Generation current temperature scaling

RD50 and EP Technical Note by
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Part-I: Theory (vs.1: 9.5.2011)
Part-II: Experimental data (vs.2: 12.7.2012)

Abstract

The document consists of two RD50 Technical Notes devoted to the temperature scaling of the current generated in Si bulk. The first one (of 9.5.2011) describes the basics of the phenomenon following from the semiconductor physics and recommends the I(T) parameterisation. The second one (of 12.7.2012) reviews the experimental data on I(T) scaling in irradiated Si sensors available in literature and obtained in Lancaster University. Both sets of results support the conclusions made in the first Note.
The current per unit area generated inside the depleted bulk can be written as

\[ J = \frac{qWn_i}{\tau_g} \]  

(1)

where \( q \) is elementary charge, \( W \) – depleted thickness, \( n_i \) – intrinsic carrier concentration and \( \tau_g \) – generation lifetime. Temperature dependence of \( n_i \) can be expressed as

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

(2)

where \( T \) is the absolute temperature, \( k \) - the Boltzmann constant and \( E_g \) - the band gap. Weak temperature dependence of the electron and hole effective masses is neglected in Eq.(2).

Assuming generation happening via a specific trap with density \( N_t \) and level \( E_t \) in the band gap the generation lifetime can be written as [1]

\[ \tau_g = \frac{1}{N_t} \left( \frac{\exp\left(\frac{\Delta_t}{kT}\right)}{v_{tn}\sigma_n} + \frac{\exp\left(-\frac{\Delta_t}{kT}\right)}{v_{tp}\sigma_p} \right). \]  

(3)

Here \( \Delta_t = E_t - E_i \) is the difference between the trap level and the intrinsic Fermi level, \( v_{tn(p)} \) is the thermal velocity and \( \sigma_{tn(p)} \) the trapping cross-section for electrons (holes). The dependence of \( \tau_g \) on \( \Delta_t \) is close to \( \cosh(\Delta_t/kT) \) (assuming \( v_{tp}\sigma_p \approx v_{tn}\sigma_n \)). The minimum \( \tau_g \) is reached and thus the most effective current generation happens when the trap level is close to \( E_i \). In this case the temperature dependence of \( \tau_g \) is the simplest: \( \tau_g \propto T^{-1/2} \), and due only to that of the thermal velocities. (The temperature dependence of the effective carrier masses is again neglected.) For \( |\Delta_t| > 1.5 \) the additional factor in \( \tau_g \) temperature dependence is reduced to \( \exp(|\Delta_t|/kT) \). Therefore the temperature dependence of the generation current is usually parameterised as

\[ I(T) \propto T^2 \exp\left(-\frac{E_g + 2\Delta}{2kT}\right). \]  

(4)
where $\Delta$ is a parameter close to the absolute value of $\Delta_t$. An excess of the energy in the exponent over the $E_a$ indicates the generation proceeding via a trap level noticeably different from $E_i$.

The temperature dependence of the current is clearly dominated by that of $n_i$. Thus it is crucial to know $n_i(T)$ in detail. The intrinsic carrier concentration is a parameter of prime importance in semiconductor physics and a vast literature exists about it. This Note relies on a relatively recent Review [2] and concentrates on the temperature interval of $\pm30^\circ$C most relevant to the present usage of silicon detectors in Particle Physics.

Ref. [2] quotes three fits of $n_i(T)$ found in different experimental studies. They are described by Eqs. (21, 22, 23) of that paper and have the form of

$$n_i(T) \propto T^m \exp\left(-E_a/kT\right)$$

where $E_a$ is so called activation energy. In Eqs. (21, 22) $m$ is set to the standard value of $3/2$ and the results can be directly compared with parameterisation (2). In eq. (23) $m$ is a free parameter of the fit and has the value of 2.365. At any temperature, $T$, the dependence (5) can be converted to the equivalent one with $m=3/2$ and activation energy $E_a^{\text{eq}}$. Denote $E_a^m$ the activation energy for the parameterisation (5) with specific $m$ and require that the relative derivative of it is equal to that with $m=3/2$. As a result one gets

$$\frac{dn_i}{n_i} \frac{dT}{T} = \frac{3}{2} + \frac{E_a^{\text{eq}}}{kT} = m + \frac{E_a^m}{kT}$$

from which it follows

$$E_a^{\text{eq}} = E_a^m + \left(m-3/2\right) kT$$

In Eq. (23) of Ref.[2] the activation energy is $k*6733K = 0.580$ eV and $m=2.365$. Using the relation (6) one obtains for $T=273K$ the equivalent activation energy of 0.601 eV. It is easy to check that in the interval from -30$^\circ$ to +30$^\circ$C the temperature dependences (5) for $m = 2.365$, $E_a = 0.580$ eV and for $m=3/2$, $E_a = 0.601$ eV differ by less than 1%.

The activation energy values in Eqs. (21, 22) of Ref.[2] are 0.605 and 0.603 eV respectively. Combining them with the value of 0.601 eV obtained above one gets the average experimental value of $E_a = 0.603 \pm 0.002$ eV where the uncertainty covers all
three experimental values. Therefore the experimental value for the effective gap energy is

\[ E_{\text{ef}} = 2E_a = 1.206 \pm 0.004 \text{ eV}. \]  \hfill (7)

This result looks incompatible with the experimental values of \( E_g \), which according to Table 1 of Ref.\[2\] are 1.1242 eV at 300K and 1.1367 eV at 250K. Note however that temperature independent \( E_{\text{ef}} \) should also incorporate temperature dependence of the band gap \( E_g \).

Consider the exponential term of Eq.(2)

\[ f(T) \propto \exp(-E_g/2kT) \]  \hfill (8)

with \( E_g \) itself a function of temperature. The relative gradient of this function is

\[ (df/f)/(dT/T) = E_g(T)/2kT - (dE_g/dT)/2k \]  \hfill (9)

If the temperature dependent \( E_g \) is replaced in Eq.(8) by a constant parameter \( E_{\text{ef}} \) then the relative gradient will be

\[ (df/f)/(dT/T) = E_{\text{ef}}/2kT \]  \hfill (10)

Requiring the gradients given by Eqs. (9) and (10) to be equal at a given temperature, \( T \), one gets for \( E_{\text{ef}} \):

\[ E_{\text{ef}} = E_g(T) - T (dE_g/dT) \]  \hfill (11)

Consider now the situation when in some temperature interval the band gap dependence can be approximated by a linear function

\[ E_g(T) = E_0 - \alpha T. \]  \hfill (12)

Here \( E_0 \) is the band gap value extrapolated to \( T = 0 \)K. In this case the effective energy gap found from Eq. (11) is

\[ E_{\text{ef}} = E_0 - \alpha T - T (-\alpha) = E_0 \]  \hfill (13)

independent of \( T \) (and also of \( \alpha \)). This conclusion can be verified by direct substitution of \( E_g \) in Eq.(8) by relation (12):

\[ A \cdot \exp(-E_g(T)/2kT) = A \cdot \exp(-E_0/2kT + \alpha/2k) = A' \cdot \exp(-E_0/2kT) \]  \hfill (14)

For temperatures above 250K and below 415K the parameterisation (12) is readily available in Ref. [2], Eq.(17). The value of \( E_0 \) in this equation is 1.206 eV in perfect agreement with the experimentally found \( E_{\text{ef}} \) presented in eq. (7). Thus there is no contradiction between the temperature dependent band gap energy and the temperature independent effective energy. To some extent surprisingly the effective
gap value happens to be outside the range of the actual band gap values in the considered temperature interval.

For non-irradiated sensors it is usually assumed that the current is generated via traps with energy levels near the mid gap i.e. the $I(T)$ is described by Eq.(4) with $A=0$ and either temperature dependent $E_g(T)$ or the effective gap $E_0$. However in non-irradiated sensors the bulk generation current is typically quite small and presents no practical problems. The high current in such sensors is usually due to other reasons e.g. soft breakdown, which makes the above analysis irrelevant. It is more appropriate for irradiated sensors where the bulk current often dominates. The information on $I(T)$ for irradiated sensors is rather scarce. The survey [3] made in 1994 produced the effective gap value of $1.24 \pm 0.06$ eV, which agrees with the mentioned above $E_0 = 1.21$ eV for $n_i$, but has a substantial uncertainty. The study of ATLAS SCT sensors irradiated by $\sim 3 \times 10^{14}$ 24 GeV protons/cm$^2$ performed in 1997-99 resulted in the effective gap value of 1.21 eV [4]. Thus until proven otherwise the same temperature dependence with $E_{ef}$ equal to 1.21 eV may be used for both irradiated and non-irradiated sensors.

In conclusion, the temperature dependence of the bulk generation current can be described as

$$I(T) \propto T^2 \exp(-1.21eV/2kT)$$

both for non-irradiated and irradiated sensors. The difference between the effective energy value and the actual gap energy is due to using temperature independent $E_{ef}$ instead of the temperature dependent $E_g(T)$.

The author is grateful to Graham Beck, QMUL, UK for helpful discussions.

References
4. ATLAS SCT Barrel Module FDR/2001, SCT-BM-FDR-7, p.19: $E_{ef}/2k = 7019K$, from which it follows: $E_{ef} = 1.21$ eV.
1. Review of 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

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

where $T$ is the absolute temperature and $k$ is the Boltzman constant. Table 1 contains the values of effective energy gap $E_{\text{eff}}$ from Refs. [1-8]. For Ref. [5] the only information available is the $E_{\text{eff}}$ value.

Some authors use the $I(T)$ dependence with $T^m$ in front of the exponential term where $m \neq 2$. As shown in Ref. [9] the $E_{\text{eff}}$ measured with such parameterisation, $E_{\text{eq}}^m$, can be at any temperature $T$ converted to an equivalent value of $E_{\text{eff}}$ corresponding to $m=2$:

$$ E_{\text{eq}}^m = E_{\text{eff}}^m + 2kT(m - 2) \quad (2) $$

Note that this approximation is valid only for the temperatures around the value of $T$ used in the eq. (2). In Ref. [3] the authors used the parameterisations with $m=0$ and $m=3/2$. The $E_{\text{eff}}$ found for the latter, 1.34 eV, was corrected to the equivalent $E_{\text{eff}}$ for $m=2$ at typical in their measurements temperature of 293K, that resulted in the value of 1.31 eV shown in Table 1.

In Ref. [10] the parameterisation with $m=0$ was used for the fits in the temperature interval of 200÷400K and the value $E_{\text{eff}}=1.30$ eV was obtained. Using eq. (2) this result can be converted to an equivalent $E_{\text{eff}}$ corresponding to $m=2$. For example at
$T=273K$ it gives the value of 1.21 eV close to the average value observed in other experiments. However since the parameterisation used in Ref. [10] differs significantly from the one shown in eq. (1) this result is omitted from Table 1.

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

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

Averaging all results and after excluding the maximum and minimum values gives practically the same answer close to 1.215 eV. The standard deviation is 0.06 eV for the first case and 0.05 eV for the second one.

2. Lancaster results

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

1 particles crossing the VELO system in LHCb detector

2 1 MeV neutron equivalent
Usually the I(T) dependence is measured at a fixed bias, typically at or slightly above the full depletion voltage. It is assumed that in this case the current is dominated by the one generated in the bulk. We have investigated the variation of I(T) dependence with bias in a wide voltage range. For bulk generation current the quality of the fit by eq. (1) should remain good and the value of $E_{\text{eff}}$ stable independently of bias voltage. Only the data satisfying these requirements were considered as representing the genuine effect. One obvious difficulty in measuring I(T) dependence is the sensor warming above the reference temperature by the power dissipation in it – so called self-heating. It leads to a steady increase of $E_{\text{eff}}$ with bias that can be suppressed by a proper choice of the bias values. More detailed discussion of the criteria for the point selection is made in Section 2.4.

Typical data set consisted of several I-V scans made at different temperatures. Then the bias points were combined to form a representative set of groups and in each group the average current was calculated at every temperature. For each bias group the current dependence on temperature was fit by eq. (1). To give equal weight to the points with significantly different absolute values a fixed relative error was assigned to the points and used in the fit.

2.1 Sensors and their irradiation

The presented data are for 5 sensors: a) 3 microstrip detectors made of $p$-type material with sensitive area of $1 \times 1 \text{ cm}^2$, 500 $\mu$m thickness and strip pitch of 80 $\mu$m and b) 2 diodes made of $n$-type material with sensitive area of $0.5 \times 0.5 \text{ cm}^2$ and 300 $\mu$m 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

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

Microstrip detectors were irradiated at -40°C and the diodes at room temperature. In all cases the sensors were irradiated without bias. After irradiation the sensors were kept at room temperature for a few days to allow some beneficial annealing. 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°C were made as brief as possible. Further details about the p-type sensors may be found in Ref. [11] and about n-type sensors in Ref. [12]. The latter describes also the measurement set-up.

2.2 Results for the p-type sensors

The I-V dependence was measured with bias voltage applied to the sensor backside, grounded innermost guard ring (GR) and the strip area grounded via an ammeter which gave the current through the central part of the sensor, $I_c$, used in this study. The bias voltage was always negative. In the text below its absolute value is used. To suppress systematic effects due to possible drift with time the temperature sequence of the I-V scans was non-monotonic. Measurements at the same temperature were made in the beginning and the end of the scan series as a cross-check. The errors used in the $I_c$ vs $T$ fit were set at 1% of the current value.

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

I-V scans were performed at 9 temperatures in the following sequence: -20°C, -32°C, -24°C, -12°C, -4°C, 0°C, -8°C, -16°C, -28°C, -20°C. The results are shown in Fig.1a.
Around 30 V the I-V curves have a “kink” indicating full depletion of the sensor. Below this voltage the current grows approximately as \((U_{\text{bias}})^{1/2}\) (shown by a line in Fig.1) and above it is almost constant. These features indicate the bulk generation as a major source of the current.

![Graph](image1.png)

**Fig.1a.** I\(_c\)-V curves for sensor x2y4 irradiated by \(10^{13}\) 1 MeV neutron equivalent fluence. The line shows \((U_{\text{bias}})^{1/2}\) dependence.

![Graph](image2.png)

**Fig.1b.** Average current vs. temperature for 3 bias groups fit by the function (1).
For the analysis 54 bias points from 5 to 490V were combined by 3 in 18 groups and fit as described on p.3. The examples of such fits are shown in Fig.1b. Typical value of $\chi^2$/Ndf was ~0.25 which shows that the spread of the current values around the fit line was about 0.5%.

The $E_{\text{eff}}$ values found in the fits are presented in Fig.2 for two temperature intervals: all points (as in Fig.1b) and with two highest temperatures omitted, i.e. from -32°C to -8°C. After relatively sharp decrease at two lowest values further bias dependence of $E_{\text{eff}}$ is rather weak. Excluding the first two points (shown in Fig.2 by open symbols) the average $E_{\text{eff}}$ value was calculated for both temperature intervals. The average of the obtained two values, 1.2156 eV, was taken as the final result and their sigma, 0.0029 eV, as its standard deviation. These results are also shown in Fig.2.

![Graph](image)

**Fig.2.** $E_{\text{eff}}$ vs. bias for x2y4 sensor in two temperature intervals. The lines are the average and standard deviation calculated for the points shown by the filled symbols.

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

I-V scans were performed at 8 temperatures in the following sequence: -20°C, -12°C, -16°C, -28°C, -24°C, -31°C, -20°C, -4°C, -8°C. The results are shown in Fig.3. Around
420 V the I-V curves exhibit a “kink” indicating full depletion of the sensor. It is clear at low temperatures but is practically invisible at the highest temperature. Below this voltage the current grows approximately as \((U_{\text{bias}})^{1/2}\) (the line in Fig.3) that indicates the bulk generation as a major source of the current at those bias values. Steady increase of the current gradient above the kink with temperature is probably due to the sensor self-heating.

Fig.3. \(I_c-V\) curves for sensor x4y1 irradiated by \(10^{14}\) 1 MeV neutron equivalent fluence. The line shows \((U_{\text{bias}})^{1/2}\) dependence.

For the analysis 80 bias points from 10 to 800V were grouped by 5 in 16 groups and fit as described above. Typical \(\chi^2/N_{\text{df}}\) values found in the fits with 1% errors were <0.5 showing that the actual errors are <0.7%.

The \(E_{\text{eff}}\) values found in the fits are presented in Fig.4. Each curve corresponds to the maximum temperature of the used interval, \(T_{\text{max}}\). The minimum temperature was always -31°C. For \(T_{\text{max}} < -12^\circ\text{C}\) the \(E_{\text{eff}}\) is about constant up to the bias of \(\sim 600\text{V}\) but grows with bias above this value. For higher \(T_{\text{max}}\) the \(E_{\text{eff}}\) grows steadily with bias. Such behaviour again indicates the sensor self-heating at high dissipated power. Therefore only the data for \(T_{\text{max}}\) up to -16°C were used in further analysis. In addition
the points for $U_{bias}>600$ V were also excluded. Using the remaining points (shown in Fig.4 by the filled symbols) the average $E_{eff}$ was calculated for each of 3 used temperature intervals. The average of the obtained 3 values, 1.219 eV, was taken as the final result and their standard deviation of 0.006 eV as its error. These data are also shown in Fig.4.

![Graph](image.png)

**Fig.4.** $E_{eff}$ for x4y1 sensor vs. average bias. Each set corresponds to a specific maximum temperature of the used interval. Solid line shows the average value and the dashed lines the standard deviation calculated using the filled points.

### 2.2.3 Sensor x5y2 irradiated by $10^{15}$ 1 MeV n equivalent fluence

I-V scans were performed at 8 temperatures in the following sequence: -32°C, -20°C, -26°C, -30°C, -28°C, -18°C, -22°C, -24°C, -20°C. The results are shown in Fig.5. The currents grow steadily with bias indicating the full depletion voltage above the value of 700 V, maximum used in the scans. At low volts the currents grow approximately as $(U_{bias})^{1/2}$ (shown by the line in Fig.5) that indicates the bulk generation as a major source of the current at those bias values. Steady increase of the current gradients with bias and temperature is probably due to the sensor self-heating.
Fig. 5. $I_c$-V curves for sensor x5y2 irradiated by $10^{15}$ 1 MeV neutron equivalent fluence. The line shows $(U_{\text{bias}})^{1/2}$ dependence.

The data fits were made for 18 groups formed by combining 54 bias points from 10 to 540 V by 3. Typical $\chi^2/\text{Ndf}$ values found in the fits with 1% errors were $\sim 0.5$ showing that the actual errors are $\sim 0.7\%$.

The $E_{\text{eff}}$ values found in the fits are presented in Fig. 6. Each curve corresponds to the maximum temperature of the used interval, $T_{\text{max}}$. The minimum temperature was always $-32^\circ\text{C}$. In all cases the $E_{\text{eff}}$ grows steadily with bias. The rate of this growth increases with bias and temperature. Such behaviour is typical for the sensor self-heating due to high dissipated power. To minimise these effects only the data for $U_{\text{bias}} < 220$ V were used. These points are shown in Fig. 6 by the filled symbols. The average $E_{\text{eff}}$ was calculated for each of 4 used temperature intervals. The average of the obtained 4 values, 1.199 eV, was taken as the final result and their standard deviation of 0.006 eV as its error. These data are also shown in Fig. 6.
Fig. 6. $E_{\text{eff}}$ for x5y1 sensor vs. average bias. Each set corresponds to a specific maximum temperature of the used interval. Solid line shows the average value and the dashed lines the standard deviation calculated using the filled points.

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 $I_c$. The current measurement accuracy in these experiments was lower than for the data presented above. Therefore the errors used in the fits were set at 5%.

2.3.1 Sensor S62

The analysed data were collected during the study described in detail in Ref. [12]. 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.7.

Fig.7. $I_c$-$V$ curves for sensor S62. Each one is the average of 16 voltage scans. The line shows $(U_{bias})^{1/2}$ dependence.

At ~30 V the curves have a “kink” which is more pronounced at low temperatures but is almost invisible at high temperature. Below this voltage the currents grow as $(U_{bias})^{0.4}$ rather than $(U_{bias})^{0.5}$ (also presented in Fig.7) expected for the current generated in the bulk. This can be due to a contribution from the currents of another type. Above the “kink” the current gradient increases with temperature indicating sensor self-heating at high dissipated power.

The current was measured twice at each bias and thus every curve contains 124 points at 62 bias voltages. Starting from $U_{bias}=5$V the points (120 in total) were grouped by 10 forming 12 bias groups used for the fits. Typical $\chi^2$/Ndf values of ~0.5 found in the fits show that the assumed 5% errors are close to the actual ones. Fig.8 shows the $E_{eff}$ vs average bias for 12 bias groups.
Fig. 8. $E_{\text{eff}}$ vs average bias for sensor S62. The average value and standard deviation is shown for 5 points marked by filled symbols.

At low voltage the $E_{\text{eff}}$ increases steeply with bias. Then it plateaus but above 250 V starts to grow again though with lower gradient. Five points around the plateau region (marked by the filled symbols in Fig. 8) have the average value of 1.208 eV and the standard deviation of 0.005 eV. These numbers are also shown in Fig. 8.

### 2.3.2 Sensor M41

The data were collected during the study described in detail in Ref. [13]. 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, -8°C, -16°C, +8°C, +16°C, +25°C, +32°C, +16°C (second time). The second round of measurements at +16°C showed systematically lower currents than in the first round. This meant 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. 9.
Fig. 9. $I_c$-V curves for sensor M41. Each curve is the average of 3 or 4 voltage scans. The line shows $(U_{bias})^{1/2}$ dependence.

At ~50 V the curves have a “kink” indicating full depletion of the sensor. Below this voltage the currents grow approximately as $(U_{bias})^{0.5}$ shown by the line in Fig. 9. Above the “kink” the current is almost constant. This behaviour corresponds to the expectations for the bulk generated current. An increase of the current gradient with temperature at high volts indicates sensor self-heating at high dissipated power.

The current was measured twice at each bias and every curve contains 54 points at 27 bias voltages. Starting from $U_{bias}=3$V 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 used for the fits. Typical $\chi^2$/Ndf values of ~0.5 found in the fits show that the assumed errors are close to the actual ones.

Fig. 10 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 is probably due to the sensor self-heating. 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 is probably self-heating again.

![Graph showing E\textsubscript{eff} vs average bias for sensor M41 in fits through all points and without +16\degree C. The average value and standard deviation is shown for the points marked by the filled symbols.]

The average value of the first 4 points for the fits without +16\degree C is 1.2143 eV and their standard deviation is 0.0026 eV. These numbers are also shown in Fig.10.

2.4 Discussion

In the investigation of the current-temperature dependence care should be taken in selecting the results corresponding to the bulk generation current and avoiding the effects of sensor self-heating. The latter usually manifests itself as a steady increase of the parameter $E_{\text{eff}}$ with bias. Four out of five sensors analysed here showed this effect and some temperature or bias points (and sometimes both) had to be excluded on this ground from the final results. For the sensor irradiated by $10^{15}$ neq/cm\textsuperscript{2} the self-heating effects could not be avoided but only minimised.
For genuine generation current $E_{\text{eff}}$ should not depend on bias. When this is not the case (after the self-heating is eliminated) it is possible that the measured current has a significant contribution from the other types of the current. On this ground several low bias points were excluded from the final result for the sensors x2y4 and S62. It is worth noting that for the latter 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. For the sensor irradiated by $10^{15}$ neq/cm$^2$ the slope of the log(I)-log(V) curve increases steadily with bias. Even at the low volts it is higher than expected value of 0.5. This can be due either to the self-heating or to more complicated dependence of the depleted thickness with bias in so heavily irradiated sensors. Note that for this sensor all measurements are made well below the full depletion voltage. Final results are summarised in Table 3.

Table 3. Summary of the results

<table>
<thead>
<tr>
<th>Sensor name</th>
<th>IV “kink” at, V</th>
<th>lnI-lnU slope</th>
<th>Bias range used, V</th>
<th>Temperature range used, °C</th>
<th>$E_{\text{eff}}$, eV</th>
<th>Standard deviation, eV</th>
</tr>
</thead>
<tbody>
<tr>
<td>x2y4</td>
<td>29</td>
<td>0.49</td>
<td>35-490</td>
<td>-32 ± 0</td>
<td>1.2156</td>
<td>0.0029</td>
</tr>
<tr>
<td>x4y1</td>
<td>420</td>
<td>0.49</td>
<td>10-600</td>
<td>-31 ± -16</td>
<td>1.2188</td>
<td>0.0063</td>
</tr>
<tr>
<td>x5y2</td>
<td>N/A</td>
<td>0.52*</td>
<td>10-210</td>
<td>-32 ± -18</td>
<td>1.1991</td>
<td>0.0062</td>
</tr>
<tr>
<td>S62</td>
<td>32</td>
<td>0.40</td>
<td>90-280</td>
<td>-24 ± +12</td>
<td>1.2076</td>
<td>0.0054</td>
</tr>
<tr>
<td>M41</td>
<td>50</td>
<td>0.48</td>
<td>3-90</td>
<td>-16 ± +8</td>
<td>1.2143</td>
<td>0.0026</td>
</tr>
</tbody>
</table>

|               | Average:       |                |                    |                          | 1.211           | 0.008                |

Second column shows the voltage at which the “kink” indicating full depletion is observed in log(I$_d$)-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, which is presented in the last two columns. Averaging the $E_{\text{eff}}$ values from column 6 with equal weight (i.e. ignoring the errors from column 7) gives 1.211 eV with a standard deviation of 0.008 eV. This information is presented graphically in Fig.11. As can be seen from this plot all results are consistent within their relatively

* For the bias range 10÷100 V.
small uncertainties despite significant difference in sensors, irradiations and measurement procedures. Absence of the analysis of a possible $E_{\text{eff}}$ dependence on bias voltage and temperature range in publications reviewed in Section 1 may be responsible for a relatively large spread of the results.

Fig. 11. $E_{\text{eff}}$ for individual sensors vs 1 MeV neutron equivalent fluence. The overall average and the standard deviation are shown by the lines.

3. Conclusions

Within uncertainties the experimental $E_{\text{eff}}$ values for all sensors investigated in Lancaster agree with the expected value of 1.21 eV obtained for temperature range of $\pm 30^\circ$C as explained in the first part of this Note [9]. The average $E_{\text{eff}}$ value of Lancaster measurement is 1.211 eV and the standard deviation of the individual sensor results is 0.008 eV. For the reviewed published results the average is 1.215 eV with the standard deviation of the individual entries of 0.05 eV for the data excluding minimum and maximum values and of 0.06 eV for all data.
References
7. ATLAS SCT Barrel Module Final Design Review, SCT-BM-FDR-7, 2002, p.19. The quoted result is \(E_{\text{eff}}/2k = 7019\)K which gives \(E_{\text{eff}} = 1.210\) eV.
10. E.Verbitskaya et al., “Temperature dependence of reverse current of irradiated Si detectors”, Talk at the 20\textsuperscript{th} RD50 Workshop, Bari, May 30 – June 1, 2012. Available at:
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