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DC characteristics of $In_{0.52}Al_{0.48}As$/ $In_{0.53}Ga_{0.47}As$/ $In_{0.53}(Al_xGa_{1-x})_{0.47}As$ NPN double heterojunction bipolar transistors

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Introduction

Recently, heterojunction bipolar transistors (HBT's) of InP related materials have received a great deal of interest. Their base materials, i.e., InGaAs and/or InGaAsP(1-4), have superior electrical properties to GaAs. And the material system is suitable for the long-wavelength optical communications(5). So far, high current gain and high unit current gain frequcency have been demonstrated (6-8). Among them, InAlAs/InGaAs heterojunction system owns the largest conduction band discontinuity(9) which can be used for hot electron launching pad (10,11). However, InAlAs/InGaAs HBT's suffer from the problem of poor breakdown characteristics. The main breakdown mechanism is the hot electron enhanced impact ionization taking place in the narrow band gap InGaAs base-collector junction (12). One solution for these problems is to use double heterostructure, i e., double heterojunction bipolar transistors (DHBT's). In this study, wide band gap materials, InAlAs and InAlGaAs, are used in the collector of the DHBTs. Base-collector designs and their effects on the DC characteristics of the DHBTs are investigated.

To use InAlAs or InAlGaAs collector, the most difficult problem is from the heterojunction spike at base-collector junction. It is well known that the spike causes the reach-through and knee-shape effects on the output characteristics of transistors(13). There are two methods being proposed to eliminate these effects. The first is to insert a thin spacer layer of the low band gap material, i. e., InGaAs in our case, between base and collector. The voltage drop across the spacer layer may suppress the heterojunction spike. This method has been successfully used in AlGaAs/GaAs(14) and InP/InGaAs DHBTs(15). The second is simply to grade the heterojunction.

Our first study was on InAlAs/InGaAs DHBTs. Both methods were used. It is found that the first method is not a useful one in InAlAs/InGaAs DHBTs(16), the devices show the reach-through and knee-shape characteristics. This is due to the large conduction band discontinuity between InAlAs and InGaAs. This special property causes a two-dimensional electron gas stored in the base-collector heterojunction and the spike is pushed up. The method of junction grading successfully solved this problem, DHBT with 500-Å-thick graded layer shows no above effects. In order to study how the discontinuity influences the output characteristics, $In_{0.53}(Al_xGa_{1-x})_{0.47}As$ collectors with three different compositions were studied. In these DHBTs, the first method with 300-Å-thick spacer layer was adopted. The sample with $x = 0.75$ still suffer from the effects. However, the reach-through region has been significantly reduced. Samples with $x = 0.5$ and 0.25 do not have the above effects. This explain why the first method can be use in InP/InGaAs DHBT. However, the smaller the composition x, the lower the breakdown voltage. There exists a optimum composition in these DHBT's.

Experiment

The epilayers of the HBT's were grown on (100) Sn-doped n^+-InP substrate by a VG V-80H solid source molecular beam epitaxy (MBE) system. The details of the HBT structures are summerized in Table 1. In this report, the HBT with spacer layer sandwiched between base and collector is called abrupt HBT. There are five $In_{0.53}(Al_xGa_{1-x})_{0.47}As$ collector compositions, 0, 0.25, 0.5, 0.75, and 1, being used. And the corresponding devices are R1, R2, R3, R4, and R5, respectively. On the other hand, the HBT with graded base-collector junction is called graded HBT. For this HBT, there is only one collector material, i. e., InAlAs, and the device is named R6. In this study, abrupt base-emitter junction is adopted for all transistors. The purpose is to perserve the hot electron induced impact ionization.

To fabricate the HBT's, an 1200-Å-thick Au-Ge-Ni was firstly deposited and lifted-off on the cap layer for the emitter ohmic contact. Solution 1 H_3PO_4 : 1 H_2O_2 : 20 H_2O was then used to remove both the cap and the emitter layer to expose the base layer. The followed 1200-Å-thick Au/Ti nonalloyed contact was then deposited and lifted-off on the base layer. Finally, the devices were isolated by mesa etching in a 1 H_3PO_4 : 1 H_2O_2 : 20 H_2O solution. The area of the E-B junction and B-C junction are 3.6×10^{-5} cm^2 and 1.8×10^{-4} cm^2, respectively.

Results and Discussions

Fig.1 is the common emitter output characteristics of abrupt DHBT R5 whose collector material is InAlAs. As can be seen, its current gain is about 480, and the breakdown voltage is 5V which is much better than that of single HBT. As shown in the figure, knee-shape and reach-through effects do exist in this device, and it reveals that the heterojunction spike of the base-collector junction is not successfully suppressed by spacer layer band bending. Because of the large conduction band discontinuity, the p^+-InGaAs/u-InGaAs/N-InAlAs heterojunction has two-dimensional electron gas (2DEG) stored in its notch. Fig 2 shows the base-collector heterojunction band diagram with the 2DEG, The source of these electrons is from the emitter-base injection current. When the electrons are passing the base-collector junction, some of them are trapped into the heterojunction notch. The trapped charges are negative and can replace part of the impurity charges in the P^+-InGaAs depletion region. This will result in a decrease in the voltage drop across the InGaAs spacer layer and P^+-InGaAs depletion region. Since the bias voltage of the base-collector junction remains unchanged, the voltage drop across the N-InAlAs depletion region must increase. The heterojunction spike is thus pushed up and begins to reflect electrons back to base. This will cause a decrease in the transport factor of the transistor and an increase in the minority carrier concentration of the base region. The sheet density of the 2DEG must also increase and the heterojunction spike is thus further pushed up. However, the lowered voltage drop accross the undoped InGaAs spacer layer will allow more electrons to escape from the notch. This, in turn, will pull down the heterojunction spike. Finally, these two mechanisms may reach a balance and a higher heterojunction spike energy is shown in Fig. 2. For abrupt HBT with InAlAs collector, a structure of InGaAs spacer layer as thick as 500 Å was also studied. However, it did not improve the reach-through effect, and the breakdown voltage was even degraded because the spacer layer was thick enough to cause hot electron induced impact ionization.

Fig. 3 shows the common emitter output characteristics of graded HBT with InAlAs collector. Its current gain is 520, it is clearly seen that the reach-through effect and knee-shape effect indeed disappear. In its saturation region, collector current rises very sharply. This indicates the heterojunction spike is smoothed-out. The breakdown voltage is better than 6V which is good enough for device application.

In previous studies on AlGaAs/GaAs and InP/InGaAs DHBT's, 300-Å-thick spacer layer is enough to supress reach-through effect. The different behavior of InAlAs/InGaAs DHBT may be due to its unusual large conduction band discontinuity. In order to prove this point, $In_{0.53}(Al_xGa_{1-x})_{0.47}As$ collectors with three different compositions were studied. Between InGaAs and InAlAs with these compositions, $x = 0.75$, 0.5 and 0.25, the corresponding conduction band discontinuity are 0.4, 0.27 and 0.14eV, respectively. Fig.4 (a) and (b) show output characteristics of an abrupt HBT with x=0.75 InAlGaAs collector in high and low current region, respectively. One can see that the knee shape and reach through characteristics appear in high current region and disappear in low current region. It is evident that that the density of 2DEG depends on the collector current density. The output characteristics of abrupt DHBT R3 is shown in Fig. 5. The collector material of this device is $In_{0.53}(Al_{0.5}Ga_{0.5})_{0.47}As$. As can be seen in the figure, the reach-through effect does not exist in this device. For the other abrupt HBT with $In_{0.53}(Al_{0.25}Ga_{0.75})_{0.47}As$ collector, the reach-through effect also does not appear. From these results, when the discontinuity is less than 0.27 eV, 300-Å-thick can effectively eliminate the reach-through effect.

Fig.6 shows the breakdown voltages of the abrupt and graded HBT's. As can be seen, the smaller the composition x, the lower the breakdown voltage. The devices with InAlAs wide bandgap collector have the highest breakdown voltages among these samples.

Conclusions

In conclusion, it is found that in InAlAs/InGaAs/InAlAs DHBT, the unusual large conduction band discontinuity results in a 2DEG stored in base-collector abrupt junction. This 2DEG will push the heterojunction spike up and cause reach-through effect even with the InGaAs space layer inserted between base-collector junction. Junction grading seems to be the only method to remove the effect. For InAlAs/InGaAs/InAlGaAs DHBT, the smaller the conduction band discontinuity, the less significant the 2DEG effect. When the discontinuity is smaller than 0.27 eV, the knee-shape and reach-through characteristics disappear. However, the smaller the x value, the lower the breakdown voltage.

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Table 1: The layer structures of abrupt and graded DHBT.

Layer	Material	Dopant	Thickness (μm) abrupt (R1-R5)	Thickness (μm) graded (R6)	Doping (cm^{-3})
Cap 1	InAs	Si	0.015	0.015	3×10^{19}
Cap 2	InGaAs	Si	0.1	0.1	3×10^{19}
Cap 3	InAlAs	Si	0.05	0.05	3×10^{19}
Emitter	InAlAs	Si	0.15	0.15	1×10^{17}
Spacer	InGaAs	undoped	0.03	0.03	$\sim 10^{15}$ (n)
Base	InGaAs	Be	0.15	0.15	4×10^{18}
Spacer	InGaAs	undoped	0.03	0.03	$\sim 10^{15}$ (n)
Graded layer	InGaAlAs	Si	–	0.05	$\sim 10^{15}$ (n)
Collector	InGaAlAs	Si	0.4	0.4	2×10^{17}
Buffer	InAlAs	Si	0.2	0.2	3×10^{19}
Substrate	InP	Sn	350	350	1×10^{18}

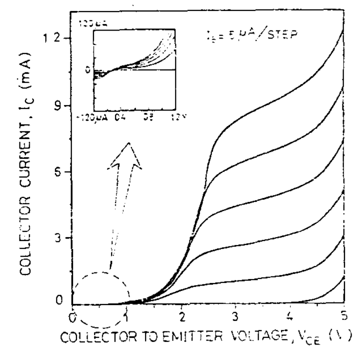


Fig. 1 The common emitter output characteristics of abrupt DHBT R5 whose collector material is InAlAs. The insert of the figure show the detailed I-V characteristics around zero point. In the figure, knee-shape and reach-through effects can be clearly seen.

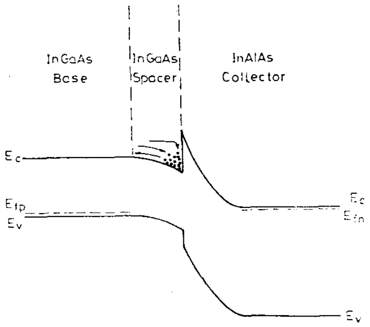


Fig. 2 The base-collector heterojunction band diagram of InAlAs/InGaAs/InAlAs DHBT with the consideration of 2DEG and a pushed-up heterojunction spike which results in knee-shape and reach-through effects.

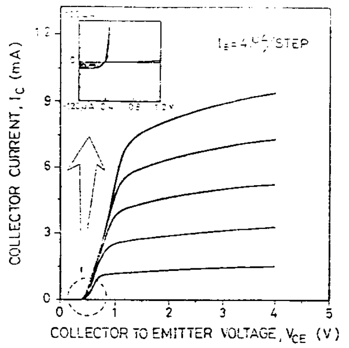
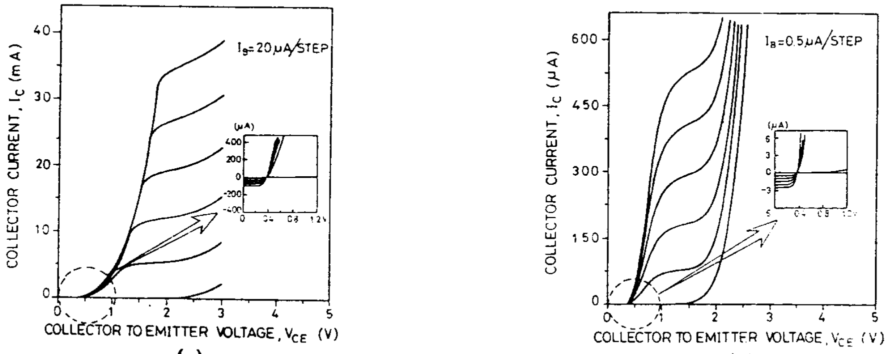


Fig. 3 The common emitter output characteristics of graded DHBT R6 whose collector material is InAlAs. The insert of the figure show the detailed I-V characteristics around zero point. In the figure knee-shape and reach-through effects indeed disappear.



(a)

(b)

Fig. 4 The common emitter output characteristics of abrupt DHBT R4 whose collector material is $In_{0.53}(Al_{0.75}Ga_{0.25})_{0.47}As$ in (a) high current region, and (b) in low current region. The inserts of the figures show the detailed I-V characteristics around zero point.

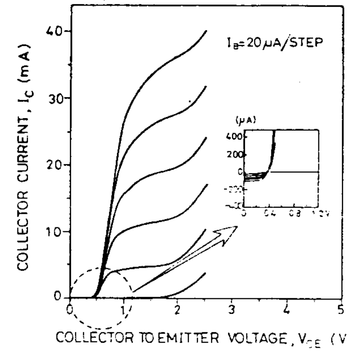


Fig. 5 The common emitter output characteristics of abrupt DHBT R3 whose collector material is $In_{0.53}(Al_{0.5}Ga_{0.5})_{0.47}As$. The inserts of the figures show the detailed I-V characteristics around zero point.

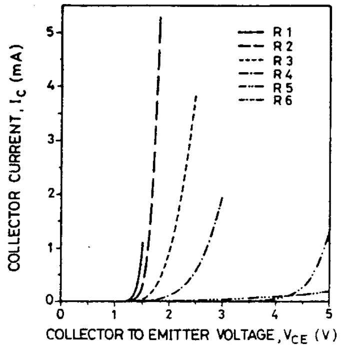


Fig. 6 The common emitter breakdown voltages of the abrupt and graded DHBT. The smaller the composition x, the lower the breakdown voltage.