Simulations of Hadron Irradiation Effects for Si Sensors Using Effective Bulk Damage Model

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Contents of presentation

- Some confusing terms
  - - Need for a coherent approach
- What is V_{FD} in hadron irradiated Si sensor ?
- Donor removal and Acceptor removal as double junction effect
- Neutron vs Charged hadron irradiation effect
- Some TCT simulation results

Some confusing terms

Most of these terms are well understood by the experts !
But can be really confusing and sometime misleading to the starting students!

Effective doping density (Neff)

- Hadron irradiation generates both acceptor and donor traps
- Ionization of traps is strongly dependent on electric fields and concentration of electron and hole
- More ionized acceptor near n^+ and more ionized donor near p^+
- Type inversion ?
  (…getting red TCT signals from both sides! A systematic study by Hannes, 23rd RD-50)
- What is full depletion voltage for hadron irradiated sensors ?

Donor Removal & Acceptor Removal

- Are donors are actually removed from the Si bulk with hadron fluence ?
- Or they are the parameterization terms used to represent the initial V_{FD} drop with fluence ?

Need for a coherent approach

- May be choose more appropriate terms!

- Realistic approach in terms of traps can be helpful in understanding complex issues

Simulation Model

Simulation structure

1x1x300µm

Bulk type = n and p type

(each with three bulk doping 2e11 cm^{-3}, 2e12cm^{-3} and 4e12cm^{-3})

Trap model

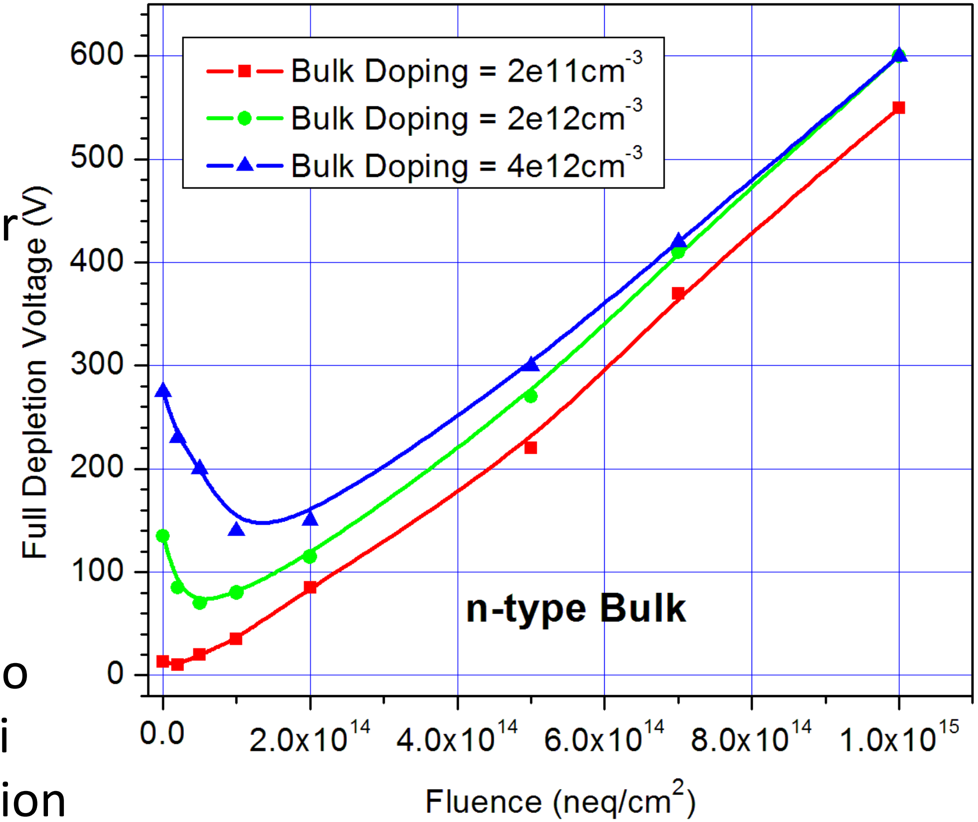
- Simple two trap model for proton irradiation
- Give correct leakage current
- Give V_{FD} ~550V at 253K for proton fluence = 1e15n_{eq}/cm^2

Trap	Energy Level	Intro.	σ_e (cm^{-2})	σ_h (cm^{-2})
Acceptor	0.525eV	1.0	$2x10^{-14}$	$5x10^{-14}$
Donor	0.48	5.0	$2x10^{-14}$	$2x10^{-14}$

Bulk model used for V_{FD} simulations

V_{FD} simulations for n-type Si

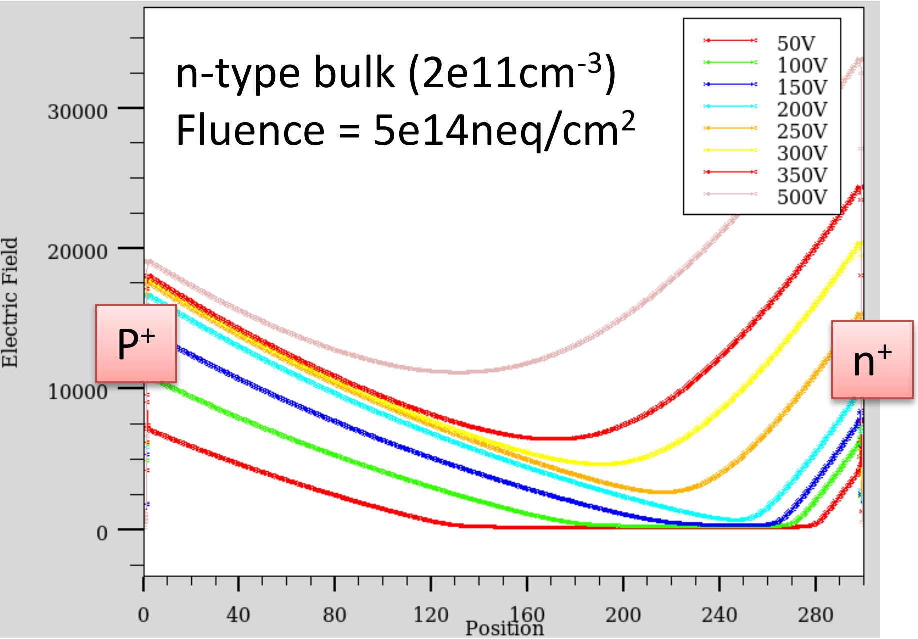
- Initial V_{FD} drop for all of the three bulk doping
- V_{FD} minimum for bulk doping 2e11cm^{-3} happen at very low fluence but for higher bulk doping, V_{FD} minimum is at higher fluence

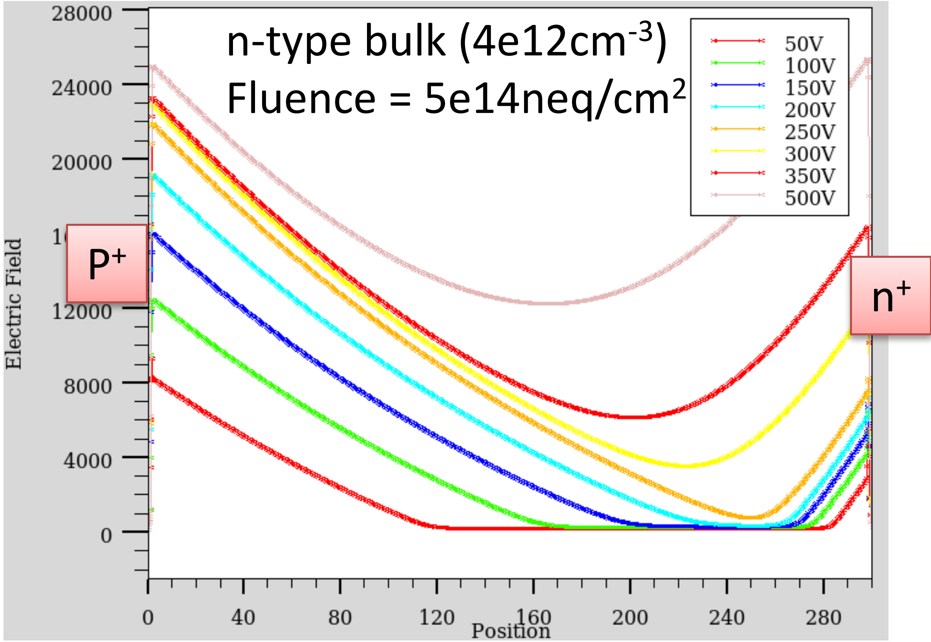


One is tempted to attribute this effect as "Donor Removal" but we have not used any donor removal in the simulations !

- The initial lowering of V_{FD} is simply due to the double junction effect in irradiated Si
- Due to the double junction effect, depletion of charge carriers starts from both sides of Si diode
- Due to depletion from the both ends, Si diodes is depleted at lower V_{FD} bias , for initial fluences.
- There may not be any need for the "Donor Removal"

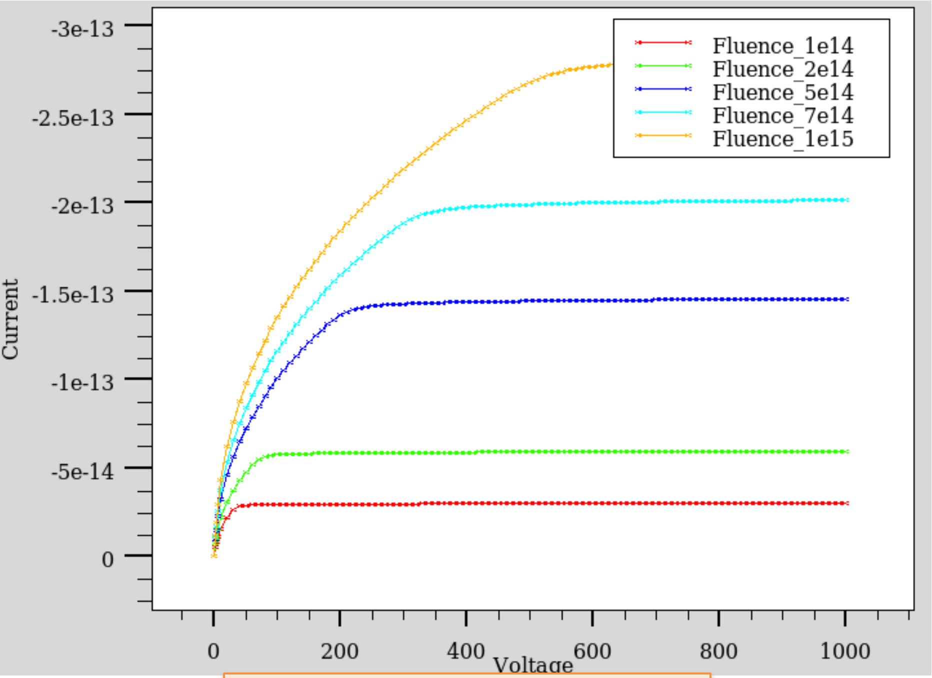
Electric field evolution for n-type Si



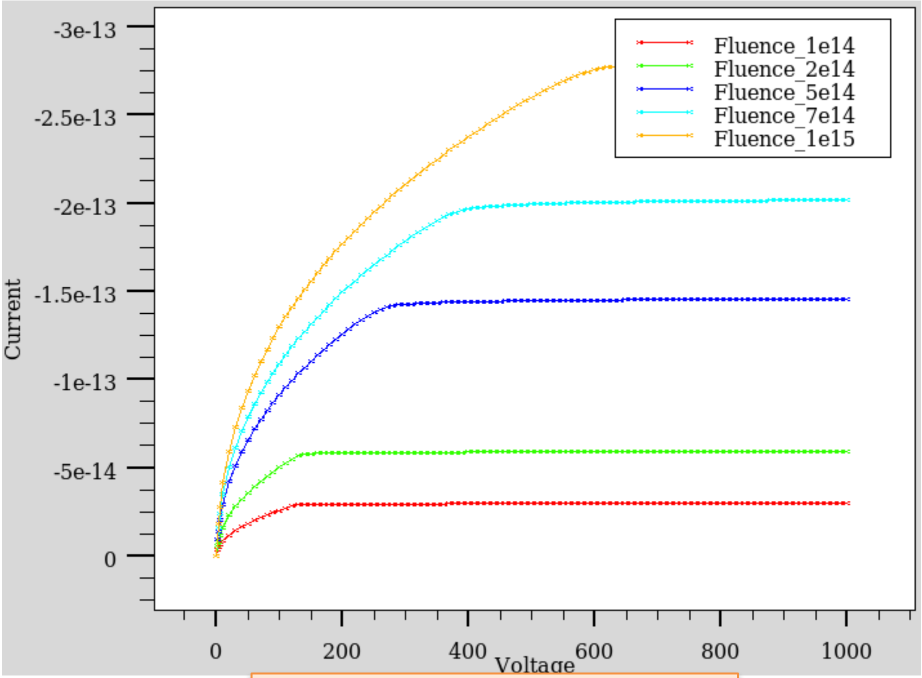


- Electric field start to grow from both sides
- V_{FD} is the bias at which electric fields from both sides meet each other (in fact V_{FD} is ~20-30V higher then this bias)
- Effect of initial bulk doping remain there but at higher fluences, space charges due to traps are much more important

Current evolution for n-type Si



n-type bulk (2e11cm^{-3})



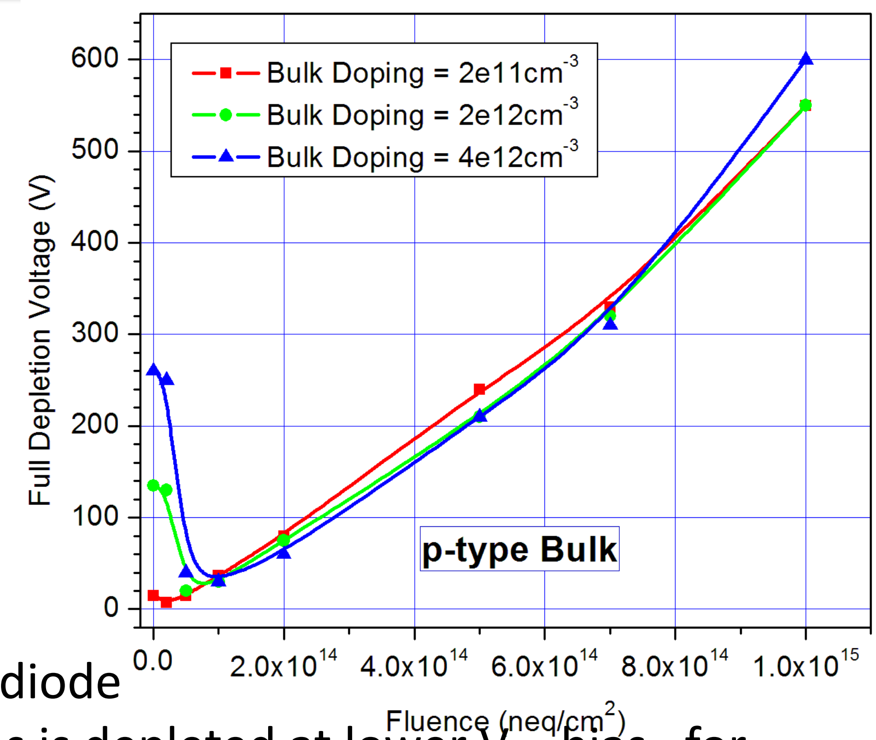
n-type bulk (4e12cm^{-3})

- Current increases with bias and saturates around V_{FD}
- Consistent picture for V_{FD} by $1/C^2$ plots, electric field plots and IV plots

V_{FD} simulations for p-type Si

- Initial V_{FD} drop for all of the three bulk doping
- Very similar V_{FD} for higher fluences

This effect is attributed to “Acceptor Removal”



- Due to the double junction effect, depletion of charge carriers starts from both sides of Si diode
- Due to depletion from the both ends, Si diodes is depleted at lower V_{FD} bias , for initial fluences.
- There may not be any need for the “Acceptor Removal”

  (A very nice study about acceptor removal in23rd RD-50 CERN, by Kramberger)

But,

- Why much more V_{FD} lowering (or Acceptor removal) with proton irradiated sensors (compare to neutron one)
- Why more V_{FD} lowering for MCz (Higher Oxygen) compare to Fz

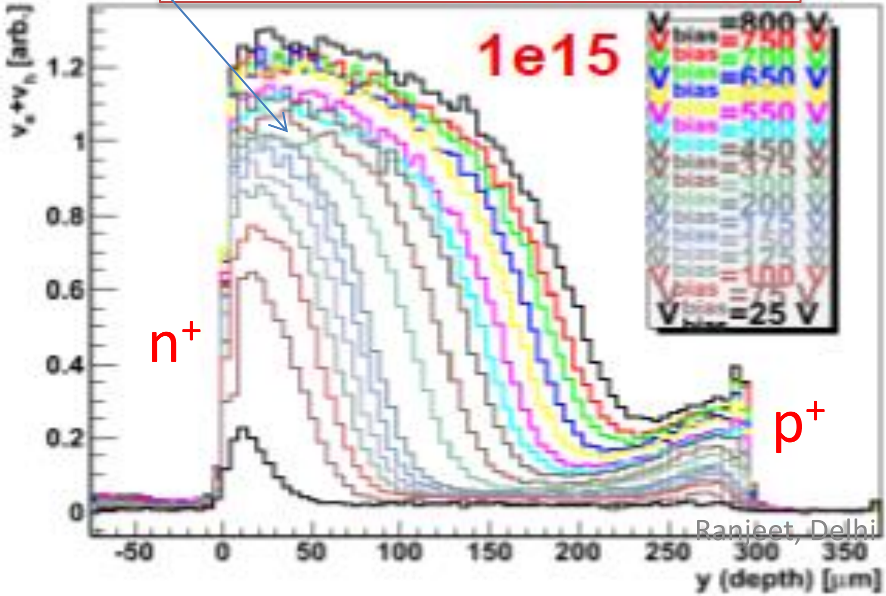
Difference between neutron and charged hadron irradiation

- Charged hadrons introduces much more E(30K) donors with energy level (E_C - 0.1) eV (NIM A 611 (2009) 52–68)
- Introduction rate of E (30K) is $6x10^{-2}cm^{-1}$ for proton irradiation, which is more then 6 times the introduction rate for neutrons irradiation ($9x10^{-3}cm^{-1}$)
- E (30K) is positively charged (almost always) during sensor operation
- More E (30K) traps are generated in Oxygen rich samples (Roxana Radu, 24th RD-50)

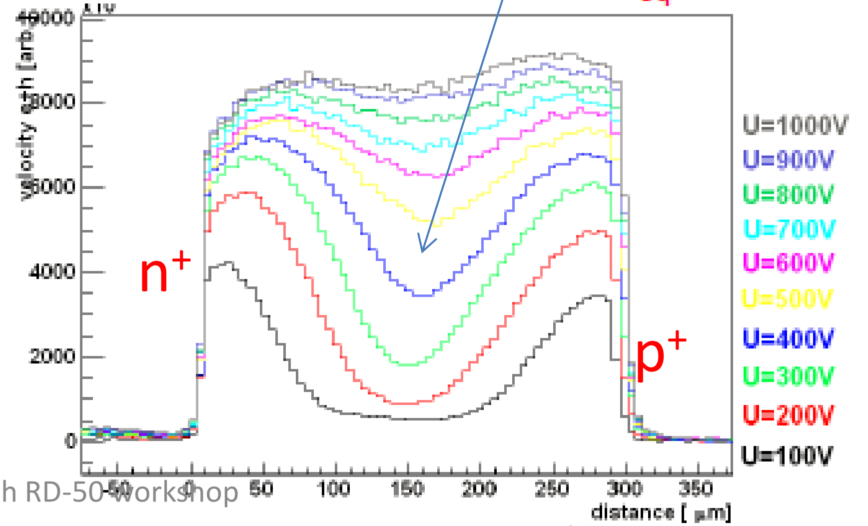
Much more negative space charge for Neutron irradiated sensors (very less amount of active donors, Higher V_{FD})

More symmetric space charge distribution for pion irradiation (Stronger double junction effect, lower V_{FD})

Neutron irradiated n^+-p sensor



HPK-ATLAS07; FZ n-p, PSI pions Φ_{eq}=1.6e15 cm^{-2}



G. Kramberger, Vertex 2012, Jeju, 16-21.9.2012

Effects of E (30K) trap on V_{FD}

Additional positive space charge for charged hadron irradiated sensors - More symmetric double junction electric fields (lower V_{FD})

For p-type sensors, stronger double junction effect for charged hadron irradiation

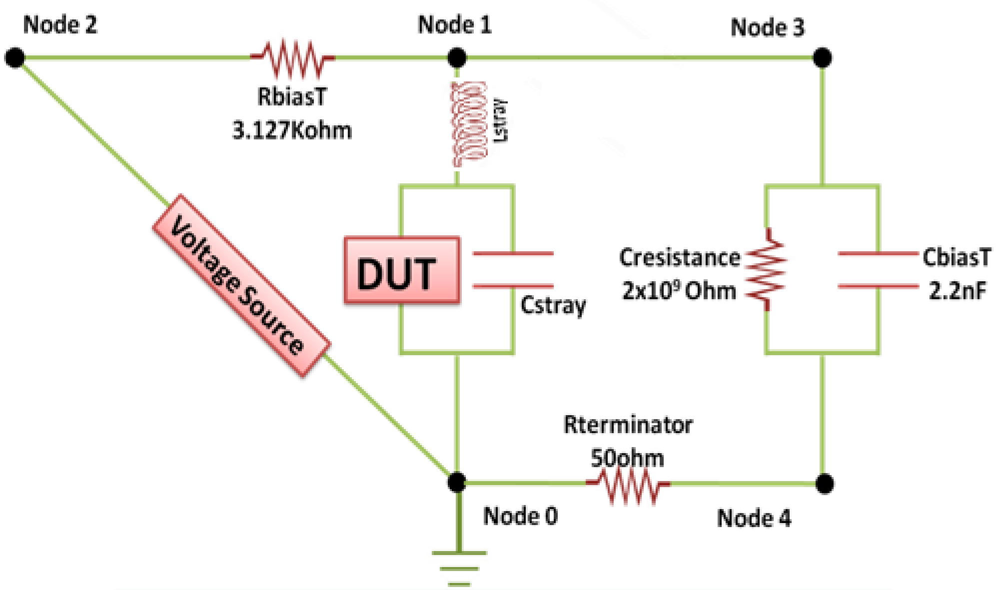
- Lowering of V_{FD} for initial fluences of charged hadrons
- For p-type sensors lowering of V_{FD} may appears as "Acceptor Removal"
- V_{FD} lowering will depend on Oxygen concentration of Si sensor (As more E (30K) levels are introduced in Oxygen rich samples)
- Much steeper slop for V_{FD} for neutron irradiated sensors

For n-type (p^+-n) sensor (Donor type initial bulk doing), initial V_{FD} lowering will happen for both neutron and charged hadrons

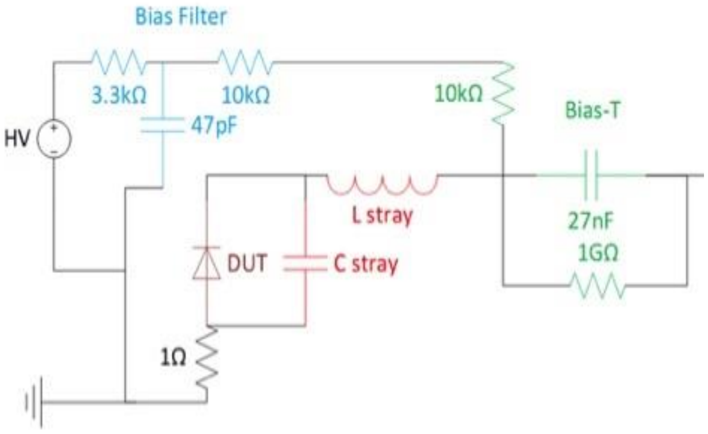
- Appears as "Donor removal"
- Oxygen concentration will affect the V_{FD} slop
- After initial dip in V_{FD}, there will be steeper slop for V_{FD} for neutron irradiated sensors

Some TCT simulations

Mix mode simulation circuit



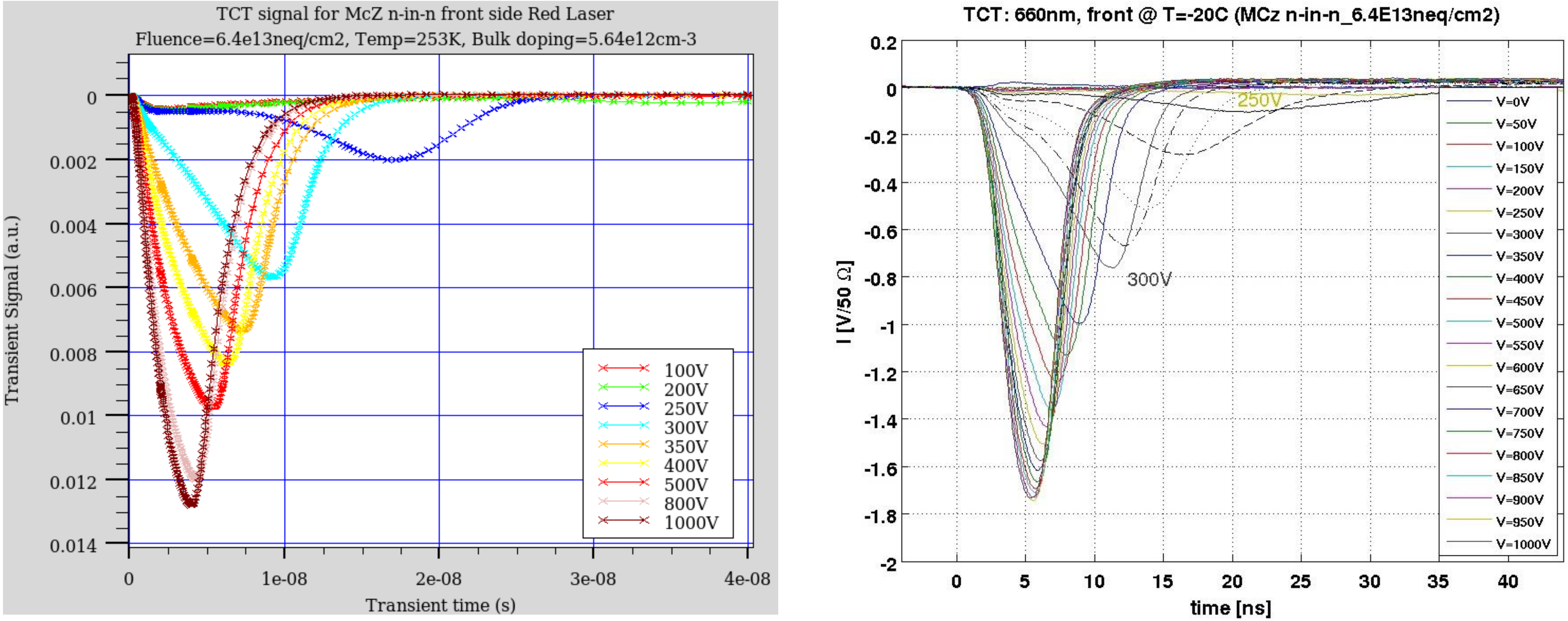
Circuit used for TCT simulations at DU



Circuit used In KIT and UHH

- Since simulated diode structure is 120µm X 1µm X 300µm only
- Cstray represent this extra capacitance and capacitance of cables or other electric components
- Lstray is stray inductance of cables, electrical circuits
- All other variables are more or less known with some confidence.
- No preamp in circuit (Can affect TCT signal)

TCT : Measurement vs Simulation

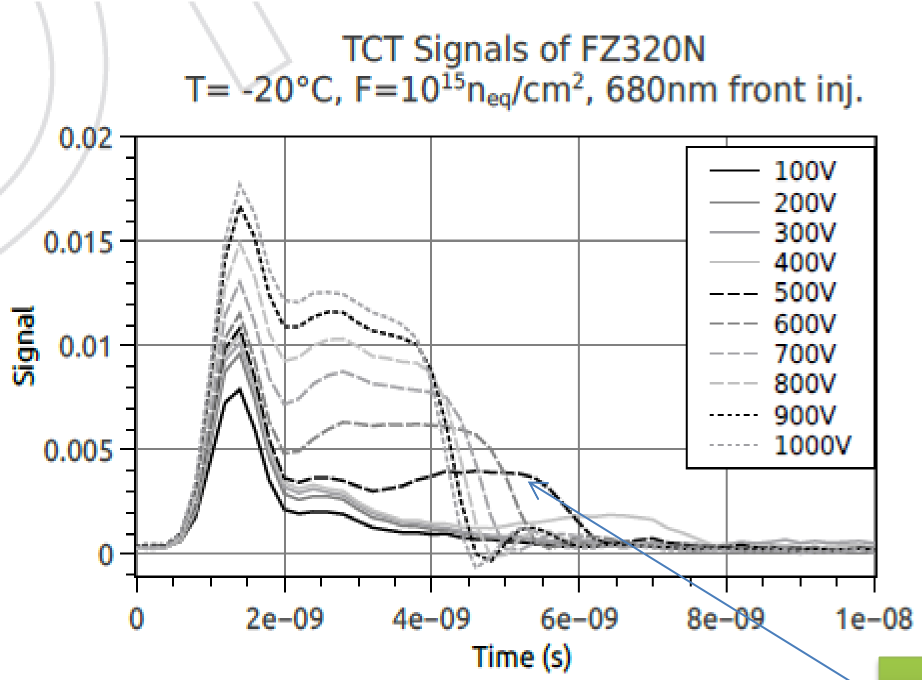


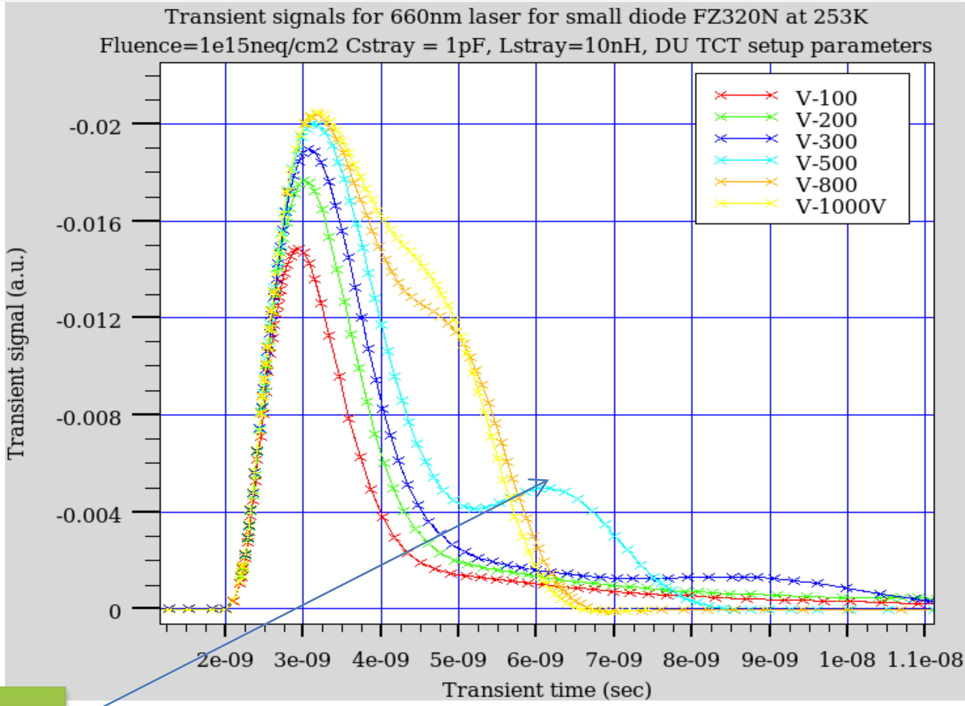
TCT signal for MCz n-in-n for front side illumination with Red laser (Fluence = 6.4e13n_{eq}/cm^2)

-TCT signals appeared only after reverse bias > 200V
(measurements at CERN, Micron diode)

- Good agreement between simulated and measured TCT trends
- Three trap model used (third trap, acceptor, Ec-0.45eV, $\sigma_e = \sigma_h = 1 \times 10^{-16} cm^{-2}$, Intro=40

TCT : Measurement vs Simulation
(Fluence = 1e15neq/cm^2 protons)





500V

- Simulation trends looks similar to measurements (at UHH)
  - Double junction is clearly visible (say at 500V)
- Measured signal start at 0.5ns but simulation start at 2ns (which of course can be shifted)
- Three level trap model is used in TCT simulations

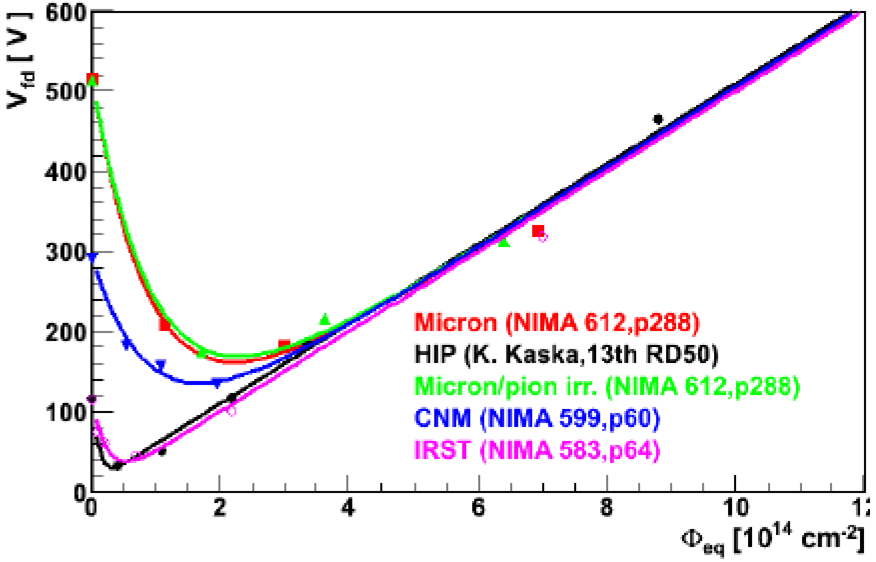
Summary/future outlooks

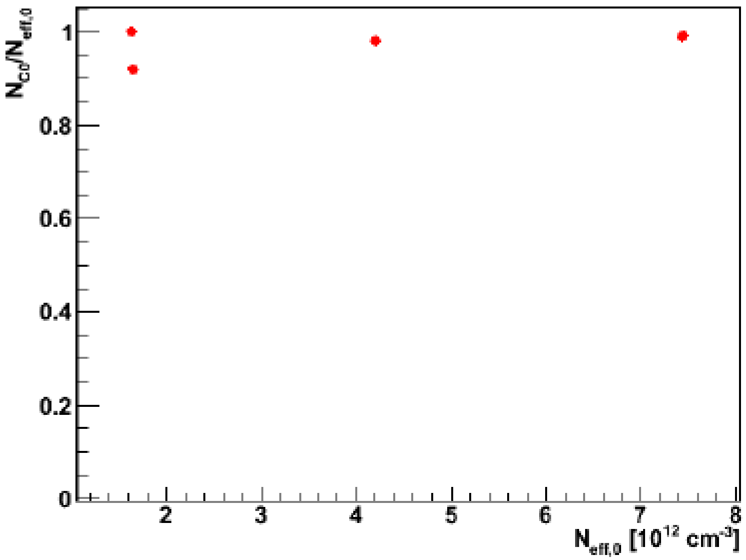
- Some familiar terms used to quantify radiation damage may lead to confusion
  - Need to follow the consistent approach based on traps
  - Can be helpful in avoiding confusion
- Due to the double junction effect, depletion of charge carriers may starts from both ends of Si diode, thus, lowering the V_{FD}
- The V_{FD} lowering for initial fluences, in n-type of sensors, may appear as “Donor Removal”
- The V_{FD} lowering for proton irradiated p-type sensors may be due to double junction effect
- The higher E (30K) donor trap may be a reason for more symmetric electric field for charged hadron and thus, higher apparent “Acceptor Removal”
- E (30K) trap may be behind higher V_{FD} for neutron irradiated sensors and better properties of oxygenated Si
  - Need more investigation
- TCT simulations & measurements for irradiated sensors can provide information about electric field inside the sensors
  - More results in future meetings!

Thanks for your attention!

Back up !

MCz-p irradiated with charged hadrons



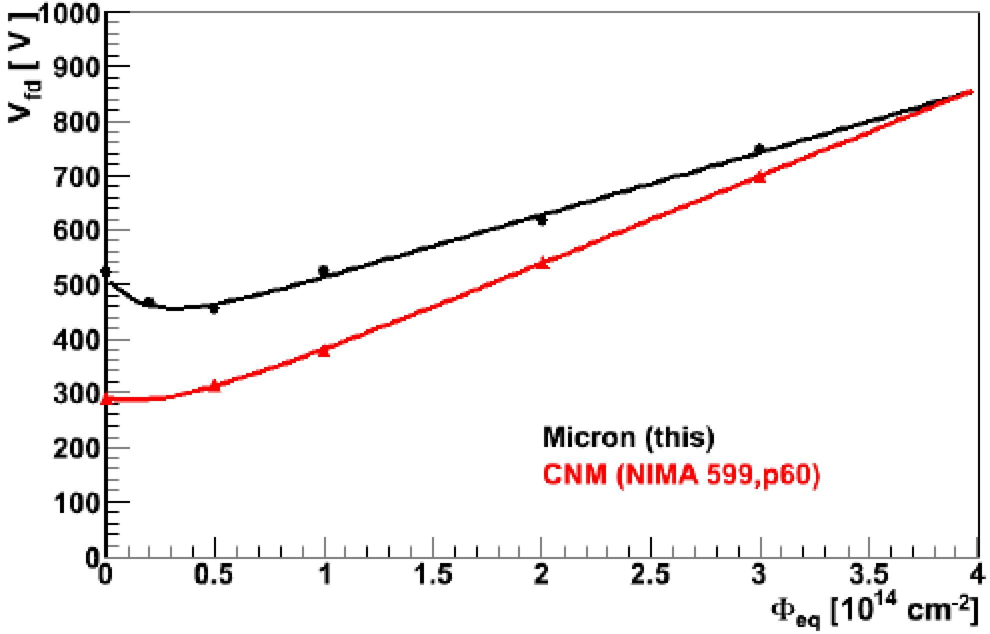


- g_{eff}=0.0071 cm^{-1} (taken from O rich measurements from RD48/50) and seems to be adequate, c and N_{C0} were determined from the fit.
- Different producers – no impact of processing on behavior

- *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)

13/11/2013 G. Kramberger, Initial acceptor removal in p-type silicon detectors, 23rd RD50 Workshop, CERN, 2013 **5**

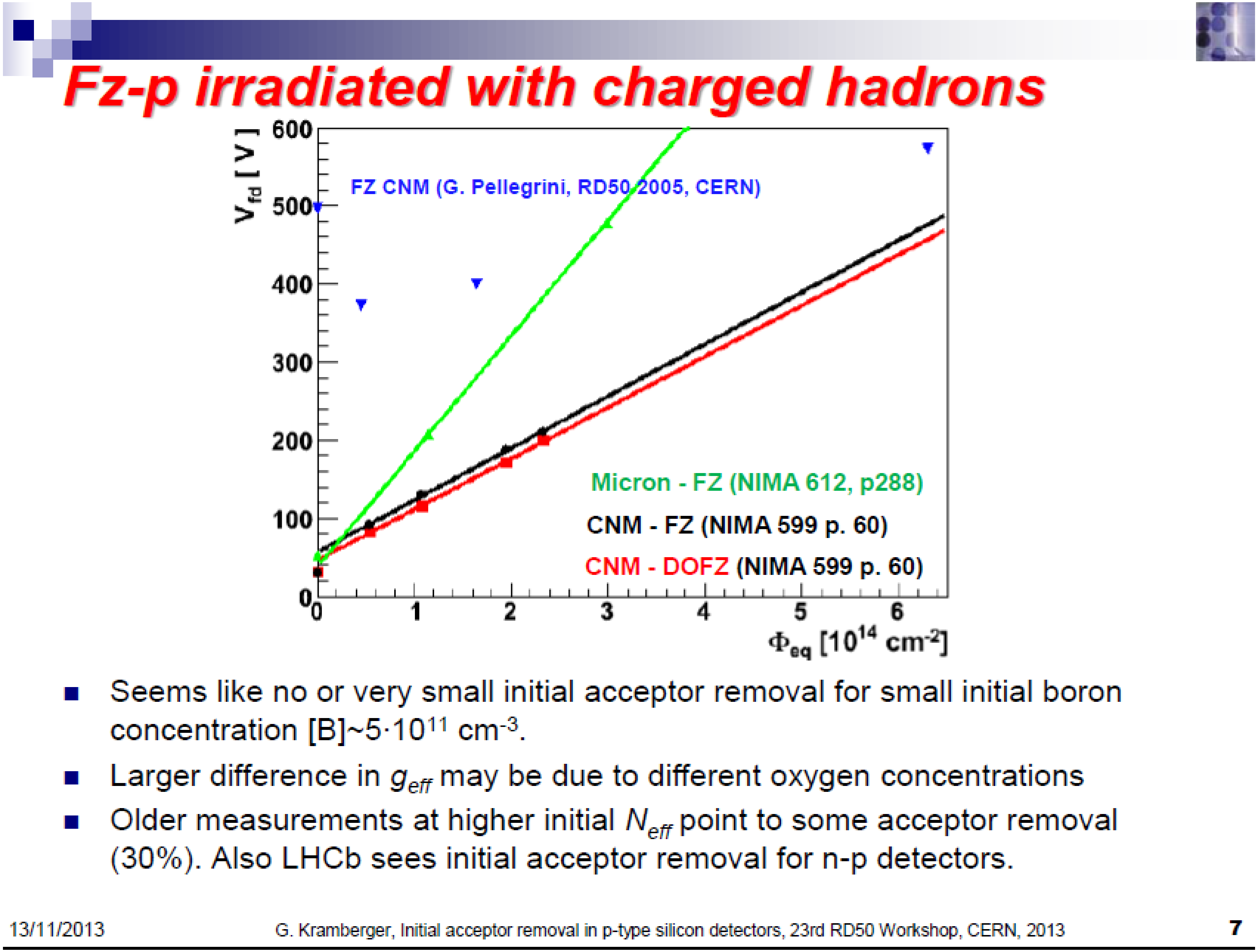
MCz-p irradiated with neutrons



- 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.

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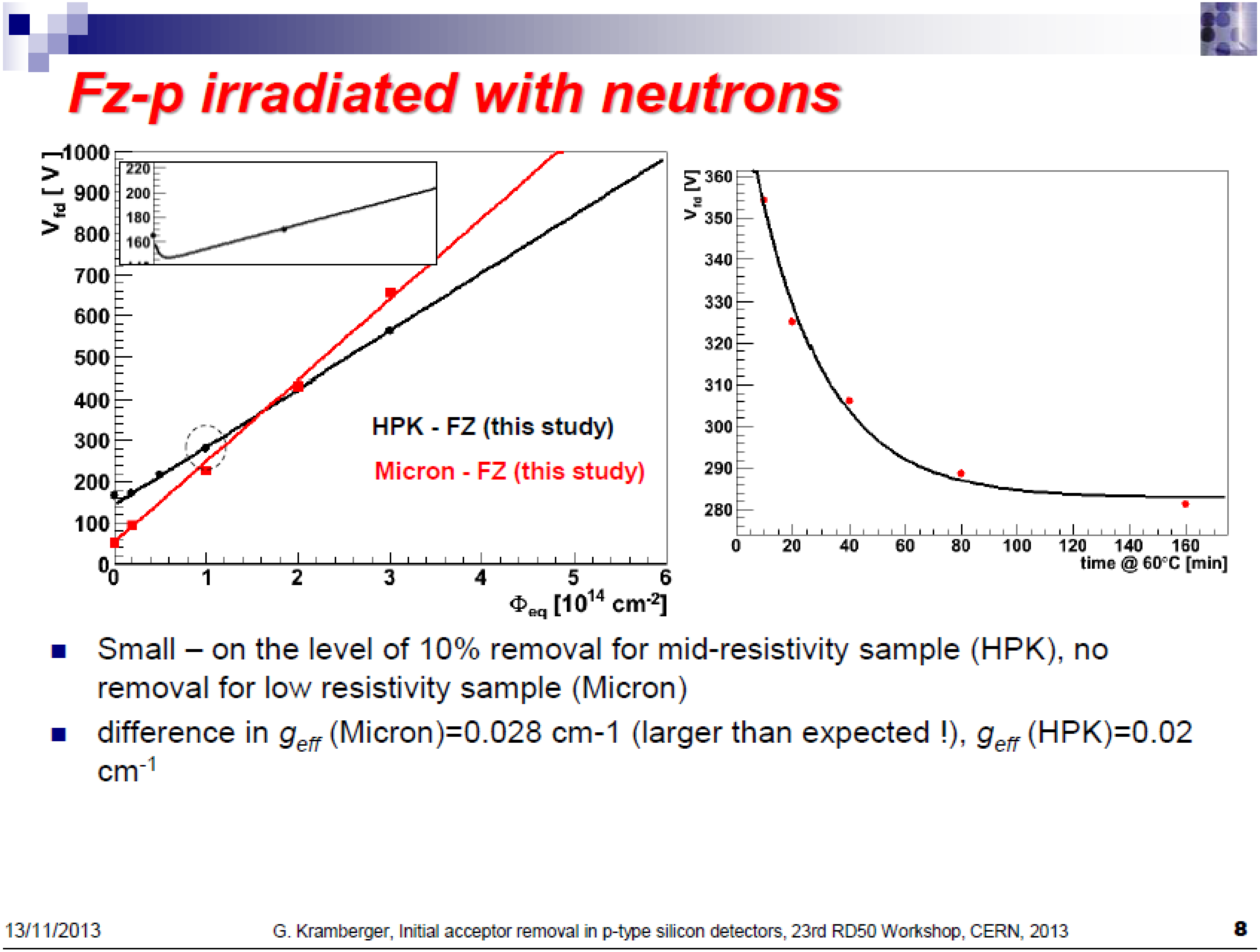

Fz-p irradiated with neutrons

- 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}

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