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Temperature dependence of the bulk current in Si

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Layout

1. Review of the published results
2. Lancaster data
3. Discussion
4. Conclusions

The talk is based on the RD50 Note: A.Chilingarov, “Generation current temperature scaling. Part-II: Experimental data”, 12.7.2012.

http://rd50.web.cern.ch/rd50/doc/Internal/rd50_2011_001-I-T_scalingExpV2.pdf

though the analysis for p-type sensors is slightly different.

1. Review of the published results

The temperature dependence is typically parameterised as:

$$I(T) \propto T^2 \exp(-E_{eff}/2kT)$$

Only the data for irradiated sensors, where the bulk generated current usually dominates, were reviewed.

Experimental results were found in the following publications:

1. T.Ohsugi et al., NIM A265 (1988) 105.
2. M.Nakamura et al., NIM A270 (1988) 42.
3. K.Gill et al., NIM A322 (1992) 177.
4. E.Barberis et al., NIM A326 (1993) 373.
5. H.Feick, PhD Thesis, DESY F35D-97-08, 1997, Table E.6. (No information on the studied sensors and their irradiation is available.)
6. L.Andricek et al., NIM A436 (1999) 262.
7. ATLAS SCT Barrel Module Final Design Review, SCT-BM-FDR-7, 2002, p.19. (The quoted result is $E_{eff}/2k$ = 7019K which gives E_{eff} =1.210 eV.)
8. A.Hickling et al., Technical Note CERN-LHCb-PUB-2011-021, December 30, 2011.

Table 1. The values of E_{eff} observed with irradiated *n*-type Si sensors

Ref.	**Irradiation made by**	**With E, GeV**	**Maximum fluence, $10^{14}/cm^2$**	**E_{eff}, eV**	**In temperature range, ^{o}C**
[1]	p	12	1.7	1.20	-35 ÷ +25
[2]	p	800	1.2	1.276	+2 ÷ +32
[3]	n	~0.001	10	1.31	around +20
[4]	p	0.65	1.25	1.20	-4 ÷ +24
[5]	N/A	N/A	N/A	1.14	N/A
[6]	p	24	3	1.26	-14 ÷ -6
[7]	p	24	3	1.21	-30 ÷ -10
[8]	mostly π[1]	few	0.5[2]	1.13	-24÷+12
			Total average:	**1.216±0.057**	
			Without max and min values:	**1.214±0.049**	

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[1] particles crossing the VELO system in LHCb detector

[2] 1 MeV neutron equivalent

Some authors use the parameterisation I(T) $\propto T^m \exp(-E_{eff}/2kT)$ with $m \neq 2$. In this case E_{eff} may be corrected at any temperature to the equivalent E_{eff} with m=2: $E_{eff.eq}=E_{eff}(m)+2kT(m-2)$. Note that this approximation is valid only for the temperatures around the value of T used in the above equation.

In Ref.3 the authors used m=3/2 and obtained E_{eff}=1.34 eV. This result was corrected to m=2 at a typical for Ref.3 data temperature T=293, which gave E_{eff}=1.31 eV presented in Table 1.

In the talk E.Verbitskaya et al., “Temperature dependence of reverse current of irradiated Si detectors”, 20th RD50 Workshop, Bari, May 30 – June 1, 2012, the value of m=0 was used for the fits in the interval 200-400K. The obtained E_{eff}=1.30 eV. Correcting this result to m=2 at T=273, characteristic for the Table 1 data, gives $E_{eff.eq}$= 1.21 eV close to the average of the values observed in other experiments. However since the I(T) parameterisation in this work differs significantly from the standard one while the temperature range used for the fit is quite wide this result was not included in Table 1.

2. Lancaster data

Table 2. Sensors and their irradiation

Sensor name	**Sensor type**	**Si type**	**Irradiation made by**	**With E, MeV**	**1MeV n equiv. fluence, $10^{14}/cm^2$**
x2y4	μ-strip	*p*	p	26	0.1
x4y1	μ-strip	*p*	p	26	1.0
x5y2	μ-strip	*p*	p	26	10
S62	diode	*n*	n	~1	0.82
M41	diode	*n*	n	~1	1.1

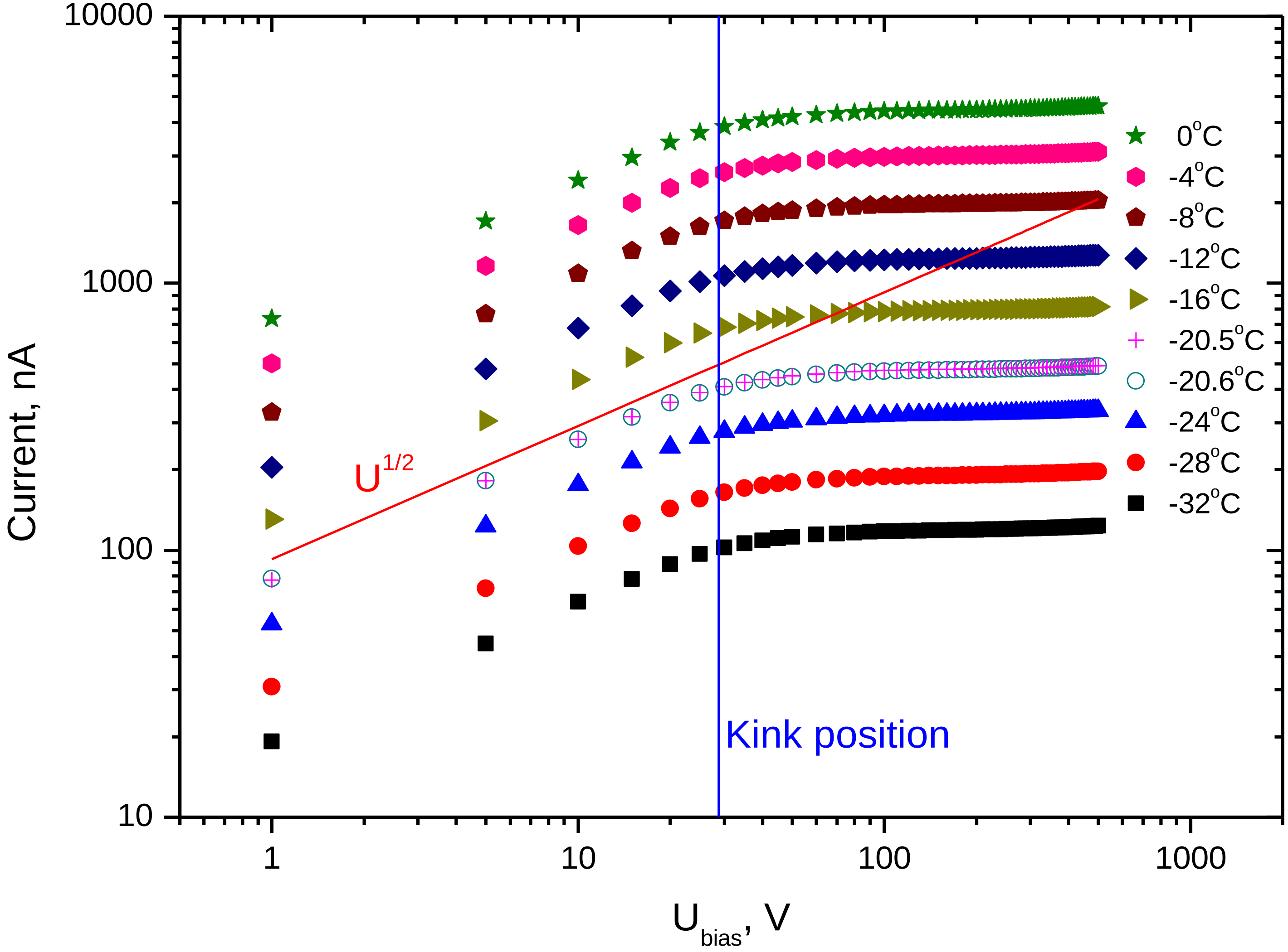
IV measurements were made with the guard ring grounded. Both total current, I_t, and that through the sensor centre, I_c, were measured.

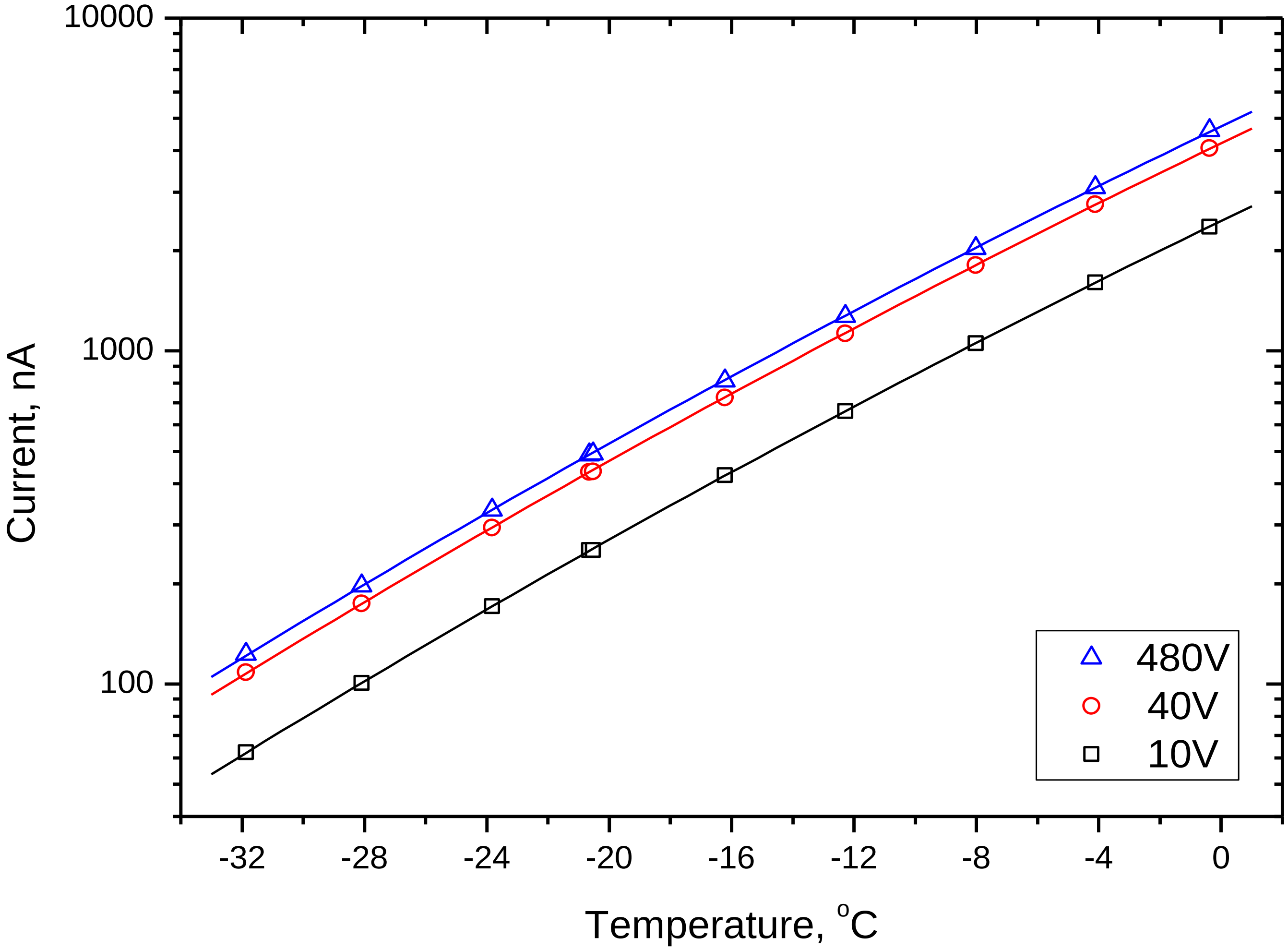
Usually I(T) dependence is measured at a fixed bias. A natural bias choice is at or just above the full depletion voltage. We have investigated the variation of I(T) dependence with bias in a wide voltage range. For the current generated in the bulk the results should not depend on bias. Thus the variation of E_{eff} with bias is a good check of consistency of the data with the assumed model.

A common problem in measuring I(T) dependence is a danger of sensor self-heating at high power dissipation. This manifests itself as a steady increase of E_{eff} with bias, which may be suppressed by a proper choice of the bias values.

Sensor x2y4 irradiated by 10^{13} n/cm^2

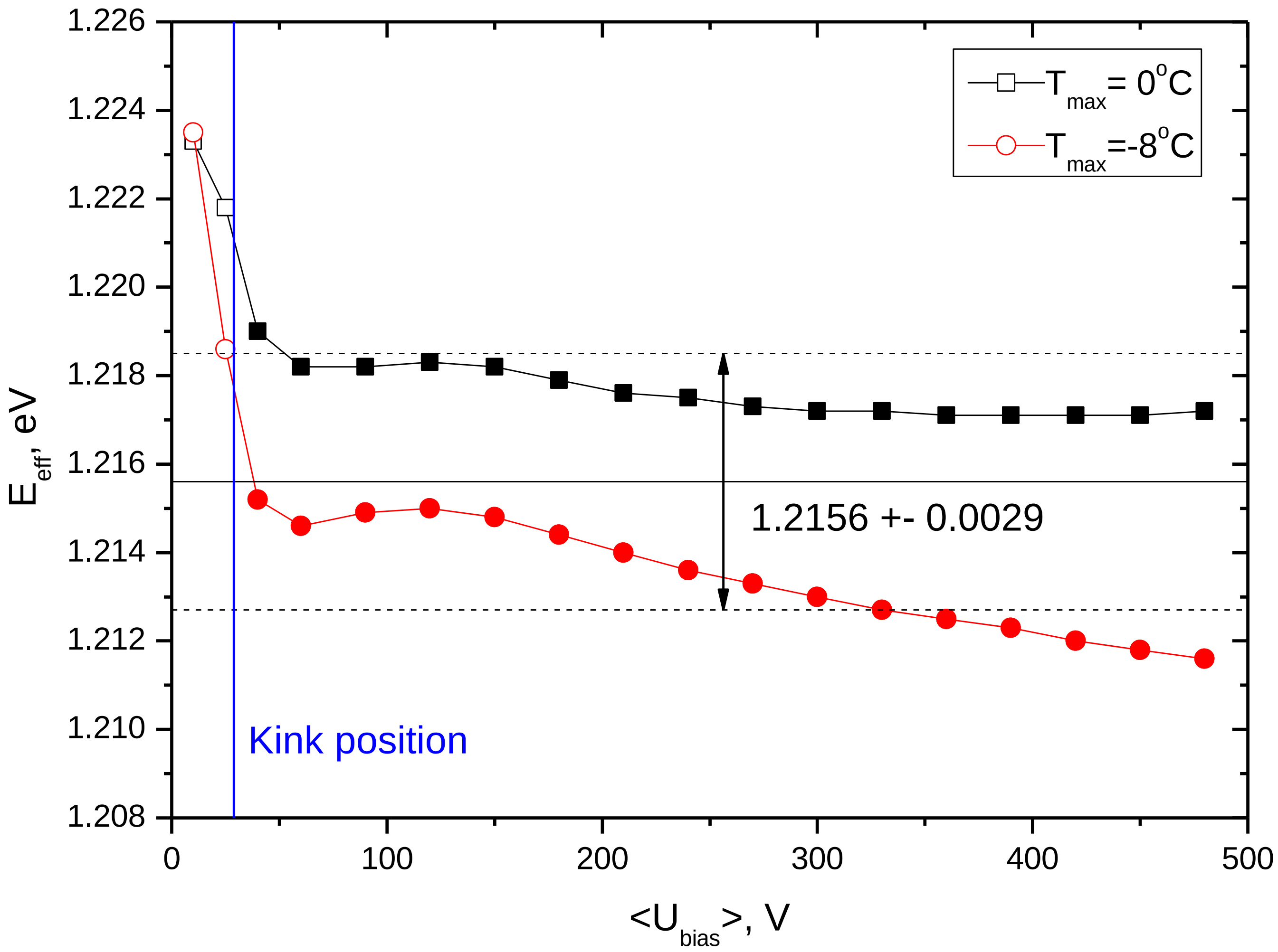
I_c-V curves





To equalise the weight of the points with very different current values the errors of 1% were assigned to the points and used in the fit. Typical χ^2/N_{df} was ~0.25, i.e. typical spread of the points around the fit curve was ~0.5%

Bias points from 5 to 490V were grouped by 3 and the average current for each group was fit by $T^2 \exp(-E_{eff}/2kT)$ as a function of temperature.

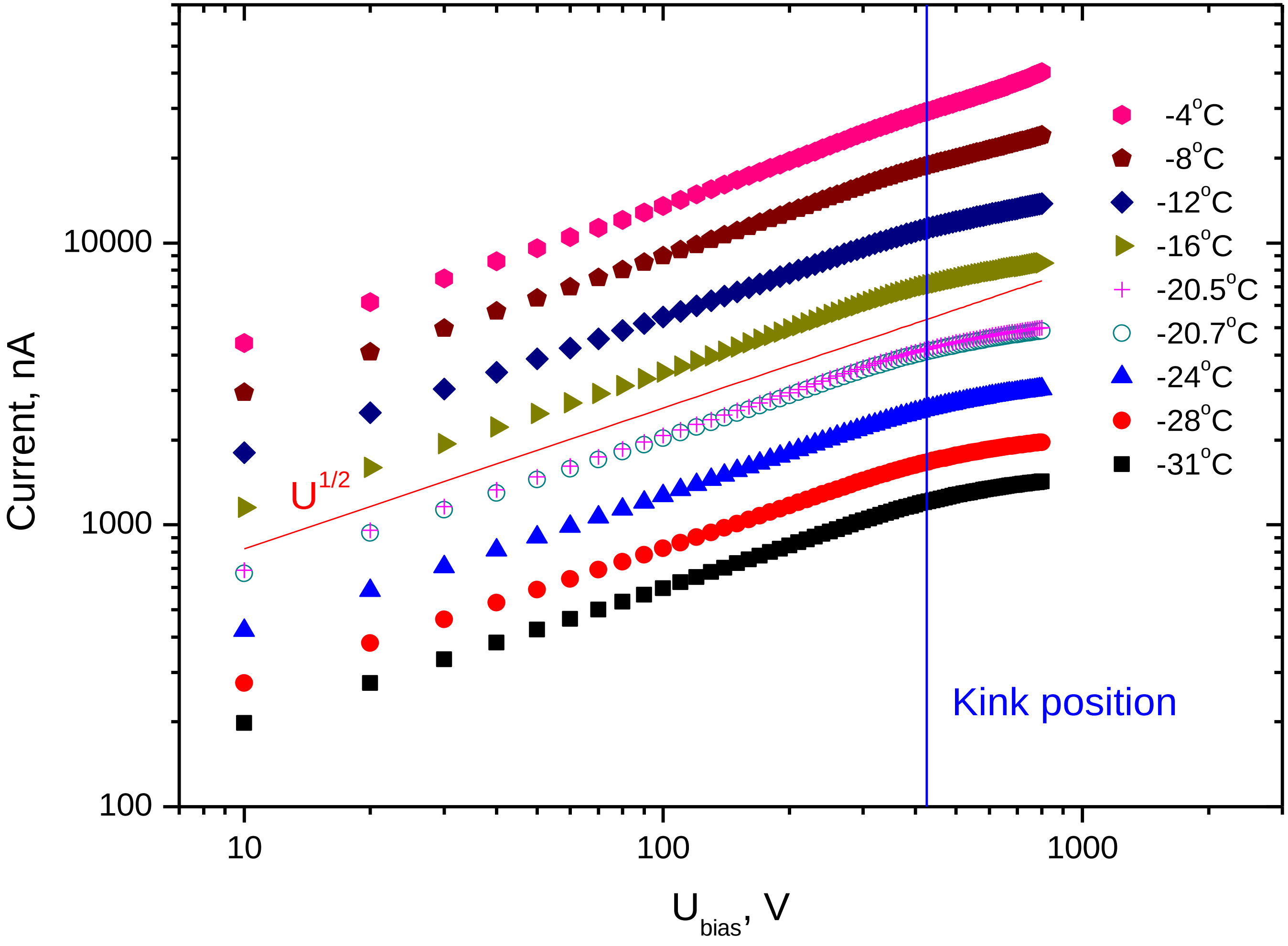


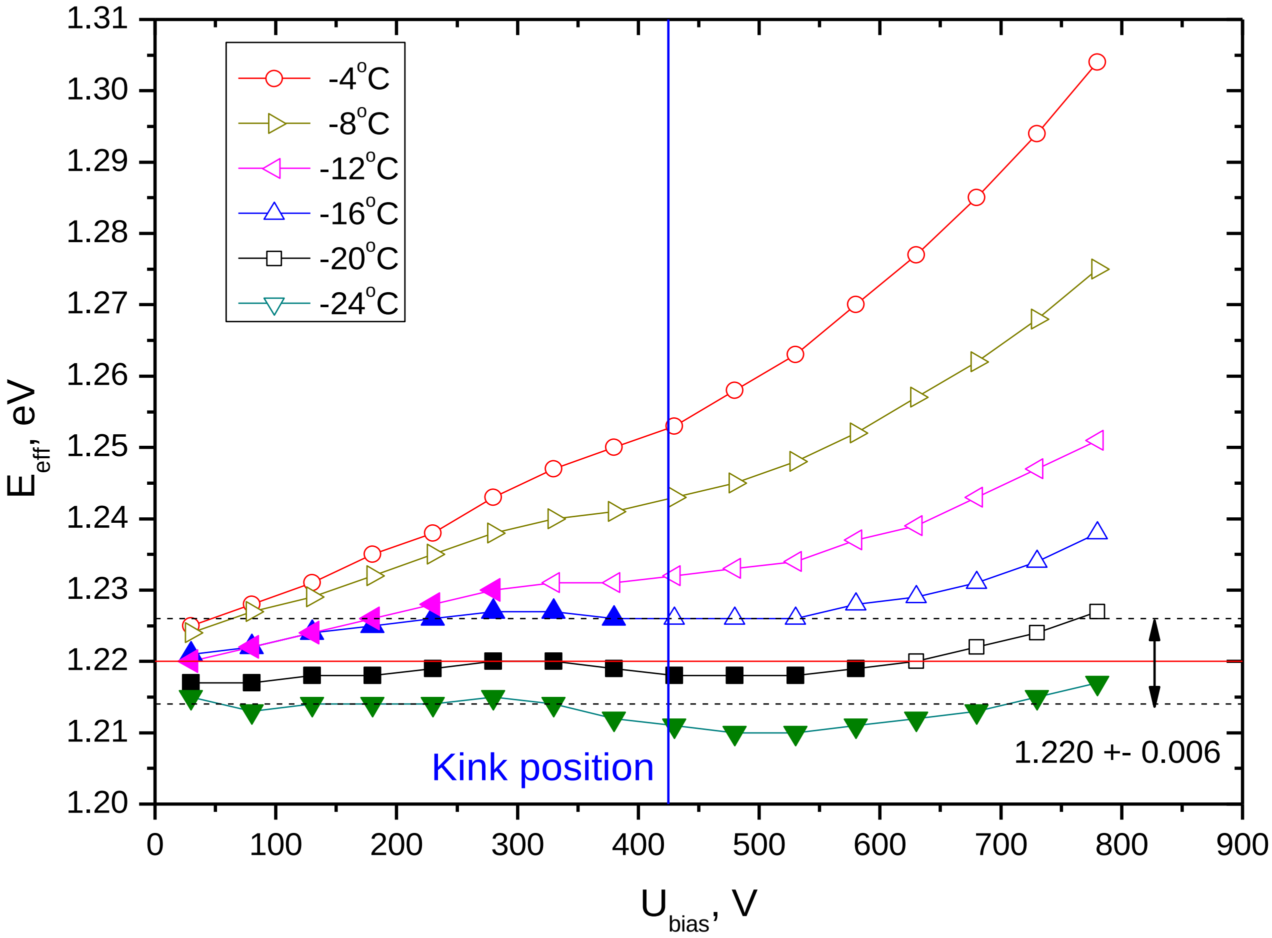
There are no signs of the sensor self-heating. Maximum dissipation power I_t*U=3 mW.

The E_{eff} values as a function of bias for the temperature ranges from -32°C to the T_{max} of 0°C and -8°C. Average value is calculated using the filled points.

Sensor x4y1 irradiated by 10^{14} n/cm^2

I_c-V curves



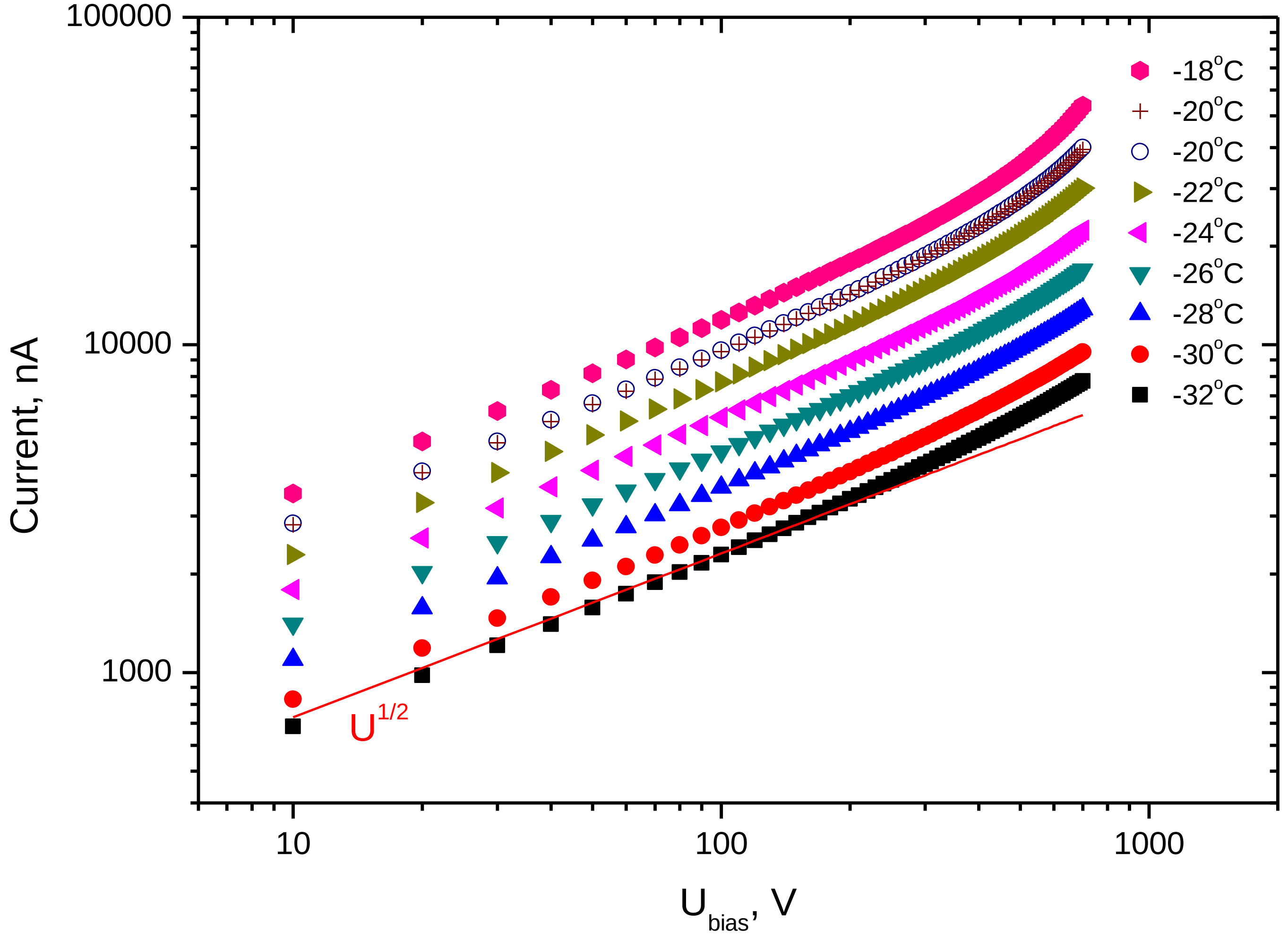


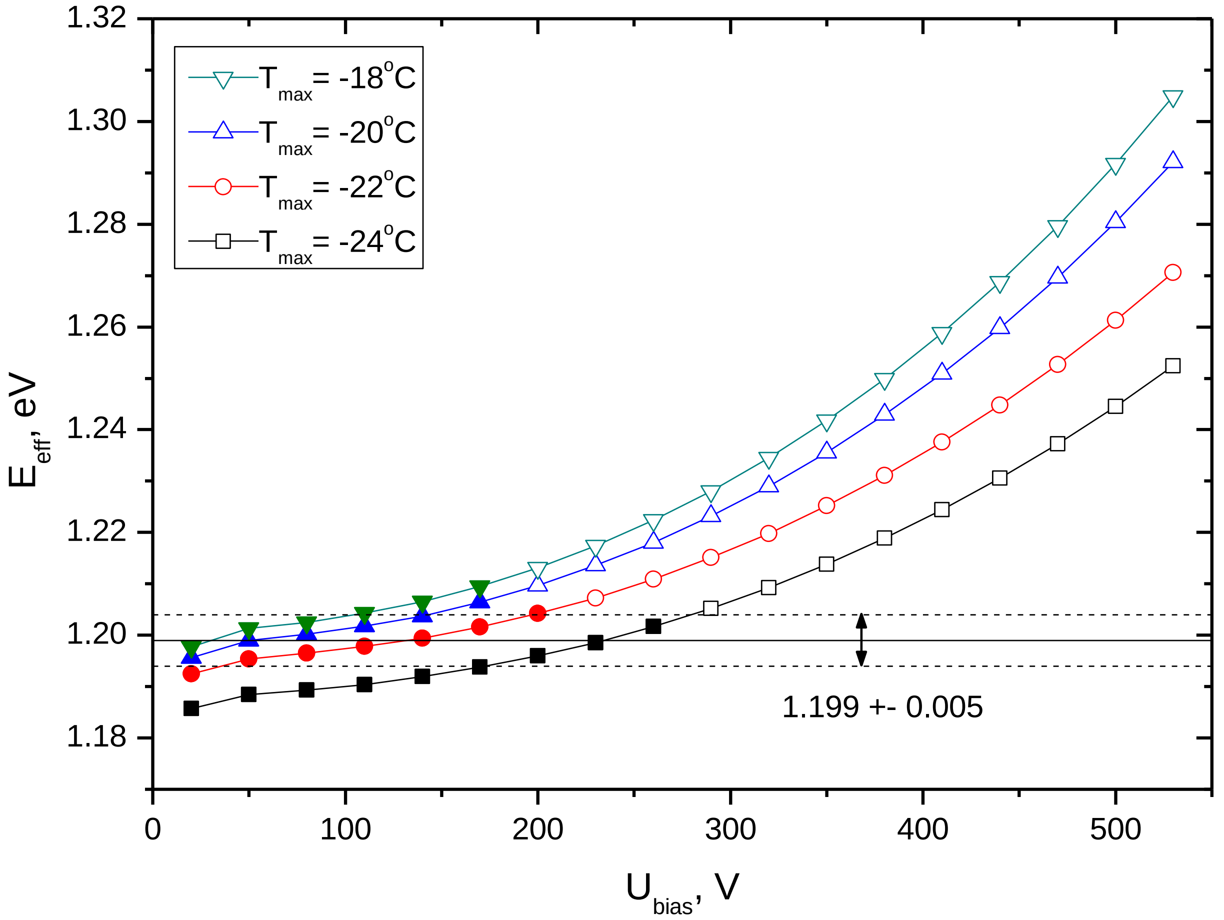
To eliminate the sensor self-heating only the points with dissipation power I_t*U<3mW were used for the final E_{eff} calculation. These points are shown by the filled symbols. Average E_{eff} was first calculated for each of four selected temperature ranges and then these values were averaged.

Bias points were grouped by 5 and the average current for each group was fit by $T^2 \exp(-E_{eff}/2kT)$ as a function of temperature with 1% errors. This was done for 6 temperature ranges with T_{min}=-31°C and T_{max} from -24°C to -4°C. The χ^2/N_{df} was <0.5 i.e. the actual errors were <0.7%.

Sensor x5y2 irradiated by 10^{15} n/cm^2

I_c-V curves



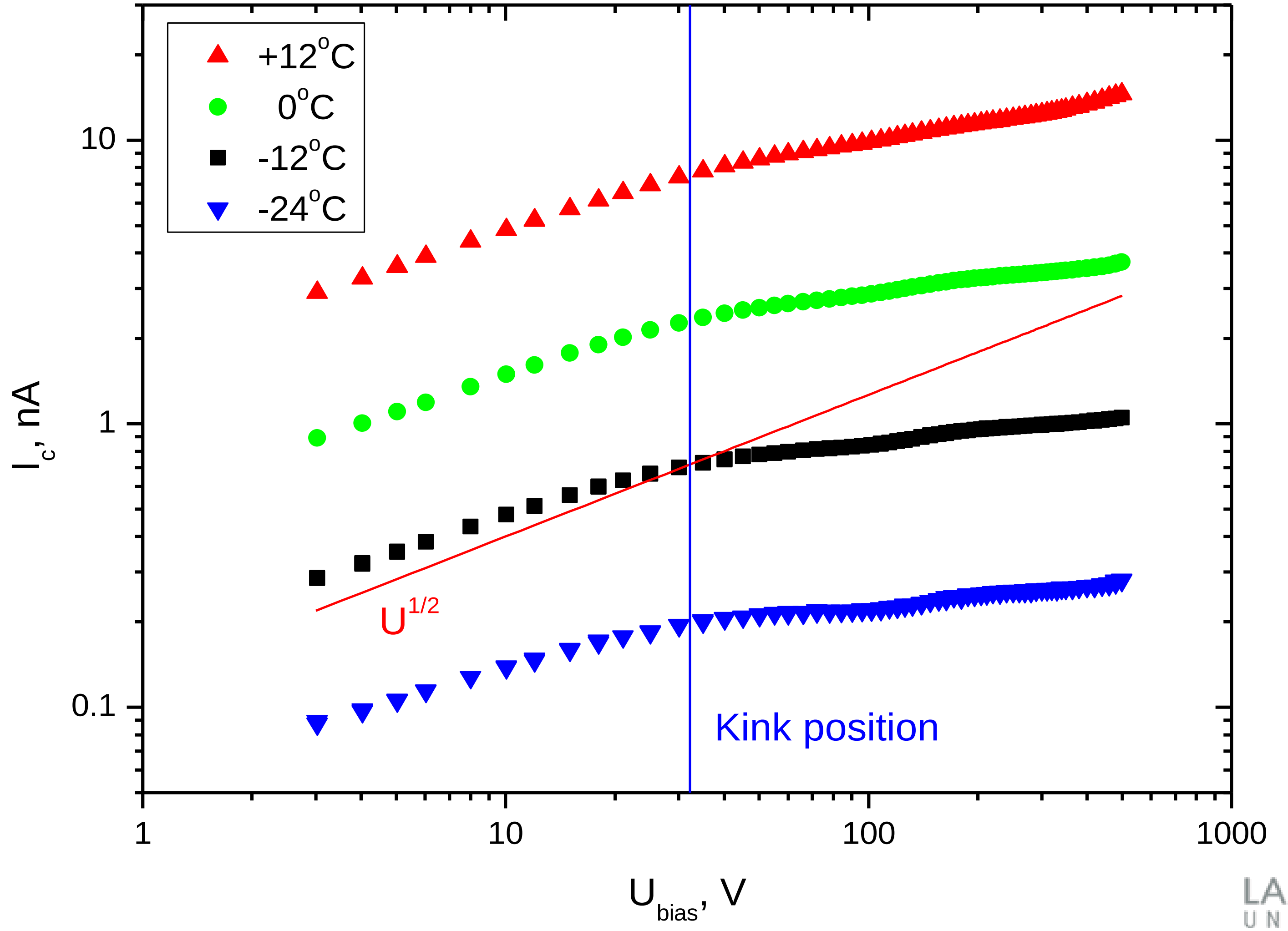


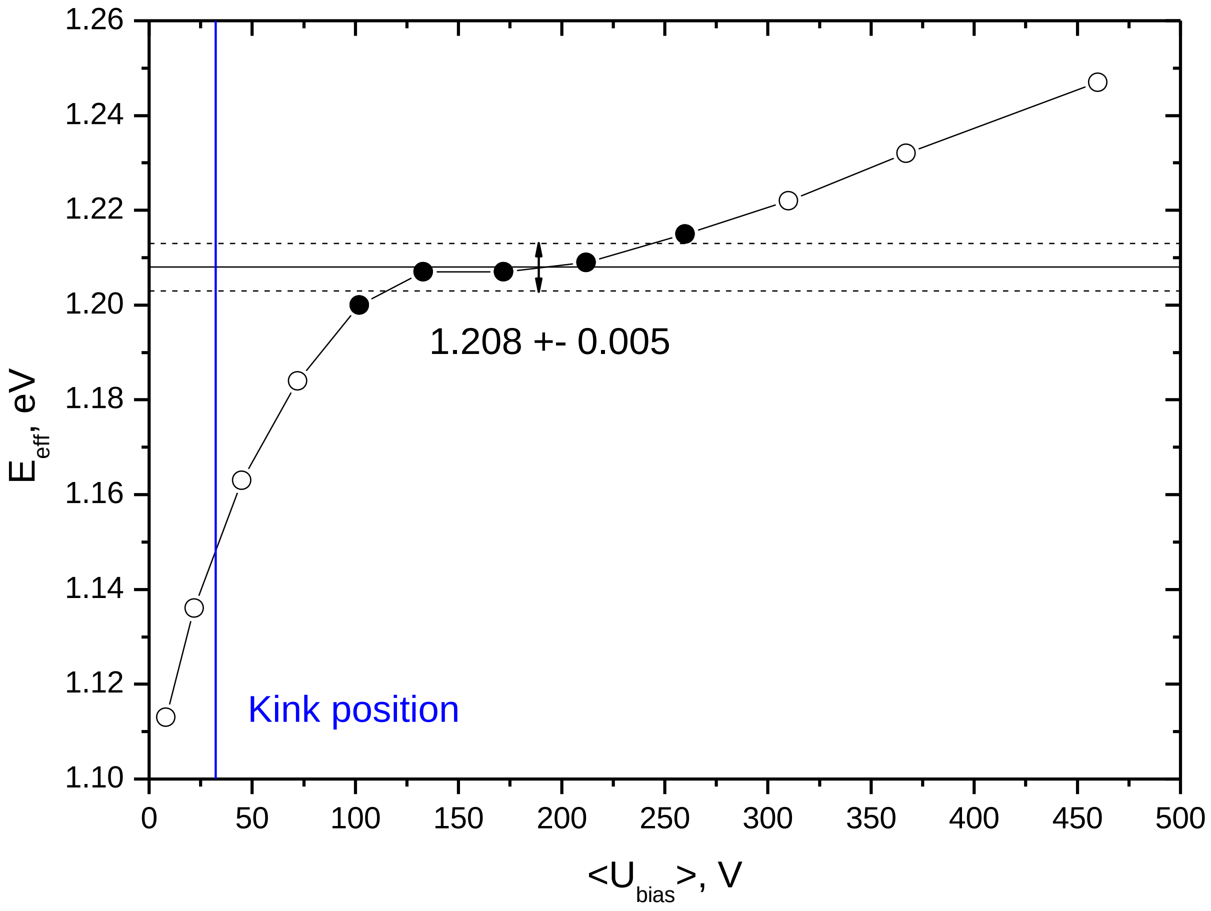
To eliminate the sensor self-heating only the points with dissipation power I_t*U<3mW were used for the final E_{eff} calculation. These points are shown by the filled symbols. Average E_{eff} was first calculated for each of four temperature ranges and then these values were averaged.

Bias points from 10 to 540V were grouped by 3 and the average current for each group was fit by $T^2 \exp(-E_{eff}/2kT)$ as a function of temperature with 1% errors. This was done for 4 temperature ranges with T_{min}=-32°C and T_{max} from -24°C to -18°C. The χ^2/N_{df} was ~0.5 i.e. the actual errors were ~0.7%.

Sensor S62 irradiated by $0.8\cdot10^{14}$ n/cm^2

I_c-V curves



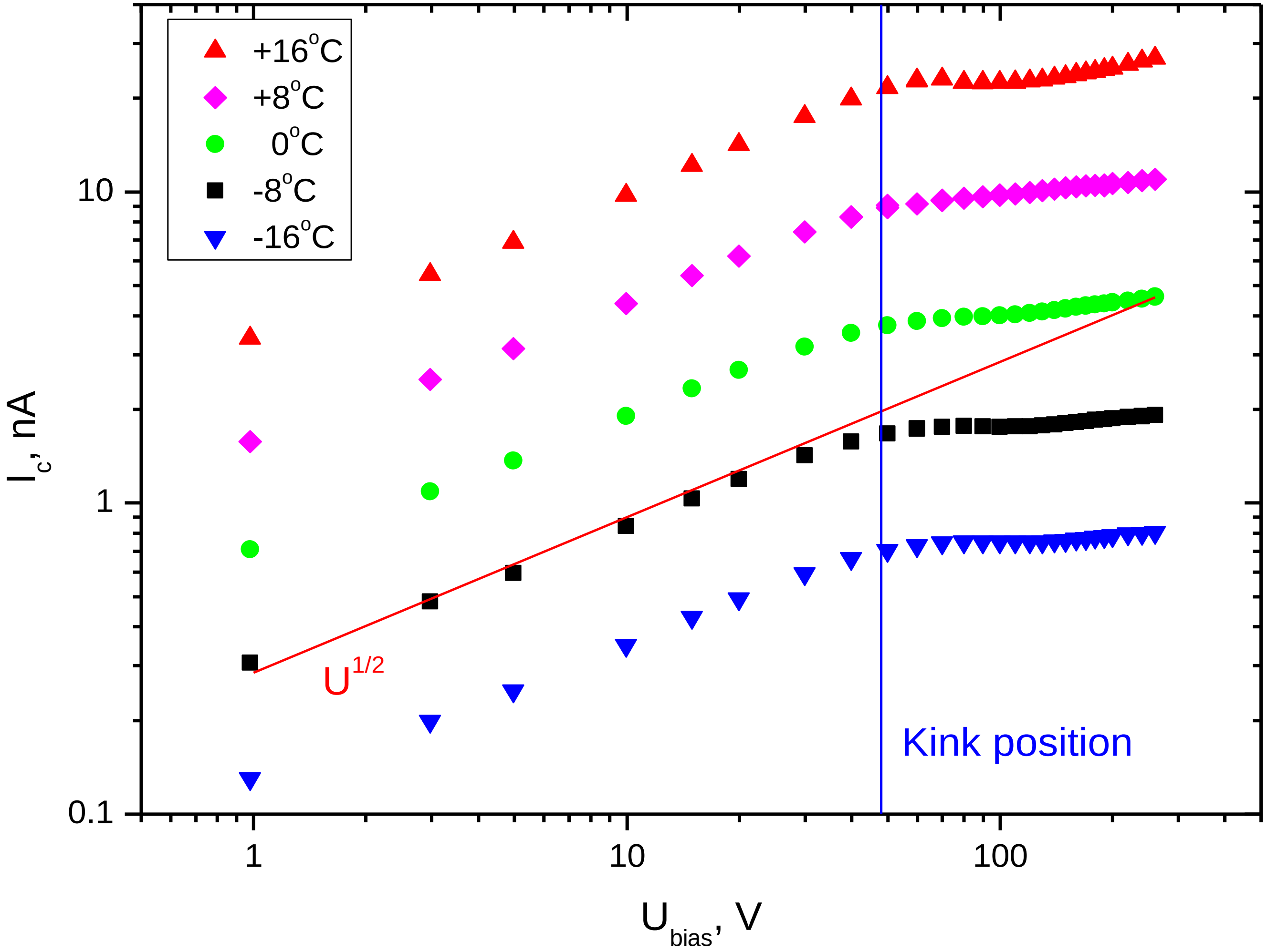


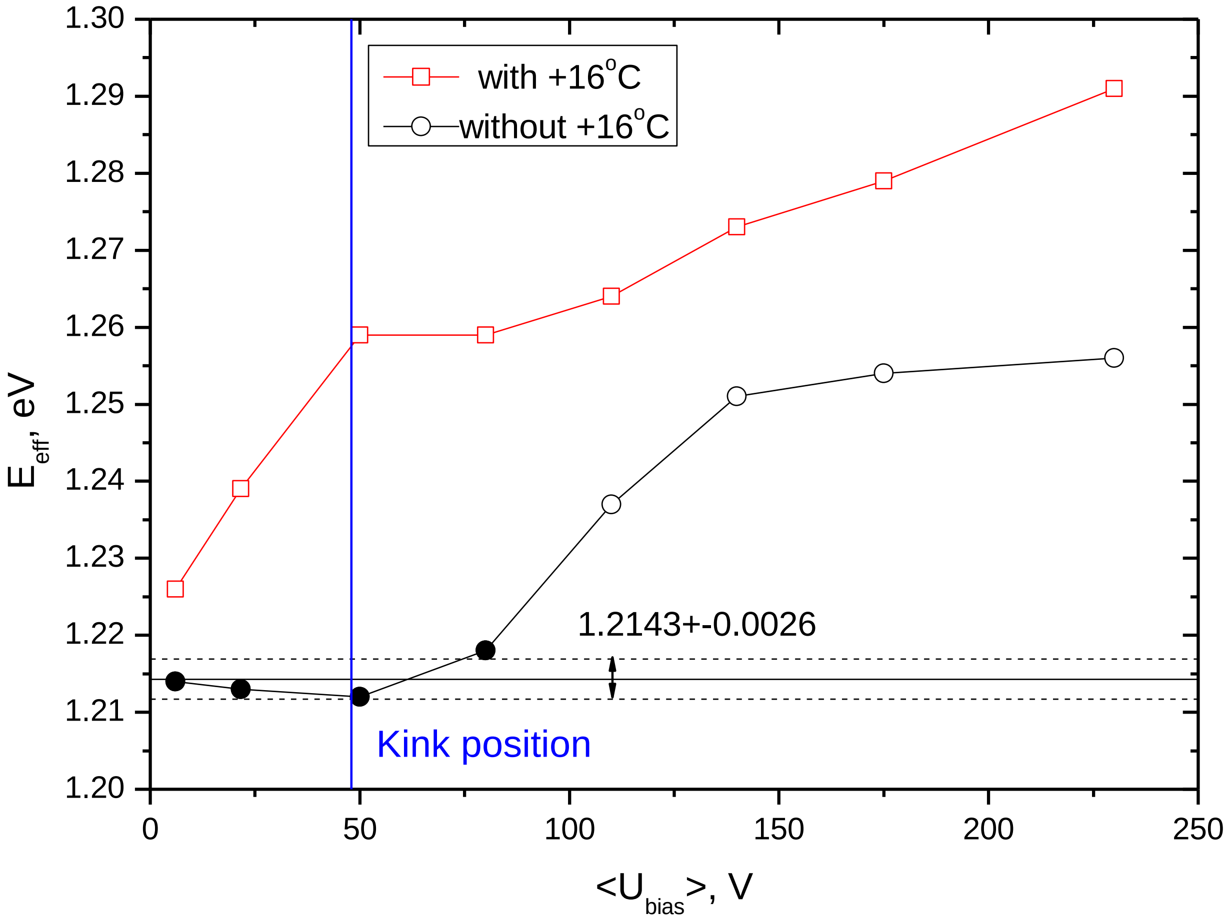
E_{eff} has a plateau between 100 and 300V. The points shown by the filled symbols were used for the final E_{eff} calculation.

Bias points from 5 to 500V were grouped by 5 and the average current for each group was fit by $T^2 \exp(-E_{eff}/2kT)$ as a function of temperature with 5% errors. The χ^2/N_{df} was ~0.5 i.e. the actual errors were ~3.5%.

Sensor M41 irradiated by $1.1 \cdot 10^{14}$ n/cm^2

I_c-V curves





E_{eff} has a plateau only for the temperature range without 16ºC. The points shown by the filled symbols were used for the final E_{eff} calculation.

Bias points from 3 to 260V were grouped by 3 or 4 in 8 bias groups. The average current for each group was fit by $T^2 \exp(-E_{eff}/2kT)$ as a function of temperature with 5% errors. This was done for 2 temperature ranges with and without T=16ºC. The χ^2/N_{df} was ~0.5 i.e. the actual errors were ~3.5%.

Table 3. Summary of Lancaster results

Sensor name	IV“kink” at, V	lnI-lnU slope	Bias range used, V	Temperature range used, °C	Eeff, eV	Standard deviation, eV
x2y4	29	0.49	35-490	-32 ÷ 0	1.2156	0.0029
x4y1	425	0.49	10-800	-31 ÷ -12	1.220	0.006
x5y2	N/A	0.52[*]	10-270	-32 ÷ -18	1.199	0.005
S62	32	0.40	90-280	-24 ÷ +12	1.208	0.005
M41	48	0.48	3-90	-16 ÷ +8	1.2143	0.0026
				Average:	**1.211**	**0.008**

Average E_{eff} was calculated with equal weight for all points i.e. ignoring the errors in the last column

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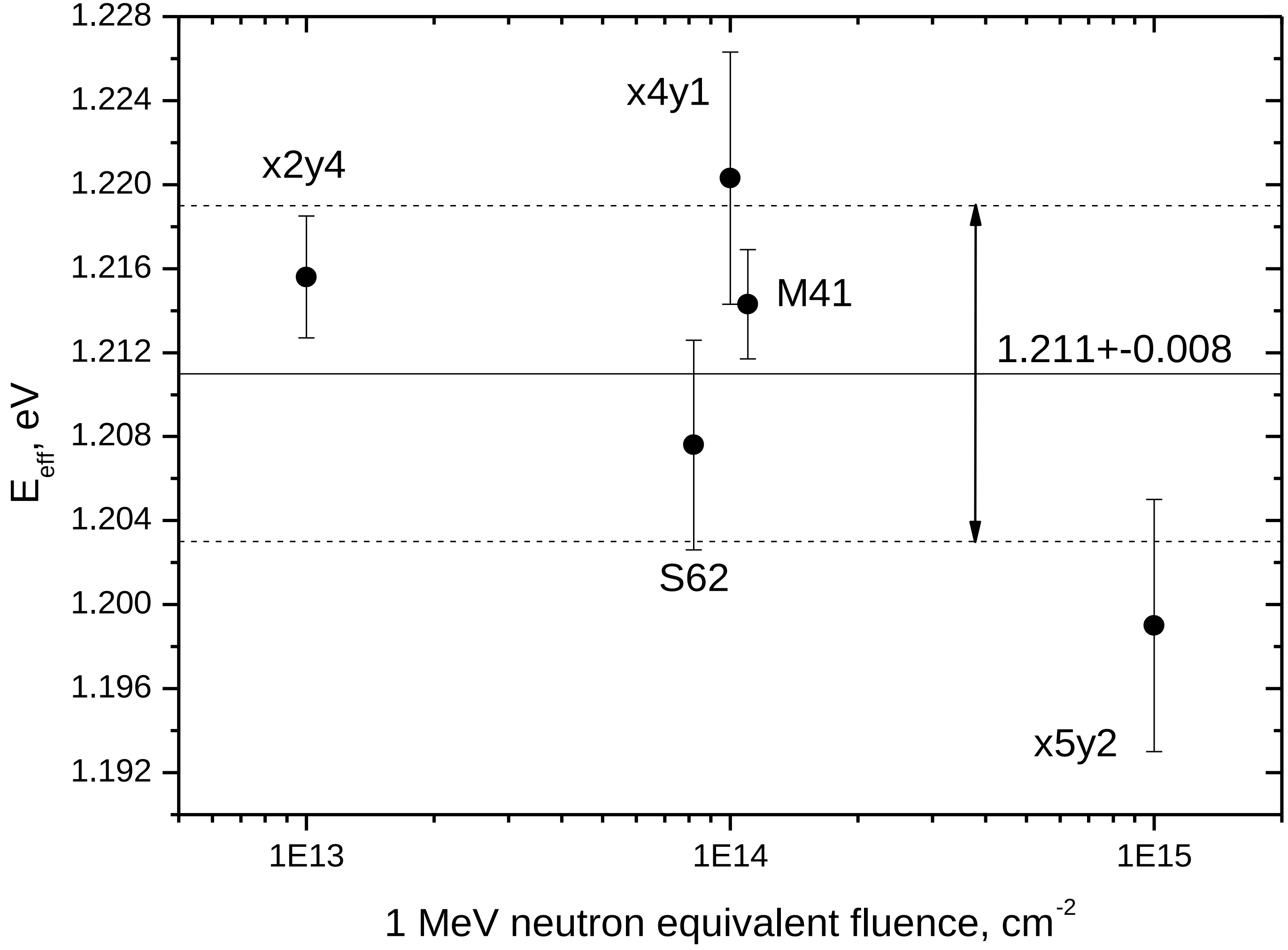
[*] For the bias range 10÷100 V.



E_{eff} from Table 3 vs. fluence. Within errors all points are consistent with their average.

3. Discussion

Bias dependence of the E_{eff} is a crucial test of the data consistency with the assumption that the measured current is dominated by that generated in Si bulk.

At high power dissipation the E_{eff} usually grows with bias because of the sensor self-heating.

There is no clear correlation between the depletion voltage and the plateau area in the E_{eff} vs. bias.

4. Conclusions

1. Lancaster measurements give E_{eff}=1.211±0.008 eV. This result is valid for both *p*-type and *n*-type sensors and for the fluence up to 10^{15} n/cm^2.
2. The published results have the average value of 1.215 eV with the spread of ~0.05 eV.
3. Both values agree with the expected E_{eff} = 1.21 eV obtained as explained in the RD50 Note **RD50-2011-01**.
4. An analysis of E_{eff} dependence on bias is crucial for selecting the data representing the bulk current. Absence of such analysis in the literature data may be responsible for a relatively wide spread of the E_{eff} values there.

Acknowledgements

The author is grateful to Graham Beck, QMUL, UK and Taka Kondo KEK, Japan for helpful and illuminating discussions.

Back-up slides

The current per unit area generated inside the depleted bulk can be written as:

$$J(T) = qWn_i/\tau_g$$

where q is elementary charge, W – depleted thickness, n_i – intrinsic carrier concentration and τ_g – generation lifetime.

Temperature dependence of n_i can be expressed as:

$$n_i \propto T^{3/2}\,exp(-E_g/2kT)$$

where E_g is the band gap.

Assuming generation happening via a trap with density N_t and level E_t in the band gap the generation lifetime can be written as:

$$\tau_g = \tau_p \exp(\Delta_t/kT) + \tau_n \exp(-\Delta_t/kT)$$

where $\Delta_t = E_t - E_i$ (E_i is intrinsic Fermi level) and $\tau_{p(n)}$ is the trapping time for holes (electrons):

$$\tau_p = 1/N_t\, v_{thp}\, \sigma_p\ ;\ \tau_n = 1/N_t\, v_{thn}\, \sigma_n\ .$$

Here $v_{thp(n)}$ is the thermal velocity and $\sigma_{p(n)}$ - trapping cross-section for holes (electrons).

Assuming that N_t and cross-sections are independent of temperature and neglecting weak temperature dependence of the effective carrier masses the trapping times can be scaled with temperature as:

$$\tau_{p(n)} \propto T^{-1/2} .$$

If $\tau_p \approx \tau_n$ the τ_g dependence on Δ_t /kT is close to $cosh(\Delta_t /kT)$. Thus τ_g is at minimum and the current generation is most effective when $\Delta_t \approx 0$. For $|\Delta_t| /kT > 1.5$ the *cosh* is reduced to $exp(|\Delta_t| kT)$. Therefore the current scaling with temperature is usually expressed as:

$$I(T) \propto T^2 exp(-(E_g+2\Delta)/2kT)$$

where Δ is a parameter close to $|\Delta_t|$ and usually is expected to be nearly zero.

The experimental value of the effective band gap for $n_i(T)$ is:

$$E_{ef} = 1.206 \pm 0.004 \text{ eV.}$$

It looks inconsistent with the actual band gap, E_g : 1.124 eV at 300K and 1.137 eV at 250K.

Note however that temperature independent E_{ef} should incorporate also the temperature dependence of E_g.

Most easily this is done if $E_g(T)$ can in some temperature interval be expressed in a linear form: $E_g = E_0 - \alpha T$, where E_0 is the extrapolation of E_g to T=0. Then:

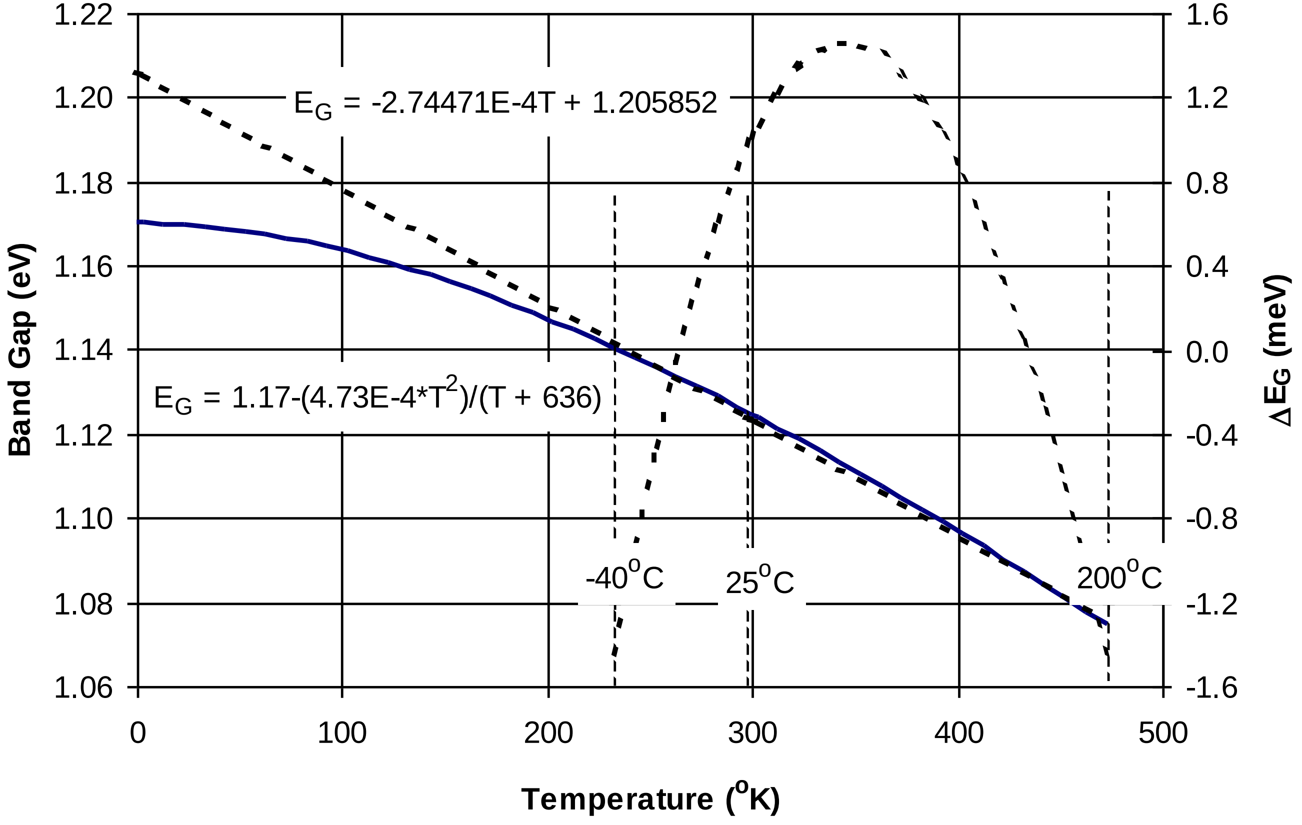
$$A \exp(-E_g/2kT) = A \exp(-E_0/2kT + \alpha/2k) = A' \exp(-E_0/2kT).$$

In the interval 250 – 415 K the $E_g(T)$ can be parameterised by the linear equation valid within 1meV accuracy with

$$E_0 = 1.206 \text{ eV}$$

in perfect agreement with the experimental results for E_{eff}.

Silicon Band Gap



This plot is taken from the 2002 talk "Band Gap Regulator Analysis" by J.B.Biard, Honeywell. (Many thanks to Graham Beck, QMUL for picking up this talk!)

From -40^o to +200^{o}C the E_g(T) can be expressed within 1.5meV accuracy by a linear equation with E_0=1.206eV.