Electric field and space charge in neutron irradiated n^+-p sensors

G. Kramberger, V. Cindro, I. Mandić, M. Mikuž[†], M. Milovanović, M. Zavrtanik

Jožef Stefan Institute, Ljubljana, Slovenia

[†] also University of Ljubljana, Faculty of Physics and Mathematics

Motivation

- Modeling the electric field for heavily irradiated n^+-p sensors
  - Input to simulations.
  - Understanding the neutron damage.
  - Where does the “standard” device model break down?

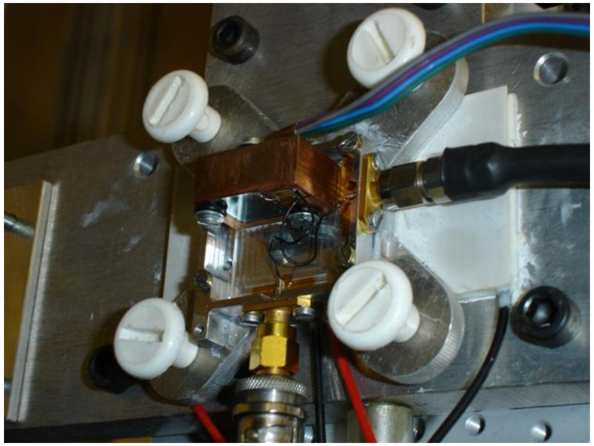
- Conventional TCT which was used to extract the electric field shape at low fluences from the time evolution of the induced currents is not possible – too much trapping. But Edge-TCT (*IEEE Trans. Nucl. Sci. Vol. 57(4), 2010, p. 2294*) can …

It aims to get an approximate agreement with measurements.
It should be easily fed to the simulators, but it does not try to quantitatively explains the reasons for space charge distribution.

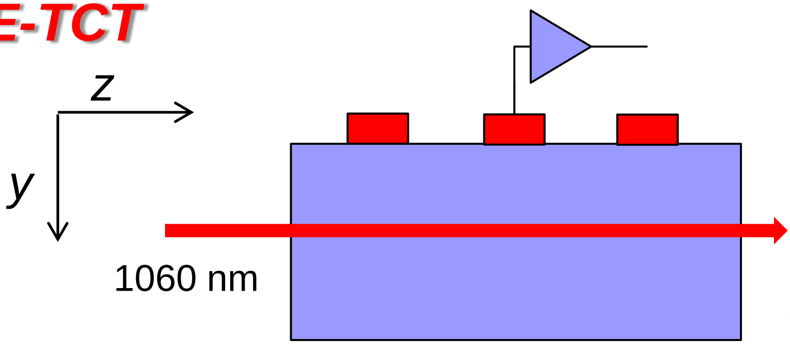
Samples and measurement technique

Samples	Fluences	Annealing
HPK (ATLAS-07 run) 1x1 cm^2, 300±20 μm thick, p-type isolation: p-stop initial V_{fd}~180-190 V	• non-irradiated (100 μm pitch) • $5\cdot10^{14}$ cm^{-2} (75 μm pitch) • $1,2,5,10\cdot10^{15}$ cm^{-2} (100 μm)	sequential steps at 60ºC up to 80 min (0,10,20,40 min)

✓Neutron irradiated samples
✓Measurements done at -20ºC
✓Annealing done with samples mounted in the setup to ensure that the same spot in the detector is illuminated at different annealing times



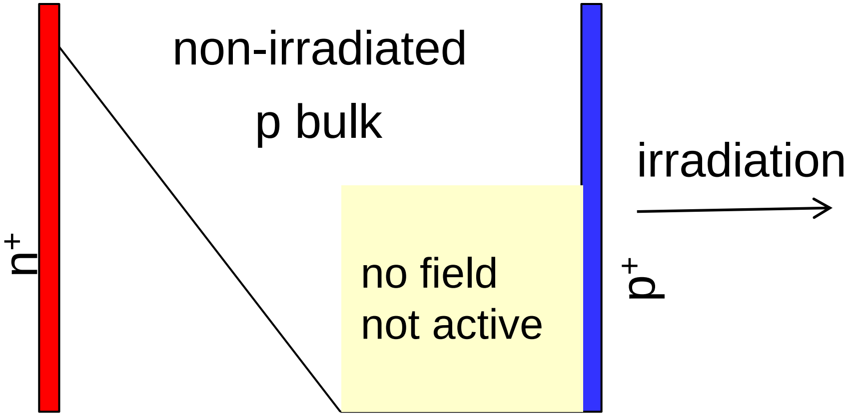
EDGE-TCT

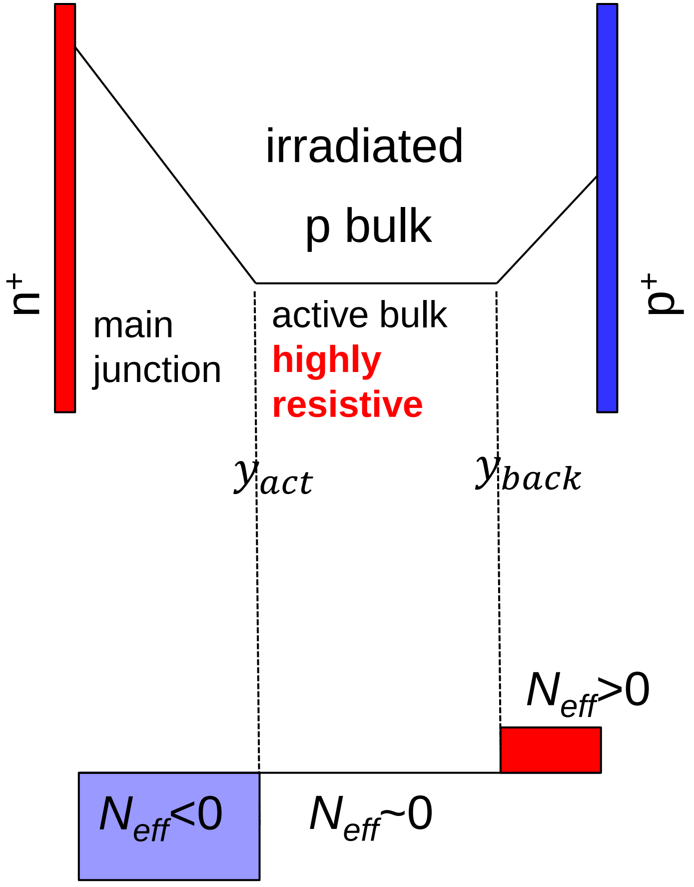


IEEE Trans. Nucl. Sci. Vol. 57(4), 2010, p. 2294.

Electric field profile

V. Eremin et al., NIM A360 (2004) 458, NIM A535 (2004) 622.
D. Menichelli et al., NIM A426 (1999) 135.,
I. Mandic et al., NIM A512 (2004) 343 and many, many more …





Corresponding space charge

- active region is only the depleted part (providing the integration time is short - LHC like)
- weighting field determined by the border of the depleted region (depends on resistivity)

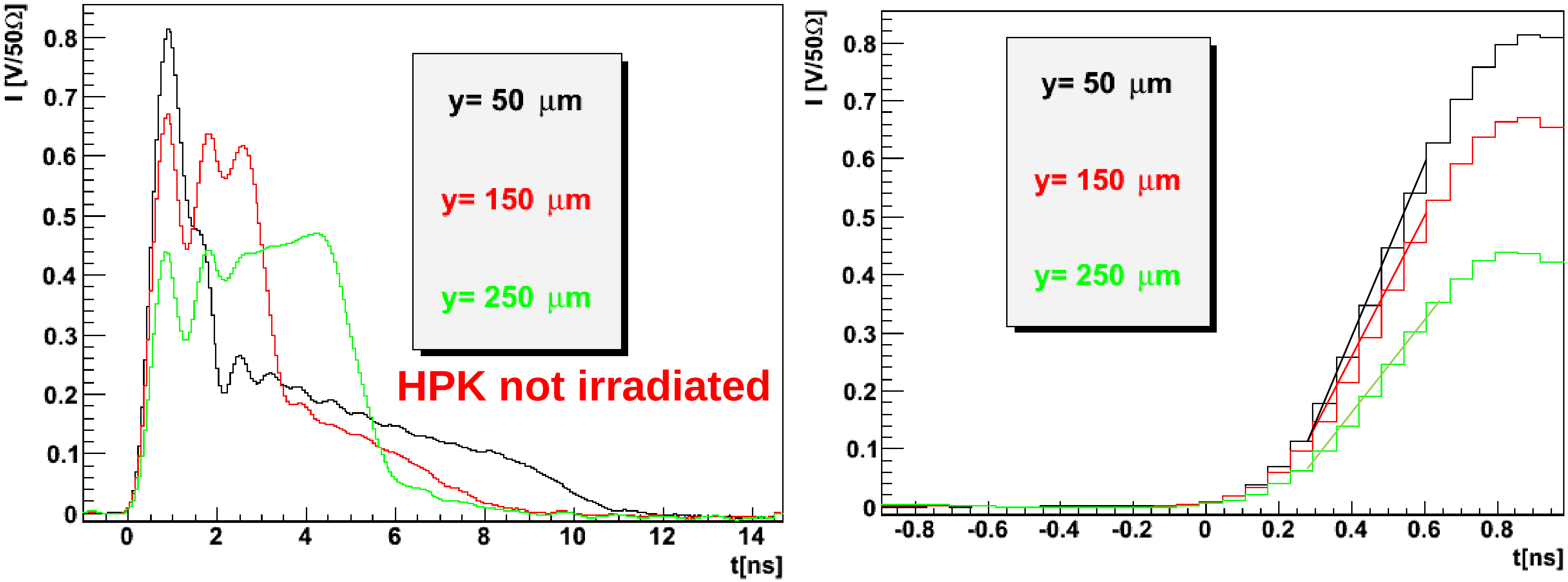
Key questions for modeling:

- shape of $N_{eff}(y)$ – in different regions
- y_{act}
- y_{back}

Velocity profile – basis of the model

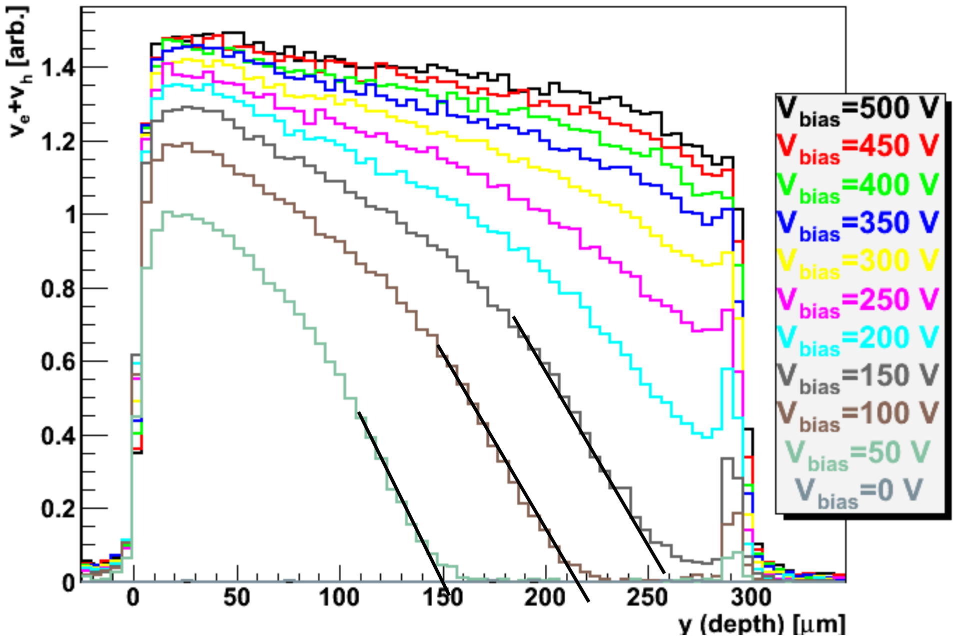
$$Q(y) = \int_0^{25ns} I(y,t)\,dt$$

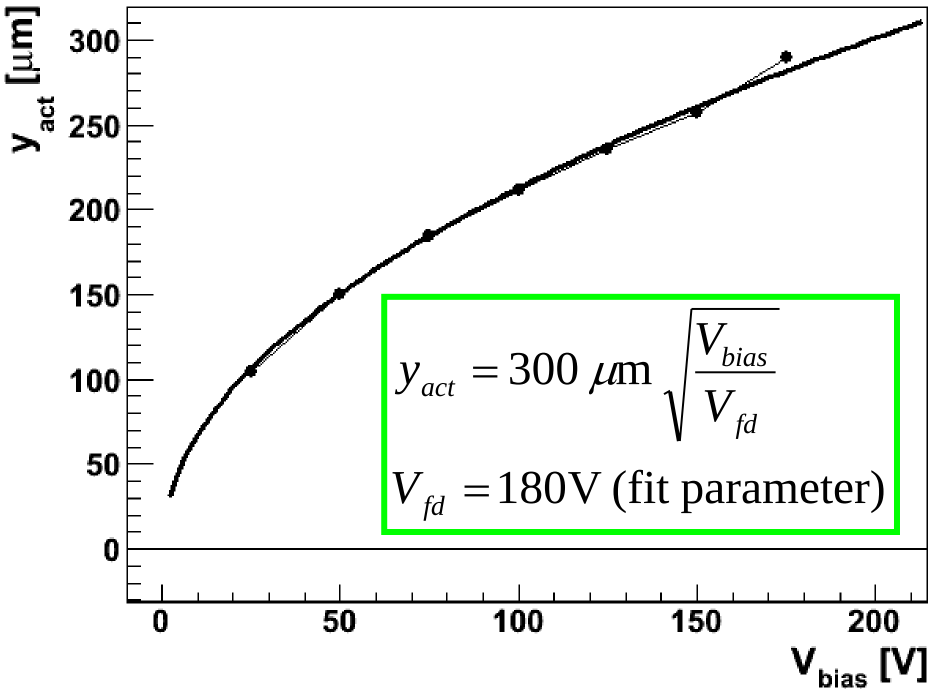
$$v_e + v_h \propto I(t \approx 0)$$



- The initial rise of the induced current signal is proportional to the drift velocity.
  - does not depend on trapping of the drifting charge
  - scanning over the depth (*y*) one can get the velocity profile

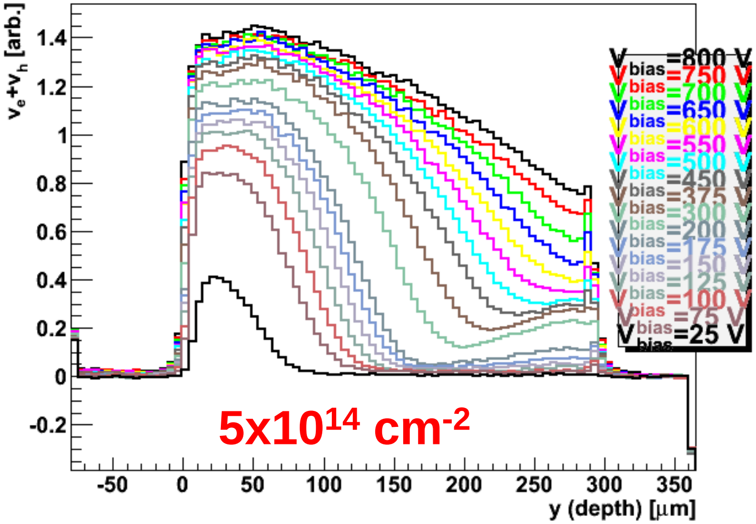
Non-irradiated p-type sensor

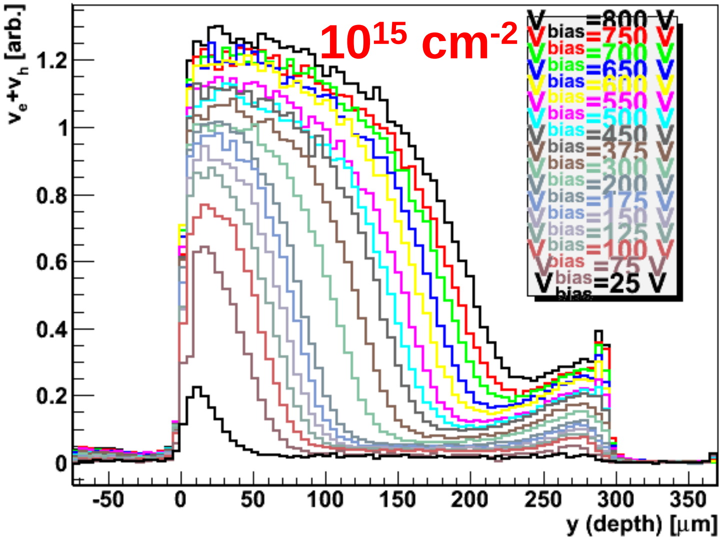




- V_{fd} from CV and CCE profile agree well.
- for $V<V_{fd}$ there is a region with E field at the back (p-p$^+$ contact), due to large difference in free hole concentration.
- at high voltages drift velocity is almost saturated in the entire detector.
- active zone is determined as region with E>0.

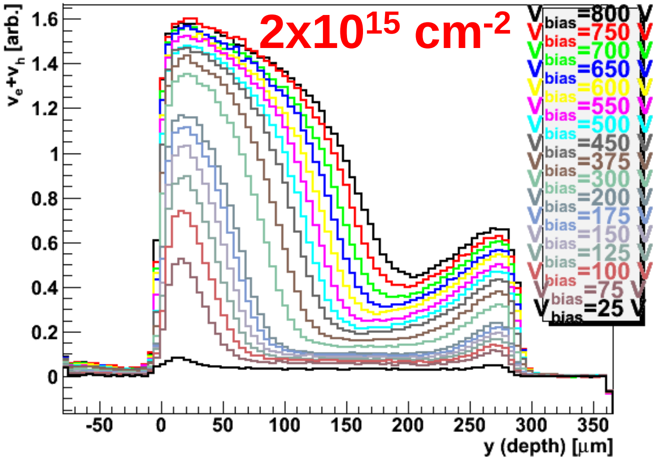
Velocity profiles for irradiated sensors

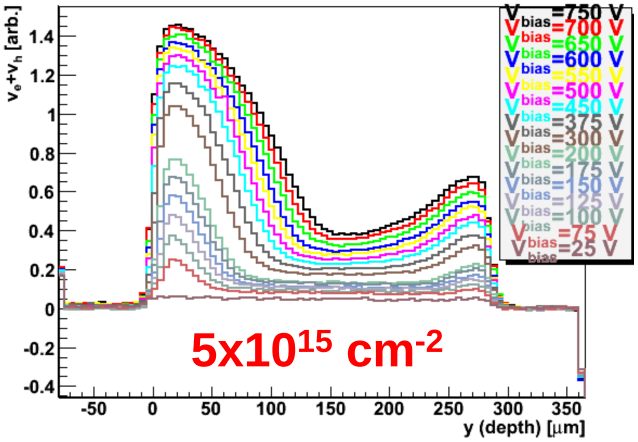

5x10^{14} cm^{-2}

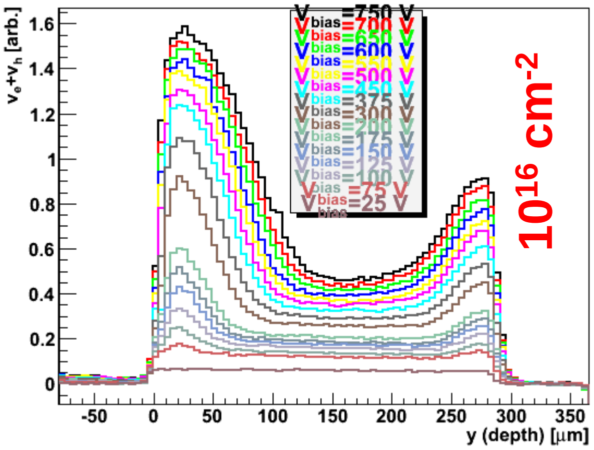

10^{15} cm^{-2}

Note that velocity close to strips does not depend on fluence

annealed for 80min@60ºC

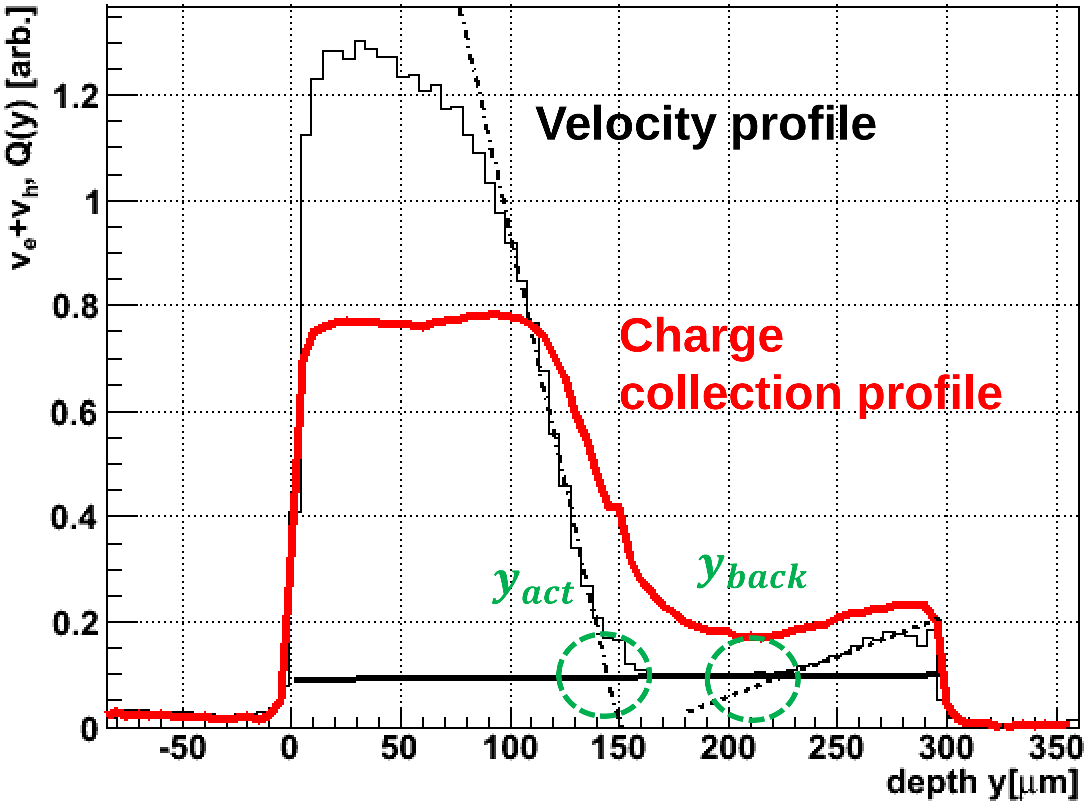

2x10^{15} cm^{-2}


5x10^{15} cm^{-2}


10^{16} cm^{-2}

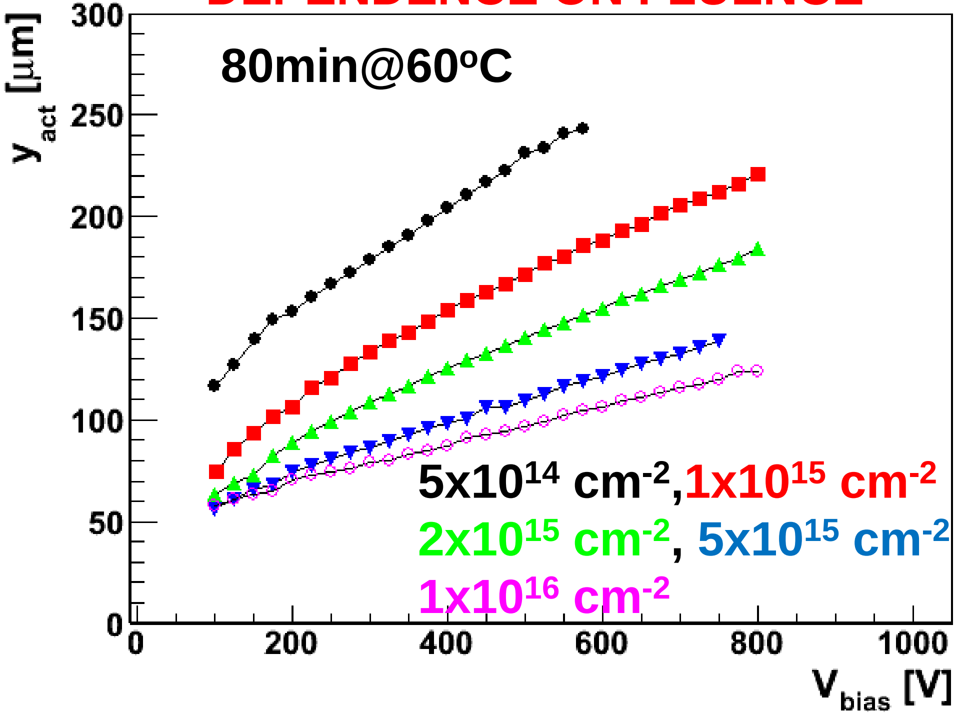
Determination for irradiated sensors

- y_{act} and y_{back} determined from intersection of the lines
- Determination from charge collection profile would give in similar values

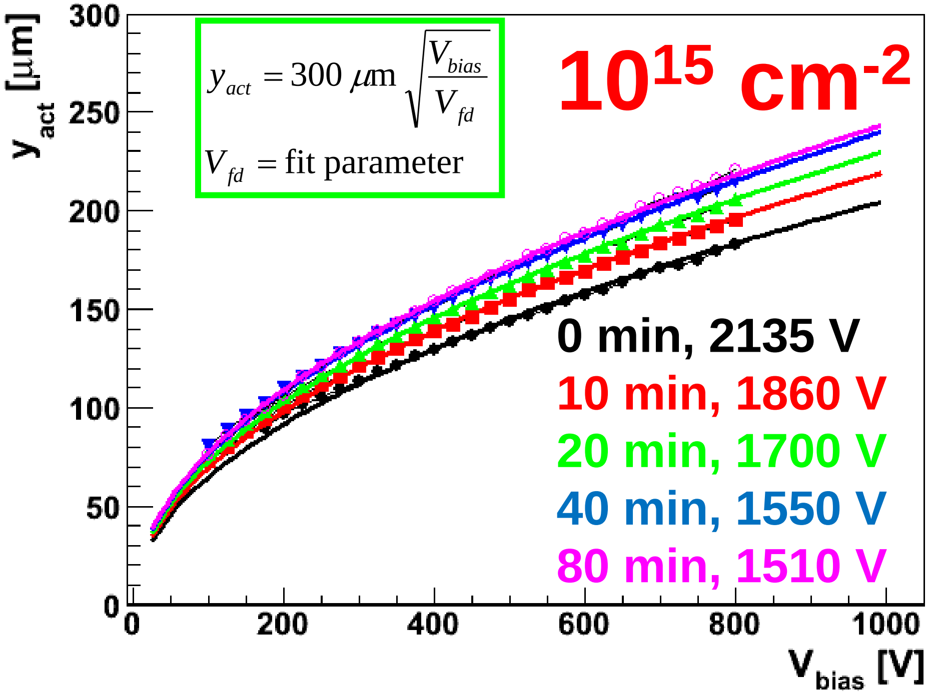


Main Junction – active zone (y_{act})

DEPENDENCE ON FLUENCE



DEPENDENCE ON ANNELING

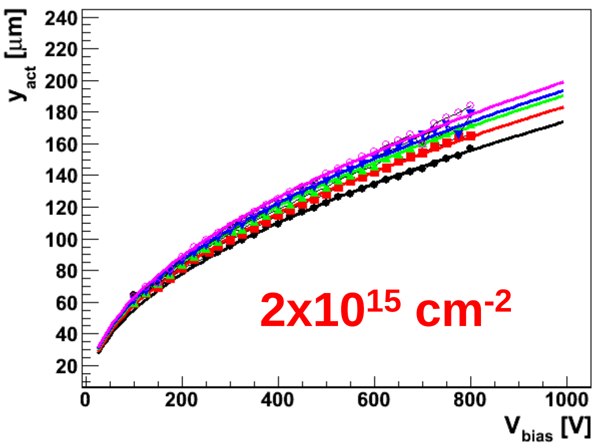

$$y_{act} = 300\ \mu\text{m}\sqrt{\frac{V_{bias}}{V_{fd}}}$$

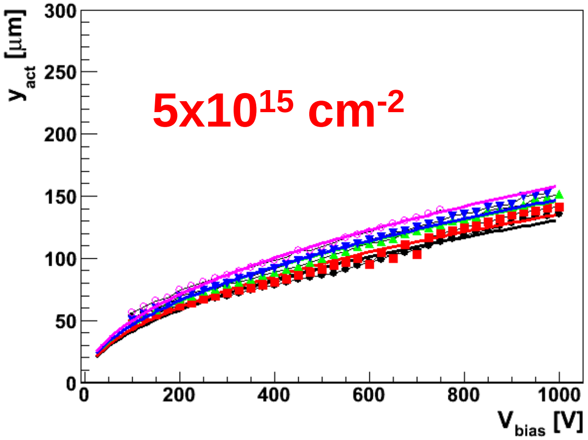
V_{fd} = fit parameter

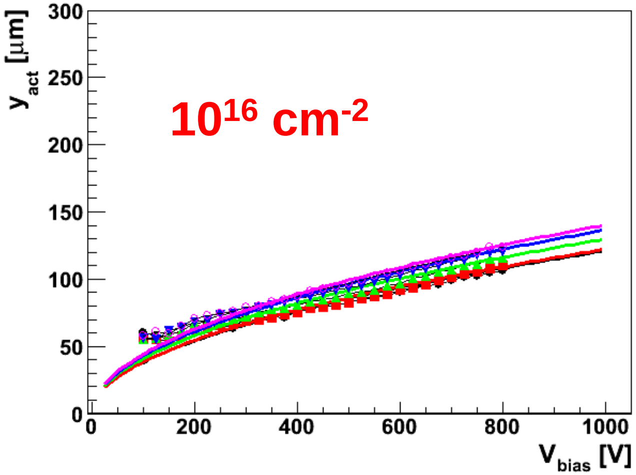
- decrease of y_{act} with fluence
- The rate of decrease tends to be smaller with fluence
- relatively large zone at very low voltages

- For the low fluences the N_{eff}=const. model works – the values of V_{fd} are consistent with expectations based on RD48/50 data.
- The voltage drop in the bulk and at the back are small compared to the main junction.

Annealing at higher fluences


2x10^{15} cm^{-2}


5x10^{15} cm^{-2}


10^{16} cm^{-2}

- Short term annealing is always beneficial
- The “standard device model” starts to break down
  - active region is larger than expected
  - the fits are getting worse at high fluences
  - active zone at low voltages is larger than expected
- The V_{fd} obtained from the fit can be used to calculate N_{eff}

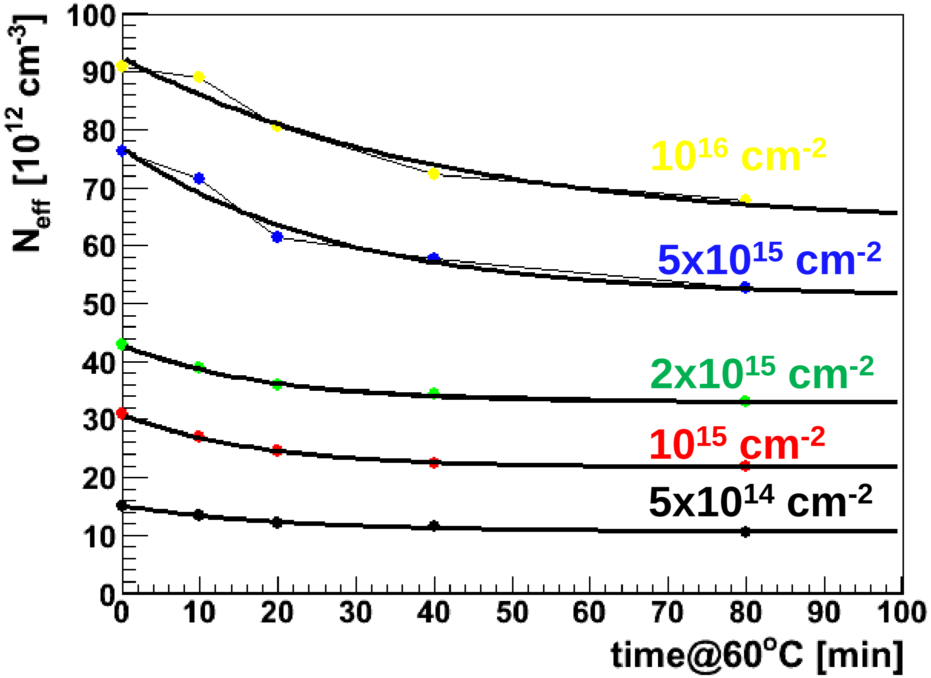
$$y_{act} = 300\ \mu\mathrm{m}\sqrt{\frac{V_{bias}}{V_{fd}}}$$

$$V_{fd} = \text{fit parameter}$$

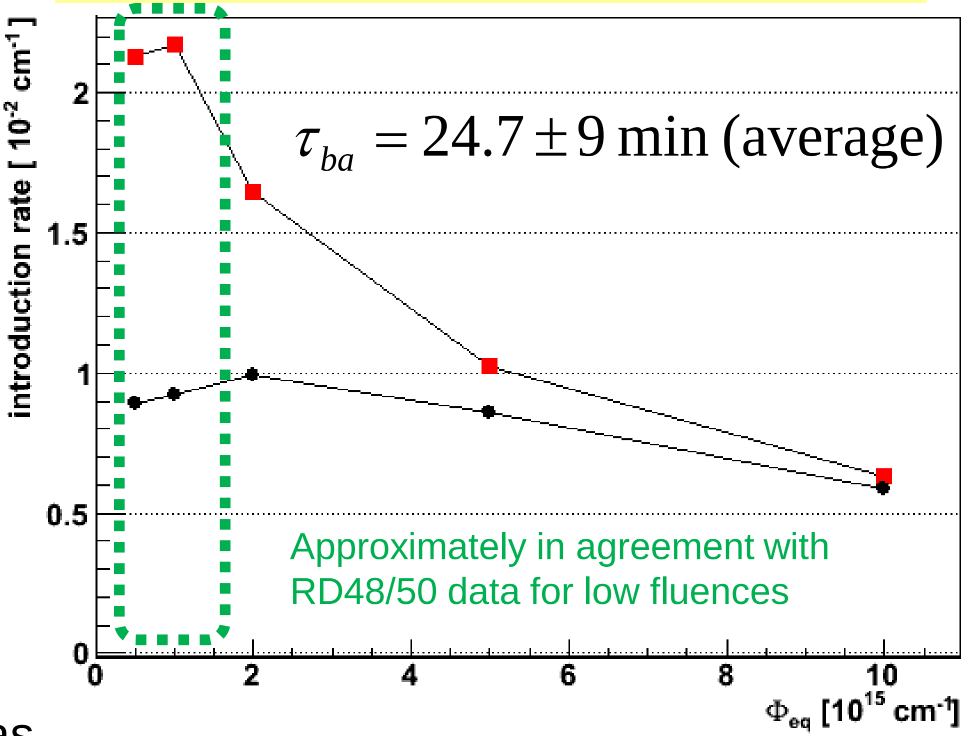
$$N_{eff} = \frac{2\varepsilon\varepsilon_0 V_{fd}}{e_0 W^2}$$

Substantial uncertainty as the voltage drop occurs also in non-depleted bulk and back junction.

Annealing at higher fluences (II)



$$N_{eff}(t) \approx g_c \Phi + g_a \cdot \Delta\Phi \cdot \exp\left(\frac{-t}{\tau_{ba}}\right)$$



$$\tau_{ba} = 24.7 \pm 9 \text{ min (average)}$$

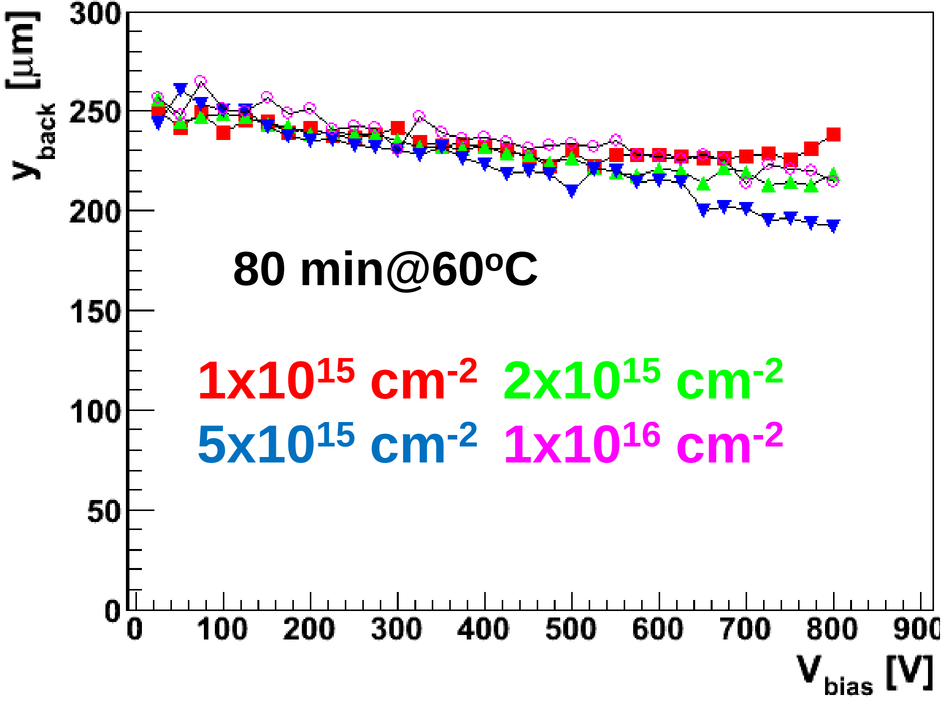
Approximately in agreement with RD48/50 data for low fluences

- up to 1-2x10^{15} cm^{-2} the device model based on N_{eff}=const. (+ active bulk) works
- At high fluences the active zone grows as if N_{eff} is smaller than predicted from low fluence values

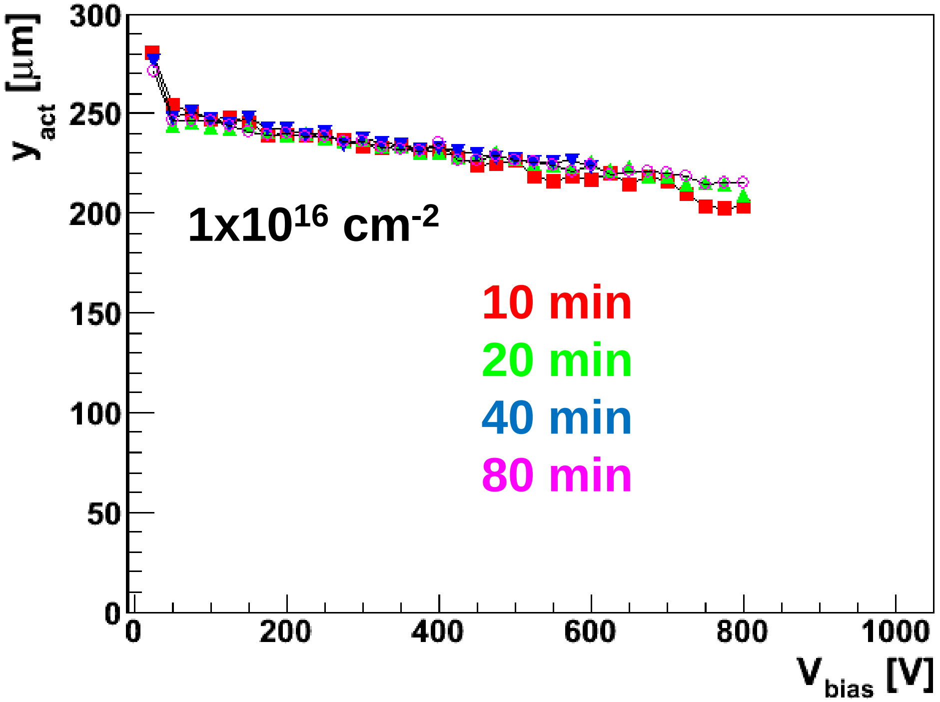
THIS INTRODUCTION RATES SHOULD ONLY BE USED TO CALCULATED y_{act} AT GIVEN VOLTAGE AND FLUENCE.

Second junction – y_{back} (I)

DEPENDENCE ON FLUENCE



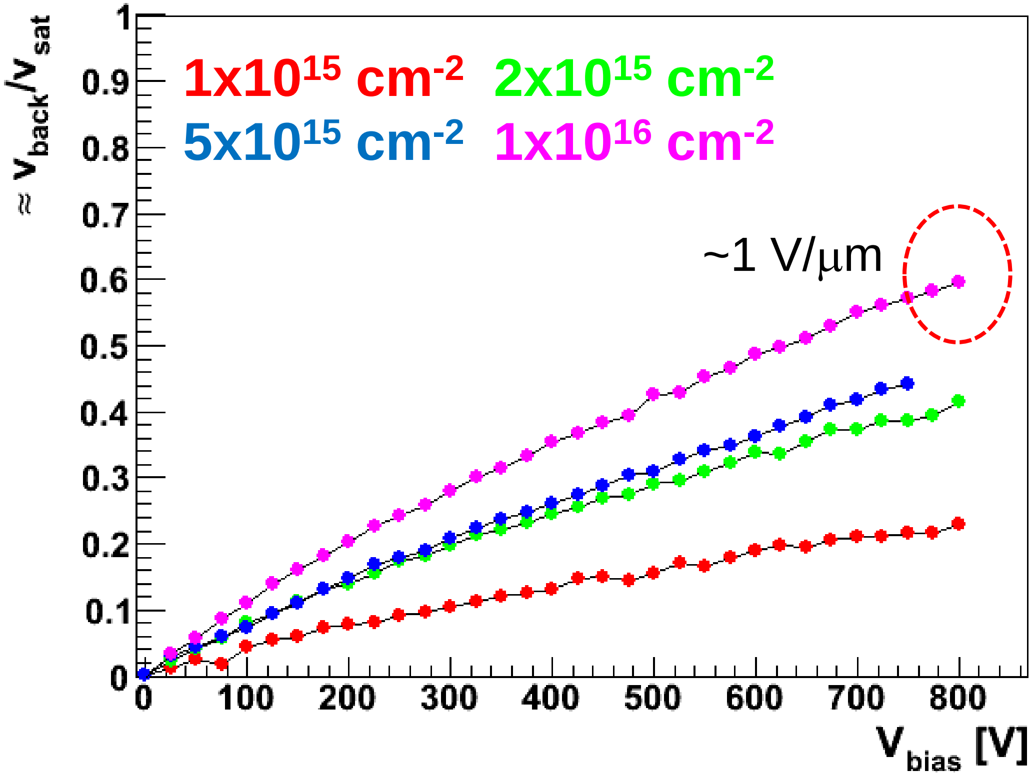
DEPENDENCE ON ANNELING



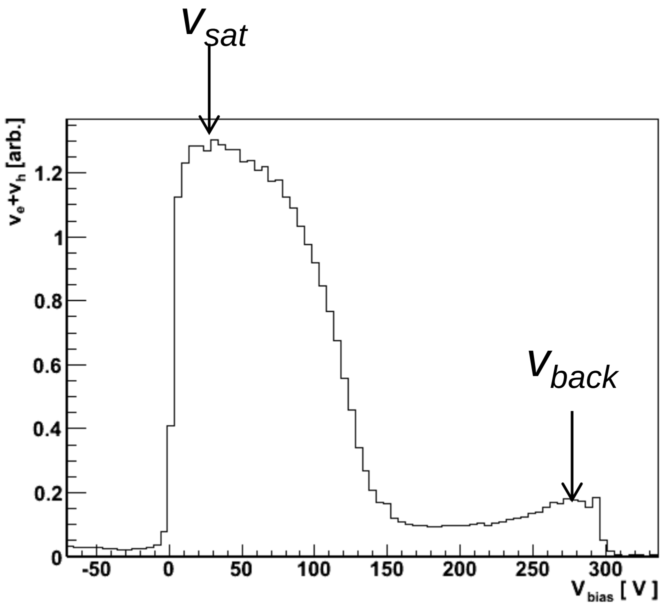
- No obvious dependence on annealing.
- Weak or no dependence on fluence – underlying physics ?

Second junction – y_{back} (II)

- Saturation of drift velocity close to strips can be exploited to determine the importance of the second peak.
- The height of the second peak increases with fluence – electric field becomes higher.

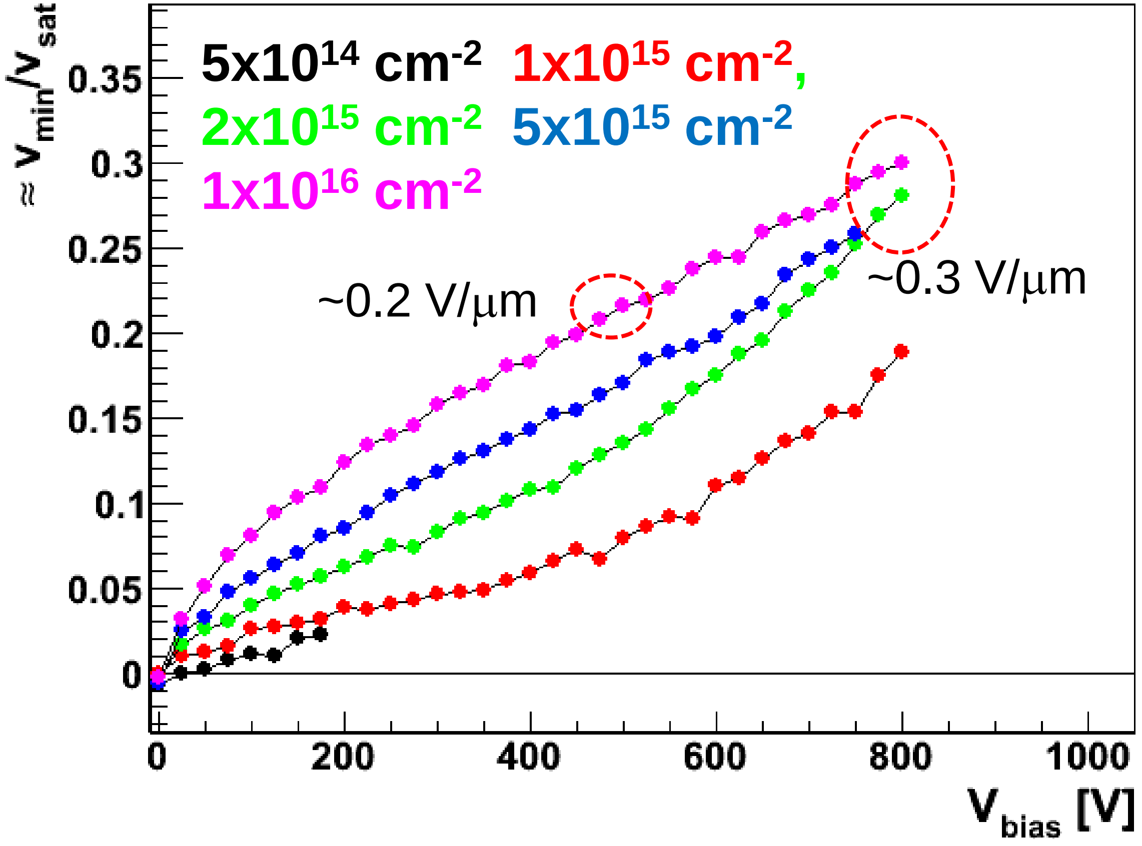


v_{sat} at the highest voltage at each fluence

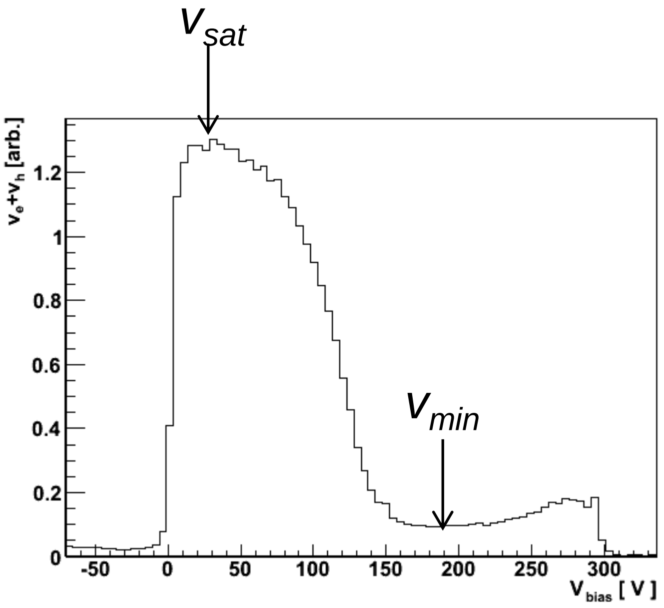


Neutral active bulk

- The electric field in active bulk becomes larger at high fluences.
- Values of electric field of order 0.2-0.3 V/μm in the active bulk.



v_{sat} at the highest voltage at each fluence



Modeling

STEP 1. – calculate border of active zone: $y_{act} = \sqrt{\dfrac{2\varepsilon\varepsilon_0 V_{bias}}{e_0 \cdot g_c(\Phi)\cdot\Phi}}$

STEP 2. – calculate border of back: $y_{back} \approx 250\,\mu\mathrm{m} - 0.0496\,\dfrac{\mu\mathrm{m}}{\mathrm{V}}\cdot V_{bias} \quad , \quad V_{bias} > 50\mathrm{V}$

STEP 3. – Set the function $N_{eff}(y<y_{act})$ e.g.:

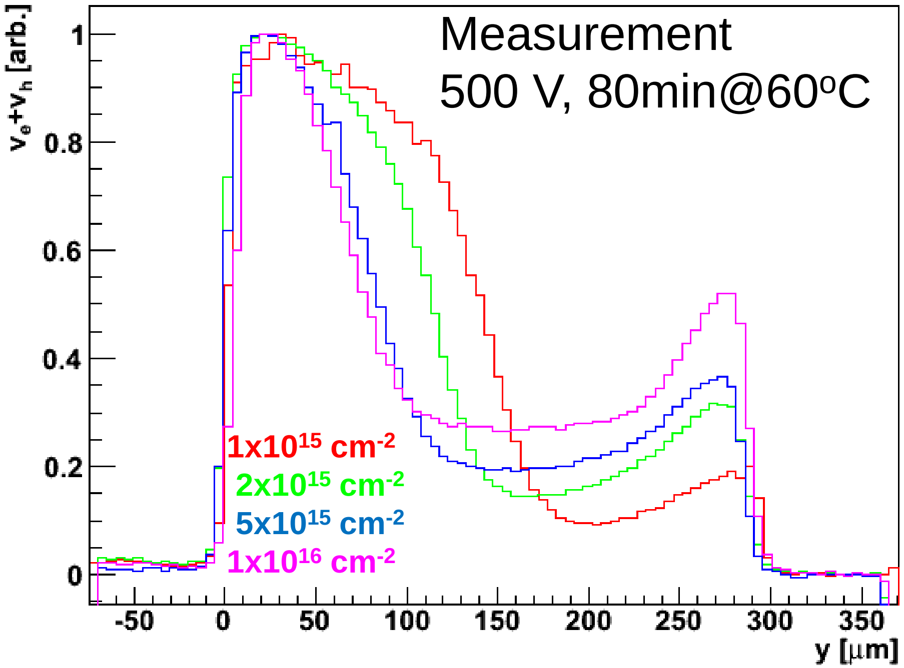
$$1.)\ N_{eff} = g_c(\Phi)\cdot(1-\zeta)\cdot\Phi$$

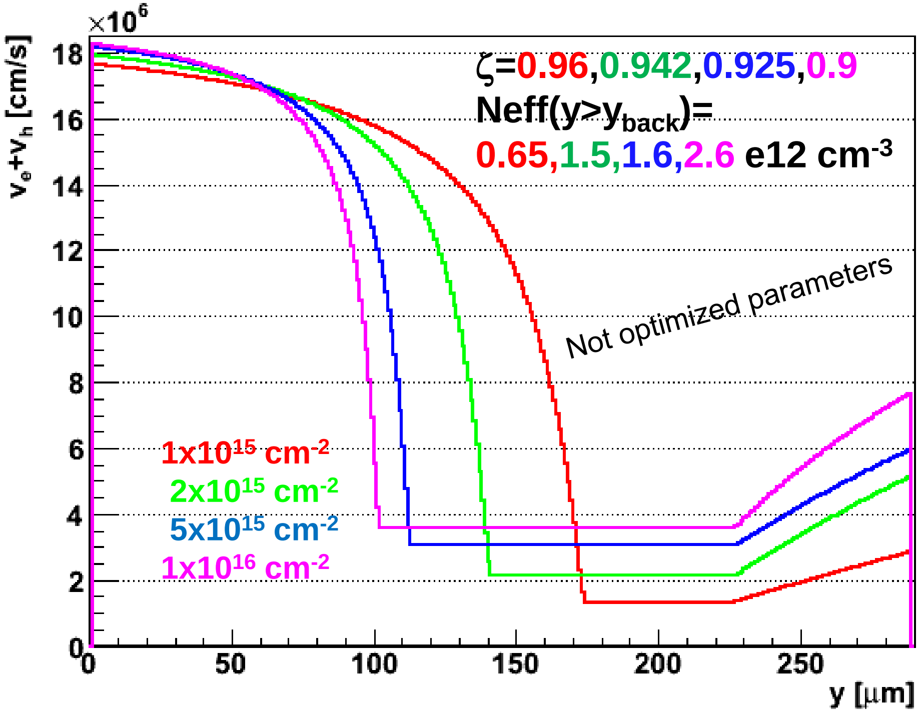
$$2.)\ N_{eff} = 3\cdot g_c(\Phi)\cdot(1-\zeta)\cdot\Phi\cdot\left(1-\frac{y}{y_{act}}\right)$$

ζ determines how much voltage drops over the active region and correspondingly over the bulk and back region

STEP 4. – Set the $N_{eff}(y>y_{back})$ and fix ζ in such a way that v_{min}/v_{sat} and v_{back}/v_{sat} are in agreement with measurements (see previous plots).

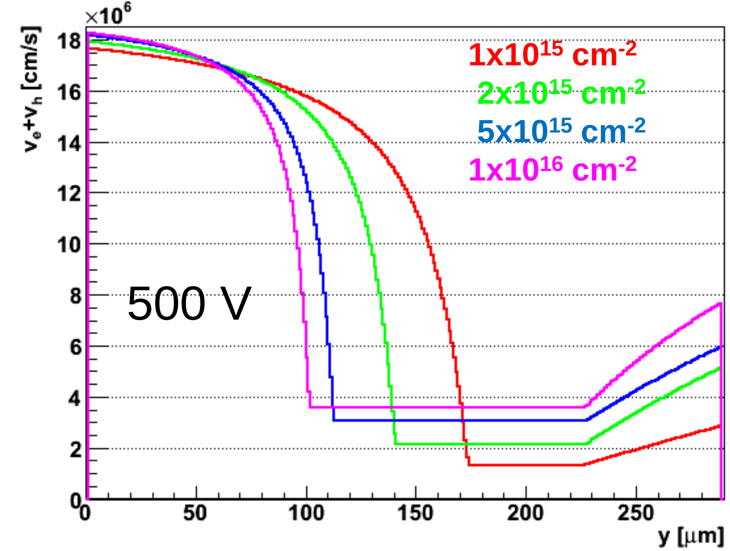
Modeling (II)

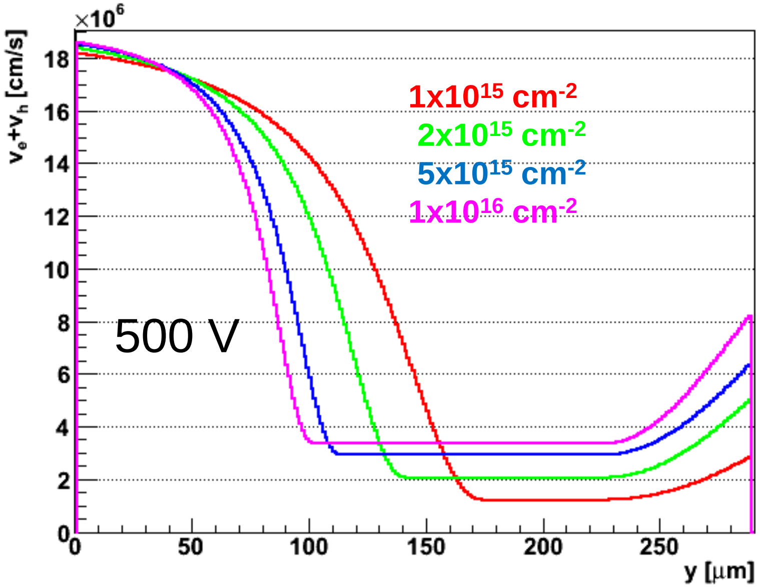


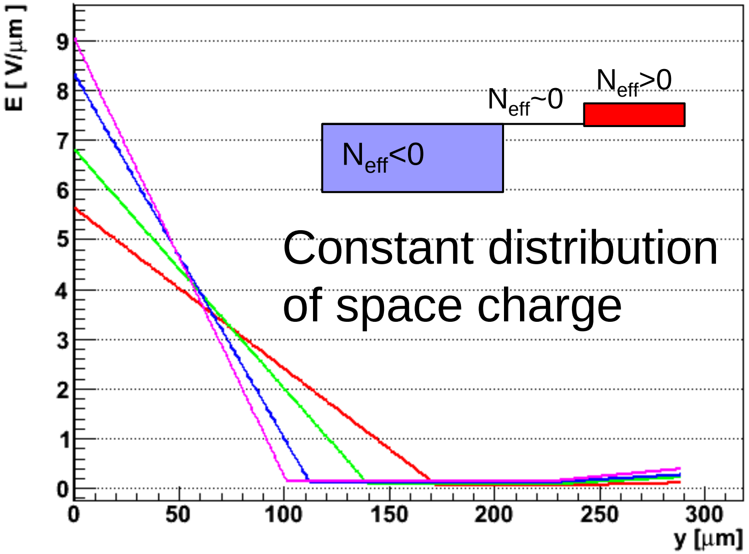


- The qualitative agreement between the measured and modeled velocity profile is reasonable:
  - measured drift velocity does not rise so sharply for $y<y_{act}$
  - measured values are normalized to 1 for velocity at strips

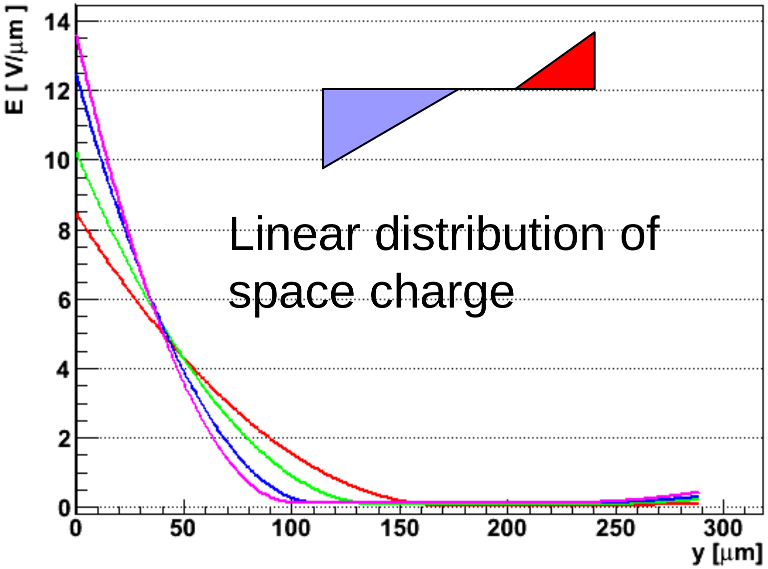
Modeling (III)







Constant distribution of space charge



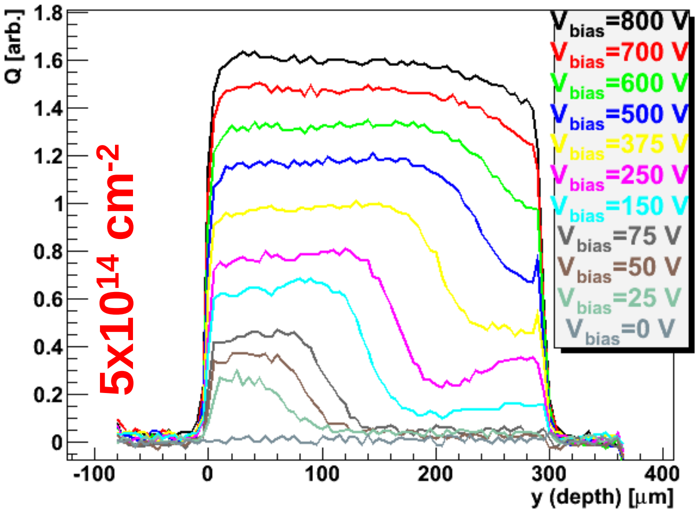
Linear distribution of space charge

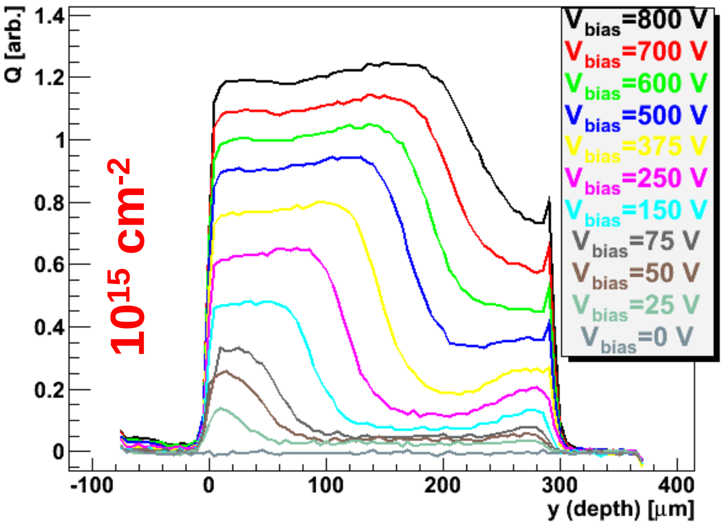
Better agreement with linear space charge – E close to multiplication threshold.

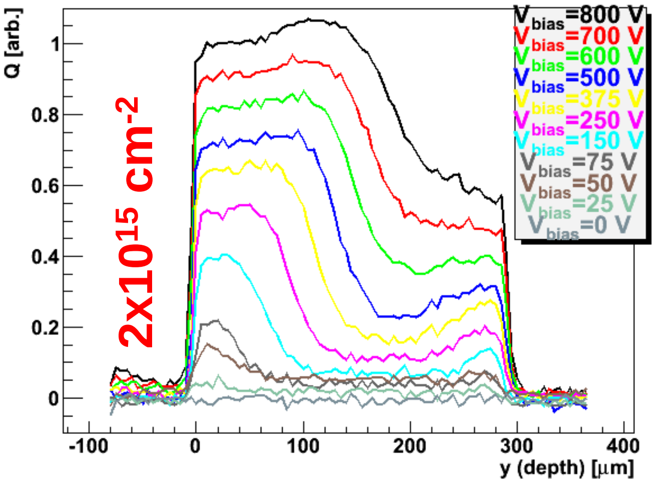
Conclusions & future work

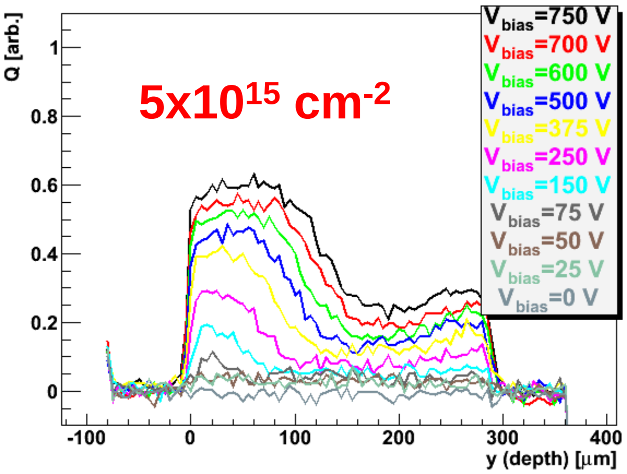
- A simple model that gives reasonable agreement with measured velocity profiles in heavily neutron irradiated silicon n-p detectors has been presented.
- The “standard” device model of the electric field works up to 1-2x10^{15} cm^{-2}
  - active bulk is present already at lower fluences, but the electric fields are smaller
  - the measured introduction rates of negative space charge is in agreement with RD48/50 data
- Simulation of signal in the modeled electric field including impact ionization
- C++ code for modeling:
  - Search for the parameters (minimization)
  - calculate the space charge distribution for given voltage fluence/annealing step
  - Publication of the code a root library
- Modeling charged hadron irradiated detectors.

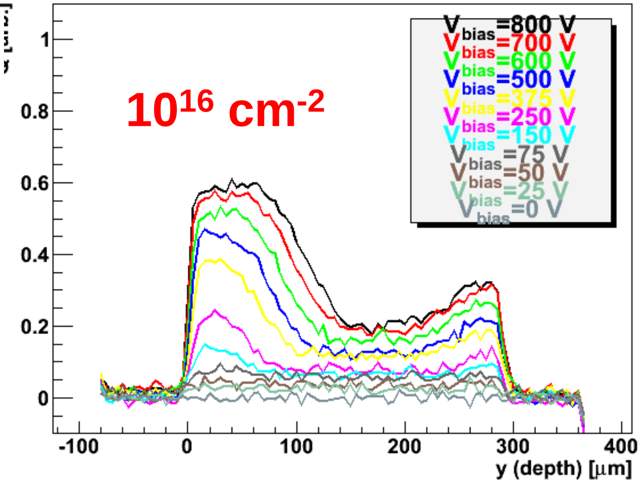
Charge collection profiles for irradiated sensors











Note that charge collection profiles depend on fluence.