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NOVEL $\text{In}_{0.41}\text{Ga}_{0.59}\text{As}/\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ STRAINED EMITTER HETEROJUNCTION BIPOLAR TRANSISTOR GROWN BY MOLECULAR BEAM EPITAXY

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Indexing terms: Bipolar devices, Transistors, Semiconductor growth

The first $\text{In}_x\text{Ga}_{1-x}\text{As}/\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ strained emitter heterojunction bipolar transistor (SEHBT), with $x = 0.41$, grown by molecular beam epitaxy on n^+ -InP substrate are reported. A small signal current gain of 480 and a small offset voltage of 56 mV were obtained. These good results were achieved with a thin emitter layer of 360 Å.

Introduction: Semiconductor devices using strained-layer epitaxy have been proposed for several applications such as lasers, photodetectors, field-effect transistors (FETs), and heterojunction bipolar transistors (HBTs) [1-4]. In HBT design, strain is tolerated as a condition for benefits derived from the bandgap difference (δE_g) between the emitter and base, and a high electron injection efficiency and thus a high current gain can be obtained. Most studies rely on the introduction of strain into the base layer such as AlGaAs/InGaAs HBTs [3] and Si/SiGe HBTs [4]. By introducing strain into the emitter layer it is easier to accommodate the constraint of the critical thickness in material growth. Keeping the base layer free of strain may avoid possible dislocations and preserve the original transport properties. Several papers have presented high performance HBTs with very thin emitter layers [5-7]. In this work, we have grown and successfully fabricated an all-InGaAs strained emitter heterojunction bipolar transistor (SEHBT) for the first time. A thin 360 Å-thick $\text{In}_{0.41}\text{Ga}_{0.59}\text{As}$ strained layer was grown as the wider gap emitter. Small

signal current gain as high as 480 and offset voltage of 56 mV are demonstrated.

Material growth and device fabrication: The detailed layer structure of the SEHBT is summarised in Table 1. The epilayers were grown on an Sn-doped (100) InP substrate by a solid source VG V-80H MBE system. The designed composition of the strained emitter is $\text{In}_{0.41}\text{Ga}_{0.59}\text{As}$. After the growth of the second grading layer, the RHEED pattern was still streaky, which indicates that the layer thickness was under the critical thickness. The surface morphology of the epilayer observed by an optical microscope was mirror-like and free of cross-hatching. Device fabrication was carried out using optical lithography and wet etching. The size of the emitter contact was $40 \times 40 \mu\text{m}^2$.

Results and discussions: Fig. 1 shows the common-emitter output characteristics of an SEHBT. As can be seen, the best

Fig. 1 Common-emitter output characteristics of SEHBT with current gain $\beta = 480$

Base current is 100 μA per step
Inset: small offset voltage of 56 mV is shown

small signal current gain is as high as 480. The offset voltage is 56 mV. However, because the current gain of the devices increases with the increasing collector current, the best current gain of 480 is actually limited by the current capability of the measurement equipment HP-4145B, 100 mA. Much higher current gain could be achieved at a higher collector current level. The Gummel plots of the SEHBT are shown in Fig. 2. In the low current region, the collector current and base current increase in parallel. However, in the high current region, the collector current increases much more quickly than the base current does. Because the effective wide energy gap emitter, i.e. the strained layer and the grading layers, of this device is only 640 Å thick, these layers are fully depleted at zero or low forward bias voltage and the voltage drop in this

Table 1 DESIGNED LAYER STRUCTURE OF SEHBT

Layer	$\text{In}_x\text{Ga}_{1-x}\text{As}$	Doping	Thickness
		cm^{-3}	Å
Cap	$x = 1$	$1.3 \times 10^{18}\text{-Si}$	150
	$x = 0.47$	$1.3 \times 10^{18}\text{-Si}$	860
	$x = 0.41 - 0.47$	$1 \times 10^{17} - 1.3 \times 10^{18}\text{-Si}$	140
Emitter	$x = 0.41$	$1 \times 10^{17}\text{-Si}$	360
	$x = 0.47 - 0.41$	$1 \times 10^{17}\text{-Si}$	140
Spacer	$x = 0.47$	—	300
Base	$x = 0.47$	$4 \times 10^{18}\text{-Be}$	1500
Lo-collector	$x = 0.47$	—	7500
Collector	$x = 0.47$	$1 \times 10^{17}\text{-Si}$	2500
Buffer	$x = 0.47$	$1.3 \times 10^{18}\text{-Si}$	2500

region reduces the wide energy gap effect, as shown in Fig. 3a. In this situation, the device behaves like a homojunction bipolar transistor. Its base current is dominated by the holes

Fig. 2 Gummel plot of SEHBT

Fig. 3 Schematic band diagram of SEHBT at zero or low bias, and higher bias

d_1 : cap layer, d_2 : grading layer, d_3 : strained emitter, d_4 : grading layer, d_5 : spacer, d_6 : base, qV_n : potential 'seen' by electrons, qV_p : potential 'seen' by holes
a Zero or low bias
b Higher bias

injected from base to emitter. Because both electron and hole injection currents have the same current transport mechanism, the base current increases in parallel with the collector current as shown in the Gummel plots. The N -side depletion edge is just at the interface between the second grading layer and strained emitter at a bias voltage of 0.35 V estimated by depletion approximation. In this case, the wide energy gap effect of the HBT begins to work; the hole carriers from the base see a larger potential barrier than the electrons do, as shown in Fig. 3b. The increase of the base current becomes slower than that of the collector current as can be seen in Fig. 2. Although in the high current region, the current gain of the device may still be dominated by hole injection from the base, the high current gain, 480, suggests that this thin strained emitter is good enough for an HBT. To further improve the current gain, the thickness of the unstrained spacer layer can be increased. In

this way, the depletion edge can be kept within the strained emitter region and the annoying problem of an increase in the strained emitter layer thickness is avoided. Furthermore, because the base layer is lattice-matched to the collector layer and substrate in our SEHBTs, the high frequency performance should be comparable to that of lattice-matched InAlAs/InGaAs HBTs.

Conclusions: We demonstrate the first InGaAs strained emitter heterojunction bipolar transistors (SEHBT) grown by molecular beam epitaxy exhibiting a high current gain of 480 and a small offset of 56 mV with a 360 Å-thick strained $\text{In}_{0.41}\text{Ga}_{0.59}\text{As}$ emitter. The performance of the device suggests that the InGaAs SEHBT is a good alternate for high gain and high speed devices. We feel that the current gain can be further increased by keeping the depletion edge within the strained emitter layer.

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HIGH SPEED ULTRALOW CHIRP 1.55 μm MBE GROWN GaInAs/AlGaInAs MQW DFB LASERS

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Indexing terms: Semiconductor lasers, Lasers

The successful realisation of high speed MBE grown InGaAs/InGaAlAs MQW active layer DFB BRS lasers is reported, with threshold currents as low as 9.5 mA, and bandwidths up to 9 GHz. The devices operate at 10 Gbit/s, with a chirp value lower than 0.1 nm; a very small α parameter value of 1.8 was measured above threshold.

Introduction: MQW lasers operating around 1.55 μm have shown their suitability for high speed low chirp operation, with successful 10 Gbit/s operation of InGaAs/InGaAsP MQW lasers [1]. In the InGaAs/InGaAlAs system, covering