Measurements of the effective bandgap and current related damage rate of highly irradiated silicon sensors

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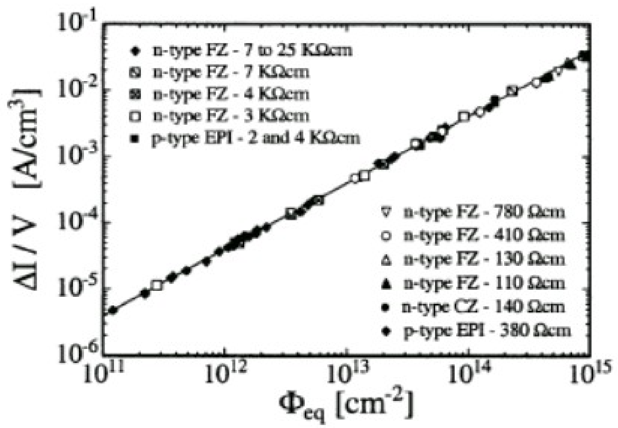
Outline

- Introduction: Leakage Current
- Setup
- Results for effective bandgap $E_{g,eff}$
- Results for current related damage rate α*
- Conclusion

Introduction: Leakage Current

Leakage current after irradiation is proportional to irradiation fluence by **Current-Related-Damage-Rate α**:

$$I(\Phi_{eq}) - I_0 = \Delta I = \alpha\, \Phi_{eq}\, V$$



Radiation damage in silicon detectors, Gunnar Lindström

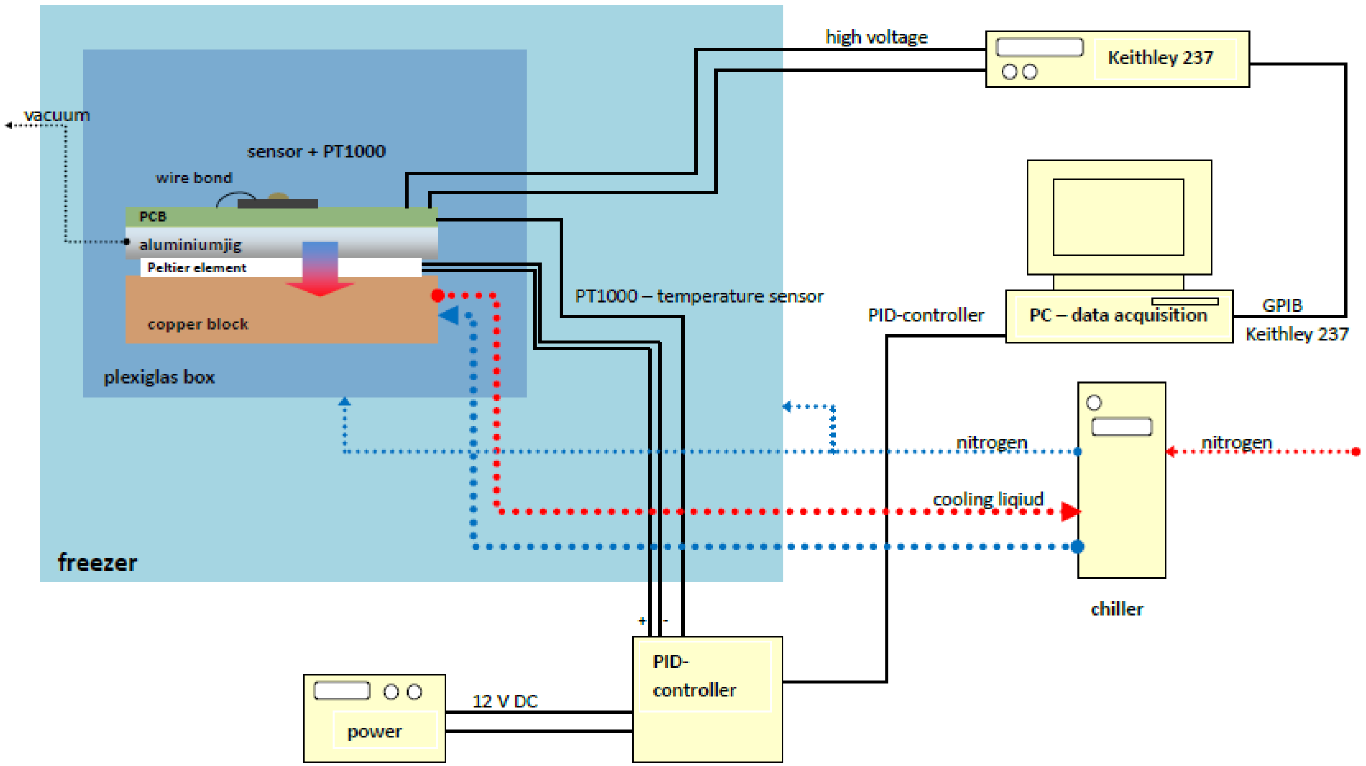
Calculation of temperaturedepence with **scalingparameter $E_{g,eff}$** :

$$I(T_2) = I(T_1) \cdot \left(\frac{T_2}{T_1}\right)^2 e^{-\frac{E_{g,eff}}{2k_B}\left(\frac{1}{T_2} - \frac{1}{T_1}\right)}$$

IV-measurements were performed at low temperatures (-23°C, -27°C, -32°C) for different sensors to estimate $E_{g,eff}$ and α*.

Depleted volume is unknown
→ physical volume is used for calculation
(see also: Sven Wonsak et al. *Measurements of the reverse current of highly irradiated silicon sensors*)

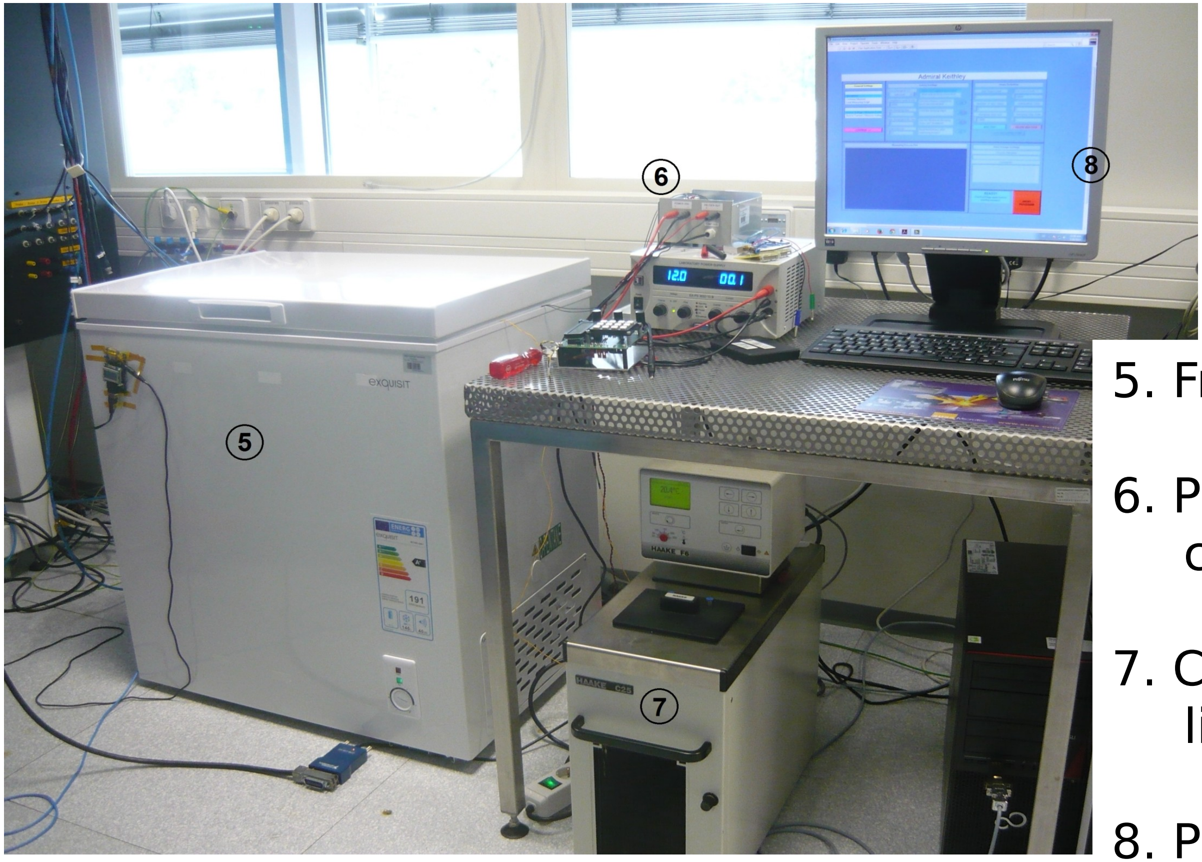
IV-Setup



Improved features of new setup:

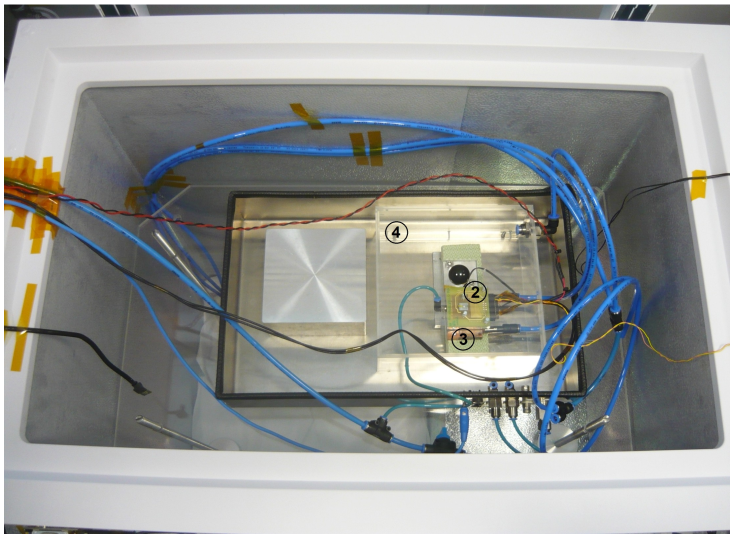
- Easy handling, due to PCBs
- Temperature measured by PT1000 directly on top of sensor
- No ingress of moisture
- Stable surrounding temperature (freezer)
- Temperature controlled by PID-Controller

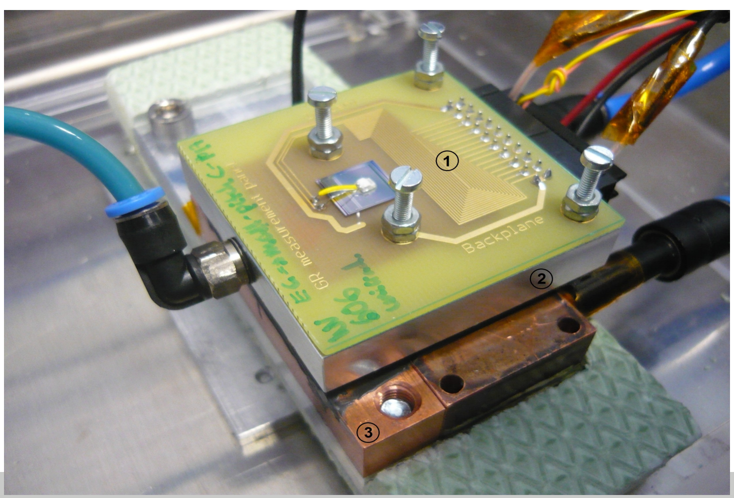
IV-Setup



5. Freezer
6. PR-59-temperature controller
7. Chiller with colling liquid
8. PC for data acquisition

IV-Setup



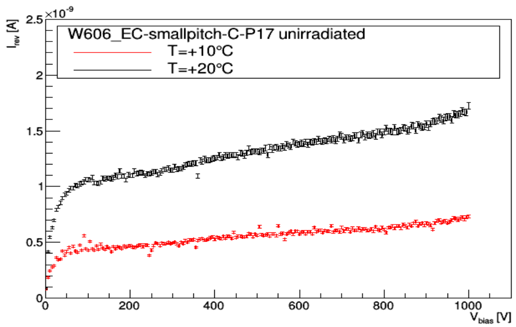


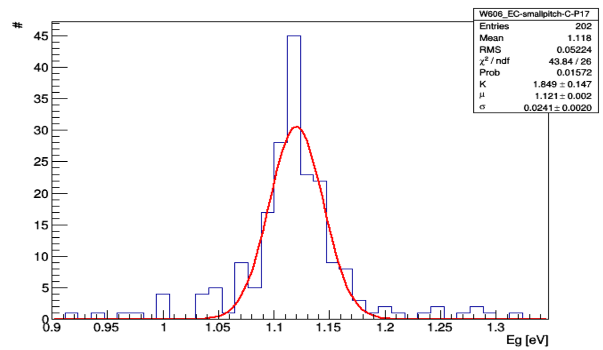
1. „Printed Circuit board“ with sensor glued on top
2. Aluminiumjig for mounting PCB
3. Cooling unit (Peltier element, copper block)
4. Plexiglas cover

Nr.	Sensor	d [μm]	Φ_{eq} [n_{eq}/cm^2]
1	HPK W277-BZ5-P23	293	$2 \cdot 10^{14}$
2	Micron 2437-14-M	143	$2 \cdot 10^{14}$
3	Micron 2437-14-O	143	$5 \cdot 10^{14}$
4	Micron 2437-14-Q	143	$1 \cdot 10^{15}$
5	HPK W264-BZ5-P23	293	$2 \cdot 10^{15}$
6	Micron 2437-14-S	143	$2 \cdot 10^{15}$
7	HPK W72-BZ3-P18	293	$5 \cdot 10^{15}$
8	Micron 2437-14-F	143	$5 \cdot 10^{15}$
9	HPK W73-BZ2-P20	293	$1 \cdot 10^{16}$
10	Micron 2437-14-G	143	$1 \cdot 10^{16}$
11	HPK W104-BZ2-P2	293	$1,5 \cdot 10^{16}$
12	HPK W104-BZ2-P17	293	$2 \cdot 10^{16}$
13	Micron 2437-14-H	143	$2 \cdot 10^{16}$
14	Micron 3107-6-3	50	$1 \cdot 10^{15}$
15	Micron 3107-6-9	50	$2 \cdot 10^{15}$
16	Micron 3107-6-10	50	$5 \cdot 10^{15}$
17	Micron 3107-6-14	50	$1 \cdot 10^{16}$
18	Micron 3107-6-21	50	$2 \cdot 10^{16}$

active area of sensors:
Hamamatsu (HPK): (0, 8348 × 0, 86)cm 2
Micron: (1, 0985 × 1, 0973)cm 2
(only n-in-p-sensors used)

Performance of setup

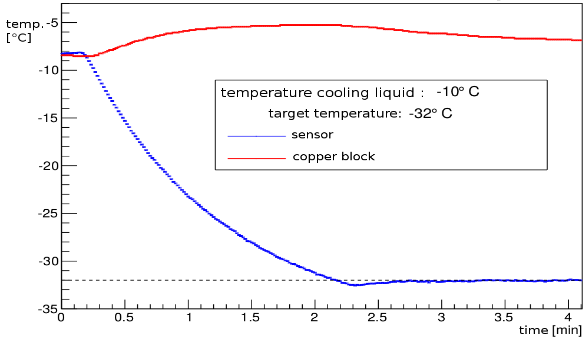


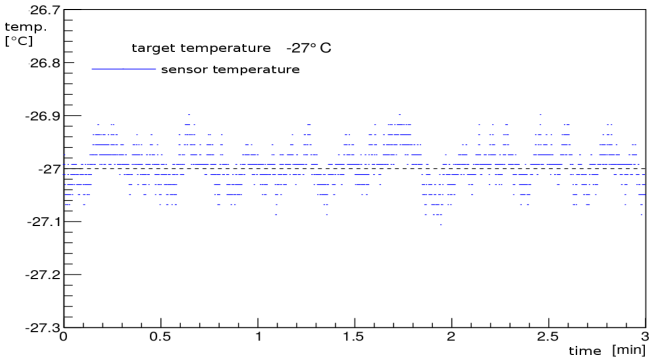


Measurement of unirradiated sensor results in expected value of $E_{g,eff} = 1.12$ eV

Ten IV-measurements of irradiated sensor at T = −23°C :

→ mean standard deviation (0, 926 ± 0, 0018) % for every current measurement



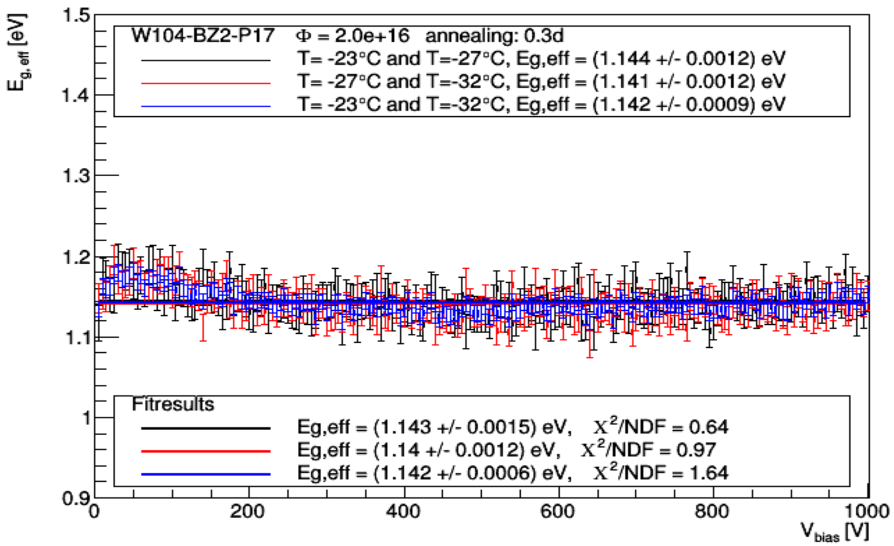


Measured sensor temperature does not deviate by more than 0.15°C from target temperature. (optimized PID parameters, unbiased sensor)

$E_{g,eff}$ - methods

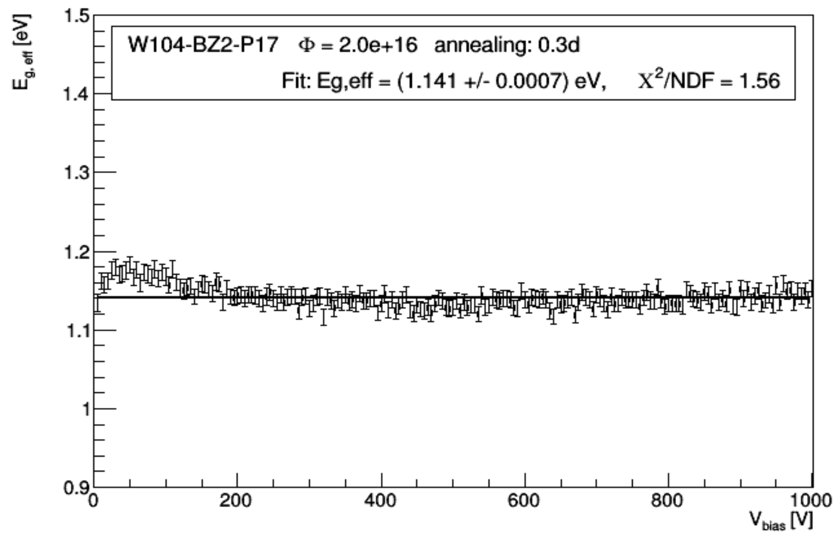
Scaling method:
Calculate $E_{g,eff}$ for every set of two temperatures

$$E_{g,eff} = -2k_B \frac{T_1 T_2}{T_1 - T_2} \cdot \ln\left[\frac{I_2 T_1^2}{I_1 T_2^2}\right]$$



Fit method:
Perform fit of set of measurements

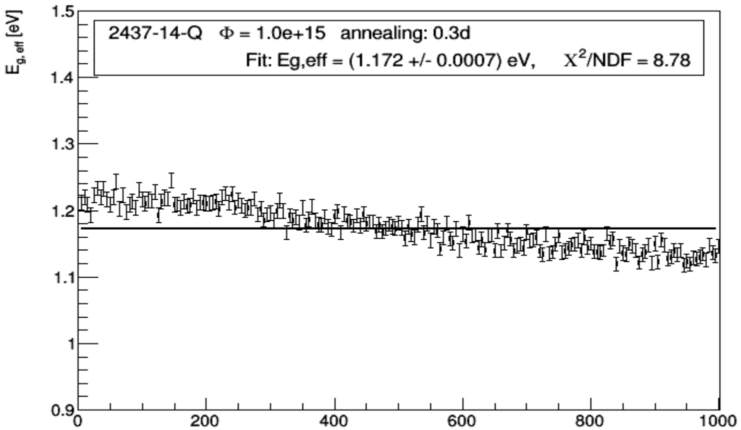
$$I(T) = A \cdot T^2 \, e^{-\frac{E_{g,eff}}{2k_B T}}$$

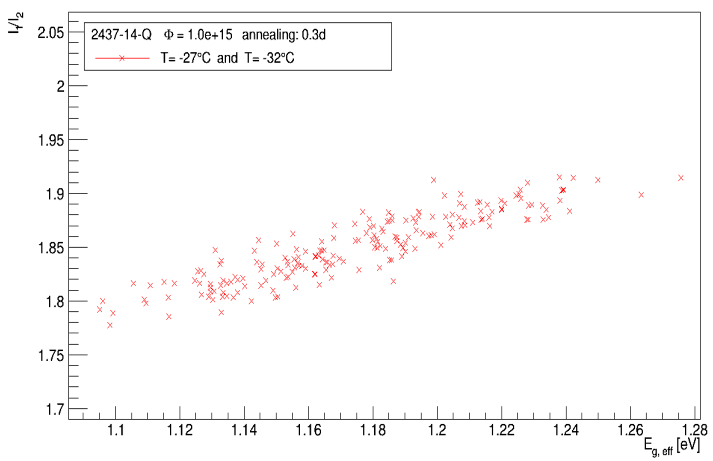


uncertainty on each value: measurement uncertainty + correlation.
but dominant uncertainty: systematic variation of calculated values with voltage. (up to 0, 1 eV for some sensors)

HPK 293 um

Caveat: $E_{g,eff}$ dependence on voltage





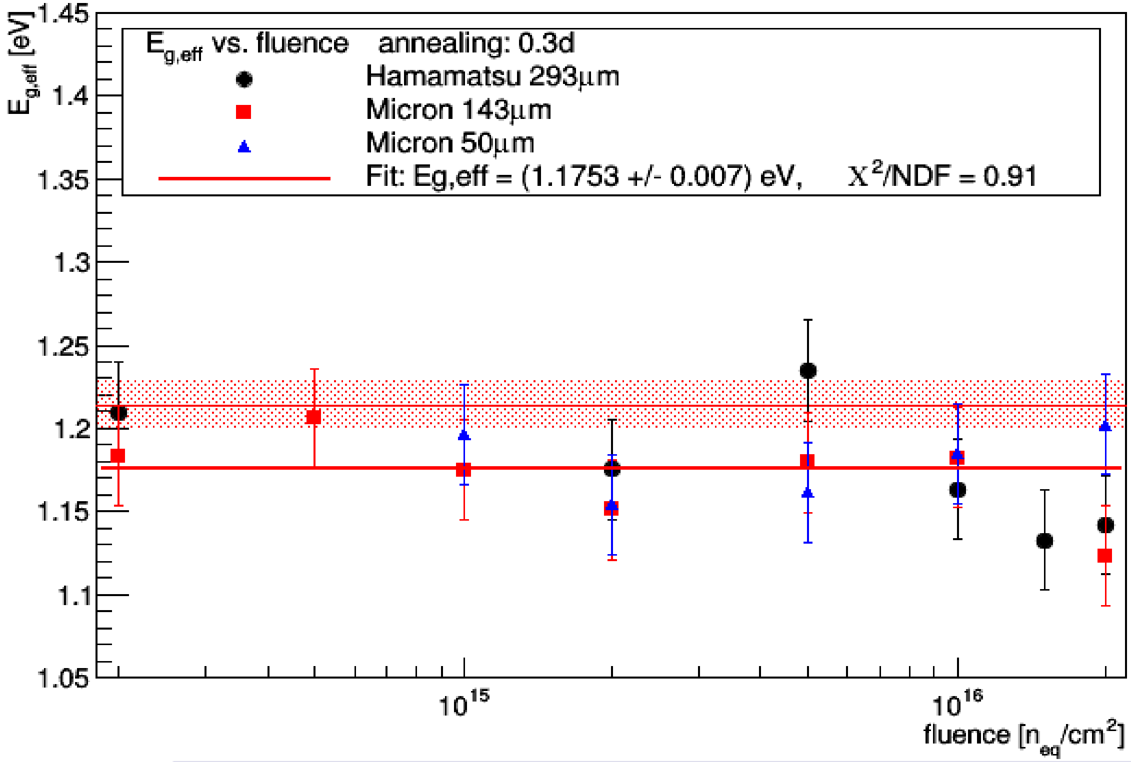
$$\frac{I(T_2)}{I(T_1)} = \left(\frac{T_2}{T_1}\right)^2 e^{-\frac{E_{g,eff}}{2k_B}\left(\frac{1}{T_2}-\frac{1}{T_1}\right)}$$

self heating of sensor might lead to
incorrect temperature measurement
→ effect more pronounced at
high voltages and higher fluences

to account for unexpected voltage dependence
a systematic uncertainty on the temperature measurement
is assumed:

$$s_{T,sys} = 0,15\,^\circ\mathrm{C} \Rightarrow s_{E_{g,eff},sys} = 0,03\,\mathrm{eV}$$

$E_{g,eff}$ vs. fluence



Additional measurement at -43°C and -39°C of 293um HPK-sensor, $2x10^{16}$neq/cm^{2}:
→ $E_{g,eff}$ = 1.116 eV (-0.026 eV)

result

$E_{g,eff} = (1,18 \pm 0,03)\,\mathrm{eV}$ (Lit. $E_{g,eff} = (1,214 \pm 0,014)\,\mathrm{eV}$ [1])

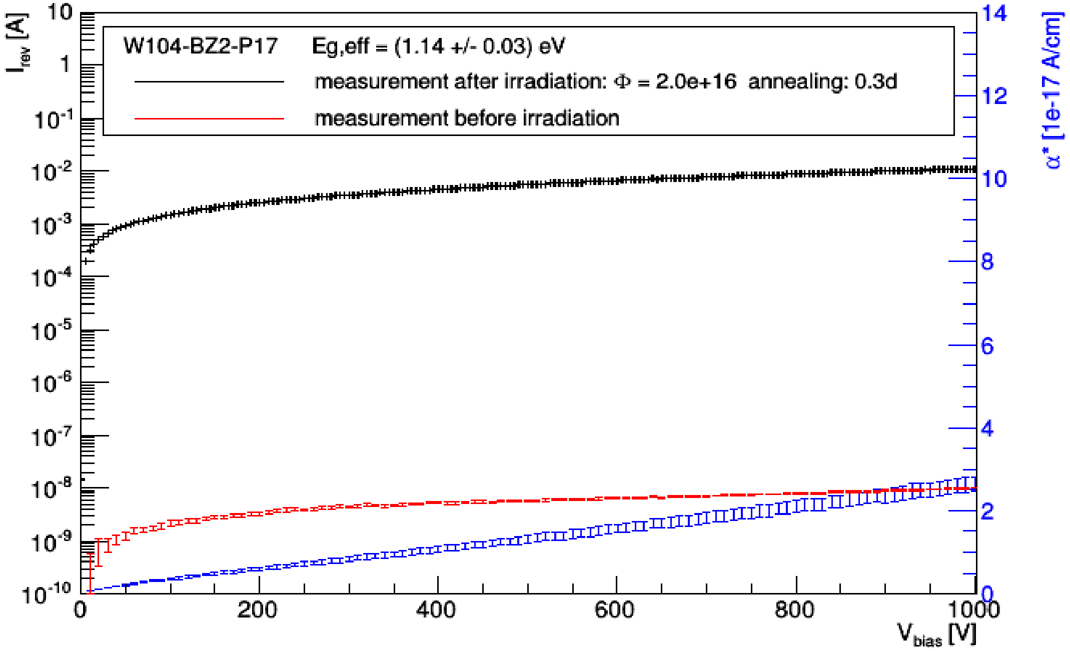
[1] A Chilingarov. *Temperature dependence of the current generated in Si-bulk*

α* vs. voltage

$I(\Phi_{eq})$: leakage current $T = -32\,^\circ C$, scaled to $21\,^\circ C$
I_0: measurement before irradiation, V: actual detector volume

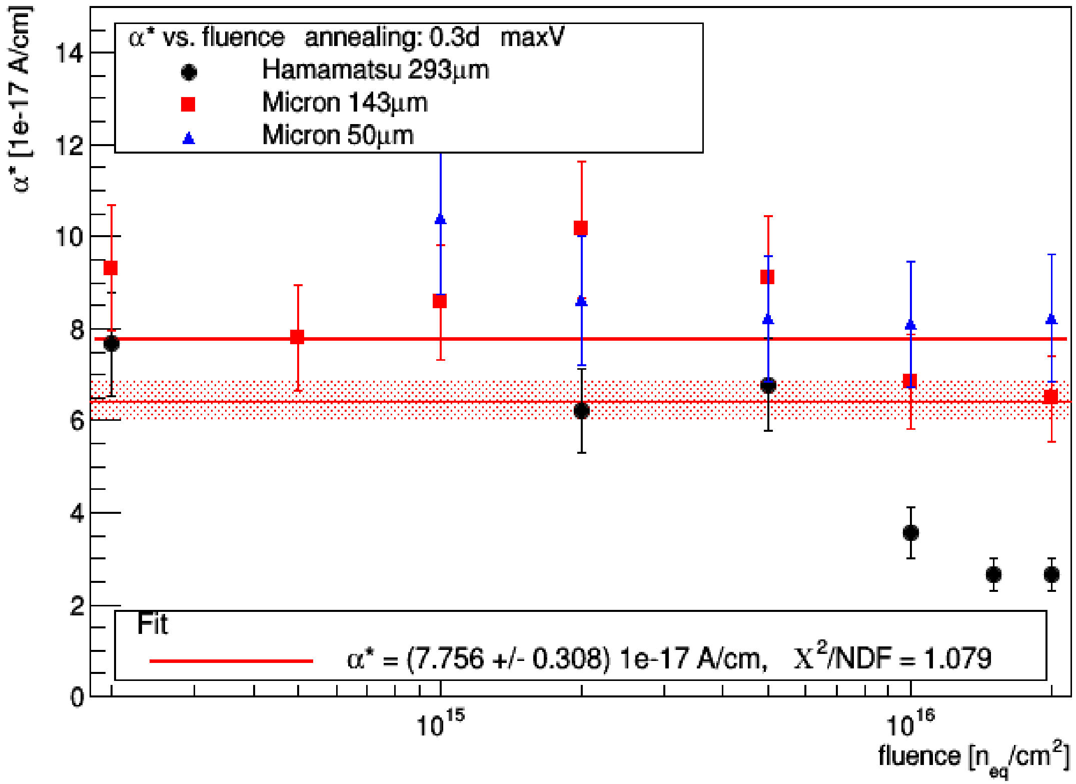
$$\alpha^* = \frac{I(\Phi_{eq}) - I_0}{\Phi_{eq} V}$$

for fully depleted sensor: $\alpha^* \equiv \alpha = \text{const}.$
Full depletion voltage usually not reached for high fluences.



HPK 293 um

α* vs. fluence



α* shown for highest voltage (350 V for 50 µm-Micron, 1000 V otherwise)

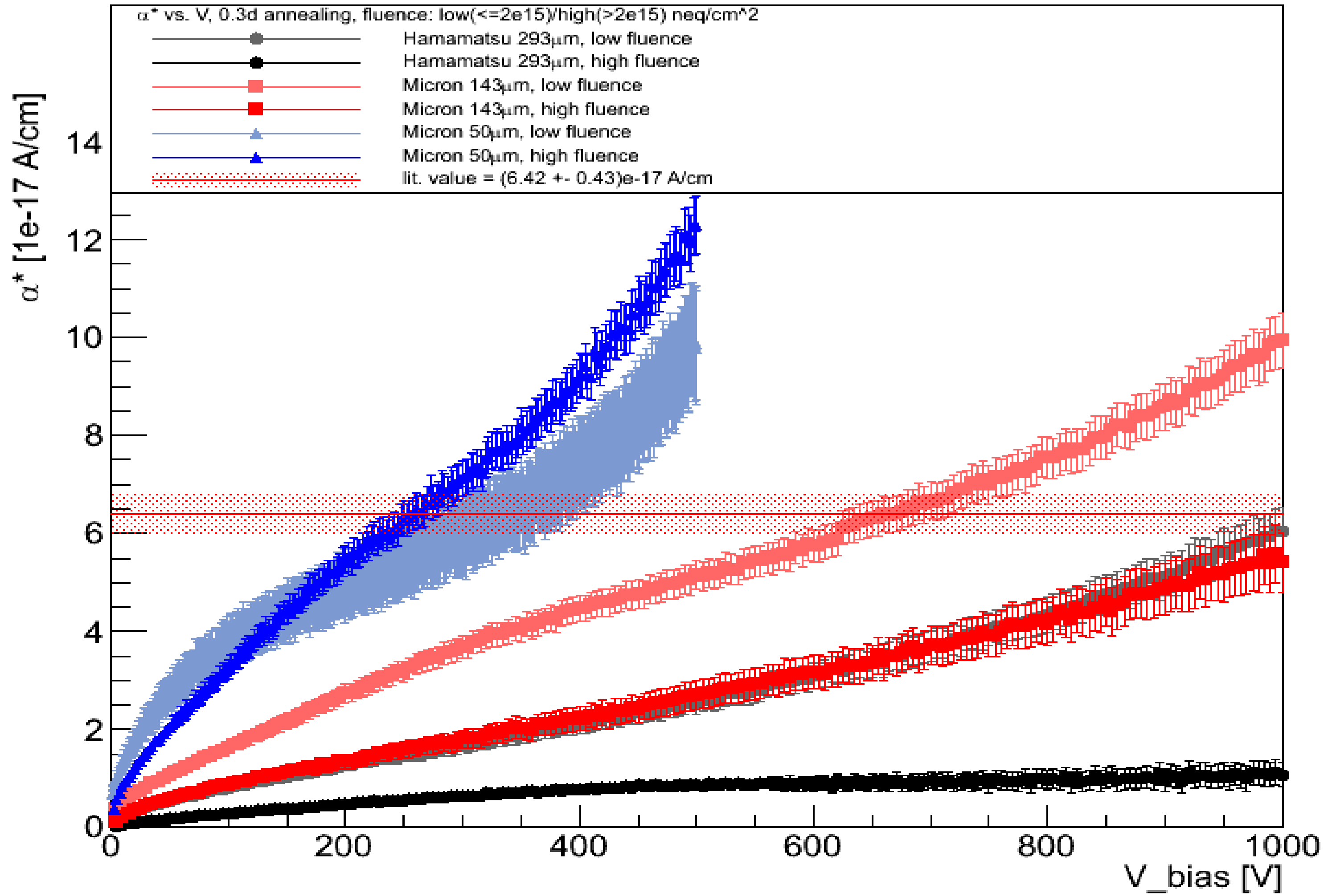
(three highest irradiated HPK-sensors not considered for fit.)

result

$\alpha^* = (7.8 \pm 0.9) \cdot 10^{-17}\ \mathrm{A/cm}$ (Lit. $\alpha = (6,40 \pm 0,43) \cdot 10^{-17}\ \mathrm{A/cm}$ [2])

[2] Sven Wonsak et al. *Measurements of the reverse current of highly irradiated silicon sensors*

α* - voltage dependence



Conclusion

IV-measurements with new setup:

Calculated $\mathbf{E_{g,eff}}$ and **α*** for 18 irradiated sensors
Three sensor types: ***293um HPK, 143um Micron, 50um Micron***
Irradiation fluences: **2×10^{14} – 2×10^{16} neq/cm^2**

- $E_{g,eff} = (1,18 \pm 0,03)\,\mathrm{eV}$
  (all measurements included)
- $E_{g,eff}^{low\Phi} = (1,19 \pm 0,03)\,\mathrm{eV}$
  (fluence up to $10^{15}\,\mathrm{n_{eq}/cm^2}$)

  literature [1]:
  $E_{g,eff}^{lit} = (1,214 \pm 0,014)\,\mathrm{eV}$
- $\alpha^* = (7.8 \pm 0.9) \cdot 10^{-17}\,\mathrm{A/cm}$
  (three sensors not included)

  literature [2]:
  $\alpha^*_{lit} = (6,40 \pm 0,43) \cdot 10^{-17}\,\mathrm{A/cm}$

$E_{g,eff}$: Tendency to lower values at high fluences observed

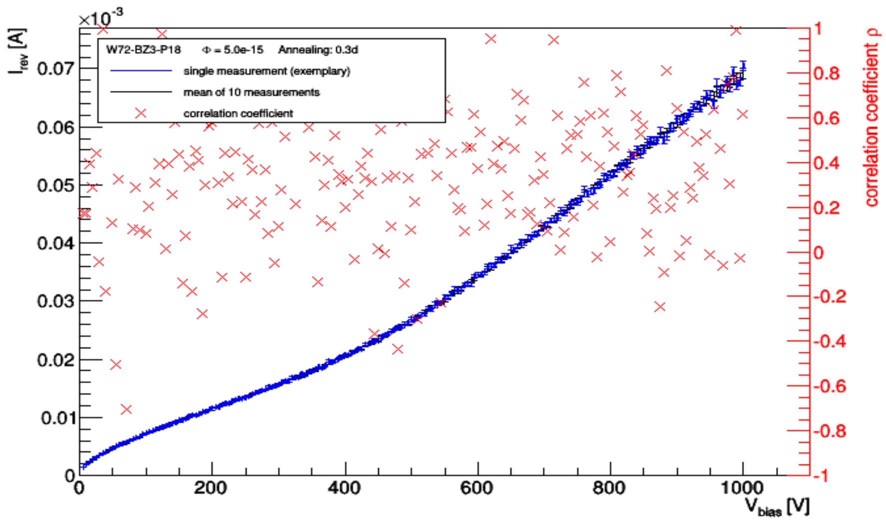
But strong dependence on efficiency of cooling system

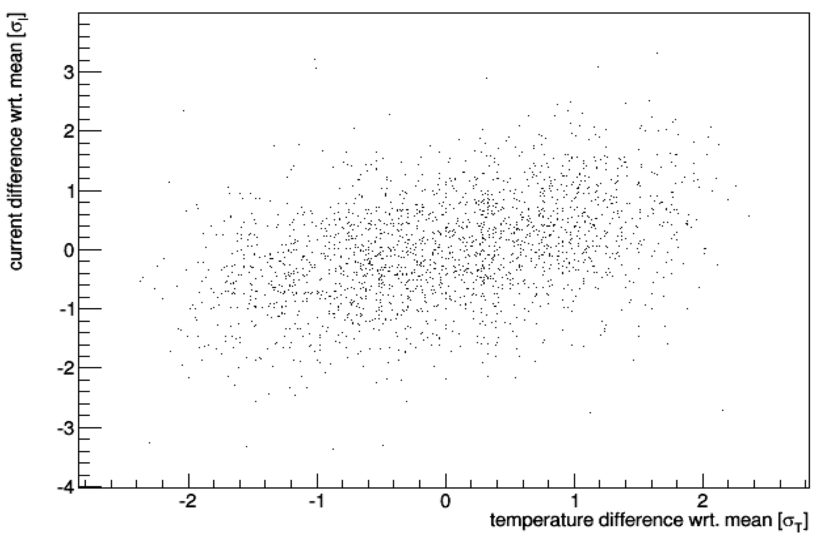
Backup

Correlation of uncertainties

Fluctuations of sensortemperature influence current measurement.
⇒ Calculation of correlation coefficient from 10 IV-measurements (T = −23 ◦ C)

$$\rho(I,T) = \frac{cov(I,T)}{\sigma_I \sigma_T} = \frac{1}{N \cdot \sigma_I \sigma_T} \sum_{i=1}^{N} (I_i - \overline{I})(T_i - \overline{T})$$





$E_{g,eff}$ for different irradiation doses

Nr.	Sensor	d [μm]	Φ_{eq} [n_{eq}/cm^2]	$E^{fit}_{g,eff}$ [eV]
1	HPK W277-BZ5-P23	293	$2 \cdot 10^{14}$	$1,2096 \pm 0,0013 \pm 0,03$
2	Micron 2437-14-M	143	$2 \cdot 10^{14}$	$1,1834 \pm 0,0015 \pm 0,03$
3	Micron 2437-14-O	143	$5 \cdot 10^{14}$	$1,2057 \pm 0,0017 \pm 0,03$
4	Micron 2437-14-Q	143	$1 \cdot 10^{15}$	$1,1747 \pm 0,0022 \pm 0,03$
5	HPK W264-BZ5-P23	293	$2 \cdot 10^{15}$	$1,1753 \pm 0,0011 \pm 0,03$
6	Micron 2437-14-S	143	$2 \cdot 10^{15}$	$1,1508 \pm 0,0019 \pm 0,03$
7	HPK W72-BZ3-P18	293	$5 \cdot 10^{15}$	$1,2347 \pm 0,0028 \pm 0,03$
8	Micron 2437-14-F	143	$5 \cdot 10^{15}$	$1,1795 \pm 0,0012 \pm 0,03$
9	HPK W73-BZ2-P20	293	$1 \cdot 10^{16}$	$1,1632 \pm 0,0014 \pm 0,03$
10	Micron 2437-14-G	143	$1 \cdot 10^{16}$	$1,1822 \pm 0,0012 \pm 0,03$
11	HPK W104-BZ2-P2	293	$1,5 \cdot 10^{16}$	$1,1327 \pm 0,0006 \pm 0,03$
12	HPK W104-BZ2-P17	293	$2 \cdot 10^{16}$	$1,1418 \pm 0,0009 \pm 0,03$
13	Micron 2437-14-H	143	$2 \cdot 10^{16}$	$1,123 \pm 0,001 \pm 0,03$
14	Micron 3107-6-3	50	$1 \cdot 10^{15}$	$1,1965 \pm 0,0015 \pm 0,03$
15	Micron 3107-6-9	50	$2 \cdot 10^{15}$	$1,1544 \pm 0,0015 \pm 0,03$
16	Micron 3107-6-10	50	$5 \cdot 10^{15}$	$1,1615 \pm 0,0017 \pm 0,03$
17	Micron 3107-6-14	50	$1 \cdot 10^{16}$	$1,1847 \pm 0,0015 \pm 0,03$
18	Micron 3107-6-21	50	$2 \cdot 10^{16}$	$1,2023 \pm 0,0012 \pm 0,03$
Lit. [1]				$1,214 \pm 0,014$

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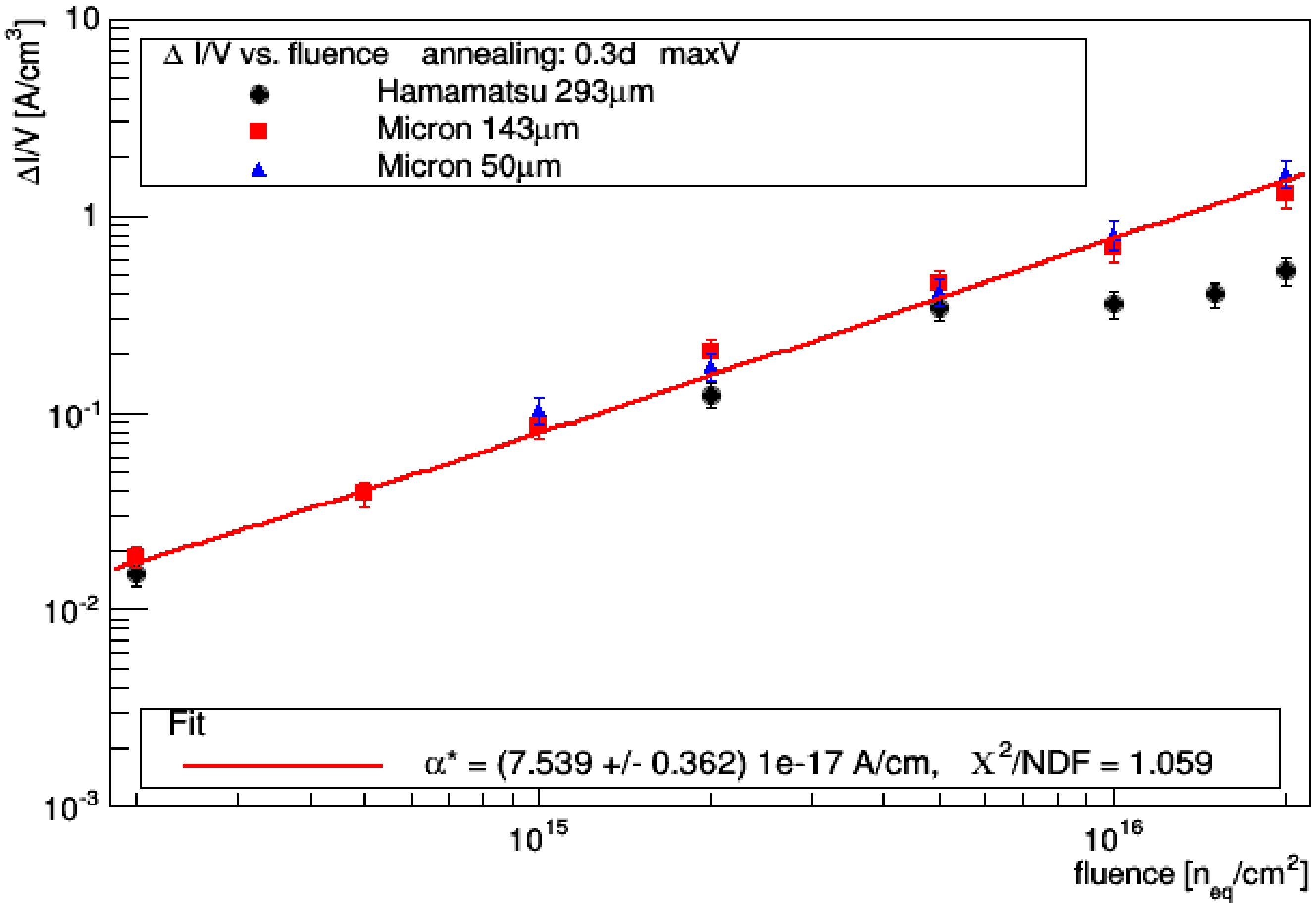
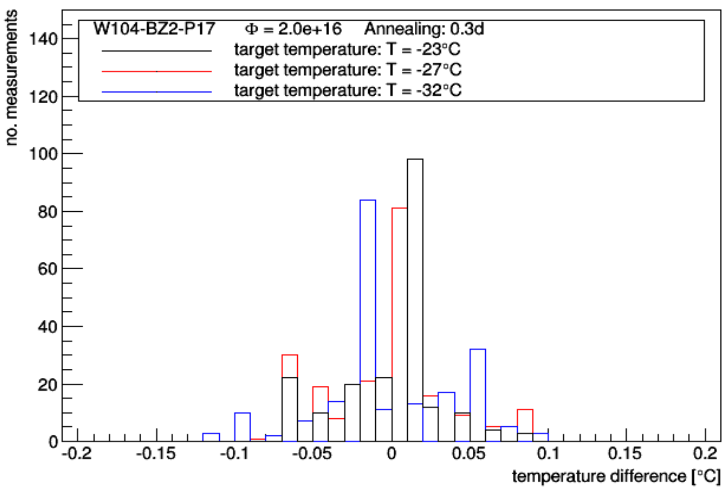
α* for different irradiation doses

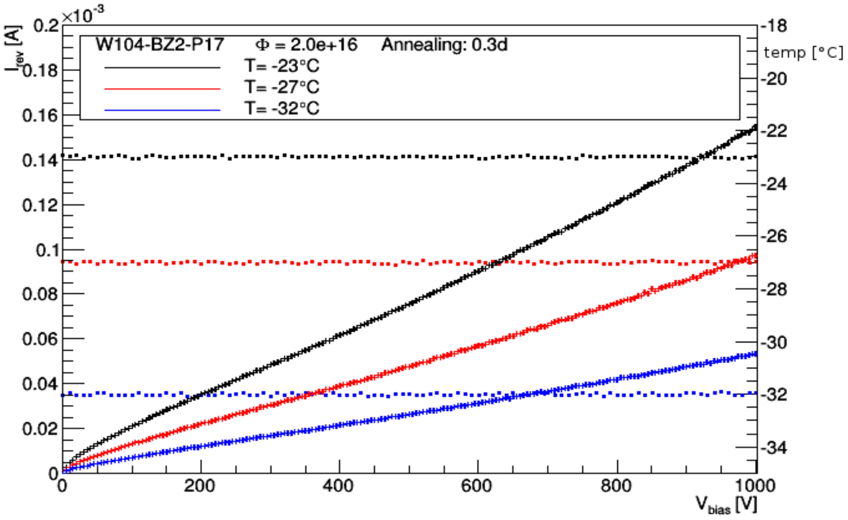
Nr.	d [μm]	Φ_{eq} [n_{eq}/cm^2]	$\alpha^*_{max\ V}$ [10^{-17} A/cm]
1	293	$2 \cdot 10^{14}$	$7,7 \pm 0,5 \pm 1,0$
2	143	$2 \cdot 10^{14}$	$9,3 \pm 0,7 \pm 1,2$
3	143	$5 \cdot 10^{14}$	$7,8 \pm 0,5 \pm 1,0$
4	143	$1 \cdot 10^{15}$	$8,6 \pm 0,6 \pm 1,1$
5	293	$2 \cdot 10^{15}$	$6,2 \pm 0.4 \pm 0,8$
6	143	$2 \cdot 10^{15}$	$10,2 \pm 0,7 \pm 1,3$
7	293	$5 \cdot 10^{15}$	$6,8 \pm 0,5 \pm 0,9$
8	143	$5 \cdot 10^{15}$	$9,1 \pm 0,6 \pm 1,2$
9	293	$1 \cdot 10^{16}$	$3,6 \pm 0,2 \pm 0,5$
10	143	$1 \cdot 10^{16}$	$6,9 \pm 0,5 \pm 0,9$
11	293	$1,5 \cdot 10^{16}$	$2,66 \pm 0,18 \pm 0,3$
12	293	$2 \cdot 10^{16}$	$2,64 \pm 0,18 \pm 0,3$
13	143	$2 \cdot 10^{16}$	$6,5 \pm 0,5 \pm 0,8$
14	50	$1 \cdot 10^{15}$	$10,4 \pm 1,0 \pm 1,3$
15	50	$2 \cdot 10^{15}$	$8,6 \pm 0,9 \pm 1,1$
16	50	$5 \cdot 10^{15}$	$8,2 \pm 0,8 \pm 1,1$
17	50	$1 \cdot 10^{16}$	$8,1 \pm 0,8 \pm 1,1$
18	50	$2 \cdot 10^{16}$	$8,2 \pm 0,8 \pm 1,1$
Lit. [2]			$6,40 \pm 0,43$

ΔI /V vs. fluence



IV-measurements at different temperatures





Procedure:

- Temperatures of $-23\,^\circ\mathrm{C}$, $-27\,^\circ\mathrm{C}$ und $-32\,^\circ\mathrm{C}$
- Voltage supply:

  positive high voltage on implants
  ground on backplane
- temperatures of cooling liquid:

  $+2\,^\circ\mathrm{C}$ at
  $-23\,^\circ\mathrm{C}$, $-27\,^\circ\mathrm{C}$-measurement
  $-10\,^\circ\mathrm{C}$ at $-32\,^\circ\mathrm{C}$-measurement

- voltage step size: $1\,\mathrm{V/s}$
- voltage constant for $10\,\mathrm{s}$ before starting each measurement
- measuring current in $5\,\mathrm{V}$-steps while ramping down voltage to $0\,\mathrm{V}$