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GROWTH AND CHARACTERIZATION OF AlGaAs/GaAs HETEROJUNCTION BIPOLAR TRANSISTOR ON GaAs (111)B SUBSTRATE BY MOLECULAR BEAM EPITAXY

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Abstract—The growth and fabrication of AlGaAs/GaAs heterojunction bipolar transistors (HBTs) on GaAs (111)B substrate was studied. The surface morphology of (111)B GaAs epilayers strongly depends on the substrate misorientation and substrate temperature. There is only a very narrow window of substrate temperature for the (111)B GaAs growth. It is found that the base leakage current in the low current region can be suppressed by using 2°-off substrates, a precise control of substrate temperature and As/Ga BEP ratio. Additionally, because of the different surface properties along the (111)B direction, the surface recombination current of HBT on (111)B 2° off substrates is smaller than that on (100) GaAs at a growth temperature of 590°C. Copyright © 1996 Elsevier Science Ltd

1. INTRODUCTION

Due to its small lattice mismatch, AlGaAs/GaAs is the most widely studied heterostructure system. Recent development of improvements in epitaxial growth and processing technologies have shown that AlGaAs/GaAs HBTs are very promising high-gain and high-speed devices for applications in microwave and millimeter wave. Traditionally, AlGaAs/GaAs HBTs are grown on (100) GaAs substrate because (100) is the easiest growth plane for molecular beam epitaxy (MBE) technology. However, there are several studies of growth on (111) GaAs substrates[1–4] because (111) GaAs growth has a lot of interesting properties. Smith[5] predicted that large polarization fields can be generated due to a piezo-electric effect [6–9] in strained superlattices made of zincblende materials grown along the [111] axis. The other important property of this growth orientation is its enhanced direct recombination. Hayakawa *et al.* [10,11] demonstrated the reduction of the threshold current of quantum well lasers by using (111)B substrate. Therefore, the development of optoelectronic integrated circuits (OEIC) based on the integration of photonic devices with AlGaAs/GaAs driving HBTs on (111)B GaAs substrates becomes very important. However, in previous works, Schottky diodes[12] on (111)B GaAs substrate and lateral *pn* junctions[13] on (111)A GaAs substrate possessed very serious leakage current in a low current region under some growth conditions. The suppression of the leakage current and the relationship between the device performance and growth conditions are still not understood. Moreover, it is well known that AlGaAs/GaAs HBTs suffer from the problem of surface recombination current, especially when the dimensions of the devices are scaled down for the sake of high frequency operation. Because of the different surface properties along the (111) direction, the surface recombination current of AlGaAs/GaAs on (111)B GaAs substrate may be different. In this study, the epitaxial growth and characterization of AlGaAs/GaAs HBTs on (111)B GaAs are investigated. The relationship between the base leakage current in the low current region and the growth conditions is also discussed. By using both misoriented substrates and a precise control of growth conditions, the performance of HBTs grown on (111)B GaAs substrates can be improved substantially. In addition, the characteristics of (111)B HBTs are compared with those of (100) devices.

2. EXPERIMENT

The epilayers were grown on (100) and (111)B GaAs semi-insulating substrates. There are three different oriented GaAs (111)B substrates used in this study, exactly (111)B, (111)B 2° off toward (110) and 2° off toward (100). These substrates were chemically cleaned by organic solvent and etched in a $5\,H_2SO_4{:}1\,H_2O_2{:}1\,H_2O$ solution at about 50°C for 120 s. (100) and (111)B GaAs substrates were then In-bonded side by side on the center of a 75 mm molyblock and immediately loaded into a VG V-80H MBE machine. In the preparation chamber, they were outgassed at 300°C for at least 1 h with a final pressure of less than 2×10^{-9} mbar. Before growth, the desorption of surface oxide was evidenced by $\sqrt{19} \times \sqrt{19}$ and 2×4 reflection high energy electron diffraction (RHEED) pattern on (111)B and (100) GaAs substrates, respectively. The growth rate was maintained at 1 μm h^{-1}. As/Ga BEP ratio was estimated by the relationship between the deposition chamber pressure and the As BEP values measured by an ion gauge at the substrate position. For the growth of GaAs epilayers, two different As/Ga BEP values were used: 90 and 30. In this MBE system, the minimum As/Ga BEP ratio to keep in the As-stabilized region, verified by 2×4 RHEED pattern, on (100) GaAs substrate at the growth temperature of 580°C is about 15. Substrate temperature, monitored with an Ircon v-series optical pyrometer with a constant emissivity value of 0.65, was varied from 490 to 710°C. Si and Be are used as the n- and p-type dopants, respectively. After growth, the surface morphology was observed by an optical microscope. The electrical properties were characterized by van der Pauw method at room temperature in a 5-K Gauss magnetic field.

The layer structures of the HBTs in this study are summarized in Table 1. In this table, the doping concentration is given by the order of magnitude, because of the slightly different doping concentrations on (100) and (111)B substrates due to the presence of a defect with donor-like properties within the GaAs epilayers on (111)B substrates[16]. The fabrication processes are described briefly as follows. Au-Ge-Ni was firstly deposited and lifted-off on the cap layer for the emitter ohmic contact. A $4\,H_2SO_4{:}4.5\,H_2O_2{:}90\,H_2O$ solution was then used to remove both the cap and the emitter layer to expose the base layer. Then a Au/Be contact was deposited and lifted-off on the base layer. Again, the $4\,H_2SO{:}4.5\,H_2O_2{:}90\,H_2O$ solution was used to remove the base, undoped collector, and collector layers. Then, Au-Ge-Ni was deposited and lifted-off on the n^+ buffer layer for collector contact. Finally, the device isolation was made by etching to the semi-insulating substrate in a $4\,H_2SO_4{:}4.5\,H_2O_2{:}90\,H_2O$ solution. To study the surface properties on (111)B substrate, a series of emitter areas was made ranging from $10 \times 10\,\mu$m to $100 \times 100\,\mu m^2$. The current–voltage (I–V) characteristics are measured by HP4145B parameter analyzer.

Table 1. The layer structures of HBTs grown on (100) and (111)B GaAs substrates

Layer	Material	Thickness (μm)			
		M511	M572	M736	Doping (cm^{-3})
Cap	GaAs	0.1	0.15	0.1	$\sim 10^{19}$ (n)
Graded	$Al_xGa_{1-x}As$	0.05	0.05	0.05	$\sim 10^{19}$ (n)
Hi-emitter	$Al_{0.5}Ga_{0.5}As$	0.1	—	0.1	$\sim 10^{19}$ (n)
Emitter	$Al_{0.5}Ga_{0.5}As$	0.15	0.15	0.15	$\sim 10^{17}$ (n)
Graded	$Al_xGa_{1-x}As$	—	0.05	0.05	undoped
Spacer	GaAs	0.025	0.025	0.025	undoped
Base	GaAs	0.15	0.12	0.12	$\sim 10^{18}$ (p)
u-Collector	GaAs	0.2	—	0.2	undoped
Collector	GaAs	—	0.3	0.1	$\sim 10^{17}$ (n)
Buffer	GaAs	0.4	0.5	0.5	$\sim 10^{19}$ (n)

3. RESULTS AND DISCUSSION

Epitaxial growth on GaAs (111)B substrates has been found to be rather difficult. There are many pyramid-like structures on the surface of epilayers grown on (111)B substrates, which was first reported by Cho[1]. Recently, many reports have indicated that off-orientation from exactly (111) plane is desirable to obtain mirror-like surface layers[12,14,15]. Figure 1 shows the substrate temperature dependence of surface morphologies grown on exactly (111)B and (111)B 2° off toward (110) substrates. The As/Ga BEP ratio is about 90 and the substrate temperature is varied from 600 to 671°C. As can be seen, the density of pyramid-like structure on the surface decreases with the increasing substrate temperature on both substrates. It is clear that a mirror-like surface can be obtained by increasing the substrate temperature up to 650°C on exactly and 620°C on 2° off (111)B substrates, respectively. Figure 2 shows the room temperature electron mobility of Si-doped GaAs on an exactly (111)B substrate as a function of substrate temperature. The carrier concentrations and layer thickness are 3×10^{17} cm^{-3} and 1 μm, respectively. There were two different As/Ga BEP ratios used here, as shown in this figure, open and filled circles represent As/Ga = 90 and 30, respectively. For the epitaxial growth of GaAs along (111)B orientation, two different surface reconstructions were observed: 2×2 and $\sqrt{19} \times \sqrt{19}$ RHEED patterns, which represent As- and Ga-stabilized growth conditions, respectively [1]. As previous reports have shown[12,16], for the case of As/Ga = 90, the room temperature electron mobility decreases dramatically as the substrate temperature is lowered down to a certain values (490°C), at which point a 2×2 RHEED pattern was observed. This means that the epitaxial growth along (111)B direction cannot be performed under the same As-stabilized conditions as that on a (100) oriented substrate. The substrate temperature should be high enough to keep in the Ga-stabilized region. The other important result is that the maximum measured electron mobility was saturated around the substrate temperature of 665°C and dropped again in the high temperature (710°C) region, at which point the growth may be pushed to the highly Ga-stabilized condition. Remember that 665°C is very close to the minimum substrate temperature to remove the pyramid-like features on the exactly (111)B substrate. Therefore, it can be understood that the defects induced by pyramid structures or generated in the highly Ga-stabilized condition have strong effects on the electron transport properties on the (111)B substrate. For the case of As/Ga = 30, as can be seen, the trend of this room temperature electron mobility was shifted to the lower substrate temperature region. This indicated that the smaller the As/Ga BEP ratio used, the lower the substrate temperature needed to keep in the Ga-stabilized region, under which condition higher electron mobility can be obtained on

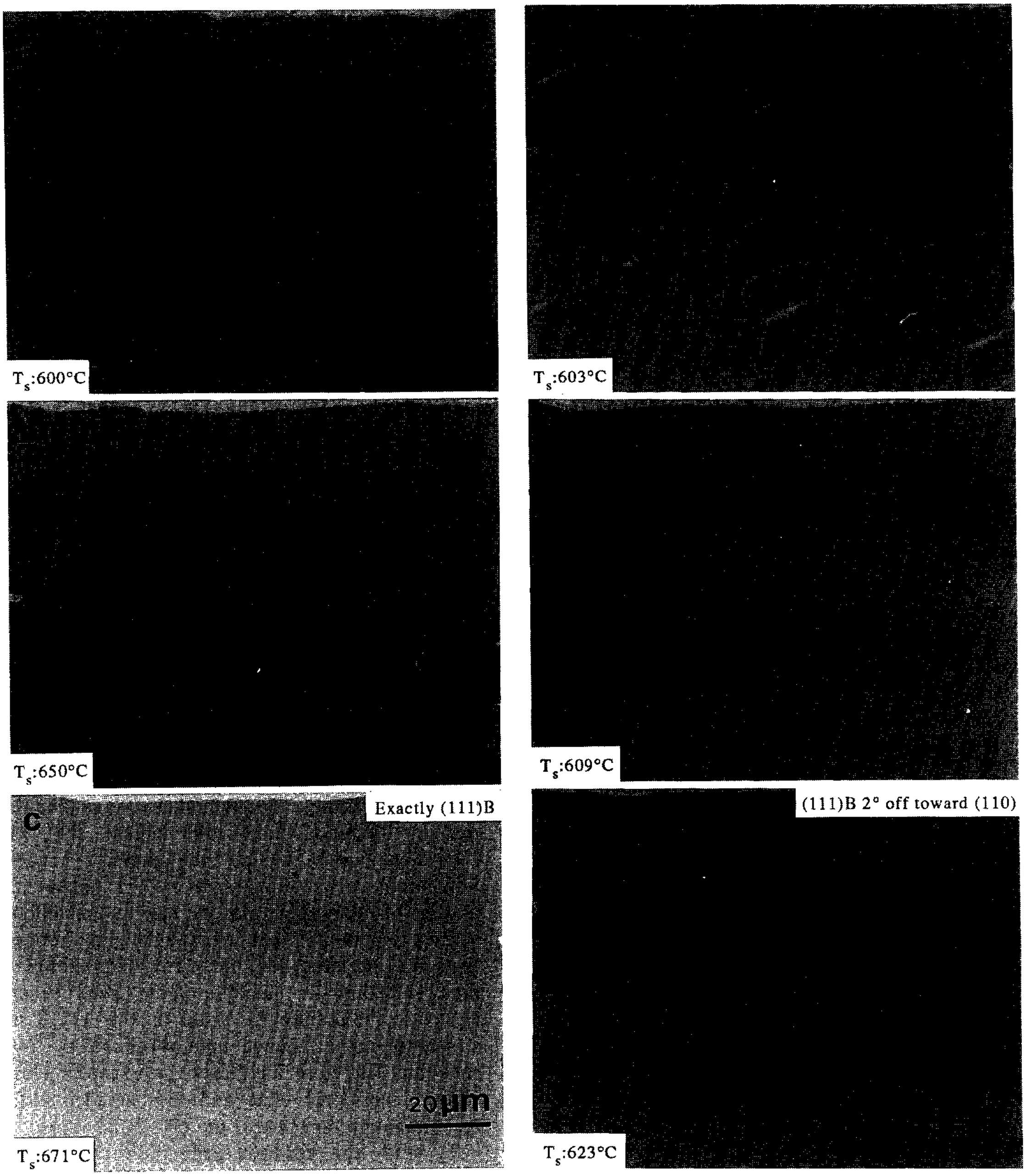

Fig. 1. The substrate temperature dependence of surface morphologies grown on (a) (b) (c) exactly (111)B and (d) (e) (f) (111)B 2° off toward the (110) substrates. The As/Ga BEP ratio is about 90.

(111)B substrate. As a result, the electrical transport properties on the (111)B substrate strongly depend on the As/Ga BEP ratio and substrate temperature. In addition, according to the electron mobility dependence on substrate temperature, the optimum growth condition on the exactly (111)B substrate with As/Ga = 90 can only be obtained within a very narrow window of substrate temperature (650°C < T_s < 700°C). This result agrees with the RHEED intensity oscillation study by Yen and Hass[17].

Four groups of HBTs were grown on (100) and (111)B substrates (named M511, M572, M617 and M736) by changing the growth conditions including substrate temperature and As/Ga BEP ratio. Their growth parameters are summarized in Table 2. Figure 3 shows the Gummel plots of these four runs. As can be seen, M511 has a much larger base leakage current in its low current region than M617 does. The differences between these two runs are the substrate orientation, substrate temperature and As/Ga BEP ratio. Note that the orientation of substrate for M511 and M617 is exact and 2° off (111)B, respectively, and the substrate temperature of M617 is 50°C higher than that of M511. Obviously, as described above, a pyramid-like surface still existed for M511, but not for M617. As for M572, although the substrate

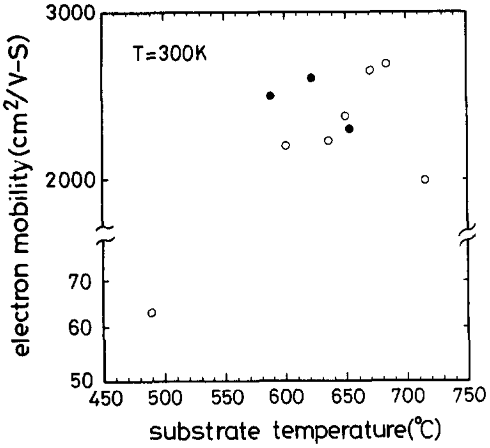

Fig. 2. The room temperature electron mobility on an exactly (111)B GaAs substrate as a function of substrate temperature. The open and filled circles represent As/Ga = 90 and 30, respectively.

temperature is high (610°C), the smaller As/Ga BEP ratio (27) pushes the growth to the highly Ga-stabilized region. As discussed in previous studies[16,18], epitaxial growth under highly Ga-stabilized region would result in poor electrical properties on the (111)B substrate. In our experiments, as shown in Fig. 2, the decrease of room temperature electron mobility of Si-doped GaAs at high substrate temperature also supports this point. Therefore, it is believed that the base leakage current may come from the defects induced by the pyramid-like structures (for example, M511) or generated in the highly Ga-stabilized condition (for example, M572). However, as we can see, all the ideality factors of the base currents of these three runs are about 2. This means that the emitter–base (EB) junction quality is still poor for (111) devices under this growth condition, even though the surface is mirror-like and the base leakage current is no longer observed. As discussed above for the 2°-off substrate, the substrate temperature used in M617 is slightly too high under this As/Ga BEP ratio. Thus, the growth condition may be pushed away from the optimum region and approaches to the highly Ga-stabilized regions. By both increasing the As/Ga BEP ratio from 55 to 61 and decreasing the substrate temperature from 650°C to 590°C for M736, the EB junction quality is improved significantly on (111)B substrate. The other possible reason may be attributed to the poor AlGaAs quality at this growth temperature (650°C) and thus results in a poor E–B junction. Hence, even using misoriented substrate, a precise control of substrate temperature and As/Ga BEP ratio is also very important for obtaining high performance HBT devices on a (111)B substrate.

It is well known that AlGaAs/GaAs HBTs suffer from the problem of surface recombination current. This current may be different in the (111) direction because of the different surface properties. In this study, three different substrates were In-bonded together for the growth of HBTs. They were (100), (111)B 2° off toward (110) and (111)B 2° off toward (100) [abbreviated as (111)B 2° → (110) and (111)B 2° → (100), respectively]. According to Ref. [19], the base current density (j_B) can be expressed as the following formula:

$$J_B = (J_{Bulk} + J_{Bscr} + J_{Bp}) + 2K_{Bsurf}\cdot\left(\frac{1}{W_E} + \frac{1}{L_E}\right), \quad (1)$$

where J_{Bulk} ($A\,cm^{-2}$), J_{Bscr} ($A\,cm^{-2}$), and J_{Bp} ($A\,cm^{-2}$) are the base bulk recombination current density, the base–emitter space-charge recombination current density, and the base to emitter back-injected current density, respectively; K_{Bsurf} ($A\,cm^{-1}$) is the surface recombination current divided by the emitter perimeter; W_E and L_E are E–B junction width and length, respectively.

In the plot of J_B vs $(1/W_E + 1/L_E)$, the slope is proportional to the surface current density; and, the Y-axis intercept is proportional to the bulk current density. The slopes and Y-axis intercepts for M736 are summarized in Table 3. As can be seen in this table, the bulk current of (100) is smaller than those of the other two. According to Hayakawa's report[20], the anisotropy of heavy-hole band in GaAs is extremely large: m_{hh} [111]/m_{hh} [100] = 2.65. So the larger bulk current of (111) may result from the heavy-hole-enhanced recombination. However, the surface recombination current of (111) is smaller than that of (100) for all the collector densities, 500, 1000, 2000 $A\,cm^{-2}$. For example, the surface recombination current of (111)B 2° → (110) is only half as large as that of (100). This may be due to the different surface structures. There are two dangling bonds of the surface As atom for (100) direction and only one for (111)B direction. Because of the fewer unshared electrons, the surface As atoms on the (111)B substrate are more inactive than those on the (100) substrate. Therefore, it is reasonable to expect a lower surface density of state and thus smaller surface recombination current for the (111)B direction.

To study the substrate temperature effects, four groups of HBTs were grown on (100) and (111)B 2° off substrates, ranging from 590 to 680°C. The As/Ga BEP ratio is kept at 60 for all these four runs. Figure 4 shows the current gain of HBTs grown on (100) and (111)B as a function of substrate temperature. It was found that the current gain decreased with increasing substrate temperature from 590°C, but increased for substrate temperature at 680°C for all of these four

Table 2. The summary of growth parameters, including substrate temperature, As/Ga BEP ratio and substrate orientation, for the HBTs, named M511, M572, M617 and M736

Run	T_s (°C)	As/Ga	Substrate
M511	600	91	(111)B 0°
M572	610	27	(111)B 2° → (110)
M617	650	55	(111)B 2° → (110)
M736	590	61	(111)B 2° → (110)

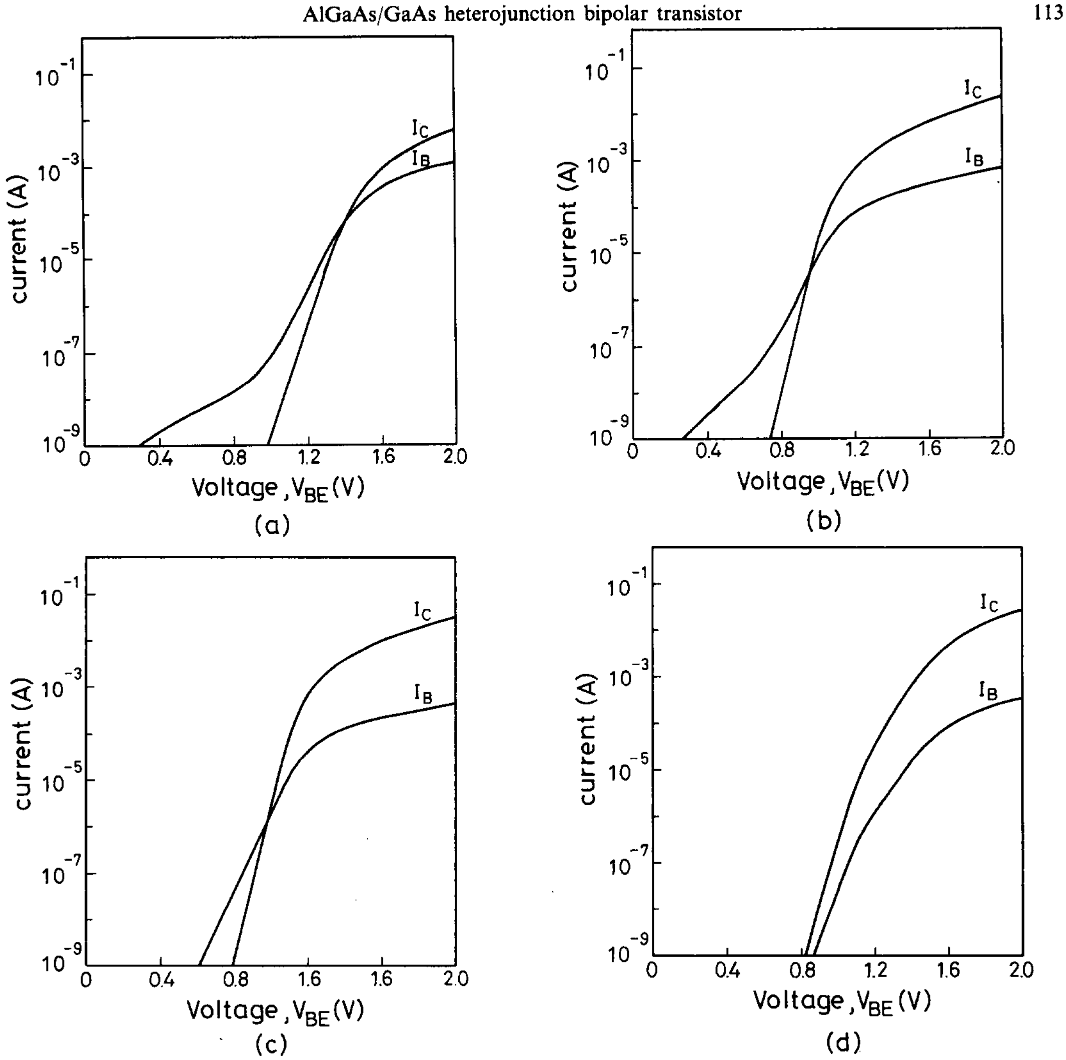

Fig. 3. The Gummel plots of HBTs on a (111)B substrate for (a) M511 (b) M572 (c) M617 and (d) M736. The base leakage current in the low current region is very serious for M511 and M572.

runs, in spite of the substrate orientation. Consider the forbidden growth temperature window for AlGaAs[21–23], many nonradiative defects are created in AlGaAs layers and thus high E–B junction recombination current occurs at the growth temperature ranging from 620 to 650°C. Therefore, the current gain decreases with increasing substrate temperature. When the substrate temperature is higher than 650°C, the quality of AlGaAs becomes better; hence, the current gain increases again.

4. CONCLUSIONS

In conclusion, a AlGaAs/GaAs heterojunction junction bipolar transistor has been successively grown and fabricated on (111)B GaAs substrates. It was found that the mirror-like surface morphology of GaAs epilayers on (111)B substrate can be obtained by increasing the substrate up to 650 and 620°C for exact and 2° off substrates. The base leakage current may be related to the defects induced by the pyramid-

Table 3. The summary of the relations between base current density and E–B junction perimeter for M736. The slope is proportional to the surface current density; and the Y-axis intercept is proportional to the bulk current density

J_c (A cm^{-2})		(100)	(111)B 2° → (100)	(111)B 2° → (110)
500	intercept (A cm^{-2})	3.5	7.2	7.5
	slope (A cm^{-1})	46	36	19
1000	intercept (A cm^{-2})	5.1	11.2	12
	slope (A cm^{-1})	96	81	37
2000	intercept (A cm^{-2})	6.8	18.2	19
	slope (A cm^{-1})	198	147	74

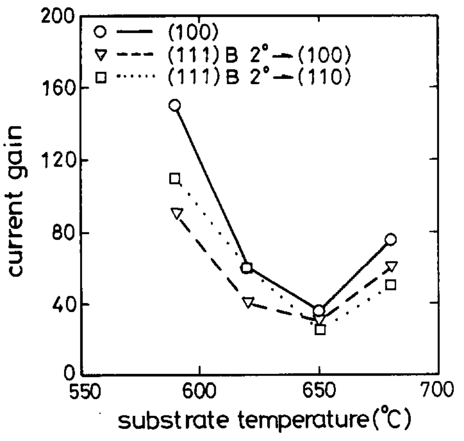

Fig. 4. The current gain of HBTs grown on (100) and (111)B as a function of substrate temperature.

like surface or generated in a highly Ga-stabilized condition. Therefore, the performance of a AlGaAs/GaAs HBT grown on a (111)B GaAs substrate can be improved by the precise control of growth conditions, including substrate misorientation, substrate temperature, and As/Ga BEP ratio. In addition, because of the different surface properties, the surface recombination current of an HBT on (111)B 2° off toward (110) is only half as large as that on (100) GaAs at a growth temperature of 590°C, which may be due to the fewer dangling bonds of the surface As atoms on the (111)B substrate. On the substrate temperature effects, the (111)B-oriented HBTs show the same current gain behavior as that of (100)-HBTs, which may be dominated by the AlGaAs properties in the forbidden growth temperature regions.

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