Commercial Production of Large Diameter InP-HBT Epiwafers by MBE

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Abstract

InP-HBTs continue to demonstrate excellent performance in high-speed applications. We present epiwafer control and reproducibility of InP-HBT production on multi-wafer MBE reactors for standard InP substrates up to 100 mm diameters. Next-generation products will also be discussed, including growth of alternate GaAsSb-base structures, metamorphic HBTs, and evaluation of recently available 150 mm InP substrates.

INTRODUCTION

InP-based HBTs have demonstrated excellent performance in 40 Gb/s fiber-optic telecommunication products with the monolithic integration with optoelectronic devices such as LEDs, lasers and photodiodes. InP-based HBTs are also promising for automotive radar applications. IQE Inc. has successfully developed mass-production molecular beam epitaxy (MBE) technology for both beryllium (Be) and carbon (C) doped InP/InGaAs/InAlAs HBTs. The material advantages of the InP, InGaAs, and InAlAs alloys include higher mobilities, lower turn-on voltages, and heavily doped base layers. This combined with the precise control of alloy grading by MBE resulted in the realization of DHBTs with f_t and f_{max} values that satisfy the application requirements for 40 Gb/s and beyond.

In this paper we present an overview of standard InP/InGaAs/InAlAs HBT production on multi-wafer MBE reactors using substrates up to 100 mm in diameter. Along with high epitaxial material quality, the uniformity and the reproducibility of device parameters are key factors for InP integrated circuit applications. Control is demonstrated via base sheet resistance and DC gain measurements on large-area test devices. We present SPC charts for critical material parameters such as lattice mismatch and surface defect density to demonstrate control and stability of the process.

IQE is also examining some next generation InP-HBT production. Recently, multiple vendors have released 150 mm diameter InP substrates. InP-HBTs grown on these substrates show the same device properties, but the material quality is not as consistent from center-to-edge for the larger wafer. The structural, morphological, optical and electrical properties of the 150 mm epiwafers are discussed. We have also investigated alternate InP-HBT structures employing GaAsSb alloys for the C-doped base layers. The use of GaAsSb for the base layer can reduce the turn-on voltage and eliminate current blocking at the base–emitter (B-E) junction without the need to employ alloy grading, hence potentially simplifying the epitaxial growth process. Growth and characterization of InP/GaAsSb HBTs are discussed, along with the technological challenges to developing a manufacturable process for this material system. Finally, another path to larger diameter HBT epiwafers is through the metamorphic growth of the InP-based HBT structure on GaAs substrates. IQE has grown MHBTs using a various metamorphic buffer designs.

INP/INGAAS VOLUME PRODUCTION

Standard InP-HBTs have been grown in a VG-Semicon V-100 MBE reactor qualified at IQE for volume growth in 3×4” and 5×3” wafer configurations. We have grown both single-heterojunction (SHBT) and double-heterojunction (DHBT) structures, and employed emitter alloys of InP and InAl(Ga)As. The InGaAs base layers were doped with Be or C in the ranges of 2–4E19 and 2–6E19 cm^{-3}, respectively. The DC and RF device performance varies considerably depending upon structure design and material quality. Extremely high RF parameters of $f_t > 280$ GHz and $f_{max} > 450$ GHz were achieved on carbon-doped DHBTs with digital grading at the B-E and B-C junctions grown at IQE [1]. This section will focus on control parameters for C-doped HBTs designed for 40 Gb/s applications.

The epiwafer material quality was evaluated by measurements of defect density, PL, and alloy lattice mismatch. On 100 mm InP-HBT wafers, the average light point defect density varied depending upon the condition of the reactor and the quality of the substrate. For high quality prime substrates, the density was nominally $20/cm^2$ for measurements of optical cross-section range 1.3–50 μm^2 on the Surfscan 6220. Using the Accent RPM 4000 scanning PL tool, full wafer maps were collected. Due to the low incident power, PL signal was only observed from the heavily doped InGaAs cap. As such, PL was only used to provide uniformity information for this alloy composition.

Double crystal x-ray diffraction (DCXD) was used to determine InGaAs and InAlAs lattice mismatch. As seen in Figure 1, the average run-to-run variation in lattice mismatch does not exceed ±500 ppm. Cross-wafer measurements reveal that the composition varies by less than 0.15% across the 100 mm epiwafer.

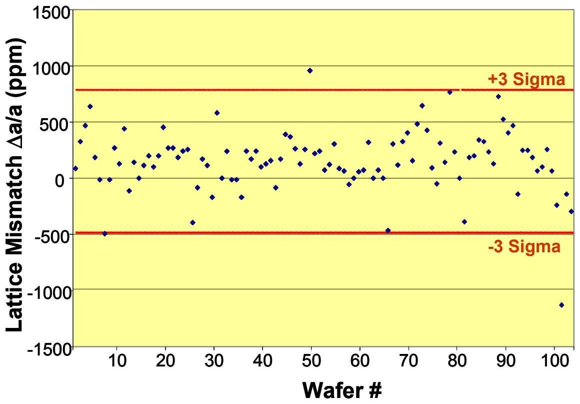

Figure 1. Lattice mismatch control chart for 100 mm InP/InGaAs-HBT growth.

Large area devices were fabricated from dedicated trial HBT wafers. Measurements of DC parameters such as gain, base sheet resistance and turn-on voltages ensured control and consistency of device performance. Figure 2 shows the gain versus base sheet resistance figure of merit curve for InP-HBTs. The individual data points are IQE device measurements of standard InP/InGaAs HBTs grown on 100 mm substrates. The line is provided as a guide to the eye, and the apparent noise is due to the wide variety of structures that have been grown. Multi-point measurements show a typical base sheet resistance variation of 3.5% across the 100 mm HBT wafer. For base-emitter junction turn-on voltages of around 530 mV, the center-to-edge variation is typically ±2 mV.

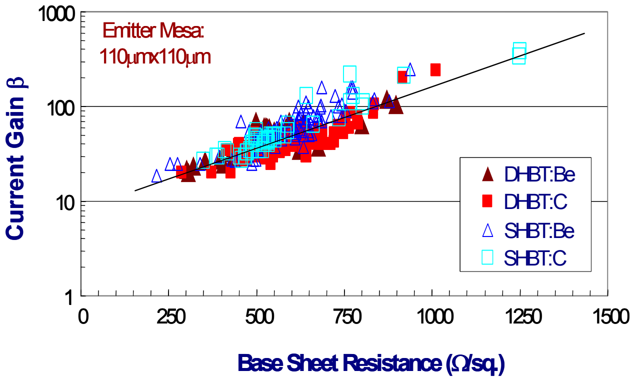

Figure 2. Universal figure of merit curve for InP/InGaAs HBTs grown on 100 mm substrates.

HBT Growth on 150 mm InP Substrates

Recently, several substrate manufacturers have produced 150 mm InP substrates for technology advancement. The move to larger diameter substrates provides potential for decreased material costs and increased device throughput. However, the move is also very challenging due to the fragile InP material and the difficulty of forming the large diameter ingots. IQE has grown on 150 mm InP substrates from multiple vendors at various stages of their process development. Substrate quality was evaluated via the growth of InP/InGaAs HBT structures in the V-100 MBE system using a single-wafer substrate holder. The base layer was C-doped at approximately 3.5E19 cm^{-3}, and the total epilayer thickness was about 1.5 μm.

Post-growth Surfscan measurements correlated well with etch-pit density (EPD) maps provided by the substrate supplier. The first set of 150 mm InP substrates from their initial development had defect densities around $200/cm^2$. Note that HBT growths on 100 mm substrates immediately before and after the 150 mm run had defects $<10/cm^2$; thus the defects on the larger diameter substrate were not MBE reactor related. The defects on the 150 mm substrate, seen in the left-hand defect map of Figure 3, predominantly were accumulated around the wafer perimeter, and were related to a lower crystal quality in that area of the substrate. A reduced-area scan to examine the equivalent inner 50 mm radius of the wafer revealed a defect density about $60/cm^2$ in that inner portion of the wafer. The higher defects around the edge of the wafer match the higher EPD, indicating that the inner portion of the ingot was of better quality than the outer. The next round of similar HBT growths on 150 mm substrates showed a much lower defect density ($20/cm^2$), as seen in the right-hand image of Figure 3. The higher defects correlating to EPD were only seen at the very edges of the substrate. The circled areas highlight the different InP substrate material quality between the two growths.

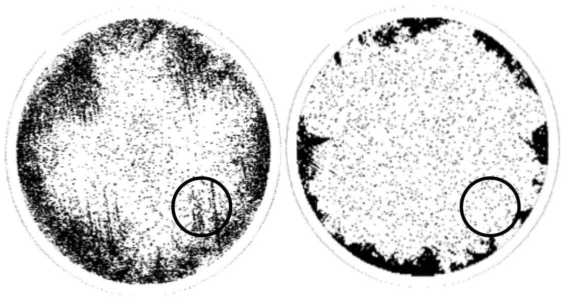

Figure 3. Surfscan maps of 150 mm diameter InP-HBT epiwafers. The left-hand image is from the initial MBE growths, while the right-hand image is from a later lot. The circled regions demonstrate improved substrate material quality closer to the perimeter of the wafer.

HBT epiwafer sheet resistance and lattice mismatch on the 150 mm substrates were very comparable to InP-HBT growth in a 3×4" configuration on the V-100. HRXRD measurements were made at multiple points across the diameter of the wafer. The lattice mismatch variation indicated an InGaAs alloy composition variation of only 0.002 mole fraction across the 150 mm wafer. The Lehighton sheet resistance map, seen in Figure 4, was dominated by the heavy Si doping in the top InGaAs/InP contact layers. For a 55-point scan, the average sheet resistance was 4.0 Ω/square, with a cross-wafer standard deviation of 0.54% and a total variation of 1.7%.

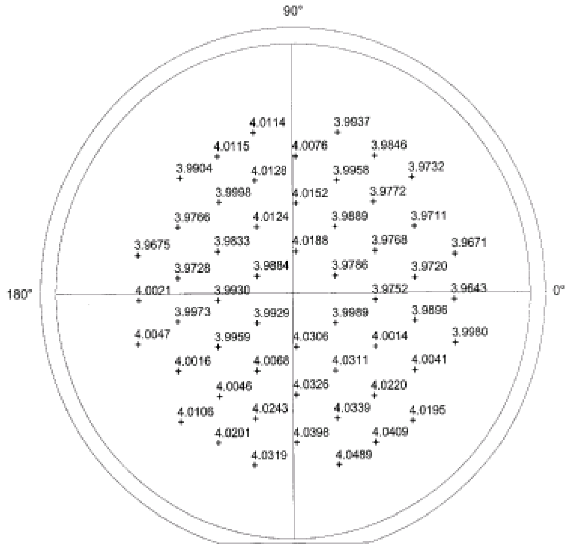

Figure 4. Lehighton Sheet resistivity map for a 150 mm InP/InGaAs HBT. Rsh=4.0 Ω/square, standard deviation=0.53%, total variation=1.2%.

Large area DC device parameters of gain, ideality factors, and breakdown were very comparable with the same HBT structure grown on 100 mm substrates. However, the base sheet resistance showed about a 20% variation from center to edge of the wafer. This was seen in multiple rounds of MBE growths on 150 mm substrates, and is possibly an indication of non-optimized temperature uniformity during the MBE growth as opposed to an inherent substrate problem.

NEXT GENERATION HBTS

Multiple research groups are investigating the InP/GaAsSb alloy system as an alternative to the traditional InP/InGaAs HBT structure. Employing a base layer material of GaAsSb may reduce the turn-on voltage and eliminate current blocking at the B-E junction without the need to employ alloy grading. Carbon-doped GaAsSb was grown using solid sources for Ga, As and Sb, while CBr_4 was used as a doping precursor. Carbon activation in GaAsSb was obtained for standard base doping levels in the 2E19 – 2E20 cm^{-3} range, with mobility values holding steady from around 40 cm^2/V-s for p > 5E19 cm^{-3}. The common emitter IV curves for a large-area InP/GaAsSb HBT structure are shown in Figure 5. The DC gain was 30 for the 4E19 cm^{-3} C-doped base, and was comparable to values obtained in similar InP/InGaAs HBTs. A major challenge in the development of GaAsSb-based HBTs is the control of the GaAsSb composition. The device parameters are very sensitive to the ternary composition, thus placing a premium on the uniformity and long-term stability of the respective As and Sb source fluxes.

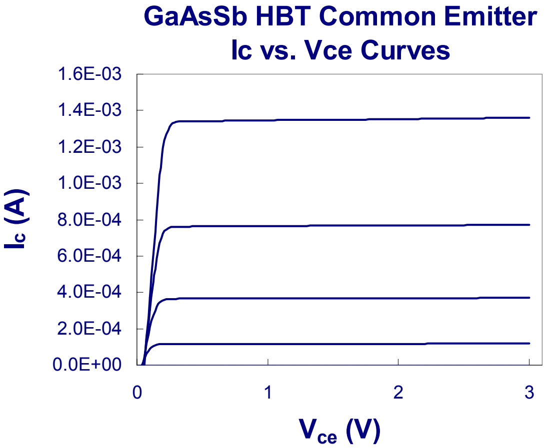

Figure 5. Common emitter IV curves for a large-area InP/GaAsSb HBT test structure.

Another next-generation alternative for large diameter InP-HBT production is through the metamorphic growth of the structures on GaAs substrates. The metamorphic buffers (M-buffers) allow for the growth of high speed InP-based alloys on GaAs substrates. The GaAs substrate is cheaper, stronger, and more mature at the larger sizes. Current MHEMT production in the industry employs graded In(Ga)AlAs M-buffers, and have gone through full reliability testing [2]. However, for higher power density MHBT circuits, the thermal characteristics of the M-buffer may play an important role. IQE has investigated the thermal properties of various M-buffer designs, and it has been shown that a binary InP M-buffer has superior thermal properties compared to graded ternary and quaternaries [3]. High performance MHBTs have also been reported using InP M-buffers [4]. IQE continues to develop this product on the multi-wafer MBE platforms, with scheduled investigations of structural and long-term device properties.

CONCLUSIONS

InP-HBTs offer multiple advantages for high speed integrated circuit applications. Standard InP/InGaAs structures are in production on multi-wafer MBE reactors using substrates up to 100 mm in diameter. Consistent device performs achieve speeds required for 40 Gb/s applications and beyond. In addition, the groundwork has been laid for multiple paths to next-generation process and device performance enhancements.

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ACRONYMS

MBE: Molecular Beam Epitaxy
HBT: Hetero-junction Bipolar Transistor
MHBT: Metamorphic Hetero-junction Bipolar Transistor
SHBT: Single Hetero-junction Bipolar Transistor
DHBT: Double Hetero-junction Bipolar Transistor
PL: Photoluminescence
HRXRD: High Resolution X-ray Diffraction
EPD: Etch Pit Density
MHEMT: Metamorphic High Electron Mobility Transistor