

THE BIPOLAR JUNCTION TRANSISTOR; A PRIMARY THERMOMETER

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Abstract: For the first time was presented a method to extract the temperature of bipolar junction transistor calibration free, independent of the transistor semiconducting materials forbidden energy band gap, doping at each region, as well as of the transistor geometry, constituting then, a primary thermometer. The temperature extraction was realized through a mathematical treatment of the collector current as a function of the emitter-base forward bias. Experimental results using commercial transistors at thermal equilibrium in a water triple point cell show that the difference between the extracted temperature and 273.16K was smaller than 50mK.

1. INTRODUCTION

Since the discovery of the **PN** junction diode and the bipolar junction transistor their ability to sense temperature was clearly established, becoming the most practical semiconductor based thermometric elements. Widely used in countless applications mainly after Verster proposition that considerable simplified the use of a bipolar transistor as thermometric element [1]. Although to now, transforming such thermometric element into a thermometer a calibration is mandatory, and even with a calibration at one temperature there is an unpredictable error at other temperatures [2-5]. In this work it will be shown that a proper mathematical treatment of the collector current as a function of emitter-base forward bias allows the extraction of the junction temperature without any calibration and independently of the transistor semiconducting materials forbidden energy band gap, their doping, as well as of the transistor geometry, constituting then, a primary thermometer.

2. THEORY; ELECTRONS IN THE CONDUCTION BAND, PN JUNCTION AND BIPOLAR TRANSISTOR CURRENT

2.1. ELECTRONS IN THE CONDUCTION BAND

In semiconducting materials the energy distribution of the free carriers $f(\epsilon)$, is given by the Fermi-Dirac (FD) statistics which, for energy levels ϵ several kT above the Fermi level (k is Boltzmann's constant and T the temperature), determines that their occupation probability has an exponential dependence on the energy level and the free

carriers gas temperature. Under the above stated conditions this dependence is given by

$$f(\epsilon) \cong e^{-\frac{\epsilon - \epsilon_f}{kT}} \quad (1)$$

where ϵ_f is the Fermi level. This function clearly states the fact that the higher the energy level the smallest the probability of being occupied at a given temperature and, the higher the temperature of a free carriers gas is, the higher the probability of a given energy allowed state above ϵ_f to be occupied. Then, in an **N** type non degenerated semiconducting material the free electron concentration n_{n0} in the conduction band, resulting from the ionization of its shallow donors, is given by [6]

$$n_{n0}(T) = N_C (T^2)^{\frac{3}{2}} e^{-\frac{E_C - E_f}{kT}} \quad (2)$$

where N_C is the conduction band effective density of states and E_C is the bottom of the conduction band. Following the same procedure used to obtain Eq. (2), it can be shown that the concentration of electrons in the conduction band having energy $E \geq E_C + E_0$, n'_{n0} is given by

$$n'_{n0}(T) = n_{n0} e^{-\frac{E_0}{kT}} \quad (3)$$

Let us now briefly review the charge transport through a **PN** junction, and later, when discussing the temperature effect, Eq. (3) will be discussed in detail.

2.2. PN JUNCTION CURRENT

Here it will be presented just the case of electrons, for the holes an equivalent description holds. Assuming that in equilibrium the **PN** junction built-in energy barrier is E_{bi} , under the same condition the free electron concentration on the **N** side with energy higher than E_{bi} , thus, facing the one at the **P** side; n_{p0} , is equal, as well, to n_{p0} . By this way both electron concentrations facing each other at each side of the **PN** junction are equal resulting in a null net electron flow through the **PN** junction, Figure 1.

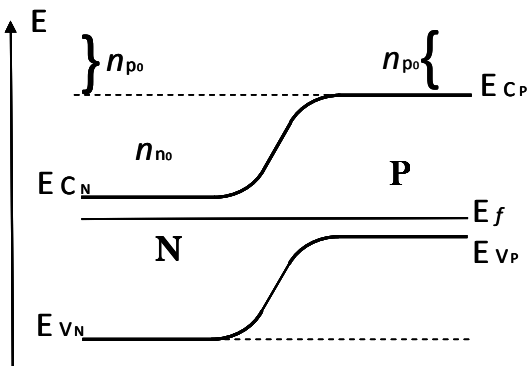


Fig. 1- Energy band diagram of a PN junction at equilibrium showing the electron concentration in the conduction band facing each other across the built-in energy barrier.

Now, when a forward bias, V , is applied the energy barrier height is reduced by qV and the electron concentration in the **N** side of the junction, n_n , having energy higher than $E_{bi}-qV$, and thus able to pass from the **N** region into the **P** region, Figure 2, is given by

$$n_n = n_{p0} e^{\frac{qV}{kT}} \tag{4}$$

This means that the electron concentration in the **N** side able to overcome the junction barrier increases exponentially with the barrier reduction qV , because the electron density increases exponentially towards the lower energies, as stated by Eq. (1) and the electron gas density through its temperature T .

According to the Schockley model, $J_n(V)$, the current due to the electron injection, i.e., the passage of electrons from the **N** type material into the neutral **P** type material, and considering the ideal case with no parasitic series resistances, is given by [6]

$$J_n(V) = q \frac{D_n}{L_n} [n_{p0} e^{\frac{qV}{kT}}] \tag{5}$$

where D_n and L_n are the electron diffusion coefficient and diffusion length in the **P** region respectively. From Eq. (5, term in brackets) is clear that this current constitutes a probe to the electron energy distribution in the **N** material and thus to the electron gas temperature. However, in a forward biased **PN** junction there are spurious currents due to parallel conduction mechanisms as; recombination in the **PN** junction space charge region, surface currents, etc., leading to a complicated behavior from which is impossible to extract the junction temperature, as there is no model to predict the values of such spurious currents. Notwithstanding the above mentioned inconvenient, **PN** junctions are widely used as thermometers, requiring individual calibration on several current-voltage points and temperatures.

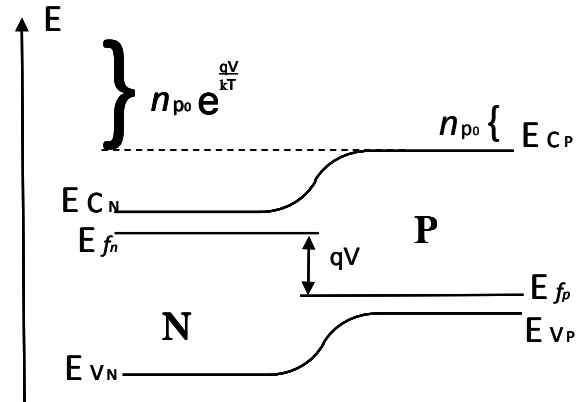


Fig. 2.- Energy band diagram of a PN junction forward biased showing the electron concentration in the **N** region able to overcome the now reduced built-in barrier, $E_{bi}-qV$.

2.3. BIPOLAR JUNCTION TRANSISTOR COLLECTOR CURRENT

On the other side the bipolar junction transistor, whose structure and functioning can be summarized as follows; three regions of semiconducting materials of different conductivity type placed in an alternated way resulting on a **PNP** or **NPN** structure, regions known as; emitter, base and collector, respectively. Now, considering a **NPN** structure, when a forward bias voltage V_{EB} is applied to the emitter-base junction, electrons are injected from the emitter into the base, exactly the same way as discussed above for the single **PN** junction.

However, the electrons injected into the base, by the solely mechanism of thermal diffusion, spread throughout the neutral base region and some electrons completely cross the neutral base region reaching the collector, constituting the collector current. According to the Shockley model, and once again considering no parasitic series resistances, the collector current, I_C , is given by the equation

$$I_C(V_{EB}) = \frac{qD_B}{L_B \sinh(l_B / L_B)} [n_{0B} e^{\frac{qV_{EB}}{kT}}] \quad (6)$$

where D_B and L_B are the base minority carriers diffusion coefficient and diffusion length respectively and n_{0B} is the equilibrium minority carrier concentration in the **P** type base neutral region, l_B is the neutral base thickness. As in the single **PN** junction case, the current of Eq. (6, term in brackets) constitutes a probe of the emitter electrons energy distribution and thus, of their temperature. The striking difference with the **PN** junction case is the absence of any other spurious currents.

Then, from Eq. (6), if the pre-exponential term is known, just one point current-voltage measure; V_{EB} and I_C , should be enough to determine the junction temperature through the equation

$$T = \frac{qV_{EB}}{k} \text{Ln}\left(\frac{I_{C0}}{I_C(V_{EB})}\right) \quad (7)$$

where I_{C0} is the pre-exponential term of Eq. (6). Using Eq. (7) to obtain the junction temperature requires knowing I_{C0} . However, n_{0B} , D_B and L_B in the pre-exponential term of Eq. (6) are technologically and temperature dependent on an unpredictable way, making this approach useless. Nevertheless, Verster in 1968, proposed the use of two collector currents; I_{C1} and I_{C2} , using the same bipolar transistor or use the same current through two identical transistors of different active area, and in any case determine the corresponding emitter-base voltages; V_{EB} 's, necessary to the obtain such currents, then using Eq. (6), it results [1]

$$T = \frac{q(V_{EB1} - V_{EB2})}{k} / \text{Ln}\left[\frac{I_{C1}(V_{EB1})}{I_{C2}(V_{EB2})}\right] \quad (8)$$

From which the junction temperature is straightforward obtained with no need at all of knowing the pre-exponential term of Eq. (6). Since then, this proposition has been used and a number

of scientific papers and patents have been produced based on it, see for instance [7-8].

It is well known that in Eq. (6) the terms D_B , L_B , transistor base minority carriers diffusion coefficient and diffusion length respectively, are temperature and technologically dependent in a way that is theoretically unpredictably. Moreover, as they are technologically dependent their value can change from run to run and even from point to point on a same wafer. The equilibrium minority carrier concentration in the p-type base neutral region, n_{0B} depends, as well, on the base transistor temperature, also in a way difficult to predict. All of these parameters are, as well, function of the material physical properties as forbidden energy band gap, carriers dispersion mechanisms, and I_{C0} depends on the transistor geometry etc. Finally, and most important, the parasitic series resistances are, as well dependent on the temperature and the current being handled. All of these dependences introduce an unpredictably error on the temperature determined using Eq. (8).

2.4. THE EFFECT OF TEMPERATURE ON THE PN JUNCTION CURRENT

Figure 3 shows a plot of the ratio of the free electrons concentration in the conduction band having energy $E \geq E_C + E_0$ to the total concentration; n'_{n0}/n_{n0} , as obtained from Eq. (3), as a function of E_0 , for several temperatures of the electron gas. This figure illustrates how the value of these two parameters impacts the amount of electrons able to overcome a **PN** junction energy barrier. To explain it, let us consider a **PN** junction barrier high of 0.3 eV (vertical line in the figure), then, if the **PN** junction is at 100K, from the total electron concentration n_{n0} in the conduction band in the **N** material only a ratio of 10^{-15} are able to overcome the junction barrier. This is because at this temperature most of the electrons in the **N** material are crowded at the bottom of the conduction band. When the temperature of the **PN** junction is 200K the same ratio of electrons able to overcome the same barrier of 0.3 eV is 10^{-8} , for $T=300K$ the ratio is 10^{-5} and for $T=400K$ the ratio is 10^{-4} , as at this last temperature more energetic levels are occupied, and so on. Then, as the forward bias of a **PN** junction is increased, reducing in the same amount the **PN** junction barrier, the electrons in the **N** material able to be injected into the **P**, because have enough energy to overcome the reduced energy barrier, will follow the curve of the Figure 3 that corresponds to the **PN** junction

temperature and by this way this electron current constitutes a probe of the electron gas temperature.

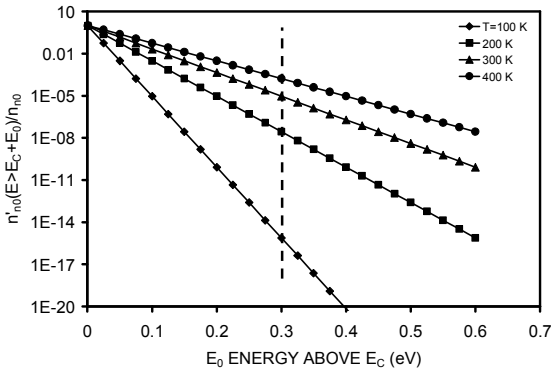


Fig. 3- Ratio of the free electrons concentration in the conduction band having energy $E \geq E_c + E_0$ to the total concentration; n'_n0/n_n0 , as a function of E_0 , for several temperatures of the electron gas.

2.5. METHOD TO EXTRAC THE TEMPERATURE OF A BIPOLAR TRANSISTOR FROM I_C - V_{EB} CURVES (CINVESTAV METHOD)

In obtaining Eqs (6 and 8), ubiquitous parasitic series resistances have been neglected and using them without considering those series resistances introduce an important error on the temperature determination that cannot be eliminated even with one point calibration. Figure 4 shows the temperature of a transistor at equilibrium with a water triple point cell obtained using Eq. (8) with current ratio of 10, using collector currents values over more than two and a half decades and its respective emitter-base voltages. As seen from this figure the temperatures obtained spread over more than 3K, are dependent on the values of the currents, and there is no way to establish which temperature value is the correct one. Using the same transistor and the method to be described here below the temperature extracted was only 45 mK different from the expected value, triple water point.

Actually, if in the bipolar transistor there are no parasitic series resistances or they are really negligible Eq. (6) is the correct one, making clear that if the temperature is going to be extracted from that equation what is needed is a method to find out the transistor operating range of collector current and emitter-base voltages where Eq. (6) really holds.

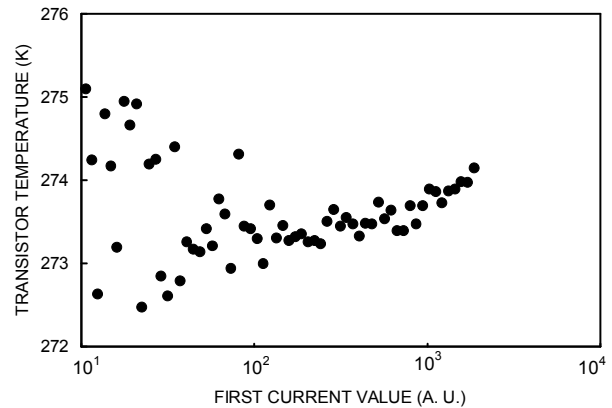


Fig. 4- Temperature of a transistor at equilibrium with a water triple point cell obtained using Eq. (8) with current ratio of 10, using currents spread over more than two and a half decades.

In this work we propose an extremely simple and straightforward method to find that range. Actually, the proposition, detailed here below, allows the direct extraction of the temperature at which the bipolar transistor electron gas is and thus, the transistor temperature. For this doing it is defined a extracting temperature function, $F(T_a)$ as

$$F(T_a) = e^{\frac{-qV_{EB}}{kT_a}} \tag{9}$$

where T_a is the extracting temperature parameter, having, evidently, temperature units. Then, by doing the product of Eqs. (6 and 9) it results

$$I_C(V_{EB})e^{\frac{-qV_{EB}}{kT_a}} = I_{C0}e^{\frac{qV_{EB}}{k}(\frac{1}{T} - \frac{1}{T_a})} \tag{10}$$

where I_{C0} is the pre-exponential term of Eq. (6). From the above obtained equation it follows directly that the bipolar junction transistor temperature is obtained when the T extracting parameter T_a , takes exactly the value of the temperature T at which was the bipolar junction transistor when the curve I_C vs V_{EB} , or the data (V_{EB}, I_C) were obtained, in which case the indicated proposed product of Eq. (10), as a function of V_{EB} , results to be a constant, given by

$$I_C(V_{EB})e^{\frac{-qV_{EB}}{kT_a}} = I_{C0} \tag{11}$$

Thus, the here proposed method does not rely on determining the value of I_{C0} , of a particular transistor or the values of its parasitic series resistances, but on using the experimental I_C vs V_{EB} curve on the range where it really follows the Shockley model

and then the function given by Eq. (10) is a constant. This constant behavior results independent of the before mentioned parameters as semiconducting material, technology used to realize the bipolar transistor, doping levels and geometry. Thus this method demonstrates that the bipolar transistor constitutes a primary thermometer, when properly treated the I_C vs V_{EB} .

Summarizing, to extract the bipolar junction transistor temperature, and thus that of a physical medium in thermal equilibrium with it, by this simple method, the product indicated in Eq. (10) should be realized and the T_a value adjusted until a constant value for that function given is obtained.

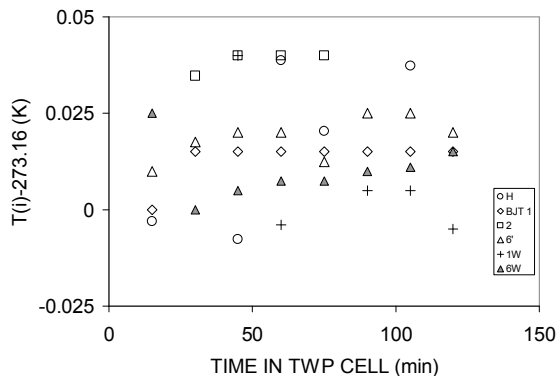


Fig. 5.- Temperature difference between the extracted using this method on six different commercial transistors in a water triple point cell.

3. RESULTS

Experimental measurements to test this proposition were done using out of the shelf commercial bipolar transistors (\$0.10 US Dollars/device), once properly wired and pre-cooled down in ice for at least 1 hour, were installed in the well of a water triple point cell (WTP), which has rested at equilibrium at least four hours. The collector current of the different devices were measured using an HP4145 semiconductor parameter analyzer. Figure 5 shows the extracted temperatures with the method here discussed as a function of the transistor time in the WTP well, as seen using junction bipolar transistors not especially designed to this measurement, the difference with the expected temperature is inferior to 50mK.

4 CONCLUSIONS

For the first time it has been presented in a detailed way a method to extract the temperature of bipolar

junction transistor that is calibration free, independent of the transistor semiconducting materials forbidden energy band gap, doping level at each region, and of the transistor geometry, constituting then, a primary thermometer. The temperature extraction is realized through a mathematical treatment of the collector current as a function of the emitter-base forward bias. Experimental results using of the shelf commercial transistors at thermal equilibrium in a water triple point cell show that the difference between the extracted temperature and 273.16 is smaller than 50mK.

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