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# Update on the temperature dependence of the bulk current in Si

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# Layout

1. Cooling with double Peltier layer
2. Updated results on $E_{eff}$ measured in Lancaster
3. Discussion
4. Conclusions

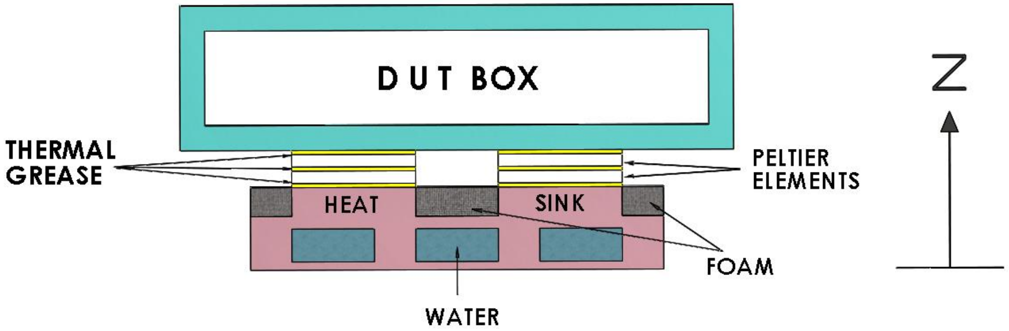
The talk is based on two recently published papers:

1. A.Chilingarov, “Operation of two stacked Peltier elements”, 2013 JINST **8** T10001,
   http://dx.doi.org/10.1088/1748-0221/8/10/T10001

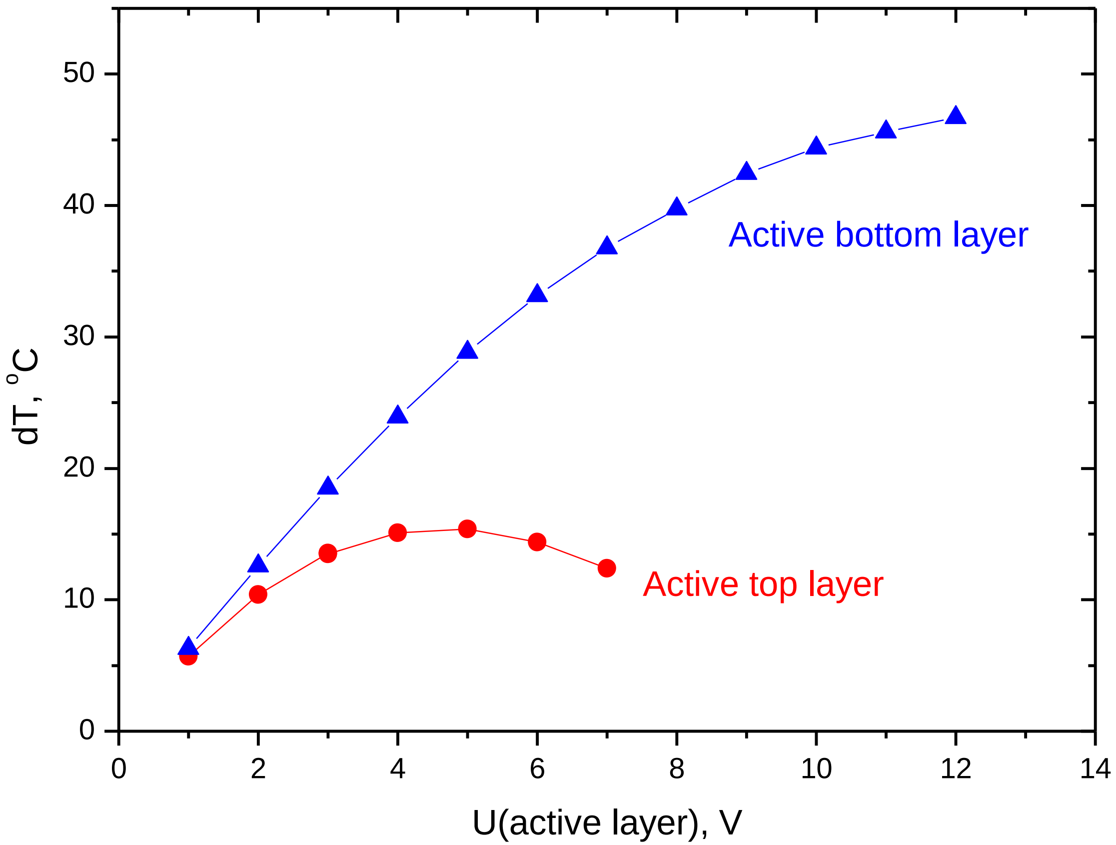
2. A.Chilingarov, “Temperature dependence of the current generated in Si bulk”, 2013 JINST **8** P10003,
   http://dx.doi.org/10.1088/1748-0221/8/10/P10003

Please use these references for more details.

# 1. Cooling with double Peltier layer




A new set-up with cooling by two stacked identical Peltier elements was built allowing lower temperatures in I(T) measurements. On the next slides the layer in the contact with the heat sink is called bottom layer and another – the top one.




Surprisingly the cooling efficiency of the layers was very different. With only one layer biased the temperature difference between the DUT box and the heat sink was much lower for the active top layer. The reason for this is its thermal shielding from the heat sink by the thermal resistance of the bottom layer.



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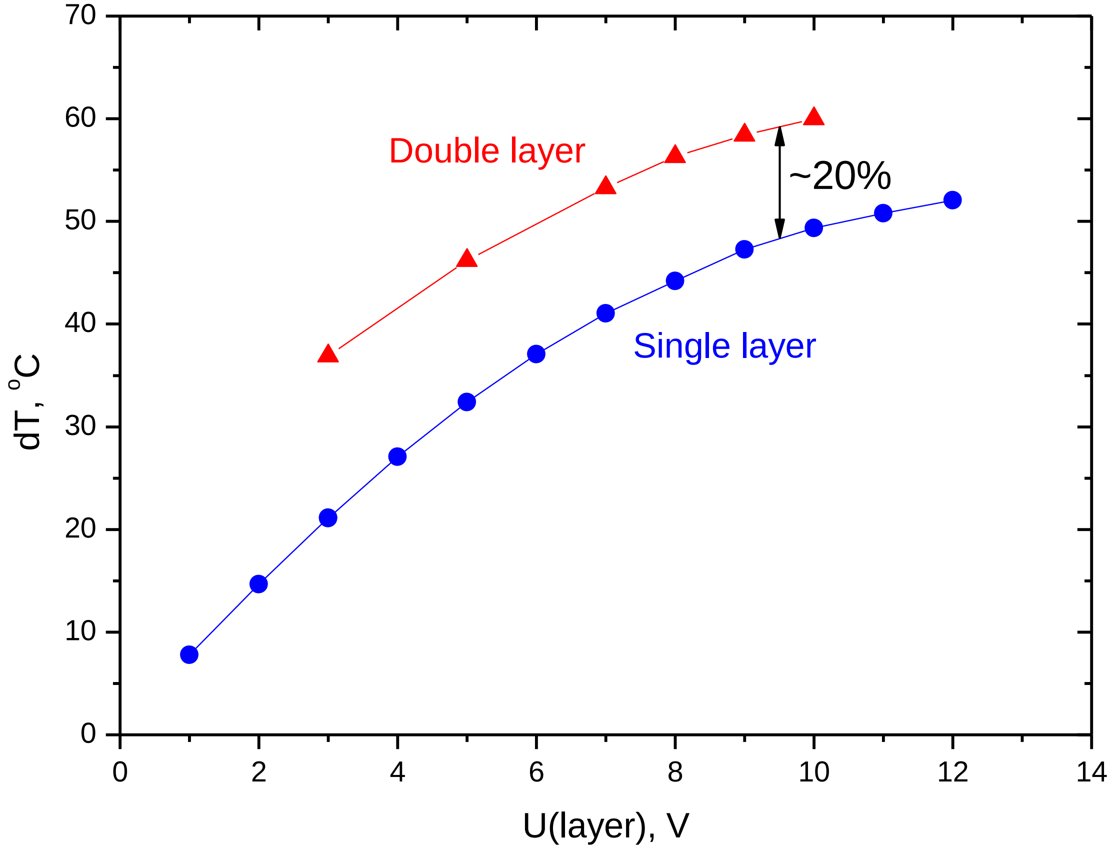


The optimal cooling with both layers active required keeping $U_{top}$ at 4V (near the maximum of its cooling curve) and varying the $U_{bottom}$. The resulting temperature difference is only by about 20% higher than what could be achieved with a single layer.

# 2. Updated results on $E_{eff}$ measured in Lancaster

The lowest temperature achievable in the new set-up was -52$^{o}$C. The *p*-type sensors irradiated by the 1 MeV neutron equivalent fluence of $10^{13}$, $10^{14}$ and $10^{15}$ per cm$^2$ were re-measured in a wider temperature range. Sensible measurements with the sensor irradiated by $10^{16}$ neq/cm$^2$ became possible.

In addition the sensor irradiated by $10^{14}$ neq/cm$^2$ was annealed by keeping it at the temperature of +65$^{o}$C for 8.5 hours. The $E_{eff}$ for the annealed sensor was also measured.

The measurement and analysis procedures are illustrated in this talk only by the data for one sensor. See the paper mentioned on slide 3 for the full set of data.



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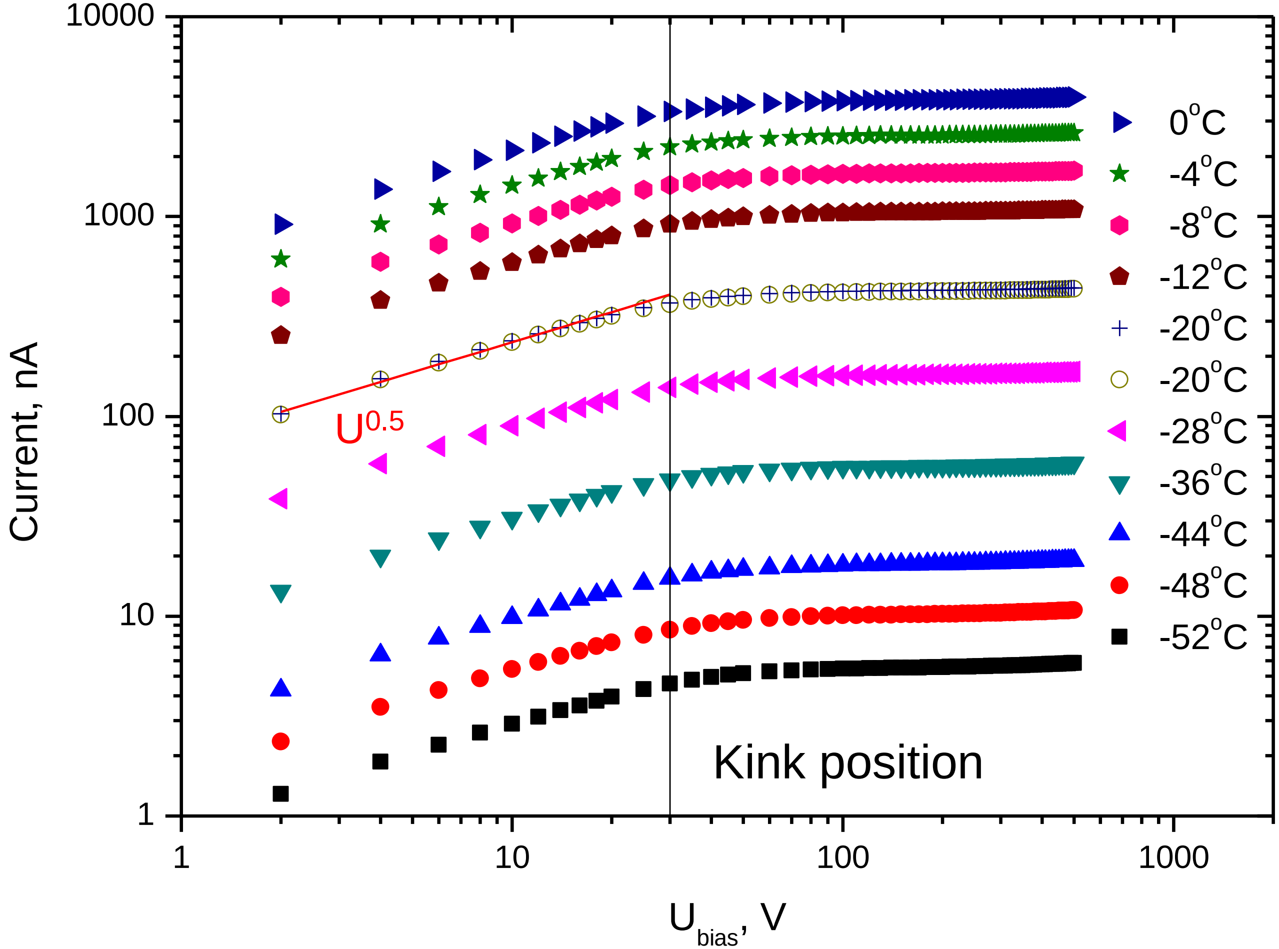
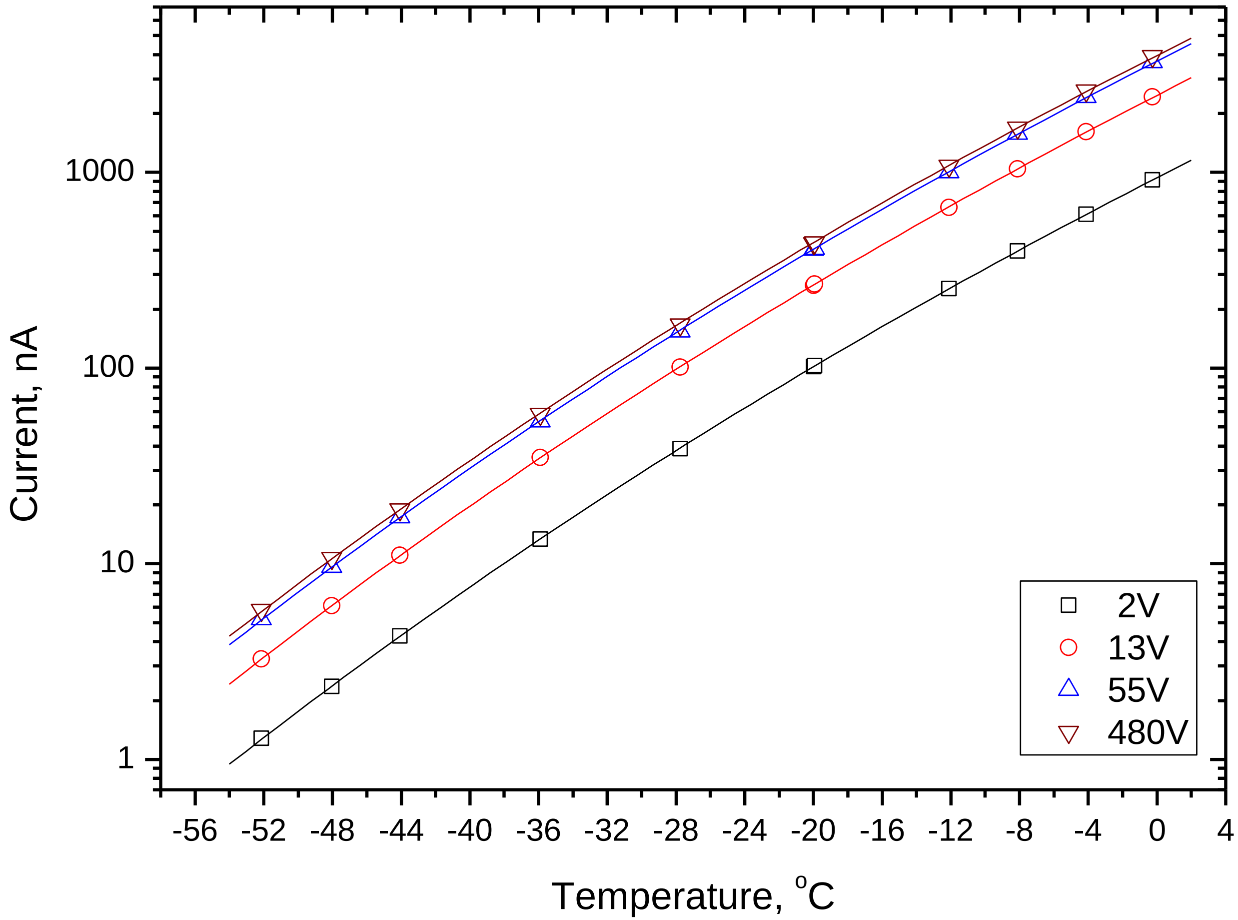
# Sensor x2y4 irradiated by $10^{13}$ n/cm$^2$
# $I_c$-V curves




Below depletion the current grows as a square root of $U_{bias}$ as expected for the current generated in the bulk.




To equalise the weight of the points with the values of the current differing by 3 orders of magnitude the errors of 1% were assigned to the points and used in the fit. Typical $\chi^2/N_{df}$ was ~1, i.e. typical spread of the points around the fit curve was ~1%

Bias points from 2 to 500V were combined in 20 groups and the average current for each group was fit by $T^2 \exp(-E_{eff}/2kT)$ as a function of temperature. The fits for 4 bias groups are shown as examples.

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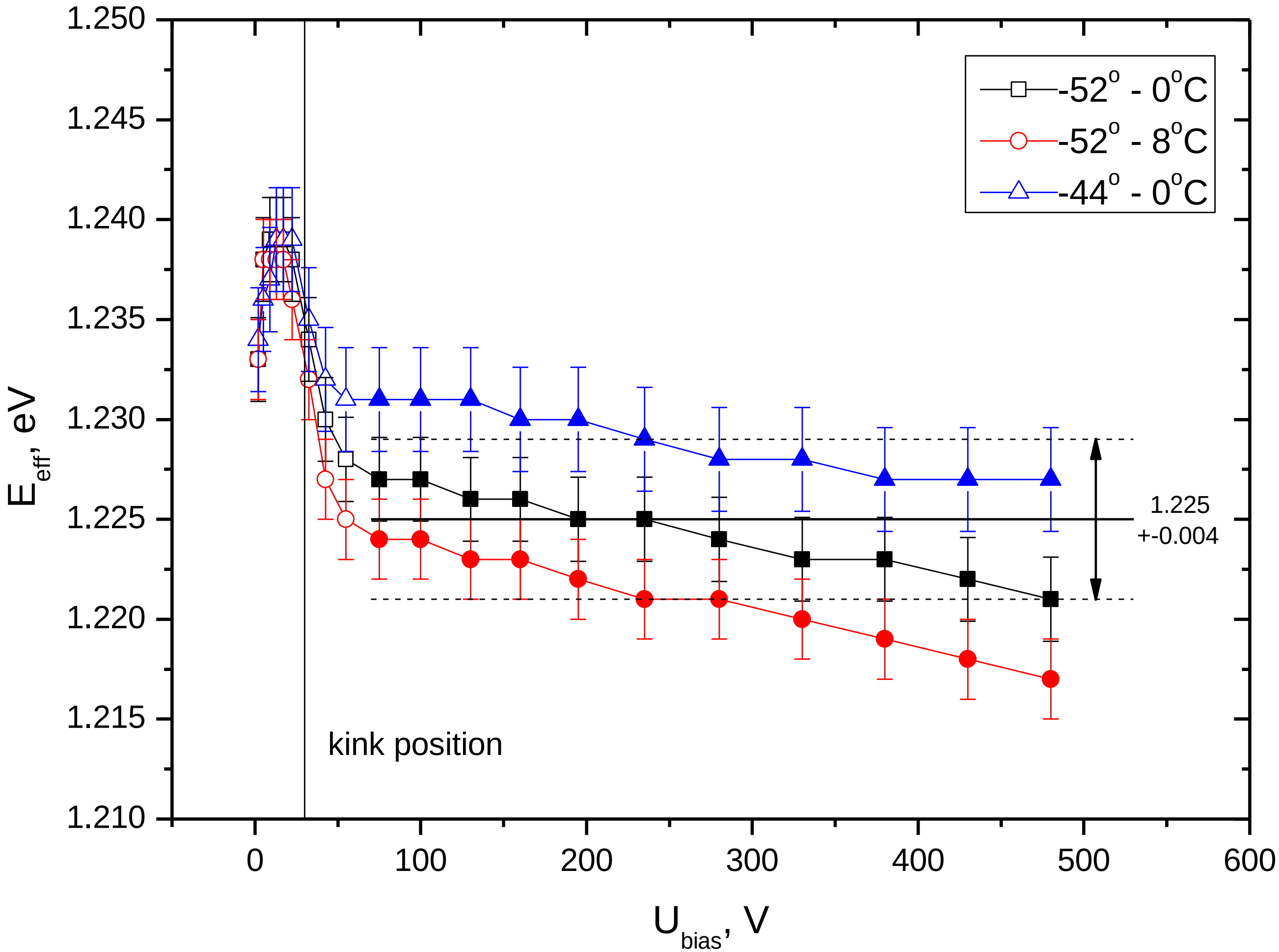
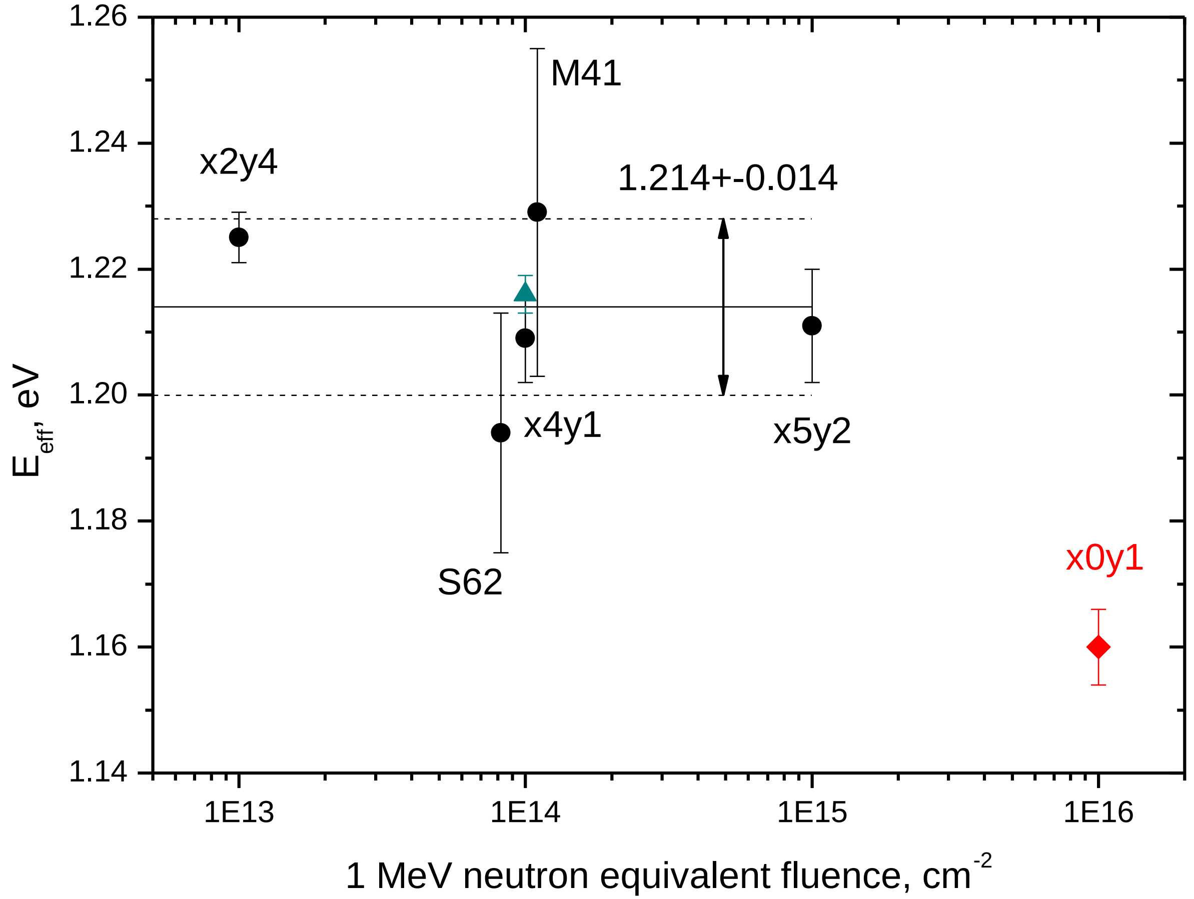



There are no signs of the sensor self-heating. Maximum power dissipation $I_{total}*U_{bias}$=3 mW. It was used as a limit in measurements with all other sensors to suppress the self-heating effects.

The $E_{eff}$ values as a function of bias for 3 temperature ranges. Average value and the standard deviation are calculated using the filled points. The error includes the $E_{eff}$ variations with bias and the temperature range.



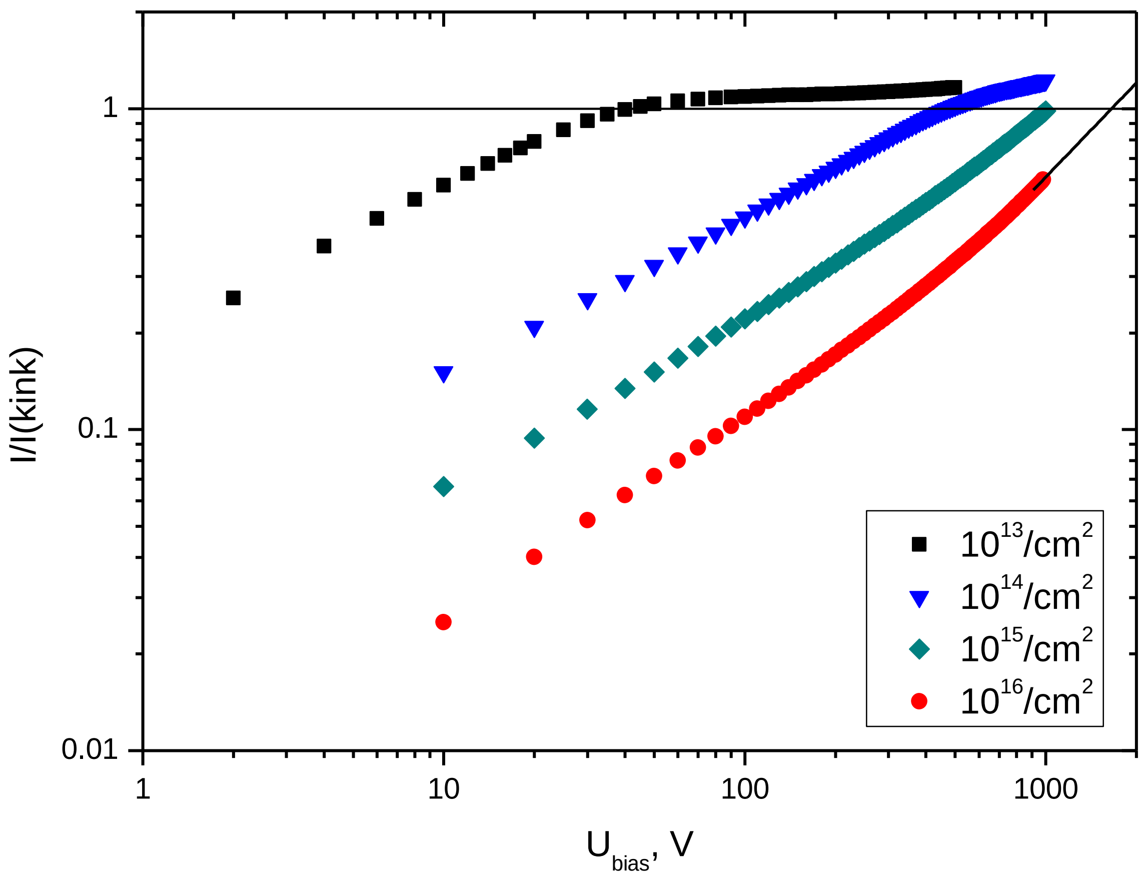

$E_{eff}$ for all investigated sensors vs. fluence. The green point is for the annealed sensor and the red for the most heavily irradiated one. The average and the standard deviation is calculated for the black points only.

# 3. Discussion

Apart from that for the sensor irradiated by $10^{16}$ neq/cm$^2$ all measured $E_{eff}$ values agree between themselves. Their average value agrees with 1.21 eV expected for the generation via a mid-gap level.

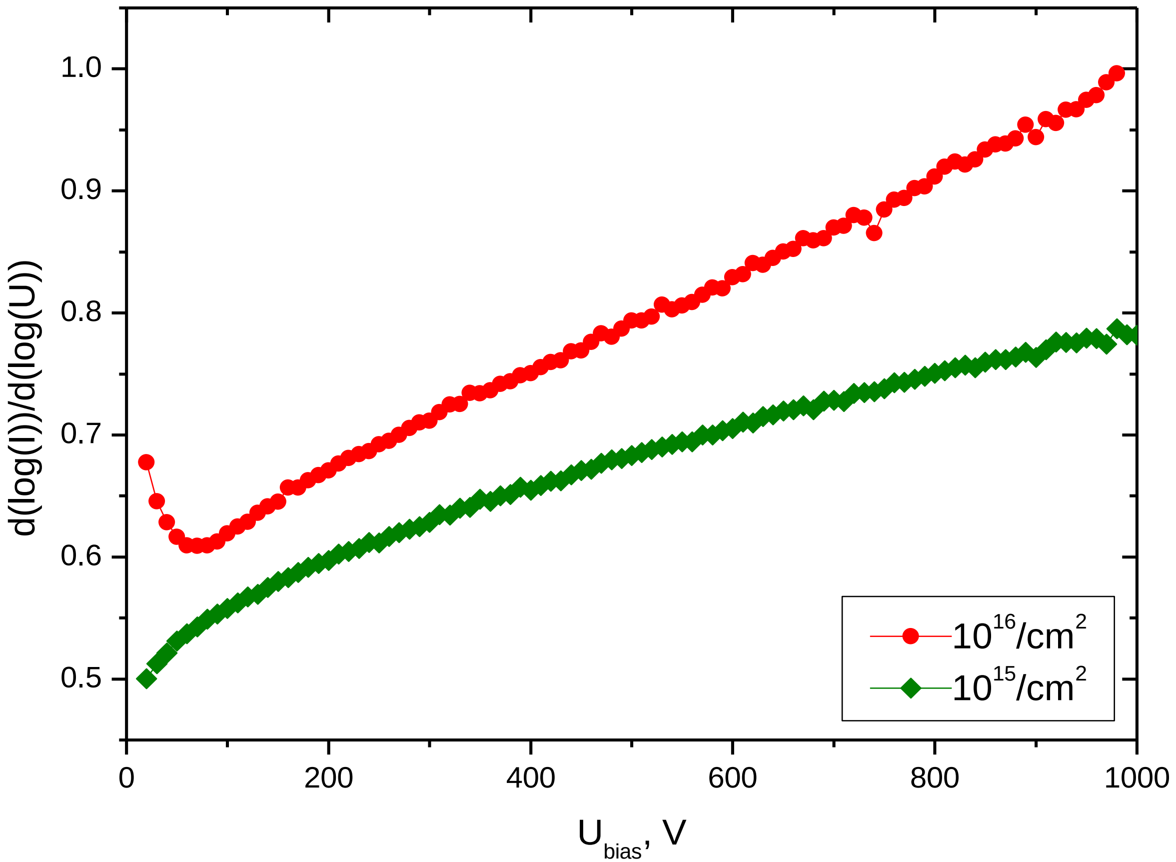
The intense annealing didn't change the $E_{eff}$ value.

Below depletion voltage the active volume is not fixed by the sensor geometry. Therefore an additional variation of the current with temperature can appear due to possible dependence of the effective depleted volume on temperature, which may distort the $E_{eff}$ value. This effect is probably responsible for the abnormally low $E_{eff}$ observed for the most heavily irradiated sensor.




The current at -52$^{o}$C normalised to the measured (for two low fluences) or projected value at the “kink” position. For $10^{13}$ and $10^{14}$ neq/cm$^2$ the “kink” voltages are 30V and 435V respectively. For the high fluences the projected “kink” voltages are surprisingly low: 1020V for $10^{15}$/cm$^2$ and 1600V for $10^{16}$/cm$^2$.

For high fluences the current reaches the value corresponding to the sensor full depletion at the voltages much lower than anticipated values. At -52$^{o}$C all points in the plot satisfy the requirement of $I_{total}$*$U_{bias}$ < 3 mW, which excludes the self-heating effects.




The slopes calculated for the curves from the previous slide for the high fluences. They indicate the current growing much faster than $U^{0.5}$ expected for the uniform space charge density in the depleted area.

The results on this and previous slide can be explained by the contribution to the current from the carriers generated in the electrically neutral bulk (ENB) and pulled out to the space charge region by the electric field existing in the ENB. The effect becomes more pronounced with irradiation.

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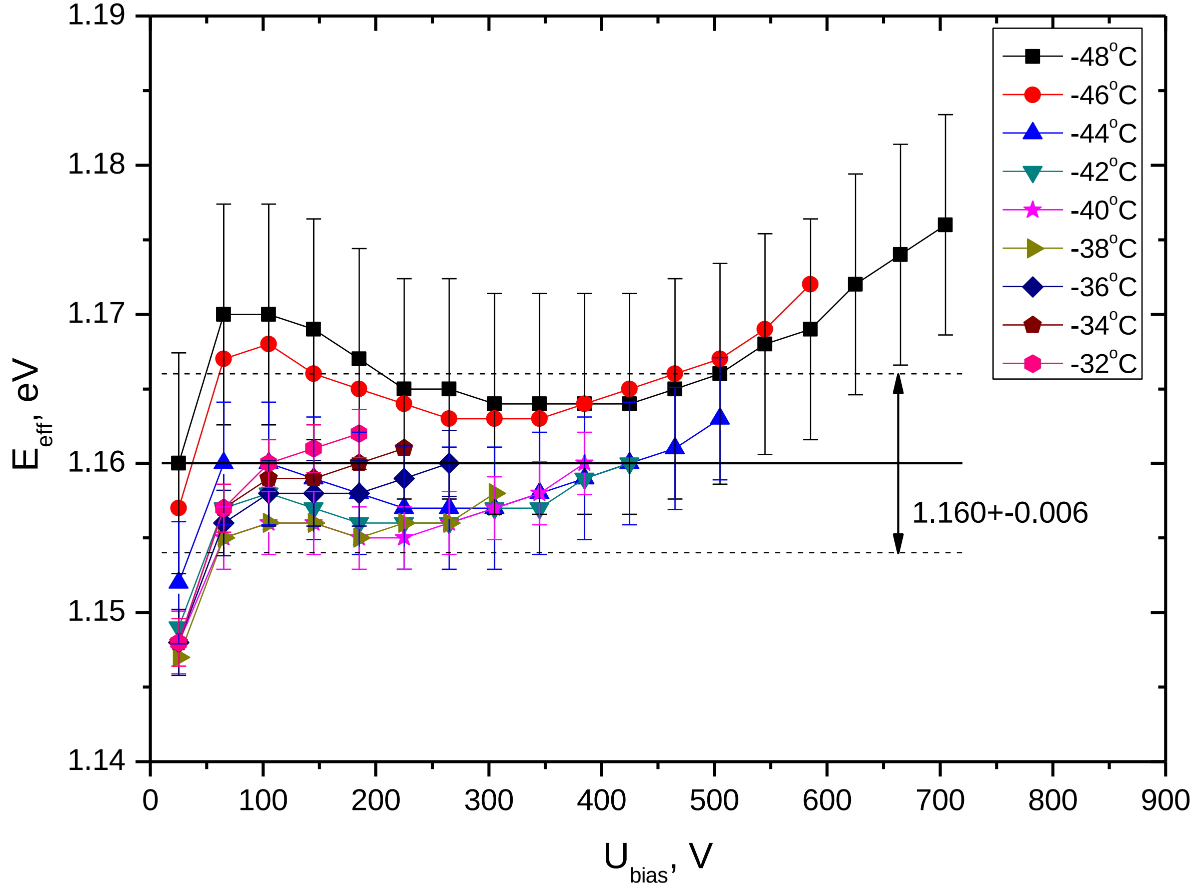
The full depletion voltage expected for the sensor irradiated by $10^{16}$ neq/cm$^2$ is very much higher than the bias voltage used in the measurements. From the previous two slides it is clear that the current in this sensor has a large contribution from the carriers generated in the ENB. Therefore a subtle temperature dependence of the fraction of these carriers pulled out to the depleted volume can affect noticeably the I(T) dependence and consequently the $E_{eff}$. Such explanation looks more plausible than the assumption of the carrier generating mechanism changing above the $10^{15}$ neq/cm$^2$ fluence.

Measurements with thinner detectors allowing their nearly complete depletion even after $10^{16}$ neq/cm$^2$ are necessary to clarify the situation. Meanwhile one can only notice that the $E_{eff}$ values measured for this sensor grow steadily with bias above 400 V as demonstrated on the next slide.




The $E_{eff}$ vs bias for the sensor irradiated by $10^{16}$ neq/cm$^2$. Different sets of data correspond to different temperature ranges with minimum temperature of -52°C and the maximum one indicated in the legend. Only the points with power dissipation <3 mW are presented.

There is no clear bias dependence and all points were used to calculate the average and standard deviation. Note however that above 400V all curves show $E_{eff}$ growing with bias.

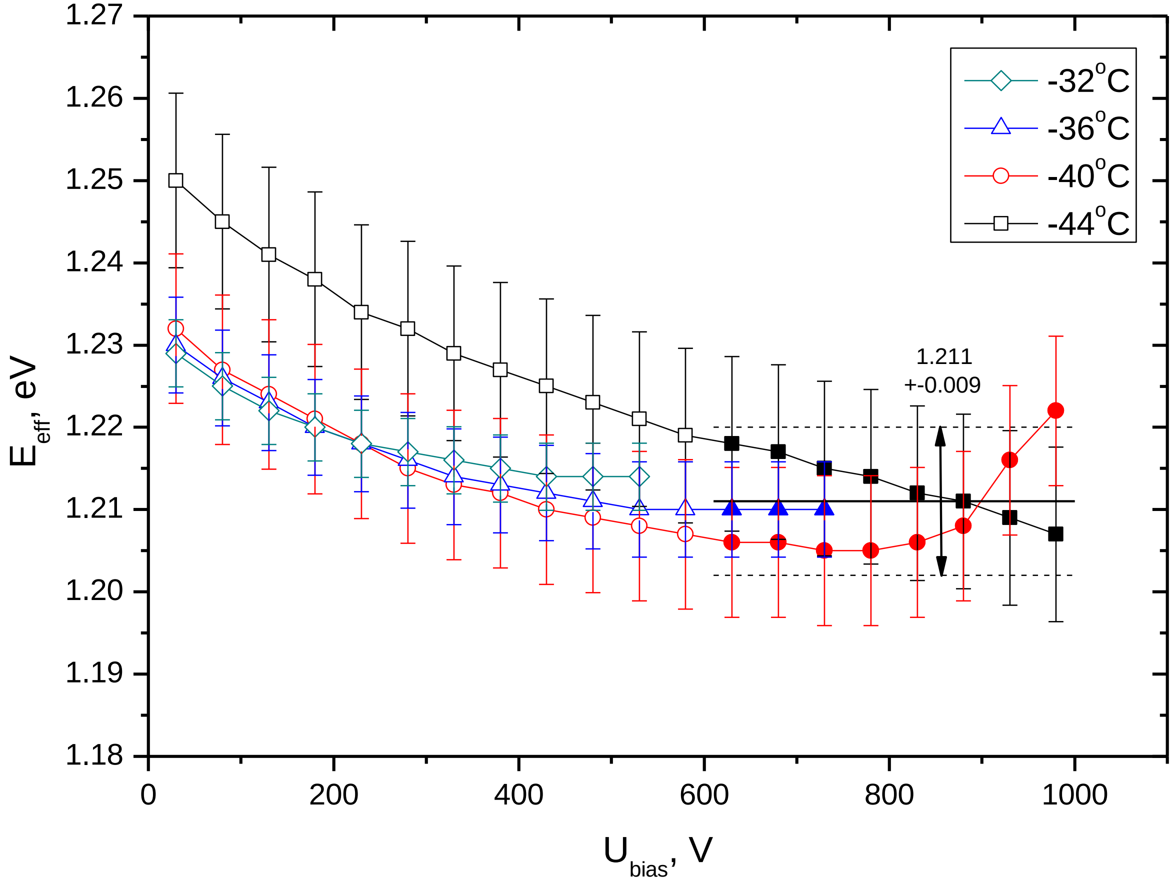
# 4. Conclusions

1. Lancaster measurements give $E_{eff}$=1.214±0.014 eV. This result is valid for both *p*-type and *n*-type sensors and for the fluence up to $10^{15}$ neq/cm$^2$. It agrees well with the value of 1.21 eV expected for the generation via a mid-gap level.
2. The annealing of one of the sensors at 65$^o$C for 8.5 hours didn't change the $E_{eff}$ value.
3. Relatively low value $E_{eff}$ = 1.160±0.006 eV observed for the sensor irradiated by $10^{16}$ neq/cm$^2$ is probably due to the sensor operation at bias much lower than that of full depletion.
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 observed there.

# Acknowledgements

The author is grateful to Graham Beck from Queen Mary University of London for numerous stimulating discussions.

# Back-up slides




$E_{eff}$ vs bias for the sensor irradiated by $10^{15}$ neq/cm$^2$ in 4 temperature ranges with $T_{min}$=-52°C and $T_{max}$ indicated in the legend. Only the points with power dissipation <3mW are shown. The average and the standard deviation were calculated for the points shown by the filled symbols.