Silicon and other sensor materials for CMS upgrade

Mara Bruzzi on behalf of the RD50 Collaboration

INFN, University of Florence, Italy

Large Scale Application of Si Detectors in LHC

Present working conditions:

$L \sim 10^{34}$ cm^{-2}s^{-1} in 10 years of LHC operation:

→ **$\phi \sim 10^{15}$ n/cm^{2} for pixels**

$\phi \sim 10^{14}$ n/cm^{2} for microstrips

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

$L \sim 10^{35}$ cm^{-2}s^{-1} → fluence up to 10^{16} cm^{-2} ***after five years***

R&D needed for the development of a detector technology able to operate safely and efficiently in such an environment.

Anticipated Radiation Environment for Super LHC

Hadron fluence and radiation dose in different radial layers of the CMS tracker for an integrated luminosity of 2500fb^{-1} . (CERN-TH/2002-078)

Radius [cm]	Fluence of fast hadrons [cm^{-2}]	Dose [KGy]
4	1.6×10^{16}	4200
11	2.3×10^{15}	940
22	8.0×10^{14}	350
75	1.5×10^{14}	35
115	1.0×10^{14}	9.3

The tracker volume can be splitted into 3 radial regions:

1.	**R > 60cm**	**improved Si strip technology**
2.	**20cm < R < 60cm**	**improved hybrid pixel technology**
3.	**R < 20cm**	**new approaches and concepts required**

The RD50 CERN Collaboration

Development of Radiation Hard Semiconductor Devices for High Luminosity Colliders

- Collaboration formed in November 2001 - http://www.cern.ch/rd50
- 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").

- Presently 272 Members from 52 Institutes

Belgium (Louvain), **Canada** (Montreal), **Czech Republic** (Prague (2x)), **Finland** (Helsinki (2x), Oulu), **Germany** (Berlin, Dortmund, Erfurt, Halle, Hamburg, Karlsruhe), **Greece** (Athens), **Israel** (Tel Aviv), **Italy** (Bari, Bologna, Florence, Milano, Modena, 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), **Sweden** (Lund) **Switzerland** (CERN, PSI), **Ukraine** (Kiev), **United Kingdom** (Exeter, Glasgow, Lancaster, Liverpool, London, Sheffield, University of Surrey), **USA** (Fermilab, Purdue University, Rutgers University, Syracuse University, BNL, University of New Mexico, University of California Santa Cruz)

- CMS groups in RD50: Helsinki HIP, Karlsruhe University, Louvain University, INFN Bari-Florence-Perugia-Pisa, Purdue University, PSI-Villigen, Rutgers University..
- Several RD50 groups are within ATLAS, LHCb, ALICE, CDF and other experiments

Scientific strategies

- **Material Engineering**

  - Defect and Material Characterisation

  - Defect engineering of silicon

  - New detector materials (SiC, ..)

- **Device Engineering**

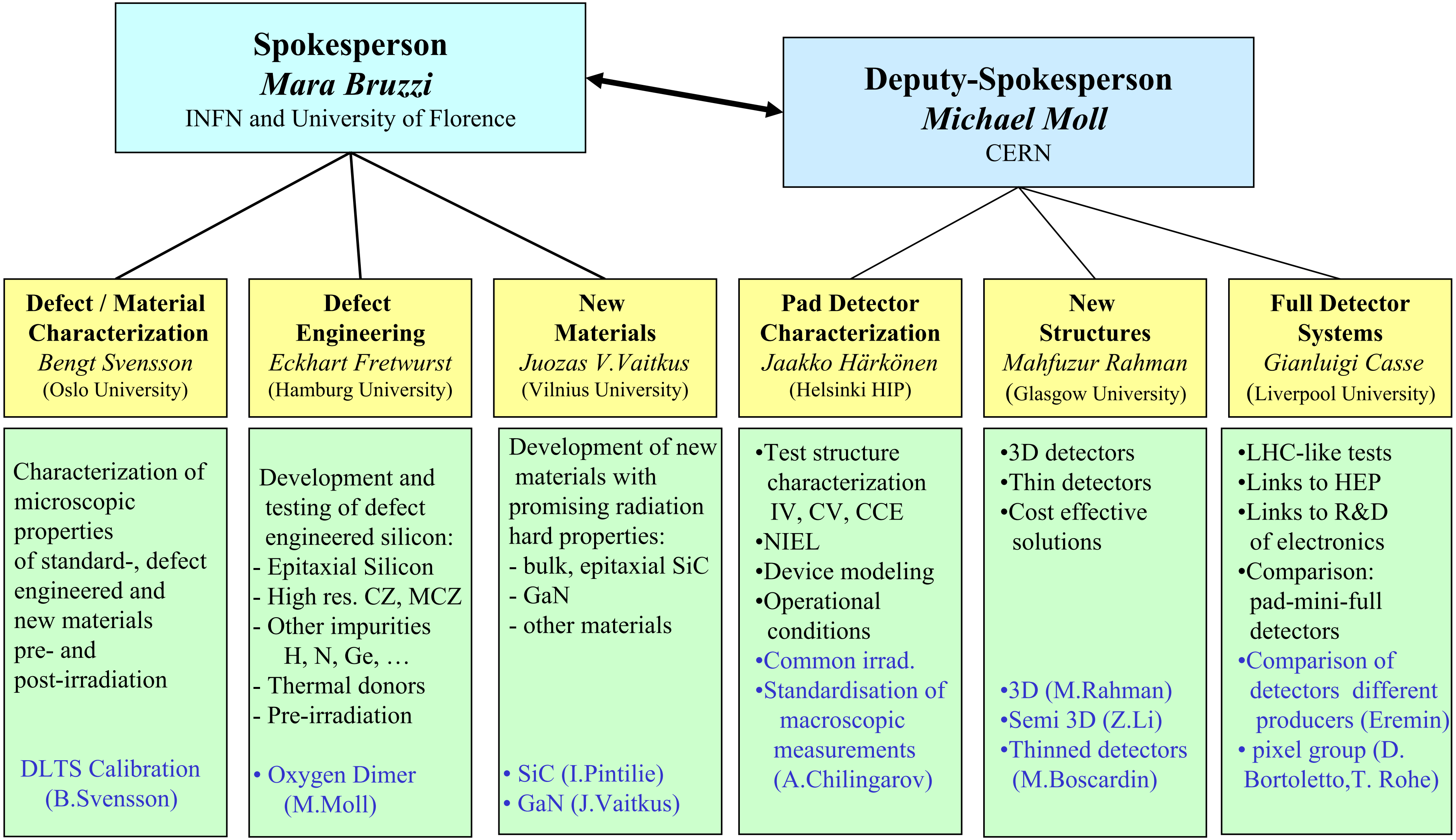
  - Improvement of present planar detector structures (3D detectors, thin detectors, cost effective detectors,…)

  - Tests of LHC-like detector systems produced with radiation-hard technology

  - Variation of the operational conditions

Scientific Organization of RD50

Development of Radiation Hard Semiconductor Devices for High Luminosity Colliders



Spokesperson
Mara Bruzzi
INFN and University of Florence

Deputy-Spokesperson
Michael Moll
CERN

Defect / Material Characterization
Bengt Svensson
(Oslo University)

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

DLTS Calibration (B.Svensson)

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

• Oxygen Dimer (M.Moll)

New Materials
Juozas V.Vaitkus
(Vilnius University)

Development of new materials with promising radiation hard properties:

- bulk, epitaxial SiC
- GaN
- other materials

• SiC (I.Pintilie)
• GaN (J.Vaitkus)

Pad Detector Characterization
Jaakko Härkönen
(Helsinki HIP)

•Test structure characterization IV, CV, CCE
•NIEL
•Device modeling
•Operational conditions
•Common irrad.
•Standardisation of macroscopic measurements (A.Chilingarov)

New Structures
Mahfuzur Rahman
(Glasgow University)

•3D detectors
•Thin detectors
•Cost effective solutions

•3D (M.Rahman)
•Semi 3D (Z.Li)
•Thinned detectors (M.Boscardin)

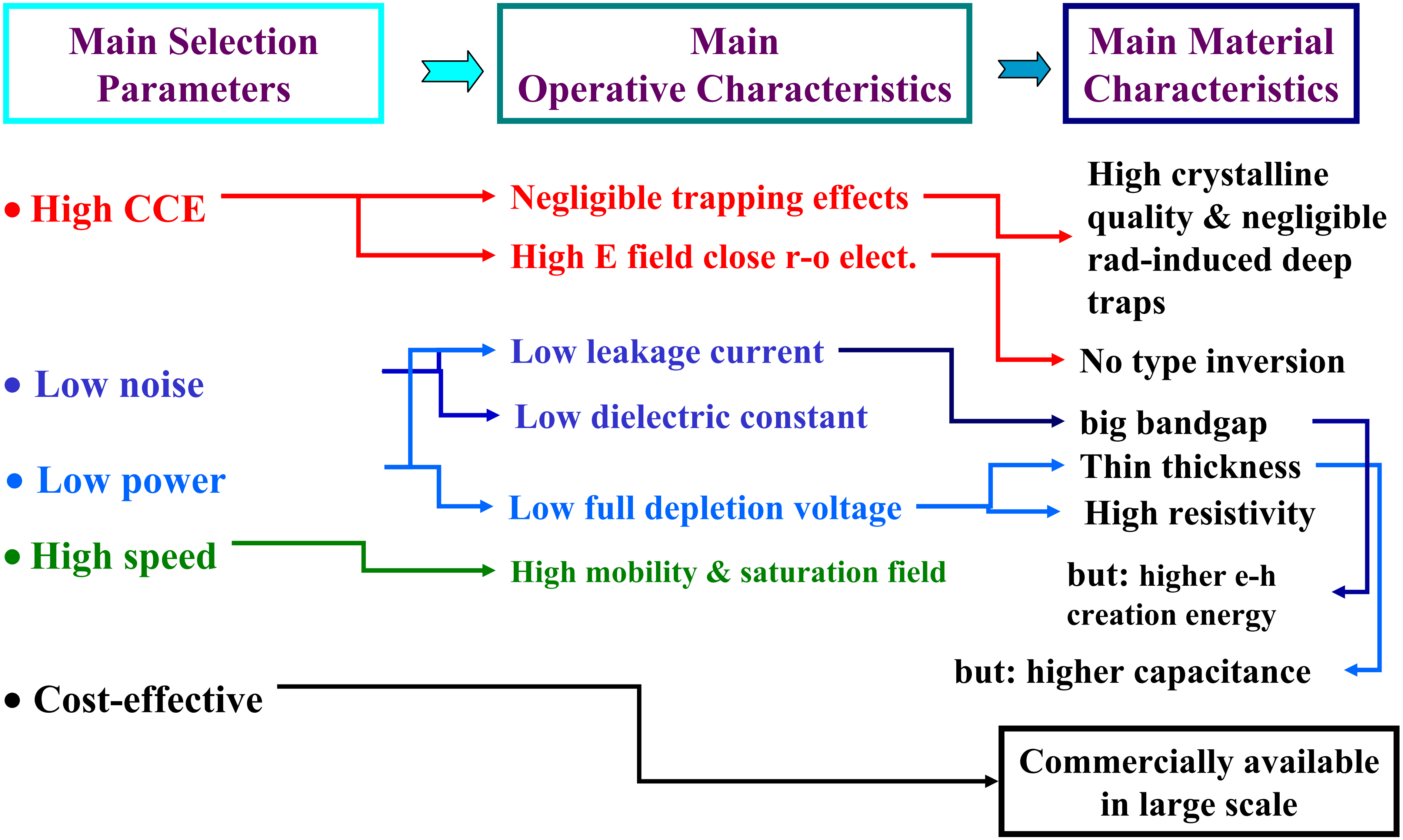
Full Detector Systems
Gianluigi Casse
(Liverpool University)

•LHC-like tests
•Links to HEP
•Links to R&D of electronics
•Comparison: pad-mini-full detectors
•Comparison of detectors different producers (Eremin)
• pixel group (D. Bortoletto,T. Rohe)

RADIATION FACILITIES within RD50

- 24 GeV/c protons, PS-CERN
  up to 10^{16} cm^{-2}
- TRIGA reactor neutrons, Ljubljana
  up to $1x10^{16}$ cm^{-2}
- 26 MeV protons, Karlsruhe
  1E14/cm2 on 10x10 cm2 in 10 minutes
- 10-50 MeV protons, Jyvaskyla +Helsinki
  up to $3x10^{14}$ cm^{-2}
- ^{60}Co dose, BNL, USA
  up to 1.5GRad
- 58 MeV Li ions, Legnaro/ Padova
- 900 MeV electrons, Trieste
- 15MeV electrons, Oslo

Selecting radiation- hard materials for tracker detectors at SuperLHC



Main Selection Parameters

Main Operative Characteristics

Main Material Characteristics

- **High CCE**
- **Low noise**
- **Low power**
- **High speed**
- **Cost-effective**

Negligible trapping effects

High E field close r-o elect.

Low leakage current

Low dielectric constant

Low full depletion voltage

High mobility & saturation field

High crystalline quality & negligible rad-induced deep traps

No type inversion

big bandgap

Thin thickness

High resistivity

but: higher e-h creation energy

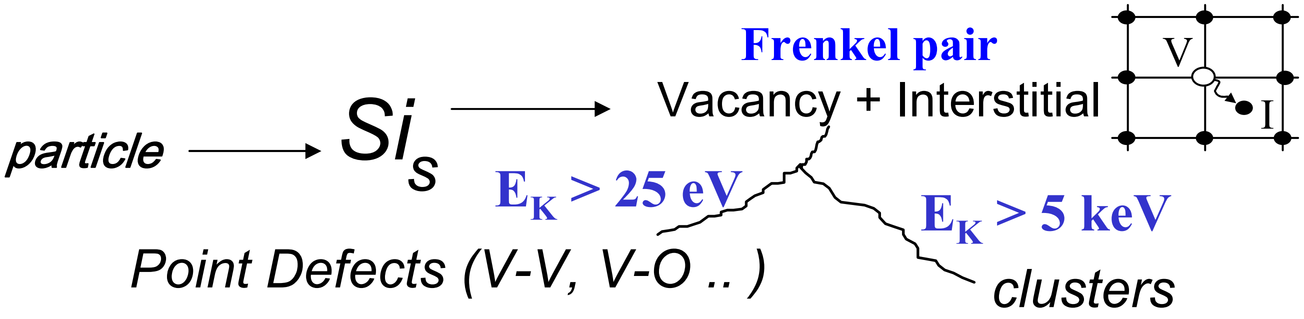
but: higher capacitance

Commercially available in large scale

Rad-Hard Materials presently under investigation

Property	Si	SiC	GaN	Diamond	
Material Quality	Cz, FZ, DOFZ, epi	4H, 6H Epi/bulk	EPI: MOSVD	Polycrystalline CVD	single crystal CVD
E_g [eV]	1.12	3.3	3.39	5.5	5.5
$E_{breakdown}$ [V/cm]	$3\cdot10^5$	$2.2\cdot10^6$	$4\cdot10^6$	10^7	10^7
μ_e [cm^2/Vs]	1450	800	1000	1800	>1800
μ_h [cm^2/Vs]	450	115	100-350	1200	>1200
v_{sat} [cm/s]	$0.8\cdot10^7$	$2\cdot10^7$	$2\cdot10^7$	$2.2\cdot10^7$	$2.2\cdot10^7$
Z	14	14/6	31/7	6	6
ε_r	11.9	9.7	9.6	5.7	5.7
e-h energy [eV]	3.6	7.6	8.9	13	13
Density [g/cm^3]	2.33	3.22	6.15	3.515	3.515
e-h/µm for mips	89	55		36	36
Max initial ccd [µm]	>500	40	12. 5	280	500
Max wafer ϕ tested	6”	2”	2”	6”	6mm
Producer	Several	Cree-Alenia, IKZ-IMM, Okmetic	Lumilog	Element-Six	Element-Six
Max fluence[cm^{-2}]	10^{16} 24 GeV p, 1MeVn	10^{16} 24GeV p	10^{16} 24GeV p, 1MeV n	2x10^{15} n, π, p	-
CERN R&Ds	RD50, RD39 ←	RD50 Cryogenic operation	RD50	RD42	RD42

Radiation Induced Microscopic Damage in Silicon



particle → Si_s →

Frenkel pair

Vacancy + Interstitial

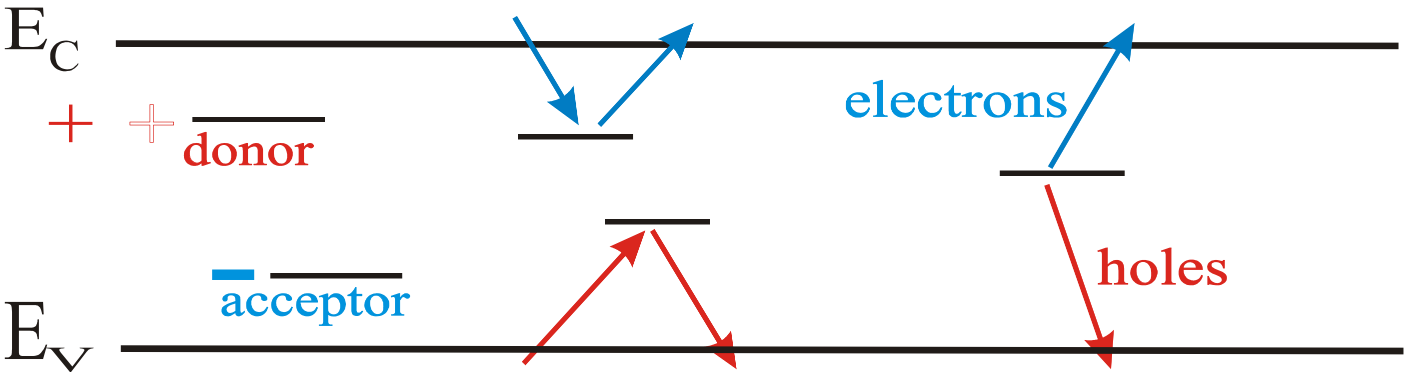
$E_K > 25$ eV

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

$E_K > 5$ keV

clusters

Influence of defects on the material and device properties



charged defects

⇒ N_{eff}, V_{dep}

e.g. donors in upper and acceptors in lower half of band gap

Trapping (e and h)

⇒ CCE

shallow defects do not contribute at room temperature due to fast detrapping

generation

⇒ leakage current

Levels close to midgap most effective

RD50 Primary Damage and secondary defect formation

- **Two basic defects**

  I - Silicon Interstitial V - Vacancy

- **Primary defect generation**

  I, I_2 higher order I (?)

  ⇒ I -CLUSTER (?) ⇐

  V, V_2, higher order V (?) **Damage?!**

  ⇒ V -CLUSTER (?) ⇐

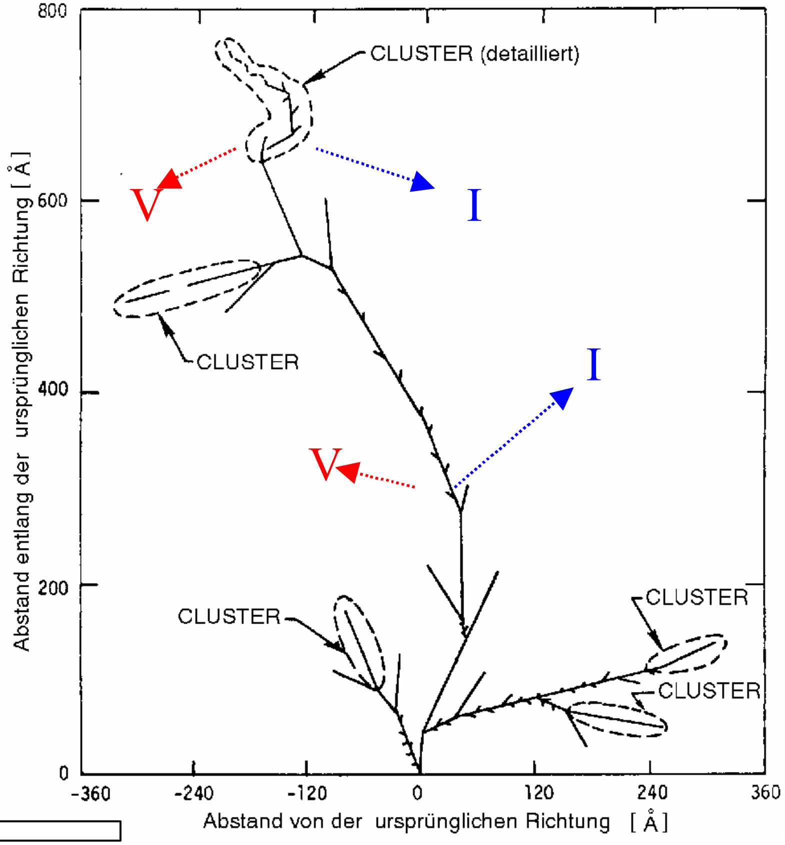
- **Secondary defect generation**

Main impurities in silicon: Carbon (C_s)
Oxygen (O_i)

$I+C_s \rightarrow C_i \Rightarrow$
$C_i+C_s \rightarrow C_iC_S$
$C_i+O_i \rightarrow C_iO_i$
$C_i+P_s \rightarrow C_iP_S$

$V+V \rightarrow V_2$ **$V+V_2 \rightarrow V_3$**
$V+O_i \rightarrow VO \Rightarrow$ **$V+VO \rightarrow \underline{V_2O}$**
$V+P_s \rightarrow VP_s$

$I+V_2 \rightarrow V$ **$I+VO \rightarrow O_i$**



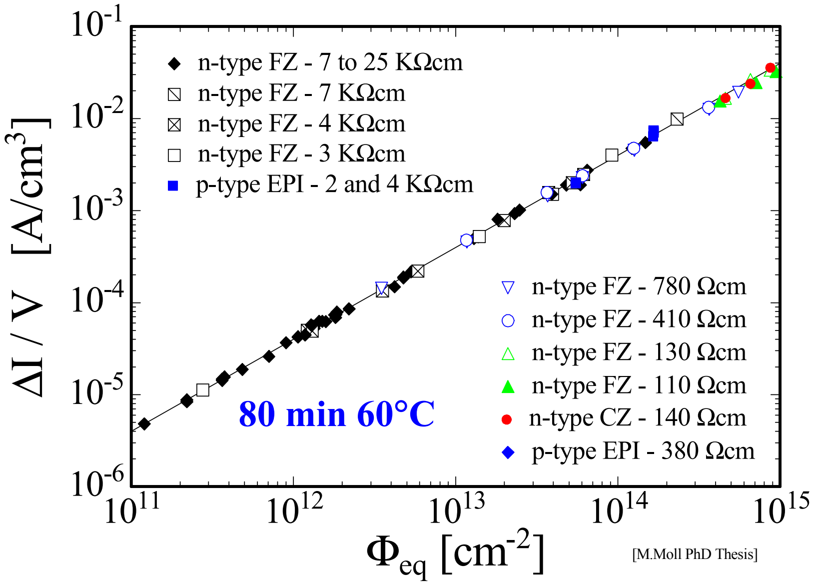
Damage?! (“V_2O-model”)

Trap parameters of radiation induced point-defects in Si

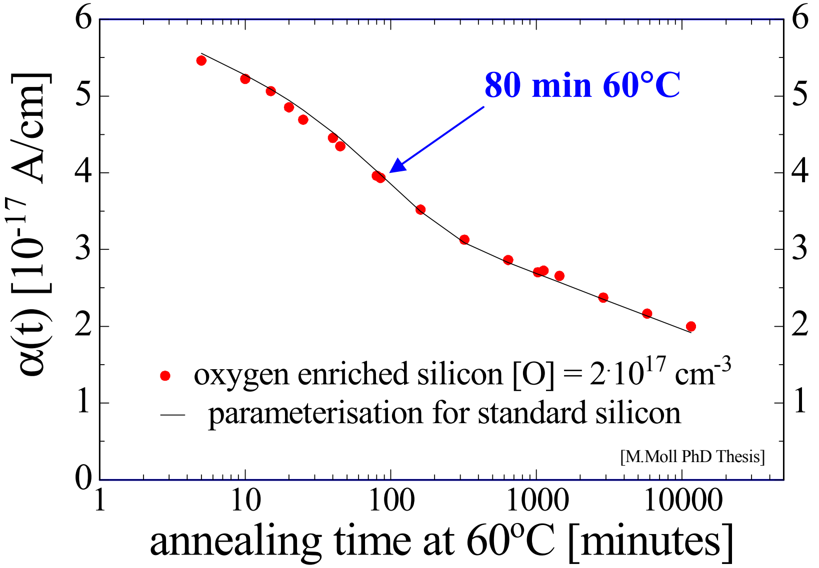
Defect	Trap Parameters		References
	E [eV]	σ [cm^2]	
V-O	E_c-0.18	$1x10^{-14}$	Svensson et al NIMB 106 (1995) 183
V_2^{--}	E_c-0.237	$2x10^{-16}$	Svensson et al NIMB 106 (1995) 183
V_2^{-}	E_c-0.42	$3.1x10^{-15}$	Simoen et al APL 69 (1996) 2858
$C_iO_i^{-}$	E_v+0.36	$2x10^{-15}$	Moll et al NIMA 388 (1997) 335
$VO^{-/0}$	E_c-0.17,	$9x10^{-15}$,	Pellegrino et al. APL 78 (2001) 3442.
$CiCs^{-/0}$	E_c-0.17	$8x10^{-18}$	Pellegrino et al. APL 78 (2001) 3442.
C_i	E_c-0.3	$9x10^{-14}$	
P-V	E_c-0.46	$4x10^{-15}$	Pellegrino et al. APL 78 (2001) 3442.
I defect - acceptor	Ec-0.545	$1.7x10^{-15}$	Pintilie et al APL 81 (2002) 165
I defect - donor	E_v + 0.23		Pintilie et al APL 81 (2002) 165
Γ defect - acceptor	E_v + 0.68		Pintilie et al APL 81 (2002) 165
X defect acceptor	E_c-0.232	$1.3x10^{-16}$	Monakhov et al. Phys. Rev. B 65, 233207
X defect acceptor	E_c-0.47	$9.6x10^{-15}$	Monakhov et al. Phys. Rev. B 65, 233207

Leakage Current

Hadron irradiation



Annealing



M. Moll, Thesis

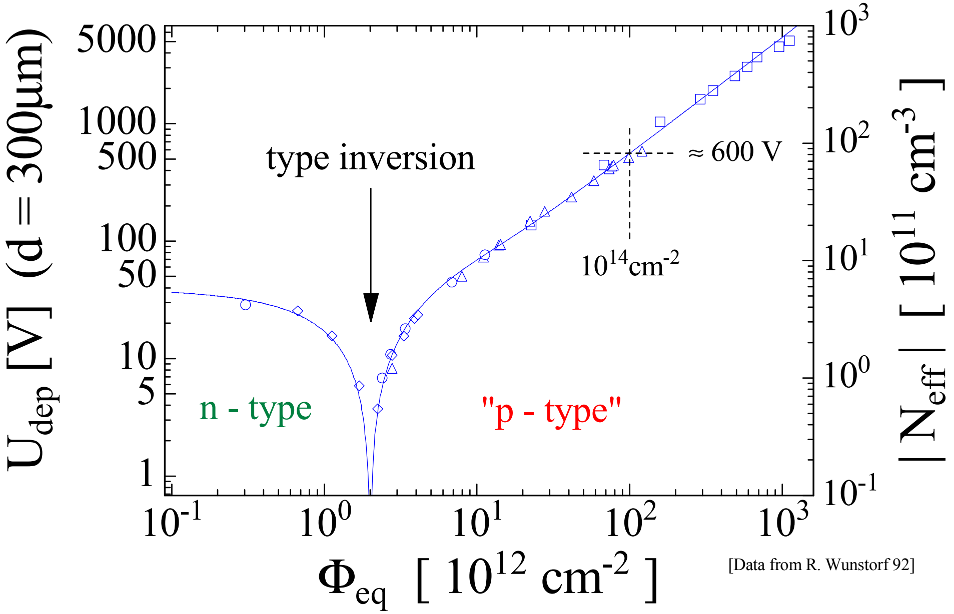
- **Damage parameter α (slope)**

$$\boxed{\alpha = \frac{\Delta I}{V \cdot \Phi_{eq}}}$$

- **α independent of Φ_{eq} and impurities**
  ⇨ used for fluence calibration (NIEL-Hypothesis)

- **Oxygen enriched and standard silicon show same annealing**
- **Same curve after proton and neutron irradiation**

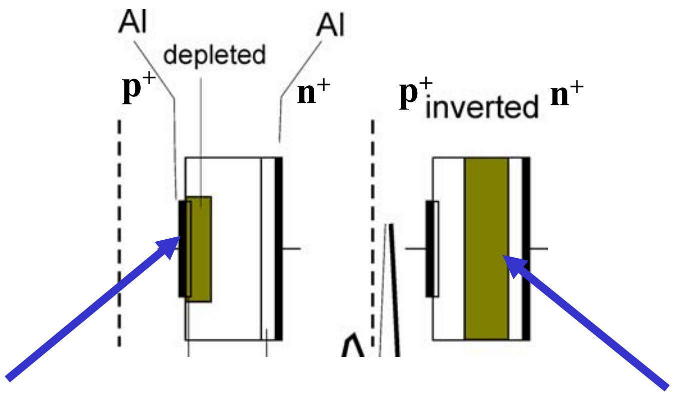
Depletion Voltage and Effective Space Charge Concentration



[Data from R. Wunstorf 92]

- **Type inversion:**

  SCSI – Space Charge Sign Inversion



before inversion

after inversion

after inversion and annealing saturation

$$N_{eff} \sim \beta \cdot \phi$$

V_{dep} and N_{eff} depends on storage time and temperature

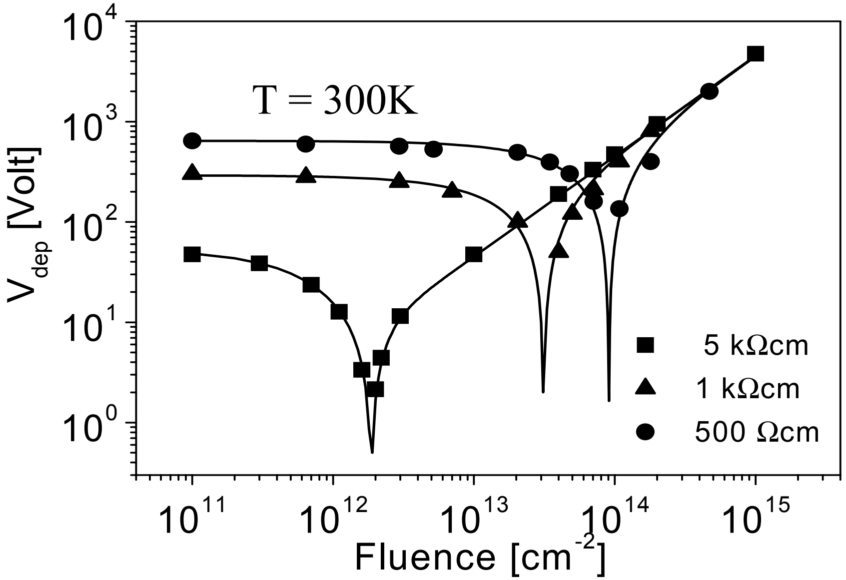
Stable Damage

$$\Delta N_{eff} = N_{C0}(1-e^{-c\cdot\phi}) + [g_c + g_a e^{-\frac{t}{\tau_a(T)}} + g_y(1-e^{-\frac{t}{\tau_y(T)}})]\phi$$

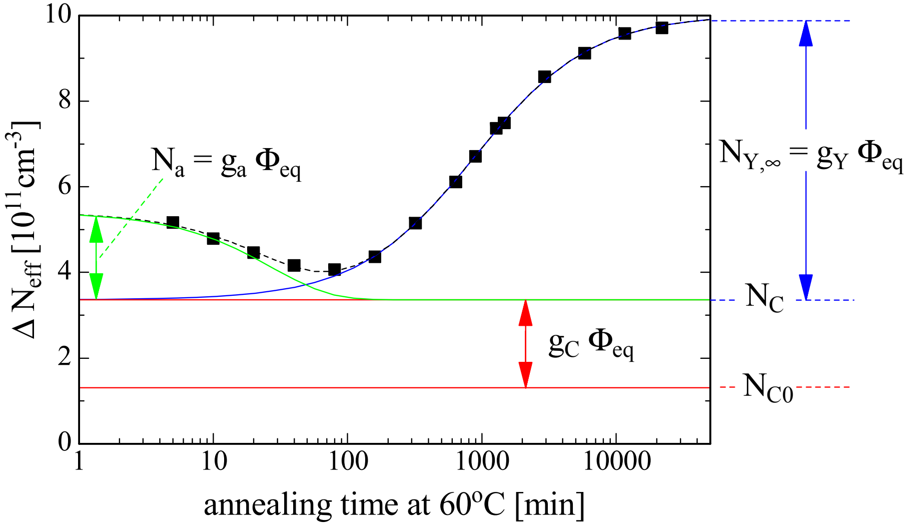
Beneficial Annealing

Reverse Annealing

ShallowDonor Removal



M. Bruzzi, Trans. Nucl. Sci. (2000)



G.Lindstroem et al, NIMA 426 (1999)

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

Charge Collection Efficiency

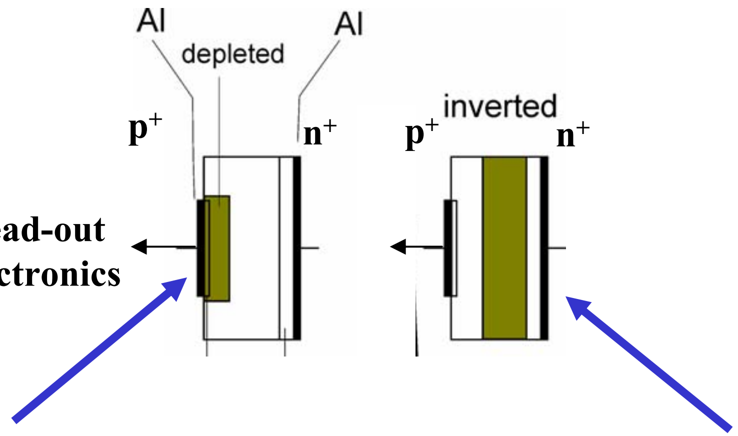
Limited by:

- **Partial depletion**
- **Trapping at deep levels**
- **Type inversion (SCSI)**

Collected Charge: $Q = Q_o \cdot \varepsilon_{\mathrm{dep}} \cdot \varepsilon_{trap}$

$$\varepsilon_{dep} = \frac{d}{W} \qquad \varepsilon_{trap} = e^{-\frac{\tau_c}{\tau_t}}$$

W: total thickness
d: Active thickness
τ_c : Collection time
τ_t : Trapping time



Read-out electronics

before inversion

after inversion
neglecting double junction

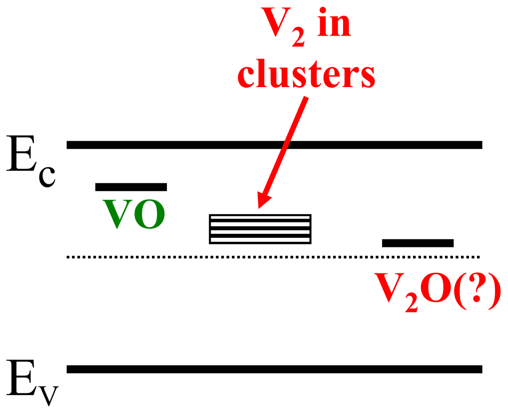
Defect Engineering of Silicon

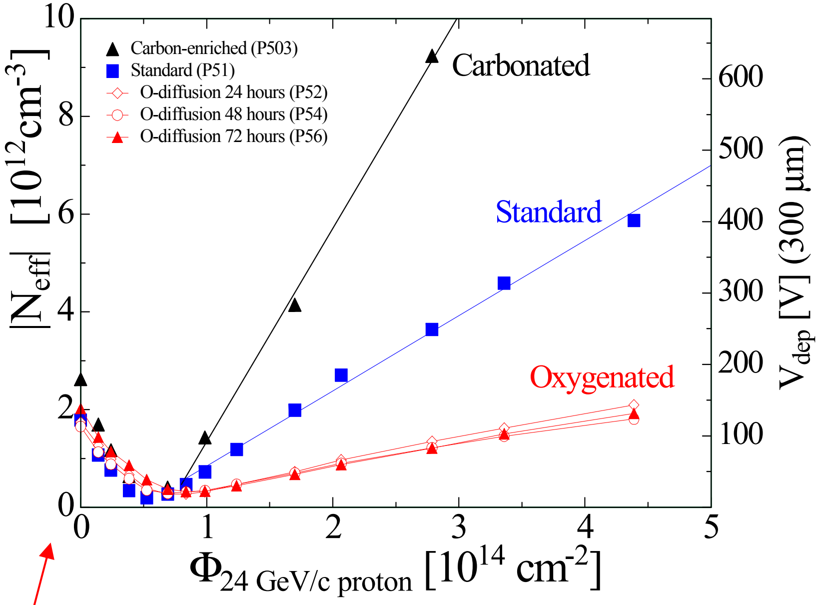
Influence the defect kinetics by incorporation of impurities or defects: Oxygen

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

•Higher oxygen content ⇒ less negative space charge
One possible mechanism: V_2O is a deep acceptor

V
O ⟶ VO (not harmful at RT)
VO ⟶ V_2O (negative space charge)





DOFZ (Diffusion Oxygenated Float Zone Silicon) RD48 NIM A465 (2001) 60

Different kind of Si materials investigated by RD50

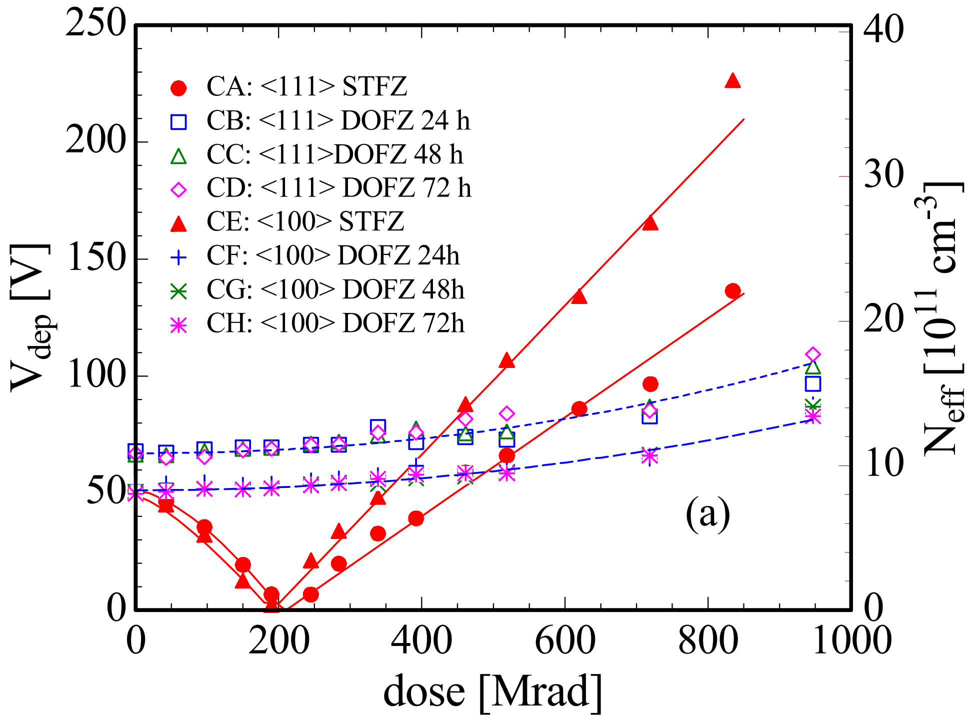
Material	Symbol	ρ Ωcm	$[O_i]$ cm^{-3}
Standard n-and p-type FZ	STNFZ	$1\text{-}7 \cdot 10^3$	$< 5\ 10^{16}$
Diffusion Oxygenated FZ p and n-type	DOFZ	$1\text{-}7 \cdot 10^3$	$\sim 1\text{-}2\ 10^{17}$
Epi-layer 50 µm on CZ n-type ITME	EPI	50-100	substrate: $1 \cdot 10^{18}$
Czochralski Sumitomo, Japan n-type	CZ	$1.2 \cdot 10^3$	$\sim 8\text{-}9\ 10^{17}$
Magnetic Czochralski Okmetic Finland n-type and p-type	MCZ	$1.2 \cdot 10^3$	$\sim 5\text{-}9\ 10^{17}$

Czochralski Si

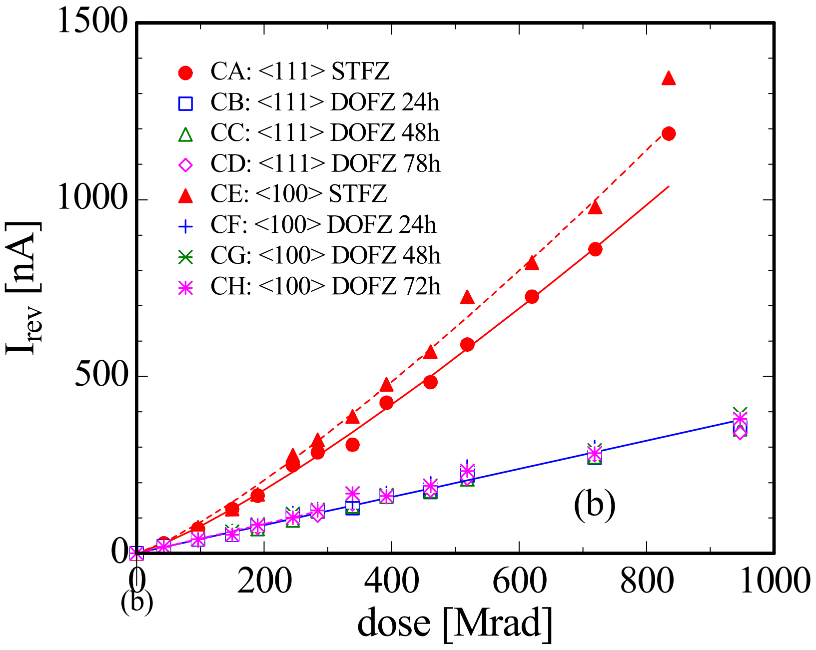
- Very high Oxygen content 10^{17}-10^{18}cm^{-3} **(Grown in SiO_2 crucible)**
- High resistivity (>1KΩcm) available only recently **(MCZ & CZ technology)**
- CZ wafers cheaper than FZ **(RF-IC industry got interested)**

DOFZ Si: Spectacular Improvement of γ-irradiation tolerance

Depletion Voltage



Leakage Current



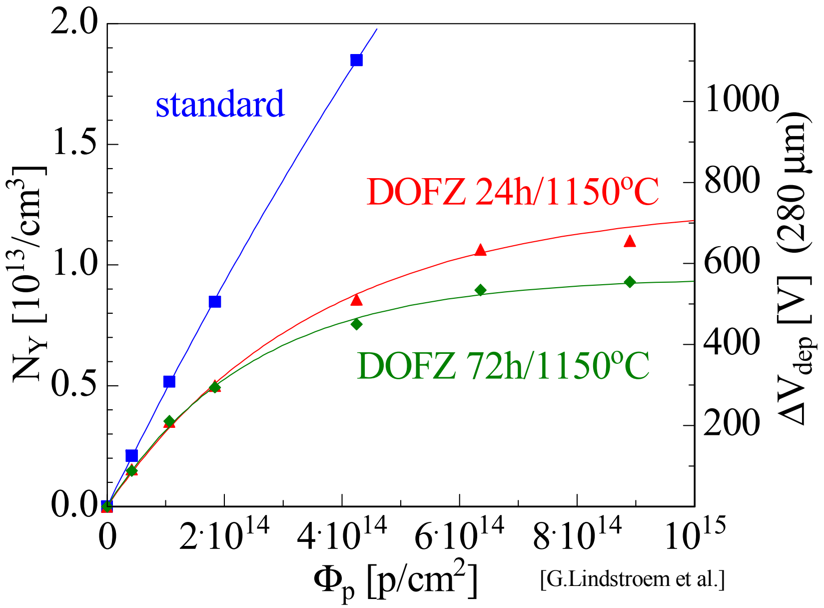
- No type inversion for oxygen enriched silicon!
- Slight increase of positive space charge

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

- Leakage increase not linear and depending on oxygen concentration

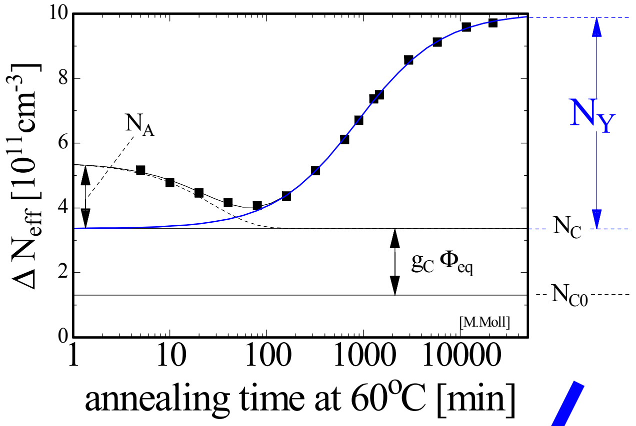
DOFZ Si Reverse annealing: saturation of amplitude and time constant linearly increasing with fluence

Data From G.Lindstrom et al.

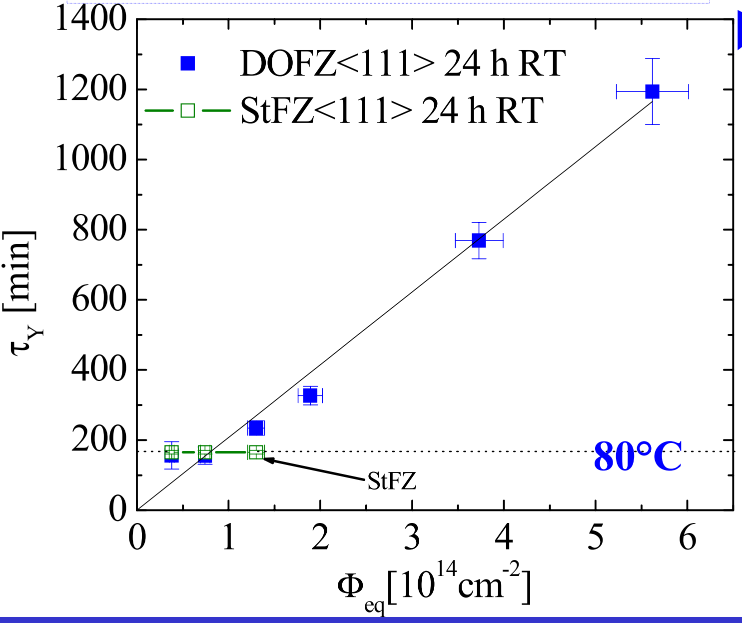


[G.Lindstroem et al.]

Saturation of amplitude



delayed reverse annealing



- Saturation of reverse annealing

  (24 GeV/c p - only little effect after neutron irradiation observed !)
- No big difference between 24h and 72h oxidation at 1150ºC
- time constant depending on fluence

Characterization of microscopic defects
- γ-irradiated silicon detectors -

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

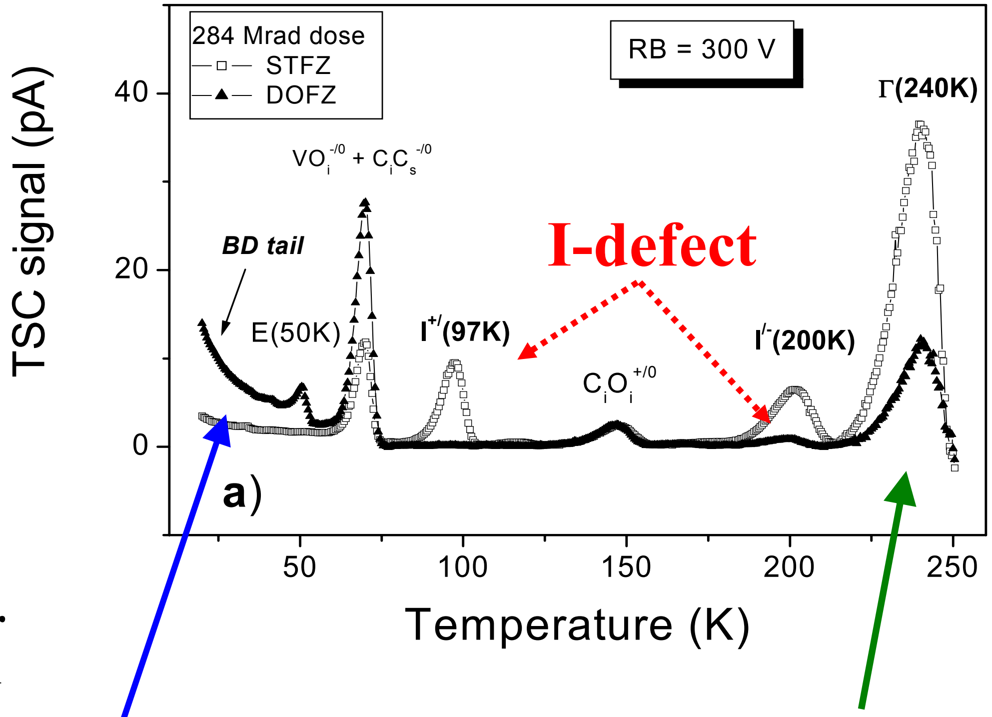
I.Pintilie et al., Applied Physics Letters,82, 2169, March 2003

Levels responsible for macroscopic changes after γ-irradiation:

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

- Γ-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)**



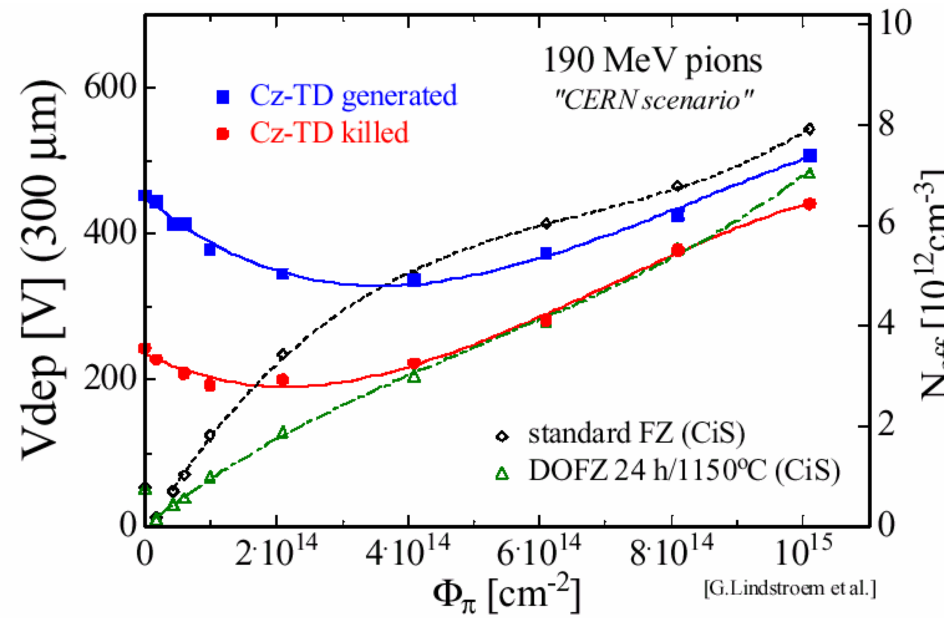
BD-defect

Γ-defect

Czochralski & Epitaxial Si

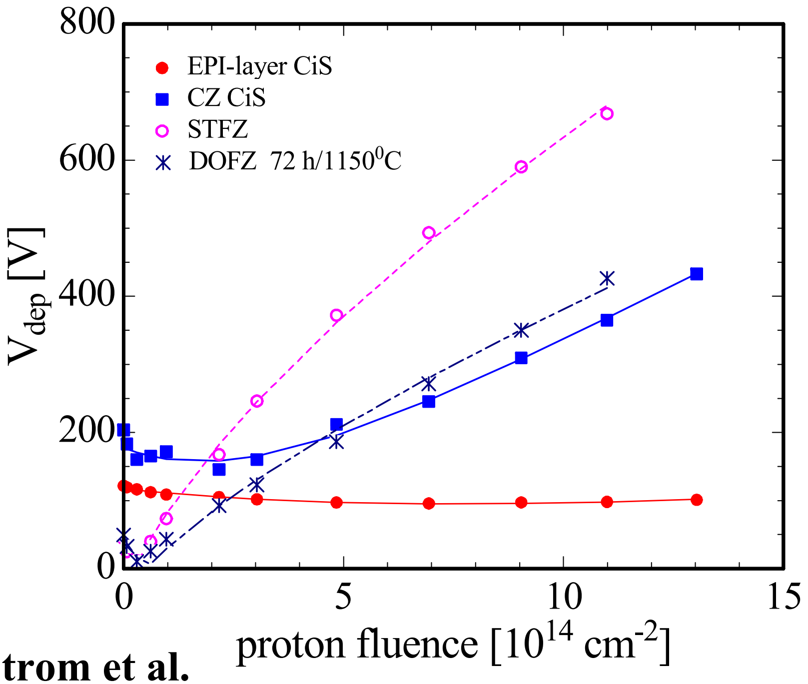
190 MeV π irradiation Villigen

Cz from Sumitomo Sitix, Japan



24 GeV/c p irradiation CERN

Cz from Sumitomo Sitix, Japan



Data From G.Lindstrom et al.

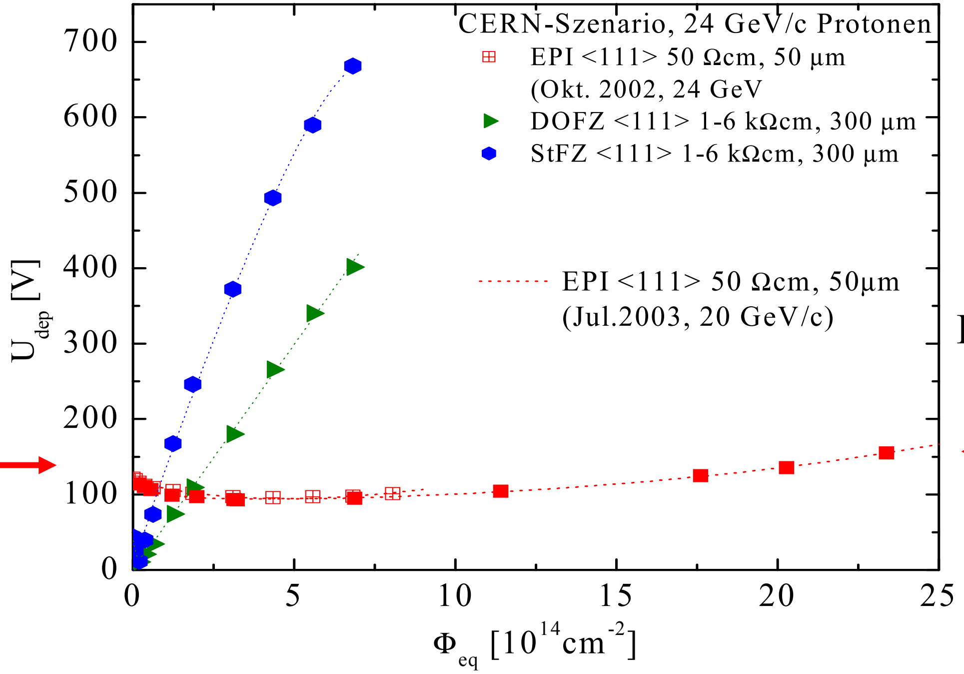
- **No type inversion (SCSI)**
- **Reverse current and charge trapping comparable to FZ silicon**

Epitaxial silicon

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

⇒ use thin detectors (50-100µm) from the beginning, with low resistivity Epitaxial Si

50µm, 50Ωcm on CZ Si made by ITME (Warsaw)



120 V →

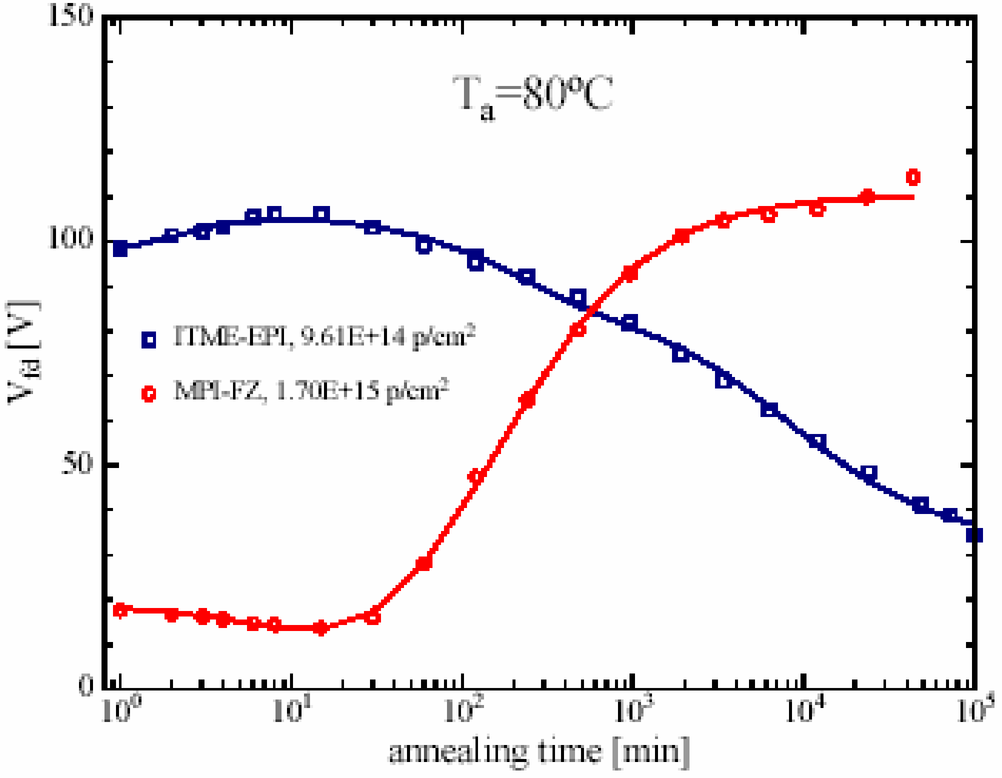
← **160 V**

Data From G.Lindstrom et al.

50µm thick, 50Ωcm

- Leakage current almost identical to CZ, FZ, DOFZ detectors
- No-type inversion
- Thickness studied: 25-75µm

different annealing behaviour in epitaxial Si → No need of low temperature in maintenance operation of SLHC



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

Main limitation at high fluence due to electron and hole trapping

Trapping times measured with Transient Current Technique (TCT) within RD50 with different n-type Si materials.

$$1/\tau_{e,h} = \beta_{e,h} \cdot \Phi_{eq}[\mathrm{cm}^{-2}]$$

Hamburg group $\beta_e = (4.68 \pm 0.15) \cdot 10^{-16}\mathrm{cm}^2\mathrm{ns}^{-1}$

(FZ,DOFZ,CZ) $\beta_h = (5.72 \pm 0.50) \cdot 10^{-16}\mathrm{cm}^2\mathrm{ns}^{-1}$

After 24 GeV/c p to a $\Phi_{eq} = 6 \cdot 10^{14}\mathrm{cm}^{-2}$

Dortmund group $\beta_e = (5.13 \pm 0.16)\ 10^{-16}\mathrm{cm}^2\mathrm{ns}^{-1}$

(DOFZ) $\beta_h = (5.04 \pm 0.18)\ 10^{-16}\mathrm{cm}^2\mathrm{ns}^{-1}$

After 24 GeV/c p up to a $\Phi_{eq} = 10^{15}\mathrm{cm}^{-2}$

→ $\tau_t \sim 1/\Phi$ $\tau_t \sim 0.2$ ns for $\Phi = 10^{16}\ \mathrm{cm}^{-2}$

No significant material difference

Recent results with n-in-p microstrip detectors

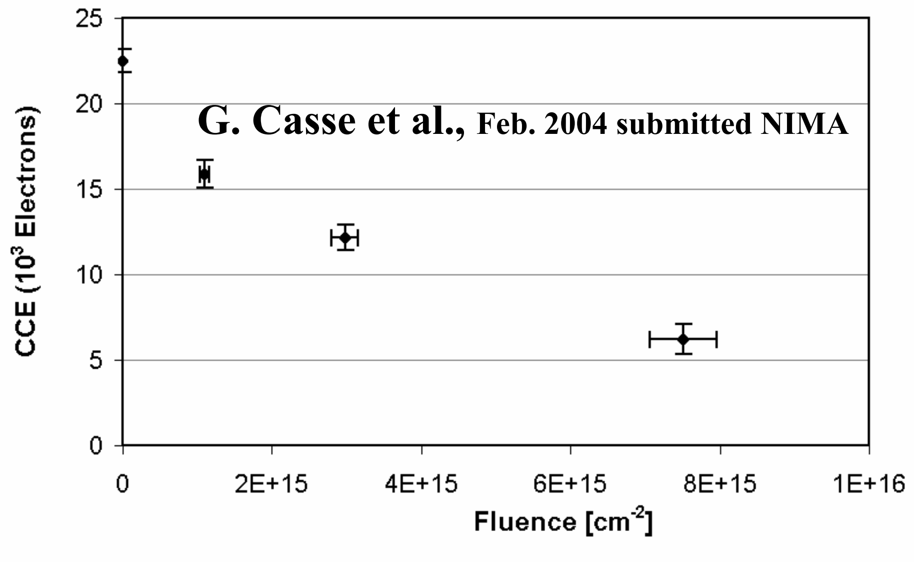
Liverpool & CNM-Barcelona within RD50

Data presented by G. Casse at Vienna Conference, February 2004

- ☐ Miniature n-in-p microstrip detectors (280µm thick) produced by CNM-Barcelona using a mask-set designed by the University of Liverpool.
- ☐ Detectors read-out with a SCT128A LHC speed (40MHz) chip
- ☐ Material: standard p-type and oxygenated (DOFZ) p-type
- ☐ Irradiation: 24GeV protons up to 3 10^{15} p cm^{-2} (standard) and 7.5 10^{15} p cm^{-2} (oxygenated)

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)



G. Casse et al., Feb. 2004 submitted NIMA

At the highest fluence Q~6500e at V_{bias}=900V. Corresponds to: ccd~90µm, trapping times 2.4 x larger than previously measured.

Activity in progress in RD50 on microstrip/pixel detectors with defect engineered Si

Miniature microstrip detectors have been produced or are under process with FZ, DOFZ, MCZ, epitaxial n-type and p-type Si by:

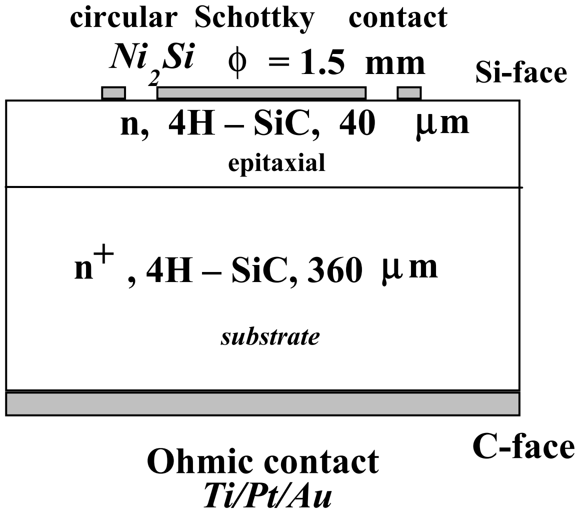
- CNM Barcelona & Liverpool
- IRST-Trento & italian groups (INFN)
- Helsinki HIP
- Common RD50 process is under way

Pixels are currently in process:

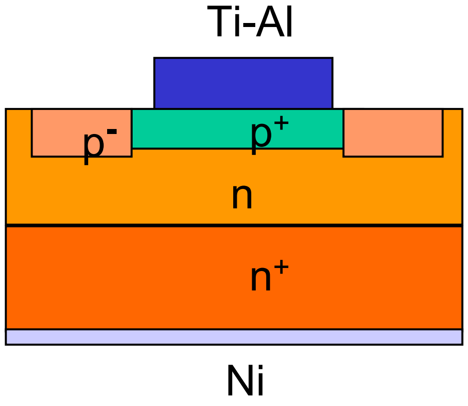
- MCz, FZ, DOFZ n-type Si with Sintef using CMS/FPix masks (Purdue)
- MCz n-type Si with pixel and strips at BNL (Purdue, Rochester, BNL)
- CMOS Active Pixel Detectors (Perugia) see D. Passeri talk next session

Silicon Carbide detectors

- **Semi-Insulating SiC**
  - CCE 60% in as-grown CREE vanadium compensated, ~55% after irradiation with 10^{13}cm^{-2} 300 MeV/c π
  - Vanadium-free semi-insulating material from Okmetic: ~100% CCE in unirradiated material
- **Epitaxial SiC**
  - 6 new 2” wafers d~50μm, $N_{eff} \geq 5 \cdot 10^{13}$cm^{-3} produced by IKZ, Berlin
  - Common RD50 test structures produced and irradiated. Tests in progress
  - 100% CCE in unirradiated material



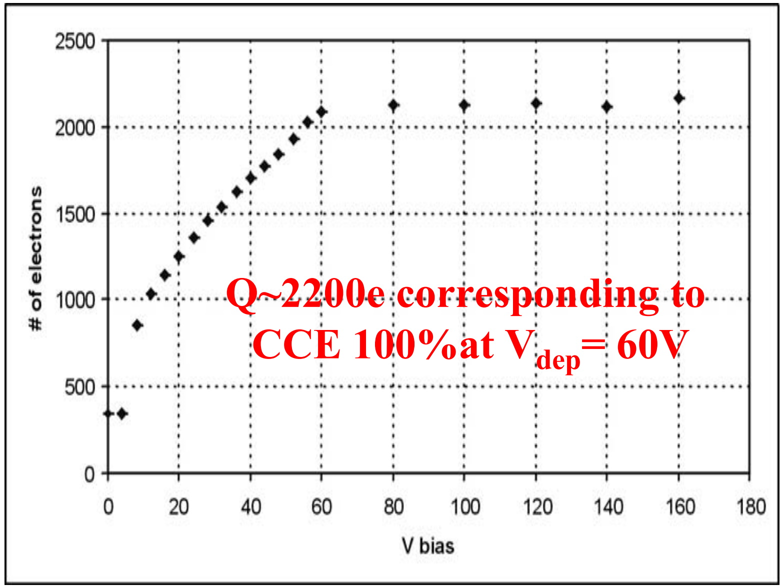
Modena&Alenia Systems, Italy



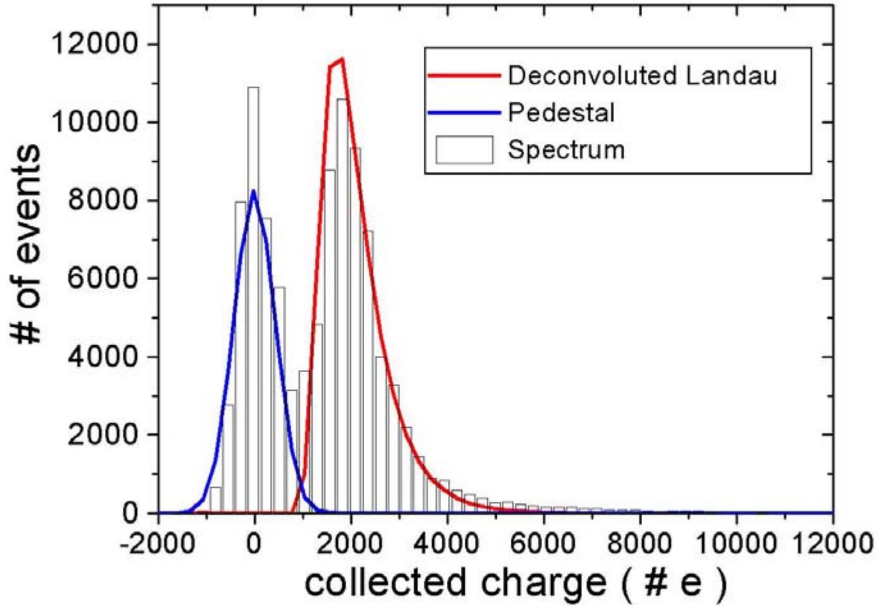
Perugia&IMM Bologna,Italy

First charge collection tests on epitaxial SiC

- n epilayer N_{eff} ~5×10^{13}cm^{-3} 40µm by IKZ Berlin on CREE substrate; Schottky contacts
- No priming effects observed
- CCE tested with β ^{90}Sr (2µs shaping time) 2200e at V_{dep} = 60V



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



F. Nava et al., IEEE Trans. Nucl. Sci, (2004)

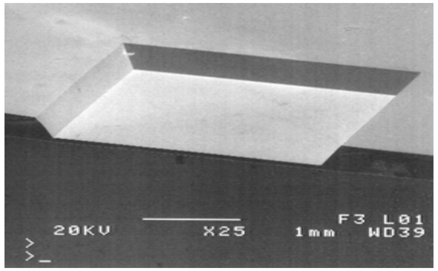
Device Engineering: thin detectors

- **Benefits:**
  - low operating voltage
  - improved radiation tolerance: 50-200μm thick, lower initial resistivity needed
- **Drawbacks**:
  - Lower mip signal in the low fluence range
- **Technical Approaches:**
  - Epitaxial Si device (shown before)
  - Thinning with chemical attacks and micro-machining

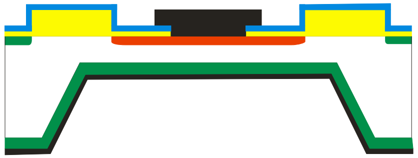
- **Thin Si pad detectors have been produced by ITC-IRS Trento thickness 50-100μm, irradiated at CERN up to 10^{16}cm^{-2} 24GeV p**

- **Purdue is currently processing thin segmented detectors with Micron (150-200 μ**
- **Miniature microstrip detectors have been produced IRST-Trento on epi Si 50μm t**

IRST: SEM of a silicon wafer thinned by TMAH



Cross section of a thinned silicon detector

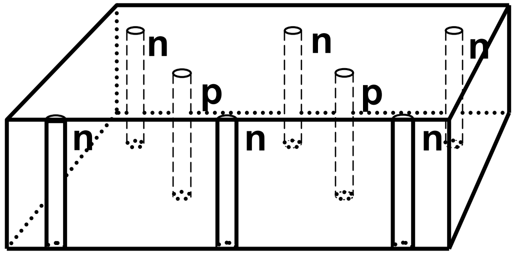


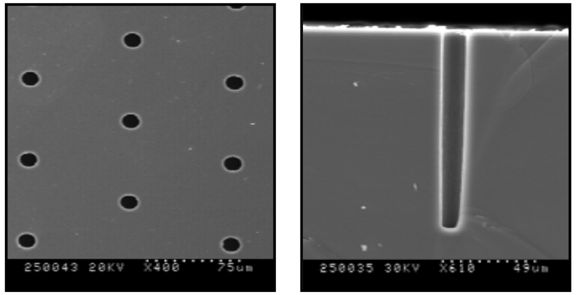
Device Engineering: 3D detectors

proposed by Sherwood Parker

- 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**

Present size up to ~1cm^2





Advantage: application possible with all radiation-hard materials.

Within RD50, IRST-Trento is developing 3D detectors, in collaboration with CNM Barcelona and Glasgow groups.

Other activities: semi-3D detectors (BNL&US groups)

Summary

- **Radiation hard materials for tracker detectors at SuperLHC are under study by the CERN RD50 collaboration.**
- **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 detectors : drawback: radiation hard electronics for low signals needed
  3D detectors: drawback: technology has to be optimized

- **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 studies after irradiation with LHC-like electronics are encouraging: CCE on microstrip n-in-p oxygenated detector irradiated up to $7x10^{15}$ [$24GeVp/cm^2$] is > 6500e.**

- **New Materials like SiC,GaN are under investigation. More radiation studies needed.**

RD50 web-site: www.cern.ch/rd50