Substantial improvement by substrate misorientation in dc performance of $Al_{0.5}Ga_{0.5}As/GaAs/Al_{0.5}Ga_{0.5}As$ double-heterojunction *NpN* bipolar transistors grown by molecular beam epitaxy

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$Al_{0.5}Ga_{0.5}As/GaAs/Al_{0.5}Ga_{0.5}As$ *NpN* double-heterojunction bipolar transistors have been grown simultaneously by molecular beam epitaxy on (100) and 3° off (100) towards ⟨111⟩*A* GaAs substrates. On the tilted substrate, the current gain is significantly higher, comparable to the maximum expected value, with a marked reduction of its dependence on current and device geometry. For 10 μm×40 μm emitter devices, maximum common emitter current gains (β) of 1630 and 725 were measured at a current density of ~6.3 kA/cm^2 on the tilted and flat substrates, respectively. On the tilted substrate, both the emitter injection efficiency and base transport factor are increased. We have used compositionally graded emitter-base (e-b) and abrupt base-collector (b-c) junctions. We find that the abrupt b-c junction does not result in an offset voltage but certainly reduces the electron collection efficiency, and hence the gain, in the region where it is forward biased. The device characteristics and the current gain on both substrates were essentially independent of temperature between 25 and 100 °C, except for a slight decrease of gain with increasing temperature.

We have studied for the first time the effect of substrate misorientation in improving the performance of AlGaAs/GaAs double heterojunction bipolar transistors (DHBTs). A DHBT has many attractive performance and processing advantages[1–4] over a single heterojunction bipolar transistor (SHBT). Interchangeability of emitter/collector and suppression of hole injection from base into collector under conditions of saturation in digital switching in a DHBT have unique implications for large-scale integrated circuits. A DHBT can also work as a laser,[4] and thus it can serve a dual purpose in optoelectronic integration. By tailoring the emitter and collector junctions, the normally observed offset voltage can be reduced or eliminated.[5,6] Depending on the band gap of the collector, the collector leakage current and the temperature sensitivity of the device can be reduced, and the collector breakdown voltage can be increased significantly. This allows separate optimization of the base and collector which gives unlimited design freedom to cover a wide spectrum of temperature ranges, current-handling and voltage-blocking capabilities in microwave and switching power transistors. Ideally, a power device requires a high blocking voltage in the OFF state, a low forward voltage drop in the ON state, minimum power losses, and is a resonable high speed.

The structures studied were grown simultaneously at 580 °C on Si-doped (100) and 3° off towards ⟨111⟩ *A* n^+-GaAs substrates. As evidence to the purity of the ambient growth conditions, very high purity GaAs and several high-performance electronic and photonic device structures have been grown in this molecular beam epitaxy (MBE) system.[7] We have used a higher AlAs content, x, of 0.5 in both emitter and collector. This higher AlAs content is desirable if the device is also to be used as a laser. With higher AlAs content, the device should also have high gain, high collector breakdown voltage, small collector leakage current, and less sensitivity to temperature. A compositional grading of 300 Å was employed at the emitter-base (e-b) junction to smooth out part of the conduction-band discontinuity.[8] The base-collector (b-c) junction was not graded to see the effect of an abrupt junction on the offset voltage and gain. To reduce series resistances, $Al_xGa_{1-x}As$ was also graded in the bulk emitter and collector regions from $x = 0.1$ to 0.5 over a 200 Å distance. The GaAs base thickness was 1000 Å of which 800 Å in the middle was doped with Be (5×10^{18} cm^{-3}) and 100 Å on each side was undoped to be used as a setback layer to prevent out-diffusion of Be into the emitter and collector.[9] The Si-doped $Al_{0.5}Ga_{0.5}As$ emitter and collector thicknesses were 0.2 and 0.5 μm with doping densities of 4×10^{17} and 1×10^{16} cm^{-3}, respectively.

Fabrication of the device was accomplished by defining the emitter mesa and etching $Al_{0.5}Ga_{0.5}As$ emitter down to the base with a solution of H_2SO_4:H_2O_2:H_2O (1:1:50). Devices of various junction areas, which are shown in Table I, were fabricated. After depositing AuBe/Ti/Au p contacts followed by annealing at 420 °C for 30 s, AuGe/Ni/Ti/Au n contacts for emitter and collector were evaporated and alloyed at 350 °C for 30 s. The collector contacts were formed on the back of the substrate. Finally, the base mesa was defined and etched down to the subcollector for device isolation.

The device characteristics were measured as a function of temperature between 25 and 100 °C using a probe station with a heated chuck and HP4145B parameter analyzer. The device yield was higher than 90% on both substrates with almost uniform characteristics. The maximum common emitter small signal current gains β (max) and the corresponding collector currents at 25 °C measured in various junction area devices on both types of substrates are summarized in Table I. Emitter resistance in our devices

TABLE I. Emitter-base junction area dependence of the maximum common emitter current gain in $Al_{0.5}Ga_{0.5}As/GaAs/Al_{0.5}Ga_{0.5}As$ *NpN* DHBTs grown on (100) and 3° off (100) towards ⟨111⟩ *A* GaAs substrates.

Emitter-base junction area ($\mu m \times \mu m$)	Substrate: 3° off (100) towards ⟨111⟩ A — Current (mA)	Substrate: 3° off (100) towards ⟨111⟩ A — Maximum gain	Substrate: (100) — Current (mA)	Substrate: (100) — Maximum gain
50×50	66	1200	58	675
28×28	46	1410	32	675
10×40	24	1630	28	725
(10×)[a]5×25	32	1060	27	210
(5×)[a]4×20	37	1000	34	124
(2×)[a]4×20	14	620	28	105
5×20	9	515	12	150

[a]Number of emitter fingers.

was relatively higher due to a nonoptimum doping density. As a result, at currents higher than those in Table I, β decreased somewhat due to the junction heating effects.[3] Table I clearly shows a marked reduction of geometry dependence of current gains and hence the surface recombination currents on the tilted substrate. In fact, initially with decreasing e-b junction area from 50 $\mu m \times 50$ μm to 10 $\mu m \times 40$ μm, β (max) increases on both the substrates. This is due to different current densities of β (max) and the dependence of heat removal rates on junction periphery.

The common emitter collector current-voltage (I_C-V_{CE}) characteristics of a typical DHBT, with 50 $\mu m \times 50$ μm emitter area, on the off-axis substrate measured at 25 and 100 °C are shown in Fig. 1. The devices on the on-axis (100) substrate had lower gain but similar (I_C-V_{CE}) characteristics, b-c junction leakage current, and breakdown voltage. Collector and base currents measured at 25 °C as a function of base-emitter voltage (V_{EB}) with collector shorted to base, i.e., $V_{CB} = 0$, are plotted in Fig. 2 for the same 50 $\mu m \times 50$ μm emitter devices on both types of substrates. The collector current dependence of small signal current gain, β, measured at $V_{CE} = 3V$ is plotted in Fig. 3 for both types of devices at 25 and 100 °C. The collector breakdown voltages V_{CB0} and V_{CE0}, measured for $I_C = 10$ nA were 14.5 and 5.5 V, respectively independent of the type of substrate.

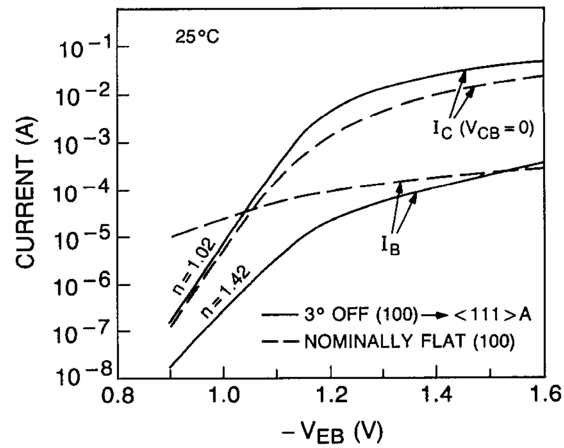

FIG. 2. Variations of base, I_B, and collector, I_C, currents with base-emitter forward bias voltage, V_{BE} for typical DHBTs on flat (100) and 3° off (100) towards ⟨111⟩ *A* GaAs substrates. The collector is shorted to the base.

The I_C-V_{CE} characteristics in Fig. 1 and the current gain in Fig. 3 have a very weak dependence on temperature between 25 and 100 °C, and the dependence is significantly reduced on the off-axis substrate. The slight decrease of gain with increasing temperature is due to decrease of both the emitter injection efficiency and the base transport factor as discussed elsewhere.[3,10] Since the collector leakage current does not increase appreciably due to the wide band-gap collector and the gain slightly decreases with increasing temperature, the I_C-V_{CE} characteristics remain stable at 100 °C. We expect these devices to show similar stable performance even at much higher temperature. At this time, it is not possible for us to test the device at > 100 °C.

Figure 3 shows that for a given I_C, on the off-axis

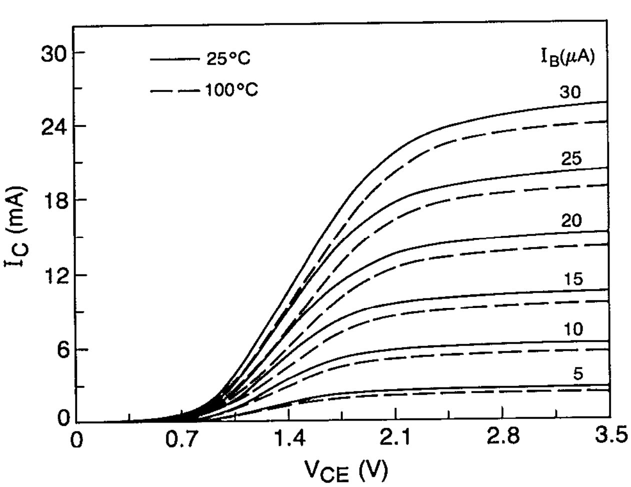

FIG. 1. Common-emitter *I/V* characteristics at 25 and 100 °C of an $Al_{0.5}Ga_{0.5}As/GaAs/Al_{0.5}Ga_{0.5}As$ *NpN* DHBT on the tilted GaAs substrate with graded emitter-base and abrupt base-collector junctions.

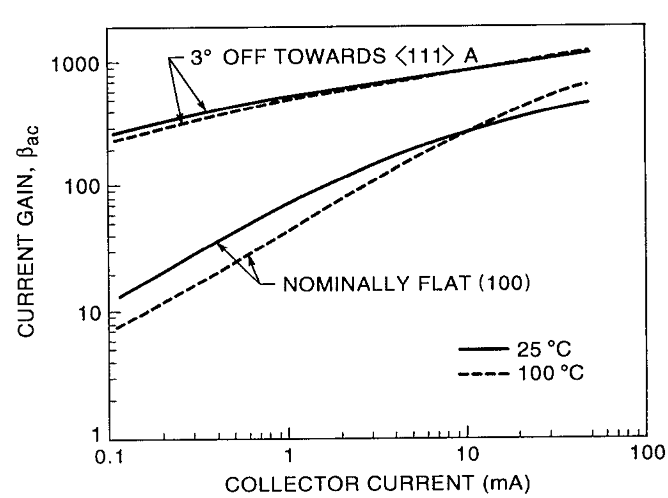

FIG. 3. Current and temperature dependence of common emitter small signal current gain, β, for the typical DHBTs on flat (100) and 3° off (100) towards ⟨111⟩ *A* GaAs substrates.

substrate the current gain is significantly higher and its dependence on current is markedly reduced. With increasing I_C, the difference in gain decreases between the two devices. Figure 2 shows that the nature of I_C-V_{EB} curves are essentially similar in both cases with an ideality factor, n, of 1.02. This combined with the similar leakage current and breakdown voltage of the b-c junction suggest that the quality of the $Al_{0.5}Ga_{0.5}As$ collector is similar on both types of substrates. The difference lies in the base current which for a given I_C is significantly larger, with higher value of n, on the on-axis (100) substrate; in fact for $V_{EB} \leqslant 1.05$ V, I_B is greater than I_C resulting in a gain of < 1. Assuming unity injection efficiency, the maximum gain in absence of avalanche multiplication for a graded e-b junction HBT is given by

$$\beta_{max} = [\cosh(W/L_n) - 1]^{-1}, \qquad (1)$$

where W is the base width and L_n is the electron diffusion length in the base region. For $W = 0.08$ μm (doped region) in our case and using the best reported[11] value of $L_n = 2$ μm in SHBT for a base doping of 5×10^{18} cm^{-3}, we obtain a $\beta_{max} = 1250$. Our maximum gain of 1630 and the actual base thickness of 0.1 μm (instead of 0.08 μm) suggest that L_n in our case is higher than 2 μm on the off-axis substrate. This means that if the substrate is suitably misoriented, the quality of GaAs base is improved.

Despite the abrupt b-c junction, the I_C-V_{CE} characteristics in Fig. 1 do not show the presence of an offset voltage, and thus the offset voltage is not caused by the lack of compositional grading at the b-c junction. Note that, as reported elsewhere,[5] in the offset region, I_C is less than zero and not zero. However, due to the abrupt b-c junction, the carrier collection efficiency is indeed poor[3,6] in the region where the b-c junction is forward biased, i.e., for lower values of V_{CE}. As a result, increase of I_C with V_{CE} is rather slow in Fig. 1 and the I_C-V_{CE} curves lack sharp knees. Due to poor electron collection efficiency, the recombination in the base may be higher, leading to a lower gain. If the b-c junction was not abrupt, the current gain might have been even higher than that in Fig. 3. For example, Su *et al.*[2] measured maximum gains of 125 and 200 in DHBTs with abrupt and graded b-c junction, respectively. Thus, for higher carrier collection efficiency, it is necessary to suitably grade the $Al_xGa_{1-x}As$ at the b-c junction to smooth out the conduction-band discontinuity.

The difference in current dependence of gain in the two devices suggests that the injection efficiency is higher, and the difference in gain at higher currents suggest that the base transport factor is higher on the off-axis substrate. This implies that the substrate tilting helps in obtaining smoother GaAs/AlGaAs heterointerfaces and in reducing defect incorporation and unwanted impurities. The difference in geometry dependence of gain, shown in Table I, suggests a reduction of surface recombination currents on the tilted substrate. Although the exact mechanism of substrate tilting on the growth kinetics is unknown, the observed results are consistent with the earlier results of bulk AlGaAs growth,[12,13] AlGaAs/GaAs heterointerfaces,[14,15] and AlGaAs/GaAs,[16] and InGaAs/GaAs quantum well lasers.[17]

The (100) GaAs surface tilted towards $\langle 111 \rangle$ *A* exposes Ga-like step edges which have less affinity for defect/impurity incorporation.[12-17] A Ga atom has three electrons in the outermost orbital, and all of them form bonds to the As atoms in the underlying layer on the (111) surface, leaving no unpaired electrons. This makes the Ga-like steps less reactive. As a result, on a (100) substrate suitably misoriented towards $\langle 111 \rangle$ *A*, the growth kinetics are modified in such a way that the incorporation of unwanted impurities like oxygen is reduced, leading to the growth of purer material and smoother surfaces and heterointerfaces. Since the surface is less reactive, the surface recombination current is also reduced. We believe this, at least partly, is responsible for the improved performance of $Al_{0.5}Ga_{0.5}As/GaAs/Al_{0.5}Ga_{0.5}As$ DHBTs on tilted substrates. We have used 3° off substrates, but the optimum tilt angle may be different from 3°. Further work on the role of substrate tilting is in progress and will be reported elsewhere.

In conclusion, we have shown that in $Al_{0.5}Ga_{0.5}As/GaAs/Al_{0.5}Ga_{0.5}As$ *NpN* DHBTs, the current gain is significantly higher and the current and device geometry dependence of gain are appreciably reduced by suitably misorienting the (100)GaAs substrate towards $\langle 111 \rangle$ *A*. Both the current injection efficiency and the base transport factor are higher on the tilted substrate while the quality of the collector is essentially the same. Between 25 and 100 °C, there is very little change in device current-voltage and current gain characteristics with temperature.

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