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High Current Gain AlGaAs/GaAs Heterojunction Bipolar Transistors with Heavily Doped Base

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Current gain in AlGaAs/GaAs heterojunction bipolar transistors (HBTs) and bias voltage dependence of the luminescence intensity in AlGaAs/GaAs heterojunction diodes (HD) are investigated. Junction ideality factors for emitter-base junction in HBT are near unity, which is consistent with the luminescence intensity dependence on the bias voltage in HD. Current gain reduction in heavily doped base HBT is interpreted as a result of a nonradiative recombination current in the base region. Practical high current gain of 80 has been achieved in the HBT whose base doping is 2×10^{19} cm^{-3}.

§1. Introduction

A great advantage of heterojunction bipolar transistors (HBTs) is the low base resistance using a heavily doped base layer without reducing current gain. In the HBT structure, the minority carrier injection from the base to a wide gap emitter can be prevented because of a large energy barrier in the valence band.[1] Extremely high current gain of HBTs up to 5500 was demonstrated[2] employing relatively low base doping of 2×10^{18} cm^{-3}. However, in practical transistor operation, a higher base doping ($p \gtrsim 1 \times 10^{19}$ cm^{-3}) is desirable. Reported current gains of heavily base doped HBT's were rather low (135 for 1×10^{19} cm^{-3} doped base,[3] 25 for 2×10^{19} cm^{-3} doped base[4]). Although the current gain has a tendency to reduce increasing the base doping level, its reduction mechanism has not been studied. This paper describes current gain characteristics of MBE grown AlGaAs/GaAs HBT with a heavily doped base layer. The temperature dependence of current gain is explained by the introduction of nonradiative recombination centers due to higher Be doping.

§2. Experiments

2.1 Diode fabrication

Prior to investigating the HBTs, N-AlGaAs /p^+-GaAs diodes with abrupt heterojunction were fabricated and the bias voltage dependence of luminescence intensity from the p^+-GaAs layer was measured. The epitaxial layer structure parameters of the heterojunction diode grown on a (100) oriented Zn doped GaAs substrate by molecular beam epitaxy are shown in Fig.1(a). The substrate temperature during the growth was 650°C. Dopants employed for n and p type layers were Si and Be, respectively. Al content in N-AlGaAs is 30 %. The wafer was mesa etched making diodes with a 200 x 300 μm^2 area, and AuGe/Ni/Ti/Au[5] ohmic contacts were fabricated on n^+-GaAs by a liftoff process. The diode has a 100 x 100 μm^2 window in the ohmic contact metal for observing the luminescence. The backside of the wafer was metalized with Cr/Au. Ohmic sintering was performed at 370°C in a pure H_2 atmosphere for 30 seconds.

	Thickness(Å)	Doping(cm^{-3})
n^+ GaAs	2000	3×10^{18}
N $Al_{0.3}Ga_{0.7}As$	10000	5×10^{17}
p^+ GaAs	10000	1×10^{19}
p^+ GaAs sub.		2×10^{19}

Fig.1(a) Epitaxial layer structure parameters of the heterojunction diode.

2.2 HBT fabrication

The epitaxial layer structure parameters of the HBTs grown on the (100) oriented semi-insulating GaAs substrate are shown in

	Thickness(Å)	Doping(cm^{-3})
n^+ GaAs	2000	3×10^{18}
N $Al_{0.3}Ga_{0.7}As$	1000	5×10^{17}
p^+ GaAs	1000	1×10^{19}, 2×10^{19}
n GaAs	3000	1×10^{17}
n^+ GaAs	10000	3×10^{18}
S.I. GaAs sub.		

Fig.1(b) Epitaxial layer structure parameters of the heterojunction bipolar transistor.

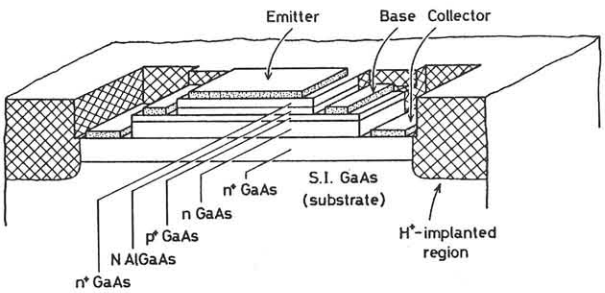

Fig.2 Schematic device structure of fabricated HBT.

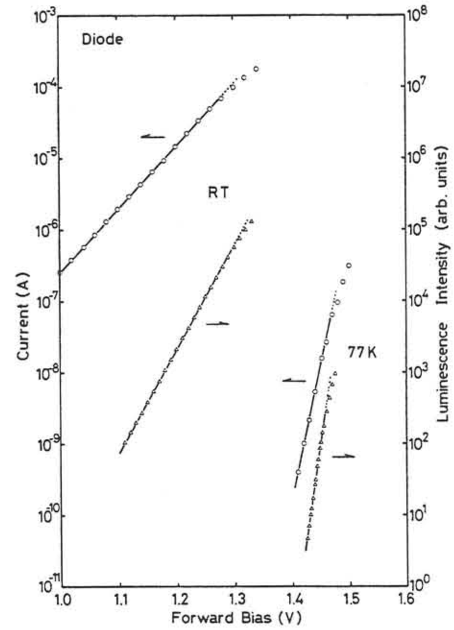

Fig.3 Bias voltage dependence of diode current and of luminescence intensity in heterojunction diodes at RT and 77 K. Junction area is 200 x 300 μm^2.

Fig.1(b). Abrupt emitter-base junction with Al content of 30 % for the emitter was employed. Two kinds of base doping of 1×10^{19} and 2×10^{19} cm^{-3} were examined with a constant base width of 1000 Å. An undoped GaAs spacer layer of 100 Å between the emitter and the base layer was utilized to prevent the shift of pn junction into AlGaAs layer due to Be diffusion. Fig.2 shows the schematic device structure of fabricated HBT, which has the emitter area of 50 x 50 μm^2. The base and collector layers were recessed by wet chemical etching to fabricate contacts. The ohmic metal, AuGe/Ni/Ti/Au was used for the emitter and collector, and Cr/Au for the base. Contact patterns were defined by the conventional liftoff process. Inter-device isolation was provided by proton implantation.

§3. Results and Discussion

The bias voltage dependencies of diode currents and diode luminescence intensities at room temperature (RT) and 77 K are shown in Fig.3. Here, the measurements were performed in a low current density range to reduce the series resistance effect in the n^+ GaAs layer. Diode current and the luminescence intensity have the exponential relationship $\propto \exp(qV/nkT)$ to the diode bias voltage. At 77 K, to obtain the same magnitude of diode current and luminescence intensity as those in the RT results, higher bias voltage is required because of the saturation current temperature dependency. Ideality factor (n) deduced from the slope of I-V characteristics in Fig.3 is 1.8 both at RT and at 77 K, indicating that the recombination current in the pN junction depletion layer is the dominant portion of the diode current in the low bias region. In contrast with the I-V characteristics, the n value deduced from the slope of V-L characteristics in Fig.3 is 1.1 both at RT and 77K. Luminescence intensity is proportional to the number of electrons which diffuse across the pN junction to the p^+ neutral layer at low injection. Therefore the results of the luminescence indicate that the electron injection current characteristics of pN heterojunction can be expressed by an exponential relationship, with $n \cong 1$; $I \propto \exp(qV/kT)$ regardless of the total junction current, both at RT and at 77K. Similar electron injection characteristics are considered

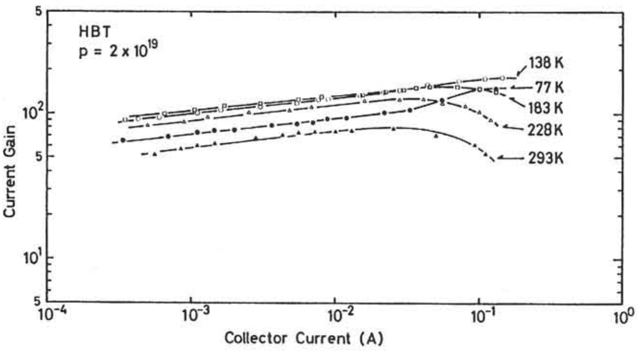

Fig.4(a) Collector current dependence of current gain for 2 x 10^{19} cm^{-3} base doped HBT with various temperatures.

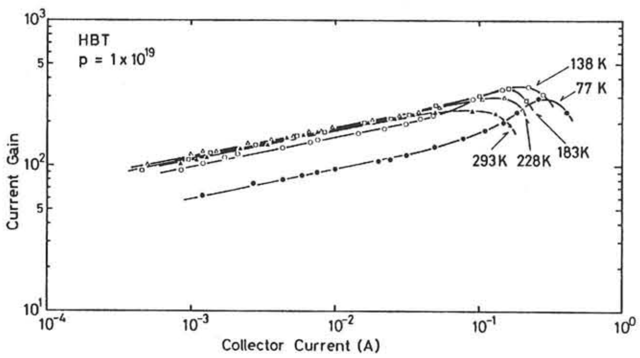

Fig.4(b) Collector current dependence of current gain for 1 x 10^{19} cm^{-3} base doped HBT with various temperatures.

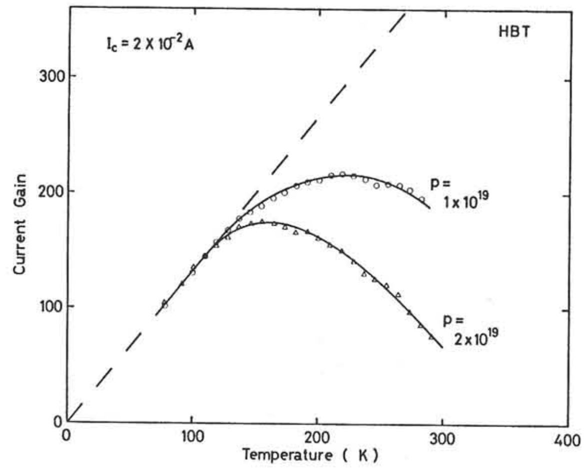

Fig.5 Temperature dependence of current gain for different base dopings.

to hold true for emitter-base junction of HBT structure.

The collector current dependencies of current gain with various temperatures for the HBT with a base doping of 2 x 10^{19} cm^{-3} are shown in Fig.4(a). Current gains increase very slowly with collector current, although thermal influences cause current gains reduction in the high collector current region over 10^{-1} A. Ideality factors deduced from the slope of the curves in Fig.4(a) are 1.1 for each temperature in the current range from 3 x 10^{-4} to 3 x 10^{-2} A, which is consistent with that in the diodes case. For the device with a 1 x 10^{19} cm^{-3} doped base, the n values are 1.2 and are independent of temperature in the current range from 1 x 10^{-3} to 5 x 10^{-2} A as shown in Fig.4(b). These near unity ideality factors show that the recombination current in the emitter-base junction is negligibly small for a high current density region and then the current gain is determined by the electron lifetime in the base layer. A small n value deviation from unity is not responsible for the recombination current as shown in the diode case and may be regarded as the effect of a spike in the abrupt heterojunction proposed by Marty et al.[6] The HBT current gain with two different base dopings at a collector current of 2 x 10^{-2} A are plotted again in Fig.5 as a function of temperature. In a higher temperature region, current gains increase with decreasing temperatures. However, at a lower temperature, current gains decrease with decreasing temperatures.

Current gain of the bipolar transistor is expressed by the following equation, neglecting the hole injection from the base to the emitter:

$$\beta = 1 / (\cosh(W_B/L_n)-1)$$

where β is the current gain, W_B is the base width and L_n is the electron diffusion length in the base region. Diffusion length is expressed as follows:

$$L_n = \sqrt{D_n \tau_n}$$

where D_n is the electron diffusion constant and τ_n is the electron lifetime in the base region. Assuming that electron mobility in the high doped p^+ region is independent of temperature, the diffusion constant has a linear variation with temperature according to the Einstein's relation, as follows:

$$D_n = \mu kT/e$$

where μ is the electron mobility in the base region, k is a Boltzman constant, T is temperature and e is an electron charge. Therefore, in cases where the radiative electron lifetime which is independent of temperature[7] is dominant, current gains are proportional to temperature (indicated by the broken line in Fig.5) as reported.[8] If the nonradiative electron lifetime with an exponential relationship to temperature[9] is dominant, current gain must have temperature dependence and reduces as temperature rises. In Fig.5, the temperature dependence of current gains in a low temperature region have linear relationship in the two HBT types, which implies less amount of nonradiative recombinations. Increasing the temperature, the current gains deviate from the linear relationship, and the current gain deviation in 2 x 10^{19} cm^{-3} base doped HBT from the broken line is larger than that of 1 x 10^{19} cm^{-3} base doped HBT. In heavily doped materials, nonradiative recombination centers can be introduced depending on the doping density.[10] Consequently, the stronger temperature variation for higher base doping HBT can be explained by the introduction of a nonradiative recombination center due to higher Be doping. Electron life times at RT deduced from obtained current gain values, assuming the electron mobility in the base 1000 cm/V·s, are 0.40 ns for 1 x 10^{19} cm^{-3} doping and 0.16 ns for 2 x 10^{19} cm^{-3} doping. The 0.16 ns value is about 5 times smaller than the expected value (0.77 ns) extrapolated from the low temperature dependence. Electron diffusion length deduced from the obtained current gain value for a 1 x 10^{19} cm^{-3} doped base HBT is 1 μm at 293 K. Although this value is largely affected by the nonradiative electron lifetime, it is comparable to previously reported values for 1 x 10^{19} cm^{-3} doped LPE grown GaAs, where lifetime is dominated by radiative process.[11] It is expected that the diffusion length becomes effectively larger because of the higher electron temperature than that of the lattice enhanced by the high energy electron injection over the abrupt emitter-base junction.[12] To evaluate the radiative and nonradiative reconbination processes more precisely, further experiments are necessary.

§4. Conclusion

Luminescence characteristics of heterojunction diodes and current gain in HBTs with heavily doped bases were analysed. Generation-recombination current in the depletion layer of the HBT emitter-base junction was negligibly small and the ideality factor was near unity. The current gain reduction mechanism in the HBT was explained in terms of a nonradiative recombination process in the base. Practical high current gain ($\gtrsim 80$) was demonstrated with base doping up to 2 x 10^{19} cm^{-3} over a wide temperature range.

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References

1) H. Kroemer : Proc. IRE 45 (1957) 1535.
2) C. Dubon, R. Azoulay, P. Desrousseaux, J. Dangla, A. M. Duchenois, M. Hountondji and D. Ankri : IEDM 83 Tech. Dig. (1983) 689.
3) D. L. Miller, P. M. Asbeck and W. Petersen : Collected Paper of MBE-CST-2 (1982) 121.
4) J. R. Hayes, F. Capasso, R. J. Malik, A. C. Gossard and W. Wiegmann : IEDM 83 Tech. Dig. (1983) 686.
5) H. Ito, T. Ishibashi and T. Sugeta : to be published.
6) A. Marty, G. Rey and J. P. Bailbe : Solid State Electron. 22 (1979) 549.
7) D. I. Kladius and P. C. Euthymiou ; J. Appl. Phys. 45 (1974) 2775.
8) M. Koyanagi, M. Katsukawa and K. Takahashi : J. Appl. Phys. 48 (1977) 4389.
9) C. H. Henry and D. V. Lang : Phys. Rev. B15 (1977) 989.
10) H. C. Casey and F. Stern : J. Appl. Phys. 47 (1976) 631.
11) H. C. Casey Jr., B. I. Miller and E. Pinkas : J. Appl. Phys. 44 (1973) 1281.
12) T. Ishibashi, H. Ito and T. Sugeta : to be published.