The RD50 Collaboration, notes for an hystorical overview

Mara Bruzzi

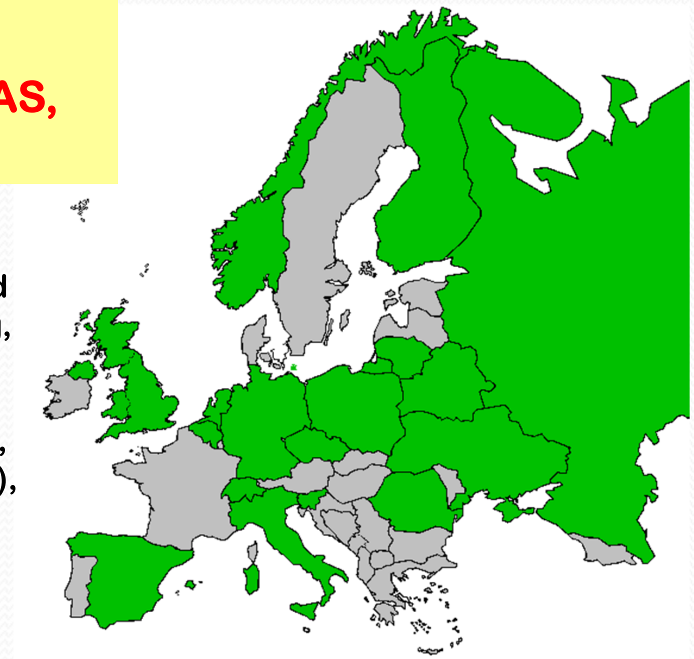
INFN and University of Florence , Italy

October 12, 2012

The RD50 Collaboration

RD50: Development of Radiation Hard Semiconductor Devices for High Luminosity Colliders

Cooperation across experimental boundaries for ATLAS, CMS, LHCb and many smaller collaborations



38 European institutes

Belarus (Minsk), Belgium (Louvain), Czech Republic (Prague (3x)), Finland (Helsinki, Lappeenranta), Germany (Dortmund, Erfurt, Freiburg, Hamburg, Karlsruhe, Munich), Italy (Bari, Florence, Padova, Perugia, Pisa, 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 (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)

257 Members from 47 Institutes

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

RD50 Scientific Organization of RD50

Development of Radiation Hard Semiconductor Devices for High Luminosity Colliders

CERN

Co-Spokespersons

Gianluigi Casse — University of Liverpool

and

Michael Moll — CERN PH-DT

Defect / Material Characterization
Mara Bruzzi
(INFN and Uni Florence)

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

- Wodean – Workshop on Defect Analysis in Silicon Detectors (G.Lindstroem)

Defect Engineering
Eckhart Fretwurst
(Hamburg University)

Development and testing of defect engineered silicon:
- Epitaxial Silicon
- High res. CZ, MCZ
- Other impurities H, N, Ge, …
- Thermal donors
- Pre-irradiation

- Wafer procurement (M.Moll)

Pad Detector Characterization
Gregor Kramberger
(Ljubljana University)

- Test structure characterization IV, CV, CCE
- NIEL
- Device modeling
- Operational conditions
- Common irradiations
- Standardisation of measurements (A.Chilingarov)
- New Materials (E. Verbitskaya)

New Structures
Richard Bates
(Glasgow University)

- 3D detectors
- Thin detectors
- Cost effective solutions

- 3D (R.Bates)
- Semi 3D (Z.Li)
- Thinned detectors (M.Boscardin)

Full Detector Systems
Gianluigi Casse
(Liverpool University)

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

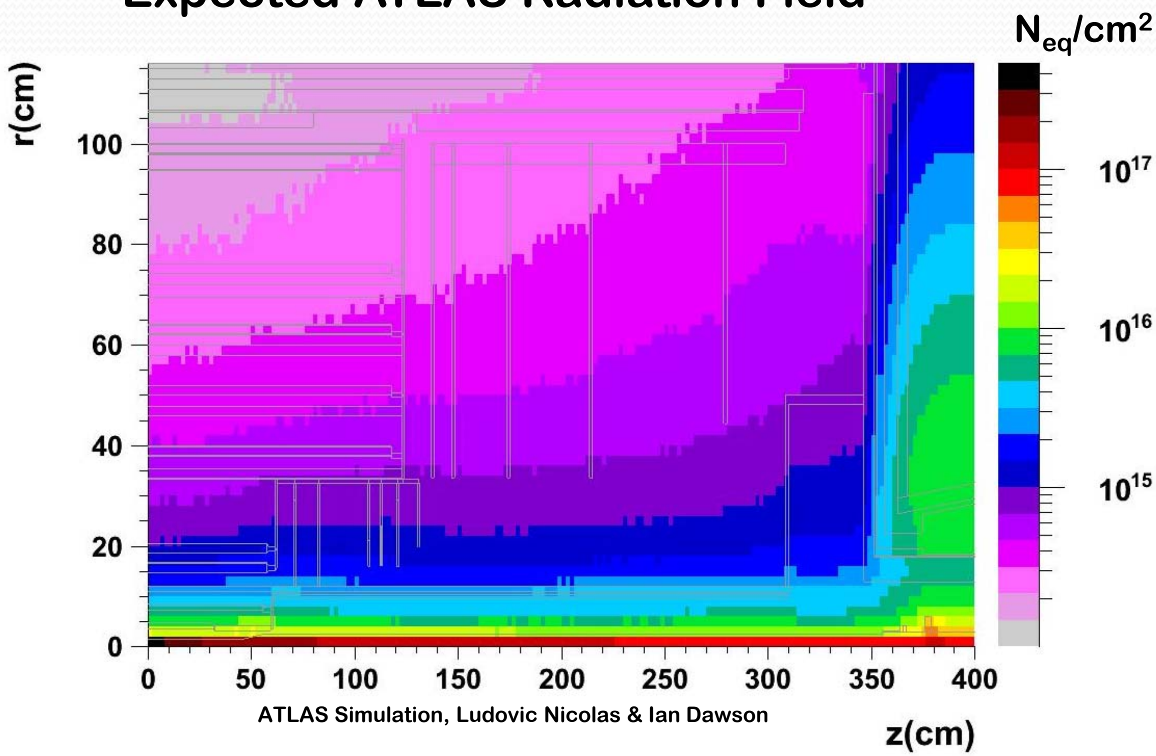
- Comparison of detectors made by different producers

CERN contact: Michael Moll

The Challenge

- **LHC Upgrade will seriously increase radiation levels**
  - **ATLAS scenario for 3000fb^{-1} (HL-LHC or Phase II)**
- **Very strong radial and significant z dependence**
- **HL-LHC is entering new area of fluences above 10^{16} N_{eq}/cm^2 at low radii**
- **LHC silicon sensors would not survive this for long**
- **Need to develop new generation of radiation hard silicon for HL-LHC**

Expected ATLAS Radiation Field



- **Radiation hardness requirements (including safety factor of 2)**
  - **2×10^{16} n_{eq}/cm^2 for the innermost pixel layers**
  - **1×10^{15} n_{eq}/cm^2 for the innermost strip layers**

RD50… quite a long track

3-5 June 2013	22nd RD50 Workshop, University of New Mexico, Albuquerque, USA
14-16 November 2012	21st RD50 Workshop, CERN, Geneva
30 May - 1 June 2012	20th RD50 Workshop, Bari, Italy
21-23 Nov.2011	19th RD50 Workshop, CERN, Geneva
23-25 May 2011	18th RD50 Workshop in Liverpool
17-19 Nov. 2010	17th RD50 Workshop, CERN, Geneva

- 16th RD50 - Workshop on Radiation hard semiconductor devices for very high luminosity colliders, Barcelona, 31 May-2 June 2010
- 15th RD50 - Workshop on Radiation hard semiconductor devices for very high luminosity colliders, CERN, 16-18 November, 2009
- 14th RD50 - Workshop on Radiation hard semiconductor devices for very high luminosity colliders, Freiburg, 3-5 June, 2009
- 13th RD50 - Workshop on Radiation hard semiconductor devices for very high luminosity colliders, CERN, 10-12 November, 2008
- 12th RD50 - Workshop on Radiation hard semiconductor devices for very high luminosity colliders, Ljubljana, Slovenia, 2-4 June, 2008
- 11th RD50 - Workshop on Radiation hard semiconductor devices for very high luminosity colliders, CERN, 12-14 November, 2007
- 10th RD50 - Workshop on Radiation hard semiconductor devices for very high luminosity colliders, Vilnius, Lithuania, 4-6 June, 2007
- 9th RD50 - Workshop on Radiation hard semiconductor devices for very high luminosity colliders, CERN, 6-8 October, 2006
- RD50 workshop on defect analysis in radiation damaged silicon detectors, University of Hamburg (DESY site), 23/24-August 2006
- 8th RD50 - Workshop on Radiation hard semiconductor devices for very high luminosity colliders, Prague, Czech Republic, 25-28 June 2006
- 7th RD50 - Workshop on Radiation hard semiconductor devices for very high luminosity colliders, CERN, 14-16 November, 2005
- 6th RD50 - Workshop on Radiation hard semiconductor devices for very high luminosity colliders, Helsinki, Finland, 2-4 June, 2005
- RD50 - Full Detector Systems - Meeting, Trento, Italy, 28 February 2005
- 5th RD50 - Workshop on Radiation hard semiconductor devices for very high luminosity colliders, Florence, Italy, 14-16 October, 2004
- 4th RD50 - Workshop on Radiation hard semiconductor devices for very high luminosity colliders, CERN, 5-7 May, 2004
- 3rd RD50 - Workshop on Radiation hard semiconductor devices for very high luminosity colliders, CERN, 3-5 November, 2003
- 2nd RD50 - Workshop on Radiation hard semiconductor devices for very high luminosity colliders, CERN, 18-20 May, 2003
- 1st RD50 - Workshop on Radiation hard semiconductor devices for very high luminosity colliders, CERN, 2-4 October, 2002
- 1st RD50 - Workshop on Radiation hard semiconductor devices for very high luminosity colliders, CERN, 28-30 November, 2001

http://www.cern.ch/rd50

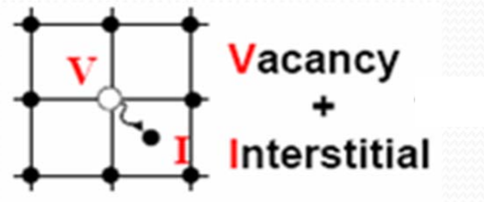
10 years!

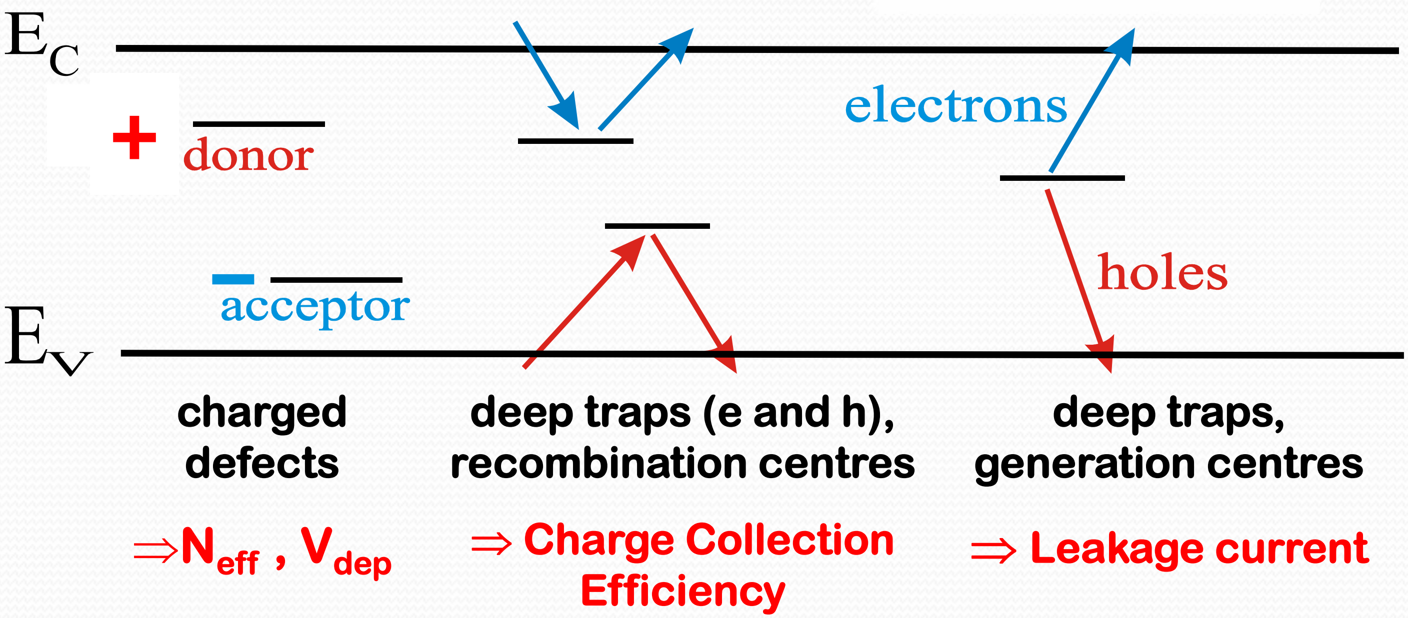
The Problem to cope with: Radiation Damage

I. **Surface Damage** due to **Ionizing Energy Loss (IEL)**
II. **Crystal (Bulk) damage due to Non-Ionizing Energy Loss (NIEL)**

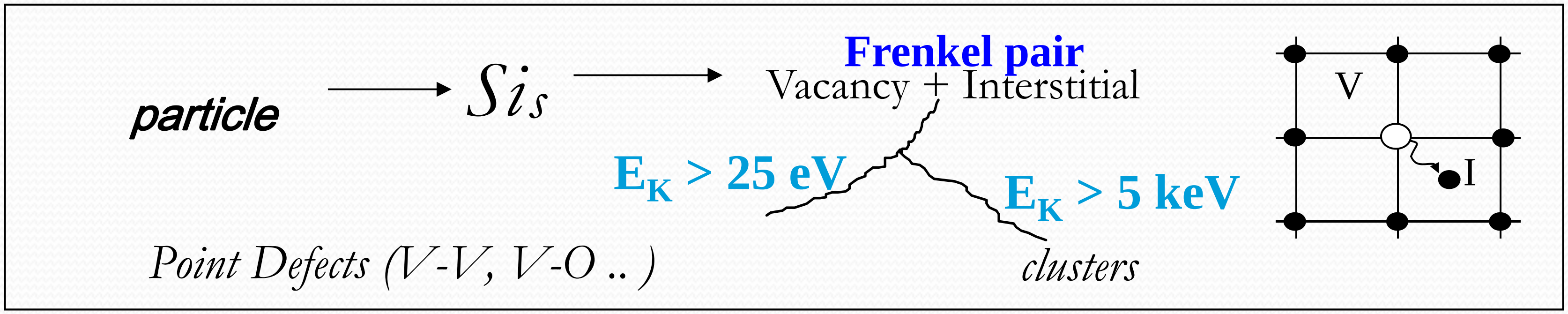
- **Defects in the crystal**
- **Point defects and "cluster" defects**

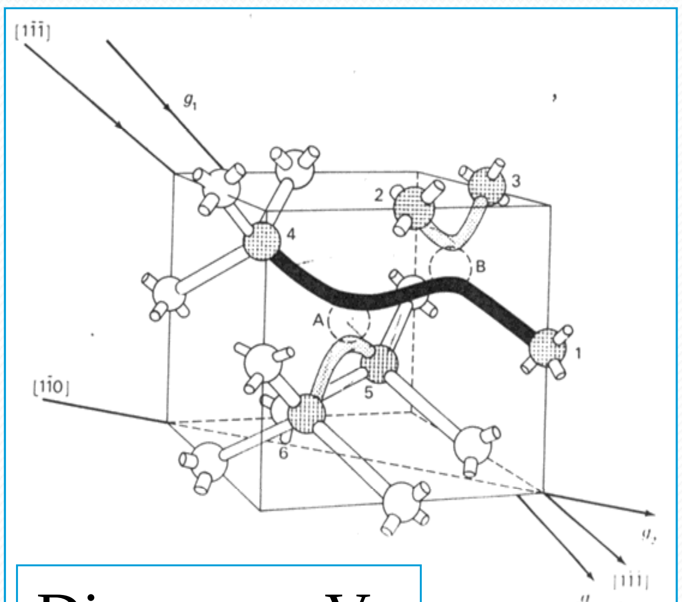
➔ New energy levels in the band gap



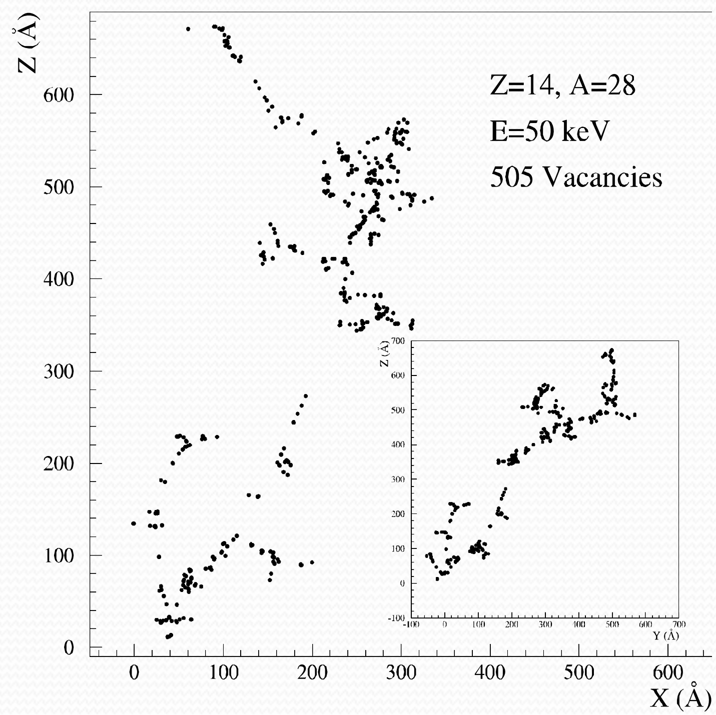


microscopic damage



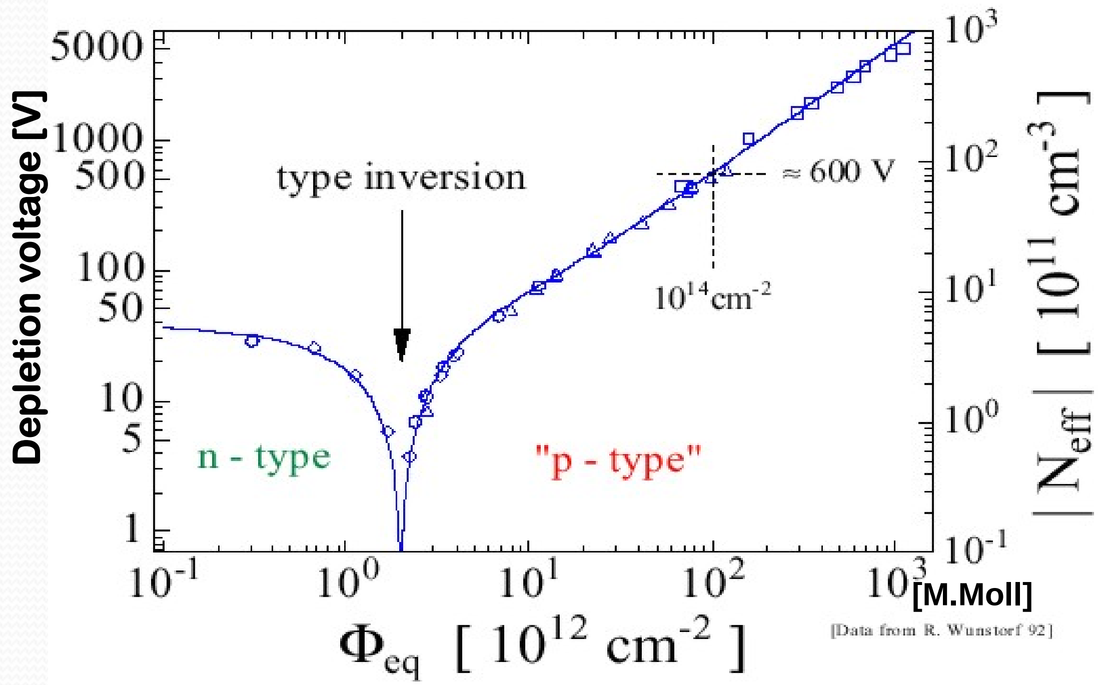


Divacancy V_2



Radiation Damage I: Doping

- Normalise dose Φ_{eq} to damage of 1-MeV-neutrons
- Damage
  - Several types of electrically active defects
  - Charged defects affect doping concentration
- Net effect: n-type Si becomes p-type „type inversion“ ➔ Space Charge Sign Inversions (SCSI)
- Detector becomes p-in-p (still with n back side)
- p-n-junction changes to back side for p-in-n Si
- This creates problems…

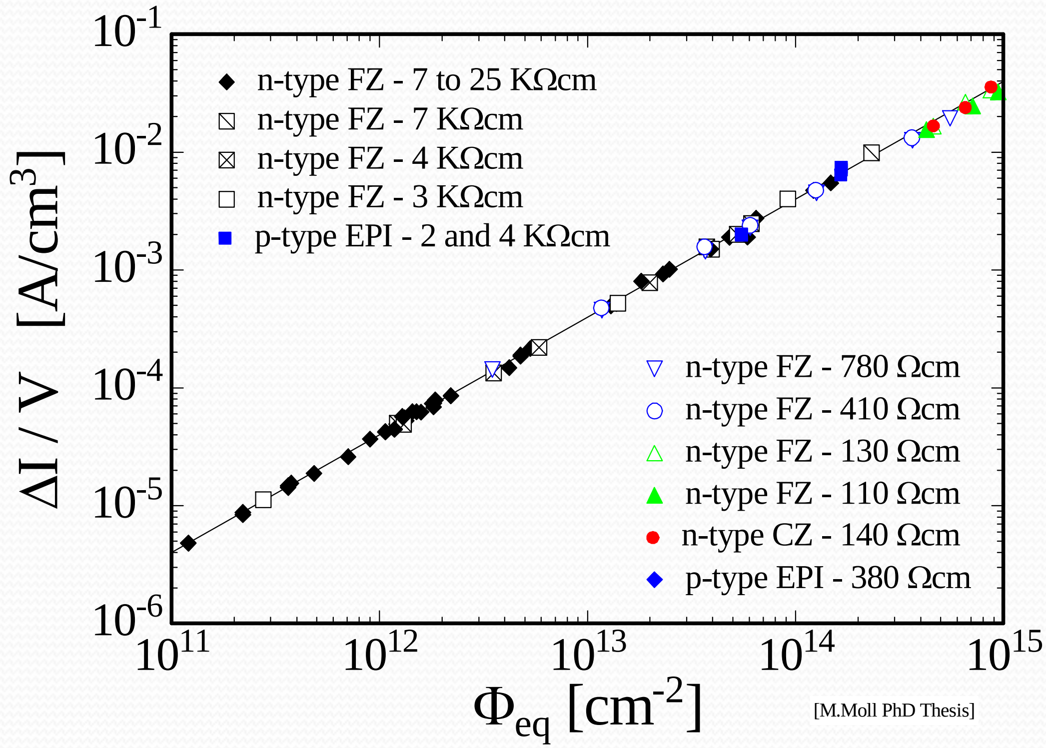


Radiation Damage II: Current

- **New energy levels deep in band gap, acting as generation centres**
- **Reverse current increases**
- **Effect independent of Si material or particle type**
- **Radiation-induced current dominates**

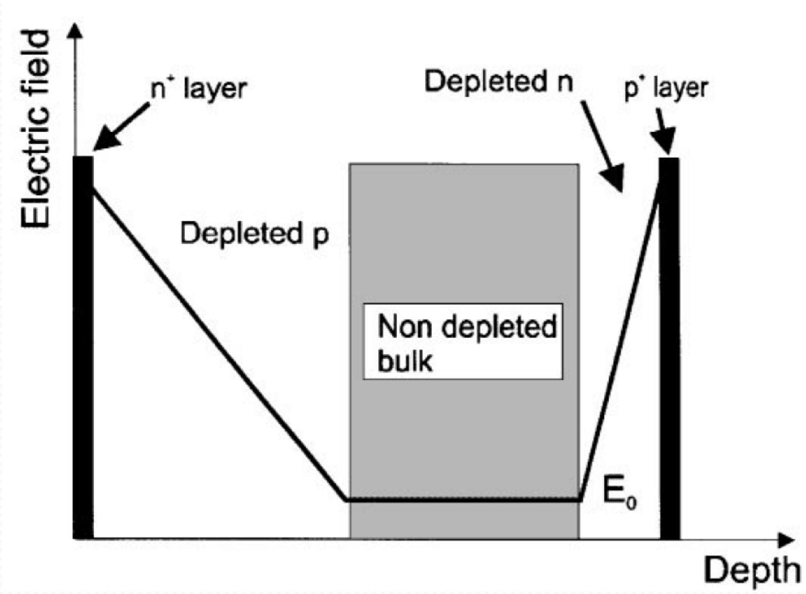
$$\frac{I_{vol}}{V} = \frac{I_{vol,\Phi=0}}{V} + \alpha\Phi_{eq}$$

- **I_{vol} has very strong temperature dependence**
  - **I_{vol} doubles ~each 8°**



- **Increased shot noise**
- **Increased power dissipation (heat)**
- **Risk of thermal runaway**

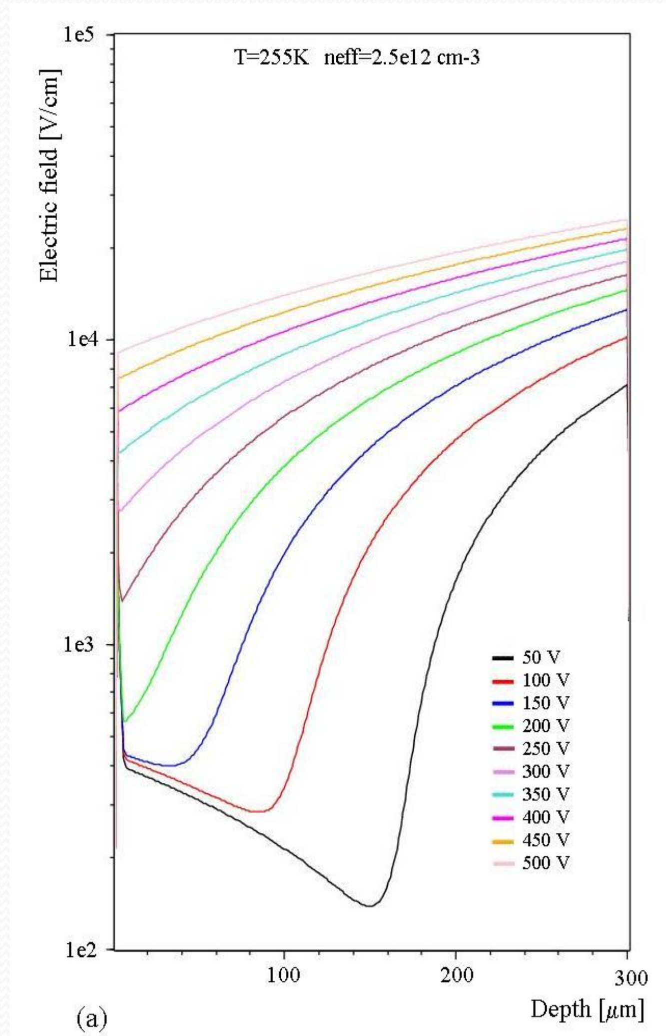
Radiation Damage III: Double Junction



In reality, after irradiation electric fields show a double junction structure with a non-depleted bulk in the middle of the sensor below the full depletion voltage

See G. Casse, et. al., NIMA 426 (1999) 140-146 and G. Kramberger, et. al., NIMA 579 (2007) 762-765 for details

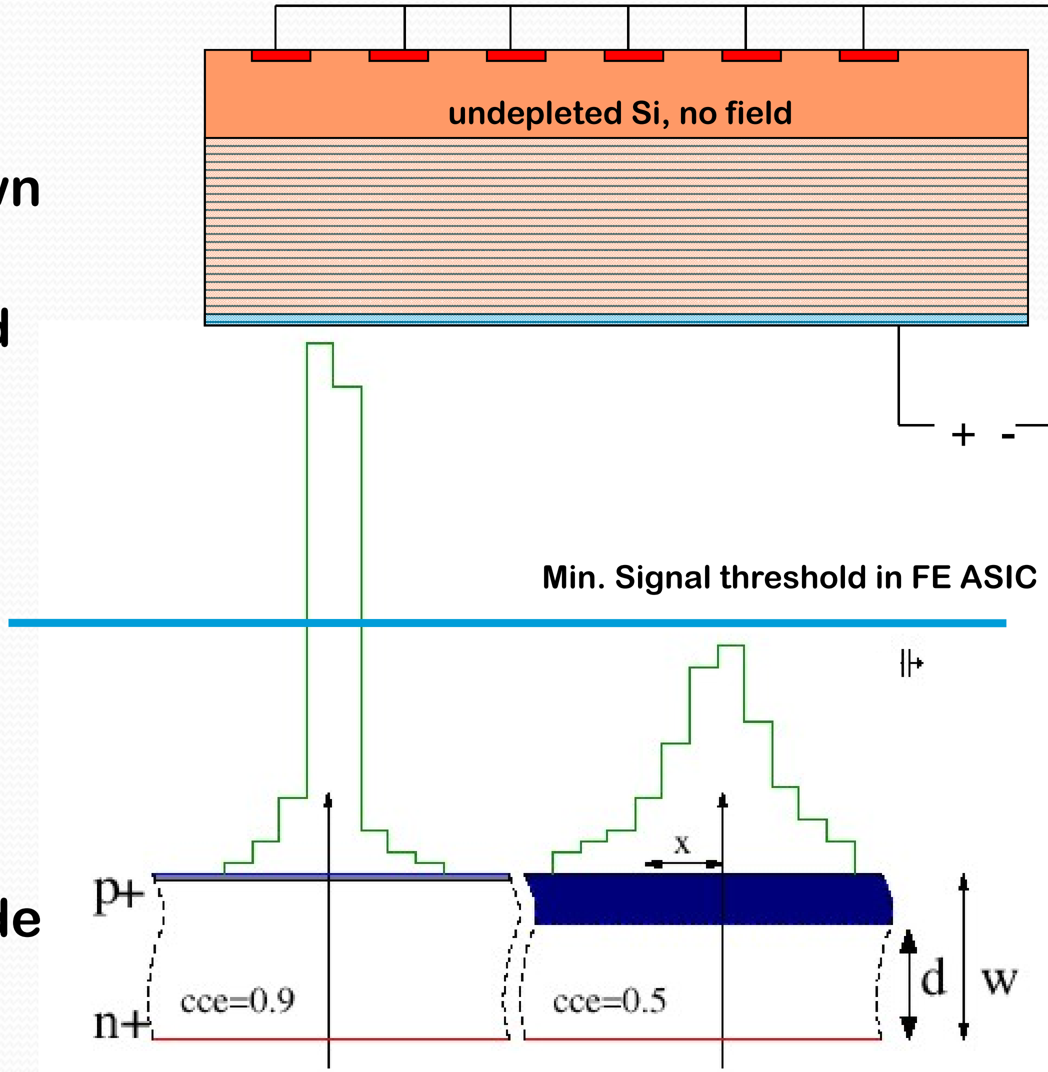
P-side **N-side**



ISE-TCAD simulation after 6. 10^{14} p cm^{-2}

Partial Depletion after Type Inversion

- Full depletion voltage V_{FD} grows with Φ
- Bias limit impose (breakdown or HV power supplies)
- Strips end up in un-depleted silicon layer
  - No measurable charge generated in this layer
  - Strips are “shorted”
  - MIPs create larger cluster, which may hide in noise
  - Problem for binary readout and small pitch
- Strips should be on back side
- N-in-p detectors



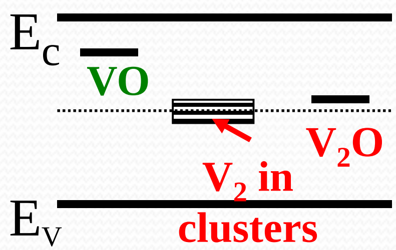
Paula Collins

Defect Engineering

Known from RD48 (ROSE)

Main Hypothesis: Oxygen beneficial as sink of vacancies

$V\text{-}O_i$ complex concentration increase → reduction of deeper levels mainly divacancy related



Typical oxygen concentration in Si:

-**FZ [Oi] $10^{15}cm^{-3}$**
-**Diffusion oxygenated FZ : DOFZ [O_i] 10^{16}-$10^{17}cm^{-3}$**
-**Czochralski Si: [O_i] up to $10^{18}cm^{-3}$**

Note: as VO is a point defect the beneficial effect of oxygen is expected especially when cluster formation by irradiation is less important than point defect formation.

RD50 starting scientific strategies:

I. Material engineering

II. Device engineering

III. Change of detector operational conditions

CERN-RD39
"Cryogenic Tracking Detectors"

- <u>Defect Engineering of Silicon</u>
  - 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 Si
  - Pre-irradiated Si
  - Influence of processing technology
- <u>New Materials</u>
  - Silicon Carbide (SiC), Gallium Nitride (GaN)
  - Diamond: CERN RD42 Collaboration
- <u>Device Engineering (New Detector Designs)</u>
  - p-type silicon detectors (n-in-p)
  - thin detectors
  - 3D and Semi 3D detectors
  - Stripixels
  - Cost effective detectors
  - Simulation of highly irradiated detectors
  - Monolithic devices

Mara Bruzzi and Michael Moll on behalf of the RD50 CERN Collaboration – LHCC, November 16, 2005

EARLY RESULTS

Silicon Materials Investigated by RD50

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

new in 2006

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

…MCz Si for particle detectors

HELSINKI INSTITUTE OF PHYSICS

Development of Particle Detectors made of Czochralski Grown Silicon

Helsinki Institute of Physics, CERN/EP, Switzerland

Microelectronics Centre, Helsinki University of Technology, Finland

Okmetic Ltd., Finland

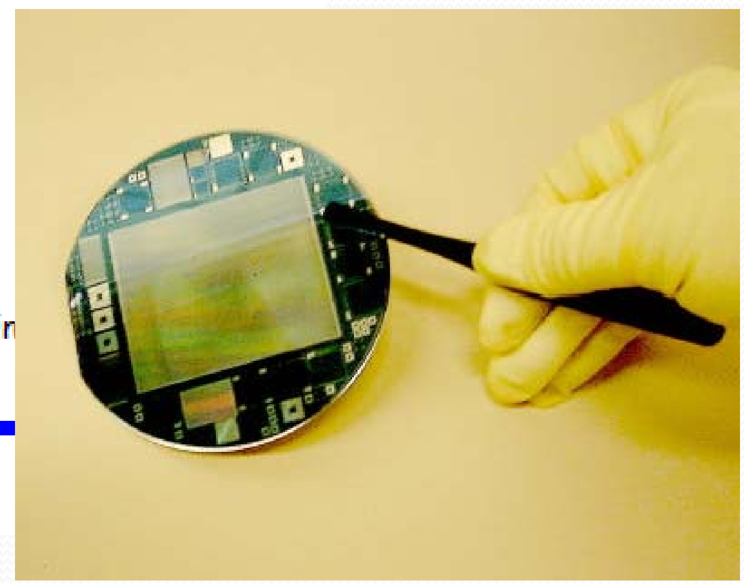
Ioffe PTI, Russia

Brookhaven National Laboratory, USA

CERN RD39 & RD50

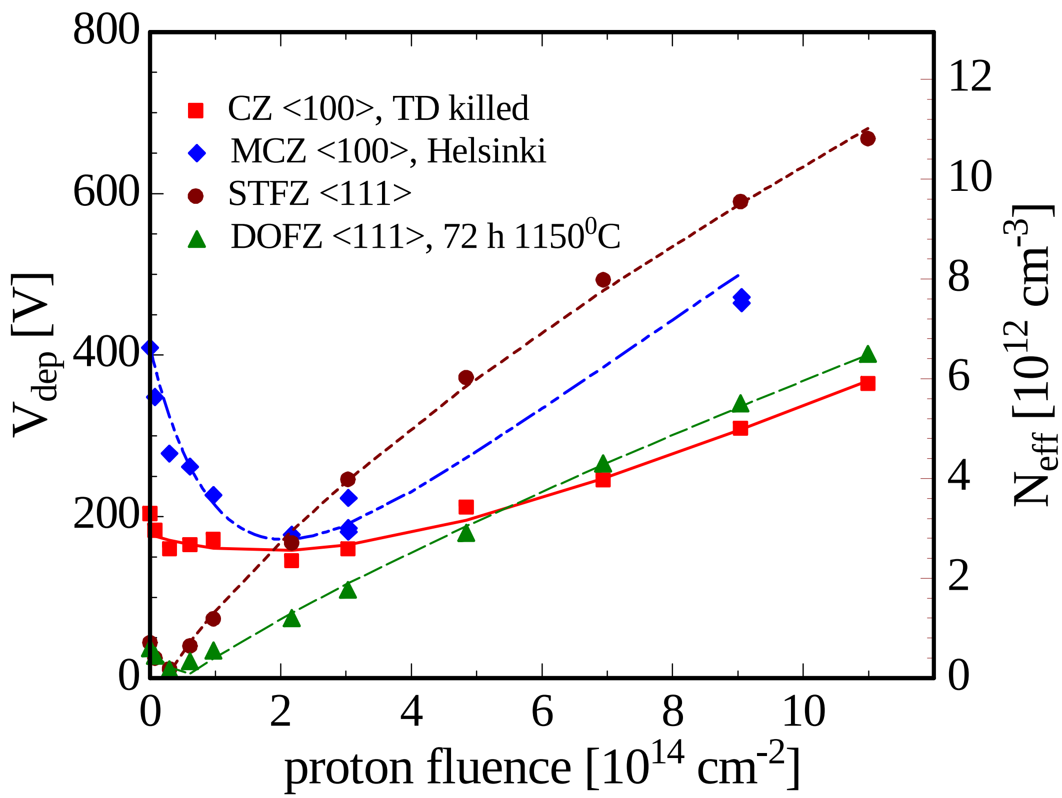
Accelerator Laboratory, University of Jyväskylä, Fin

Eija Tuominen
RD50 Workshop 03.10.2002



Standard FZ, DOFZ, Cz and MCz Silicon

- **Standard FZ silicon**
  - type inversion at ~ 2×10^{13} p/cm^2
  - strong Neff 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 (SCSI)</u> in the overall fluence range

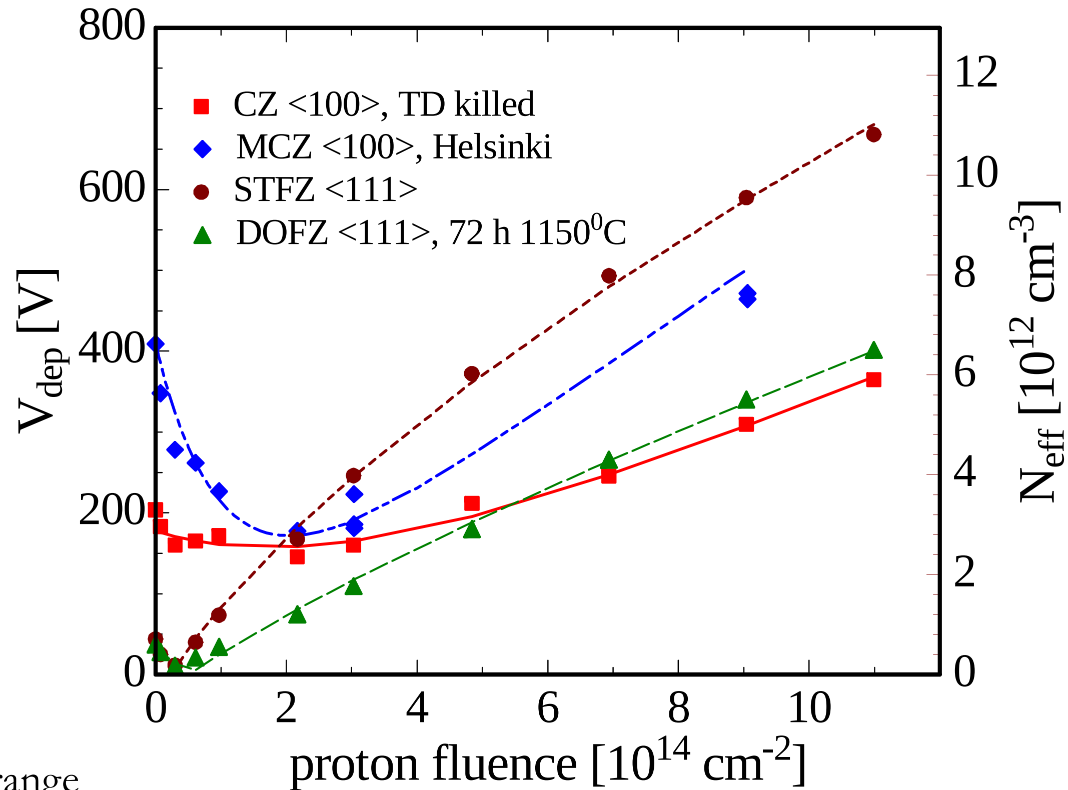
    ⇒ donor generation overcompensates acceptor generation in high fluence range

Standard FZ, DOFZ, Cz and MCz Silicon

24 GeV/c proton irradiation

- Standard FZ silicon
  - type inversion at ~ 2×10^{13} p/cm^2
  - strong Neff 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
  - no type inversion in the overall fluence range

    ⇒ donor generation overcompensates acceptor generation in high fluence range
- Common to all materials:
  - same reverse current increase
  - same increase of trapping (electrons and holes) within ~ 20%



...p-type sensors

THE UNIVERSITY of LIVERPOOL

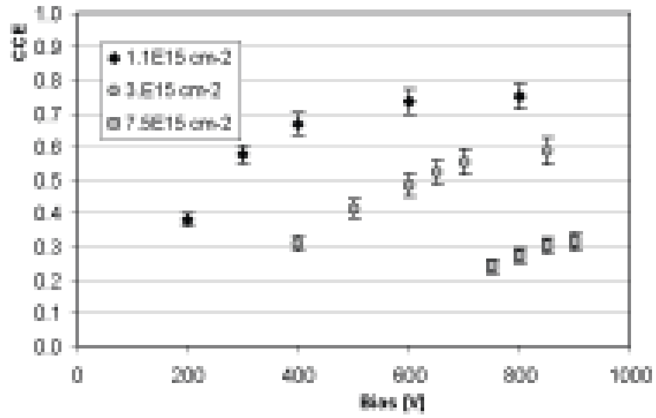
Recent results with n-in-p miniature microstip detectors after heavy proton irradiation

G. Casse – University of Liverpool

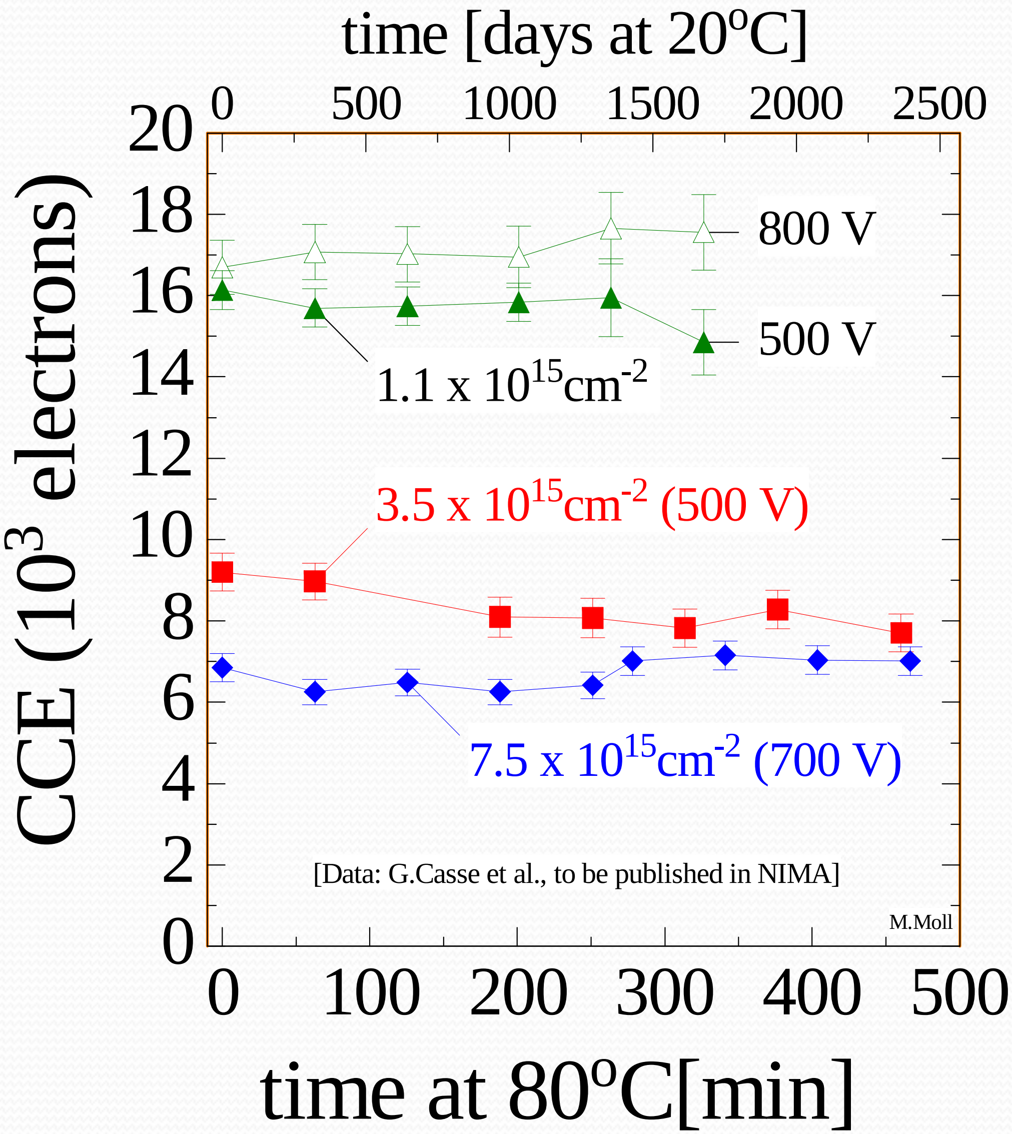
CONCLUSIONS:

Oxygenated p-type substrates have been successfully used to produce miniature microstrip detectors which were able to operate adequately for use as tracking detectors after doses of up to 7.5 10^{15} p cm^{-2}.

Identical devices made with standard p-type silicon were succesfully operated after 3. 10^{15} p cm^{-2}. Further studies are required to investigate whether the oxygenation of p-type substrates brings any advantage, but such detectors appear to be suitable to be used for silicon detectors experiencing extremely high level of hadron radiation.



…Annealing of p-type sensors



- p-type strip detector (280μm) irradiated with 23 GeV p
  (7.5×10^{15} p/cm^2)
- expected from previous CV measurement of V_{dep}:
  - before reverse annealing:

    $V_{dep} \sim 2800$V

  - after reverse annealing

    $V_{dep} > 12000$V

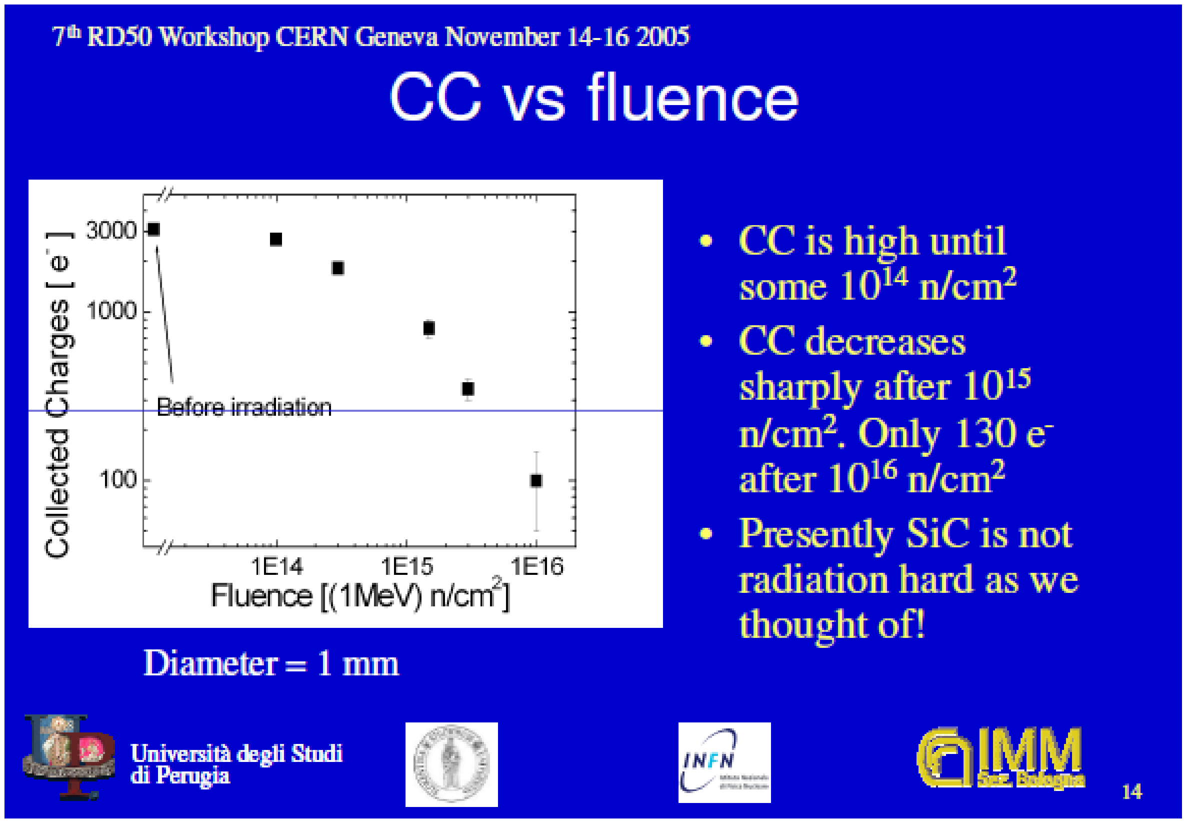
- no reverse annealing visible in the CCE measurement !

G.Casse et al.,10th European Symposium on Semiconductor Detectors, 12-16 June 2005

....New Materials ? No thanks...

Radiation Hardness of Minimum Ionizing Particle Detectors Based on SiC p+n Junctions

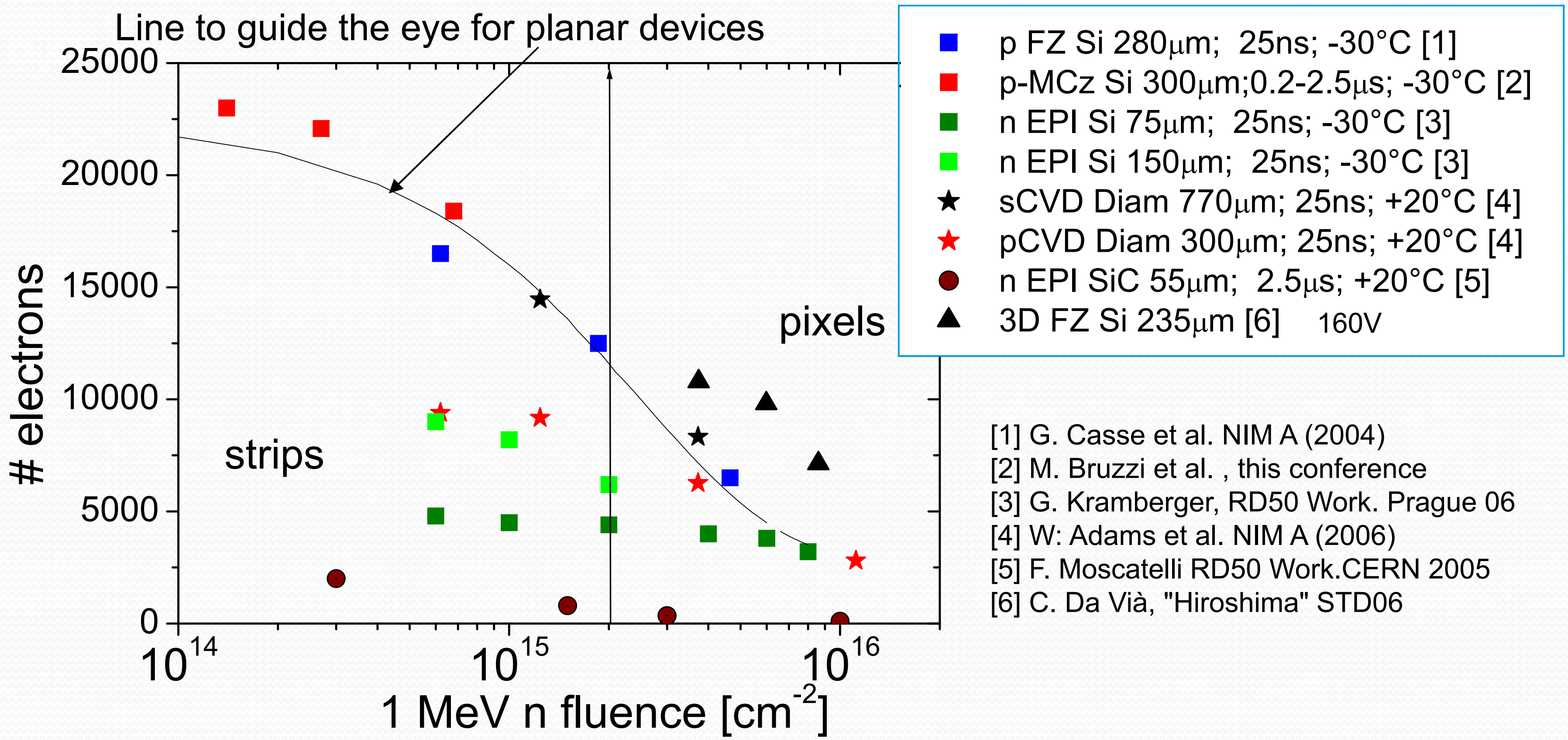
F. Moscatelli, A. Scorzoni,, A. Poggi, M. Bruzzi, S. Sciortino, S. Lagomarsino, G. Wagner and R. Nipoti
DIEI and INFN of Perugia, Italy CNR-IMM of Bologna Italy Dipartimento di Energetica and INFN of Florence, Italy Institut für Kristallzüchtung, Berlin, Germany



7th RD50 - Workshop on Radiation hard semiconductor devices for very high luminosity colliders CERN, 14-16 November, 2005

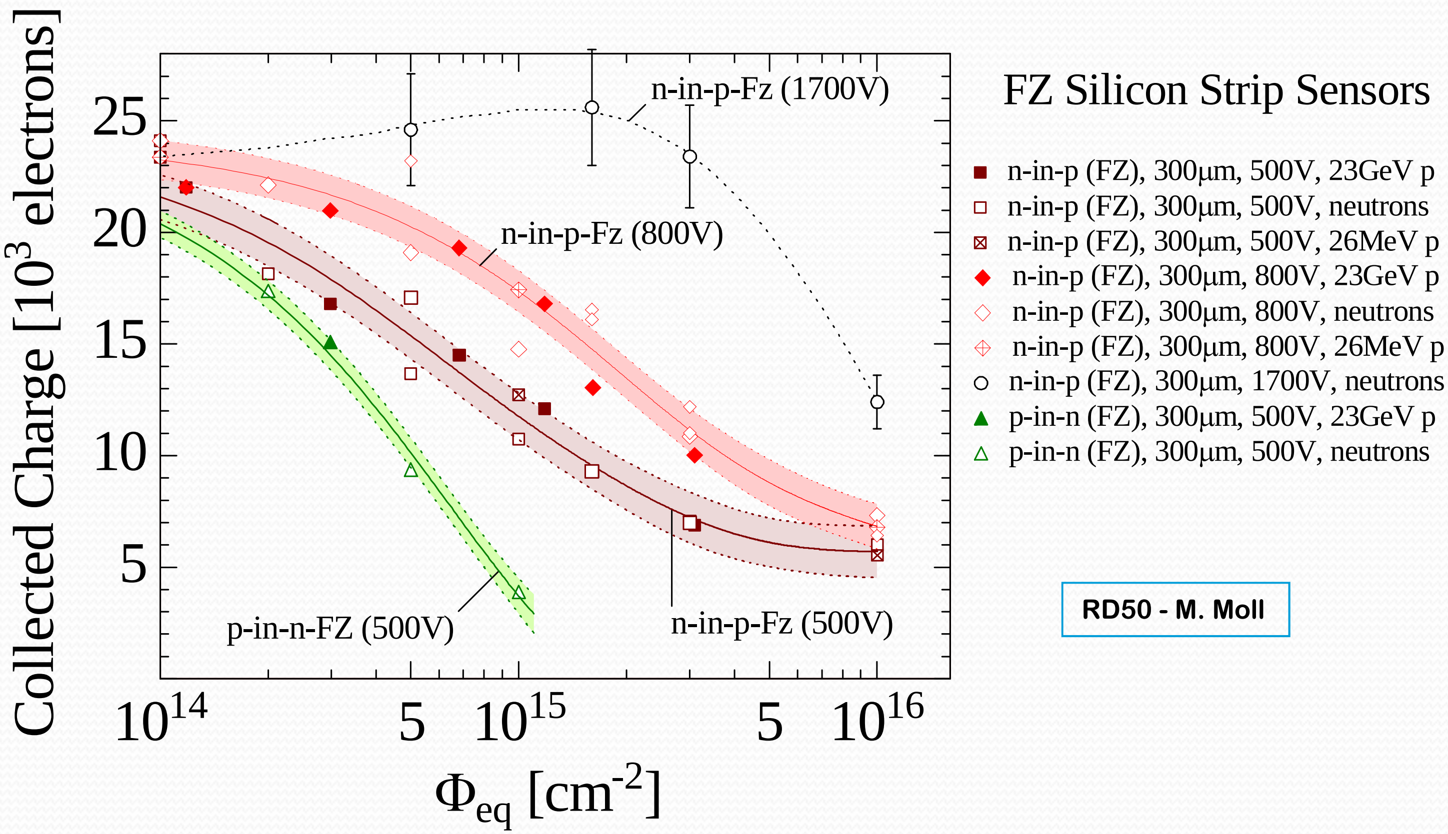
First Planar Detector compilation

Thick p-type planar detectors can work in partial depletion, collected charge higher then 12000e up to $2x10^{15}cm^{-2}$. Highest values of collected dcharge for the 3D Si. Silicon always comparable or even better than diamond in terms of collected charge (BUT leakage current higher for Si).



[1] G. Casse et al. NIM A (2004)
[2] M. Bruzzi et al. , this conference
[3] G. Kramberger, RD50 Work. Prague 06
[4] W: Adams et al. NIM A (2006)
[5] F. Moscatelli RD50 Work.CERN 2005
[6] C. Da Vià, "Hiroshima" STD06

The planar detector compilation today



- p-in-n fades away well before $10^{15} N_{eq}/cm^2$
- n-in-p still gets 50% charge at $10^{16} N_{eq}/cm^2$ at high bias voltages
- n-in-p benefits from charge multiplication (at high bias voltages)
- n-in-p (n-in-n) superior material for high radiation environments

microscopic towards macroscopic

- **2003: Major breakthrough on γ-irradiated samples**
  - **For the first time macroscopic changes of the depletion voltage and leakage current** [APL, 82, 2169, March 2003]
    can be explained by electrical properties of measured defects !
- **2005: Shallow donors generated by irradiation in MCz Si and epitaxial silicon after proton irradiation observed**

Levels responsible for depletion voltage changes after proton irradiation:

Almost independent of oxygen content:

- Donor removal
- "Cluster damage" ⇒ negative charge

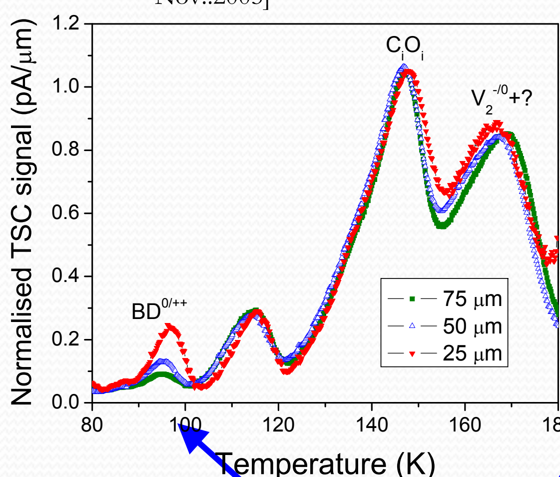
Influenced by initial oxygen content:

- I–defect: deep acceptor level at E_C-0.54eV (good candidate for the V_2O defect) ⇒ negative charge

Influenced by initial oxygen dimer content (?):

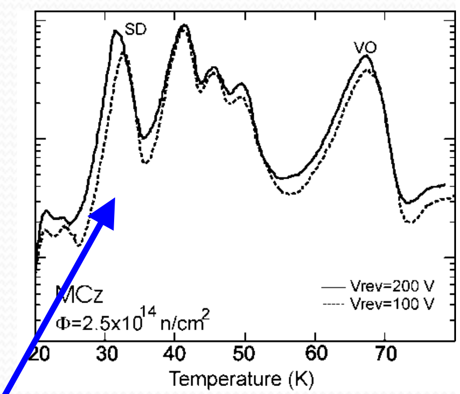
- BD-defect: bistable shallow thermal donor (formed via oxygen dimers O_{2i}) ⇒ positive charge

[G. Lindstroem, RD50 Workshop, Nov..2005]



Epi 50μm 23 GeV p irradiated, Φ=4×10[14] cm[-2]

[D. Menichelli, RD50 Workshop, Nov..2005]



MCz n-type 26 MeV p irradiated, $\Phi=4\times10^{14}$ cm^{-2}

BD-defect

The WODEAN Working group

WODEAN (WOrkshop on DEfect ANalysis),
1st meeting in Hamburg, 23-25 August 2006
idea triggered by Gordon Davies' talk at RD50, CERN, Nov. 2005
we need all available tools (not only DLTS, TSC)
for thorough defect analysis and possible defect engineering

11th RD50 workshop - CERN 12/13-November-07

Outline of Correlated Project

- **Main issue:**
  Φ_{eq} to be tolerated in S-LHC: 1.5E16 n/cm².
  charge trapping: ultimate limitation for detector applications
  responsible trapping source: so far unknown!
- **Charge trapping:**
  independent of material type (FZ, CZ, epi) and properties (std, DO, resistivity, doping type).
  independent of irradiating particle type and energy (23 GeV protons, reactor neutrons), if Φ normalised to 1 MeV neutron equivalent values (NIEL).
  In contrast to I_{FD} and N_{eff} there are only small annealing effects (as studied up to T = 80°C)
- **Correlated project:**
  use all available methods:
  DLTS, TSC, PITS, PL, τ_{recomb}, FTIR, PC, EPR, diode C/V, I/V and TCT
  concentrate on single material only: MCz chosen with extension to std. FZ for checking of unexpected results (FZ supposed to be cleaner, MCz has larger O concentration)
  Use only one type of irradiation, most readily available (TRIGA reactor at Ljubljana) and do limited number of Φ steps between 3E11 and 3E16 n/cm² (same for all methods!)
  Use same isothermal annealing steps for all methods
  Reach first results within one year

Main Defects Affecting the Device Properties

Point defects

- $E_i^{BD} = E_c - 0.225$ eV
- $\sigma_n^{BD} = 2.3 \cdot 10^{-14}$ cm^2

- $E_i^{I} = E_c - 0.545$ eV
  - $\sigma_n^{I} = 1.7 \cdot 10^{-15}$ cm^2
  - $\sigma p^{I} = 9 \cdot 10^{-14}$ cm^2

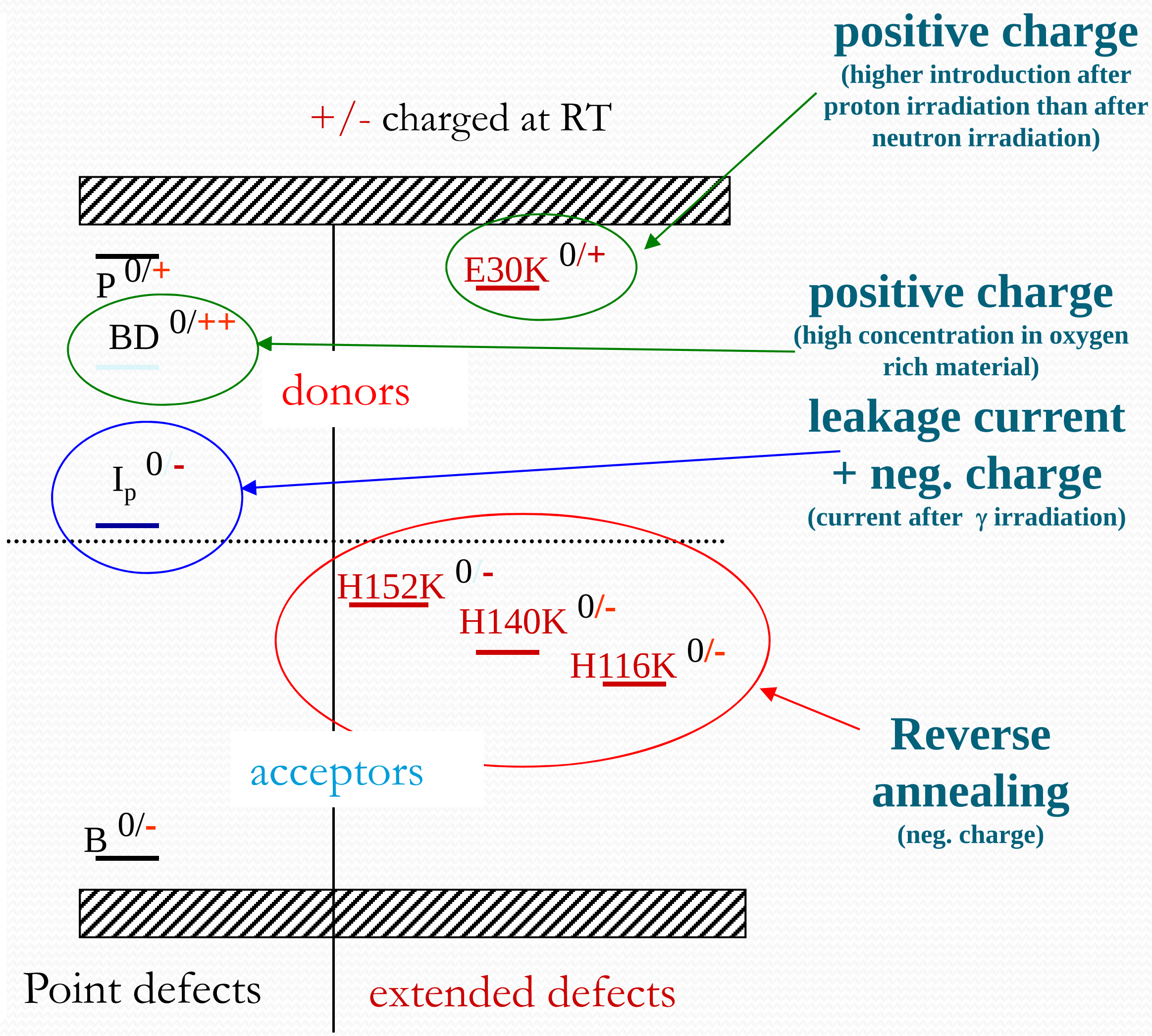
Cluster related centers

- $E_i^{116K} = E_v + 0.33$eV
- $\sigma_p^{116K} = 4 \cdot 10^{-14}$ cm^2

- $E_i^{140K} = E_v + 0.36$eV
- $\sigma_p^{140K} = 2.5 \cdot 10^{-15}$ cm^2

- $E_i^{152K} = E_v + 0.42$eV
- $\sigma_p^{152K} = 2.3 \cdot 10^{-14}$ cm^2

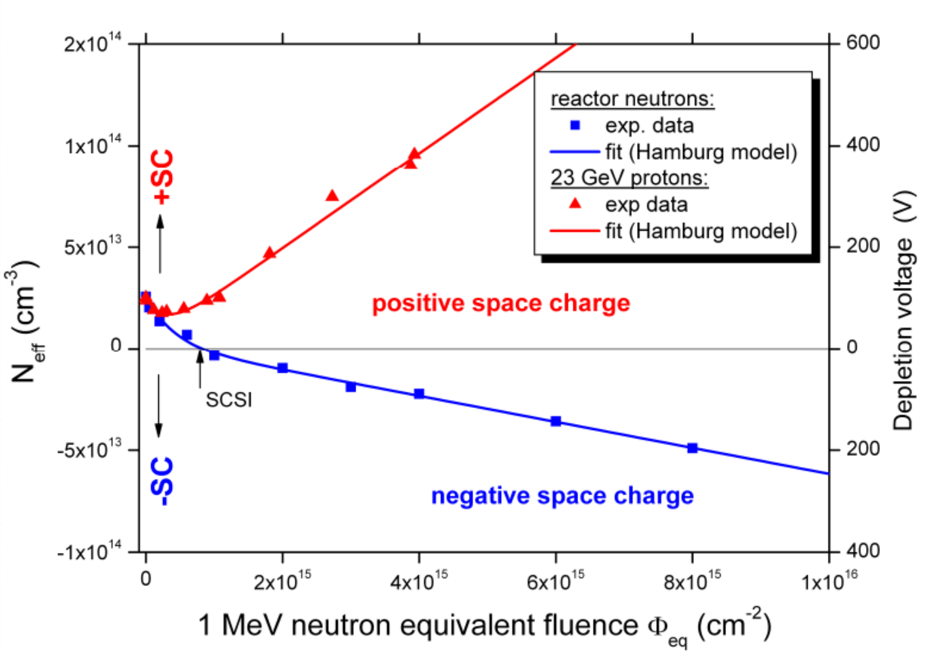
- $E_i^{30K} = E_c - 0.1$eV
- $\sigma_n^{30K} = 2.3 \cdot 10^{-14}$ cm^2

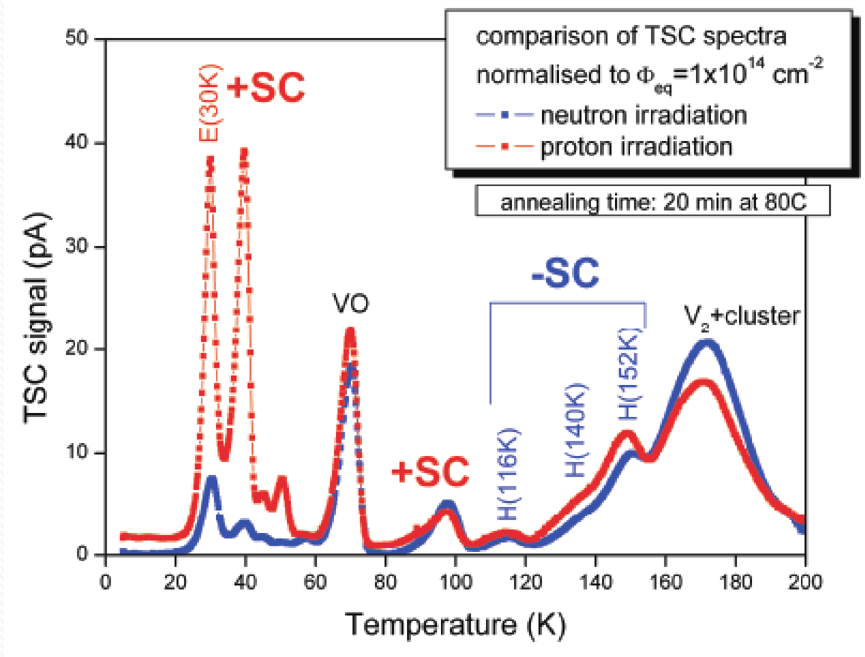


[I.Pintilie et al., Appl. Phys. Lett.92 024101,2008]

N_{eff} changes explained with TSC

Epi-Si irradiated with 23 GeV protons and reactor neutrons



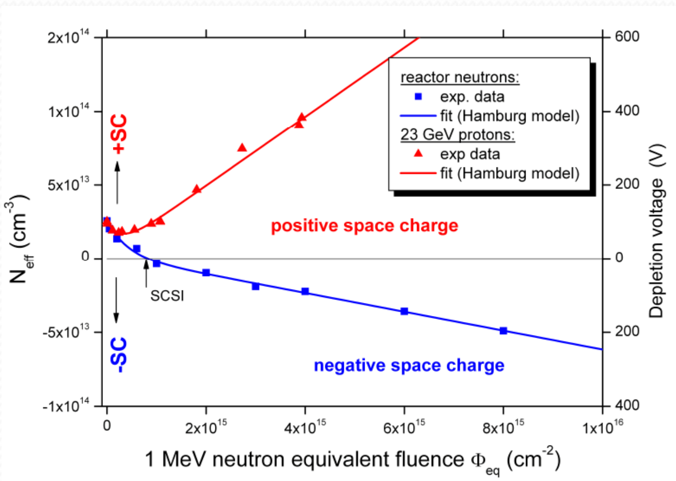


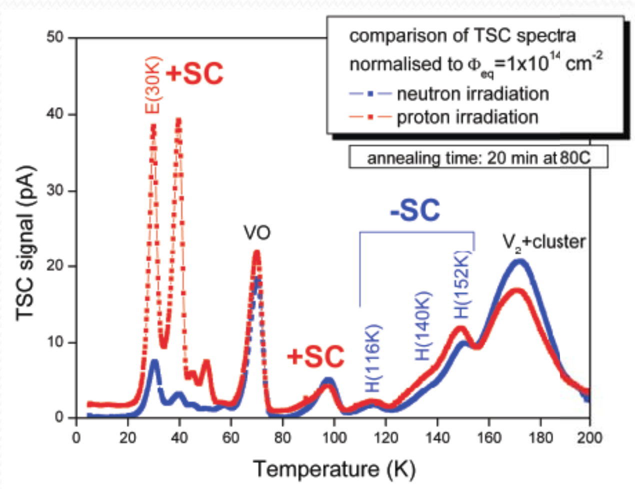
- SCSI "Type Inversion" after neutrons but not after protons
- donor generation enhanced after proton irradiation

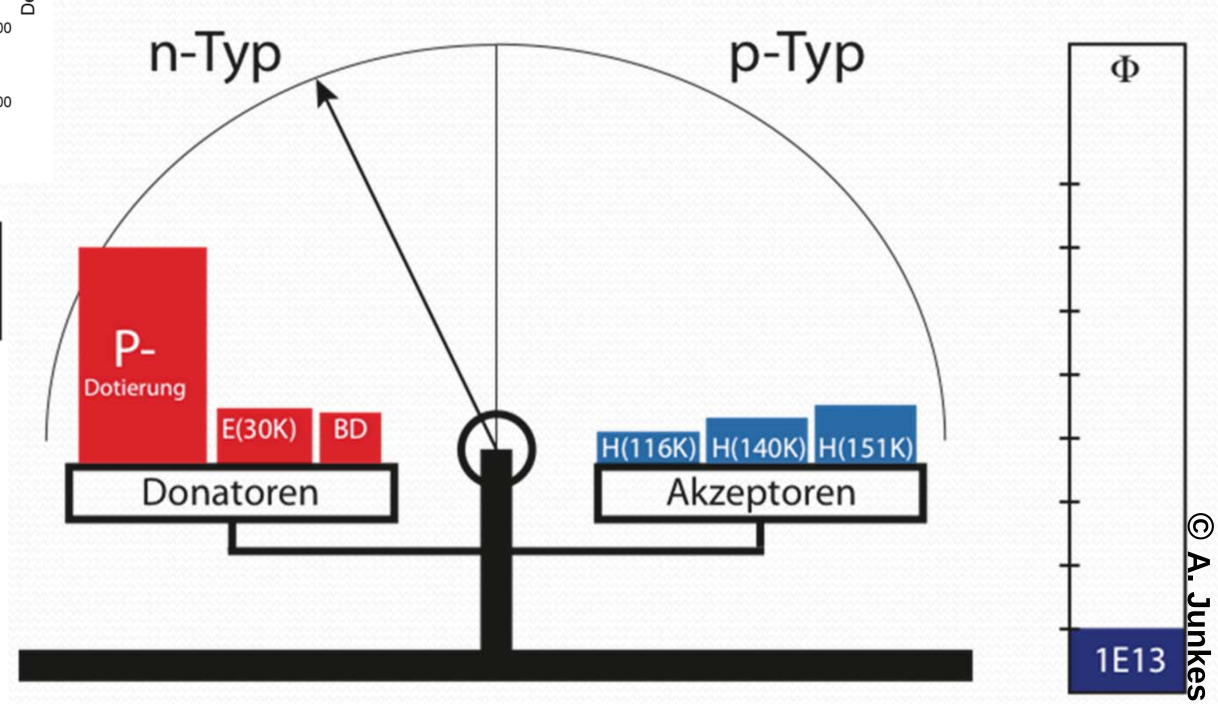
[Pintilie, Lindstroem, Junkes, Fretwurst, NIM A 611 (2009) 52–68]

N_{eff}: Neutron irradiation

Epitaxial silicon (*EPI-DO, 72µm, 170Ωcm, diodes)* irradiated with reactor neutrons







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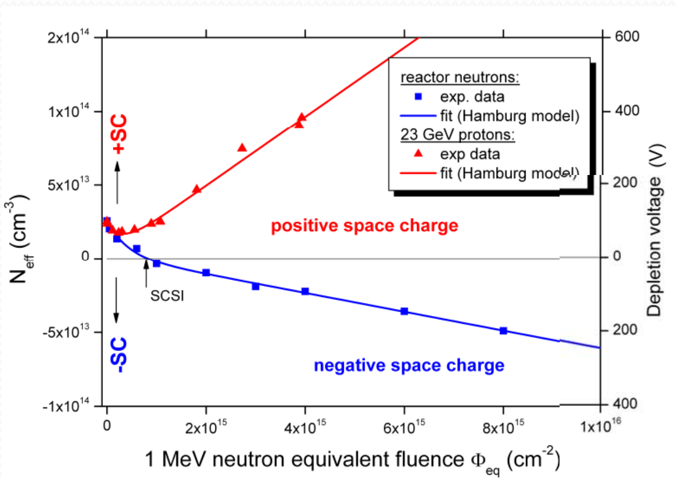
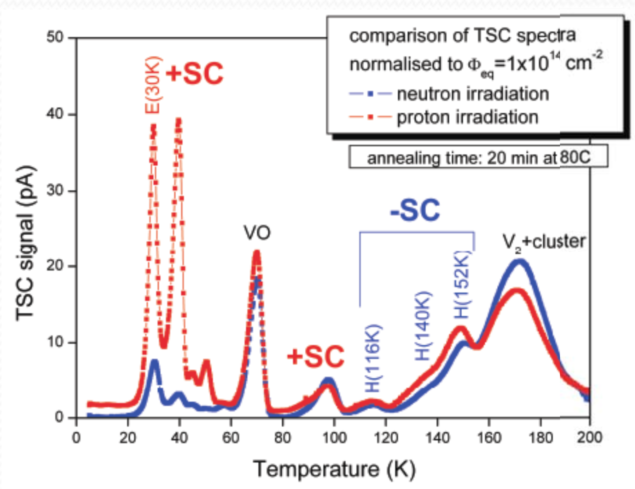
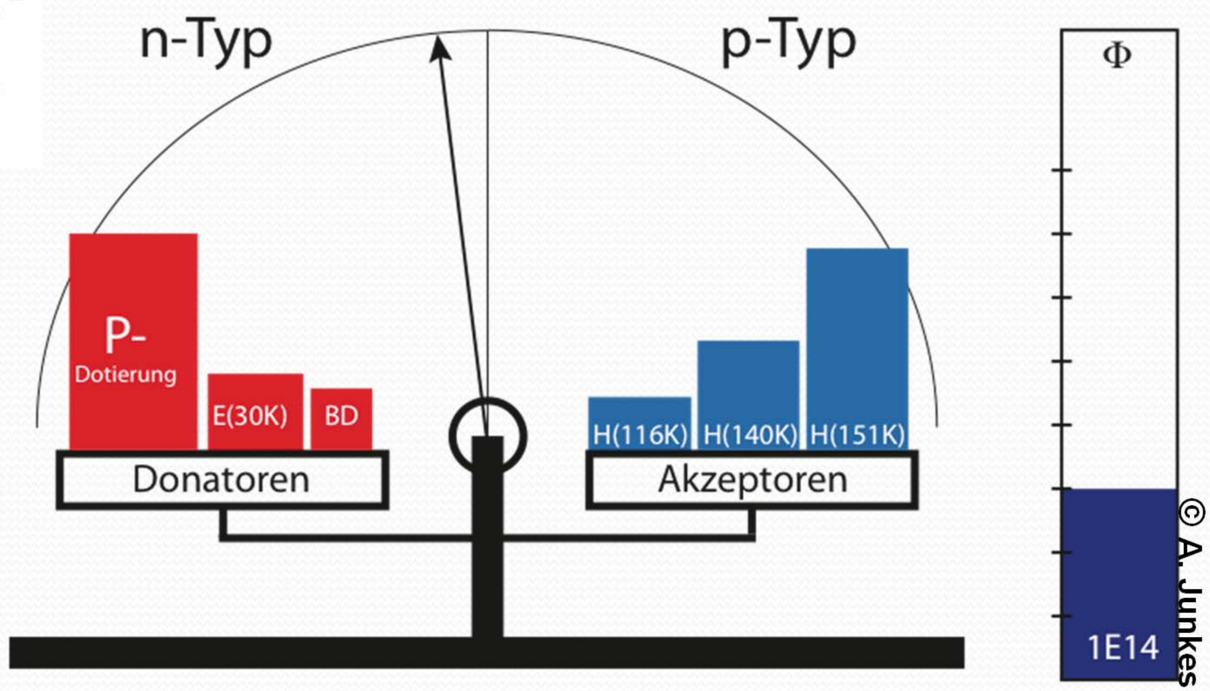
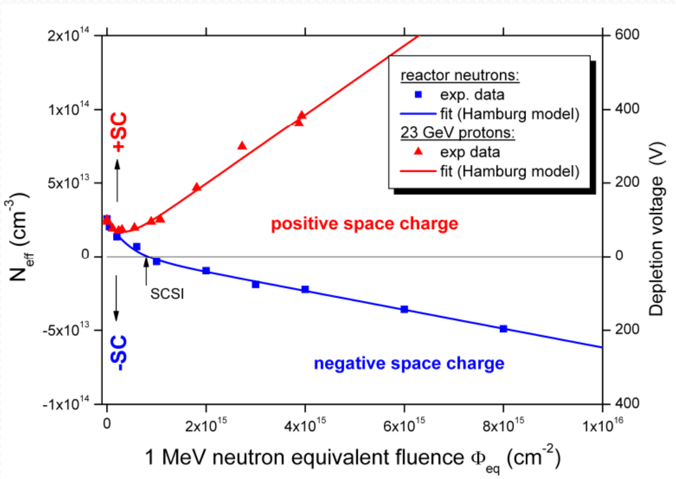


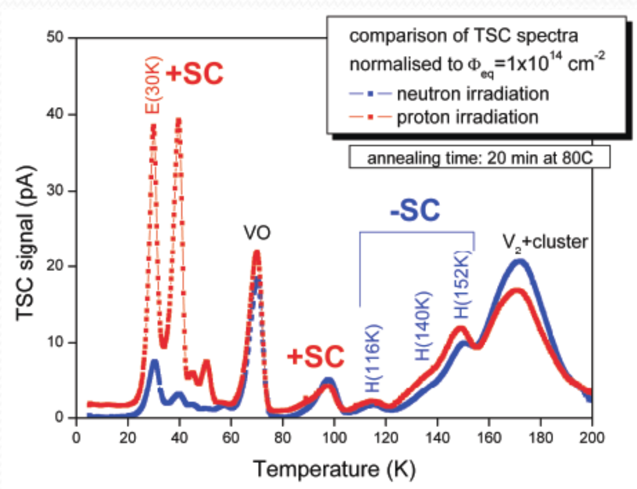


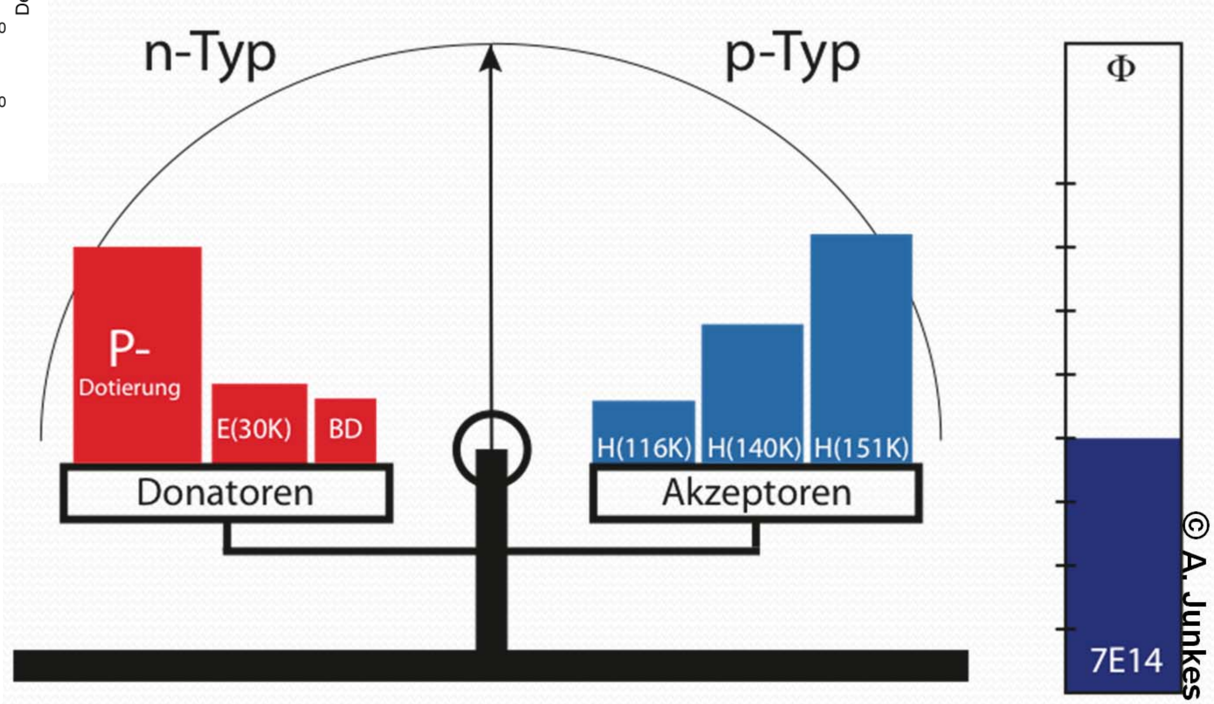


N_{eff}: Neutron irradiation



Epitaxial silicon (*EPI-DO, 72µm, 170Ωcm, diodes)*
irradiated with reactor neutrons





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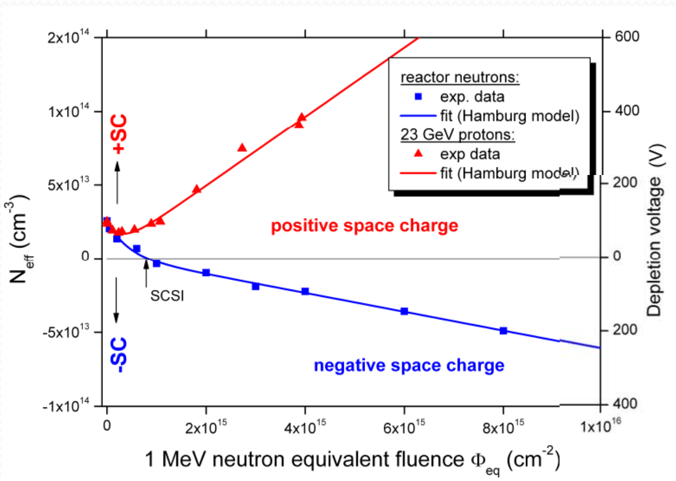
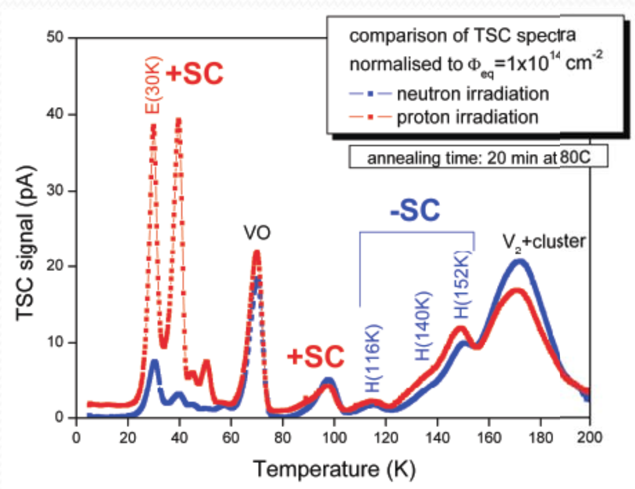
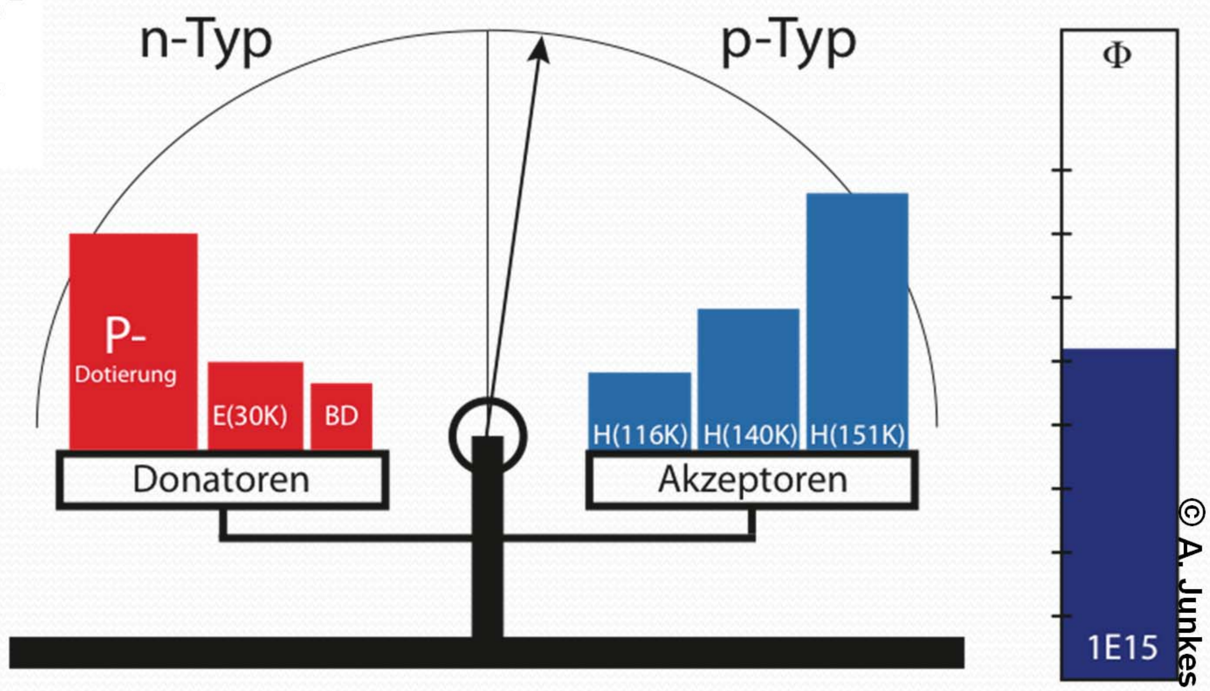
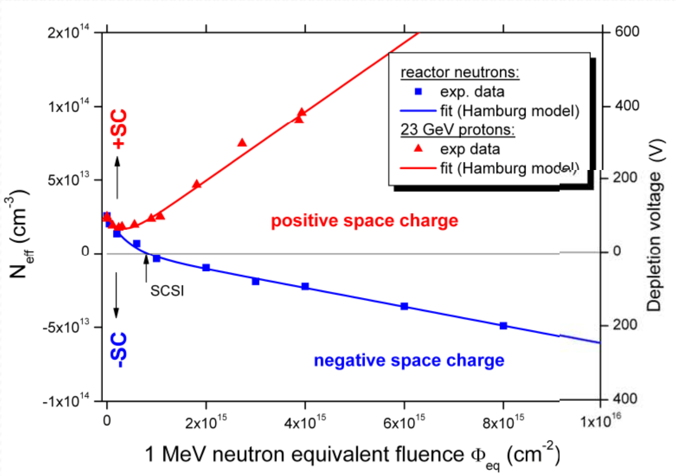


Epitaxial silicon (*EPI-DO, 72µm, 170Ωcm, diodes)* irradiated with reactor neutrons





N_{eff}: Neutron irradiation



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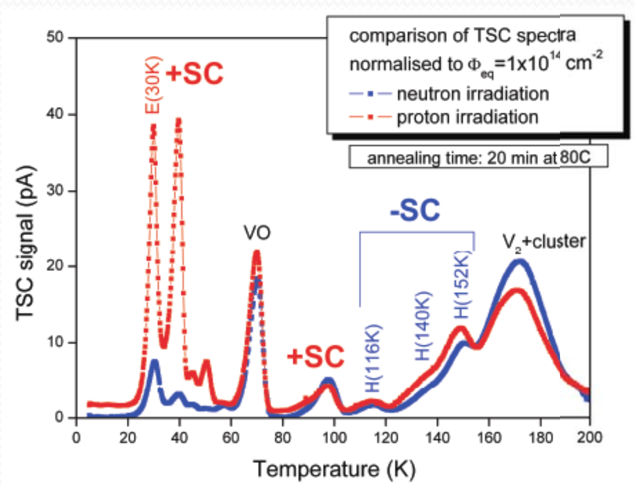
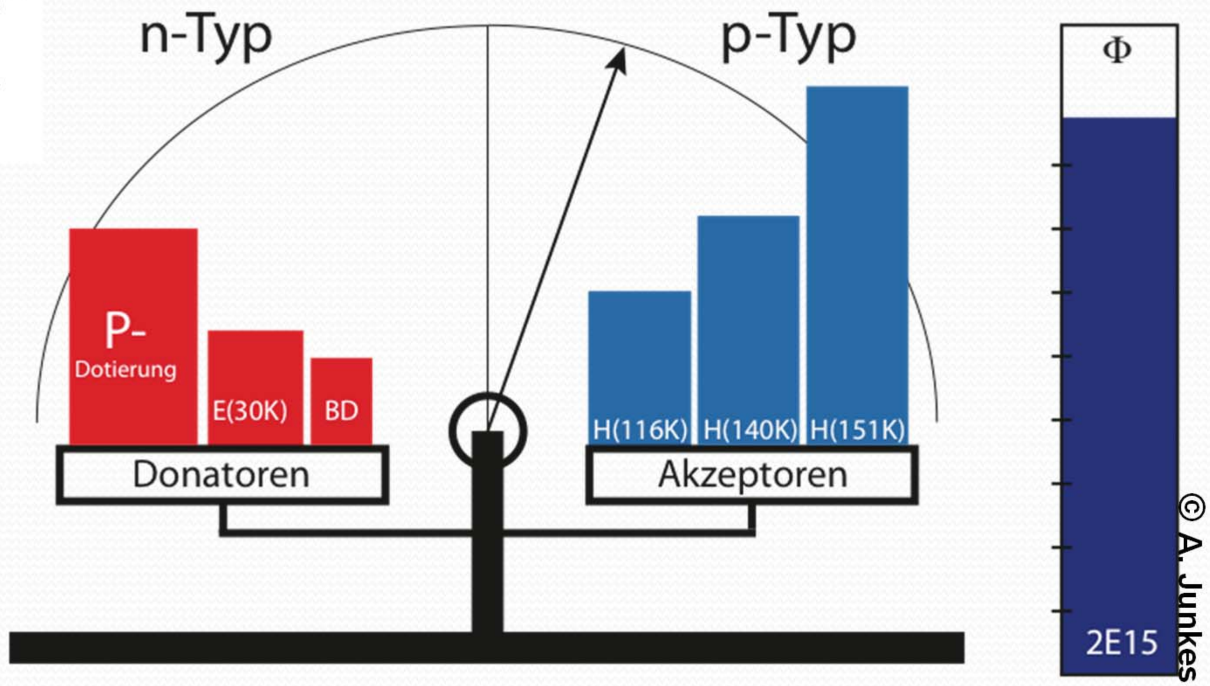
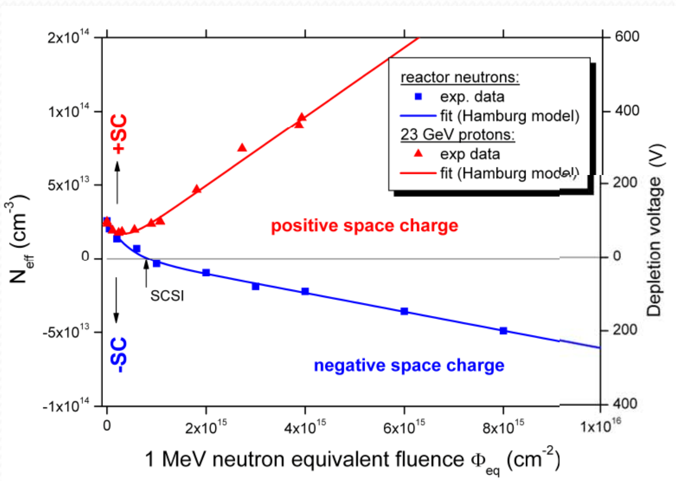
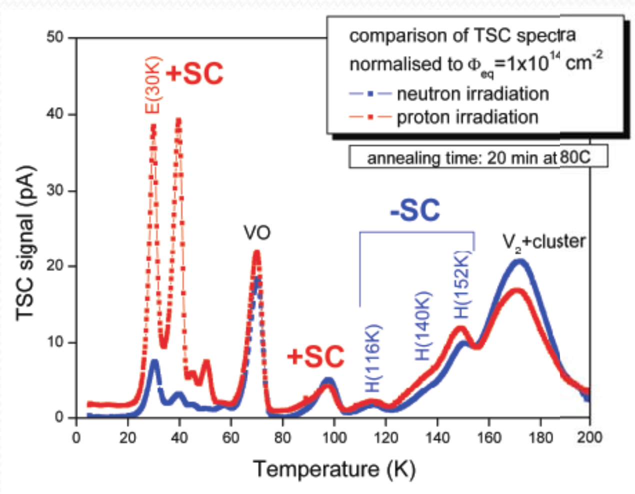


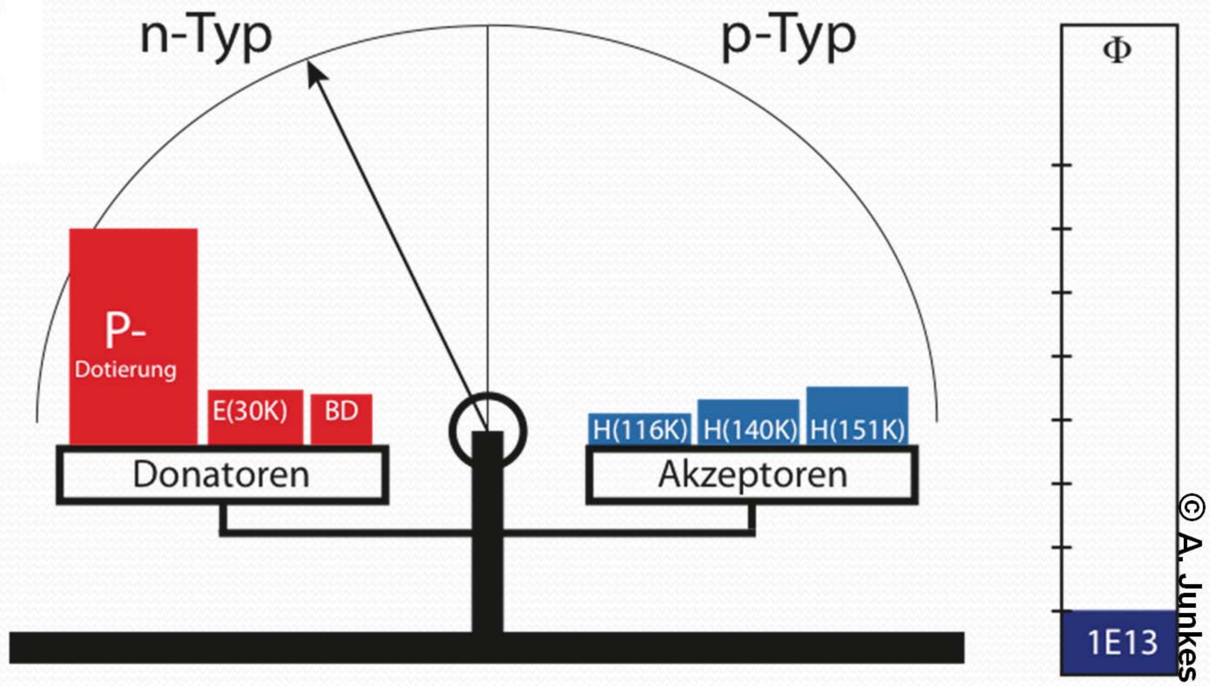


N_{eff}: Proton irradiation

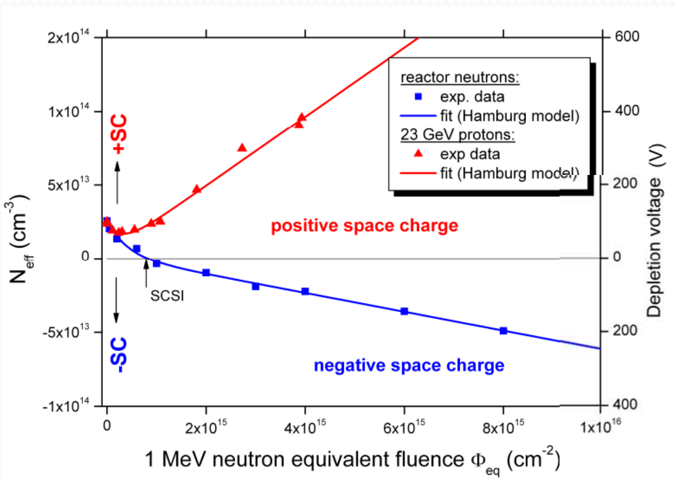




Epitaxial silicon (*EPI-DO, 72µm, 170Ωcm, diodes)*
irradiated with 23 GeV protons



N_{eff}: Proton irradiation



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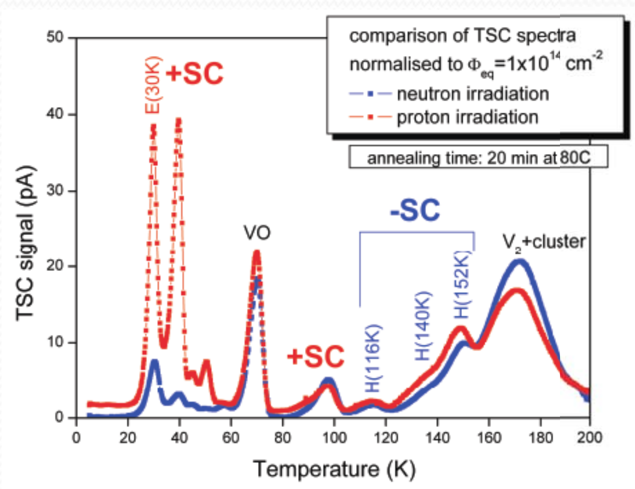

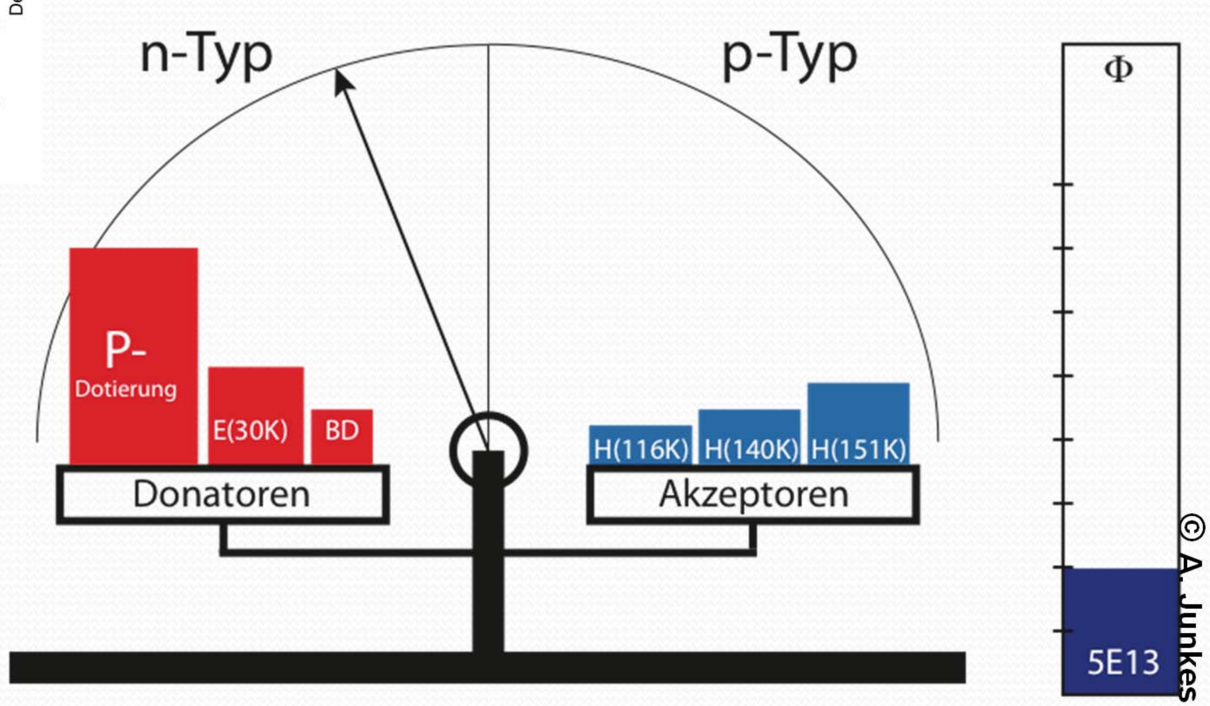

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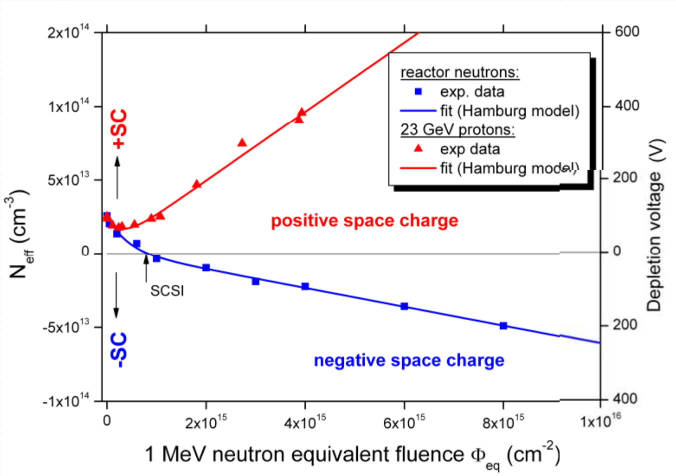

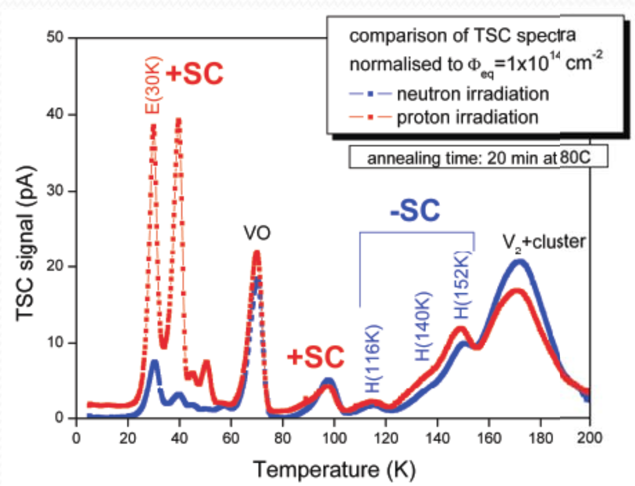

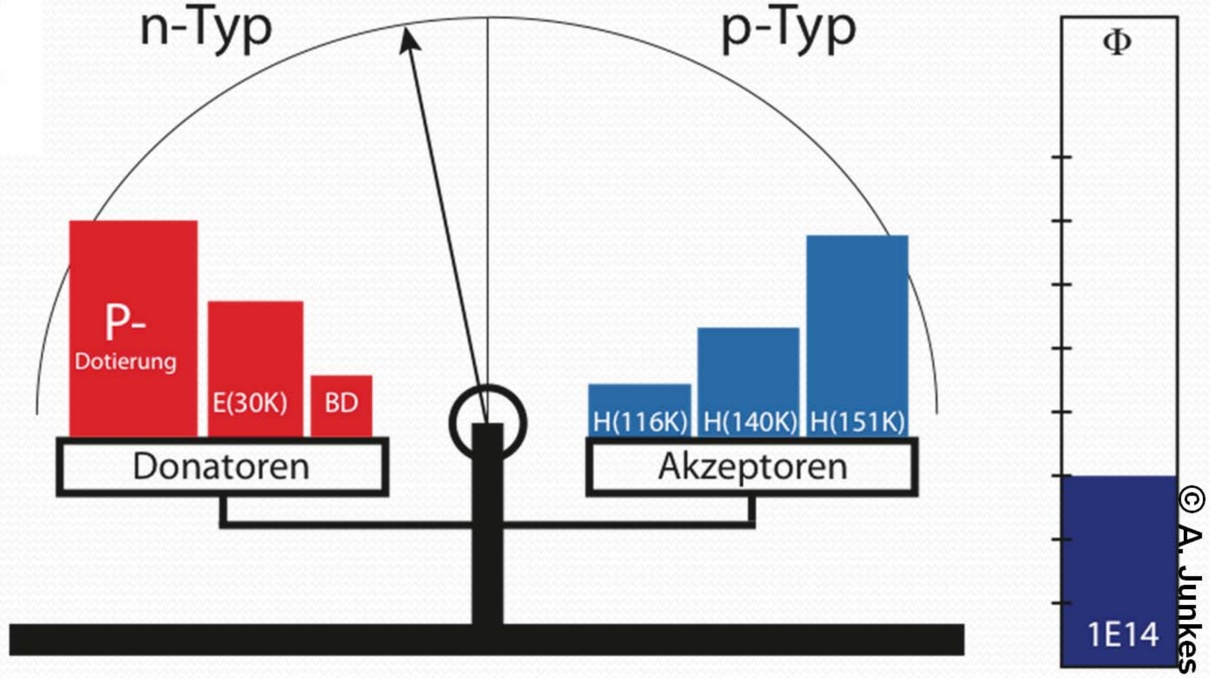

N_{eff}: Proton irradiation

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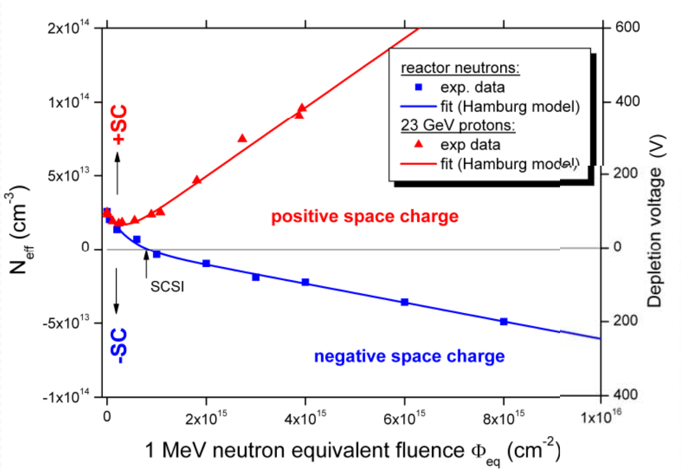

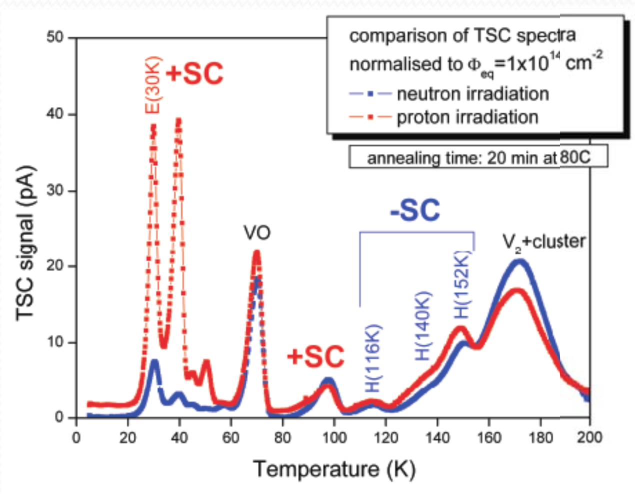

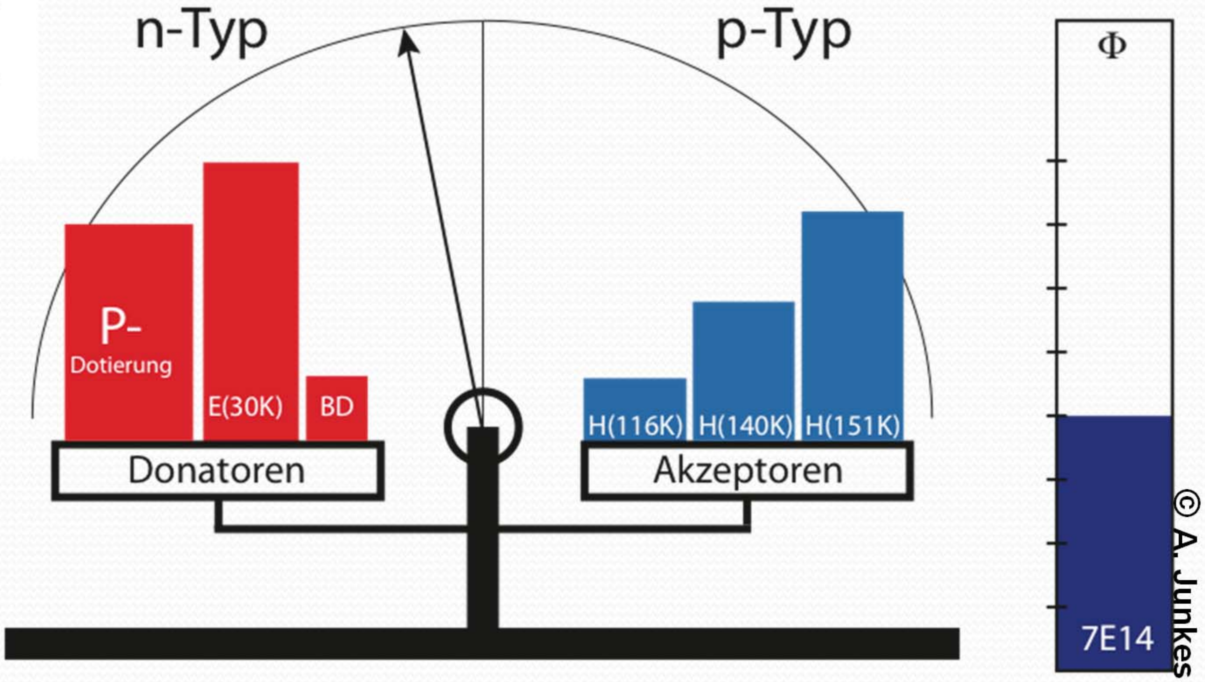

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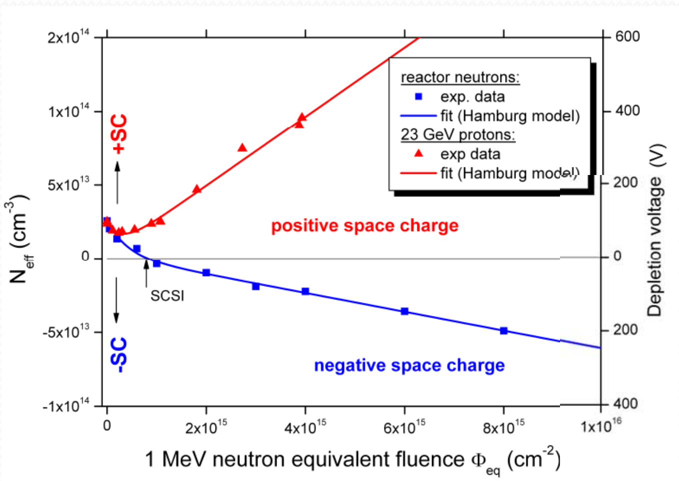

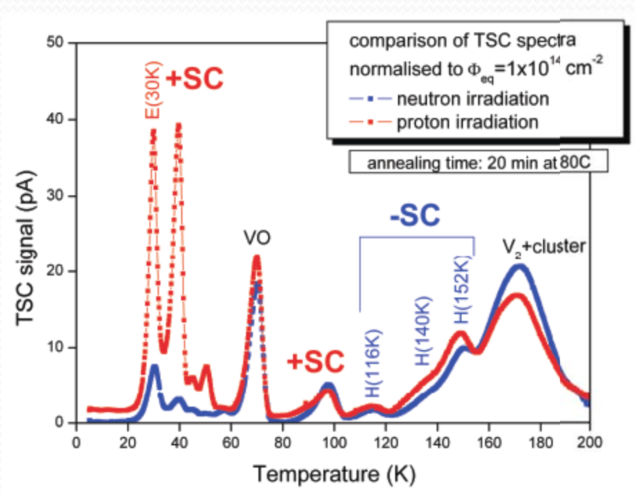

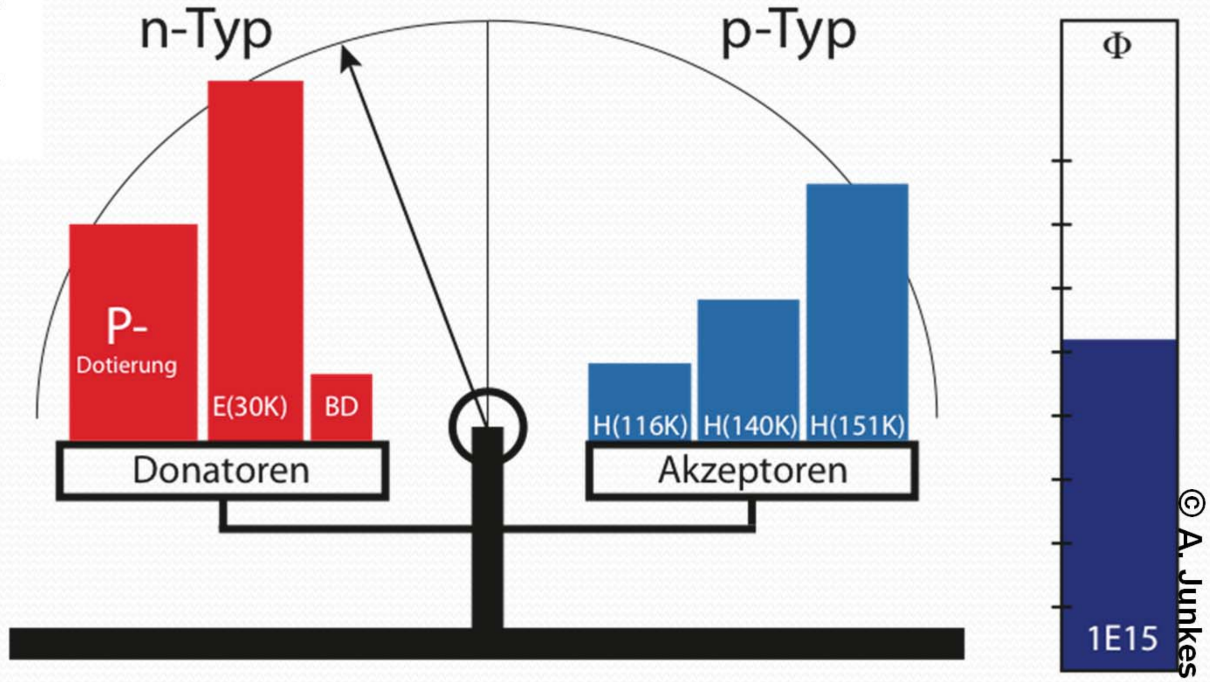

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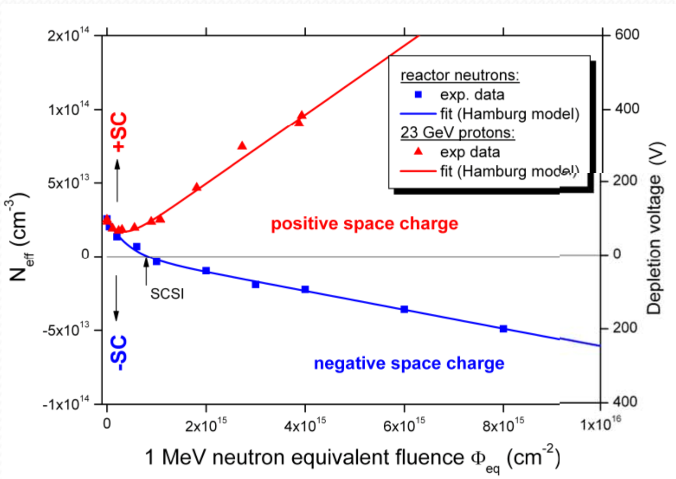

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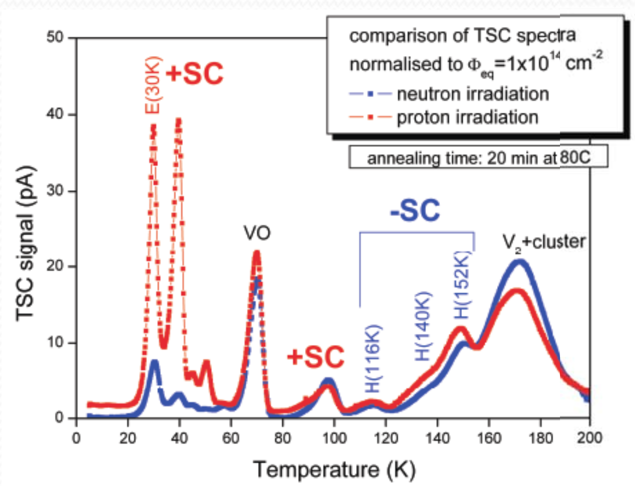
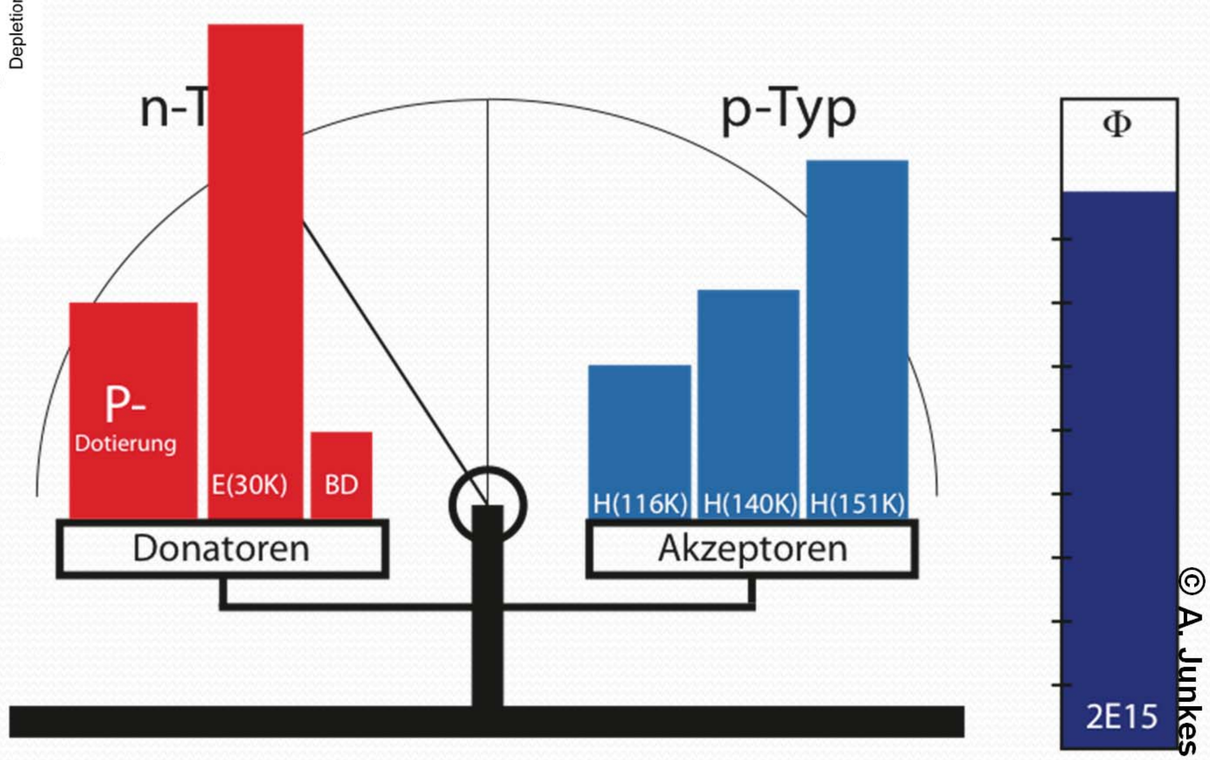
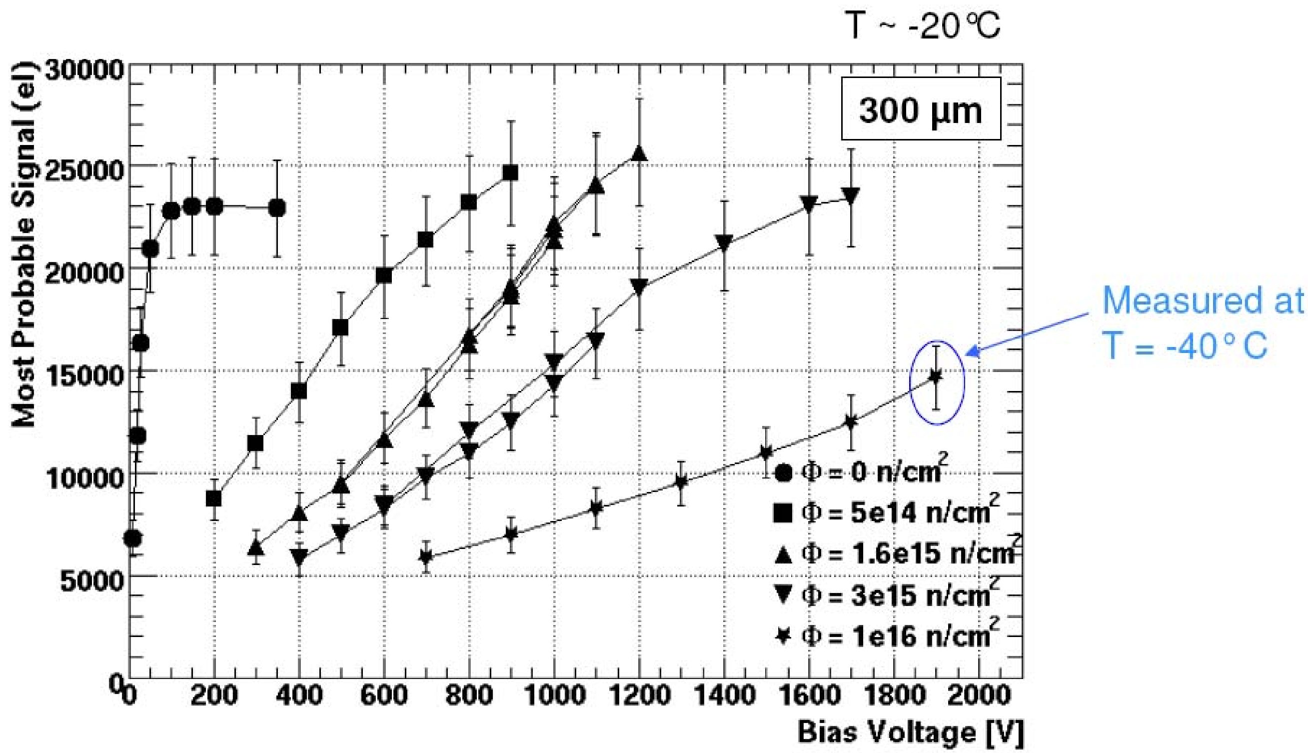




Charge Multiplication

CCE measured with p-type Si microstrip detectors at very high fluences shows evidence of a charge multiplication effect: 100% CCE seen after 3×10^{15} n/cm^2, 15000 electrons after 10^{16}n/cm^2

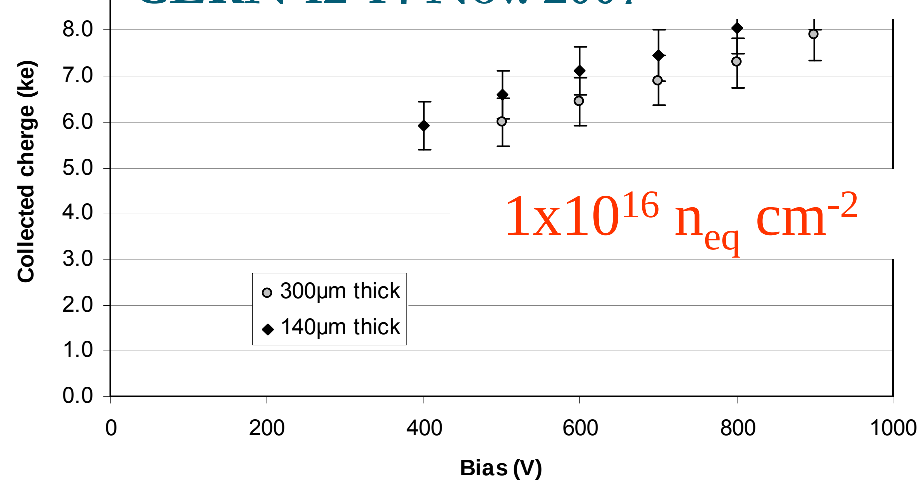


Increase of the electric field close to the strips causing impact ionization/carrier injection when high concentrations of effective acceptors are introduced at very high fluences.

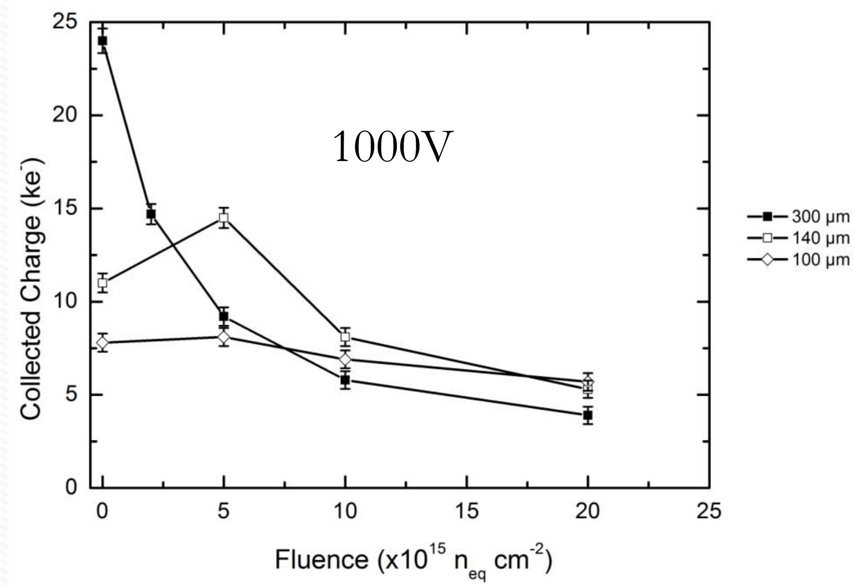
.. thin detectors

Choice of optimal thickness can be dictated by the need of reducing the detector mass rather than increase of the signal after irradiation (at least up the remarkable dose of $1x10^{16}$ n cm^{-2}!!).

G. Casse 11^{th} RD50 Workshop, CERN 12-14 Nov. 2007



G. Casse,20th RD50 Workshop, Bari 31/05-02/06 2012

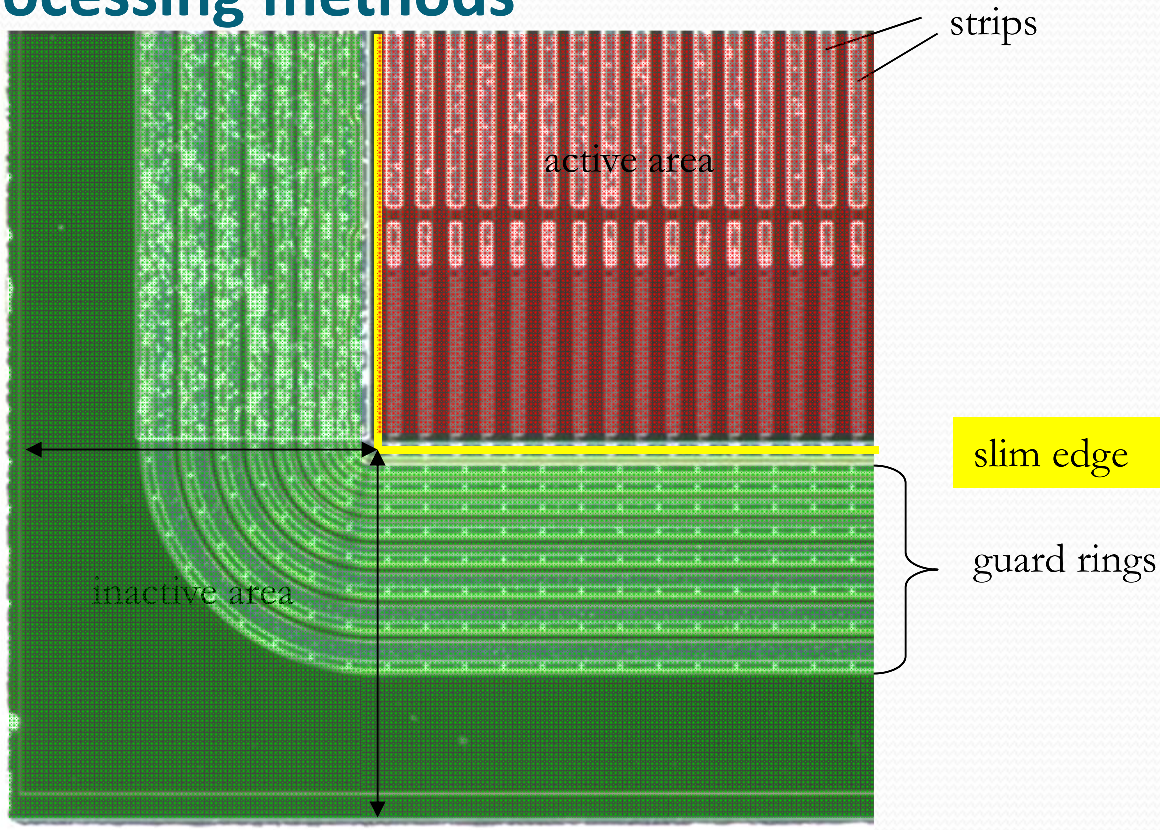


For modelling see E. Verbitskaya talk, this conference

On going common RD50 Projects

Common RD50 Projects - 2011
Development of "slim edges" using cleaving and ALD processing methods

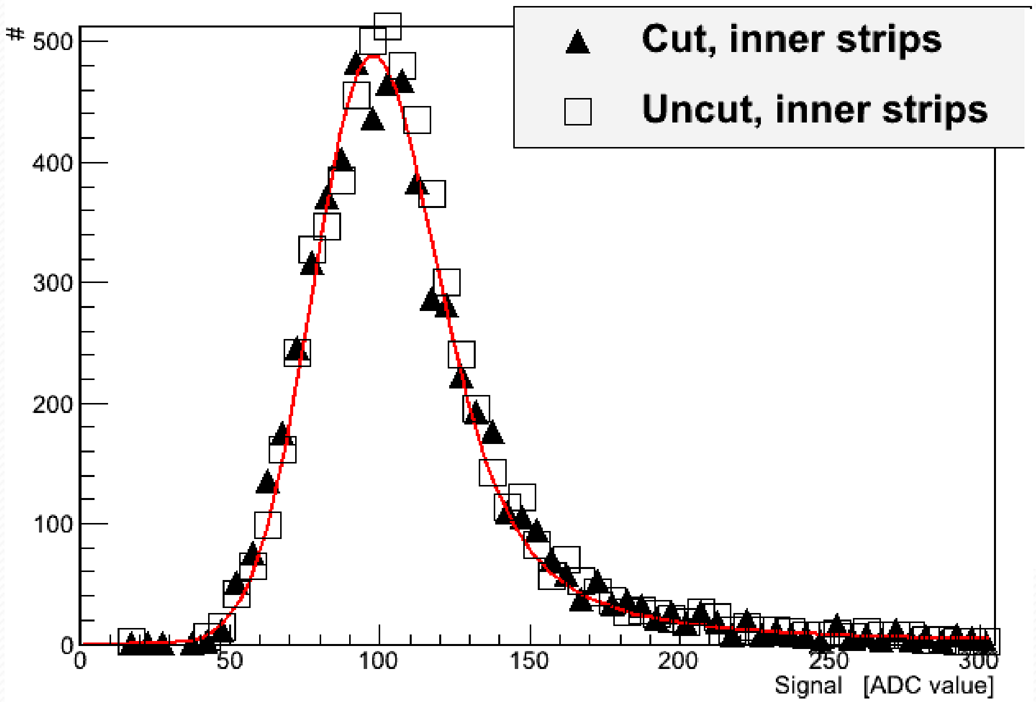
Conventional planar silicon detectors are characterized by insensitive border regions, of typically 1 mm width, occupied by guard-ring structures used to gradually reduce the voltage applied to the detector sensitive-area, or by implants reducing the voltage drop across the edge. Slim-edge detectors with a minimized dead border width would be very useful in many applications.

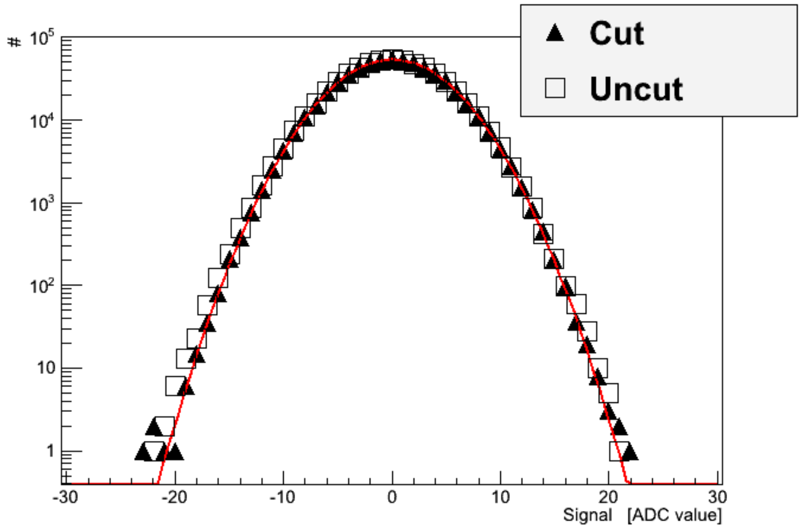


Optical micrograph

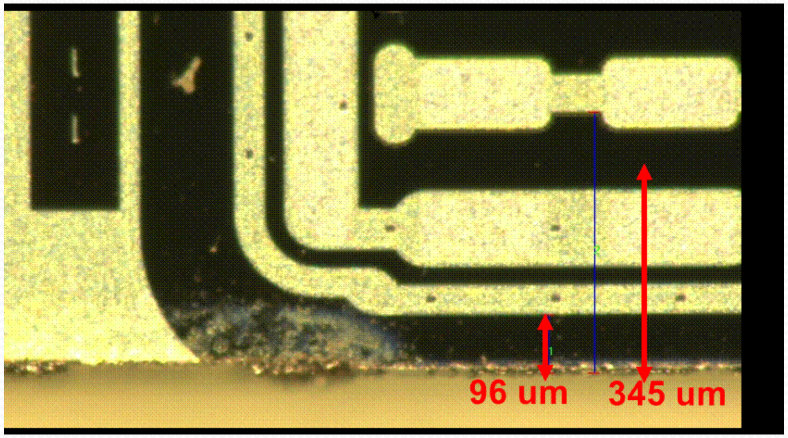
See H. Sadrozinski talk, this conference

Charge collection and noise measurements





The signal from a beta source before and after cutting is the same within 4%. The noise on all strips, including the one adjacent to the slim edge, is not changed by the cut.



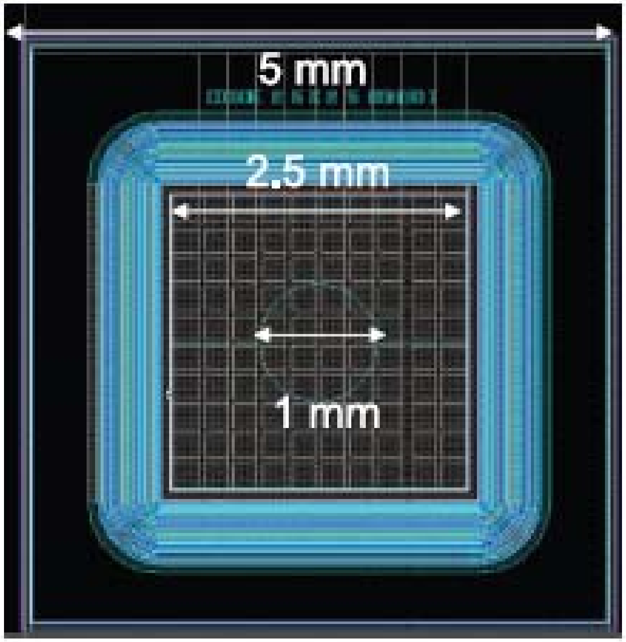
Production of n-in-p structures at CiS – 6"

n-in-p diodes with multi-guard rings (active side 2.5 mm or 5.0 mm)

- Characterization of trap parameters of main radiation induced defects with spectroscopic methods as DLTS, TSC, HRPITS (High Resolution Photo Induced Spectroscopy), EPR (Electron Paramagnetic resonance), FTIR (Fourier Transform InfraRed), PL (PhotoLuminescence).

- Understanding of their charge state under operation as well as on electric field profile with TCT (Transient Current Technique), Edge TCT, Photoconductivity decay.

- Cross-correlation of results got with different techniques and cross-links with simulation to get a detailed knowledge on radiation hardness of n-on-p devices and understanding of charge multiplication effects.



Common RD50 Project 2012: G. Pellegrini et al.: Fabrication of new p-type strip detectors with trench to enhance charge multiplication effect in the n-type electrodes

- Up to now, semiconductor sensors have supplied precision data only for the 3 space dimensions (diodes, strips, pixels, even "3D"), while the time dimension has had limited accuracy (e.g. to match the beam structure in the accelerator).
- We believe that being able to resolve the time dimension with ps accuracy would open up completely new applications not limited to HEP
- Proposal: Combined-function pixel detector will collect electrons from thin n-on-p pixel sensors read out with short shaping time electronics
- Charge multiplication with gain *g* increases the collected signal
- Need very fast pixel readout

Ultra Fast Silicon Detectors (UFSD) Pixel Collected Charge

Signal = thickness*EPM

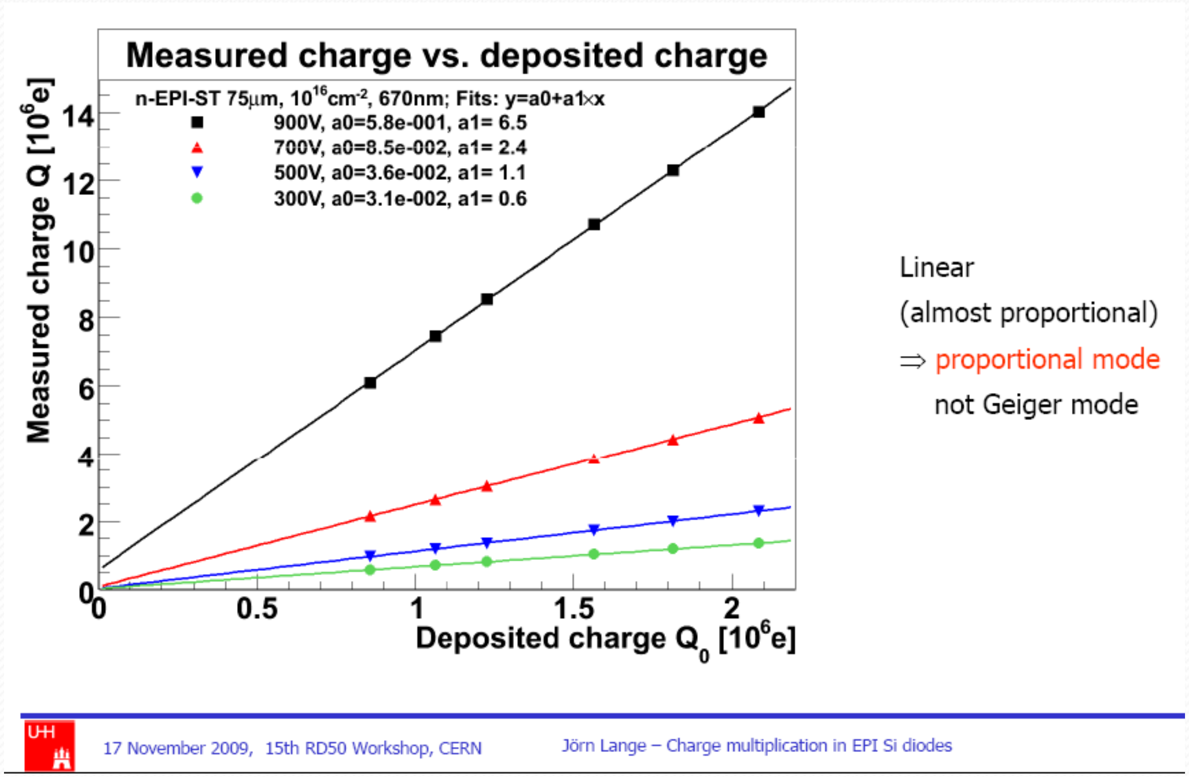
Collection time = thickness/vsat (vsat = 80μm/ns)

Thickness [um]	BackPlane Capacitance [fF]	Signal [# of e-]	Coll. Time [ps]	Gain req. for 2000 e	
0.1	2500	8.3	1.3	241.0	Realistic gain & cap
1	250	83	12.5	24.1	
2	125	166	25.0	12.0	↓
5	50	415	62.5	4.8	
10	25	830	125.0	2.4	↑
20	13	1660	250.0	1.2	Good time resolution
100	2.5	8300	1250.0	0.2	
300	0.8	24900	3750.0	0.1	

For thickness > 5 um, Capacitance to the backplane Cb << Cint

For thickness = 2 um, Cb ~ ½ of Cint, and we might need bipolar (SiGe)?

Problem: non-uniform E-Field across a pixel/strip results in charge collection difference. Diode is characterized by uniform field. Example: Epitaxial Si



Epi, short drift distances and planar diode gives g = 6.5

Early results: see Poster on on 4D - UFSD this conference

Conclusions

- RD50 working across experiment boundaries on developing radiation-hard silicon detectors for e.g. the HL-LHC : 10 years activity !!
- Large progress in understanding macroscopic damage with microscopic studies
- Planar detectors do better than expected
  - P-type detectors reduce trapping effects and can operate partially depleted
  - Significant electric field exists in undepleted region
  - Charge multiplication gives extra signal

- HL-LHC Si detector recommendations:
- N-in-p (n-in-n) planar detectors
  - good enough for most regions, well understood, expect this to be the default material at HL-LHC
- 3D detectors (not covered in this presentation)
  - could add extra radiation hardness and facilitate operation at lower voltage if required for innermost HL-LHC tracking layer(s)
  - watch out for extra costs and risks