SNIC – Stanford Linear Accelerator, April 5, 2006

Radiation Tolerant Tracking Detectors

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on behalf of the CERN RD50 Collaboration

INFN and University of Florence, Italy

http://www.cern.ch/rd50

The LHC Upgrade

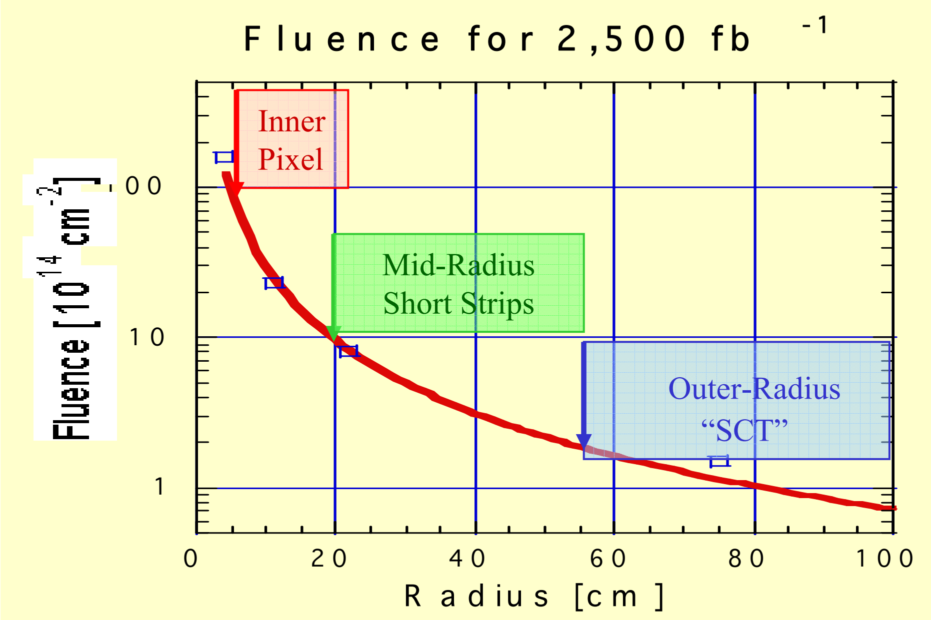
Present working conditions: **$L \sim 10^{34}$ cm^{-2}s^{-1} (10 years operation)**

→ **$\phi \sim 10^{15}$ n/cm^2 (pixels) ; $\phi \sim 10^{14}$ n/cm^2 (microstrips)**

- **An increase of luminosity of LHC up to 10^{35}cm^{-2}s^{-1} discussed since 2002.**
- **Anticipated date for installation of the upgrades in CMS-ATLAS experiment around 2015.**
- **Upgrade will allow a 20-30% increase in mass reach for each experiment and the continuation of measurements on rare processes that are statistics limited after several years of data collection.**

Main constraint is the survival of the Si detector tracker to the exceptionally high fluences of fast hadrons

Fast hadron fluence up to $\phi \sim 10^{16}$ cm^{-2}



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The CERN RD50 Collaboration

http://www.cern.ch/rd50

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

- formed in November 2001
- approved as RD50 by CERN 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 260 members from 53 institutes

Belarus (Minsk), Belgium (Louvain), Canada (Montreal), Czech Republic (Prague (3x)), Finland (Helsinki, Lappeenranta), Germany (Berlin, Dortmund, Erfurt, Freiburg, Hamburg, Karlsruhe, Munich), Israel (Tel Aviv), Italy (Bari, Bologna, Florence, Padova, Perugia, Pisa, Trento, Turin), Lithuania (Vilnius), 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, Oxford, Sheffield, Surrey), USA (Fermilab, Purdue University, Rochester University, SCIPP Santa Cruz, Syracuse University, BNL, University of New Mexico)

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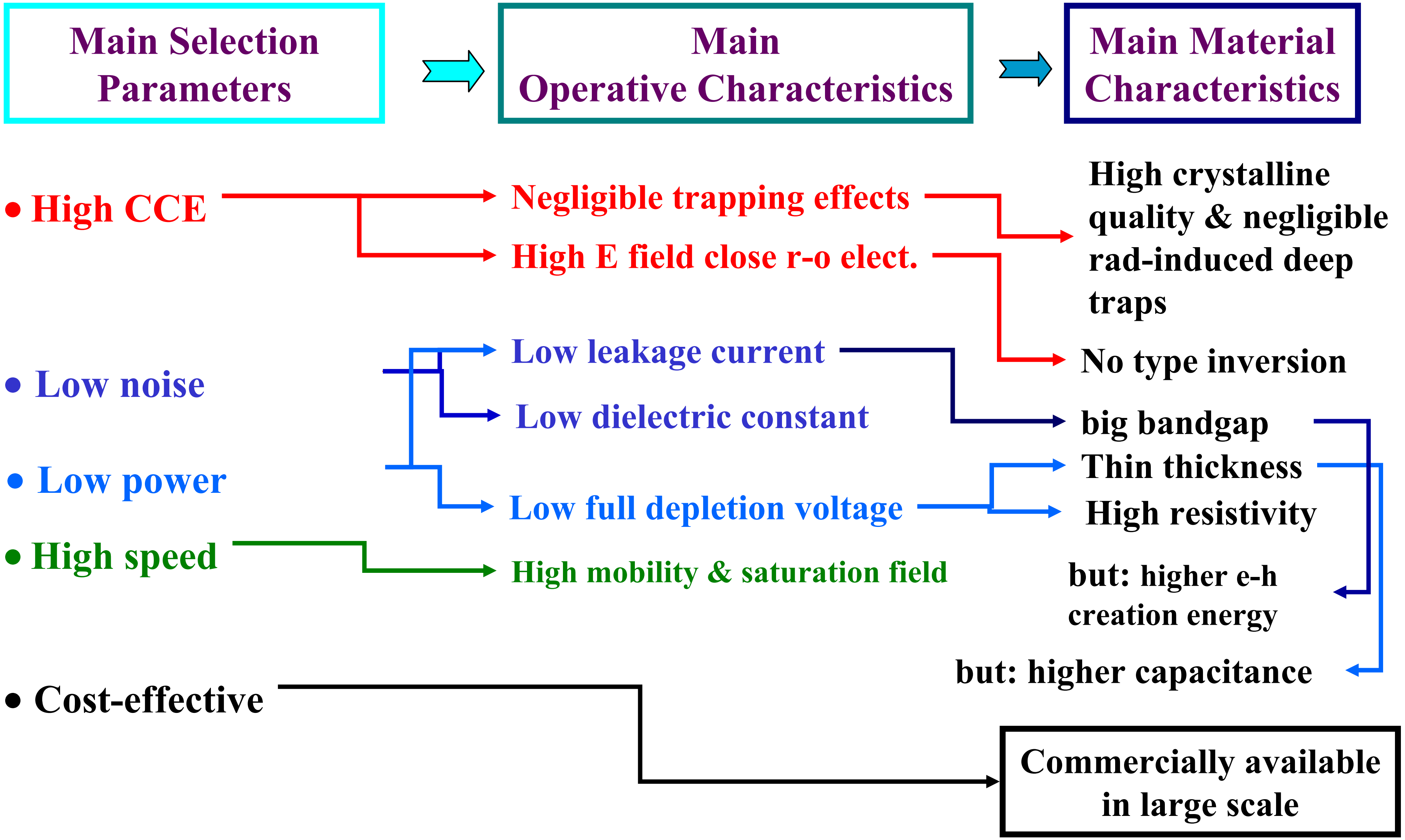
Selecting radiation- hard materials for tracker detectors at SuperLHC



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

Approaches to develop radiation harder tracking detectors

Scientific strategies:

I. **Material engineering**

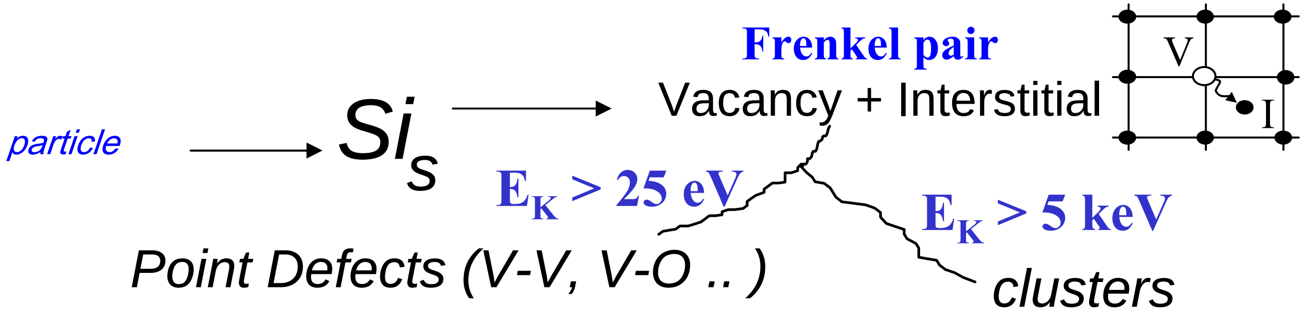
II. **Device engineering**

III. **Change of detector operational conditions**

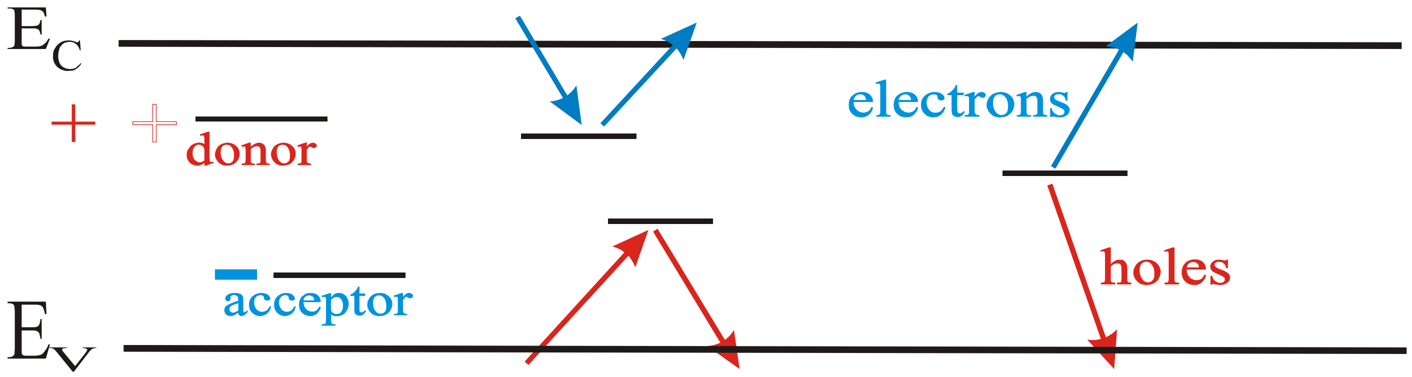
CERN-RD39
"Cryogenic Tracking Detectors"

- **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 Si**
  - **Pre-irradiated Si**
  - **Influence of processing technology**
- **New Materials**
  - **Silicon Carbide (SiC), Gallium Nitride (GaN)**
  - **Diamond: CERN RD42 Collaboration**
- **Device Engineering (New Detector Designs)**
  - **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**

Radiation Induced Microscopic Damage in Silicon



Influence of defects on the material and device properties



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

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

generation
$\Rightarrow$ **leakage current**
Levels close to midgap most effective

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 (?) ⟸

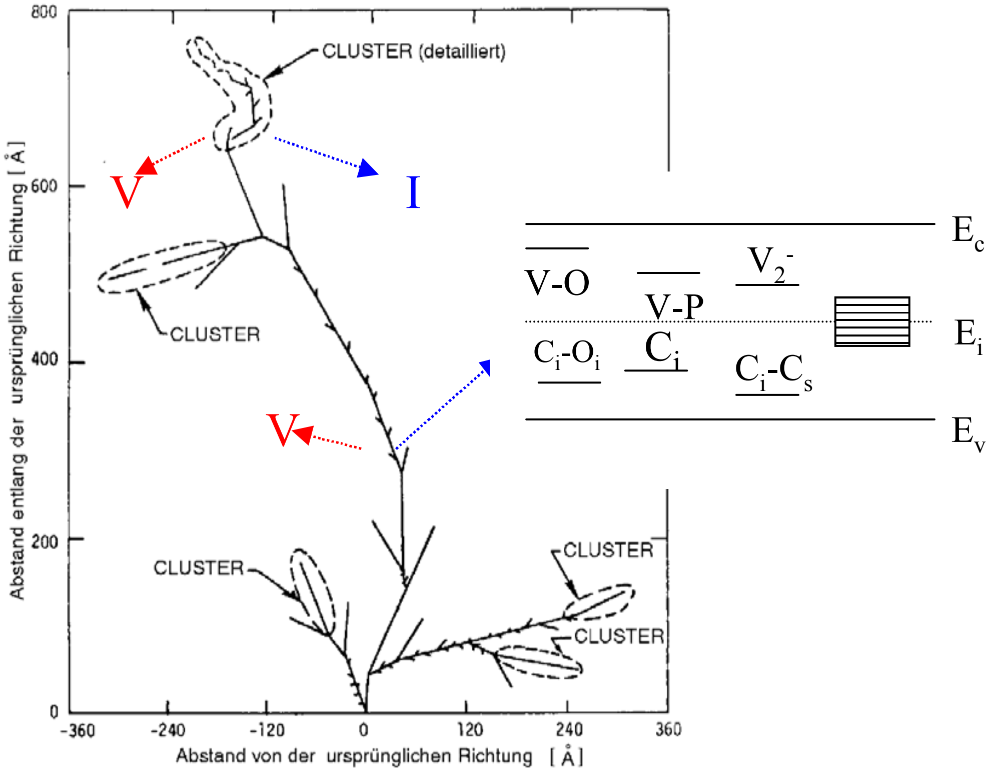
- **Secondary defect generation**

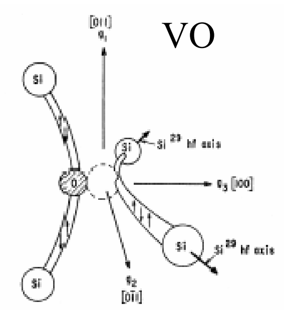
Main impurities in silicon: Carbon (C_s)
Oxygen (O_i)

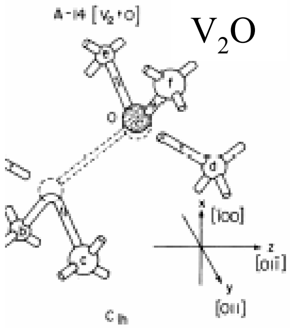
$I+C_s \rightarrow C_i \Rightarrow C_i+C_s \rightarrow C_iC_s$
$C_i+O_i \rightarrow C_iO_i$
$C_i+P_s \rightarrow C_iP_s$

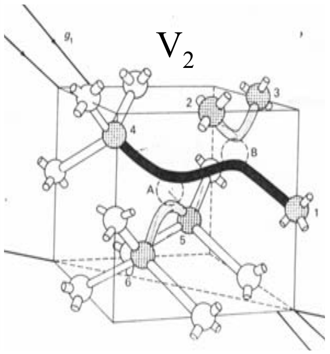
$V+V \rightarrow V_2$ $V+V_2 \rightarrow V_3$
$V+O_i \rightarrow VO \Rightarrow V+VO \rightarrow V_2O$
$V+P_s \rightarrow VP_s$

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









Vacancy amount and distribution vs particle kind and energy

^{60}Co-gammas

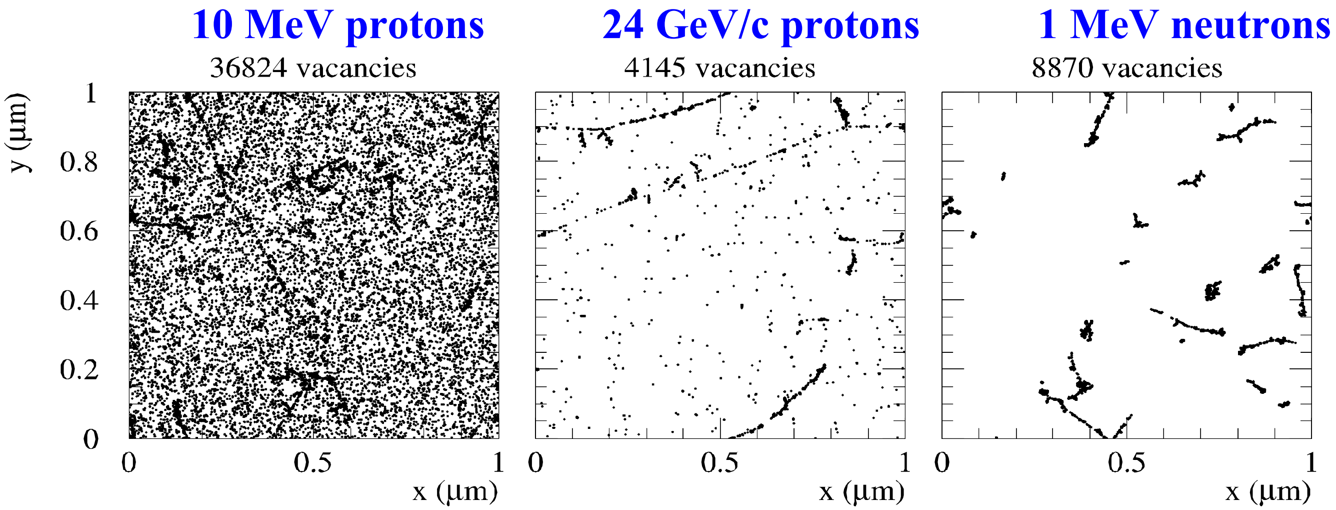
- Compton Electrons with max. $E_\gamma \approx 1$ MeV (no cluster production)

Neutrons (elastic scattering)

- $E_n > 185$ eV for displacement
- $E_n > 35$ keV for cluster

Only point defects ⟷ point defects & clusters ⟷ Mainly clusters

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

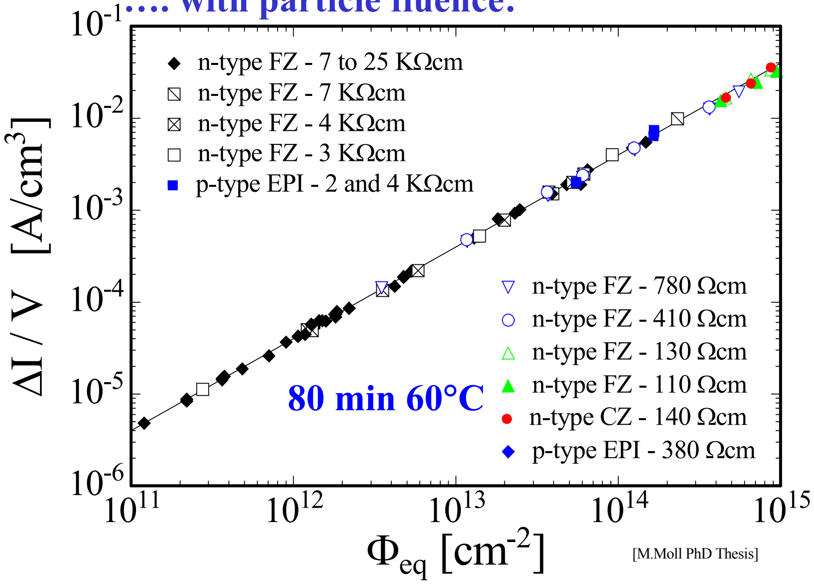


[Mika Huhtinen NIMA 491(2002) 194]

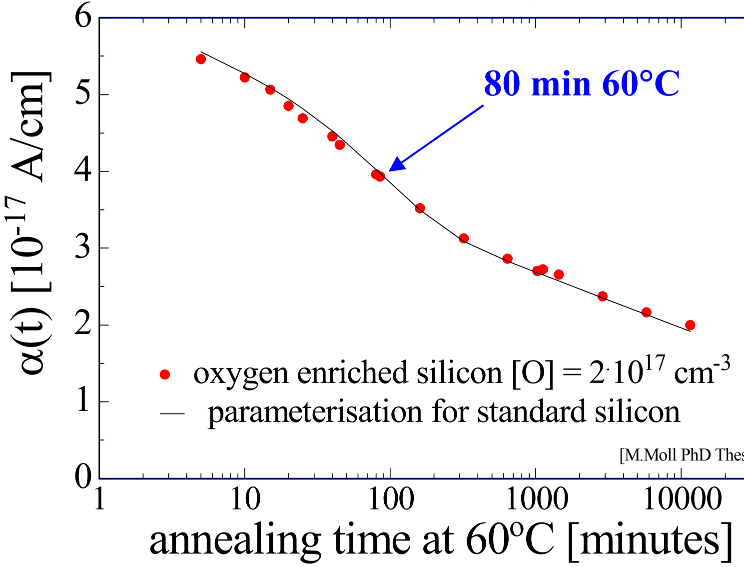
RD50 Radiation Damage – I. Leakage Current

- **Change of Leakage Current (after hadron irradiation)**

…. with particle fluence:



…. with time (annealing):



- **Damage parameter α (slope in figure)**

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

Leakage current per unit volume and particle fluence

- **α is constant over several orders of fluence and independent of impurity concentration in Si**
  ⇨ **can be used for fluence measurement**

- **Leakage current decreasing in time (depending on temperature)**
- **Strong temperature dependence**

$$I \propto \exp\left(-\frac{E_g}{2k_B T}\right)$$

Consequence:

Cool detectors during operation!
Example: I(-10°C) ~1/16 I(20°C)

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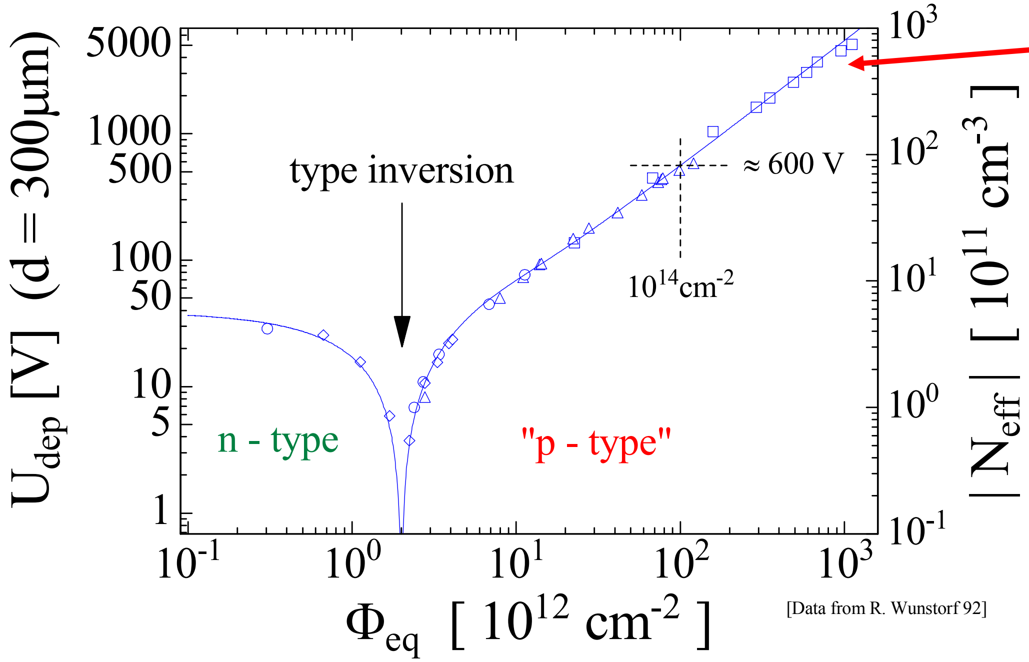
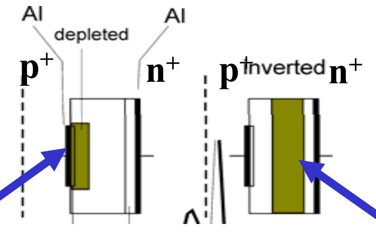
II. Depletion Voltage and N_{eff} vs fluence



[Data from R. Wunstorf 92]

We expect $V_{fd} > 10^3V$ @ $10^{15}cm^{-2}$: high resistivity FZ Si no viable solution



before inversion

after inversion

neglecting double junction

SCSI – Space Charge Sign Inversion

After inversion and annealing saturation

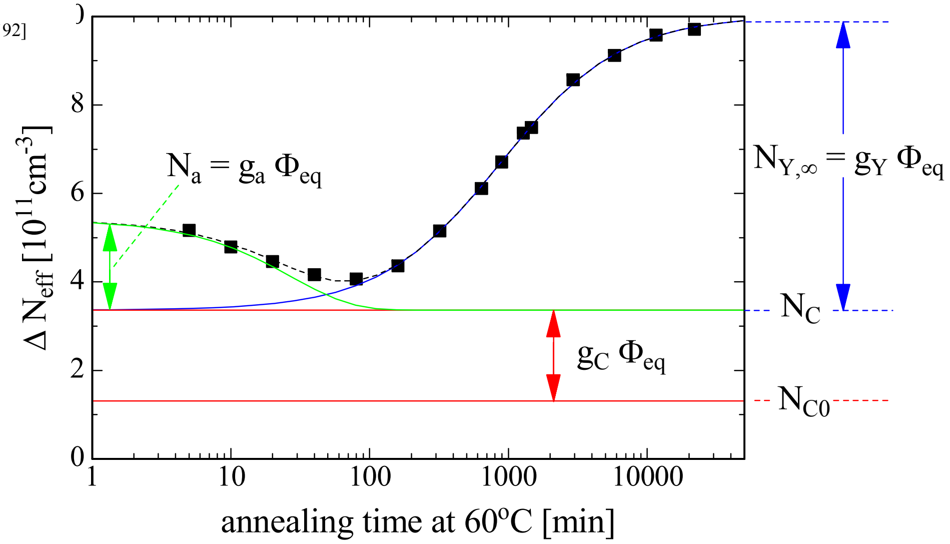
$$N_{eff} \sim \beta \cdot \phi$$

- Short term: "**Beneficial annealing**"
- Long term: "**Reverse annealing**"

  time constant : ~ 500 years (-10°C)

  ~ 500 days (20°C)

  ~ 21 hours (60°C)



III. Decrease of CCE

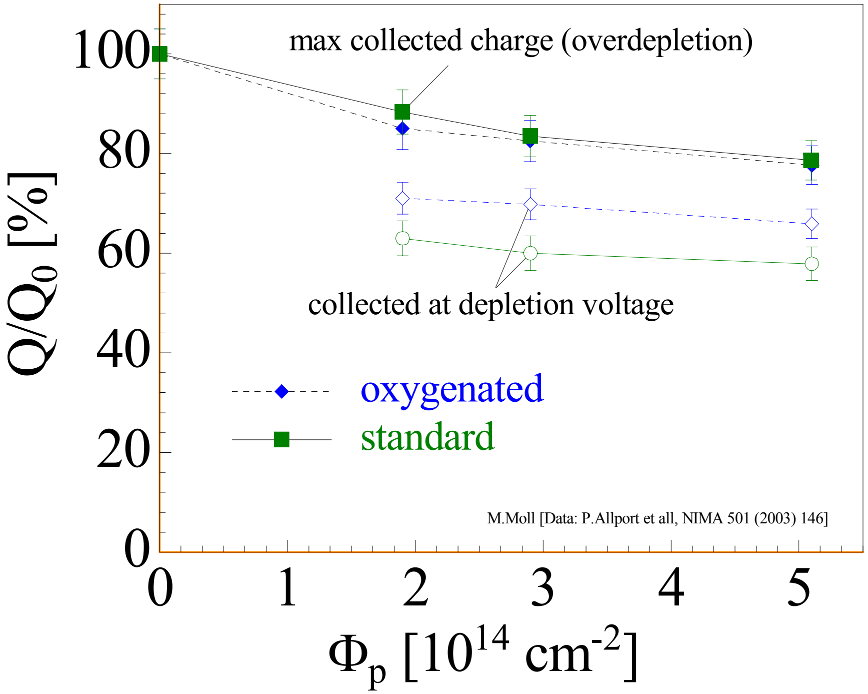
$$Q = Q_o \cdot \varepsilon_{dep} \cdot \varepsilon_{trap}$$

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

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

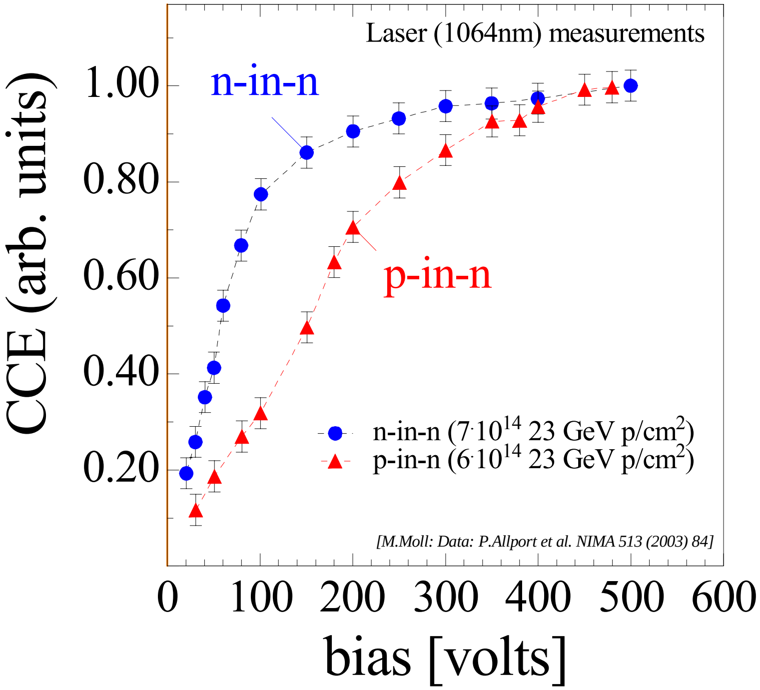
Limited by:
- **Partial depletion**
- **Trapping at deep levels**
- **Type inversion (SCSI)**

- **p-in-n : oxygenated versus standard FZ**
  - beta source
  - 20% charge loss after 5×10^{14} p/cm^2 (23 GeV)



M.Moll [Data: P.Allport et all, NIMA 501 (2003) 146]

- **n-in-n versus p-in-n**
  - same material, ~ same fluence
  - over-depletion needed



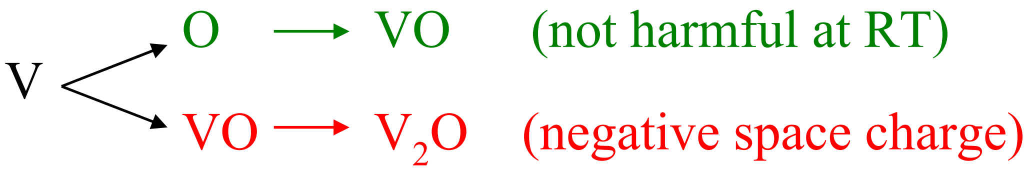
[M.Moll: Data: P.Allport et al. NIMA 513 (2003) 84]

RD50 Defect Engineering of Silicon

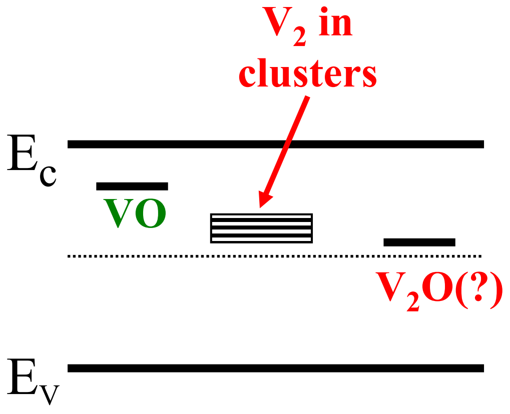
Influence the defect kinetics by incorporation of impurities or defects: <u>Oxygen</u>

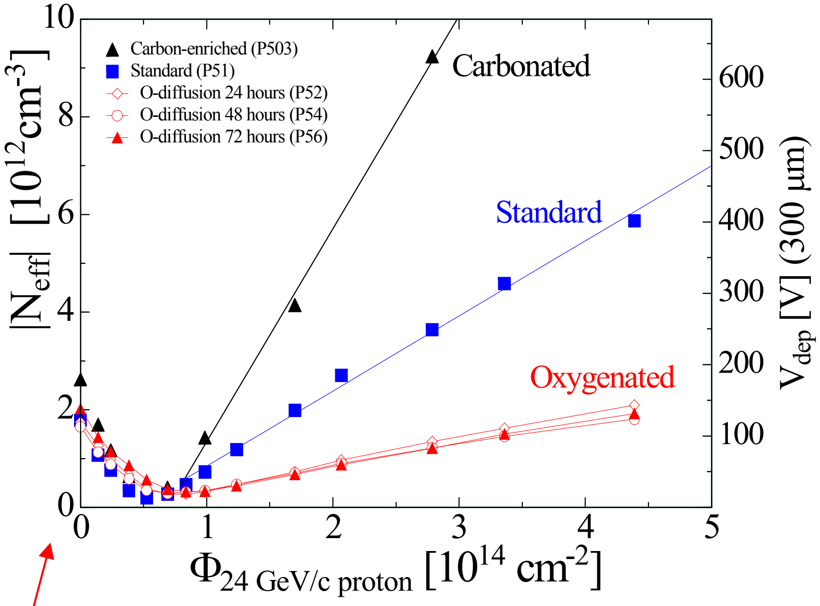
Initial idea: **Incorporate Oxygen to getter radiation-induced vacancies**
⇒ **prevent formation of Di-vacancy (V_2) related deep acceptor levels**

•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

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Silicon Materials under Investigation by RD50

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

- **CZ silicon:**
  - high O_i (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)

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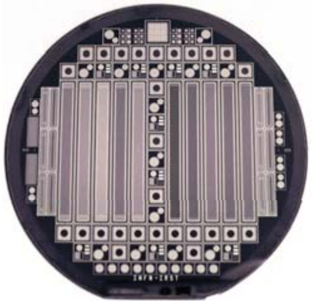
Process of segmented Si sensors

Development of MCz & FZ Si n- and p-type microstrip/pixel sensors

Two runs 20 wafers each 4”
mini-strip 0.6x4.7cm^2, 50 and 100µm pitch, AC coupled
37 pad diodes and various text structures
P-type: two p-spray doses 3E12 amd 5E12 cm^{-2}
Wafers processed by IRST, Trento on 200-500µm



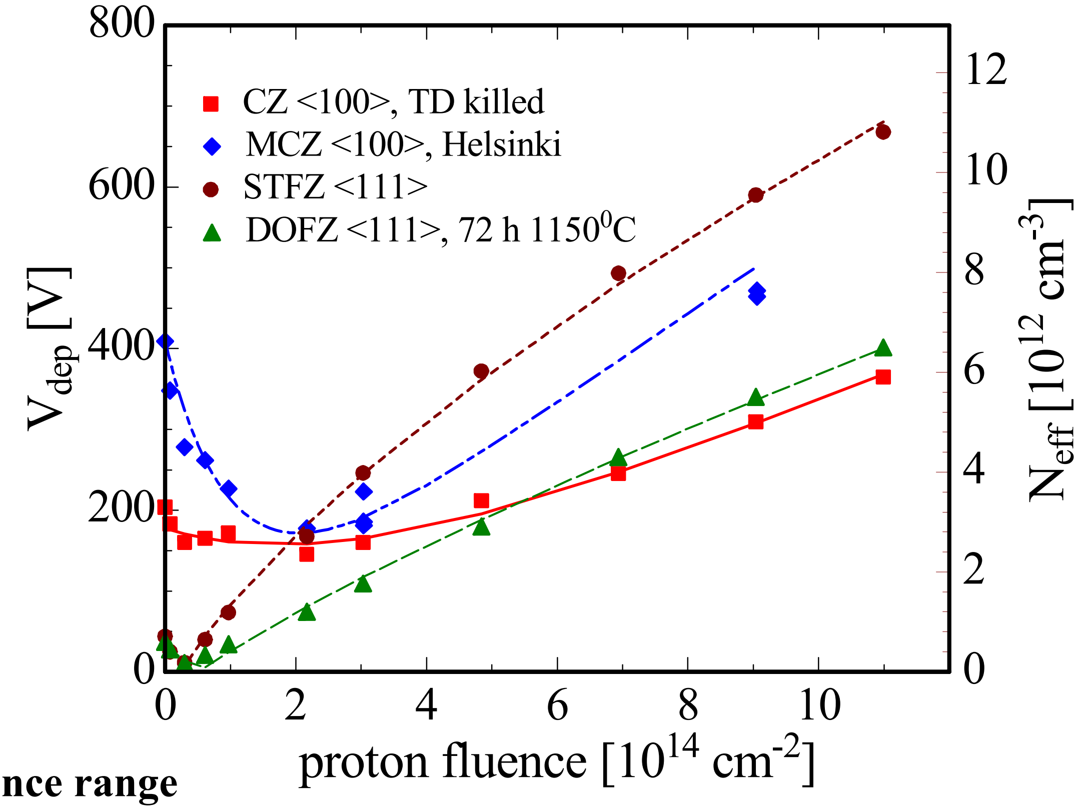
CNM, Barcelona p-in-n and n-in-p, FZ and DOFZ Si
Mask set designed by RD50
Surface insulation provided only by p-spray

n-type MCZ and FZ Si Wafers processed by SINTEF
300µm, within USCMS forward pixel project

Micron will produce microstrips on 300µm and 140µm thick 4” p-type FZ and DOFZ Si. By June 2006 devices from 6” MCz and FZ Si will be produced also.

RD50 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%

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Levels responsible for depletion voltage changes after proton irradiation in oxygenated Si (MCz, DOFZ)

Almost independent of oxygen content:
- **Donor removal**
- **“Cluster damage” ⇒ negative charge**

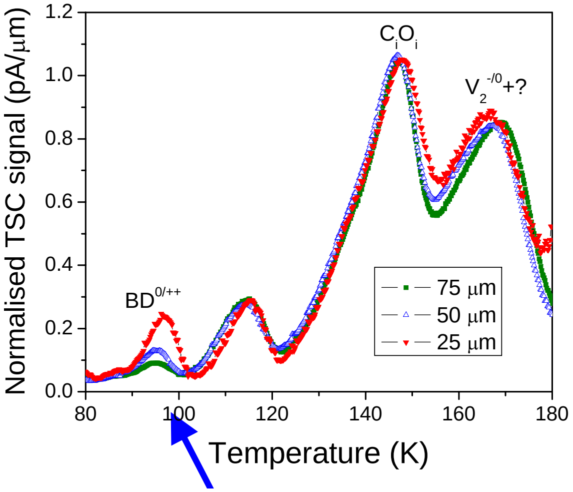
Influenced by initial oxygen content:
- **I–defect:** deep acceptor level at E_C-0.54eV
  (good candidate for the V_2O defect)
  ⇒ **negative charge**

significantly reduced in DOFZ, MCz EPI Si

Influenced by initial oxygen (dimer ?) content:
- **BD-defect:** bistable shallow thermal donor
  (formed via oxygen dimers O_{2i})
  ⇒ **positive charge**

Radiation induced in DOFZ, MCz, EPI Si

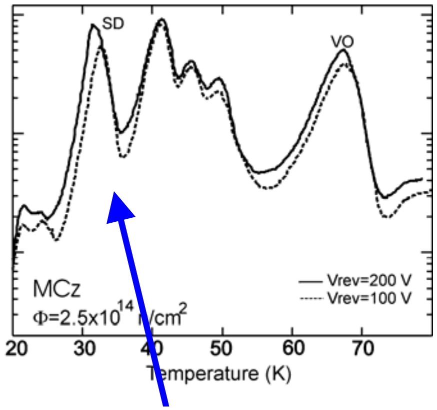
[G. Lindstroem, RD50 Workshop, Nov..2005]



Epi 50µm 23 GeV p irradiated, Φ=4×10^{14} cm^{-2}

Bistable Donor component

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



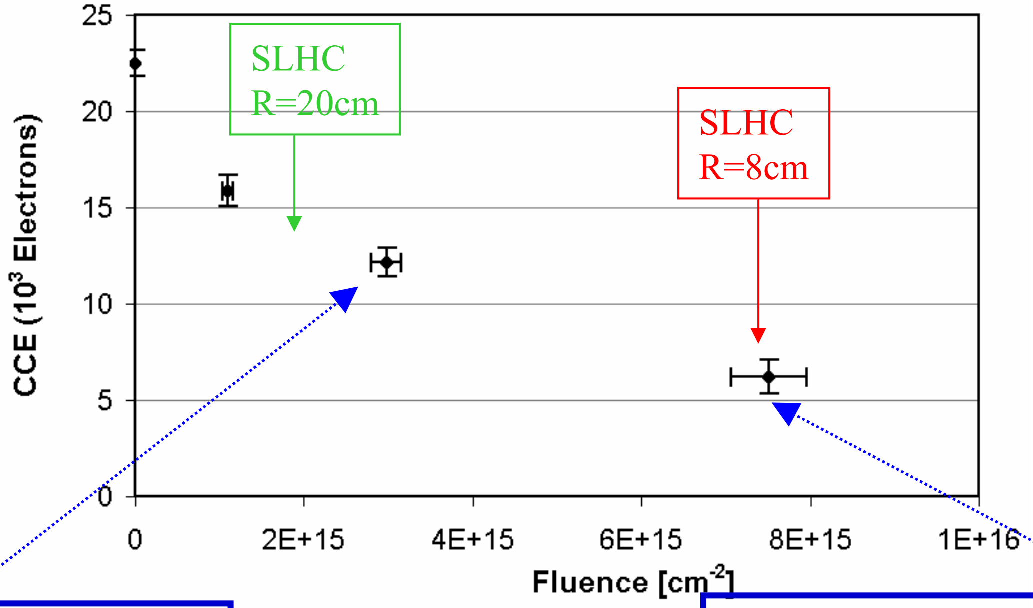
MCz n-type 26 MeV p irradiated, Φ=4×10^{14} cm^{-2}

charged shallow defect

RD50 n-on-p microstrip detectors FZ & DOFZ

n-on-p: - no type inversion, high electric field stays on structured side
- collection of electrons

- 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., NIMA535(2004) 362

At the highest fluence Q~6500e at V_{bias}=900V

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)

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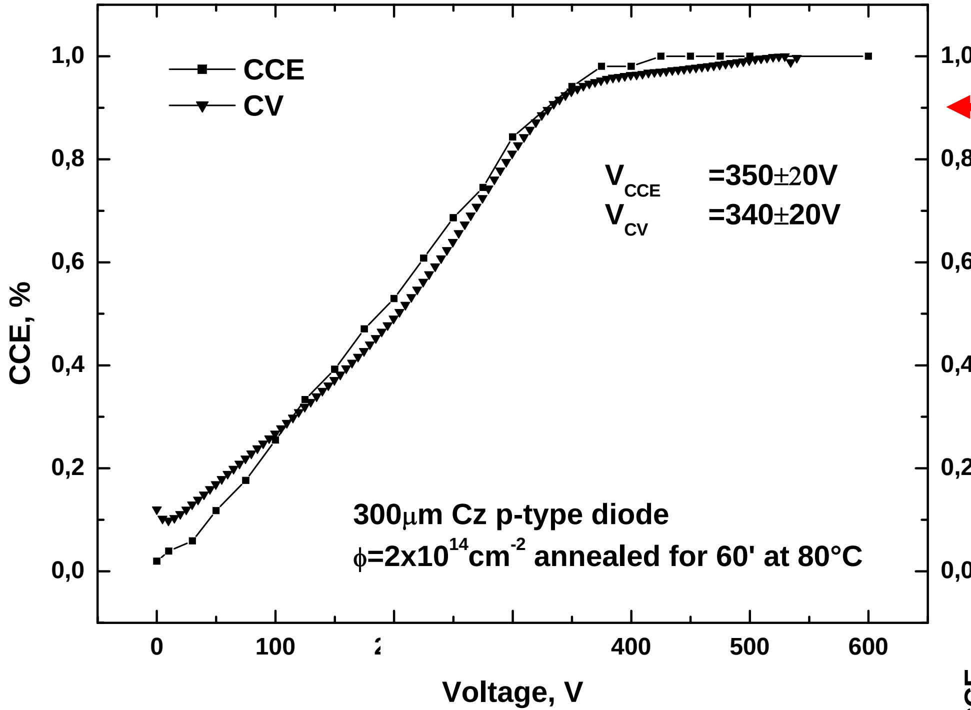
CCE of single pad MCz Si n-on-p detectors after 26MeV p irradiation



Φ = 1.36 10^{14} cm^{-2} (1MeV n eq)

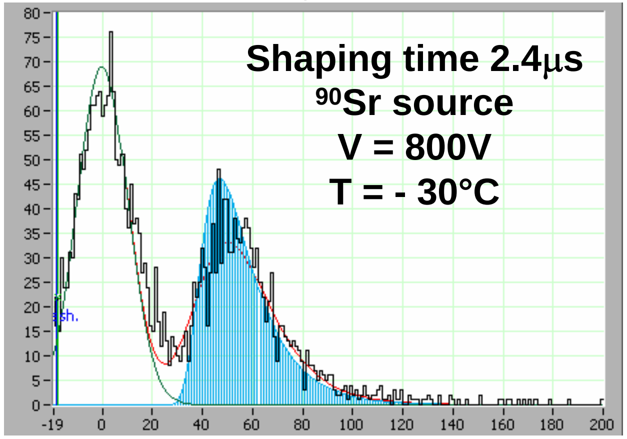
CCE 100%

at full depletion V_{CCE} ~ V_{CV} = 340V

Φ = 6.8 10^{14} cm^{-2} (1MeV n eq)

CCE 75 % @ V_{fd} = 350V

CCE 90% @ 700V

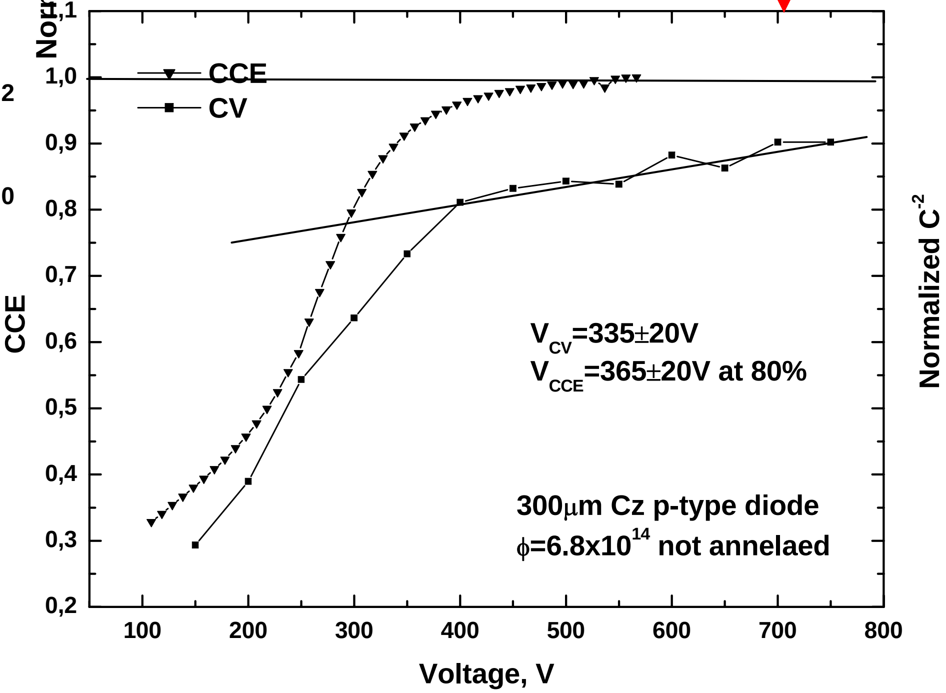


Shaping time 2.4μs

^{90}Sr source

V = 800V

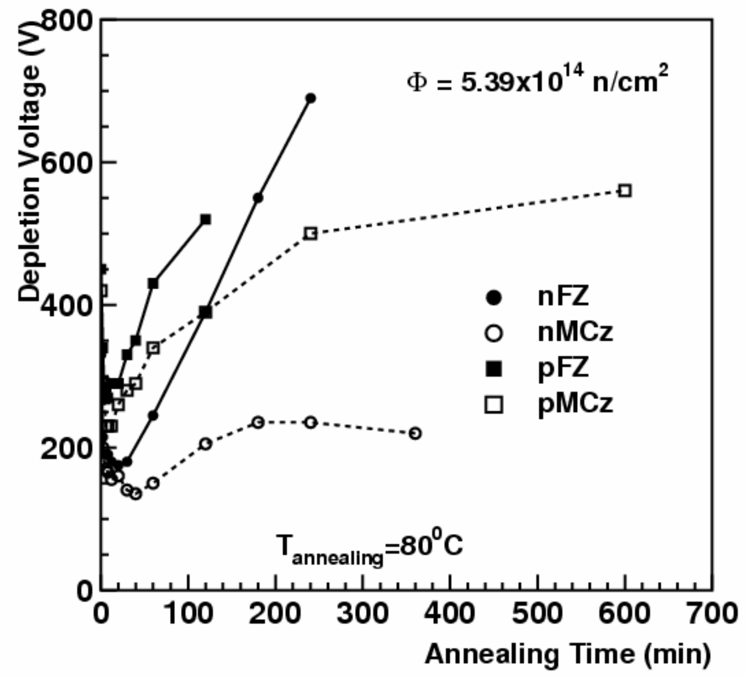
T = - 30°C



M. Bruzzi et al., presented at Advanced Silicon Radiation Detectors, ITC-IRST, Trento February 13-14, 2006

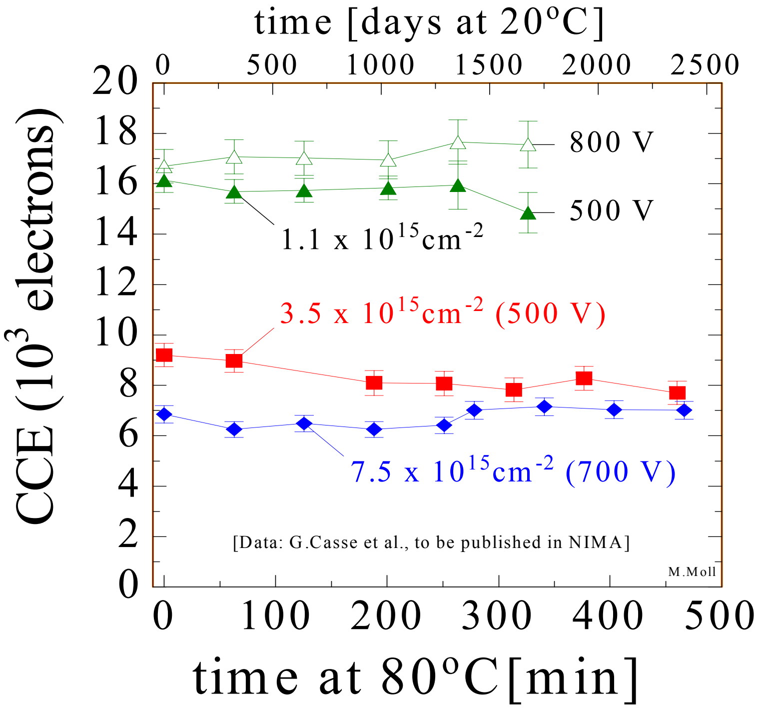
RD50 Annealing of MCz and FZ Si after proton irradiation

n- and p-type MCz vs FZ Si 300μm



G. Segneri et al., presented at the Liverpool Conference, Sept. 2005

p-type Fz Si 280μm



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

CV tests Reverse annealing significantly reduced in MCz Si after irradiation with 26 MeV and 24GeV/c up to 2x10^{15} cm^{-2} (1MeV n eq).

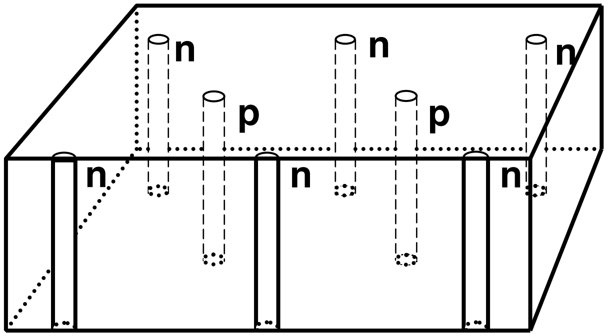
CCE tests No reverse annealing effect in the CCE after irradiation with 23 GeV p up to 7.5 × 10^{15} p/cm^{2}

RD50 - Detectors for the innermost layer -

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.

Investigated options are:

- ☐ New Rad-Hard Materials
- ☐ Thin/EPI Si detectors
- ☐ 3D detectors: process performed at IRST-Trento of 3D-sct in 2005



See also talk of Kenney

■ Epitaxial silicon

- Chemical-Vapor Deposition (CVD) of Silicon
- CZ silicon substrate used ⇨ in-diffusion of oxygen
- growth rate about 1μm/min
- excellent homogeneity of resistivity
- up to 150 μm thick layers produced
- price depending on thickness of epi-layer but not extending ~ 3 x price of FZ wafer

RD50 New Materials: Diamond, SiC, GaN

Property	Diamond	GaN	4H SiC	Si
E_g [eV]	**5.5**	**3.39**	**3.26**	**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**	20	**25**	**13-20**

- **Wide bandgap (3.3eV)**

⇒ **lower leakage current than silicon**

- **Signal:**

Diamond	**36 e/μm**
SiC	**51 e/μm**
Si	**89 e/μm**

⇒ **more charge than diamond**

- **Higher displacement threshold than silicon**

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

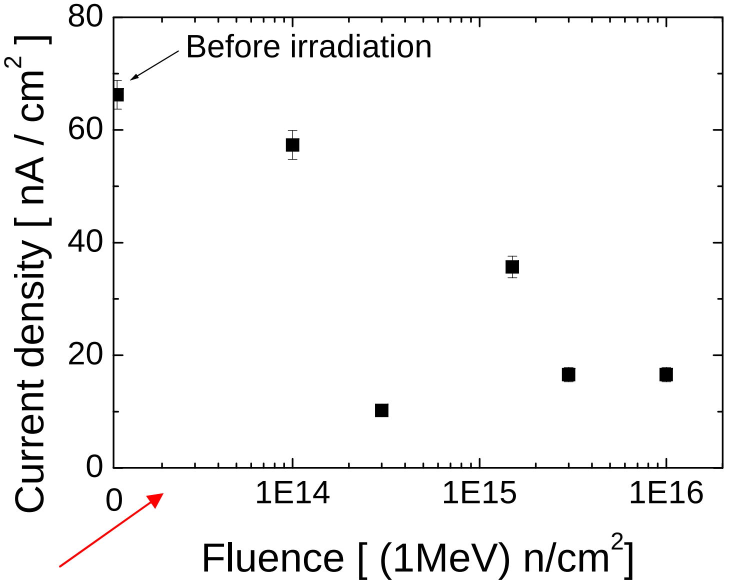
R&D on diamond detectors:
RD42 – Collaboration
http://cern.ch/rd42/

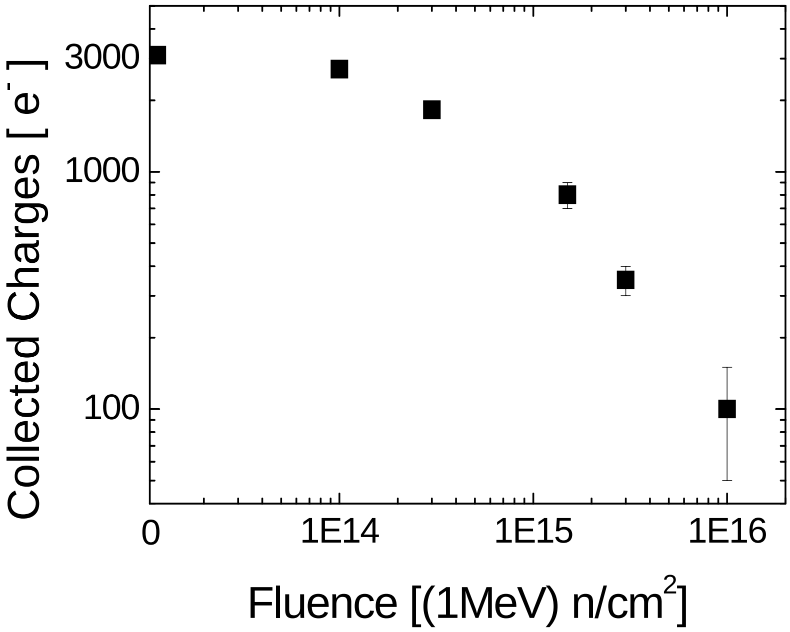
Epitaxial SiC after irradiation

p^+/n diodes. Produced by Perugia on IKZ Berlin 50 μm epitaxial layers

- **CCE before irradiation**
  - **100 % with α particles and MIPS**
  - **tested thickness up 50μm**

- **CCE after irradiation**
  - **with MIP particles**
  - **neutron irradiated samples**
  - **material produced by CREE**
  - **50 μm thick layer**





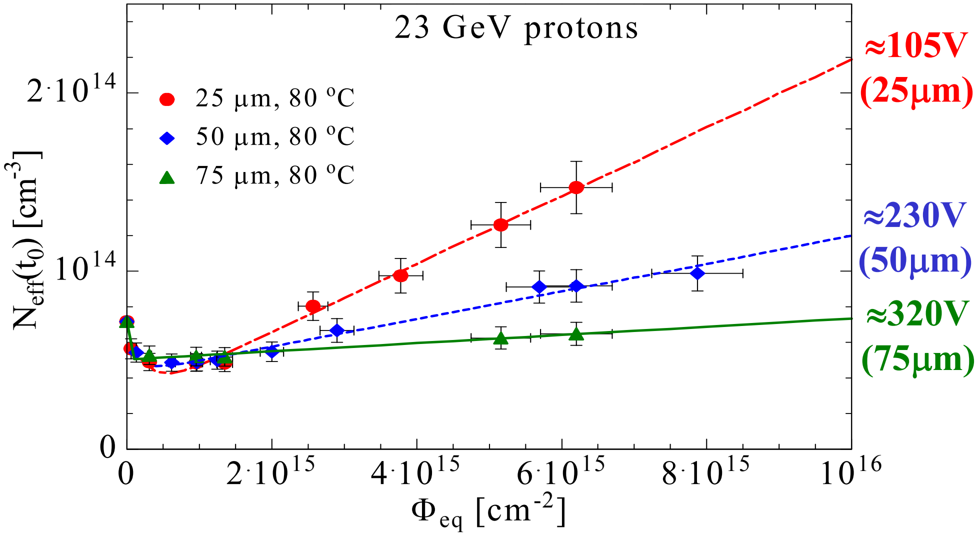
[F. Moscatelli et al., presented at IEEE-NSS MIC Puerto Rico, 2005]

Radiation damage has no negative effect on leakage current. For fluences above 3 ×10^{15} n/cm^2 the signal is lower than 400 e-

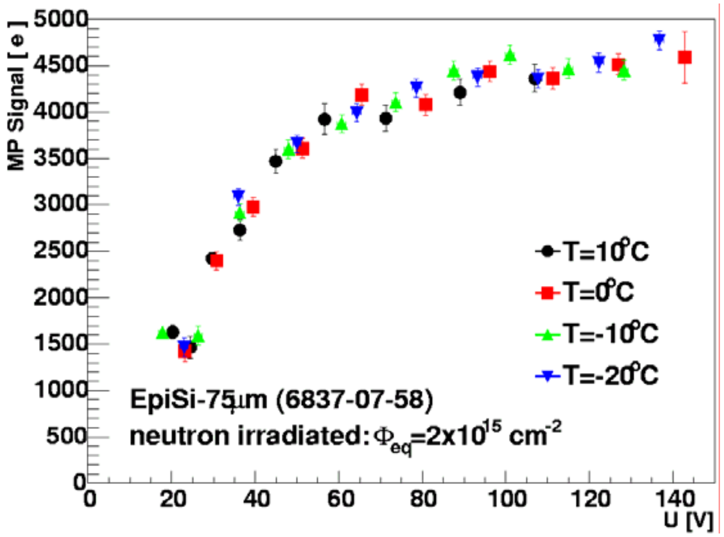
Si Epitaxial Devices

- **Epitaxial silicon grown by ITME**
  - **Layer thickness: 25, 50, 75 μm; resistivity: ~ 50 Ωcm**
  - **Oxygen: [O] ≈ 9×10^{16}cm^{-3}; Oxygen dimers (detected via IO_2-defect formation)**

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



No type inversion in the full range up to ~ 10^{16} p/cm^2 and ~ 10^{16} n/cm^2 (type inversion only observed during long term annealing)



- **CCE measured with ^{90}Sr mips shaping time 25 ns**

CCE measured after n- and p-irradiation

→ **CCE($\Phi_p=10^{16}$ cm^{-2}) = 2400 e (mp-value)**

Now epitaxial Si detectors available up 100-150μm thickness – first irradiation performed at Ljubljana

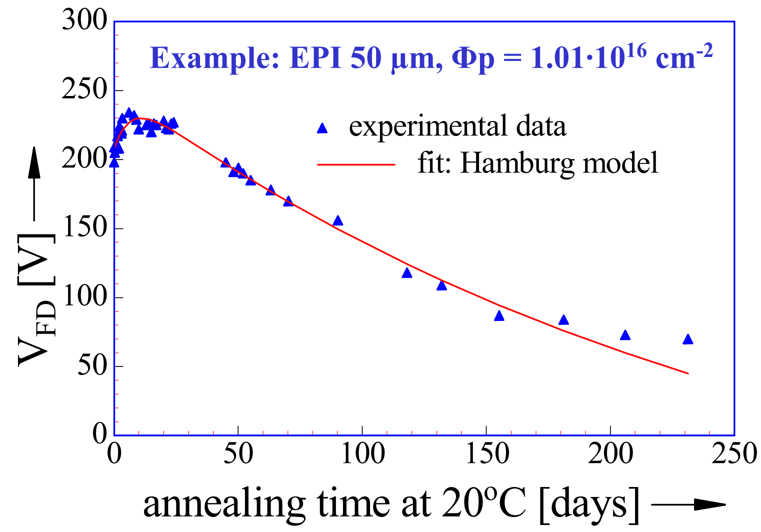
RD50

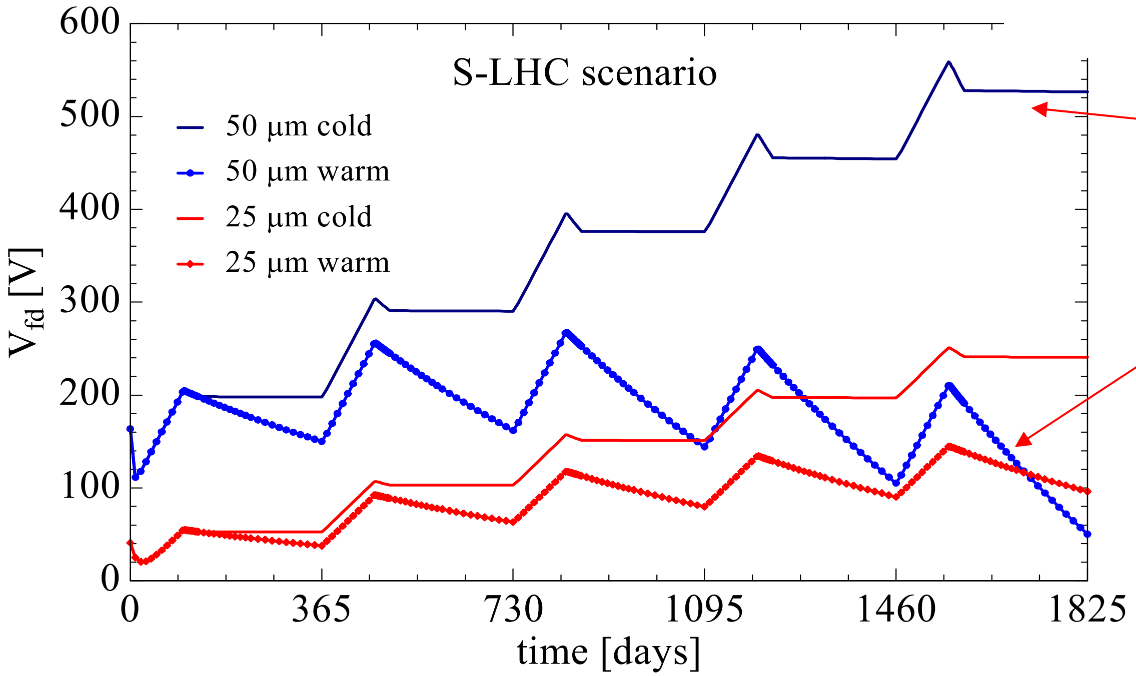
Damage Projection – SLHC
- 50 µm EPI silicon -

G.Lindström et al.,10th European Symposium on Semiconductor Detectors, 12-16 June 2005 (Damage projection: M.Moll)

- **Radiation level (4cm):** Φ_{eq}(year) = 3.5 × 10^{15} cm^{-2}
- **SLHC-scenario:**

1 year = 100 days beam (-7°C)
30 days maintenance (20°C)
235 days no beam (-7°C or 20°C)



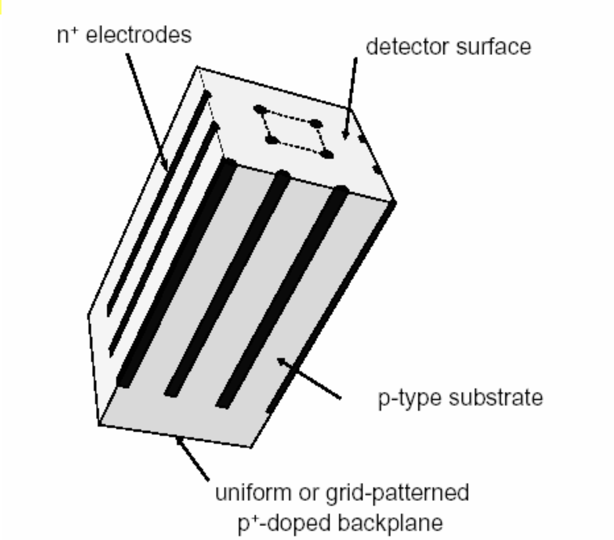


Detector with cooling when not operated

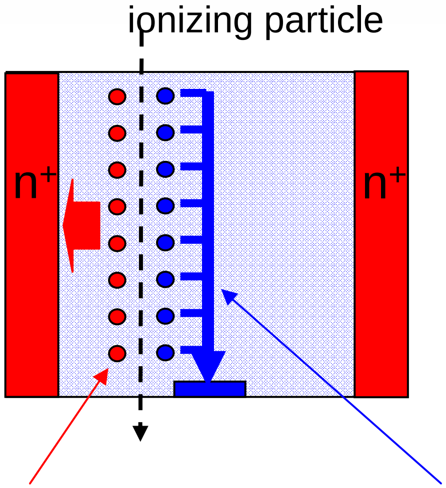
Detector without cooling when not operated

G. Lindstroem et al., 7th RD50 Workshop, Nov. 14-16, 2005

RD50 STC-3D detectors - by IRST-Trento



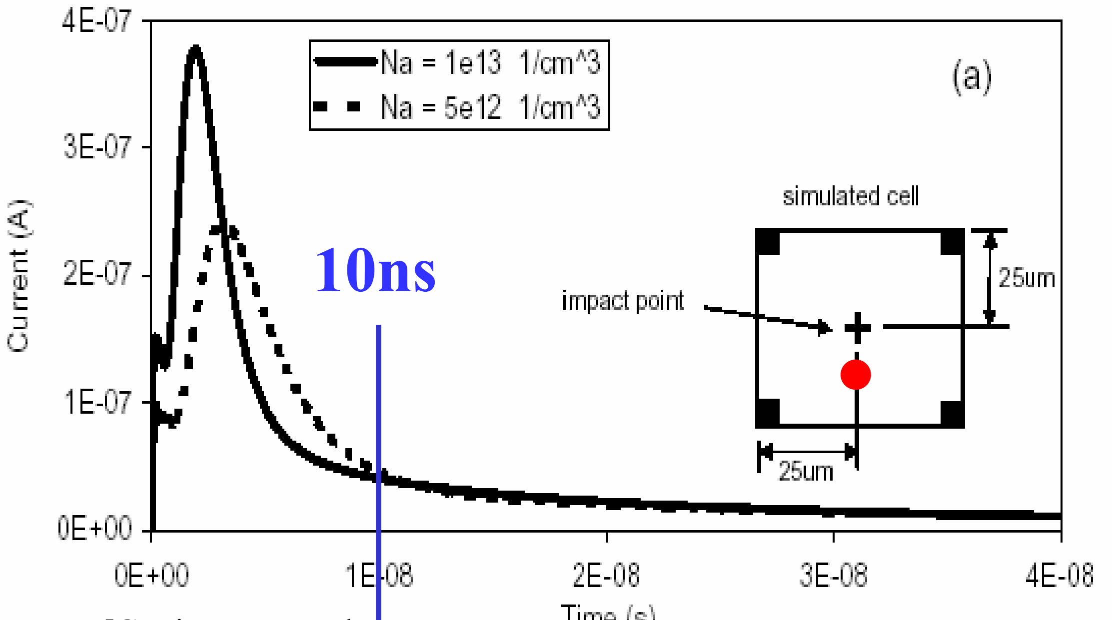
- **Simplified 3D architecture**
  - n^+ columns in p-type substrate, p^+ backplane
  - operation similar to standard 3D detector
- **Simplified process**
  - hole etching and doping only done once
  - no wafer bonding technology needed



cross-section between two electrodes

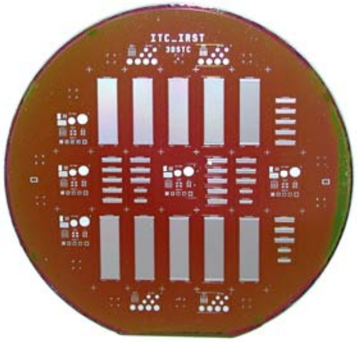
electrons are swept away by the transversal field

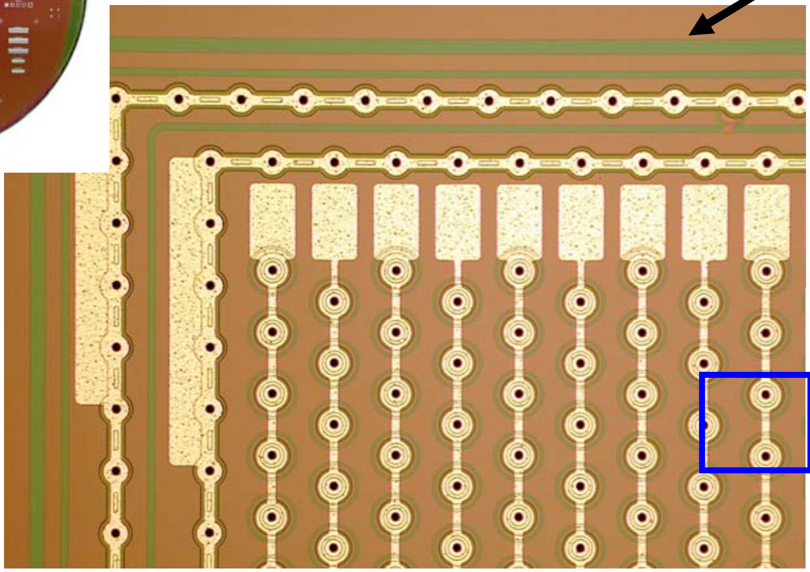
holes drift in the central region and diffuse towards p+ contact

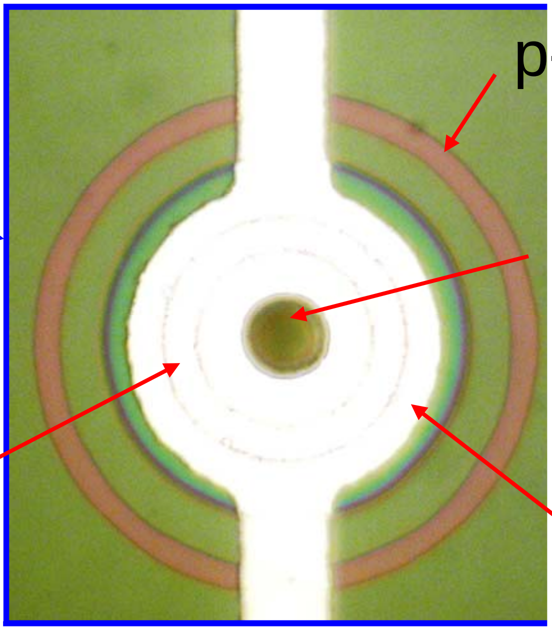


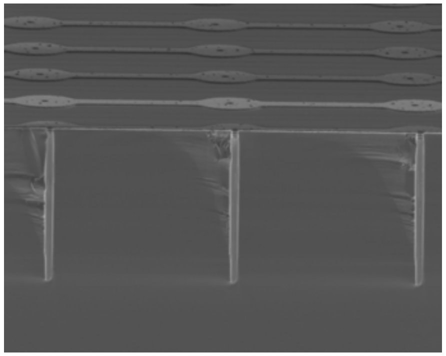
[C. Piemonte et al., NIM A541 (2005) 441]

STC 3D Strip detectors – layout

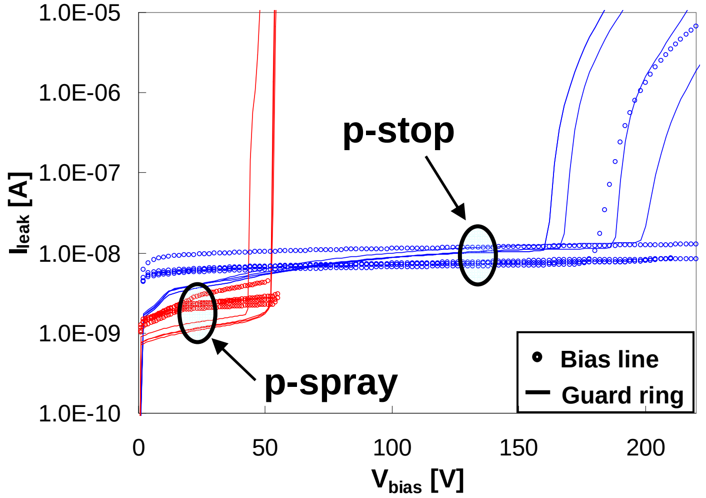




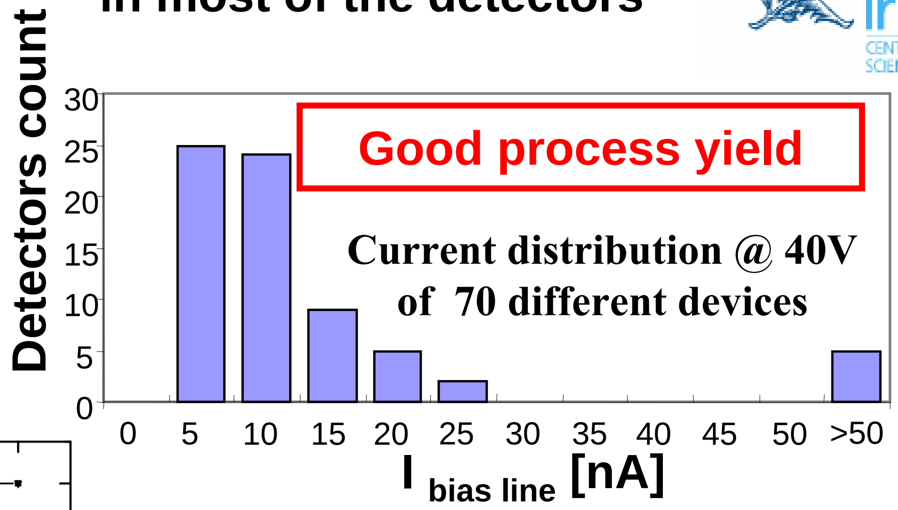




RD50 STC 3D detectors – measurements

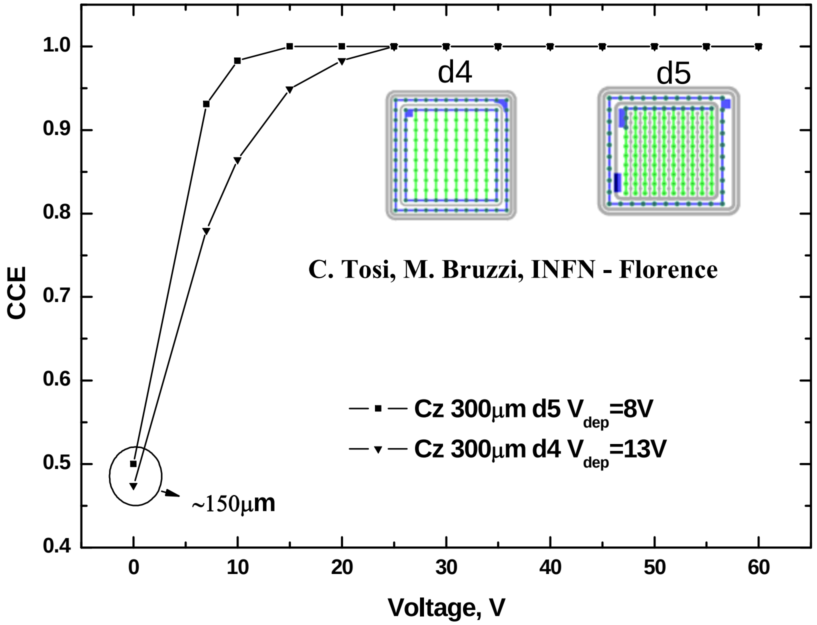


Leakage current < 1pA/colum
in most of the detectors



Good process yield

Current distribution @ 40V of 70 different devices



C. Tosi, M. Bruzzi, INFN - Florence

^{90}Sr electrons - shaping time 2.4µs

100% CCE measured at V_{rev} = 20- 80V

Referenced to a planar detector with same thickness

Irradiation now in progress

Future RD50 program: 3D with 2-type columns

- Summary (I) -

- 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 silicon detectors could be a cost-effective radiation hard solution
    (no type inversion, use p-in-n technology)
  - oxygenated p-type silicon microstrip detectors show very encouraging results:
    CCE ≈ 6500 e; $\Phi_{eq} = 4\times10^{15}$ cm^{-2}, 300µm
  - First MCZ p-type silicon tested CCE 90% $\Phi_{eq} = 6.8\times10^{14}$ cm^{-2}, 300µm, V = 700V
  - No reverse annealing visible in the CCE measurement in 300µm-thick p-type FZ Si detectors irradiated with 24GeV p up to 7x10^{15}cm^{-2} if applied voltage 500-800V.
  - n- and p-type MCz Si show reduced reverse annealing than FZ Si.
  - n-MCz Si not type inverted up to a 23GeV proton fluence of 2x10^{15}cm^{-2}.

- New Materials like SiC and GaN (not shown) have been characterized.
  Tests made on SiC up to 10^{16}cm^{-2} showed that detectors suffer no increase of leakage current but CCE degrade significantly. Maximum thickness tested: 50µm.

- Summary (II) -

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

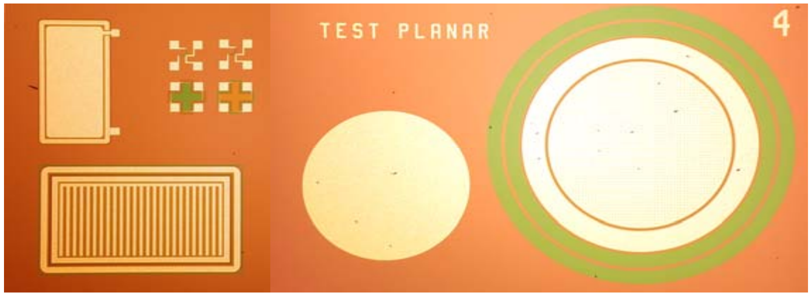
no reverse annealing – room T maintenance beneficial
thickness tested: up to 75µm.
CCE measured with ^{90}Sr e, shaping time 25 ns, 75µm
$\Phi p = 10^{16}$ cm^{-2} = 2400 e (mp-value)
processing of 150µm n-epi and p-epi under way

3D detectors: process performed at IRST-Trento of 3D-sct in 2005

- feasibility of 3D-stc detectors
- **Low leakage currents (**< 1pA/column)
- Breakdown @ 50V **for p-spray** and >100V **for p-stop structures**
- Good process yield **(typical detector current < 1pA/column)**
- **CCE 100% before irradiation**
- **first radiation hardness tests under way**
- **Future RD50 program: 3D with 2-type columns**

- SPARE -

Planar test structures measurements



Standard planar test structures

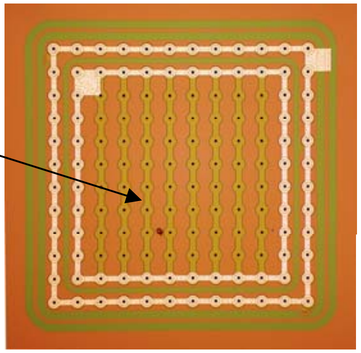
Parameter	Unit	typical range	
		p-spray	p-stop
Na	[1E12 cm-3]	1 - 3.5	
Vdep	[V]	200 - 500	
Ileak	[nA/cm2]	1 - 20	
Vbreak	[V]	50 - 60	155 - 175
Tox	[nm]	570 - 585	860 - 875
Qox	[1E10cm-2]	9.5 - 11	6 - 9.6
So	[cm/s]	1.3 - 1.7	7 - 7.5

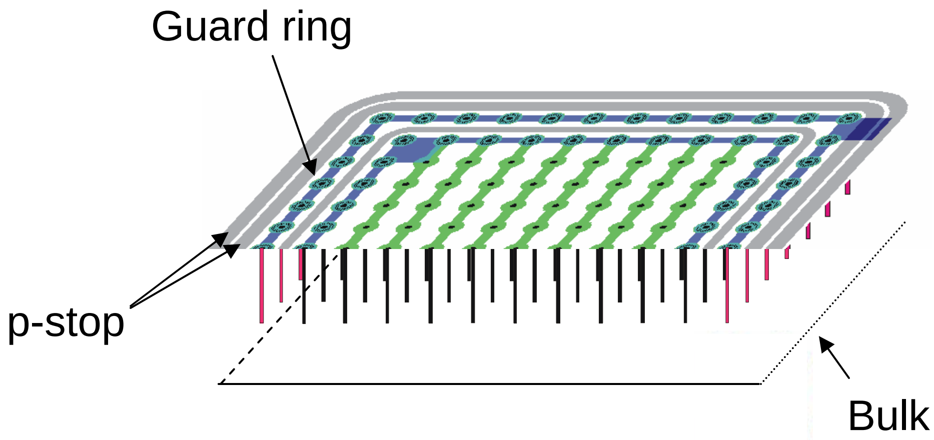
High variation due to different substrates

Ileak measured below full depletion due to Vbreak

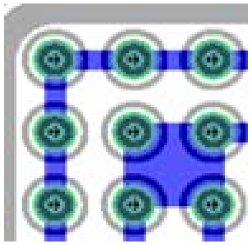
Electrical parameters compatible with standard planar processes

3D diode – layout:

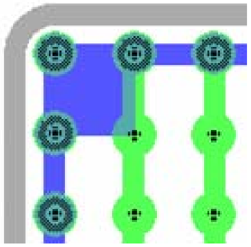




Single hole p-stop

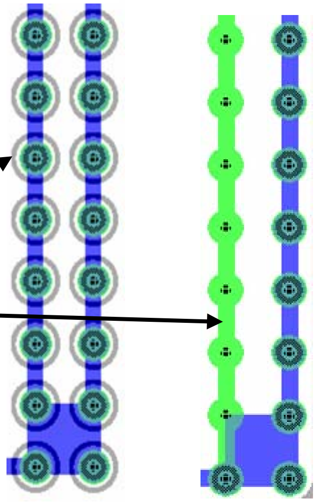


p-stop around
the entire region



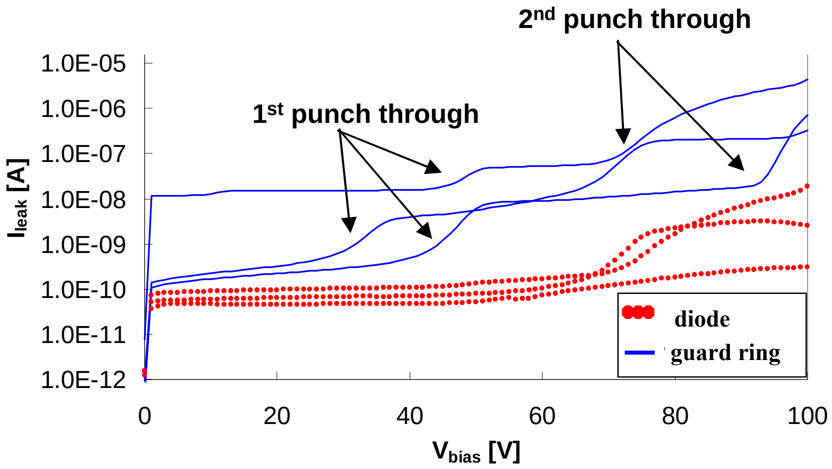
Different 3D-diode layouts:

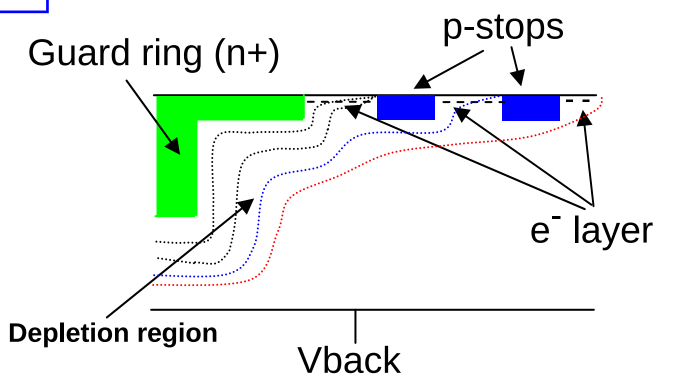
- Different isolation geometry (p-stop)
- Different column connections
- Different inter-colum distances (ranging from 80µm to 100µm)



RD50 3D diode – IV measurements:

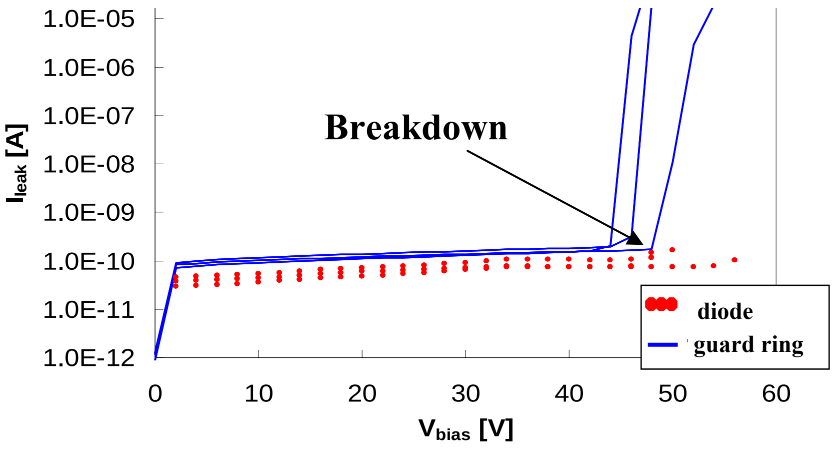
p-stop case

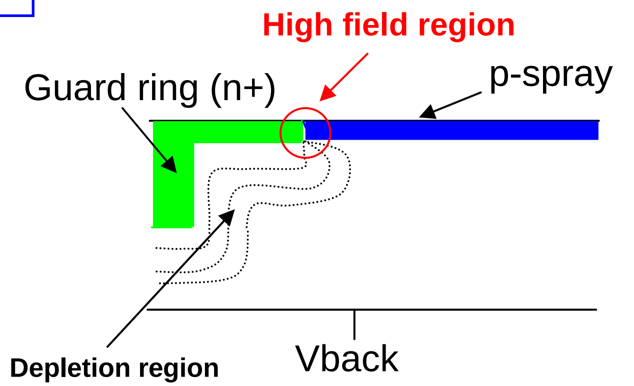




I_{leak} = 0.68 ± 0.2 pA/column @ 20V

p-spray case

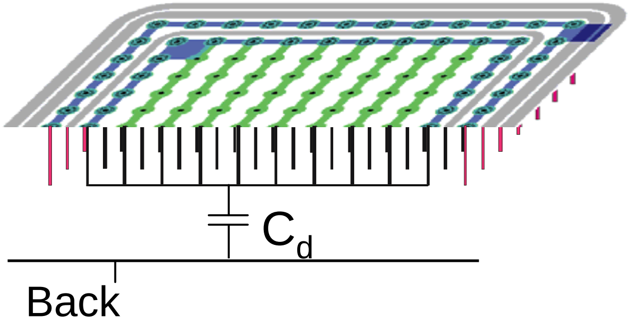




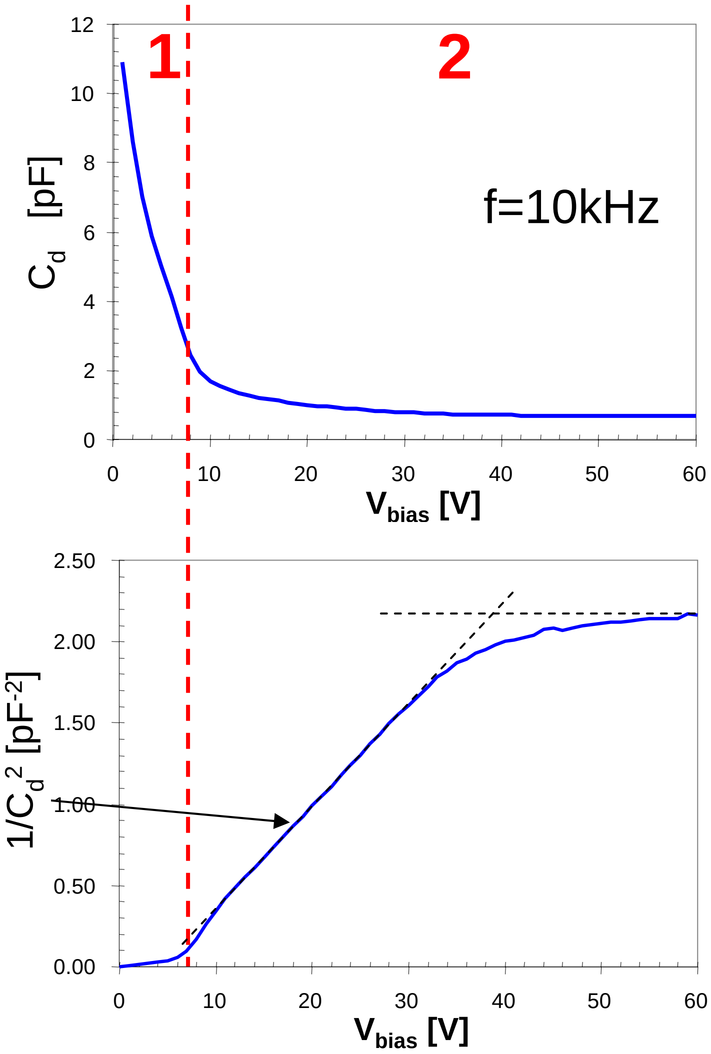
I_{leak} = 0.59 ± 0.12 pA/column @ 20V

RD50 3D diode – CV measurements

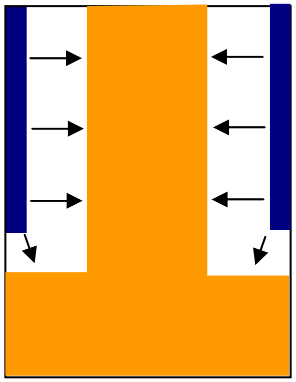
(preliminary)



Capacitance measurement versus back on a **300⌠m thick wafer** **with ~150µm deep columns, 100µm picth**



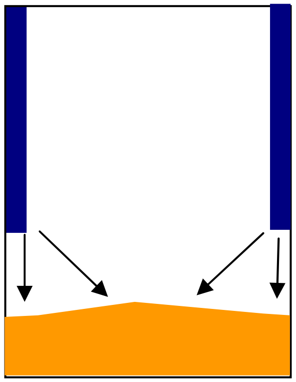
Phase **1**



region between col.
is not fully depleted
⇒ large capacitance

full dep. between columns ~ 7V

Phase **2**



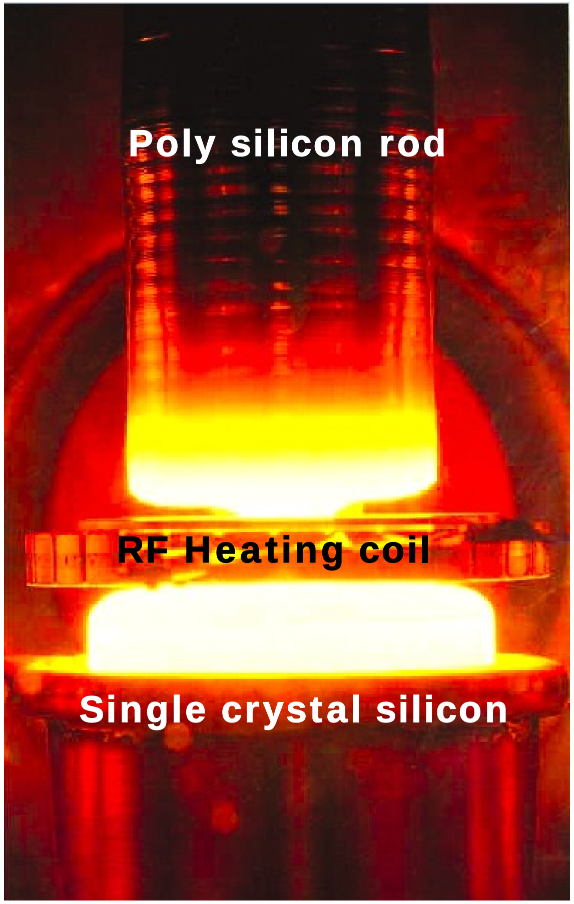
region between col.
is fully depleted
⇒ depletion proceeds
only towards the back
(almost like a planar diode)

full depletion ~40V
depletion width of ~150µm

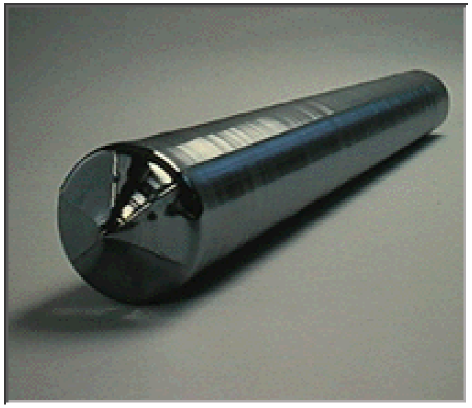
Material: Float Zone Silicon (FZ)

Float Zone process

- Using a single Si crystal seed, melt the vertically oriented rod onto the seed using RF power and "pull" the monocrystalline ingot



Mono-crystalline Ingot



Wafer production

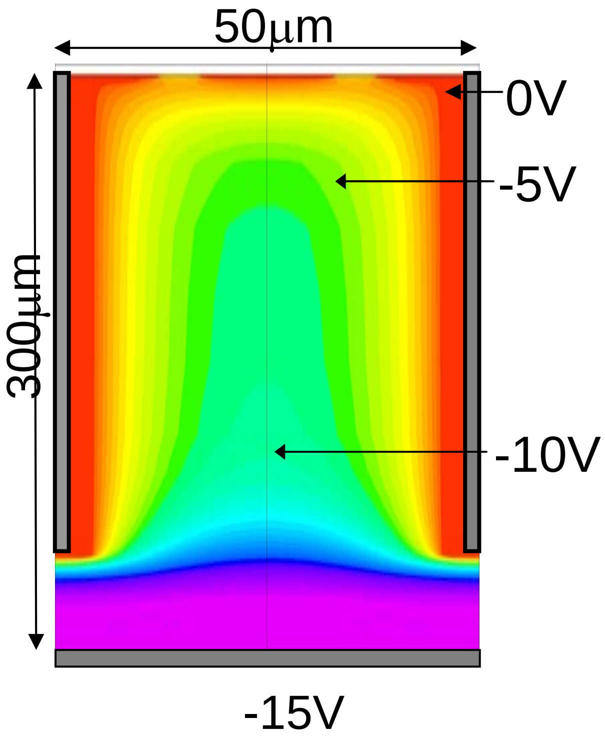
- Slicing, lapping, etching, polishing

Oxygen enrichment (DOFZ)

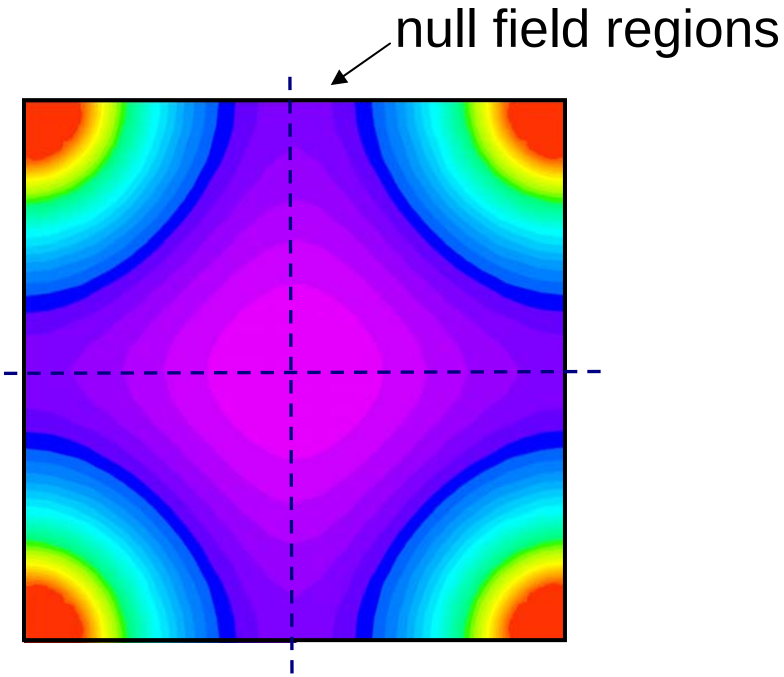
- Oxidation of wafer at high temperatures

3DSTC detectors - 3D simulations

Potential distribution
(vertical cross-section)



Potential distribution
(horizontal cross-section)



Drawbacks:

- once full depletion is reached it is not possible to increase the electric field between the columns
- large low field region

Both can be improved using higher substrate doping concentration

Expected Performance for p-type SSD

Details in : “Operation of Short-Strip Silicon Detectors based on p-type Wafers in the ATLAS Upgrade ID
M. Bruzzi, H.F.-W. Sadrozinski, A. Seiden, SCIPP 05/09

Conservative Assumptions:

$\alpha_p = 2.5 \cdot 10^{-17}$ A/cm (only partial anneal)

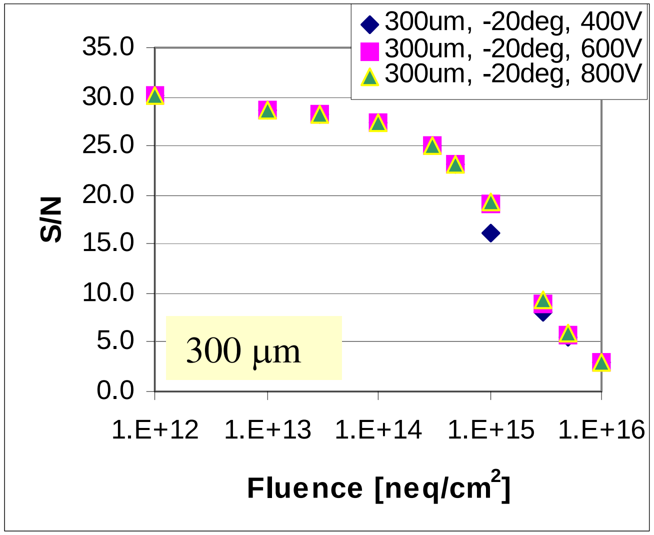
$C_{total} = 2$ pF/cm

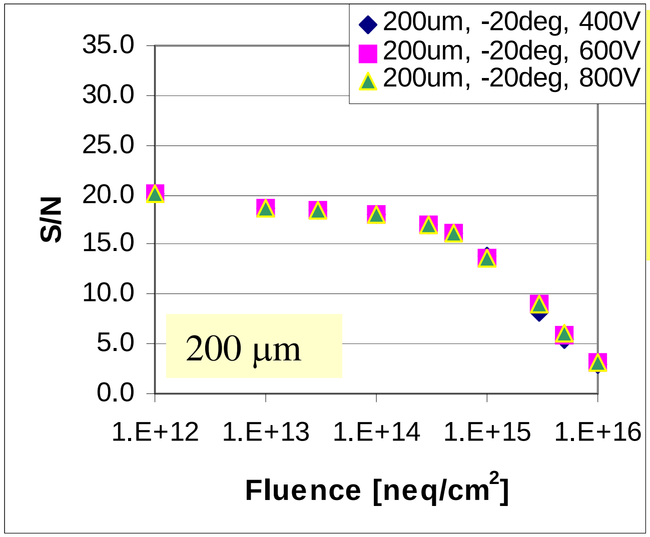
$V_{dep} = 160\text{V} + \beta * \Phi$ (with $2.7 * 10^{-13}$ V/cm^2) (no anneal)

(= 600V @ $\Phi = 10^{16}$ neq/ cm^2)

$\sigma^2_{Noise} = (A + B \cdot C)^2 + (2 \cdot I \cdot \tau_s)/q$ A = 500, B = 60

S/N for short strips vs. fluence for different bias voltages:





no need for thin detectors,
unless n-type:
depletion vs. trapping
600V seems to be sufficient

do need

update on fluences

Radiation Damage in Silicon Sensors

A review in 5 slides

- **Two general types of radiation damage to the detector materials:**

  - **Bulk (Crystal) damage due to Non Ionizing Energy Loss (NIEL)**
    - displacement damage, built up of crystal defects –

    I. **Change of effective doping concentration (higher depletion voltage, under- depletion)**

    II. **Increase of leakage current (increase of shot noise, thermal runaway)**

    III. **Increase of charge carrier trapping (loss of charge)**

  - **Surface damage due to Ionizing Energy Loss (IEL)**
    - accumulation of positive in the oxide (SiO_2) and the Si/SiO_2 interface –
    affects: interstrip capacitance (noise factor), breakdown behavior, …

- **Impact on detector performance and Charge Collection Efficiency**
  (depending on detector type and geometry and readout electronics!)

  Signal/noise ratio is the quantity to watch

  ⇒ Sensors can fail from radiation damage !

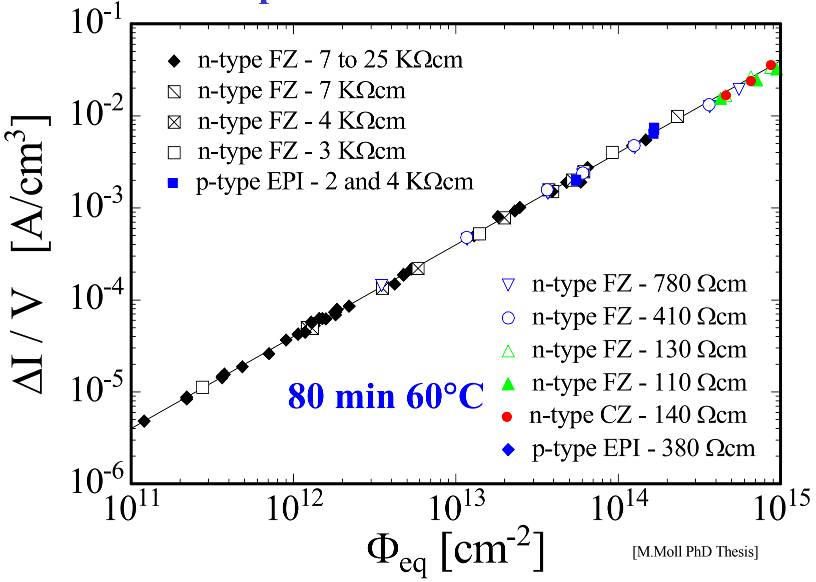
RD50

Radiation Damage – II. Leakage Current

Review (3/5)

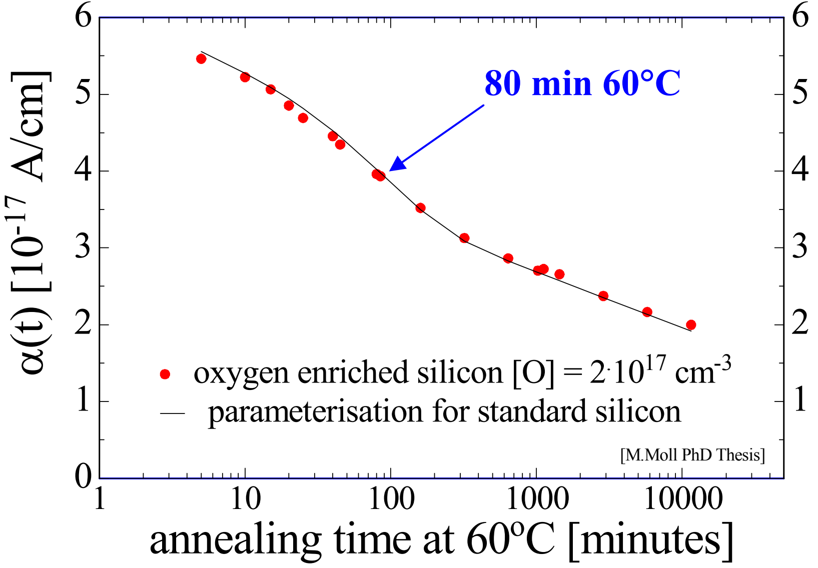
Change of Leakage Current (after hadron irradiation)

…. with particle fluence:



[M.Moll PhD Thesis]

…. with time (annealing):



[M.Moll PhD Thesis]

- Damage parameter α (slope in figure)

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

Leakage current per unit volume and particle fluence

- α is constant over several orders of fluence and independent of impurity concentration in Si
  ⇨ can be used for fluence measurement

- Leakage current decreasing in time (depending on temperature)
- Strong temperature dependence

$$I \propto \exp\left(-\, {E_g}\big/{2k_B T}\right)$$

Consequence:

Cool detectors during operation!
Example: *I*(-10°C) ~1/16 *I*(20°C)

RD50 Radiation Damage – III. Trapping

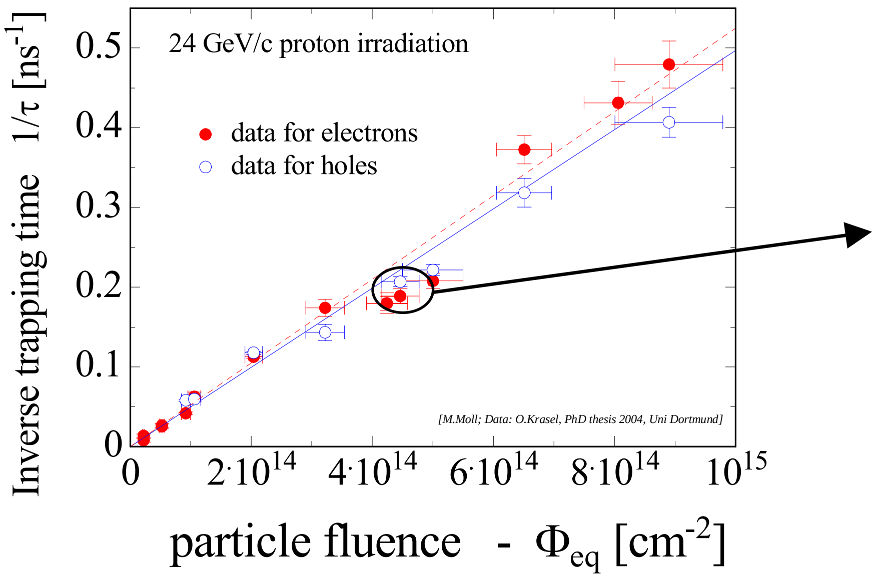
Review (4/5)

- **Deterioration of Charge Collection Efficiency (CCE) by trapping**

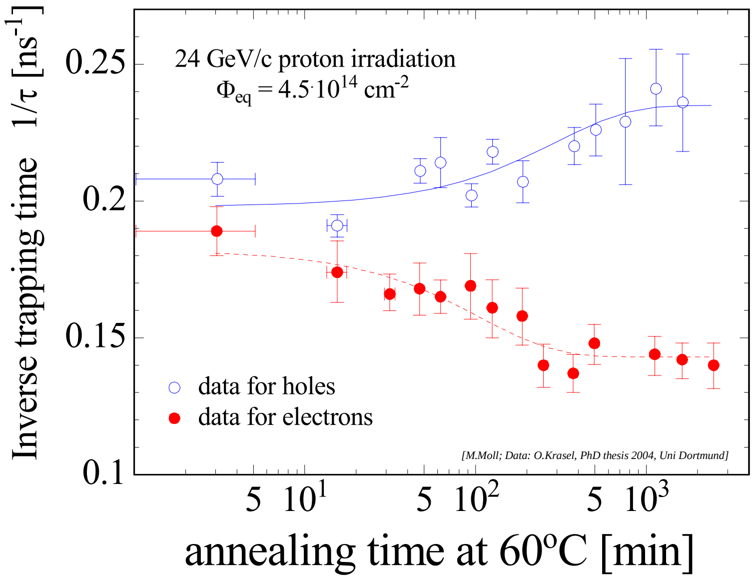
Trapping is characterized by an effective trapping time τ_{eff} for electrons and holes:

$$Q_{e,h}(t) = Q_{0e,h} \exp\left(-\frac{1}{\tau_{eff\ e,h}} \cdot t\right) \qquad \text{where} \qquad \frac{1}{\tau_{eff\ e,h}} \propto N_{defects}$$

Increase of inverse trapping time (1/τ) with fluence



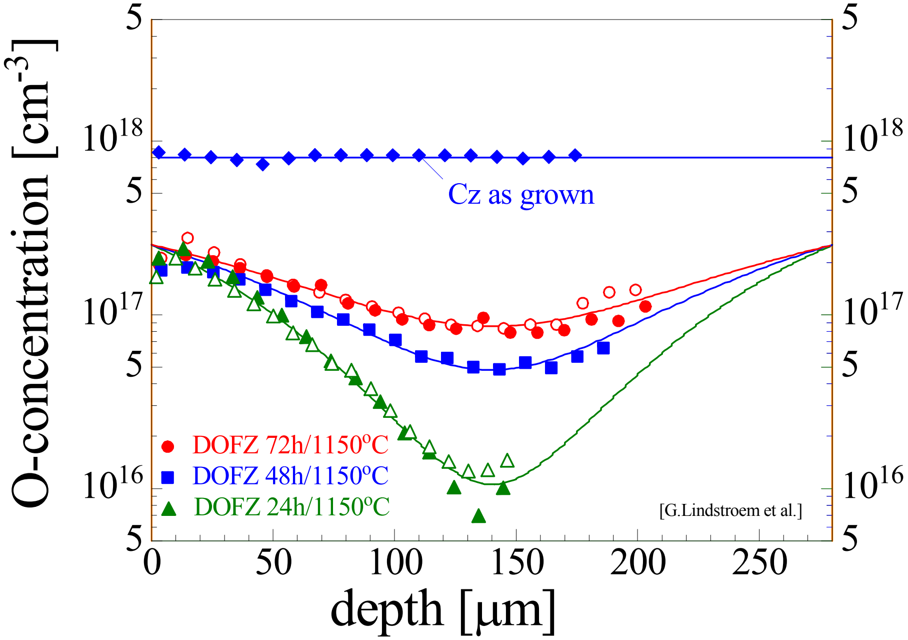
….. and change with time (annealing):



Oxygen concentration in FZ, CZ and EPI

Cz and DOFZ silicon

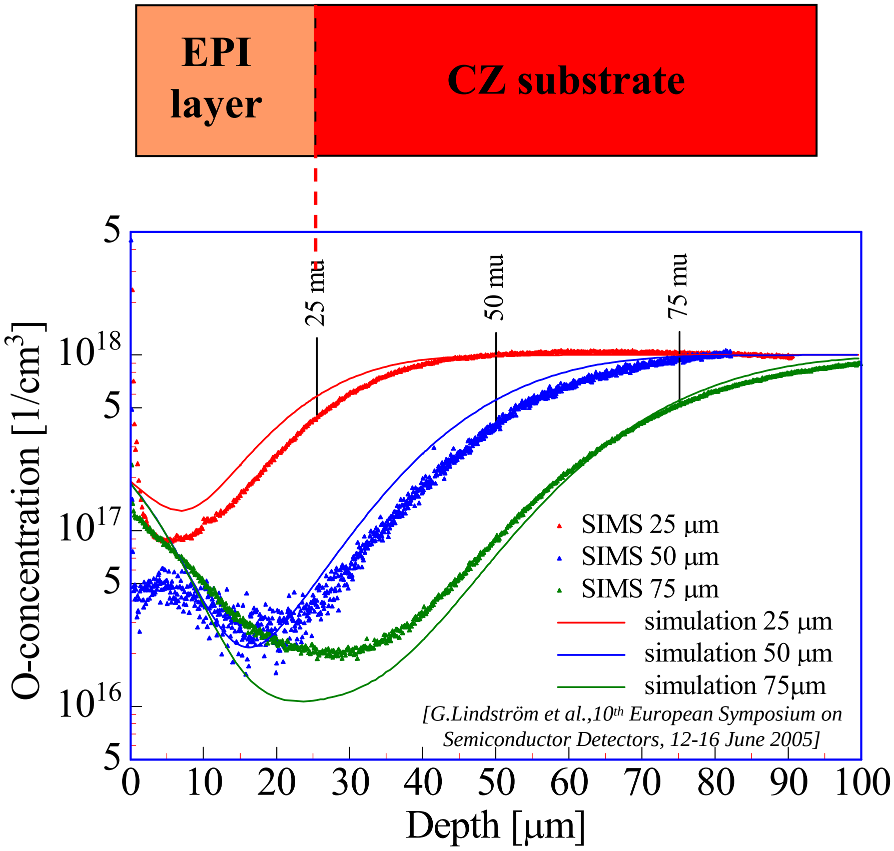
- **CZ: high O_i (oxygen) and O_{2i} (oxygen dimer) concentration (homogeneous)**
- **CZ: formation of Thermal Donors possible !**



[G.Lindstroem et al.]

- **DOFZ: inhomogeneous oxygen distribution**
- **DOFZ: oxygen content increasing with time at high temperature**

Epitaxial silicon



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

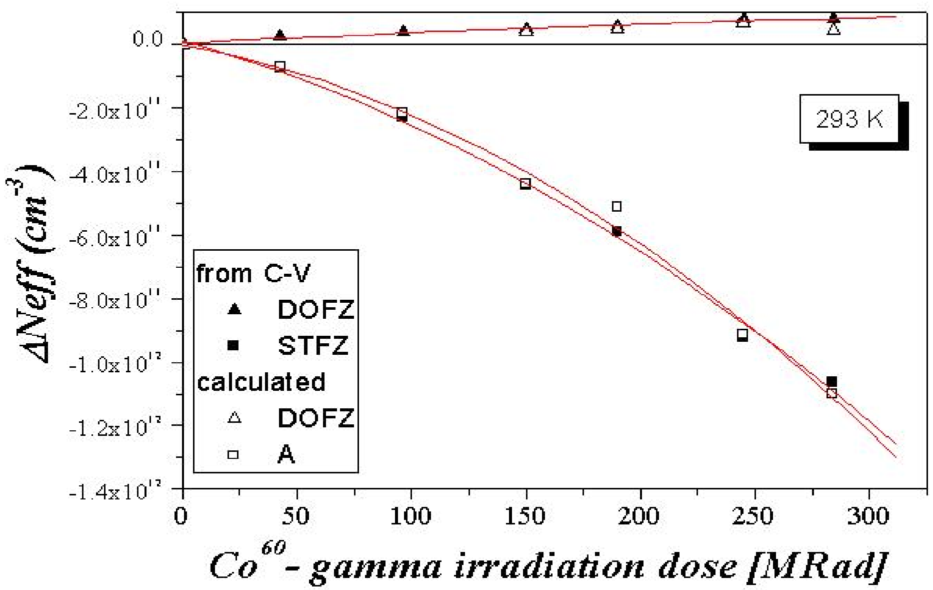
- **EPI: O_i and O_{2i} (?) diffusion from substrate into epi-layer during production**
- **EPI: in-homogeneous oxygen distribution**

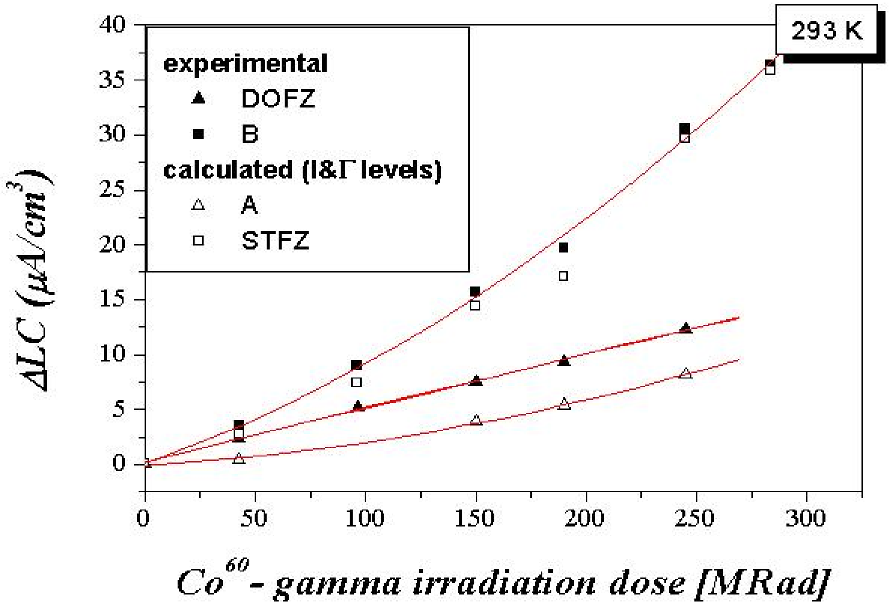
RD50

Microscopic defects ⇔ Macroscopic properties

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

- Comparison for effective doping concentration (left) and leakage current (right) for two different materials
  - as predicted by the microscopic measurements (open symbols)
  - as deduced from CV/IV characteristics (filled symbols)





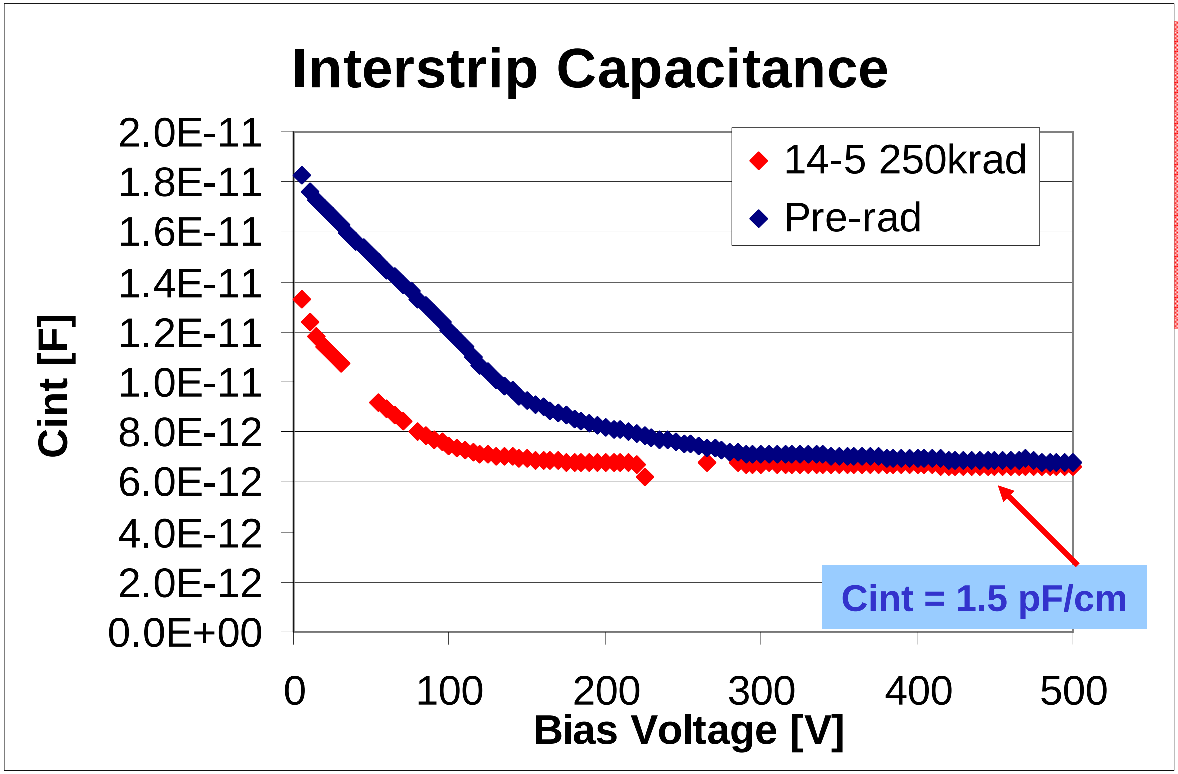
[I.Pintilie et al.,Applied Physics Letters,82, 2169, March 2003]

Inter-strip Capacitance

One of the most important sensor parameters contributing to the S/N ratio

Depends on the width/pitch ratio of the strips and on the isolation technique (p-stops, p-spray).

SMART reported large bias dependence on p-type detectors, due to accumulation layer.



Irradiation with ^{60}Co (250 krad) reduces the bias dependence, as expected (c.f. talk by C. Piemonte)

SMART 14-5
p-type FZ
low-dose spray
w/p = 15/50
V_{dep} = 85 V
(I. Henderson, J. Wray, D. Larson, SCIPP)

3D Fabrication process (2)

- Substrates used for this production:

Si High Resistivity, p-type, <100>

- **FZ (500 μm) resistivity > 5.0 kΩ cm**
- **Cz (300μm) resistivity > 1.8 kΩ cm**

- Surface isolation:
  - **p-stop**
  - **p-spray**

- Sintering
  - **Standard @ 420˚C for FZ**
  - **380˚C for Cz to minimize thermal donor activation**

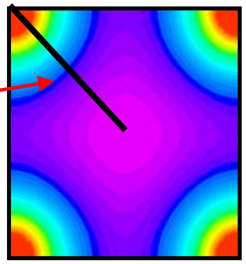
Conclusion

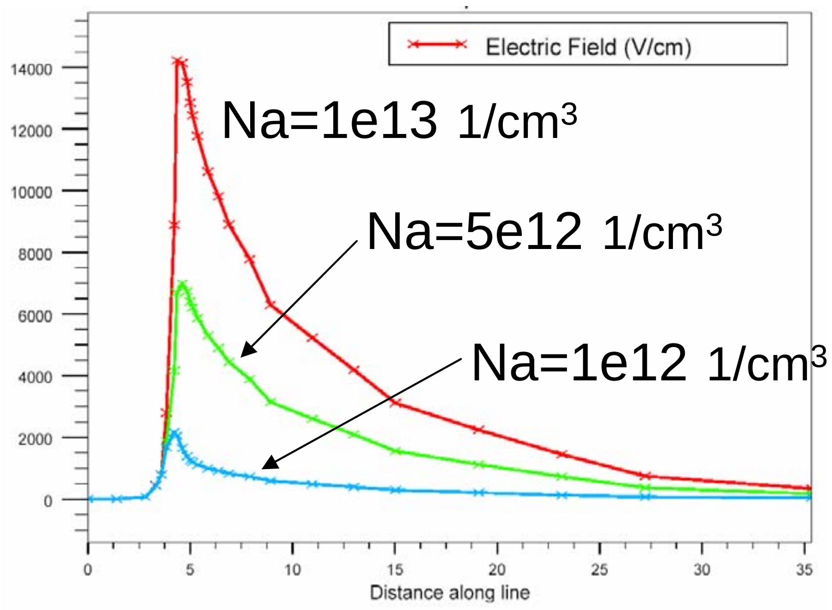
- The first production has proved:
  - **The** feasibility of 3D-stc detectors
  - **Low leakage currents (**< 1pA/column)
  - Breakdown @ 50V **for p-spray** and >100V **for p-stop structures**
  - Good process yield **(typical detector current < 1pA/column)**

- Samples have been given to:
  - Glasgow (UK): **CCE measurements with α, β, γ on 3D diodes**
  - SCIPP (USA): **CCE measurements on large strips**

3D-stc TCAD simulations

Simulation of the electric field along a cut-line from the electrode to the center of the cell





<u>DRAWBACK:</u>

3D-stc: once full depletion is reached it is not possible to increase the electric field between the columns

<u>Maximum electric field depends on substrate doping</u>

RD50

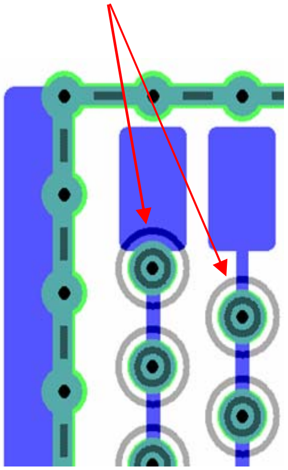
Strip detectors – layout (II)

Different strip-detector layouts:

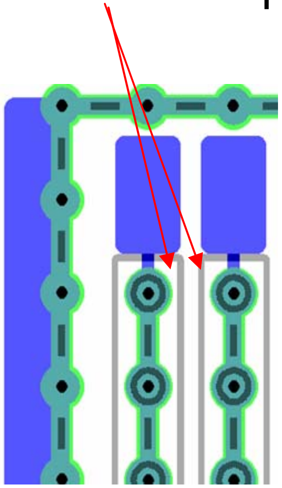
- Number of columns ranging from 12000 to 15000
- Inter-columns pitch 80-100 μm
- Holes Ø 6 or 10 μm

- **Two different p-stop layouts:**

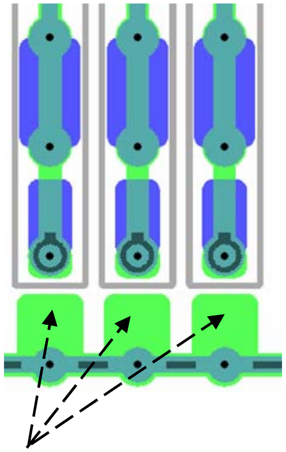
Single p-stop for each hole



Common p-stop for each strip

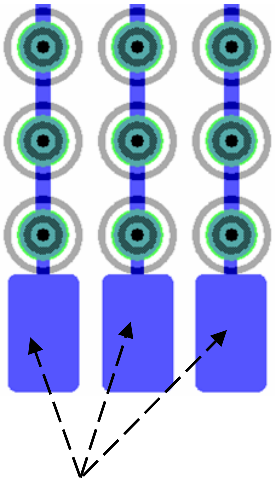


- **AC coupling:**



Punch-through structures

- **DC coupling:**

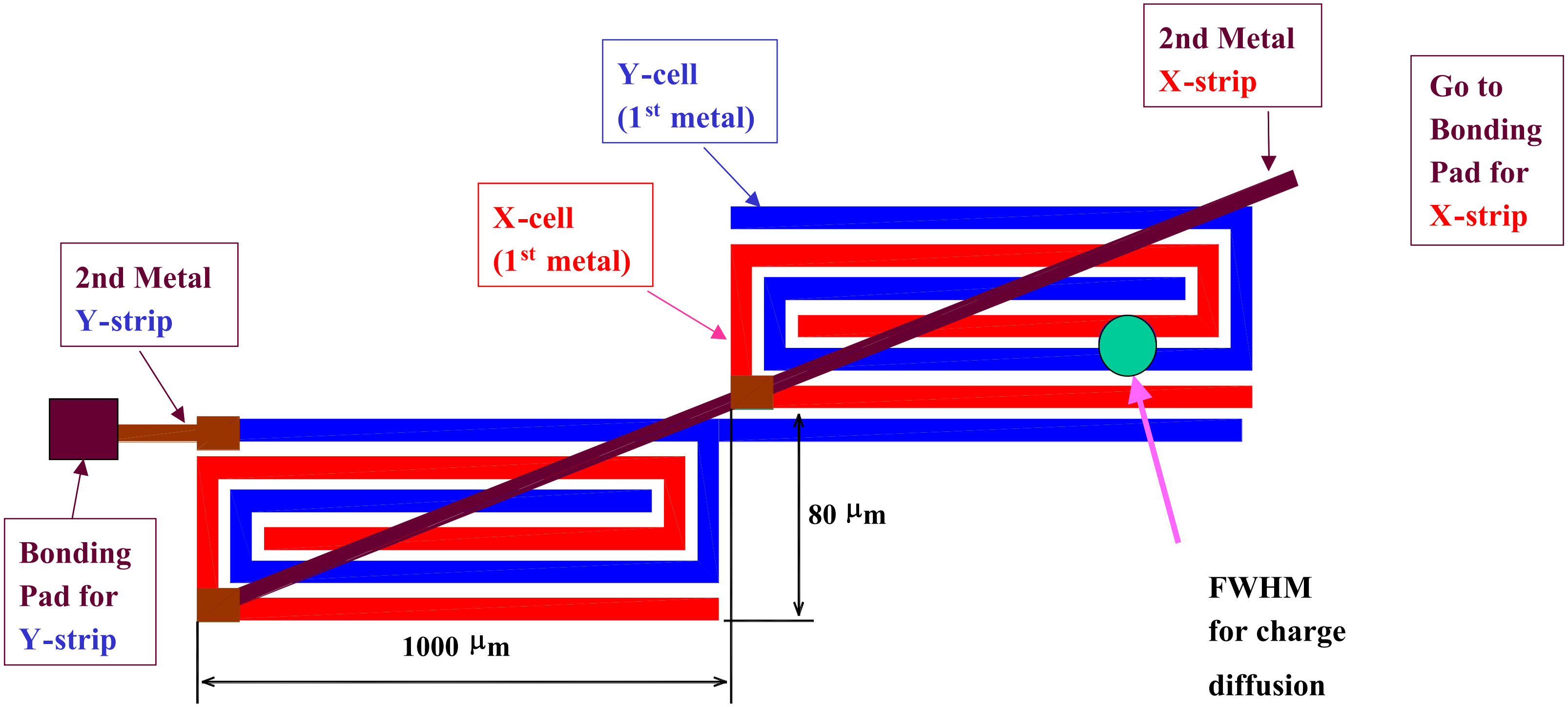


DC pads

Example for new structures - Stripixel

- **New structures: There is a multitude of concepts for new** (planar and mixed planar & 3D) **detector structures aiming for improved radiation tolerance or less costly detectors** (see e.g. Z.Li - 6th RD50 workshop)

- **Example: Stripixel concept:**



2nd Metal
X-strip

Y-cell
(1st metal)

Go to
Bonding
Pad for
X-strip

X-cell
(1st metal)

2nd Metal
Y-strip

80 μm

Bonding
Pad for
Y-strip

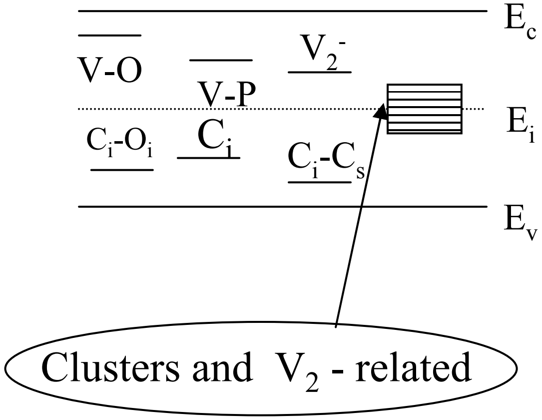
1000 μm

FWHM
for charge
diffusion

Z. Li, D. Lissauer, D. Lynn, P. O'Connor, V. Radeka

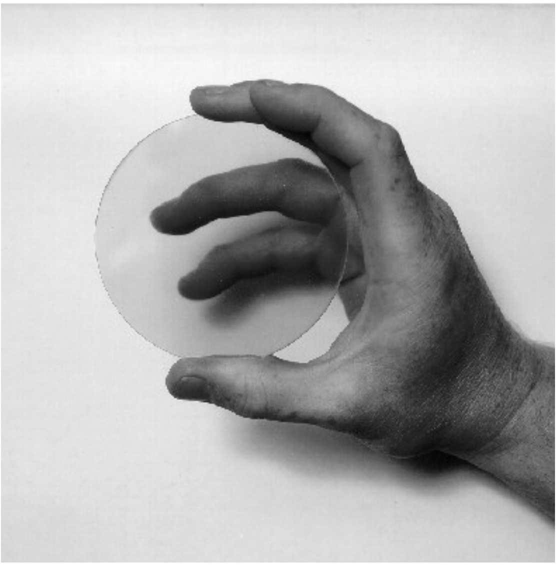
RD50 Trap parameters of radiation induced defects in Si

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



CVD Diamond detectors

CERN RD42 Collaboration



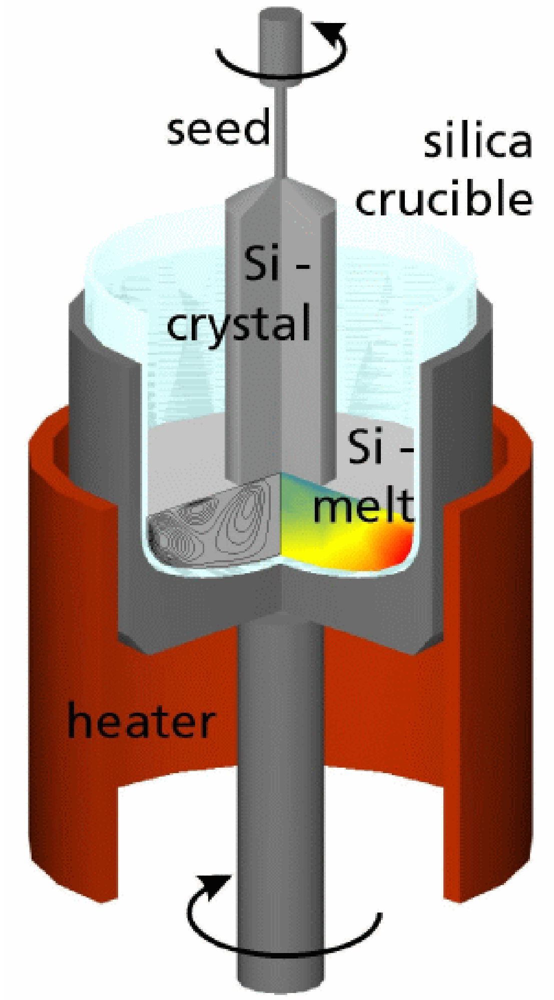
- Chemical Vapour Deposition - DeBeers
- Wafer diameter 5-6 inch
- Metalization Cr/Au, Ti/Au, Ti/W → new
- 1V/µm Operation, Drift velocity saturated
- Test procedure: dot → strip → pixel

Diamond - polycrystalline Chemical Vapour Deposited : achieved 270µm ccd (mip signal: 8000e), deteriorates to 80% after $2\times10^{15}\text{cm}^{-2}$ 24GeV p, need to extend measurements to 10^{16}cm^{-2}.

Diamond single crystal CVD: achieved 550µm CCE. Limited size of 6mm diameter, no radiation hardness study available in literature.

RD50 Czochralski silicon (Cz) & Epitaxial silicon (EPI)

Czochralski silicon



- Pull Si-crystal from a Si-melt contained in a silica crucible while rotating.
- Silica crucible is dissolving oxygen into the melt ⇨ high concentration of O in CZ
- Material used by IC industry (cheap)
- Recent developments (~2 years) made CZ available in sufficiently high purity (resistivity) to allow for use as particle detector.


Czochralski Growth

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

RD50

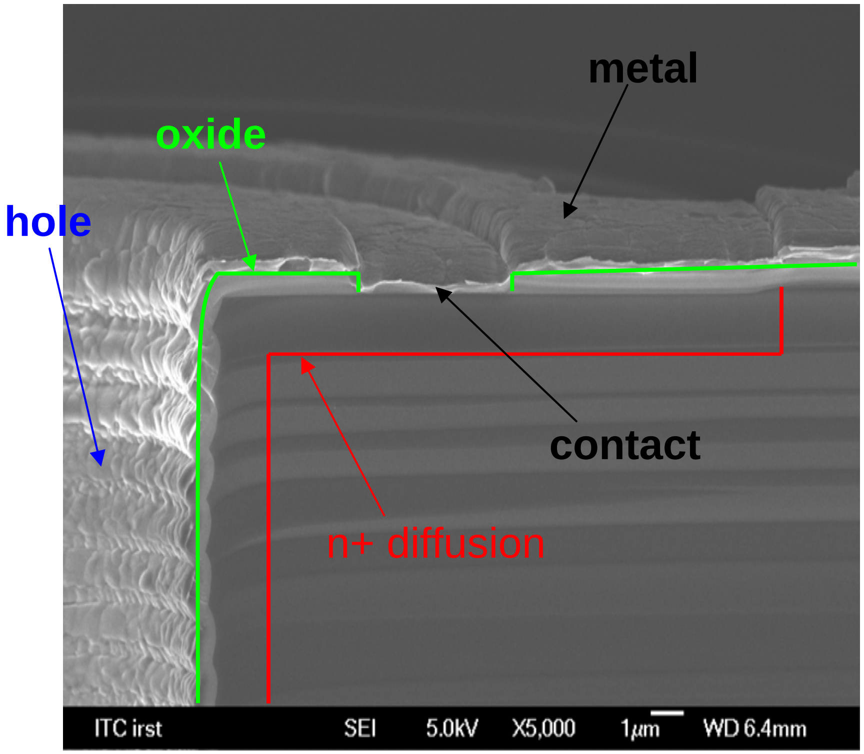
Scientific Organization of RD50

Development of Radiation Hard Semiconductor Devices for High Luminosity Colliders

Spokespersons
Mara Bruzzi, Michael Moll
INFN Florence, CERN ECP

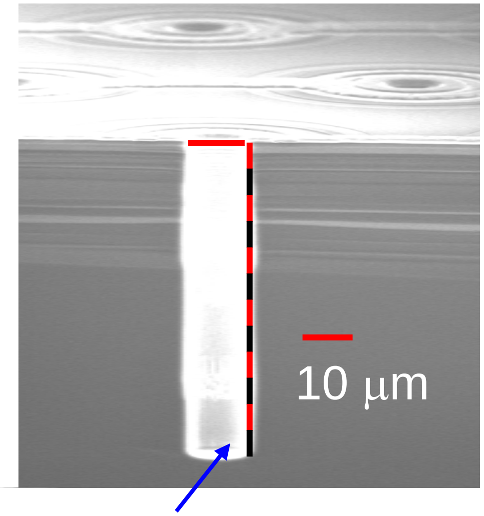
Defect / Material Characterization *Bengt Svensson* (Oslo University)	**Defect Engineering** *Eckhart Fretwurst* (Hamburg University)	**New Materials** *E: Verbitskaya* (Ioffe St. Petersburg)	**Pad Detector Characterization** *G. Kramberger* (Ljubljana)	**New Structures** *R. Bates* (Glasgow University)	**Full Detector Systems** *Gianluigi Casse* (Liverpool University)
Characterization of microscopic properties of standard-, defect engineered and new materials pre- and post-irradiation	Development and testing of defect engineered silicon: - Epitaxial Silicon - High res. CZ, MCZ - Other impurities H, N, Ge, … - Thermal donors - Pre-irradiation	Development of new materials with promising radiation hard properties: - bulk, epitaxial SiC - GaN - other materials	•Test structure characterization IV, CV, CCE •NIEL •Device modeling •Operational conditions •Common irrad. •Standardisation of macroscopic measurements (A.Chilingarov)	•3D detectors •Thin detectors •Cost effective solutions •3D (M. Boscardin) •Semi 3D (Z.Li)	•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)
DLTS Calibration (B.Svensson)	• Oxygen Dimer (M.Moll)	GaN (J.Vaitkus)			

Fabrication process in 2005



MAIN STEPS:

1. Hole etching with Deep RIE machine
   (step performed at CNM, Barcelona, Spain)
2. n+ diffusion (column doping)
3. passivation of holes with oxide
4. contact opening
5. metallization



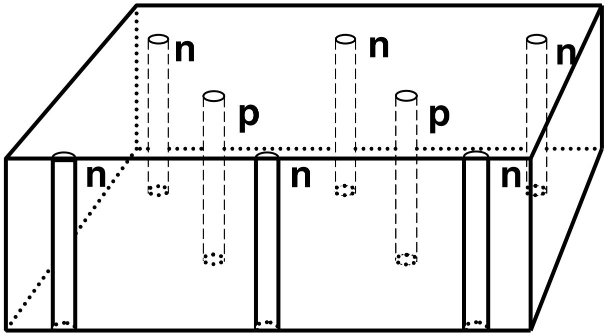
Hole depth: 120µm

CHOICES FOR THIS PRODUCTION:

- No hole filling (with polysilicon)
- Holes are not etched all through the wafer
- Bulk contact provided by a uniform p+ implant

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) 30:1



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

3D detector developments within RD50:

1) Glasgow University – pn junction & Schottky contacts

Irradiation tests up to 5x10^{14} p/cm^2 and 5x10^{14} π/cm^2:

V_{fd} = 19V (inverted); CCE drop by 25% (α-particles)

2) IRST-Trento and CNM Barcelona (since 2003)

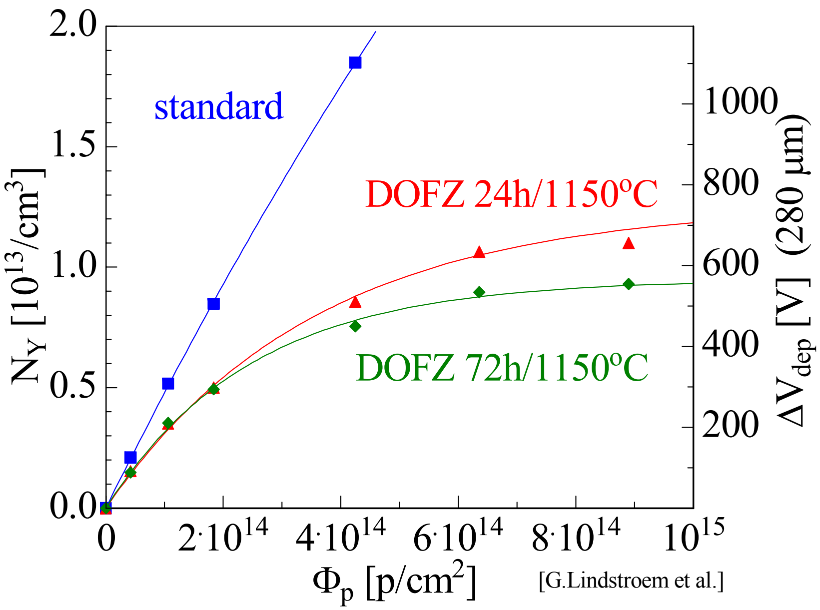
CNM: Hole etching (DRIE); IRST: all further processing

diffused contacts or doped polysilicon deposition

RD50

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

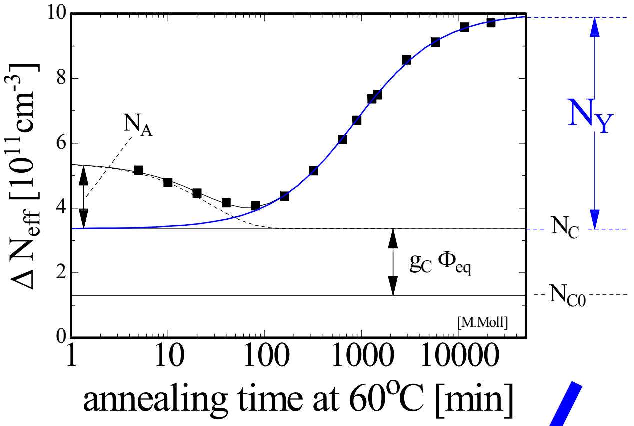
Data From G.Lindstrom et al.



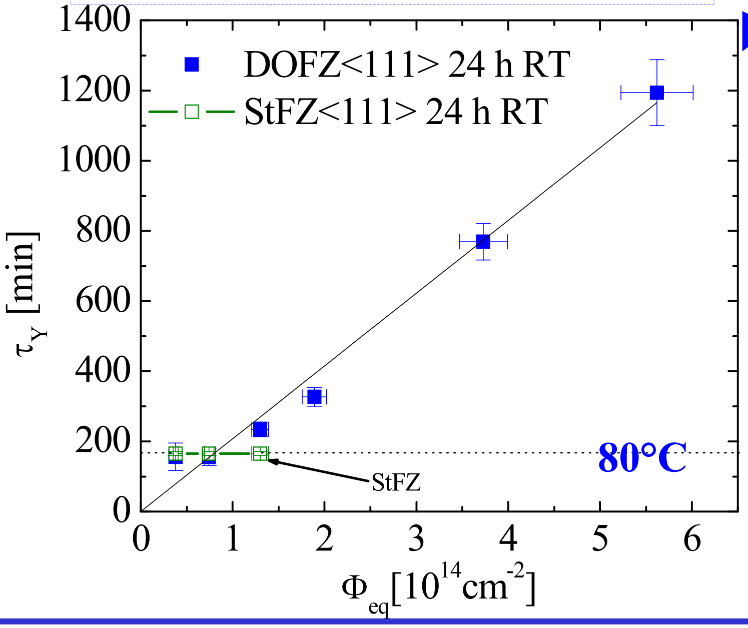
- **Saturation of reverse annealing**
  (24 GeV/c p - only little effect after neutron irradiation observed !)
- **No big difference between 24h and 72h oxidation at 1150°C**

- **time constant depending on fluence**

Saturation of amplitude

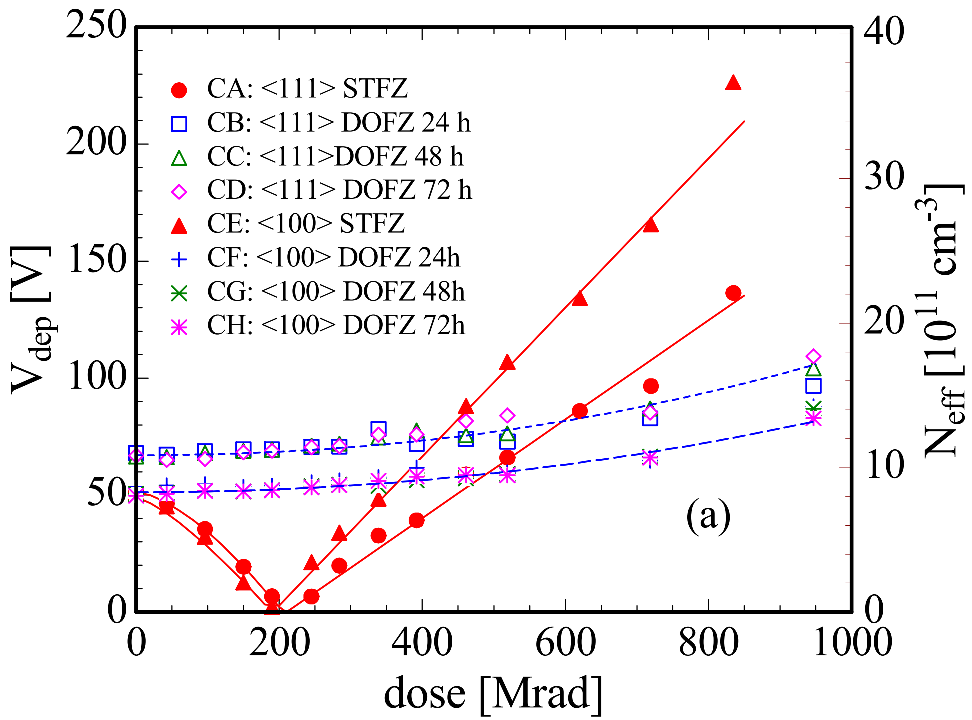


delayed reverse annealing



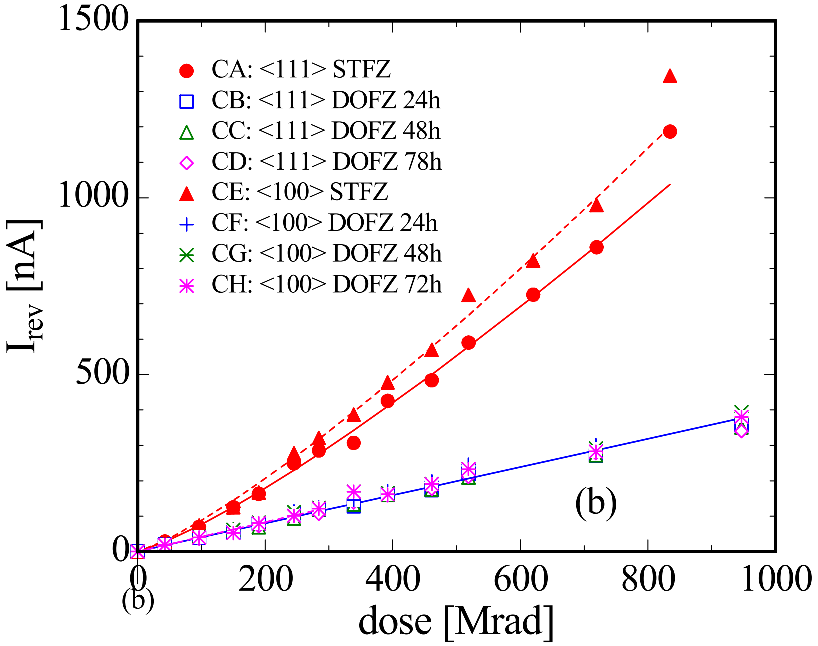
RD50 DOFZ Si Improvement of γ-irradiation tolerance

Depletion Voltage



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

Leakage Current



[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**