Electric Fields in Irradiated Silicon Pad Detectors

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- deconvolution of measured pulse shapes
- deep level concentrations
- simulation of pulse shapes

4th RD50 Workshop on
Radiation Hard Semiconductor Devices
for Very High Luminosity Colliders
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Charge Collection in Silicon Sensors

- charge dQ induced on electrodes by drifting charge q (Ramo's theorem):

$$dQ = \frac{q(t)}{d}\, dx = \frac{q(t)}{d}\, v(t)\, dt$$

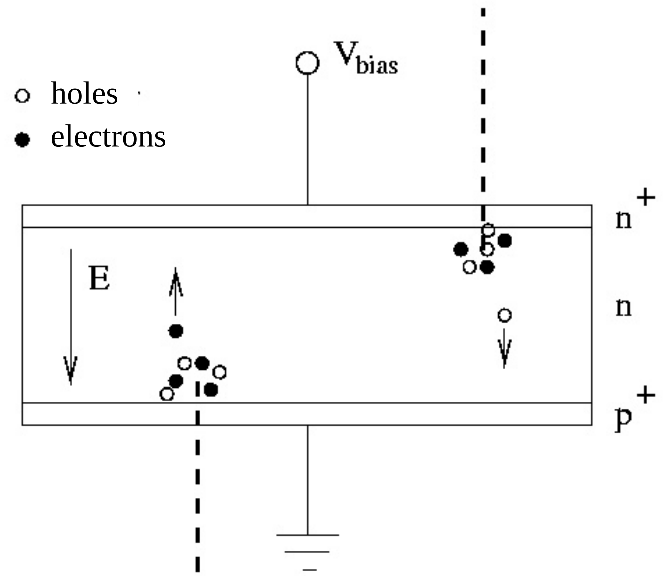
- trapping leads to charge carrier loss:

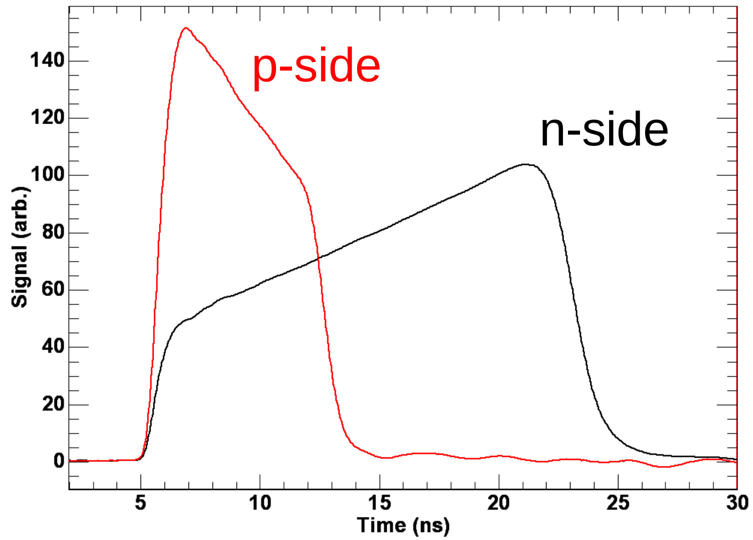
$$dq(t) = -\frac{1}{t_{eff}} q(t) dt, \quad \text{with } t_{eff} = t_{eff}(\Phi_{eq})$$

- resulting (measured) signal current:

$$i_m(t) = \frac{q_0}{d} v(t) \exp(-t / t_{eff})$$

- injection with short range laser from one side allows to distinguish between electron and hole signal





Aim

- task: find model for numeric simulation of charge drift

- two models for electric field are compared:

1. electric field depends linearly on substrate depth *x*

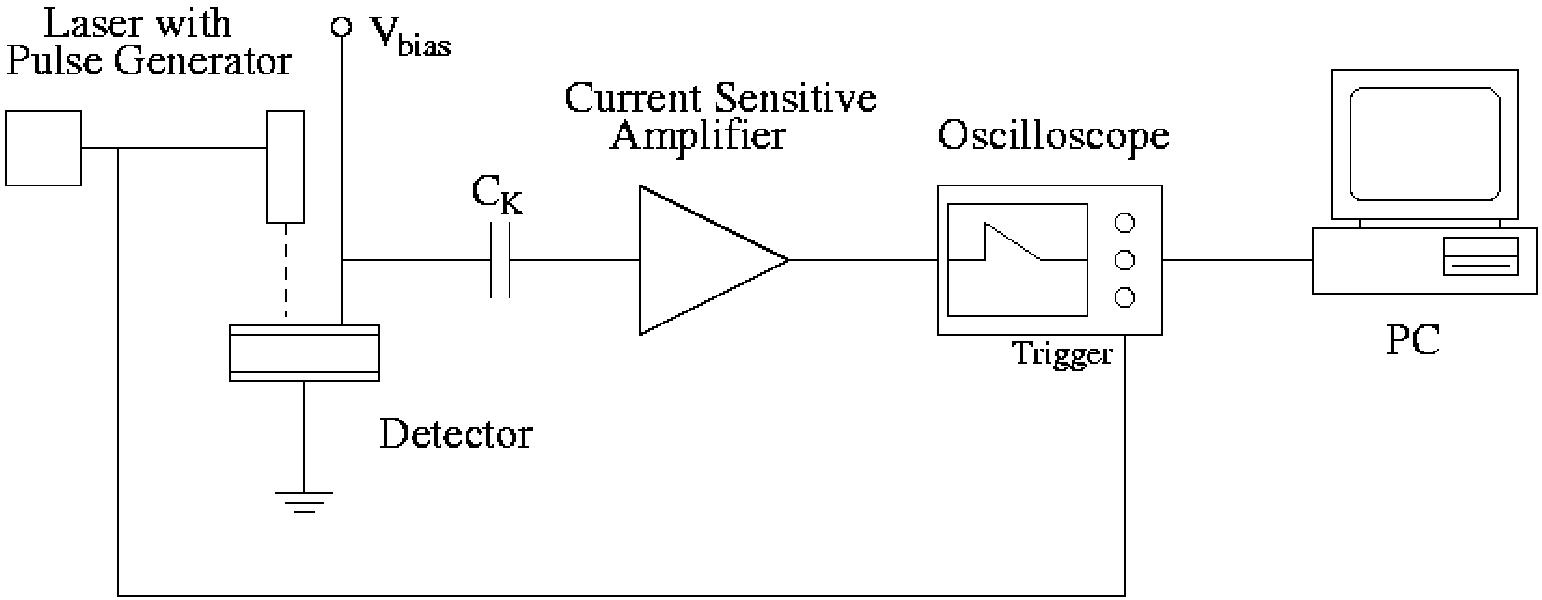
$$N_{\text{eff}}(x) = const.$$

2. deep level model as proposed by V. Eremin et al.,
   see 3rd RD50 workshop / NIM A 476 (2002) 556-564

$$N_{\text{eff}}(x) = F^{+} N_{DD} - F^{-} N_{DA} + N_{sh}$$

parameters are extracted from TCT measurements

Transient Current Technique, Set-up



- 672nm red laser (3.6µm absorption length, FWHM = 44ps),
- applicable bias voltage range 0-1200V
- fast pulse amplifier (10×, 100 kHz - 1.8 GHz), (*current sensitive!*)
- oscilloscope (Tektronix TDS 784D, band width 1 GHz)
- rise time of system (incl. detector) about 1 ns
- PC readout system (LabVIEW)
- cooling system (-20°C - +20°C, rms 0.2°C)

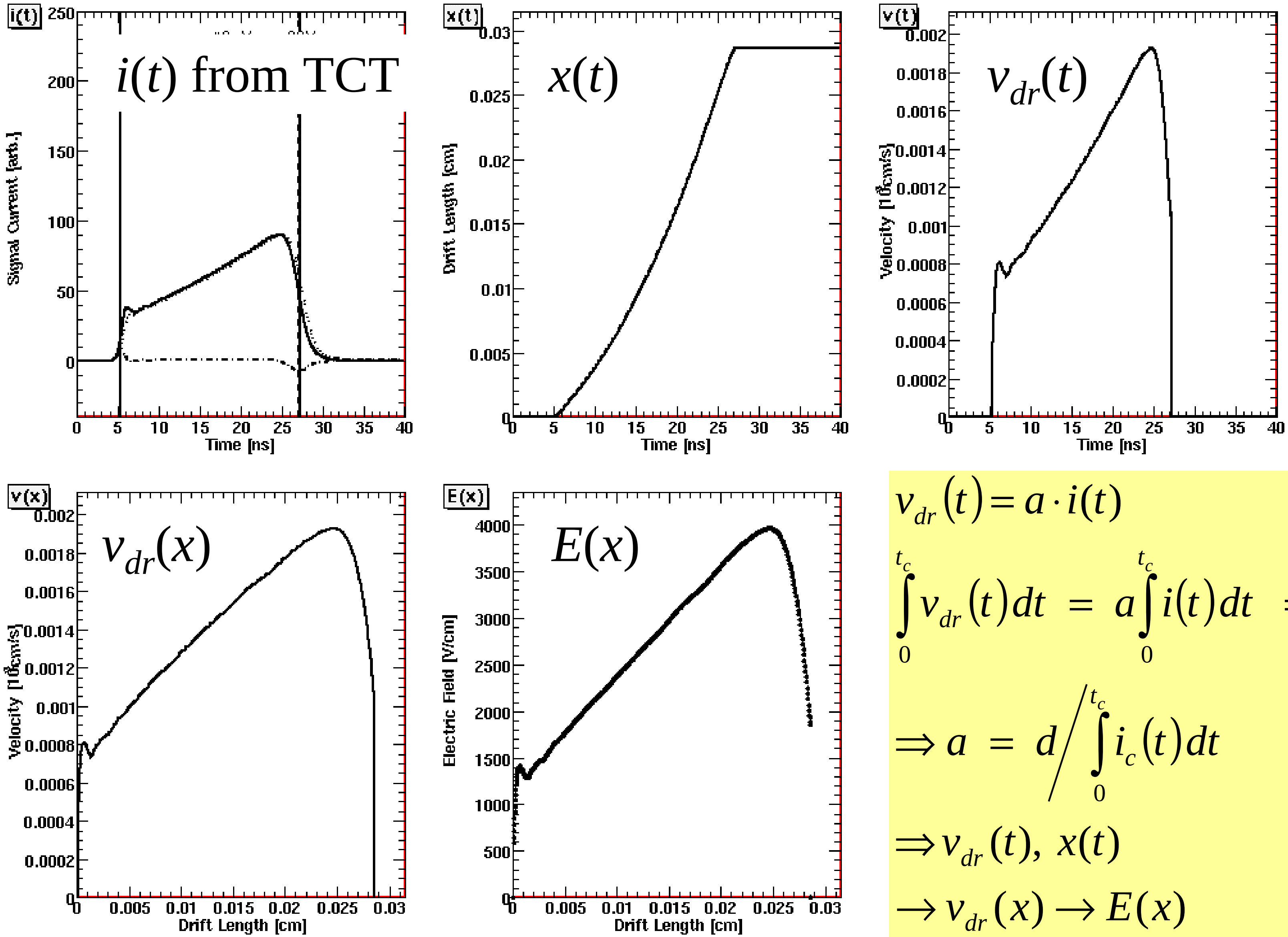
Oxygenated Silicon Samples

- 5×5 mm^2 n-bulk pad detectors, thickness 250-300 μm, manufactured by CiS (Erfurt/Germany)
- ⟨111⟩ crystal orientation, oxygenation 24h at 1200°C
- proton irradiation with 24 GeV protons at CERN-PS (0.92 - 5.00) $\cdot 10^{14}$ n_{eq}/cm^2 or neutron irradiation at TRIGA reactor, Ljubljana (1 - 4) $\cdot 10^{14}$ n_{eq}/cm^2
- no biasing during irradiation
- detectors annealed to minimum V_{dep} at 60°C

Acknowledgement

For the proton irradiation of the samples I want to thank M. Glaser, M. Moll (CERN), P. Sicho (Academy of Sciences, Prague). Neutron irradiations were done by M. Mikuž and V. Cindro (Jožef Stefan Institute, Ljubljana)

Deconvolution: $i(t) \rightarrow v(x), E(x)$



$$v_{dr}(t) = a \cdot i(t)$$

$$\int_0^{t_c} v_{dr}(t)\,dt \;=\; a\int_0^{t_c} i(t)\,dt \;\overset{!}{=}\; d$$

$$\Rightarrow a \;=\; d \Big/ \int_0^{t_c} i_c(t)\,dt$$

$$\Rightarrow v_{dr}(t),\; x(t)$$

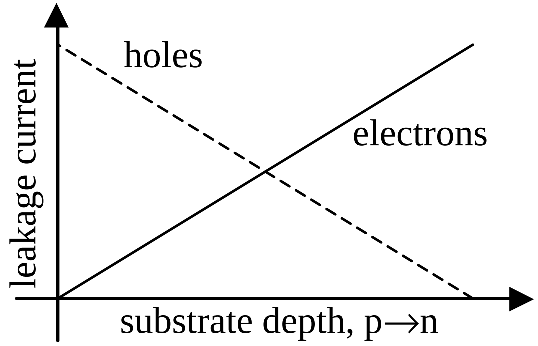
$$\rightarrow v_{dr}(x) \rightarrow E(x)$$

Drift Velocities → Carrier Densities

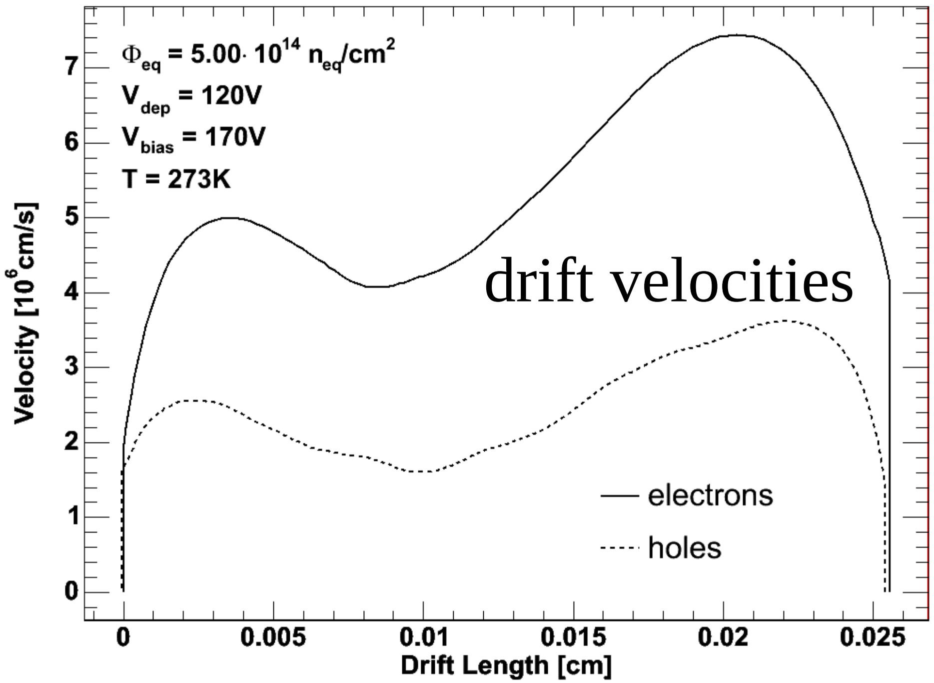
Use deep level model for further analysis:

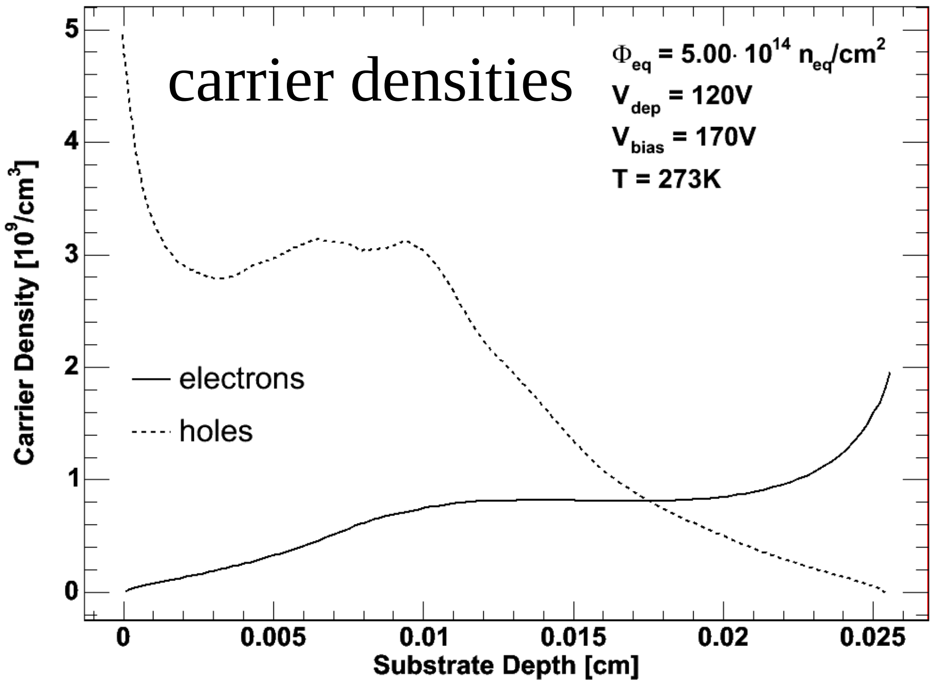
- use drift velocities obtained from deconvolution
- carrier densities $n_{e,h}$ calculated from drift velocity with

$$n_e = \frac{j_e(x)}{q_0 \, v_{dr,e}(x)}, \quad n_h = \frac{j_h(x)}{q_0 \, v_{dr,h}(x)}$$



$$j_e = Gx, \quad j_h = G(d-x)$$



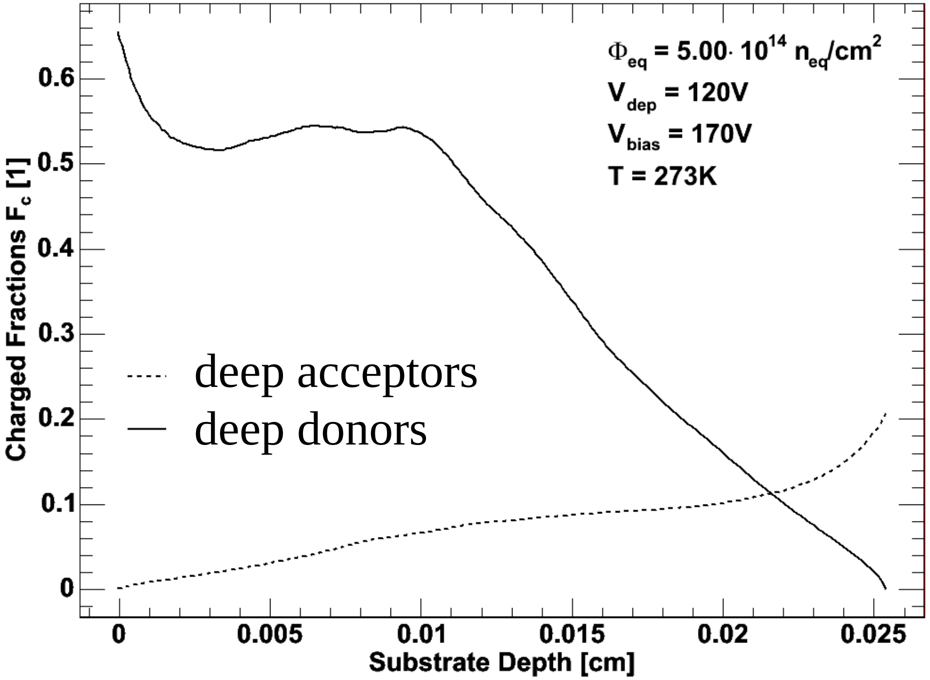


Carrier Densities → Charged Deep Levels

- free carriers are trapped by deep levels

⇒ additional space-charges

- deep level model uses only two deep level defects
- with F^+ / F^- as charged fraction of deep donors/acceptors



deep acceptor :

$E_t = E_C - 0.52\,\text{eV},$

$s_e = 10^{-15}\,\text{cm}^2, s_h = 10^{-15}\,\text{cm}^2,$

deep donor :

$E_t = E_V + 0.53\,\text{eV},$

$s_e = 10^{-15}\,\text{cm}^2, s_h = 3\cdot 10^{-14}\,\text{cm}^2$

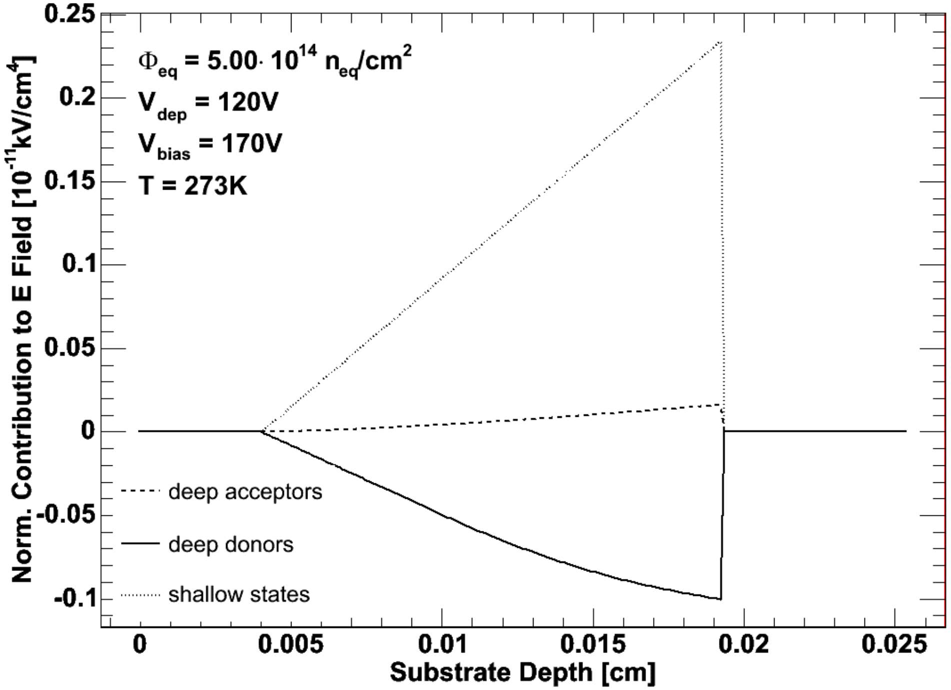
$$F^- = \frac{F}{1+F}, \quad F^+ = \frac{1}{1+F} \quad \text{with} \quad F = \frac{n_t}{N_t - n_t} = \frac{c_e n_e + v_{th,h} s_h N_V \exp(-(E_t - E_V)/kT)}{c_h n_h + v_{th,e} s_e N_C \exp(-(E_C - E_t)/kT)}$$

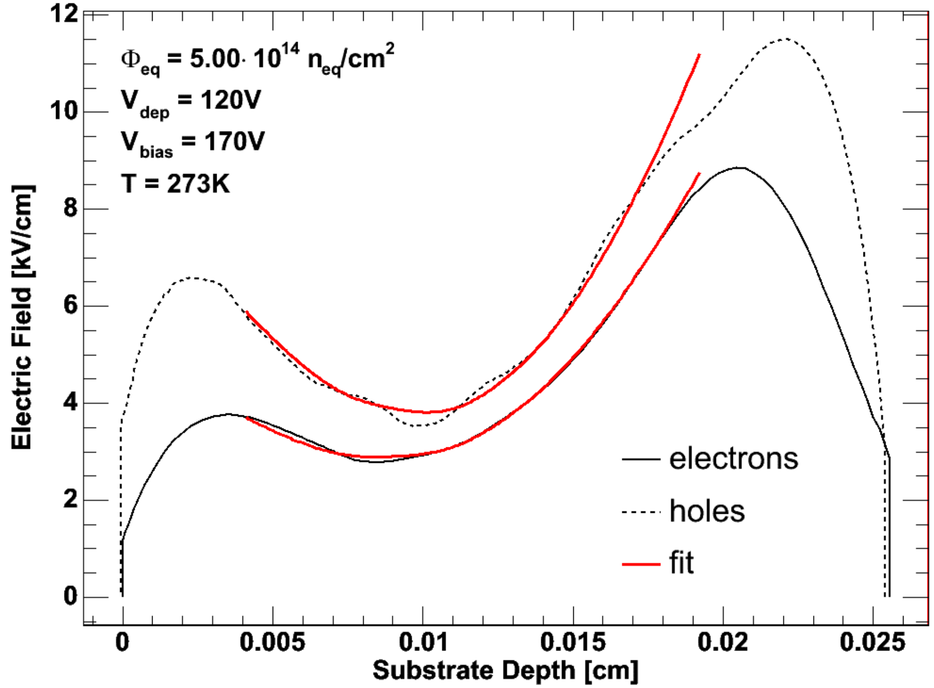
Charged Deep Levels → Contribution to E-Field

$$N_{\mathrm{eff}}(x) = F^{+} N_{DD} - F^{-} N_{DA} + N_{sh}$$

$$\rightarrow \quad E(x) = E(x_1) - \frac{q_0}{\varepsilon_0 \varepsilon_{\mathrm{Si}}} \int_{x_1}^{x} N_{\mathrm{eff}}(x')\, dx'$$ is fitted to measured $E(x)$

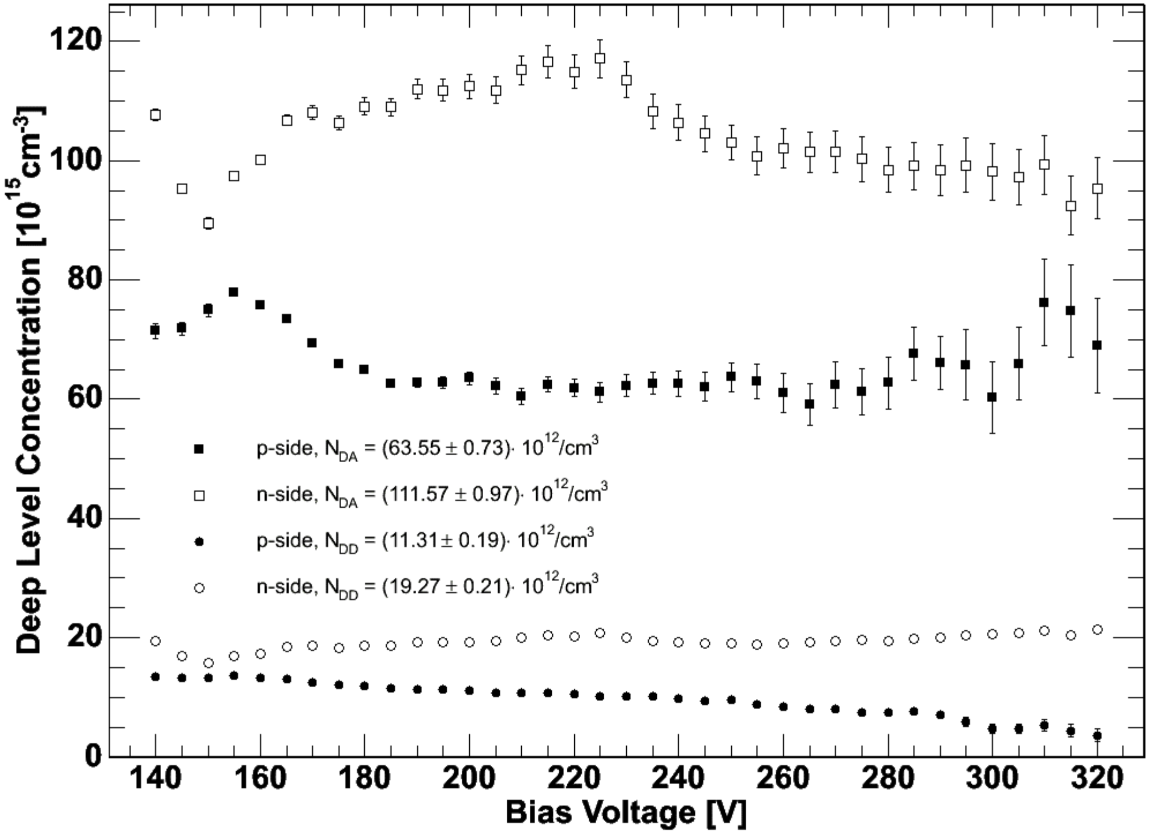
- N_{DA}, N_{DD} are fit parameters,
- N_{sh} is calculated from Hamburg model (stable damage)





Deep Level Concentrations vs. V_{bias}

N_{DA}, N_{DD} are obtained from p- and n-side signals for various V_{bias}:



- ■ N_{DA}, p-side
- □ N_{DA}, n-side
- ● N_{DD}, p-side
- ○ N_{DD}, n-side

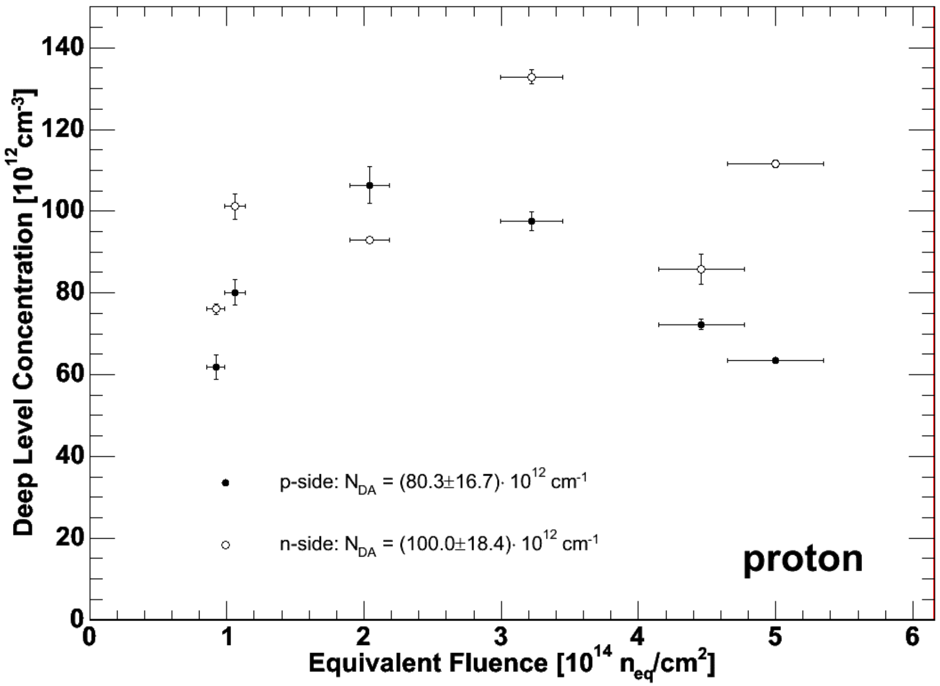
- variation with V_{bias}
- incompatible results from p- and n-side

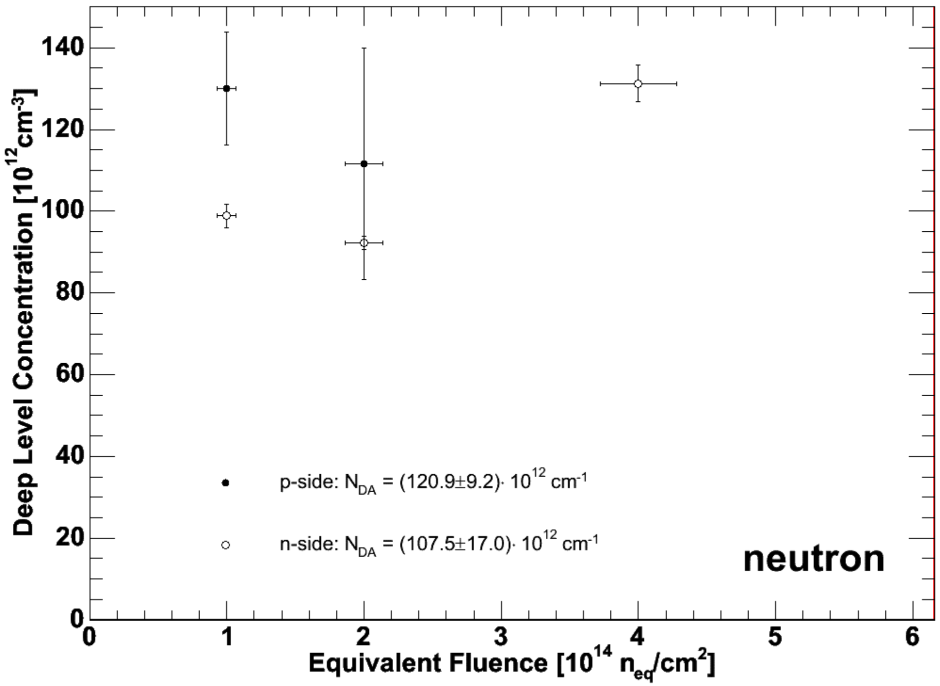
→ for further analysis N_{DA}, N_{DD} are averaged over $V_{dep} + 50V \leq V_{bias} \leq V_{dep} + 100V$

Deep Acceptor Concentration vs. Fluence

24 GeV protons

reactor neutrons





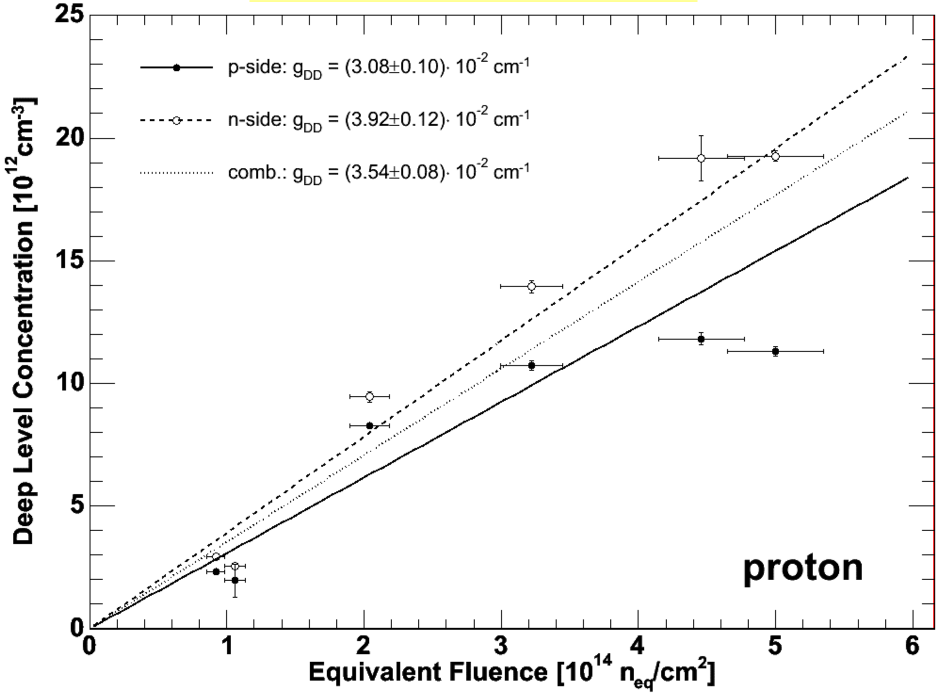
- no linear dependence or saturation visible

$\rightarrow$ N_{DA} = const. assumed (N_{DA} strongly correlated with fluence dependent N_{sh})

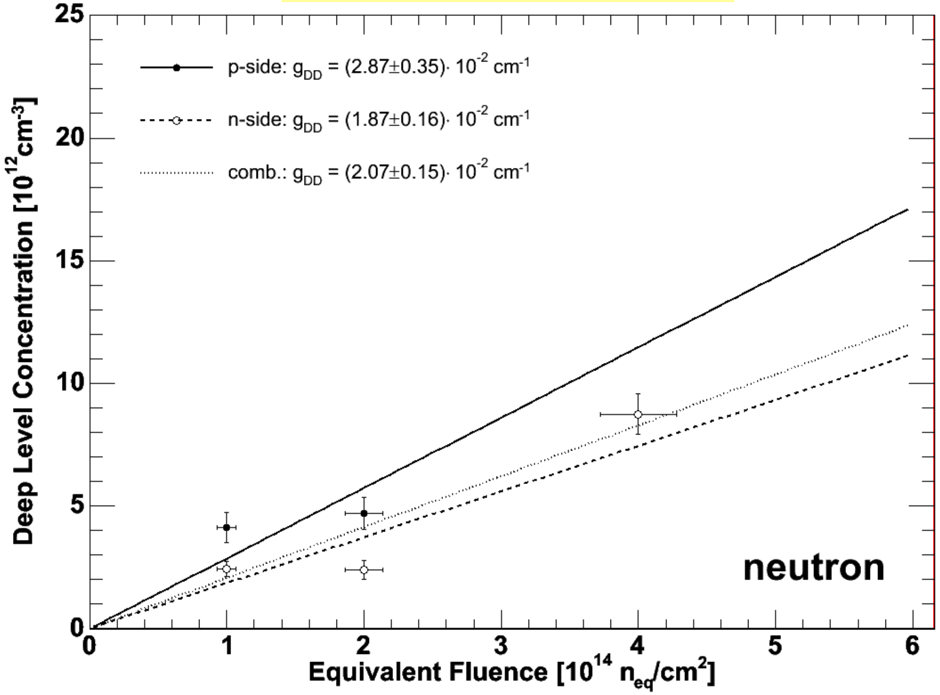
$$N_{DA} = \begin{cases} (80 \pm 17) \cdot 10^{12} / \mathrm{cm}^3 & \text{for protons, p-side} \\ (120 \pm 9.2) \cdot 10^{12} / \mathrm{cm}^3 & \text{for neutrons, p-side} \end{cases}$$

Deep Donor Concentration vs. Fluence

24 GeV protons



reactor neutrons



- data suggest linear introduction of deep donors:

$\rightarrow N_{DD} = g_{DD} \cdot \Phi_{eq}$

$$g_{DD} = \begin{cases} (3.08 \pm 0.10) \cdot 10^{-2}\,/\,\text{cm} & \text{for protons, p-side} \\ (2.87 \pm 0.35) \cdot 10^{-2}\,/\,\text{cm} & \text{for neutrons, p-side} \end{cases}$$

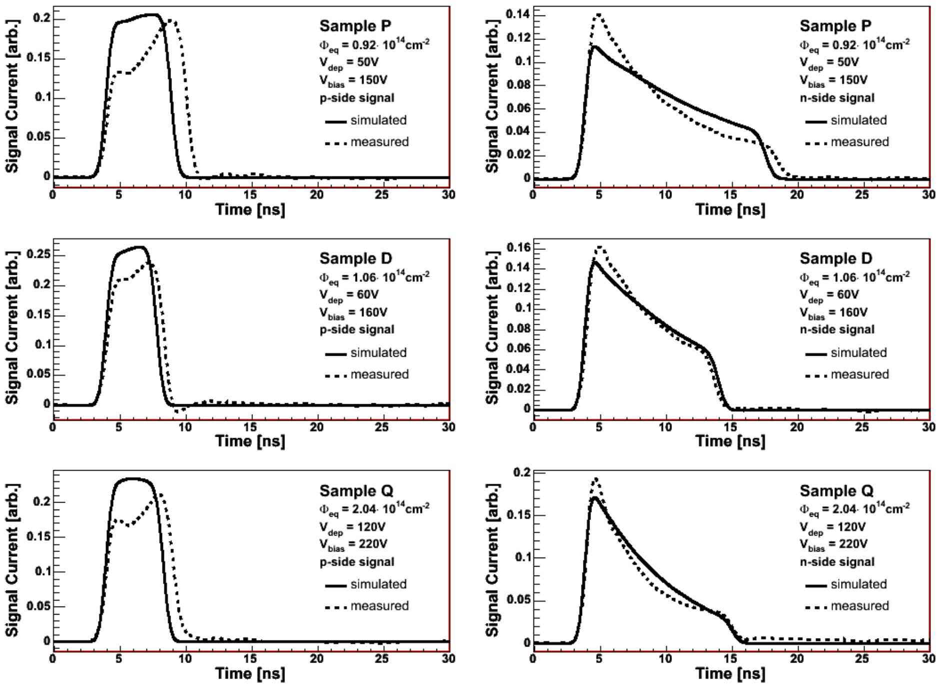
Pulse Shape Simulation: Electric Fields, Fluence

- **simulation of charge drift with two models for electric field**

- $V_{bias} = V_{dep}$ + 100V
- red laser on pad-detector, sample-fluences and -thicknesses
- simulation considers diffusion, trapping, signal distortion
- measured signals are corrected for bandwidth limitation (adding of derivative)

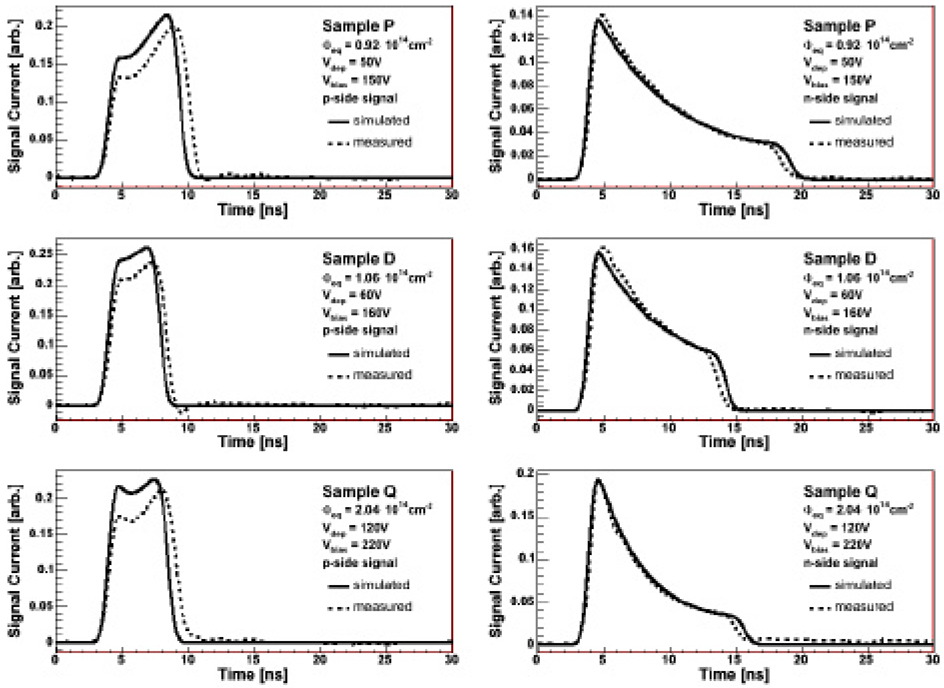
linear E-field

p-side n-side



deep level model

p-side n-side



Pulse Shape Simulation: Temperature

- temperature dependend properties:
- leakage current → carrier densities
- occupation probabilities → charged fractions of deep levels
- temperature dependence checked with two neutron irradiated samples

$1\cdot10^{14} n_{eq}/cm^2$, $V_{bias}=V_{dep}$ + 80V

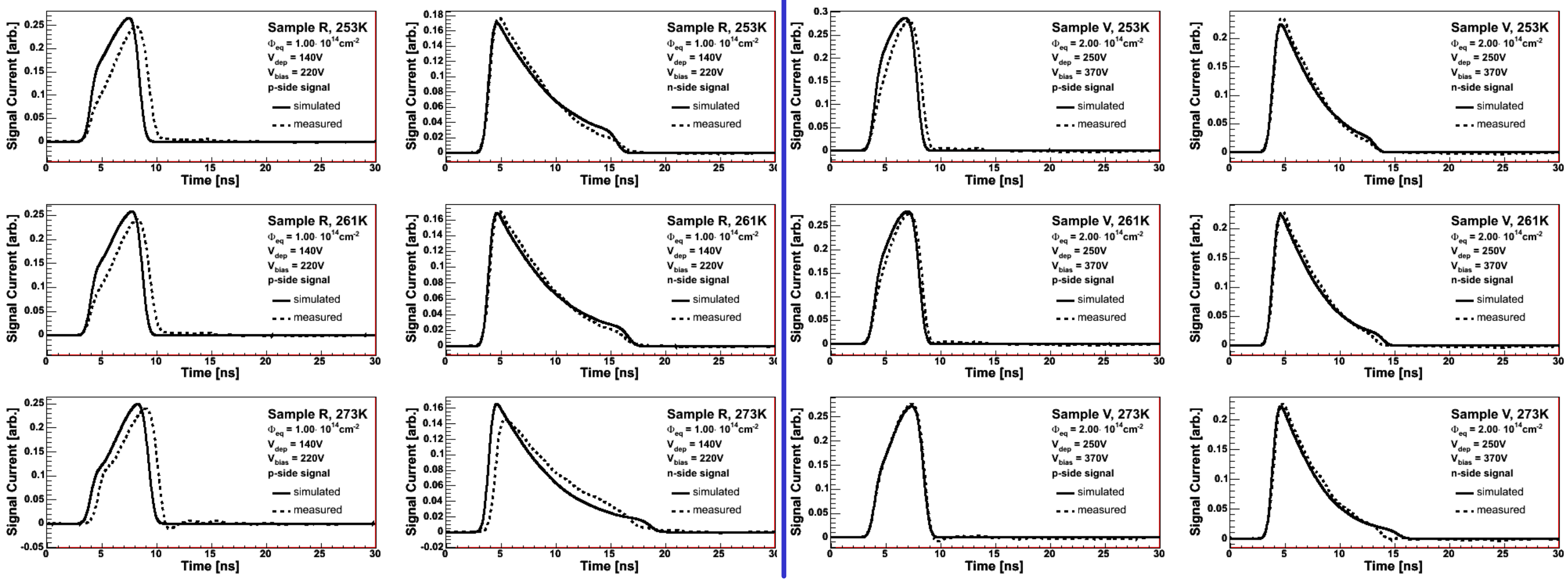
$2\cdot10^{14} n_{eq}/cm^2$, $V_{bias}=V_{dep}$ + 120V

p-side n-side p-side n-side

253K

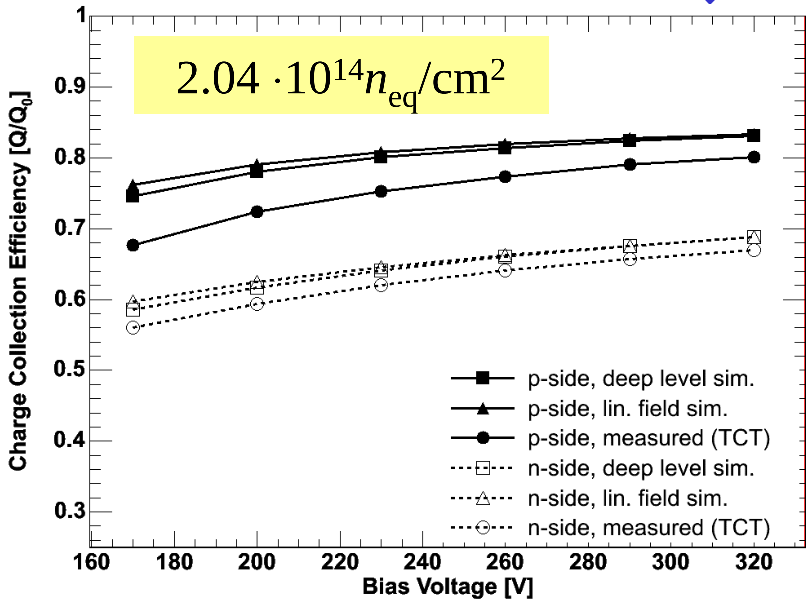
261K

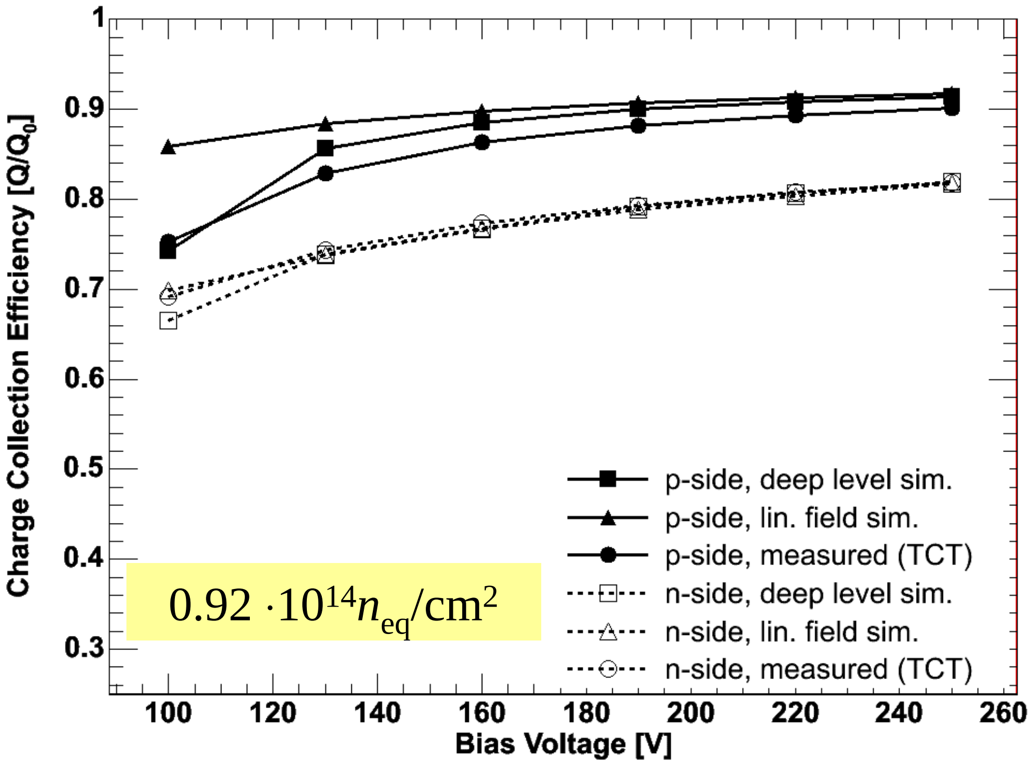
273K

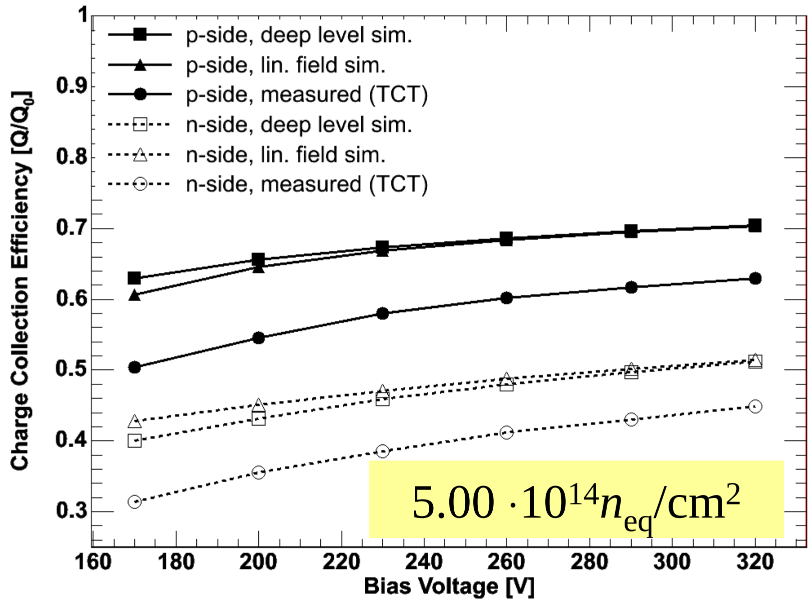


CCE vs. V_{bias}, proton irradiation

- simulation of CCE vs. V_{bias} with linear field and deep level model
- measured CCE from TCT, charge crossing method
- proton-irradiated samples
- $V_{bias} \geq V_{dep}$ + 50V







CCE vs. V_{bias}, neutron irradiation

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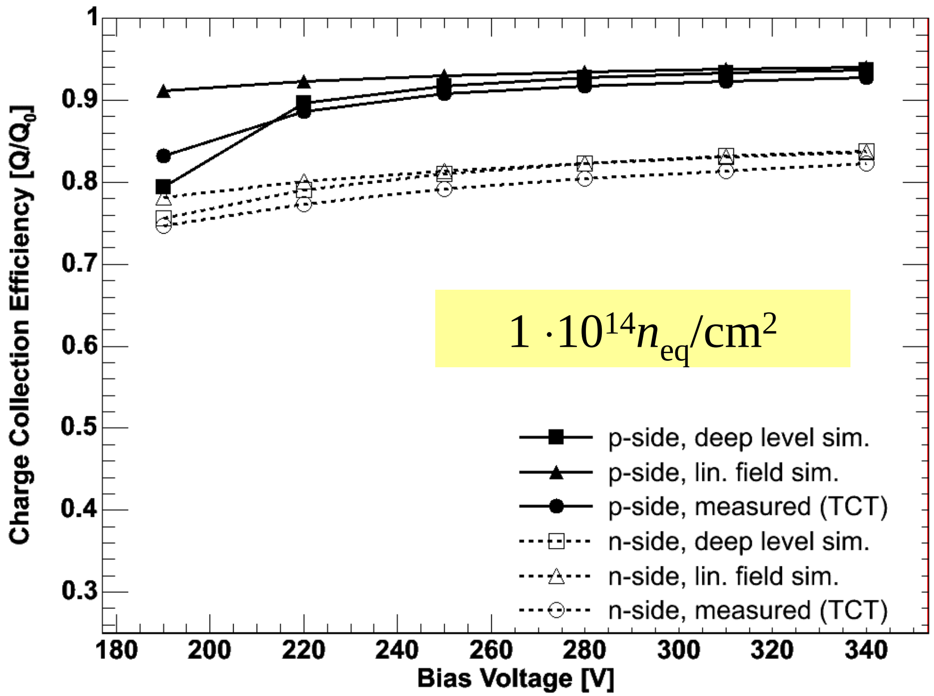
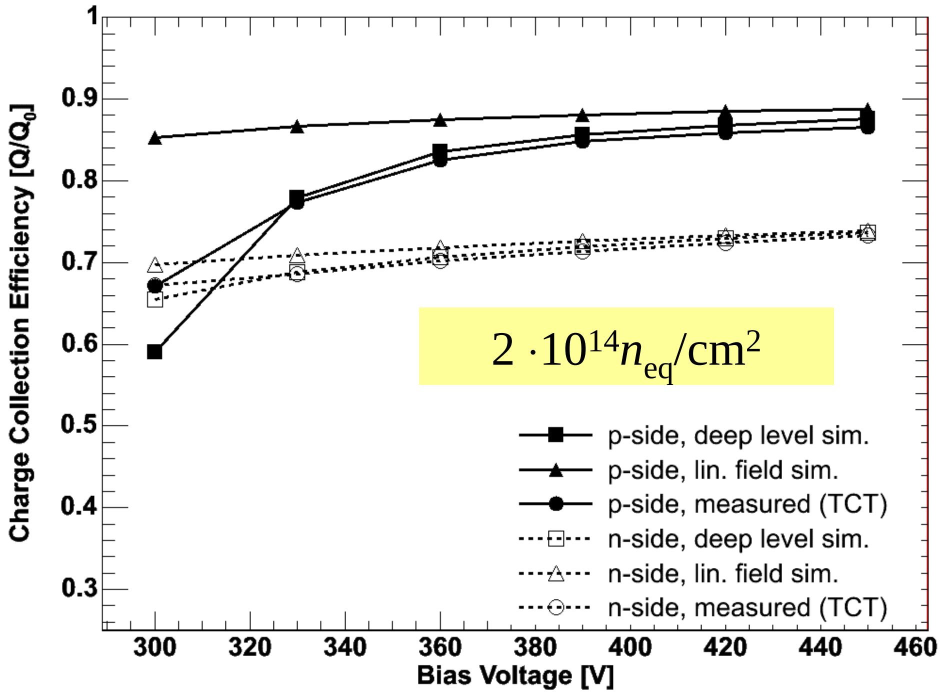




Conclusions

- parameters for deep level model obtained from pulse shapes (TCT)

- parameter values depend strongly on V_{bias}, illuminated side
- N_{DA} shows strange behaviour, either

- fluence dependence is „shadowed“ by stable shallow defects or
- saturation already at low fluences
- N_{DD} shows linear introduction

$\Rightarrow$ values for N_{DA} , N_{DD} should only be used within this model!

- two models for electric field have been used for simulation
- deep level model is superior to linear model in describing pulse shape, especially towards low bias voltages,

but: (mathematical?) problems below V_{dep}+50V

Finally...

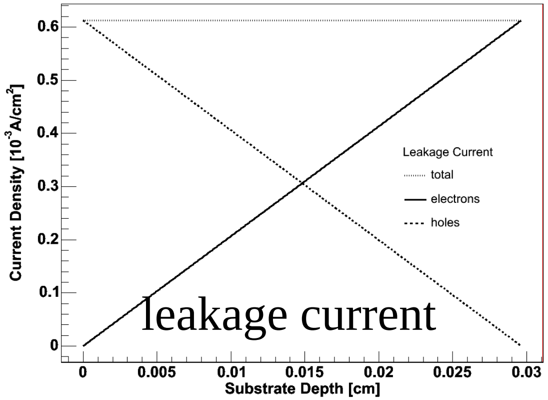
THE

END

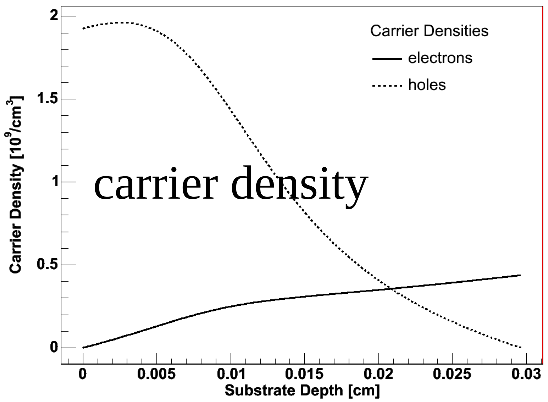
Calculation of Electric Field

- starting with linear field
- 10-15 iterations

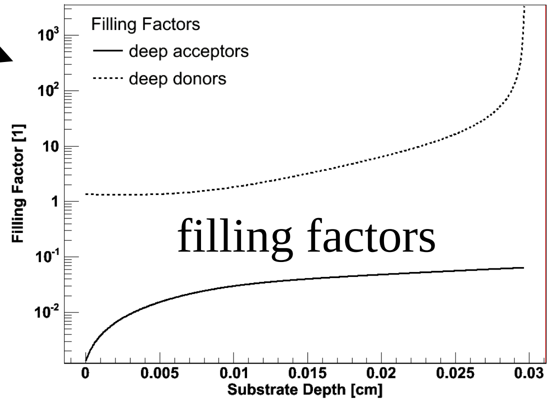
$$j_e = Gx, \quad j_h = G(d-x)$$



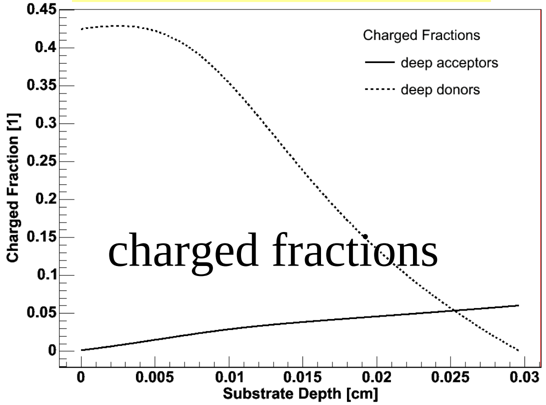
$$n_e = \frac{j_e(x)}{q_0 \, v_{dr,e}(E(x))}, \quad n_h = \frac{j_h(x)}{q_0 \, v_{dr,h}(E(x))}$$



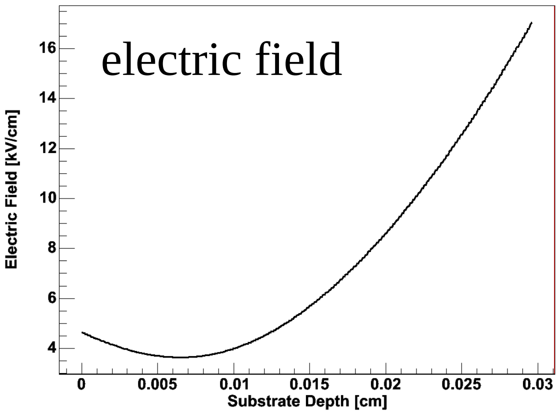
$$F = \frac{n_t}{N_t - n_t} = \frac{c_e n_e + v_{th,h} s_h N_V \exp(-(E_t - E_V)/kT)}{c_h n_h + v_{th,e} s_e N_C \exp(-(E_C - E_t)/kT)}$$



$$F^- = \frac{F}{1+F}, \quad F^+ = \frac{1}{1+F}$$



Gauss' law



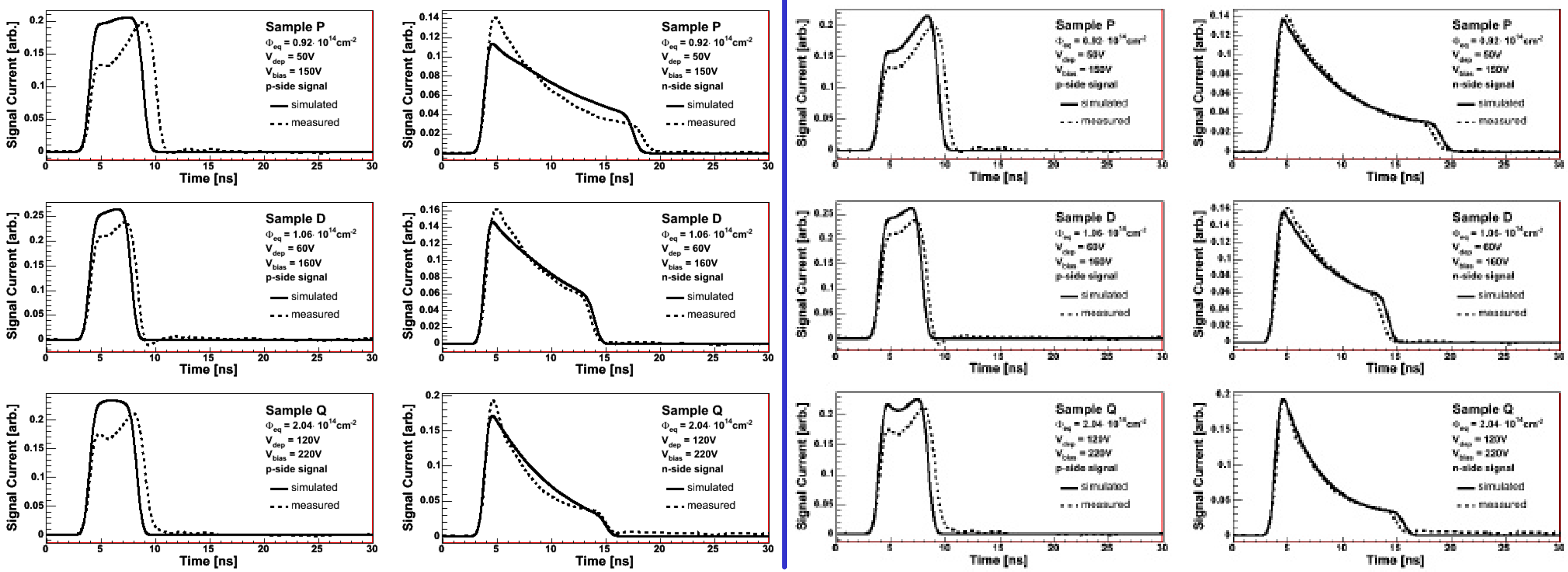
Pulse Shape Simulation: Electric Fields, Fluence

- simulation of charge drift with linear field and deep level model (p-side data)
- red laser on pad-detector, fluences and thicknesses same as in samples
- simulation considers diffusion and trapping
- simulated signals are convoluted with gaussian (σ=400ps)
- measured signals are corrected for bandwidth limitation (adding of derivative)

linear E-field | deep level model

p-side | n-side | p-side | n-side

$2.04 / 1.06 / 0.92 \cdot 10^{14} n_{eq}/cm^2$



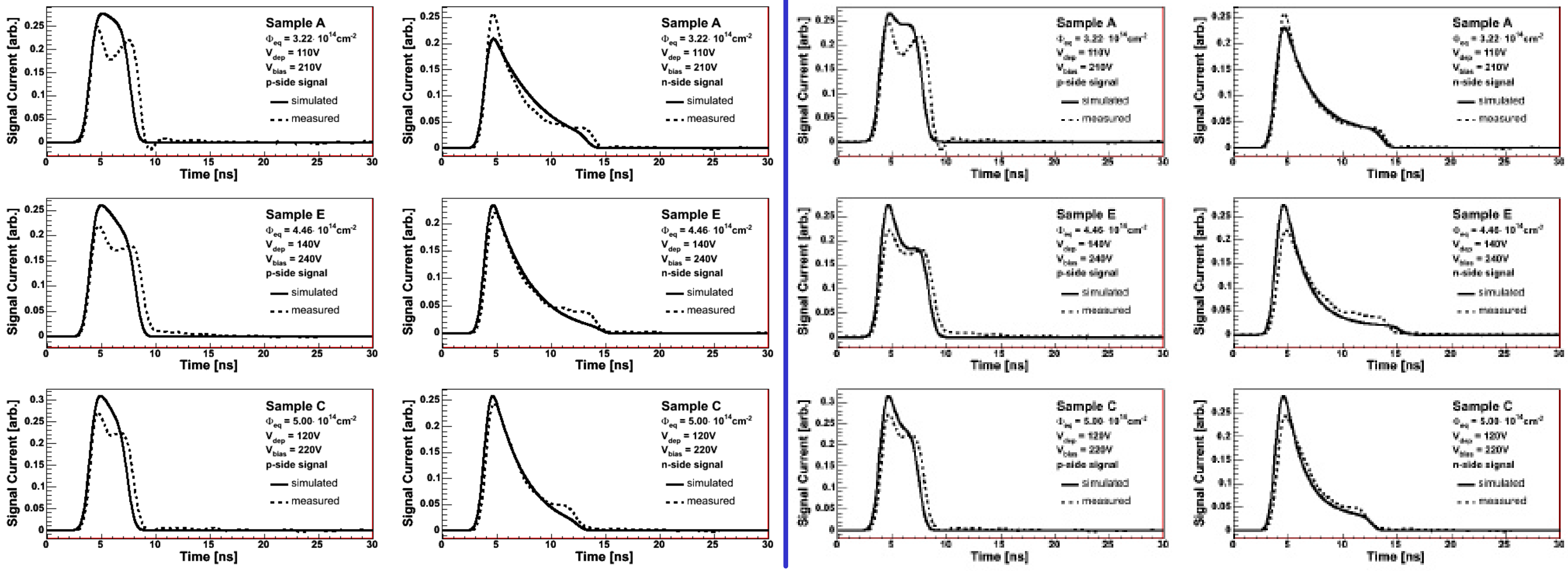
Pulse Shape Simulation: Electric Fields, Fluence (2)

- simulation of charge drift with linear field and deep level model (p-side data)
- red laser on pad-detector, fluences and thicknesses same as in samples
- simulation considers diffusion, trapping, sim. signals are convoluted with gaussian (σ=400ps)
- measured signals are corrected for bandwidth limitation (adding of derivative)

linear E-field | **deep level model**

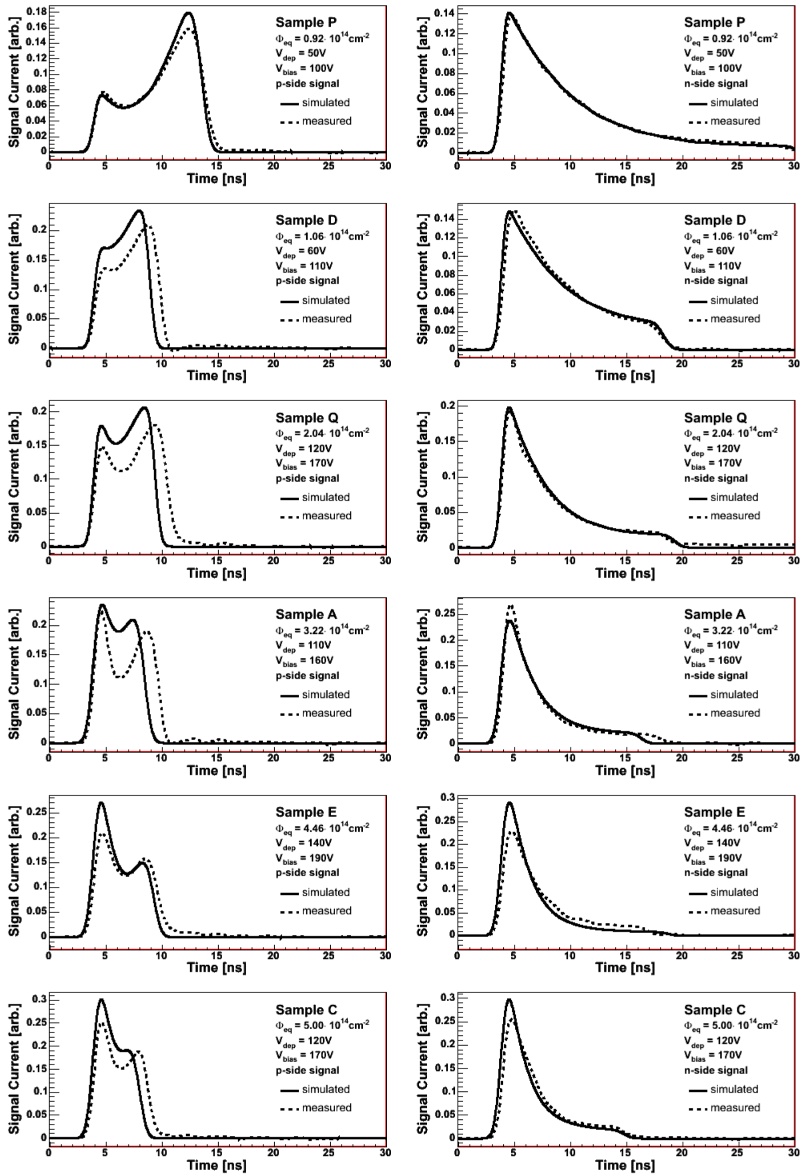
p-side | n-side | p-side | n-side

$5.00 / 4.46 / 3.22 \cdot 10^{14} n_{eq}/cm^2$

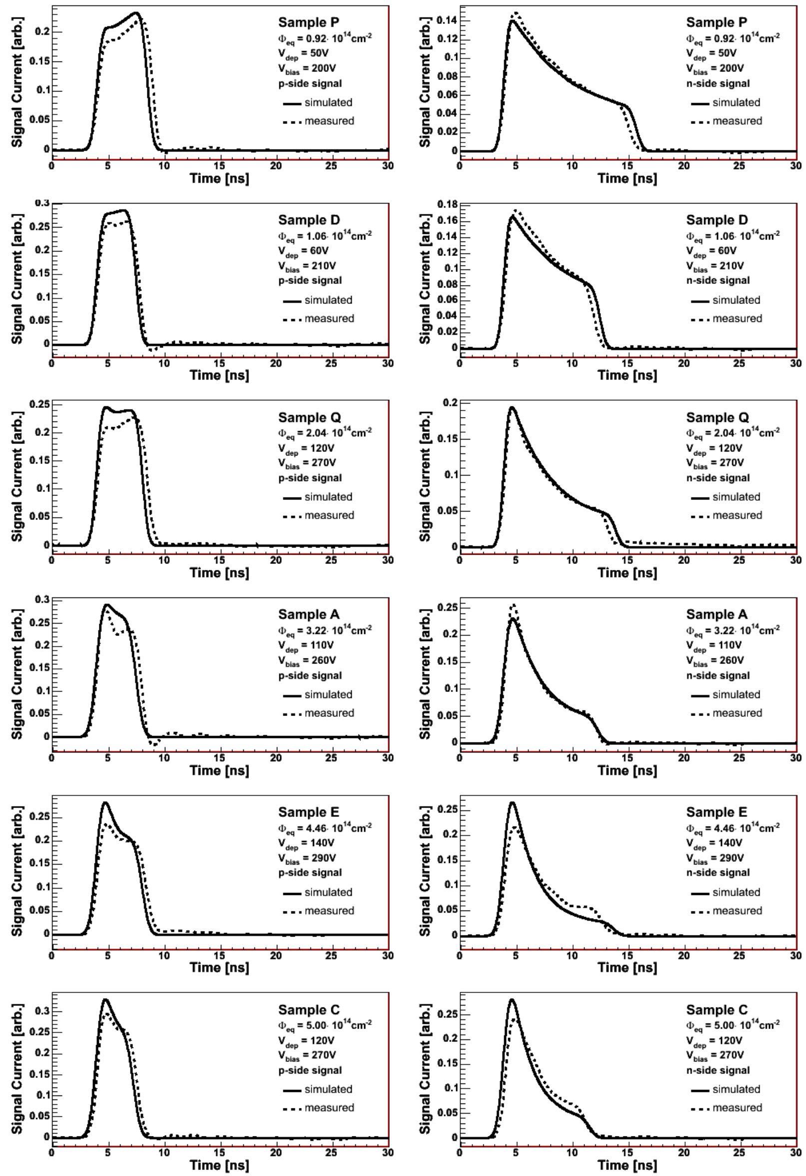


Pulse Shape Simulation, $V_{bias}=V_{dep}$+50V, +150V

p-irradiated, $V_{bias}=V_{dep}$ + 50V

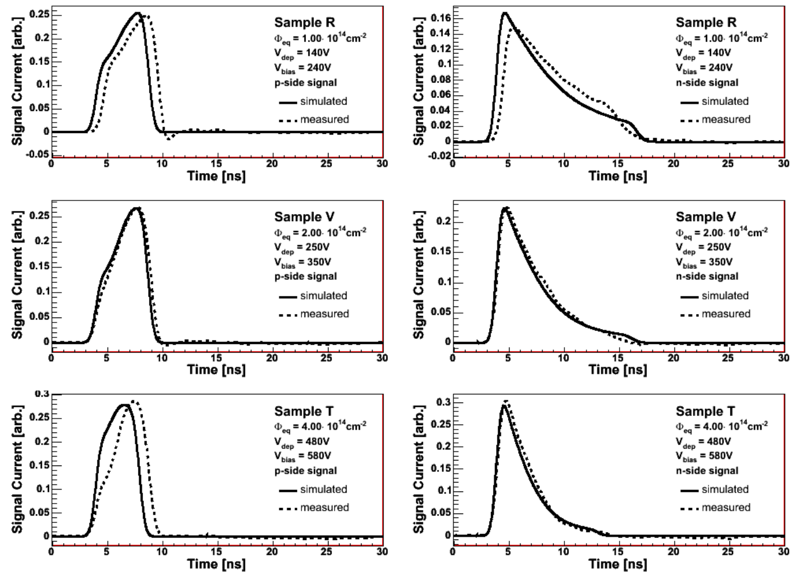


p-irradiated, $V_{bias}=V_{dep}$ + 150V

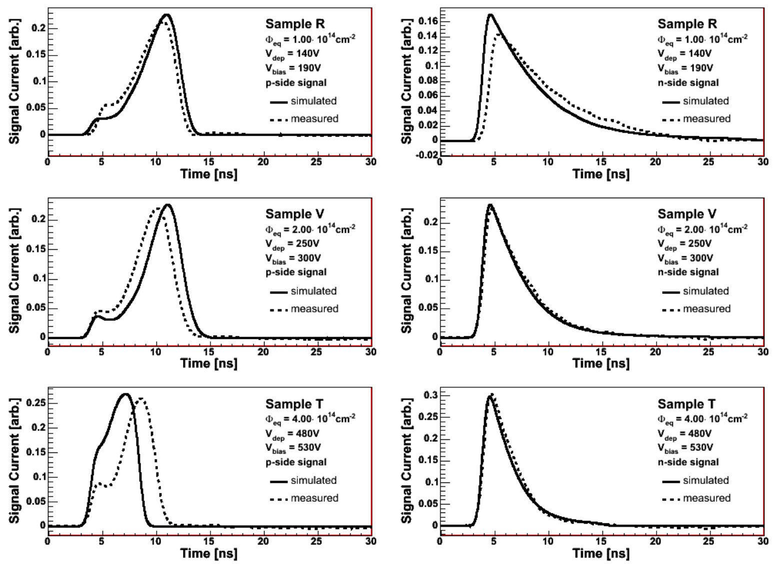


Pulse Shape Simulation, $V_{bias}=V_{dep}$+50V -150V

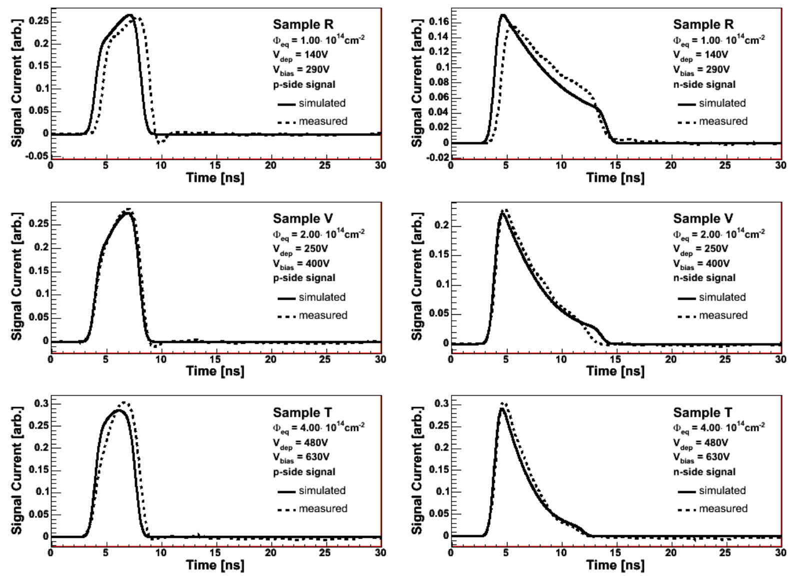
n-irradiated, $V_{bias}=V_{dep}$ + 100V



n-irradiated, $V_{bias}=V_{dep}$ + 50V



n-irradiated, $V_{bias}=V_{dep}$ + 100V



CCE: Fluence Dependence