Recent Advancement in the Development of Radiation Hard Semiconductor Detectors for Very High Luminosity Colliders
- the RD50-Collaboration -

E. Fretwurst

on behalf of the RD50-Collaboration

Institute for Experimental Physics,University of Hamburg

- Motivation
- RD50-Collaboration
- Radiation Damage – a brief review
- Strategies for radiation hardening of detectors
  - Material engineering
  - Device engineering
- Summary

Motivation

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

LHC: $L = 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1} \xrightarrow{\text{10 years}}$ $\phi(R=4\,\mathrm{cm}) \sim 3\cdot10^{15}\,\mathrm{cm}^{-2}$

$\phi(R=75\,\mathrm{cm}) \sim 3\cdot10^{13}\,\mathrm{cm}^{-2}$

⇨ Technology available ⇨ However, serious radiation damage!

× 5

S-LHC: $L = 10^{35}\,\mathrm{cm}^{-2}\mathrm{s}^{-1} \xrightarrow{\text{5 years}}$ $\phi(R=4\,\mathrm{cm}) \sim 1.6\cdot10^{16}\,\mathrm{cm}^{-2}$

⇨ 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
- 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** (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

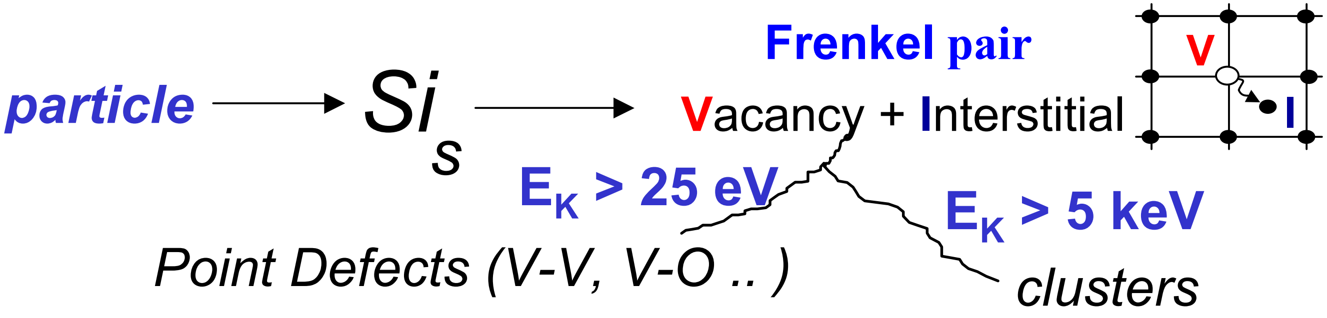
Belarus (Minsk), Belgium (Louvain), Canada (Montreal), Czech Republic (Prague (2x)), Finland (Helsinki, Lappeenranta), Germany (Berlin, Dortmund, Erfurt, Hamburg, Karlsruhe), Israel (Tel Aviv), Italy (Bari, Bologna, Florence, Milano, Padova, Perugia, Pisa, Trento, Trieste, Turin), Lithuania (Vilnius), 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, ..)

- 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

Radiation induced defects and impact on device performance


particle → Si_s → **Frenkel pair**

Vacancy + Interstitial

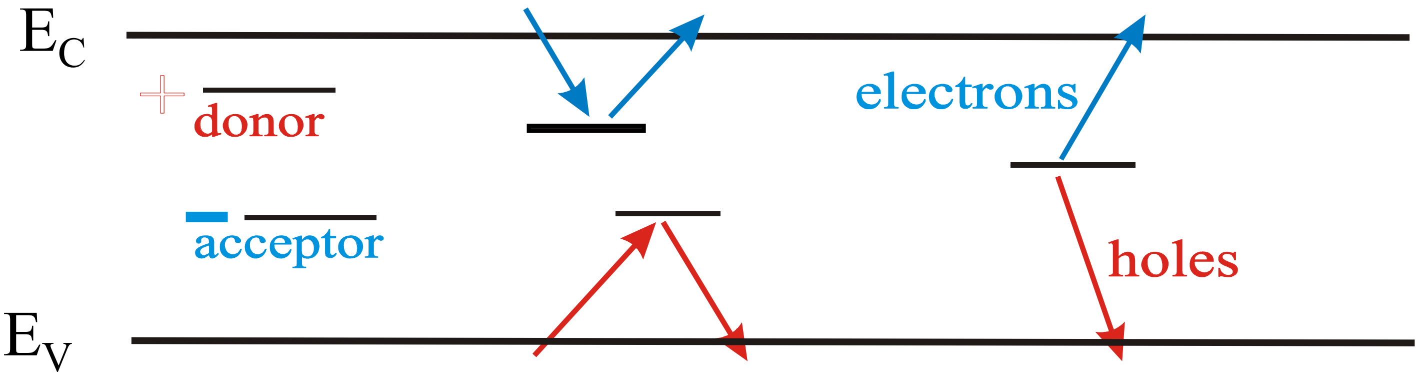
$E_K > 25$ eV

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

$E_K > 5$ keV

clusters

Influence of defects on the material and device properties



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

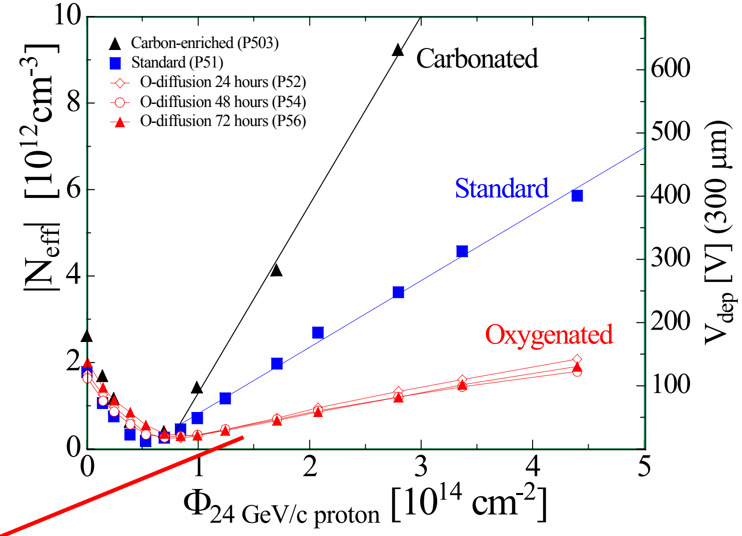
trapping (e and h)
⇒ **CCE**
shallow defects do not contribute at room temperature due to fast detrapping

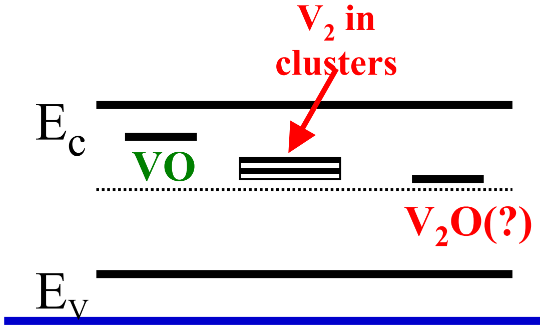
generation
⇒ **leakage current**
levels close to midgap most effective

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: $V + O_2 \rightarrow VO_2$ (electrically not active)
  getters interstitials I: $I + O_2 \rightarrow IO_2$
  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 Material under Investigation by RD50

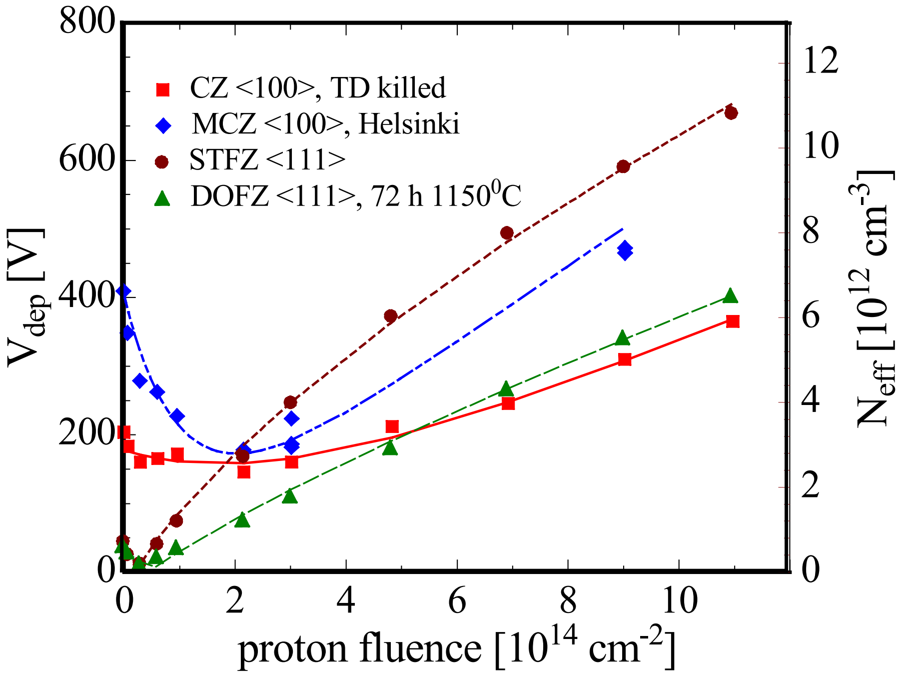
Material	Symbol	ρ (Ωcm)	$[O_i]$ (cm^{-3})
Standard n- or p-type FZ	StFZ	$1–7\times10^3$	$< 5\times10^{16}$
Diffusion oxygenated FZ, n- or p-type	DOFZ	$1–7\times10^3$	$\sim 1–2\times10^{17}$
Czochralski Sumitomo, Japan	Cz	$\sim 1\times10^3$	$\sim 8\text{-}9\times10^{17}$
Magnetic Czochralski Okmetic, Finnland	MCz	$\sim 1\times10^3$	$\sim 4\text{-}9\times10^{17}$
Epitaxial layers on Cz-substrates, ITME	EPI	50 - 100	$< 1\times10^{17}$

- **Cz-silicon:**
  high O_i and O_2 concentration, formation or deactivtion of TDs possible
  transformation of p- to n-type by TDs possible (see *J. Härkönen, this conference*)
- **EPI-silicon:**
  O_i concentration $\sim 10^{17}$, very inhomogenious
  O_2 concentration expected to be high due to out-diffusion from the Cz substrate
  thin layers ⇒ high doping (posphorus) possible

Standard FZ, DOFZ, Cz and MCz Silicon

CERN-scenario experiments

23 GeV protons

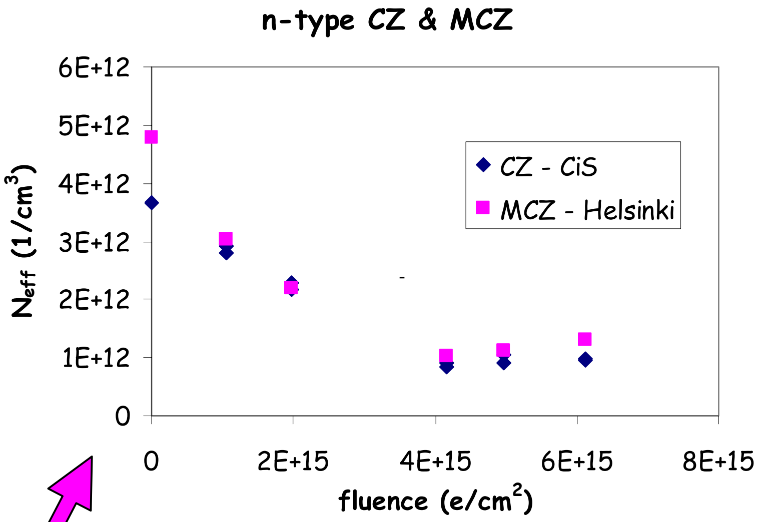


- **Standard FZ (STFZ)**
  type inversion at ~ 2×10^{13} p/cm^2
  strong N_{eff} increase at high fluence
- **Oxygenated FZ (DOFZ)**
  type inversion at ~ 2 ×10^{13} p/cm^2
  reduced N_{eff} increase at high fluence
- **Cz and MCz**
  no type inversion in the overall fluence range, verified by TCT measurements (G. Kramberger, 4-th RD50 workshop)
  ⇒ 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%

Cz and MCz Silicon

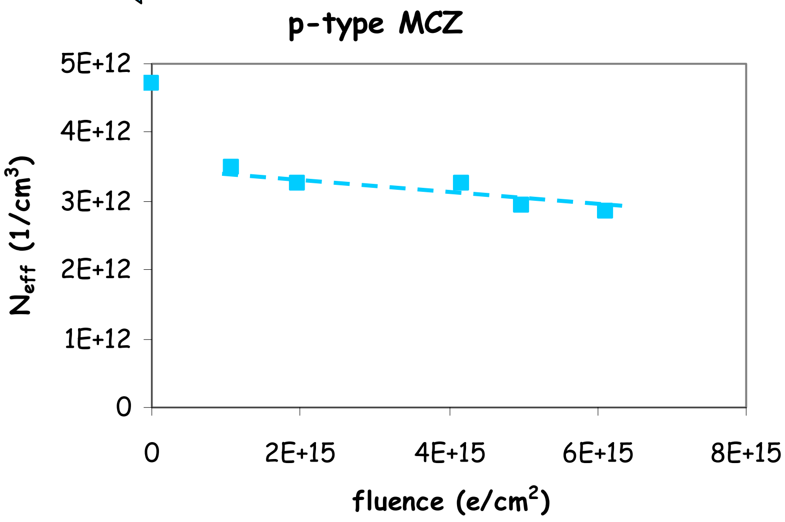
Damage induced by 900 MeV electrons (*S. Dittongo et al., IWORID-2004*)

(experimental hardness factor relative to 1 MeV neutrons: $\kappa_{exp} = 2.0\times10^{-2}$)



P-type MCz silicon:

- very small decrease with fluence above ~ 1×10^{15} cm^{-2}
  corresponding rate:
  $\beta = 1.2\times10^{-4}$ cm^{-1}



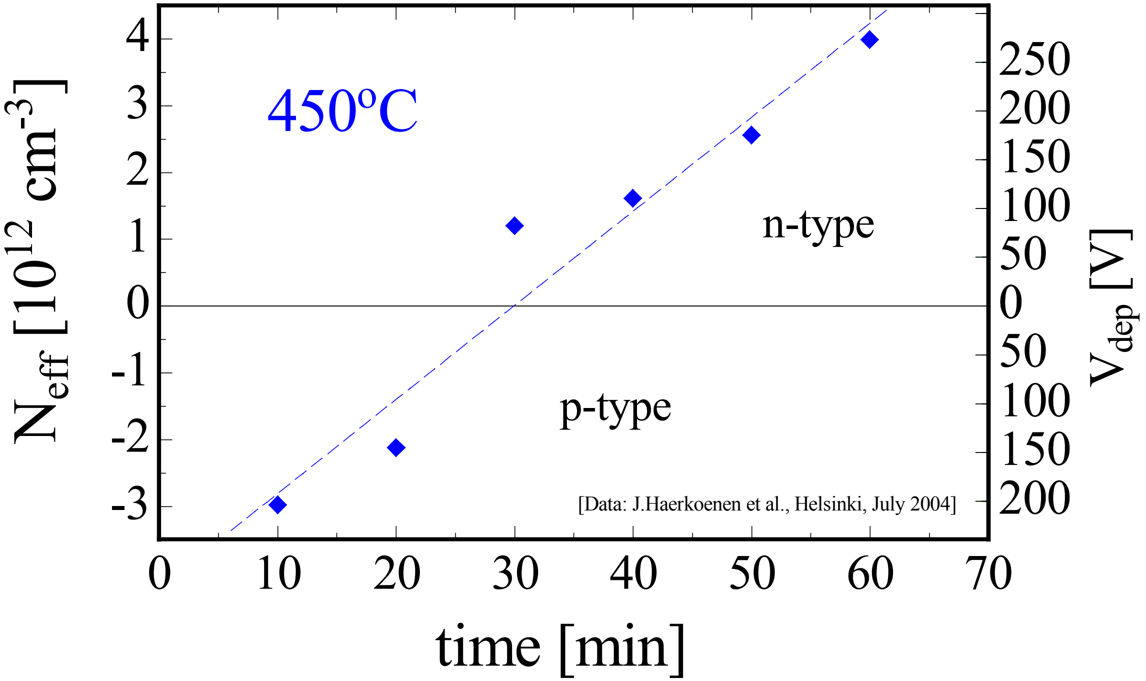
N-type Cz and MCz silicon:

- development of N_{eff} versus fluence nearly the same for both materials
- after initial decrease a small increase at high fluences observed

Transformation of MCz Silicon from P- to N-Type

- **Thermal Donor generation due to heat treatment at 450°C**
- **Effective doping concentration (depletion voltage) can be tailored**

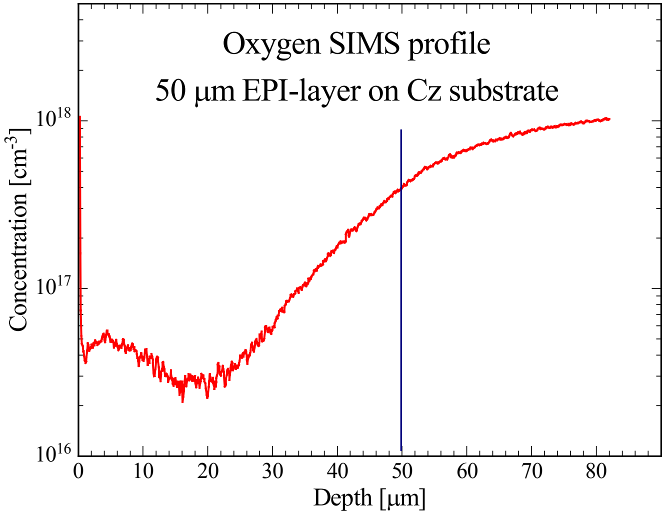
(here: starting with p-type material and converting it to n-type)

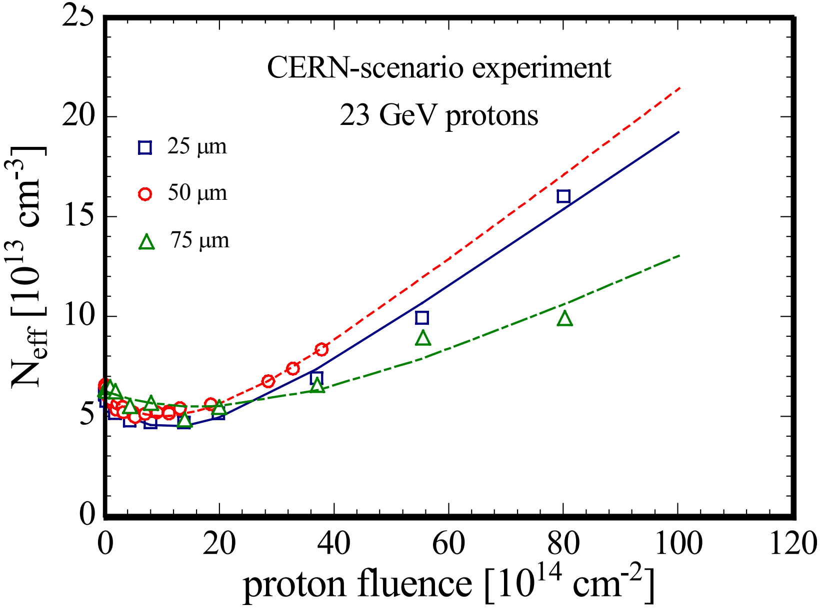


- **Radiation hardness of thermal donor doped MCZ under test → J. Härkönen et al., this conference**

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

EPI Devices – 23 GeV Protons





Epitaxial silicon grown by ITME

Layer thickness: 25, 50, 75 µm

Resitivity: ~ 50 Ωcm

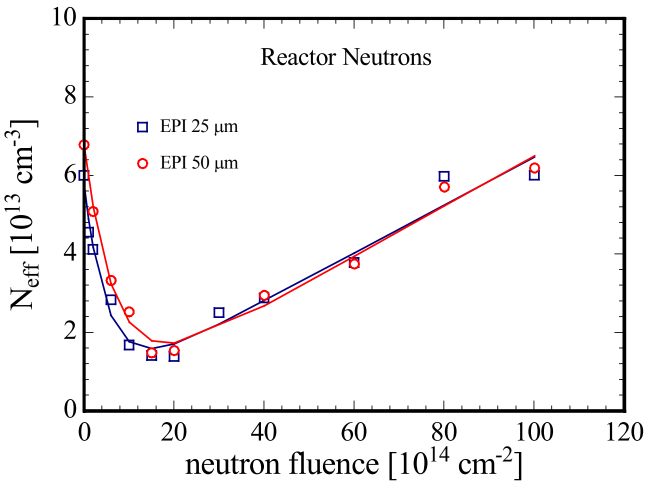
Oxygen: [O] ≈ 9×10^{16} cm^{-3}
out-diffusion from Cz substrate into EPI-layer

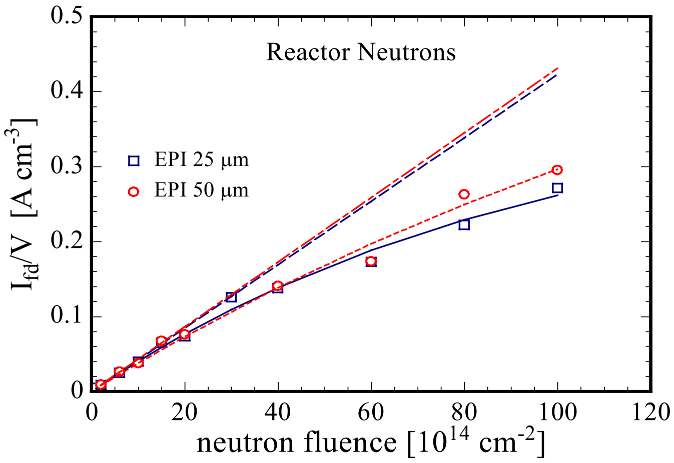
O-dimers: presence detected by the formation of the IO_2-defect

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

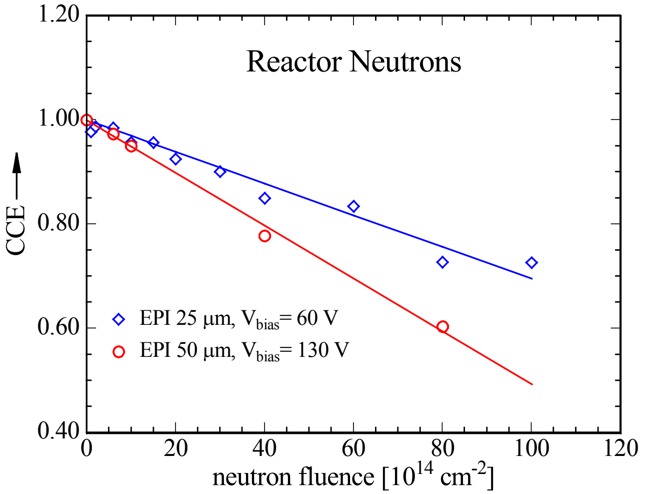
(more details, see G. Lindström, this conference)

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
  $\alpha = 4.3 \times 10^{-17}$ A/cm
  reduction at 10^{16} cm^{-2} ≈ 31-36% with respect to linear fit
- **Charge collection efficiency for 5.8 MeV α-particles:**
  25 µm: CCE(10^{16} cm^{-2}) ≈ 70%
  50 µm: CCE(10^{16} cm^{-2}) ≈ 50%

(*CCE for mips see G. Kramberger, this conference*)

Defects responsible for macroscopic properties

Review ^{60}Co gamma results:

(I. Pintilie et.al., NIMA 514(2003) 18)

Deep acceptors:

I-defect (V_2O?): Introduction ∝ Dose^2

→ second order process

Γ-defect: introduction ∝ Dose

Both defects are responsible for ΔN_{eff} and reverse current increase in standard FZ devices;

In DOFZ material both defects are suppressed

Donor:

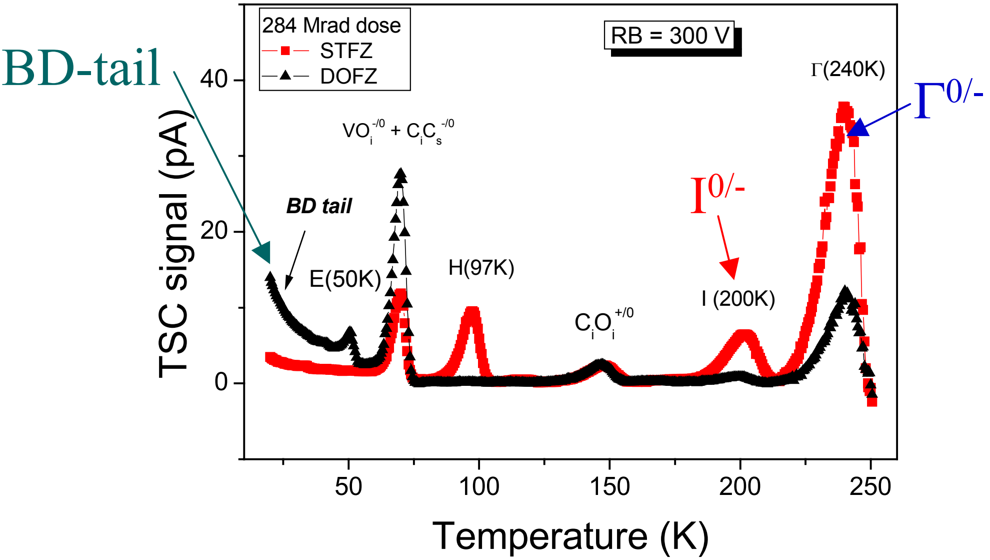
BD-defect: bistable donor, $BD^{+/++}$ (BD-tail) can be tranformed into $BD^{0/++}$ (like early thermal double donors TDD1 and TDD2)

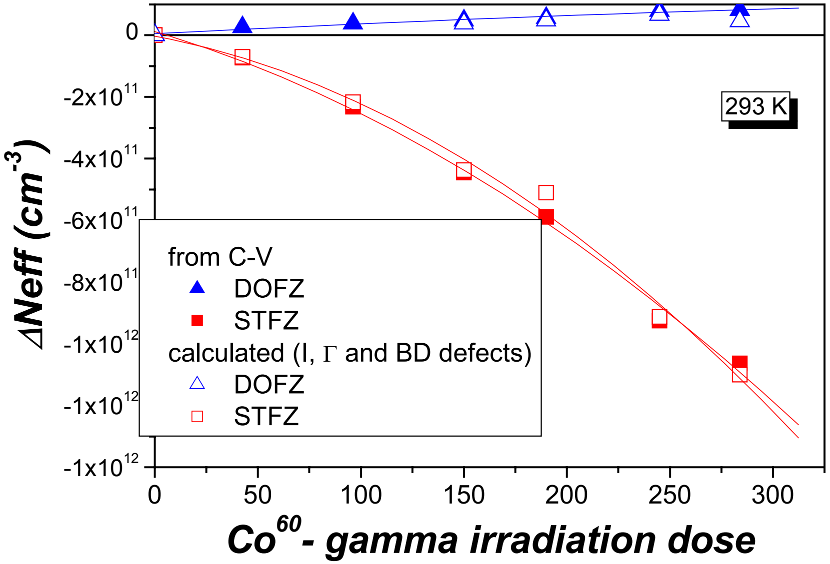
Only detected in DOFZ

introduction rate BD > introduction rate acceptors

⇒ in DOFZ-Si space charge remains positive
no type inversion

These 3 defects can fully explain the changes in the macroscopic detector properties





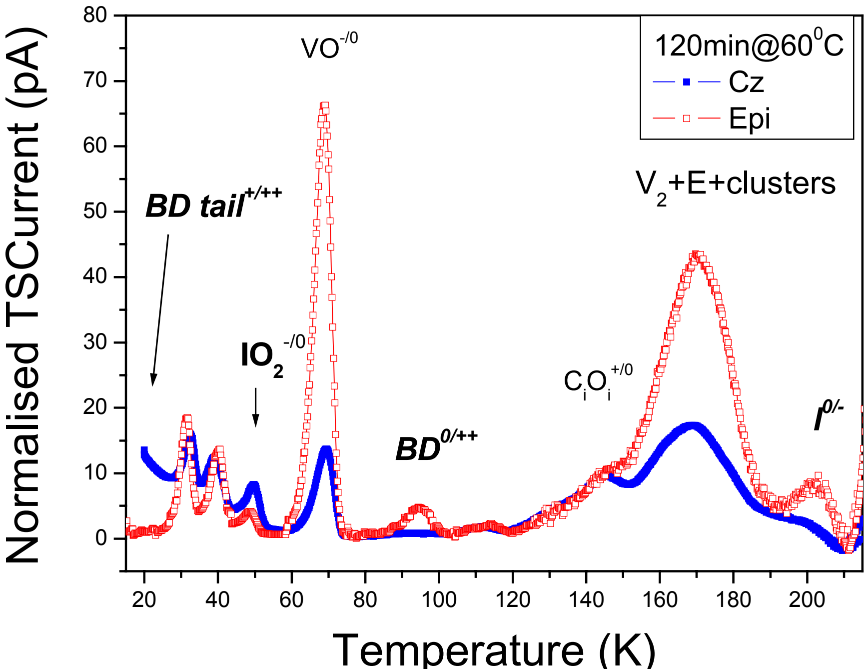
Defects responsible for macroscopic properties

Defects in Cz- and EPI-silicon after 23GeV proton irradiation:

(*I. Pintilie et al., this conference*)

Fluence: 1.8×10^{14} cm^{-2}

- **Deep acceptors:**
  Introduction of negative space charge
  I-defect
  $V_2 + V_2$ clusters
  VP (E-center) in EPI, high P concentration
  Γ-defect not detectable
- **Shallow donors:**
  Introduction of positive space charge
  Bistable donor BD,BD tail (+/++) in Cz
  BD(0/++) in EPI
- **IO_2 defect:**
  observed in Cz and EPI
  indicates presence of O_2 in both materials



TSC-spectra for a CZ- and EPI-device after annealing for 120 min at 60°C

(*further microscopic studies, see session 2 and poster session, this conference*)

Hydrogen in Silicon

Hydrogen in FZ silicon

(*L. Makarenko, this conference*)

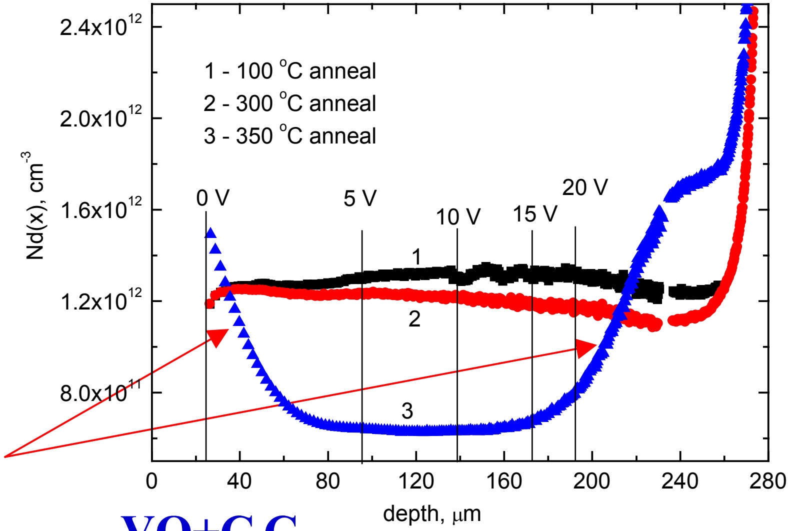
Residual hydrogen in high resistivity FZ device observed after electron irradiation and isochronal annealing

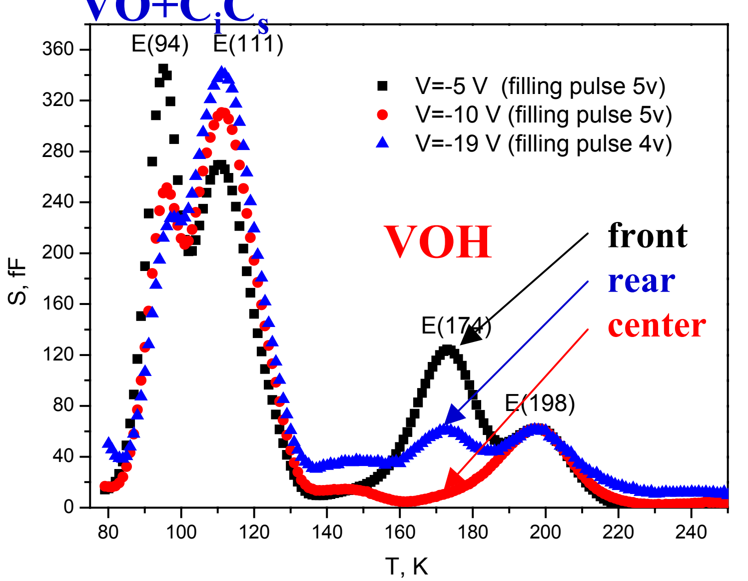
- **Carrier depth profiles after 3×10^{12} e/cm^2**
  1: annealed at 100°C, 2: at 300°C, 3: at 350°C
  in-diffusion of H from both sides up to ~ 80 µm

- **DLTS spectra**
  corresponding to indicated depth regions
  5 V – 0 V → ~ (90 – 20) µm, front
  10V – 5 V → ~ (140 – 90) µm, center
  19 V – 15 V → ~ (190 – 170) µm, rear

  known defects: VO, C_iC_s and VOH

(*see also E.V. Monakhov, this conference*)





New Materials: SiC

- a material between Silicon and Diamond -

Property	**Diamond**	**GaN**	**4H SiC**	**Si**
E_g [eV]	**5.5**	**3.39**	**3.3**	**1.12**
$E_{breakdown}$ [V/cm]	10^7	$4\cdot10^6$	$2.2\cdot10^6$	$3\cdot10^5$
μ_e [cm^2/Vs]	1800	1000	800	1450
μ_h [cm^2/Vs]	1200	30	115	450
v_{sat} [cm/s]	$2.2\cdot10^7$	-	$2\cdot10^7$	$0.8\cdot10^7$
Z	6	31/7	14/6	14
ε_r	5.7	9.6	9.7	11.9
e-h energy [eV]	**13**	**8.9**	**7.6-8.4**	**3.6**
Density [g/cm3]	3.515	6.15	3.22	2.33
Displacem. [eV]	**43**	**≥15**	**25**	**13-20**

- **Wide bandgap (3.3eV)**
  ⇒ lower leakage current than silicon
- **Signal:**
  Diamond 36 e/mm
  SiC 51 e/mm
  Si 89 e/mm
  ⇒ more charge than diamond
- **Higher displacement threshold than silicon**
  ⇒ radiation harder than silicon (?)

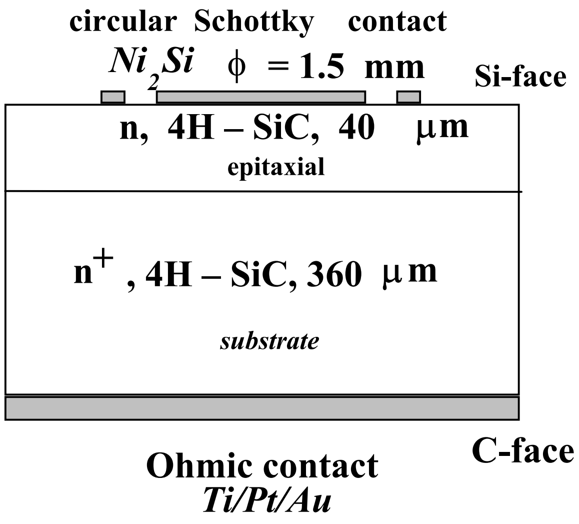
R&D on diamond detectors:
RD48 – Collaboration
http://cern.ch/rd48/

see J.Vaitkus and E. Gaubas
this conference

New Materials: SiC

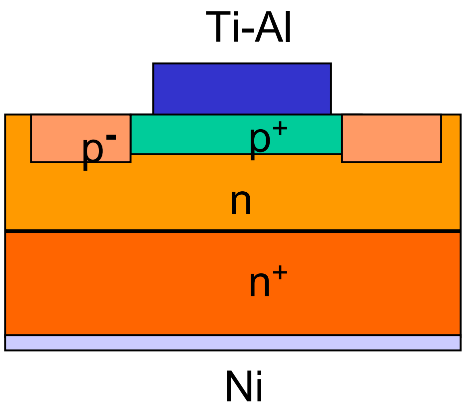
- **Semi-Insulating SiC** (*see session 8, this conference*)
  – $\rho > 10^{11}\Omega$cm due to vanadium compensation
  - CCE 60% in as-grown, ~55% after irradiation with 10^{13}cm^{-2} 300 MeV/c π
  - Vanadium is responsible of incomplete charge collection
- **Epitaxial 4H-SiC**
  - 6 new 2” wafers d~50µm, $N_{eff} \geq 5 \cdot 10^{13}$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

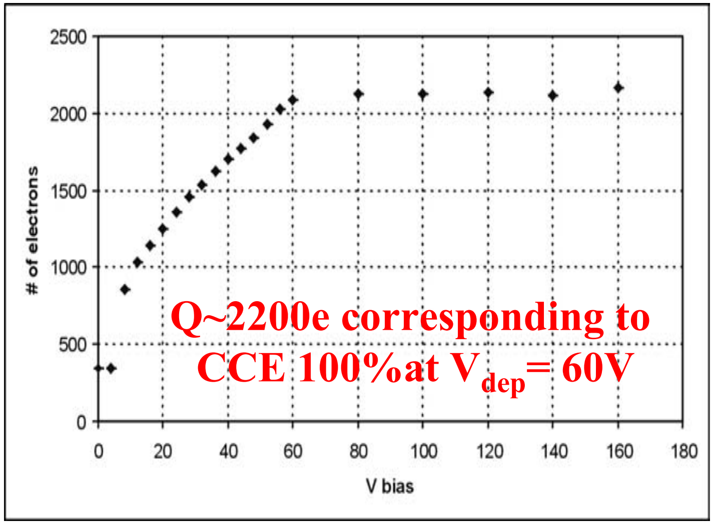


Perugia&IMM Bologna,Italy

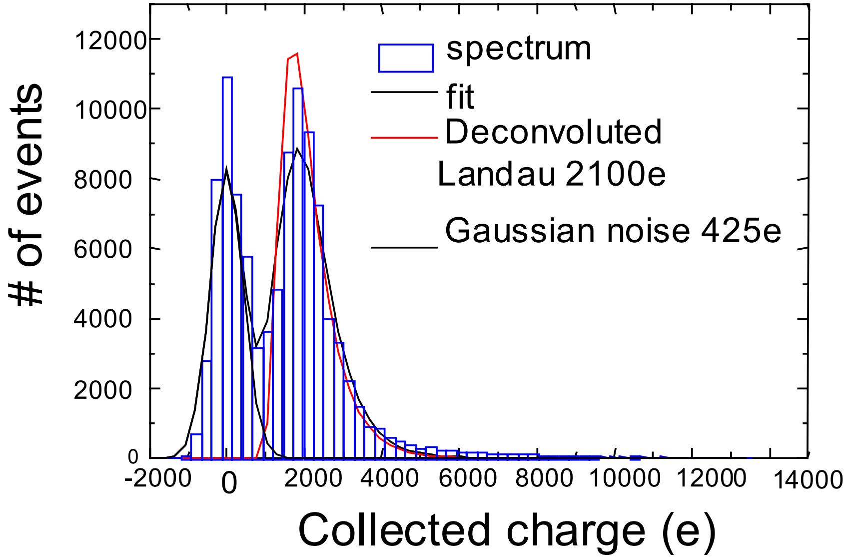
Epitaxial SiC Schottky Barriers

- n epilayer N_{eff} ~$5\times10^{13}cm^{-3}$ 40mm by IKZ Berlin on CREE substrate; Schottky contacts
- No priming / polarization effects observed
- Charge collection efficiency tested with α´s (^{241}Am) and β´s (^{90}Sr)

  100% before irradiation: 2200e with mips



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

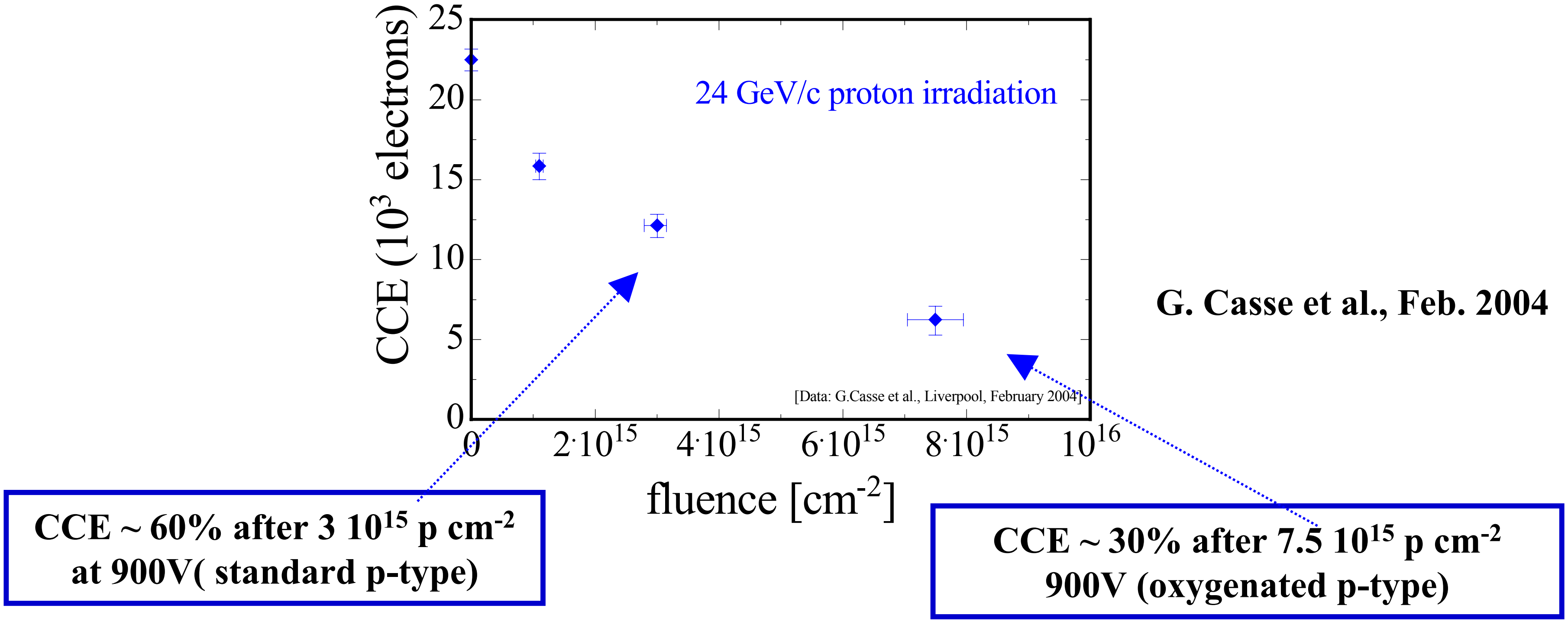


- **Irradiations: (Analysis in progress, first results)**
  - deep levels identified with DLTS (0.18-1.22eV)
  - CCE (alpha) going down to 80% after $10^{14}cm^{-2}$ 8MeV protons

(*Data from F. Nava, S. Sciortino, M. Bruzzi et al., IEEE Trans. Nucl. Sci, (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
- Irradiation:



G. Casse et al., Feb. 2004

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

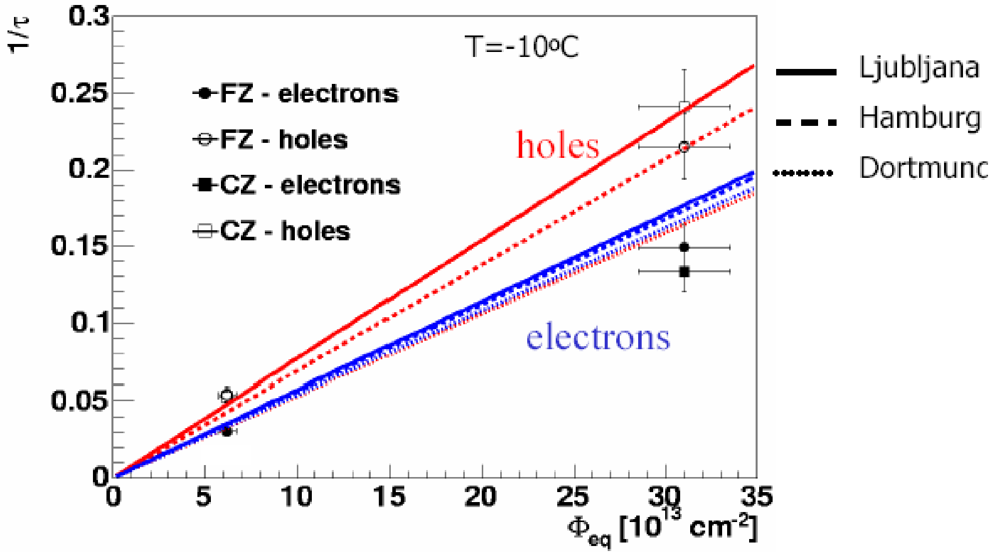
CCE ~ 30% after 7.5 10^{15} p cm^{-2} 900V (oxygenated p-type)

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

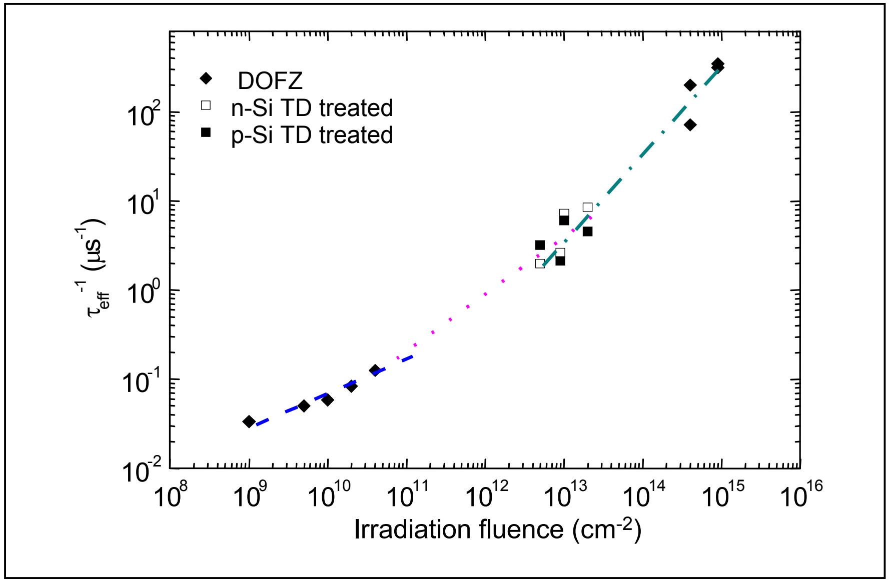
Device Engineering - Thin Detectors

Motivation for using thin detectors:

- **Smaller leakage current:** $I_{leak} \propto W$, W sensitive detector thickness
- **Smaller voltage for total depletion:** $V_{dep} \propto W^2$
- **Charge collection at very high fluences is limited by carrier trapping**
  Extrapolated mean free drift length (G. Kramberger) at 10^{16} n/cm²:
  $\lambda_e \approx 20\ \mu m$, $\lambda_h \approx 10\ \mu m$
- **Drawback:** mip signal ~ 3500e-h pairs



(*G. Kramberger, 4-th RD50 Workshop, May 2004*)



(*J.Vaitkus et al., IWORID-6, July 2004, Glasgow*)

Device Engineering - Thin Detectors

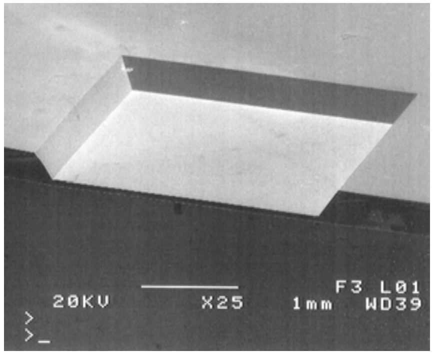
Technical Approaches

ITC-IRST, Trento, Italy

Thinning with chemical attacks

Cross section of a thinned silicon detector

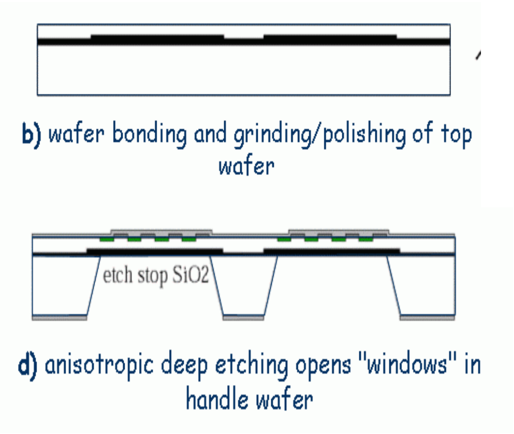
IRST: SEM of a silicon wafer thinned by TMAH



(E. 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

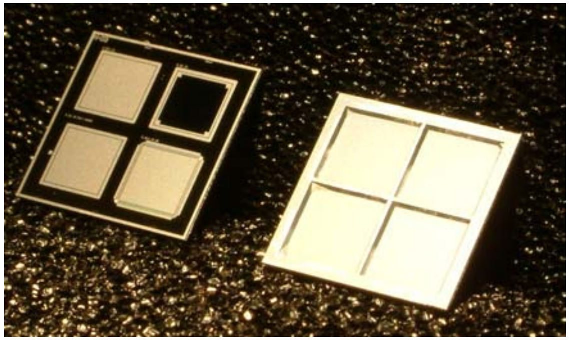
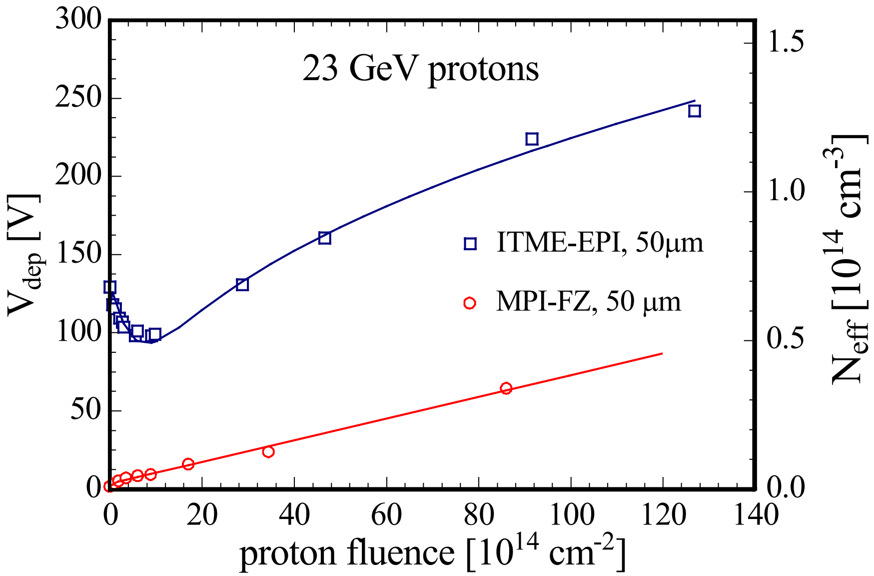
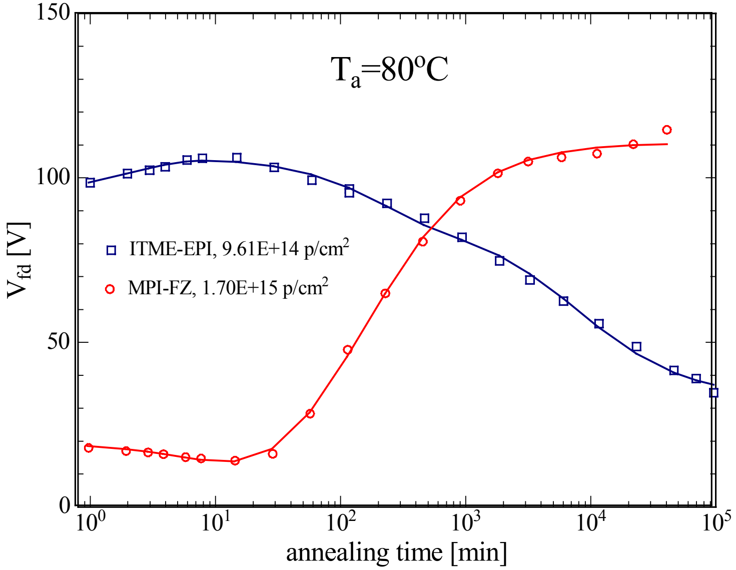


Photo:
front (left) and back (right) view of thinned devices

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

Thin Detectors – MPI chips compared with EPI





Effective introduction rates:

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

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

Annealing of V_{dep}:

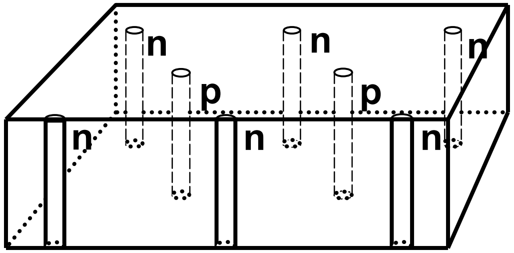
- **MPI chip: short term decrease, long term increase → type inverted**

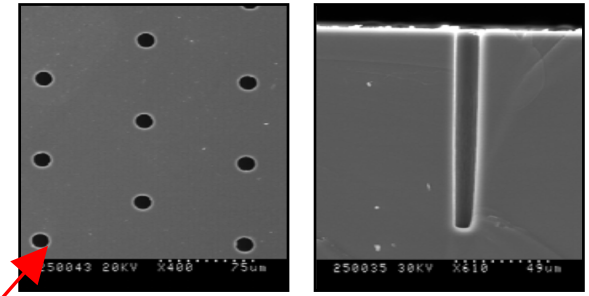
- **EPI device: short term increase, long term decrease → not type inverted**

Device Engineering –3D Detectors

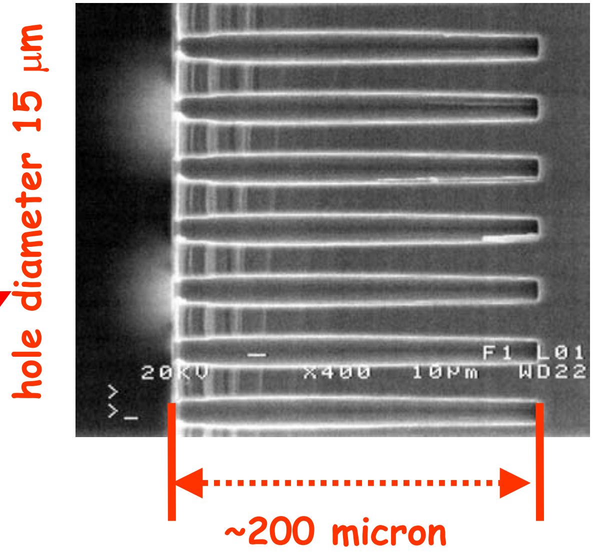
(Introduced by S.I. Parker et al., NIMA 395 (1997) 328)

- **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)

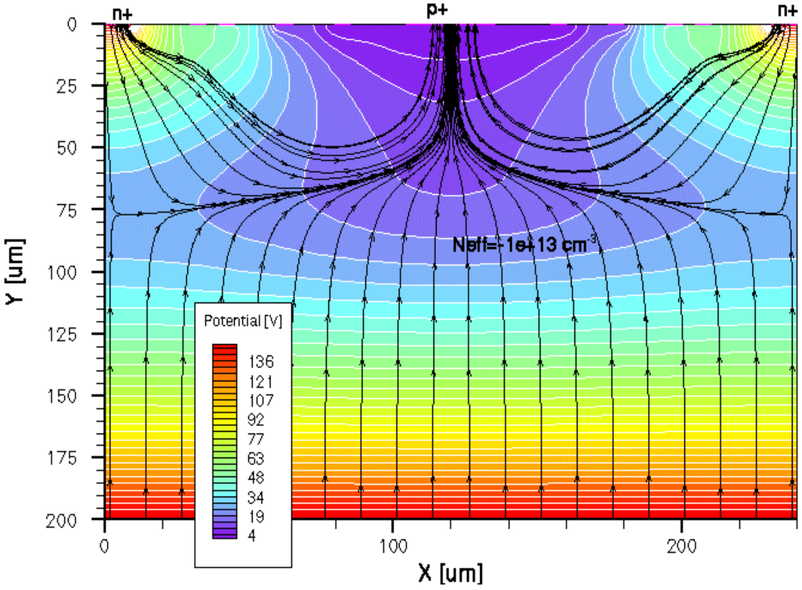
Device Engineering –Semi-3D Detectors

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

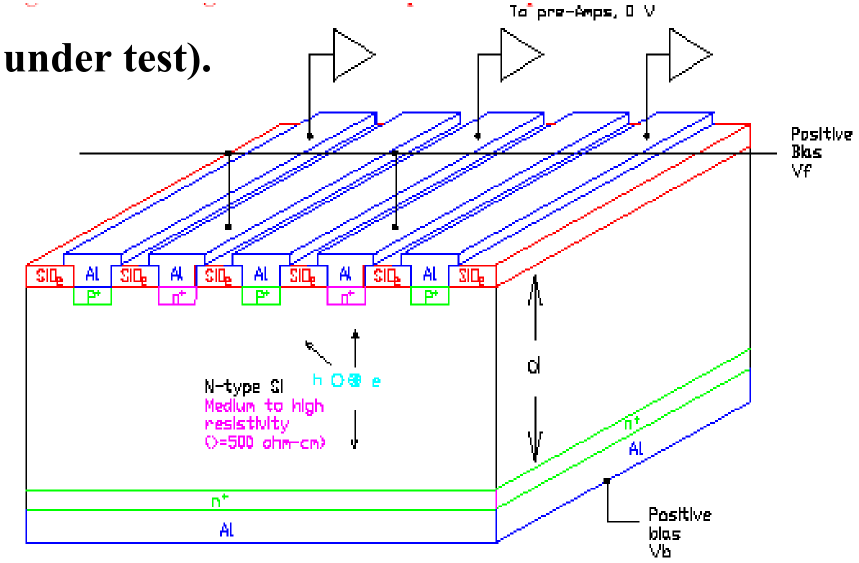
- Planar technology easier to process than 3D sensors
- Single-sided processing
- Large reduction in detector full depletion voltage after type inversion
- Processing of first prototype completed (presently under test).

See talk presented by D. Bortoletto at this conference

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: radiation hard electronics for small signals needed
  3-D detectors; drawback: complicated technology which 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)**

- **New Materials like SiC and GaN have been characterized. However, thicker samples and more radiation studies are needed to evaluate the radiation hardness of these materials.**