Neutron Irradiations and Punch-Through-Biasing Studies with DEPFETs for BELLE II

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Outline

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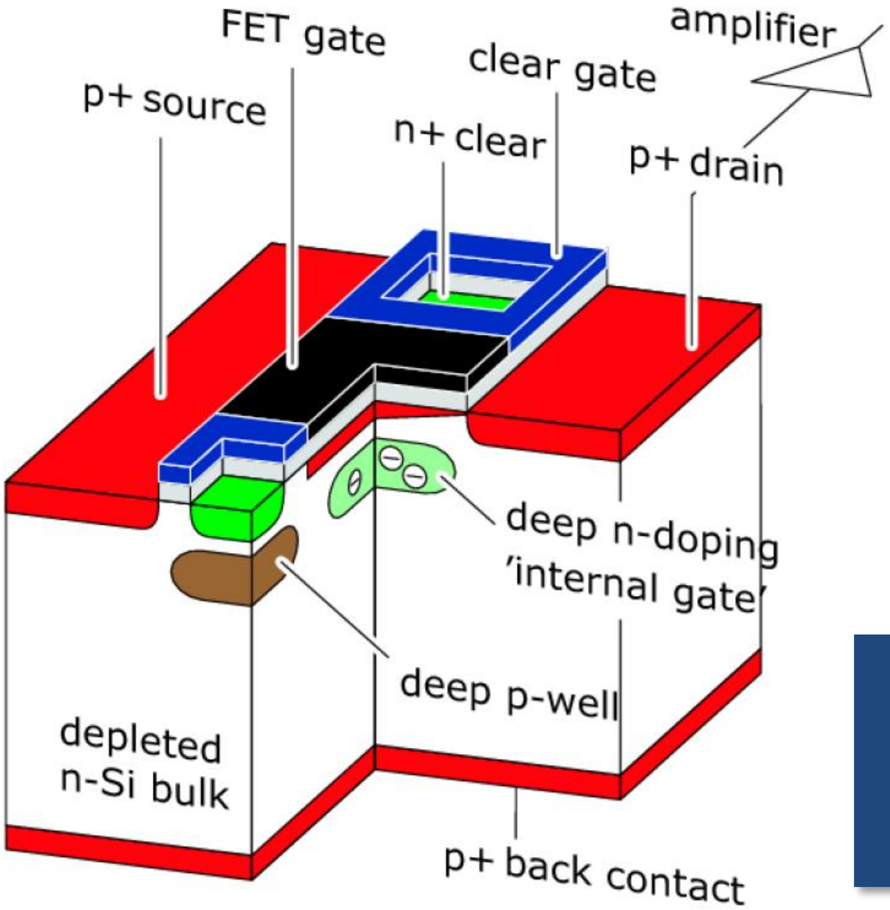
  1. DEPFET
  2. Radiation Damage
  3. Punch-through biasing
  4. Punch-through noise
- **II. DUTs and irradiations**
- **III. Results**
  1. Increase of leakage current
  2. Change in full depletion voltage
  3. DEPFET performance
  4. Punch-through biasing and noise

Theoretical Background

DEPFET

The two innermost layers of the vertex detector of BELLE II will consist of Depleted p-Channel Field Effect Transistor (**DEPFET**) pixel sensors



- a DEPFET consists of a MOSFET structure on top of a sidewards depleted silicon bulk
- electrons will be stored in the internal gate and modulate the signal of the MOSFET channel

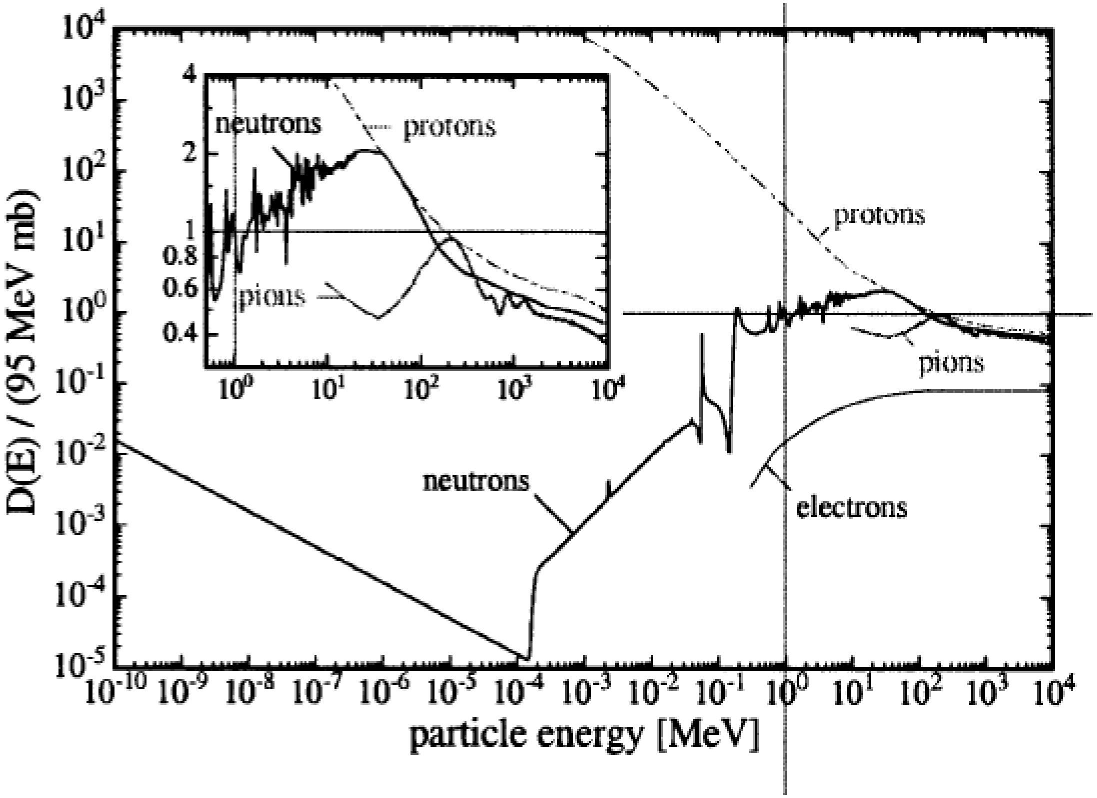
→ Internal amplification

- removal of charge with a clear mechanism

→ thin detector structures
→ non-destructive readout
→ Low energy consumption
→ high signal-to-noise ratio

Bulk Damage – NIEL Hypothesis

- incident particle hits atom in the lattice and creates a PKA (Primary Knock on Atom)
- incident particle and PKA are able to traverse through the bulk and loose energy via ionization and the creation of additional crystal displacements -> Cluster
- PKA and vacancies can also interact with impurity atoms to form point defects
- different types of particles have different impacts on the bulk

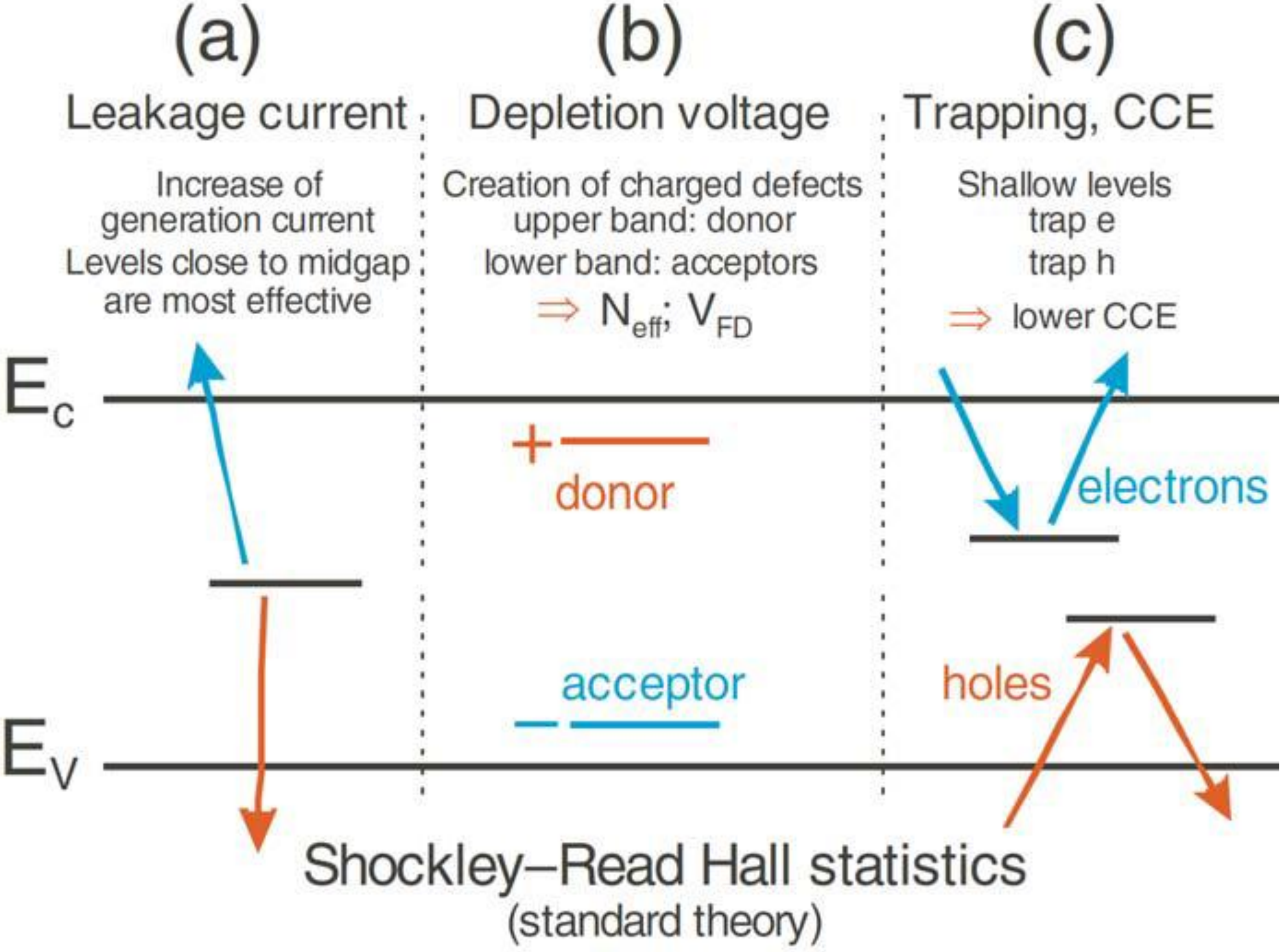


→ **NIEL-scaling hypothesis**

Particles have different hardness factors in order to compare them to neutrons

→ Allows calculation of the equivalent of 1 MeV neutron-induced damage

Bulk Damage – Defect energy levels

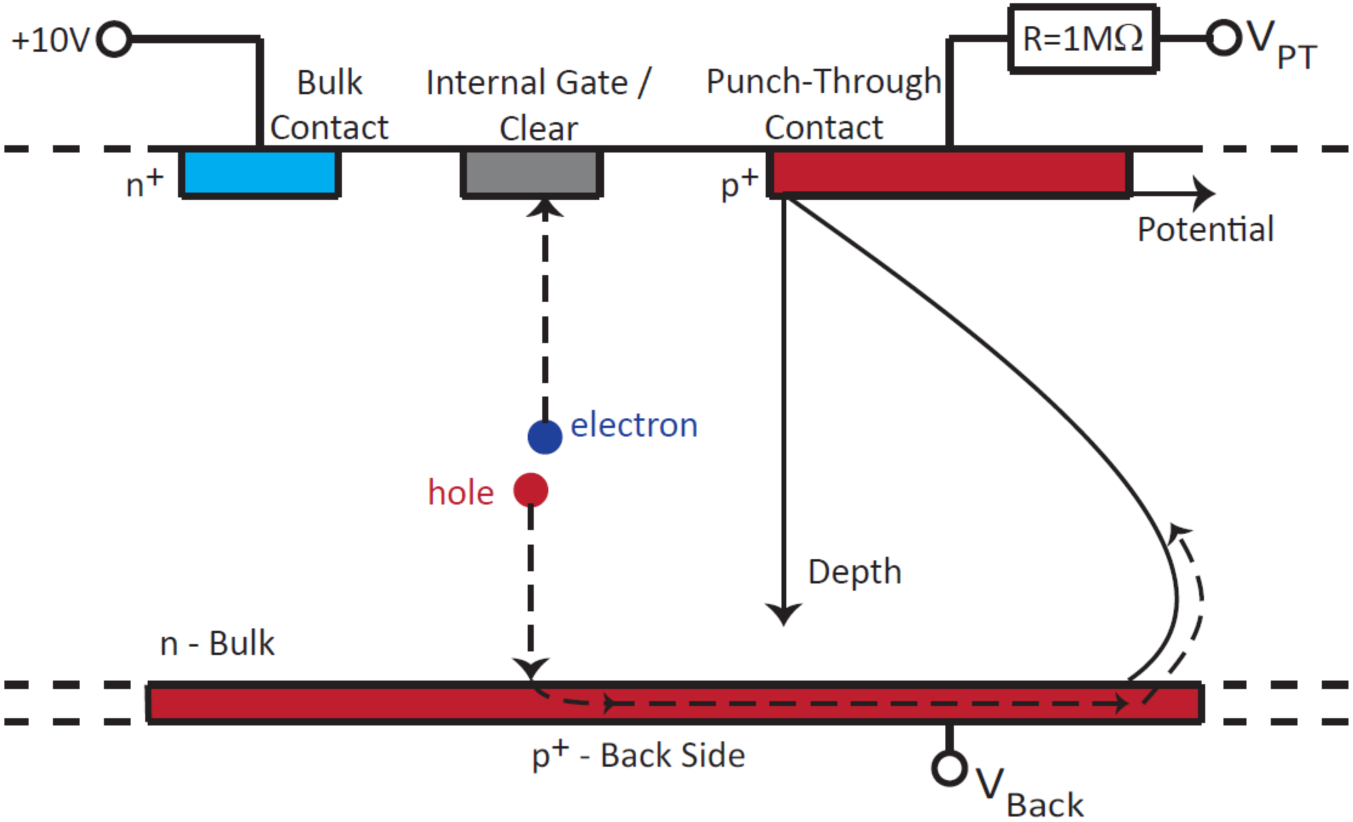


Evolution of Silicon Sensor Technology in Particle Physics.

Frank Hartmann. Springer, 2008.

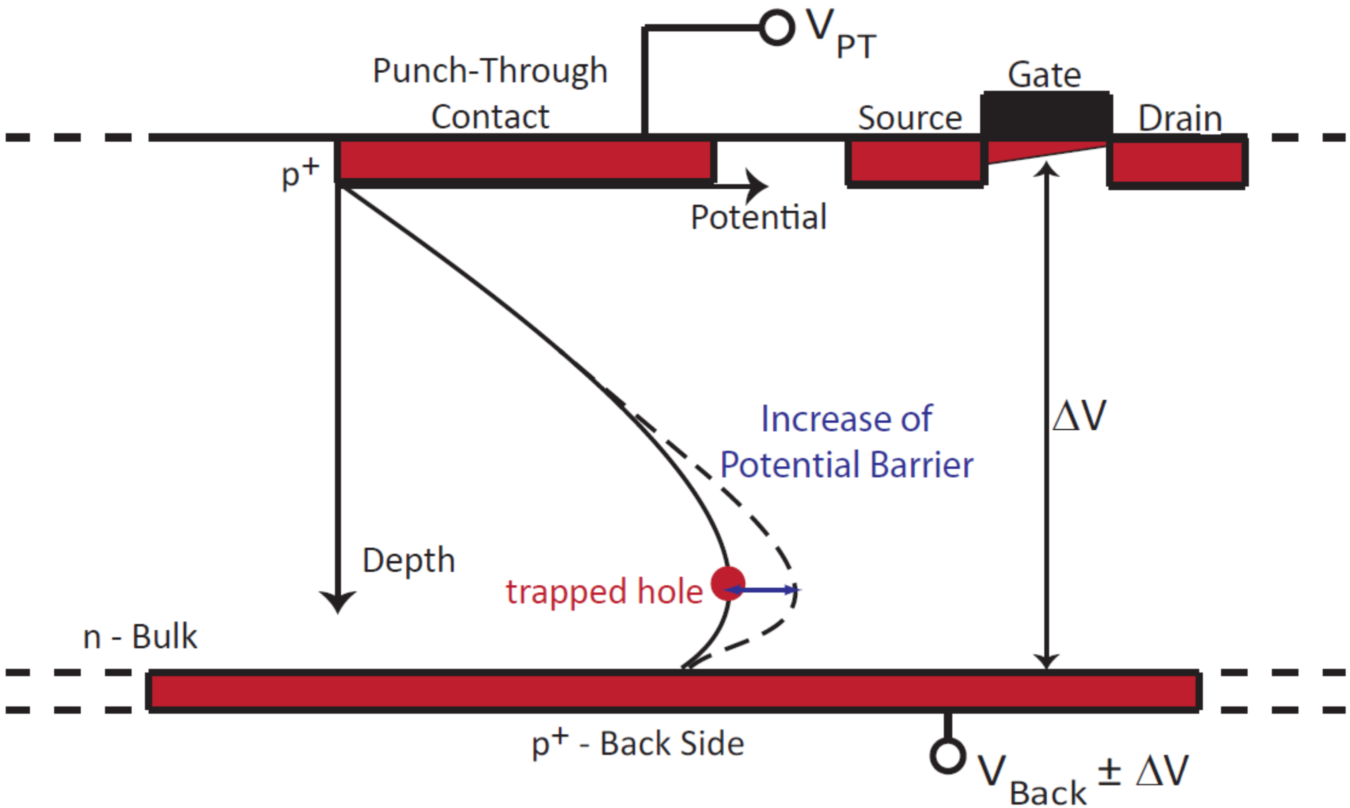
Punch-Through Biasing

Applying a negative voltage at the punch-trough contact on the top side will result in a smaller negative potential on the backside.



- the punch-through current will be formed by holes traversing from the back to the punch-through contact, while overcoming a potential barrier in the bulk
- for thin structures (as the DEPFETs) capacitive couplings will initiate the change of the back side potential

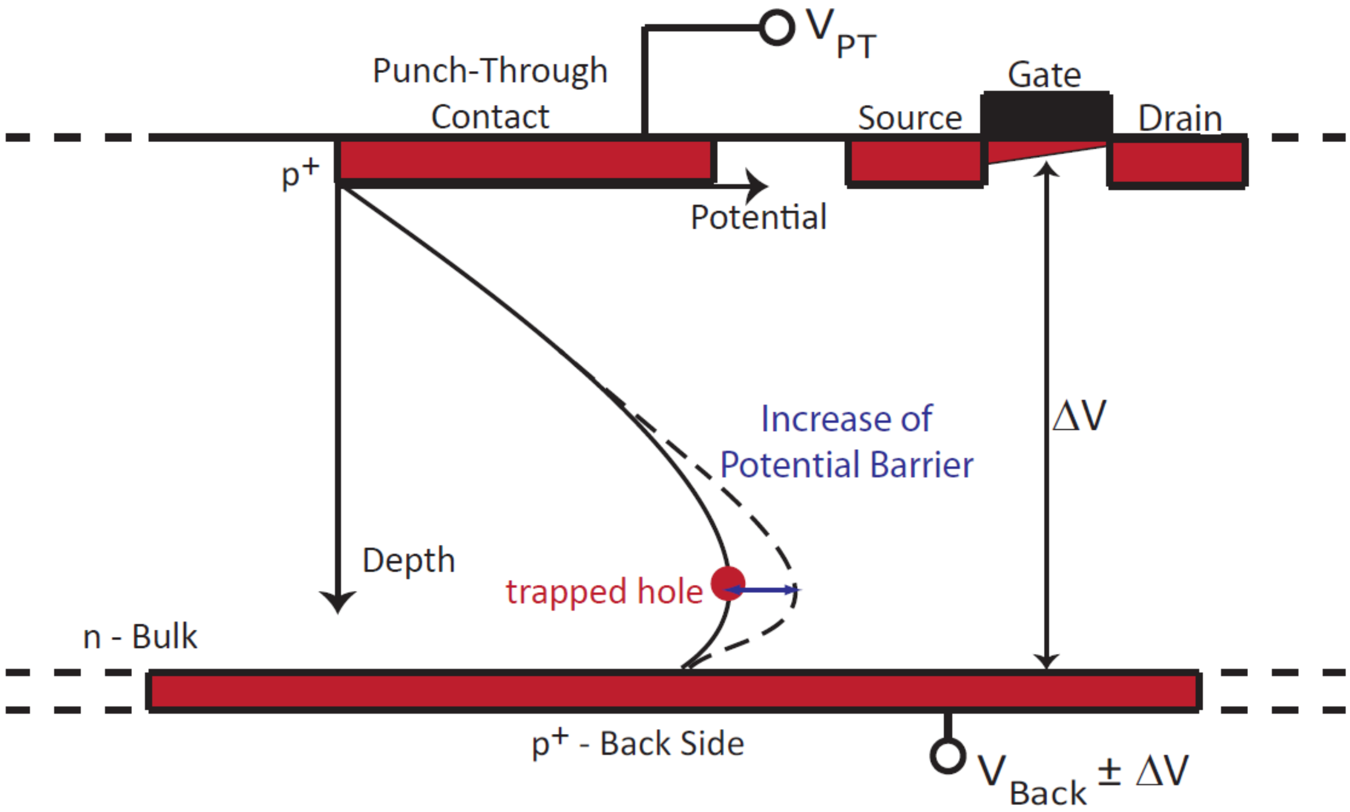
Punch-Through Noise



Bulk defects can trap holes and thereby affect the potential on the backside of the detector:

- while charges are trapped the potential barrier becomes more difficult to overcome and thus more holes remain on the backside → + ΔV
- releasing the trapped charges results in an abrupt “slop over“ of holes which leads to a drastic decrease in hole-concentration on the backside → - ΔV

Punch-Through Noise



➔ variations ±ΔV of the backside-potential are able to affect the signal of the MOSFET structure by means of capacitive couplings to the MOSFET channel

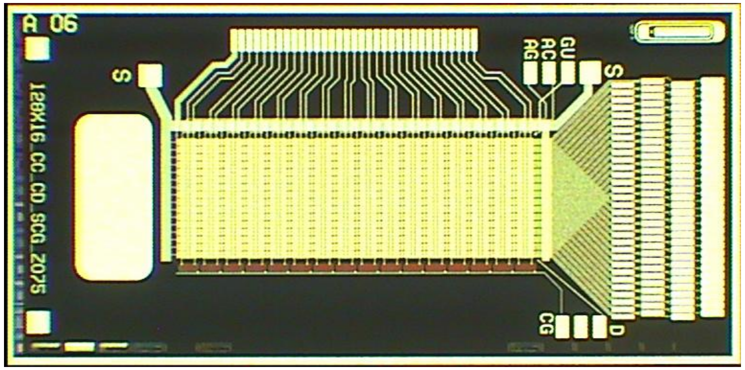
Goals

- measurement of the punch-through biasing characteristics
- characterization of punch-through noise
- investigation of the behavior of punch-through biasing characteristics and punch-through noise after neutron irradiation
- measurement of type inversion and leakage current increase after neutron irradiation on both diodes and DEPFET matrices
- evaluation of the change in behavior of the DEPFET matrices after certain radiation doses due to radiation induced damages in the bulk

→ analysis if these effects have a significant impact on the PXD performance at BELLE II

DUTs and irradiations

DEPFET matrices and diodes

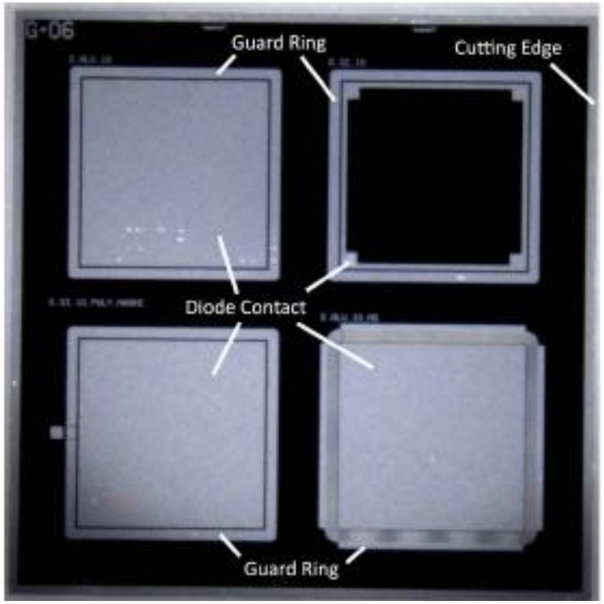


DEPFET PXD6 Matrices:

- 50µm x 75µm pixel size, 50µm thickness, capacitive coupled cleargate
- 400 Ωcm resistivity
- punch-through and direct back side biasing
- measurements were performed with the MiniMatrix (MiMa) setup
- 48 available DEPFET pixels (8 drains and 6 gates)

Silicon diode chips:

- two sets of diode chips with 100 Ωcm and 400 Ωcm resistivity
- each chip contains 4 diodes with A = 0.1 cm^2 and 75µm/ 50µm thickness (100 Ωcm/400 Ωcm)
- guard ring
- back side biasing via the cutting edge



Neutron irradiations

- all devices were irradiated at the JSI TRIGA reactor in Ljubljana, Slovenia

- both sets of diodes were irradiated with neutron fluences (according to NIEL scaling) ranging from 10^{11}, $5x10^{11}$, 10^{12}, … to $5x10^{14}$ neq/cm^2

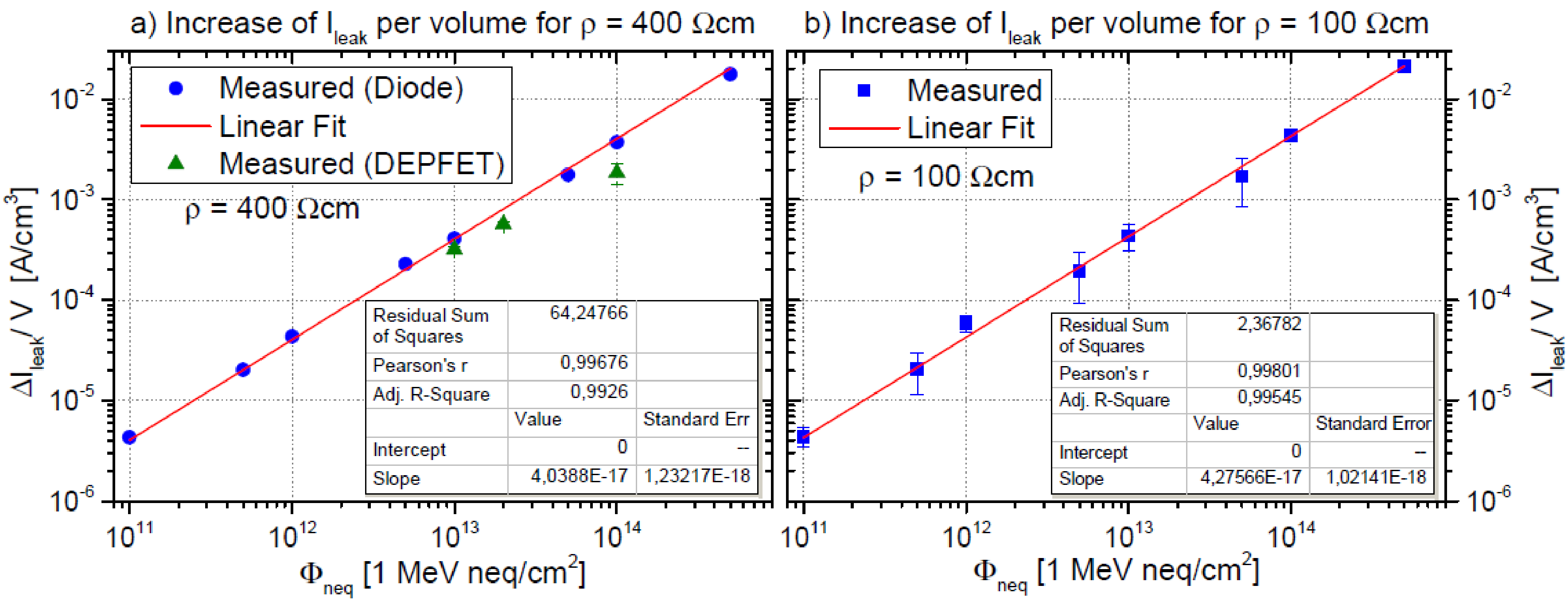
- matrices were irradiated with neutron fluences of $1x10^{13}$, $2x10^{13}$ and $1x10^{14}$ neq/cm^2

- expected final BELLE II fluence after ten years of operation (calculated with NIEL scaling): $\phi_{neq} = 2x10^{13}$ neq/cm^2

→ the chosen neutron fluences should cover the entire BELLE II operation time span

Results

Increase of leakage current


a) Increase of I_{leak} per volume for ρ = 400 Ωcm

b) Increase of I_{leak} per volume for ρ = 100 Ωcm

a)

Residual Sum of Squares	64,24766	
Pearson's r	0,99676	
Adj. R-Square	0,9926	
	Value	Standard Err
Intercept	0	--
Slope	4,0388E-17	1,23217E-18

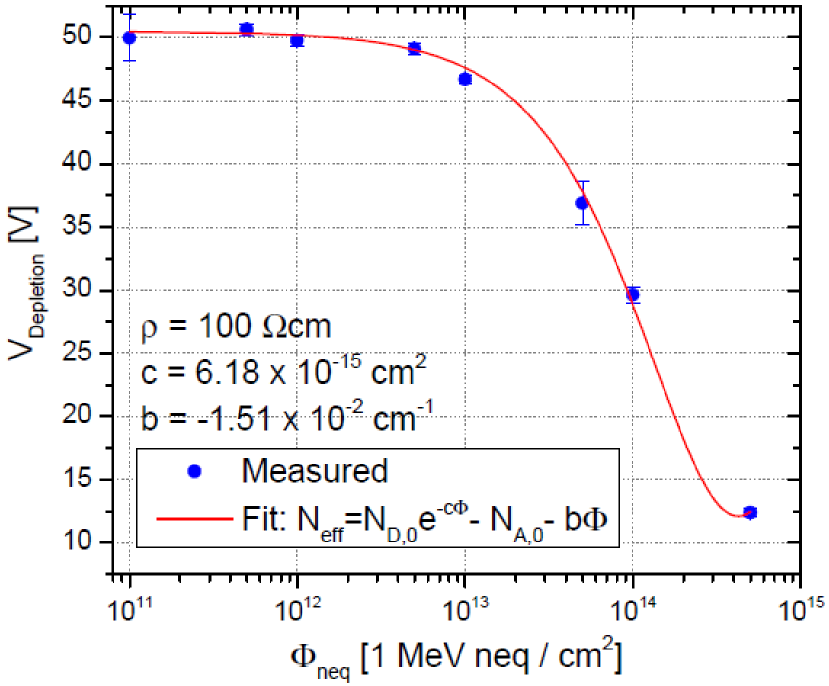
b)

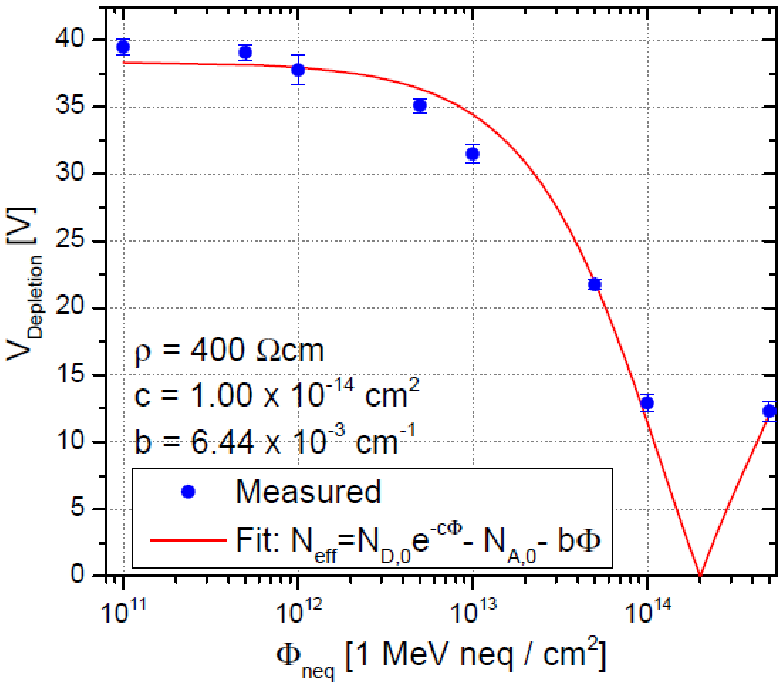
Residual Sum of Squares	2,36782	
Pearson's r	0,99801	
Adj. R-Square	0,99545	
	Value	Standard Error
Intercept	0	--
Slope	4,27566E-17	1,02141E-18

- measurement of leakage currents per volume of diodes and DEPFET matrices after neutron irradiation
- all values normalized to the reference temperature of 20°C

→ material independent increase of leakage currents
→ in excellent agreement with previous studies

Change in full depletion voltage





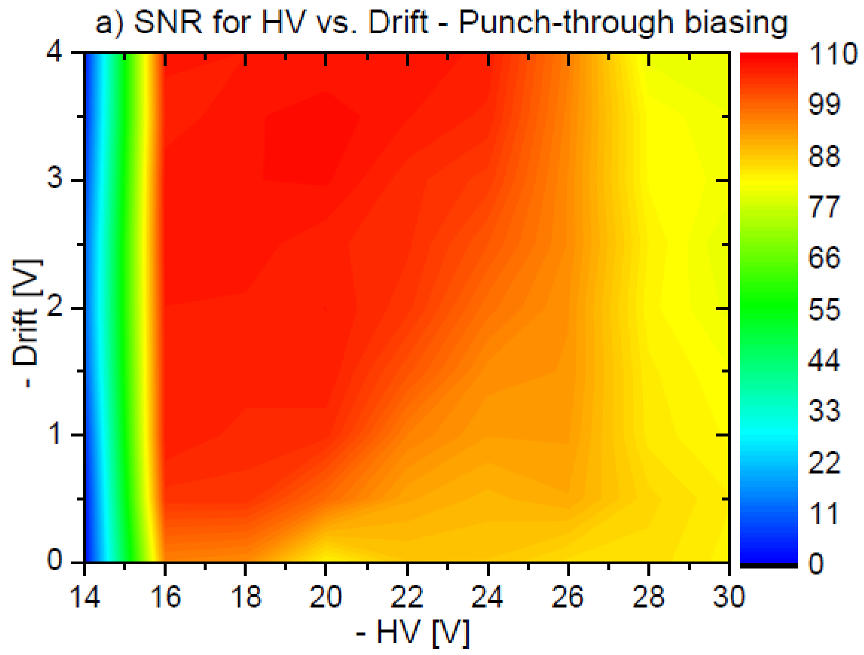
Measurement of full depletion voltage of diodes after different neutron fluences:

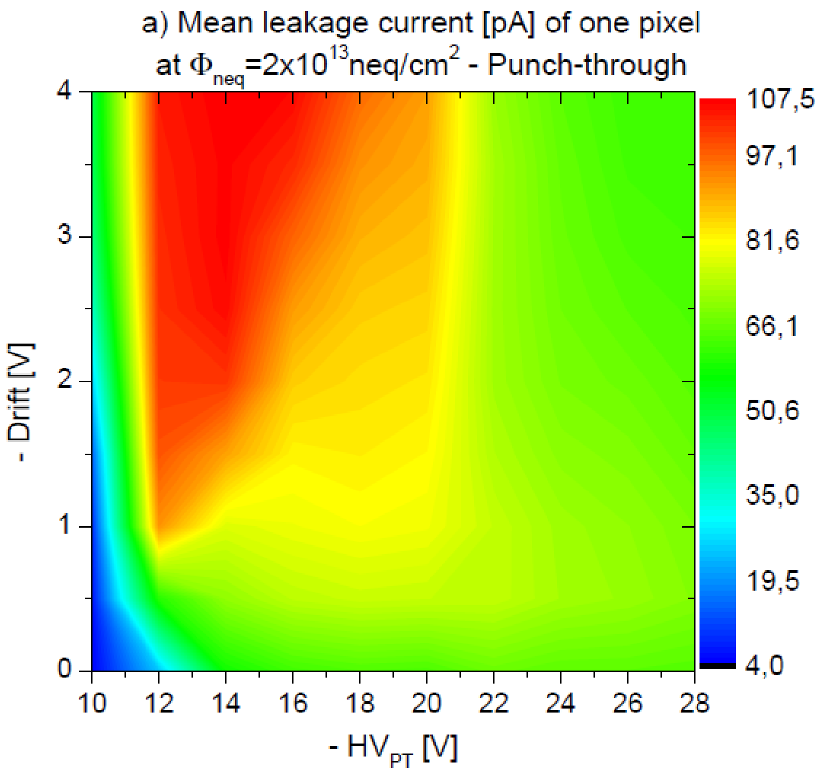
- initial decrease of depletion voltage in both cases
- type inversion of 400 Ωcm material at approximately 2x10^{14} neq/cm^2
- increase of depletion voltage after type inversion
- no type inversion in the case of 100 Ωcm material

$$V_{dep} = \frac{q}{2\varepsilon\varepsilon_0}\left|N_{eff}\right|d_s^2$$

→ lower resistivity material is more radiation hard in terms of type inversion
→ no type inversion of DEPFET structures after ten years of BELLE II operations
(ϕ = 2x10^{13} neq/cm^2)

Performance of DEPFET matrices


a) SNR for HV vs. Drift - Punch-through biasing

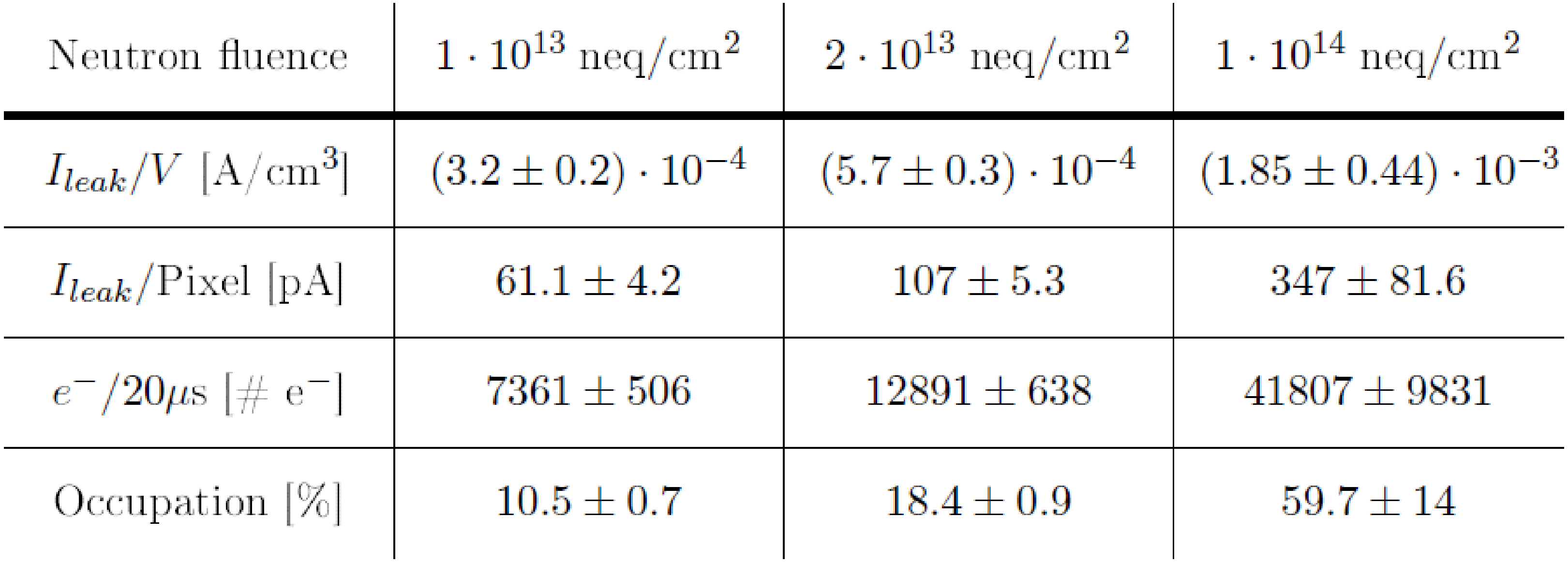

a) Mean leakage current [pA] of one pixel at Φ_{neq}=2x10^{13}neq/cm^2 - Punch-through

<u>Measurements of DEPFET matrix behavior after certain neutron fluences showed:</u>

- DEPFET matrices were still functional up to a neutron fluence of $\phi = 1 \times 10^{14}$ neq/cm^2
- shift of optimal voltage parameters due to decreasing full depletion voltage and threshold voltage shifts of the gate structures

Performance of DEPFET matrices

- no type inversion up to ϕ = 1x10^{14} neq/cm^2
- decrease in charge handling capacity of the internal gate due to the threshold voltage shift of the clear gate
- increased leakage currents should pose no threat (@ 20°C) for the charge handling capacity of the internal gate, if adjustments to the clear gate and clear low voltages are made



Neutron fluence	$1 \cdot 10^{13}$ neq/cm^2	$2 \cdot 10^{13}$ neq/cm^2	$1 \cdot 10^{14}$ neq/cm^2
I_{leak}/V [A/cm^3]	$(3.2 \pm 0.2) \cdot 10^{-4}$	$(5.7 \pm 0.3) \cdot 10^{-4}$	$(1.85 \pm 0.44) \cdot 10^{-3}$
I_{leak}/Pixel [pA]	61.1 ± 4.2	107 ± 5.3	347 ± 81.6
$e^-/20\mu s$ [# e$^-$]	7361 ± 506	12891 ± 638	41807 ± 9831
Occupation [%]	10.5 ± 0.7	18.4 ± 0.9	59.7 ± 14

→ additional measurements with type inverted DEPFETs desirable

Punch-through biasing and noise

Measurements of the punch-through biasing characteristics after irradiation have shown:

- linear correlation between punch-through and back side voltage still present
- decreased voltage drop within the bulk due to the change in N_{eff}

→ punch-through biasing still operational up to a neutron fluence of
$\phi = 1\text{x}10^{14}$ neq/cm^2
→ no negative effects on the detector performance

Four different methods for determination of the punch-through noise were applied:

- correlated double sampling
- linear fitting of the increasing pixel signal
- detailed evaluation of the time evolution of the pixel noise
- Fast Fourier Transformation of the measured signal and determination of the resulting power spectral density

All methods were applied in both biasing modes in order to determine noise differences

→ no additional 1/f noise component due to punch-through biasing could be detected in the measurements of all different measurement methods
→ no detectable impact of the punch-through noise up to a neutron fluence of
$\phi = 1\text{x}10^{14}$ neq/cm^2

Summary

Studies of this master‘s thesis have shown:

- punch-through biasing characteristics before neutron irradiation
- no negative impact on the noise performance due to punch-through biasing before irradiations
- increased radiation hardness of lower resistivity material in terms of type inversion
- new fit parameters for type inversion analysis
- radiation hardness of DEPFET sensors for ten years of BELLE II operations (and even longer) in terms of type inversion
- operability of DEPFETs at 20°C in terms leakage currents and charge handling capacity of internal gates
- radiation hardness of the punch-through biasing method (despite negative impacts of the biasing resistor)
- no detectable punch-through noise up to a fluence of $\phi = 1\text{x}10^{14}$ neq/cm^2

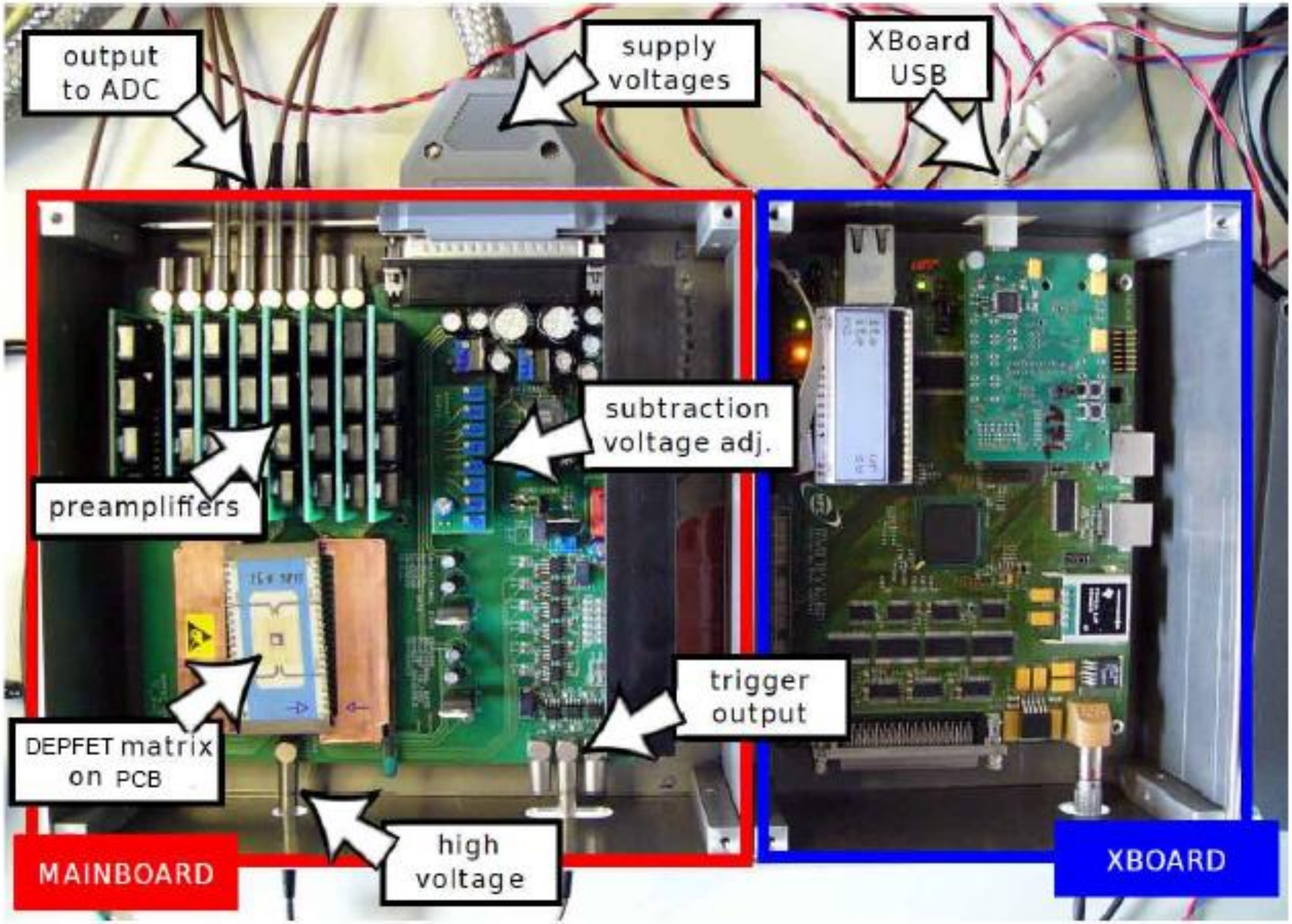
→ overall radiation hardness of DEPFET sensors for deployment at BELLE II
→ the punch-through biasing method is a suitable means of biasing the DEPFET without negative effects of the noise performance

The End

Thank you for your attention!

Backup

Experimental Setup: MiMa



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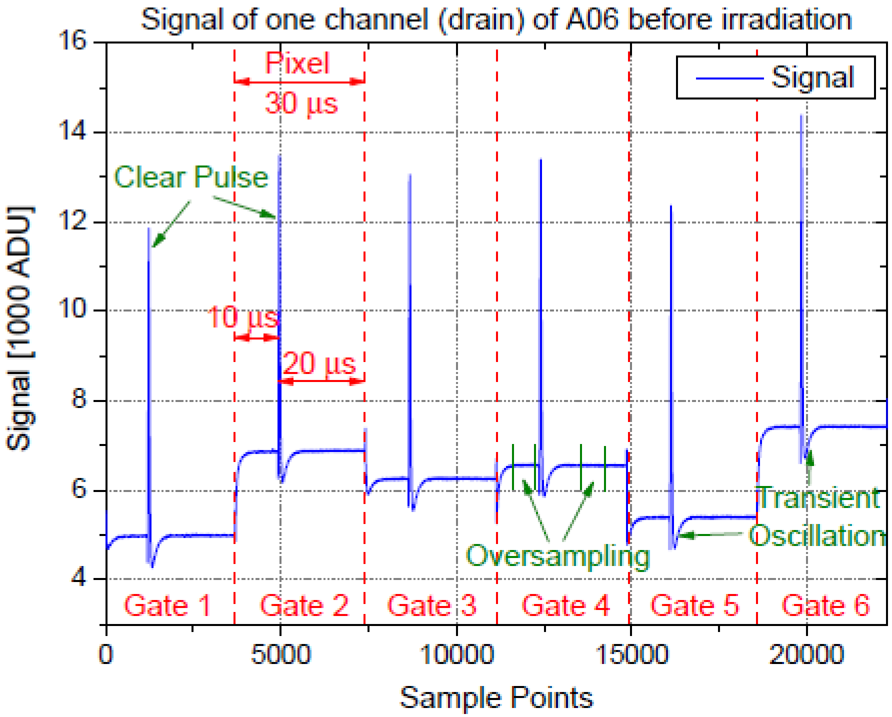
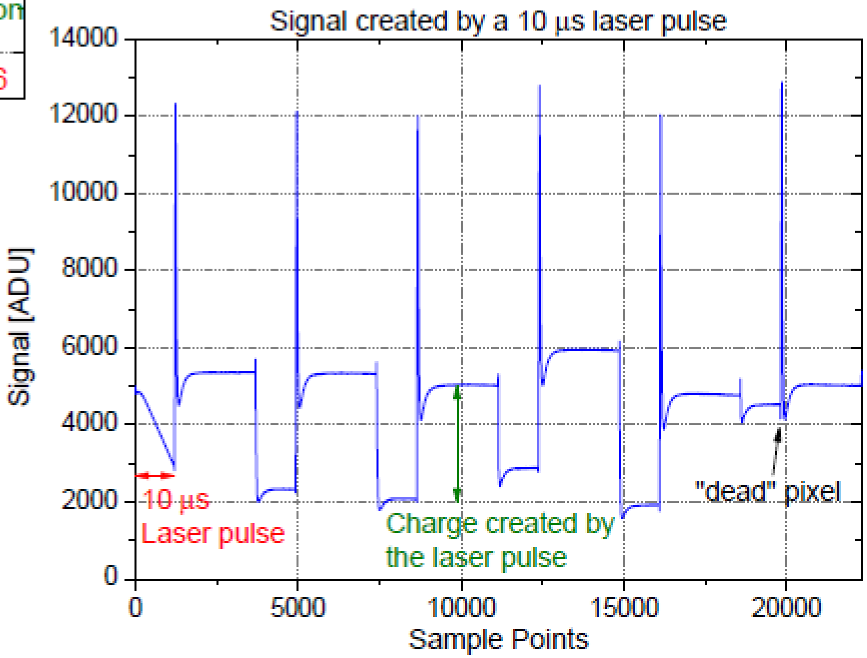


“Dark measurement”

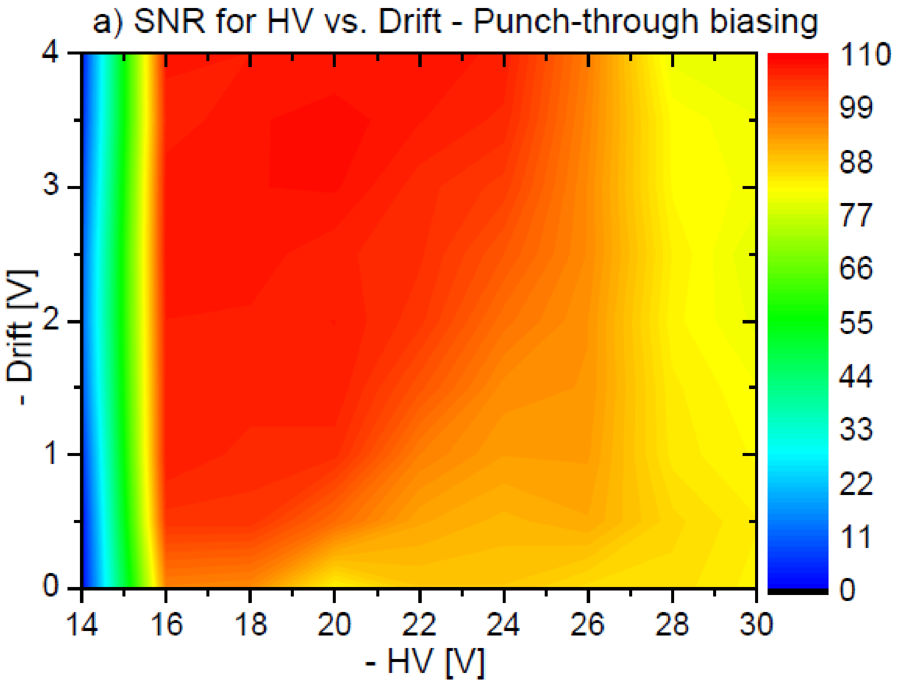


Measurement with a laser pulse

Pre-characterizations: Matrices and diodes

- pre-characterization of diodes in terms of depletion voltage and leakage current with a probe station
- DEPFET matrix characterizations in both biasing methods included:
  - – laser measurements for different voltage parameters (HV, Drift, ClearLow, ClearHigh, ClearGate) in order to determine the optimal operation point of each matrix
  - – measurements of the Fe^{55} spectrum, allowing the determination of the internal amplification
  - – dark measurements in order to evaluate the leakage current and noise of each pixel

→ no negative impact of the punch-through biasing method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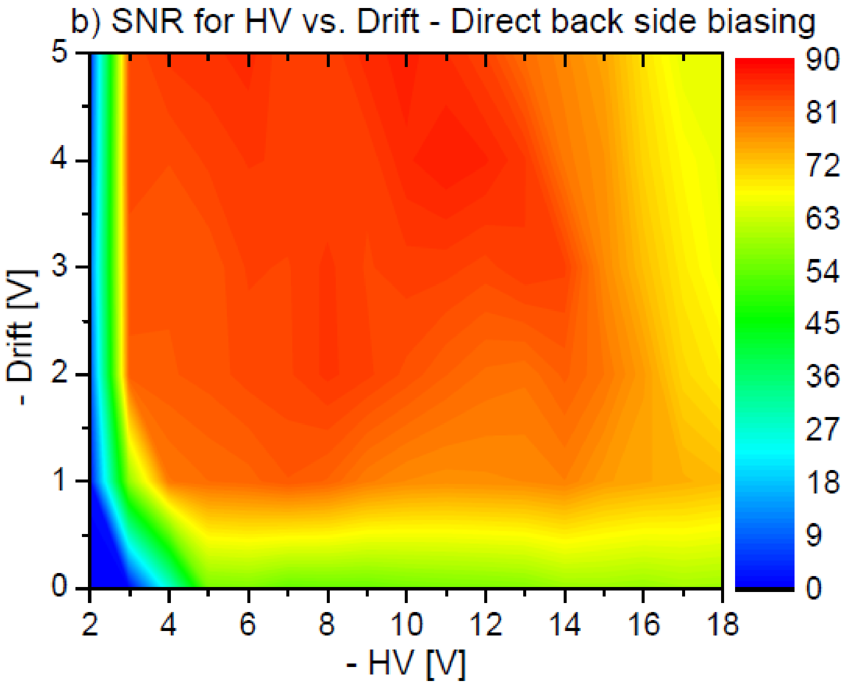
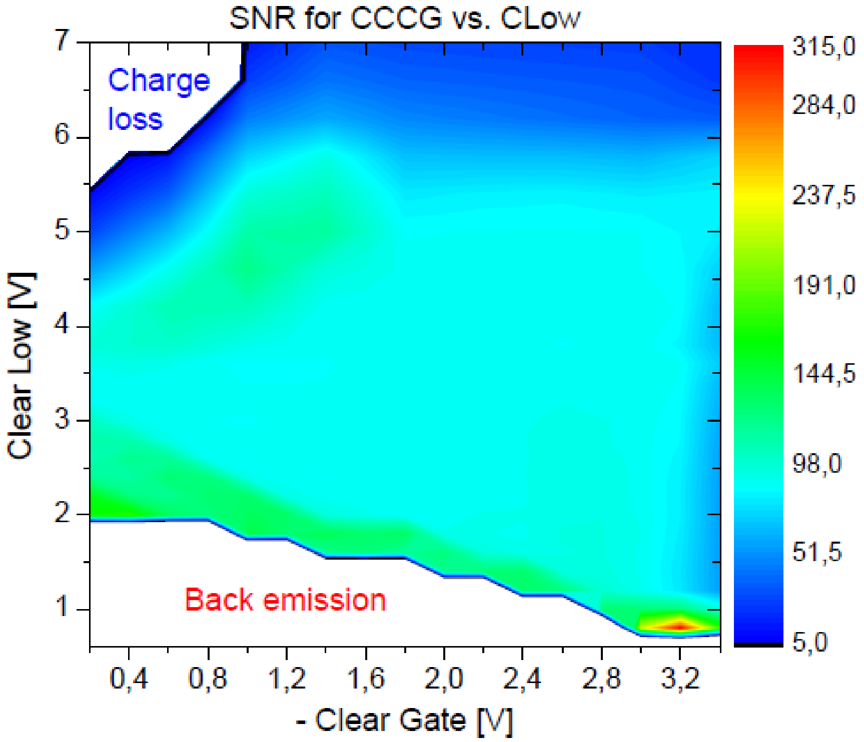
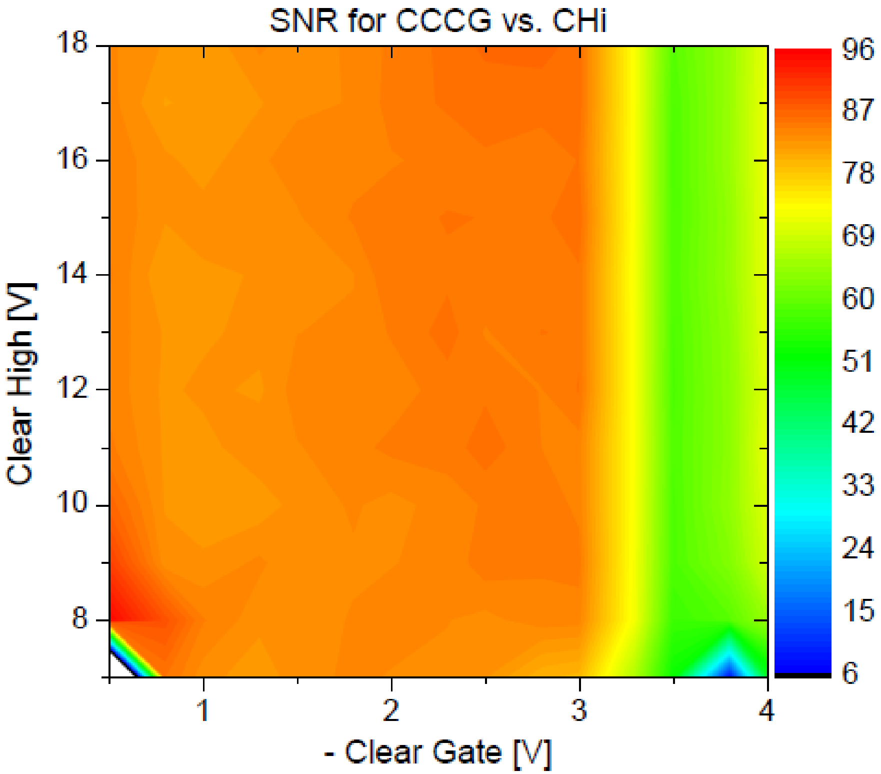

b) SNR for HV vs. Drift - Direct back side biasing

Pre-characterizations: Matrices and diodes





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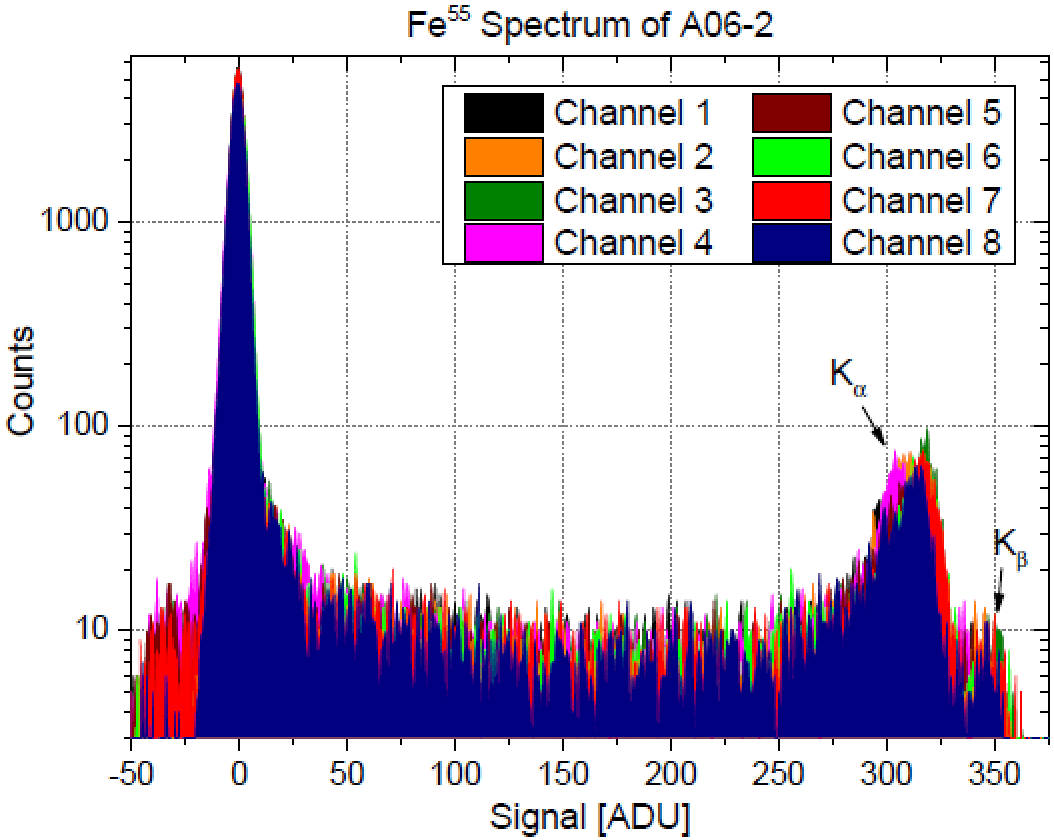
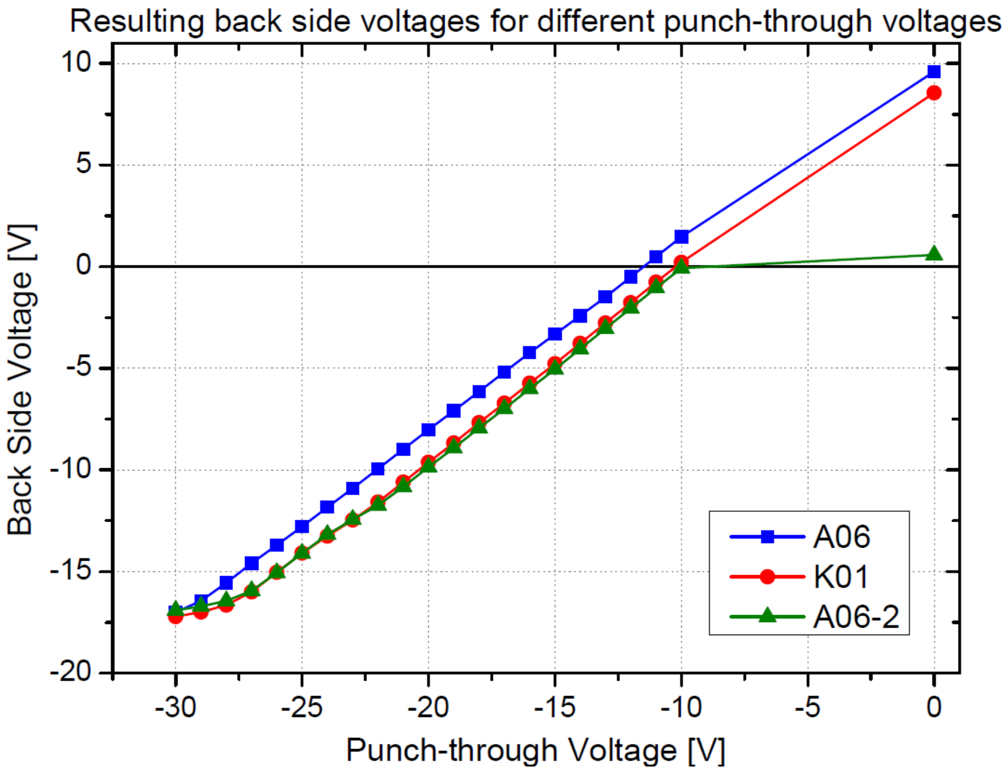


Calibration of the internal amplification of the DEPFETs with a Fe^{55} source

	A06	K01	A06-2
g_q [pA/e^-]	391.3 / 454.1	401.6	391.2
ADU-to-electron	1 ADU $\widehat{=}$ 5.26 / 4.53 e^-	1 ADU $\widehat{=}$ 5.12 e^-	1 ADU $\widehat{=}$ 5.26 e^-

Pre-characterizations: Punch-through biasing



→ change in back side potential even before the punch-through current is established

→ result of capacitive couplings to the back side electrode

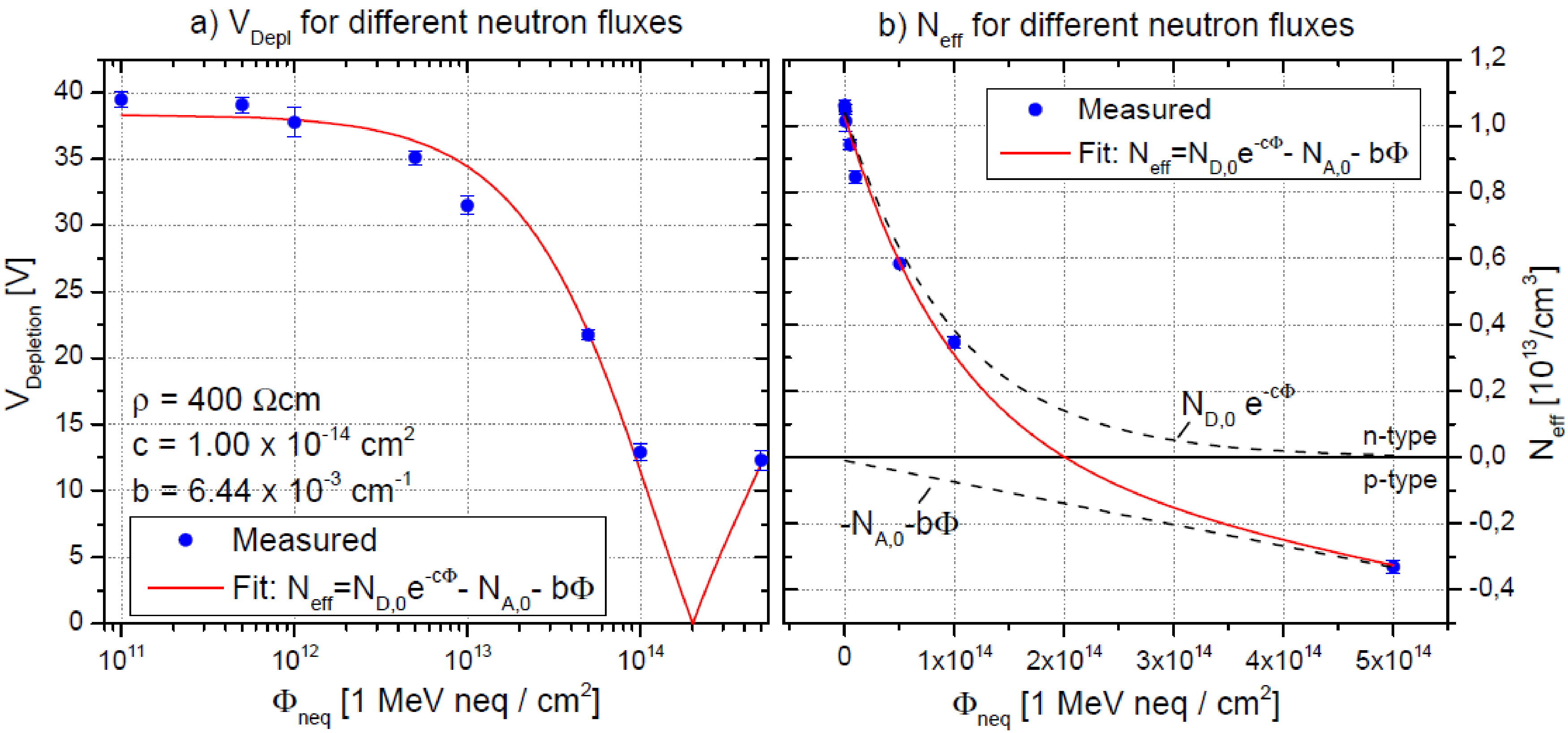
<u>Measurements of the punch-through biasing characteristics with an external source meter:</u>

- resulting back side voltage for different applied punch-through voltages
  →linear correlation

- back side voltage – bulk current characteristics
  →exponential behavior

- resulting back side voltage in dependence of the bulk current
  → only very small changes for increasing bulk current

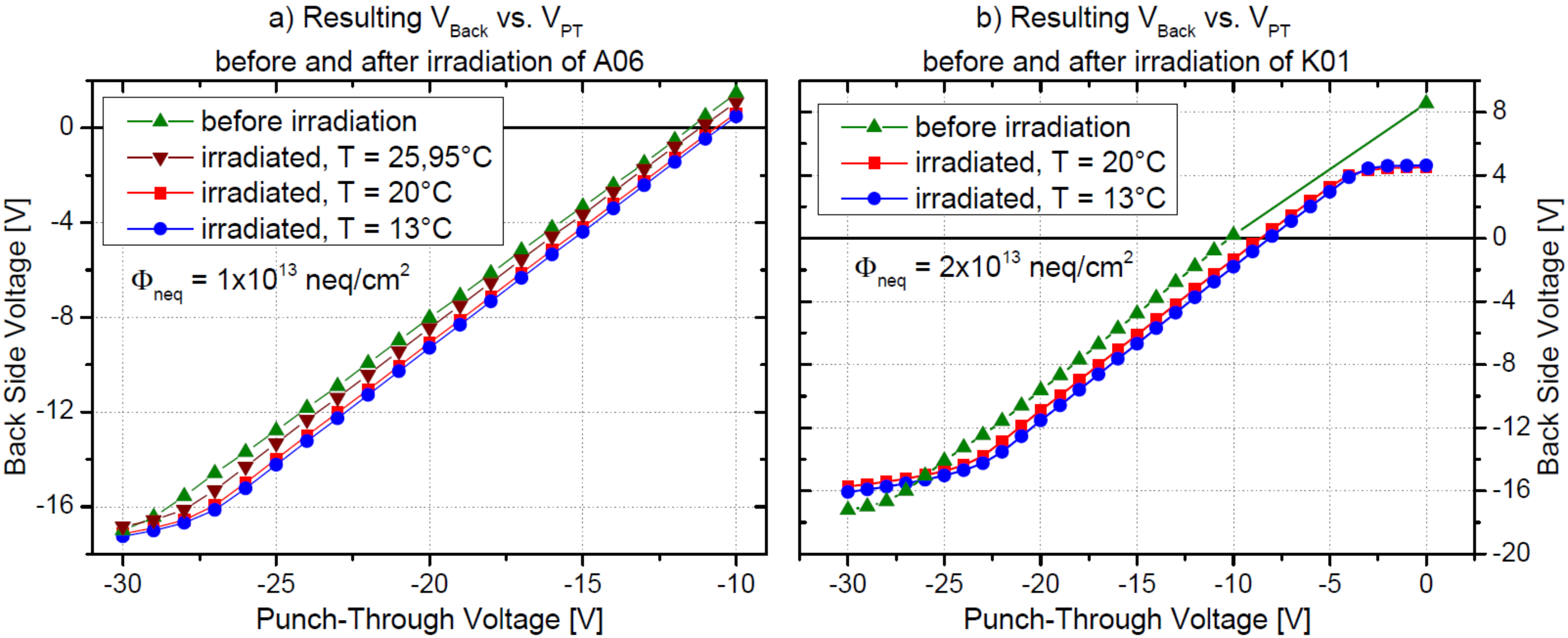
Type inversion – Fit parameter



- applying a fit function on the measured data in order to obtain the fit parameters c and b
- fit parameters were extracted for both resistivities and compared to previous studies

→ comparisons were possible but additional investigations are required

Punch-through biasing



- repetition of the punch-through biasing measurements showed a smaller voltage drop in the detector bulk after irradiation

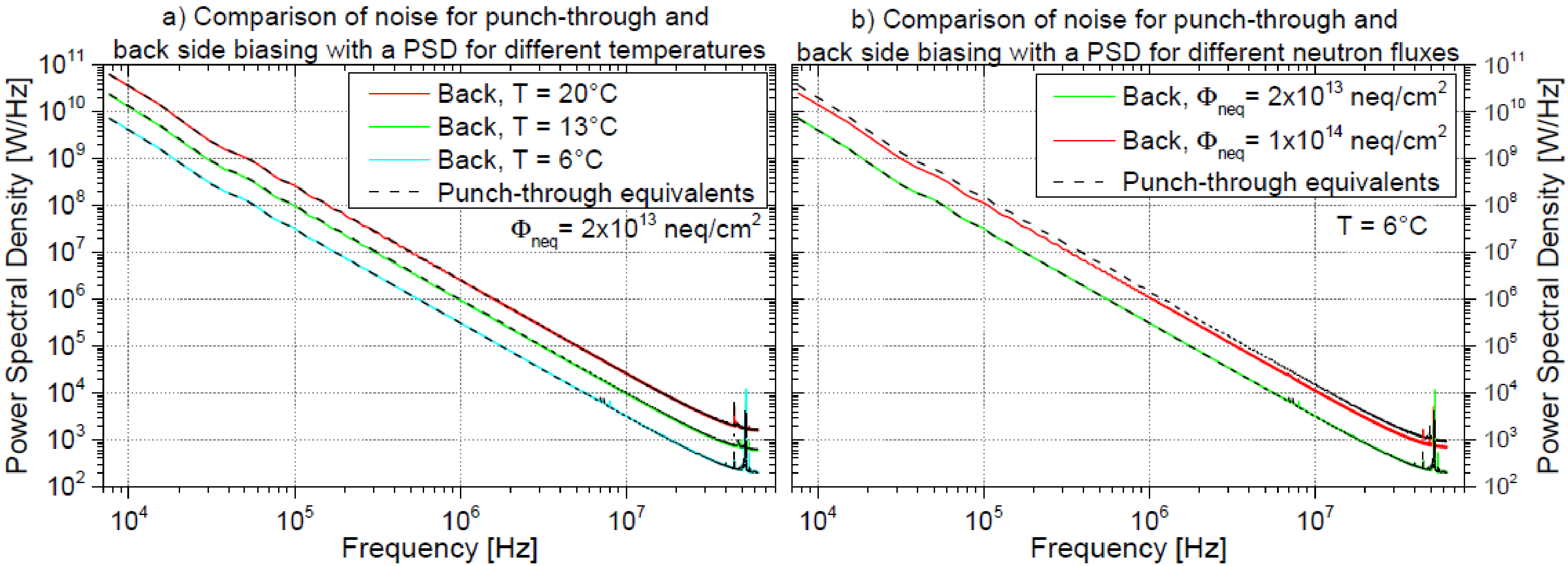
→ linearity mostly still present

→ decrease in voltage drop to change in effective dopant concentration

- behavior for large bulk currents was unfortunately dominated by the high resistivity bias resistor (R = 1 MΩ)

→ increased voltage drop at bias resistor leads to a decreasing effective punch-through voltage

Punch-through noise



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