Exercise on Semiconductor Detectors

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1 Introduction

This report describes the result from the exercise on semiconductor detectors as a part of the Research Training Course in Detector Technology for Particle Physics.

2 PN-junction

In this section the focus is on a PN-junction in equilibrium. The effect of changing the temperature, semiconductor material and donor/acceptor concentration is studied.

The original configuration has the following values:

- Material = "Si"
- Temperature $T = 300\text{K}$
- Donor/acceptor concentration $\rho = 10^{16}\text{cm}^{-3}$

In the three other configurations one of these values is changed one at the time to the values seen in Table 1. The table shows the junction potential, electrical field and build in junction width for the four different configurations. Here the value of the junction width is the FWHM found by looking at the graphs on Figure 1-4.

It is seen that the width is almost identical for the first three configurations. It is very clear that the width is much smaller for the configuration with $\rho = 10^{17}\text{cm}^{-3}$.

Configuration	Junc. potential [V]	E-field [V/cm]	Junc. width [μm]
Original	0.710	3.13e4	~1.0
$T = 400$K	0.511	2.53e4	~1.0
Material = "Ge"	0.299	1.61e4	~1.0
$\rho = 10^{17}$cm^{-3}	0.826	1.04e5	~0.3

Table 1: *The junction potential, electric field and junction width for the four different configurations.*

Configuration	Junc. potential [V]	Junc. width [μm]
Original	0.726	0.437
$T = 400$K	0.524	0.371
Material = "Ge"	0.323	0.338
$\rho = 10^{17}$cm^{-3}	0.845	0.149

Table 2: *The theoretical values for the junction potential and junction width for the four different configurations.*

When changing from silicon to germanium both the junction potential and electrical field get smaller. The same is true when changing the temperature from $T = 300$K to $T = 400$K, even though it is not as much. Making the donor/acceptor concentration 10 times higher only makes the potential a little higher but the electrical field a lot higher.

Table 2 shows the theoretically calculated values for the junction potential and the junction width. The junction potential is found with the equation:

$$\Psi_0 = \frac{k_B T}{q} \ln\left(\frac{N_A N_D}{n_i^2}\right) \tag{1}$$

where $k_B = 1.381 \cdot 10^{-23}$J/K, $q = 1.602 \cdot 10^{-19}$C, N_A and N_D are the acceptor and donor concentrations and n_i is the intrinsic carrier density (the used values are taken from Example 2.4b on this page).

The junction width is then found with the equation:

$$d = \sqrt{\frac{2\epsilon_0\epsilon_r}{q}\frac{N_A + N_D}{N_A N_D}\Psi_0} \tag{2}$$

where $\epsilon_0 = 8.854 \cdot 10^{-12}$F/m, $\epsilon_r = 11.9$ for silicon and $\epsilon_r = 16$ for germanium.

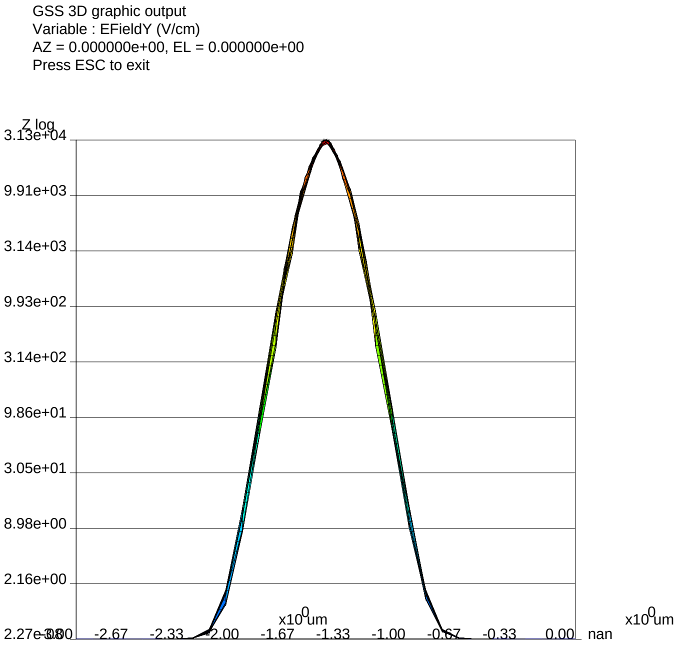


Figure 1: *Electrical field for the original configuration.*

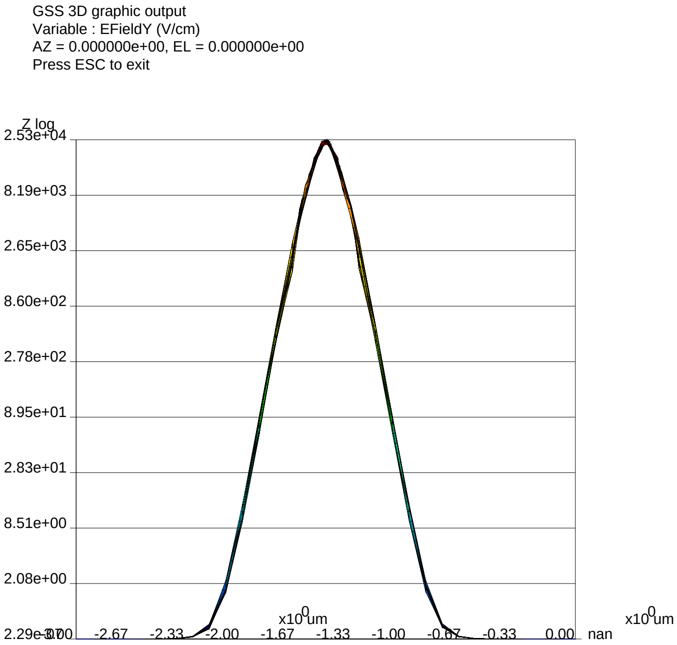


Figure 2: *Electrical field for the configuration with* $T = 400K$.

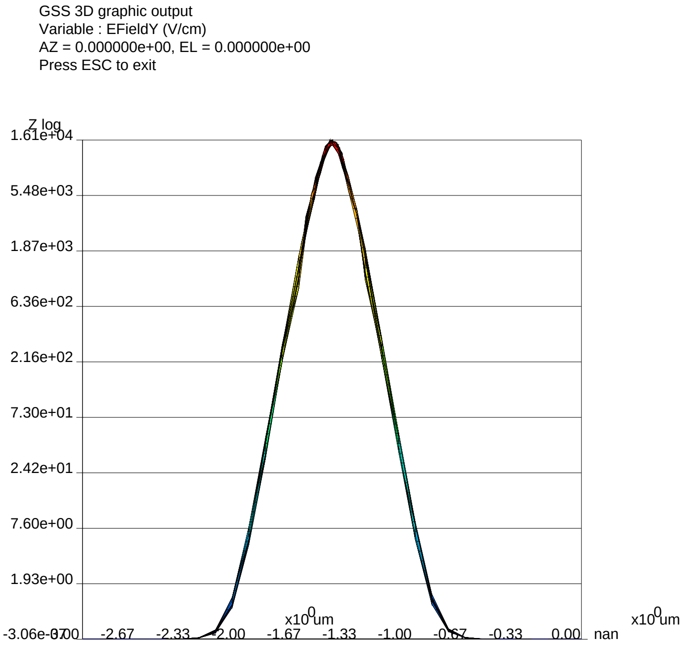


Figure 3: *Electrical field for the configuration with Material = "Ge".*

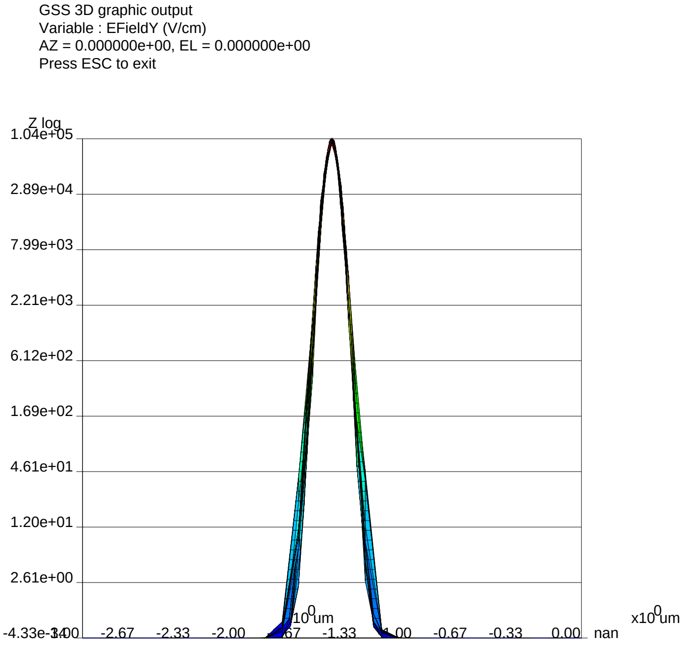


Figure 4: *Electrical field for the configuration with $\rho = 10^{17} cm^{-3}$.*

By comparing the numbers in Table 1 and Table 2 it is seen that the simulated values are pretty close to the theoretical ones for the junction potential.

The theoretical values for the junction width are all less than half of the simulated ones, but that might just be because the width should not be read as the FWHM of the peak. It is seen that the width for the first three configurations are quite similar but the last one is much narrower, which agrees with the simulations.

2.1 IV curve

In this part of the exercise a 100 micron thick sensor with highly doped ($\rho = 10^{17}\text{cm}^{-3}$) 3 micron thick implants on a low doped ($\rho = 10^{14}\text{cm}^{-3}$) bulk is simulated. The original configuration again has the values:

- Material = "Si"
- Temperature $T = 300\text{K}$

Two other configurations are simulated: One with the temperature changed to $T = 400\text{K}$ and one with the material changed to Material = "Ge". Figure 5-7 shows (a) forward bias and (b) reverse bias IV curves for the three configurations.

The width of the depleted region is given by an equation very similar to (6). The external voltage Ψ_{ext} is just added to the build in junction potential.

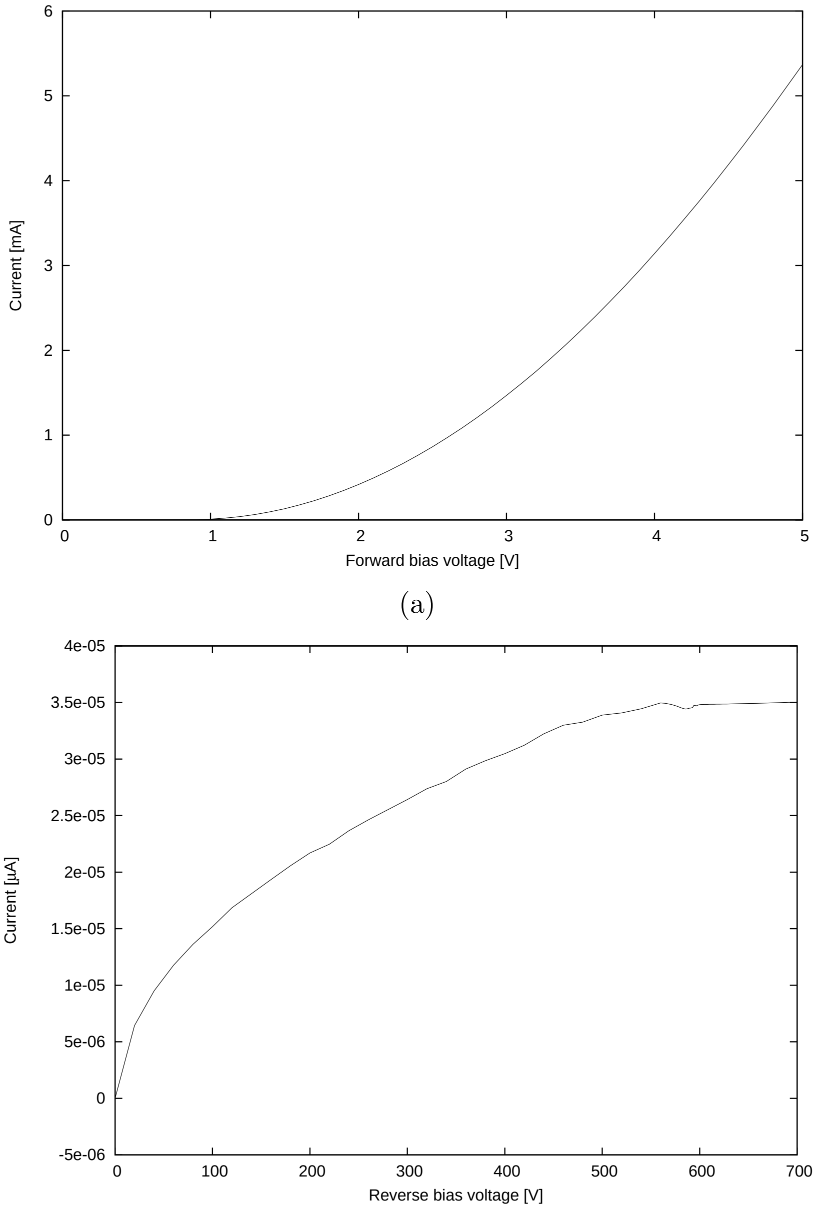
$$d = \sqrt{\frac{2\epsilon_0\epsilon_r}{q}\frac{N_A + N_D}{N_A N_D}\left(\Psi_0 + \Psi_{\text{ext}}\right)} \tag{3}$$

The needed external voltage to fully deplete the diode is therefore

$$\Psi_{\text{fd}} = \frac{d_{\text{fd}}^2 q}{2\epsilon_0\epsilon_r}\frac{N_A N_D}{N_A + N_D} - \Psi_0 \tag{4}$$

where $d_{\text{fd}} = 0.0094\text{cm}$ and Ψ_0 is given by 5. The values for the concentrations are now $N_A = 10^{17}\text{cm}^{-3}$ and $N_D = 10^{14}\text{cm}^{-3}$. Table 3 shows the results using this formula.

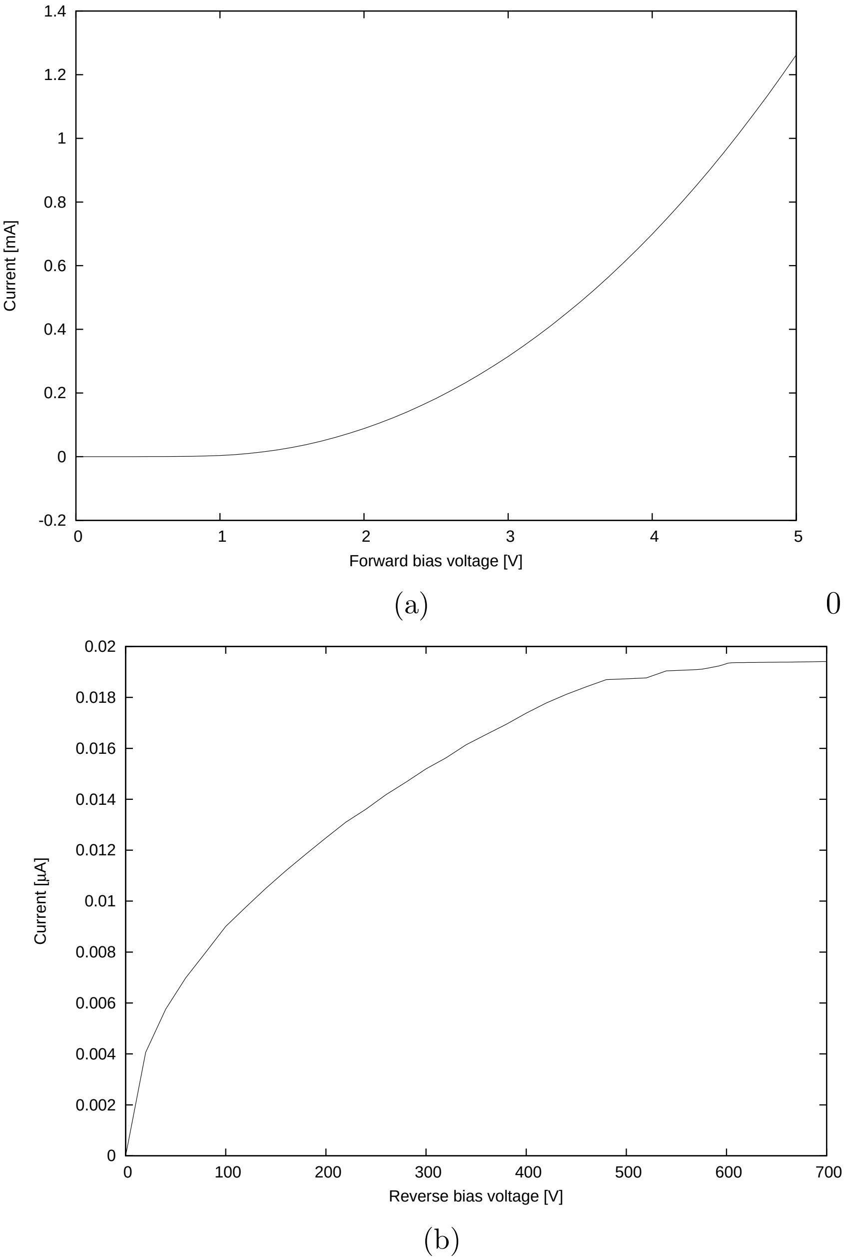
By comparing the numbers to the graphs for the reverse bias in Figure 5-7, it is seen that the theoretical values matches the simulations beautifully. In Figure 5b) and 6b) it is seen that the current saturates around the value of the depletion voltage and in Figure 7b) the turning point of the graph is close to the value of the depletion voltage.



(a)

(b)

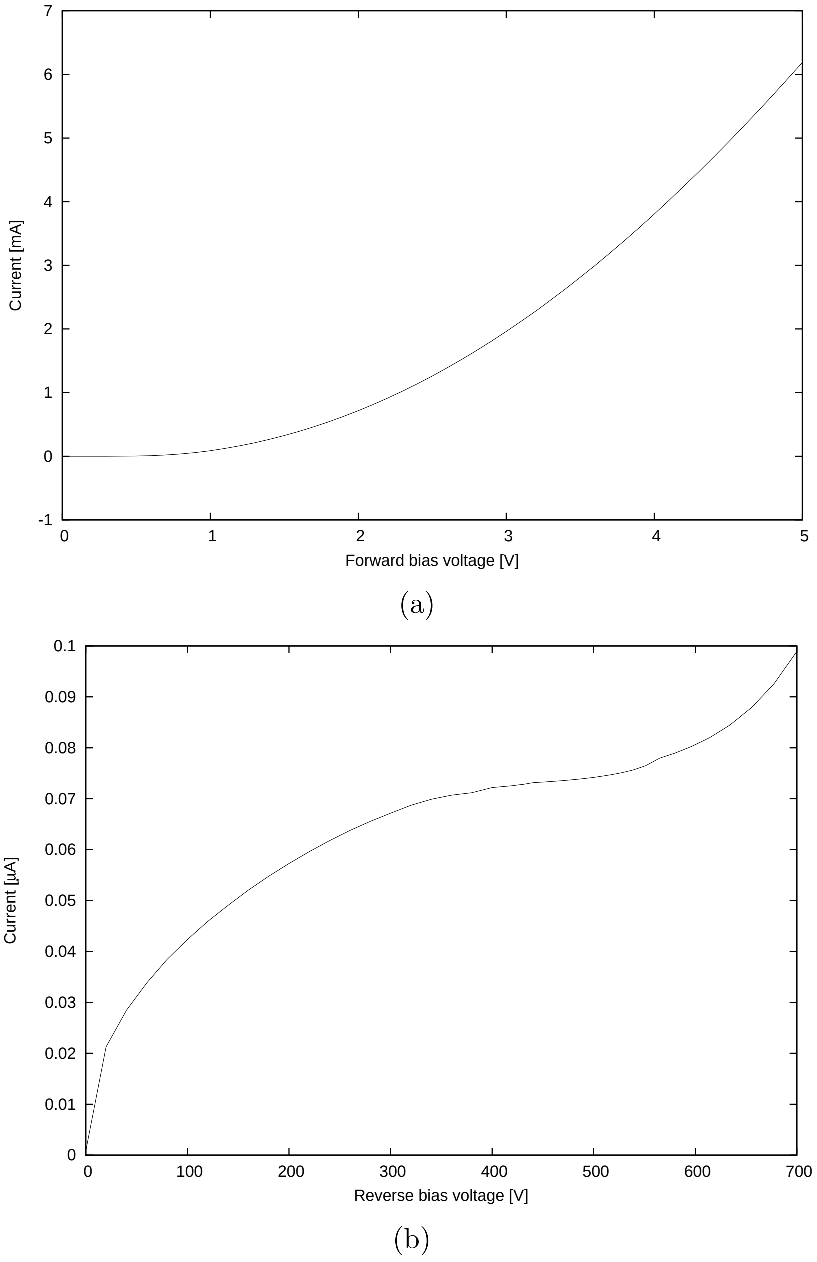
Figure 5: *IV curve for original configuration for a) forward bias and b) reverse bias.*



(a) 0.827

(b)

Figure 6: *IV curve for the configuration with $T = 400K$ for a) forward bias and b) reverse bias.*



(a)

(b)

Figure 7: *IV curve for the configuration with Material = "Ge" for a) forward bias and b) reverse bias.*

Configuration	Depletion voltage [V]
Original	670.4
$T = 400\text{K}$	670.7
Material = "Ge"	498.8

Table 3: *The theoretical voltage needed to fully deplete the junction for the three different configurations.*

Configuration	Junc. potential [V]	E-field [V/cm]	Junc. width [μm]
Original	0.886	4.40e4	~0.5
$T = 400\text{K}$	0.771	4.04e4	~0.5
$\phi = 4.5$	0.586	3.42e4	~0.5
$N_A = 10^{15}\text{cm}^{-3}$	0.827	2.01e4	~2.0

Table 4: *The junction potential, electric field and junction width for the four different configurations for the Schottky contact.*

3 Schottky contact

In this part the Schottky contact is investigated. Like for the PN-junction the effect of changing the temperature and the doping concentration is examined. Furthermore the work function of the metal is also considered. The original configuration for the Schottky contact is

- Material = "Si"
- Temperature $T = 300\text{K}$
- Acceptor concentration $N_A = 10^{16}\text{cm}^{-3}$
- Work function $\phi = 4.2$

The junction potential, electrical field and build in junction width for this configuration and the three configurations where one of variables are changed can be seen in Table 4. The width is just an approximative value read from Figure 8-11, which show the electrical field for the different configurations.

Like for the PN-junction it is seen that the only thing that really effects the width is changing the doping concentration.

Configuration	Junc. potential [V]	Junc. width [μm]
Original	0.775	0.319
$T = 400$K	0.700	0.303
$\phi = 4.5$	0.475	0.250
$N_A = 10^{15}\text{cm}^{-3}$	0.715	0.970

Table 5: *The theoretical values for the junction potential and junction width for the four different configurations for the Schottky contact.*

The theoretical values for the junction potential and the junction width are seen in Table 5. The junction potential is given by:

$$\Psi_0 = \chi + \frac{E_g}{q} - \phi - \frac{k_B T}{q} \ln\left(\frac{N_v}{N_A}\right) \tag{5}$$

where $\chi = 4.05$V, $\frac{E_g}{q} = 1.12$V and $N_v = 1.83 \cdot 10^{19}$ at 300K and $N_v = 2.82 \cdot 10^{19}$ at 400K.

The junction width is then found with the equation:

$$d = \sqrt{\frac{2\epsilon_0\epsilon_r}{q}\frac{1}{N_A}\Psi_0} \tag{6}$$

Again the numbers for the potential is reasonable but the numbers for the width is approximately half of the simulated ones.

3.1 IV curve

In this part a Schottky contact is simulated that has similar geometry and doping concentrations as the original configuration for the 100 micron PN-junction.

The reverse bias IV curve of the Schottky contact is seen in Figure 12. By comparing to Figure 5b) it is seen that the Schottky contact is fully depleted at a much lower voltage than the PN-junction. Unfortunately, it has a much higher leakage current. The leakage current for the PN-junction is $I_{\text{leakage}} =\sim 3.5 \cdot 10^{-5}$A, where for the Schottky contact it is $I_{\text{leakage}} =\sim 80$A.

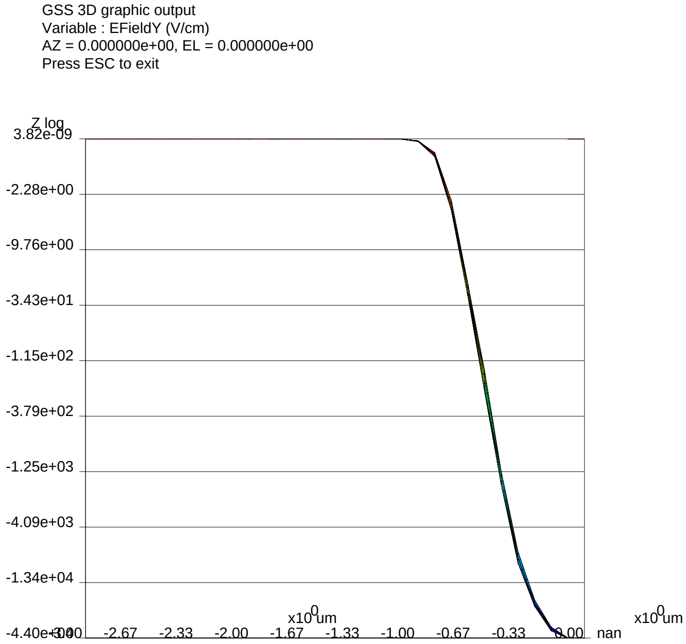


Figure 8: *Electrical field for the original configuration for the Schottky contact.*

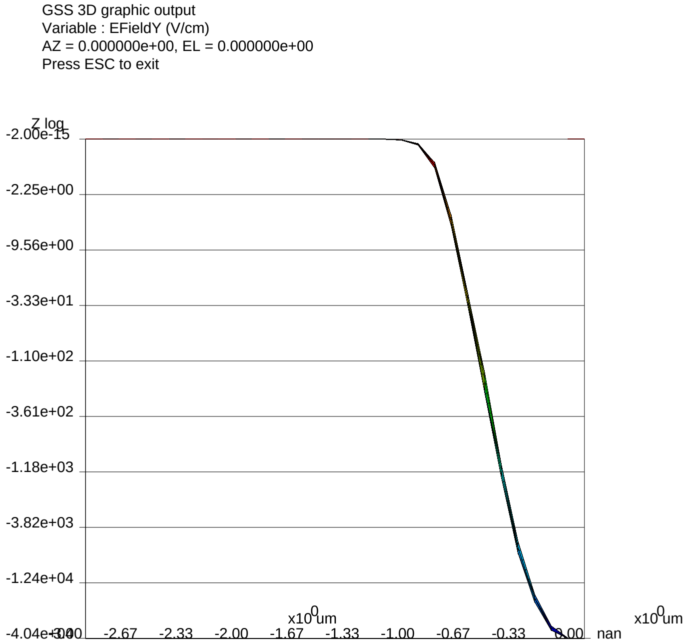


Figure 9: *Electrical field for the configuration with $T = 400K$ for the Schottky contact.*

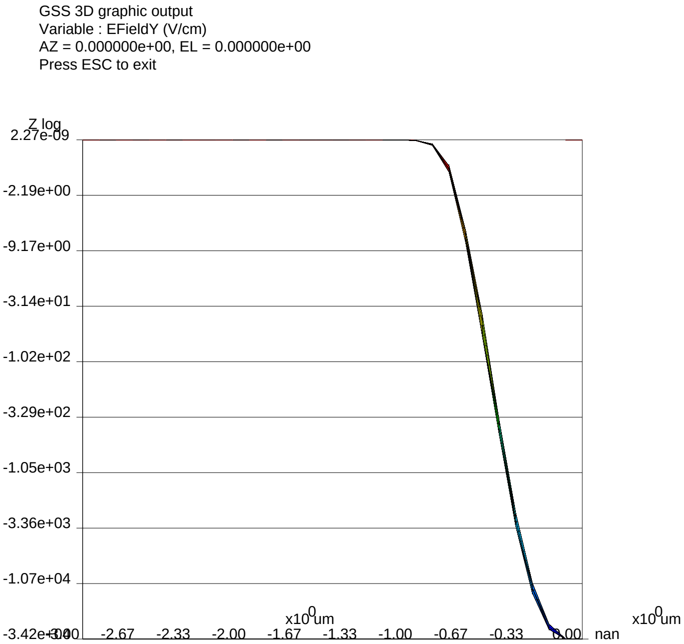


Figure 10: *Electrical field for the configuration with* $\phi = 4.5$ *for the Schottky contact.*

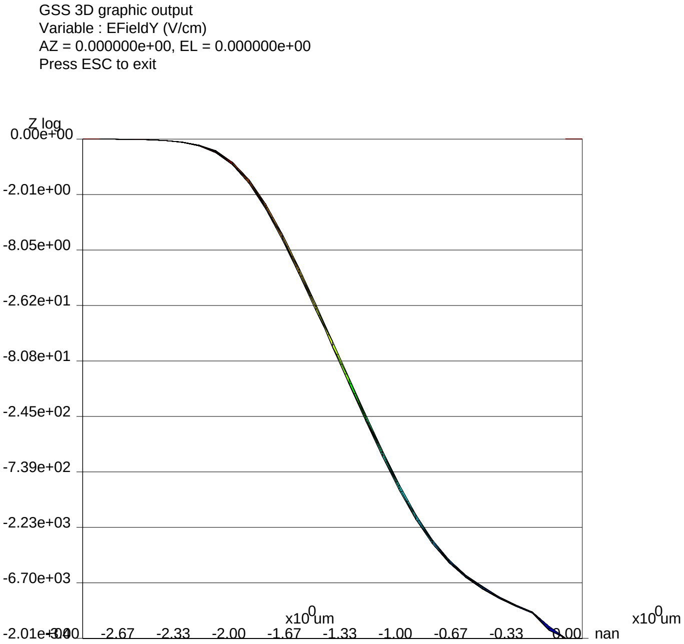


Figure 11: *Electrical field for the configuration with* $N_A = 10^{15} cm^{-3}$ *for the Schottky contact.*

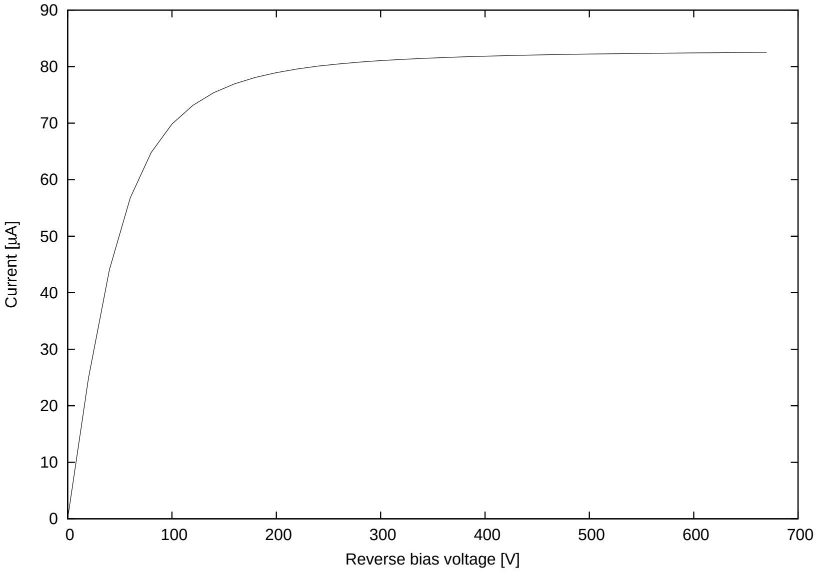


Figure 12: *Reverse bias IV curve for the Schottky contact.*

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