

ON THE POSSIBILITY OF USING A BIPOLAR TRANSISTOR AS A THERMOMETER

J. Mimila-Arroyo

Centro de Investigación y de Estudios Avanzados del Instituto Politécnico Nacional
Av. Instituto Politécnico Nacional No 2508, México D.F., CP 07300, México
Tel(52) 55 50 61 38 00x6251, fax (52) 55 50 61 39 78, jmimila@cinvestav.mx

Abstract: In a bipolar transistor the collector current can be used as a probe of the charge carrier gas density and through it determine its temperature, becoming a thermometer. This probe results to be insensitive of the value and evolution of its physical and technological derived properties. Theoretically, the measure of the temperature results independent of the transistor charge transport parameters, its current gain and to parasitic elements as well as to their evolution. We illustrate its operation through examples of temperature measurements between 100 and 400 K using commercial transistors of different materials, structures and current gain.

1. INTRODUCTION

In semiconductors the charge transport properties are several fold dependent on the temperature. The carriers concentration might be temperature dependent because of impurity or defects, introducing allowed levels in the forbidden band gap, ionize, or because intrinsic carriers are thermally generated by their excitation through the forbidden band gap. The carriers transport properties as mobility, diffusion coefficient and minority carriers diffusion length might be also temperature dependent. Finally, the energy distributions of the electron and hole gases in the conduction and valence band are, according to the Fermi-Dirac statistics, exponentially dependent on the temperature. The manifestation of one or several of these dependences on the temperature has allowed the realization of temperature detectors as well as, when calibrated, thermometers. Usually two types of devices are considered with this purpose; resistances and pn junctions [1, 2]. However, these semiconductor based temperature sensors and thermometers have strong draw backs, the main one is that they have to be calibrated on a one to one basis and if their use induces some evolution of their electrical properties, even slight ones, periodical calibrations are mandatory. In this work we will show that a bipolar transistor can behave like a self-calibrated thermometer independent of the charge transport properties of its constituents and of their evolution, of the technological process used to elaborate the transistor, as well as of the evolution of its pn junction parameters as ideality factors or parasitic elements as series and parallel resistances.

2. THEORY; PN JUNCTION AND BIPOLAR TRANSISTOR CURRENTS

In the pn junction the current as a function of the bias voltage has, generally, contributions due to the mechanisms of injection-diffusion of minority carriers and by recombination of both types of carriers in the junction space charge region. Additionally, there are spurious contributions whose origin is complex as surface and through parallel resistances currents. The diffusion components are due to the electrons (holes) injected from the n(p)-type material into the p(n)-type: I_{NPn} (I_{PNh}), that diffuse and recombine respectively in the region where were injected. The recombination contribution is caused by the recombination of both types of carriers in the space charge region of the pn junction. Considering the Shockley diffusion model for the diffusion currents, semi-infinite p and n regions, neglecting parasitic parallel and series resistances, surface currents, considering a unitary area and that the bias voltage $V_a > 3kT$, the simplest equation for the diode diffusion current is given by[3]

$$I(V_a) = q \left[\frac{D_p p_{n0}}{L_p} + \frac{D_n n_{p0}}{L_n} \right] e^{\frac{qV_a}{\eta kT}} \quad (1)$$

where q is the electron charge, D_n (D_p), L_n (L_p) are the electron (hole) diffusion coefficients and diffusion lengths respectively, n_{p0} , (p_{n0}) are the electron (hole) concentrations in the p(n) regions respectively, η is the so called "ideality factor", normally 1.0, k is the Boltzmann's constant and T is the operating temperature. The first term in the brackets is I_{PNh} and the second one is I_{NPn} respectively. The ideality factor, although its existence is not predicted by Schockley's model, it had to be introduced on an

empiric base in order to fit the pn junction experimental data as they seldom follow Eq. 1 with $\eta=1$. There have been several propositions to explain its origin as, spurious surface currents through the device periphery and others. Moreover, the η value can vary from diode to diode even for diodes on the same wafer and it might be temperature and bias dependent and above all is strongly dependent on the whole diode technology. Until now there is no theoretical model capable of predict its value. Additionally to these diffusion currents, there is the space charge recombination contribution. However, as pn junction thermometers are operated where this current contribution is negligible it will not be considered here. In Eq. 1 all the terms involved in the right hand side but q and k are temperature dependent in a way that is hardly predicted theoretically. Moreover, some of them are technologically dependent and their value can change from point to point even on a same wafer.

Using the mass action law and the dependence of the intrinsic carriers concentration as a function of the semiconductor band gap, E_g , and the temperature, Eq. 1 can be written as

$$I(V_a)=I_s(T)e^{(qV_a-\eta E_g(T))/\eta kT} \quad (2)$$

where $I_s(T)$ is temperature and technologically dependent and $E_g(T)$ is the effective band gap of the semiconductor constituting the pn junction. As already said, I_s temperature dependence is complicated to be obtained in a theoretical basis as it depends, at least, on doping level, impurities ionization energies, substrate quality and operating temperature [3].

The diode temperature sensitivity stems from all the terms in Eq.(2), that are temperature dependent, but it is mainly due to the exponential terms; related to the ability of the valence band electrons to be thermally excited through the forbidden band gap into the conduction band and to the ability of electrons and holes to overcome the pn junction built-in energy barrier. In other words, to the electron and hole gases energy distribution given by the Fermi-Diract statistics. Thus, when the pn junction is operated in the current region where the diffusion mechanism dominates at a constant forward current condition, I_f , the needed forward voltage bias, to obtain this current, is temperature dependent and is given by

$$V_a(I_f,T)=(\eta/q)[E_g(T)+kT\ln(I_f/I_s(T))] \quad (3)$$

In Eq.(3) E_g , η and I_f are dependent on the temperature and, as said before, the two later on a way that is, until now, theoretically unpredictable. Thus, if pn junction diodes are to be used as reliable thermometers a one to one diode calibration becomes necessary.

For the bipolar transistor, its three electrodes allows to apply two independent biases; V_{EB} and V_{CB} , that produce three currents; I_E , I_B and I_C . For the charge transport model that we resume here below, let us consider that we are dealing with a NPN bipolar transistor, however, all the obtained results are, as well, equally applicable to the PNP one. The emitter-base current will be considered as being due to the mechanisms of injection-diffusion of minority carriers into the neutral regions and recombination in the space charge region, following the Shockley diffusion and the Shockley-Read-Hall recombination models respectively. The emitter-base diffusion current has, as in the case of a single pn junction discussed above, two components; a current of holes injected from the base into the emitter, I_{BEh} and an electron current injected from the emitter into the base, I_{EBn} , part of which reaches the base-collector junction becoming the collector current. According to the Schockley model, considering a semi-infinite emitter thickness, neglecting parasitic series and parallel resistances, surface currents, and the contribution from the reverse polarized base-collector junction, the simplest equations for I_{BEh} and I_{EBn} are, considering an unitary area and $V_{EB} > 3kT$, given by[3]

$$I_{BEh}(V_{EB})=\frac{qp_{0E}D_E}{L_E}e^{\frac{qV_{EB}}{\eta kT}} \quad (4)$$

and

$$I_{EBn}(V_{EB})=\frac{qn_{0B}D_B\coth(l_B/L_B)}{L_B}e^{\frac{qV_{EB}}{\eta kT}} \quad (5)$$

where D_E (D_B), L_E (L_B) are the emitter (base) minority carriers diffusion coefficients and diffusion lengths respectively and p_{0E} (n_{0B}) are the minority carrier concentration in the n-type emitter (p-type base) neutral region at the edge of the emitter-base space charge region, i.e., at the place where the injection of minority carriers takes place, l_B is the neutral base thickness, all other terms have been already

defined. Additionally to these currents, there is the space charge recombination contribution, however we will assume that the transistor operates on a V_{EB} range where this current is negligible. The collector current corresponds to the part of the current given by Eq. (5), i.e., electrons injected from the emitter into the base that reach and cross the base-collector junction. Under the same assumed conditions and considering that $V_{CB} \sim 0$, the collector current is given by

$$I_C(V_{EB}) = \frac{qn_{0B}D_B}{L_B \sinh(l_B/L_B)} e^{\frac{qV_{EB}}{kT}} \quad (6)$$

where all the parameters have been already defined. However, in this equation it should be observed that we are not considering the ideality factor in it. This assumption constitutes the main hypothesis of our proposition. Then, let us discuss below why such affirmation can be made.

The collector current originates from the part of the emitter current given by Eq. 5, that is to say, electrons that because of the built-in junction barrier energy reduction by the applied voltage, had been injected into the base, then, only by the mechanism of thermal diffusion, they reach the base-collector space charge region that they cross, becoming the collector current. That clearly means; first, that only electrons that had been *injected* into the base can be part of this current and, second, once injected the *solely* physical mechanism by which they can reach the collector junction is the *thermal diffusion*. That also means that for other spurious currents crossing the emitter-base pn junction, that make necessary the introduction of the ideality factor in Eq. 5 are, by no way, part of the collector current. Now, it should be stressed that the two physical processes undergone by the carriers constituting the collector current are exactly Schockley diffusion model main assumptions. Due to these two facts, origin and mechanism producing the collector current, the ideality factor in Eq. 6 should be equal to 1.0. Equation 6 can be written as

$$I_C(V_{EB}) = I_{C0} e^{\frac{qV_{EB}}{kT}} \quad (7)$$

where I_{C0} is the preexponential term of Eq. 6. Obviously in this case I_{C0} , as already discussed for the single pn junction, is also technologically and temperature dependent and theoretically

unpredictable. However from Eq. 7 the transistor temperature can be obtained in a straightforward way according to the equation

$$T = \frac{q}{k} \left[\frac{\partial(\ln(I_C(V_{EB})))}{\partial V_{EB}} \right]^{-1} \quad (8)$$

It should be observed that in this equation the pre-exponential term of Eq. 7, that includes all the semiconductor charge transport parameters dependent on the temperature and technology, has been suppressed and the temperature measurement is completely independent of it and thus, independent of its evolution as well. Moreover, as the collector current is the only one used to determine the temperature, this temperature determination results independent of the transistor base current and thus independent of the transistor current gain whichever its value could be. Clearly the temperature determination using the collector current of the bipolar transistor and the method here proposed results independent of the evolution of any one of the charge transport parameters of any of the constituents of the bipolar structure. Then, it results to be particularly well adapted to harsh conditions where some evolution of the transport parameters is often observed.

3. RESULTS

Experimental measurements to test this proposition were done using commercial bipolar transistors. The devices were mounted on the cold stage of a cryostat whose temperature was measured with a Pt resistance calibrated thermometer. The collector current of the different devices were measured at different temperatures using an HP4145 semiconductor parameter analyzer. Figure 1 shows a typical Gummel plot, $I_C(V_{EB})$ and $I_B(V_{EB})$ for a bipolar transistor, as shown by the theoretical fit in it, $I_C(V_{EB})$ follows reasonable well Eq. 7. On the other hand, $I_B(V_{EB})$ shows the presence of spurious currents that take it quite far away from Schockley's model. In this figure it can be observed, for the high current range, the well known deviation of the straight line due to the presence of a parasitic series resistance. On the low current region some noise appears due to the smallest current that the equipment can measure.

Figure 2 shows, for out of the shelf Germanium, Silicon, GaInP/GaAs heterojunction bipolar transistor and a degraded transistor their current gains

obtained from their respective Gummel plots, measured at arbitrary different temperatures. It should be observed that the current gain is arbitrarily different for each transistor. Figure 3 shows only the $I_C(V_{EB})$ for each one of these transistors.

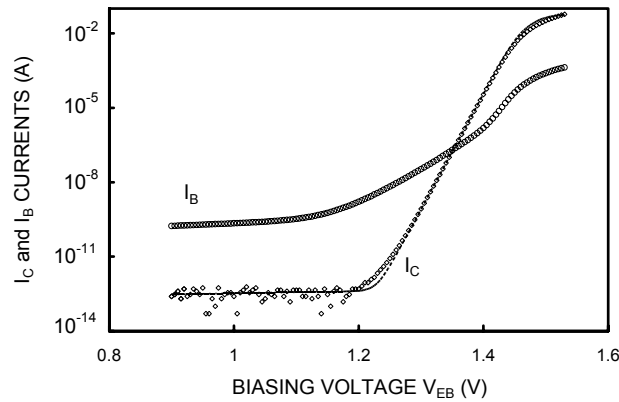


Fig. 1 Typical Gummel plot ($I_C(V_{EB})$ and $I_B(V_{EB})$) of a bipolar transistor.

4. DISCUSSION

In Fig. 3 from the part of the data where the parasitic series resistance can be neglected, using Eq. 8 and the last square fit method, the slope of the data $\ln(I_C(V_{EB}))$ for each curve was obtained and with it the temperatures at which each one of these data set was acquired. The obtained temperatures agree with the ones measured with the calibrated Pt resistance within 0.5%, values are given in Table I.

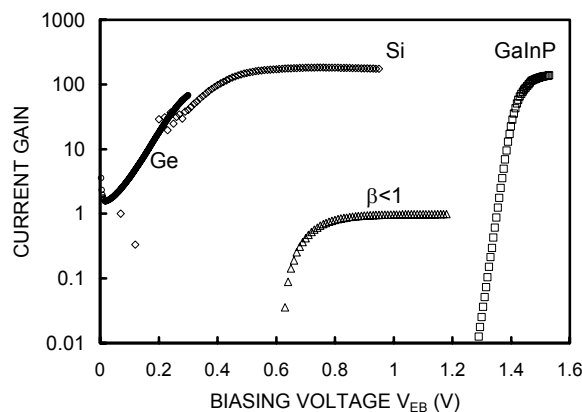


Fig. 2 Current gain of the; Ge, Si, GaInP/GaAs transistors and of a degraded one ($\beta < 1$), at arbitrary different temperatures.

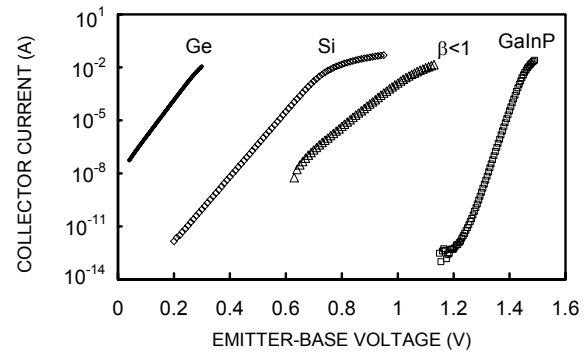


Fig. 3 Collector current for each one of the transistors of figure 2 as a function of V_{EB} at different arbitrary temperatures.

Table I. Current gain, slopes (I_C 's from Fig. 3) and temperatures measured with transistors of different semiconductor materials and structures.

Transistor	Current gain (β)	Slope of $\ln(I_C - V_{EB})$	Temperature (K)
Ge	70	48.05	241.44
Si	180	42.35	273.93
GaInP/GaAs	140	64.23	108.60
Degraded	0.98	29.31	395.80

5. CONCLUSIONS

In conclusion, we have shown that in the normal operation region of a bipolar transistor it can be used as a thermometer. The temperature measurement is possible by the dependence of the energy distribution of the electron and hole gases, and to the fact that the transistor collector current is due only to the minority carriers injected from the emitter into the base which by thermal diffusion reach the collector. Those two facts make the ideality factor in the collector current voltage equation to take the ideal value of 1.0. This behavior of the collector current is independent of the bipolar transistor type; homojunction or heterojunction at any or both of the transistor junctions, to the materials constituting the active regions of the transistor as well as independent of the transistor current gain and thus to their physical evolution.

ACKNOWLEDGEMENTS

The author thanks M. en C. R. Huerta for valuable technical assistance.

REFERENCES

- [1] C. J. Yeager and S. S. Courts, IEEE Sensors Journal, Vol 1, 2001, 352 (.
[2] X J. E. Pallett, Electronic Engineering . Liu, Jpn. J. Appl. Phys. 32, (1993), L713.
[3] S. M. Sze, "Physics of Semiconductor Devices", John Wiley, New York (1969)