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Generation current temperature scaling

Part-II: Experimental data

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1. Review of the published results

Bulk generation current plays an important role in heavily irradiated sensors where it usually dominates in the observed current. In non-irradiated sensors the generation current is typically quite small and can easily be obscured by a current over the physical edge, soft breakdown, etc. Therefore the review below covers only the results obtained with irradiated Si sensors.

The I(T) dependence is supposed to be described by

$$I(T) \propto T^2 \exp\left(-\frac{E_{eff}}{2kT}\right). \qquad (1)$$

where T is the absolute temperature and k is the Boltzman constant. Table 1 contains the values of effective energy gap E_{eff} from References [1-7].

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, ^oC**
[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
			Full average:	**1.23±0.06**	
			Without max and min values:	**1.23±0.04**	

Averaging all results and after excluding the maximum and minimum values gives the same answer: 1.23 eV. In the first case the standard deviation. is 0.06 eV and in the second 0.04 eV.

2. Lancaster results

The results presented in this section were obtained by analysis of the data collected in different studies in Lancaster with irradiated Si sensors. It is worth noting that those studies were not aimed at the investigation of Current-Temperature dependence and therefore were not optimised for this purpose.

2.1 **Sensors and their irradiation**

The analysed data are for 4 sensors: a) two microstrip detectors made of *p*-type material with sensitive area of 1x1 cm^2 , 500 μm thickness and strip pitch of 80 μm and b) two diodes made of *n*-type material with sensitive area of 0.5x0.5 cm^2 and 300 μm thickness. The information about the irradiation is presented in Table 2. The quoted fluence is equivalent to that of 1 MeV neutrons.

Table 2. The 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	25	0.1
x4y1	μ-strip	*p*	p	25	1.0
S62	diode	*n*	n	~1	0.82
M41	diode	*n*	n	~1	1.1

Irradiations were performed at room temperature and without bias. After irradiation the sensors were kept at room temperature for a couple of days to allow beneficial annealing to happen. After this the sensors were stored and the measurements with them were made at sub-zero temperature to prevent further annealing. For the same reason rare measurements at temperatures above 0^oC were made as brief as possible.

Further details about the *p*-type sensors may be found in Ref.[8] and about *n*-type sensors in Ref.[9]. The latter describes also the measurement set-up.

2.2 **Results for the *p*-type sensors**

I-V dependence was measured with bias voltage applied to the sensor backside, grounded sensitive area and the innermost guard ring (GR) grounded via an ammeter. The difference between the total current flowing from the HV source-meter and separately measured GR current allowed finding the current through the central part of the sensor I_c. The bias voltage was always negative. In the text below its absolute value is used.

2.2.1 **Sensor x2y4 irradiated by 10^{13} 1 MeV *n* equivalent fluence**

I-V scans were performed at -20°C, -1°C and at -20°C second time. The results are shown in Fig.1.

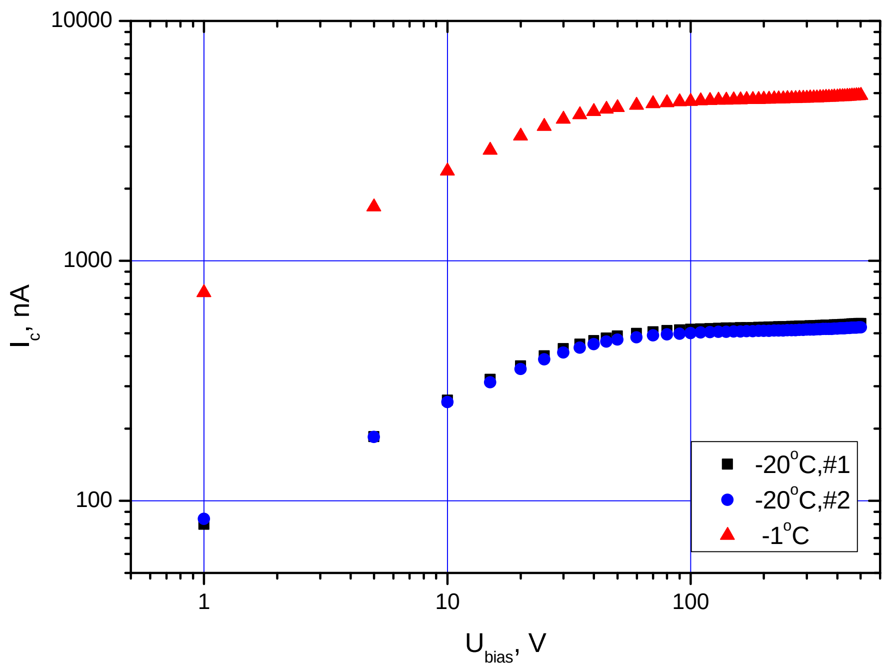

Fig.1. I-V curves for sensor x2y4 irradiated by 10^{13} 1 MeV *n* equivalent fluence.

Around 35V the I-V curves have a "kink" indicating full depletion of the sensor. Below this voltage the current grows approximately as $(U_{bias})^{1/2}$ and above it is almost constant. These features indicate the bulk generation as a major source of the current.

For further analysis 30 bias points from 5 to 250V were grouped by 3 (altogether 10 groups) and the average current $<Ic>$ was calculated for each I-V curve in each group. These were plotted versus temperature and fit by the function (1). To give equal weight to the points with significantly different current values the 5% errors were assigned to the points and used in the fit. With only 3 temperature points, and two of them at almost the same temperature, the quality of the fit with 2 free parameters reflects not the validity of the model but the spread of the points at -20^{o}C. Typical value of χ^2/Ndf was <0.01 which shows that the spread of the currents at -20^{o}C was less than 0.1 of the assumed 5% i.e. <0.5%.

The E_{eff} values found in the fits are presented in Fig.2. They show no clear bias dependence and have a small spread. Their average is 1.220 eV with the standard deviation of 0.0029 eV (these results are also included in Fig.2).

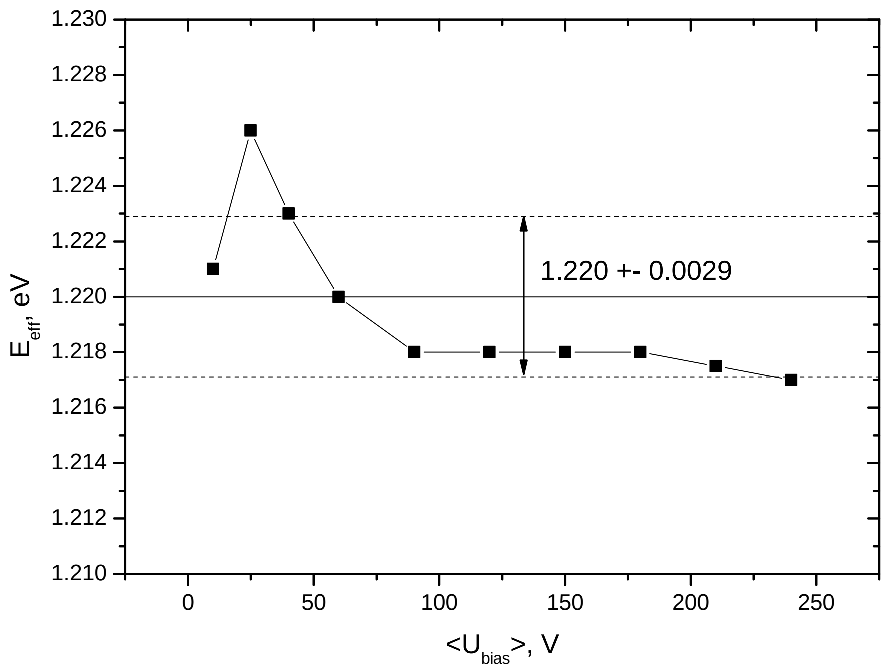

Fig.2. *Eeff* from the fits for x2y4 sensor vs. average bias in 10 voltage groups. Solid line shows the average value and the dashed lines the standard deviation.

2.2.2 **Sensor x4y1 irradiated by 10^{14} 1 MeV *n* equivalent fluence**

I-V scans were first performed twice at -20^{o}C (with ~24 hours interval), then at -10^{o}C, -28^{o}C and two more times at -20^{o}C. The results are presented in Fig.3. For clarity only the first and the last measurements are shown for -20^{o}C.

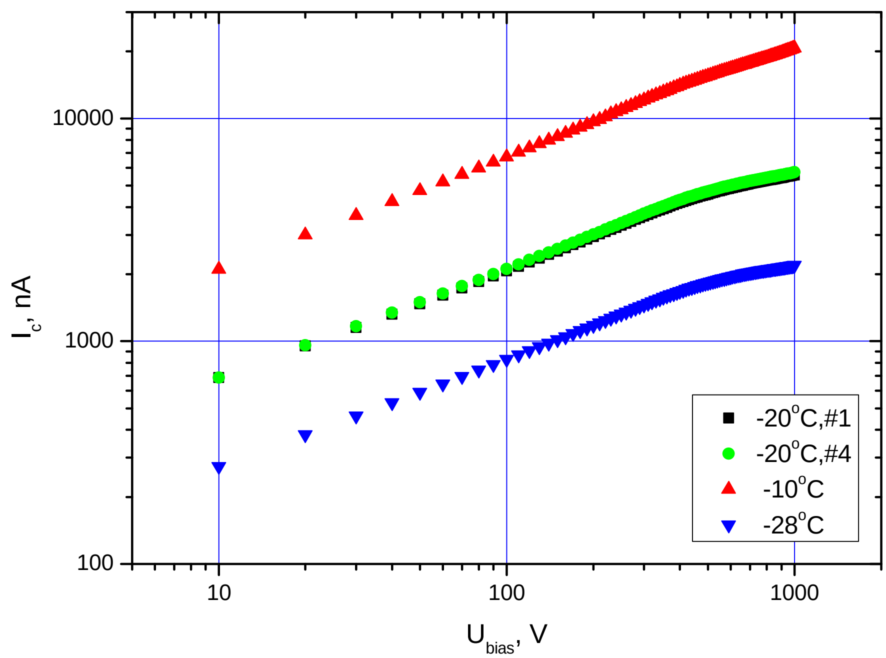

Fig.3. I-V curves for sensor x4y1 irradiated by 10^{14} 1 MeV *n* equivalent fluence.

Around 440 V the I-V curves exhibit a “kink” indicating full depletion of the sensor. It is more pronounced at lower temperature and is almost indistinguishable at higher temperature. Below this voltage the current grows approximately as $(U_{bias})^{1/2}$ that indicates the bulk generation as a major source of the current at those bias values.

For further analysis 65 bias points from 10 to 650V were grouped by 5 (altogether 13 groups) and the average current <*Ic*> was calculated for each I-V curve in each group. These were plotted versus temperature and fit by the function (1). As in previous case the 5% errors were assigned to the points and used in the fit. Typical χ^2/Ndf values of ~0.1 found in the fits show that the actual errors are ~1/3 of the assumed 5%.

The E_{eff} values found in the fits are presented in Fig.4. When all temperature points are used E_{eff} grows steadily with bias. This can be due to the sensor self-heating because of insufficient cooling. If the points at -10°C are excluded from the fit the E_{eff} is much more stable. The average E_{eff} in this case is 1.215 eV and the standard deviation 0.005 eV (these results are also shown in Fig.4). Averaging E_{eff} for all temperatures and all bias points gives 1.237±0.016 eV.

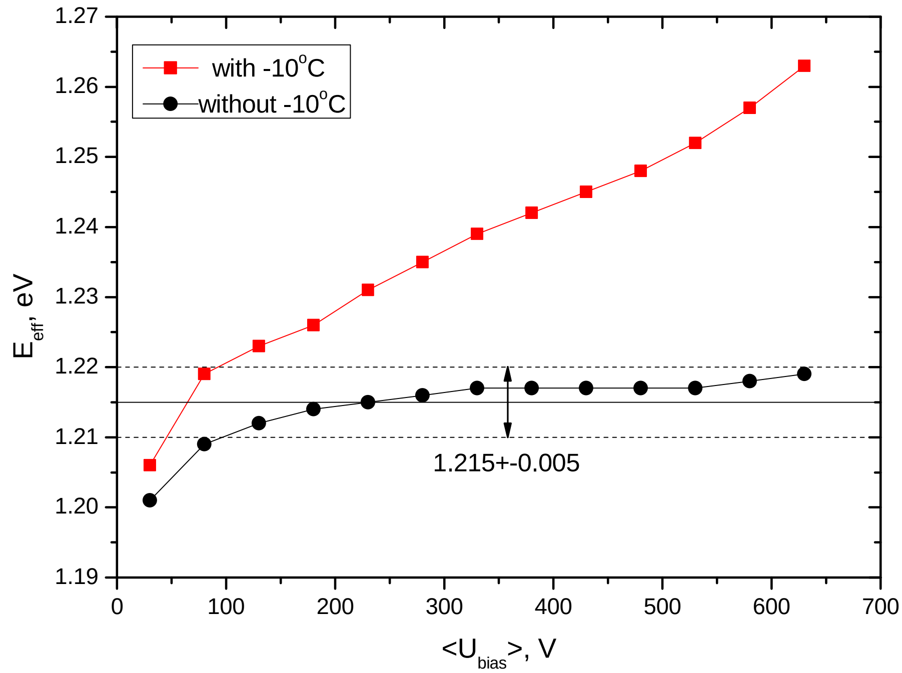

Fig.4. *Eeff* for x4y1 sensor vs. average bias in 13 voltage groups. Red points include the data at -10°C and the black ones don't. Solid line shows the average value and the dashed lines the standard deviation for the black points.

Another hint to possible self-heating of the sensor is significantly steeper growth of the current with bias above the depletion voltage in the I-V curve at -10°C compared to those at lower temperatures (see Fig.3).

2.3 **Results for the *n*-type sensors**

I-V dependence was measured with positive bias voltage applied to the sensor backside, grounded guard ring and the sensitive area grounded via an ammeter, which measured the current through the central part of the diode I_c.

2.3.1 **Sensor S62**

The analysed data were collected during the study described in detail in Ref.[9]. The I_c-V measurements were performed simultaneously with C-V measurements, which were the main point of investigation. The temperature sequence was the following: 0°C, -24°C, -12°C, +12°C. Typically 16 bias voltage scans were made at each temperature. For the present analysis the average I_c-V curve was produced for each temperature. They are shown in Fig.5.

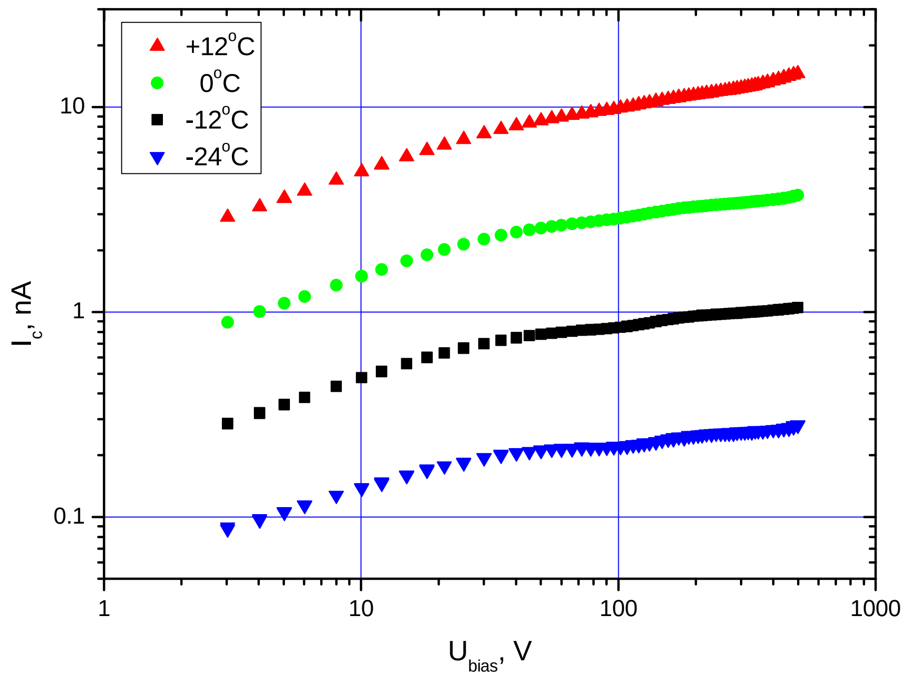

Fig.5. I-V curves for sensor S62. Each one is the average of 16 voltage scans.

At ~30 V the curves have a "kink" which is more pronounced at low temperatures and almost invisible at high temperature. Below this voltage the currents grow as $(U_{bias})^{0.4}$ rather than $(U_{bias})^{0.5}$ expected for the current generated in the bulk that indicates a contribution from the currents of another type. Above the "kink" the rate of the current growth with bias steadily increases with temperature.

The current was measured twice at each bias and thus every curve contains 124 points at 62 bias voltages. Starting from U_{bias}=5V the points (120 in total) were grouped by 10 forming 12 bias groups. For each group the average current was calculated at every temperature and fit by function (1). As in previous cases 5% errors were assigned to the current values and used in the fit. Typical χ^2/Ndf values of ~0.5 found in the fits show that the assumed errors are close to the actual ones. Fig.6 shows the E_{eff} vs average bias for 12 bias groups.

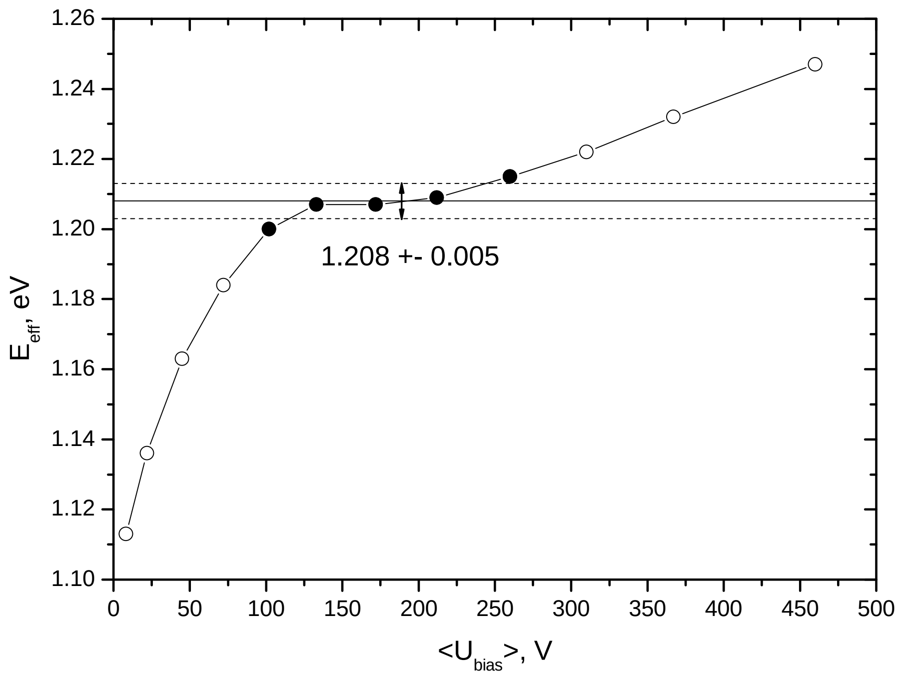

Fig.6. E_{eff} vs average bias for sensor S62. The average value and standard deviation is shown for 5 points (marked as filled ones) around the plateau.

At low voltage the E_{eff} quickly grows with bias. Then it plateaus but above 250 V starts to grow again though less steeply. Five points around the plateau region (marked by the filled symbols in Fig.6) have the average value of 1.208 eV and the standard deviation of 0.005 eV. These numbers are also shown in Fig.6. For all points the average is 1.195 eV and the standard deviation 0.039 eV.

2.3.2 **Sensor M41**

The data were collected during the study described in detail in Ref.[10]. The I_c-V measurements were performed simultaneously with C-V measurements, which were the main point of investigation. The temperature sequence was the following: 0^{o}C, -8^{o}C, -16^{o}C, +8^{o}C, +16^{o}C, +25^{o}C, +32^{o}C, +16^{o}C (second time). The second round of measurements at +16°C showed systematically lower currents than in the first round. This means that a noticeable annealing happened during the measurements at +25°C, and +32°C. Therefore only the results for the first five temperature series (up to the first +16°C) were analysed here. At each temperature typically 4 bias voltage scans were made. For the present analysis the average I_c-V curve was produced for each temperature. They are shown in Fig.7.

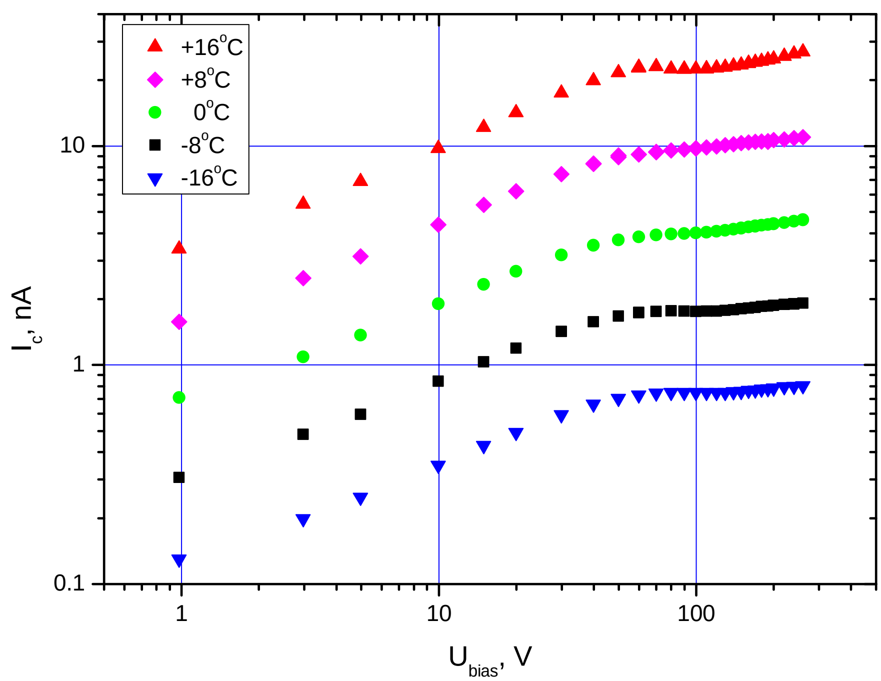

Fig.7. I-V curves for sensor M41. Each one is the average of 3-4 voltage scans.

At ~50 V the curves have a "kink" indicating full depletion of the sensor. Below this voltage the currents grow approximately as $(U_{bias})^{0.5}$ expected for the current generated in the bulk. Above the "kink" the current is almost constant especially at low temperatures.

The current was measured twice at each bias and every curve contains 54 points at 27 bias voltages. Starting from U_{bias}=3V the points (52 in total) were grouped by 6 for the first 36 points and then by 8 for the remaining 16 points thus forming 8 bias groups. For each group the average current was calculated at every temperature and fit by function (1). As in previous cases 5% errors were assigned to the current values and used in the fit. Typical χ^2/Ndf values of ~0.5 found in the fits show that the assumed errors are close to the actual ones. Fig.8 shows the E_{eff} vs average bias for 8 bias groups. For the fits made through all 5 temperature points the E_{eff} value steadily grows with bias that probably indicates self heating of the sensor. If +16°C points are excluded from the fits the E_{eff} is about constant in the first 4 points but starts to grow quickly with bias above 100V. The reason for this can be seen in Fig.7. Above 100 V the currents grow with bias faster at higher temperatures than at lower ones.

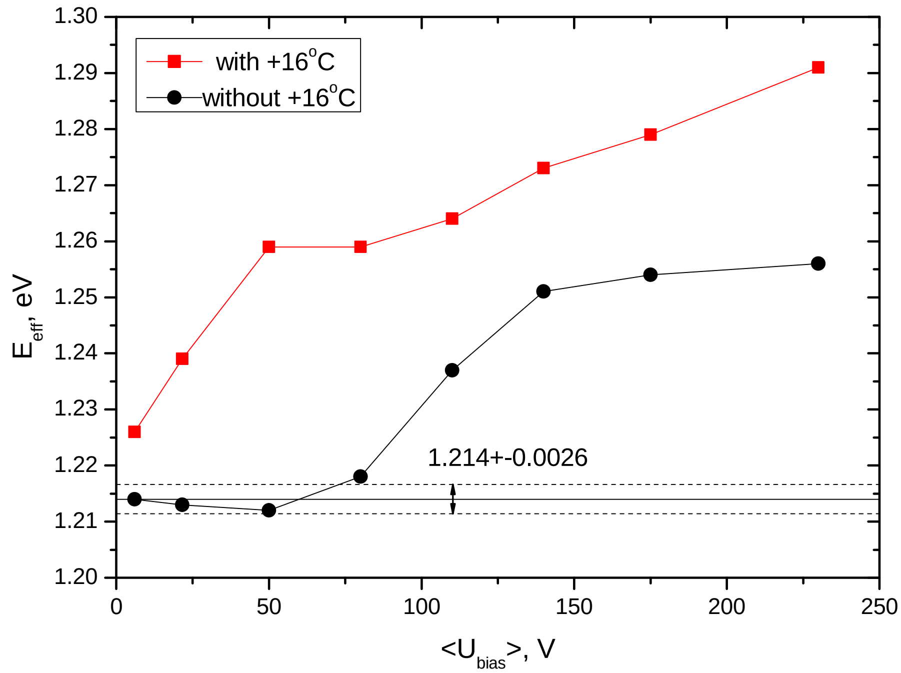

Fig.8. E_{eff} vs average bias for sensor M41 for the fits through all points and excluding +16°C. The average value and standard deviation is shown for first 4 points of the fits without +16°C.

The average value of the first 4 points for the fits without +16°C is 1.214 eV and their standard deviation is 0.0026 eV. These numbers are also shown in Fig.8. For all points without +16°C the average is 1.232 eV and the standard deviation 0.020 eV.

2.4 **Discussion**

In investigation of the current-temperature dependence a care should be taken to selecting the results corresponding to the bulk generation current and avoiding the effects of sensor self-heating. The latter manifests itself as a steady increase of the parameter E_{eff} with bias. Three out of 4 sensors analysed here showed this effect and some temperature or bias points (or both) had to be excluded on this ground from the final results.

For genuine generation current E_{eff} should not depend on bias. When this is not the case (after the self-heating is eliminated) it is likely that the measured current has a significant contribution from the other types of the current. On this ground four low bias points were excluded from the final result for the sensor S62. It is worth noting that for this sensor the current growth with bias below depletion differs from the expected $(U)^{1/2}$ dependence that is also an indication of another current type contribution. The results obtained after applied selections are summarised in Table 3.

Table 3. Summary of the results

Sensor name	**IV"kink" at, V**	**lnI-lnU slope**	**Bias range used, V**	**Temperature range used, ^oC**	**Eeff, eV**	**Standard deviation, eV**
x2y4	34	0.48	5-250	-20 ÷ -1	1.220	0.0029
x4y1	440	0.51	10-650	-28 ÷ -20	1.215	0.005
S62	32	0.40	90-280	-24 ÷ +12	1.208	0.005
M41	50	0.48	3-90	-16 ÷ +8	1.214	0.0026

Second column shows the voltage at which the "kink" indicating full depletion is observed in log(I)-log(V) plot and the third column the slope in this plot below the "kink". The fourth and fifth columns show the bias and temperature ranges used in the final result that is presented in the last two columns. Averaging the E_{eff} values from column 6 with equal weight (i.e. ignoring the values from column 7) gives 1.214 eV with a standard deviation of 0.005 eV. This is presented graphically in Fig.9. As can be seen from this plot all results are well consistent within their relatively small uncertainties despite significant difference in sensors, irradiations and measurement procedures.

Absence of the analysis of a possible E_{eff} dependence on bias voltage in publications reviewed in Section 1 may be responsible for a relatively large spread of the results.

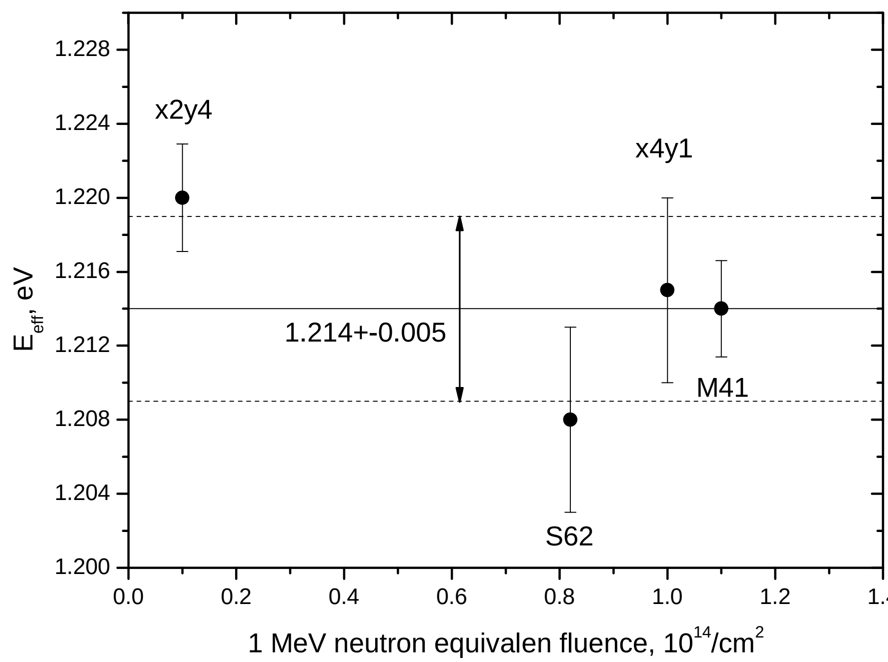

Fig.9. Final results for individual sensors vs 1 MeV neutron equivalent fluence. The global average and the standard deviation are shown by the lines.

3. Conclusions

Within their uncertainties the experimental values of the effective gap energy E_{eff} from equation (1) agree with 1.21 eV expected from the generation via mid gap level and well known temperature dependence of the intrinsic carrier density for Si. This value was obtained for temperature range ±30°C as explained in the first part of this Note [11]. The average E_{eff} value of reviewed published results is 1.23 eV with the standard deviation of 0.04 eV for the data excluding minimum and maximum values and of 0.06 eV for all data. The Lancaster results with careful analysis of the E_{eff} dependence on bias voltage and appropriate selections give 1.214 eV with the standard deviation of 0.005 eV.

References

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