Initial acceptor removal in p-type silicon detectors

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Motivation

- Understanding and planning of the initial phase of detector operation
- Understanding defect kinetics – role of B, V-I, C, O in the detector operation
- **Understanding operation of LGAD - is removal of initial acceptor responsible for degradation of the gain after irradiation?**

RD50 has never really looked in a detailed way in the acceptor removal and looking at old RD50 papers/presentations the following came out:

- there are surprisingly (or not so) few “dense” measurements at relatively low fluences ($< 2\cdot10^{14}$ cm^{-2})
- there are more pad detector measurements for MCz-p than for FZ-p at these fluences (remember completed short term annealing is required)
- FZ-p measurements look less consistent with respect to the increase of N_{eff} with fluence than MCz-p

Samples and procedures

Our measurements (neutron irradiated sensors)

- C-V (10 kHz, 20^{o}C) was used up to the fluences of max. few 10^{14} cm^{-2}. All the curves with any dubious shape were not taken into account.
- Samples were neutron irradiated and annealed at 60^{o}C until the short term annealing was completed (between 80 and 160 min @ 60^{o}C)
- Samples (different [O], different resistivity) :
  - HPK FZ-p (ATLAS 07) with initial V_{fd}~170 V
  - Micron FZ-p (2551-3,7) with initial V_{fd}~50 V ,
  - Micron MCz-p (2552-7) with initial V_{fd}~510 V

Other measurements (fast charged hadrons irradiated sensors)

- Collection of $V_{fd}(\Phi_{eq})$ measurements after beneficial annealing from different RD50 groups including our.
- Only samples from 24 GeV p irradiations were chosen – mostly due to consistency in evaluation of MCz results.

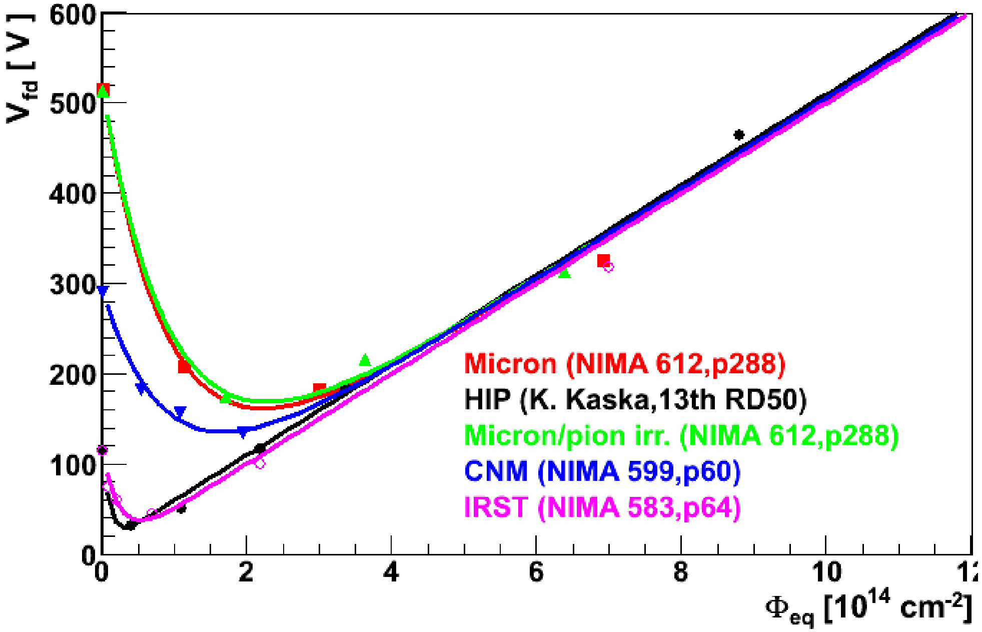
Evaluation of measurements

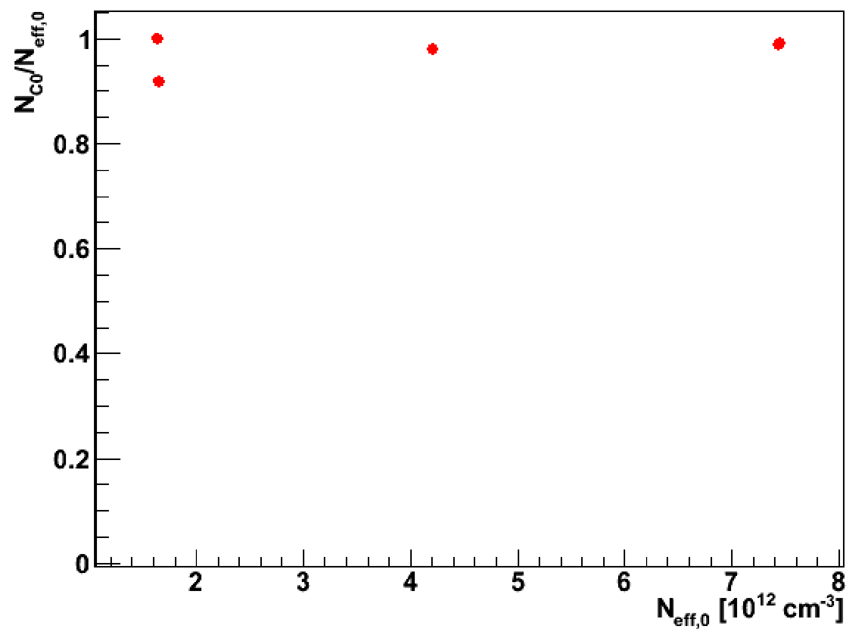
$$V_{fd} = \frac{e_0 N_{eff} W^2}{2\epsilon\epsilon_0}$$

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

- Assumptions (for the purpose of the study uncertainty due to assumptions are not crucial/can be neglected)
  - V_{fd} is a valid parameter for evaluation of N_{eff}
  - N_{eff}=const.
  - N_{BA} and N_{RA}~0 (around 80-160 min at 60ºC this should be approximately true)
- Free parameters of the fit: N_{C0}, c, g_{eff}
- Detectors are all equally thick (300 μm) therefore $N_{eff} \propto V_{fd}$
- Interested in initial acceptor removal dependence on:
  - oxygen concentration/wafer production (MCz,FZ),
  - damage creation (neutron, fast charged hadrons)
  - resistivity

MCz-p irradiated with charged hadrons

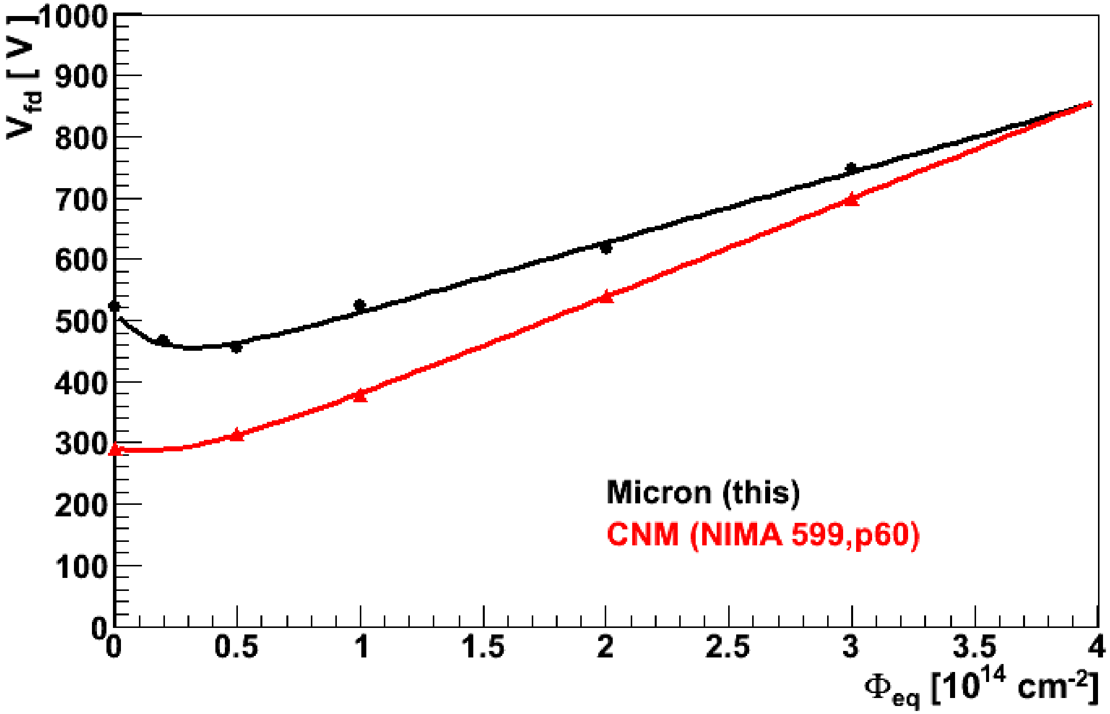




- g_{eff}=0.0071 cm^{-1} (taken from O rich measurements from RD48/50) and seems to be adequate, c and N_{C0} were determined from the fit.
- Different producers – no impact of processing on behavior

- *Acceptor removal seems to be complete*
- c~$1\cdot10^{-14}$ cm^2 (seems larger for lower resistivity, but uncertainty is too large for any firm conclusion)

MCz-p irradiated with neutrons

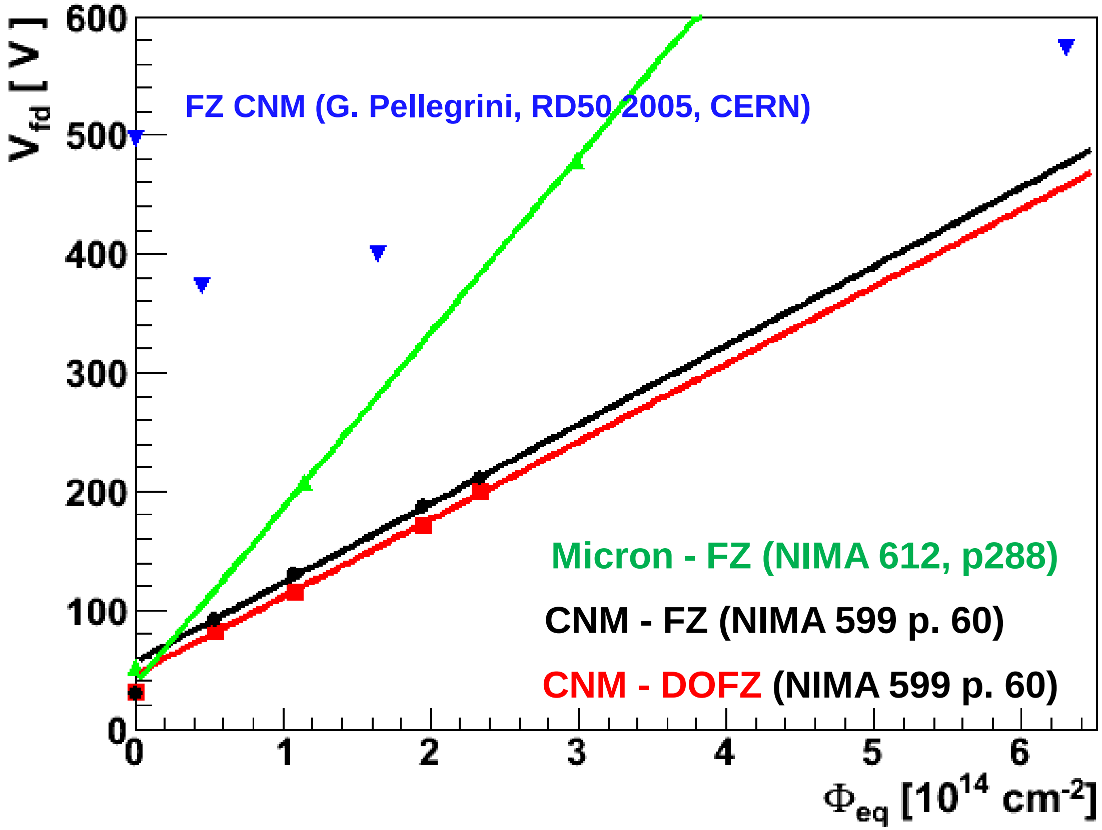


- g_{eff}=0.017 cm^{-1}
- c~6·10^{14} cm^2
- N_{CO}/N_{eff}~0.242

- g_{eff}=0.022 cm^{-1}
- c~3·10^{14} cm^2
- N_{CO}/N_{eff}~0.254

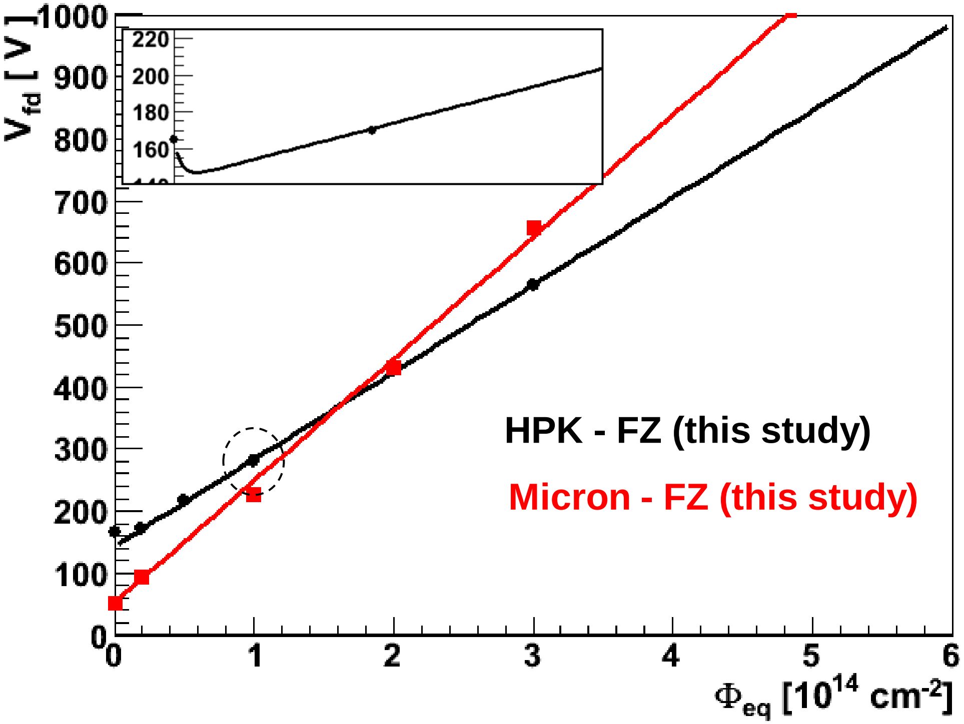
- **Incomplete initial acceptor removal** – around ¼ of initial acceptors are removed
- Removal constant seems to be larger than for charge hadron irradiated MCz-p type samples, i.e. **"faster removal"**, but not conclusive
- Some difference in the introduction rate of radiation induced acceptors

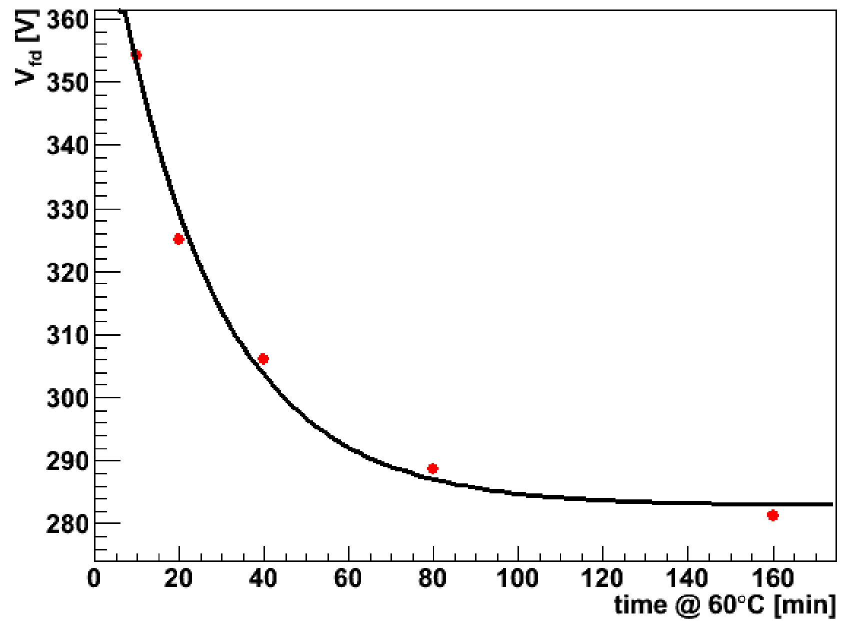
Fz-p irradiated with charged hadrons



- Seems like no or very small initial acceptor removal for small initial boron concentration [B]~$5\cdot10^{11}$ cm^{-3}.
- Larger difference in g_{eff} may be due to different oxygen concentrations
- Older measurements at higher initial N_{eff} point to some acceptor removal (30%). Also LHCb sees initial acceptor removal for n-p detectors.

Fz-p irradiated with neutrons





- Small – on the level of 10% removal for mid-resistivity sample (HPK), no removal for low resistivity sample (Micron)
- difference in g_{eff} (Micron)=0.028 cm-1 (larger than expected !), g_{eff} (HPK)=0.02 cm^{-1}

Conclusion

- Acceptor removal increases with concentration of oxygen
  - complete for charged hadron irradiated MCz-p detectors
  - around 1/4 of the acceptors removed for the neutron irradiated samples
  - fast removal rate of $c \geq 10^{14}$ cm^2
- Inconclusive results for FZ material
  - "high resistivity" material shows almost no removal for charge hadron irradiated and neutron irradiated sample
  - "low/medium resistivity" material shows some initial acceptor removal in order of $N_{CO}/N_{eff} \sim 0.1$ *for* neutron irradiated samples and possibly more for charged hadrons.

Removal of initial acceptors with neutrons in the past: *R. Wunstorf, NIMA 377 (1996) 228.)*

Explanation

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)

"Low doping "[B] << [C]

Interstitials:

$I + Cs \rightarrow Ci$ dominant I sink

$I + Bs \rightarrow Bi$ less probable unless C is exhausted

$Ci + Oi \rightarrow CiOi$

$Ci + Cs \rightarrow CiCs$

"High doping "[B] >> [C]

Interstitials:

$I + Bs \rightarrow Bi$ dominant I sink

$I + Cs \rightarrow Ci$ less probable

$Bi + Oi \rightarrow BiOi$ Donor (Ec-0.23 eV)

$Bi + Bs \rightarrow BiBs$ not electrically active

Vacancies:

$V + Bs \rightarrow V - B$ complex – anneals out at T~0^{o}C (can not play a role)

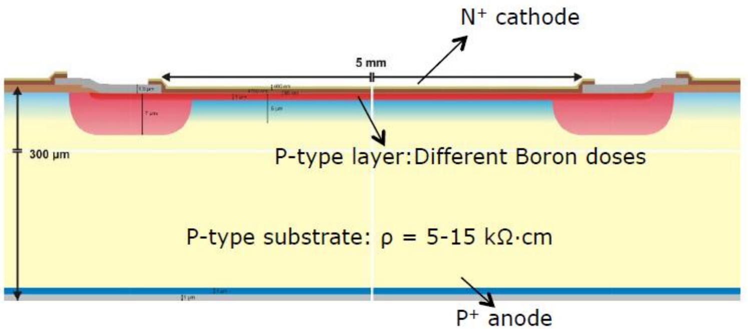
Presumed influence of [O] on acceptor removal: defect complex should either

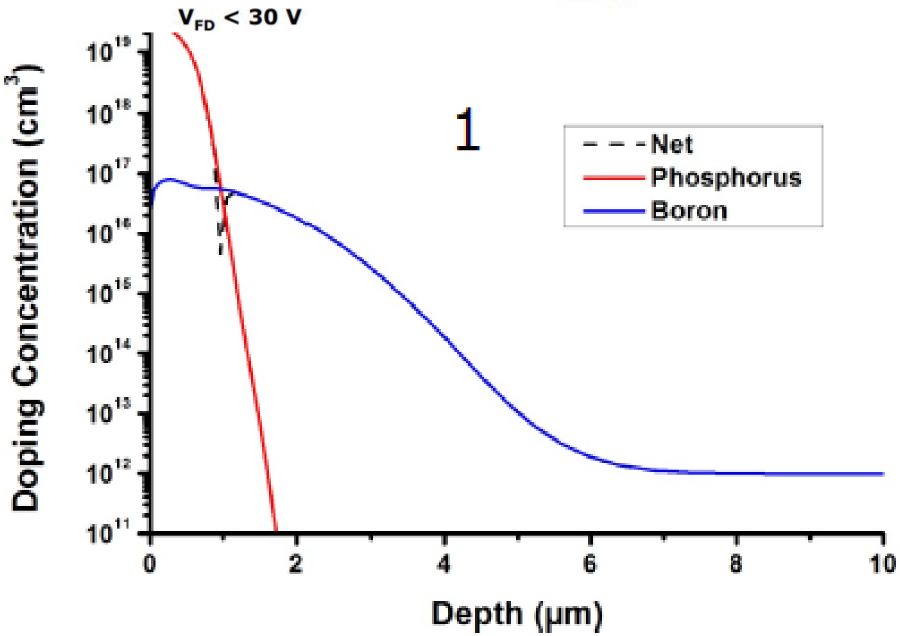
- include O
- O should suppress reaction channels which compete with B removal

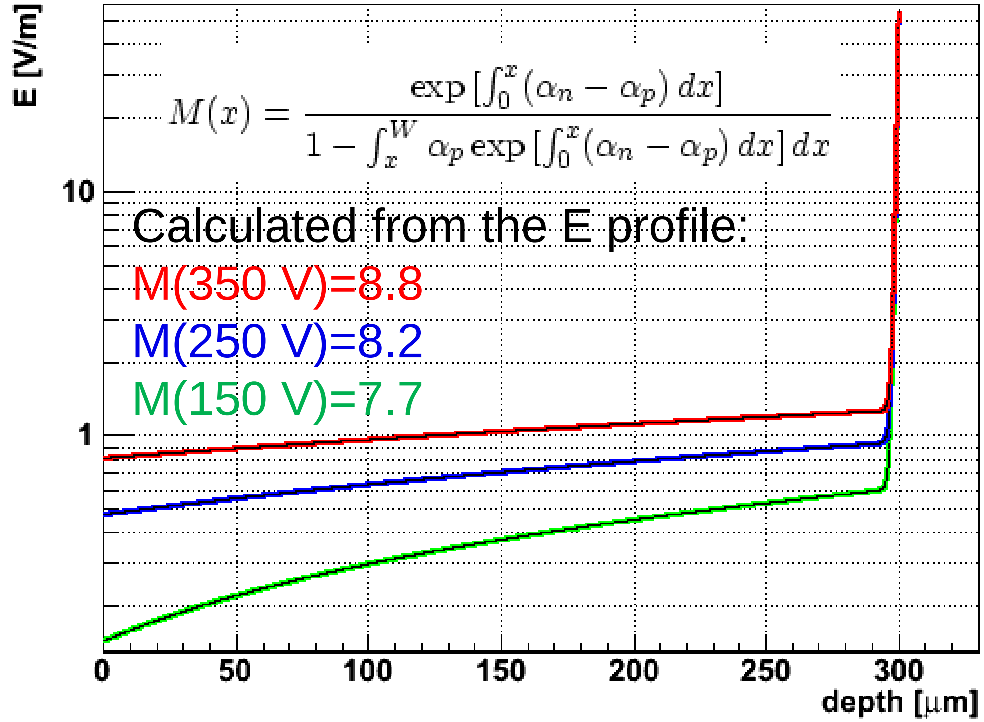
(e.g. V+O->VO instead of V+I->Si_s leaving more interstitials available)

LGAD degradation of performance (I)

What are the implications of initial acceptor removal on LGAD operation?







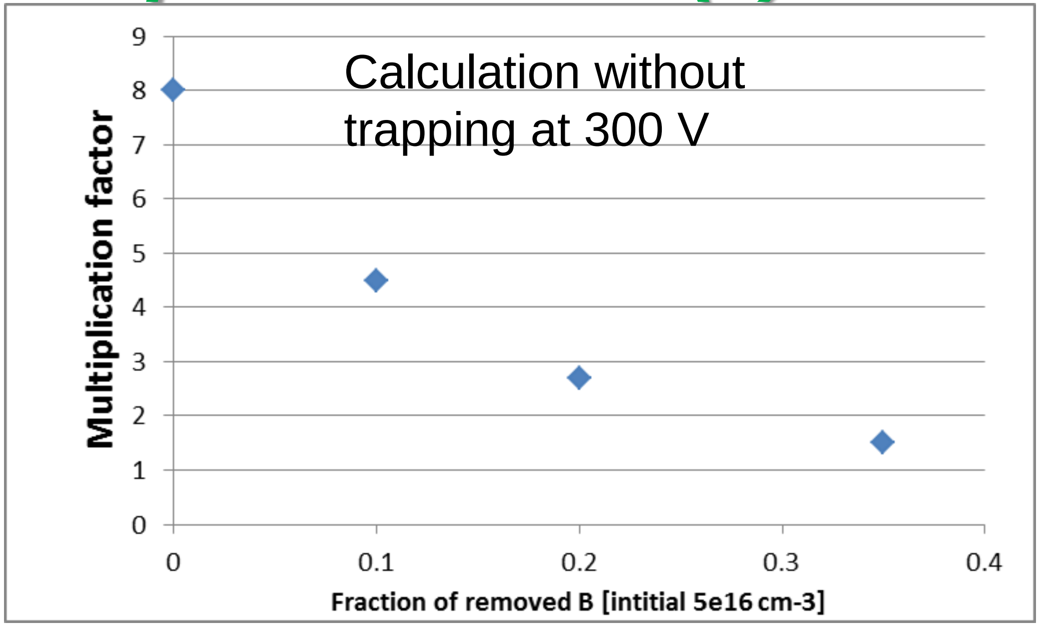
Diodes from W8 (see talk at 22nd RD50 Workshop)

Calculated multiplication for non-irradiated detector is approximately equal to the measured value of multiplication at all voltages!

LGAD degradation of performance (II)

After irradiation the degradation of multiplication is due to:

- Trapping of drifting carriers
- Reduction of multiplication, due to reduction of electric field in the p^+ layer



- **The removal of initial acceptors significantly impacts the performance!**
- **The increase of radiation induced acceptors is obviously too slow to compensate for removal**
- Shallow acceptor have very fast de-trapping – more effective than deep ones in the presence of free carriers

The case with our LGAD measurements:

- [B]>>[C] -> more removal than shown for normal diodes
- Neutron irradiation should be better than charged hadron ones.

Future work

Does the initial acceptor removal limit (i.e. equalizes their operation with normal diodes) the operation of LGAD in very high radiation environments?

How do we prevent shallow acceptor removal?

- Increase of [C]?
- Reduction of [O]?
- Change of dopant -> Ga?