

Germanium diode I-V Characteristics: Ideal behavior analysis

José María Román

Photovoltaic Cell and Module Technology

EN547

March 28, 2004

Abstract

This paper is devoted to the analysis of experimental results for a Germanium diode, and its comparison with the ideal diode theory. In particular, the I-V characteristics is measured for two different temperatures, showing a qualitative agreement with the predictions of the theory. Deviations from the ideal theory are presented and taken into account in a more detailed analysis of the forward bias characteristic. The temperature dependence of the reverse saturation current yields a value of the contact potential in good agreement with the known value of the gap for germanium.

1 Introduction

We analyze in this paper the experimental results for the I-V characteristics for a Germanium transistor ACY20, and compare them to the ideal diode theory. The ideal theory is based in simple assumptions of how the junction of two opposite doped semiconductors behaves when put together [1, 2, 3].

Measurements of the voltage and current across the diode at two different temperatures, $t = 20^\circ C$ and $t = 80^\circ C$, are taken, showing a qualitative agreement with the predictions of the theory. Possible deviations from the ideal theory [1, 2, 3] are considered in a more detailed study of the forward bias characteristics, leading to several ranges of voltage where the ideal or ideal together with other mechanisms seem to dominate the current through the diode. The temperature dependence of the reverse saturation current allows us for obtaining an estimate of the contact potential, the potential barrier established between the two semiconductors of the junction. This value is in good agreement with the known value of the gap for germanium.

In section 2 we present the main features of semiconductors and junctions. Section 3 develops the simplest theory for the ideal diode, with a detailed calculation of the reverse saturation current from the underlying theory. Non-ideal mechanisms are outlined in section 4. The experimental set-up and measurement procedure are given in section 5, and section 6 contains the experimental results and their analysis. Finally our conclusion are presented in section 7.

2 The ideal diode

A diode is formed by the junction of two semiconductors doped with opposite sign, i.e., a p-n junction. The different electric character of the dopants at both sides of the junction establishes an electric field across the junction which determines the properties of the current which crosses the diode in the two different directions.

A n-type semiconductor is doped with elements called donors, because have electrons in excess of the intrinsic semiconductor elements (a semiconductor free of impurities or lattice defects is called intrinsic), e.g. phosphorous in silicon. The heavy doping density of donors, N_D , determines the level of majority carriers, electrons in this case, so that $n_{n0} = N_D$, while the density of minority carriers is determined from the mass action formula

$$np = n_i^2 = N_V N_C e^{-E_g/kT}, \quad (2.1)$$

which leads to

$$n_{n0} = N_D, \quad p_{n0} = \frac{n_i^2}{N_D} = \frac{N_V N_C}{N_D} e^{-E_g/kT}, \quad (2.2)$$

where N_V and N_C are the density of states at the top of the valence and at the bottom of the conduction band respectively, and E_g is the band gap of the semiconductor.

Equally a p-type semiconductor is doped with acceptors, which have less electrons than the main element of the material (boron in silicon), and then trap one electron leaving a vacancy in the valance band, which is represented as a hole. Again, the doping density of acceptors, N_A , determines the hole concentration in a heavily doped material, and the electron concentration is obtained from the mass action formula:

$$p_{p0} = N_A, \quad n_{p0} = \frac{n_i^2}{N_A} = \frac{N_V N_C}{N_A} e^{-E_g/kT}. \quad (2.3)$$

Now that we know the main features of n-type and p-type semiconductors isolated we put them next to each other. We assume here that we can treat electrons and holes independently. In this case the excess of electrons in the n-type side will diffuse into the p-type side. This diffusion effect produces a depletion of carriers around the interphase, known as the *depletion region*, the depletion will be supposed to be complete. Therefore producing an uncompensated charge to both sides of the junction which gives rise to an electric field (assumed to be contained exclusively within the depletion region). This electric field, in turn, generates a drift current opposite to the diffusion current, until an equilibrium between the two processes is reached.

$$\begin{aligned} I_{\text{diff}} &= qD_p \frac{dp}{dx}, \\ I_{\text{drift}} &= qp\mu_p E, \quad E = -\frac{dV}{dx}. \end{aligned} \quad (2.4)$$

Taking into account the Einstein relation $D_p = kT\mu_p/q$ it is straightforward to obtain a relationship between the carrier density to both sides of the junction,

$$\frac{p_{p0}}{p_{n0}} = \frac{n_{n0}}{n_{p0}} = e^{qV_0/kT}, \quad (2.5)$$

where $V_0 = V_n - V_p$ is the potential drop across the junction generating the drift electric field, also known as built-in or contact potential. By using eqs. (2.2), (2.3) and (2.1) into (2.4) we can write

$$qV_0 = kT \log \frac{N_A N_D}{n_i^2} = E_g + kT \log \frac{N_A N_D}{N_V N_C}, \quad (2.6)$$

which relates linearly the contact potential and the gap up to an additive factor depending on temperature, doping and density of states.

3 I-V Characteristic for an ideal diode

We can determine the general shape of the current flow through the junction considering a general argument for the mechanisms implied in the formation of the diode (see for example ref. [1], page 169).

As it was shown before there are two mechanisms which give rise to the diode conducting properties. On one hand there is the diffusion of electrons from the n-type side into the p-type side. These electrons have to overcome the potential barrier (contact potential) established by the electric field of the junction. This is achieved by a pure thermal activation mechanism

$$n \sim e^{qV_0/kT}, \quad (3.1)$$

and therefore the density of carriers overcoming the potential barrier depend on the height of the barrier (given by the contact potential V_0), and the temperature.

This diffusion current is compensated by a drift current originated by the electric field across the junction. Differently to the diffusion mechanism this drift current is not very much affected by the variations in the contact potential between the two sides of the junction, since the electric field acts on the minority carriers, and is the small density of them which determines the flow rather than the electric field itself.

We can assume therefore that in equilibrium $V = 0$ the diffusion and drift currents are compensated, and are both given by I_0 . When we apply a forward bias on the diode $V > 0$ the potential barrier is reduced from V_0 to $V_0 - V$, and therefore the diffusion current increases by a factor $e^{qV/kT}$, while the drift current remains unchanged. In the case of applying a reverse bias $V < 0$ the diffusion current will be reduced by a factor $e^{-q|V|/kT}$, while again the drift current is unaffected.

From the previous argument we can establish the I-V characteristic for the diode

$$I = I_0 \left(e^{qV/kT} - 1 \right), \quad (3.2)$$

where I_0 represents the equilibrium diffusion and drift current for $V = 0$. Notice that for and infinity reverse bias the diffusion current goes to zero and the only remaining one is the drift, such that $I(V = -\infty) = -I_0$, a small finite value known as *reverse saturation current*. On the other hand, for large forward bias the current across the junction increases exponentially, and it is completely dominated by diffusion.

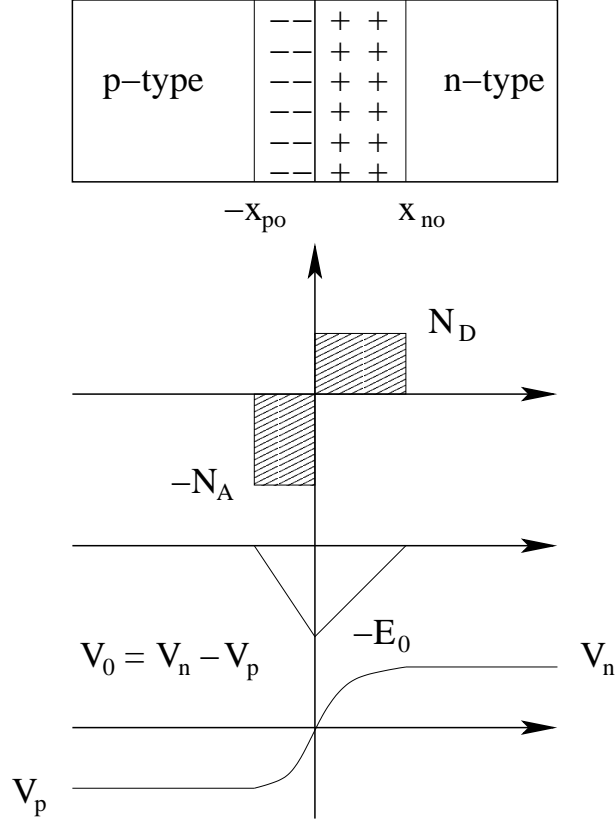


Figure 1. Ideal abrupt p-n junction, charge distribution, profile of the electric field and contact potential across the junction.

3.1 Reverse saturation current I_0

Now that we have obtained the general expression for the I-V characteristics of the current across a p-n junction we will turn to compute the value of the reverse saturation current I_0 under the assumption that it is generated by low level (minority carrier) injection. In this approximation the majority carrier density is unaffected.

As shown in fig. 1 we suppose as a good approximation that we can treat electrons and holes independently, and that the drop of the contact potential is produced within the depletion region.

Assuming that the depletion region is completely depleted of carriers we have two regions with opposite charge, and densities equal to the doping, N_A for the p-type side, and N_D for the n-type one. This uniform charge produces a linearly spatially distributed electric field and a quadratically distributed contact potential, as show in fig. 1.

Under the previous conditions the current across the junction is established by the minority carrier injection on the other side of the junction. For example, holes will be injected

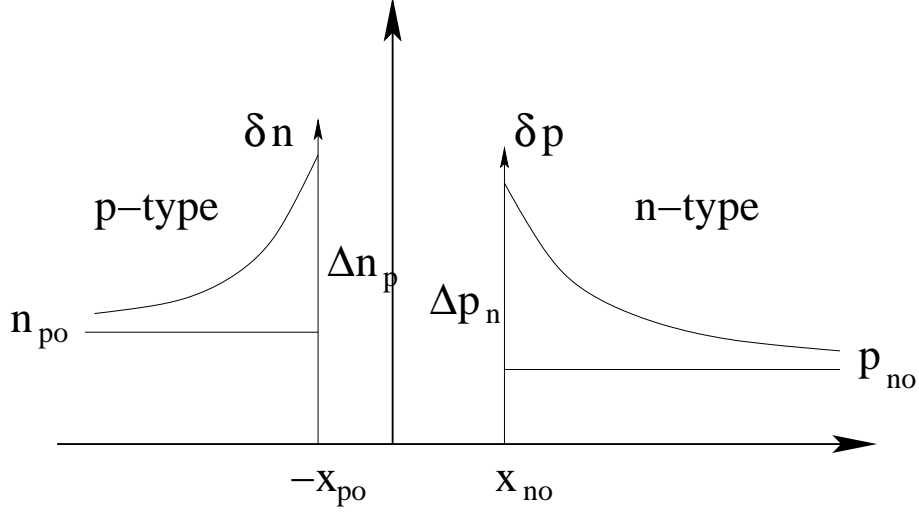


Figure 2. Profile of the low level injection in the p-n abrupt junction.

from the p-type side into the n-type side, and its concentration will decay to the equilibrium n-type hole concentration, p_{n0} , due to recombination of the injected holes, as shown in fig. 2. Then, the concentration of holes in the n-type semiconductor is given by

$$\delta p = \Delta p_n e^{-(x-x_{n0})/L_p}, \quad (3.3)$$

and a similar expression for electrons,

$$\delta n = \Delta n_p e^{(x+x_{p0})/L_n}, \quad (3.4)$$

where x_{n0} , x_{p0} , L_p , L_n are the border of the depletion region in the n-type and p-type sides and the hole and electron diffusion lengths. $\Delta p_n \equiv p(x_{n0}) - p_{n0}$ is the excess of holes over the bulk n-type hole concentration at the n-type border of the depletion region. Similarly for $\Delta n_p \equiv n(-x_{p0}) - n_{p0}$ for the p-type side.

The current passing through x_{n0} is given by the diffusion

$$I_p(x_{n0}) = -qAD_p \left. \frac{d(\delta p)}{dx} \right|_{x_{n0}}. \quad (3.5)$$

A similar expression to that in eq. (2.5) for the relation of carriers to both sides of the junction under equilibrium conditions can be derived for the case of a forward bias, i.e. $V > 0$. The effect of a forward bias is to reduce the potential barrier to $V_0 - V$, and therefore the relationship between the holes in both sides of the junction is now given by

$$\frac{p(-x_{p0})}{p(x_{n0})} = e^{q(V_0-V)/kT} \quad \longrightarrow \quad \Delta p_n \equiv p(x_{n0}) - p_{n0} = p_{n0}(e^{qV/kT} - 1). \quad (3.6)$$

Plugging (3.6) into (3.5) and differentiating we obtain an expression for the current at the border of the depletion region x_{n0}

$$I_p(x_{n0}) = qA \frac{D_p p_{n0}}{L_p} (e^{qV/kT} - 1), \quad (3.7)$$

and therefore the total current, adding up the electronic part, is given by

$$I = qA \left[\frac{D_p p_{n0}}{L_p} + \frac{D_n n_{p0}}{L_n} \right] (e^{qV/kT} - 1), \quad (3.8)$$

from where we can easily read I_0 .

After using eqs. (2.2), (2.3) and (2.5) we can rewrite the reverse saturation current as

$$I_0 = qA \left[\frac{D_p}{N_D L_p} + \frac{D_n}{N_A L_n} \right] N_V N_C e^{-E_g/kT} = qA \left[\frac{D_p N_A}{L_p} + \frac{D_n N_D}{L_n} \right] e^{-qV_0/kT}, \quad (3.9)$$

which provide an explicit exponential dependence on the temperature and energy gap, or contact potential, assuming the terms inside the square brackets cancel each other or have a subdominant temperature dependence.

4 Non-ideal mechanisms

There are several aspects which have not been taken into account in the above derivation of the I-V characteristics, and further complicate the understanding of the diode behavior (ref. [1], page 211):

Recombination within the depletion region: We assumed that there was no generation-recombination processes in the depletion region. For material with a small density of carriers the depletion region can be quite large and then the probability of recombination inside the depletion region is higher even dominating the shape of the curve. The recombination rate is proportional to

$$R \sim 1/n_i \sim e^{qV/2kT}. \quad (4.1)$$

Generation within the depletion region: For reverse bias what it is important is the rate of generation, since as soon as pairs are generated they are swept away by the enhanced electric field

$$G \sim W \sim \sqrt{V}. \quad (4.2)$$

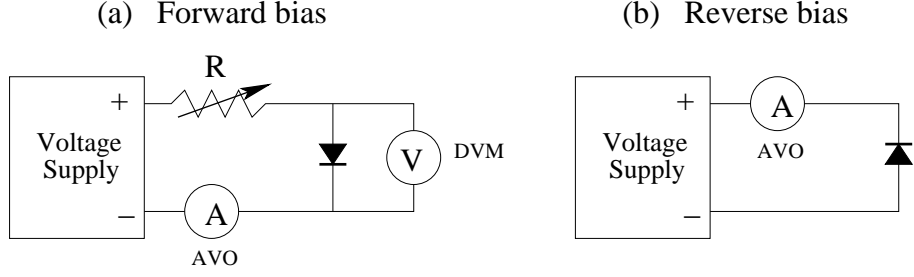


Figure 3. Experimental set-up for the forward and reverse bias configuration of the electric circuits to measure the I-V characteristic of the diode.

High level injection: As commented before we supposed that the density of majority carriers was not affected. However, as we increase the potential drop a large amount of carriers is taken from one side of the junction to the other, and injection for the majority carriers must be considered. When this is done we can see that the forward bias is dominated by the following form of the current:

$$I \sim e^{qV/2kT}. \quad (4.3)$$

Ohmic losses: The potential drop inside the p and n regions, as well as that in the contacts, can be taken into account by introducing a series resistance R_s in the diode, which will influence the measurements as we use an external tension $V = V_{\text{ext}} - IR_s$.

5 Experimental Procedure

In order to compare the theory of the ideal diode with the real diode behavior we will measure the current crossing a Germanium transistor ACY20 when a tension is applied across it, in forward and reverse bias.

As shown in fig. 3a for forward bias an external voltage is applied to the diode and a series varistor, and the voltage drop on the diode, as well as the current, are measured. In fig. 3b the set-up for measuring reverse bias is shown. In this case the varistor is not necessary any more, since the variations in current as voltage is changed are small, and therefore the tension drop can be directly read from the voltage source.

At room temperature we measure the I-V characteristics by controlling the current for forward bias ($I < 40mA$), and taking care of obtaining enough data for small values of the voltage ($0V < V < 0.2V$) in order to capture the expected exponential behavior of the characteristic. For reverse bias we can control the voltage itself and stop the reading before reaching the breakdown point.

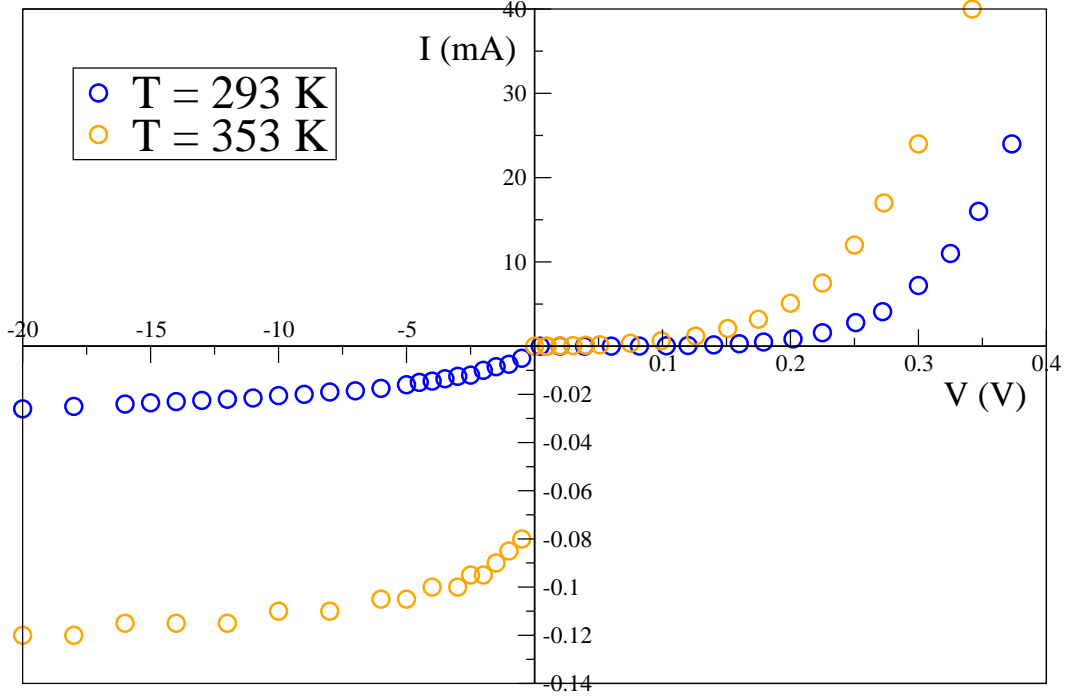


Figure 4. I-V Characteristics: values for $t = 20^\circ\text{C}$ and $t = 80^\circ\text{C}$. Notice that the scale for positive and negative axis is different.

In order to verify the exponential behavior of the reverse saturation current I_0 with temperature (and energy gap E_g or contact potential V_0), we heat the sample, while in the reverse bias set-up, for a given value of the applied voltage, $V = -5\text{V}$, from room temperature up to a temperature of about $t = 80^\circ\text{C}$.

A new measurement of the I-V characteristic at about $t = 80^\circ\text{C}$ is performed following the same procedure used for the room temperature case. We should obtain an increment of the current, in both forward and reverse bias, due to the thermal activation of the density of carriers, as predicted by the theory.

6 Experimental Results

We present in this section our results obtained from the previously described experimental set-up for a germanium diode. First of all, in fig. 4 we can see the I-V characteristic for forward and reverse bias, at room temperature ($t = 20^\circ\text{C}$) and $t = 80^\circ\text{C}$. (Notice the different scale used for the positive and negative axes of voltage and current).

For forward bias we notice an exponential behavior (a more detailed study is presented in fig. 5) of the characteristics, and how the higher temperature characteristic allows for higher

values of current in agreement with the assumption of a larger number of carriers available due to thermal activation.

In the reverse bias scenario we can see how the current tends to saturation. A saturation point is not reached probably because of generation current within the depletion region, or other kind of non-ideal mechanism as we will discuss later. Again the higher temperature curve yields a higher current.

The confirmation of the exponential behavior for the forward bias characteristic is presented in fig. 5. According to eq. (3.2), by plotting $\log(I + I_0)$ against V we should obtain a straight line if the diode followed the ideal behavior. When non-ideal mechanisms are considered, as those presented in section 4, different regimes should be identified as the slope of the curve changes, since

$$\frac{qV}{kT} \longrightarrow \frac{qV}{AkT}, \quad (6.1)$$

where A is known as the *ideality factor*. Usually $A = 1$ for the ideal mechanism, corresponding to low injection current, and $A = 2$ for high injection current (large voltage) or recombination current within the depletion region. In general intermediate values are expected since all the effects work at once.

There is a further uncertainty, since we do not know with precision the value of the reverse saturation current I_0 . Although in principle we are asked to take the value for a voltage of $V = -5V$, $I_0 = 0.016mA$, we will argue that it is as reasonable to choose as saturation current the value for $V = -0.05V$, $I_0 = 0.0023mA$. Other intermediate values of the saturation current would lead to intermediate results for ideality factors in the low voltage region. Curves for both saturation currents chosen are shown in fig. 5.

We can divide the points in fig. 5 in three regions, low voltage ($0V < V < 0.1V$, (region 1), low-intermediate voltage ($0.1V < V < 0.2V$, region 2), and large voltage ($V > 0.3V$, region 3) regions. By determining the slope of the linear fitting in each region we can obtain different ideality factors for each region and curve ($m = q/AkT$, see eq. (6.1)). The results for A are presented in table 1.

Region	I_0 (mA)	A
1	0.016	3.10
2	0.016	1.45
3	0.016	2.58
1+2	0.0023	1.31

Table 1. Ideality factor for the different regions and curves in fig. 5

Our first curve ($I_0 = 0.016mA$) presents, in the low voltage region, a much larger value

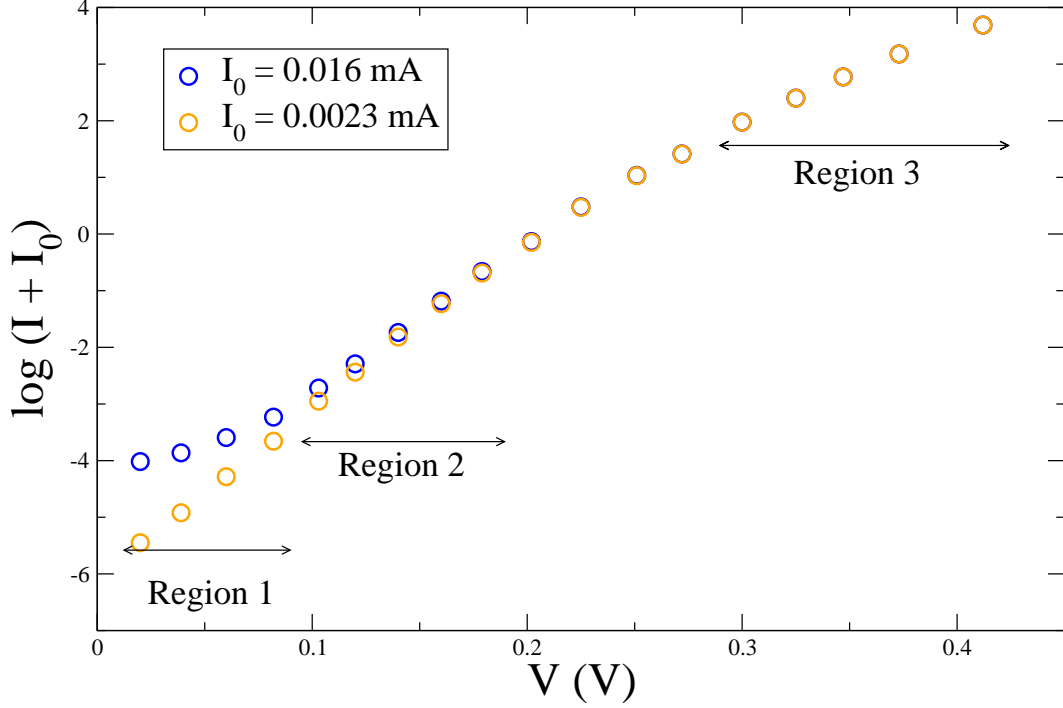


Figure 5. Ideality Factor: measurements in forward bias. Three different regions are identified, corresponding to different dominant mechanisms. Low voltage (region 1), low-intermediate voltage (region 2), and large voltage (region 3) regions are indicated in the figure.

of A than expected from a recombination in the depletion region mechanism. In the low-intermediate region we could suggest a mix presence of recombination and ideal mechanisms. For the high voltage region a high value of $A = 2.58$ is obtained, which suggests that not only high level mechanisms are present. For slightly smaller values of the voltage drop ($0.25V < V < 0.35V$) a better agreement with high level injection current can be achieved. The large value of A suggests that ohmic losses must be considered, which reduces the net current through the device.

We have considered as well the value $I_0 = 0.0023mA$ because at room temperature, $kT \sim 25meV$, the saturation of the current in reverse bias should be obtained for values of the reverse voltage as small as $V \sim -0.05V$. The existence of other effects in reverse bias (ref. [1], fig. 5-37, page 218), as pair generation in the depletion region, enhances the current, which will be misleading when trying to fit the ideal behavior. The smaller value of the saturation current in this case smoothers the curve for low voltages, and we can obtain a nice linear behavior spanning regions 1 and 2, with a value of the ideality factor $A = 1.31$, which is closer to ideallity. This value can be obtained when considering recombination in the depletion region due to interphase recombination, or defects in excess to what would be

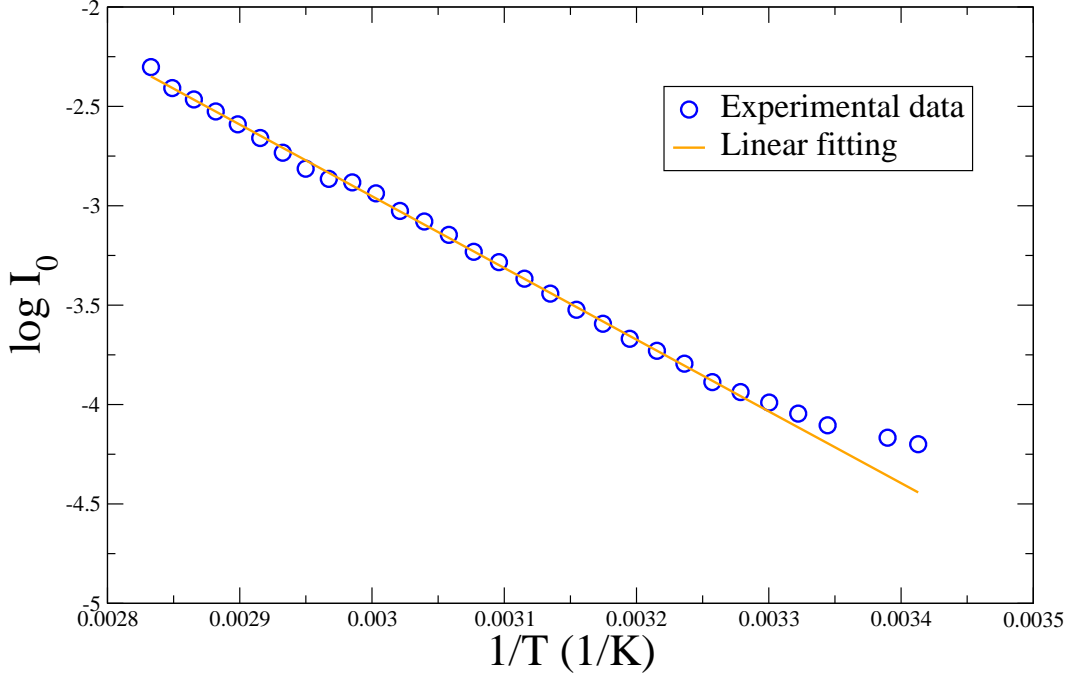


Figure 6. The contact potential is obtained from the slope of the linear fitting. This value is to be compared with the energy gap for Germanium. In the linear fitting the five most right experimental points were dropped.

ideal.

Eq. (3.9) provides an explicit temperature dependence of the reverse saturation current with temperature, namely, an exponential behavior (provided we assume that the temperature dependence of the terms in square brackets cancels each other, or at least is subdominant). We can use the data of the saturation current, measured at $V = -5V$ in the range of temperatures of $t = 20^\circ - 80^\circ C$ to obtain a value for the contact potential.

In fig. 6 we plot the $\log I_0$ against $1/T$, and from the slope of the linear fitting ($m = 3607.9K$) the value of the contact potential is $V_0 = 0.31V$. This value of the contact potential is directly related to the value of the gap of the semiconductor through eq. (2.6), which tells us that the value of the gap is given by the contact potential up to an additive term depending on the temperature, the doping, and the density of states. Therefore we can assume that the values of the gap and contact potential must be within the same order of magnitude, as it is the case since for Germanium $E_g = 0.67eV$.

As in the case of the ideality factor, here we also have to consider the uncertainty in the saturation current I_0 . The results for $V = -5V$ could be affected by other effects which produce uncontrolled deviations of the values of the contact potential and gap.

7 Conclusions

We have studied the behavior of a Germanium p-n junction, developing the simplest theory to explain it, namely, ideal behavior of an abrupt junction with low level injection current. We also outlined several corrections to this theory, which must be considered when analyzing the experimental data.

The I-V characteristic for the germanium diode was presented for room temperature ($t = 20^{\circ}C$) and $t = 80^{\circ}C$, showing the expected qualitative dependence with the applied potential, exponential increment with forward bias, and small values quite independent of the reverse bias.

A further study of the forward bias regime was presented to try to fit the different mechanisms involved in the transport of carriers through the junction. It was found that the low voltage region is consistent with the ideal behavior plus, possibly, generation within the depletion region. The high voltage region is consistent with a high level injection current mechanism and ohmic losses.

The dependence on temperature of the reverse saturation current I_0 ($V = -5V$) yields a value for the contact potential generated by the junction, which is directly related to the energy gap of germanium. It was found that both values are within an order of magnitude, and the doping density and density of states account for the difference between them.

Acknowledgments

I would like to thank Rodrigo R  iz Campo for his enthusiastic view of laboratory work, and very fruitful discussions. I also want to acknowledge discussions with Susana Fern  ndez Robledo.

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