Overview of the recent activities of the RD50 collaboration on radiation hardening of semiconductor detectors for the SLHC

G. Casse

OUTLINE:

- Presentation of RD50
- Silicon materials currently under investigation
- RD50 masks and detector structures
- Results with diode measurements
- Results with segmented detectors
- 3-d detector activity
- Summary and future work

RD50: Radiation hard semiconductor devices for very high luminosity colliders

See http://rd50.web.cern.ch/rd50/

Spokespersons
Mara Bruzzi, Michael Moll
INFN Florence, CERN ECP

Defect / Material Characterization
Bengt Svensson
(Oslo University)

Characterization of microscopic defects
- properties of standard-, defect engineered and new materials pre- and post-irradiation

Defect Engineering
Eckhart Fretwurst
(Hamburg University)

Defect engineered silicon:
- Epitaxial Silicon
- CZ, MCZ
- Other impurities H, N, Ge, …
- Thermal donors
- Pre-irradiation
- Oxygen Dimer

~~**New Materials**~~
~~*E: Verbitskaya*~~
~~(Ioffe St. Petersburg)~~

~~Development of new radiation tolerant materials:~~
- ~~SiC~~
- ~~GaN~~
- ~~other materials~~

Pad Detector Characterization
G. Kramberger
(Ljubljana)

- Test structure characterization IV, CV, CCE
- NIEL
- Device modeling
- Common irrad.
- Standardization of measurements

New Structures
R. Bates
(Glasgow University)

Evaluation of new detector structures

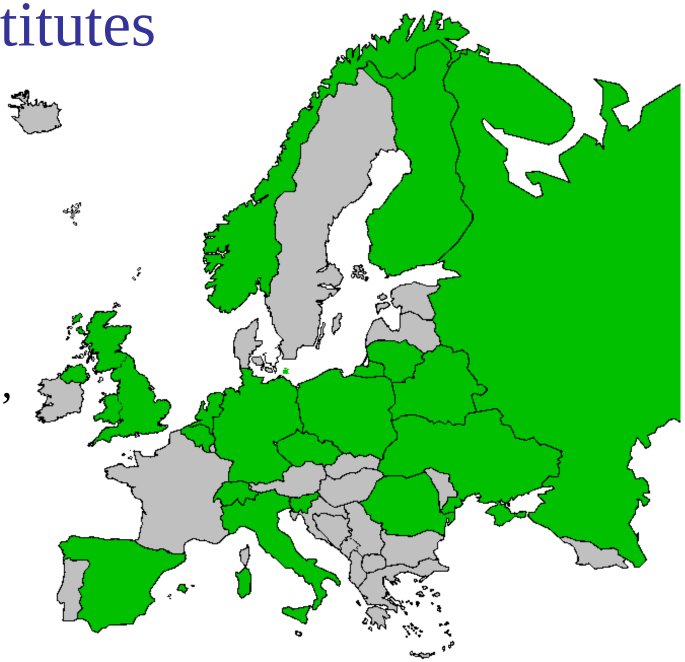
- 3D detectors
- Thin detectors
- Cost effective solutions
- Semi 3D

Full Detector Systems
Gianluigi Casse
(Liverpool University)

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

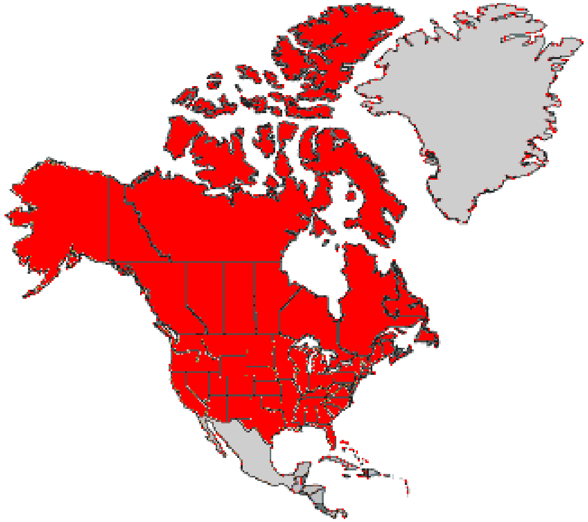
Development of Radiation Hard Semiconductor Devices for High Luminosity Colliders

257 Members from 50 Institutes



41 European and Asian institutes

Belarus (Minsk), **Belgium** (Louvain), **Czech Republic** (Prague (3x)), **Finland** (Helsinki) , Laappeenranta), **Germany** (Dortmund, Erfurt, Freiburg, Hamburg, Karlsruhe, Munich), **Italy** (Bari, Bologna, Florence, Padova, Perugia, Pisa, Torino, Trento), **Lithuania** (Vilnius), **Netherlands** (NIKHEF), **Norway** (Oslo (2x)), **Poland** (Warsaw(2x)), **Romania** (Bucharest (2x)), **Russia** (Moscow, St.Petersburg), **Slovenia** (Ljubljana), **Spain** (Barcelona, Valencia), **Switzerland** (CERN, PSI), **Ukraine** (Kiev), **United Kingdom** (Exeter, Glasgow, Lancaster, Liverpool)



8 North-American institutes

Canada (Montreal), **USA** (BNL, Fermilab, New Mexico, Purdue, Rochester, Santa Cruz, Syracuse)

1 Middle East institute

Israel (Tel Aviv)

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

RD50 approaches to develop radiation hard detectors

- Material Engineering - Defect Engineering of Silicon
  - Understanding radiation damage
    - **Macroscopic effects and Microscopic defects**
    - **Simulation of defect properties & kinetics**
    - **Irradiation with different particles & energies**
  - Oxygen rich Silicon
    - **DOFZ, Cz, MCZ, EPI**
  - Oxygen dimer & hydrogen enriched Silicon
  - Influence of processing technology

- Material Engineering-New Materials **(work concluded)**
  - Silicon Carbide (SiC), Gallium Nitride (GaN)

- Device Engineering (New Detector Designs)
  - p-type silicon detectors (n-in-p)
  - thin detectors
  - 3D detectors
  - Simulation of highly irradiated detectors
  - Semi 3D detectors and Stripixels
  - Cost effective detectors

- Development of test equipment and measurement recommendations

Radiation Damage to Sensors:

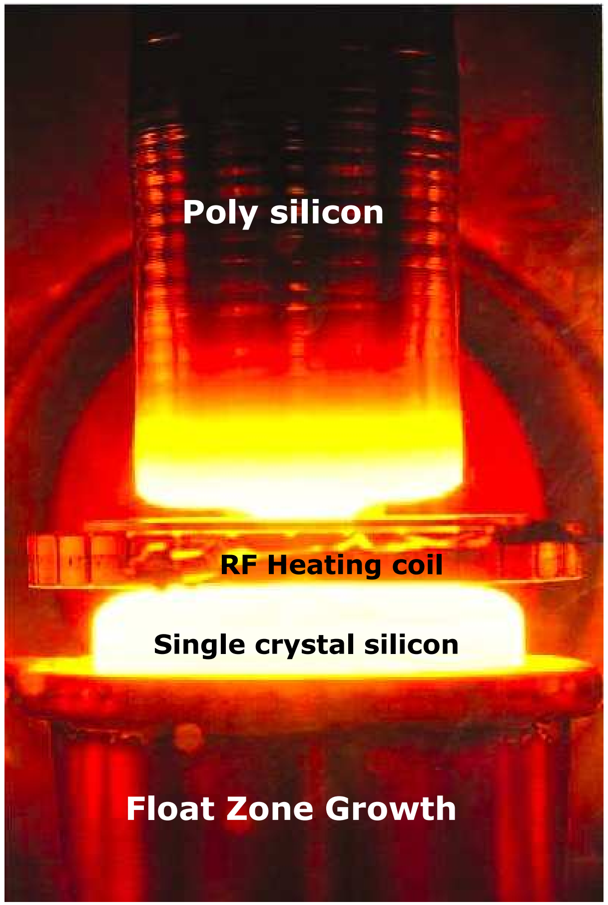
- Bulk damage due to NIEL
  - Change of effective doping concentration
  - Increase of leakage current
  - Increase of charge carrier trapping
- Surface damage due to IEL (accumulation of positive charge in oxide & interface charges)

Related Works – Not conducted by RD50

- **“Cryogenic Tracking Detectors”** (CERN RD39)
- **“Diamond detectors”** (CERN RD42)
- **Monolithic silicon detectors**
- **Detector electronics**

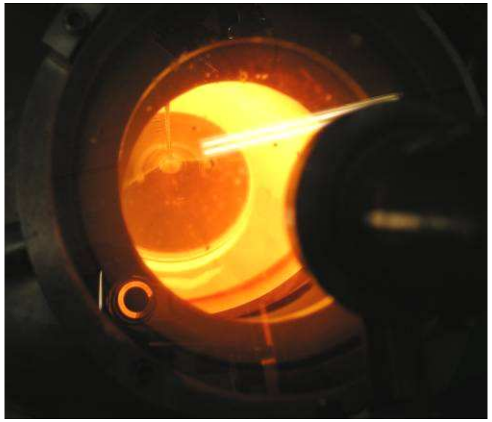
Silicon Growth Processes

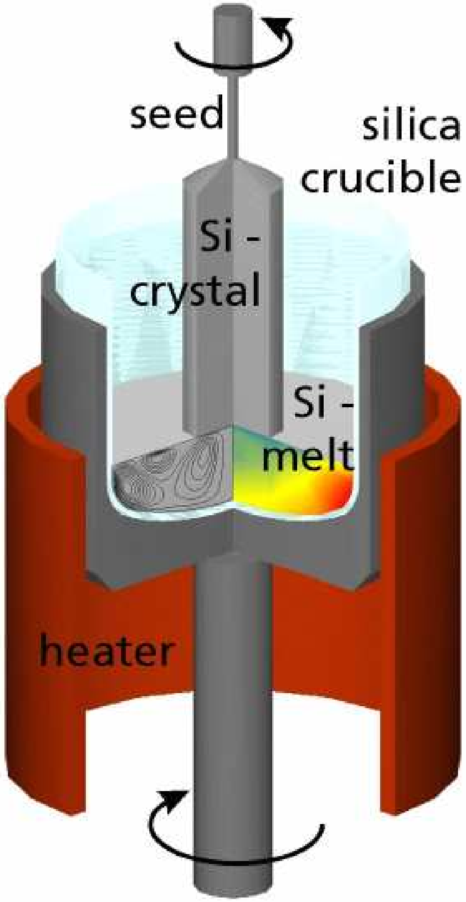
- **Floating Zone Silicon (FZ)**



- Basically all silicon detectors made out of high resistivity FZ silicon

- **Czochralski Silicon (CZ)**
  - The growth method used by the IC industry
  - Difficult to produce very high resistivity





- **Epitaxial Silicon (EPI)**
  - Chemical-Vapor Deposition (CVD) of Si
  - up to 150 µm thick layers produced
  - growth rate about 1µm/min

Silicon Materials under Investigation

standard for particle detectors

used for LHC Pixel detectors

“new” silicon material

Material	Thickness [µm]	Symbol	ρ (Ωcm)	$[O_i]$ (cm^{-3})
Standard FZ (n- and p-type)	50,100,150, 300	FZ	$1–30\times10^{3}$	$< 5\times10^{16}$
Diffusion oxygenated FZ (n- and p-type)	300	DOFZ	$1–7\times10^{3}$	$\sim 1–2\times10^{17}$
Magnetic Czochralski Si, **Okmetic, Finland (n- and p-type)**	100, 300	MCz	$\sim 1\times10^{3}$	$\sim 5\times10^{17}$
Czochralski Si, **Sumitomo, Japan (n-type)**	300	Cz	$\sim 1\times10^{3}$	$\sim 8\text{-}9\times10^{17}$
Epitaxial layers on Cz-substrates, **ITME, Poland (n- and p-type)**	25, 50, 75, 100,150	EPI	50 – 100	$< 1\times10^{17}$
Diffusion oxyg. Epitaxial layers on CZ	75	EPI–DO	50 – 100	$\sim 7\times10^{17}$

• DOFZ silicon	- Enriched with oxygen on wafer level, inhomogeneous distribution of oxygen
• CZ/MCZ silicon	- high Oi (oxygen) and O_{2i} (oxygen dimer) concentration (homogeneous) - formation of shallow Thermal Donors possible
• Epi silicon (inhomogeneous)	- high O_i , O_{2i} content due to out-diffusion from the CZ substrate - thin layers: high doping possible (low starting resistivity)
• Epi-Do silicon	- as EPI, however additional O_i diffused reaching homogeneous O_i content

Irradiation facilities

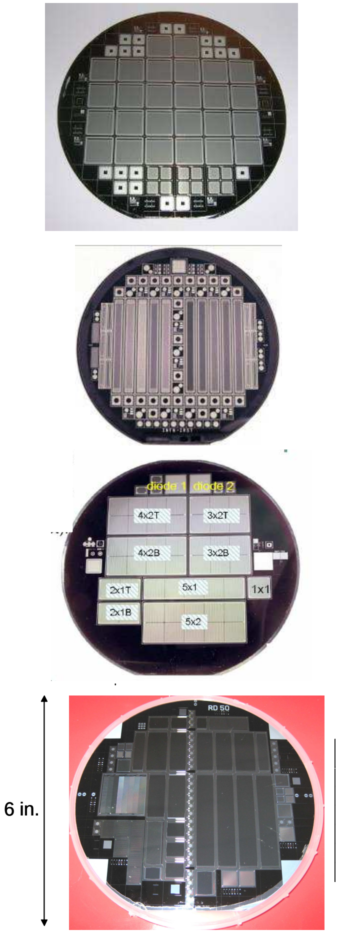
RD50 institutes enjoy access to several world class irradiation facilities.

In particular, the irradiations of the silicon detectors here shown have been performed in the CERN/PS Irrad1 (maintained by Maurice Glaser) and in the Triga nuclear reactor of the J. Stefan Institute of Ljubljana.

Many thanks for the irradiation!

Test Sensor Production Runs (2005/2006/2007)

- **Recent production of Silicon Strip, Pixel and Pad detectors (<u>non exclusive list</u>):**
  - <u>CIS Erfurt, Germany</u>
    - 2005/2006/2007 (RD50): Several runs with various epi 4” wafers only pad detectors
  - <u>CNM Barcelona, Spain</u>
    - 2006 (RD50): 22 wafers (4”), (20 pad, 26 strip, 12 pixel),(p- and n-type),(MCZ, EPI, FZ)
    - 2006 (RD50/RADMON): several wafers (4”), (100 pad), (p- and n-type),(MCZ, EPI, FZ)
  - <u>HIP, Helsinki, Finland</u>
    - 2006 (RD50/RADMON): several wafers (4”), only pad devices, (n-type),(MCZ, EPI, FZ)
    - 2006 (RD50) : pad devices, p-type MCz-Si wafers, 5 p-spray doses, Thermal Donor compensation
    - 2006 (RD50) : full size strip detectors with 768 channels, n-type MCz-Si wafers
  - <u>IRST, Trento, Italy</u>
    - 2004 (RD50/SMART): 20 wafers 4” (n-type), (MCZ, FZ, EPI), mini-strip, pad 200-500μm
    - 2004 (RD50/SMART): 23 wafers 4” (p-type), (MCZ, FZ), two p-spray doses 3E12 amd 5E12 cm^{-2}
    - 2005 (RD50/SMART): 4” p-type EPI
    - 2006 (RD50/SMART): new SMART mask designed
  - <u>Micron Semiconductor L.t.d (UK)</u>
    - 2006 (RD50): 4”, microstrip detectors on 140 and 300μm thick p-type FZ and DOFZ Si.
    - 2006/07 (RD50): 93 wafers, <u>6 inch wafers</u>, (p- and n-type), (MCZ and FZ), (strip, pixel, pad)
  - <u>Sintef, Oslo, Norway</u>
    - 2005 (RD50/US CMS Pixel) n-type MCZ and FZ Si Wafers
  - Hamamatsu, Japan (Not RD50 but surely influenced by RD50 results on this material)
    - In 2005 Hamamatsu started to work on p-type silicon in collaboration with ATLAS upgrade groups



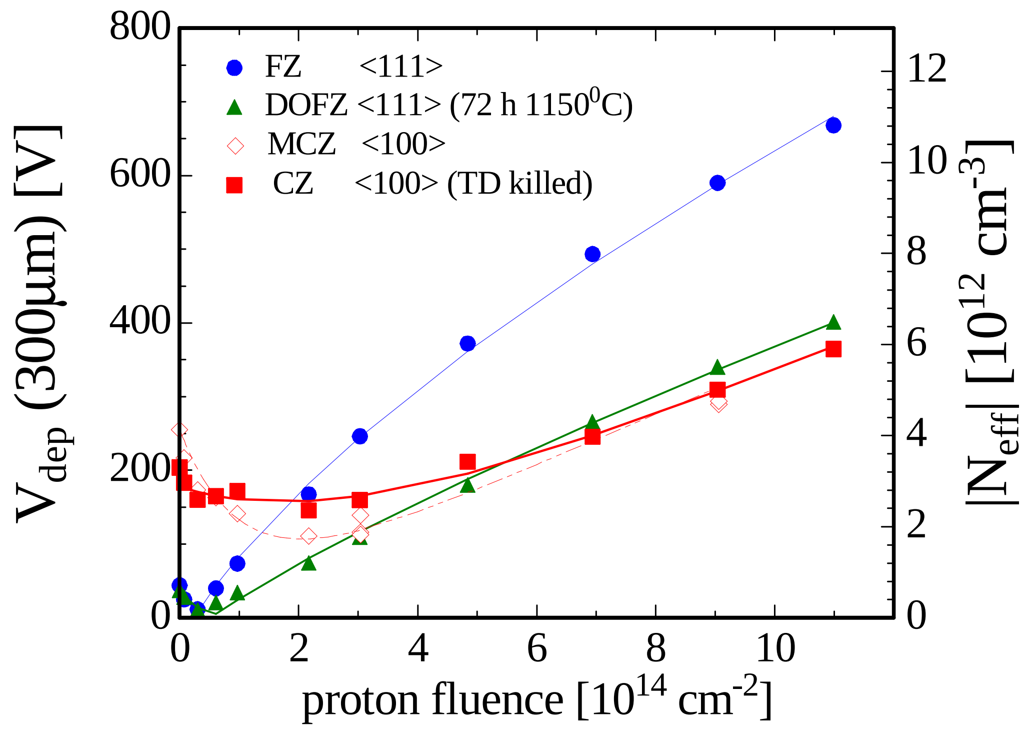
Pad, strip and pixel sensors available for further tests …… we are open for any collaboration.

- M.Lozano, 8th RD50 Workshop, Prague, June 2006
- A.Pozza, 2nd Trento Meeting, February 2006
- G.Casse, 2nd Trento Meeting, February 2006
- D. Bortoletto, 6th RD50 Workshop, Helsinki, June 2005
- N.Zorzi, Trento Workshop, February 2005

Standard thickness diode: n-type FZ, DOFZ, Cz and MCz Silicon

24 GeV/c proton irradiation

- Standard FZ silicon
  - 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 silicon and MCZ silicon
  - <u>no type inversion</u> in the overall fluence range (verified by TCT measurements)
    (verified for CZ silicon by TCT measurements, preliminary result for MCZ silicon)
    Strong indications for a reduced reverse annealing in MCZ silicon (2006)

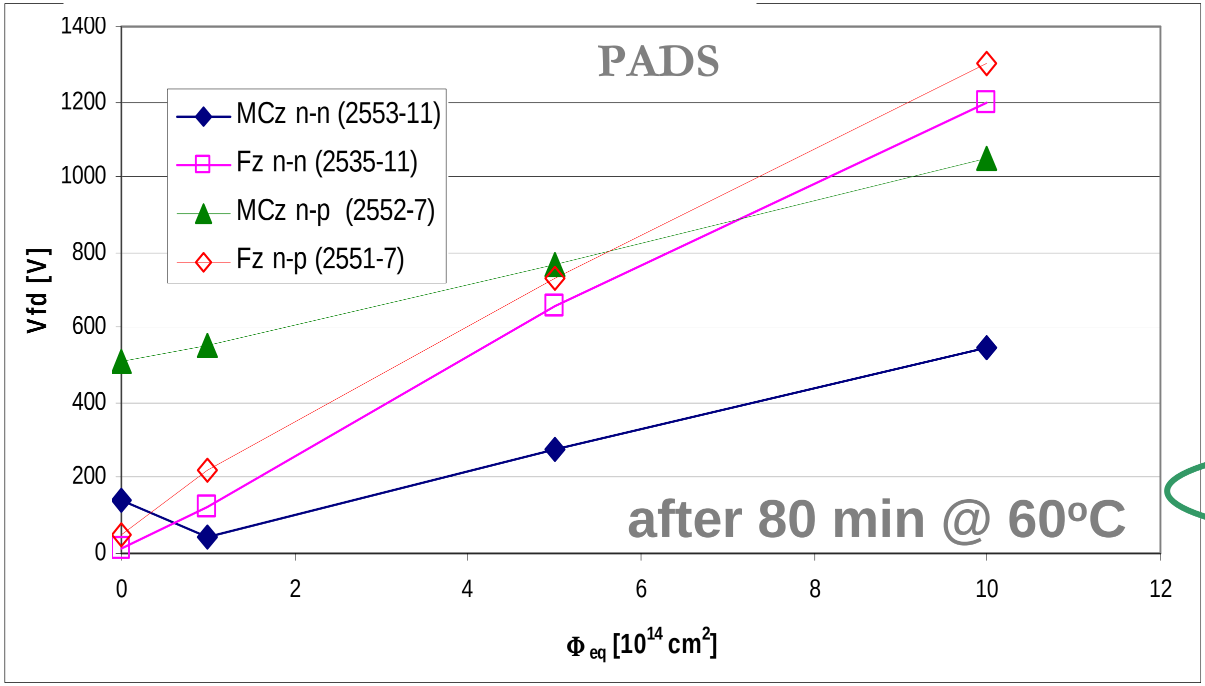
- Common to all materials (after hadron irradiation):
  - reverse current increase
  - increase of trapping (electrons and holes)

From:

Michael Moll – CERN, 20. March 2007

Diode results: Standard FZ, DOFZ, Cz and MCz Silicon

C-V Measurements



- all detectors have negative space charge (decrease of V_{fd} during short term annealing)
- Leakage current agrees with expectations ($\alpha \sim 3.5\text{-}5.5 \cdot 10^{-17}$A/cm)

Neutron irradiation

G. Kramberger, *Measurements of CCE on different RD50 detectors*, ATLAS tracker upgrade workshop, Valencia, December 2007

Slope of V_{fd} increase with fluence

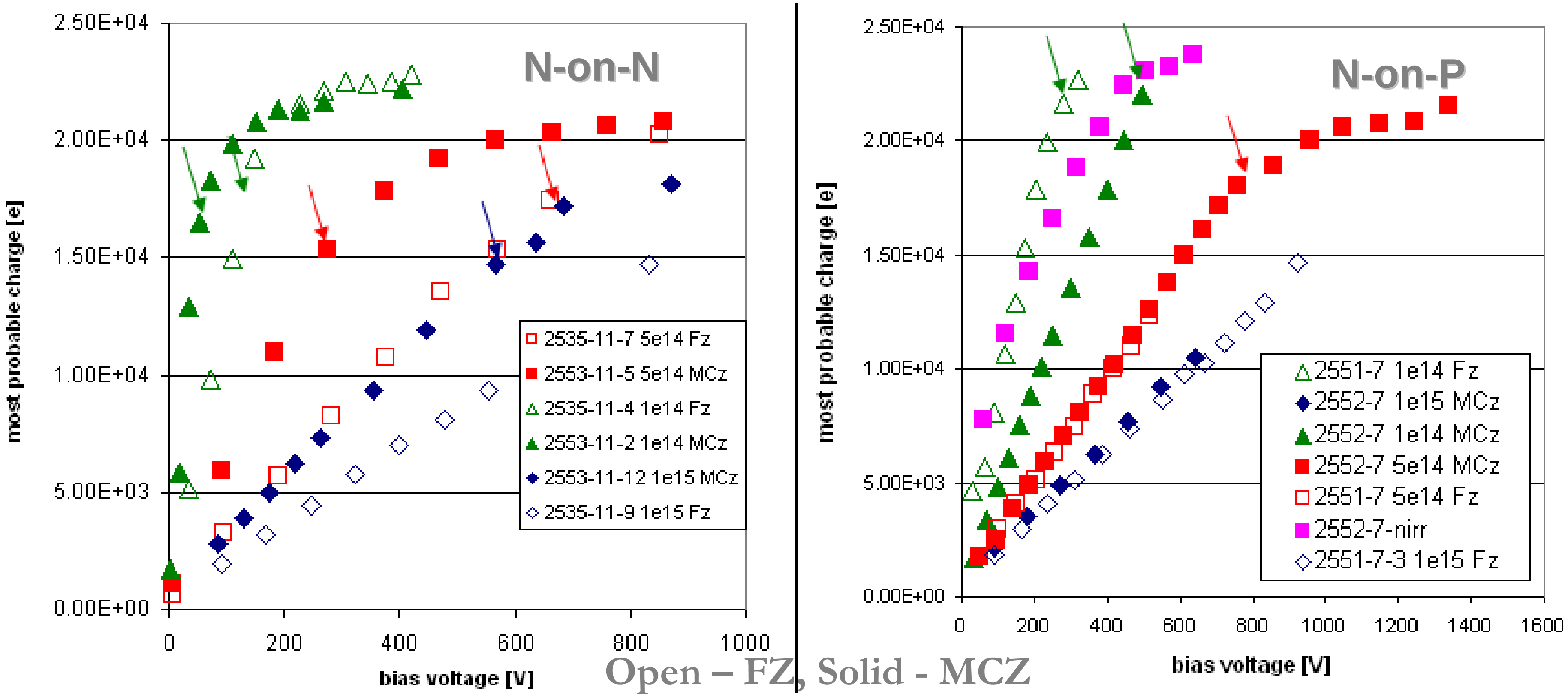
- MCz (p and n type): 55 V/10^{14} cm^{-2} ($g_c \sim 0.8$ cm^{-2}) – **lower stable damage than seen before ?**
- Fz (p and n type): 125 V/10^{14} cm-2 ($g_c \sim 1.8$ cm^{-2}) – in agreement with previous results

There is no evidence of acceptor removal (neutron irradiated samples)

⬇

It seems that MCz should perform better – do we see this performance in CCE?

N-irradiation: Charge collection (pads)



Open – FZ, Solid - MCZ

G. Kramberger, *Measurements of CCE on different RD50 detectors*, ATLAS tracker upgrade workshop, Valencia, December 2007

- V_{fd} from CV (denoted by arrows) agrees well with the kink in CCE
- The slope of charge increase with voltage is directly related to V_{fd}:
  - increase of V_{fd} can be measured by the change of slope and vice versa
  - Similar V_{fd} = similar slope -> same E field or not very important, true for pads
- High resistive non-depleted bulk is well reflected in linear increase of charge – different from non-irr.

Diode results: thin FZ detectors and epitaxial Si

- **Why thin detectors?**

  Advantage:

  lower depletion voltage ($V_{fd} \propto d^2$), full depletion at large Φ possible

  lower leakage current (??) ($I_{rev} \propto d$): if yes lower noise contribution, lower power dissipation

  smaller collection time ($t_c \propto d$), less charge carrier trapping

  Draw back:

  smaller signal for mips (signal $\propto$ d)

  larger capacitance (Cdet $\propto$ 1/d), larger electronic noise

  → find an optimal thickness

- **Questions:**

Motivation

- depend the damage effects on the device thickness?

- which impurities play a major role in the damage (P, O, C, H, others)?

E. Fretwurst et al., 11th RD50 workshop

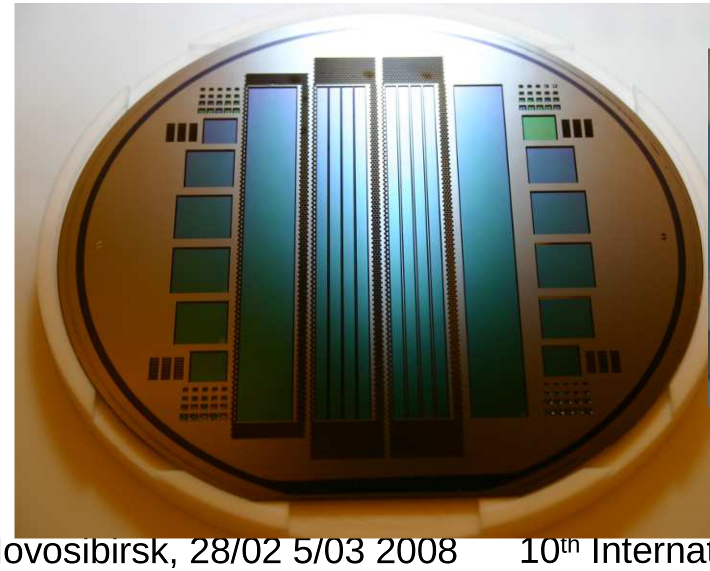
Thinning Technology

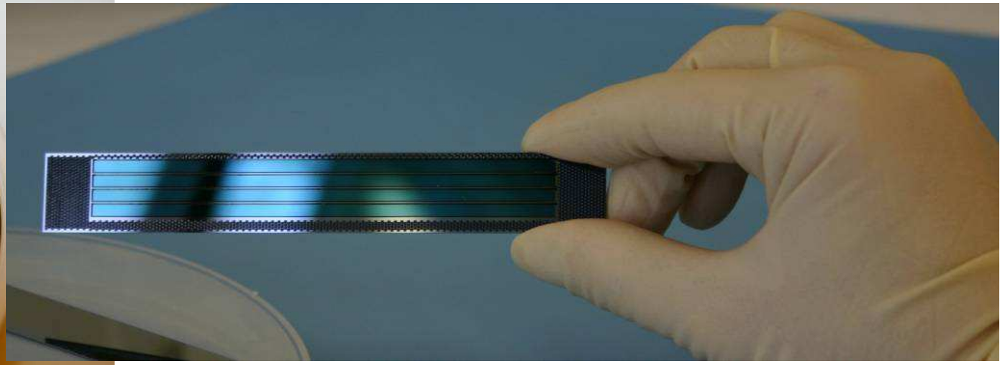
1. implant backside on sensor wafer
2. bond sensor wafer to handle wafer
3. thin sensor side to desired thickness
4. process DEPFETs on top side
5. structure resist, etch backside up to oxide/implant

- Sensor wafer: high resistivity d=150mm FZ wafer.
- Bonded on low resistivity “handle” wafer”.
- (almost) any thickness possible

Thin (50 μm) silicon successfully produced at MPI.

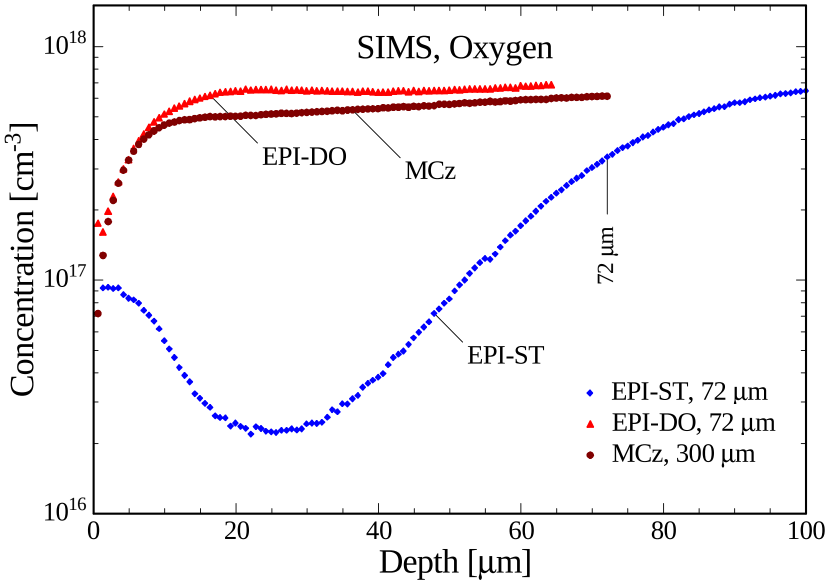
- MOS structures
- diodes
-No deterioration of detector properties, keep I_{leak} <100pA/cm^2

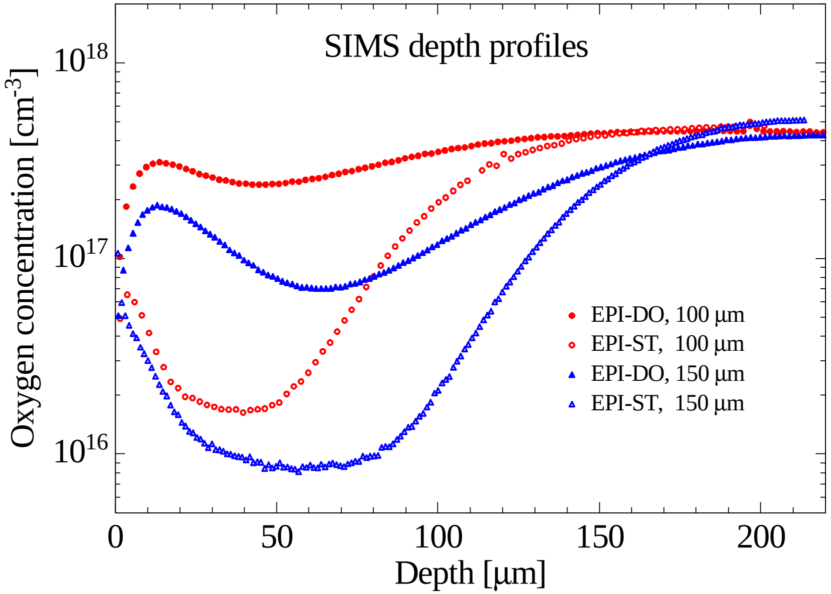




H. G. Moser, 11th RD50 workshop

Oxygen depth profiles





- EPI-ST, 72 µm: [O] inhomogeneous, <[O]> = 9.3 10^{16} cm^{-3}
- EPI-DO, 72 µm: [O] homogeneous, except surface, <[O]> = 6.0 10^{17} cm^{-3}
- MCz: [O] homogeneous, except surface <[O]> = 5.2 10^{17} cm^{-3}

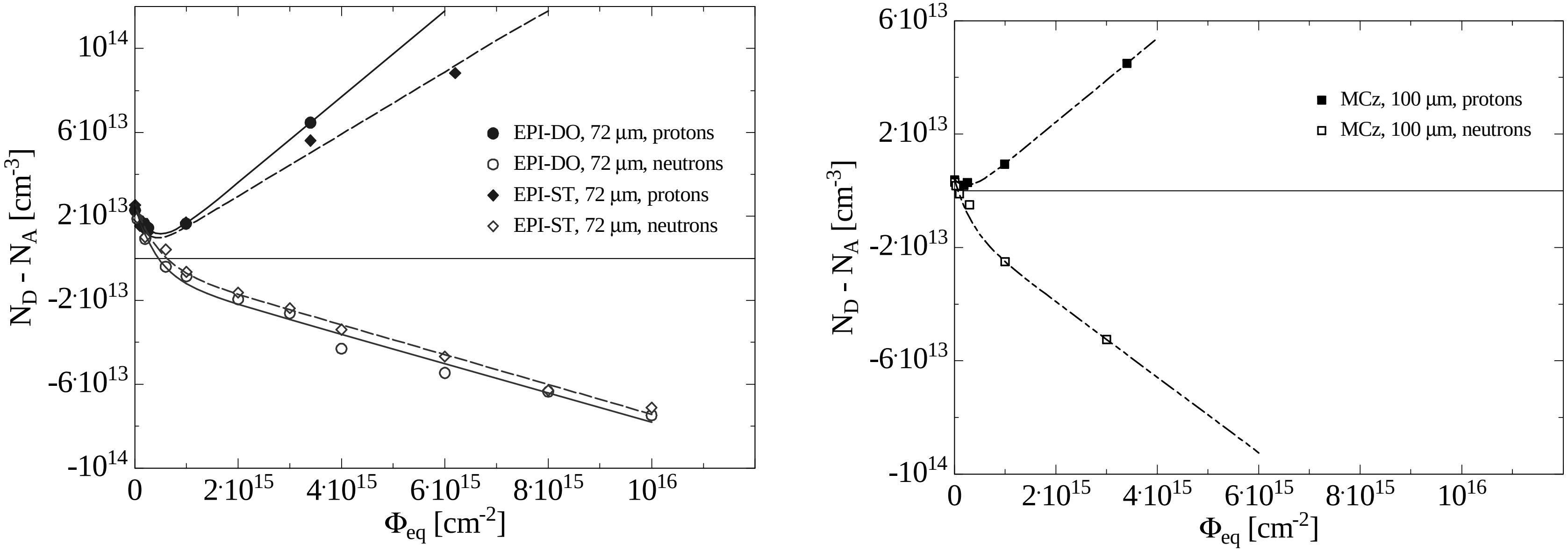
E. Fretwurst et al., 11th RD50 workshop

- **EPI-ST, 100/150 µm: [O] inhomogeneous, <[O]> = 5.4 10^{16} / 4.5 10^{16} cm^{-3}**
- **EPI-DO, 100/150 µm: [O] more homogeneous,**

  <[O]> = 2.8 10^{17} / 1.4 10^{17} cm^{-3}
- **FZ 50 µm: inhomogeneous <[O]> = 3.0 10^{16} cm^{-3}**
- **FZ 100 µm: homogeneous, except surface <[O]> = 1.4 10^{16} cm^{-3}**

Comparison protons versus neutrons

EPI-72 µm, MCz-100 µm



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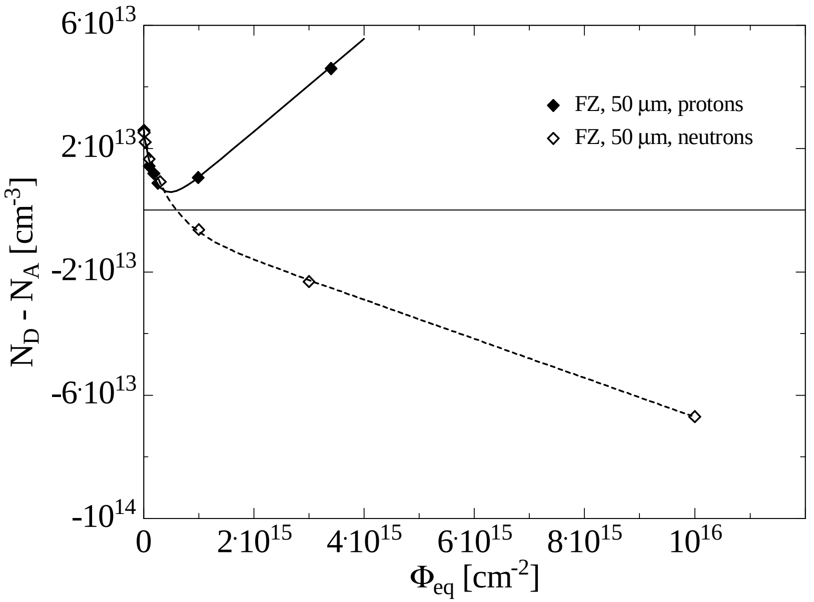
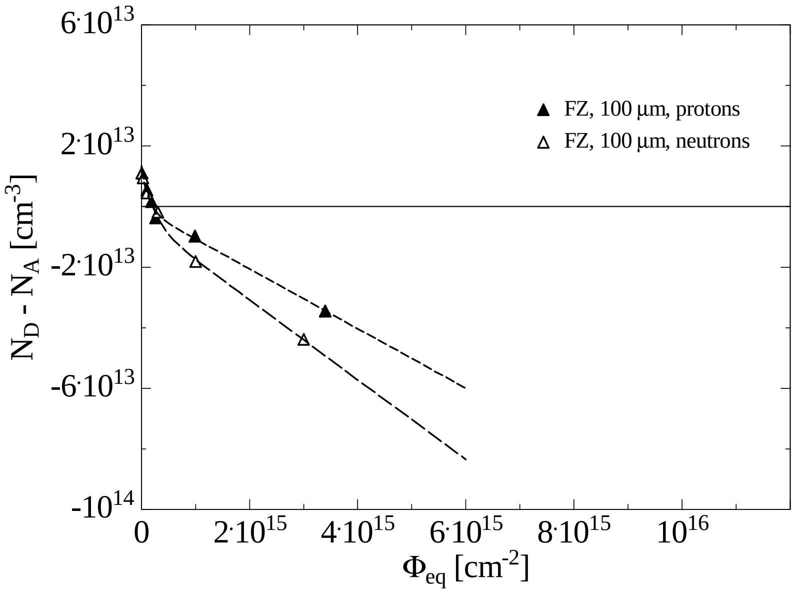
- **EPI-devices (here 72 µm) reveal no SCSI after proton damage contrary to neutron damage**
- **Same behavior holds for thin MCz-diodes**
- **β > 0 (dominant donor creation) for protons (more point defects than clusters)**
- **β < 0 (dominant acceptor creation) for neutrons (more clusters than point defects)**

Comparison protons versus neutrons

FZ-50 µm, FZ-100 µm





FZ-50 µm:

- $\beta > 0$ for protons (dominant donor creation)
- $\beta < 0$ for neutrons (dominant acceptor creation)

FZ-100 µm:

- $\beta < 0$ for protons and neutrons (dominant acceptor creation)

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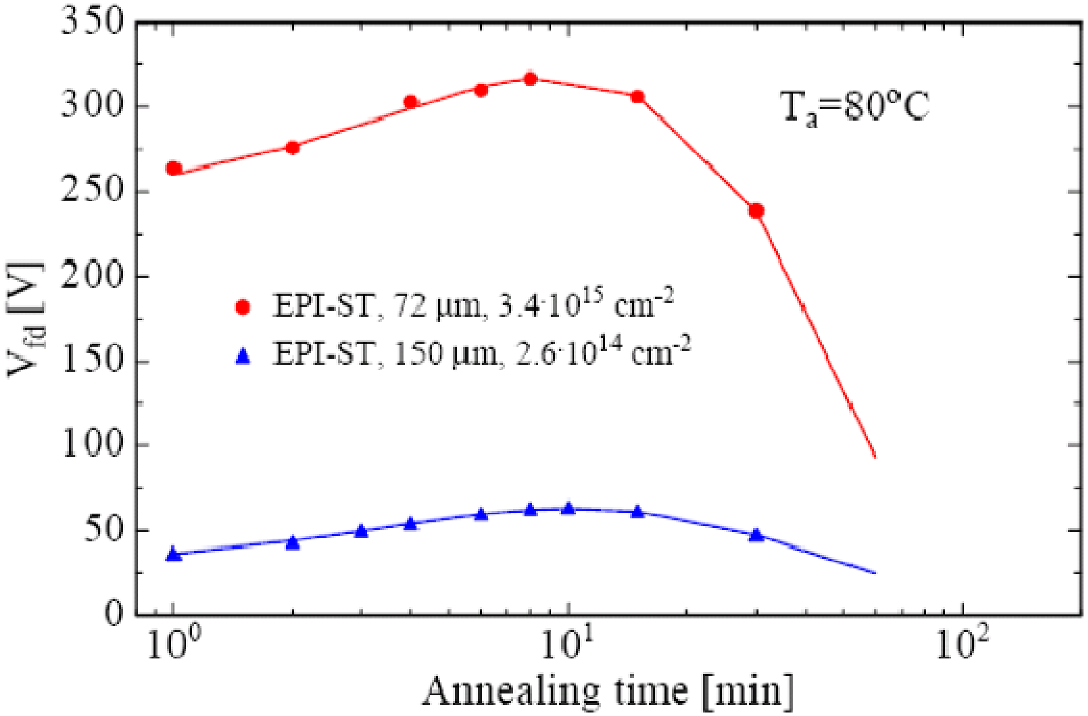
Possible advantages of non-inverted detectors: reverse reverse-annealing



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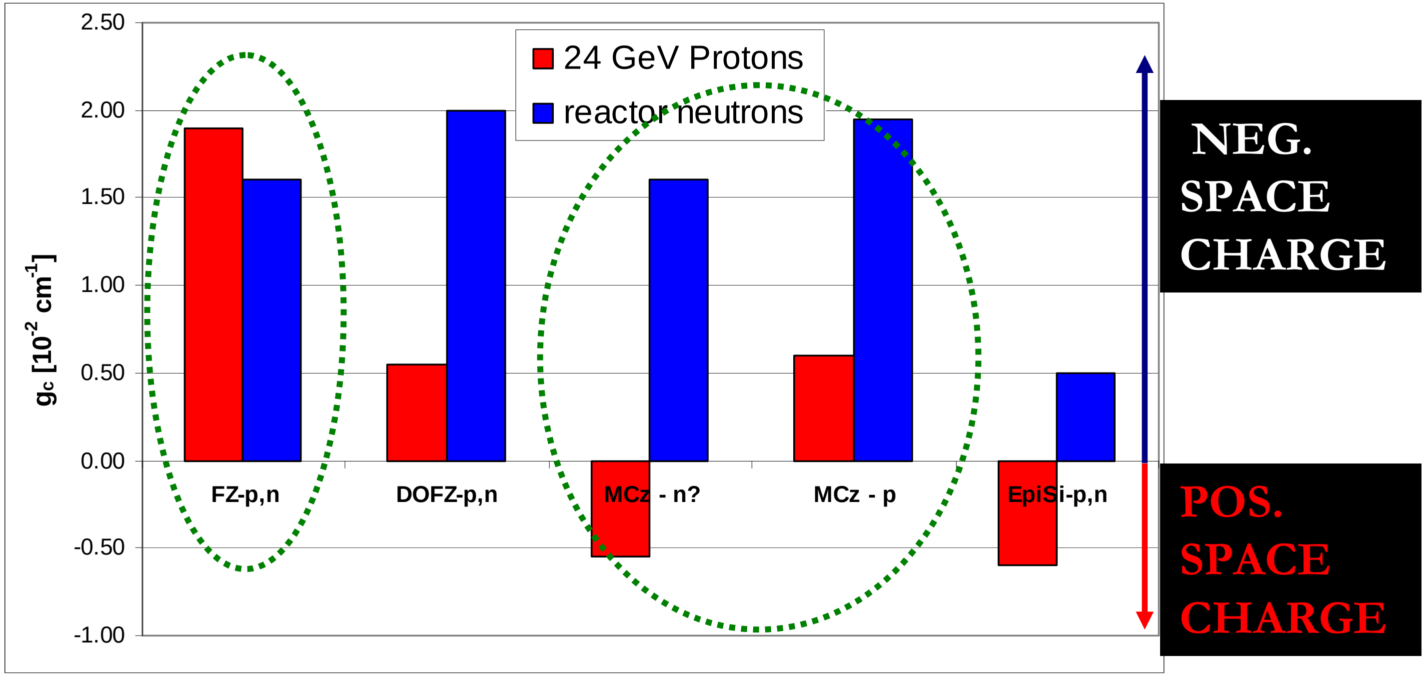
Thick diodes RD50 results in short

- Leakage current – invariant on material type $$\frac{\Delta I}{V} = \alpha \cdot \Phi_{eq}$$
- Trapping times – invariant on material type (seem to exhibit non-linear dependence at high fluences) $$1/\tau_{eff,e,h} = \beta_{e,h} \cdot \Phi_{eq}$$
- Materials:

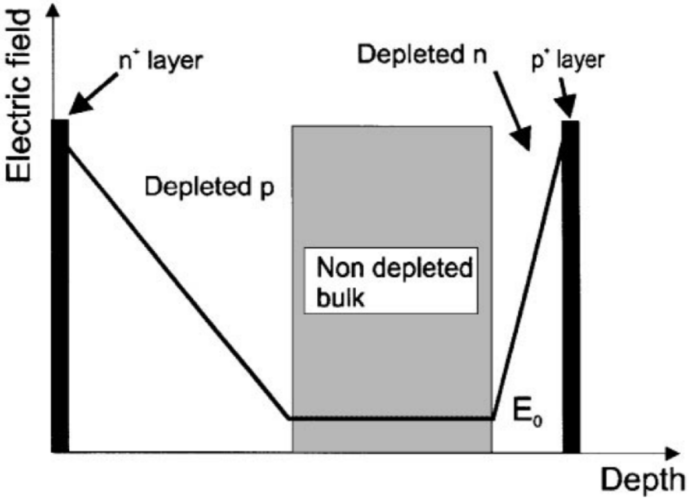


Reverse annealing: acceptors always introduced, τ_{ra} depends on oxygen – the more the longer…

Segmented detectors: side matters!!

N-side read-out for tracking in high radiation environments?

Schematic changes of Electric field after irradiation



Effect of trapping on the Charge Collection Efficiency (CCE)

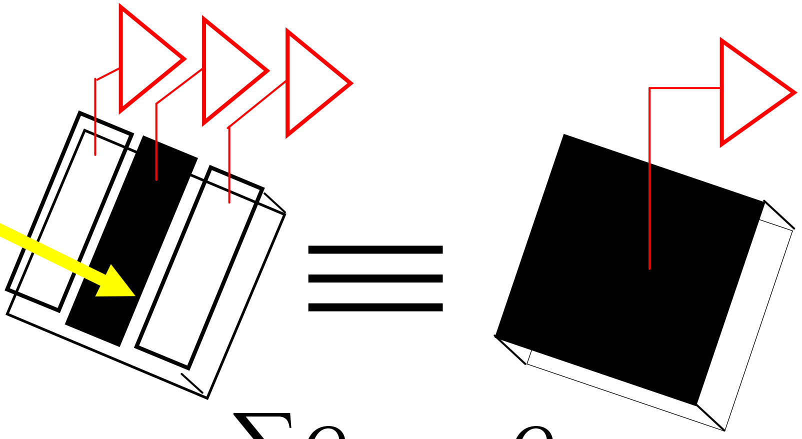
$$Q_{tc} \cong Q_0 \exp(-t_c/\tau_{tr}),\ 1/\tau_{tr} = \beta\Phi.$$

Collecting electrons provide a sensitive advantage with respect to holes due to a much shorter t_c. P-type detectors are the most natural solution for *e* collection on the segmented side.

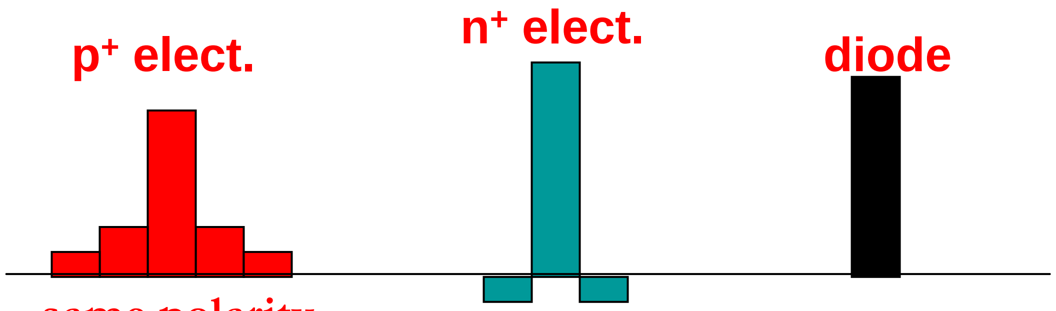
N-side read out to keep lower t_c

Trapping induced charge sharing (G. Kramberger)

electrode
hit in the
center by
ionizing
particle



$$\sum_{\substack{all\ electrodes\\(pitch-implant\ width)\to 0}} Q_i \equiv Q_{diode}$$



same polarity

$Q_{hit} < Q_{diode}$

↓

wider clusters

opposite polarity

$Q_{hit} > Q_{diode}$

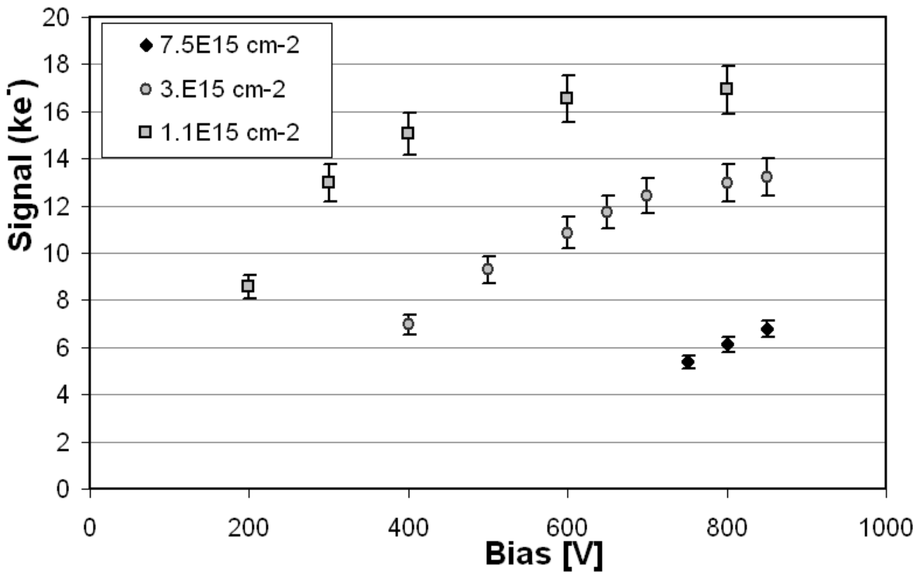
↓

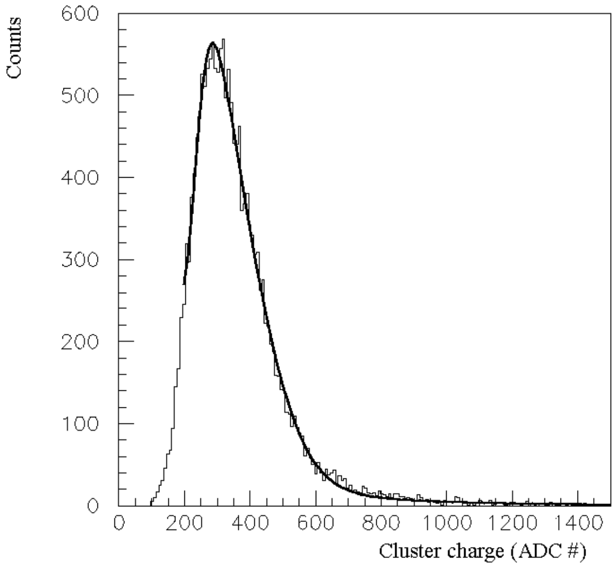
larger signals

Proton irradiations

P-type miniature detectors from CNM

Extremely good performances in term of charge collection after unprecedented doses (1., 3.5., and 7.5 10^{15} p cm^{-2}) were obtained with these devices!!



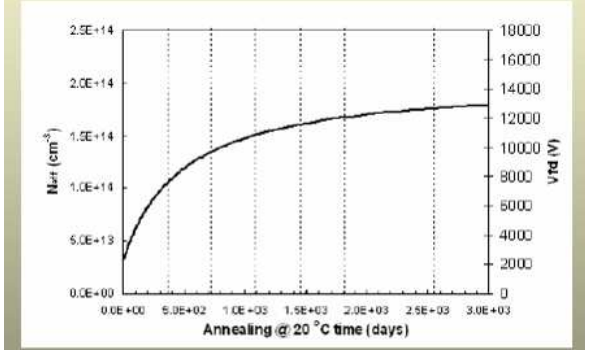


G. Casse et al., NIM A 568(2006)

P-type miniature detectors from CNM

For the first time the CCE was measured as a function of the accelerated annealing time with LHC speed electronics (SCT128A chip), and the results were really surprising!!

Initial V_{FD} ~ 2800V



Predictions from RD48 parameters for Oxygen enriched devices (best scenario: after 7 RT annealing years the V_{fd} goes from ~2800V to ~12000 V!

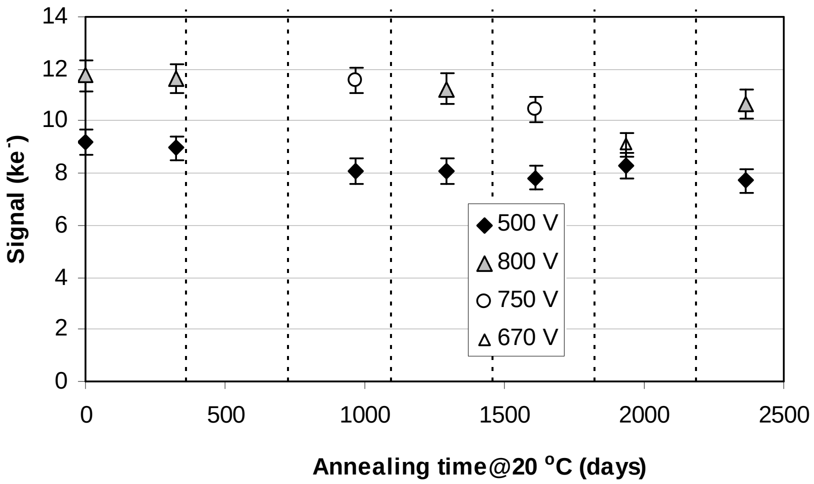
3.5 10^{15} p cm^{-2}

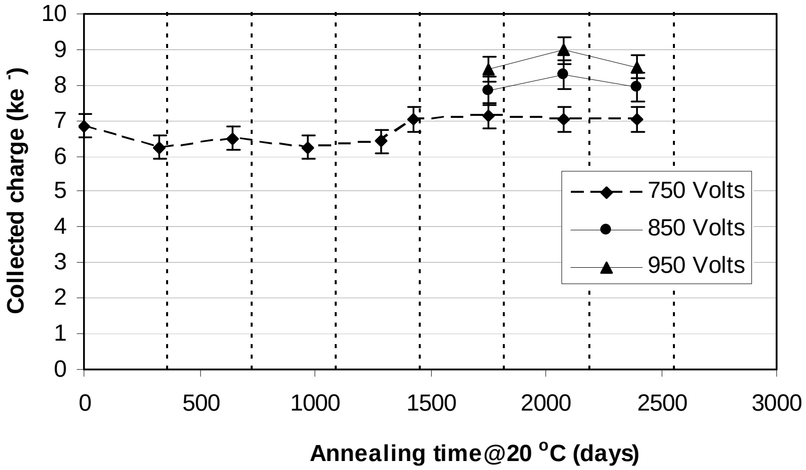
Initial V_{FD} ~ 1300V

final ~ 6000V

7.5 10^{15} p cm^{-2}

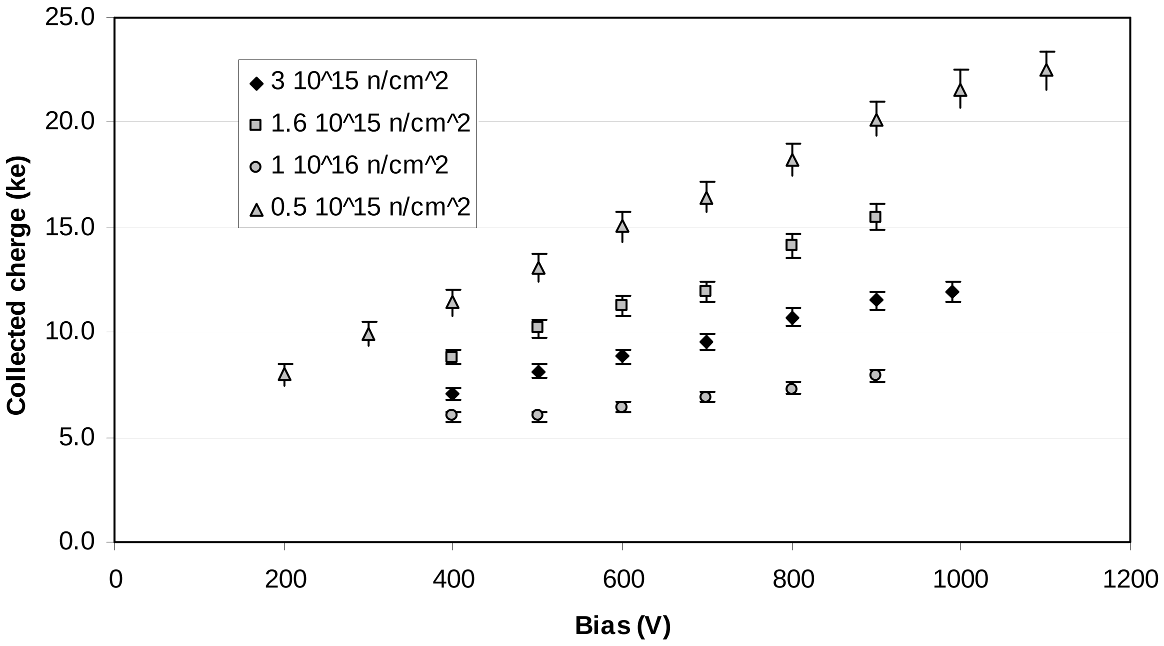
Initial V_{FD} ~ 2800V, final ~12000 V!





G. Casse et al., NIM A 568(2006)

Results with neutron irradiated Micron detectors



Now μ-strip detector CCE measurements up to 1x10^{16} n cm^{-2}!!

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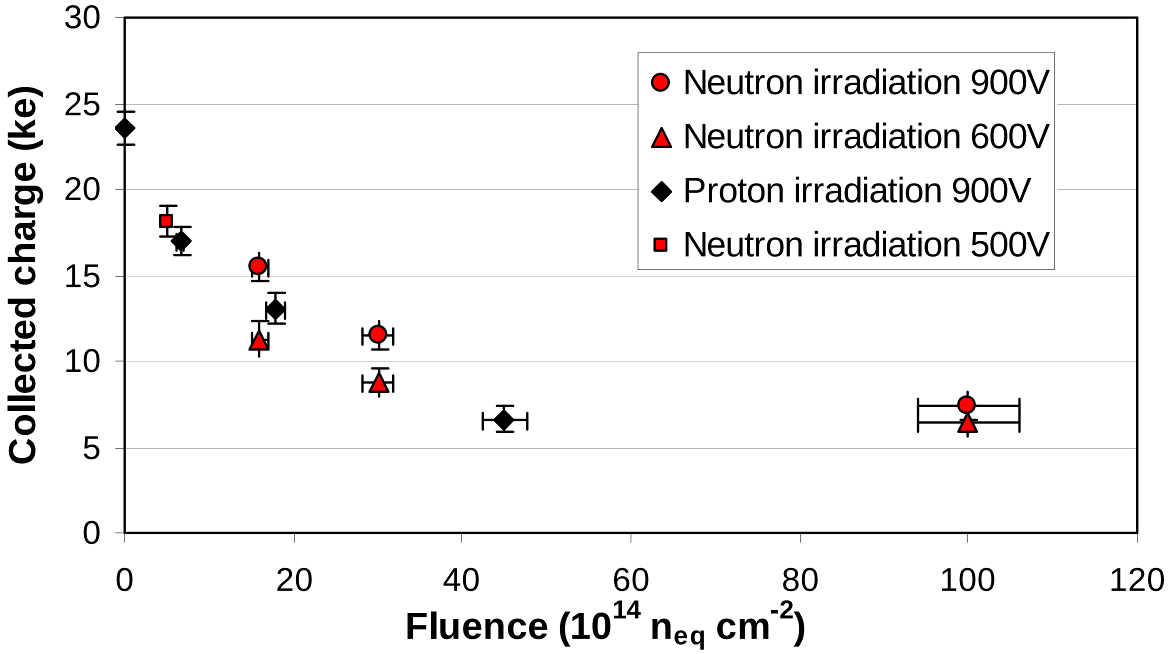
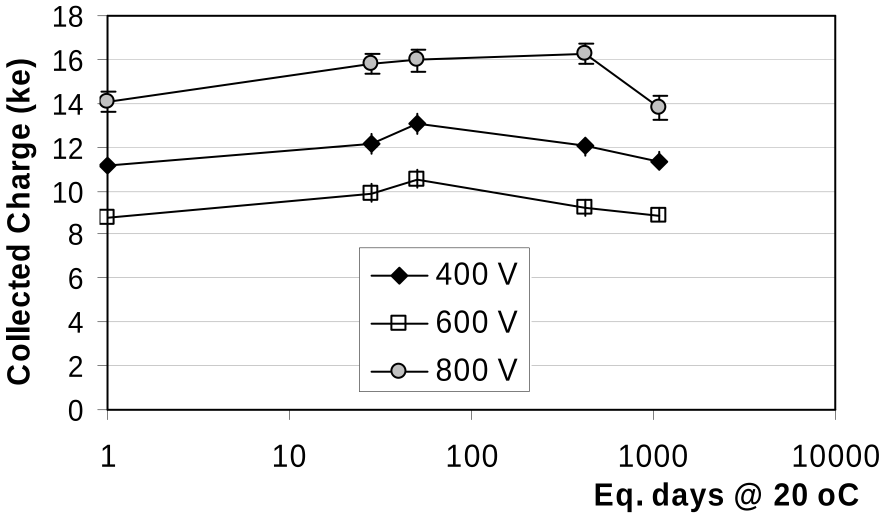
Charge collection efficiency vs fluence for micro-strip detectors irradiated with n and p read-out at LHC speed (40MHz, SCT128 chip).



Neutron irradiation: p-type miniature detectors from Micron

Annealing characterisation.

1.6 10^{15} n cm^{-2}



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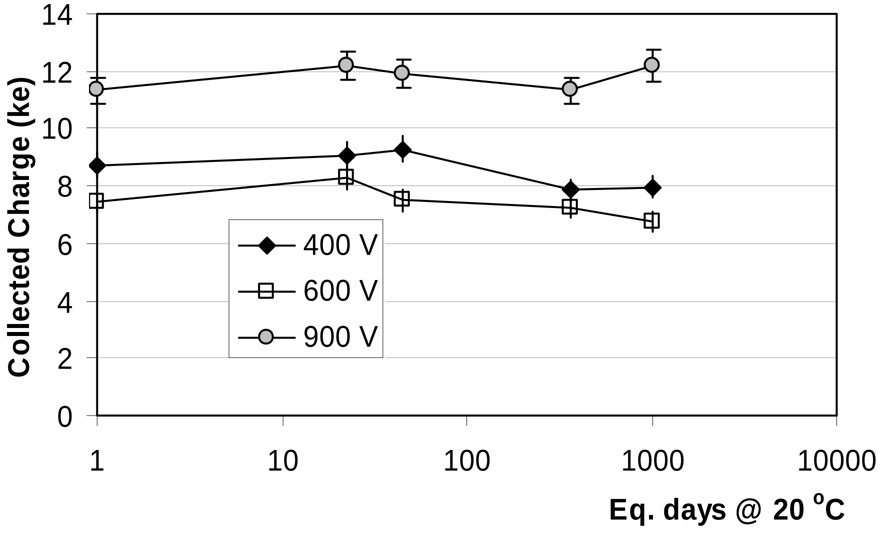
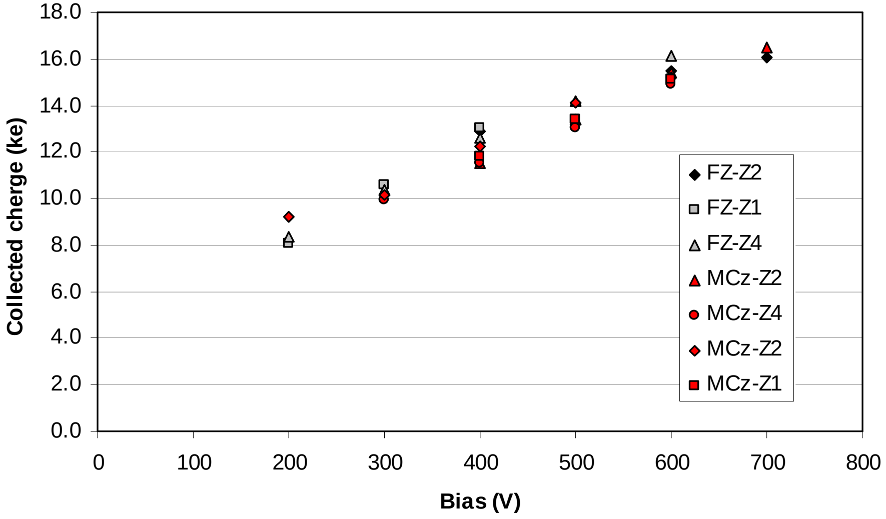
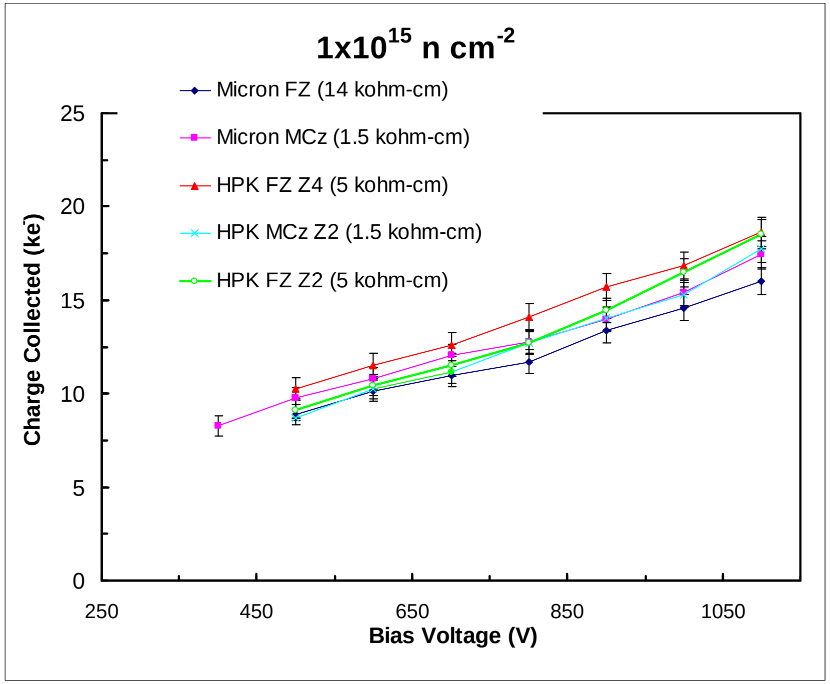
3.0 10^{15} n cm^{-2}

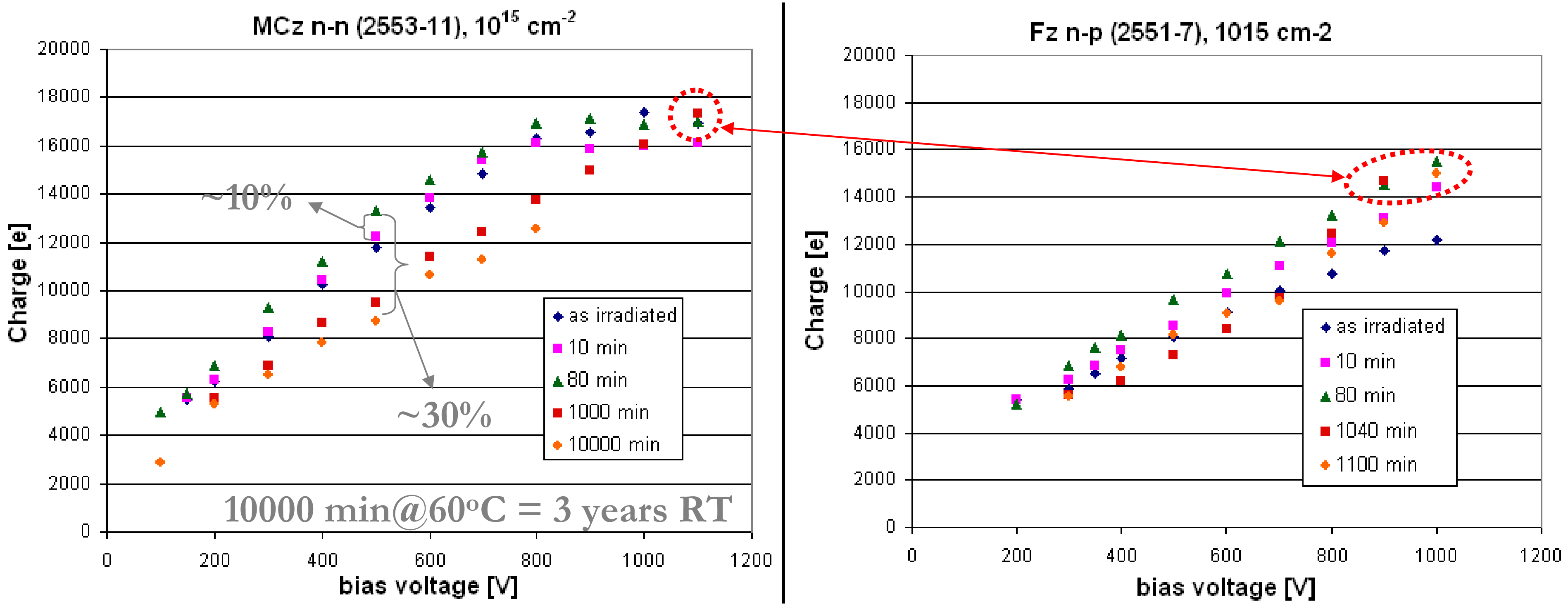


Partial comparison of CCE between FZ and MCz materials (p-type only).





Long term annealing (strips, binary)



MCz n-n (2553-11), 10^{15} cm^{-2}

Fz n-p (2551-7), 1015 cm-2

~10%

~30%

10000 min@60°C = 3 years RT

Only some points measured so far:

From H. Sadrozinski et al. 11th RD50 workshop

The CCE follows the trend of the V_{fd}:

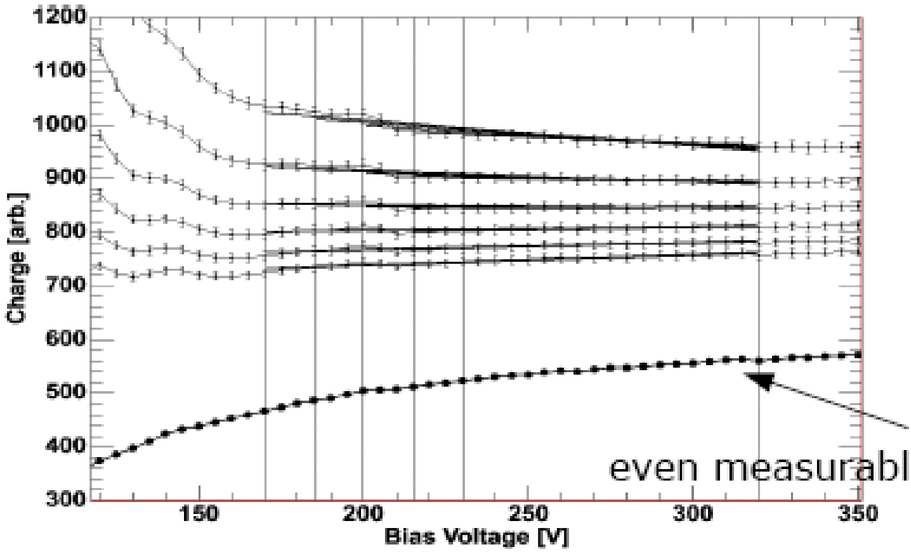
- initial rise (beneficial annealing) increase in collected charge by ~10% (@500V)
- decrease by again 20-30% (@500V) during the reverse annealing 1000 min
- Smaller effect for Fz-p detector due to larger V_{fd} after irradiation (relatively smaller effect)

CCE at higher voltages shows annealing of electron trapping times → one of the reasons why long term annealing is not so damaging.

Important parameter:

Trapping Time Constants

→ collected charge for different V_{bias} depends on trapping time



even measurable with thin diodes

calculate: $i_m(t) = i_0(t)\exp(-t/\tau_{eff})$

with different τ

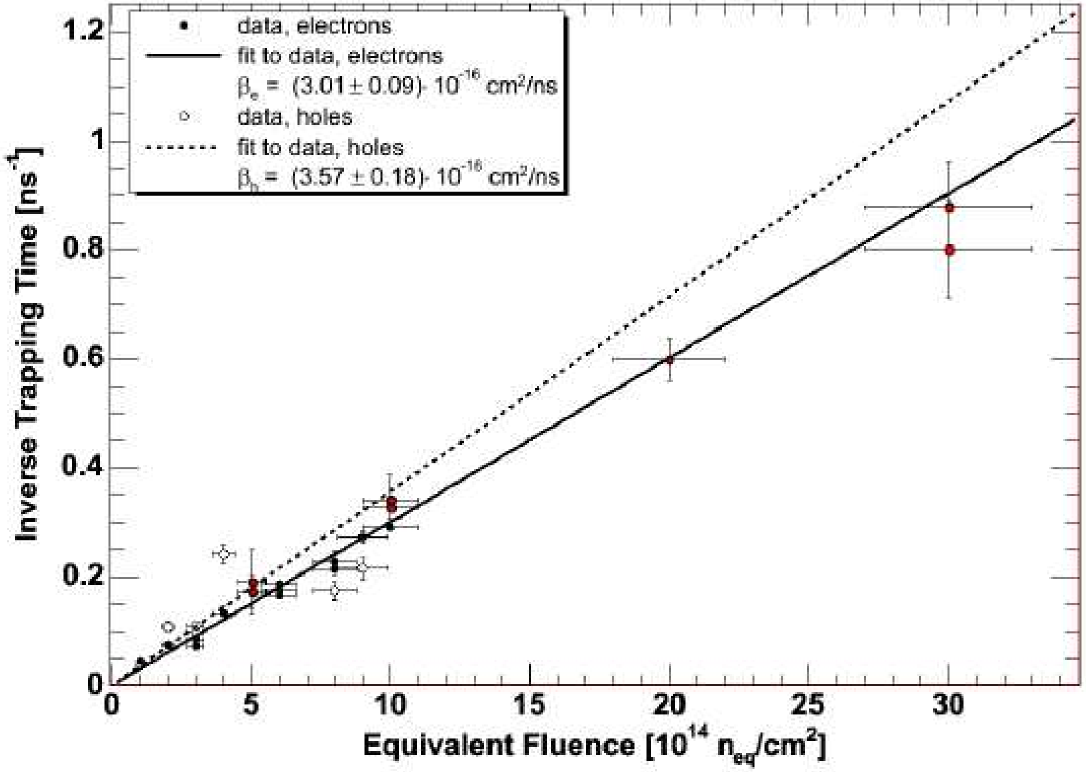
→ if slope = 0, trapping time determined

J. Weber,

Determination of Trapping Time Constants
in Neutron-Irradiated
Thin Silicon Pad Detectors

11th RD50 Workshop
12 - 14 November 2007
CERN

Inverse Trapping Time vs. Fluence (DOFZ + epi)



$$\beta_{n,e} = (3.01 \pm 0.09) \cdot 10^{-16}\ \mathrm{cm}^2/\mathrm{ns},$$

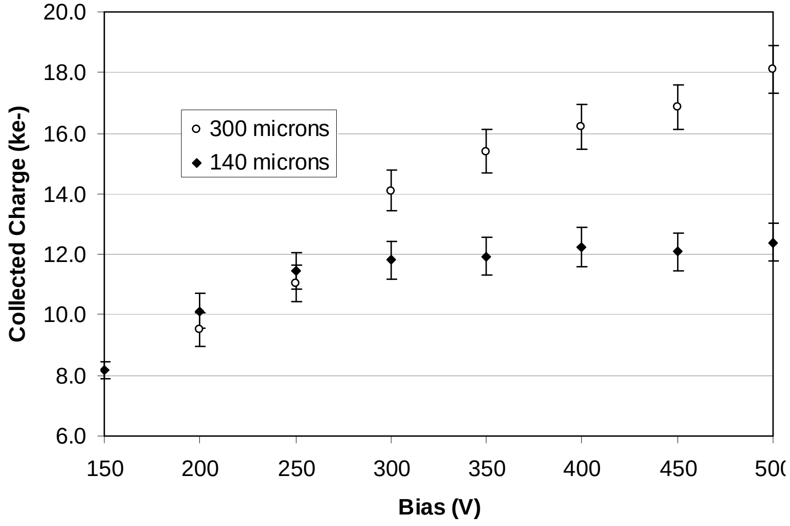
J. Weber, 11th RD50 Workshop
12 - 14 November 2007
CERN

Thin and thick segmented detectors

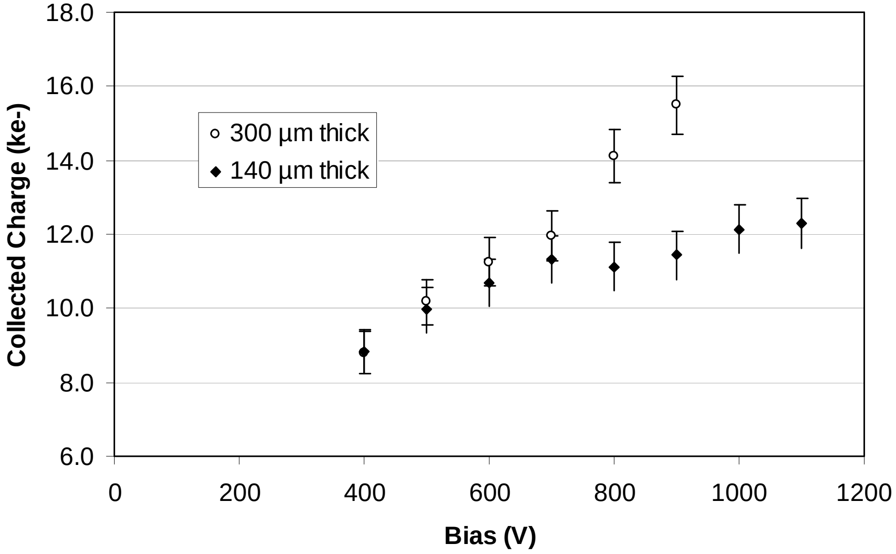
G. Casse, 11th RD50 workshop

Comparison of CCE with 140µm and 300µm thick detectors from Micron irradiated to various n fluences, up to $1x10^{16}$ cm^{-2}!

$5x10^{14}$ n_{eq} cm^{-2}



$1.6x10^{15}$ n_{eq} cm^{-2}

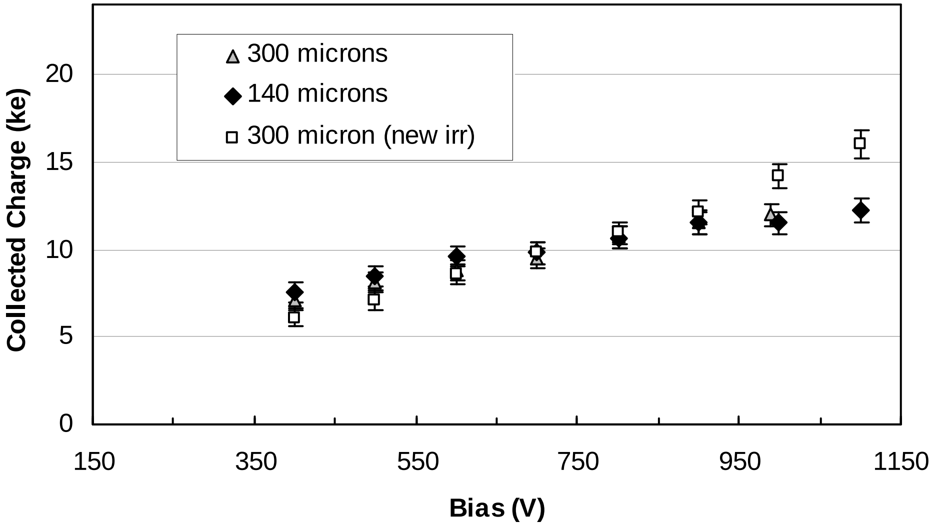


Thin and thick segmented detectors

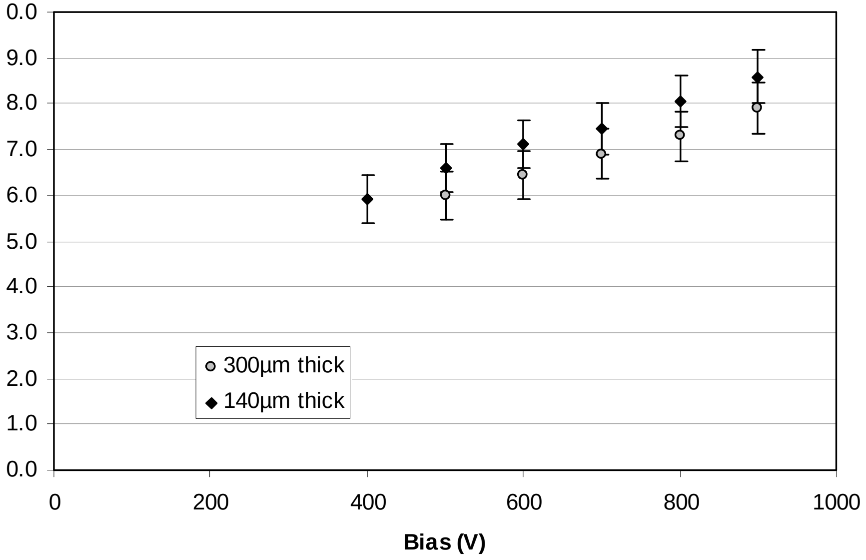
Comparison of CCE with 140µm and 300µm thick detectors from Micron irradiated to various n fluences, up to $1x10^{16}$ cm^{-2}!

G. Casse, 11th RD50 workshop

$3x10^{15}\ n_{eq}\ cm^{-2}$

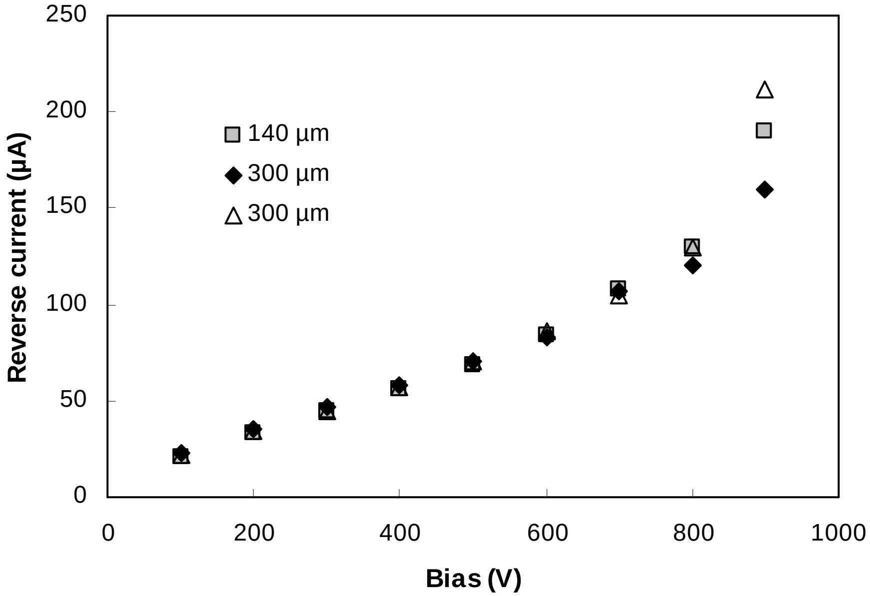


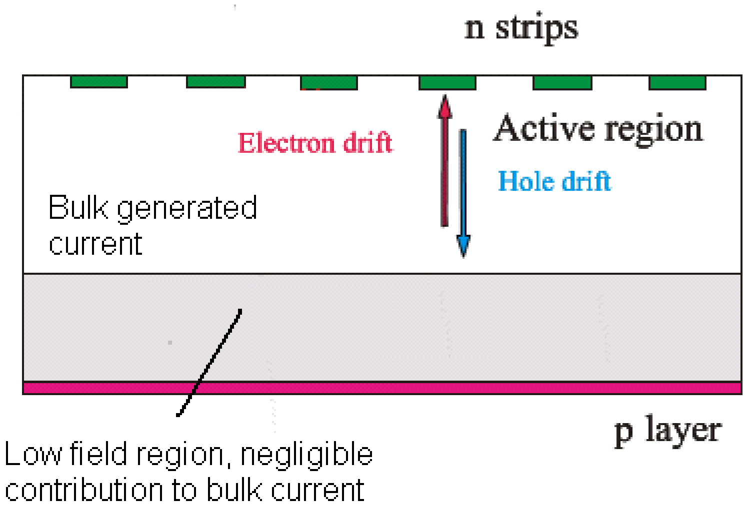
$1x10^{16}\ n_{eq}\ cm^{-2}$



Thin and thick segmented detectors

Comparison of reverse current between 140µm and 300µm thick detectors from Micron irradiated to $1x10^{16}$ cm^{-2}!

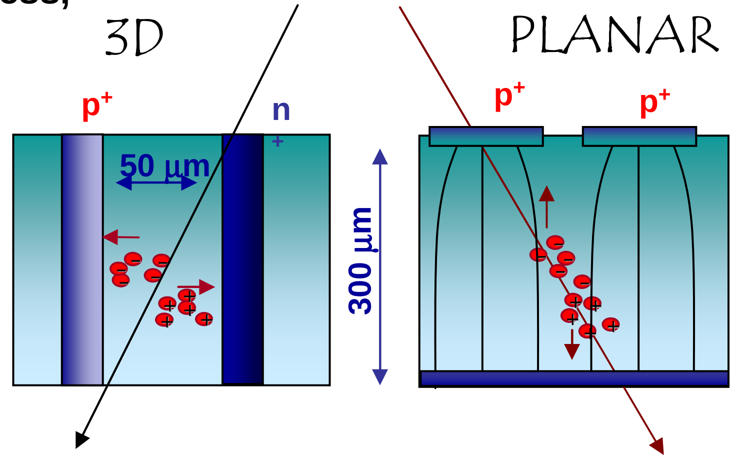


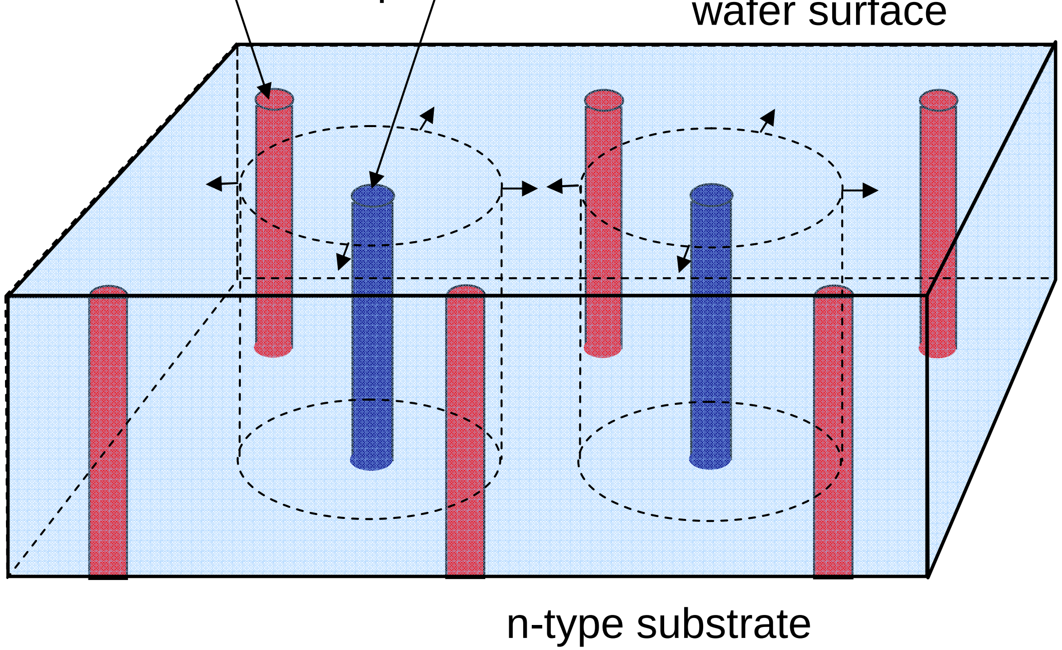


SURPRISE: reverse current is the same!

Alternative geometries: 3D detectors

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



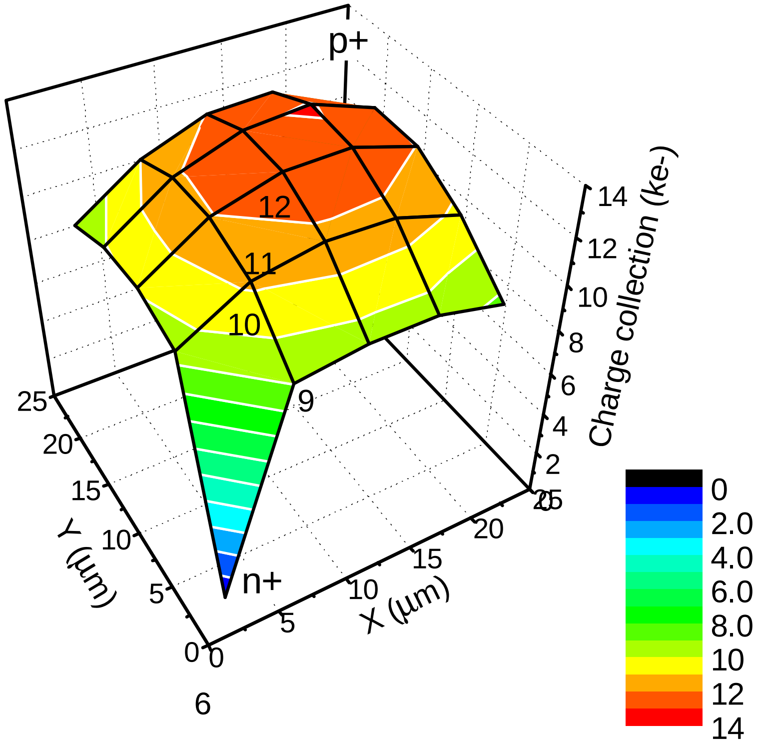


Introduced by: S.I. Parker et al., NIMA 395 (1997) 328

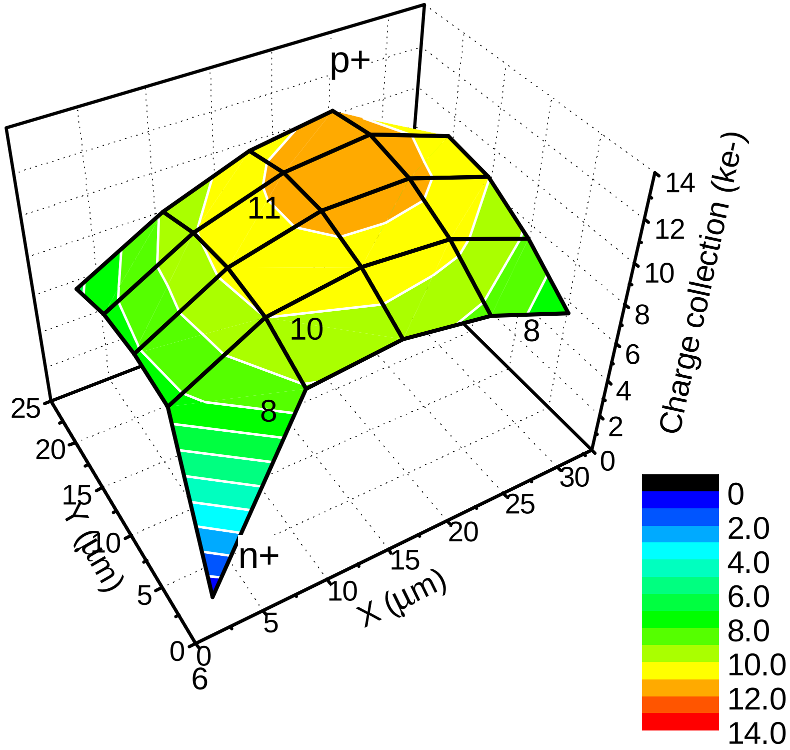
3D activities: simulations

- Simulated MIPs passing through detector at 25 positions, to roughly map the collection efficiency. 150V bias. Charge sharing not taken into account. Dose $10^{16} n_{eq}/cm^2$
- Low collection within n^+ and p^+ columns (seen experimentally)

8 columns

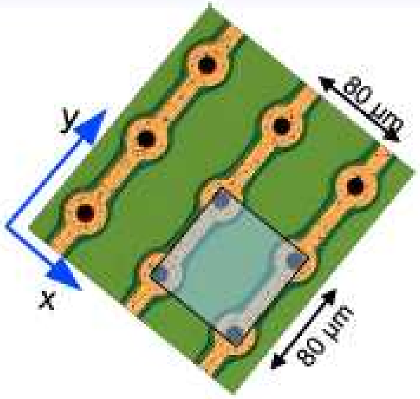


6 columns

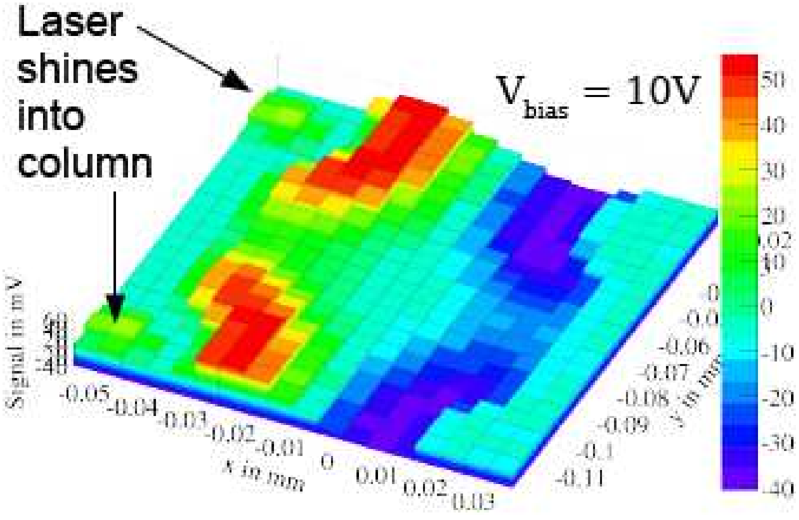


D. Pennicard, 11th RD50 workshop

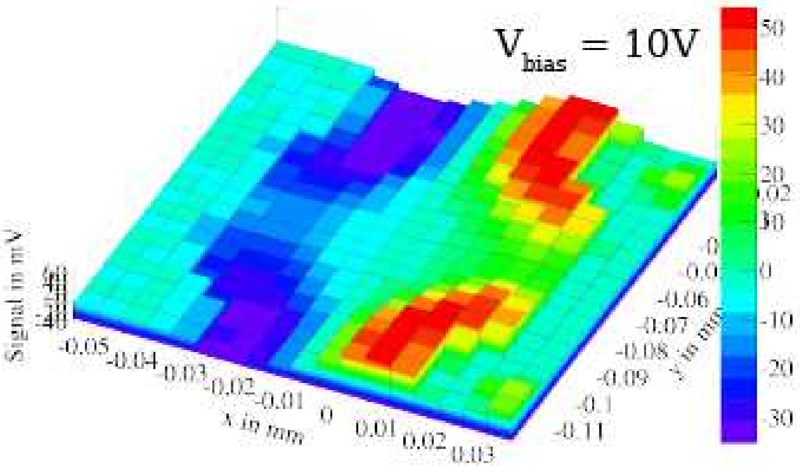
3-D strip detector measurements



- Cz p-spray, unirradiated
- 5µm step size
- 80µm x 80µm area
- *y* axis along the strips
- At variable bias voltage



signal on left strip



signal on right strip

11th RD50 Workshop, CERN, 13 November 2007 Gregor Pahn, Universität Freiburg

OUTLOOK:

Investigation of n-MCz detectors with proton irradiation

Further Investigation of O and thickness effects

Systematic investigation of the effect of initial wafer resistivity

Investigate best solution for interstrip isolation

Investigation of optimal solution for diode geometry in 3D devices.

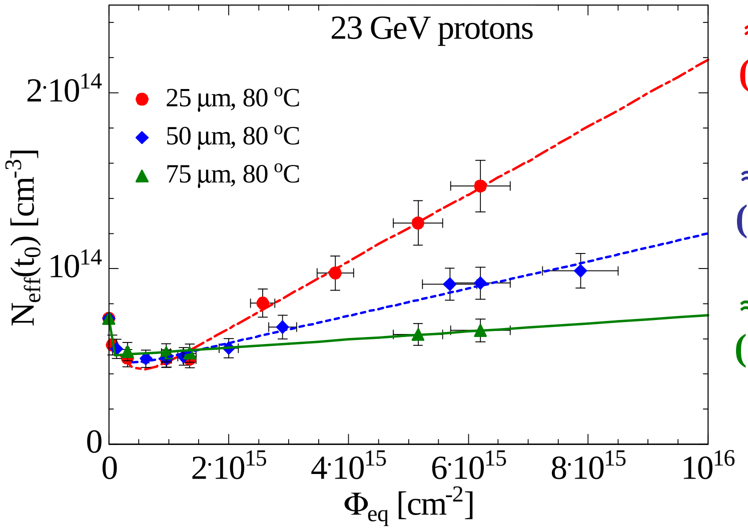
Quest for satisfactory microscopy model with accurate prediction of the electrical properties of the devices

SPARES

EPI Devices – Irradiation experiments

G.Lindström et al.,10th European Symposium on Semiconductor Detectors, 12-16 June 2005
G.Kramberger et al., Hamburg RD50 Workshop, August 2006

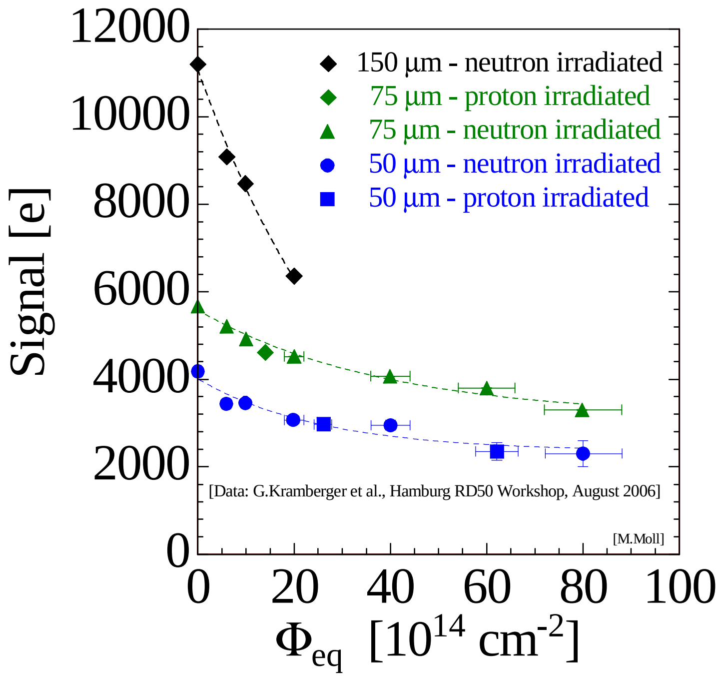
- Epitaxial silicon
  - Layer thickness: 25, 50, 75 μm **(resistivity: ~ 50 Ωcm);** 150 μm **(resistivity: ~ 400 Ωcm)**
  - Oxygen: [O] ≈ 9×10^{16}cm^{-3}; Oxygen dimers **(detected via IO$_2$-defect formation)**



≈105V (25μm)

≈230V (50μm)

≈320V (75μm)



[Data: G.Kramberger et al., Hamburg RD50 Workshop, August 2006]

- Only little change in depletion voltage

- No type inversion up to ~ 10^{16} p/cm^2 and ~ 10^{16} n/cm^2
  ⇨high electric field will stay at front electrode!

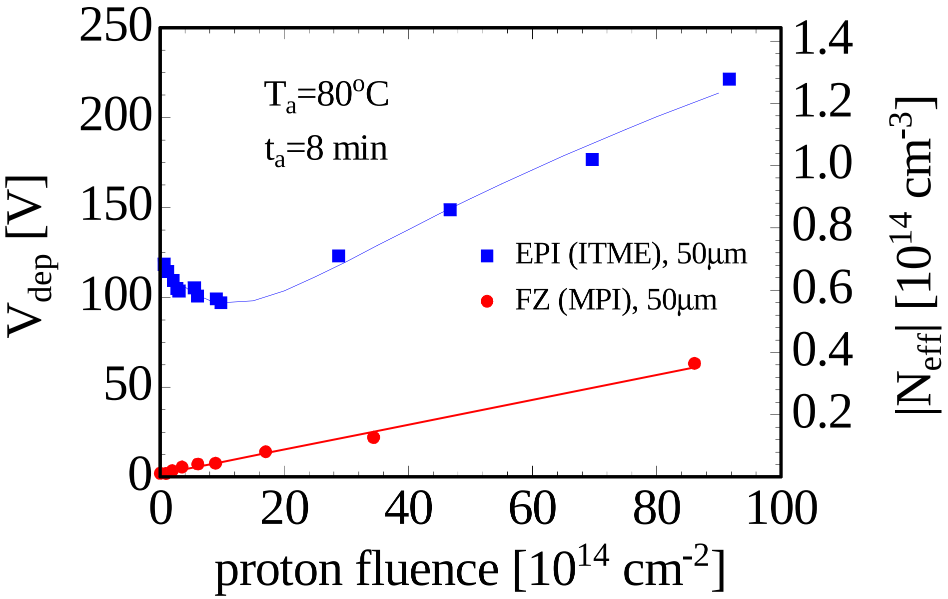
- Explanation: introduction of shallow donors is bigger than generation of deep acceptors

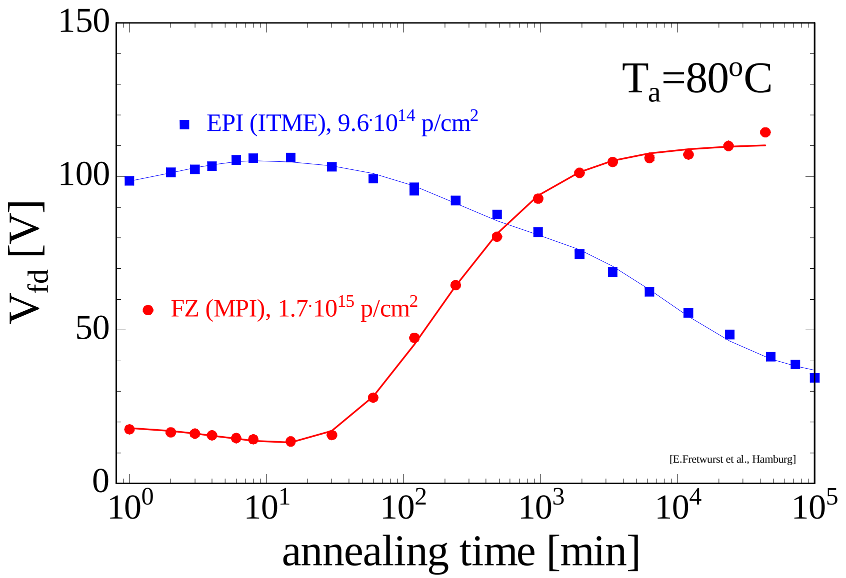
- CCE (Sr^{90} source, 25ns shaping):
  ⇨ 6400 e (150 μm; 2x10^{15} n/cm^{-2})
  ⇨ 3300 e (75μm; 8x10^{15} n/cm^{-2})
  ⇨ 2300 e (50μm; 8x10^{15} n/cm^{-2})

Epitaxial silicon – Thin silicon - Annealing

MPI Munich project:
Thin sensor interconnected to
thinned ATLAS readout chip
(ICV-SLID technique)

- 50 µm thick silicon can be fully depleted up to 10^{16} cm^{-2}
  - **Epitaxial silicon (50Ωcm on CZ substrate, ITME & CiS)**
  - **Thin FZ silicon (4KΩcm, MPI Munich, wafer bonding technique)**

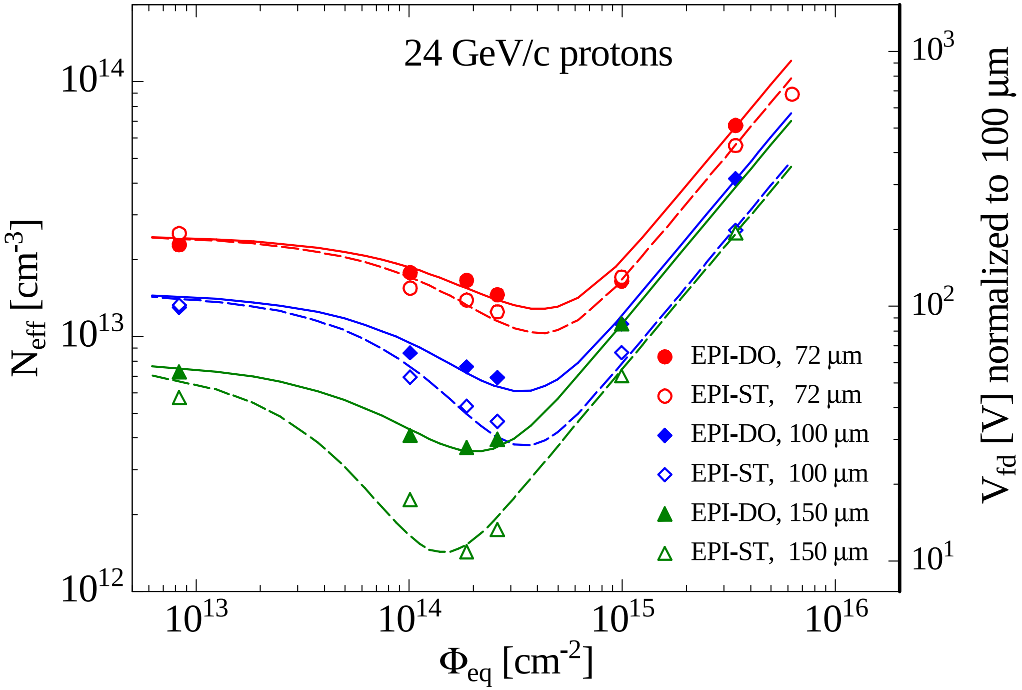




- **Thin FZ silicon**: **Type inverted**, increase of depletion voltage with time
- **Epitaxial silicon**: **No type inversion**, decrease of depletion voltage with time
  ⇒ No need for low temperature during maintenance of experiments!

[E.Fretwurst et al., NIMA 552, 2005, 124]

Proton irradiation: N_{eff} (V_{fd}) normalized to 100 µm EPI



- **Low fluence range:**
  Donor removal, depends on $N_{eff,0}$,
  Minimum in $N_{eff}(\Phi)$ shifts to larger Φ for higher doping
- **High fluence range:**
  EPI-DO and -ST:
  $\beta(72) > \beta(100) \approx \beta(150)$ → initial doping?
  and
  β(EPI-DO) > β(EPI-ST)→oxygen effect?

- **NO TYPE INVERSION, $\beta > 0$**

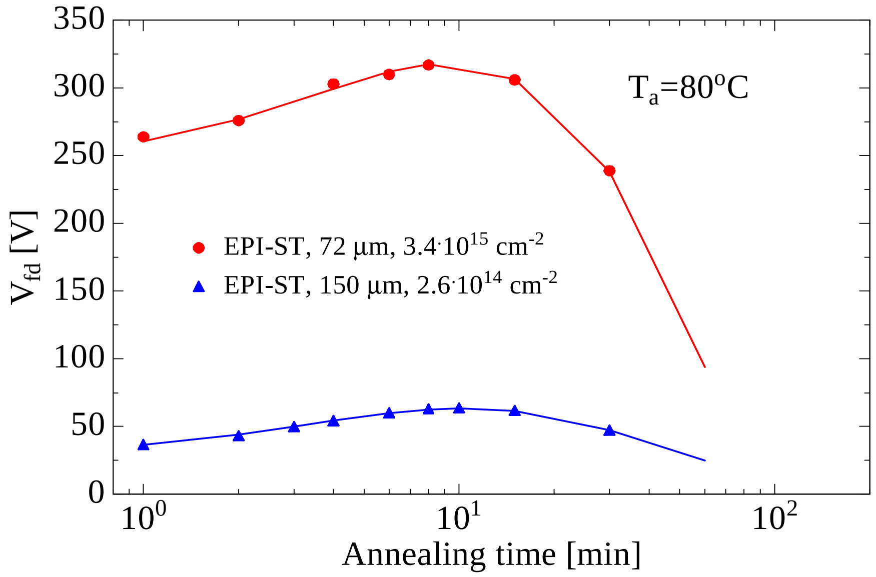
$$N_{eff}(\Phi) = N_{eff,0} \cdot \exp(-c \cdot \Phi) + \beta \cdot \Phi$$

$\beta > 0$, dominant donor generation

$\beta < 0$, dominant acceptor generation

Proton irradiation: annealing of V_{fd} at 80 °C

EPI diodes



- **Typical annealing behavior of non-inverted diodes:**

→ V_{fd} increase, short term annealing

→ $V_{fd,max}$ (at $t_a \approx 8$ min), stable damage

→ V_{fd} decrease, long term annealing

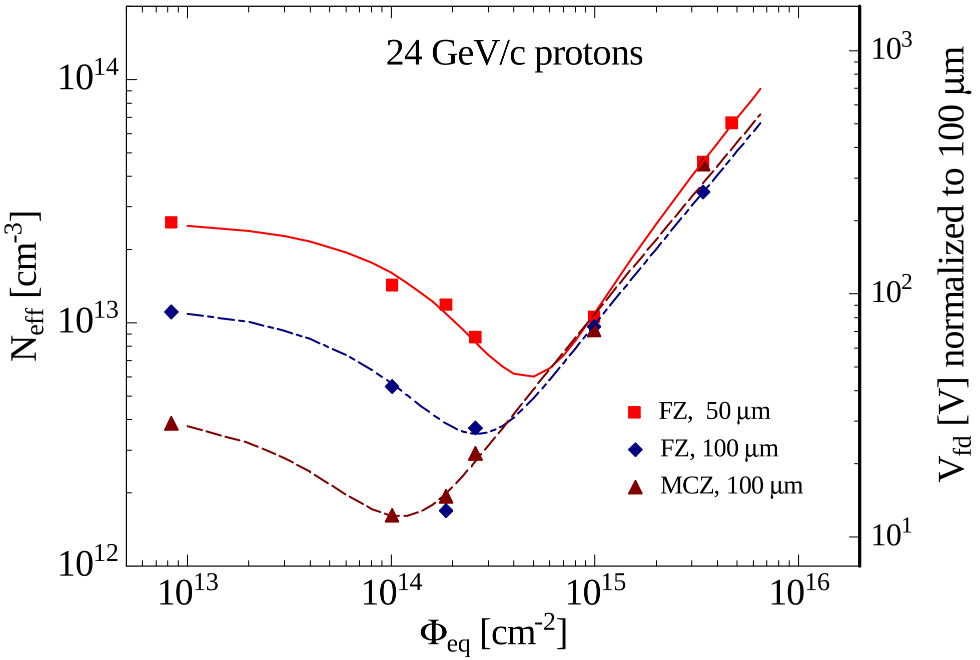
$$V_{fd}(\Phi,t) = V_C(\Phi) \pm V_a(\Phi,t) \pm V_Y(\Phi,t)$$

→ stable damage ± short term ± long term annealing

→ + sign if inverted

→ – sign if not inverted

Development of N_{eff} resp. V_{fd} normalized to 100 µm
FZ and MCz



- **Low fluence range:**
  Donor removal, depends on $N_{eff,0}$, Minimum in $N_{eff}(\Phi)$ shifts to larger Φ for higher doping
- **High fluence range:**
  β(FZ-50) ≈ β(MCz-100) > β(FZ-100)
- **β > 0 or < 0 ?:**

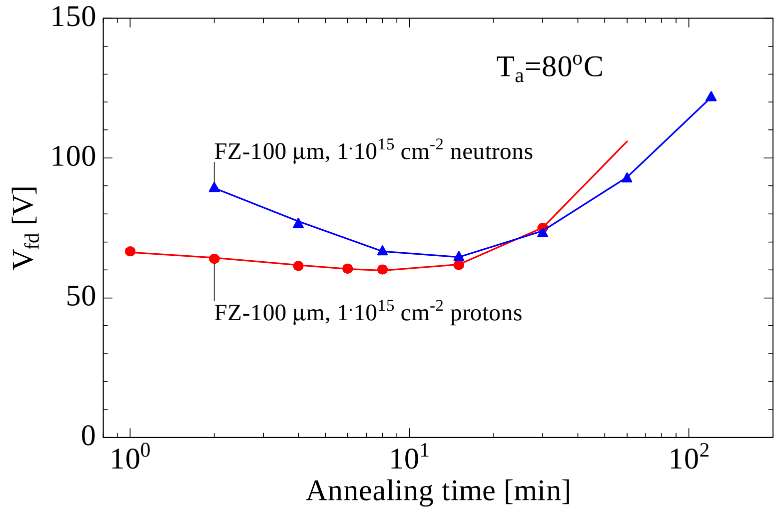
  Expected:

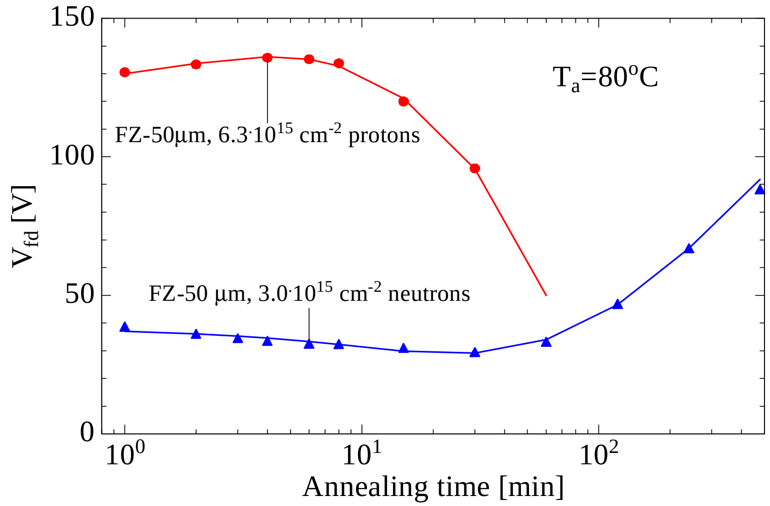
  FZ-50, FZ-100 → $\beta < 0$, inversion, low [O]

  MCz-100 → $\beta > 0$, no inversion, high [O]

Annealing of V_{fd} at 80 °C

FZ diodes





- **Annealing behavior of FZ-100 µm:**
  Inverted diode
  V_{fd} decrease (short term component)
  $V_{fd,min}$ (stable component)
  V_{fd} increase (long term component)

  for protons and neutrons

- **Annealing behavior of FZ-50 µm:**

  Surprise??

- **€after proton damage no inversion**

  after neutron damage inversion

Thickness effect?