons/cm^{2}: Change of the depletion voltage and the large area to be covered are the major problems.
  High resistivity Cz detectors might be a cost-effective radiation hard solution.
  Inner layers exposed up to 10^{16} hadrons/cm^{-2} : The sensitive detector thickness is strongly reduced due to carrier trapping. Two promising options are:
  Thin/EPI detectors; drawback: rad. hard electronics for small signals needed
  3-D detectors; drawback: complicated technology, has to be optimized

- **Miniature micro-strip and pixel detectors on defect engineered Si were fabricated by RD50. First tests with LHC like electronics are encouraging: CCE » 6500 e for n-in-p oxygenated microstrip detectors irradiated up to 7´ 10^{15} cm^{-2} (23 GeV protons)**