An AlGaAs double-heterojunction bipolar transistor grown by molecular-beam epitaxy

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To study AlGaAs *p-n* heterojunctions and optical and transport properties of electrically injected minority carriers (electrons) in p-$Al_{0.25}Ga_{0.75}As$, we have tested the performance of $Al_{0.6}Ga_{0.4}As/Al_{0.25}Ga_{0.75}As/Al_{0.6}Ga_{0.4}As$ *NpN* double-heterojunction bipolar transistors (DHBTs). The transistors exhibited a common emitter current gain (β) as high as 400 at a current density of 2 kA cm^{-2}. From the Gummel plots, the ideality factors (n) of emitter-base and base-collector junctions were as low as 1.37 and 1.01, respectively, indicating high quality of both the junctions. Assuming a unity current injection efficiency, we obtain an electron diffusion length of 1.2 μm for an acceptor density of 6.0×10^{18} cm^{-3} in p-$Al_{0.25}Ga_{0.75}As$. Due to the wide band-gap materials, the device has the potential for useful operation at very high temperatures. The device also works as a bright red light emitter when the emitter-base junction is forward biased and the collector is either floating or forward biased, indicating dominance of radiative recombination in the base. Furthermore, the device also works as a phototransistor for detection of short wavelengths (<710 nm) with no sensitivity to longer wavelengths.

The search for semiconductor materials for photonic devices operating in the visible and ultraviolet spectrum range, and electronic devices operating at very high temperatures has over the years lead significant research on large band-gap materials such as semiconducting diamond, SiC, II-VI semiconductors, $GaP/Al_xGa_{1-x}P$, $GaP/GaAs_yP_{1-y}$, GaInP/AlInP, and AlGaAs/GaAs. The intrinsic carrier density (n_i) in a semiconductor is an exponential function of band gap and temperature. The leakage or saturation current (I_{CO}) at room temperature and above in typical junction diodes and transistors varies as n_i or n_i^2 depending on whether the current is due to carrier generation within or outside the space-charge region, respectively, and is therefore extremely band-gap and temperature sensitive. However, if I_{CO} is very small, such as in the above large band-gap material devices, the effects of temperature variation in the output characteristics will be minimized (even when multiplied by $\beta+1$ in common emitter operation of a transistor, where β is the current gain), and the device will have a greater operating temperature range. For example, useful operation of GaP/AlGaP heterojunction bipolar transistors (HBTs) has been obtained up to 550 °C.[1]

Among the various materials systems listed above, $Al_xGa_{1-x}As$/GaAs is most common for HBTs, using a GaAs base. In this work, we have fabricated DHBTs entirely in $Al_xGa_{1-x}As$ by varying x from 0.6 for the emitter and collector to 0.25 in the base. Besides examining the transistor action, our goals were to study (i) the optical and transport properties of minority carriers (electrons) in the p-$Al_{0.25}Ga_{0.75}As$ base, (ii) the AlGaAs *p-n* heterojunctions, and (iii) the stability or aging effects due to exposure of Al in the base. Since $Al_xGa_{1-x}As$ has a large band gap, the device has the potential of operating at very high temperatures provided the series resistances can be suitably reduced. Furthermore, $Al_{0.25}Ga_{0.75}As$ is suitable as an active material for red LEDs or lasers, and for photodetection of visible or shorter wavelength radiations with no sensitivity to background infrared signal. Indeed, we have found the device also working as a red light emitter and as a phototransistor. Details of the study are reported here.

The DHBTs were grown by molecular-beam epitaxy (MBE) at substrate temperatures of 700 and 580 °C. The schematic of the structure grown at 700 °C is shown in Fig. 1. Growth times and cell temperatures were the same for the structure grown at 580 °C. As a result, the thicknesses were 20% higher and the AlAs mole fraction was 20% lower due to the unity sticking coefficient of Ga at 580 °C and <1.0 at 700 °C. The DHBTs employ a compositionally graded emitter-base (*e-b*) and abrupt base-collector (*b-c*) junctions. A GaAs cap layer is utilized to lower contact resistance to the high band-gap emitter. The bulk emitter and collector were also compositionally graded to reduce the series resistances. The base was doped in the middle with Be at 6×10^{18} cm^{-3}, and 80 Å regions on both sides were undoped to act as setback layers for Be outdiffusion.[2] The structures were grown on n^+-GaAs substrates misoriented 3° off (100) towards <111>A which were chosen because our recent study showed a substantial improvement in dc performance of GaAs base DHBTs by substrate misorientation.[3]

Fabrication of the devices was accomplished by defining the emitter mesas of varying dimensions and etching down to the base. The AuBe/Ti/Au p contacts to the base were first deposited and annealed. Then n contacts to the emitter and collector using AuGe/Ni/Ti/Au were deposited and annealed. After etching the base mesa down to the subcollector for device isolation, 3000 Å Si_3N_4 was deposited for contact pads. Contact holes were etched through the Si_3N_4 using reactive-ion etching and overlay metal contact pads of Ti/Au were then deposited.

0.2μm	GaAs	n^+ (6.0×10^{18} cm^{-3})
175Å	$Al_xGa_{1-x}As$ ($x = 0.6\rightarrow0.15$)	n (1.5×10^{18} cm^{-3})
0.2μm	$Al_{0.6}Ga_{0.4}As$	n (5.0×10^{17} cm^{-3})
250Å	$Al_xGa_{1-x}As$ ($x = 0.25\rightarrow0.6$)	n (5.0×10^{17} cm^{-3})
80Å	$Al_{0.25}Ga_{0.75}As$	Undoped
675Å	$Al_{0.25}Ga_{0.75}As$	p^+ (6.0×10^{18} cm^{-3})
80Å	$Al_{0.25}Ga_{0.75}As$	Undoped
0.4μm	$Al_{0.6}Ga_{0.4}As$	n (1.5×10^{16} cm^{-3})
175Å	$Al_xGa_{1-x}As$ ($x = 0.15\rightarrow0.6$)	n^+ (1.5×10^{18} cm^{-3})
0.4μm	GaAs	n^+ (6.0×10^{18} cm^{-3})

n^+ GaAs 3° off (100) → <111>A substrate

FIG. 1. Schematic cross-section of the DHBT structure grown at 700 °C.

The common-emitter characteristics of the devices were measured at room temperature using an HP 4145B parameter analyzer. We were not able to test the devices at high temperatures at this time. The *I-V* characteristics are shown in Fig. 2 for a DHBT grown at 700 °C with a 50×50-μm^2-size emitter. The devices grown at 580 °C had similar *I-V* characteristics, but significantly lower gain. A summary of maximum current gains (β_{max}) with corresponding collector currents in both devices with varying emitter-base (*e-b*) junction areas are given in Table I. In Table I, β_{max} decreases from 400 to 75 with decreasing *e-b* junction area in devices grown at 700 °C, but varies between 35 and 18 in devices grown at 580 °C. With further increasing I_C, β decreased due to junction heating effects and is more pronounced in devices grown at 700 °C. These devices have higher emitter resistance,[4] which was measured to be 34 Ω as compared to 14 Ω for the devices grown at 580 °C. The comparatively higher R_E for 700 °C devices is due to increased donor compensation in AlGaAs grown at 700 °C and an even higher AlAs content as compared to 580 °C devices.[5] As a result, in Table I, I_C in devices grown at 700 °C corresponding to β_{max} is relatively smaller in all sizes of devices as compared to the devices grown at 580 °C.

The aging properties of the device grown at 700 °C were tested. Continuous operation was maintained over a

TABLE I. Emitter-base junction area dependence of the maximum common emitter current gain in $Al_{0.6}Ga_{0.4}As/Al_{0.25}Ga_{0.75}As/Al_{0.6}Ga_{0.4}As$ *NpN* DHBTs grown on (100) and 3° off (100) towards <111>*A* GaAs substrates.

Emitter-base junction area (μm$\times\mu$m)	Growth temperature 700 °C I_C	β_{max}	580 °C I_C	β_{max}
50×50	50	400	57	25
28×28	5	330	65	35
10×40	6	310	47	35
$(10\times)^a5\times25$	15	135	75	18
$(5\times)^a4\times20$	5	75	50	20
$(2\times)^a4\times20$	5	85	33	24
5×20	2	100	18	27

[a]No. of emitter fingers.

period of time while maintaining the constant collector current (I_C) around 1.1 kA/cm^{-3} by adjusting the base current (I_B) appropriately. Operation was only momentarily suspended to take data. Over a 4-h continuous operation, I_B had to be increased by 9% while the current gain fell about 6%. This slight deterioration is again thought to be due to junction heating effects.

The ideality factors of the collector and base currents obtained from the Gummel plots, shown in Fig. 3, were 1.02 and 1.37 for the device grown at 700 °C and 1.09 and 1.84 for the device grown at 580 °C, respectively. Variation of small-signal current gains with I_C in both types of devices are shown in Fig. 4 for a $V_{CE} = 3$ V. From Table I and Figs. 2 and 3, it is obvious that the current gain performance of devices grown at 700 °C is significantly better than those grown at 580 °C. These results are consistent with the performance variation of GaAs/AlGaAs lasers with growth temperature.[6]

The junction ideality factors, I_C-V_{CE} characteristics, and current dependence of gain of devices grown at 700 °C are comparable to the typical GaAs base DHBTs reported recently,[3] except that β_{max} is about a factor of 4 lower in these devices. The comparatively lower current gain is not

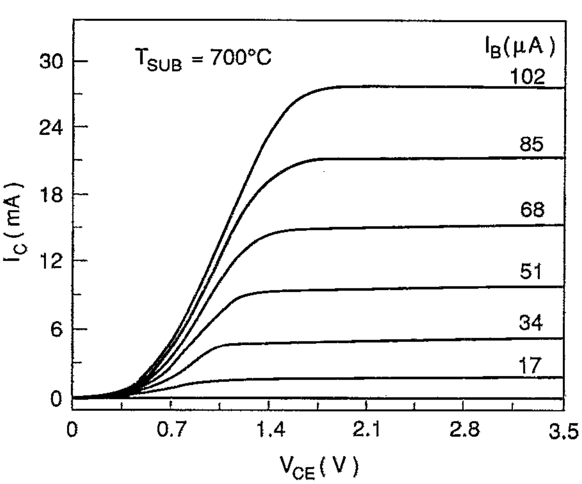

FIG. 2. *I-V* characteristics of an $Al_{0.25}Ga_{0.75}As$ base DHBT grown at 700 °C with a 50×50-μm^2-size emitter.

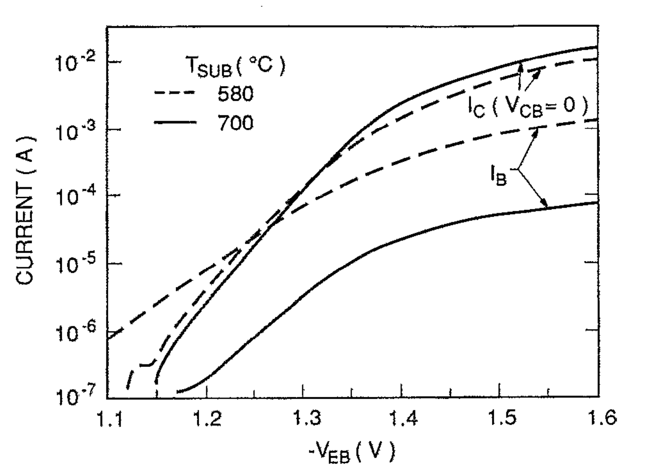

FIG. 3. Gummel plot of an $Al_xGa_{1-x}As$ base DHBT grown at 700 °C (solid line) and 580 °C (dashed line) with a 50×50-μm^2-size emitter.

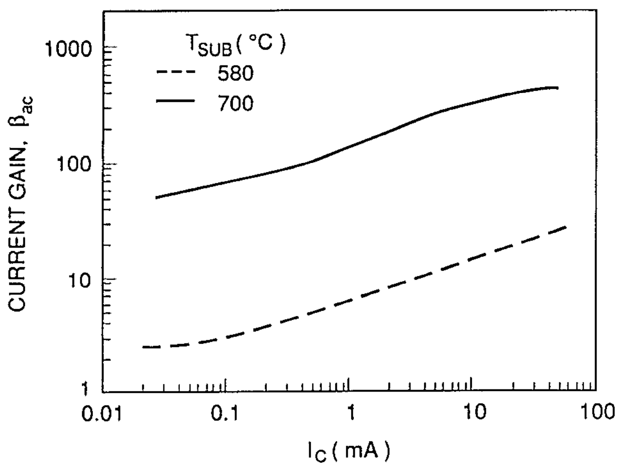

FIG. 4. Current gain characteristics of an $Al_xGa_{1-x}As$ base DHBT grown at 700 °C (solid line) and 580 °C (dashed line) with emitter dimensions 50×50 μm^2.

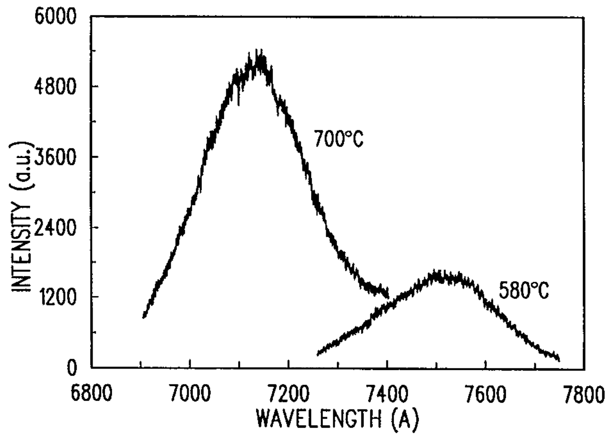

FIG. 5. Electroluminescence spectrum from DHBTs grown at 700 and 580 °C with the *e-b* junction forward biased and the collector floating.

due to any reduction of emitter injection efficiency (η), but due to reduction of base transport factor which is the result of lower electron mobility and hence the lower diffusion coefficient in p-$Al_{0.25}Ga_{0.75}As$. For a unity emitter injection efficiency, the electron diffusion length (L_n) is calculated to be 1.2 μm for the 700 °C device, using a base width (W_B) of 835 Å, and current gain (β_{max}) of 400, in the expression

$$\beta_{max}=[\cosh(W_B/L_n)-1]^{-1}. \tag{1}$$

Since η is normally less than unity, L_n in $Al_{0.25}Ga_{0.75}As$ has to be >1.2 μm for $p=6\times 10^{18}$ cm^{-3}, which is a reasonably high value. The lower gain in devices grown at 580 °C, is due both to reduction in base transport factor and emitter injection efficiency resulting from the increased bulk and space-charge recombination currents, respectively.

To further study the quality of the *e-b* junction and bulk $Al_{0.25}Ga_{0.75}As$ base, the *e-b* junction was forward biased while floating the collector. At currents above 15–20 mA, an intense red electroluminesence (EL) signal was observed near the periphery of the emitter mesas in both types of devices. The spectrum of emitted light from both DHBTs is shown in Fig. 5. It was not possible to measure the total optical power emitted since the light leaked out laterally in all directions from the emitter mesa. The peak luminescence wavelength corresponds to emission from the bulk base region, indicating absence of radiative recombination in the space-charge region. This suggests a high optical quality of the $Al_xGa_{1-x}As$ *p-n* heterojunction and highly doped p-$Al_{0.25}Ga_{0.75}As$ base. It should also be noted that the sample grown at 580 °C shows a dramatic shift of EL to lower energy as well as a reduction in luminescence intensity due to relatively lower AlAs content in the base ($x=0.18$) and lower growth temperature of AlGaAs, respectively.

The device grown at 700 °C was also used successfully as a floating base phototransistor using 633-nm light from an HeNe laser source. The measured optical gain was higher than 180 for a device with a 28×28-μm^2 emitter area.

In summary, we have fabricated a high dc performance heterojunction bipolar transistor fully in $Al_xGa_{1-x}As$. The device has the potential of operating at very high temperatures due to the larger band gap of AlGaAs, and can also be used as a visible light source and as a detector for short wavelengths. The present devices, however, suffer from higher emitter resistance which need to be decreased by increasing the doping density and reducing the thickness of the emitter.

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