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Thermal Characteristics of InP, InAlAs, and AlGaAsSb Metamorphic Buffer Layers Used in $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ Heterojunction Bipolar Transistors Grown on GaAs Substrates

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$In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ heterojunction bipolar transistors (HBTs) were grown metamorphically on GaAs substrates by molecular beam epitaxy. In these growths, InAlAs, AlGaAsSb, and InP metamorphic buffer layers were investigated. The InAlAs and AlGaAsSb buffer layers had linear compositional grading while the InP buffer layer used direct binary deposition. The transistors grown on these three layers showed similar characteristics. Bulk thermal conductivities of 10.5, 8.4, and 16.1 W/m K were measured for the InAlAs, AlGaAsSb, and InP buffer layers, as compared to the 69 W/m K bulk thermal conductivity of bulk InP. Calculations of the resulting HBT junction temperature strongly suggest that InP metamorphic buffer layers should be employed for metamorphic HBTs operating at high power densities.

Key words: Metamorphic, heterojunction bipolar transistor, thermal conductivity

INTRODUCTION

Research in high-speed, heterojunction bipolar transistors (HBTs) is driven by applications in high-frequency communications and radar. The HBTs, with layers lattice matched to InP substrates, presently show the best high-frequency performance. Such HBTs can have $In_{0.52}Al_{0.48}As$ or InP emitters, $In_{0.53}Ga_{0.47}As$ or $GaAs_{0.52}Sb_{0.48}$ base layers, and InP or $In_{0.53}Ga_{0.47}As$ collector layers. We will refer to such devices as InP-based HBTs. Their superior performance results from the high material qualities of In-based materials including high electron mobility, large Γ-L energy separation, and low contact resistances. Unfortunately, InP substrates are expensive and are available only in smaller diameters (10 cm vs. 15 cm) than GaAs substrates. Further, large (10-cm) InP substrates are fragile and are readily broken during semiconductor manufacturing. There has been extensive progress reported regarding metamorphic growth of InAlAs/InGaAs high-mobility electron transistors (HEMTs) on GaAs substrates.[1,2] More recently, several groups[3,4] have reported InP-based HBTs grown on GaAs substrates using InGaP or InGaAs buffer layers. There the work has focused on the physical and electrical quality of the HBT epitaxial layers and the HBT electrical performance. Compared to HEMTs, HBTs have much larger active-device volumes, are fabricated in integrated circuits with larger scales of integration, and typically operate at much higher power densities. Therefore, for metamorphic HBTs, both crystal defect density and buffer-layer thermal conductivity are serious concerns.

Here, we study the thermal characteristics of metamorphic buffer layers and compute the resulting HBT junction temperatures. For the first time, metamorphic HBTs with InP buffer layers are reported. The InP buffer layers offer significantly reduced junction temperatures for devices operating at high power densities.

GROWTH

The samples were grown using a Varian Gen II, molecular beam epitaxy system equipped with a valved phosphorous (P) cracker cell, a valved arsenic (As) cracker cell, and a valved antimony (Sb) cracker cell. Three buffer-layer materials were used for this study: InAlAs, AlGaAsSb, and InP. All were grown at 490°C, as measured by a pyrometer. The InAlAs and AlGaAsSb buffers were graded in composition from that matched to a GaAs lattice to that matched to an InP lattice. The AlGaAsSb buffer consisted of an AlAsSb/GaAsSb superlattice whose period was 50

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nm. After a 1.3-μm linearly graded AlAsSb/GaAsSb superlattice layer, a 200-nm $AlAs_{0.56}Sb_{0.44}$ buffer was grown that had a constant composition matched to the InP lattice constant. $In_xAl_{1-x}As$ had a 1.3-μm linear grading from x = 0 to x = 0.52, followed by a 200-nm $In_{0.52}Al_{0.48}As$ layer. The InP buffer layer was deposited directly on the GaAs substrate to a thickness of 1.5 μm. In all three cases, metamorphic buffer-layer growth was followed by growth of a $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As/In_{0.53}Ga_{0.47}As$ single HBT structure (Table I). The reflection, high-energy electron diffraction (RHEED) pattern was observed during buffer layer growth. As expected, the RHEED pattern showed diffraction streaks during growth of the InAlAs and AlGaAsSb buffer layers. These streaks suggest relatively smooth epitaxial growth with a continuous increase in the lattice constant during the growth process. Even during InP buffer-layer growth, low-intensity streaks were observed in the RHEED pattern. This indicates that there was no catastrophic morphology change into three-dimensional island mode on the growth surface.

Table I. Layer Structure of the Metamorphic $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ HBT Grown on GaAs Substrate

Emitter cap	$In_{0.53}Ga_{0.47}As$: Si ($1x10^{19}$ cm^{-3})	1000 Å
Emitter grade	$In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$: Si ($1x10^{19}$ cm^{-3})	200 Å
Emitter	$In_{0.52}Al_{0.48}As$: Si ($1x10^{19}$ cm^{-3})	700 Å
	$In_{0.52}Al_{0.48}As$: Si ($8x10^{17}$ cm^{-3})	500 Å
Grade	$In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$: Si ($8x10^{17}$ cm^{-3})	300 Å
Base	$In_{0.53}Ga_{0.47}As$: Be ($1.5x10^{19}$ cm^{-3})	400 Å
Collector	$In_{0.53}Ga_{0.47}As$: Si ($1x10^{16}$ cm^{-3})	400 Å
	$In_{0.53}Ga_{0.47}As$: Si ($1x10^{17}$ cm^{-3})	50 Å
	$In_{0.53}Ga_{0.47}As$: Si ($1x10^{16}$ cm^{-3})	1600 Å
Sub collector	$In_{0.53}Ga_{0.47}As$: Si ($1x10^{19}$ cm^{-3})	750 Å
Buffer	$In_{0.52}Al_{0.48}As$ or $AlAs_{0.56}Sb_{0.44}$ or InP	2000 Å
	AlAs -> $In_{0.52}Al_{0.48}As$ or AlAs/GaAs -> $AlAs_{0.56}Sb_{0.46}/GaAs_{0.52}Sb_{0.48}$ or InP	1.3 μm
GaAs (100) semi-insulating substrate		

Table II. Surface Roughness and Thermal Conductivity Data of Three Metamorphic Buffer Layers

Material	Thermal Conductivity (W/m K)	RMS Roughness (nm)
Metamorphic InAlAs	10.5	11.7
Metamorphic AlGaAsSb	8.4	4.0
Metamorphic InP	16.1	9.5
GaAs bulk	44	—
InP bulk	68	—

EXPERIMENTAL RESULTS AND DISCUSSION

Measurements of the metamorphic HBTs (MHBTs) included surface roughness measurement by atomic force microscope (AFM), thermal conductivity, HBT junction leakage currents, and the DC current-voltage (I–V) characteristics of large-junction-area HBTs. Surface roughness and thermal conductivity data are shown in Table II. We observe larger surface roughness than other reported work[5,6] and are presently adjusting our growth conditions to reduce roughness.

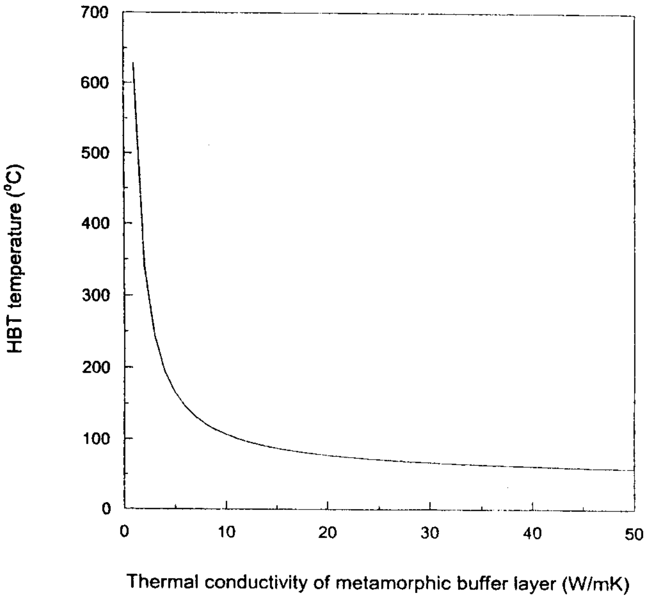

Fig. 1. The thermal conductivity of metamorphic buffer-layer dependence of HBT temperature. Metamorphic buffer-layer thickness is 1.5 μm.

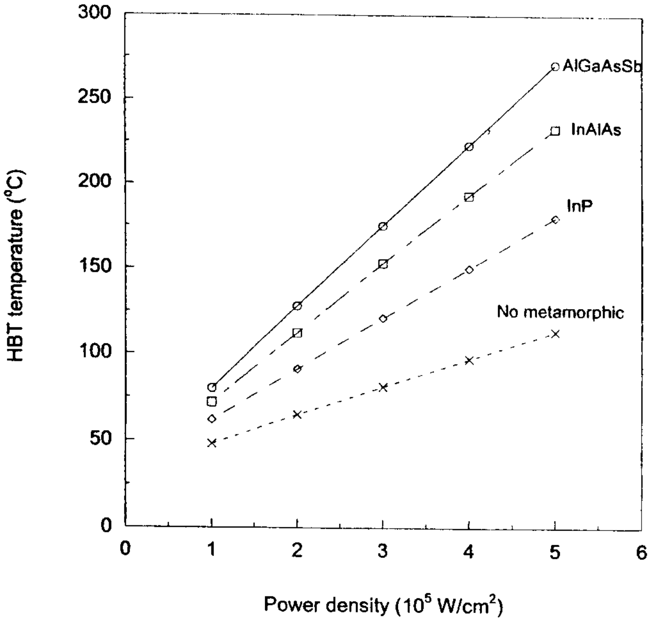

Fig. 2. The HBT device temperature according to power density.

Buffer-layer thermal conductivities were determined by measuring the thermal impedance of 1 μm × 100 μm Pt conductors of 50-nm thickness.[7] These were deposited on the buffer layers after removing the HBT layers by wet etching. The InP buffer layer shows the highest measured thermal conductivity although the conductivity is much smaller than known for bulk InP, most probably due to the poor crystal quality of the metamorphic layer. In order to determine the influence of metamorphic buffer-layer thermal conductivity on device temperature, the expected HBT collector-junction temperature was calculated by solving the Laplace heat-flow equation in three dimensions. A 45-μm device-device separation was assumed for 30 HBTs, typical of an integrated circuit. The assumed HBT emitter size was 8 μm × 0.5 μm, and the power density was 2×10^5 W/cm^2 of the emitter area. A 1.5-μm buffer-layer thickness, a GaAs substrate, and the HBT layer structure of Table I were assumed. These calculations (Fig. 1) indicated that the HBT junction temperature is strongly influenced by the thermal conductivity of the metamorphic layer and that the measured differences in thermal conductivity between InAlAs, AlGaAsSb, and InP buffer layers will have substantial impact on HBT junction temperature.

The expected HBT junction temperature was calculated to be 128°C, 112°C, and 89°C for AlGaAsSb, InAlAs, and InP buffer layers for the preceding device dimensions and powers. This should be com-

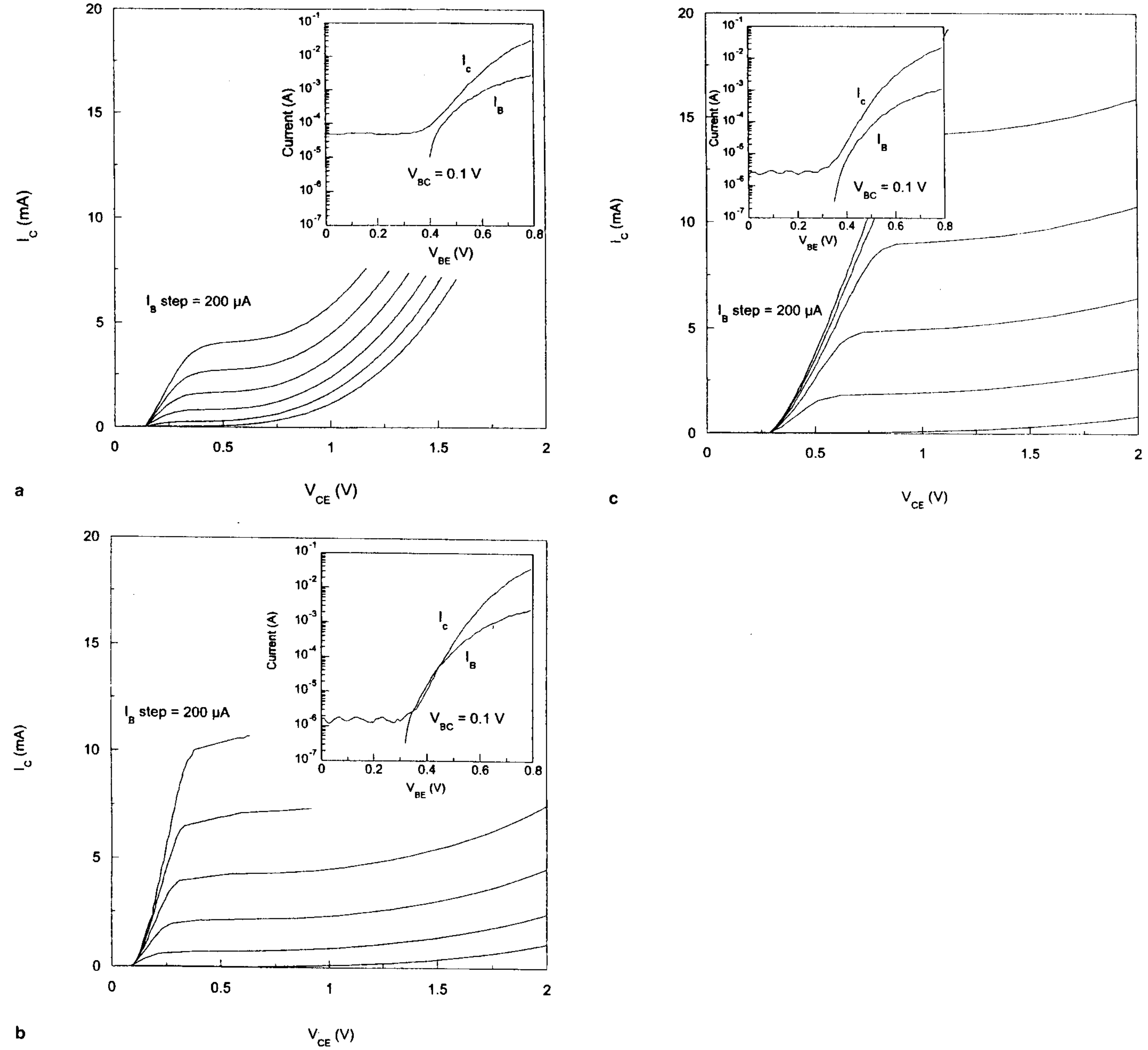

Fig. 3. The I-V characteristics of the HBT with 60 μm × 60 μm emitter size. Insert shows the Gummel plot. (a) InAlAs buffer, (b) AlGaAsSb buffer, and (c) InP buffer.

pared to a computed 65°C junction temperature that would result for a buffer layer of negligible thickness. Using the InP-based HBT reliability data,[8] the calculated HBT lifetime is reduced by two orders of magnitude when the junction temperature is increased from 100°C to 150°C, and the lifetimes of HBTs operating at 2×10^5 W/cm^2 power density, using the InAlAs and AlGaAsSb buffer layers, would be expected to be approximately 20:1 and 100:1 shorter than that of the HBT using an InP buffer layer. As HBT device and circuit speed is increased, HBT power density must be increased to above 2×10^5 W/cm^2.[9] Improvements in the metamorphic-layer thermal conductivity are, thus, extremely important in device design. Computed device junction temperatures as a function of power density are shown in Fig. 2.

Figure 3 shows common-emitter I-V characteristics of large-area metamorphic HBTs with a 60 μm × 60 μm emitter-base junction area and 100 μm × 130 μm collector-base junction area, indicating good material quality. The insert shows the log(I)-V (Gummel) characteristics. The poor properties of the InAlAs buffer were probably caused by rough surface morphology. Despite the large collector-base junction area and the low-bandgap $In_{0.53}Ga_{0.47}As$ collector (which, therefore, has large thermal generation currents per unit volume), the collector-base leakage current for the samples with InP and AlGaAsSb buffer layers is relatively small. The MHBTs, having $In_{0.53}Ga_{0.47}As$ collectors, showed reverse collector-base leakage currents (I_{CBO}) at 0.5 V bias of 240 μA for the InAlAs buffer, 30 μA for the AlGaAsSb buffer, and 12 μA for the InP buffer. As a standard of comparison, lattice-matched HBTs of similar layer structures and identical $In_{0.53}Ga_{0.47}As$ collectors showed 3 μA I_{CBO} at the same bias. It should be noted that the leakage currents are high, in part, due to the large 100 μm × 130 μm collector-junction areas and, in part, due to the narrow-bandgap $In_{0.53}Ga_{0.47}As$ collectors; lattice-matched HBTs of similar geometry and InP collector material showed <1 μA I_{CBO}. This suggests that the metamorphic growth has not greatly degraded the transistor characteristics. Further, we note that the metamorphic HBT grown with an InP buffer layer shows low collector-base leakage. This suggests, in contrast to prior published work, that compositional grading of the buffer layer does not appear to be necessary. Abandoning compositional grading, the InP buffer layers offer a marked advantage in thermal conductivity. Small junction-area metamorphic HBTs are now being fabricated to determine high-frequency transistor characteristics.

CONCLUSIONS

Three buffer layer materials, InAlAs, AlGaAsSb, and InP, were grown metamorphically on GaAs substrates, establishing a lattice constant equal to that of InP. $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ HBTs were grown on those buffer layers and their DC parameters measured. The HBTs showed similar electrical characteristics and had performance typical of large-area devices. The InP metamorphic buffer layer showed the best thermal conductivity. Given the measured buffer-layer thermal conductivities, the HBT operating junction temperature was calculated. Measured thermal conductivities of InAlAs and AlGaAsSb metamorphic buffer layers appear to be too low to permit reliable operation of HBTs at the high power densities required for either microwave power amplifiers or >10 GHz digital-integrated circuits. Given that HBT power density must progressively increase as device and circuit bandwidth is increased, thermal conductivity of the metamorphic buffer layer is critical. These thermal considerations, thus, strongly favor the use of InP metamorphic buffer layers.

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