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Calculation of the base current components and determination of their relative importance in AlGaAs/GaAs and InAlAs/InGaAs heterojunction bipolar transistors

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The base current density J_B is an important parameter in determining the common-emitter current gain β of heterojunction bipolar transistors (HBTs). To develop an analytical β model with which a circuit designer can quickly estimate the current gain in a HBT, it is also important to identify the dominant component of J_B so that minimum computations are required. Based on heterojunction device physics, the three components of J_B have been calculated, namely, the recombination current density in the base J_{RB} , the recombination current density in the space-charge region J_{SCR} , and the injection current density from the base to the emitter J_{RE} , and have determined their relative importance to J_B for abrupt AlGaAs/GaAs and InAlAs/InGaAs HBTs under normal bias conditions. It is found that relative importance of the three current densities depends strongly on the bias condition, strongly on the density of states N_{IH} at the emitter-base heterointerface, but weakly on the density of trapping states N_{tB} in the bulk of the emitter-base space-charge region. Also, J_B is relatively insensitive to device makeup such as doping concentration and layer thickness. Depending on N_{IH} and on the bias condition, either J_{SCR} or J_{RE} is the dominant component for AlGaAs/GaAs HBTs and either J_{SCR} or J_{RB} is the dominant component for InAlAs/InGaAs HBTs. Effects of base and heterojunction grading on the present findings are also addressed.

I. INTRODUCTION

Heterojunction bipolar transistors (HBTs) can possess large common-emitter dc current gain β^{1-3} when they operate in the forward-active mode. Many numerical studies on β of HBTs exist in the literature,^{4,5} in which all components of the base current, e.g., the recombination current in the base, recombination current in the space-charge region, and hole injection from the base into the emitter, are included via the charge transport equation or detailed particle simulations such as the Monte Carlo simulation. In regard to modeling β analytically, however, it is desirable to identify the dominant component of the base current so that a simple model providing physical intuition can be developed. Further, such a model allows HBT device designers to optimize β performance by varying the HBT device makeup prior to the actual device fabrication. Nonetheless, uncertainties often arise to as which current component contributes most of the base current and thus contributes most to the degradation of β in HBTs; a recent work⁶ assumes that the base current stems mainly from electron-hole recombination current in the emitter-base heterojunction and hole injection from the p -type base into the n -type emitter while another⁷ believes that the decrease in the current gain is due mostly to recombination current in the quasineutral base region.

In this paper, we calculate all components of the base current density J_B in InAlAs/InGaAs and AlGaAs/GaAs HBTs having abrupt junctions for a wide range of bias conditions and various device parameters. The resulting information should be useful to HBT designers to determine the relative importance of J_B components and to

quickly estimate the base current for predicting β in HBTs. The effects of the junction of grading and base grading, which are two popular approaches to enhance the HBT performance, on the base current components will also be discussed.

II. THEORY

Consider an $n/p^+/n$ AlGaAs/GaAs or InAlAs/InGaAs HBT (Fig. 1) under normal bias conditions (emitter-base applied voltage $V_{BE} > 0$ and base-collector applied voltage $V_{BC} < 0$). In Fig. 1, X_1 and X_2 are the edges of the emitter-base space-charge region and X_3 and X_4 are the edges of the base-collector space-charge region. The base current density J_B consists of the following components: (i) recombination current density J_{RB} in the quasineutral base; (ii) recombination current density J_{SCR} in the emitter-base space-charge region, which includes both the recombination current density in the bulk of the space-charge region (J_{SCRB}) and the recombination current density at the heterointerface (J_{SCR1}); and (iii) hole current density J_{RE} injected from the base into the emitter. Surface recombination current density J_S in the extrinsic base region is neglected in our treatment. According to a two-dimensional analysis by Hiraoka and Yashida,⁸ J_S is suppressed and is insignificant in a HBT having a very thin base. Thus the present one-dimensional treatment suffices for some HBTs with a base width less than or equal to about 1000 Å (Ref. 8) or for HBTs with an emitter edge-thinning structure proposed by Lin and Lee.⁹ For other HBTs, however, J_S is important and needs to be taken into account.

FIG. 1. Schematic illustration of an $n/p^+/n$ heterojunction bipolar transistor structure.

A. J_{RR}

To model J_{RB} , we employ a two-valley recombination model in which electrons in the base are assumed to reside predominately in L and Γ valleys, as evidenced from the Monte Carlo simulation by Rockett¹⁰ and from a self-consistent particle simulation by Katoh and Kurata.¹¹ Figure 2 shows schematically the electron currents in the base based on this model. In the figure, $J_n(X_2)$ is the electron current density injected from the emitter into the base and⁷

$$\gamma = 1/(1 + n_{\Gamma}/n_I), \quad (1)$$

where n_L is the electron density in the L valley and n_Γ is the electron density in the Γ valley. Also⁷

$$n_{\Gamma}/n_L = 1/[4(m_L/m_{\Gamma})^{1.5} \exp(-\Delta E_{\Gamma-L}/kT)], \quad (2)$$

where m_L and m_Γ are the effective masses for L - and Γ -valley electrons, $\Delta E_{\Gamma-L}$ is the energy difference between Γ and L valleys, k is Boltzmann constant, and T is the absolute temperature. Also α_L and α_Γ are the base transport factors in L valley and Γ valley, respectively:

$$\alpha_L = 1/\cosh[W_B/(D_L\tau_L)^{0.5}]$$

and

$$\alpha_{\Gamma} = 1/\cosh[W_B/(D_{\Gamma}\tau_{\Gamma})^{0.5}], \quad (3)$$

where W_B is the quasineutral base width, D_L and D_Γ are the average electron diffusion coefficients in L and Γ valleys of the base, and τ_L and τ_Γ are the electron lifetimes in L and Γ valleys of the base. Note that $W_B = X_3 - X_2$

FIG. 2. Qualitative illustration of the recombination current in the base of the HBT based on two-the-valley recombination model.

$\approx X_{jc} - X_{je}$ (Fig. 1) because the base region is doped heavier than the emitter and collector regions in HBTs.

Because of the presence of the conduction-band discontinuity (or spike) at the heterointerface ($x = X_{JE}$) and the velocity overshoot phenomenon in the thin base region due to high electric field in the base-collector junction, the conventional drift-diffusion model is no longer applicable in describing the free-carrier injection from the emitter to the base in HBTs;^{3,4} instead, thermionic and tunneling become the dominant charge-transport mechanisms in the emitter-base space-charge region.^{3,4} Using the thermionic-tunneling model suggested in,³ we have

$$J_n(X_2) = (qv_n/4) [n(X_{jE}^-) - n(X_{jE}^+) \exp(-\Delta V_c/V_T)] \xi, \quad (4)$$

where V_T is the thermal voltage, ξ is the electron tunneling coefficient defined in Ref. 3, and ΔV_c is the conduction-band discontinuity at X_{JE} (Refs. 12, 13):

$$\Delta V_c = |\chi_E - \chi_R|, \quad (5)$$

where χ_E and χ_B are the electron affinity in the emitter and in the base. Also,³

$$v_n = [8kT/(\pi m_n)]^{0.5}, \quad (6)$$

$$n(X_{jE}^-) = N_E \exp(-V_{B1}/V_T), \quad (7)$$

$$n(X_{iE}^+) = N_E(n_{iB}/n_{iE})\exp[-(V_{B1} + \Delta V_i)/V_T]. \quad (8)$$

In the above equations, $m_n \approx 0.5(m_L + m_T)$ is the average effective electron mass, N_E is the emitter doping concentration, V_{B1} is the base side of the junction barrier height, n_{iE} and n_{iB} are the emitter and base intrinsic carrier concentrations, and ΔV_i is the intrinsic Fermi potential discontinuity at X_{jE} .^{12,13}

$$V_{B1} = (V_{bi} - V_{BE}) \{1 - [N_{E\epsilon E} / (N_{E\epsilon E} + N_{B\epsilon B})]\}, \quad (9)$$

$$\Delta V_i = -|\chi_E - \chi_B| + (0.5/q)|E_{\text{GE}} - E_{\text{GB}}| + 0.5V_T \ln(N_{\text{CE}}N_{\text{VB}}/N_{\text{CB}}N_{\text{VE}}). \quad (10)$$

N_B is the base doping concentration, ϵ_E and ϵ_B are the emitter and base dielectric permittivities, E_{GE} and E_{GB} are the energy band gaps in the emitter and in the base, N_{CE} and N_{CB} are the effective density states in the conduction band of the emitter and the base, N_{VE} and N_{VB} are the effective density states in the valence band of the emitter and the base, and V_{bi} is the junction builtin potential.^{12,13}

$$\begin{aligned} V_{\text{bi}} = & |\chi_E - \chi_B| - (0.5/q)|E_{\text{GE}} - E_{\text{GB}}| \\ & + V_T \ln(N_E N_B / n_{iE} n_{iB}) \\ & + 0.5 V_T \ln(N_{\text{CB}} N_{\text{VF}} / N_{\text{CF}} N_{\text{VB}}). \end{aligned} \quad (11)$$

Finally,

$$J_{RB} = J_n(X_2) [\gamma(1 - \alpha_L) + (1 - \gamma)(1 - \alpha_R)]. \quad (12)$$

B. J_{RE}

Since the emitter of a HBT is usually very thin and lightly doped, the recombination current in the bulk of the

TABLE I. Device and material parameters used for AlGaAs/GaAs HBTs (Refs. 3, 20, 22).

σ (cm ²)	N_{IB} (cm ⁻³)	N_{IL} (cm ⁻²)	$\Delta E_{\Gamma-L}$ (eV)	D_L (cm ² /s)	D_{Γ} (cm ² /s)	τ_L (ps)	τ_{Γ} (ps)	m_L/m_e	m_{Γ}/m_e	E_{GE} (eV)	E_{GB} (eV)	χ_E (eV)	χ_B (eV)
10^{-14}	10^{14}	10^{12}	0.33	19	190	250	120	0.56	0.063	1.79	1.42	3.74	4.07

quasineutral emitter can be assumed negligible. This, together with the diffusion-current-only assumption, leads to

$$J_{RE} \approx q D_p p(X_1)/X_1 \quad (13)$$

where D_p is the average hole diffusion coefficient in the emitter, X_1 can be calculated from the conventional depletion model,¹⁴ and, if the quasi-Fermi potentials are assumed flat in the space-charge region,

$$p(X_1) = N_B \exp(n_{iE}/n_{iB}) \exp[-(V_{bi} - V_{BE} + \Delta V_i)/V_T]. \quad (14)$$

C. J_{SCR}

In homojunction bipolar transistors, J_{SCR} involves only the recombination current density J_{SCRB} in the bulk of the space-charge region. For HBTs, however, the recombination current density J_{SCRI} at the heterojunction interface states is not negligible due to sizeable interface states resulting from lattice mismatch between the two different materials.¹⁵ Thus,

$$J_{SCR} = J_{SCRI} + J_{SCRB}. \quad (15)$$

1. J_{SCRB}

The free-carrier recombination mechanism in the bulk of the space-charge region can be described by the Shockley-Read-Hall (SRH) model.⁶ The widely used and simplest SRH model is based on the assumption that there is only one type of trap that dominates the recombination process and that the traps are uniformly distributed in the middle of the energy band gap.¹⁷ From this, together with the assumption that the space-charge region resides entirely in the emitter side of the junction, we obtain the bulk recombination rate U_B :

$$U_B = \sigma v_n N_{IB} n_{iE}^2 [\exp(V_{BE}/V_T - 1)] / (n + p + 2n_{iE}), \quad (16)$$

where σ is the capture cross section, N_{IB} is the trapping density in the bulk of the space-charge region. Therefore

$$J_{SCRB} = q \int_{X_1}^{X_2} U_B dx \approx q \int_{X_1}^{X_{jE}} U_B dx. \quad (17)$$

U_B becomes U_{Bmax} when $n=p$ (Ref. 17):

$$U_{Bmax} = 0.5 \sigma v_n N_{IB} n_{iE} \exp(V_{BE}/2V_T). \quad (18)$$

The conventional approach is then to assume $n=p$ occurs in the entire space-charge region. This and Eq. (17) yield $J_{SCRB} \approx q U_{Bmax} (X_{jE} - X_1)$. This model is incorrect because, as pointed out recently by Shur,¹⁸ $n=p$ does not occur in the entire space-charge region and thus $X_{jE} - X_1$ in the model should be replaced by a width within which U_{Bmax} occurs. Using Taylor series to expand the function in Eq. (17), Shur more accurately obtains¹⁸

$$J_{SCRB} = q(\pi/2)^{0.5} V_T n_{iE} \sigma v_n N_{IB} \{q N_E [2V_T \ln(N_E/n_{iE}) - V_{BE}/\epsilon_B]\}^{-0.5} \exp(V_{BE}/2V_T). \quad (19)$$

2. J_{SCRI}

Since interface states are arranged along $x = X_{jE}$ plane,¹⁵ J_{SCRI} can be expressed as¹⁹

$$J_{SCRI} = q \int_{X_1}^{X_2} U_I \delta(x - X_{jE}) dx = q U_I, \quad (20)$$

where U_I is the SRH recombination rate at the interface states and δ is the delta function. Putting the condition $n \approx p$ at $x = X_{jE}$ into the SRH model yields¹⁹

$$J_{SCRI} \approx q U_{Imax} = 0.5 q \sigma v_n N_{IL} n_{iE} \exp(V_{BE}/2V_T), \quad (21)$$

where N_{IL} (#/cm²) is the trapping density at the heterojunction interface.

III. ILLUSTRATION AND DISCUSSION

We consider both abrupt Al_{0.3}Ga_{0.7}As/GaAs and In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As HBTs, which are prominent devices for microwave and electro-optics applications. Material parameters such as energy band gap, electron effective mass, and electron affinity for Al_{0.3}Ga_{0.7}As/GaAs and In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As HBTs can be found in Refs. 20 and 21 and are given in Tables I and II, respectively.

Components of the base current density versus V_{BE} for an Al_{0.3}Ga_{0.7}As/GaAs HBT and for an In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As HBT are plotted in Figs. 3 and 4, respectively. Practical device parameters used for calculations for AlGaAs/GaAs and InAlAs/InGaAs HBTs^{3,7,22} also appear in Tables I and II, respectively. Values of N_{IB} and N_{IL} chosen are usual for MBE-grown abrupt AlGaAs/GaAs heterojunctions.^{3,22} The HBTs have a typ-

TABLE II. Device and material parameters used for InAlAs/InGaAs HBTs (Refs. 7 and 21).

σ (cm ²)	N_{IB} (cm ⁻³)	N_{IL} (cm ⁻²)	$\Delta E_{\Gamma-L}$ (eV)	D_L (cm ² /s)	D_{Γ} (cm ² /s)	τ_L (ps)	τ_{Γ} (ps)	m_L/m_e	m_{Γ}/m_e	E_{GE} (eV)	E_{GB} (eV)	χ_E (eV)	χ_B (eV)
10^{-14}	10^{14}	10^{12}	0.5	4.0	40	250	120	0.2	0.045	1.47	0.77	4.38	4.88

FIG. 3. Comparison of the components of the base current density vs the emitter-base applied voltage for an AlGaAs/GaAs HBT.

ical device makeup of $N_E = 10^{17} \text{ cm}^{-3}$, $N_B = 10^{19} \text{ cm}^{-3}$, $X_{JE} = 1000 \text{ Å}$, and $X_{JC} = 2000 \text{ Å}$. As shown in Figs. 3 and 4, all components increase with increasing V_{BE} , and J_{SCR} is the most important base-current component in both HBTs for small medium V_{BE} . For larger V_{BE} , J_{RE} and J_{RB} become the dominant component in AlGaAs/GaAs and InAlAs/InGaAs HBTs, respectively. In Figs. 5–14, the parameters in Tables I and II and the above device makeup are still used except that one of the parameters is varied. Also, V_{BE} is fixed at 1.4 V, which is the voltage at which most HBT circuits are designed to operate. Figures 5 and 6 illustrate the dependencies of J_B components on W_B . It is shown that J_{RB} increases slightly as W_B increases, but this variation does not alter notably the trends shown in Figs. 3 and 4 regarding the relative importance of J_B components. Figures 7 and 8 show the dependencies of J_{RB} and J_{RE} with respect to N_B . Variation

FIG. 4. Comparison of the components of the base current density vs the emitter-base applied voltage for an InAlAs/InGaAs HBT.

FIG. 5. Comparison of the components of the base current density vs the base width for an AlGaAs/GaAs HBT.

of τ alters moderately J_{RB} (Figs. 9 and 10) and changing N_{IB} has no effect on J_{SCR} at this particular voltage (Figs. 11 and 12). However, J_{SCR} is very sensitive to N_{II} in both devices as shown in Figs. 13 and 14.

To assess the validity of the present analysis, data available in the literature^{23,24} are presented here to provide a comparison with the theoretical predications, as shown in Figs. 15 and 16 for an AlGaAs/GaAs HBT and an InAlAs/InGaAs HBT, respectively. The present model predicts fairly accurately the total base current density of the AlGaAs/GaAs HBT, but discrepancies are found between the present model and measurement for the InAlAs/InGaAs HBT. When the InAlAs/InGaAs HBT is subject to large forward voltages, the model overestimates the base current density by at most a factor of about 10. This may be attributed to high-level injection and the non-negligible voltage drops in the quasineutral regions of the HBT at

FIG. 6. Comparison of the components of the base current density vs the base width for an InAlAs/InGaAs HBT.

FIG. 7. Comparison of the components of the base current density vs the base doping density for an AlGaAs/GaAs HBT.

FIG. 9. Comparison of the components of the base current density vs the base minority-carrier lifetime for an AlGaAs/GaAs HBT.

such a bias condition, neither of which was accounted for in the model. On the other hand, the model underestimates the total base current density of the InAlAs/InGaAs HBT by at most a factor of about 4 as the voltage becomes small. This is perhaps due to the fact that the surface recombination current is neglected by our analysis, which, as discussed in Sec. II, is adequate for a HBT with a base width less than or equal to about 1000 Å like the device in Fig. 15 but is questionable for the HBT in Fig. 16 which has a base width of 2000 Å. The overall disagreement shown in Fig. 16 may also result from the deviation of the material and process parameters used in our calculations (listed in Table II). The present model does predict a trend that agrees reasonably well with experimental results for both devices. Thus the model permits a degree of insight into the influence of various device parameters on HBT base current performance and allows an estimate into the relative im-

portance of the base current components in AlGaAs/GaAs and InAlAs/InGaAs HBTs.

IV. CONCLUSION

The following conclusions can be made.

- (i) Depending on N_B and on the bias condition, either J_{SCR} or J_{RE} is the dominant J_B component for AlGaAs/GaAs HBTs and either J_{SCR} or J_{RB} is the dominant J_B component for InAlAs/InGaAs HBTs.
- (ii) For typical AlGaAs/GaAs and InAlAs/InGaAs HBTs, J_{SCR} dominates J_B when the emitter-base junction is not highly forward biased. As the voltage increases, however, J_{RE} and J_{RB} become important for AlGaAs/GaAs and InAlAs/InGaAs HBTs, respectively.
- (iii) J_B components are relatively insensitive to the variations of base doping concentration, base layer thickness, and base minority-carrier lifetime.

FIG. 8. Comparison of the components of the base current density vs the base doping density for an InAlAs/InGaAs HBT.

FIG. 10. Comparison of the components of the base current density vs the base minority-carrier lifetime for an InAlAs/InGaAs HBT.

FIG. 11. Comparison of the components of the base current density vs the bulk space-charge-region trapping density for an AlGaAs/GaAs HBT.

(iv) J_{SCR} depends very strongly on N_{II} but very weakly on N_{IB} , suggesting that the total base current, and thus the current gain, is influenced heavily by N_{II} . This indicates that care should be taken during device fabrication so that lattice mismatch between emitter and base, which causes N_{II} , is minimized. On the other hand, one does not need to worry too much about deep-level traps in the bulk emitter-base space-charge region, which yields N_{IB} , introduced predominantly by the diffusion of impurity dopant (e.g., Be) from the p -type base into the n -type emitter.²⁵

(v) Increasing N_E , which reduces J_{RE} , will reduce the total base current and thus increase the current gain in typical AlGaAs/GaAs HBTs if V_{BE} is large, but not otherwise. Also, increasing N_E will not benefit the current gain in InAlAs/InGaAs HBTs because J_{RE} is relatively unimportant in such devices.

FIG. 12. Comparison of the components of the base current density vs the bulk space-charge-region trapping density for an InAlAs/InGaAs HBT.

FIG. 13. Comparison of the components of the base current density vs the heterointerface state density for an AlGaAs/GaAs HBT.

(vi) For a HBT with a graded base, the charge transport in the base is enhanced by the builtin field, which reduces J_{RB} . Also, base grading does not affect J_{SCR} and J_{RE} . Therefore, at a typical operation voltage $V_{BE} \approx 1.3$ – 1.4 V, base grading will not improve significantly the current gain of a typical AlGaAs/GaAs HBT but will improve considerably the current gain of a typical InAlAs/InGaAs HBT.

(vii) A numerical study⁴ and experimental observation²⁶ have found that the elimination of the spike by grading the emitter-base heterojunction leads to an increase in $J_n(X_2)$, and thus J_{RB} . Also, heterojunction grading increases electron-hole recombination in the emitter-base space-charge region,⁴ which increases J_{SCR} , but results in a larger emitter-base valence-band discontinuity,²⁷ which reduces J_{RE} . Thus J_{SCR} is still the dominant component of base current density for both AlGaAs/GaAs and InAlAs/

FIG. 14. Comparison of the components of the base current density vs the heterointerface state density for an InAlAs/GaAs HBT.

FIG. 15. Dependence of total base current on emitter-base voltage calculated from the present model and from data reported in Ref. 26 for an AlGaAs/GaAs HBT.

InGaAs HBTs with heterojunction grading when they operate at small and medium voltages. For higher voltages, either J_{SCR} or J_{RB} will become the dominant component depending on the degree of grading which affects the degree of increase in J_{SCR} and J_{RB} .

FIG. 16. Dependence of total base current on emitter-base voltage calculated from the present model and from data reported in Ref. 27 for an InAlAs/InGaAs HBT.

(viii) InAlAs/InGaAs HBTs are sometimes operated at a lower V_{BE} (about 0.8 V) than the typical HBT operation voltage of 1.4 V due to the much smaller band gap of InGaAs. For this bias condition, J_{SCR} is the dominant component in J_B .

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