Considerations of dopant-dependent bandgap narrowing for accurate device simulation in abrupt HBTs*

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Abstract: Heavy doping of the base in HBTs brings about a bandgap narrowing (BGN) effect, which modifies the intrinsic carrier density and disturbs the band offset, and thus leads to the change of the currents. Based on a thermionic-field-diffusion model that is used to the analyze the performance of an abrupt HBT with a heavy-doped base, the conclusion is made that, although the BGN effect makes the currents obviously change due to the modification of the intrinsic carrier density, the band offsets disturbed by the BGN effect should also be taken into account in the analysis of the electrical characteristics of abrupt HBTs. In addition, the BGN effect changes the bias voltage for the onset of Kirk effects.

Key words: HBTs; bandgap narrowing; intrinsic carrier density; band offsets; Kirk effects

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1. Introduction

Bandgap narrowing (BGN) due to heavy doping of the base is an important effect in heterojunction bipolar transistors (HBTs). In most of the published literature dealing with the influence of the BGN on the device electrical characteristics of abrupt HBTs, the BGN is only used to modify the intrinsic carrier density n_i that determines the minority carrier density[1−4]. This is not accurate because the BGN causes the perturbation of the band offsets ΔE_c and ΔE_v at the base–emitter interface in abrupt HBTs, which also changes the device characteristics[5, 6]. However, in the BGN considerations[5, 6], there are no comparisons of the simulation results with regard to whether the perturbation of the band offsets is included. There is also no analysis why the band offset disturbance is important for the carrier transport.

In this paper, we present the simulation results of the currents with different BGN considerations based on the thermionic-field-diffusion model[7, 8], which combines the drift-diffusion transport in the bulk of the transistor with the thermionic emission and tunneling at the base–emitter interface in abrupt HBTs. Furthermore, the reason for the difference between these obtained results is given.

2. Numerical model

In the bulk of the transistor, the current transport is controlled by drift and diffusion mechanisms, and the electron current is given by

$$J_n = -q\mu_n n \nabla\psi_n, \tag{1}$$

where μ_n is the electron mobility and ψ_n is the electron quasi-Fermi potential.

The transport model in the abrupt emitter-base heterojunction interface ($x = x_j$) is based on the Grinberg equation[9], which integrates the tunneling transmission through the energy spike and the thermionic emission above it. The electron current density through a spike in the conduction can be calculated by

$$J_{n,i} = -q\frac{v_n}{4}\left[n(x_j^-) - n(x_j^+)\exp\left(-\frac{\Delta E_c}{kT}\right)\right](1+\delta_n), \tag{2}$$

where v_n is the mean thermal velocities of the electrons. The contribution of electron tunneling through the conduction band in an npn transistor is represented by a tunneling factor δ_n, which is[9]:

$$\delta_n = \frac{\exp\left(\dfrac{E_c(x_j^-)}{kT}\right)}{kT}\int_{E_{min}}^{E_c(x_j^-)}\exp\left(-\frac{E_x}{kT}\right) \times\exp\left(-\frac{4\pi}{h}\int_{x_E}^{x_j}\{2m_n^*[E_c(x)-E_x]\}^{1/2}\mathrm{d}x\right)\mathrm{d}E_x, \tag{3}$$

where m_n^* is the electron tunneling mass, E_x is the energy of the conduction band at $x = x_E$ ($x_N \leqslant x_E \leqslant x_j$), and $E_{min} = \max[E_c(x_N), E_c(x_j^+)]$. x_N represents the boundary of the p-n junction depletion in the wide bandgap emitter side. The electron concentrations $n(x_j^-)$ and $n(x_j^+)$ are given by

$$n(x_j^-) = n_E(x_N)\exp\left(-\frac{qV_N}{kT}\right), \tag{4}$$

$$n(x_j^+) = n_B(x_p)\exp\left(\frac{qV_p}{kT}\right), \tag{5}$$

where V_N and V_p are obtained from the band edge profile, as shown in energy band diagram in Fig. 1, and can be written as

$$V_N = \frac{N_A\varepsilon_B(V_{bi}-V_{BE})}{N_A\varepsilon_B + N_D\varepsilon_E}, \tag{6}$$

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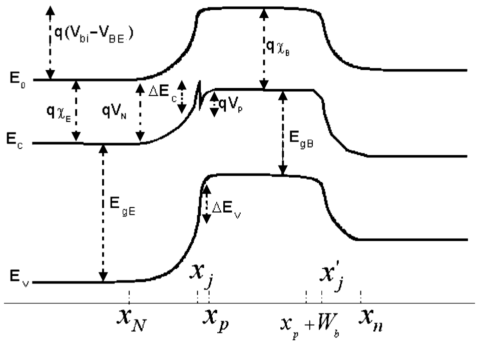

Fig. 1. Energy band diagram of an abrupt HBT.

$$V_p = \frac{N_D\varepsilon_E(V_{bi} - V_{BE})}{N_A\varepsilon_B + N_D\varepsilon_E}, \quad (7)$$

where V_{BE} is the base–emitter voltage, and the built-in potential V_{bi} can be expressed by[10]

$$V_{bi} = \frac{E_{gB} + \Delta E_c - \psi_N - \psi_p}{q}, \quad (8)$$

where E_{gB} is the bandgap of the base, ΔE_c is the conduction band offset, and ψ_N and ψ_p are the differences between the bands and the Fermi level energies.

The high doping concentrations of the base in HBTs produce a significant BGN,

$$E_{gB} = E_{gB0} - \Delta E_{gB}^{bgn}, \quad (9)$$

where E_{gB0} is the bandgap value for low doping levels and ΔE_{gB}^{bgn} is the shrinkage of the bandgap because of the heavy doping effect. Because of the importance of BGN on the electrical characteristics of the device, most device simulators take this into account only through the modification of the intrinsic carrier density as[11]:

$$n_i^2 = pn = n_{i0}^2 \exp\left(\frac{\Delta E_{gB}^{bgn}}{kT}\right)\exp\left(\frac{E_F - E_V}{kT}\right)F_{1/2}\left(\frac{E_V - E_F}{kT}\right), \quad (10)$$

where n_{i0} is the intrinsic carrier concentration with low doping in the semiconductor. However, this approach is questionable for the high base doping level in abrupt HBTs, because it is evident from Eqs. (2)–(8) that the currents flowing through the emitter-base interface have an exponent dependancy on the built-in potential, which can be disturbed by the dope-induced BGN distribution between bands. So, it is important to use an accurate distribution model for the BGN between bands. The Jain–Roulston model[11] has been used in this work, and the results are shown in Fig. 2.

With an increase of the forward-biased base-emitter junction, the effective base thickness in HBTs will widen. This is known as the Kirk effect[12]. The collect current density corresponding to the onset of the Kirk effect is given by[10]

$$J_{Kirk} = qN_C v_{sat}\left[1 + \frac{2\varepsilon_c(V_{bi\_bc} + V_{BC})}{qN_C W_C^2}\right], \quad (11)$$

where N_C and W_C are the collector doping and collector thickness, respectively, and V_{bi_bc} is the built-in potential of the base–collector junction.

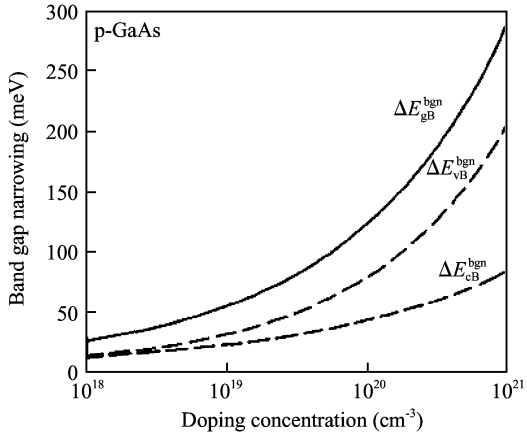

Fig. 2. Bandgap narrowing ΔE_{gB}^{bgn} and the distributions between the conduction ΔE_{cB}^{bgn} and the valence band ΔE_{vB}^{bgn} in p-GaAs.

Table 1. Device parameters of the AlGaAs/GaAs HBT.

Parameter	Emitter	Base	Collector
Length (nm)	150	100	500
Doping (cm^{-3})	5×10^{17}	5×10^{19}	2×10^{16}

Table 2. Values of V_{bi} for three different BGN cases.

Different BGN cases	V_{bi} (V)
Case a	1.5822
Case b	1.6195
Case c	1.7036

3. Results and discussion

The model described in the previous sections has been used to analyze an AlGaAs/GaAs HBT, whose doping profile and device parameters are shown in Table 1. In order to demonstrate the importance of dealing with a doping-induced bandgap narrowing model in the device simulation, the following cases have been considered.

Case a: Considering BGN only modifies the intrinsic carrier density n_i.

Case b: Considering BGN modifies the intrinsic carrier density n_i and disturbs the band offsets by ΔE_c and ΔE_v.

Case c: Neglecting the BGN.

Transport through an interface where energy levels present significant discontinuities is controlled by tunneling and thermionic emission instead of the conventional drift and diffusion mechanisms. The value of these currents at the interface depends on the form and height of the barrier energies. Table 2 and Figure 3 show the calculated results of V_{bi} and the tunnel factor δ_n, respectively, for the three above-mentioned different BGN cases for the AlGaAs/GaAs HBT. The dopant-dependent BGN leads to the variance of the built-in potential V_{bi}, which disturbs the form and height of the energy barriers in the HBT. This changes the currents resulting from both thermionic emission and tunneling at the base-emitter interface.

Figure 4 shows the current results when tunneling is neglected, labeled as case d, together with the results of the three

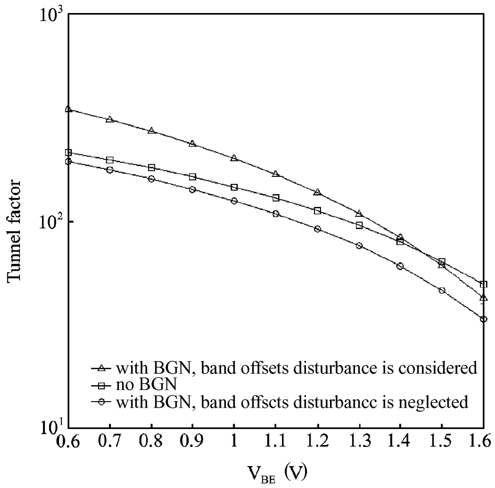

Fig. 3. Tunnel factor δ_n versus base emitter voltage for the AlGaAs/GaAs HBT.

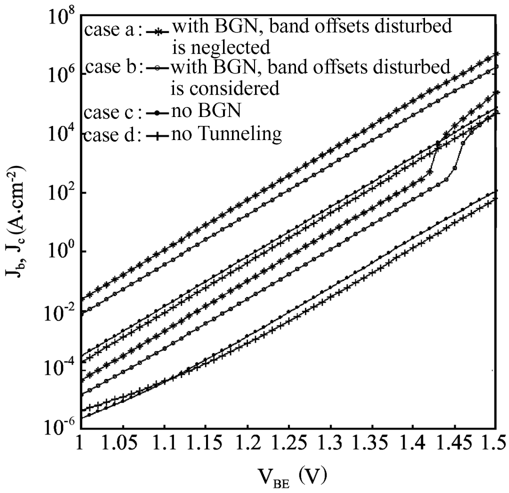

Fig. 4. Gummel plots of collector and base currents for the AlGaAs/GaAs HBT.

above-mentioned BGN cases. The currents are underestimated when the BGN effect or the tunneling is not considered in the device simulation; thus, both two effects have a significant importance for the performance of abrupt HBTs.

In Fig. 4, it can be seen that the difference of the currents between case a and case b is less serious than the difference of the currents between case b and case c. Therefore, the BGN effect obviously changes the currents by a modification of the intrinsic carrier density n_i. However, a difference of the currents between case a and case b is also evident, and so the band offsets caused by the BGN effect is important for the carrier transport in abrupt HBTs.

Figure 4 shows that the currents in case a is larger than in the other cases, although the tunnel factor δ_n in case a is the smallest, as shown in Fig. 3. Therefore, it is concluded that dopant-dependent BGN is more important to the currents resulting from thermionic emission than from tunneling. The reason is that the currents from thermionic emission are exponentially related to the build-in potential, which is raised more in case b than in case a when the band offsets are disturbed by BGN effects. This brings about the obvious decrease of the currents in case b compared to that in case a because of the further hindering of the carriers across the barrier by ways of thermionic emission.

Furthermore, it is evident in Fig. 4 that the different considerations of the BGN model result in the appreciable variations of the base-emitter bias voltage for the onset of the Kirk effect. The reason is that dissimilar shifts of the conduction and valence bands are assumed in the different considerations of the BGN model, which leads to varied energy profiles of the barrier across the emitter-base heterojunction. Therefore, different BGN considerations in the model can have different currents and, consequently, are distinguished by the base-emitter bias voltage for the onset of the Kirk effect at roughly the same threshold current density defined by Eq. (11).

4. Conclusion

Heavy doping of the base in abrupt HBTs leads to the BGN effect, which means that the change of the currents is due not only to the modifications of the intrinsic carrier density, but also due to a disturbance of the band offsets, which causes the carrier transport by means of thermionic emission and tunneling at the base-emitter interface.

In this paper, we demonstrate that dopant-dependent BGN is more important to the currents resulting from thermionic emission than for currents resulting from tunneling at the base–emitter interface. This results from the exponential dependence of the thermionic emission on the build-in potential, which can be disturbed by the doping-induced bandgap narrowing between bands. In addition, the BGN brings about a change of the bias voltage for the onset of Kirk effects.

Therefore, it is concluded that effects on the energy band structure of the transistor caused by heavy doping are very important and a dopant-dependent model of the BGN distribution between bands should be used for the accurate simulation of electrical characteristics of abrupt HBTs.

References

[1] Ahn H, Ei-Nokali M, Han D Y. An efficient algorithm for optimizing the electrical performance of HBT's. Int J Numer Model, 2003, 16(4): 353

[2] Mohammad S N. Doping induced design considerations for $InP/In_{0.53}Ga_{0.47}As$ heterojunction bipolar transistors. Solid-State Electron, 2002, 46(6): 867

[3] Palankovski V, Grujin G K, Selberherr S. Study of dopant-dependent band gap narrowing in compound semiconductor devices. Mater Sci Eng, 1999, B66: 46

[4] Reddy K V, DasGupta A. A unified analytical model for charge transport in heterojunction bipolar transistors. Solid-State Electron, 2004, 48(9):1613

[5] Shi Y, Niu G, Cressler J D, et al. On the consistent modeling of band-gap narrowing for accurate device-level simulation of scaled SiGe HBTs. IEEE Trans Electron Devices, 2003, 50(5): 1370

[6] Lopez J M, Prat L. The importance of bandgap narrowing distribution between the conduction and valence bands in abrupt

HBTs. IEEE Trans Electron Devices, 1997, 44(7): 1046

[7] Yang K, East J R, Haddad G I. Numerical modeling of abrupt heterojunction using a thermionic-field emission boundary condition. Solid-State Electron, 1993, 36(3): 321

[8] Yang K, East J R, Haddad G I. Numerical study on the injection performance of AlGaAs/GaAs abrupt emitter heterojunction bipolar transistors. IEEE Trans Electron Devices, 1994, 41(2): 138

[9] Grinberg A A, Shur M S, Fischer R J, et al. An investigation of the effect of graded layers and tunneling on the performance of AlGaAs/GaAs heterojunction bipolar transistors. IEEE Trans Electron Devices, 1984, 31(12): 1758

[10] Liu W. Fundamentals of III–V devices：HBTs, MESFETs, and HFETs/HEMTs. USA: John Wiley & Sons, 1999

[11] Jain S C, Roulston D J. A simple expression for bandgap narrowing (BGN) in heavily-doped Si, Ge, GaAs, and Ge_xSi_{1-x} strained layers. Solid-State Electron, 1991, 34(5): 453

[12] Kirk C T. A theory of transistor cut-off frequency (f_T) falloff at high current densities. IRE Trans Electron Devices, 1962, 9(4): 164