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HIGH CURRENT GAIN AlGaAs/GaAs HETEROJUNCTION BIPOLAR TRANSISTOR GROWN BY MOLECULAR BEAM EPITAXY

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Abstract—The fabrication and characteristics of *Npn* AlGaAs/GaAs single heterojunction bipolar transistors (HBTs) with an emitter edge-thinning structure have been studied. A new and simple selective wet etching method was used to make the emitter edge-thinning structure. The best device obtained shows a common emitter differential current gain of 8700. To our knowledge, this is the highest current gain of AlGaAs/GaAs HBT grown by MBE reported to date. The Gummel plot of this device is analyzed and compared with another HBT which has no emitter edge-thinning structure and was fabricated on the same epiwafer. It is found that the base current of the emitter edge-thinning device is one-tenth smaller than that of the controlled device. In low current region, the effect of emitter edge-thinning structure is even more significant. Because of the reduction of 2-kT surface recombination current, the emitter edge-thinning device reveals its intrinsic 1-kT base current in high current region.

1. INTRODUCTION

AlGaAs/GaAs heterojunction bipolar transistors (HBTs) are gaining more and more attention in many applications such as high speed digital and microwave circuits for their capability of high frequency operation[1–3]. In an *Npn* HBT, since the electron injection efficiency is very close to 1, the base doping level can be increased without degrading the current gain[4]. However, due to the high surface state density of GaAs, the emitter injection efficiency, and thus the current gain, is limited by the surface recombination current at emitter–base junction perimeter. This problem is especially annoying for the scaling down of the device at high frequency operation[5].

Emitter edge-thinning structure was first proposed to reduce the surface recombination current of AlGaAs/GaAs HBT by Lin *et al.*[6]. However, the fabrication process is very crucial. In this study, we report a new and simpler selective wet etching method to make the emitter edge-thinning structure and detailed analysis on the device characteristics. The best result of the fabricated device shows a common emitter differential current gain of 8700. To our knowledge, this is the highest current gain of AlGaAs/GaAs HBT grown by MBE reported to date. In low current region, the device also has very good performance. A high current gain of 800 is achieved at a base current as low as 5 nA. The Gummel plot of this device is analyzed and compared with another HBT which has no emitter edge-thinning structure and was fabricated on the same epiwafer. It is found that the base current of the emitter edge-thinning device is one-tenth smaller than that of the controlled device. In low current region, the effect of emitter edge-thinning structure is even more significant. The saturation current of the 2-kT surface recombination current is found to decrease as the bias voltage decreases. Because of the reduction of 2-kT surface recombination current, the emitter edge-thinning device reveals its intrinsic 1-kT base current in high current region.

2. DEVICE FABRICATION

The epilayers were grown on Si-doped (100) GaAs substrate using a VG V-80H MBE system. The layer structure is summerized in Table 1. In this structure, the 200-Å-thick undoped GaAs spacer layer and the following 500-Å-thick undoped $Al_xGa_{1-x}As$ grading layer were inserted between the 1500-Å-thick Be-doped GaAs base and the Si-doped $Al_{0.5}Ga_{0.5}As$ emitter. The purposes of these two layers are two-fold, to eliminate the effect of the heterojunction spike and to be used to form the depleted emitter edge-thinning structure. A 1000-Å-thick n^+-$Al_{0.5}Ga_{0.5}As$ highly doped emitter and a 500-Å-thick n^+-$Al_xGa_{1-x}As$ grading layer followed by a 2000-Å-thick n^+-GaAs cap layer were grown on the top of the emitter for the preparation of ohmic contact.

To begin with the device fabrication, the Au/Ge/Ni ohmic contact was first lifted-off on the cap layer. The collector contact which was also Au/Ge/Ni alloy was formed on the back of the wafer. Both contacts were alloyed simultaneously at 430°C for 30 s in H_2 ambience. The emitter edge-thinning structure was formed by using the following steps. After the emitter was defined by photolithography, the cap layer, highly doped grading layer and part of the emitter

Table 1. The designed layer structure of the *Npn* AlGaAs/GaAs HBT

Layer	Material	Doping (cm^{-3})	Thickness (Å)
Cap	GaAs	5×10^{18}—Si	2000
Grading 2	AlGaAs	5×10^{18}—Si	500
Hi-emitter	AlGaAs	5×10^{18}—Si	1000
Emitter	AlGaAs	1.7×10^{17}—Si	4000
Grading 1	AlGaAs	—	500
Spacer	GaAs	—	200
Base	GaAs	5×10^{17} – Be	1500
Lo-collector	GaAs	—	2000
Collector	GaAs	1.7×10^{17}—Si	6000
Buffer	GaAs	5×10^{18}—Si	2000

layer were etched away using a nonselectively etching solution, 1 H_2SO_4:1 H_2O_2:24 H_2O. The etching depth was approximately 6000-Å-thick. Then, a buffered hydrofluoric acid solution, 1 HF:1 H_2O, which selectively etches $Al_xGa_{1-x}As$ as with x larger than 0.45, was used. This selective etching solution etched away the rest emitter layer and stopped in the undoped grading layer. A photomask was used to define the emitter edge-thinning region and the base contact region simultaneously. The 1 H_2SO_4:1 H_2O_2:24 H_2O solution was then used to expose the base layer, and thus resulted in a thin ledge around the emitter. This thin ledge structure, i.e. the emitter edge-thinning structure, is composed of the undoped AlGaAs grading layer and the undoped GaAs spacer layer. Its width and thickness are 15 μm and 600 Å, respectively. Au/Zn was then evaporated and lifted-off onto the exposed base to form the base contact. Finally, devices were isolated using a faster 1 H_2SO_4:8 H_2O_2:55 H_2O etchant. Figure 1 shows the schematic diagram of a finished HBT. The effective emitter is circular with a diameter of 130 μm.

In order to examine the effect of the emitter edge-thinning structure, a low base doping of 5×10^{17} cm^{-3} was used. Therefore, the intrinsic 1-kT base current will be very small, and we can pay all our attention to the 2-kT surface recombination base current. For comparison, another controlled HBT without emitter-edge thinning structure, was fabricated on the same epiwafer.

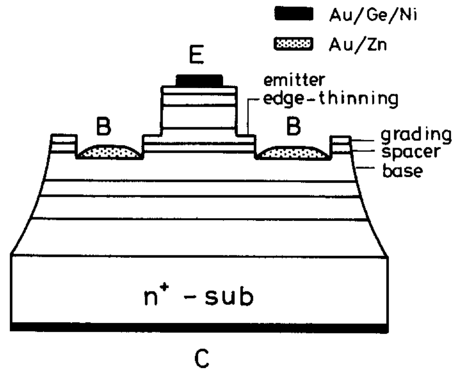

Fig. 1. The schematic diagram of a finished emitter edge-thinning AlGaAs/GaAs HBT. The effective emitter is circular with diameter of 130 μm. The width of the thinned emitter ledge is 15 μm.

3. RESULTS AND DISCUSSION

The common emitter output characteristics of the emitter edge-thinning device is shown in Fig. 2(a). As can be seen, a differential current gain as high as 8700 is obtained. To our knowledge, it is the highest value of AlGaAs/GaAs HBT grown by MBE reported to date. Because the base is low doped, early effect is clearly seen in this output characteristics. Figure 2(b) shows the common emitter output characteristics of the same device in low collector current region. The step of base current is only 5 nA. A considerably high current gain of 800 is still obtained. It exhibits that the emitter edge-thinning design greatly improves the characteristics in low operating current. This is useful in the application of phototransistors since they are operated at low

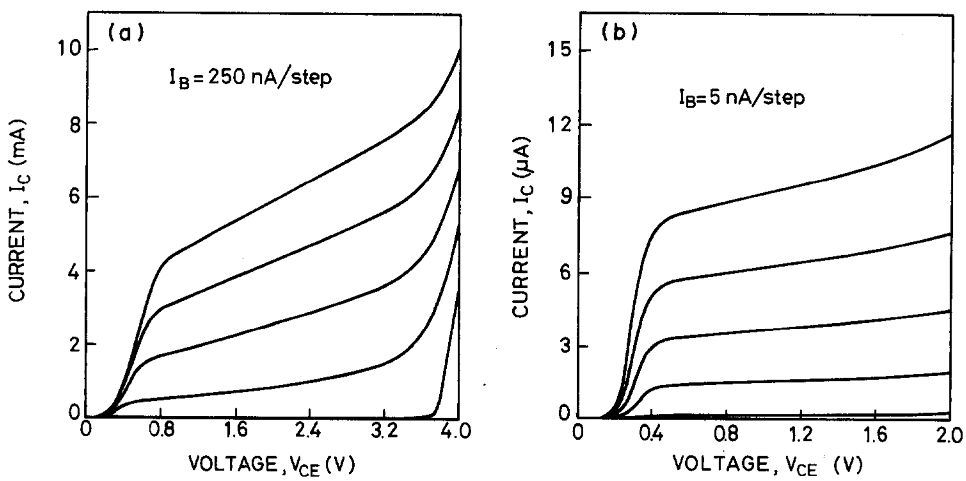

Fig. 2. (a) The common-emitter output characteristics of the emitter edge-thinning AlGaAs/GaAs HBT. The base current per step is 250 nA. The differential current gain is 8700. (b) The common emitter output characteristics of the emitter edge-thinning AlGaAs/GaAs HBT at low current operation. The base current per step is 5 nA. The differential current gain is 800.

current level. The offset voltage obtained is only 0.1 V, which indicates that the heterojunction spike has been suppressed successfully[7].

Figure 3 shows the Gummel plots of the emitter edge-thinning device and controlled device. Under the measurement, their base-collector junctions were fixed at zero biased to avoid the Early effect as can be seen in Fig. 2(a). The solid lines represent the currents of the emitter edge-thinning device. In low current region, the junction ideality factor of the collector current is 1.03, which indicates no heterojunction spike existing in emitter-base junction[8]. And the junction ideality factor of the base current, instead of 2, shows a lower value of 1.10, which indicates an unusual current transport mechanism and will be discussed later. The dashed lines represent the currents of the controlled device. As can be seen, the collector current is almost the same as that of the emitter edge-thinning device and the junction ideality factor is also 1.03. But its base current is at least one order of magnitude higher than that of emitter edge-thinning device in low current region. The junction ideality factor is 1.85, which is close to 2 and is the typical value of surface recombination current[9]. Comparing the base current levels and junction ideality factors, it is clear that the emitter edge-thinning structure indeed decreases the base current and thus greatly improves the current gain of AlGaAs/GaAs HBT.

In Fig. 3, not only the collector current but also the base current of the emitter edge-thinning device has a close to unity junction ideality factor. Therefore, the common emitter current gain should be slightly dependent on the collector current level. But, as can be seen in Fig. 2(a) and (b), the device shows a current gain of 800 in low current region but a 10-times larger current gain of 8700 in high current region. Because the junction ideality factors were determined from the lower linear section of the Gummel plot, the above discussion indicates that in the higher curved

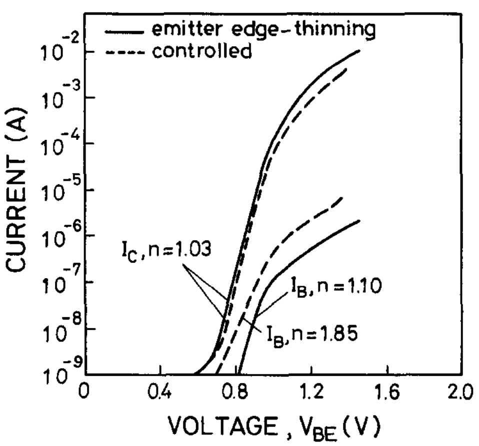

Fig. 3. The Gummel plot, which was measured with base and collector zero biased and base-emitter forward biased. The solid lines show the currents of the emitter edge-thinning HBT and the dashed lines the controlled HBT.

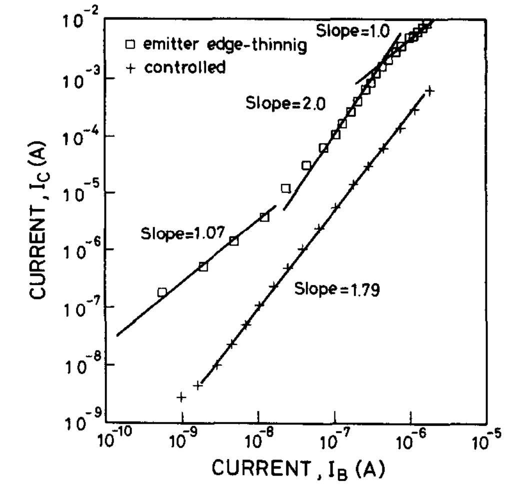

Fig. 4. The redrawing of the collector current vs base current of the emitter edge-thinning HBT and the controlled HBT shown in Fig. 3.

section of the Gummel plot, although embedded in series resistance effect, the behavior, i.e. the junction ideality factor, of the base current must be changed. In order to see how it changes, Fig. 3 is replotted and is shown in Fig. 4. In this I_C vs I_B plot, the series resistance effect does not appear. The series resistance causes extra voltage drop and increasing V_{BE}. Since V_{BE} is not involved in Fig. 4, the series resistance effect disappears. It can be shown that the slope of the curves in Fig. 4 is the ratio of the ideality factor of I_B to that of I_C. The square and cross points represents the characteristics of the emitter edge-thinning device and the controlled device, respectively. As can be seen, the slope of the controlled device curve is 1.79 which is just the ratio of the junction ideality factors measured from Fig. 3. Notice that the slope keeps unchanged even in high current region. It indicates the behavior of its base current does not change in our measurement range. However, the curve of the emitter edge-thinning device shows very complicated characteristics. In low current region, the slope is 1.07 which is just the ratio of the junction ideality factors measured from Fig. 3. But, in higher current region, the slope approaches to 2. Because the junction ideality factor of the collector current is 1.03, it indicates that the junction ideality factor of the base current changes from 1.10 to 2. We believe that this change is not due to the competition between two different base currents. The reason is that 1.10-kT current increases much faster than 2-kT current does when the bias voltage increases. If there were two base currents, the 2-kT current would not dominate in high current region. Our explanation on this change is as follows. There is only one base current, i.e. 2-kT surface recombination current. With decreasing bias voltage, the depletion region of the base-emitter junction expands, and the emitter edge-thinning region of the device gets better pinch-off. Therefore, the saturation current of the 2-kT surface recombination current decreases[6]. The decreasing saturation current distorts the junction ideality factor, and the base current looks like 1.10-kT current in low current region.

In much higher current region, it is found that the slope of the curve of the emitter edge-thinning device changes from 2 to 1. The change of collector current is impossible because the collector current density on the turning point is only 10 A/cm^2. In such current density, high injection effect, Kirk effect or current crowding effect will not occur. We believe that this change is due to the appearance of the intrinsic 1-kT base current. Because of the very high injection efficiency due to the wide band gap emitter, this 1-kT base current must be the transport loss current in the neutral base region. The ratio between the collector current and this 1-kT base current can be determined from Fig. 4. It is about 5000, slightly less than the maximum differential current gain because of less Early effect. Electron diffusion length derived from this current gain is 7.5 μm, which reveals that the material quality of the MBE grown base is good.

4. CONCLUSIONS

The fabrication and characteristics of *Npn* AlGaAs/GaAs HBT with emitter edge-thinning structure have been studied. A much easier and more reliable auto-etching-stop process is proposed to make the emitter edge-thinning structure. The fabricated device shows a differential current gain as high as 8700. To our knowledge, this is the highest current gain of MBE grown AlGaAs/GaAs HBT reported to date. In low current region, the device also has very good performance, a high current gain of 800 is achieved at a base current as low as 5 nA. Compared with a controlled device, the Gummel plot of the emitter edge-thinning device is analyzed. It is found that the base current of the emitter edge-thinning device is one-tenth smaller than that of the controlled device. In low current region, the effect of emitter edge-thinning structure is even more significant. The saturation current of the 2-kT surface recombination current is found to decrease as the bias voltage decreases. Because of the reduction of 2-kT surface recombination current, the emitter edge-thinning device reveals its intrinsic 1-kT base current in high current region. And the derived electron diffusion length in the base is 7.5 μm, which indicates the quality of the MBE grown GaAs base is quite good.

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