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Temperature-Dependent Measurements of n^+-in-n Pixel Sensors

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9th International "Hiroshima" Symposium
on the Development and Application of Semiconductor Tracking Detectors,
HSTD-9, Hiroshima, Japan, 1-5 September 2013

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Temperature-Dependent Measurements of n^+-in-n Pixel Sensors

Karola Dette, Temperature and high voltage dependent measurements of an irradiated n^+-in-n ATLAS FE-I4A Single Chip Assembly, Diploma Thesis, TU Dortmund, August 2013

Felix Wizemann, Annealing abhängige Messungen an einem hochbestrahlten planaren n^+-in-n Silizium-Pixelsensor-FE-I3-Assembly, Bachelor Thesis, TU Dortmund, Juli 2013

Till Plümer, Fanout enabled charge collection measurements of planar n^+-in-n ATLAS silicon pixel sensors, Diploma Thesis, TU Dortmund, December 2012

Mona Abt, Aufbau eines Messplatzes zur automatischen IV-Charakterisierung von Fanout-basierten n^+-in-n planaren Siliziumpixelsensoren, Bachelor Thesis, TU Dortmund, September 2013

Sergej Schneider, Temperaturabhängige Charakterisierung von Widerstandsschleifen auf FE-I4 Sensoren, Bachelor Thesis, TU Dortmund, February 2012

Tobias Wittig, Slim Edge Studies, Design and Quality Control of Planar ATLAS IBL Pixel Sensors, PhD Thesis, TU Dortmund, April 2013

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Temperature-Dependent Measurements of n$^+$-in-n Pixel Sensors

Introduction

Temperature Dependence @ $6.8\times10^{15}\ n_{eq}cm^{-2}$ (p)
Annealing Study @ $2\times10^{16}\ n_{eq}cm^{-2}$ (n)
Single Pixel Measurements, non-irradiated

On-Sensor Temperature Resistors
Sensor Design for LHC Phase II Upgrades

Conclusion: Summary & Outlook

Reiner Klingenberg, TU Dortmund University

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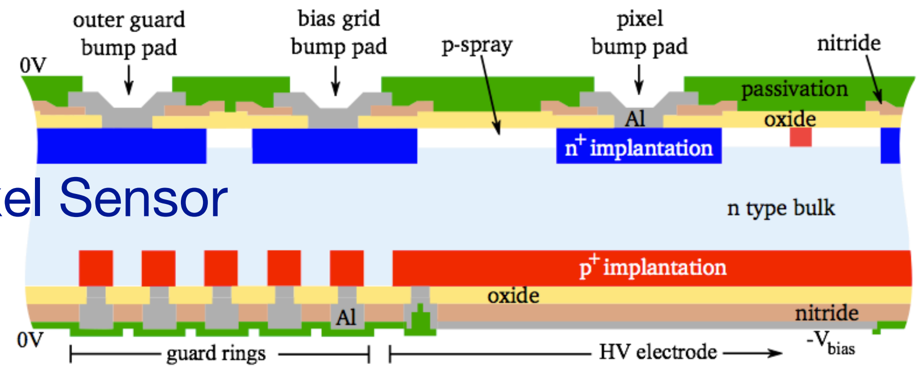
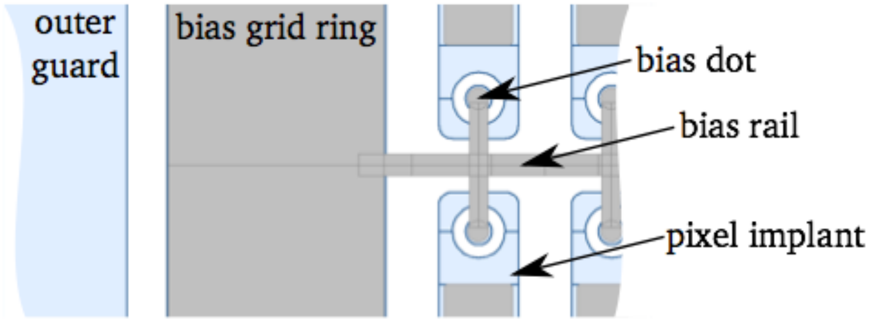
ATLAS Pixel Module: n^+-in-n Sensor + Front-End

Pixel Sensor



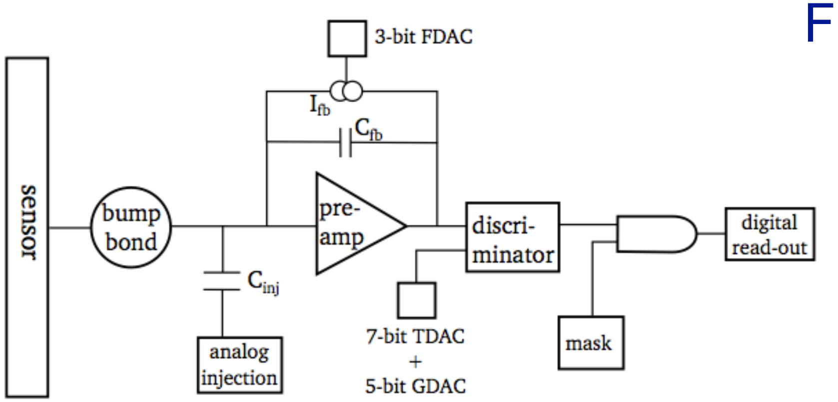
Side View



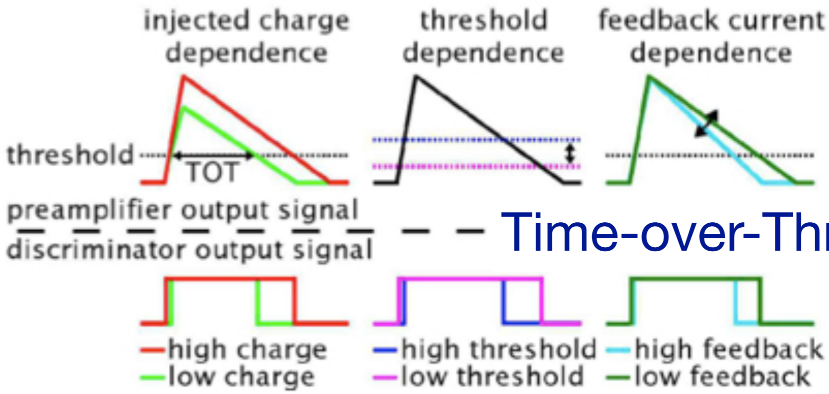
Top View

FE-I3: 400 × 50 μm^2, 250 μm

FE-I4: 250 × 50 μm^2, 200 μm



Front-End Electronics



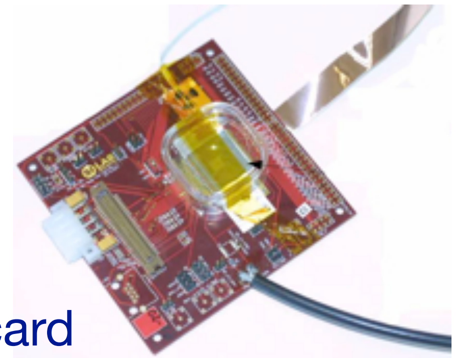
Time-over-Threshold

Results are based on Single Chip Sensor Measurements in Lab-Setups

- sensor bonded to front-end electronics FE-I3 or FE-I4 read-out chips
- charge injection with help of radioactive sources
- sensors are characterized electrically with IV characteristics
- alternatively, (arrays of) single pixels are connected to a fan-out

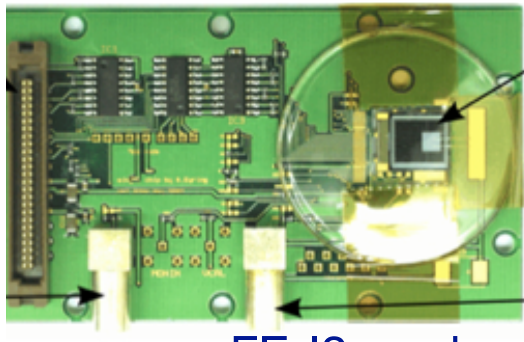
single chip adapter card

sensor+FE



FE-I4 card

20.3 mm × 16.8 mm
26880 pixel channels
5 bit ToT



FE-I3 card

7.6 mm × 8.2 mm
2880 pixel channels
8 bit ToT

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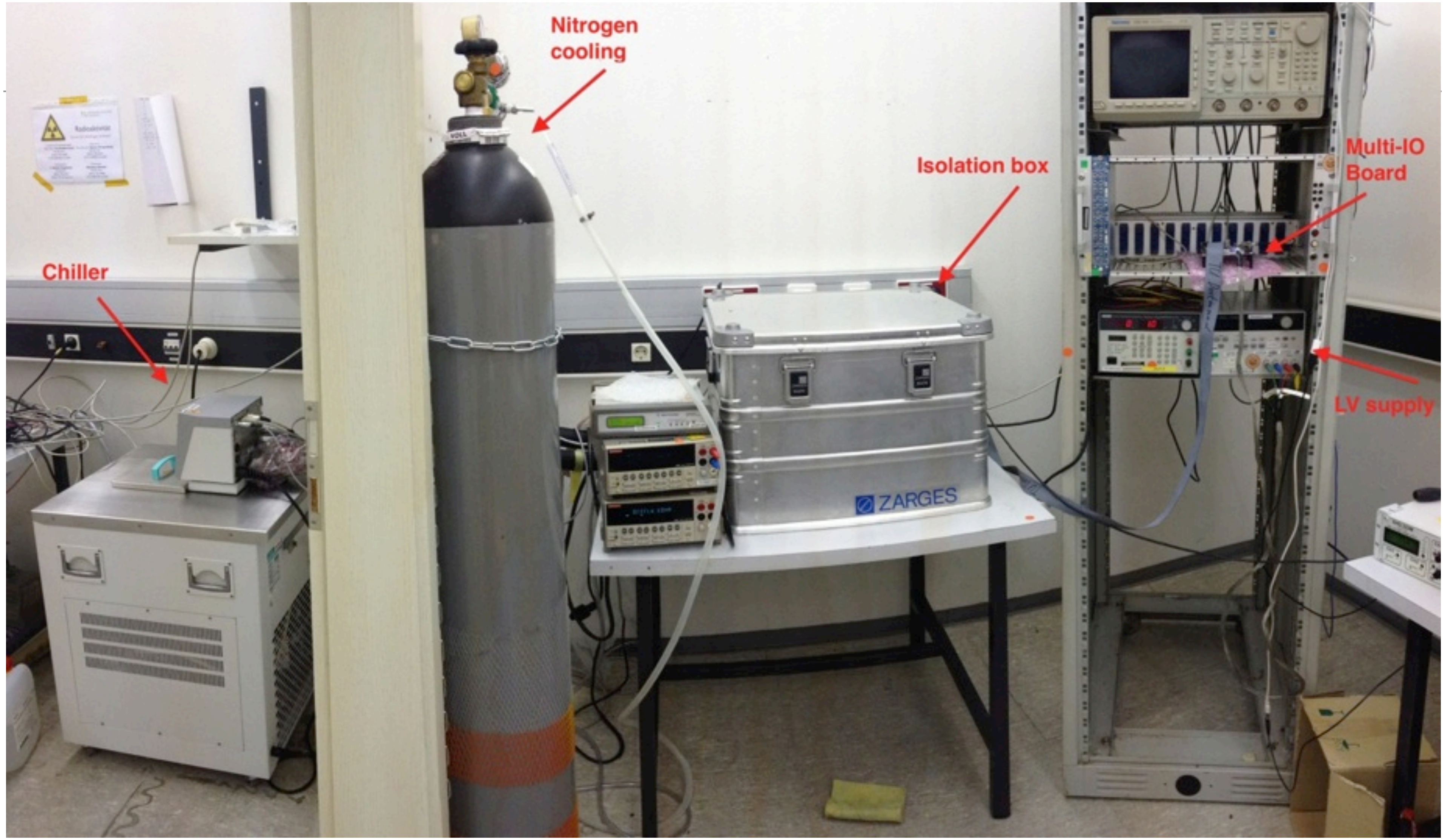
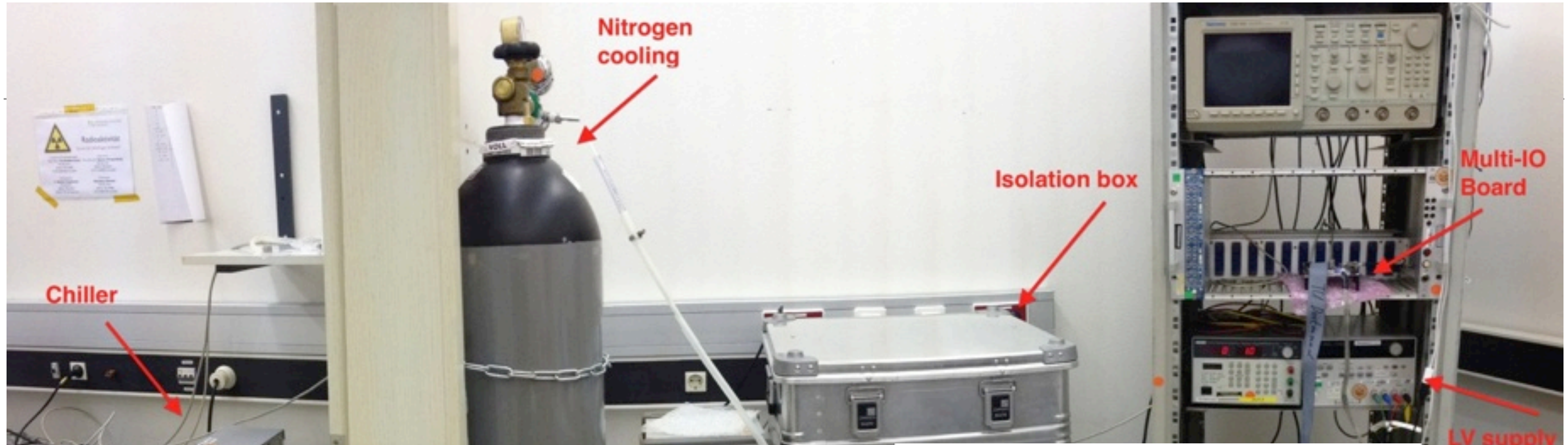
Temperature Dependence of FE-I4 Assembly

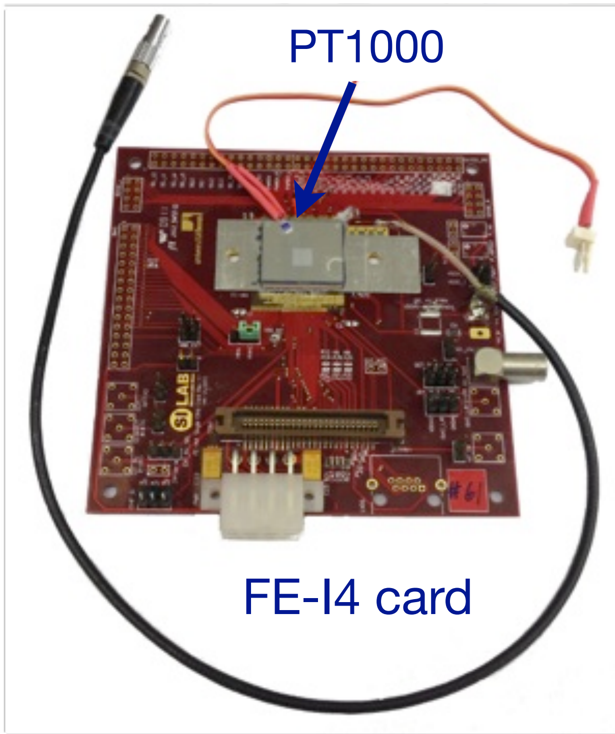


Temperature Dependence of FE-I4 Assembly



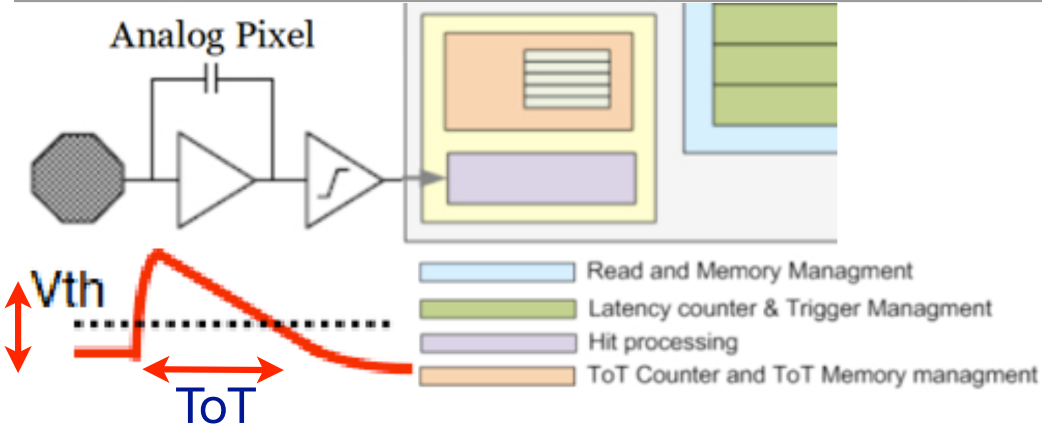
investigated assembly:

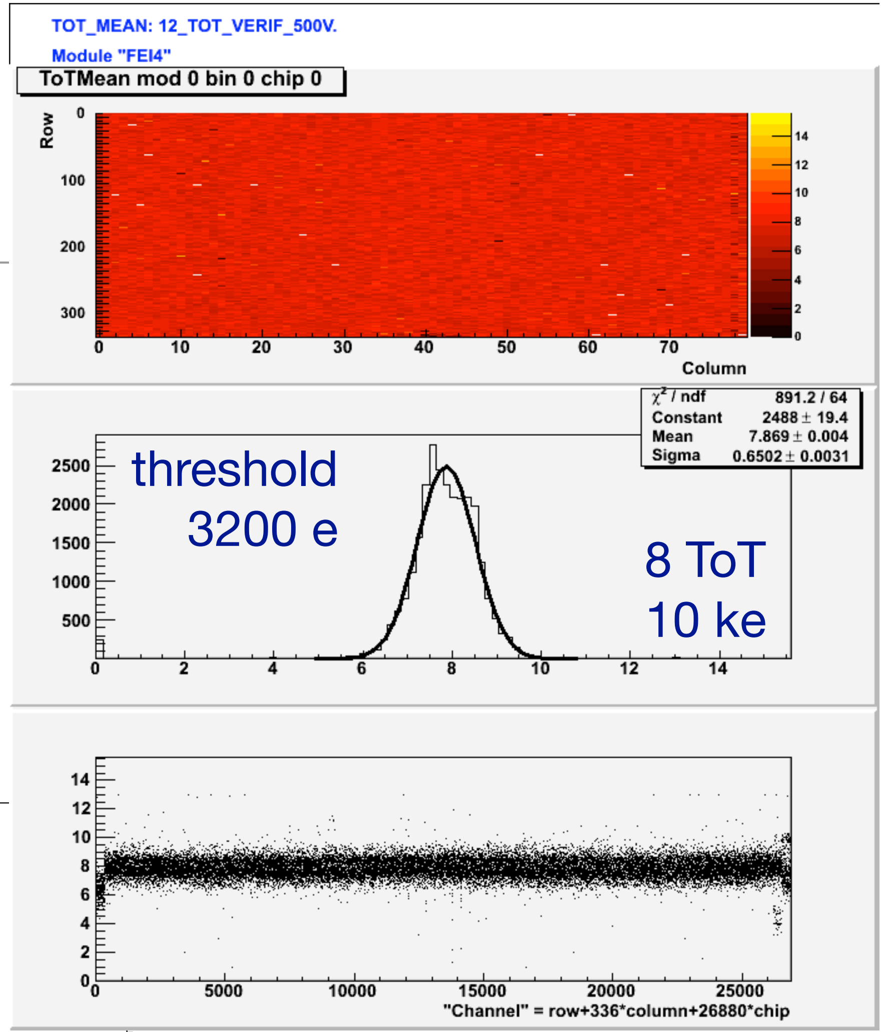
- n^{+}-in-n FE-I4 pixel sensor, 200 μm p irradiation of $6.8\times10^{15}\ n_{eq}cm^{-2}$ i.e. IBL-like conditions
- measurements of FE-tuning
- measurements of leakage current @ different temperatures

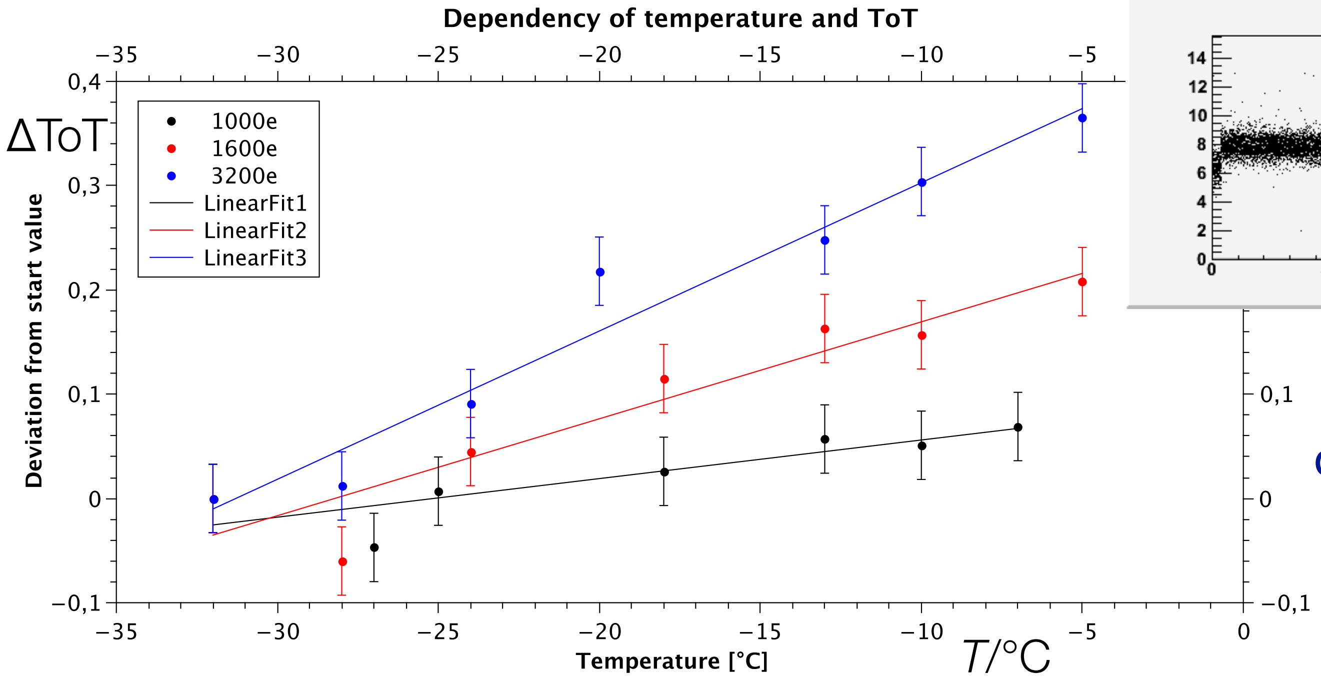


$6.8\times10^{15}\ n_{eq}cm^{-2}$

FE-I4 Time-over-Threshold



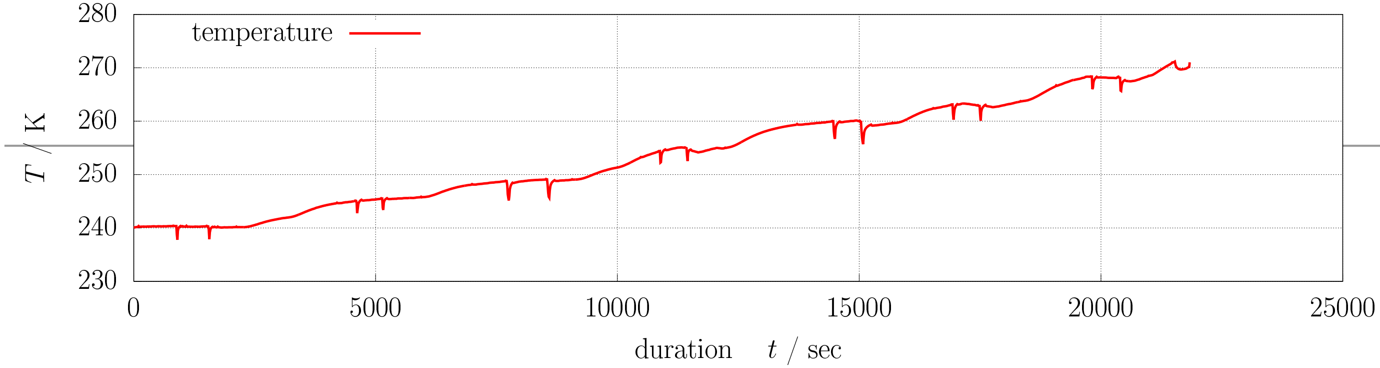


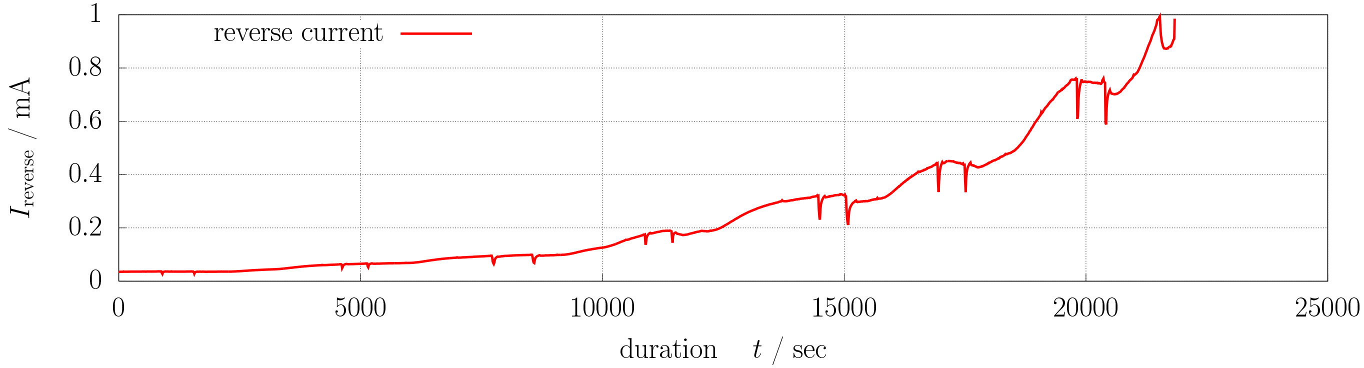


observe a slight change of the ToT with temperature

Measurements by Karola Dette, TU Dortmund

Reverse Current Scaling w/ Temperature $6.8{\times}10^{15}\ n_{eq}cm^{-2}$

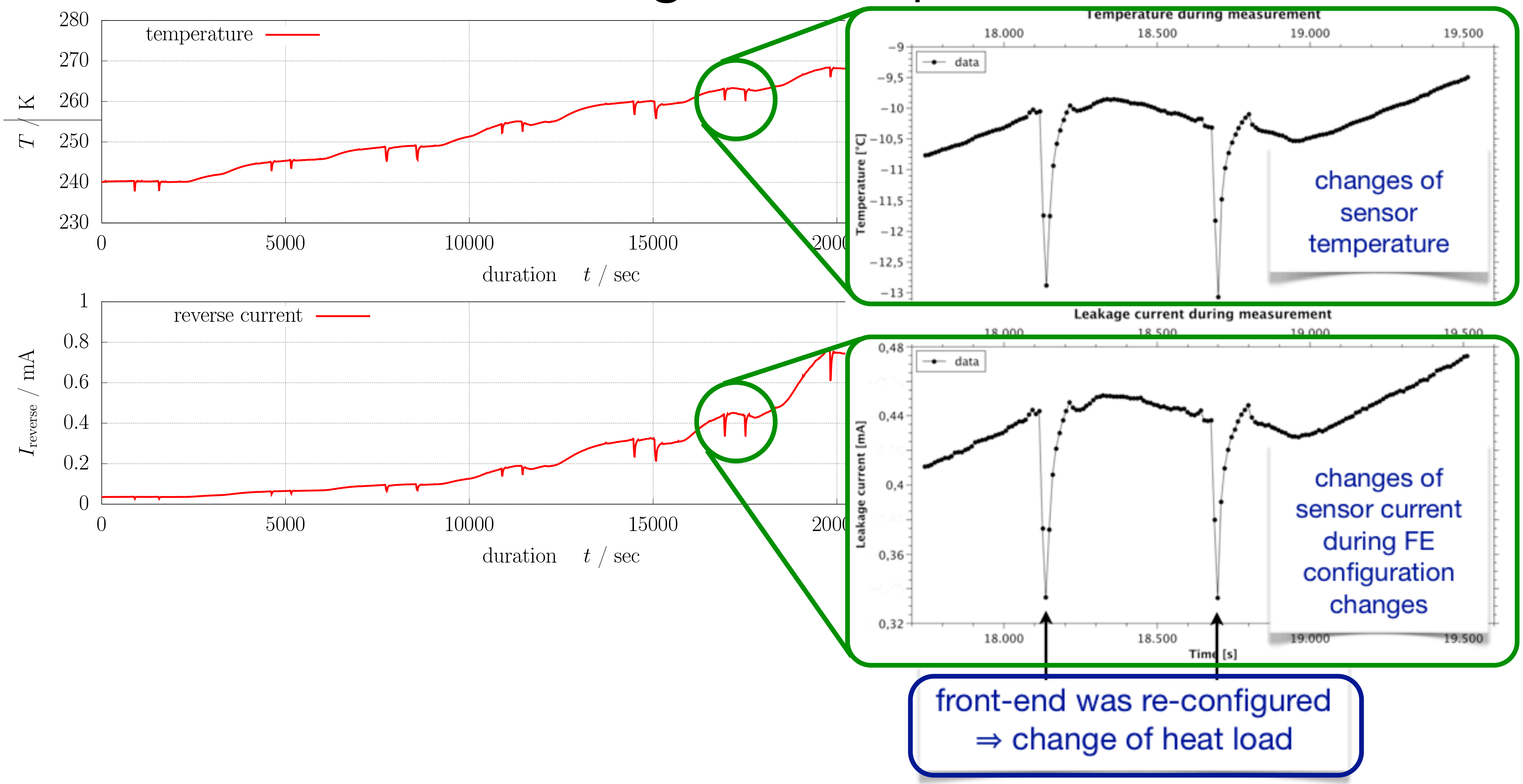




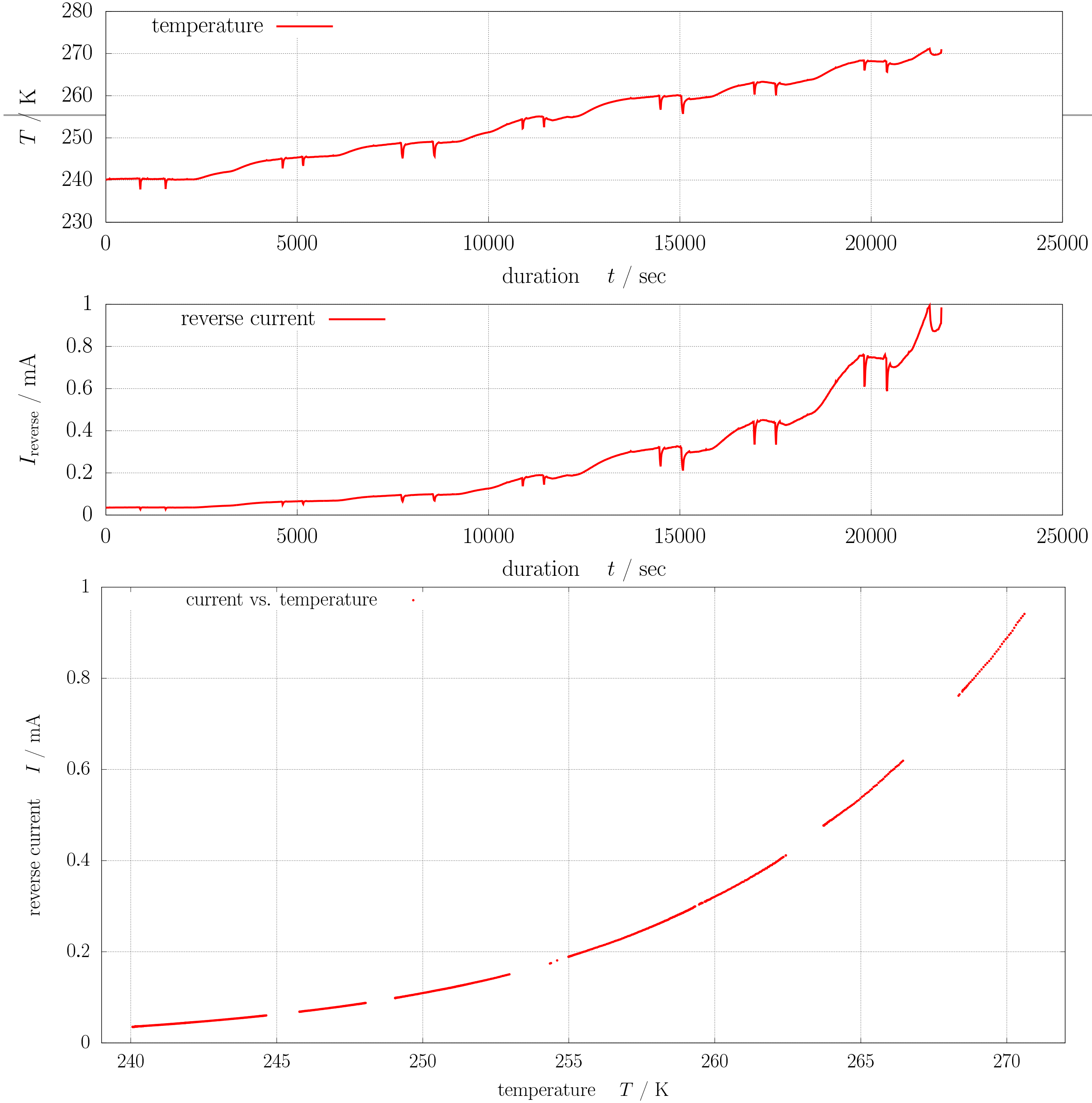
time evolutions

during 7 hours

Reverse Current Scaling w/ Temperature $6.8\times10^{15}\,n_{eq}cm^{-2}$



Reverse Current Scaling w/ Temperature $6.8{\times}10^{15}\ n_{eq}cm^{-2}$



time evolutions

during 7 hours

exclude measurements during FE re-configuration

reverse current *vs*. temperature

U_{bias} = 500 V

Reverse Current Scaling w/ Temperature

$$I \propto T^m \exp -\frac{E_g}{2kT}$$

$$-2kT \cdot \ln \frac{I}{T^m} = p_1(T) = B + C \cdot 2k \cdot T$$

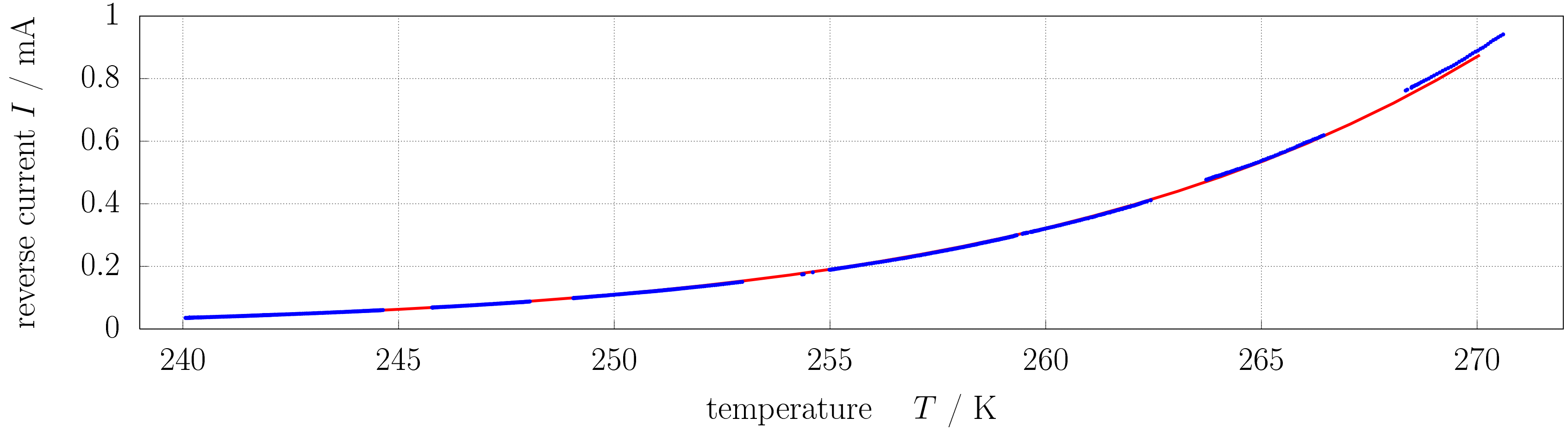
identification of parameters: $E_g = B \quad A = \exp(-C) \qquad m \equiv 2$

$$I = A \cdot T^m \exp -\frac{E_g}{2kT}$$

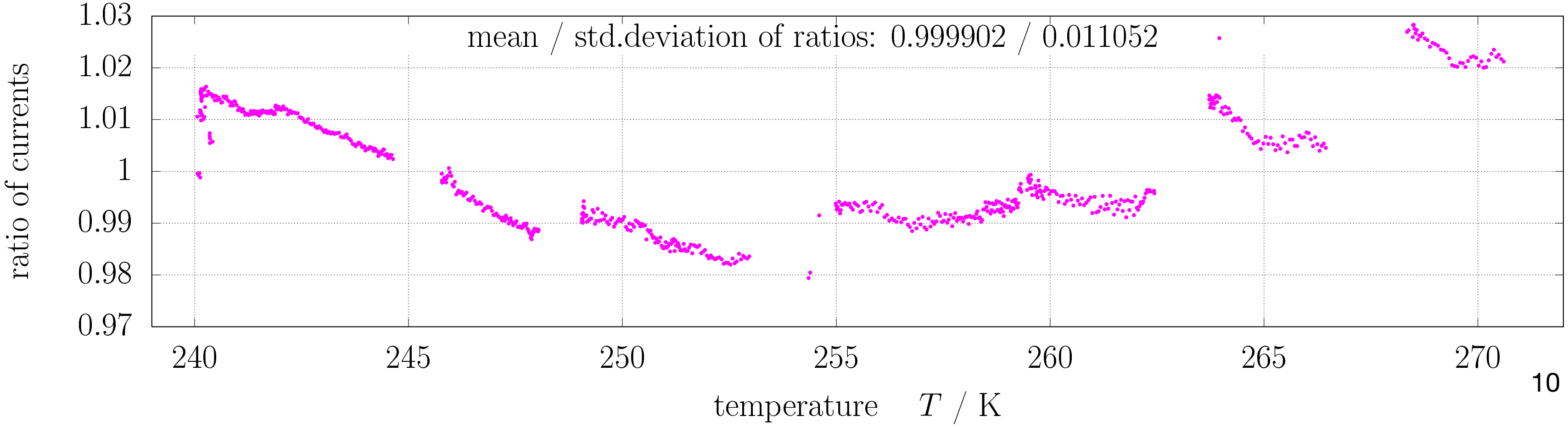
$$p_1(T) = E_g - \ln(A) \cdot 2kT$$

$I(T)$ / mA

measured & **fit**



ratio of measured to fit



$6.8\times10^{15}\,n_{eq}cm^{-2}$

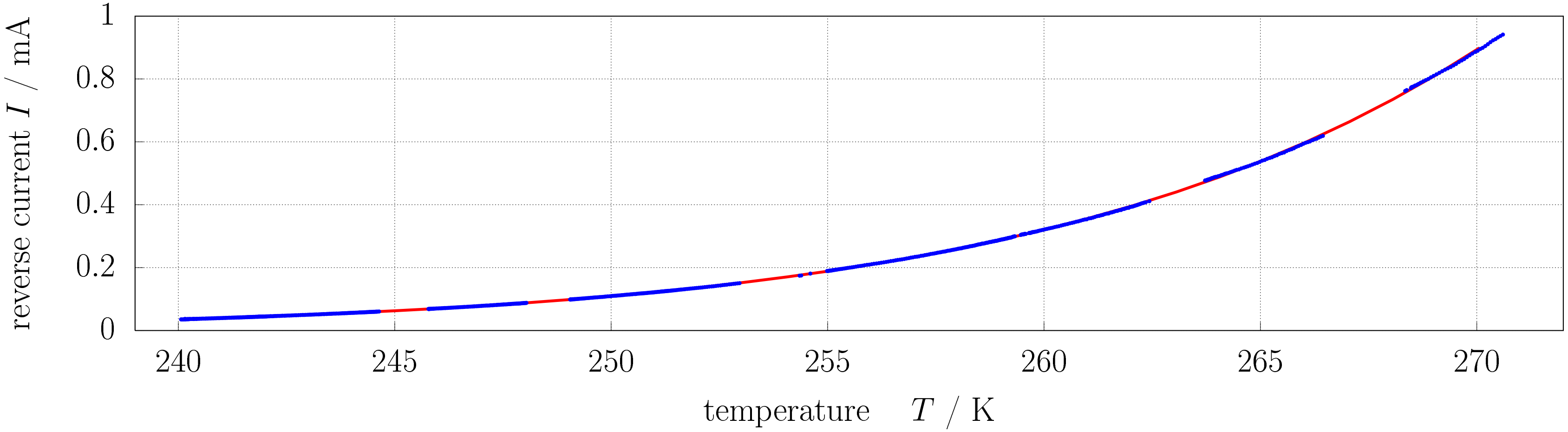
Reverse Current Scaling w/ Temperature

$$I = A \cdot T^m \exp - \frac{E_g(T)}{2kT} \qquad -2kT \cdot \ln \frac{I}{A \cdot T^m} = p_2(T)$$ 2nd, 3rd order polynomials

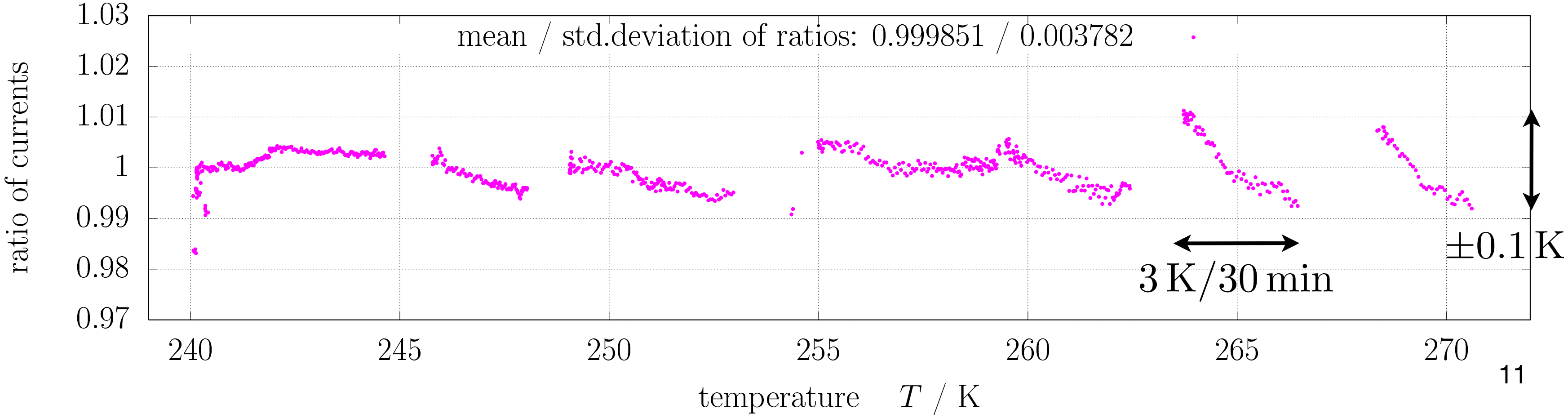
identification of parameters: $p_2(T) = E_g(T)$ $\quad m \equiv 2$

$I(T)$ / mA

measured & **fit**



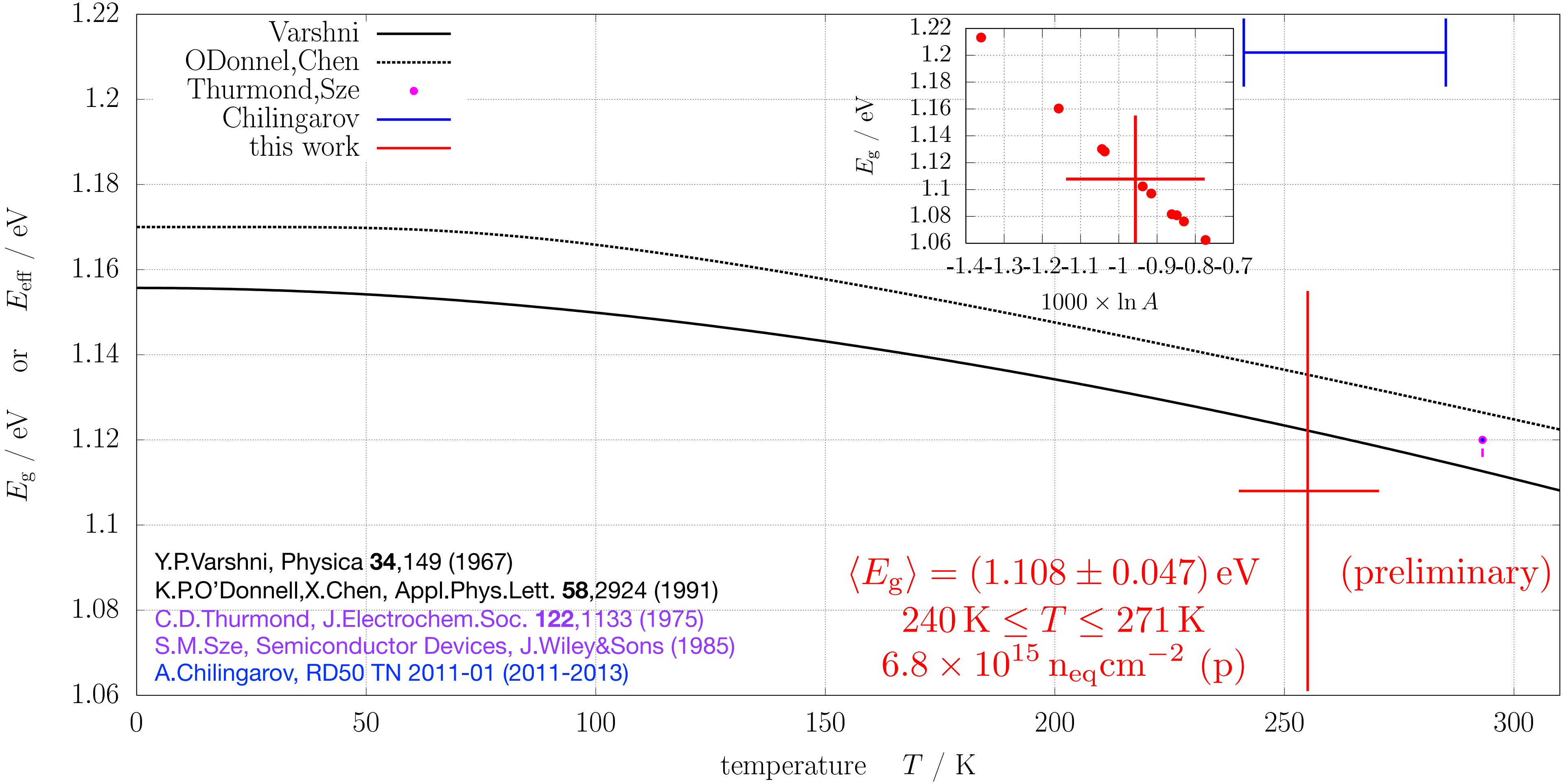
ratio of measured to fit



Current Scaling Parameter E_g

$$m \equiv 2$$

$$I = A \cdot T^m \exp - \frac{\langle E_g \rangle}{2kT}$$



Systematics: if $\Delta T_{\text{Sensor}} = +1.035\,\text{K} \Rightarrow \langle E_g \rangle = (1.1200 \pm 0.0005)$ eV

if $\Delta T_{\text{Sensor}} = +10.73\,\text{K} \Rightarrow \langle E_g \rangle = (1.2100 \pm 0.0012)$ eV

Temperature Dependence @ $6.8\times10^{15}\,n_{eq}cm^{-2}$

investigated **FE-I4** n^{+}-in-n pixel assembly @ **$6.8\times10^{15}\,n_{eq}cm^{-2}$** (p), **IBL-like**

temperature dependence 240 K ≤ *T* ≤ 271 K

- observe (slight) changes in **FE tuning** with temperature
- checked scaling of **reverse current** with temperature
- improve **systematics** of temperature measurements

Reiner Klingenberg, TU Dortmund University

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Temperature-Dependent Measurements of n^+-in-n Pixel Sensors

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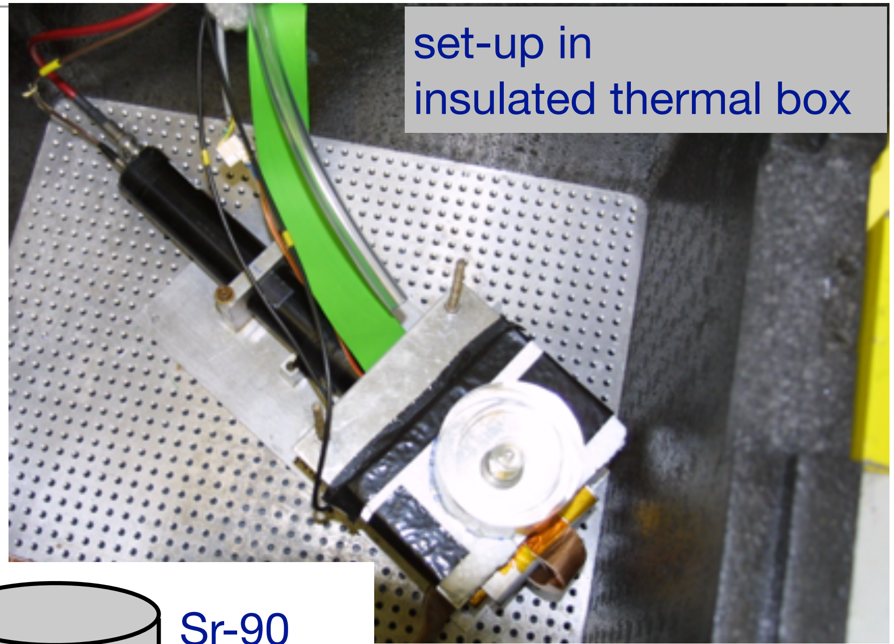
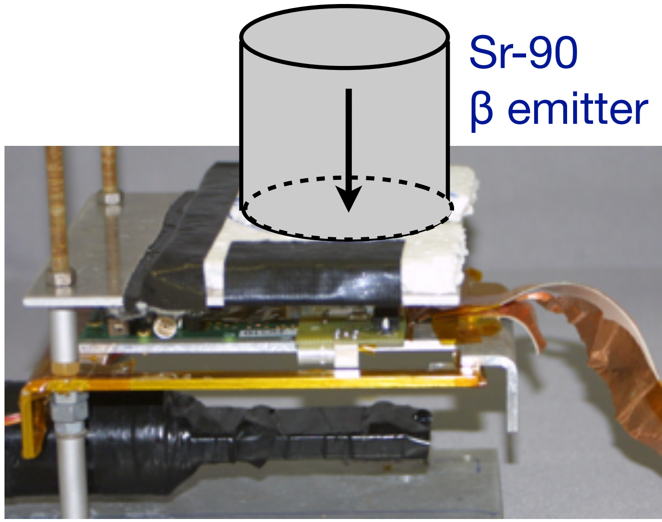
Annealing Study of an Irradiated Assembly

investigated assembly (DO10):

- n^{+}-in-n FE-I3 pixel sensor, 250 µm
  n irradiation of $2\times10^{16}\,n_{eq}cm^{-2}$
- annealing in 4 steps à 20 min @ +60 °C
- measurement of leakage current, digitized charge (ToT, β source)

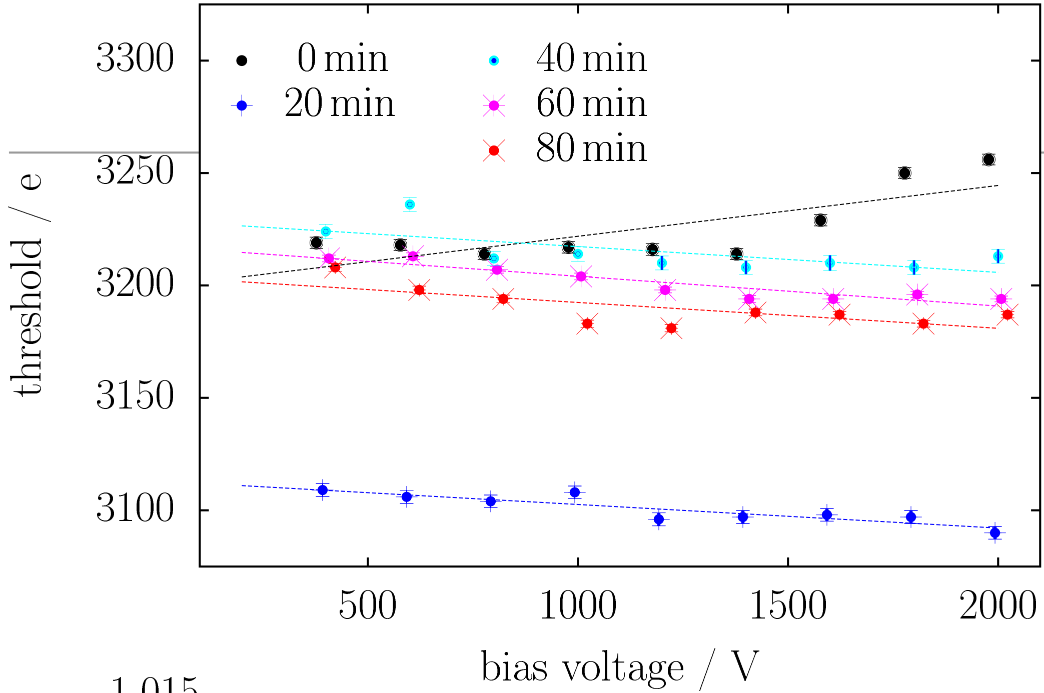




Measurements by Felix Wizemann, TU Dortmund

Annealing Study of an Irradiated Assembly $2\times10^{16}\,n_{eq}cm^{-2}$

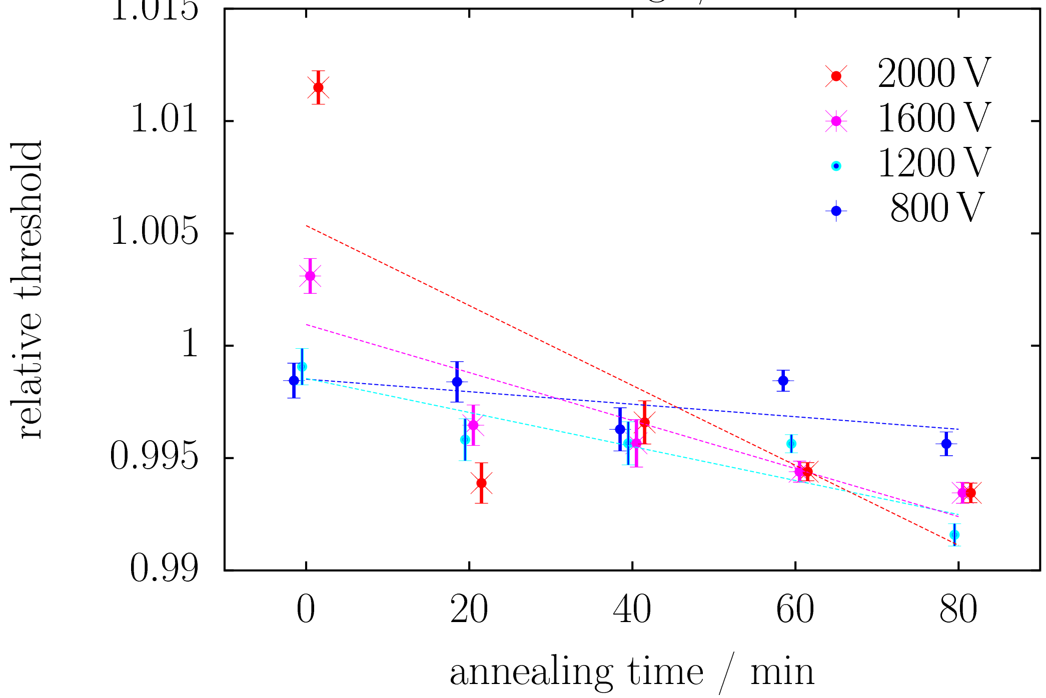
— FE-I3 Threshold —



i.e. electrical characteristics of the front-end chip during annealing

values are derived due to "tuning" steps of the front-end electronics

threshold stays practically constant with sensor bias voltage

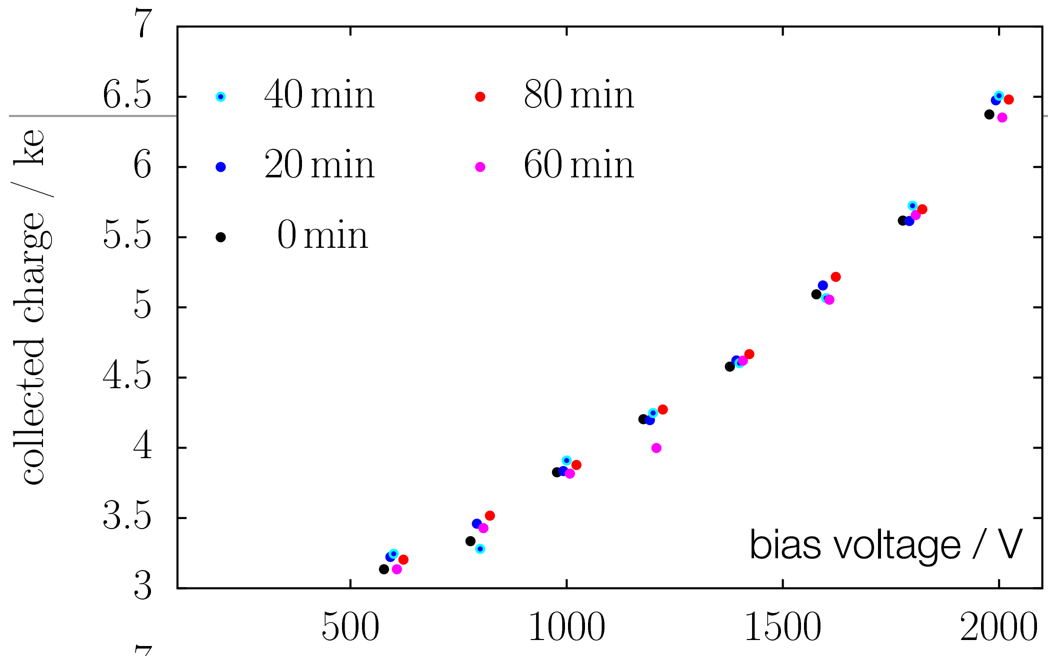


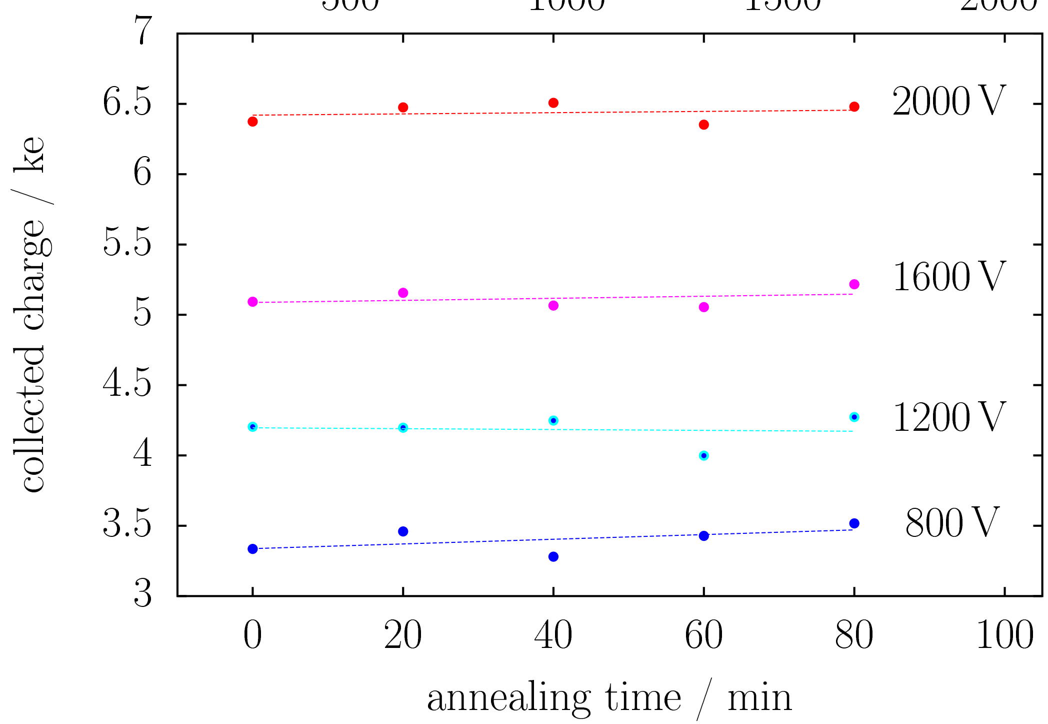
thresholds are compared to values obtained @ 400 V bias voltage

threshold decreases slightly with annealing steps

Annealing Study of an Irradiated Assembly $2\times10^{16}\,n_{eq}cm^{-2}$

— Collected Charge —





i.e. detector characteristics of the pixel sensor during annealing

values are derived from the signal of impinging β particles

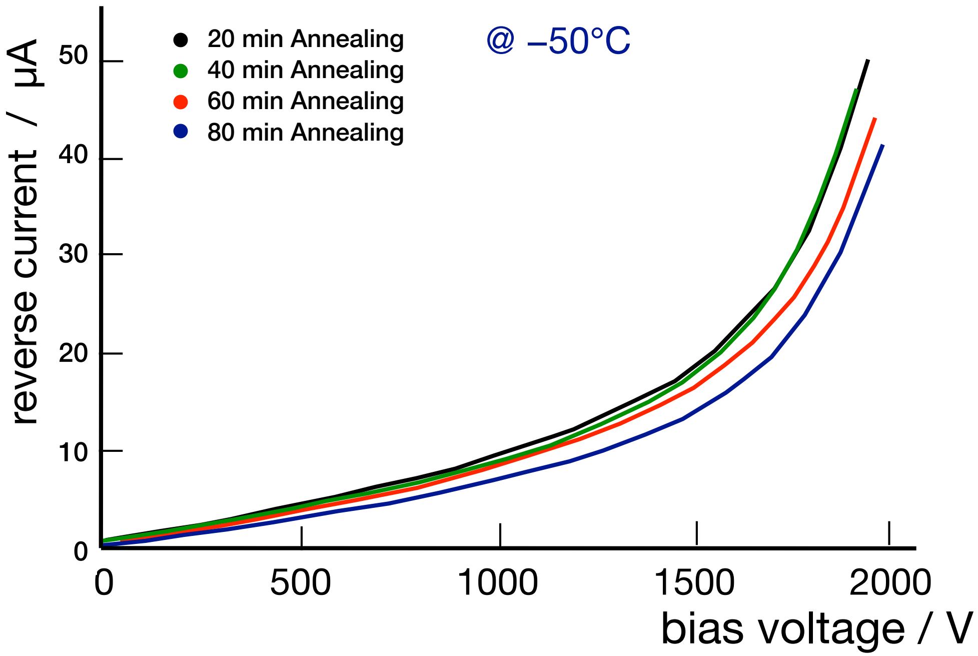
calibrated cluster charge from single pixels

→ collected charge stays constant during annealing

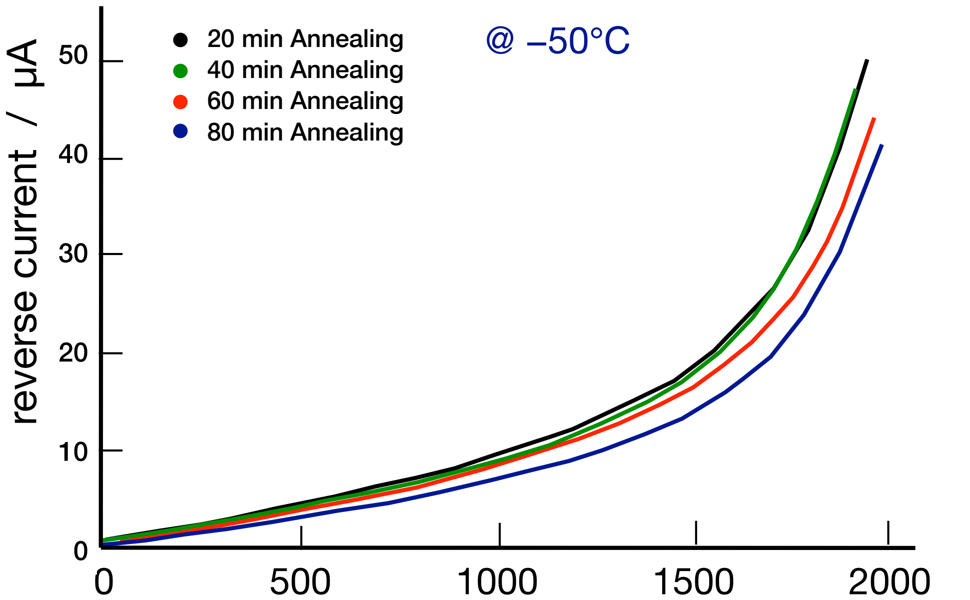
Measurements by Felix Wizemann, TU Dortmund

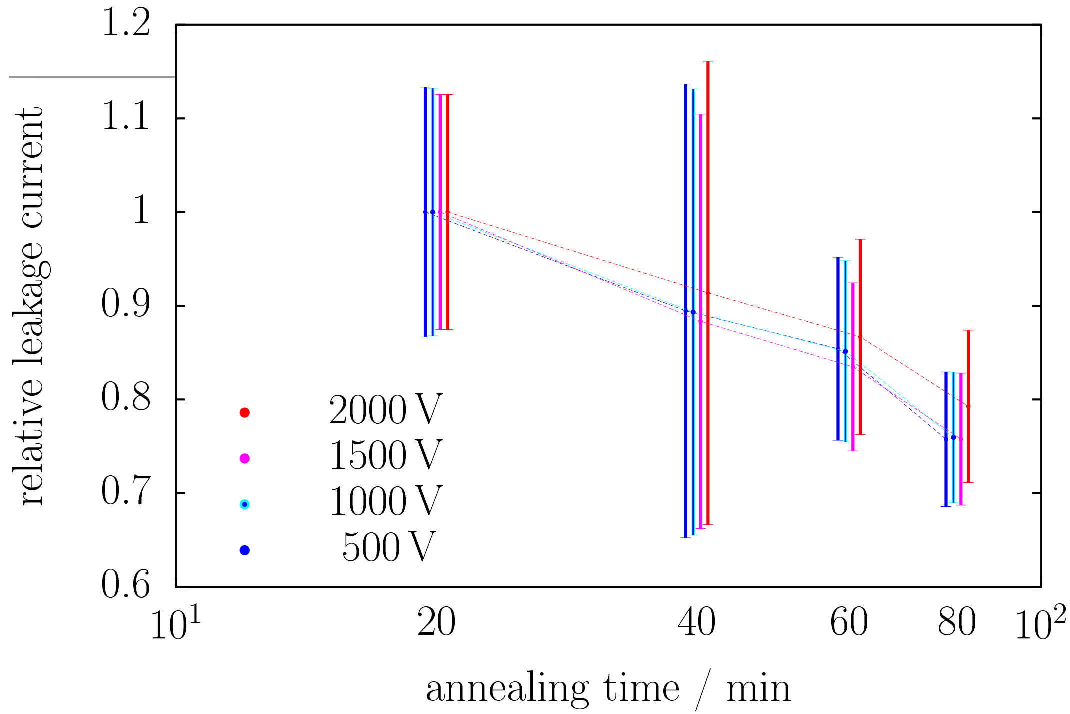
Annealing Study of an Irradiated Assembly $2{\times}10^{16}\ n_{eq}cm^{-2}$

— Leakage Current —



Annealing Study of an Irradiated Assembly — Leakage Current — $2{\times}10^{16}\,n_{eq}cm^{-2}$



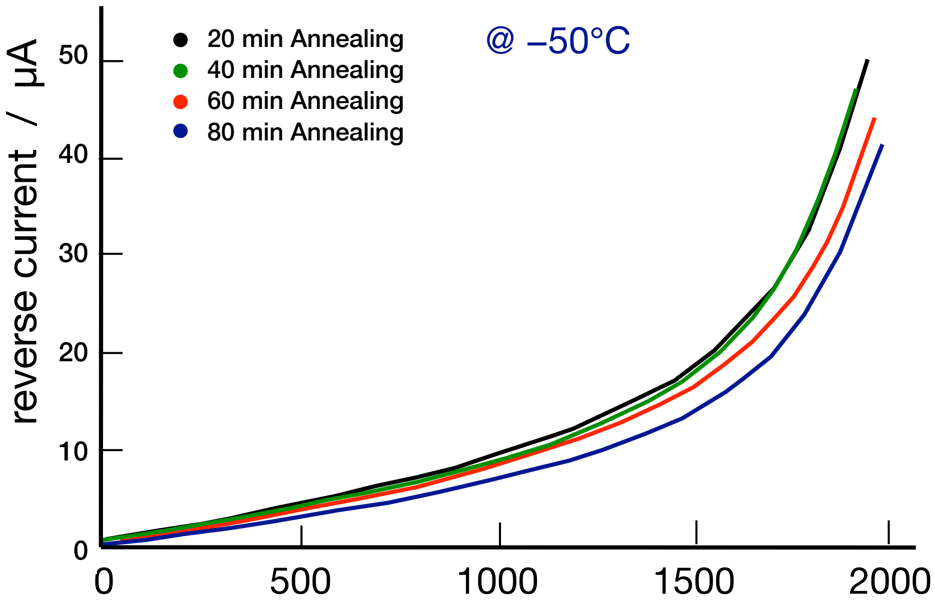


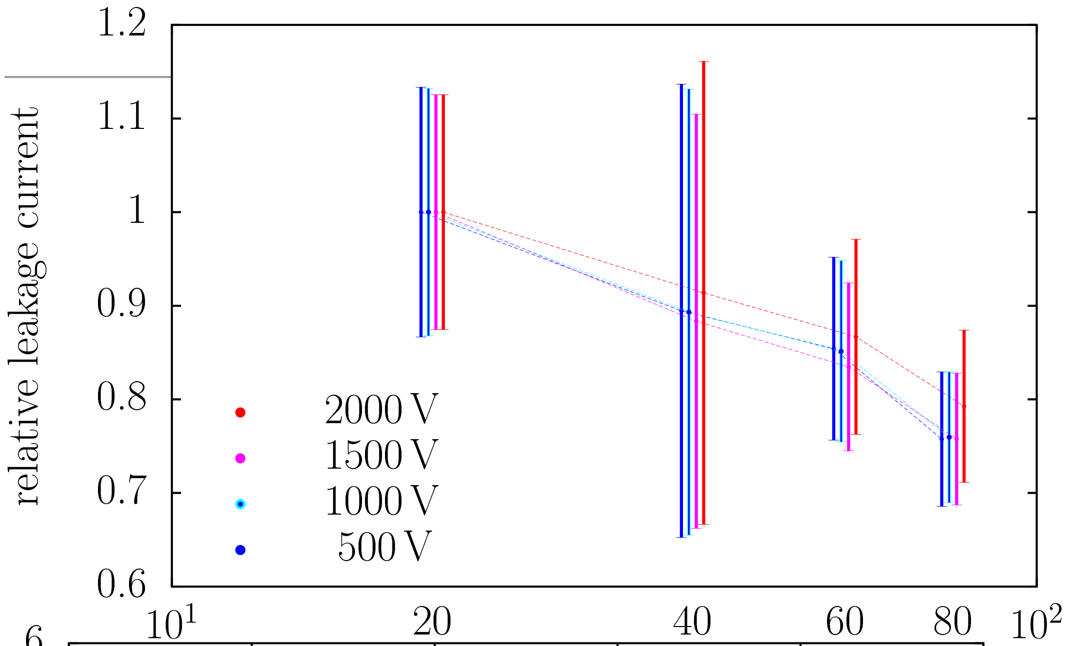
- leakage current decreases during annealing

Measurements by Felix Wizemann, TU Dortmund

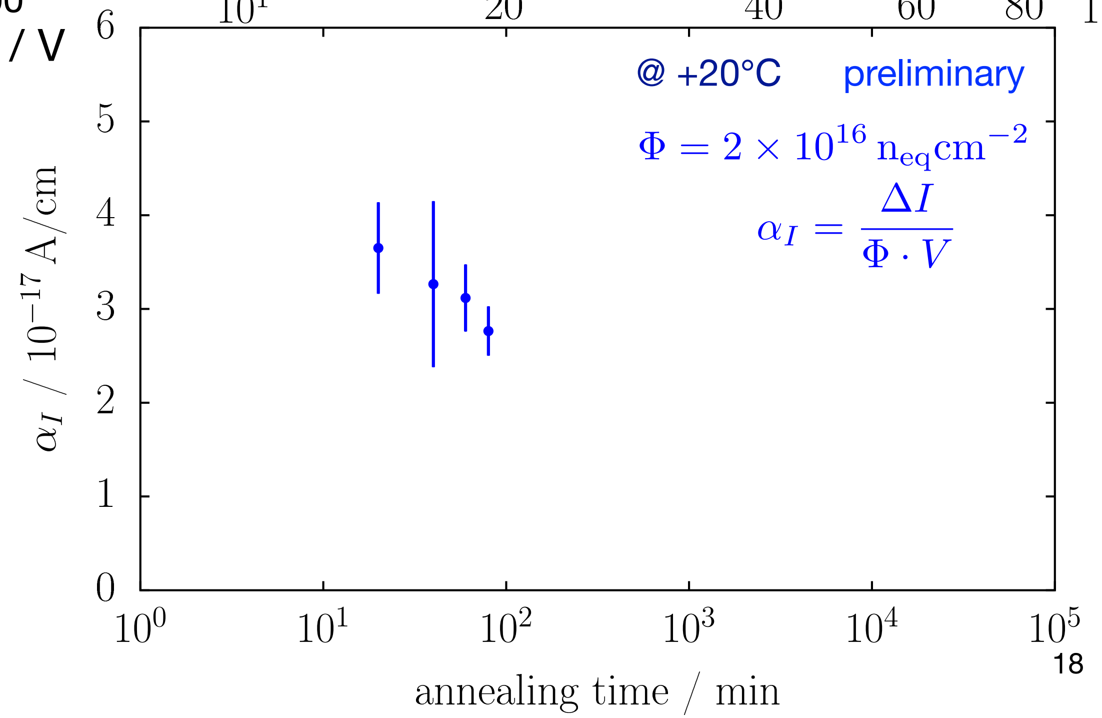
Annealing Study of an Irradiated Assembly — Leakage Current —

$2\times10^{16}\ n_{eq}cm^{-2}$



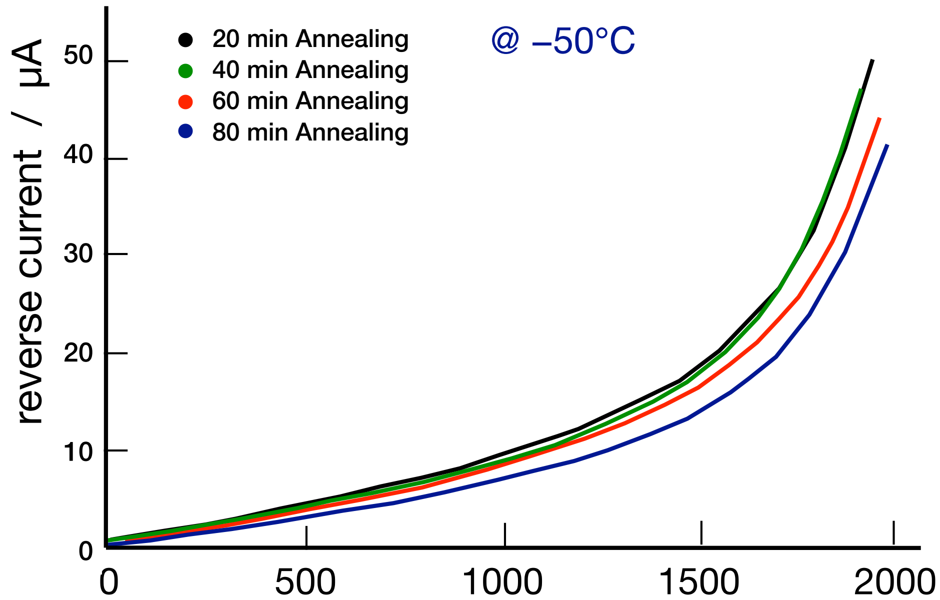


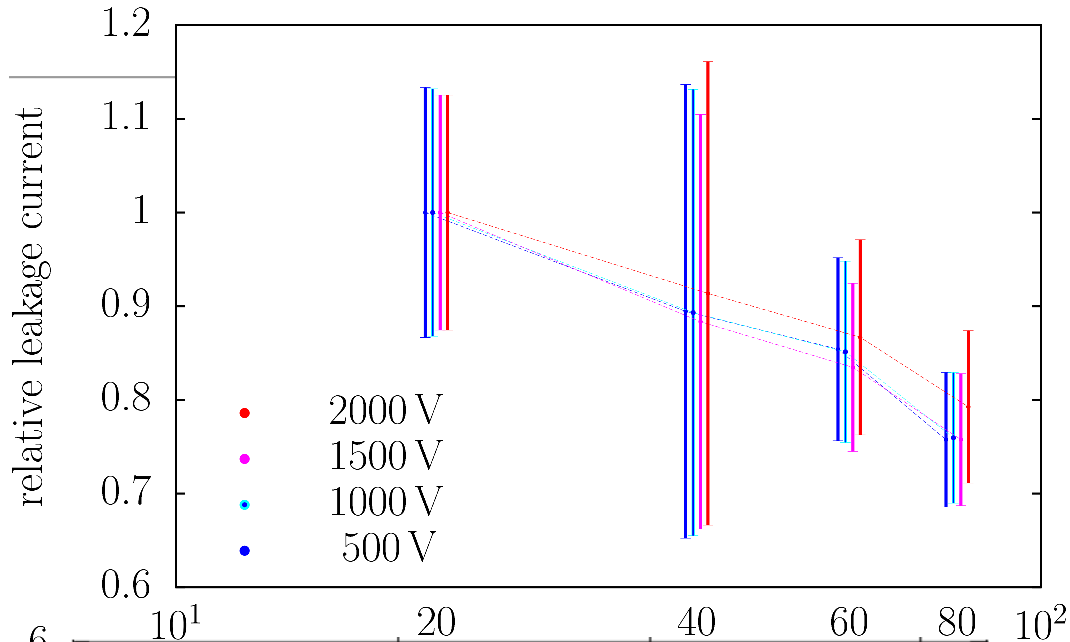
- leakage current decreases during annealing
- current related damage α_I decreases; U_{bias} = 500 V, assuming *full* depletion



Measurements by Felix Wizemann, TU Dortmund

Annealing Study of an Irradiated Assembly — Leakage Current — $2\times10^{16}\,n_{eq}cm^{-2}$





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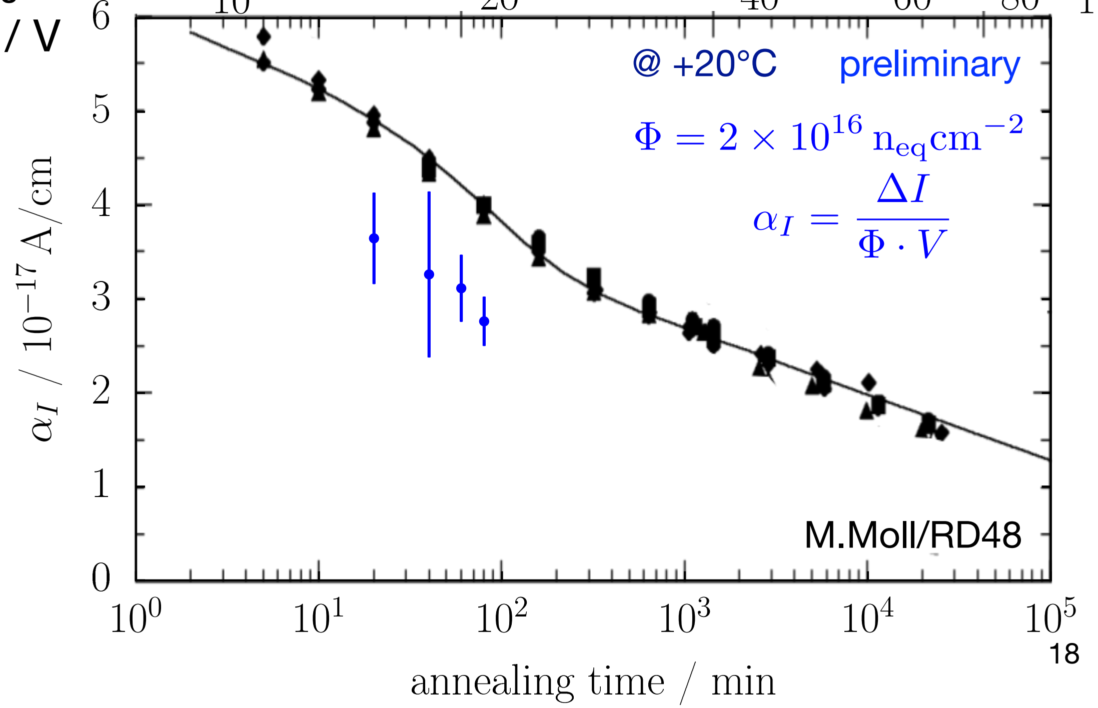
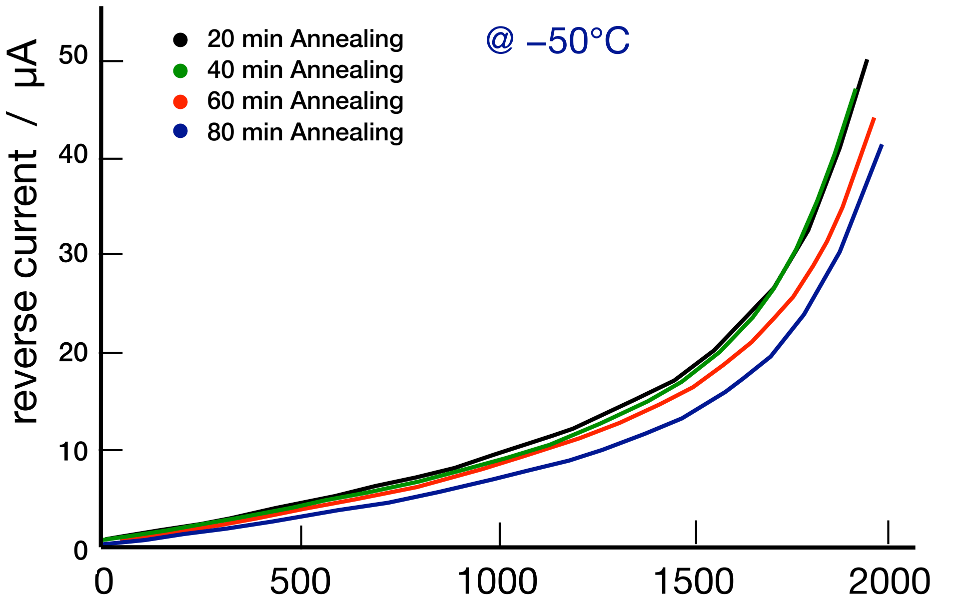


Annealing Study of an Irradiated Assembly $2{\times}10^{16}\,n_{eq}cm^{-2}$

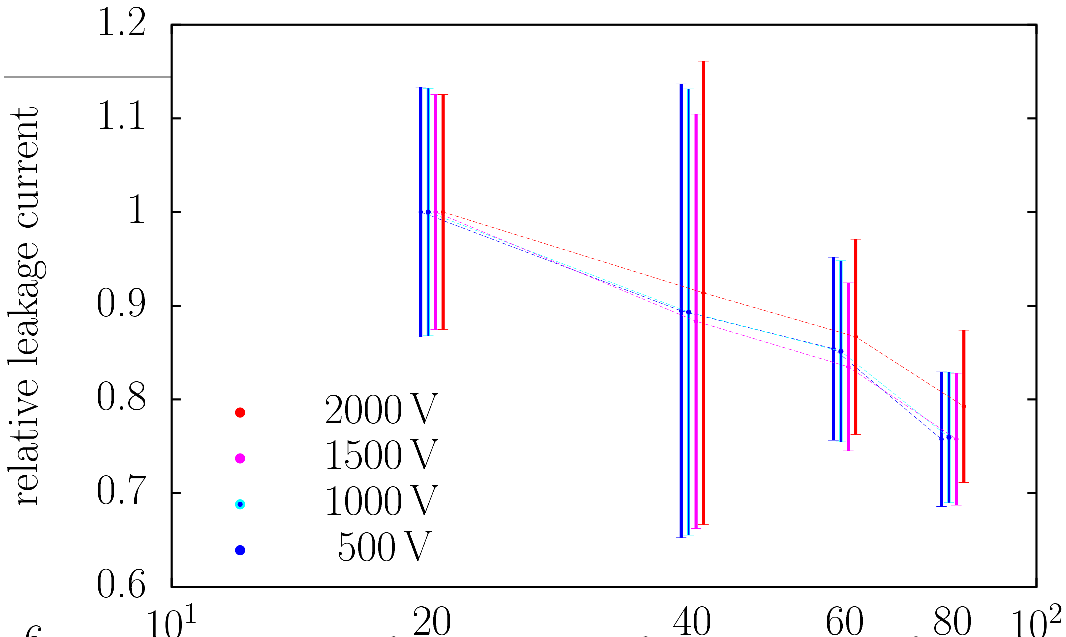
— Leakage Current —

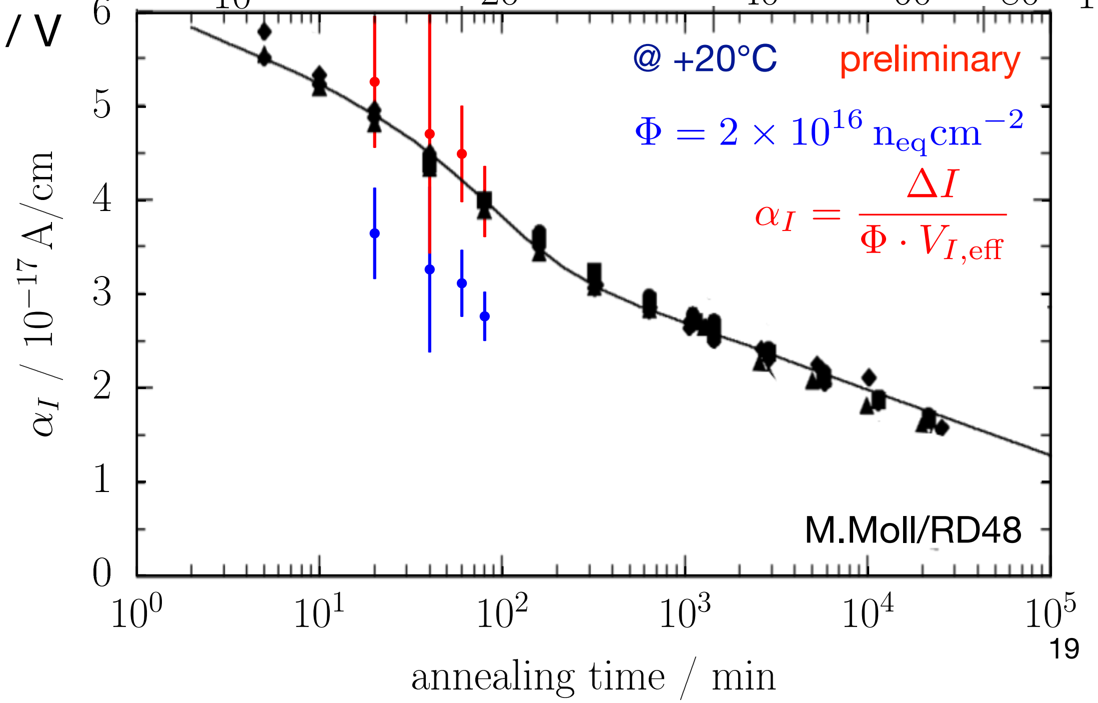


- leakage current decreases during annealing
- current related damage α_I decreases; U_{bias} = 500 V, assuming *full* depletion
- if we assume, that @ 80 min w/ 60°C $\alpha_I = (3.99 \pm 0.03) \times 10^{-17}\,\mathrm{A/cm}$ stays valid for $\Phi = 2 \times 10^{16}\,\mathrm{n_{eq}cm^{-2}}$ we *tentatively* get a current related effective volume of $V_{I,\mathrm{eff}}/V_{\mathrm{geo}} \approx 70\,\%$

41%/38% if E_{eff}=1.21eV/1.12eV/ 1.11eV

$V_{I,eff}/V_{geo}$ ≈ 160%/91%/86% @ U_{bias} = 1000 V





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Annealing Study @ $2\times10^{16}\,n_{eq}cm^{-2}$

investigated **FE-I3** n^+-in-n pixel assembly @ **$2\times10^{16}\,n_{eq}cm^{-2}$** (p), **HL-LHC-like**

annealing @ +60°C in 4 steps à 20 min & measurements @ $T \approx -50$°C

- observe (slight) changes in **FE tuning** with annealing
- observe stable **charge collection** with annealing
- **leakage currents** decrease with annealing, comparison with $\boldsymbol{\alpha_I}$ (@ +20°C)

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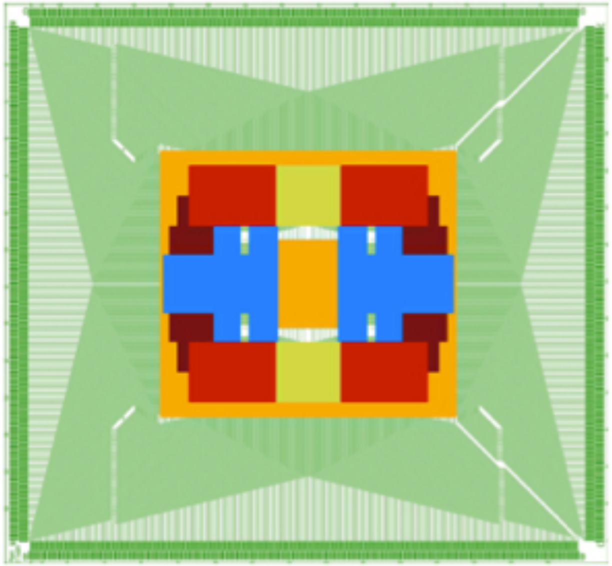
Study of Single Pixels on n-in-n Sensors



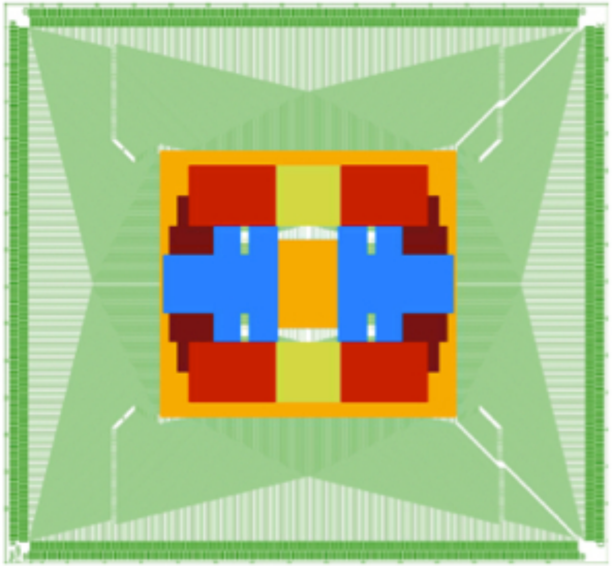
FE-I3 Fan-out

- single pixel
- 33 % of possible single pixels
- 20 % of possible single pixels
- pseudo strip structure (four pixel interconnected in one row)
- pseudo pad structure (interconnected pixels of diverse quantity)

Design by Georg Troska, TU Dortmund

single pixels
arrays of 2 pixels
arrays of 4 pixels
arrays of 15 pixels
arrays of 32 pixels
arrays of 60 pixels

Study of Single Pixels on n-in-n Sensors



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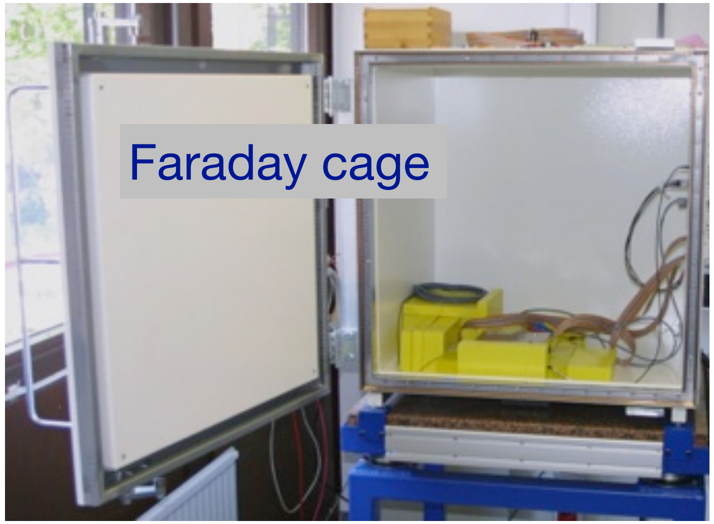
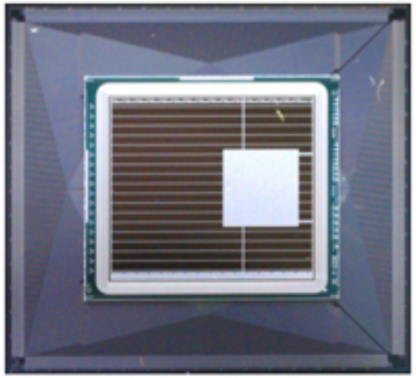
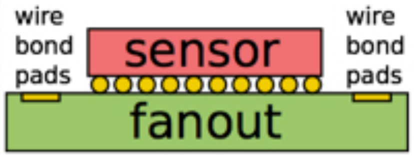
Design by Georg Troska, TU Dortmund

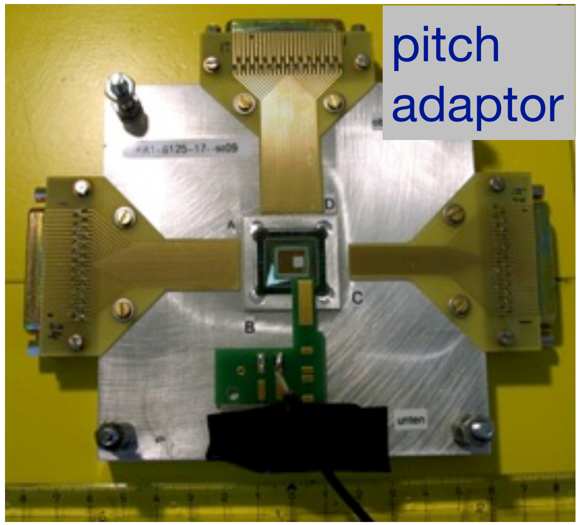


single pixels
arrays of 2 pixels
arrays of 4 pixels
arrays of 15 pixels
arrays of 32 pixels
arrays of 60 pixels

FE-I3 Fan-out



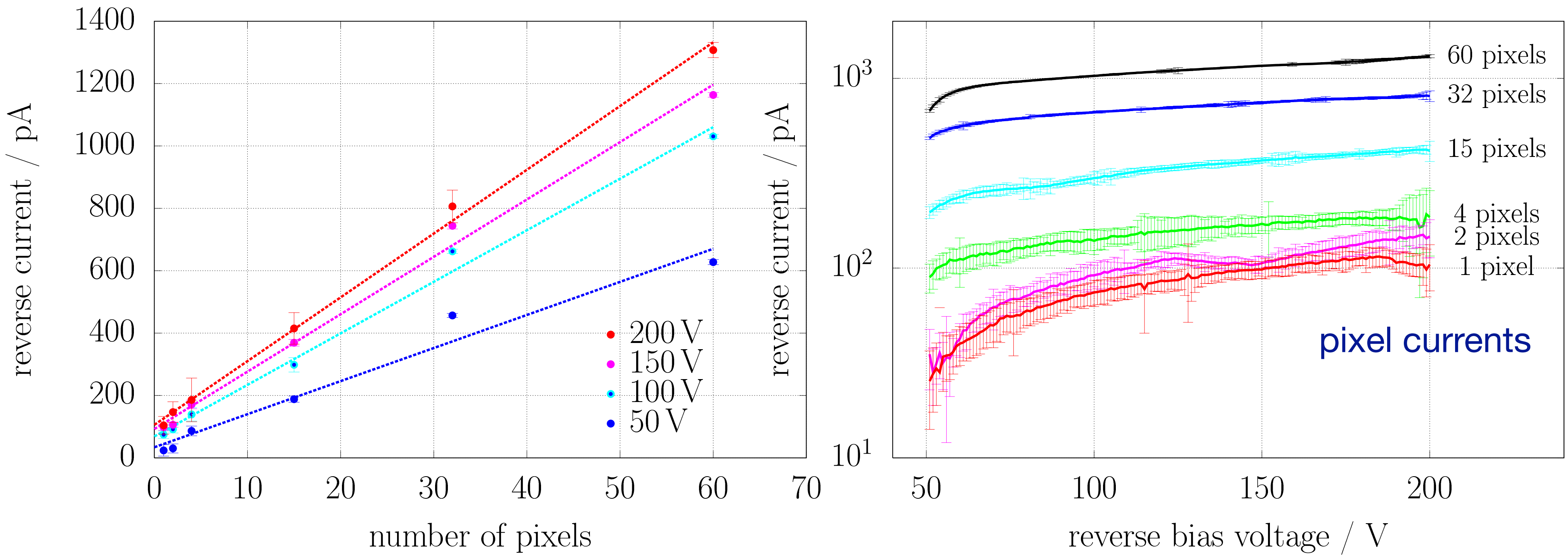




Measurements by Mona Abt, TU Dortmund

non-irradiated, room temperature

Leakage Currents



currents at fixed voltages

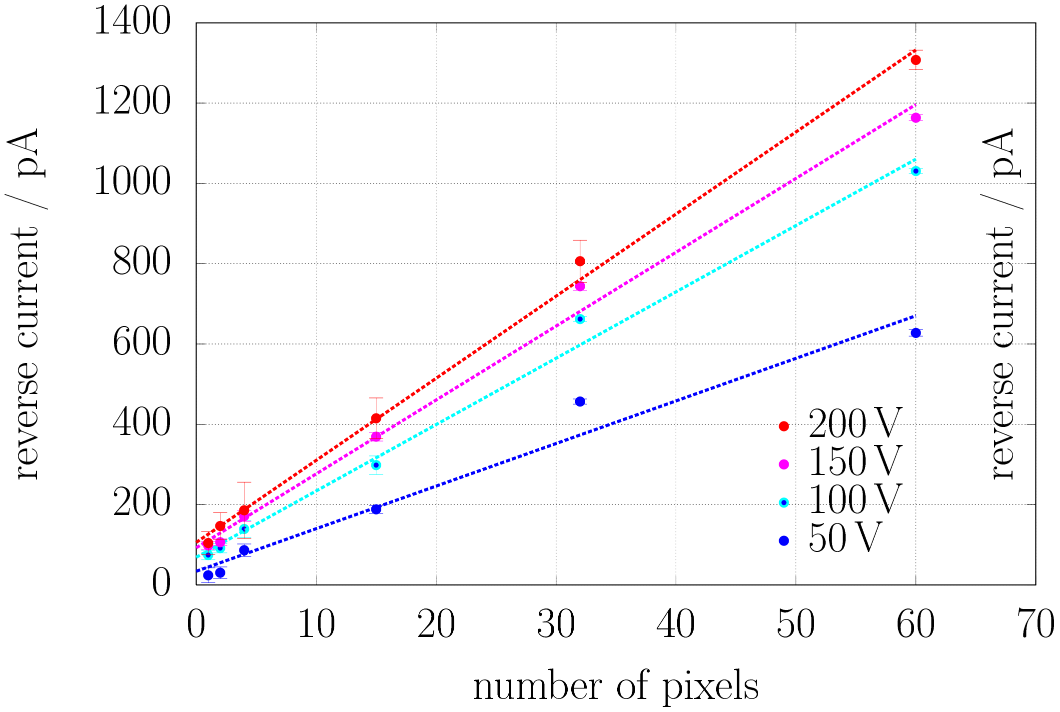
- linear trend of current *vs*. number of pixels

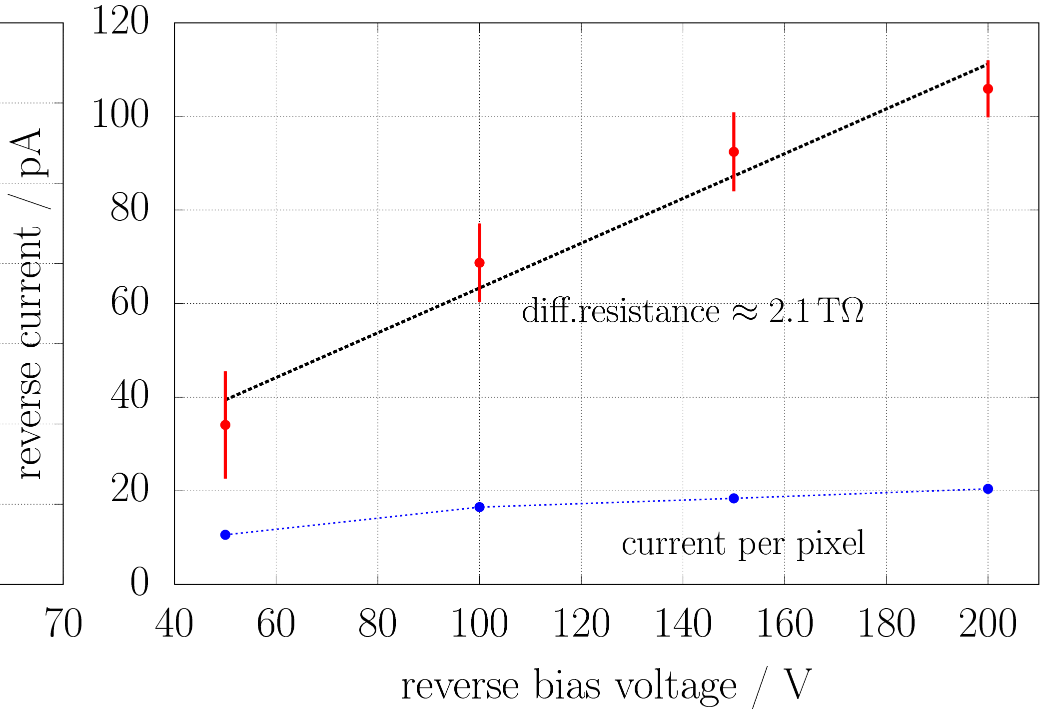
- non-irradiated sensors deplete at around 80 V bias voltage
- typical operation voltage 150 V

Measurements by Mona Abt, TU Dortmund

non-irradiated, room temperature

Leakage Currents





currents at fixed voltages

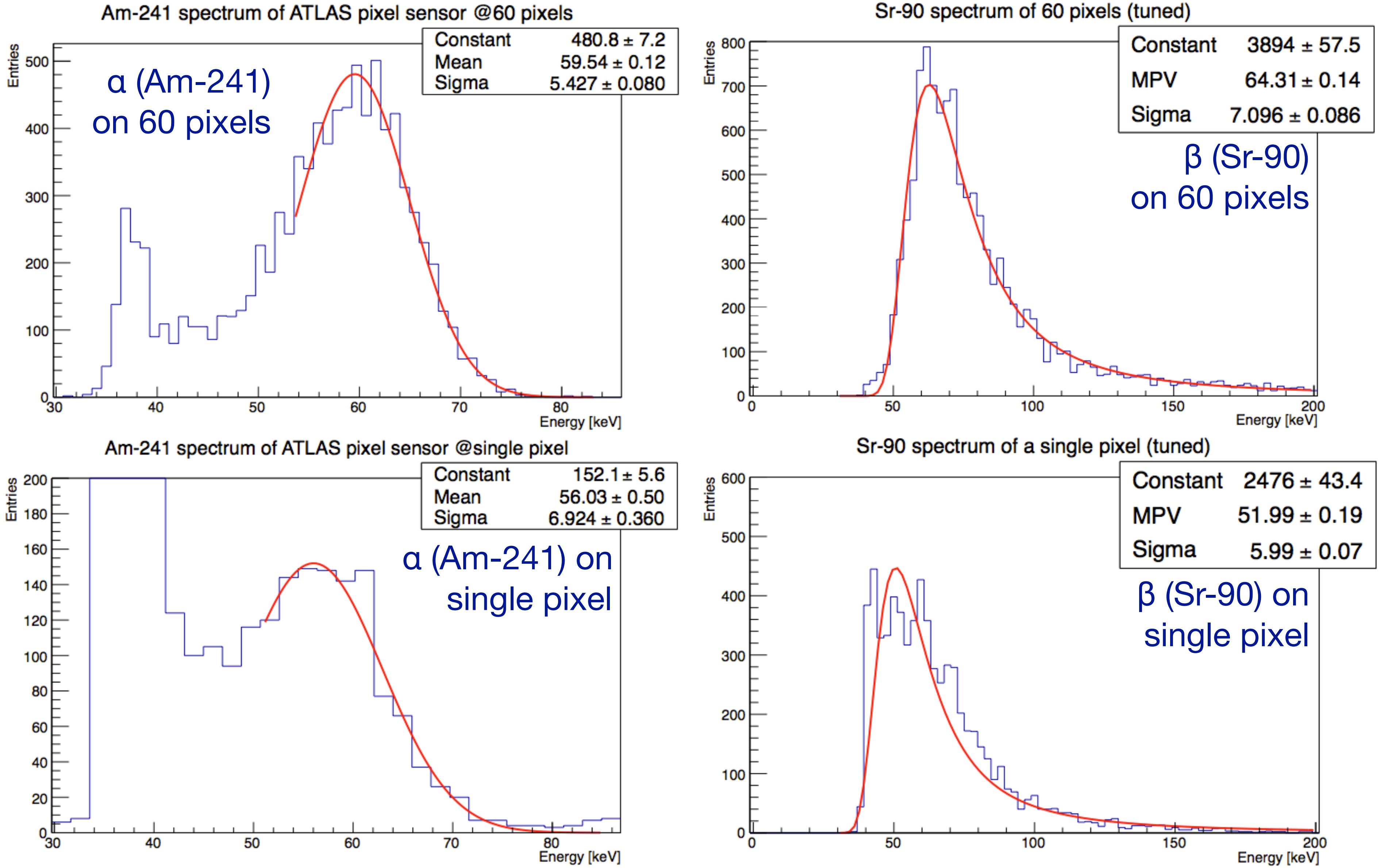
- linear trend of current *vs*. number of pixels

currents per pixel

- typical values ≈ 10 to 20 pA
- sensitive to parallel resistance / conductance of ≈ 2 TΩ or 0.5 pS ⇔ current offsets of 40 to 100 pA

non-irradiated, room temperature

Energy Calibration and Charge Collection

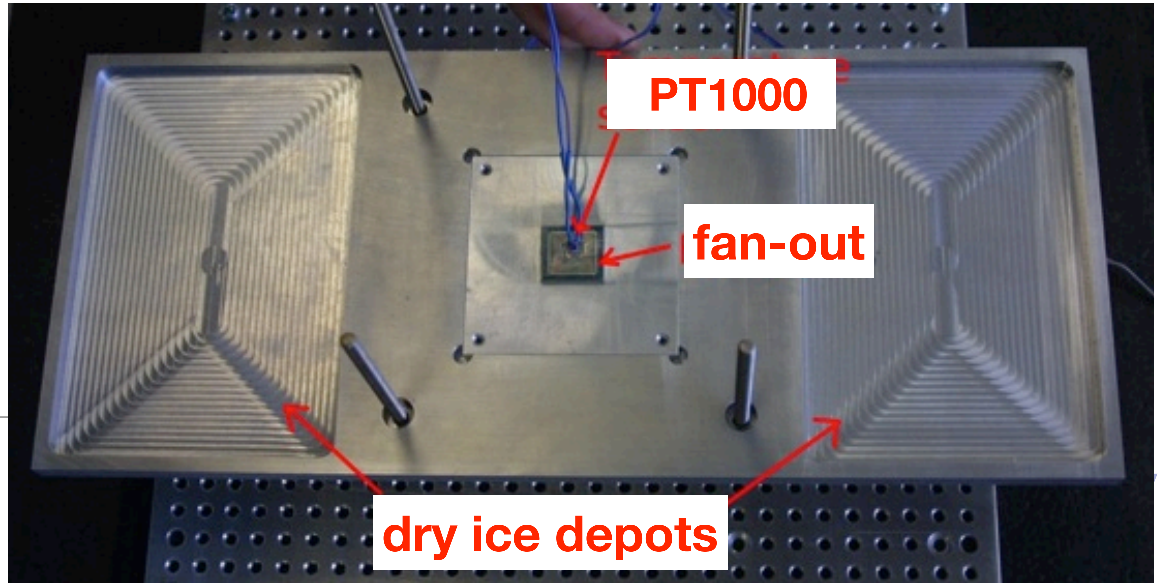


Study of Single Pixels on n^+-in-n Sensors

so far, measurements at room temperature on non-irradiated sensors

- were able to **measure** & **read-out single pixels** w/o front-end electronics
- plan to measure **irradiated** sensors at **lower temperatures**

FE-I3 fan-out
with cooling block,
PT1000 sensor,
and dry ice depots



Temperature-Dependent Measurements of n-in-n Pixel Sensors

Introduction

Temperature Dependence @ $6 \times 10^{15}\ n_{eq}cm^{-2}$ (p)
Annealing Study @ $2 \times 10^{16}\ n_{eq}cm^{-2}$ (n)
Single Pixel Measurements, non-irradiated

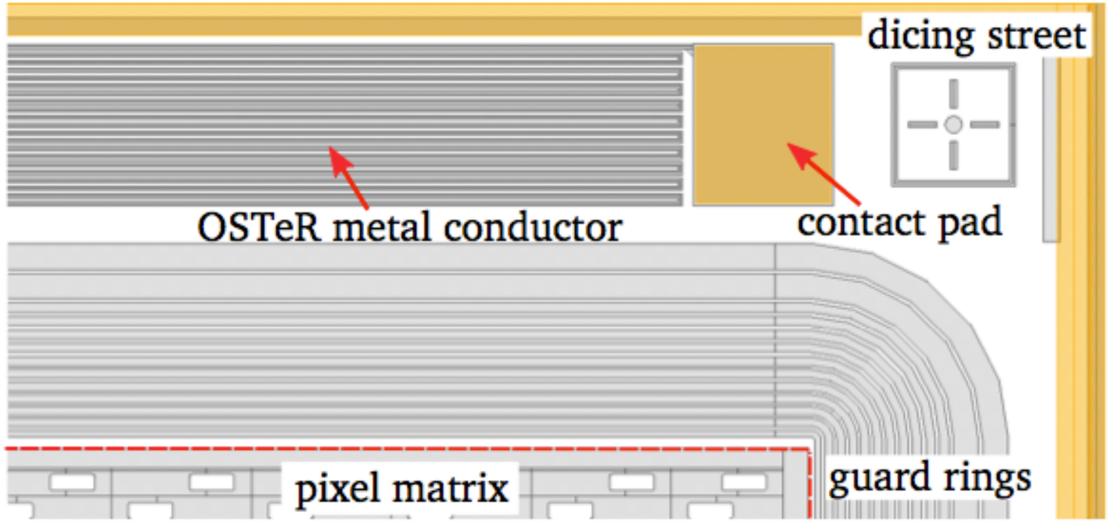
On-Sensor Temperature Resistors
Sensor Design for LHC Phase II Upgrades

Conclusion: Summary & Outlook

Reiner Klingenberg, TU Dortmund University

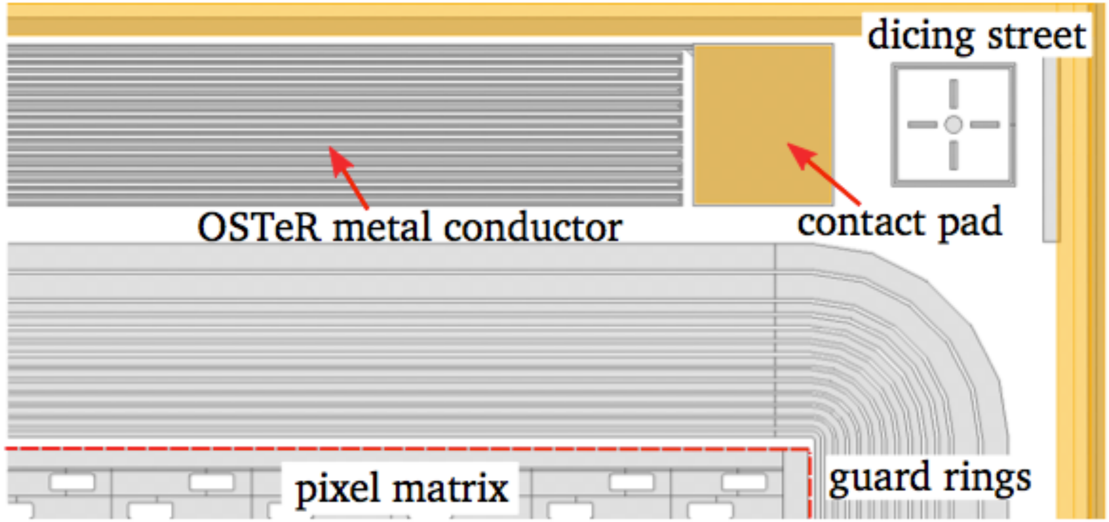
GEFÖRDERT VOM Bundesministerium für Bildung und Forschung

On-Sensor Temperature Resistors



- on FE-I4 single-chip and 2×1 double-chip sensors on-sensor temperature resistors have been placed
- conductor AlSi ~7 μm wide, 203 mm long
- typical resistance ~700 to 800 Ω

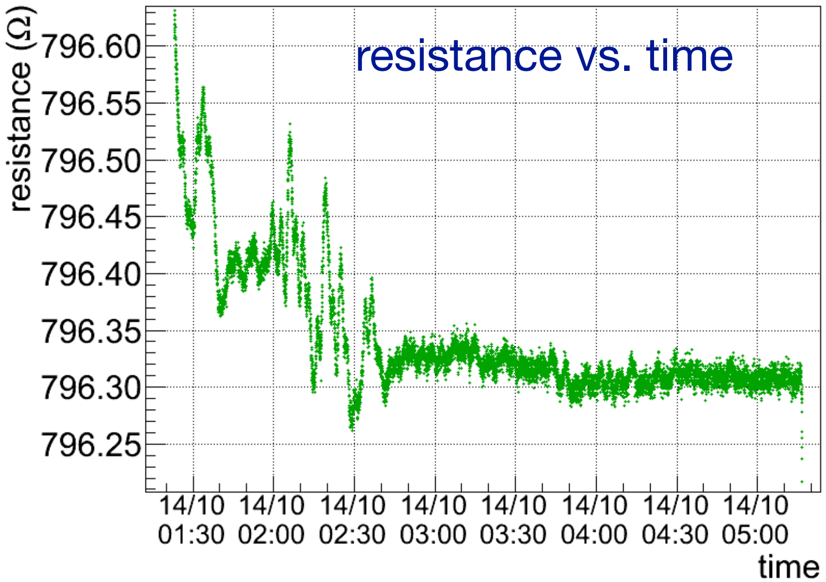
On-Sensor Temperature Resistors

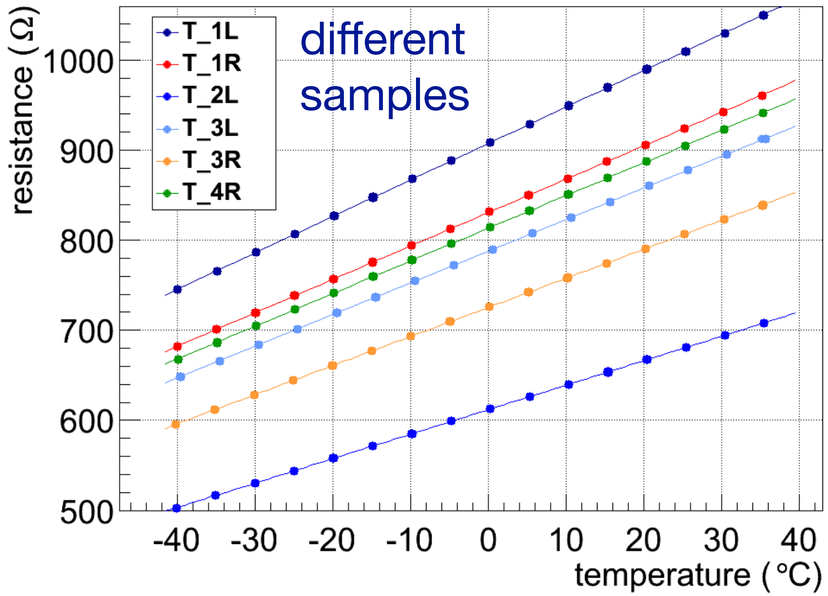


- on FE-I4 single-chip and 2×1 double-chip sensors on-sensor temperature resistors have been placed
- conductor AlSi ~7 μm wide, 203 mm long
- typical resistance ~700 to 800 Ω

validate and calibrate temperature dependence

$$R(T) = R(T_0) + m \cdot (T - T_0)$$



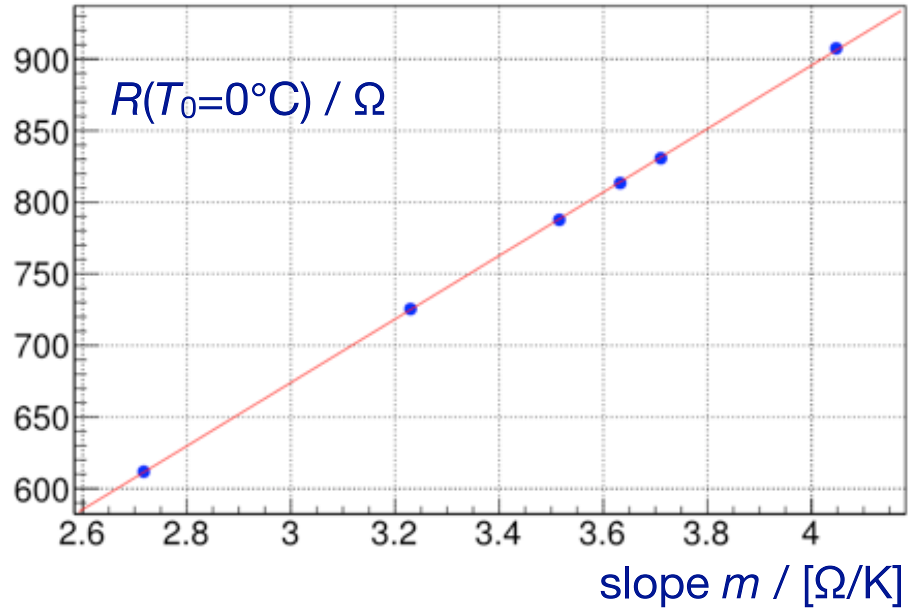


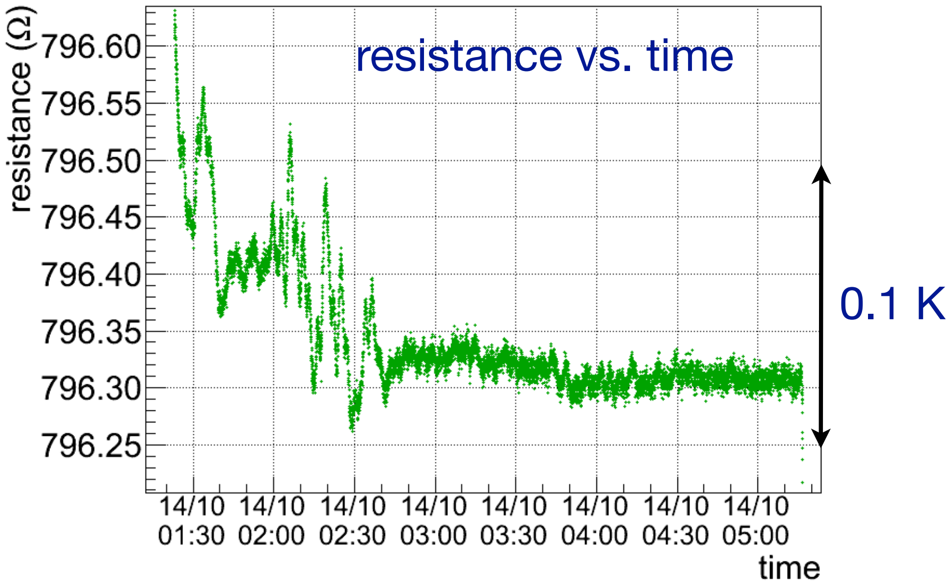
On-Sensor Temperature Resistors: Calibration

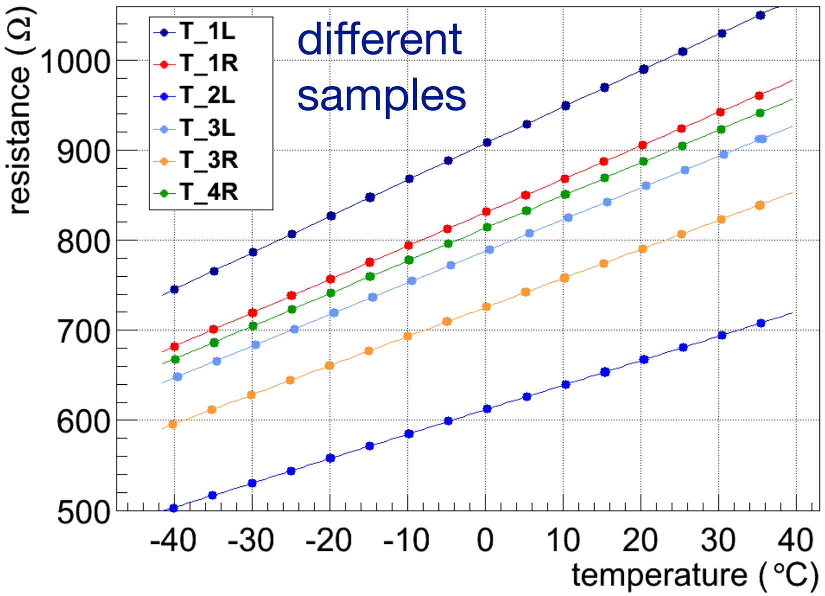
correlation between off-set resistance and slope *m* allows to calibrate temperature sensors with a single measurement

$$R(T) = R(T_0) + m \cdot (T - T_0)$$

expected (statistical) accuracy ≲ 0.1 K

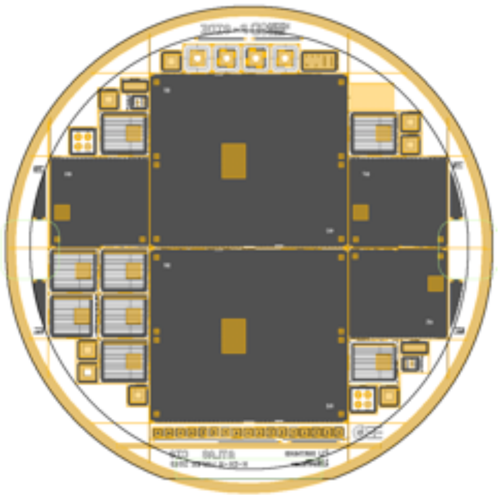


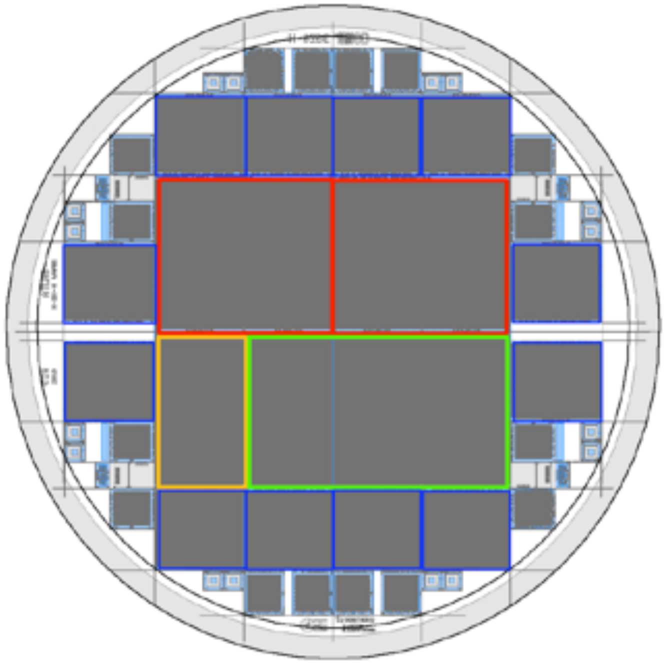




Design by T.Wittig & A.Kompatscher, TU Dortmund/CiS

n^+-in-n Pixel-Sensor Design for LHC Phase II Upgrades





4" wafer production started at CiS

includes 3 FE-I4 SC
and 2 FE-I4 2×2 QUADS

⟨111⟩ and ⟨100⟩

first wafers ready for tests

laser direct imaging

6" wafer production is foreseen

includes FE-I4 SC
and 2 FE-I4 2×2 QUADs

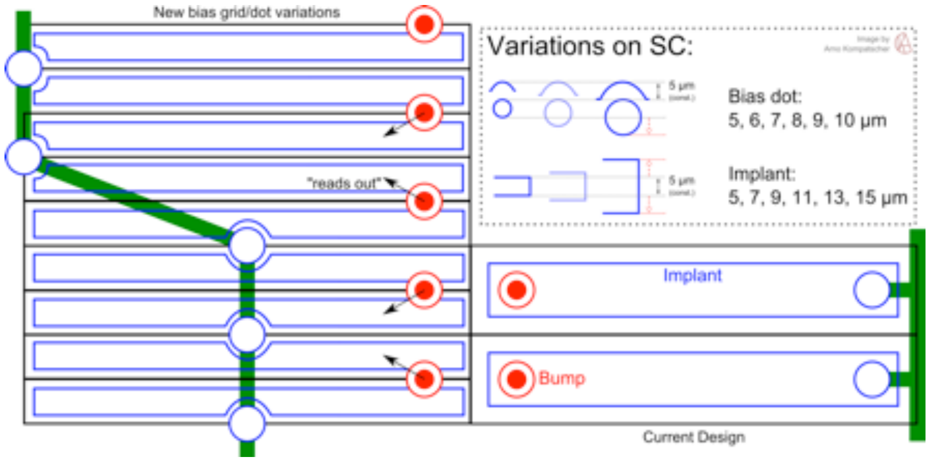
plus 1×2 ALPINEs
and 3×2 HEXs

design ready by end of September 2013

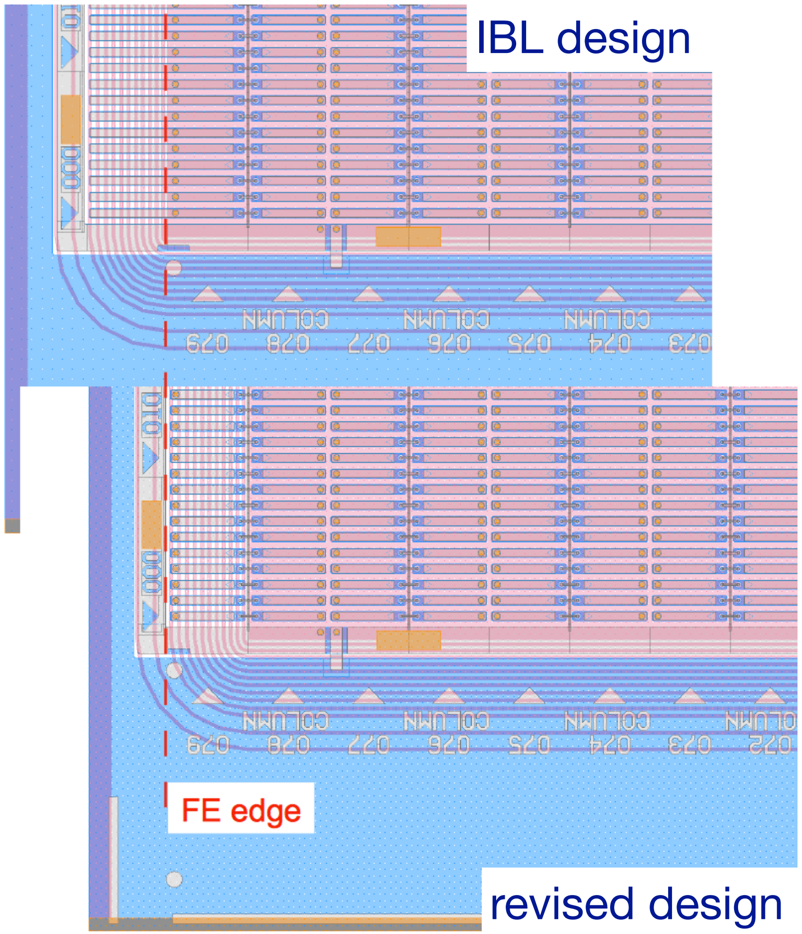
Some Design Details

all designs include on-sensor temperature resistors

SC for R&D: study various pixel sizes & shapes, implants, bias grid sizes & positions



will reduce sensor edge by shrinking edge pixel length from 400 to 250 µm



technische universität dortmund

Conclusion: Summary & Outlook

- **IBL-like conditions**: investigated front-end tuning with temperature, measured reverse current changes and checked parameterizations
- **HL-LHC-like irradiation**: annealing study, checked FE features & charge collection, current related damage α_I decreases with annealing
- **single-pixel measurements** on non-irradiated sensors @ room temperature, reverse currents & charge collection with single pixels
- **design studies**
  on-sensor temperature resistors & sensors for LHC phase II upgrades

Reiner Klingenberg, TU Dortmund University

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