Analysis of the electrical characteristics of GaInP/GaAs HBTs including the recombination effect

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Abstract: An analytical model is used to predict the effects of surface recombination current on the gain and transit time of GaInP/GaAs heterojunction bipolar transistors (HBTs). The present analysis shows that consideration of the recombination current gives current gain values that are comparable to those of the experimental results. The dependence of current gain on temperature, base doping and emitter area are also analyzed, and the variation in collector current with emitter–base voltage, temperature and doping is considered.

Key words: GaInP/GaAs HBT; current gain; transit time; recombination current; surface recombination; ideality factor

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1. Introduction

GaInP/GaAs heterojunction bipolar transistor (HBT) technology has attracted much attention due to its high gain, reliability[1] and uniformity[2, 3]. It has also proven its importance in high-voltage applications. Current gain and transit time are two important factors that determine the performance of a HBT. Due to the presence of dangling bonds at unpassivated base surfaces, surface recombination plays an important role in determining the gain of these HBTs. To avoid dislocations due to lattice mismatch at heterojunctions, the mole fraction of gallium in GaInP is chosen such that it is lattice matched with GaAs. In this study, an analytical derivation of the recombination current is performed to predict the effect of recombination on the gain and transit time. The effect of mobility degradation with doping concentration and temperature is also considered in the analysis, and the variation in gain with emitter area is shown. The dependence of the collector current on the emitter to base voltage, temperature and emitter doping is also analyzed analytically. The parameters used in this analysis are taken from the experimental results found in the literature.

2. Theory

For an HBT with donor (acceptor) distribution in the emitter (base) as $N_{\mathrm{D}}(y)$ $[N_{\mathrm{A}}(y)]$, the DC current gain (β) of the HBT can be given by[5]

$$\beta = \frac{\displaystyle\int_0^{W_{\mathrm{E}}} \frac{N_{\mathrm{D}}(y)}{D_{\mathrm{P}}(y)}\mathrm{d}y}{\displaystyle\int_0^{W_{\mathrm{B}}} \frac{N_{\mathrm{A}}(y)}{D_{\mathrm{n}}(y)}\mathrm{d}y} \exp\frac{\Delta E_{\mathrm{g}}}{kT}, \tag{1}$$

where ΔE_{g} is the band gap difference between the emitter and base, W_{E} (W_{B}) is the thickness of the emitter (base), D_{n} (D_{p}) is the diffusion constant of the electron (hole) in the base (emitter) and y is the position coordinate.

For uniform emitter and base doping, β reduces to[5]

$$\beta_0 = \frac{N_{\mathrm{DE}} W_{\mathrm{E}}}{N_{\mathrm{AB}} W_{\mathrm{B}}} \frac{D_{\mathrm{nB}}}{D_{\mathrm{pE}}} \exp\frac{\Delta E_{\mathrm{g}}}{kT}, \tag{2}$$

where N_{DE} (N_{AB}) is the emitter (base) doping concentration. However, this expression is only valid in the case of graded junction HBTs. In the case of abrupt junction, current conduction is affected slightly by the conduction band spike. So for abrupt junction HBTs, the analytical equation for current gain is expressed by only considering the valance band off-set (ΔE_{V}) as[4]

$$\beta_0 = \frac{N_{\mathrm{DE}} W_{\mathrm{E}}}{N_{\mathrm{AB}} W_{\mathrm{B}}} \frac{D_{\mathrm{nB}}}{D_{\mathrm{pE}}} \exp\frac{\Delta E_{\mathrm{V}}}{kT}. \tag{3}$$

The variation in base current (I_{B}) and collector current (I_{C}) with base–emitter voltage (V_{BE}) is given by[4]

$$I_{\mathrm{B}} = \frac{qA_{\mathrm{E}} D_{\mathrm{pE}}}{W_{\mathrm{E}}} \frac{n_{\mathrm{iE}}^2}{N_{\mathrm{DE}}} \exp\frac{qV_{\mathrm{BE}}}{kT}, \tag{4}$$

$$I_{\mathrm{C}} = \frac{qA_{\mathrm{E}} D_{\mathrm{nB}}}{W_{\mathrm{B}}} \frac{n_{\mathrm{iB}}^2}{N_{\mathrm{AB}}} \exp\frac{qV_{\mathrm{BE}}}{kT}, \tag{5}$$

where q is the electronic charge, A_{E} is the emitter area, n_{iE} (n_{iB}) is the intrinsic carrier concentration of the emitter (base), k is the Boltzmann constant and T is the temperature, in Kelvin.

If only thermionic field emission is considered, then the collector current is expressed by[4]

$$I_{\mathrm{C}} = I_0 \exp\frac{qV_{\mathrm{BE}}}{(1+K)E_0\coth(E_0/kT)}\left[1-\exp\left(-\frac{qV_{\mathrm{BE}}}{kT}\right)\right], \tag{6}$$

where $E_0 = \dfrac{qh}{4\pi}\left(\dfrac{N_{\mathrm{DE}}}{m_{\mathrm{e}}^* \varepsilon_{\mathrm{s}}}\right)^{0.5}$, $K = 1 + \dfrac{\varepsilon_{\mathrm{N}} N_{\mathrm{DE}}}{\varepsilon_{\mathrm{P}} N_{\mathrm{AB}}}$, m_{e}^* is the effective mass of the electron in the emitter, and ε_{N} (ε_{P}) is the

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permittivity of the n (p) type material. For an emitter–base voltage greater than zero volts, the collector current ideality factor (η) can be expressed as[4]

$$\eta = \frac{(1+K)E_0}{kT} \coth \frac{E_0}{kT}. \tag{7}$$

There are two other important currents that need to be considered when calculating gain, and they are volume recombination current (I_{VR}) and surface recombination current (I_{SR}). Volume recombination current can be found out by dividing the total minority carrier charge ($n_{\mathrm{p}}(0)$) at the emitter–base junction by the minority carrier lifetime (τ_{n}) in the base. Considering the linear distribution of the minority carrier in the base, volume recombination current can be expressed by[19]

$$I_{\mathrm{VR}} = \frac{q n_{\mathrm{p}}(0) W_{\mathrm{B}} A_{\mathrm{E}}}{2\tau_{\mathrm{n}}}, \tag{8}$$

where τ_{n} is the minority carrier lifetime in the base. Surface recombination current can be expressed by[19]

$$I_{\mathrm{SR}} = \frac{S n_{\mathrm{p}}(0) A_{\mathrm{S}} q}{2}, \tag{9}$$

where S is the surface recombination velocity and A_{S} is the surface recombination area.

Transit time is another important characterizing parameter of HBTs used for high-speed switching circuit applications. Very high base doping in HBT decreases junction capacitance, which diminishes the transit time and enhances operating frequency. Forward transit time (τ_{F}) consists of base transit time (τ_{B}) and emitter transit time (τ_{E}). For uniform base and emitter doping, they are expressed as[6]

$$\tau_{\mathrm{B}} = \frac{W_{\mathrm{B}}^2}{2D_{\mathrm{n}}}, \tag{10}$$

$$\tau_{\mathrm{E}} = \frac{W_{\mathrm{E}}^2}{2D_{\mathrm{P}}\beta}, \tag{11}$$

$$\tau_{\mathrm{F}} = \tau_{\mathrm{E}} + \tau_{\mathrm{B}}. \tag{12}$$

The reciprocal of τ_{F} gives the forward transit frequency of the transistor, which is expected to be very high. So forward transit frequency is expressed as

$$f_{\mathrm{F.Transit}} = \frac{1}{2\pi\tau_{\mathrm{F}}}. \tag{13}$$

3. Analysis

Modern advances in deposition techniques like MBE and MOCVD make it possible to grow high-quality heterostructures. However, MBE is preferred for the fabrication of high-speed devices like HBT and HEMT, as very precise doping can be done under ultra high vacuum. While considering heterostructures, both of the heterojunction materials should have almost the same lattice constants and thermal coefficients, as without this there is a dislocation at the interface and the performance of the device deteriorates from its desired performance characteristics. This limitation can be overcome by growing thin layers (less than critical thickness), which create strained layer heterostructures with attractive properties. $\mathrm{Ga}_x\mathrm{In}_{1-x}\mathrm{P}$ is good lattice matched with GaAs at $x = 0.51$[4], and this mole fraction is considered in the present analysis.

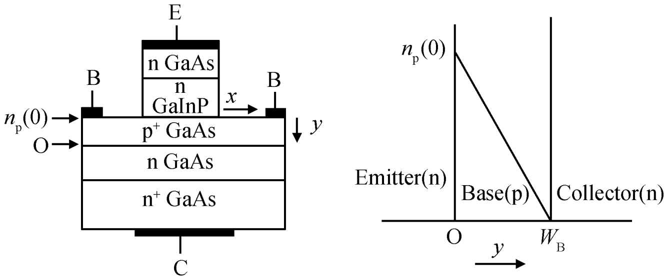

Fig. 1. The structure of the GaInP/GaAs HBT, and the minority carrier profile in the base region.

To achieve higher gain in BJT, emitter doping the BJT level needs to be higher compared to the base. However, lower doping in the base results in higher base resistance, which reduces the operating frequency. So for high-frequency operation, base doping should be higher and emitter doping should be lower, resulting in lower base resistance and lower base–emitter junction capacitance. In this analysis we considered the following design parameters for the GaInP/GaAs HBT.

The design parameters of the HBT used for the analysis are as follows: emitter area 3 × 1.4 μm^2, emitter thickness 700 Å and doping 3 × 10^{17} cm^{-3}, base thickness 500 Å and doping 3 × 10^{19} cm^{-3}.

As the base is very heavily doped, the mobility of the electron in the GaAs base decreases due to impurity scattering. For heavily doped p-GaAs, electron mobility variation has been experimentally determined[7]. This variation in mobility has been taken for the current analysis. Though electrons have a high mobility in GaAs (8500 cm^2/(V·s)), in the heavily doped p-base region, electron mobility (μ_{n}) reduces to 1820 cm^2/(V·s)[13], and from Einstein's relationship[17] the electron diffusion constant can be found as 47.32.

In an n–p–n HBT, current gain (β) increases due to a reduction in the back-injected hole current into the emitter, which results in less I_{B}. This is done by creating a low-energy barrier for electrons compared to holes at the emitter–base heterojunction. For $\mathrm{Ga}_{0.51}\mathrm{In}_{0.49}\mathrm{P}$/GaAs HBTs, the hole barrier energy (ΔE_{V}) is 0.40 eV and the electron barrier energy (ΔE_{C}) is 0.03 eV[4]. From Eq. (3), the current gain for this abrupt junction HBT will come out to be 9.5 × 10^5, though the experimental result shows a much lower gain[14]. The most probable reason for this is that in Eq. (3) the contribution of the recombination current has not been considered[14].

The minority carrier distribution in the base has been taken as linear because of very high doping in the base region. Figure 1 shows the distribution of the minority carrier in the base along the x direction. From Eq. (8), it is clear that the recombination current increases with increasing emitter area. A small value of the minority carrier lifetime at the base (3.8 × 10^{-8} s)[13] makes the volume recombination current significantly higher compared to the thermionic base current. Some other studies have reported an even smaller electron lifetime in p-GaAs[16].

Another type of recombination current is the surface recombination current. In vertical HBTs, the unpassivated base

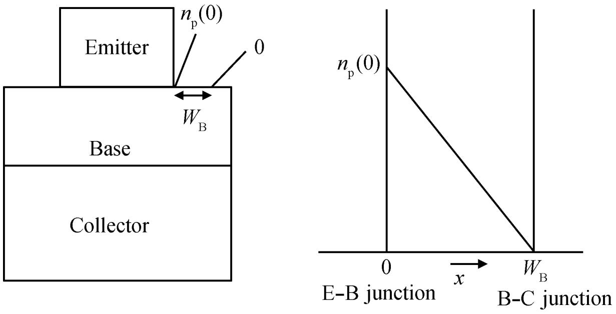

Fig. 2. The surface recombination and minority carrier profile along the base surface.

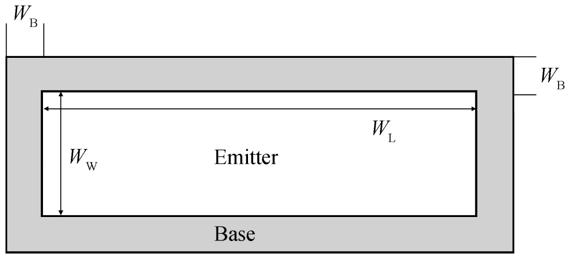

Fig. 3. The recombination area.

area is open to the ambient. At open base surface area, there are lots of unsaturated bonds (dangling bonds) of surface atoms. These will act as a recombination centre for the base current. Surface recombination current is an important factor in the GaAs base due to higher surface recombination velocity in GaAs.

Recombination at the surface causes a minority carrier distribution profile along the open surface (x-direction, Fig. 2). Analysis shows that minority carrier concentration reduces to zero at distance W_B along the x-direction. Surface recombination current is proportional to the total minority carrier charge under the minority carrier distribution profile. For materials like Si, surface recombination current is generally neglected because of low surface recombination velocity (S). However, for GaAs the value of S is in the range of 10^7 cm/s[9], and surface recombination current (I_{SR}) in the p-GaAs base gets significant magnitude (9). As mentioned earlier, minority carrier distribution exists in a region of width W_B. The surface recombination area (Fig. 3) can be expressed by

$$A_S = 2(W_L + W_W)W_B + 4W_B^2, \tag{14}$$

where W_L and W_W are the emitter length and width, respectively.

Considering two types of recombination currents, i.e. surface and volume recombination, the gain of the HBT at 300 K can be written as

$$\beta_2 = \frac{I_C}{I_{VR} + I_{SR}}, \tag{15}$$

$$\beta_2 = \frac{I_C}{I_{VR}\left(1 + \dfrac{I_{SR}}{I_{VR}}\right)}, \tag{16}$$

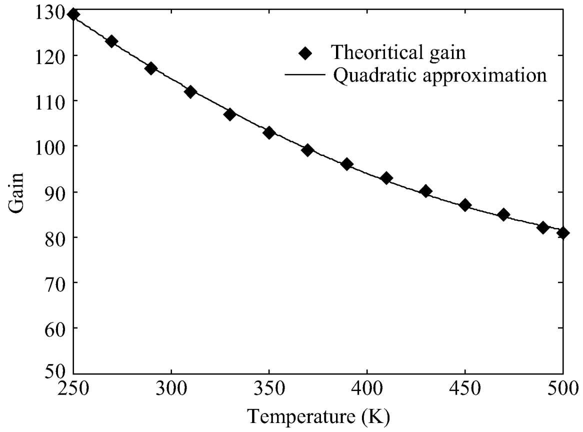

Fig. 4. Variation in current gain with temperature of $Ga_{0.51}In_{0.49}P$/GaAs HBTs considering recombination currents.

$$\beta_2 = \frac{\beta_0}{1 + \dfrac{S\tau_n}{W_B}\dfrac{A_S}{A_E}}. \tag{17}$$

The current gain β_2 with design parameters, described earlier, comes out to be 114 at room temperature. The total current gain can be given by[10]

$$\frac{1}{\beta} = \frac{1}{\beta_1} + \frac{1}{\beta_2}, \tag{18}$$

where β_1 is the current gain from Eq. (3). The value of β_1 is much higher compared to β_2. So from Eq. (18) it is clear that the effect of β_2 will be prominent and current gain is determined primarily by β_2. So considering recombination currents, the current gain of abrupt junction HBTs can be expressed as

$$\beta = \frac{\dfrac{N_{DE}W_E}{N_{AB}W_B}\dfrac{D_{nB}}{D_{pE}}\exp\dfrac{\Delta E_V}{kT}}{1 + \dfrac{S\tau_n}{W_B}\dfrac{A_S}{A_E}}. \tag{19}$$

So, for abrupt $Ga_{0.51}In_{0.49}P$/GaAs HBTs, current gain at 300 K comes out to be 114, which shows a close proximity with the experimental current gain value of 105[8]. Again, the current gain is temperature dependent. With the change in temperature, the mobility changes significantly, so the gain changes. Considering the degradation of electron mobility in GaAs with temperature as $T^{-2/3}$[11], the variation in the electron mobility in the base can be expressed as

$$\mu_n = 1820 \times \left(\frac{300}{T}\right)^{2/3}. \tag{20}$$

Figure 4 shows the dependence of current gain on temperature (19). The current gain of GaInP/GaAs HBT decreases from 114 at 300 K to 82 at 500 K. The variation in gain with temperature can be approximated by

$$\beta(T) = 42 \times 10^{-5}T^2 - 0.504T + 227.98. \tag{21}$$

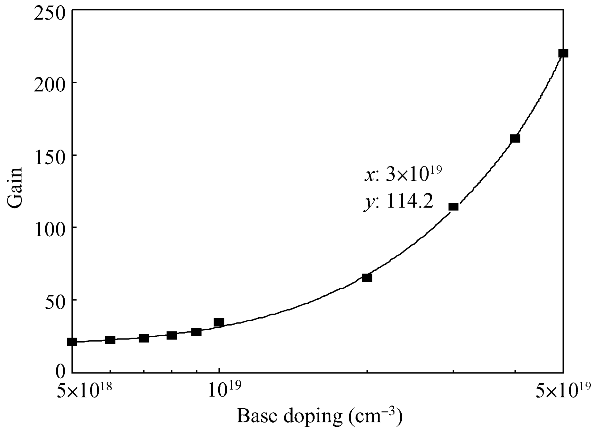

Fig. 5. Variation in current gain with base doping in $Ga_{0.51}In_{0.49}P$/GaAs HBTs at 300 K

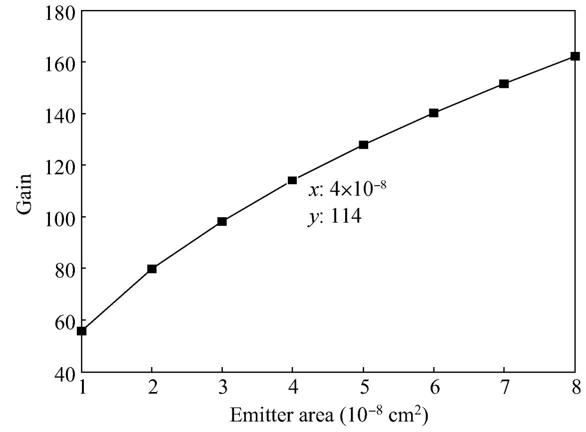

Fig. 6. Variation in current gain with emitter area considering surface recombination for the square emitter area.

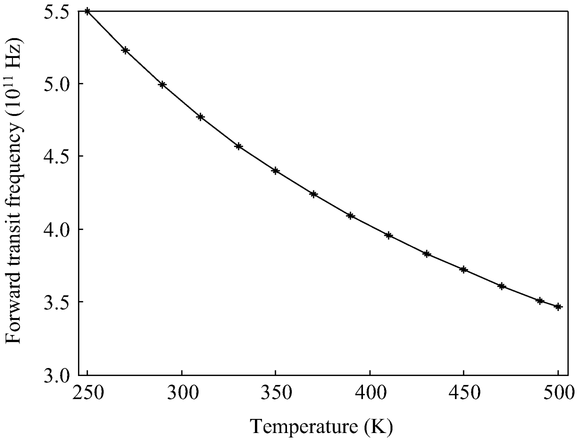

Fig. 7. Variation in forward transit frequency of $Ga_{0.51}In_{0.49}P$/GaAs HBTs with temperature.

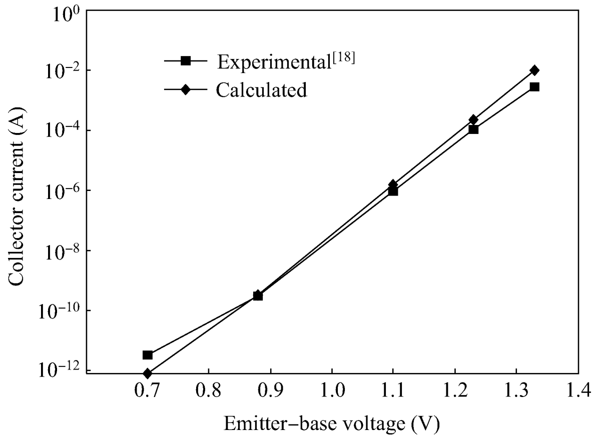

Fig. 8. Plot of collector current versus emitter–base voltage (linear region) for $Ga_{0.5}In_{0.5}P$/GaAs HBTs with an emitter area of 6×6 μm^2, and uniform base and emitter doping for $N_{AB} = 3 \times 10^{19}$ cm^{-3}, $N_{DE} = 3 \times 10^{17}$ cm^{-3}, $W_E = 700$ Å and $W_B = 500$ Å, keeping the collector to base voltage at zero.

This approximation, which closely follows the theoretical results, is also shown in Fig. 4. Also, with the change in doping concentration, the gain of a HBT changes. With the doping change in the base region, the electron mobility and lifetime changes, which has a direct influence on the gain of an HBT (19). The variation in mobility and lifetime of the minority carrier (electron) in the p-GaAs base with doping is taken from the experimental results[13]. Figure 5 shows the variation in current gain with base doping. The HBT gain increases significantly with increasing base doping concentration, and the reasons behind this increment (19) are the increase in electron diffusion constant[7] and the decrease in electron lifetime[13] in the p-GaAs base in this doping range. Consideration of the recombination current reduces the current gain significantly in vertical HBTs. Again, surface recombination current depends on the emitter area (9, 14). For a very small emitter area, A_S would be significant compared to A_E, and as a result gain decreases (Fig. 6). For a comparatively higher emitter area, gain increases, however, a small emitter area is preferable for higher packing density. Recombination at the surface can be reduced by covering the open surface with a sulphur layer using $Na_2S{\cdot}9H_2O$, as reported[15]. Another way to decrease surface recombination current is by passivating the base with a sulphur monolayer using $(NH_4)_2S_x$ with 8% excess sulphur solution[15].

With the increase in temperature, both the mobility and gain of the HBT decreases, and as a result forward transit frequency decreases (10, 11, 12 and 13). Figure 7 shows the variation in forward transit frequency with temperature, which varies from 4.8×10^{11} Hz at 300 K to 3.5×10^{11} Hz at 500 K. This forward transit frequency is higher compared to the practical operating frequency (f_T) of GaInP/GaAs HBTs, as f_T is also dependent on the junction transit times, sub-collector transit times and parasitic components associated with the device. Forward transit frequency is one of the basic properties of an HBT, and its variation with temperature is analyzed here. Variation in forward transit time with temperature in the case of GaInP/GaAs HBTs is less compared to AlGaAs/GaAs HBTs[12]. Collector current variation with base–emitter voltage (5) is plotted in Fig. 8, with an emitter area of 6×6 μm^2. Figure 8 shows that the theoretical collector current value almost follows the experimental current value in the linear region[18]. For lower and higher base–emitter voltages, the collector current ideality factor (η) increases significantly, and in these regions the theoretical value of the collector current will

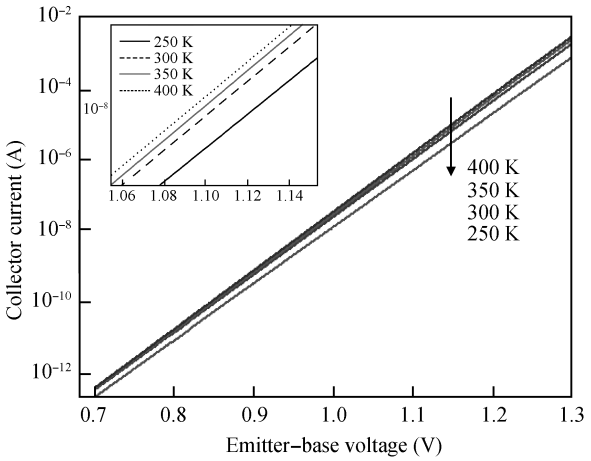

Fig. 9. The variation in collector current for different temperatures, keeping the base and emitter doping constant. The inset shows the enlarged variation in I_c for an emitter–base voltage of 1.06 to 1.14 V. The emitter area 6×6 μm^2.

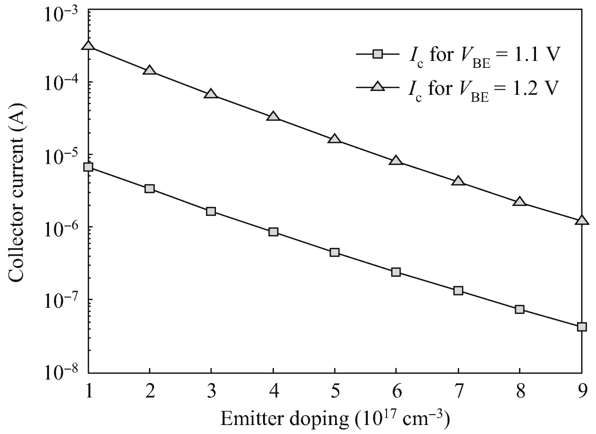

Fig. 10. Variation in collector current with emitter doping for different emitter to base biases. Here, base doping is kept constant. The emitter area is 6×6 μm^2.

not follow the experimental one. Again, the collector current ideality factor is sensitive to temperature variation (7), and η decreases with an increase in temperature. At room temperature, the collector current ideality factor for GaInP/GaAs HBTs is found as 1.054. η is also dependent on doping concentration, as E_0 and K are doping concentration dependent. Temperature is a crucial factor in describing device characteristics. Device characteristics change significantly with a variation in temperature. Figure 9 shows the variation in collector current (5) with temperature for different emitter–base voltages. Collector current increases with an increase in temperature, and a variation in collector current with emitter doping is also considered in the analysis. With an increase in emitter doping, from Eq. (5) it is clear that collector current decreases, which is shown in Fig. 10 for two different V_{BE} values.

This model gives the variation in current gain of an HBT considering recombination currents, temperature effects, the size of the emitter area, doping effects and the material properties of the base region. So this is a compact model used to determine the gain of an HBT considering the effect of all possible properties. Analysis proves that this model gives a GaInP/GaAs HBT gain value that is closely matched with the experimental results (Table 1). This analytical model also describes the variation in collector current with forward bias voltage, temperature and emitter doping concentration.

Table 1. Comparison of the current gain of GaInP/GaAs HBTs by experimental and analytical methods.

GaInP/GaAs HBT (n–p–n) parameters	Experimental gain (β)	Analytical gain (β)
$A_E = 3 \times 1.4$ μm^2 $W_E = 700$ Å $N_{DE} = 3 \times 10^{17}$ cm^{-3} $W_B = 500$ Å $N_{AB} = 3 \times 10^{19}$ cm^{-3} [see Ref. [8]]	105	114
$A_E = 30 \times 2$ μm^2 $W_E = 3000$ Å $N_{DE} = 3 \times 10^{17}$ cm^{-3} $W_B = 1200$ Å $N_{AB} = 1.2 \times 10^{20}$ cm^{-3} [see Ref. [20]]	63	59.8

4. Conclusions

Recombination current plays an important role in determining the gain of an HBT. Very high values of surface recombination velocity in GaInP/GaAs HBTs leads to a high surface recombination current. Surface recombination current increases with decreasing emitter area, and the forward transit frequency for this HBT decreases significantly with increasing temperature.

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