New sensor materials

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(results from RD42, RD50 collaborations, so many thanks to all)

Outline

- Motivation
- Radiation damage basics
- MCz/Cz/Epi
  - V_{fd} evolution (donor generation)
  - Annealing
  - Mixed radiation
  - Charge collection
- CCE in FZ n^+-p strip detectors
- Diamond detectors

Motivation (I)

Silicon detectors used in almost all working experiments!

"If it works it is already obsolete", *Marshall McLuhan*

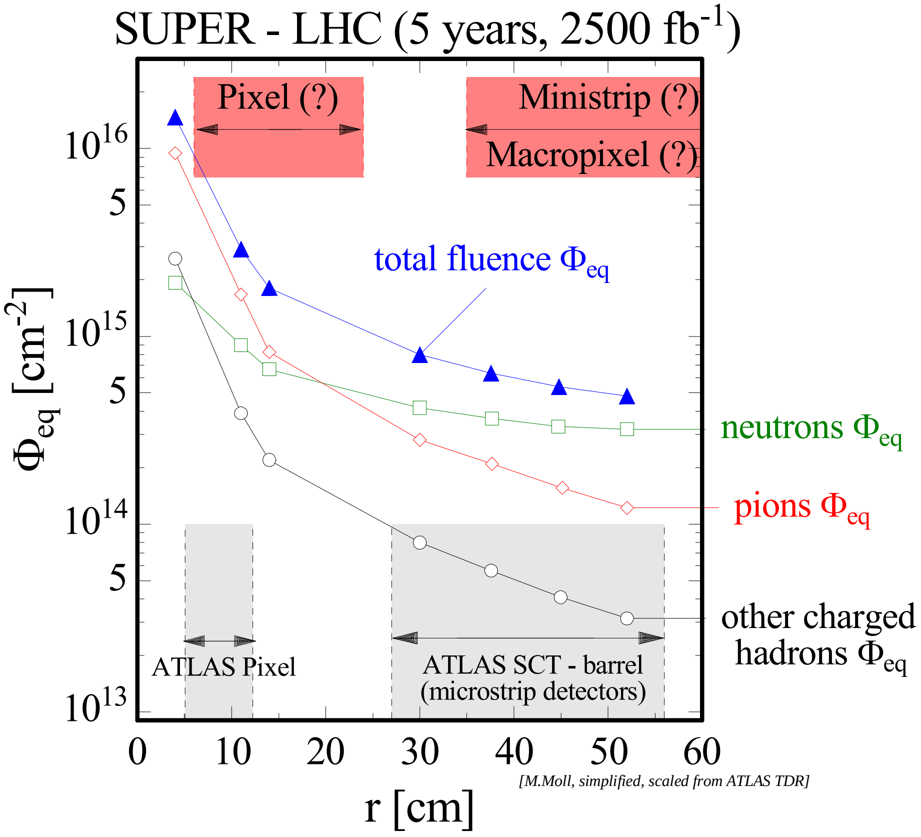
Almost all presently operated detectors (to my knowledge all) are currently:

- n-type
- processed on Float Zone Silicon (Diffusion Oxygenation used for pixel detectors at LHC)
- Are either single sided with p^+ *(p^+-n-n^+ device)* or n^+ (*n^+-n-p+ device*) read-out or double sided.

Why do we need better material for SLHC?

- Primarily to achieve sufficient charge collection efficiency to allow tracking
- If large area are covered the cost affordable solution is sought

Motivation (II)



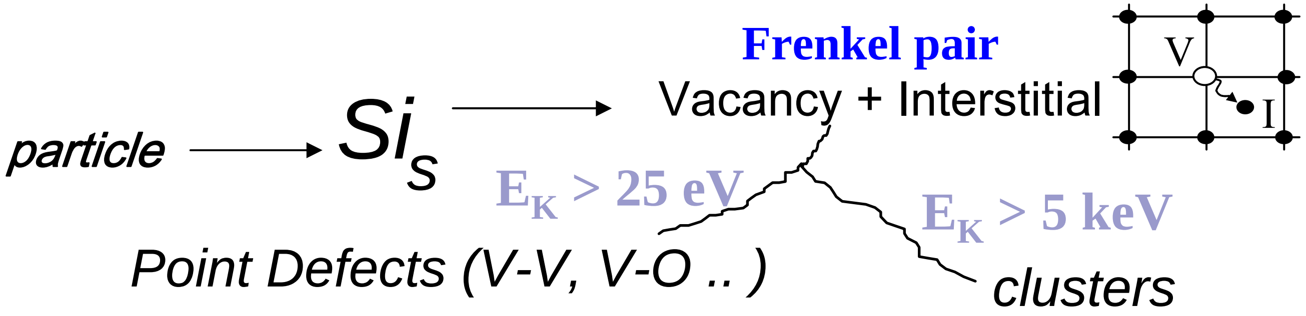
[M.Moll, simplified, scaled from ATLAS TDR]

SLHC tracker

- Inner tracker r<30 cm
  (pixel detector)
  - rad-hard material and/or new design (3D, rad-hard 2D, diamond, gossip)
- Middle tracker 30<r<60 cm
  (short strips, macropixels)
  - rad-hard material
- Outer tracker 60<r<107 cm
  (long strips)
  - existing technology/new rad-hard material

At present there is no complete solution for tracking at SLHC, but extensive R&D is going on! This is R&D talk and issues such as availability and costs are not addressed.

Basics of radiation damage (I)



particle → Si_s → **Frenkel pair**

Vacancy + Interstitial

$E_K > 25$ eV

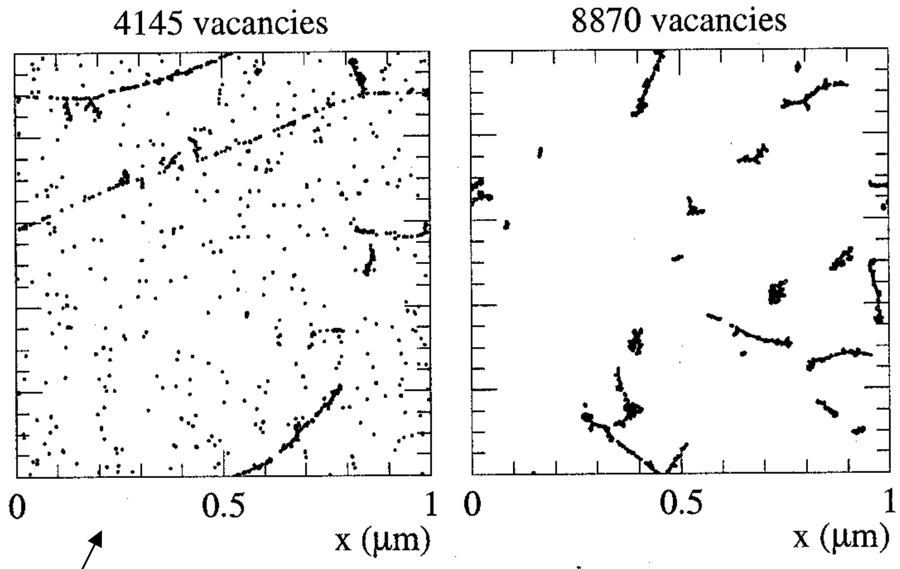
$E_K > 5$ keV

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

clusters

Damage effects generally scales with NIEL, however differences between proton & neutron damage

important for defect generation in silicon bulk



distribution in 1 μm^3 afer 1e14 neq

24 GeV protons
clusters+point defects

Reactor neutrons
mainly clusters

Basics of radiation damage (II)

- Silicon
  - ☐ Leakage current
    - Anneals in time

$$\boxed{\Delta I = \alpha(t,T)\,\Phi_{eq}\,V}$$

  - ☐ Effective trapping times
    - $\beta_h > \beta_e$ (~20%)
    - β_h anti-anneals, β_e anneals (~20-30%)
    - charged hadrons somewhat more damaging than neutrons (~20%)

$$\boxed{\frac{1}{\tau_{eff,e,h}} = \beta_{e,h}(t,T)\,\Phi_{eq}}$$

Invariant on any Si material property: [O],[C], type (p,n), resistivity, wafer production

Omitted in the talk!

  - ☐ $N_{eff} \rightarrow V_{fd}(\Phi_{eq})$ ←

Depends on silicon

- Diamonds
  - ☐ wide band -> no leakage
  - ☐ Neff -> 0 ; homogenous field (polarization in presence of traps)
  - ☐ charge trapping

Drift equation -signal

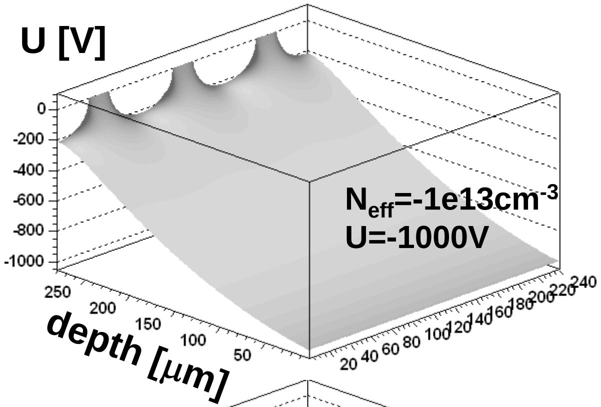
$I = q\vec{v}\vec{E}_w$ ← drift current of a single carrier

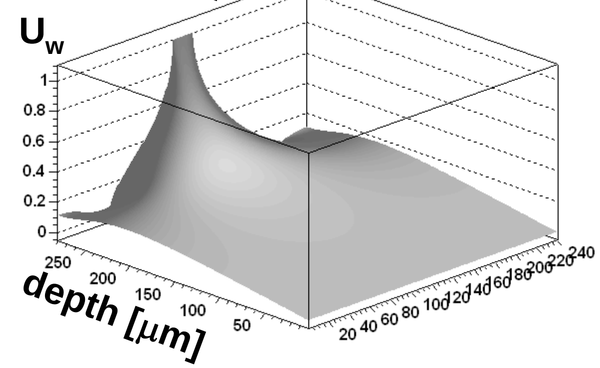
$$Q(t) = \sum_{e-h\ pairs} \int_{t=0}^{t_{\mathrm{int}}} I\,dt = \sum_{e-h\ pairs} q \int_{t=0}^{t_{\mathrm{int}}} \exp(-\frac{t}{\tau_{eff,e,h}})\,\mu_{e,h}\,\vec{E}\cdot\vec{E}_w\,dt$$

geometry factor peaked at electrodes

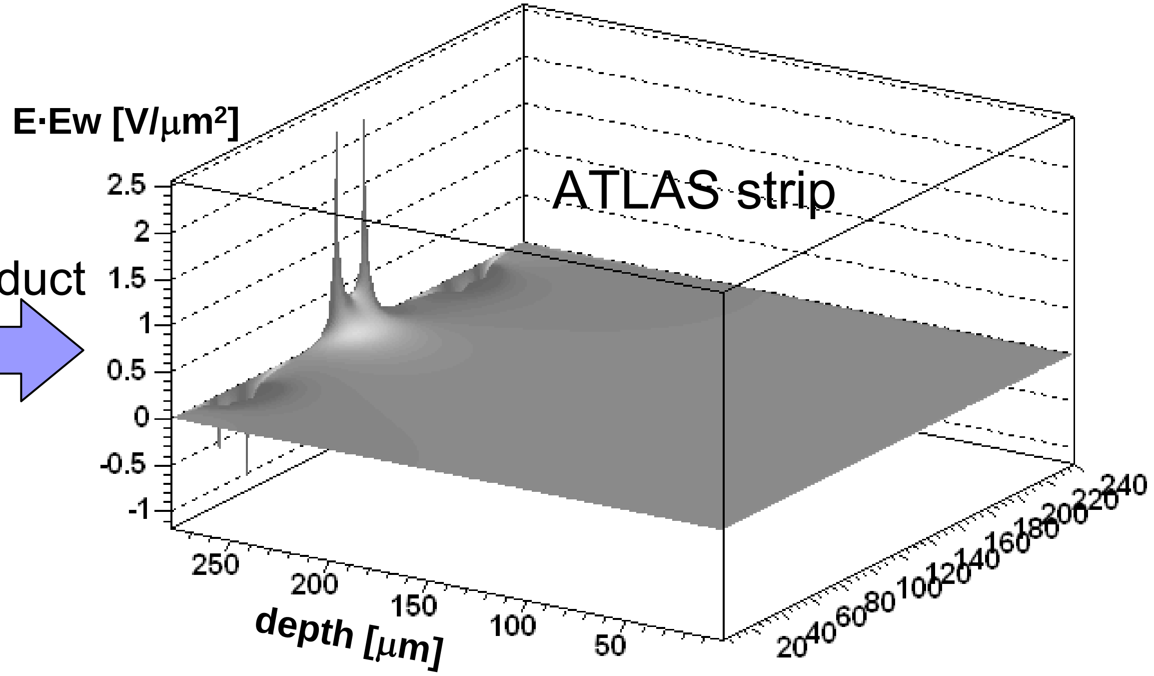
- trapping term ($\tau_{eff,e} \sim \tau_{eff,h}$)
- drift velocity ($\mu_e \sim 3\mu_h$)

- electrons get less trapped
- they should drift to the strips/pixels and contribute most to Q (n^+ readout for silicon)

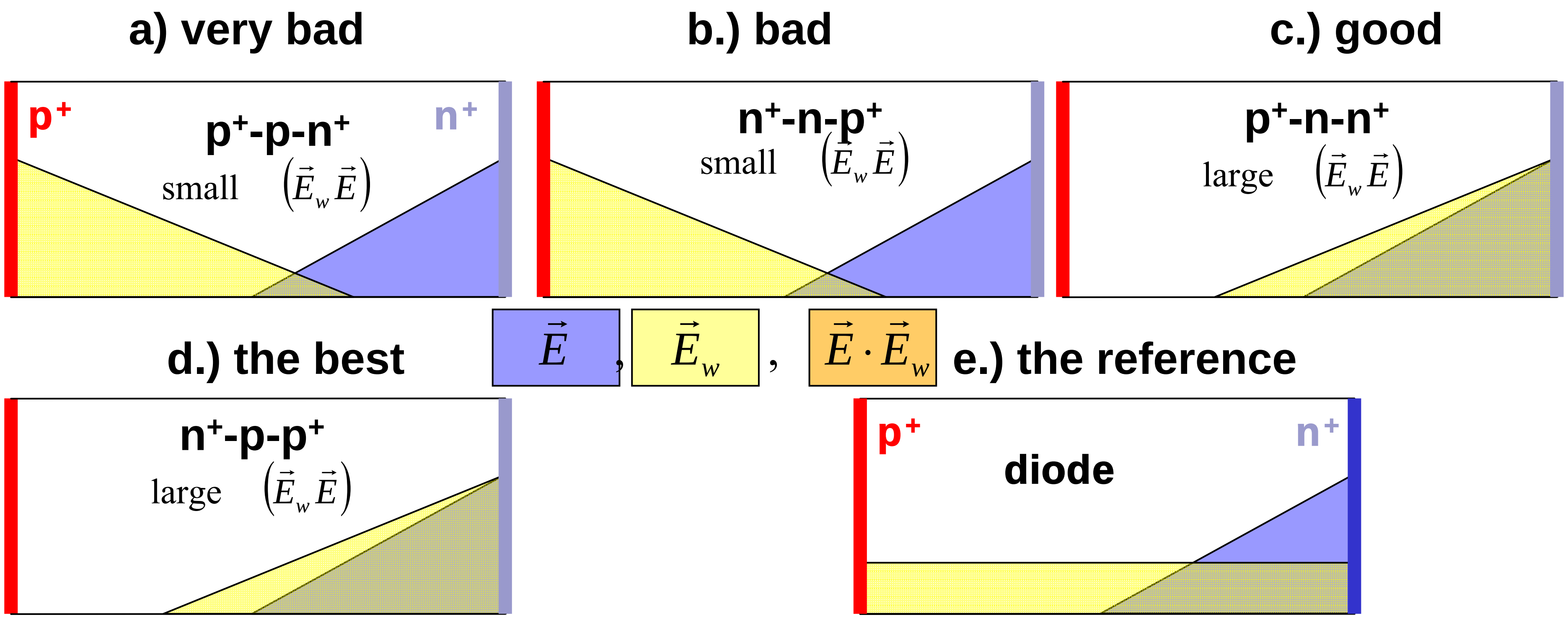




dot product



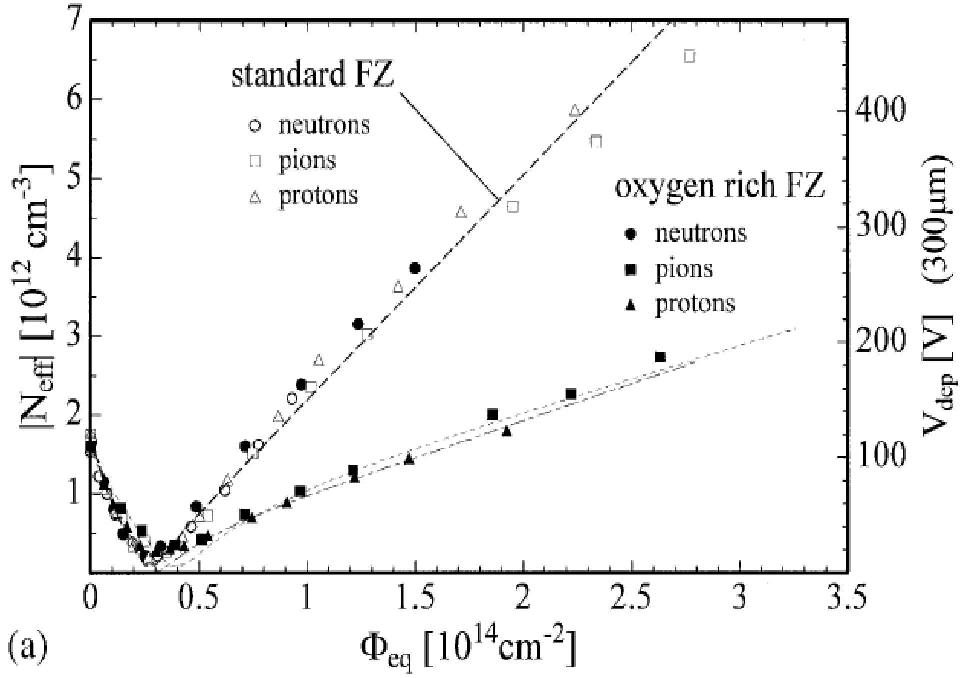
Options for the strip/pixel type and geometry in Si



If detectors can be fully depleted the order goes **a.->c.->b->d.**
At sufficiently overdepleted device **b.~d. > a.~c.**

Diamond is resistive enough to have ohmic contacts –
the collecting particles are chosen by polarity of the bias!.

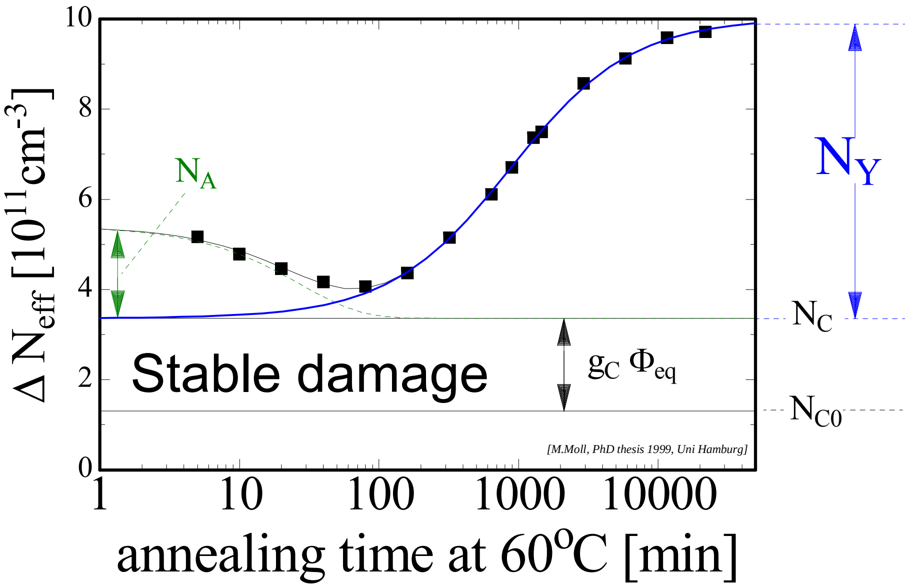
V_{fd} dependence on fluence (RD48)



- ➢In FZ detectors irradiation introduces effectively negative space charge!
- ➢For detectors irradiated with <u>charged hadrons</u>

❖**RD48:** Higher oxygen content ⇒ less negative space charge Oxygen getters radiation-induced vacancies ⇒ prevent formation of Di-vacancy (V_2) related deep acceptor levels (VO complex is inactive at room temperature)

- ➢"Cluster damage" ⇒ negative charge, [O] concentration low in clusters therefore no effect



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

- time constant depends on temperature:

~ 500 years (-10°C)
~ 500 days (20°C)
~ 21 hours (60°C)

- **Consequence:** Detectors must be cooled even when the experiment is not running!

Questions for RD50

- We know that we need n^+-p junction, so p-type material …
- What happens at much higher oxygen concentration, in DOFZ [O]=2e17 cm^{-3}?
- Are there any new silicon materials that we overlooked?

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 - 500	$< 1\times10^{17}$ very low [C]

Processing pads/strips/pixels done by: IRST-Trento, CNM Barcelona, CiS Erfurt, Micron

Epi-Si:

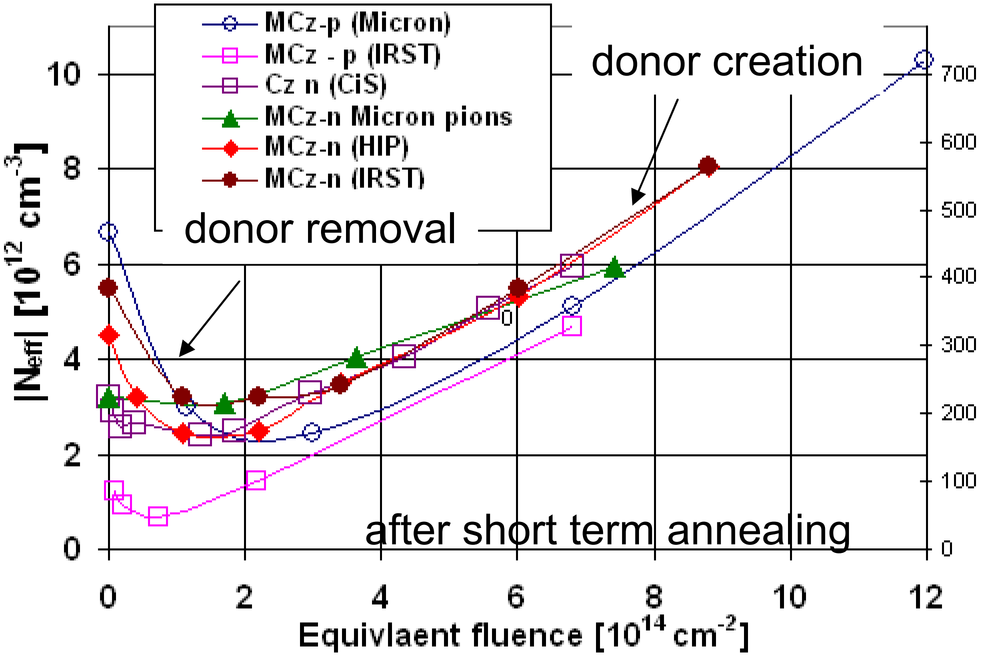
•only up to 150 μm -> $v_{sat}\cdot\tau_{eff}$~40 μm at 1e16 cm^{-2} -> no need for thicker device

•grown on Cz substrate, therefore double sided processing is not possible

MCz/Cz silicon:

•Can have problems with homogeneity over the wafer!

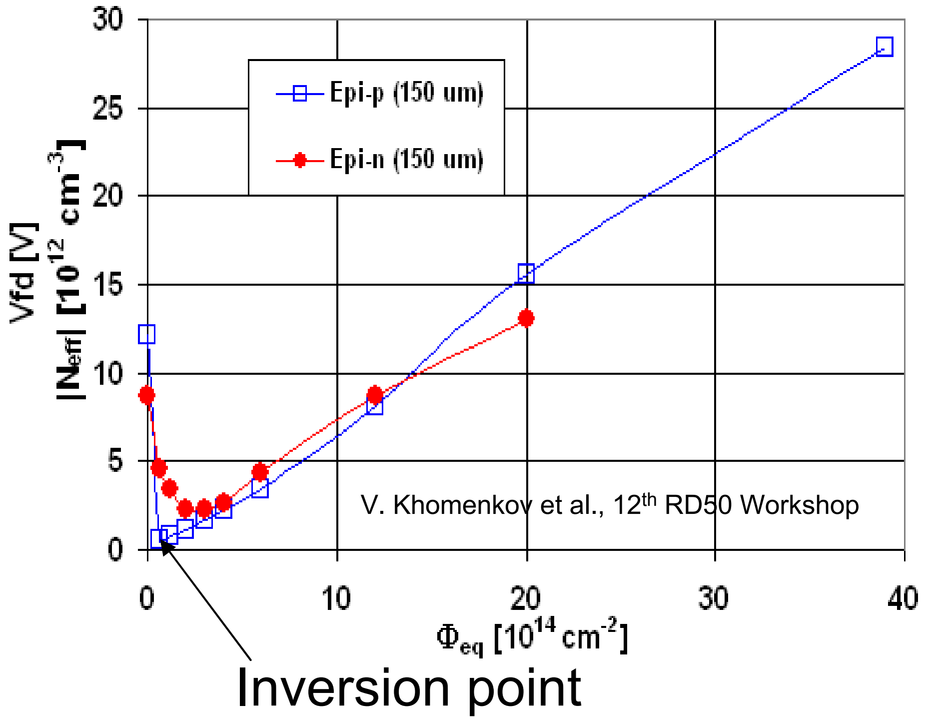
Epi and MCz/Cz after charge hadron irr.



donor creation

donor removal

after short term annealing



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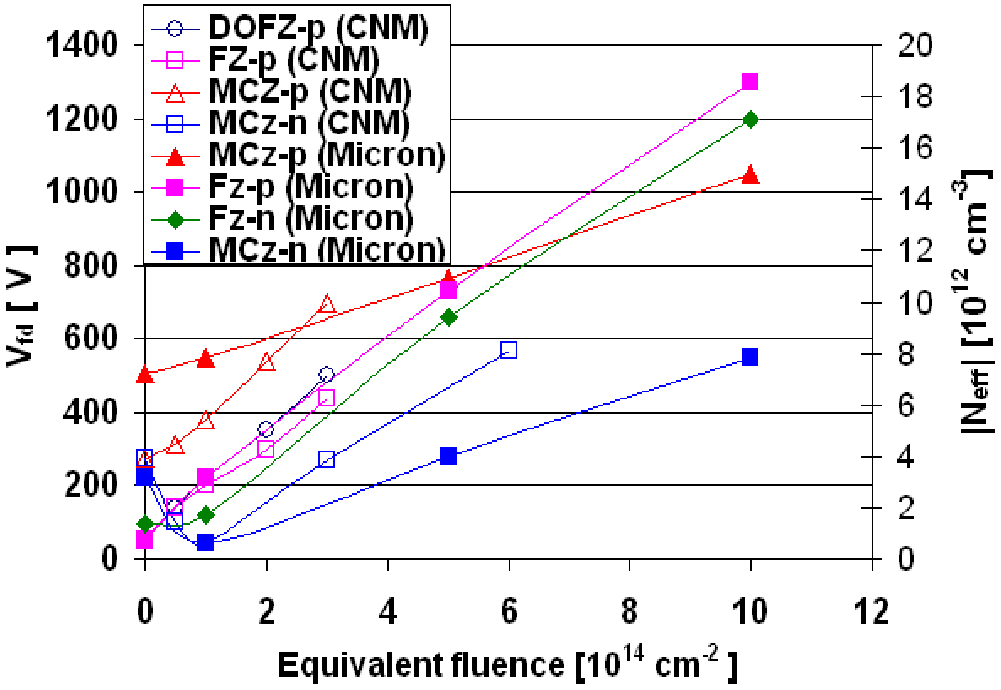
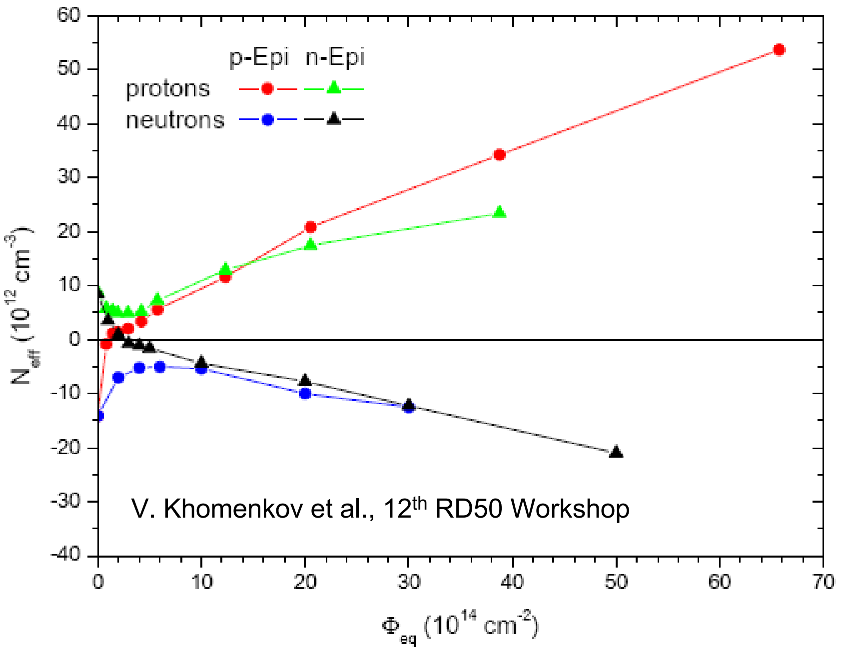
Inversion point

- MCz/Cz-n **positive space charge introduced** ($|g_c|$~0.0077 cm^{-1} ~ similar to DOFZ ?)
- It appears as MCz-p remains p-type (V_{fd}>>0), but N_{eff} is not constant and the dominant junction can move at V_{fd}>0 (“double junction” effect)
- No influence of initial donors at high fluence (complete donor removal) for MCz-n
- Strong acceptor removal for MCz-p

- Epi-n,p **positive space charge introduced** ($|g_c|$~0.0075 cm^{-1}) -> but epi is O and C lean material
- The introduction rate depends on thickness of epitaxial silicon 0.024-0.0075 cm^{-1} (25-150 μm)
- CiS and IRST processes show similar results

Epi and MCz/Cz after neutron irradiations





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Universal behavior for the neutron irradiated 300 μm thick samples

✓g_c~0.02 cm^{-1} **(negative space charge)**

✓no acceptor removal

Up to now the only difference is seen in Micron processed MCz material, which has a g_c~0.01 cm^{-1}

Epi-Si (150 μm) shows smaller damage than standard after neutron irradiations:

g_c~0.004-0.005 cm^{-1}(150 μm,500 Ωcm)

g_c~0.007 cm^{-1} (75 μm,150Ωcm)

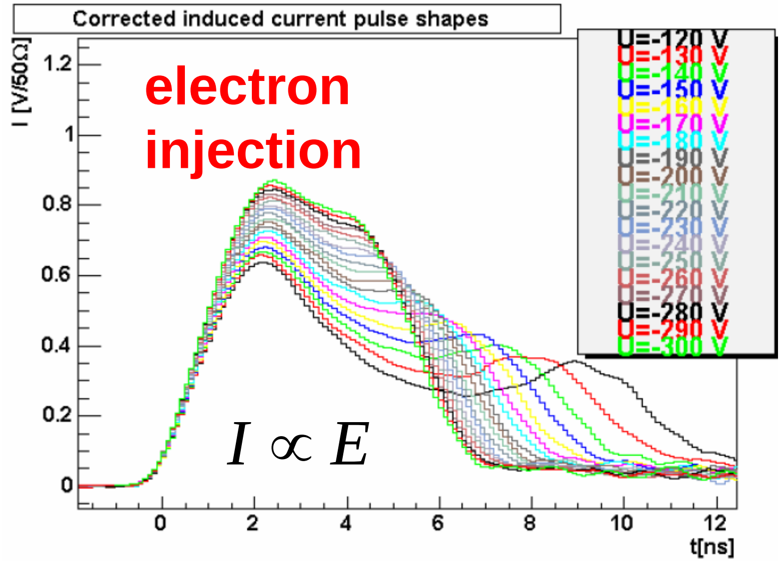
g_c~-0.008 cm^{-1} (donors) (50 μm, 50Ωcm)

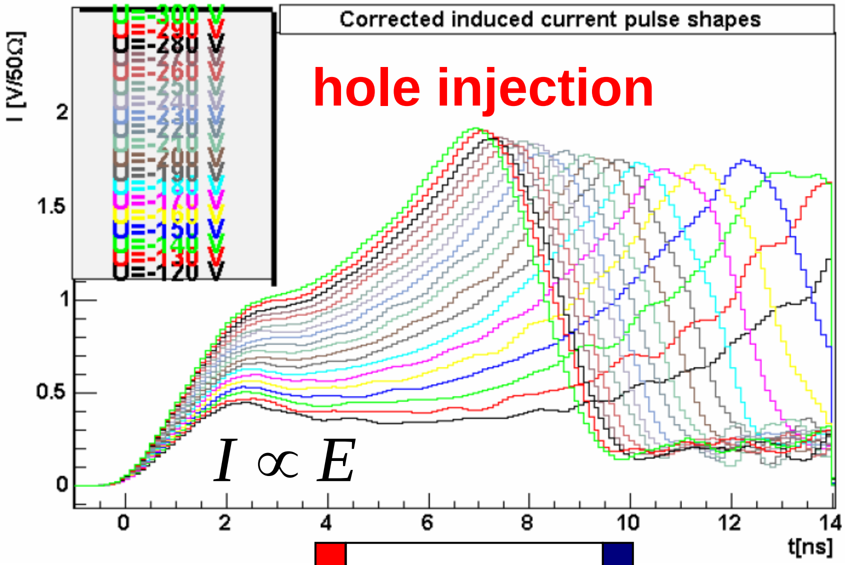
Also other materials may show smaller damage at lower resistivity!

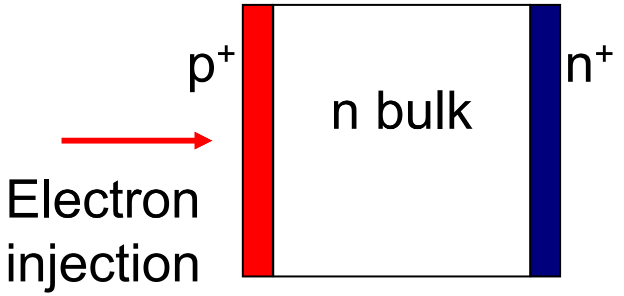
- What is the explanation of positive space charge?
  - It is related to oxygen and point defects!
    - ^{60}Co γ irradiated DOFZ samples -> introduction of positive space charge!
    - After neutron irradiation we see negative space charge!
  - An explanation of positive space charge with oxygen dimmer (O_{2i}) is likely
    - Oxygen dimmers influence formation of BD (probably TDD2)!
    - in MCz/Cz (high intrinsic O_i and O_{2i})
    - in Epitaxial silicon O_{2i} out-diffuses (very mobile) from low resistivity Cz substrate (influence of thickness)
- How do we know that the dominant space charge is really positive?
  - TCT signals (probing the electric field profile)
  - Annealing plot (decay of acceptors-plateau-generation of acceptors)
  - Mixed irradiations (compensation of donors and acceptors)

How do we know $N_{eff}>0$ – TCT signals

MCz-n detector at T=-10°C after 5e14 pcm^{-2} annealed ~14 days at RT (V_{fd}~110 V)





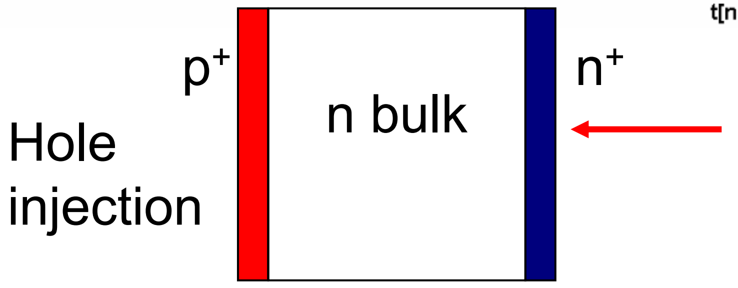


p$^+$

n bulk

n$^+$

Electron injection



p$^+$

n bulk

n$^+$

Hole injection

For e/h injection high field region is at the p$^+$ contact, hence $N_{eff}>0$
(dominant space charge determining the main junction)

At very high fluences the derivation of space charge from TCT becomes very sensitive to the value of τ_{eff}!

Annealing behavior of MCz, epi-Si detectors

Finger print of positive space charge seen in annealing

1. decay of acceptors -> increase of V_{fd}
2. local maximum of V_{fd} (plateau)
3. generation of acceptors -> decrease of V_{fd}
4. inversion of space charge at late stages, **but V_{fd} never really goes to ~0 (double junction)**
5. further generation of acceptors increase of V_{fd}

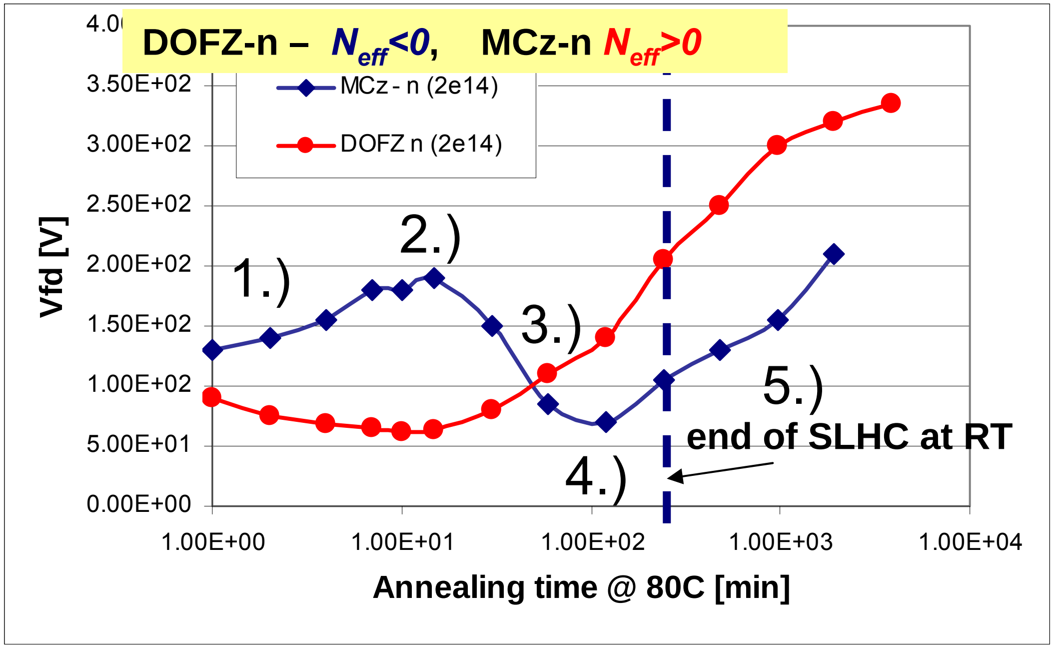
Long term annealing similar as in FZ!

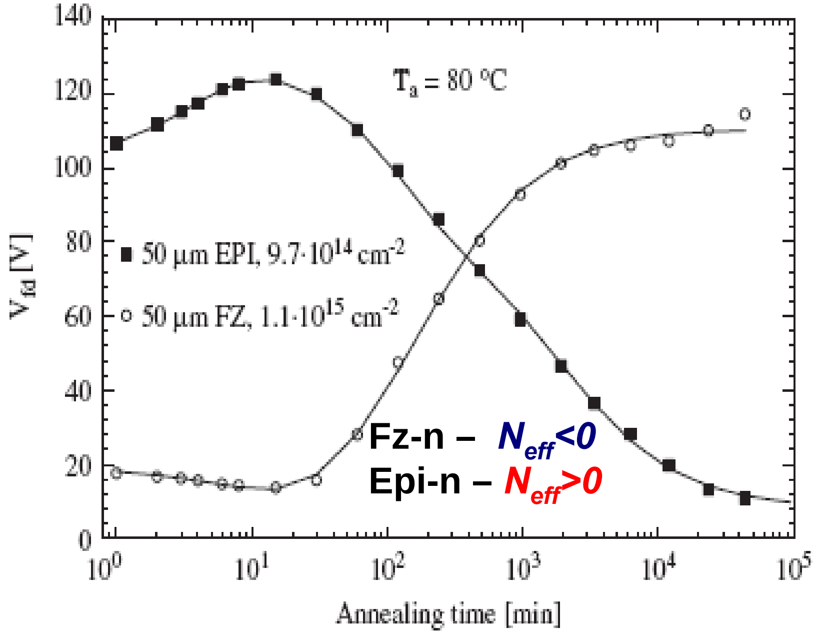
Long term amplitude: g_Y~3-5 10^{-2} cm^{-1}

Time constants : τ_{ra}*~few 100 min@80°C*

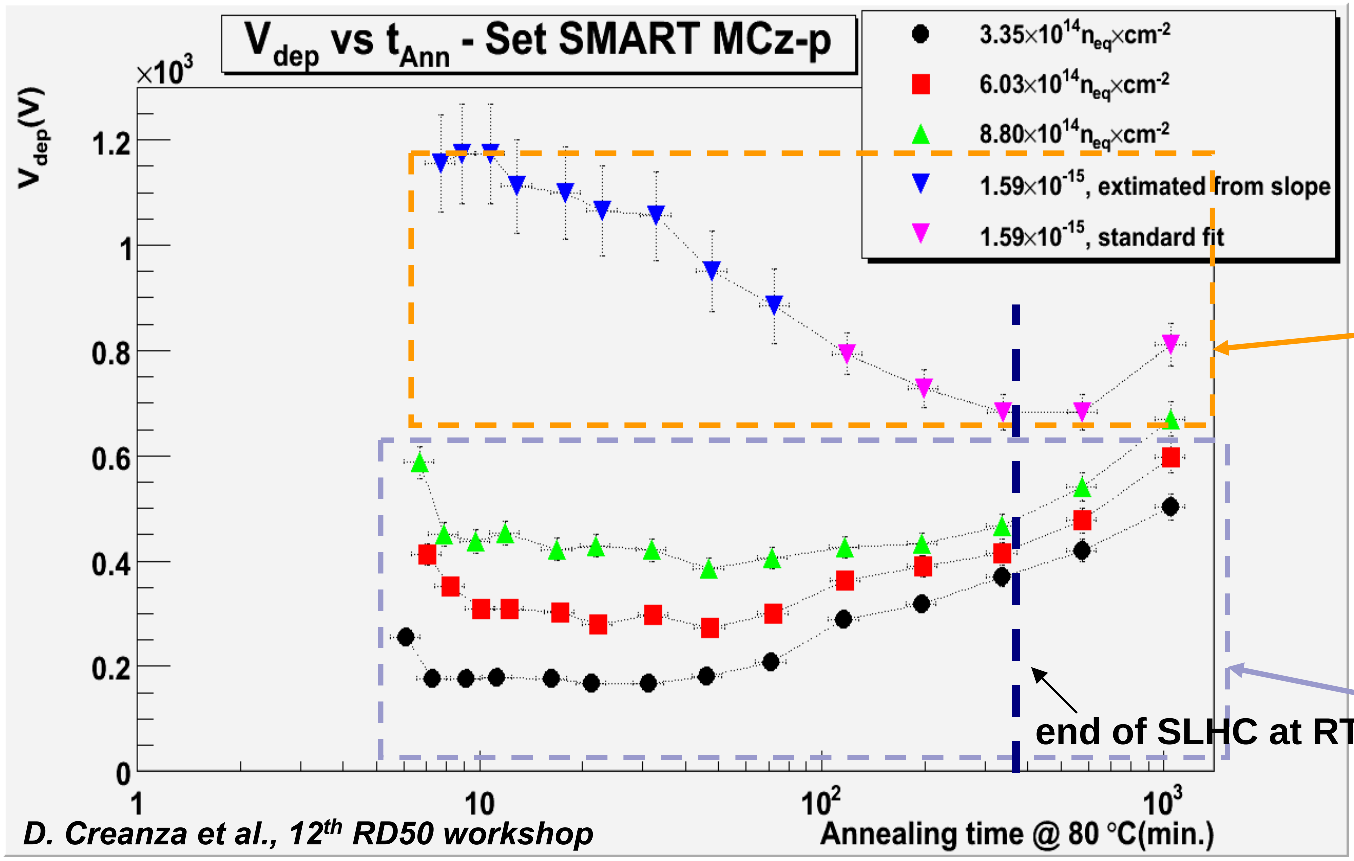
(τ_{ra}~ 80 min @ 80°C for FZ = 1.2y at RT)

In epitaxial silicon at late stages (beyond the interest of SLHC) a second component appears.





Annealing behavior of MCz-p detectors



D. Creanza et al., 12th RD50 workshop

The most irradiated diode shows an n-like annealing behaviour

“p-like” annealing behaviour

- At higher fluences donors are introduced (TCT, anneal)
- At lower fluences (TCT – donors, annealing acceptors)

preliminary

Mixed irradiations - a more real SLHC env.

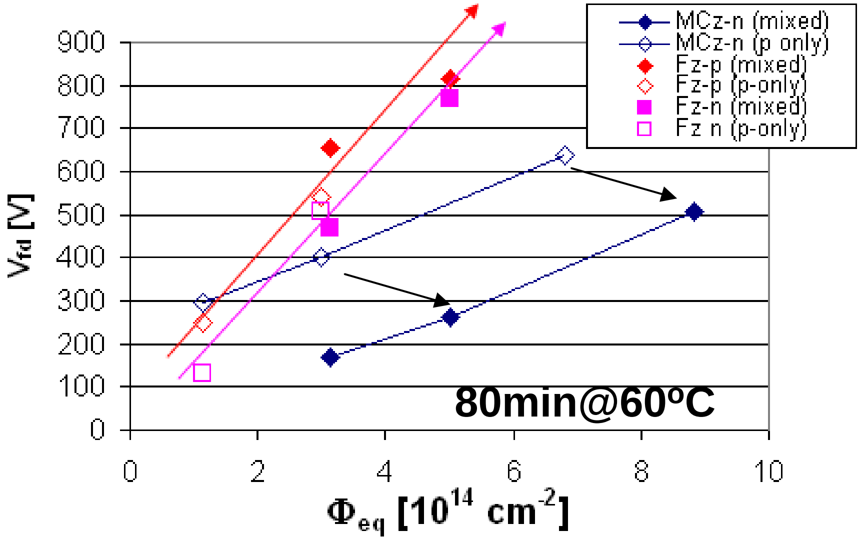
Detectors irradiated with charged hadrons can have positive or negative space charge

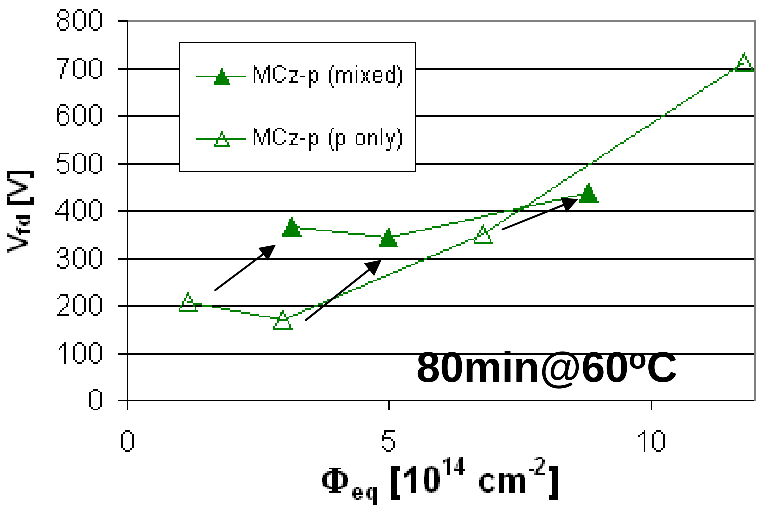
Irradiation with neutrons introduces acceptors

$N_{eff}>0$: Positive space charge is compensated **V_{fd} decreases** ($g_{c,n}>0$ $g_{c,p}<0$)

$N_{eff}<0$: Negative space charge is added **V_{fd} increases** ($g_{c,n}>0$, $g_{c,p}>0$)

Micron diodes irradiated with protons first and then with 2e14 n cm^{-2} (control samples p-only, open marker)



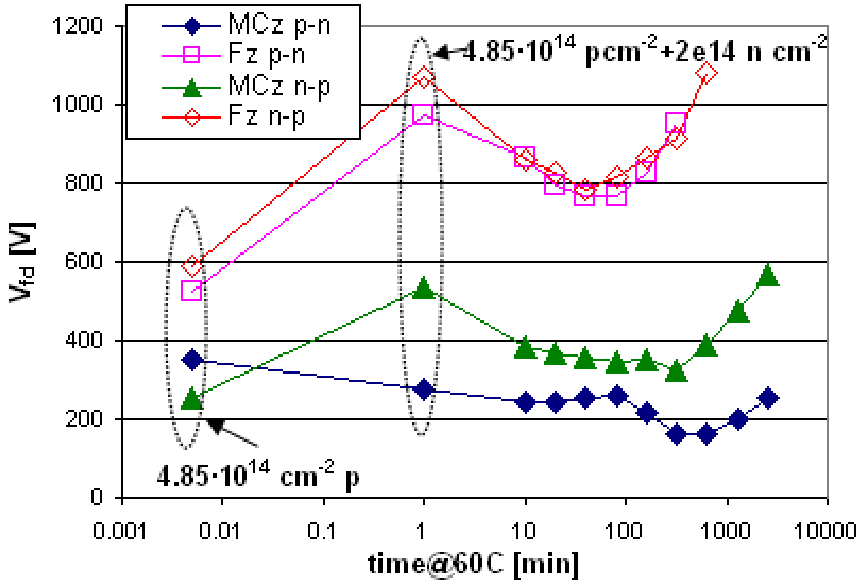


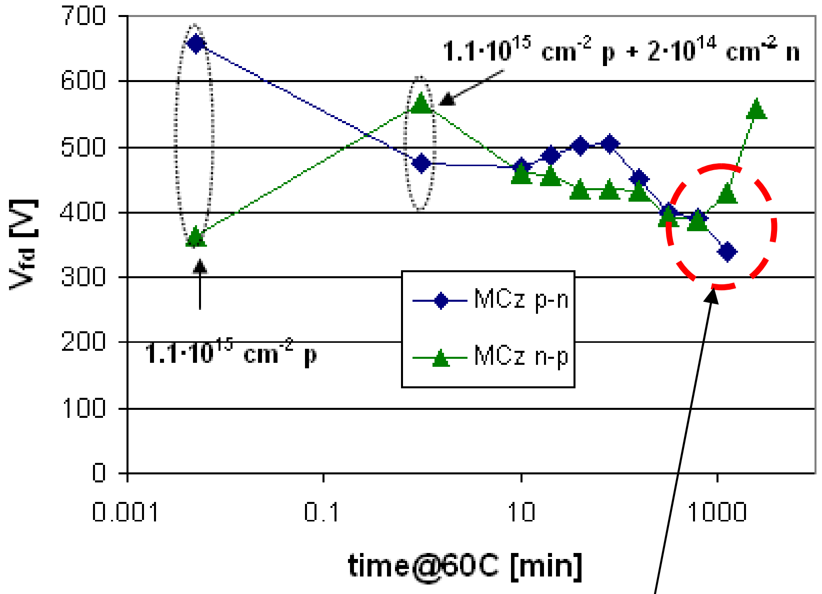
- FZ-p,n as expected – increase of V_{fd} proportional to Φ_{eq}
- MCz-n as expected – decrease of V_{fd} for the expected amount
- **MCz-p at larger fluences the increase of V_{fd} is not proportional to the added fluence –as if material becomes more "n-like" with fluence – same as observed in annealing plots**

preliminary

Mixed irradiations (II) - annealing

Micron diodes irradiated with protons first and then with neutrons (the first point is before n irr.)





The “picture” is also confirmed in the annealing:

- Fz n,p – expected behavior for $N_{eff}<0$
- MCz-n – expected behavior for $N_{eff}>0$ (note the decrease of V_{fd} after neutron irr.)
- MCz-p points to $N_{eff}<0$, but at higher fluence the increase of V_{fd} is smaller than expected

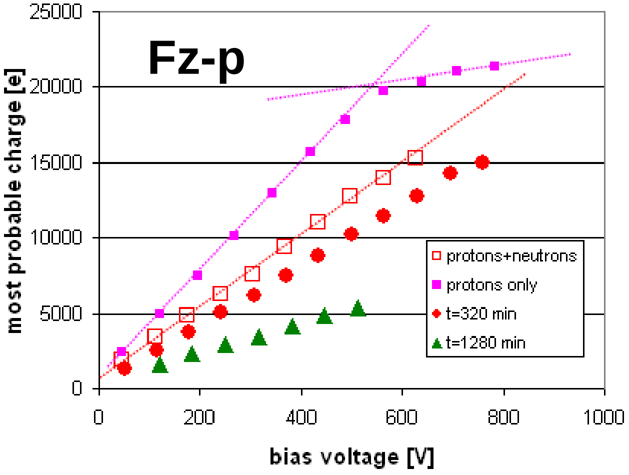
Note: $\Phi_{eq}=9e14$ cm^{-2}, $V_{fd}\sim400$ V

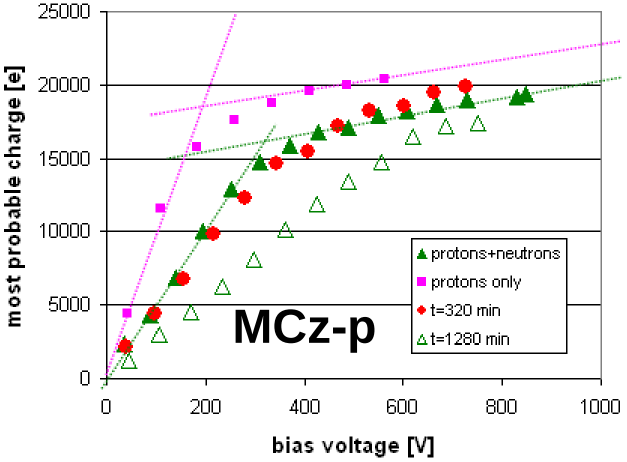
- 1.5 y at 20°C
- ~1/3 of the SLHC fluence at $r=15$ cm with proper mix

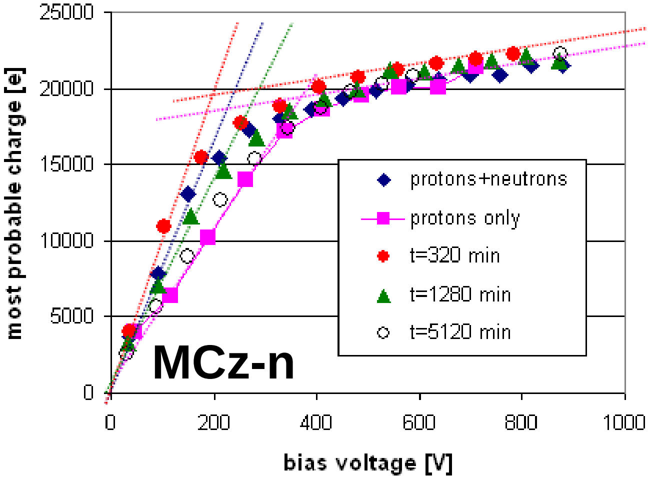
preliminary

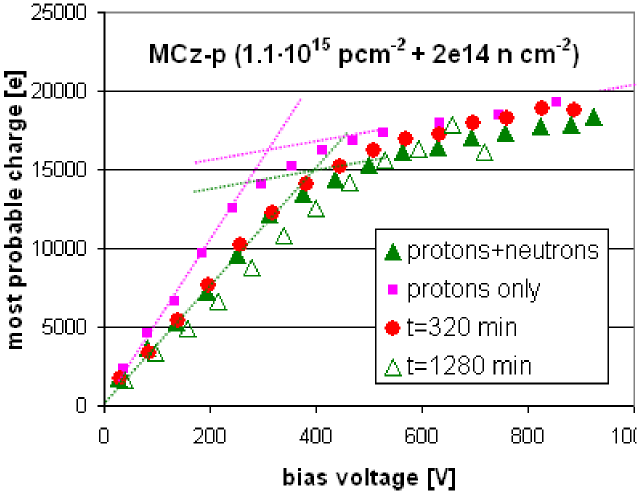
Mixed irradiations (III) - CCE

Φ=4.81e14 p cm^{-2} + 2e14 n cm^{-2} (half of the SLHC fluence for short-strip region r=30 cm)









The V_{fd} evolution from C-V is confirmed in CCE!

- **For MCz-n the V_{fd} is always better than after p-only**
- MCz-p it seems that reverse annealing gets “delayed” with fluence

↓

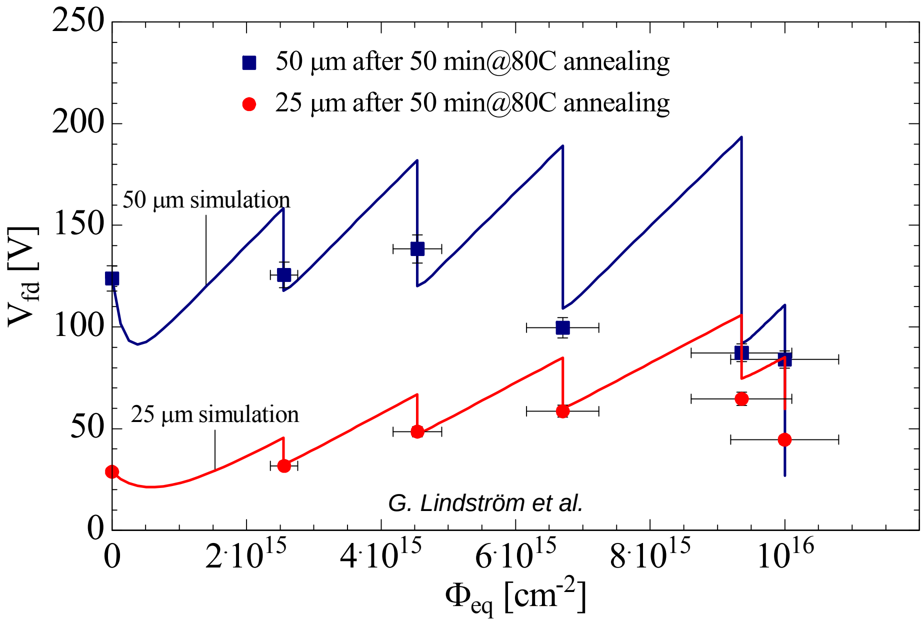
At fluence of Φ_{eq}=9e14 cm^{-2} the full depletion voltage of MCz materials is below 500 V even if detectors are kept most of the time at room temperature.

What are the benefits of epi/MCz !

Introduction of positive space charge for fast charged hadrons

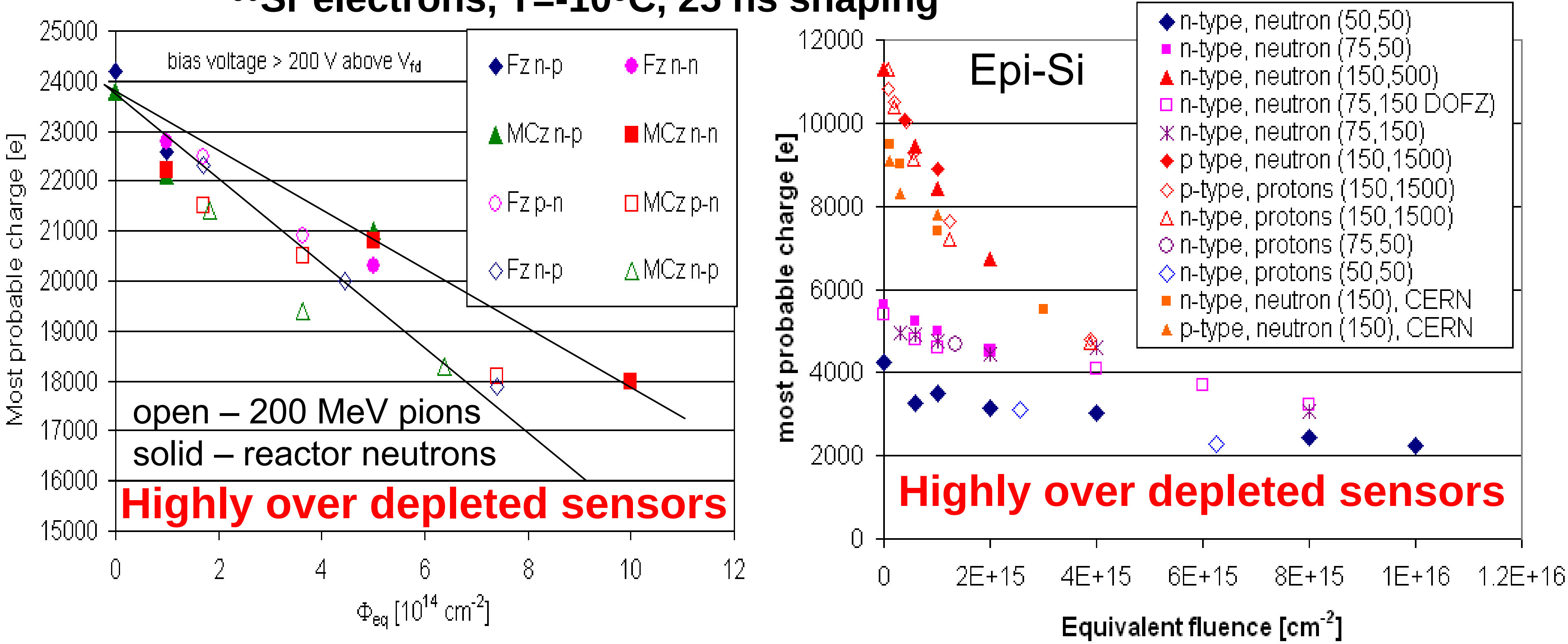
- ☺ It enables to control the space charge
  - $|g_c|<|g_Y|$ with g_c and g_Y of opposite signs – proper design of operation scenario can lead to compensation and reduction of V_{fd}
  - g_c for neutrons and g_c for charged hadrons are of different sign – mixed field will reduce the full depletion voltage
- ☺ There are other benefits from long term annealing of detectors:
  - **Smaller leakage current**
  - **Longer trapping times from electrons**

warm CERN scenario (50 min @ 80°C) experiment



Charge collection efficiency (epi/MCz/Fz)

^{90}Sr electrons, T=-10°C, 25 ns shaping

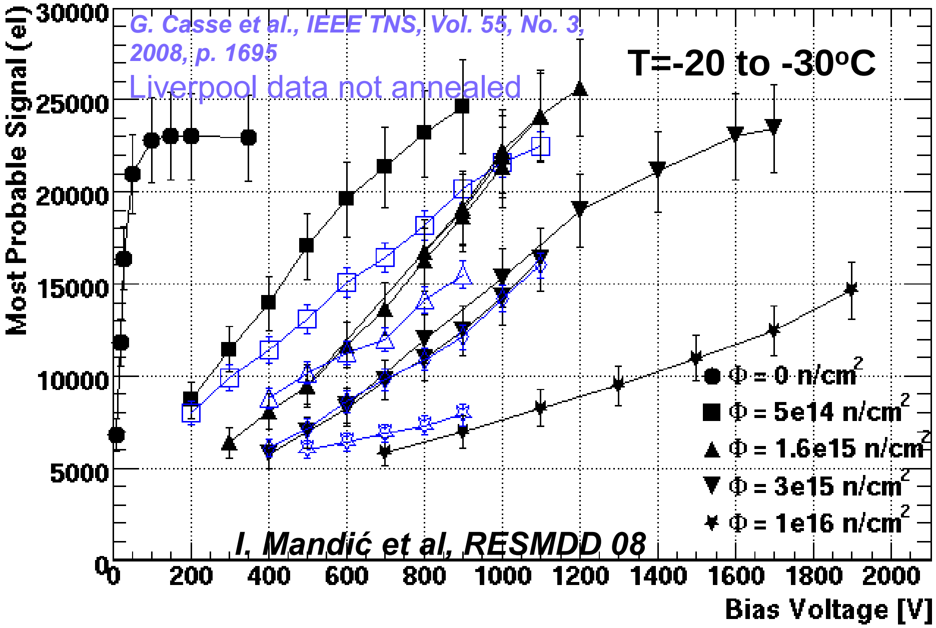


The effect of electric field is taken out by over depleting the sensors – CCE determined by trapping only:

- within the error margin all materials behave the same!
- CCE for Epi-Si up to 2-3e15 cm^{-2} agrees with predictions (not shown here)
- pions are at the same Φ_{eq} ~20% more damaging than neutrons
- at large fluences the thick and thin detectors come together in terms of collected charge.

CCE measurements for strip Fz/MCz detectors up to 1e15 cm^{-2} show good agreement with diodes!

Measurements with FZ n$^+$-p strip detectors

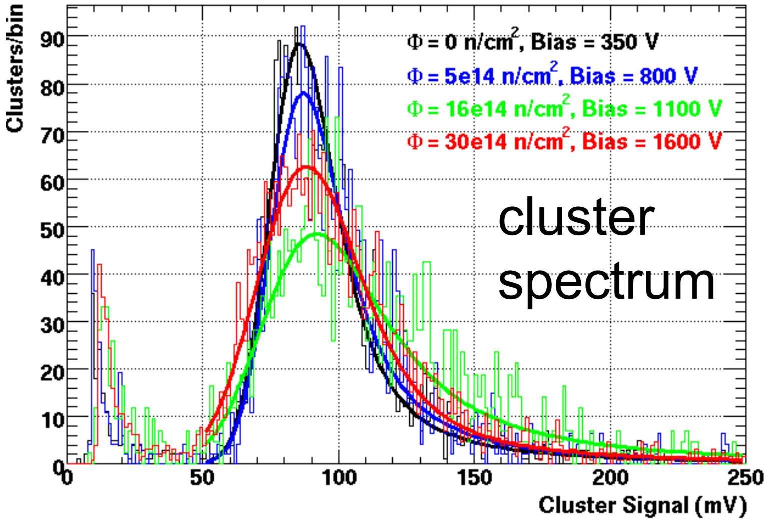

G. Casse et al., IEEE TNS, Vol. 55, No. 3, 2008, p. 1695

Liverpool data not annealed

T=-20 to -30°C

I. Mandić et al, RESMDD 08

SCT 128A, 25ns, ^{90}Sr electrons
detector FZ-p Micron, n irradiated



CCE~100% at 3e15 cm^{-2} , CCE~60% at 1e16 cm^{-2}

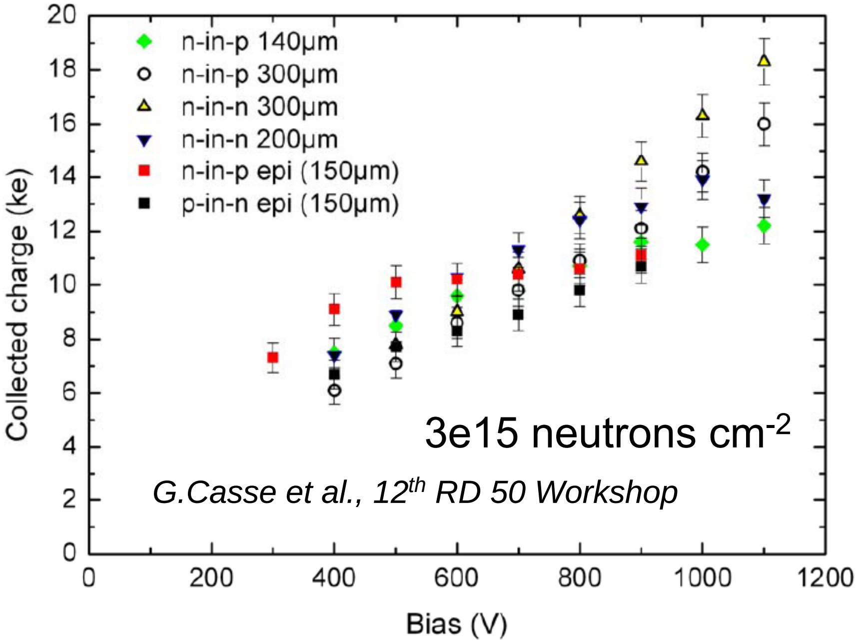
To explain the measurements there should be:

- No trapping (but we do see it with pad detectors)
- g_c should be far from measured – expected V_{fd}(3e15cm^{-2})=3500 V, measured from CCE~1400 V! Un-depleted bulk is highly resistive-> some field exits at $V<V_{fd}$ which enables the drift. But also true for operation in forward bias mode where CCE<<100%

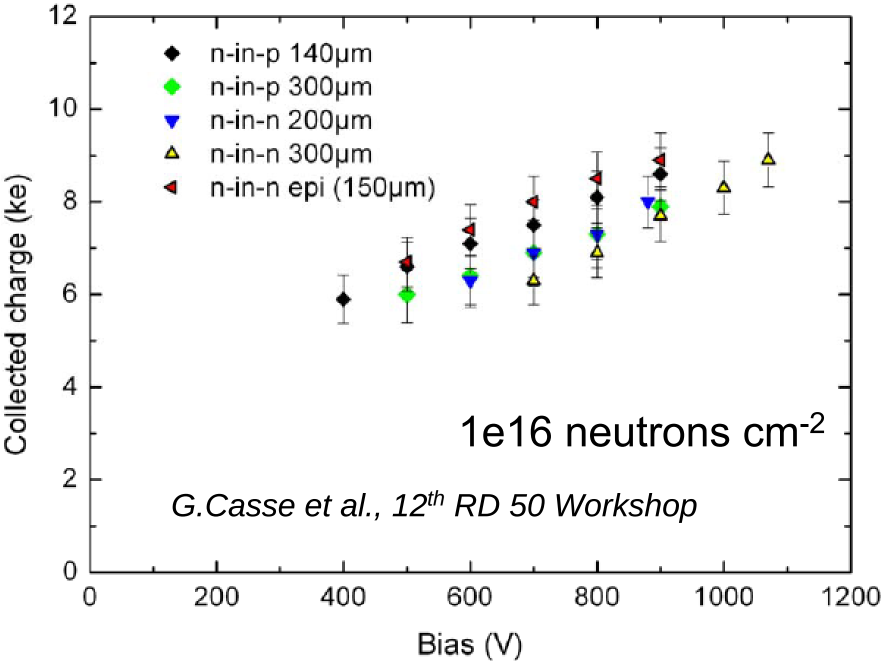
It is better to have high charge collection efficiency and not understand it, than know exactly why is it too low for successful operation…

Measurements with FZ/Epi n^+-p strip detectors

SCT 128A, 25ns, ^{90}Sr electrons
Detectors processed by Micron, neutron irradiated



G.Casse et al., 12th RD 50 Workshop



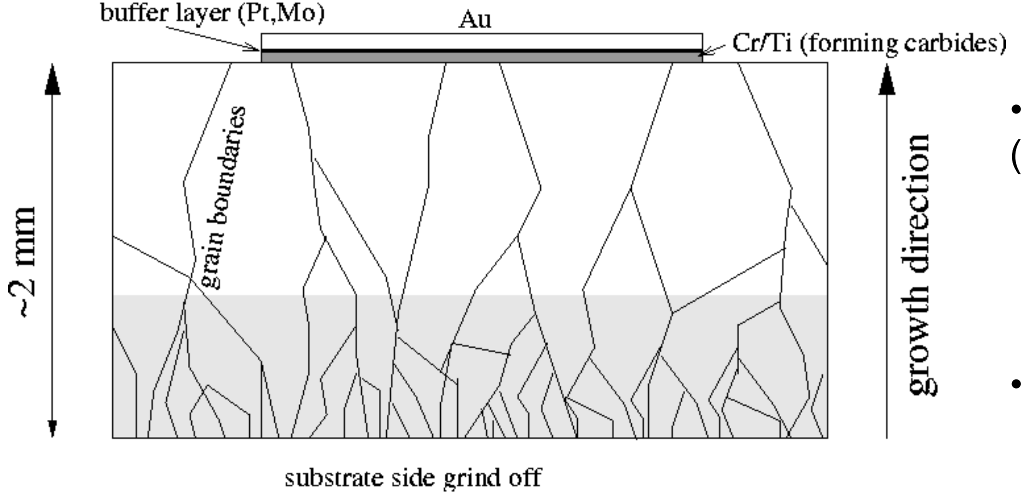
G.Casse et al., 12th RD 50 Workshop

If you are limited with bias to ~500-600 V thin epi-Si is slightly better than thick at very high fluences. Nevertheless 6-8 ke can be collected at 1e16 cm^{-2}.

Diamond detectors

Property	Diamond	Silicon	
Band gap [eV]	5.5	1.12	☺ Low leakage
Breakdown field [V/cm]	10^7	$3\text{x}10^5$	
Intrinsic resistivity @ R.T. [Ω cm]	$> 10^{11}$	$2.3\text{x}10^5$	
Intrinsic carrier density [cm^{-3}]	$< 10^3$	$1.5\text{x}10^{10}$	
Electron mobility [cm^2/Vs]	1900	1350	
Hole mobility [cm^2/Vs]	2300	480	
Saturation velocity [cm/s]	0.9(e)-1.4(h)x 10^7	0.82x 10^7	
Density [g/cm^3]	3.52	2.33	
Atomic number - Z	6	14	
Dielectric constant - ε	5.7	11.9	☺ Low capacitance
Displacement energy [eV/atom]	43	13-20	☺ Radiation hard
Thermal conductivity [W/m.K]	2000	150	☺ Heat spreader
Energy to create e-h pair [eV]	13	3.61	
Radiation length [cm]	12.2	9.36	
Spec. Ionization Loss [MeV/cm]	4.69	3.21	
Aver. Signal Created / 100 μm [e_0]	3602	8892	☹ Low signal
Aver. Signal Created / 0.1 X_0 [e_0]	4401	8323	

Diamonds basics (I)



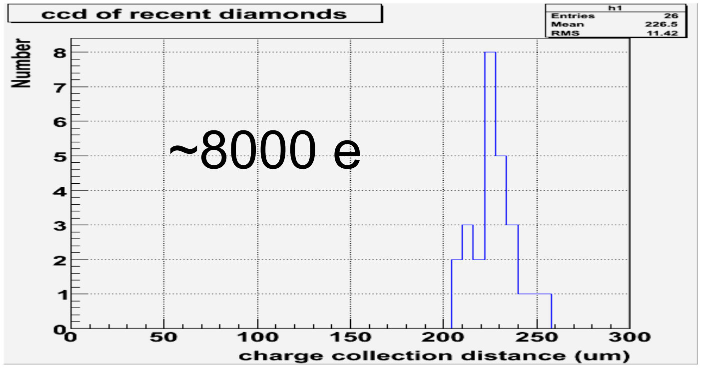
- •Polycrystalline Chemical Vapour Deposition (pCVD)
  - •Exist in Φ = 12 cm wafers, >2 mm thick
  - •Grown in μ-wave reactors on non-diamond substrate
  - •Base-line diamond material for pixel sensor
- •Single crystalline (scCVD)

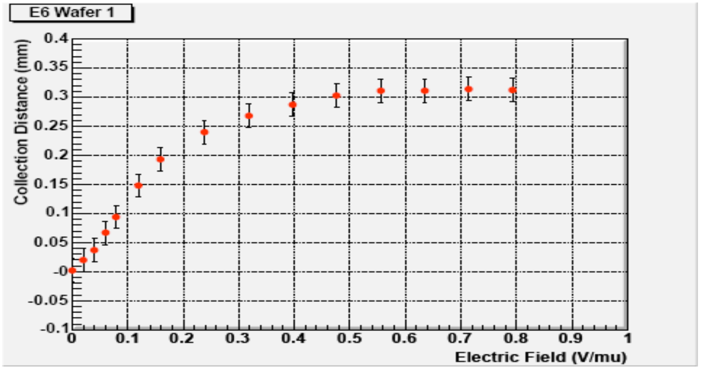
- No processing: put electrodes on, apply electric field
- Trapping on grain boundaries and in bulk
  - much like in heavily irradiated silicon
- Parameterized with Charge Collection Distance, defined by
- CCD = average distance e-h pairs move apart
- Coincides with trapping distance in infinitely thick detector (CCD=λ)

$$CCD = \frac{< Q_{col} >}{36 \frac{e_0}{\mu m}}$$

☝ **mean** not **most probable**
Usually defined at 1 or 2 V/μm

$$\lambda = \mu_e \tau_{eff,e} E + \mu_h \tau_{eff,h} E$$





Diamonds - Radiation Damage (I)

Radiation induced effect	**Diamond**	**Operational consequence**	**Silicon**	**Operational consequence**
Leakage current	small & decreases	none	$I/V = \alpha\Phi$ $\alpha \sim 4\mathrm{x}10^{-17}$ A/cm	**Heating** **Thermal runaway, shot noise**
Space charge	~ NO/YES (polarization)	None/moderate increase of bias	$\Delta N_{eff} \approx -\beta\Phi$ $\beta \sim 0.15\ \mathrm{cm}^{-1}$	**Increase of full depletion voltage**
Charge trapping	**Yes**	**Charge loss** **Polarization**	$1/\tau_{eff} = \beta\Phi$ $\beta \sim 5\text{-}7\mathrm{x}10^{-16}\ \mathrm{cm}^2/\mathrm{ns}$	**Charge loss** **Polarization**

- Charge trapping the only relevant radiation damage effect
  - NIEL scaling questionable *a priori , NIEL an order of magnitude smaller than in Si*
- E_{gap} in diamond 5 times larger than in Si
  - Many processes freeze out
  - Typical emission times order of months
- Like Si at 300/5 = 60 K – Boltzmann factor
  - Lazarus effect ?
  - Time dependent behaviour
- ✓ A rich source of effects and (experimental) surprises !
- ✓ Even before the irradiation there are defects at grain boundaries which reduce the CCD -> priming/pumping (exposure to ionizing radiation) improves the CCE as it fills the traps

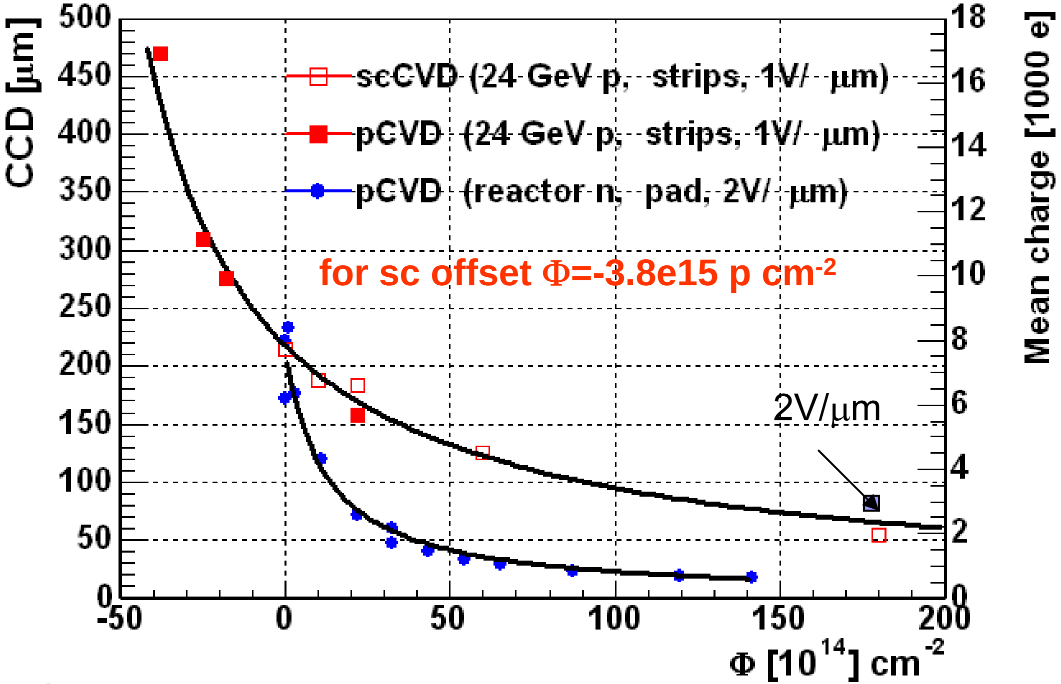
Diamonds - Radiation Damage (II)

Degradation of charge collection efficiency:

$$\frac{1}{\lambda} = \frac{1}{\lambda_0} + k \times \Phi$$

$$\downarrow \text{thickness} >> \lambda$$

$$\frac{1}{CCD} = \frac{1}{CCD_0} + k \times \Phi = k(\Phi + \Phi_0)$$



Preliminary data of recent irradiations:

- scCVD (4) and pCVD (2) with PS 24 GeV: *k* ~ 0.8x10^{-18} µm^{-1}cm^{-2}, ~same as old pCVD proton data
- pCVD (2) with reactor neutrons up to 8x10^{15} n$_{eq}$/cm^{2} (in 5 steps); *k* ~ 3.7x10^{-18} µm^{-1}cm^{-2}
- pCVD with PSI 200 MeV pions up to 6x10^{14} π/cm^{2}; *k*~1-3x10^{-18} µm^{-1}cm^{-2} (hard to reach high fluences at PSI)

Diamonds - Radiation Damage (III)

For the most exposed sensors at SLHC (where diamond is a contender) around 2000 e which is less than in Si, but ...

- Diamonds don't need cooling to low temperatures (much smaller X_0) – maybe more space points per layer
- Break down voltage is very high, higher bias than 1000 V will make some difference
- Noise is smaller (leakage + capacitance)

Readout (FE-I3)	Diamond	Planar-Si
Pixel noise	140e	180e
Threshold	1500e	2300e
In time treshold	2300e	3600e

3D-Si sensors may require up to 7000e

Conclusions

If one can tolerate voltages up to or more than 1000 V any detector with n^+ readout gives enough charge to achieve desired signal. But,

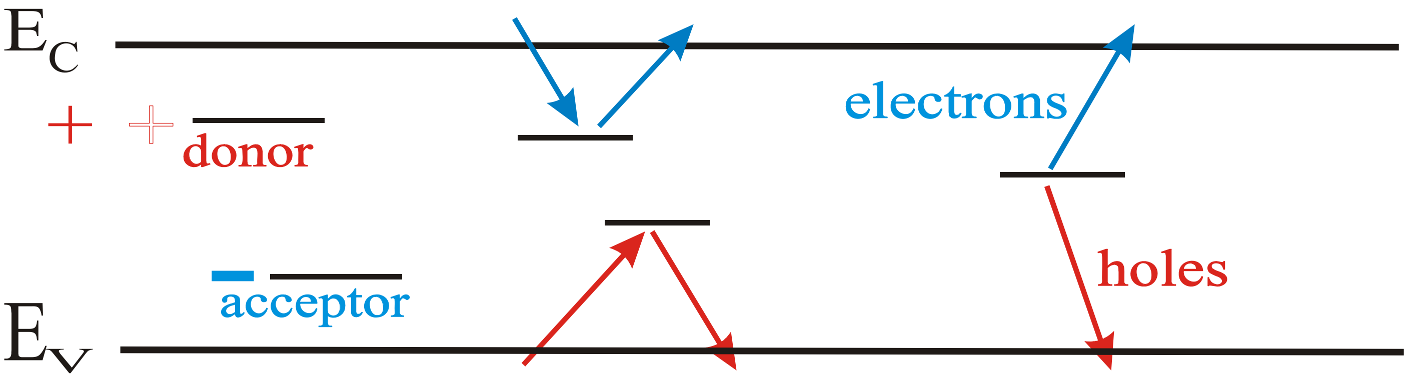
- Stability of operation?
- **We should understand why CCE is so high!**

If we want to limit the bias voltage to values significantly below 1000V …

- r=4-12cm cm (2e15-1.6e16 cm^{-2}) Epi-p with proper running scenario is a candidate as the trapping renders thickness unimportant. Diamond should be also considered - small X_0 is crucial for vertexing. Innermost layer may need replacement.
- r=12-25 cm (1-2e15 cm^{-2}) the composition of neutrons to charged hadrons is such that compensation and proper running scenario (annealing)would be large and V_{fd} could be kept <500 V with MCz-n, Epi-p (thickness?) and maybe also with MCz-p.
- r>25-60 cm (5e14-1e15 cm^{-2}) the damage is more and more dominated by neutrons.
  - MCz-p (Epi-p suffers from smaller thickness) is the best candidate particularly for Micron process.
- r>60 cm (<5e14 cm^{-2}) Fz n^+-p or MCz n^+-p or even present detectors.

Basics of radiation damage (II)

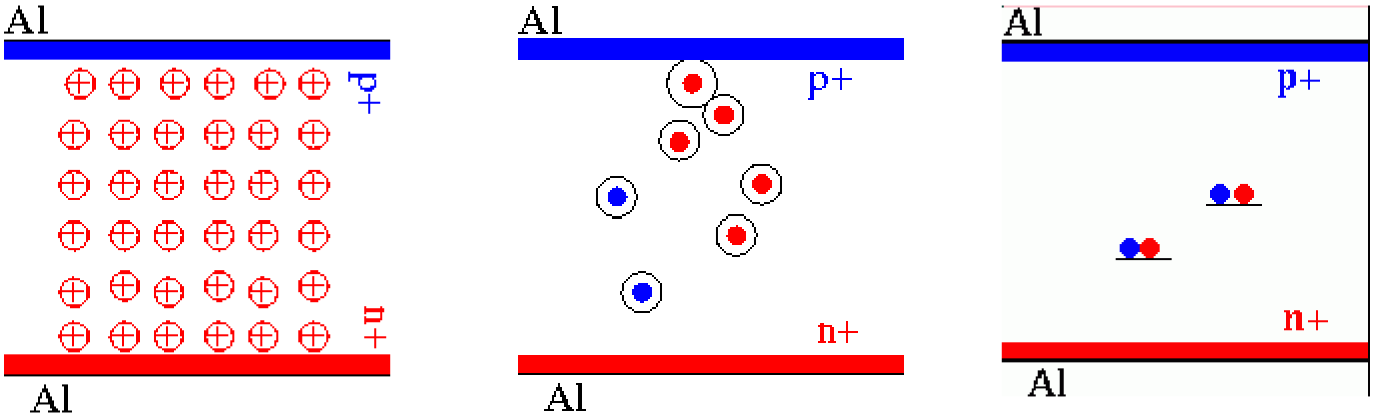
Influence of defects on the material and device properties



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



Drift equation -signal

$I = q\vec{v}\vec{E}_w$ ⟵ drift current of a single carrier

$$Q(t) = \sum_{e-h\ pairs} \int_{t=0}^{t_{\text{int}}} I dt = \sum_{e-h\ pairs} q \int_{t=0}^{t_{\text{int}}} \exp\left(-\frac{t}{\tau_{eff,e,h}}\right) \mu_{e,h} \vec{E} \cdot \vec{E}_w dt$$

Weighting field

$\Delta U_w = 0$

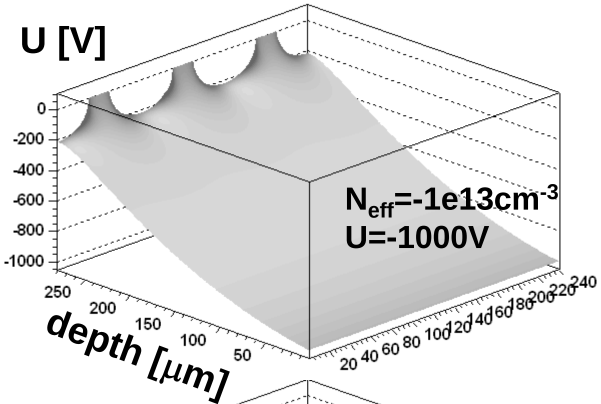
$U_w = 1$ ⟶ sensing electrode

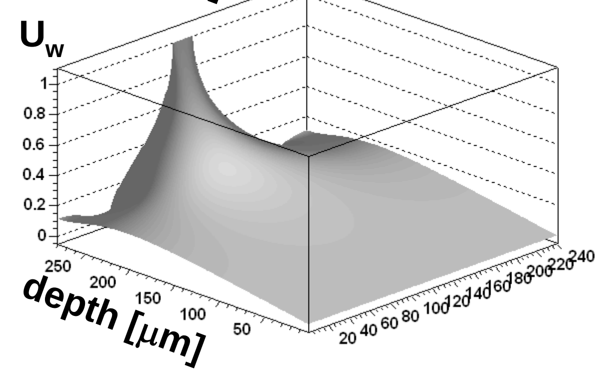
$U_w = 0$ ⟶ all other electrodes

- trapping term ($\tau_{eff,e} \sim \tau_{eff,h}$)
- drift velocity ($\mu_e \sim 3\mu_h$)

}

- electrons get less trapped
- they should drift to the strips/pixels and contribute most to Q (n^+ readout for silicon)





dot product