IWORID 04, Glasgow 25 – 29th July 2004,
Sixth International Workshop on Radiation Imaging Detectors

Recent Developments on Radiation Hard Semiconductor Detectors for SuperLHC

- CERN-RD50 project -

Michael Moll

on behalf of RD50
CERN - Geneva - Switzerland

OUTLINE

- **Motivation to develop radiation harder detectors**
- **The RD50 collaboration**
- **Radiation Damage – a very brief review**
- **Approaches to obtain radiation hard sensors**
  - **Material engineering**
  - **Device engineering**
- **Summary**

http://www.cern.ch/rd50

Motivation

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

LHC: L = 10^{34}cm^{-2}s^{-1} $\xrightarrow{\text{10 years}}$ **f(R=4cm) ~ $3\cdot10^{15}$cm^{-2}**
f(R=75cm) ~ $3\cdot10^{13}$cm^{-2}

´ 5

⇨ Technology available ⇨ However, serious radiation damage!

S-LHC: L = 10^{35}cm^{-2}s^{-1} $\xrightarrow{\text{5 years}}$ **f(R=4cm) ~ $1.6\cdot10^{16}$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.

RD50

The CERN RD50 Collaboration

http://www.cern.ch/rd50

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

- 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)

Approaches of RD50 to develop radiation harder tracking detectors

Scientific strategies:

I. **Material engineering**

II. **Device engineering**

III. **Variation of detector operational conditions**

CERN-RD39
"Cryogenic Tracking Detectors"
http://cern.ch/rd39

Defect Engineering of Silicon

- **Understanding radiation damage**
  - **Macroscopic effects and Microscopic defects**
  - *Simulation of defect properties and defect kinetics*
  - *Irradiation with different type of particles at different energies*
- **Oxygen enriched silicon**
  - **DOFZ – Diffusion Oxygenated Float Zone Silicon**
  - **Cz - Czochralski Silicon**
  - **MCZ - Magnetic Czochralski**
  - **EPI – Epitaxial silicon grown on CZ substrate**
- *Oxygen dimer enriched silicon*
- *Hydrogen enriched silicon*
- *Pre-irradiated silicon*

New Materials

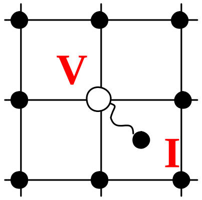
- **Silicon Carbide (SiC)**
- *Gallium Nitride (GaN)*
- *(Diamond: CERN RD42 Collaboration)*

Device Engineering (New Detector Designs)

- **Thin detectors**
- **3D detectors**
- **Semi 3D detectors**
- *Cost effective detectors*
- **p-type silicon detectors**
- *Simulation of highly irradiated detectors*

Radiation Damage – Microscopic Effects

particle → Si_s → E_K>25 eV



Vacancy + Interstitial → *point defects (V-O, C-O, ..)*

Si_s → E_K > 5 keV *point defects and clusters of defects*

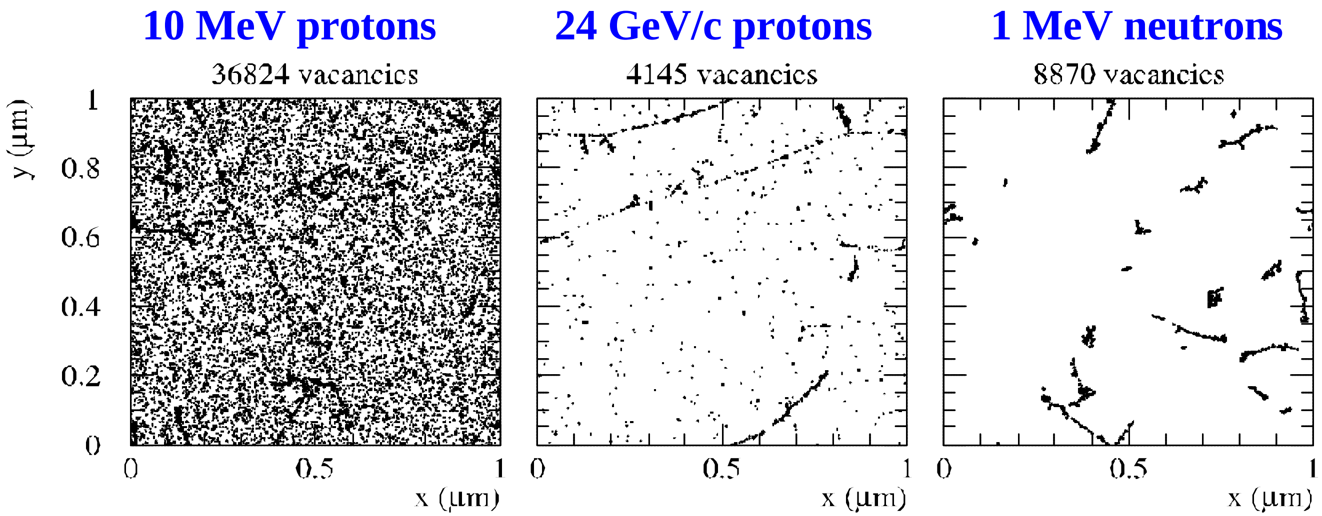
- **^{60}Co-gammas**
  - Compton Electrons with max. $E_\gamma \approx$1 MeV (no cluster production)
- **Electrons**
  - E_e > 255 keV for displacement
  - E_e > 8 MeV for cluster
- **Neutrons (elastic scattering)**
  - E_n > 185 eV for displacement
  - E_n > 35 keV for cluster

Only point defects ⟺ **point defects & clusters** ⟺ **Mainly clusters**

Simulation:

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

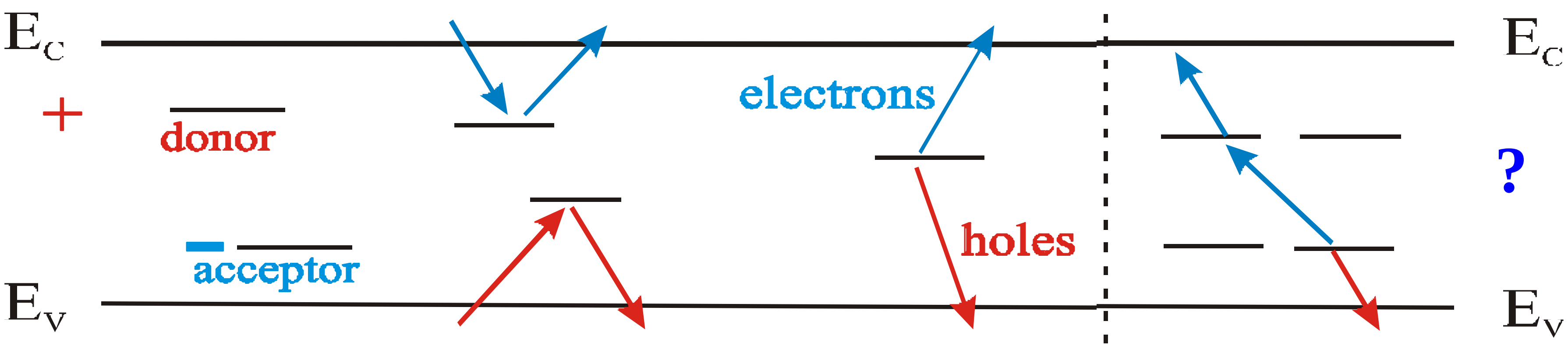
[Mika Huhtinen NIMA 491(2002) 194]



RD50 Impact of Defects on Detector properties

Shockley-Read-Hall statistics (standard theory)

Inter-center charge transfer model (inside clusters only)



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

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

generation
Þ **leakage current**
Levels close to midgap most effective

enhanced generation
Þ **leakage current**
Þ **space charge**

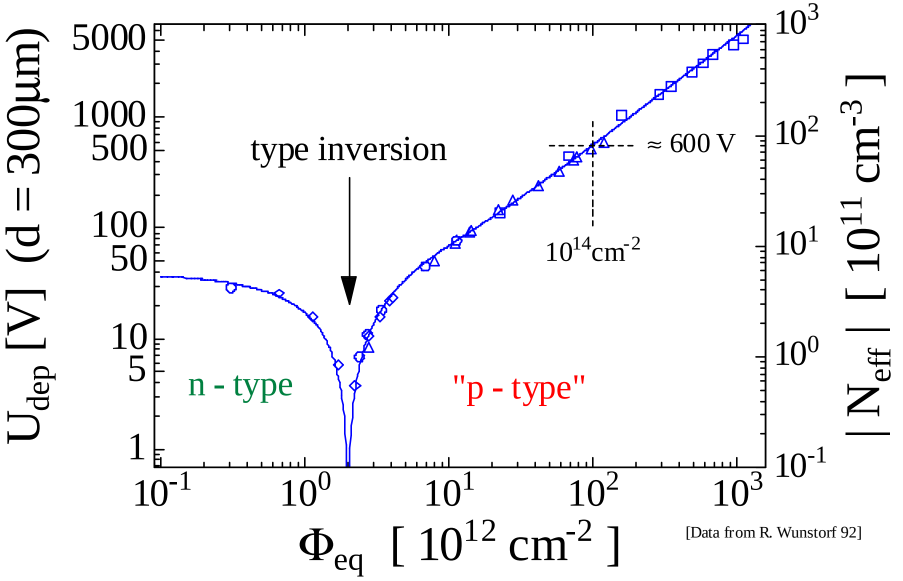
[S.Watts et al., IEEE TNS 43(6):2587,1996]
[K.Gill et al., J.Appl.Phys.,82(1):126,1997]

Impact on detector properties can be calculated if all defect parameters are known:

$s_{n,p}$: cross sections **DE : ionization energy** **N_t : concentration**

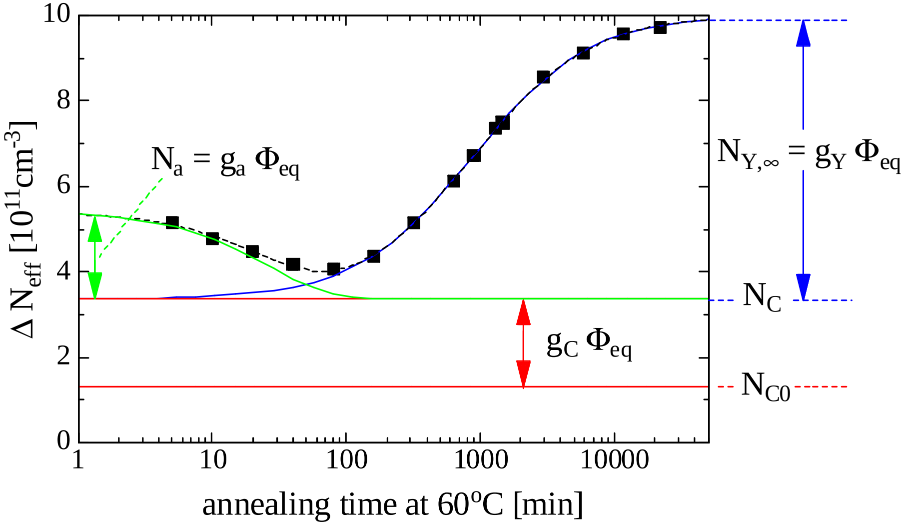
RD50 Macroscopic Effects – I. Depletion Voltage

Change of V_{dep} (N_{eff})



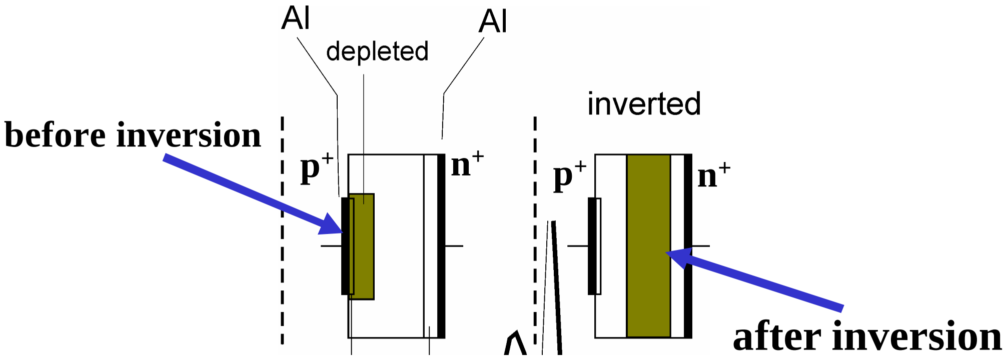
[Data from R. Wunstorf 92]

Annealing



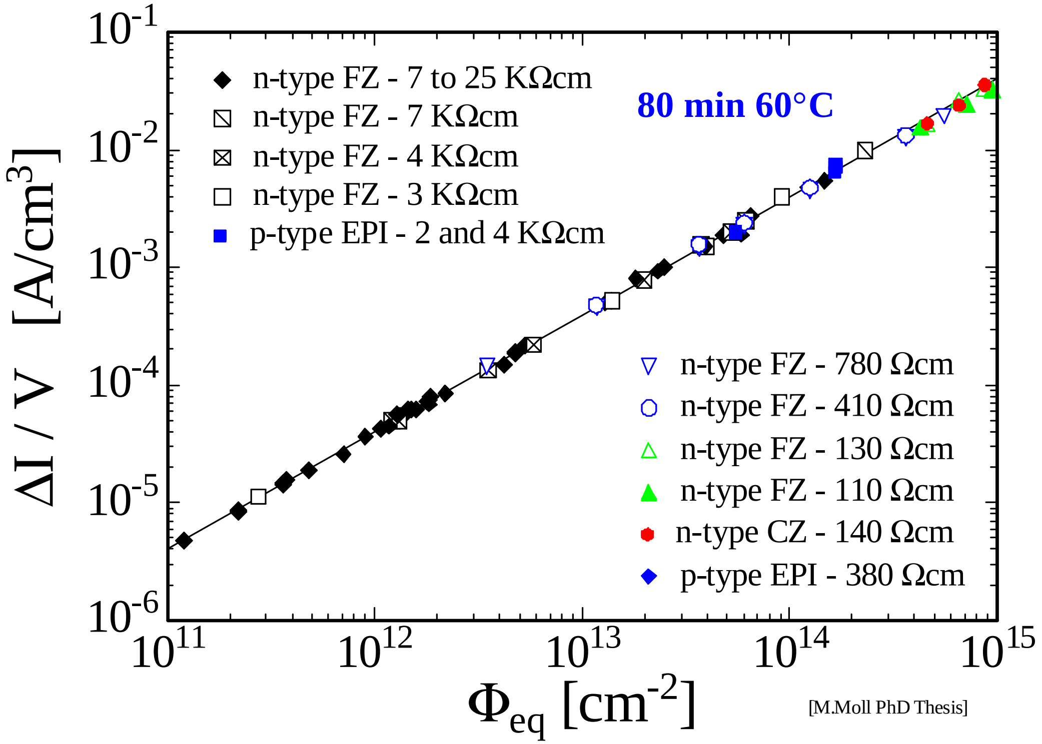
- Type inversion:
  SCSI – Space Charge Sign Inversion

- Short term: "**Beneficial annealing**"
- Long term: "**Reverse annealing**"
  time constant :
  ~ 500 years (-10°C)
  ~ 500 days (20°C)
  ~ 21 hours (60°C)



Macroscopic Effects – II. Leakage Current

Hadron irradiation



[M.Moll PhD Thesis]

- Damage parameter α (slope) independent of fluence
- α independent of Φ_{eq} and impurities

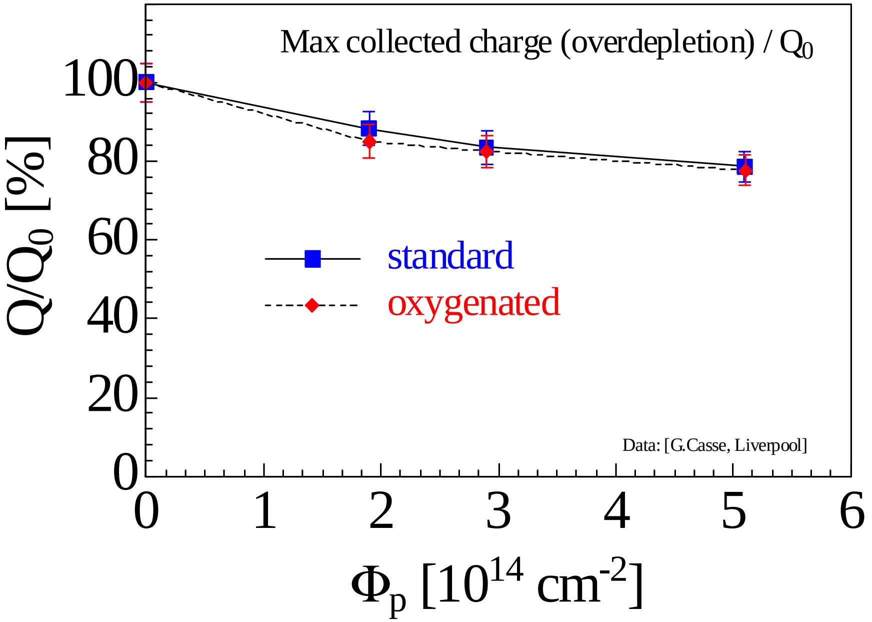
  ⇨ can be used for fluence calibration (NIEL-Hypothesis)
  (take care about annealing effects!)

Macroscopic effects - III. CCE

Deterioration of the Charge Collection Efficiency

- **Mechanisms reducing collected charge:**
  - **Trapping (electrons and holes)**
  - **Underdepletion (detector design and geometry)**
  - **Type inversion**

ATLAS microstrip + RO electronics



Data: Gianluigi Casse; 1st Workshop on Radiation Hard Semiconductor Devices for High Luminosity Colliders; CERN; 28-30 November 2002

- **Oxygenation has no influence on trapping.**
- **After $5\cdot10^{14}$ p/cm^2 (24GeV/c)**
  - 80% of charge collected (25ns)
  - overdepletion needed !

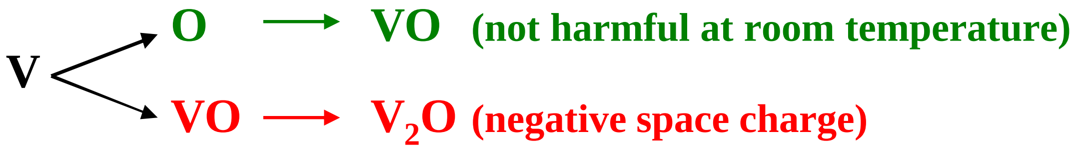
Defect Engineering of Silicon

- **Influence the defect kinetics by incorporation of impurities or defects**
- **Best example: <u>Oxygen</u>**

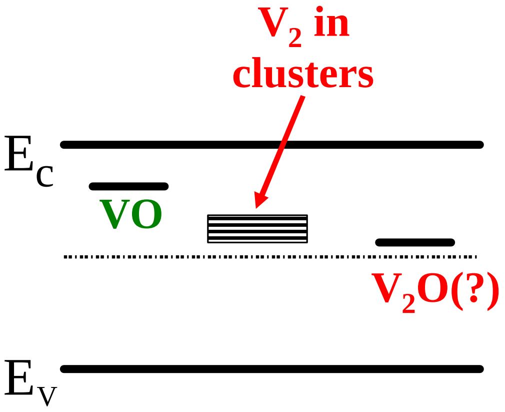
Initial idea: Incorporate Oxygen to getter radiation-induced vacancies
Þ prevent formation of Di-vacancy (V_2) related deep acceptor levels

Observation: **Higher oxygen content Þ less negative space charge**
(less charged acceptors)

- **One possible mechanism: V_2O is a deep acceptor**

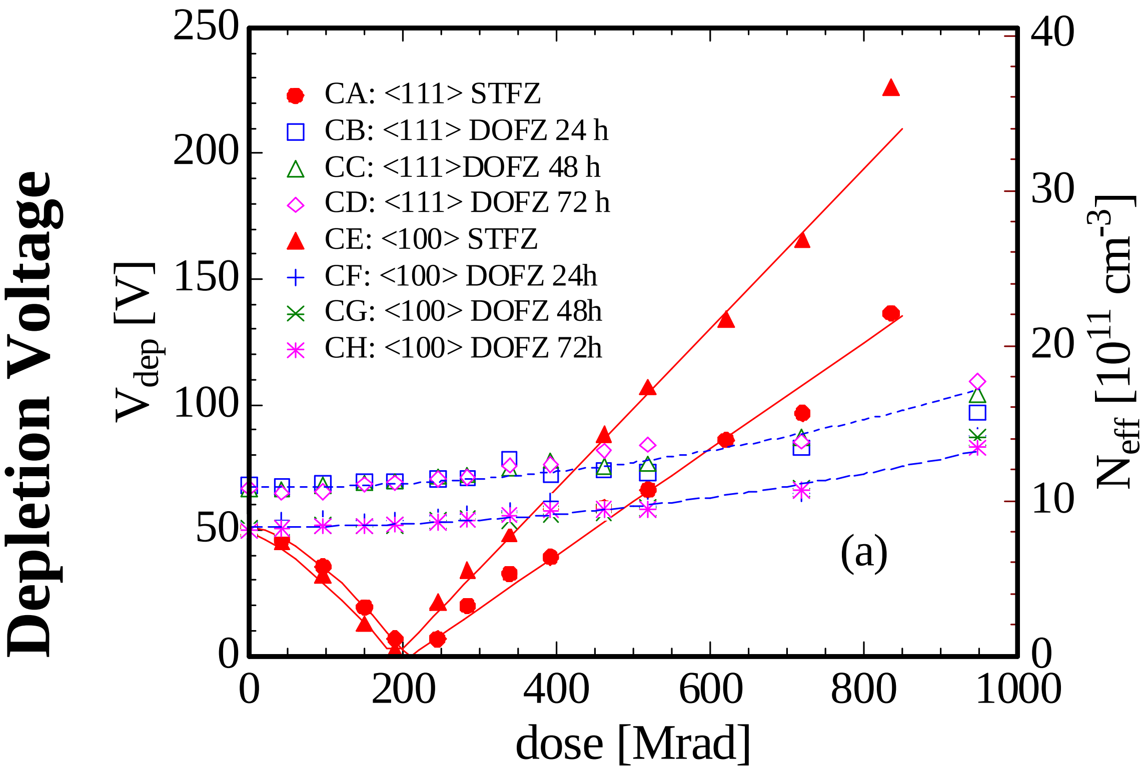


V → O → VO (not harmful at room temperature)
V → VO → V_2O (negative space charge)



Oxygen enriched silicon:

Spectacular Improvement of g-irradiation tolerance



[E.Fretwurst et al. 1st RD50 Workshop]
See also:
- Z.Li et al. [NIMA461(2001)126]
- Z.Li et al. [1st RD50 Workshop]

- **No type inversion for oxygen enriched silicon!**
- **Slight increase of positive space charge**

  (due to Thermal Donor generation?)

RD50

Characterization of microscopic defects

- g-irradiated silicon detectors -

- <u>For the first time</u> **macroscopic changes of the depletion voltage and leakage current can be explained by electrical properties of measured defects → Major breakthrough!**

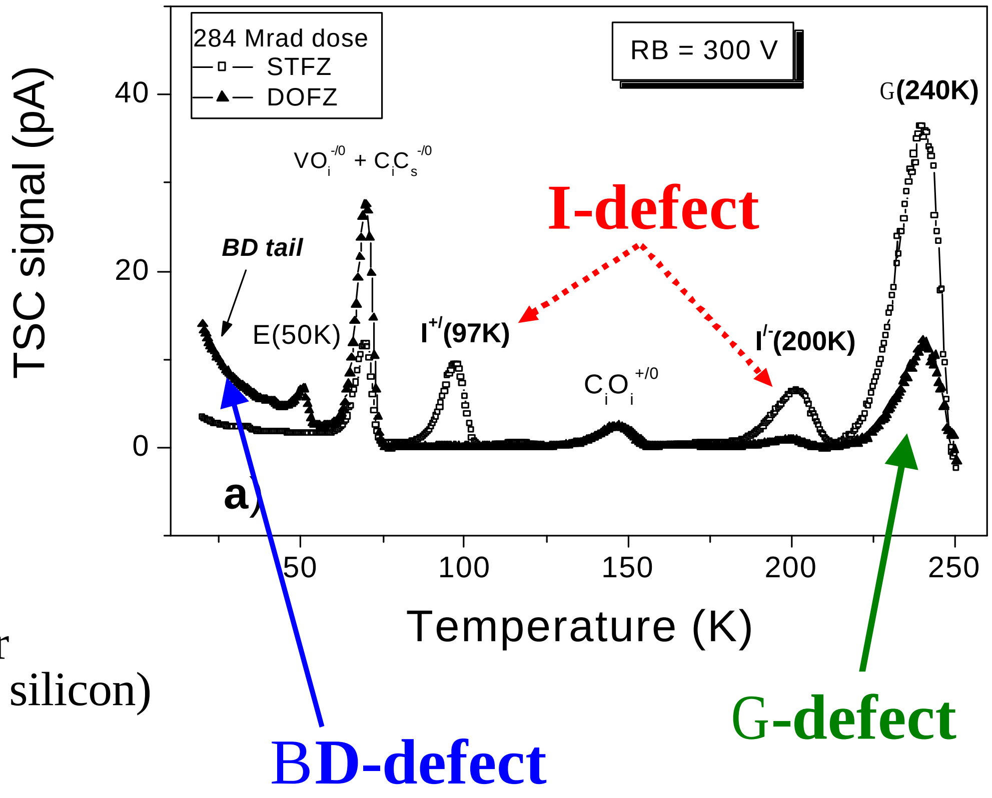
[Applied Physics Letters,82, 2169, March 2003]

Levels responsible for macroscopic changes after g-irradiation:

- **I–defect:** acceptor level at E_C-0.54eV (coming up for approx. 85% of damage)
  <u>peculiarity</u>: quadratic dose dependence
  Þ good candidate for the V_2O defect

- G**-defect:** acceptor level at E_V+0.68eV (coming up for approx. 10% of damage)

- **BD-defect:** bistable shallow thermal donor (important in oxygen enriched silicon)

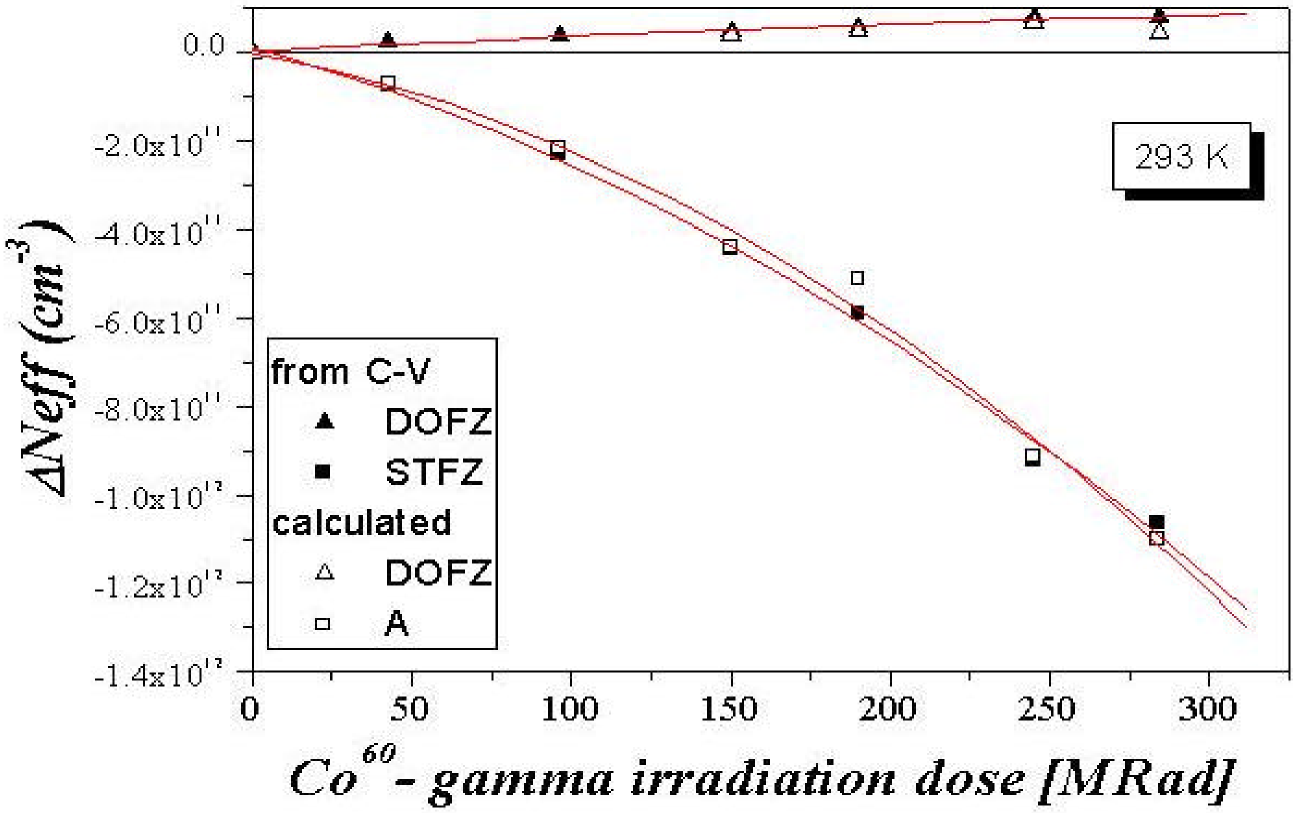


RD50

Microscopic defects Û Macroscopic properties

- Co^{60} g-irradiated silicon detectors -

- **Comparison for effective doping concentration for two different materials**
  - as predicted by the microscopic measurements (open symbols)
  - as deduced from CV characteristics (filled symbols)



[I.Pintilie et al., NIMA514, 18, 2003]

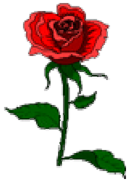
- **Excellent agreement also for the increase of leakage current (not shown here)**

RD50

Oxygen enriched silicon - DOFZ

- **DOFZ (Diffusion Oxygenated Float Zone Silicon)**
  - 1982 First oxygen diffusion tests on FZ [Brotherton et al. J.Appl.Phys.,Vol.53, No.8.,5720]
  - 1995 First tests on detector grade silicon [Z.Li et al. IEEE TNS Vol.42,No.4,219]
  - **1999 Introduced to the HEP community by RD48 (ROSE)**

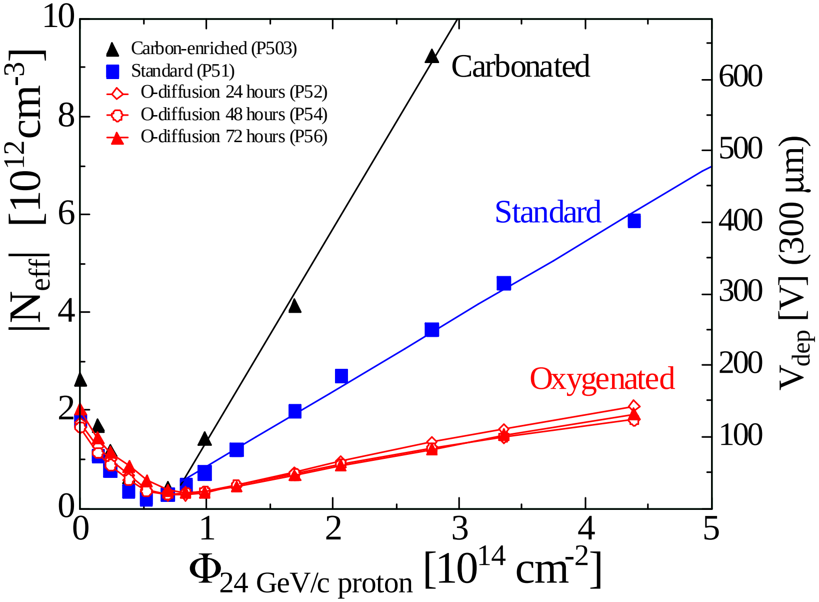
ROSE
RD48



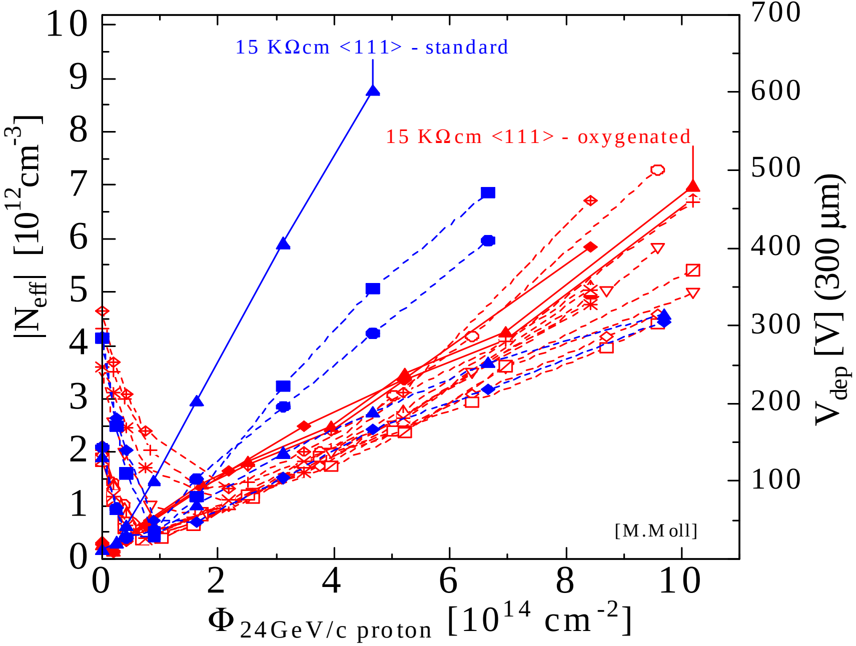
http://cern.ch/rd48

First tests in 1999 show clear advantage of oxygenation

Later systematic tests reveal strong variations with no clear dependence on oxygen content



[RD48-NIMA 465(2001) 60]

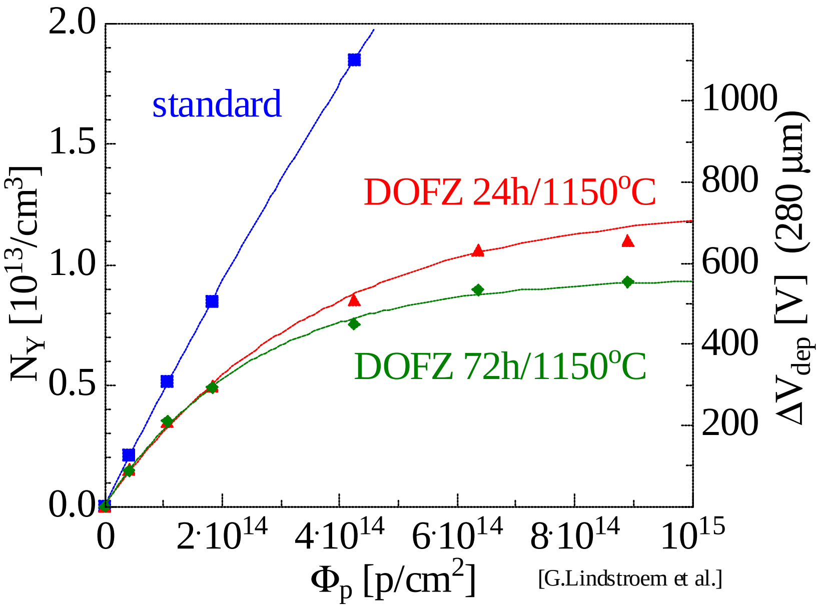


[RD50-NIMA 511 (2003) 97]

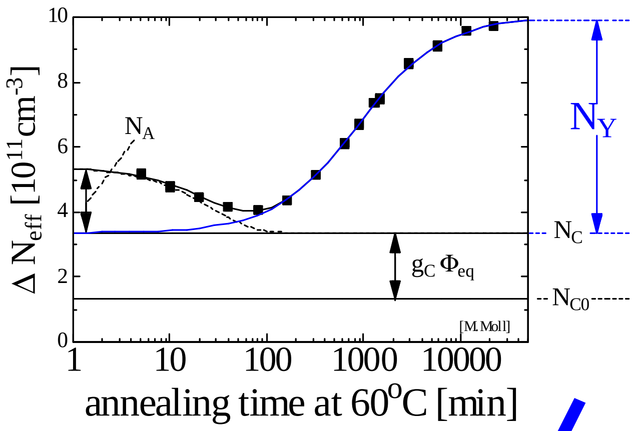
RD50

Oxygen enriched silicon - DOFZ

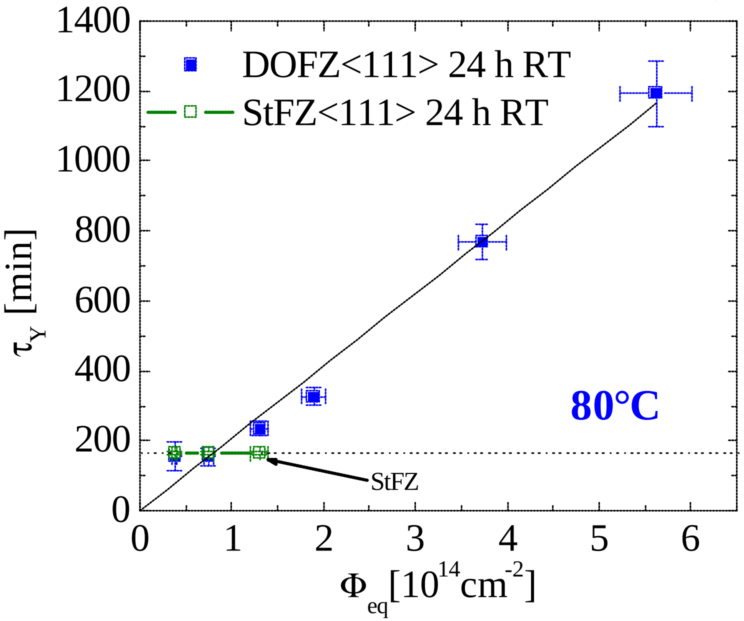
Reverse Annealing



Saturation of amplitude



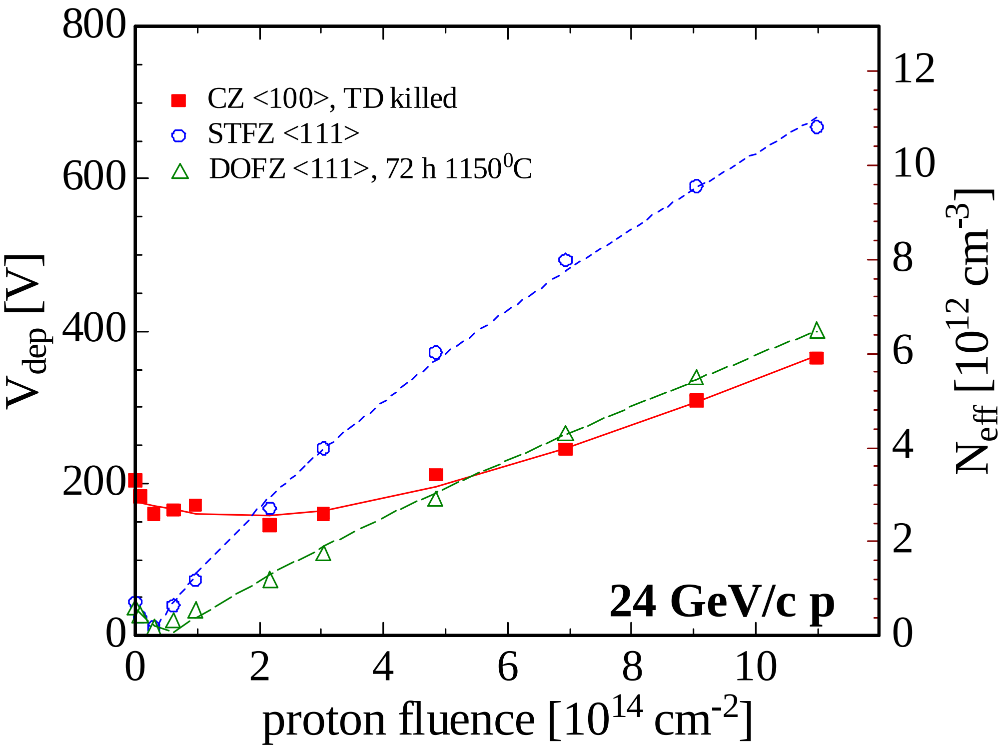
delayed reverse annealing



- **DOFZ: Saturation of reverse annealing**
  (24 GeV/c p - only little effect after neutron irradiation observed !)
- **DOFZ: No big difference between 24h and 72h oxidation at 1150°C**
- **DOFZ : time constant depending on fluence**

Czochralski silicon (CZ)

- **Very high Oxygen content 10^{17}-10^{18}cm^{-3}** (Grown in quartz (SiO_2)crucible)
- **High resistivity (>1KWcm) available only recently** (Magnetic CZ technology)



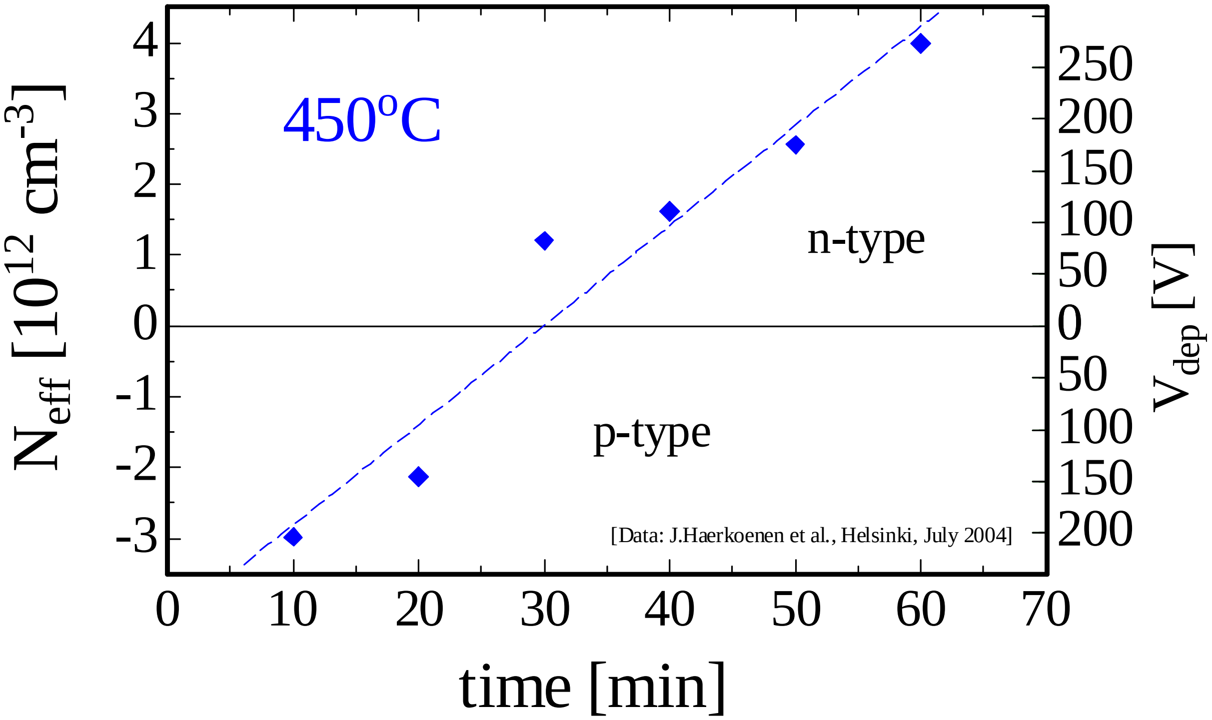
Irradiation of test-structures:

- **Only small change in V_{dep}**
  - $1 \cdot 10^{15}$ (190 MeVπ)/cm^2
  - $1 \cdot 10^{15}$ (24 GeV/c p)/cm^2
  - $5 \cdot 10^{14}$ (10 MeV p)/cm^2
- **No type inversion (Sumitomo CZ)**
  (However, type inversion observed for Okmetic MCZ after $5 \cdot 10^{14}$ (10 MeV p)/cm^2)
- **Leakage current and charge trapping as for FZ silicon**
- **Very high oxygen content: Beware of thermal donors !**

p-type (Magnetic CZ)

- **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)



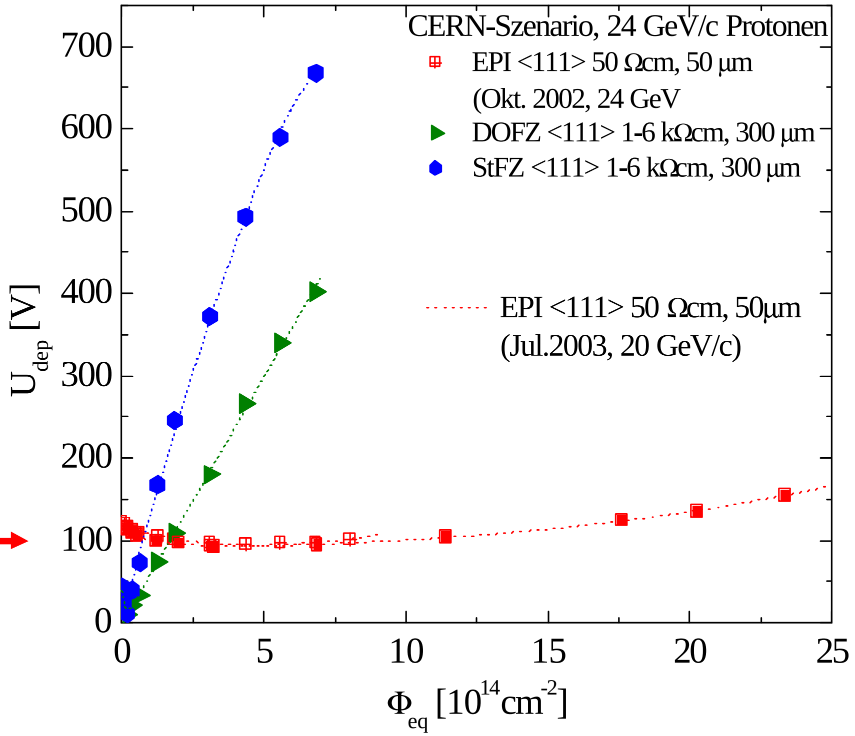
[Data: J.Haerkoenen et al., Helsinki, July 2004]

- **Radiation hardness of thermal donor doped MCZ under test**

Epitaxial silicon

- **Detectors: ITME epi-silicon** (50µm, 50Ωcm layer on CZ-substrate) **processed by CiS**
- **Irradiations:** 24 GeV/c protons, 58 MeV Li and reactor neutrons (up to $1 \cdot 10^{16} cm^{-2}$);
  no type inversion observed for proton irradiation

120 V



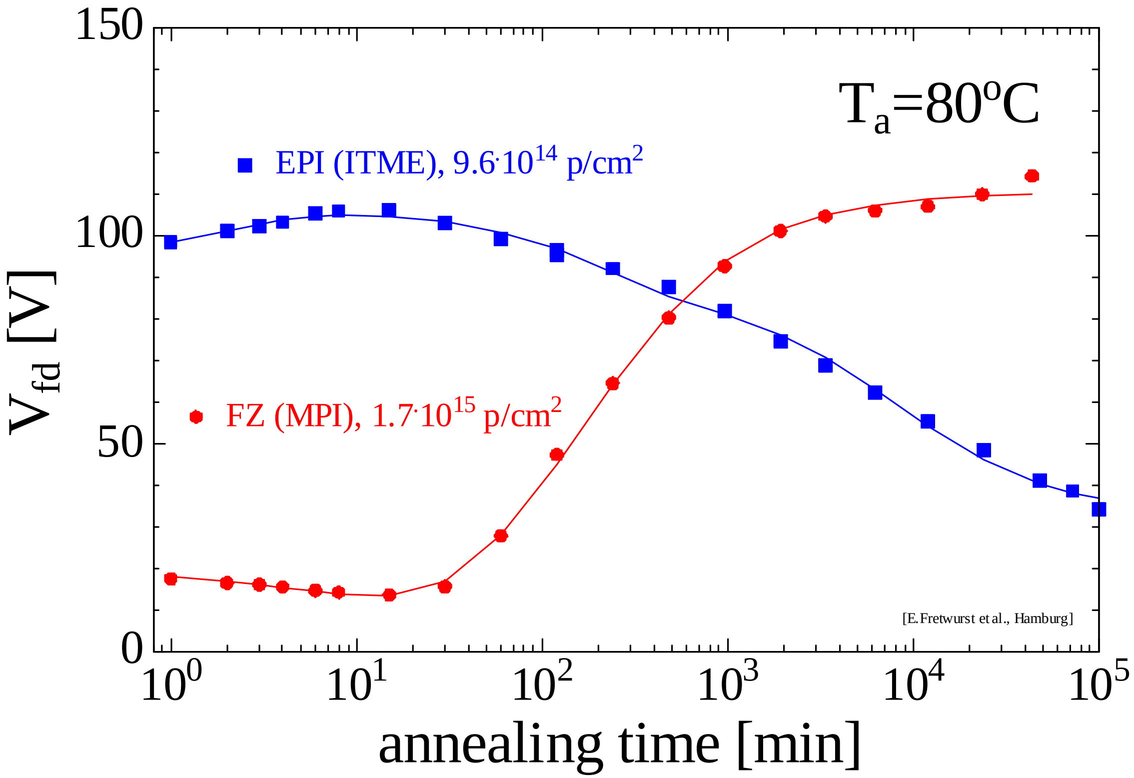
160 V

[G.Lindstroem et al.,
3^{rd} RD50 Workshop,
3-5 November 2004]

- **Leakage current almost identical to CZ, FZ, DOFZ detectors**

Epitaxial silicon - Annealing

- **50 mm thick silicon detectors:**
  - Epitaxial silicon (50Wcm on CZ substrate, ITME & CiS)
  - Thin FZ silicon (4KWcm, MPI Munich, wafer bonding technique)



[E.Fretwurst et al.,4th RD50 Workshop, 4-7 May 2004]

- **Thin FZ silicon: Type inverted, increase of depletion voltage with time**
- **Epitaxial silicon: No type inversion, decrease of depletion voltage with time**

Þ No need for low temperature during maintenance of SLHC detectors!

New Materials: Epitaxial 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	$4 \cdot 10^6$	$2.2 \cdot 10^6$	$3 \cdot 10^5$
μ_e [cm^2/Vs]	1800	1000	800	1450
μ_h [cm^2/Vs]	1200	30	115	450
v_{sat} [cm/s]	$2.2 \cdot 10^7$	-	$2 \cdot 10^7$	$0.8 \cdot 10^7$
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**	^{3}**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**

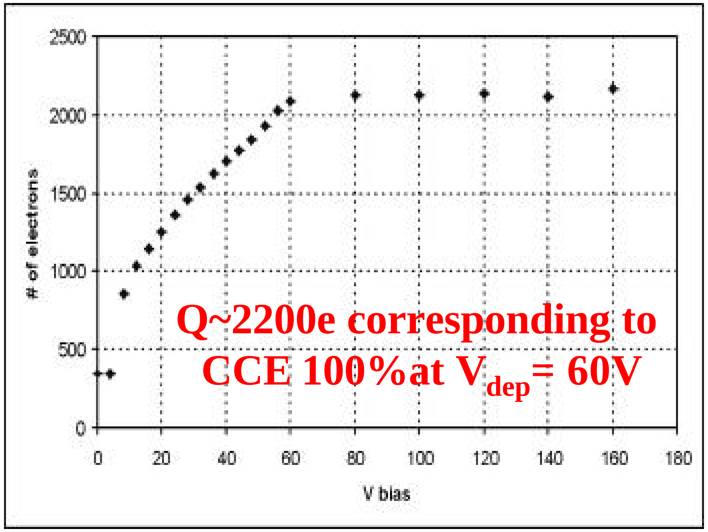
- **Higher displacement threshold than silicon**

⇒ **radiation harder than silicon (?)**

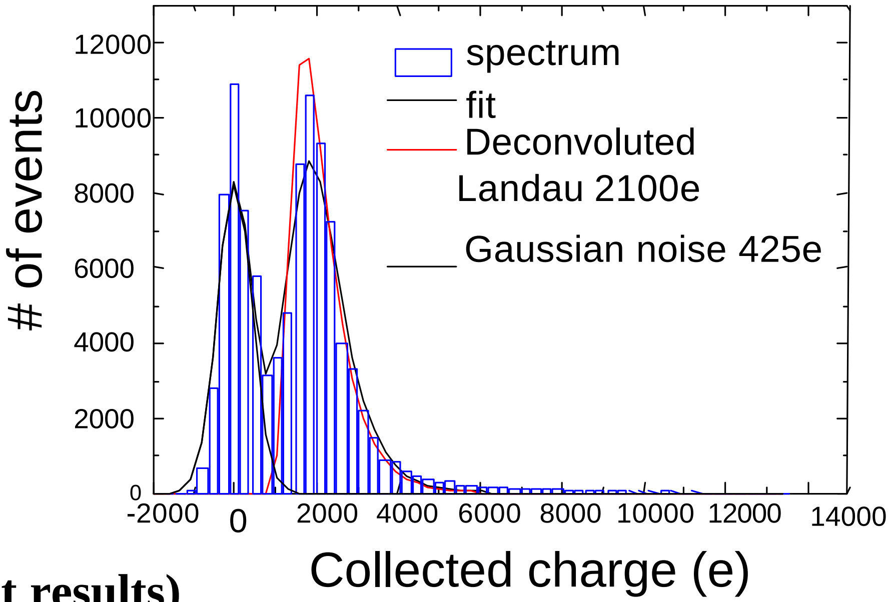
R&D on diamond detectors:
RD48 – Collaboration
http://cern.ch/rd48/
See talk of H.Kagan on Monday

New Materials: SiliconCarbide

- **Semi-Insulating SiC**
  - – ρ>10^{11}Ωcm 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**
  - - N_{eff} ~ 5·10^{13}cm^{-3}; 40µm by IKZ Berlin on CREE substrate (Schottky contacts)



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**

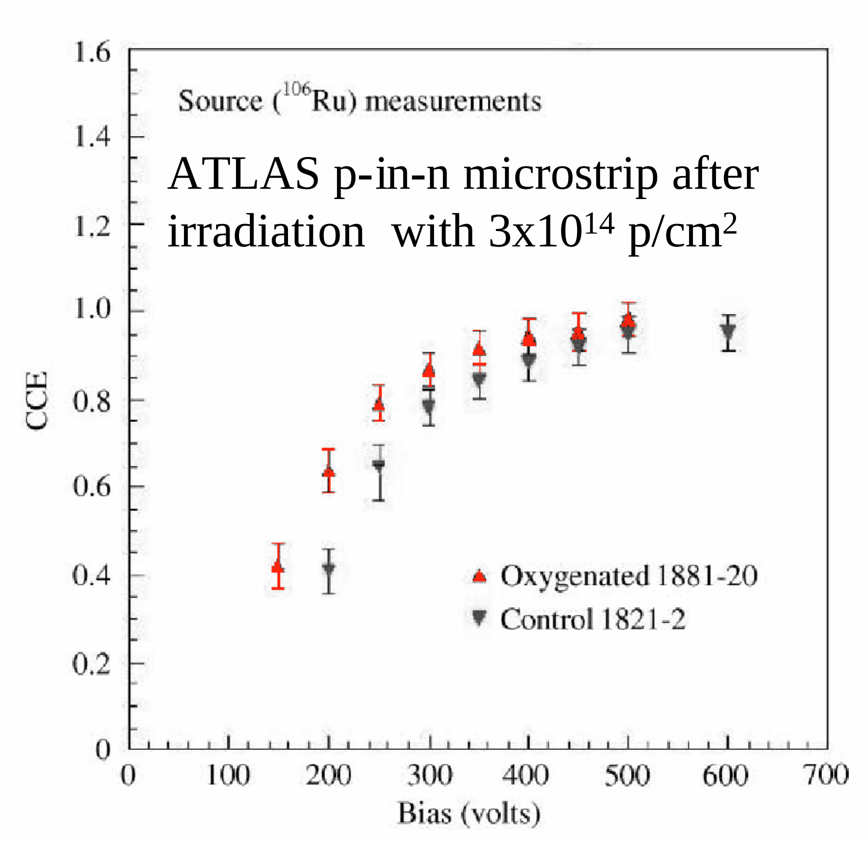
See following presentation by James Grant (Glasgow)

Device engineering

CCE: p-in-n versus n-in-n detectors

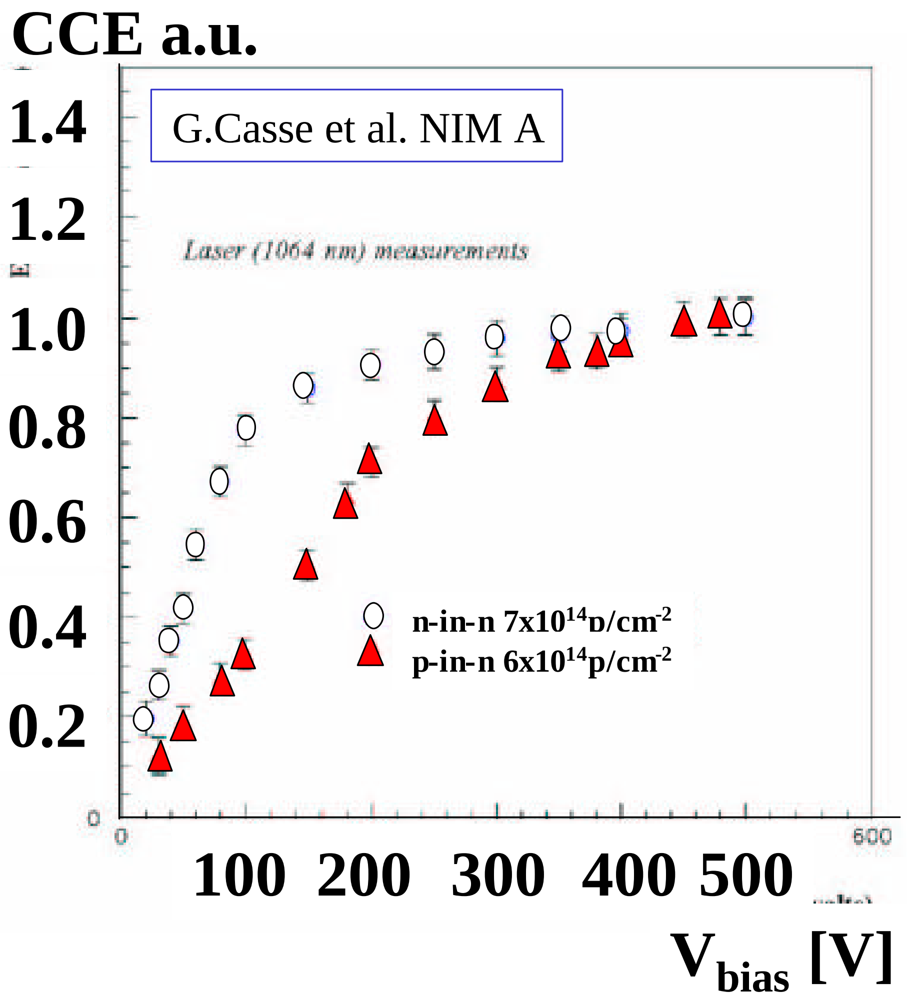
- **Beneficial effect of oxygen in p-irradiated DOFZ p-in-n microstrips almost disappears due to type inversion!**

- **Using n-in-n devices instead results in higher CCE.**



ATLAS p-in-n microstrip after irradiation with $3x10^{14}$ p/cm^2

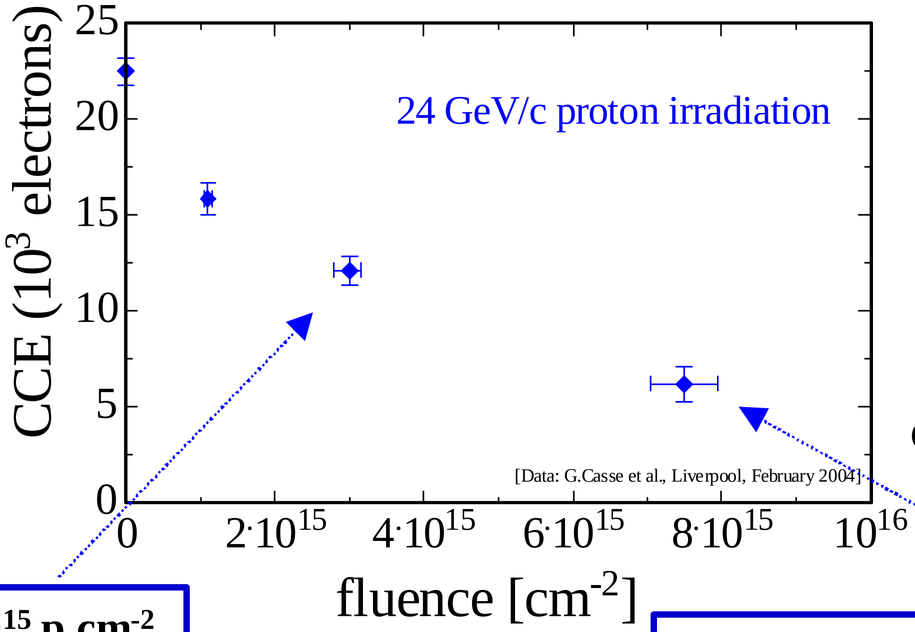
[G.Casse et al. NIM A 466 (2001) 335-344]



G.Casse et al. NIM A

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

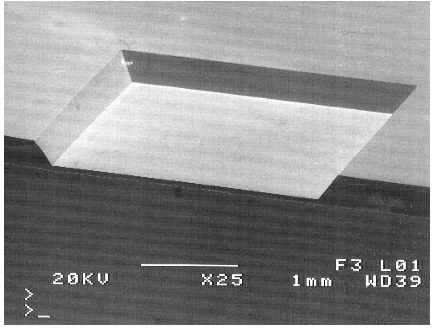
Motivation: **After 1 MeV neutron irradiation to 10^{15} cm^{-2}**
the effective drift length for e is ~150mm and for h ~50mm

Þ **use thin detectors (50-100mm) from the beginning**

- **Benefits:**
  - low operating voltage
  - improved radiation tolerance: - 50µm thick, 50Ωcm Si detector (V_{dep} = 200V):
    - type inversion only after 10^{15} cm^{-2}
- **Drawbacks**:
  - mip signal ~ 3500e-h pairs
- **Technical Approaches:**
  - Epitaxial Si device (shown before)
  - Thinning with chemical attacks (IRST, Italy) and wafer bonding technology (MPI Munich, Germany)

See following presentation by Marco Petasecca on thin Si detectors

IRST: SEM of a silicon wafer thinned by TMAH



Cross section of a thinned silicon detector

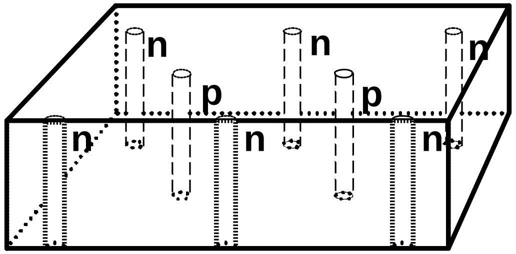
Devices produced end of 2003 (up to 11mm^2):

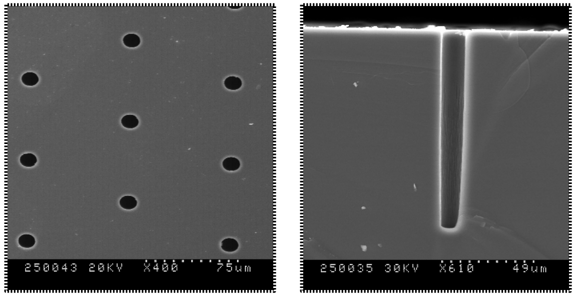
Thickness [mm]	Leakage Current [nA/cm^3]	V_{dep} [V]
300	80	12
99	30	~1
57	55	<1

RD50 Device Engineering: 3D detectors

- **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)

See overview talk by:
Sherwood Parker (Monday)

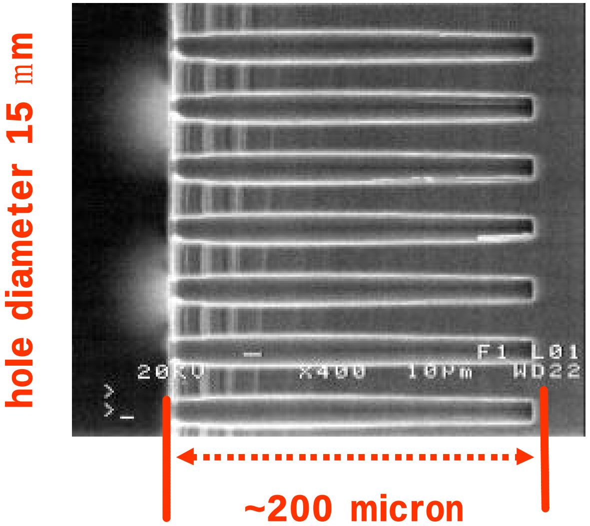



Glasgow University

3D detector developments within RD50:

1) Glasgow University – Schottky contacts
(see Poster of Victoria Wright)

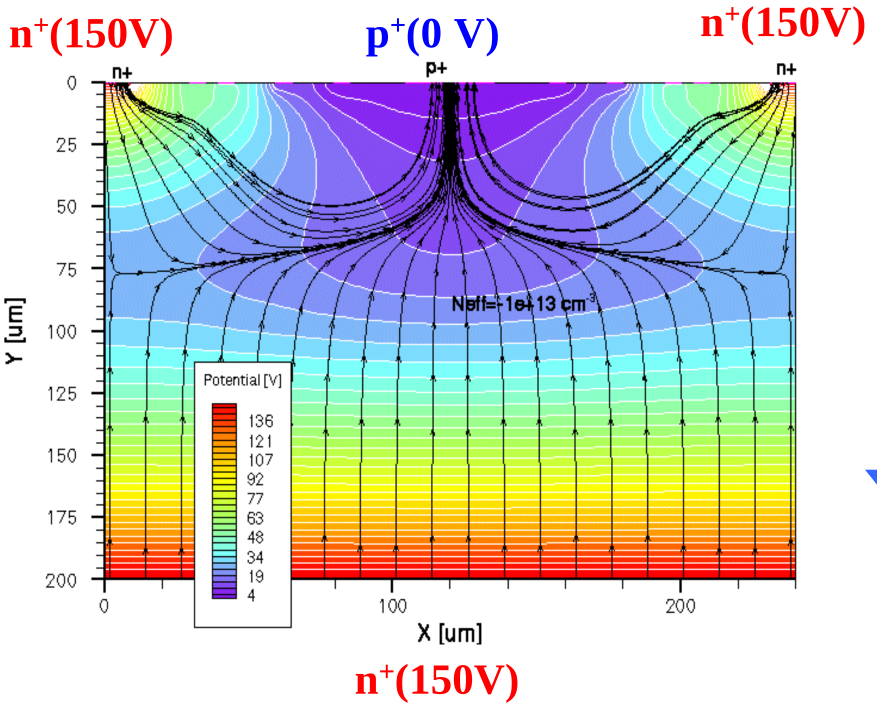
2) IRST-Trento and CNM Barcelona (since 2003)
CNM: Hole etching (DRIE); IRST: all further processing
diffused contacts or doped polysilicon deposition

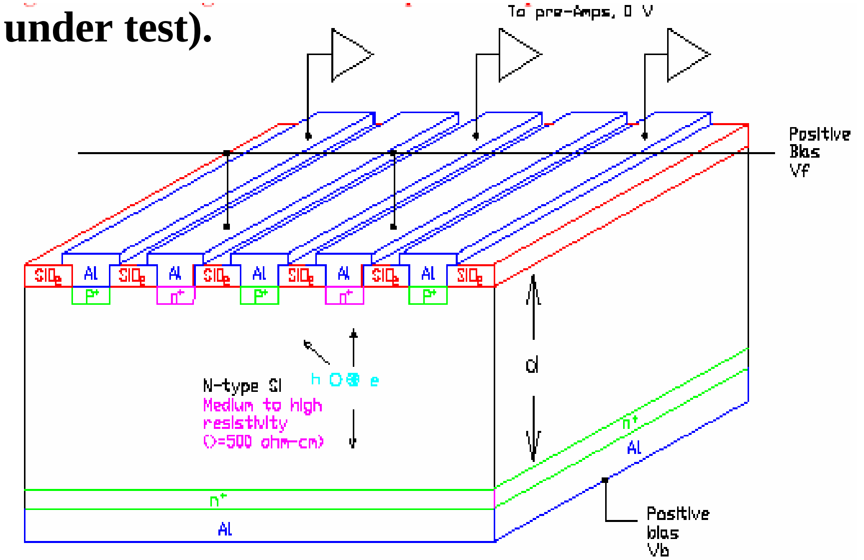


Semi-3D detectors

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).





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

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

Summary

- **Radiation hard materials and new device concepts for Super LHC tracking detectors are under study by the RD50 collaboration.**

- **At fluences up to 10^{15}cm^{-2} (Outer layers of a SLHC detector) the change of the depletion voltage and the large area to be covered by detectors is the major problem. CZ detectors could be a cost-effective radiation hard solution.**

- **Miniature microstrip and pixel detectors made with defect engineered Si have been fabricated by RD50 or are in process. First tests with LHC like electronics are encouraging: CCE on microstrip n-in-p oxygenated detectors irradiated up to 7×10^{15} [24 GeV/c p/cm^2] is > 6500 e.**

- **At the fluence of 10^{16}cm^{-2} (Innermost layer of a SLHC detector) the active thickness of any silicon material is significantly reduced due to trapping. The two most promising options so far are:**
  Thin/EPI detectors : drawback: radiation hard electronics for low signals needed
  3D detectors : drawback: technology has to be optimized

- **New Materials like SiC and GaN have been characterized. However, thicker samples and more radiation studies are needed to assess if these materials could be an alternative to Silicon.**

Further information: http://cern.ch/rd50/