Initial acceptor removal in p-type silicon

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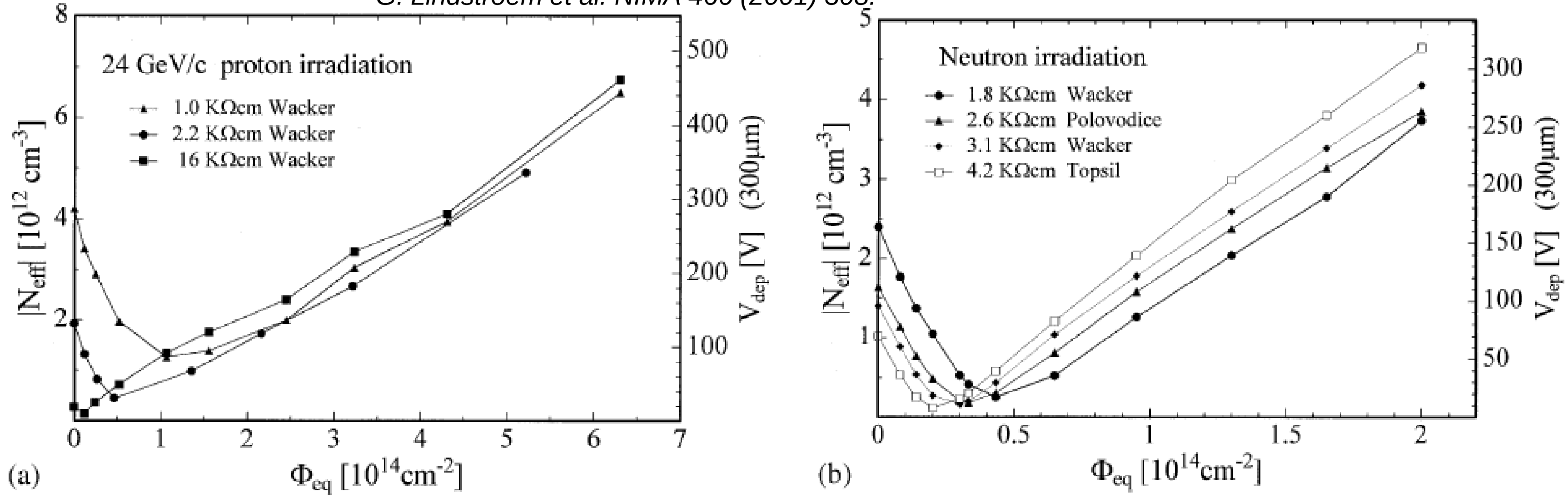
Motivation

Initial dopant removal well studied for n-type material during the LHC construction:

G. Lindstroem et al. NIMA 466 (2001) 308.



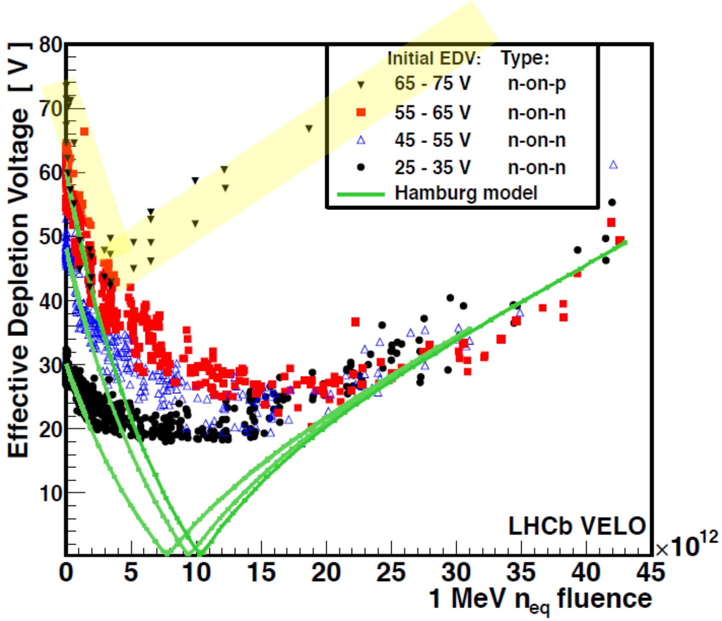
HL-LHC projects have concentrated to p-type material but aimed for much higher fluences and initial dopant removal was not a topic of interest:

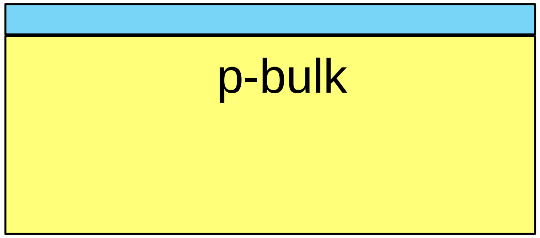
- The effects of removal play a small role (not always) in CCE(V) at high fluences
- Few systematic studies (particle dependence, resistivity dependence, silicon producer, process …) were performed

However the issue of "effective initial acceptor" removal is crucial for new detector technologies such as LGAD and HVCMOS sensors!

Motivation

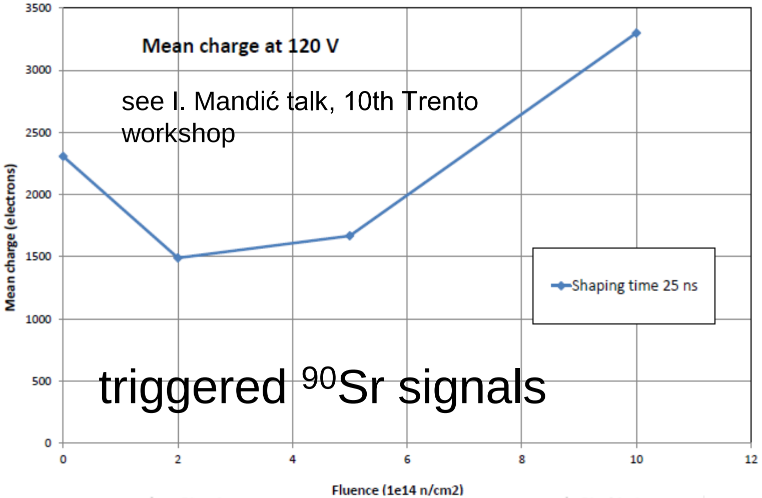
- LHCb Velo uses n-p sensor and has observed the effect of removal in V_{fd}





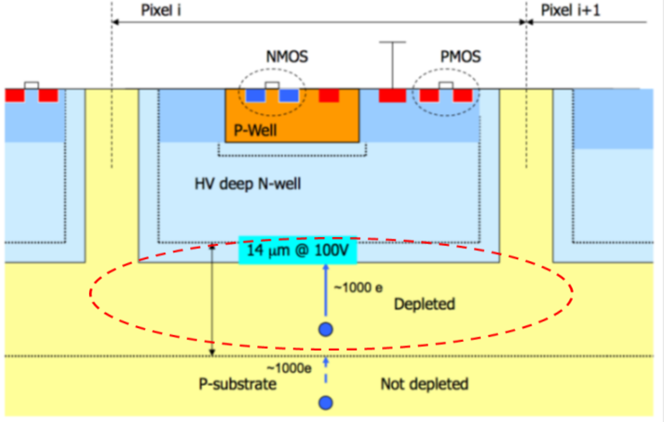
Initial $N_{eff,0}$~10^{12} cm^{-3}
almost negligible effect for operation

- HV-CMOS sensors (passive diode CCE vs fluence)



see I. Mandić talk, 10th Trento workshop

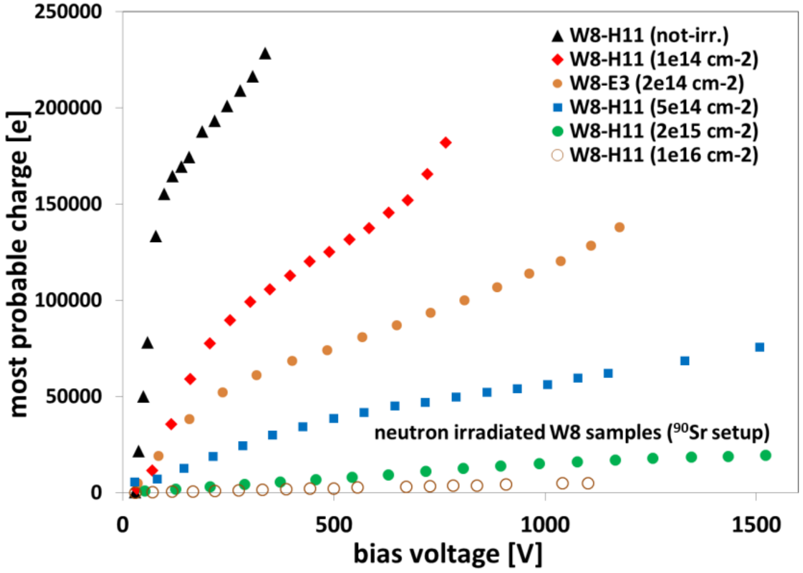
triggered ^{90}Sr signals

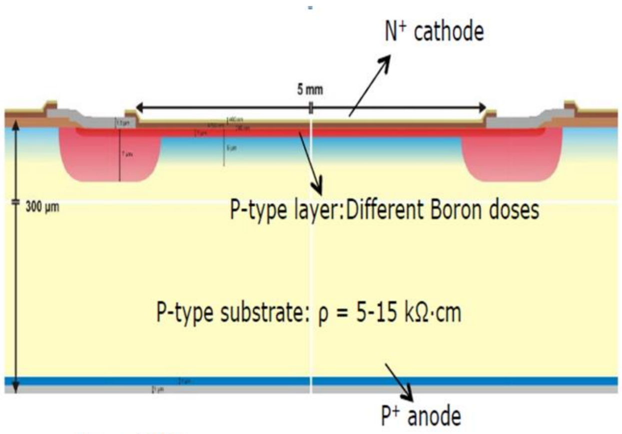


Initial $N_{eff,0}$~10^{15} cm^{-3}
BENEFICIAL – increase of active depth

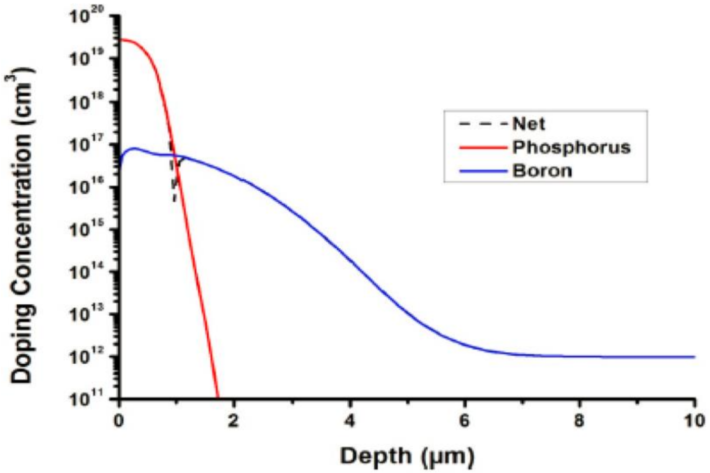
Motivation

- LGAD sensors (effective acceptors removal reduces the field and by that the multiplication in the multiplication layer)





$V_{FD} < 30$ V



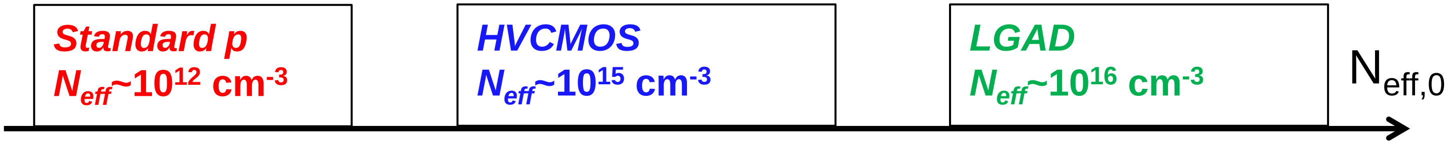
Initial N_{eff}~10^{15} cm^{-3} to N_{eff}~10^{17} cm^{-3}

DAMAGING effect – reduction of amplification

Motivation

- How does the removal rate depend:
  - irradiation particle type
  - initial resistivity
  - Oxygen, carbon... concentrations
- Is the removal complete?
- What are the undelaying reactions?
- Can we mitigate the effects by using different initial dopants?

Measuring properties of p-layers of huge difference in initial doping concentrations under bias (effective acceptors) is not an easy task. There are limited number of techniques to do it with limited precision!



Standard p
N_{eff}~10^{12} cm^{-3}

HVCMOS
N_{eff}~10^{15} cm^{-3}

LGAD
N_{eff}~10^{16} cm^{-3}

$N_{eff,0}$

R. Wunstorf et al, NIMA 377 (1996) 228.)
J. Adey, PhD Thesis, Univeristy of Exceter, 2004
J. Adey et al., Physica B 340–342 (2003) 505–508

Acceptor removal

$$dN_A = -\sum_i c_i \cdot N_A \, d\Phi \quad , \quad c = \sum_i c_i([O],\overset{?}{[C]},[B])$$

Radiation produces V and I – their spatial distribution depends on irradiation particle (large concentration of V,I in the cluster but small supply of [B] in the cluster)

Vacancy channel : $V + B_s \rightarrow VB$ (complex anneals out at T~0°C - no role)

Interstitial channel : $I + B_s \rightarrow B_i$ (dominant channel for B removal)

B_i = highly reactive ⇨ Can form different complexes with impurities resulting in:

- Acceptors in lower part of the band gap (negative space charge- BiBsH) – <u>incomplete removal</u>
- Donors in upper part of the band gap (positive space charge – BiOi) – <u>larger effective removal rate</u>
- Electrically inactive defects

Carbon rich environment: $I + C_s \rightarrow C_i$ concurrent reaction (smaller removal rate)

Oxygen rich environment: apart from forming complexes plays role in enhancing/reducing the concurrent reaction channels:
(e.g. V+O->VO instead of V+I->Si_s leaving more interstitials available)

High resistivity silicon – standard detectors

$$V_{fd}=\frac{e_0 N_{eff} W^2}{2\epsilon\epsilon_0}$$

free parameters of the fit

$$|N_{eff}| = |N_{eff,0}| + g_{eff}\cdot\Phi_{eq} - N_{C0}\left[1-\exp\left(-c\cdot\Phi_{eq}\right)\right] + \cancel{N_{BA}} + \cancel{N_{RA}}$$

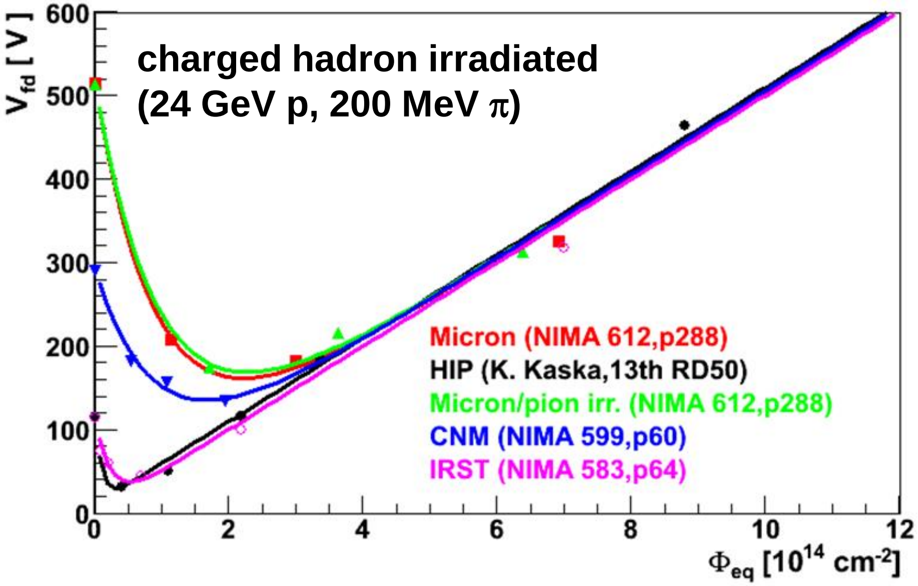
- Assumptions (not trivial at all)
  - ☐ V_{fd} is a valid parameter for evaluation of N_{eff}
  - ☐ N_{eff}=const.
  - ☐ N_{BA} and $N_{RA}\sim 0$ (around 80-160 min at 60°C this should be approximately true)

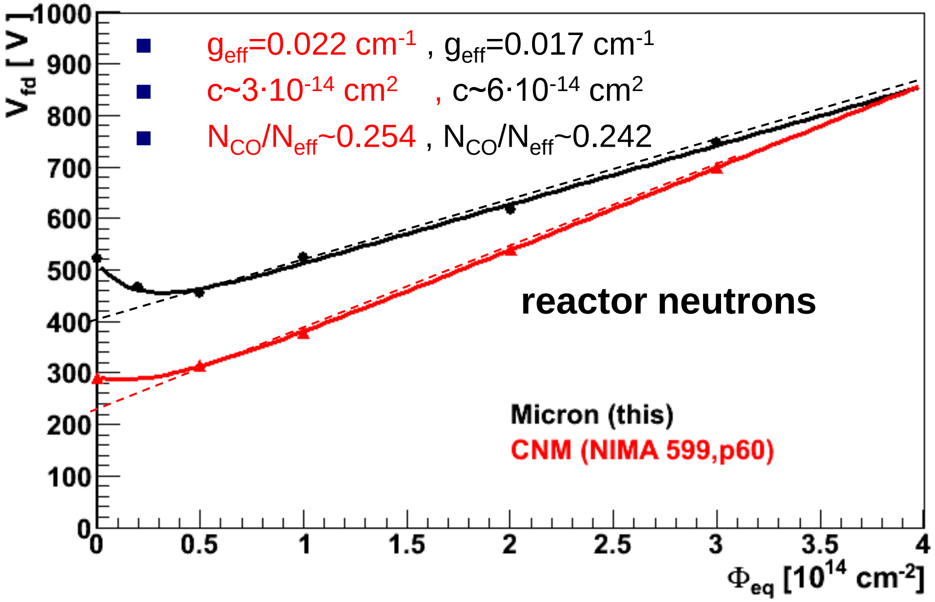
- TCAD simulations with tuned deep trap levels can to some extent also explain $V_{fd}(\Phi_{eq})$ behavior without acceptor/donor removal

R. Dalal et al., 24th RD50 Workshop, Bucharest 2014

- However:
  - ☐ The effects of “removal” are seen already at very low fluences where “double junction” effects are negligible (not the case in simulations)
  - ☐ The measurements at high $N_{eff,0}$ can not be explained otherwise

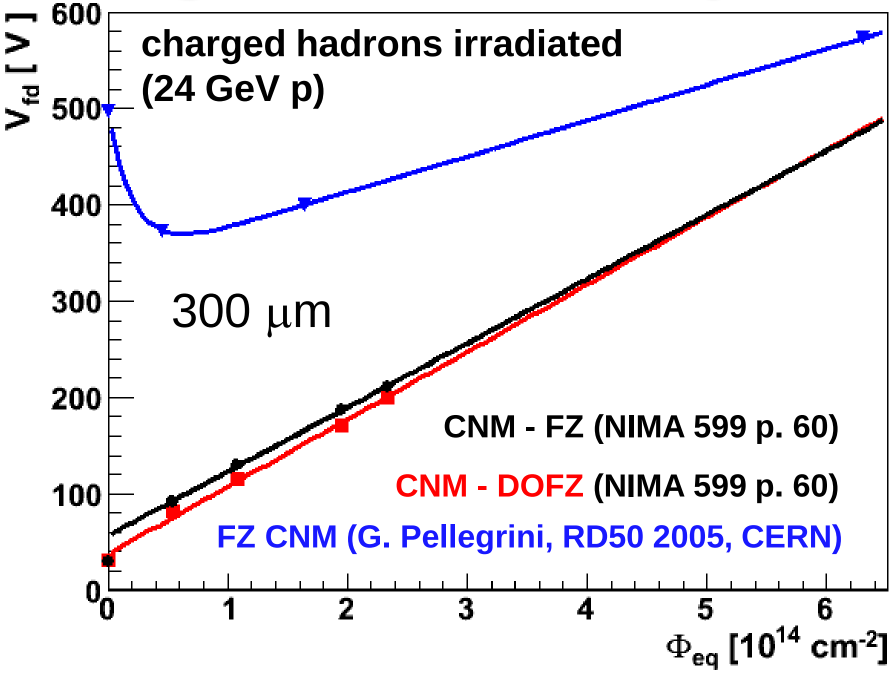
High resistivity silicon (oxygen rich)

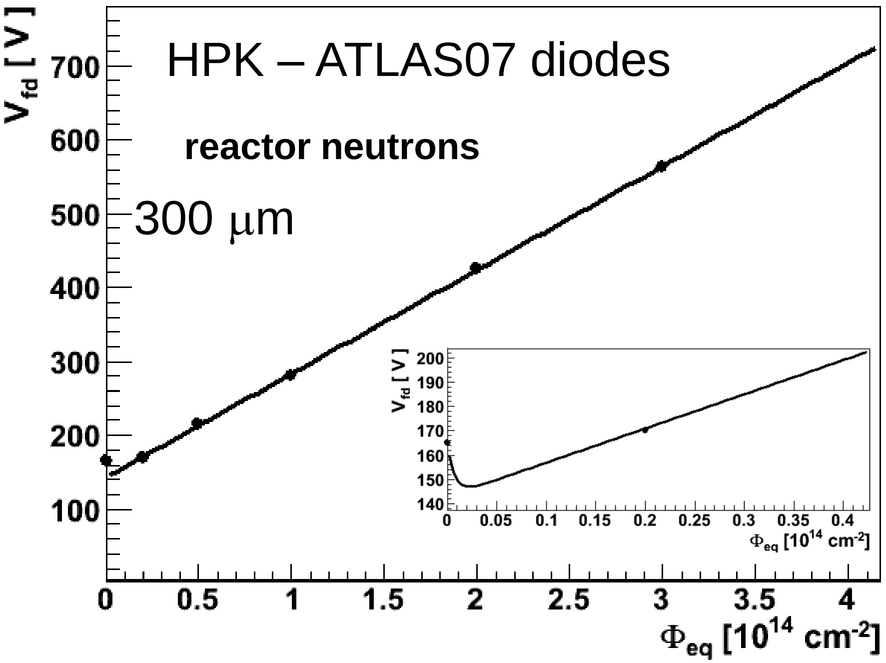




- g_{eff}=0.0071 cm^{-1} (taken from O rich measurements from RD48/50) and seems to be adequate, *c* and N_{C0} were determined from the fit.
- Different producers no impact of processing on behavior
- *Acceptor removal seems to be complete* N_{CO}/N_{eff}~1
- *c*~1·10^{-14} cm^{-2} (seems larger for lower resistivity, but uncertainty is too large for any firm conclusion)
- Incomplete initial acceptor removal – around ¼ of initial acceptors are removed
- Removal constant seems to be larger than for charge hadron irradiated MCz-p type samples, but not conclusive!
- Some difference in the introduction rate of radiation induced acceptors

High resistivity silicon (Float-zone)





- Unclear picture for FZ material ([O],[C],small [B])
- If material is compensated it is difficult to measure initial dopant removal rate
- N_{CO}/N_{eff}~0.3, c~$4\cdot10^{-14}$ cm^2

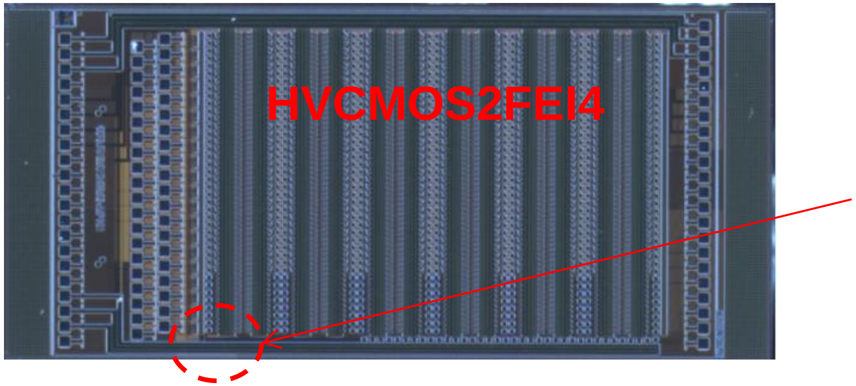
- Small effect of removal, if any....
- N_{CO}/N_{eff}~0.1-0.15

?

If you have studies at “low fluences” please disseminate them….

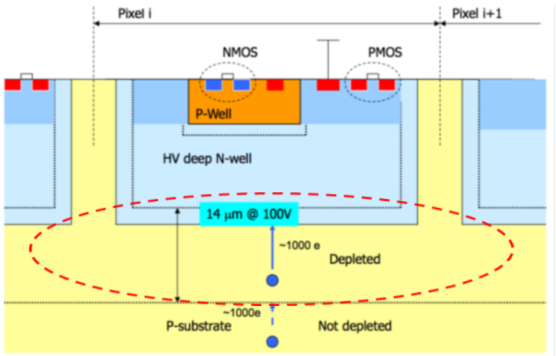
HVCMOS – N_{eff}~10^{15} cm^{-2}

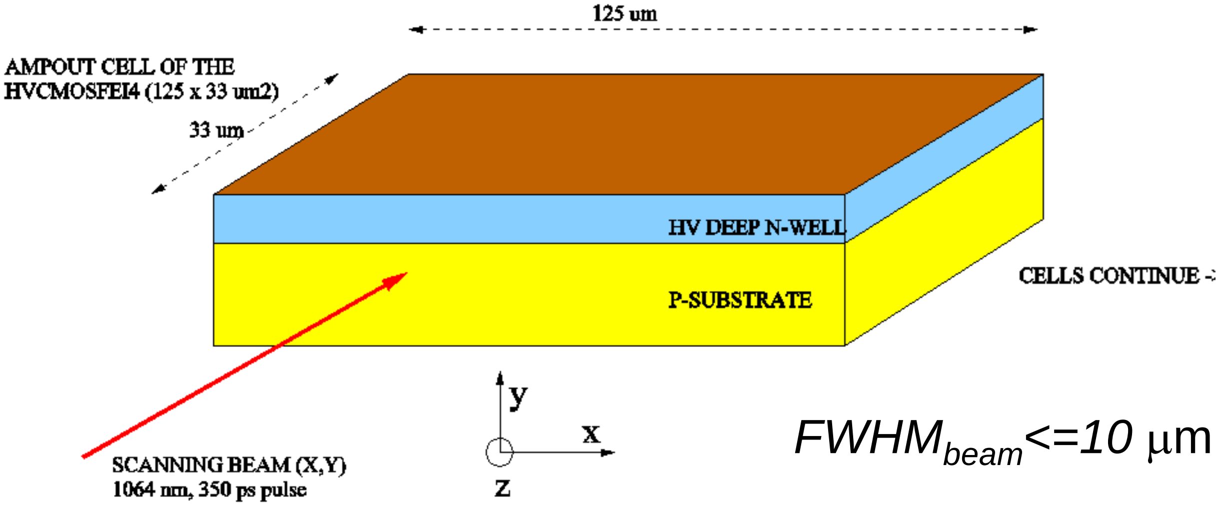
- Edge-TCT measurements of the detector -> probing the charge collection profile



A single cell of 125 x 33 μm^2 was investigated – output to readout after the charge sensitive amplifier.

Not ideal (not observing induced current) , but good enough!





$FWHM_{beam}$<=10 μm

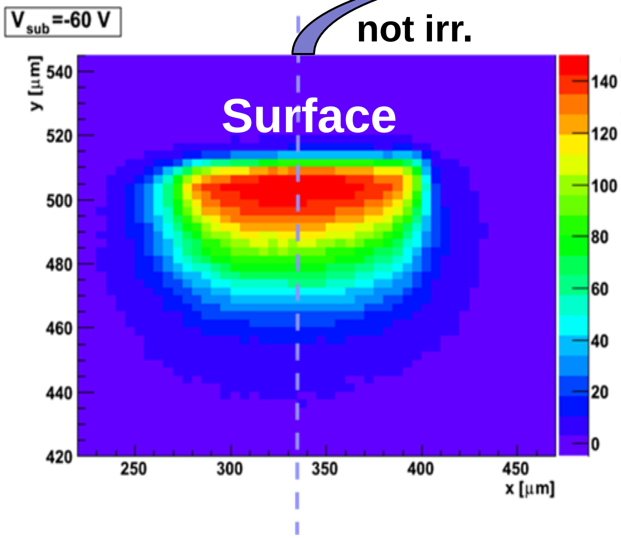
HVCMOS – N_{eff}~10^{15} cm^{-2}

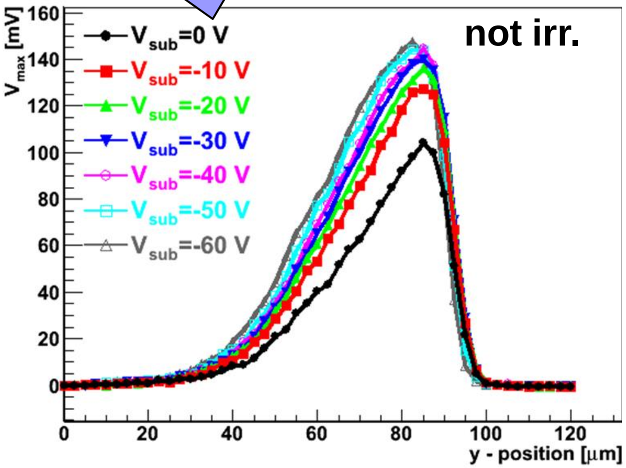
Profile width (FWHM) is a measure of charge collection region (diffusion + depleted)

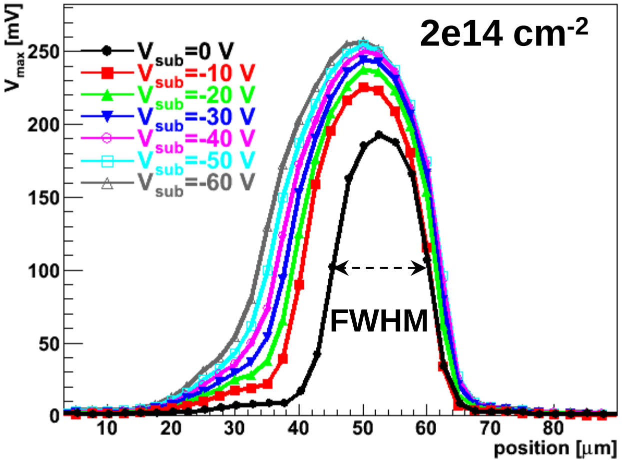
profile along the line

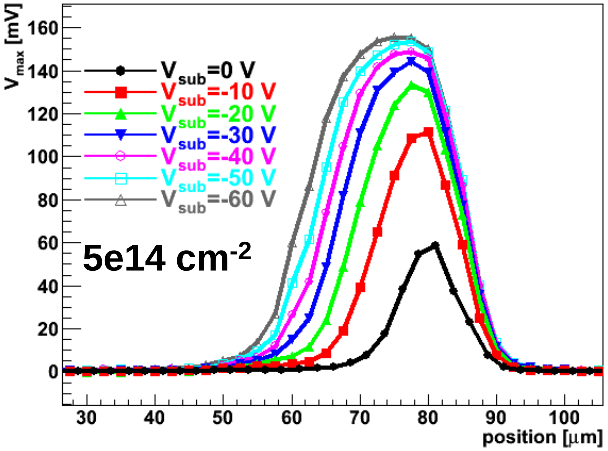
$$FWHM_{measured}^2 \sim FWHM_{coll.region}^2 + FWHM_{beam}^2$$

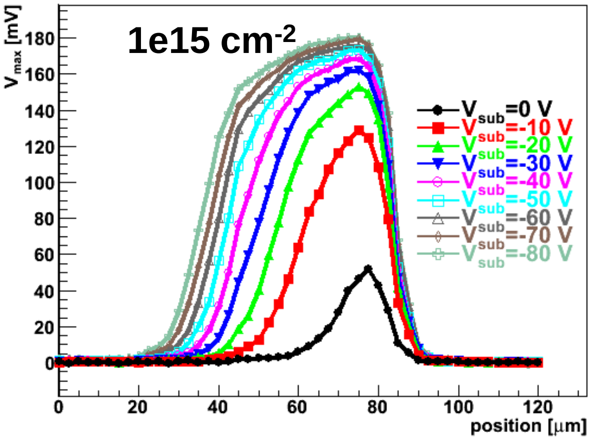
not irr.

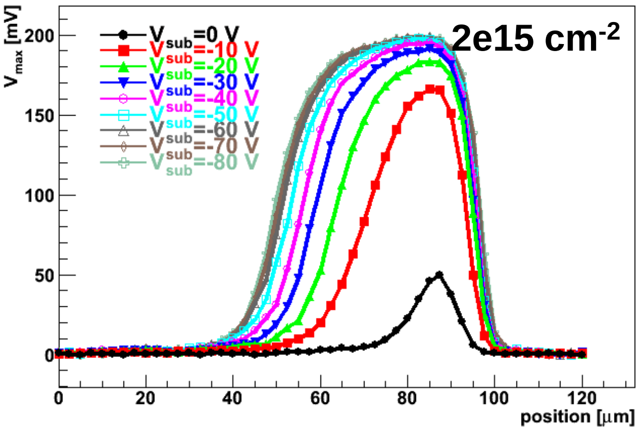




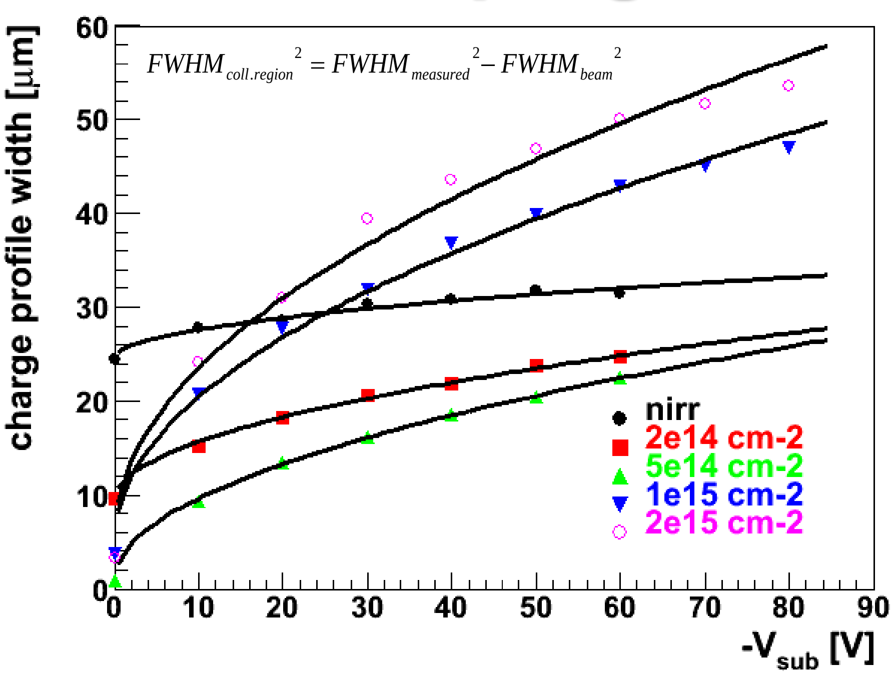


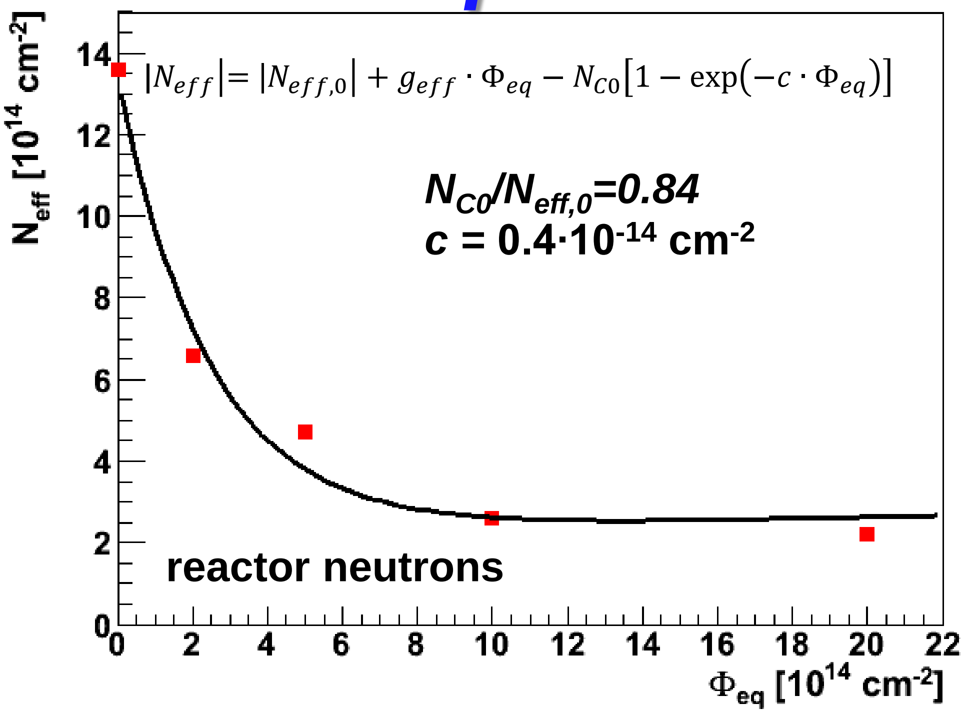






Effective doping concentration in p substrate





- Dependence of depleted region on substrate bias for constant space charge
  - At $V_{sub}=0$ V it is assumed that charge is collected by diffusion (note the FWHM of the beam)
  - Any additional bias depletes the certain amount which adds to the diffusion contribution:

$$d = \frac{2\varepsilon\varepsilon_0}{e_0 N_{eff}} \sqrt{V_{sub}}$$

Effective doping concentration is extracted from the fit for each fluence!

- The effective doping concentration seems to decrease with fluence – depletion region penetrates deeper after irradiation! This points to effective acceptor removal – not conclusive enough to claim B removal.

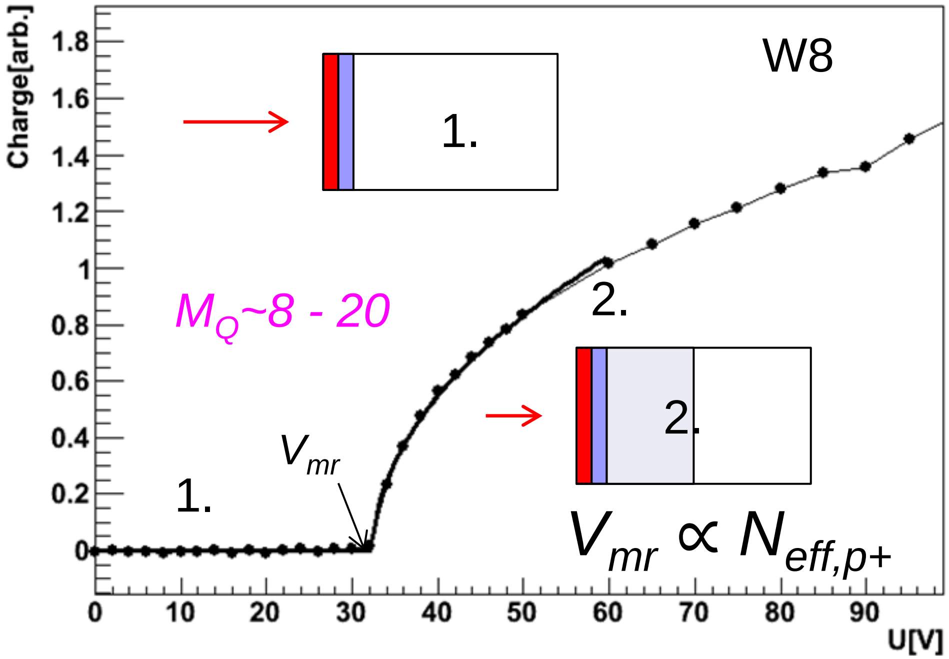
LGAD – Amplification layer probing

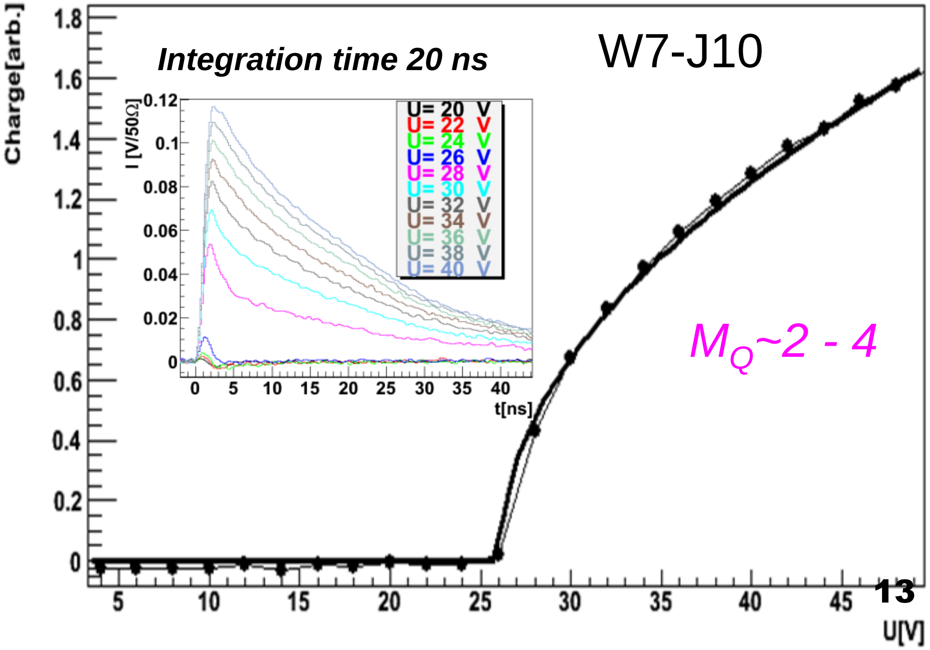
It is essential that multiplication layer is depleted for the gain. The multiplication layer depletion can be probed by TCT (illumination of n^{++}-p^{+} contact) for bulk of p-type:

1.) the layer is not depleted the e-h generated by red laser don’t drift in the bulk – no signal
2.) when the multiplication layer is depleted the depletion extends into the bulk and charge increases as they drift over increasing amount of the weighting potential.

Threshold voltage V_{mr} indicates the depletion of the multiplication layer

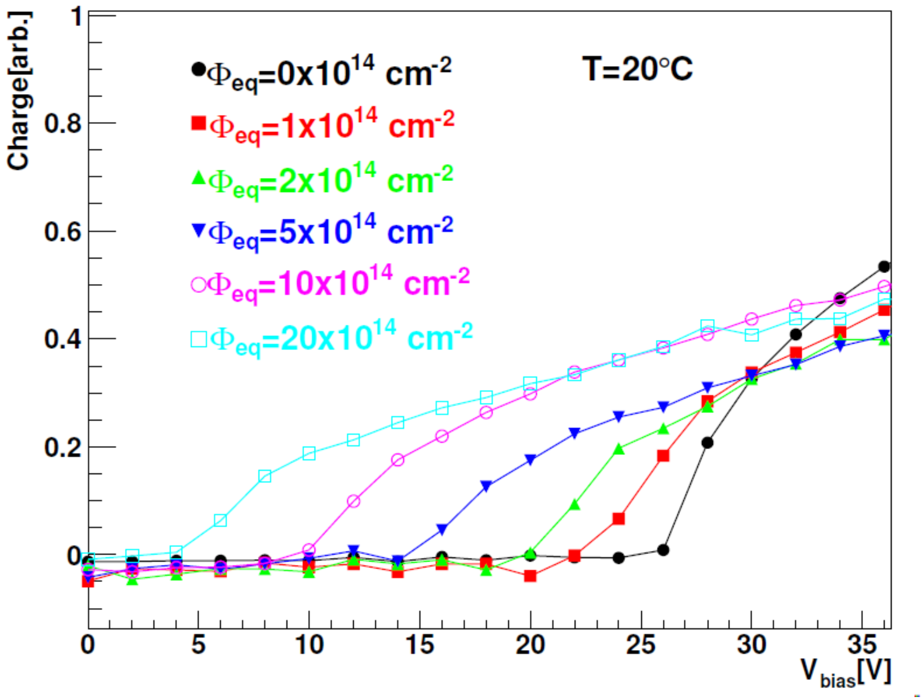
Strong dependence of multiplication on $N_{eff,p+}$ (~7 V in V_{mr} difference between M_Q~3 and M_Q~10)



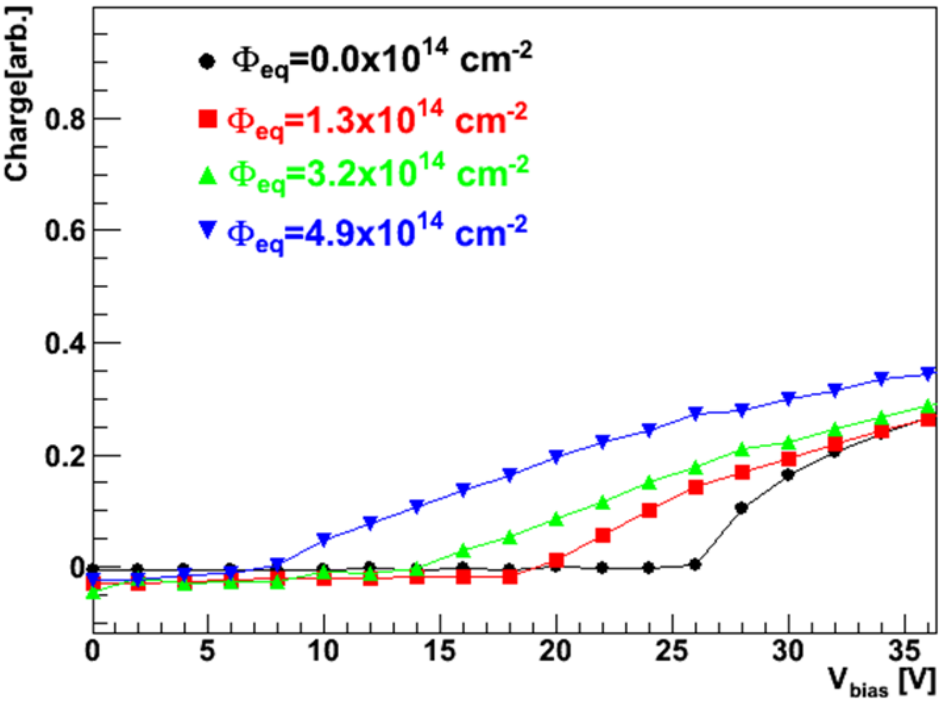


LGAD – probing of V_{mr} with TCT

W7 - neutron irradiated

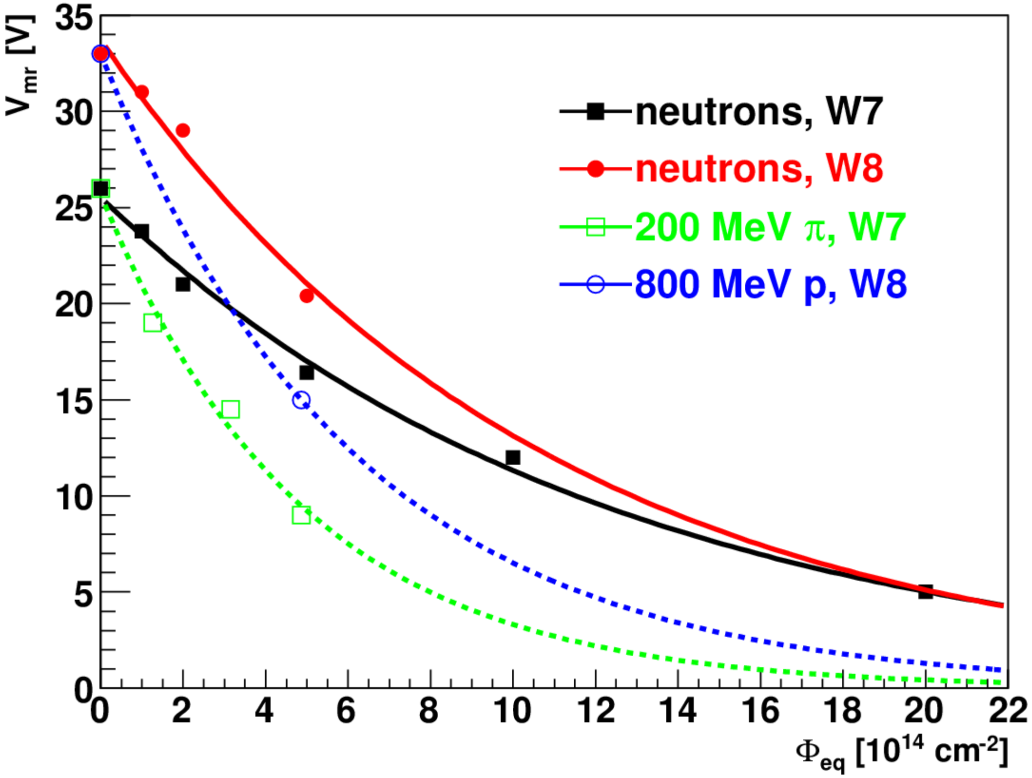


W7 – 200 MeV π irradiated



- V_{mr} decreases with fluence – smaller voltage drop over n^{++}-p^{+} -> smaller electric field
- V_{mr} decreases more for 800 MeV protons than reactor neutrons
- This correlates well with the observed difference in gain!

V_{mr} dependence on fluence



V_{mr} decreases due to removal of effective acceptors

$$\nabla^2 V = -\frac{e_0}{\varepsilon\varepsilon_0} N_{eff,p+}$$

If the effective acceptors are removed with the same rate in whole multiplication layer:

$$V_{mr} \propto N_{eff,p+}$$

$$V_{mr} = V_{mr,0} \cdot \exp(-c \cdot \Phi_{eq})$$

c(neutrons) = 9.4· 10^{-16} cm^{-2}

c(neutrons) = 8.1· 10^{-16} cm^{-2}

c(200 MeV π)= 20 · 10^{-16} cm^{-2}

c(800 MeV p) ≈ 16· 10^{-16} cm^{-2}

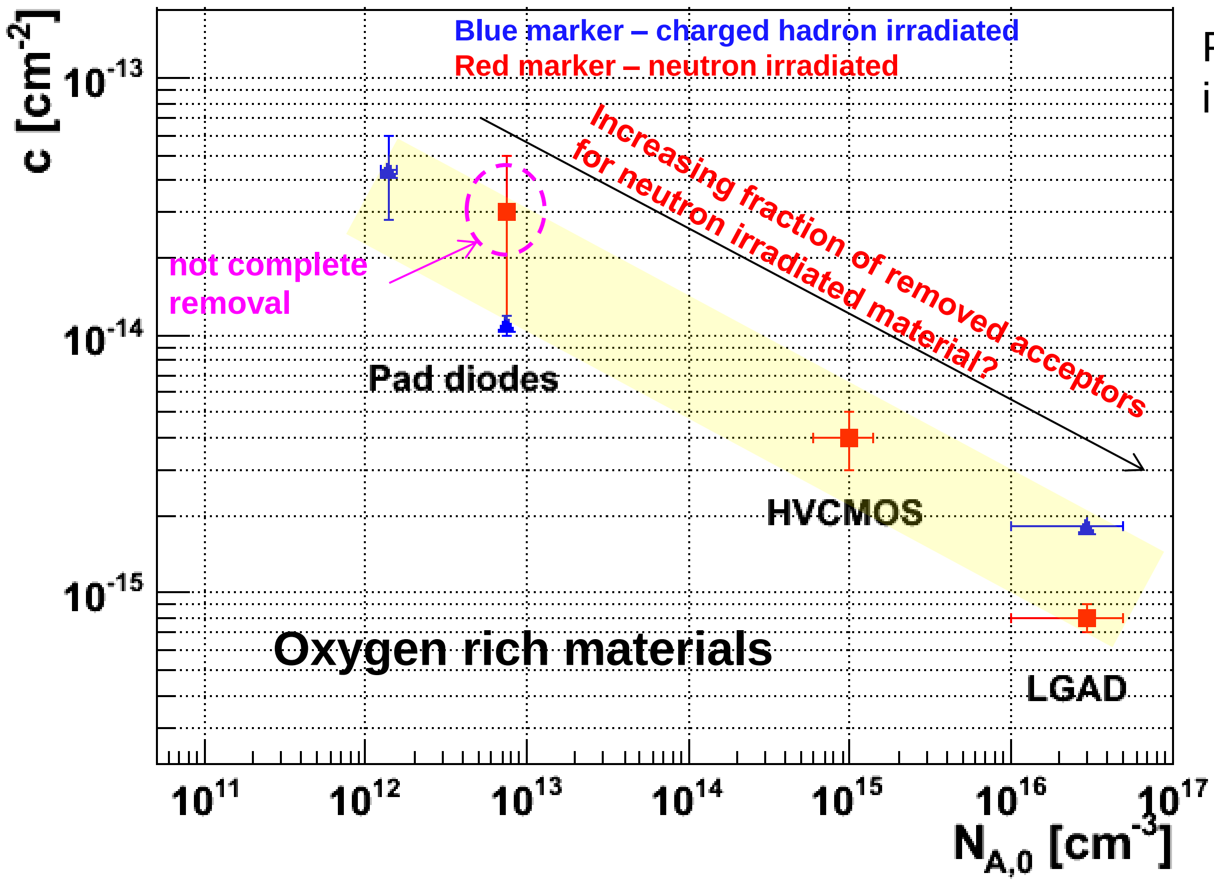
- Removal constant for charged hadrons is larger than for neutron irradiated detectors
- Removal seem to be complete for all

It seems that removal of shallow acceptors is responsible for gain degradation (frequency and temperature scans show no strong dependence).

Can we replace B with Ga? Hopefully we will know soon…

Effective acceptor removal constant - overview

Effective acceptor removal rate under bias for different initial concentrations



Previous measurements in high-resistivity Si:

$c = 2 \cdot 10^{-13}\ \mathrm{cm}^2$

R. Wunstorf, NIMA 377 (1996) 228.

Why the decrease?

Obviously an understanding of effective acceptor removal requires more studies...

Conclusions

- Effective acceptor removal is of minor importance for operation of standard p-type sensors, but plays a major role in understanding the performance of irradiated LGAD and HV-CMOS sensors
- Removal constants have been measured (estimated) and found to depend on initial doping concentrations. They get smaller at larger initial concentrations – large span of initial concentrations is covered.
- Removal seems to be complete for fast charge hadron irradiated sensors, while for neutron irradiated sensors the removed fractions seems to be larger at larger initial concentrations
- It is clear that further studies are needed at initial acceptor concentrations of interest to be able to reliably predict sensor behaviorr and understand the underlying reactions.
- Investigations of other dopants?