MODELING OF HETEROJUNCTION BIPOLAR TRANSISTORS OPERATING IN FORWARD MODE

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ABSTRACT

An analytic model is proposed to calculate the heteroemitter current-voltage and 1/f noise characteristics of heterojunction bipolar transistors. The proposed model uses the modified form of conventional drift-diffusion formalism to determine the current transport across the forward biased emitter/base heterojunction. This model satisfies the conservation of total electric charge across the PN junctions which requires that the net recombination rates be proportional to the densities of other type carriers across the heterointerface. Discussion is given about the effect of heterointerface properties on the static current-voltage and 1/f noise properties of forward biased Np heteroemitter of Npn (Al,Ga)As/GaAs heterojunction bipolar transistors.

I. INTRODUCTION

Compound semiconductor based heterojunction bipolar devices have been proven to be very important for high speed and high frequency device operations. The use of a widegap semiconductor as emitter and a narrow bandgap semiconductor as base is known to lower the minority carrier transit time across the neutral base and across base/collector depletion regions that are the main requirements for achieving high frequency operation [1]. For example, the use of widegap N-(Al,Ga)As and a narrow bandgap p-GaAs base permits the fabrication of Npn heterojunction bipolar transistors (HBTs) with heavily doped base and lightly doped emitter regions to reduce the base resistance and emitter capacitance, without lowering the current gain and reducing the operation speed. Because of the considerable large bandgap difference between emitter and base, HBTs based on group III-V compounds such as Npn (Al,Ga)As/GaAs have a number of advantages for high speed and high power operation over the conventional Si and GaAs FETs and BJTs [2].

Advances in the compound heterojunction bipolar device technology cannot be complete without an adequate and reliable analytic method for the calculation of device performance. There are two main issues to be considered in the modeling of heterojunction Np diodes and heterojunction bipolar transistors (HBTs): (a) the emitter-base space charge electron-hole recombination and (b) influence of conduction and valence band offsets across the emitter-base heterointerface on carrier transport. Review of currently used models (drift-diffusion, thermionic emission, diffusion, and tunneling, charge control concepts, and Monte Carlo simulations) to calculate the static performance of HBTs can be found in Ref. 1. Present HBT models use mathematically complex and numerically sophisticated techniques and fail to provide convincing physical insight about the effects of the heterojunction emitter/base space charge recombination on the dc current-voltage and current gain characteristics of HBTs. The purpose of this paper is to provide a model to calculate effect of heterointerface properties on the current-voltage and 1/f noise characteristics of forward biased heteroemitter in HBTs.

II. MODELING OF HETEROEMITTER FORWARD CURRENT

Following low level expressions of Shockley [3] will be used to derive the current-voltage characteristics of Np heteroemitter with the aid of current continuity, and Poisson equations:

$$J_n(x) = qn(x)\mu_n F(x) + qD_n \frac{\partial n(x)}{\partial x} \quad (1)$$

$$J_p(x) = qp(x)\mu_p F(x) - qD_p \frac{\partial p(x)}{\partial x} \quad (2)$$

$$J = J_n(x) + J_p(x) \quad (3)$$

$$\frac{\partial J_n(x)}{\partial x} = -\frac{\partial J_p(x)}{\partial x} = qR(x) \quad (4)$$

$$\frac{\partial^2 \phi(x)}{\partial x^2} = -\frac{q}{\epsilon}[p(x) - n(x) - (p_0 - n_0)] \quad (5)$$

where μ_n and μ_p mobilities, and D_n and D_p the diffusion constants of minority electrons and holes of densities n(x) and p(x). q is the electronic charge and ϵ the static dielectric constant. $R(x)$ is the classical Shockley-Read-Hall (SRH) electron-hole net recombination rate across the space charge region [4,5]

$$R(x) = \frac{n(x)p(x) - n_t(x)p_t(x)}{\tau_n[p(x) + p_t(x)] + \tau_p[n(x) + n_t(x)]} \quad (6)$$

$n_t(x)$ and $p_t(x)$ are the densities and τ_n and τ_p the lifetimes of electrons and holes trapped at the localized deep levels of N_T density. The densities of free and trapped electrons and holes are described by the Maxwell-Boltzmann approximation

$$n(x) = n_{iN}(x)\exp(\frac{E_{Fn}(x) - E_{iN}}{kT}) \quad (7)$$

$$p(x) = n_{ip}(x)\exp(\frac{E_{ip} - E_{Fp}(x)}{kT}) \quad (8)$$

$$n_t(x) = n_{iN}(x)\exp(\frac{E_{TN}(x) - E_{iN}}{kT}) \quad (9)$$

$$p_t(x) = n_{ip}(x)\exp(\frac{E_{ip} - E_{Tp}(x)}{kT}) \quad (10)$$

$E_{Fn}(x) = E_{Fn} + q\phi(x)$ and $E_{Fp}(x) = E_{Fp} + q\phi(x)$ are the electron and hole position dependent quasi-Fermi levels, and E_{Fn} and E_{Fp} the Fermi levels. $E_{TN}(x) = E_{TN} + q\phi_N(x)$ and $E_{Tp}(x) = E_{Tp} + q\phi_p(x)$ are the position dependent trap levels, E_{iN} and E_{ip} the intrinsic Fermi levels, and $n_{ip}(x)$, and $n_{iN}(x)$ the intrinsic carrier densities in p and N regions. k is Boltzmann's constant. Equations (7) and (8) are used to write the product of free electron and hole densities at heterointerface as

$$n(x_j)p(x_j) = n_i^2(x_j)\exp(\frac{qV}{kT}) \quad (11)$$

where $E_{Fn}(x_j) - E_{Fp}(x_j) = E_{Fn} - E_{Fp} - q[\phi_N(x_j) - \phi_p(x_j)] = qV$ since $\phi_N(x_j) = \phi_p(x_j) = \phi(x_j)$ for small forward biases. The effective intrinsic carrier density at heterointerface is

$$n_i(x_j) = \left[n_{iN}(x_j)n_{ip}(x_j)\right]^{1/2} \exp(-\frac{\Delta E_i(x_j)}{2kT}) \quad (12)$$

where $n_{iN}(x_j)$ and $n_{ip}(x_j)$ are the intrinsic carrier densities of N and p regions at the heterointerface [6] and are assumed, for simplicity, to be equal to their bulk values n_{iN} and n_{ip} and $\Delta E_i(x_j)$ is the intrinsic Fermi level discontinuity at heterointerface, obtained using a position dependent reference Fermi level as

$$E_i(x) = \frac{E_c(x) + E_v(x)}{2} = E_v + \frac{E_g}{2} - \frac{\Delta}{6} - q\phi(x) \quad (13)$$

$E_c(x) = E_c - q\phi(x)$ and $E_v(x) = E_v - q\phi(x)$ are the position dependent conduction and valence bands [7] shifted by electrostatic potential $-q\phi(x)$ relative to homogeneous band edges E_c and E_v. $\Delta/3$ is the spin orbit splitting of top of valence band. Evaluating equation (13) at $x = x_j$ one obtains

$$\Delta E_i(x_j) = \frac{\Delta E_g}{2} - \Delta E_v - \frac{\delta\Delta}{6} \quad (14)$$

where $\delta\Delta = \Delta_N - \Delta_p$ is the difference in the spin-orbit energies and $\phi_N(x_j) = \phi_p(x_j)$. $\Delta E_g(x_j) = [E_{gN} - E_{gp}]$ is the difference between bandgaps, which are temperature and pressure dependent [8].

The most effective trap level $E_T(x_j)$ is obtained by minimizing the SRH recombination rate R(x) with respect to $E = E_T(x_j)$ at the heterointerface:

$$E_{TN}(x_j) = E_{iN} - \frac{1}{2}\Delta E_i(x_j) + \frac{1}{2}kT\ln[\frac{\tau_n n_{ip}}{\tau_p n_{iN}}] \quad (15)$$

$$E_{Tp}(x_j) = E_{ip} + \frac{1}{2}\Delta E_i(x_j) + \frac{1}{2}kT\ln\left[\frac{\tau_n n_{ip}}{\tau_p n_{iN}}\right] \quad (16)$$

which state that $E_T(x_j)$ is shifted roughly by $\Delta E_i(x_j)/2$ relative to bulk E_{ip} in the p neutral region and by $-\Delta E_i(x_j)/2$ relative to bulk E_{iN} in the N neutral region. Since $E_T(x_j)$ is located at halfway between the electron and hole quasi-Fermi levels [3] one can also write

$$E_{TN}(x_j) = E_{iN} - \frac{1}{2}\Delta E_i(x_j) + \frac{1}{2}kT\ln[\frac{N_d n_{ip}}{N_a n_{iN}}] \quad (17)$$

$$E_{Tp}(x_j) = E_{ip} + \frac{1}{2}\Delta E_i(x_j) + \frac{1}{2}kT\ln[\frac{N_d n_{ip}}{N_a n_{iN}}] \quad (18)$$

which are same as equations (15) and (16) except that the τ_p/τ_n ratio is now replaced by the N_a/N_d ratio. Combining equations (15)-(18) one obtains

$$\frac{\tau_p}{\tau_n} = \frac{N_a}{N_d} \quad \text{or} \quad (\frac{1}{\tau_n})/(\frac{1}{\tau_p}) = \frac{N_a}{N_d} \quad (19)$$

This is the conservation of total electric charge that must be satisfied in order to derive the space charge recombination current and 1/f noise across a forward biased Np heterojunction or conventional np junction at small forward biases.

According to low level injection theory of Shockley [3], the integral of equations (1) and (2) gives

$$n_N(x) = n(x_N)\exp\left[\frac{q}{kT}(\phi_N(x) - \phi_{mN})\right] \quad (20)$$

$$p_p(x) = p(x_p)\exp\left[-\frac{q}{kT}(\phi_p(x) - \phi_{mp})\right] \quad (21)$$

where $\phi_N(x_N) = \phi_{mN} = 0$ and $\phi_p(x_p) = \phi_{mp} = -(V_0 - V)$ are the boundary potentials and $n_N = n(x_N) \approx N_d$ and $p_p = p(x_p) \approx N_a$ are the boundary densities. Combining equations (20) and (21) with equation (6) one then writes $R(x_j)$ as

$$R(x_j) = \frac{n_N(x_j)p_p(x_j) - n_t(x_j)p_t(x_j)}{\tau_p N_d \exp(U_N) + \tau_n N_a \exp(-U_p) + 2\tau_r n_i(x_j)} \quad (22)$$

where $\tau_r = (\tau_n\tau_p)^{1/2}$is the recombination lifetime, $U_N = q\phi(x_j)/kT$ and $U_p = q[\phi(x_j) - \phi_{mp}]/kT$ with $\phi_{mN} = 0$ and $\phi_{mp} = -(V_0 - V)$. Minimizing $R(x_j)$ with respect to $\phi(x_j)$ one then obtains the low level injection expression for $\phi(x_j)$

$$-q\phi(x_j) = \frac{1}{2}q(V_0 - V) + \frac{1}{2}kT\ln[\frac{N_d\tau_p}{N_a\tau_n}] \quad (23)$$

where $\tau_p N_d/\tau_n N_a = 1$ according the conservation of total electric charge given by equation (19). The built-in potential energy $qV_0 = q\phi_N(x_{0N}) - q\phi_p(x_{0p})$ is obtained by combining equations (1) and (2) at equilibrium ($E_{Fn} = E_{Fp} = E_F$)

$$qV_0 = \Delta E_i(x_j) + kT\ln\left[\frac{N_a N_d}{n_{iN}n_{ip}}\right] \quad (24)$$

where $n_{0N} \approx N_d$ and $p_{op} \approx N_a$.

The density of free and trapped electrons and holes at heterointerface are obtained using the minimization condition for R(x) at the heterointerface. One first writes n(x) and p(x) in terms of their values $n(x_j)$ and $p(x_j)$ at the heterointerface as

$$n_N(x) = n(x_j)\exp\left[\frac{q}{kT}(\phi_N(x) - \phi_N(x_j)\right] \quad (25)$$

$$p_p(x) = p(x_j)\exp\left[-\frac{q}{kT}(\phi_p(x) - \phi_p(x_j))\right] \quad (26)$$

where $\varphi_N(x) = q(\phi_N(x) - \phi(x_j))/kT$ and $\varphi_p(x) = q(\phi_p(x) - \phi(x_j))/kT$ are the normalized electrostatic potentials on the N and p sides of the space charge region. Combining equations (25) and (26) with equation (6) and minimizing R(x) with respect to $x = x_j$ one obtains the density of free electrons and holes at heterointerface:

$$n_N(x_j) = \frac{\tau_n}{\tau_p}p_p(x_j) = (\tau_p/\tau_n)^{1/2}n_i(x_j)\exp(\frac{qV}{2kT}) \quad (27)$$

which shows that $n(x_j)$ and $p(x_j)$ are equal only if $\tau_n = \tau_p$. Combining equations (9) and (10) with equations (15) and (16) one obtains the density of recombined electrons and holes at heterointerface

$$n_t(x_j) = (\tau_n/\tau_p)p_t(x_j) = (\tau_n/\tau_p)^{1/2}n_i(x_j) \quad (28)$$

which states that the density of trapped electrons and holes at the most effective trap level located at heterointerface are equal only if their lifetimes are equal.

An analytic expression for the recombination current $I_r(x_j)$ can now be obtained by integrating $R(x_j)$, with a constant value for D(x) at $x = x_j$. This is obtained using continuity of electric flux: $D_N(x_j) = D_p(x_j)$ which gives $D(x_j) = (D_N(x_j) + D_p(x_j))/2$. Substituting equations (27) and (28) in equation (22) and integrating it over space charge region, with the use of integral tables [9], one obtains the recombination current $I_r(x_j)$:

$$I_r(x_j) = \frac{4qA(kT/q)K_r\epsilon_N n_i(x_j)}{D(x_j)\tau_r(4-b^2)^{1/2}}\sinh(\frac{qV}{2kT}) \quad (29)$$

where $\tau_r = (\tau_n + \tau_p)/2 = (\tau_n\tau_p)^{1/2}$ is the electron-hole recombination lifetime and K_r is

$$K_r = \left[\frac{\pi}{2} - \frac{\epsilon_N - \epsilon_p}{\epsilon_N}\arctan\frac{b+2}{(4-b^2)^{1/2}})\right] \quad (30)$$

$b = 2\exp(-qV/2kT) << 1$ for forward biases greater than thermal voltage ($V >> kT/q$), . When $\epsilon_N = \epsilon_p$, equation (29) reduces to its counterpart for Np homojunction, derived by van der Ziel [10]. The minority carrier diffusion current, sum of the electron and hole currents I_{ne} and I_{pe}, can be obtained by solving carrier transport equations (1) and (2) in the quasineutral N- and p-regions of a short base Np heteroemitter and is given by

$$I_{de} = qA_e\left[\frac{D_p n_i^2(x_j)}{L_p N_d} + \frac{D_n n_i^2(x_j)}{W_p N_a}\right]\exp(\frac{qV}{kT}) - 1) \quad (31)$$

Equations (29) and (31) can now be easily used to determine the heteroemitter current and 1/f noise in a uniformly doped Npn heterojunction bipolar transistor (HBT) operating in the forward active mode.

III. MODELING OF HETEROEMITTER AND COLLECTOR 1/F NOISE

Based on the proof given in equation (19) about the total electronic charge across Np heterojunctions, one can easily derive the heteroemitter 1/f noise in Npn HBT at small forward emitter/base biases (Sah-Noyce-Shockley (SNS) recombination mode [5]). Following van der Ziel and Handel [11], the 1/f noise across the Np heteremitter at small forward biases can be written as

$$S_{I_r}(f) = \frac{\alpha_{Hr}q^2A_{eb}}{f(\tau_n + \tau_p]}\int_0^W R(x)dx = \frac{q\alpha_{Hr}I_r(x_j)}{f(\tau_n + \tau_p)} \quad (32)$$

where f is the frequency and W the thickness of the space charge region. α_{Hr} is so called Hooge's 1/f noise coefficient for its recombination component [11]

$$\alpha_{Hr} = \frac{4\alpha}{3\pi c^2}\frac{[2q(V_0 - V) + 6kT]}{[m_n^{1/2} + m_p^{1/2}]^2} \quad (33)$$

$\alpha = 1/137$ is the Sommerfold's Fine structure constant, c speed of light, and m_n and m_p electron and hole effective masses.

As the injected emitter electrons enter heteroemitter space charge region, they loose an average energy of $q(V_0 - V)$, whereas the electrons extracted from the base gain an average energy of $q(V_0 - V)$. In both cases electrons are decelerated or accelerated and produce 1/f noise which can be described by the following expression for an Np heteroemitter at moderate forward biases (Shockley minority electron diffusion mode [3])

$$S_{I_{ne}}(f) = \frac{q\alpha_{Hn}}{f\tau_{nd}} I_{ne} = \frac{\alpha_{Hn} q^2 A_e D_n n_i^2(x_j)}{f\tau_{ne} W_b N_{ab}} \left[\exp(\frac{qV}{kT}) - 1\right] \quad (34)$$

where $\tau_{ne} = W_b^2/2D_{nb}$ the diffusion transit time with D_{nb} the diffusion constant for minority electrons in the neutral base region of W_b width. α_{Hn} is the 1/f noise coefficient, so called the Hooge's parameter, for its diffusion component

$$\alpha_{Hn} = \frac{4\alpha}{3\pi} \frac{2q(V_0 - V)}{m_n c^2} \quad (35)$$

where $\alpha = 1/137$ the Sommerfold's fine structure constant, c the speed of light, and m_n the effective mass of electrons in the base.

Following van der Ziel [12], the collector component of 1/f noise in Npn HBTs can be determined according to

$$S_{I_{cn}}(f) = \frac{\alpha_{Hn} I_{cn}}{f W_b^2} \int_0^{W_b} \frac{I_{cn}(x)dx}{n_b(x)} \quad (36)$$

where $I_{cn}(x)$ is the collector current

$$I_{cn}(x) = qA_c n_b(x) v_{nb}(x) + qA_c D_{nb} \frac{\partial n_b(x)}{\partial x} \quad (37)$$

A_c is the area of base/collector homojunction and $v_{nb}(x)$ the field dependent electron velocity [10]. The electron density at the emitter end of the neutral base is

$$n_b(0) = (n_{ib}^2/N_{ab}) \exp(qV_{be}/kT) \quad (38)$$

with n_{ib} intrinsic carrier density and N_{ab} doping density. Since the electric field strength across the reverse biased base/collector pn junction is close to its maximum value $F(W_b) = F_c$, the minority electrons will move into the neutral collector region with saturation velocity of v_{ns}. The electron density at collector end of neutral base is

$$n_b(W_b) = I_{cn}/qA_c v_{ns} = n_b(0) - I_{cn} W_b / qA_c D_{nb} \quad (39)$$

One then writes $n_b(0)/n_b(W_b) = (D_{nb} + v_{ns} W_b)/D_{nb}$.

The injected electrons entering the base/collector p/n junction are subject to a critical field $F(W_b) = F_c$ there and one can take $v_n(W_b) = \mu_n F_c/2 = v_{ns}/2$ for the maximum drift velocity at $x = W_b$. Using the definition of scattering length (mean free path) for electrons in inhomogeneous semiconductors [7] one can write $l_n \approx 3D_{nb}/v_{ns}$ for the scattering length (mean free path) for the minority electrons in the neutral base. Carrying out the integral in equation (36) one then obtains the collector 1/f noise as

$$S_{I_c}(f) = K_{bc} \frac{q\alpha_{Hn} I_{cn}}{2f\tau_{nb}} \ln\left(1 + \frac{3W_b}{l_{nb}}\right) \quad (40)$$

where $\tau_{nd} = W_b^2/2D_{nb}$ the diffusion transit time with D_{nb} the diffusion constant for minority electrons in the neutral base region of W_b width. K_{bc} is the dimensionless coefficient

$$K_{bc} = 1 + \frac{(v_{ns}/v_{nB})}{\ln(v_{ns}/v_{nB}^*)} = 1 + \frac{3}{2} \frac{(W_B/l_{nB})}{\ln(1 + 3W_B/l_{nB})} \quad (41)$$

This is the correction factor to the following equation derived by van der Ziel [12] for the collector 1/f noise

$$S_{I_c}(f) = \frac{\alpha_{Hn} q I_{cn}}{2f\tau_{dn}} \ln \frac{n_b(0)}{n_b(W_b)} \quad (42)$$

Equation (40) states that the correction to $S_{I_c}(f)$, given by equation (42), should be at least a factor of two ($W_b = l_{nb}$) or greater ($W_b >> l_{nb}$).

IV. DISCUSSIONS

The proposed model is used to gain some qualitative understanding of the effect of heteroemitter on static current-voltage and quantum 1/f noise properties of Npn (Al,Ga)As/GaAs heterojunction bipolar transistors (HBTs) in forward operation mode. The device characteristics are compared with those of npn GaAs bipolar junction transistor (BJT) for the same design parameters. The neutral p-base region thickness is taken to be smaller than the minority carrier diffusion length but greater than its mean free path ($L_{np} >> W_p >> l_{np}$). The doping densities are N_{de}=2x10$^{17}cm^{-3}$, N_{ab}=1x10$^{18}cm^{-3}$, and N_{dc}=2x10$^{17}cm^{-3}$ for emitter, base, and collector respectively. The neutral base thickness is $0.15\mu m$.

Figure 1 shows the variation of total emitter current $I_e = I_r(x_j) + I_{de}$, recombination current $I_r(x_j)$ and diffusion current $I_{de} = I_{ne} + I_{pe} \approx I_{ne}$ of Np (Al,Ga)As/GaAs heteroemitter with forward bias. The magnitude of I_{de} increases exponentially with via the factor of $\exp(qV/kT)$ at small and medium forward biases (Shockley minority carrier diffusion theory). On the other hand, the magnitude of $I_r(x_j)$ slowly increases exponentially with V via the factor of

$(V_0 - V)^{-1/2}\exp(qV/nkT)$ (Sah-Noyce-Shockley recombination theory [2]), where the ideality factor is large, $n \approx 2$, for small forward biases and it begins to decrease at moderate forward biases.

The emitter/base current-voltage characteristics comparison in Figure 1 indicates a strong intrinsic emitter/base junction resistance to the current conduction process in Np (Al,Ga)As/GaAs heteroemitter as compared to that in np GaAs/GaAs emitter for a wide range of forward biases. The intrinsic emitter/base junction resistance to the diffusing minority electrons is much stronger at small forward biases as compared with that to the recombined electrons and holes in both np GaAs/GaAs emitter and Np (Al,Ga)As/GaAs heteroemitter. But at higher biases, the intrinsic junction resistance to the diffusing electrons become small as compared with that to recombined electrons and holes. The decrease in the intrinsic junction resistance with increasing V_{be} leads to an increase in the magnitude of junction velocity of recombined electrons and holes.

This will influence the emitter injection efficiency and quantum 1/f noise in Npn HBT. The heteroemitter electron injection efficiency is defined as

$$\gamma = \frac{I_{ne}}{I_{ne} + I_{pe} + I_r(x_j)} = \frac{\gamma_o}{1 + \gamma_o(I_r(x_j)/I_{ne})} \quad (43)$$

$\gamma_o = I_{ne}/(I_{ne}+I_{pe})$ is the electron injection efficiency in the absence of $I_r(x_j)$, where I_n and I_p are the minority electron and hole components of I.

Furthermore, the total contribution of Np heteroemitter to 1/f noise in Npn HBT is also influenced by the heteroemitter junction resistance, which is written as

$$S_{I_{eb}}(f) = \frac{q\alpha_{Hn}}{f\tau_{nd}} I_{ne} + \frac{q\alpha_{Hr} I_r(x_j)}{2f\tau_r} = \frac{q\alpha_{Hn}}{f\tau_{nd}} I_{ne}\left[1 + \frac{\alpha_{Hr}}{\alpha_{Hn}}\frac{\tau_{nd}}{2\tau_r}\frac{I_r(x_j)}{I_{ne}}\right] \quad (44)$$

The $I_r(x_j)/I_{ne}$ ratio is a slow function of V at small biases. As shown in Figure 2, the decrease in S_I is gradual for smaller biases and tends to be very rapid as V increases.

When the emitter currents obey the Sah-Noyce-Shockley recombination-diffusion regime [5] at small forward biases, very few minority holes and electrons can pass the heteroemitter interface. Much of the injected emitter electrons and base holes recombine with each other at the effective deep levels localized at the junction. For small forward biases, I_{ne} is small as compared to $I_r(x_j)$. There exists a forward bias at which $I_r(x_j)$ and I_d are equal which is given by

$$\frac{I_r(x_j)}{I_d} = \frac{\pi(kT/q)N_a W_p n_i(x_j)}{L_{np}\tau_r D(x_j) n_{ip}^2}\frac{\exp(qV/2kT) - 1}{\exp(qV/kT) - 1} \quad (45)$$

which is usually very large at small forward biases, and then approaches to zero as the exponential factor takes over. This ratio is unity at about 1.0 V for Np (Al,Ga)As/GaAs heterojunction and at about 0.75 V for np GaAs/GaAs homojunction. Below these biases, the total current obeys SNS recombination-diffusion theory and it obeys the Shockley minority carrier diffusion theory above them.

The effect of band offsets at the heteroemitter interface on the emitter current and quantum 1/f noise is best understood by analysing the $n_i(x_j)/n_{ip}^2$ ratio in equation (40)

$$\frac{n_i(x_j)}{n_{ip}^2} = (\frac{n_{iN}}{n_{ip}^3})^{1/2}\exp(-\frac{\Delta E_i}{2kT}) = (\frac{n_{iN}}{n_{ip}^3})^{1/2}\exp\left(\frac{\Delta E_v - \Delta E_c}{4kT} + \frac{\delta\Delta}{12kT}\right) \quad (46)$$

where $\delta\Delta/12kT$ is relatively small and can be neglected and $\Delta E_v = 30\%\Delta E_g$ and $\Delta E_c = 70\%\Delta E_g$, where $\Delta E_c + \Delta E_v = \Delta E_g$. Increasing ΔE_c (or decreasing ΔE_v) decreases (increases) $n_i(x_j)$. This decrease (increase) in $n_i(x_j)$ causes the SRH recombination rate at heterointerface $R(x_j)$ to decrease (increase) which in turn causes a corresponding decrease (increase) in the saturation value of $I_r(x_j)(x_j)$.

V. CONCLUSION

A drift-diffusion type analytic model is presented to incorporate the band offsets in the Shockley-Read-Hall electron-hole net recombination rate used in determining the recombination contribution to the current and 1/f noise forward biased heteroemitter of HBTs. It is found that most effective trap level at heterointerface shifted roughly by $\Delta E_i(x_j)/2$ relative to bulk E_{ip} in the p neutral region and by $-\Delta E_i(x_j)/2$ relative to bulk E_{iN} in the N neutral region. The numerical results suggest that the forward active mode current and 1/f noise properties of Npn (Al,Ga)As/GaAs HBTs with $l_{nB} << W_B << L_{nB}$ can be described by two main components; (i) the emitter/base recombination component which dominates at low forward biases, and (ii) the minority electron diffusion component which dominates at moderate forward biases.

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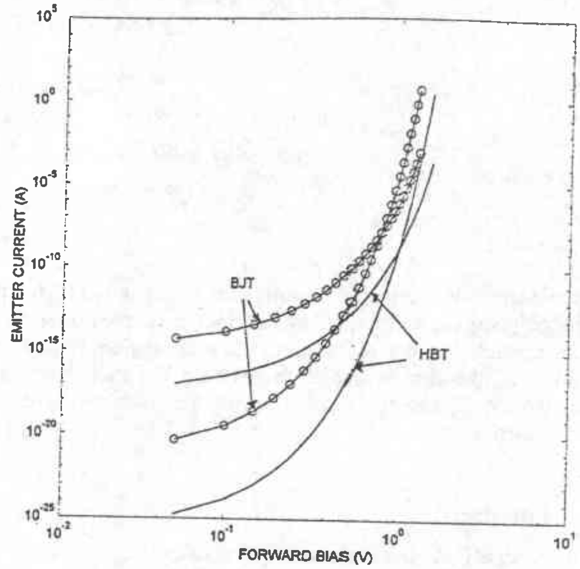

Fig. 1. Comparison of emitter current of Npn AlGaAs/GaAs HBT and that of npn GaAs BJT in forward active mode.

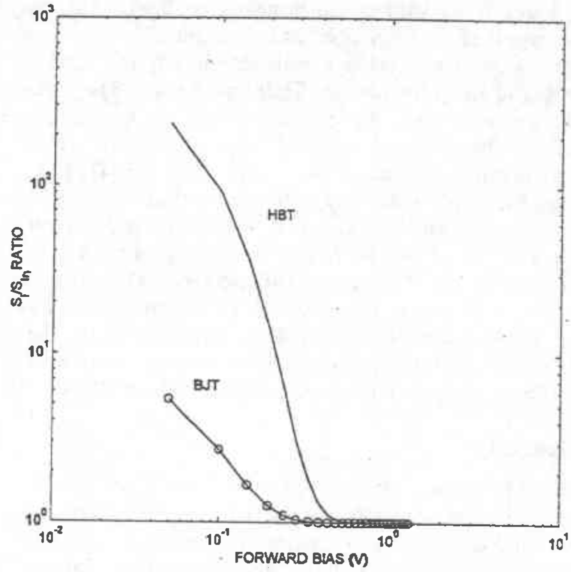

Fig. 2. Comparison of emitter 1/f noise of Npn AlGaAs/GaAs and that of npn GaAs BJT in forward active mode.