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Electrical determination of the bandgap energies of the emitter and base regions of bipolar junction transistors

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A pure electrical method is presented to extract emitter and base bandgaps of a bipolar junction transistor (BJT) at the locations where the minority carrier injection takes place. It is based on the simultaneous measurement of the collector and base currents as a function of the emitter-base forward bias (Gummer plot) and the corresponding current gain. From the obtained saturation currents as a function of temperature, we extract the bandgap energies. The accuracy of the method is demonstrated for InGaP-GaAs, Si, and Ge commercial devices. For InGaP-GaAs transistors, the results can be understood if the emitter-base heterojunction is not an abrupt but a gradual one. The presented method is a reliable tool that can aid in the development of new compound semiconductor based BJTs whose bandgap energies are highly sensitive to their composition. *Published by AIP Publishing*. [http://dx.doi.org/10.1063/1.4966609]

I. INTRODUCTION

The availability and maturity of the epitaxial growth techniques, mainly molecular beam epitaxy and chemical vapor deposition using metalorganic precursors, have conducted to an explosive development of new semiconducting materials, which can be binary, ternary, or even quaternary with highly controlled composition and doping levels as well as other physical properties. With them, semiconducting structures displaying high quality interfaces can be constructed, even when totally different materials are involved. Such availability of new materials and structures with so tight controlled physical properties offer additional technological degrees of freedom, which might be applied to develop devices with better performances. However, the physical properties of semiconducting alloys might be highly sensitive to their composition, itself strongly dependent on the growth conditions.[1] Moreover, thermal treatments often involved in device manufacture might change the bandgap of the involved alloys as well as the location of the metallurgical and electrical junctions. Thus, for each new compound, determining its bandgap is mandatory to proper device design. Moreover, its knowledge provides the necessary feedback to the fine-tuning of the technological processes involved in its manufacture. Although actually determining the bandgap of a homogeneous semiconducting material is no more an issue, obtaining it once a device is finished, for instance, a bipolar junction transistor (BJT), is almost impossible. Generally, in the literature, the reports on the methods for extracting the transistor charge transport parameters, from which the bandgap could be obtained, are scarce. Some ask for complicated numerical methods involving high order polynomial functions without any link between their terms and the material physical properties and been useless for providing the required feedback.[2] Optical methods are also difficult to manage inside a device. Trying to understand the so called "Burn-in effect" on InGaP/GaAs heterojunction bipolar transistors (HBTs) we already reported a way to obtain the emitter bandgap through the painful ordinary method, which involves the usual way of measuring the sample temperature and the fit of the experimental current data.[3] This time, we use simpler versions of the required theoretical equations and particularly a completely new way to determine the true junction temperature, which does not involve the use of any external secondary thermometer, thermocouple or other,[4] as well as an easier and new way to obtain the base diffusion and recombination saturation currents. All of these improvements make the method here presented much easier to apply and yield a more accurate value for the extracted bandgap energies.

Here, we present a reliable all electrical method to extract the emitter and the base bandgap energies at both edges of their space charge region. That means precisely at the place where the minority carrier injection takes place under forward bias, simultaneously obtaining the energy level of the dominant recombination center in that junction space charge region. We stress that with this method the bandgap obtained corresponds to the effective value for all the semiconducting material surfaces through which the minority carriers are injected, contrary to the optical methods where the obtained value corresponds to the point where the optical excitation occurs. The method relies on the simultaneous measurement of the collector (I_C) and base (I_B) currents as a function of the emitter−base forward bias (V_{EB}), Gummel plot, maintaining the collector-base junction short circuited. From them, the corresponding current gain ($\beta\,(V_{EB})$) is obtained, all of this at different transistor temperatures. These experimental data are fitted, according to the model of Shockley, considering two conduction mechanisms through the emitter-base junction: injection-diffusion in their quasi-neutral regions and recombination in their junction space charge region. The different transistor temperatures were

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extracted by a simple and reliable method using the collector current data, which simultaneously provides the collector saturation current (I_{C0}) at the corresponding temperature.[4] For each temperature, the remaining data, base current and current gain, are both fitted simultaneously by just two additional parameters, the pre-exponential terms of the currents; first the one due to the diffusion in the base or the emitter (I_{EB0}) and the second one due to the recombination in the space charge region (I_{EBR0}). The bandgap energies are obtained from the plot of the pre-exponential terms of those three currents as a function of the temperature. The method was applied to InGaP-GaAs, Silicon, and Germanium commercial bipolar junction transistors, and the extracted bandgap values are 1.62 eV and 1.65 eV for the GaAs and InGaP materials of the InGaP-GaAs transistors and 1.14 eV and 0.76 eV for Si and Ge transistors, respectively.

II. THEORY: BIPOLAR JUNCTION TRANSISTOR CHARGE TRANSPORT

Since their discovery, bipolar junction transistors have been the subject of continuous and very dynamic development that was based on new semiconducting materials as well as new structures.[5–17] Let us briefly review their charge transport properties considering a ***NPN*** structure. Note that the charge transport in the ***PNP*** structure occurs in a similar way. We assume that the emitter and base semiconducting materials have energy bandgaps, E_{Eg} and E_{Bg}, with majority and minority carriers concentrations n_{E0}, p_{B0} and p_{E0} and n_{B0}; minority carriers diffusion lengths L_E and L_B; and carrier diffusivities D_E and D_B, respectively. As known, in this three terminal device, two independent biases can be applied: emitter-base, V_{EB}, and base-collector, V_{BC}, resulting in emitter I_E, base I_B, and collector I_C currents.

When the transistor emitter-base junction, at temperature T, is forward biased with a voltage V_{EB}, an emitter current, $I_E(V_{EB},T)$, results, due to two different mechanisms: recombination of electrons and holes in the junction space charge region, $I_{EBR}(V_{EB},T)$, and injection-diffusion-recombination in the quasi-neutral regions at each side of its space charge region. The first current results from the fact that the forward bias increases the concentrations of electrons and holes in the junction space charge region highly above their equilibrium values, triggering the recombination process. This current, assuming no parasitic series resistance, is given by[8,18]

$$I_{EBR}(V_{EB},T) = I_{EBR0}(T)[e^{qV_{EB}/n_r kT} - 1], \tag{1}$$

where I_{EBR0} is the junction recombination saturation current, k is Boltzmann's constant, q is the electron charge, and η_r is the so called ideality factor which according to the model of Shockley-Read-Hall should be equal to 2.[8,18] Although η_r almost never takes such a value and usually is handled as an empirical fitting parameter. The recombination saturation current I_{EBR0} is due to near mid-bandgap energy recombination centers and is given by[8]

$$I_{EBR0}(T) = \frac{1}{2} q\sigma v_{th} N_T n_i w_E, \tag{2}$$

where N_T is the recombination center concentration in the emitter-base space charge region, σ is the recombination center capture cross section, W_E is the emitter-base junction space charge region width, v_{th} is the carrier's thermal velocity, and n_i is the intrinsic carrier concentration of the semiconductor where the recombination takes place. Through this last parameter, I_{EBR0} depends exponentially on the device temperature.

The emitter injection-diffusion current $I_{ED}(V_{EB},T)$ has two components: one due to electrons injected from the n-type emitter into the neutral region of the base. This current being at the origin of the transistor effect. The other one is due to holes injected from the p-type base into the emitter neutral region, I_{EBn} and I_{BEh}, respectively, i.e., $I_{ED}(V_{EB},T) = I_{EBn}(V_{EB},T) + I_{BEh}(V_{EB},T)$. The electrons injected into the base, by the solely mechanism of thermal diffusion, spread throughout the base neutral region where some recombine contributing to the base current due to the injection-diffusion mechanism. Nevertheless, in a well-designed transistor, most of the electrons injected into the base reach the collector-base junction where they are swept and transferred to the neutral collector region contributing to the collector current; this is, of course, the transistor effect.[5] According to the model of Shockley, considering a semi-infinite emitter thickness, a unitary junction area, $V_{EB} > 3kT$, neither parasitic series nor parallel resistances, and a short circuited base-collector junction ($V_{CB} = 0$), the injected electron and hole currents are given by[8]

$$\begin{aligned} I_{EBn}(V_{EB},T) &= \frac{qD_B n_{Bi}^2 Coth(l_B/L_B)}{p_{B0}L_B} e^{qV_{EB}/kT} \\ &= I_{EB0}(T)e^{qV_{EB}/kT}. \end{aligned} \tag{3}$$

And

$$I_{BEh}(V_{EB},T) = \frac{qD_E n_{Ei}^2}{n_{E0}L_E} e^{qV_{EB}/kT} = I_{BE0}(T)e^{qV_{EB}/kT}, \tag{4}$$

where n_{Bi} and n_{Ei} are, respectively, the emitter and base intrinsic carrier concentrations at the precise location where the minority carrier injection takes place at each side of the space charge region of the emitter-base junction, l_B is the neutral base thickness, and other parameters have already been defined. Although the hole current I_{BEh} injected into the emitter has no impact on the transistor effect, it has a negative one on the current gain. Its study might provide useful information on the dominant diffusion base current and on the emitter bandgap energy. The total emitter current is due to all the above discussed currents; recombination in the space charge region and injection-diffusion in the neutral regions of the junction, i.e.

$$I_E(V_{EB}) = I_{EBR}(V_{EB},T) + I_{ED}(V_{EB},T). \tag{5}$$

In normal bipolar transistor operation, the emitter and collector junctions are simultaneously biased, usually the first forwardly and the second reversely. However, considering that the base-collector junction is short circuited, $V_{CB} = 0$, the collector current $I_C(V_{EB},T)$ is due to the electrons injected into the base that by the sole mechanism of thermal diffusion reach the collector. According to the model of Shockley and considering a semi-infinite collector thickness of unitary junction area, $V_{EB} > 3kT$, neither series nor parallel parasitic resistances, I_{CD}, the collector current is given by[8]

$$I_C(V_{EB}, V_{BC} = 0, T) = \frac{qD_B n_{Bi}^2}{p_{0B} L_B \sin h(l_B/L_B)} e^{qV_{EB}/kT} = I_{C0} e^{qV_{EB}/kT}, \tag{6}$$

where I_{C0} is the pre-exponential term, and all other parameters have been already defined.

The base current is due to the three contributions already presented: the recombination in the emitter-base space charge region, Eq. (1); the one due to holes injected into the emitter, Eq. (4); and finally, the one due to the electrons injected from the emitter into the base neutral region that do not reach the collector and recombine in the base, which is given by the difference of Eq. (3) minus Eq. (6). Then, from Eqs. (3), (4), and (6), the transistor base current is given by

$$I_B(V_{EB}) = \left\{ \frac{qD_E n_{Ei}^2}{n_{E0} L_E} + \frac{qD_B n_{Bi}^2 [\cos h(l_B/L_B) - 1]}{p_{B0} L_B \sin h(l_B/L_B)} \right\} \times e^{qV_{EB}/kT} + I_{BR0} e^{qV_{EB}/kT} \tag{7}$$

which can be written as

$$I_B(V_{EB}) == [I_{BE0} + I_{EB0}] e^{qV_{EB}/kT} + I_{EBR0} e^{qV_{EB}/\eta_r kT}. \tag{8}$$

It should be stressed that the two pre-exponential terms of Eq. (7) related to the injection-diffusion mechanism, I_{BE0} and I_{EB0}, for any given emitter-base junction, cannot be strictly equal, which is to say, that one of them will dominate the diffusion current component of the base.

The transistor current gain, $\beta(V_{EB})$ $[= I_C(V_{EB})/I_B(V_{EB})]$, will be given by either Eqs. (9) or (10), depending on which base injection-diffusion current dominates. Equation (9) applies when the base diffusion current is dominated by the recombination of electrons injected into the neutral base region. Equation (10) rules when that current is dominated by the recombination of holes injected into the emitter

$$\beta(V_{EB}, T) = \frac{I_{C0} e^{qV_{EB}/kT}}{I_{EB0} e^{qV_{EB}/kT} + I_{EBR0} e^{qV_{EB}/\eta_r kT}} \tag{9}$$

or

$$\beta(V_{EB}, T) = \frac{I_{C0} e^{qV_{EB}/kT}}{I_{BE0} e^{qV_{EB}/kT} + I_{EBR0} e^{qV_{EB}/\eta_r kT}}. \tag{10}$$

In Eqs. (9) and (10), the dependence of each pre-exponential term on their respective intrinsic carrier concentration and thus on their corresponding bandgap energy and temperature is included.

According to this brief review of the charge transport properties of the ***BJT***, experimental data for $I_{CD}(V_{EB}, T_E)$, $I_B(V_{EB}, T_E)$, and β (V_{EB}, T_E), at temperature T_E, should be properly fitted by Eqs. (6), (8), (9), or (10), through just three parameters: $I_{C0}(T_E)$, $I_{BE0}(T_E)$ **or** $I_{EB0}(T_E)$, *and* $I_{EBR0}(T_E)$.

By another way, it is well known that the bandgap energy depends on the temperature according to $E_g(T) = E_{g0} - \alpha T^2/(T + \beta)$, where E_{g0} is the energy bandgap at 0 K, and α and β are material dependent constants. However, in the temperature range experimentally explored here $77 \leq T \leq 450$ K and given the values of the constants α and β, we use the approximation n_i^2 α $exp(-E_{g0}/kT)$.[19] By this way, the dependence of the pre-exponential factors of Eqs. (6) and (8) on the respective values of their bandgap energies and temperature is given by

$$I_{C0}(T) \propto n_{Bi}^2 \propto T^3 e^{-E_{Bg0}/kT}, \tag{11}$$

$$I_{BE0}(T) \propto n_{Ei}^2 \propto T^3 e^{-E_{Eg0}/kT}, \tag{12}$$

$$I_{EB0}(T) \propto n_{Bi}^2 \propto T^3 e^{-E_{Bg0}/kT}. \tag{13}$$

For Eq. (2), the corresponding dependence is given by

$$I_{EBR0}(T) \propto T^{3/2} e^{-E_A/kT}, \tag{14}$$

where E_A is the activation energy of the recombination mechanism in the emitter-base space charge region.[18] Finally, according to Eqs. (11)–(14), the bandgap energies can be obtained from the slopes of the semi-logarithmic plots of $I_{C0}(T)T^{-3}$, $I_{BE0}(T)T^{-3}$ [or $I_{EB0}(T)T^{-3}$], and $I_{EBR0}(T)T^{-3/2}$ versus the reverse of the temperature.

III. EXPERIMENTAL: MEASUREMENTS, TEMPERATURE, AND CHARGE TRANSPORT PARAMETERS EXTRACTION

The results presented below were obtained on commercial Germanium and Silicon homo-junction BJTs and n-GaInP/p-GaAs/n-GaAs hetero-junction bipolar transistors (HBTs). Measurements were done using an HP4145 Semiconductor Parameter Analyzer maintaining the base-collector junction at zero bias. The transistor temperature was varied and stabilized by placing it in a cryostat. For each transistor, Gummel data were obtained, and from these data, the transistor current gain was obtained. Temperature was varied in the range of $77 \leq T \leq 450$ K. Figure 1 shows typical Gummel plots for Germanium, Silicon BJTs, and n-GaInP/p-GaAs HBT, under the bias conditions discussed above. From the data of Fig. 1, the respective transistors current gains are obtained and shown in Fig. 2.

For each Gummel measurement, the transistor temperature, T_i, at which the data were obtained, was extracted through the function, $M(I_C, V_{EB}, T_i, T_0) = I_C(V_{EB}, T_i) exp(-qV_{EB}/kT_0)$, where T_0 is a parameter having units of temperature and $I_C(V_{EB}, T_i)$. Substituting Eq. (6) in this function, it becomes $M(V_{EB}, T_i, T_0) = I_{C0}(T_i) exp[qV_{EB}(1/kT_i - 1/kT_0)]$, and it is clear that there is a value for the parameter T_0; T_{0i}, for which the function $M(V_{EB}, T_i, T_{0i})$ becomes a constant $I_{C0}(T_i)$. This T_{0i} value corresponds to the transistor temperature, T_i, at the time of being measured.[4] Note that this procedure does not constitute a fit, and we simultaneously extract the transistor temperature as well as its

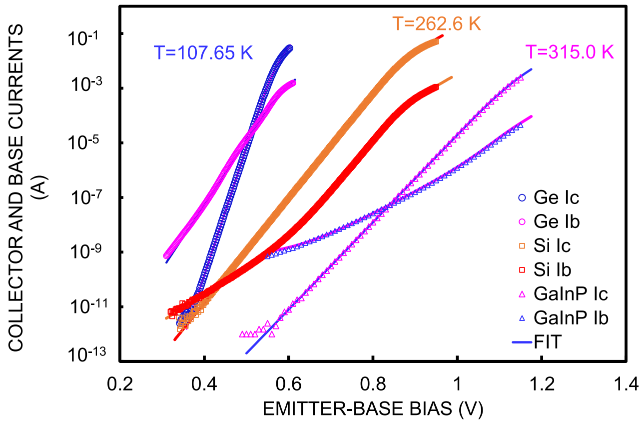

FIG. 1. Collector and base currents at $V_{BC}=0$ as a function of emitter-base forward bias, V_{EB}, for commercial transistors of Germanium, Silicon, and n-GaInP/p-GaAs at different arbitrary temperatures. Full lines are the fit using Eqs. (6) and (7).

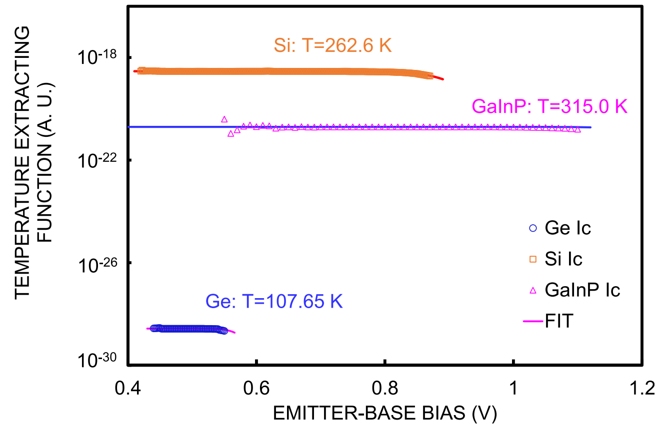

FIG. 3. Plot of the temperature extracting function; M (V_{EB}, T_i, T_{0i}) $[=I_{C0}(V_{EB})\exp(-qV_{EB}/kT_{0i})]$, using the proper T_{0i} values which satisfy the condition M (V_{EB}, T_i, T_{0i}) = *cte.* $= I_{C0}(T_i)$, for the collector current data of Figure 1.

collector saturation current at that temperature. Figure 3 shows plots of the function $M(V_{EB}, T_i, T_{0i})$, for the corresponding $I_C(V_{EB}, T_i)$ data for the three transistors of Fig. 1, where the corresponding T_0 value that yields $M(V_{EB}, T_i, T_0)$ = *cte*, for each set of data, has been used. The extracted temperatures were 107.65 K, 262.6 K, and 315.0 K, and the corresponding I_{C0} values are 2.65×10^{-29} A, 2.88×10^{-19} A, and 1.97×10^{-21} A for Ge, Si, and InGaP/GaAs transistors, respectively. It is emphasized that the above extracted values for $I_{C0}(T_i)$ and T_i directly fit the corresponding $I_C(V_{EB},T_i)$ data, as shown in Fig. 1, by the continuous lines. These same values, $I_{C0}(T_i)$ and T_i, are used to fit the corresponding current gain data through Eqs. (9) or (10), by finding just the proper values for $I_{BE0}(T)$ (or $I_{EB0}(T)$) and $I_{BR0}(T)$, considering $\eta_r=2$. For the data of Fig. 2, the obtained values are I_{BE0} *[or* I_{EB0}*]* (107.65 K) $=9.75\times10^{-31}$ A and I_{EBR0} (107.65 K) $=2.3\times10^{-17}$ A for the Ge BJT, I_{BE0}*[or* I_{EB0}*]* (262.65) $=5.5\times10^{-21}$ A and I_{EBR0} (262.65 K) $=4.0\times10^{-15}$ A for the Si transistor, and I_{BE0}*[or* $I_{EB0}(T)$*]* (315.0 K) = 3.05 $\times10^{-23}$ A and I_{EBR0} (315.0 K) $=1.0\times10^{-14}$ A for the InGaP/GaAs transistor. The fits are shown in Fig. 2, by the continuous lines. Of course, the last obtained pre-exponential

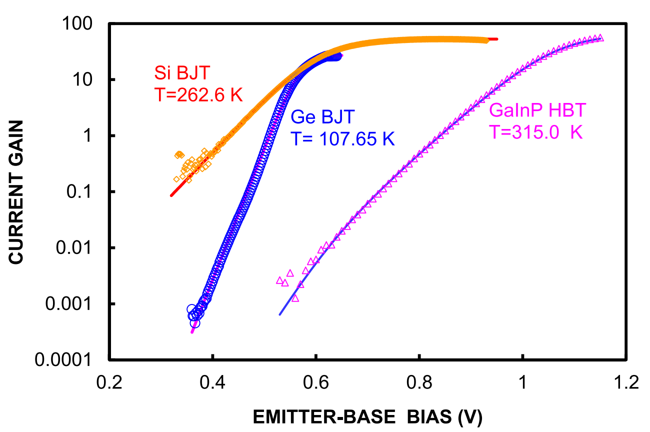

FIG. 2. Current gain as a function of emitter-base forward bias, V_{EB}, with $V_{BC}=0$, for the Germanium, Silicon *BJTs*, and n-GaInP/p-GaAs Heterojunction bipolar commercial transistors, using the data of Figure 1. Full lines are the fit using Eqs. (9) or (10).

terms, $I_{BE0}(T)$ (or $I_{EB0}(T)$) and $I_{BR0}(T)$, simultaneously fit the base current data, as shown in Fig. 1, by the continuous lines. We want to stress that the current gain fit spans between two and five decades, depending on the transistor temperature and the transistor semiconducting material. Following this simple and straightforward procedure, the transistor temperature and its charge transport parameters $I_{C0}(T)$, $I_{BE0}(T)$ *[or* $I_{EB0}(T)$*]*, and $I_{EBR0}(T)$ are obtained. Then, from their behavior as a function of temperature, the corresponding bandgap energies are extracted.

IV. BANDGAP ENERGY EXTRACTION AND DISCUSSION

The bandgap energies, E_{Bg} and E_{Eg}, and the recombination activation energy, E_A, in the emitter-base space charge region, are extracted from the slope of the semi-logarithmic plots of $I_{C0}(T)T^{-3}$, $I_{BE0}(T)T^{-3}$ [or $I_{EB0}(T)T^{-3}$], and $I_{EBR0}(T)T^{-3/2}$ versus the reverse of the temperature. These plots, for the three types of transistors studied, whose current data are shown in Fig. 1, are shown in Fig. 4, and the extracted values are given in Table I. Note the huge number of decades through which spans the obtained data in Fig. 4. From the $I_{C0}(T)T^{-3}$vs 1/T curves, according to Eq. (11), the bandgap energies for the base regions of the different transistors studied are extracted; these are $E_{Bg0}=0.76$ eV (Ge), 1.157 eV (Si), and 1.62 eV (GaAs base for the InGaP transistor). The E_{Bg0} values for Ge and Si agree reasonable well with those reported in the literature,[8,20,21] mainly considering the bandgap dependence with the doping level.[22] For the base material of the InGaP/GaAs transistor, the bandgap should be $E_{Bg0}=1.52$ eV;[8,23] however, the extracted value is 100 meV higher than expected. For the same device, the bandgap extracted from the base diffusion current, Eqs. (12) or (13), is 1.65 eV, i.e., 30 meV higher than the one found for the base. As this value is different from the one obtained before through $I_{C0}(T)$, this means that the base diffusion current is due to the injection of minority carriers into the emitter rather than into the base. However, the value of 1.65 eV is lower than the expected InGaP bandgap energy, 1.85 eV.[24] All of this points to the conclusion that the emitter-base

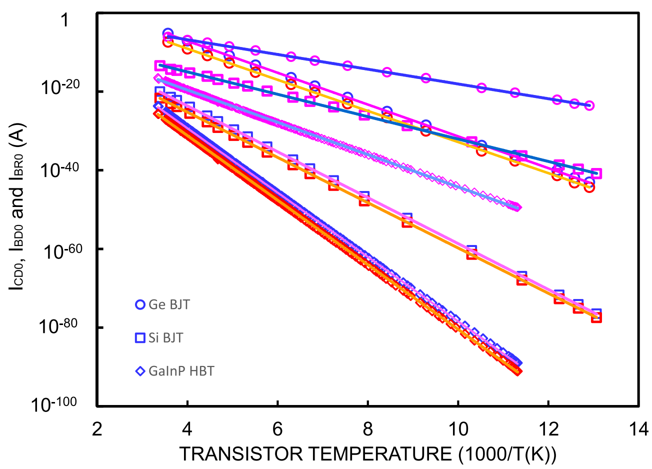

FIG. 4. Plot of $I_{C0}(T)T^{-3}$ (blue), $I_{BE0}(T)T^{-3}$ or $I_{EB0}(T)T^{-3}$ (red), and $I_{BR0}(T)T^{-3/2}$ (fuchsia) as a function of the reverse of the device temperature, the corresponding extracted bandgap energies or activation energy are given in Table I.

TABLE I. InGaP/GaAs, Silicon, and Germanium BJTs base and emitter bandgap energies. The base bandgap values are obtained from the collector diffusion saturation current, I_{C0} (second column). The emitter bandgap, if different from the value of the second column, is obtained from I_{BE0} and the main recombination level (fourth column) from I_{EBR0}.

	E_{Bg0} (eV)	$E_{E/Bg0}$ (eV)	E_A (eV)
Germanium	0.760	0.750	0.355
Silicon	1.157	1.142	0.564
GaInP/GaAs	1.620	1.650	0.815

"heterojunction" is a homo-junction located in a bandgap graded material, as we already reported in our previous work.[3] InGaP/GaAs HBTs from two different vendors were studied with the same results. The recombination activation energies extracted for the three types of transistors' emitter-base junctions are 0.355 eV (Ge), 0.564 eV (Si), and 0.815 eV (InGap-GaAs), all of them quite close to the middle of their respective bandgap. It is noteworthy that the recombination activation energy for the InGaP/GaAs HBT lays just half way between the values extracted for the emitter and the base at each edge of their space charge region.

V. CONCLUSION

In conclusion, we have shown that for a bipolar junction transistor it is possible to extract the bandgap energies of the emitter and base materials precisely at the place where the minority carrier injection takes place as well as the activation energy of the dominant recombination center in the space charge region of its emitter-base junction through simple electrical measurements. The method to extract the bandgap energies relies on Gummel plots taken at different transistor temperatures. For each set of data, the transistor temperature and the collector saturation current are simultaneously extracted by a new simple and reliable method free of any external thermometer. Then, using these data, the base saturation currents, for the different conduction mechanisms displayed by the transistor, are obtained by the fit of the current gain data as a function of the emitter-base forward bias. Finally, the bandgap energies are extracted from the behavior of the collector and base saturation currents as a function of the temperature. The present procedure has been applied to InGaP/GaAs, Silicon, and Germanium commercial BJTs, yielding bandgap energies that agree within 2% of the best accepted values.

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