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Simulation of the Effect of Emitter Doping on the Delay Time in AlGaAs/GaAs Heterojunction Bipolar Transistors

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The influence of the emitter doping level (5×10^{17}–5×10^{18} cm^{-3}) on the delay time in AlGaAs/GaAs heterojunction bipolar transistors is investigated using numerical simulation based on a drift-diffusion model. The results reveal that the emitter delay time (τ_E) decreases with higher emitter doping (5×10^{18} cm^{-3}), allowing a very short delay time (<0.2 ps). It is shown that τ_E is affected by excess charge accumulation due to the built-in electric field at the cap/emitter (n^+-GaAs/n-AlGaAs) isotype heterojunction, more than at the emitter/base (n-AlGaAs/p^+-GaAs) heterojunction, under high-current operation ($>10^4$ A/cm^2).

KEYWORDS: gallium, arsenic, aluminium, drift-diffusion model, heterojunction bipolar transistor, cap, emitter, delay time, charge accumulation

§1. Introduction

AlGaAs/GaAs heterojunction bipolar transistors have attracted considerable interest as high-speed devices because of their very high cut-off frequency (f_T) of 171 GHz and maximum oscillation frequency (f_{max}) of 350 GHz.[1,2] HBT's with wide-gap emitters have three inherent advantages over homojunction bipolar transistors:[3] (i) a heavily doped base can be used due to the wide-band-gap emitter, reducing the base resistance, (ii) near-ballistic transport can be obtained, reducing collector transit time, and (iii) emitter doping can be decreased, reducing the emitter depletion-layer capacitance.

Although (i) and (ii) have been widely reported for many AlGaAs/GaAs HBT's,[4,5] only a few detailed studies on emitter doping (iii) have been reported. A low emitter doping level reduces the emitter depletion-layer capacitance. In the forward-bias condition, however, the emitter capacitance is not determined by the depletion-layer width, but by the number of excess carriers injected into the emitter region, which corresponds to the diffusion capacitance. Therefore, to estimate the emitter delay time (τ_E) in forward-bias operation, the behavior of excess carriers injected into the emitter region should be analyzed by numerical simulation.

In this letter, the influence of higher emitter doping on the delay time in AlGaAs/GaAs HBT's is analyzed using two-dimensional numerical simulation based on a drift-diffusion model.[6,7] The results reveal that the emitter delay time in AlGaAs/GaAs HBT's with heavily doped emitters (0.2 ps for 5×10^{18} cm^{-3}) is much lower than that in lightly doped emitters (1 ps for 5×10^{17} cm^{-3}) under high-current operation (above 1×10^4 A/cm^2). This is because τ_E is affected by excess charge accumulation due to the built-in electric field at the cap/emitter (n^+-GaAs/n-AlGaAs) isotype heterojunction, more than at the emitter/base (n-AlGaAs/p^+-GaAs) heterojunction under high-current operation. This electrical behavior of the cap/emitter junction is not an intrinsic phenomenon, but a kind of parasitic one. However, since the n^+-GaAs cap layers are indispensable for actual HBT's, the simulation presented here suggests a new guideline for cap/emitter doping in AlGaAs/GaAs HBT's.

§2. Device Modeling

The carrier behavior in AlGaAs/GaAs HBT's is analyzed by two-dimensional simulation using a classical drift-diffusion model in which the electrostatic potentials and carrier-density distribution in the HBT are obtained from the self-consistent calculation of Poisson's equation and the current continuity equation, as Otoshi *et al.*[6] and Mizuta *et al.*[7] reported.

In this simulation, the carrier recombination process is assumed to follow the Shockley-Read-Hall model with a carrier lifetime of 1 ns for electrons and holes. The dependence of the electron drift velocity on the internal electric field is assumed to be as given by Yoshida *et al.*,[8] in which the saturation level of drift velocity is assumed to be 10^7 cm/s at 10^4 kV/cm. The conduction-band and valence-band discontinuities, ΔE_c and ΔE_v, at the $Al_{0.3}Ga_{0.7}As$/GaAs heterojunction are assumed to be 60% and 40% of the Γ-band energy-gap difference. We use the DX center model for n-$Al_{1-x}Ga_xAs$ emitters, assuming Fermi-Dirac statistics for the ionized deep-donor density.[7] The donor energy level in n-$Al_{1-x}Ga_xAs$ measured from the conduction-band edge is assumed to be 60 meV at $x=0.3$.

The cut-off frequency f_T of the bipolar transistor is estimated from the following formula:[8]

$$f_T=1/2\pi\tau_{EC}, \tag{1}$$

where τ_{EC} is the delay time from the emitter to the collector. The delay time τ_{EC} is obtained by evaluating the increase in excess charge corresponding to an increase in collector current, i.e.,

$$\begin{aligned}\tau_{EC}&=\tau_E+\tau_B+\tau_C\\&=(\Delta Q_E/\Delta J_c)+(\Delta Q_B/\Delta J_c)+(\Delta Q_C/\Delta J_c),\end{aligned} \tag{2}$$

where J_c is the collector current, and delay times τ_E, τ_B, and τ_C are defined by the transit and charging times of the excess charge in the emitter, base, and collector regions, respectively. Q_E, Q_B, and Q_c represent the total charge of excess electrons in each region.

§3. Calculated Results and Discussion

The doping and Al composition profiles of the AlGaAs/GaAs HBT are shown in Fig. 1, which is for the conventional device structure, except for the emitter doping. The donor density of the emitter, denoted Ne, is varied from 5×10^{17} cm^{-3} to 5×10^{18} cm^{-3}. A 50-nm-thick graded $Al_xGa_{1-x}As$ (x: 0–0.3) is introduced between the cap and emitter.

The calculated energy-band diagrams, and electron and hole density distributions under four bias conditions ($V_{be}=0$, 1.2, 1.5, and 1.7 V, $V_{ce}=2$ V) for HBT's with Ne$=1\times10^{18}$ cm^{-3} are shown in Figs. 2(a), 2(b), 2(c) and 2(d). Note that the number of holes injected into the emitter region increases as the forward-bias voltage increases. At a high forward bias, such as $V_{be}=1.5$ V or 1.7 V, it is likely that injected holes will strongly affect the carrier distribution in the emitter, as described later.

The dependence of the delay times τ_E, τ_B, and τ_C on the collector current are shown in Figs. 3(a) and 3(b) with Ne

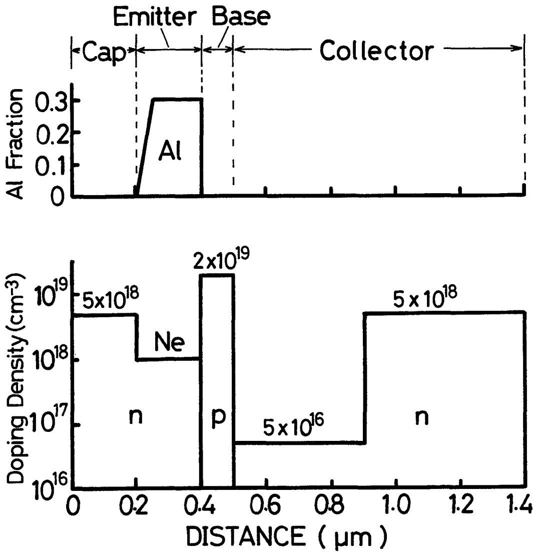
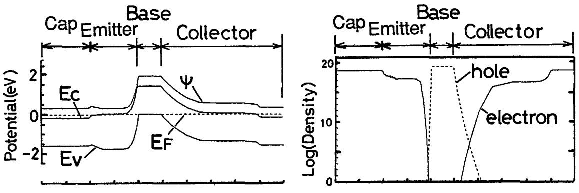
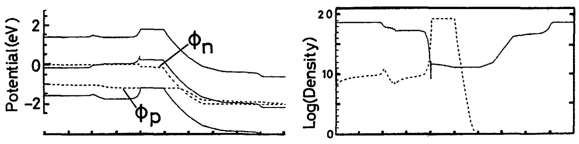


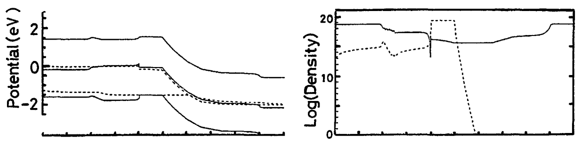
Fig. 1. Doping and Al composition profiles of the AlGaAs/GaAs HBT used in the simulation.



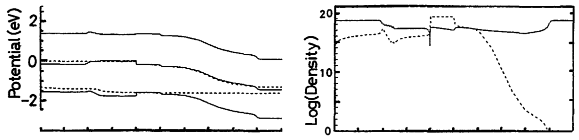
(a) Vbe = 0 , Vce = 0



(b) Vbe=1.2 v , Vce= 2 v

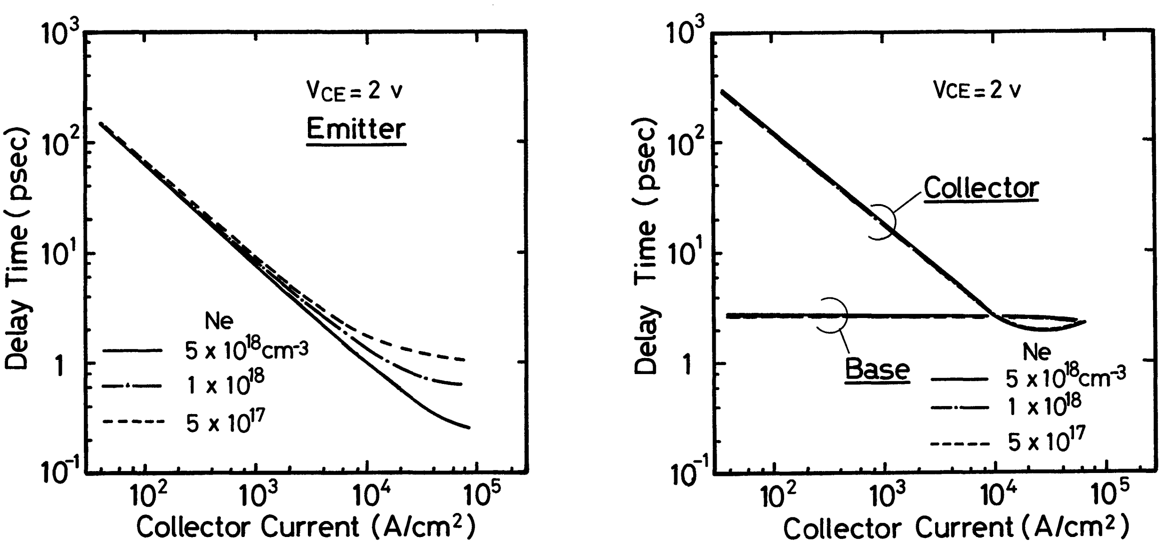


(c) Vbe =1.5 v , Vce = 2 v



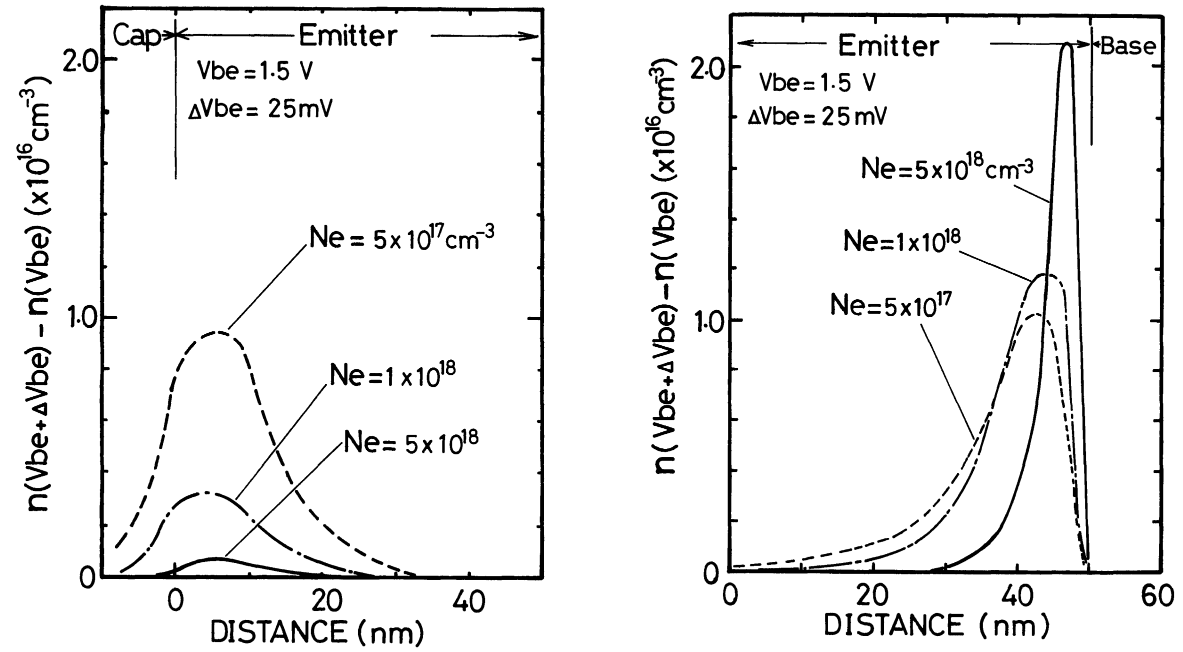
(d) Vbe=1.7 v , Vce = 2 v

Fig. 2. Calculated profiles of energy band structures and carrier densities under four different bias conditions: (a) base-emitter bias voltage (V_{be}) is zero, collector-emitter bias voltage (V_{ce}) is zero, (b) $V_{be}=1.2$ V, $V_{ce}=2.0$ V, (c) $V_{be}=1.5$ V, $V_{ce}=2.0$ V, and (d) $V_{be}=1.7$ V, $V_{ce}=2.0$ V.



(a) (b)

Fig. 3. Collector current density versus calculated delay time with emitter doping density Ne as a parameter. (a) Emitter delay time (τ_E) (b) Base and collector delay times (τ_B, τ_C).



(a) (b)

Fig. 4. Calculated profiles of the increase in excess electrons ($n(V_{be}+\Delta V_{be})-n(V_{be})$) induced by a small change in emitter/base bias voltage ($\Delta V_{be}=25$ mV) for $V_{be}=1.5$ V with the emitter doping density (Ne) as a parameter. (a) At the cap/emitter junction. (b) At the emitter/base junction.

as a parameter. The base delay time τ_B and the collector delay time τ_C shown in Fig. 3(b) are independent of Ne. τ_B is independent of J_c, because τ_B corresponds to the transit time, as determined by the diffusion of minority carriers into the base. The decrease in τ_C with increasing J_c is due to the reduction in charging time of the base-collector capacitance. The minimum τ_C, about 2 ps, corresponds to the carrier transit time in the collector depletion layer with a saturation velocity of 10^7 cm/s. The increase in τ_C at a J_c higher than 4×10^4 A/cm^2 may be due to an expansion of the collector depletion layer caused by the high injection current, as shown in Fig. 2(d).

The emitter delay time τ_E decreases with increasing Ne, as shown in Fig. 3(a). For instance, the minimum τ_E is about 0.2 ps for Ne$=5\times10^{18}$ cm^{-3}. These results show that τ_E of AlGaAs/GaAs HBT's can be reduced by increasing Ne under high-current operation.

In order to understand the dependence of τ_E on Ne shown in Fig. 3(a), we examined the profiles of the small increases in the number of excess electrons in the emitter region, denoted $n(V_{be}+\Delta V_{be})-n(V_{be})$ ($=\Delta n(V_{be})$), induced by small changes ($\Delta V_{be}=25$ mV) in the emitter/base bias voltage for $V_{be}=1.5$ V ($J_c\approx10^4$ A/cm^2). The calculated results for the vicinity of the emitter/base junction and the cap/emitter junction are shown in Figs. 4(a) and 4(b). Note that the dependence of $\Delta n(V_{be})$ on Ne is apparent for the cap/emitter junction but not for the emitter/base junction. These results show that τ_E is determined by excess electrons at the cap/emitter junction as well as at the emitter/base junction. In addition, the Ne dependence of τ_E corresponds to the Ne dependence of $\Delta n(V_{be})$ at the cap/emitter junction. As mentioned above, the distribution of excess electrons in the emitter should be influenced by the number of injected holes. The distribution of electrons and holes near the cap/emitter junction at $V_{be}=1.5$ V is shown in Fig. 5. It is clear that the number of injected holes is reduced by increasing emitter doping. It is also shown that injected holes accumulate near the cap/emitter junction due to the built-in electric field of the n$^+$-GaAs/n-AlGaAs isotype heterojunction. Therefore, the reduction of emitter delay time by higher emitter doping is due to the suppression of injected holes accumulating at the built-in electric field at the cap/emitter (n$^+$-GaAs/n-AlGaAs) heterojunction.

On the other hand, at a low bias of $V_{be}=1.2$ V, since the number of injected holes accumulating at the cap/emitter junction is $\sim10^{12}$ cm^{-3}, (Fig. 2(b)), (which is

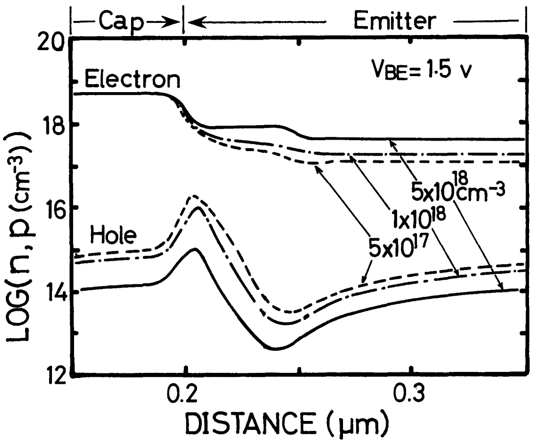


Fig. 5. Distributions of electrons and holes near the cap/emitter junction under a forward bias of $V_{be}=1.5$ V with the emitter doping density (Ne) as a parameter.

much lower than that for $V_{be}=1.5$ V in Fig. 5), τ_E is mainly determined by the number of excess electrons at the emitter/base junction, which is independent of Ne, as shown in Fig. 4(b). This is why τ_E is independent of Ne at currents less than 10^3 A/cm^2, as shown in Fig. 3(a).

§4. Conclusions

In conclusion, we have analyzed the influence of the emitter doping levels in AlGaAs/GaAs HBT's on emitter delay time by two-dimensional numerical simulation based on a drift-diffusion model. It has been shown that the emitter delay time decreases with higher emitter doping under high-current operation. This is because a higher emitter doping suppresses the undesirable accumulation of injected holes at the built-in electric field of the cap/emitter (n^+-GaAs/n-AlGaAs) isotype heterojunction. This electrical behavior of the cap/emitter junction is a kind of parasitic phenomena and is basically independent of the intrinsic part of HBT's. However, since the n^+-GaAs cap layers are indispensable for actual HBT's, these results suggest new guidelines for cap/emitter doping in AlGaAs/GaAs HBT's.

References

1) T. Ishibashi, H. Nakajima, H. Ito, S. Yamahata and Y. Matsuoka: *48th Annual Device Res. Conf., Santa Barbara, California, 1990* (IEEE, New York, 1990).
2) W. J. Ho, N. L. Wang, M. F. Chang, A. Sailer and J. A. Higins: *50th Annual Device Res. Conf., Cambridge, Massachusetts, 1992* (IEEE, New York, 1992).
3) H. Kroemer: Proc. IEEE **70** (1982) 13.
4) O. Nakajima, H. Ito, T. Nittono and K. Nagata: *IEEE-IEDM, Technical Digest* (IEEE, New York, 1990) p. 673.
5) T. Ishibashi and Y. Yamauchi: IEEE Trans. Electron Devices **ED-35** (1988) 401.
6) T. Otoshi, K. Yamaguchi, C. Nagaoka, T. Uda, Y. Murayama and N. Chinone: Solid-State Electron. **30** (1987) 627.
7) H. Mizuta, K. Yamaguchi, M. Yamane, T. Tanoue and S. Takahashi: IEEE Trans. Electron Devices. **ED-36** (1989) 2307.
8) J. Yoshida, M. Kurata, K. Moritsuka and A. Hojo: IEEE Trans. Electron Devices **ED-32** (1985) 1714.