Comparison of As- and P-based metamorphic buffers for high performance InP heterojunction bipolar transistor and high electron mobility transistor applications

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Metamorphic buffers (M-buffers) consisting of graded InAlAs or bulk InP were employed for the production of InP-based epiwafers on GaAs substrates by molecular-beam epitaxy. The graded InAlAs is the standard for production metamorphic high electron mobility transistors (M-HEMTs), while the bulk InP offers superior thermal properties for higher current density circuits. The surface morphology and crystal structure of the two M-buffers showed different relaxation mechanisms. The graded InAlAs gave a cross-hatched pattern with nearly full relaxation and very effective dislocation filtering, while the bulk InP had a uniform isotropic surface with dislocations propagating further upwards towards the active layers. Both types of M-buffers had atomic force microscopy root-mean-square roughness values around 20–30 Å. The Hall transport properties of high electron mobility transistors (HEMTs) grown on the InAlAs M-buffer, and a baseline HEMT grown lattice matched on InP, both had room-temperature mobilities >10,000 cm²/V s, while the M-HEMT on the InP M-buffer showed a decrease to 9000 cm²/V s. Similarly, the dc parameters of a double heterojunction bipolar transistor (DHBT) grown on the InAlAs M-buffer were much closer to the baseline heterojunction bipolar transistor than a DHBT grown on the InP M-buffer. A high breakdown voltage of 11.3 V was achieved on an M-DHBT with the InAlAs M-buffer. We speculate that the degradation in device characteristics on the InP M-buffer was related to the incomplete dislocation filtering. © 2004 American Vacuum Society. [DOI: 10.1116/1.1691412]

I. INTRODUCTION

Through the use of a metamorphic buffer (M-buffer) layer, the high-speed performance of InP-based devices becomes available on the more mature GaAs substrates. InP-based heterojunction bipolar transistors (HBTs) and high electron mobility transistors (HEMTs) have demonstrated excellent performance in wireless, fiber optic, and automotive radar applications, with high speeds of 40 Gb/s and beyond. The superior electronic properties of the InP/InGaAs/InAlAs alloys, combined with the precise control of alloy composition and grading by molecular-beam epitaxy (MBE), enable these high speeds. One challenge for cost effective volume manufacturing is the InP substrates, which are more expensive, brittle, and only now developing 6-inch diameter. A variety of M-buffers have been used to facilitate the growth of InP-based devices on GaAs substrates. As circuit density, power, and speeds increase, the need to dissipate heat from the device circuits will become more important. It has been demonstrated that a thick InP M-buffer offers higher thermal conductance compared to ternary and quaternary M-buffers. This article compares the structural, electrical, and thermal properties of metamorphic HBTs (M-HBTs) and metamorphic HEMTs (M-HEMTs) grown with M-buffers of In(Ga)As, In(Ga)P, and InP alloys.

The basic requirement of the metamorphic buffer is to accommodate the lattice mismatch between the GaAs substrate and the InP-based alloys of the device structure. The M-buffer must absorb this strain while minimizing the propagation of dislocations into the device layers. The resulting surface should have low roughness and minimal warp for device reliability and processing requirements. Device and circuit isolation requires high electrical resistance in the M-buffer. For higher-power density circuits, the thermal characteristics of the M-buffer play an important role as the ability to extract heat from the device layers will affect performance and reliability. Various schemes have been employed to accomplish these goals: Graded layers of InGaAs, InAlAs, InGaAlAs, InGaP, and InAlP, and bulk layers of InAlAs and InP. The InGaAs and InGaP alloys exhibit lower electrical resistance, and the InAlP typically has a higher surface roughness, thus eliminating these alloys from consideration. Graded InAlAs and InGaAlAs alloys are standard for production of M-HEMT circuits and have passed full reliability testing. The thermal characteristics of the various M-buffers and M-HBTs were studied using scanning thermal...
microscopy and single-substrate-temperature techniques. The thermal resistance of a M-HBT grown on the InP M-buffer (275 °C/W) is orders of magnitude lower than the same M-HBT grown on InAlAs M-buffers. The remainder of this article focuses on the comparison of M-HEMTs and M-HBTs grown on graded InAlAs and bulk InP M-buffers.

II. EXPERIMENTAL DETAILS

The epitaxial growths for this work were performed in a single-wafer Varian GEN-II reactor and in a multiwafer Thermo-VG V-100 MBE system. Both MBE systems were equipped with As and P valved crackers, and with conventional solid-source effusion cells for the group-III materials. The M-HEMTs and M-HBTs were grown on 3, 4, and 6 in. diameter GaAs substrates. Baseline lattice-matched (LM) structures were grown on 3 and 4 in. InP substrates. The InAlAs M-buffer contained two separate layers: A linear grade to a high In%, followed by a thinner inverse grade back to the target device composition. The total M-buffer thickness was 1.1 μm. The InP M-buffer was a straightforward binary growth with total thickness 1.1–1.5 μm. The growth temperatures were calibrated using an optical pyrometer. All device layers were grown in the 460–520 °C range, as was the InP M-buffer layers. The InAlAs graded M-buffer was grown at temperatures below the pyrometer measurement limit of ~450 °C.

Two basic device structures were used to evaluate and compare the quality of the M-buffers. The single-pulse-doped HEMT structure included a 200 Å InGaAs channel. The majority of these HEMTs used a 53% InGaAs channel composition corresponding to lattice matching with InP. The flexibility of the graded InAlAs M-buffer allowed M-HEMTs with nonstandard channel compositions to be evaluated as well. The generic double HBT (DHBT) structures employed InP collector and emitter layers, and an InGaAs base doped at 3×10^19 cm^-3 with carbon. A digital alloy grade was used at the base–collector junction, while the base–emitter junction was abrupt. Nominally identical structures were grown on GaAs substrates using both the InAlAs and the InP M-buffers. Control samples were grown on InP substrates and used for baseline data.

Multiple techniques were used to analyze the quality of the various metamorphic structures. Surface morphology and roughness were compared via Nomarski optical microscope and a Veeco D5000 atomic force microscope (AFM). The structural properties were evaluated using high resolution x-ray diffraction (XRD) and transmission electron microscopy (TEM). For the latter, cross-sectional samples were prepared by dimpling followed by ion milling to electron transparency. TEM was performed with a JEOL ARM operated at 800 kV having a point-to-point resolution of 1.5 Å. The free-standing warp and total thickness variation (TTV) of the epilayers were measured on a Tropel Autoselect 8020 using a HeNe laser-based interferometer with an integral image analysis system. Transport properties were measured by the Hall effect using the van der Pauw geometry at 300 and 77 K. Large-area devices were fabricated and the dc characteristics measured for both the metamorphic and baseline structures. The HEMT gate size was 2×200 μm, and the HBT base–emitter junction dimension was 110×110 μm.

III. RESULTS AND DISCUSSIONS

Figure 1 demonstrates the surface morphology of M-HEMTs [Figs. 1(a)–1(c)] and M-HBTs [Figs. 1(d) and
grown on different M-buffers as observed through Nomarski microscope and AFM (5×5 μm scans). The morphology of the graded InAlAs M-buffers shows a cross-hatched pattern, Figs. 1(a), 1(b), and 1(d), while the bulk InP M-buffer has a more isotropic surface roughness, Figs. 1(c) and 1(e). We attribute this to the difference in strain relaxation mechanisms. The cross hatching of the graded M-buffer is the result of continual introduction of strain and consequent relaxation through a network of misfit dislocations. The anisotropic nature of the cross hatching is due to unequal nucleation and glide properties of the orthogonal dislocations. The linear grade with the inverse grade results in nearly complete relaxation and in a very low density of threading dislocations at the surface. One the other hand, the nucleation of the mismatched bulk InP M-buffer introduces all of the strain at the interface between the substrate and the M-buffer. The film relaxes through the development of a three-dimensional growth front. The surface is isotropic and smooths with increasing buffer thickness. The magnitude of the surface roughness is dependent upon the epilayer thickness and the growth conditions, in addition to the total dislocation density. Thicker active layer structures can somewhat mask the underlying morphology of the M-buffer, especially the cross hatching of the InAlAs grade. For example, the cross hatching for the thick M-HBT of Fig. 1(d) is not as striking as in the M-HEMTs of Figs. 1(a) and 1(b). Both M-buffer schemes obtain similar AFM root-mean-square (rms) roughness values of 20–30 Å. Note that the lowest rms, 19 Å in Fig. 1(b), corresponds to an InAlAs M-buffer terminating at a 40% InGaAs channel HEMT. The lower In composition has less strain and thus a slightly smoother surface.

The dislocation evolution through the M-buffers was studied via TEM. Figure 2 shows the low magnification overview image of a full M-HBT structure with a graded InAlAs M-buffer. Qualitatively, this is very similar to TEM images which we published previously for M-HEMTs. The image clearly demonstrates a filtering of the dislocations as the InAlAs grade progresses and the M-buffer thickness increases. Three regions with distinct transitions appear within the 1.1 μm thick M-buffer: An area of high dislocation density within the first ~3000 Å next to the substrate, a ~2000 Å middle region with reduced dislocations, and the top section with minimal dislocations. From high-resolution TEM images (not shown), stacking faults and dislocations are observed at the substrate/M-buffer interface, but no dislocations are found at the interface between the top of the M-buffer and the device layers. Similar features are observed for devices with the bulk InP M-buffer. The high-resolution TEM image of Fig. 3(a) demonstrates stacking faults in the bulk InP, expanded in Fig. 3(b), and regularly spaced misfit dislocations at the substrate/M-buffer interface, expanded in Fig. 3(c). The latter, which is not seen for the InAlAs M-buffer, is evidence of immediate relaxation of the 3.8% strain between the GaAs and InP. The thick InP M-buffer allows for a smoothing of the growth front and good interfaces with the device layers.

**FIG. 2.** Low magnification TEM overview image of an M-HBT structure with graded InAlAs M-buffer. Layers with different chemical composition are recognized by their contrast difference.

**FIG. 3.** (a) High-resolution TEM image of the interface (indicated by the horizontal arrow) between the GaAs substrate and the bulk InP M-buffer in an M-HBT. The areas highlighted by the white rectangles are expanded in greater detail below to highlight (b) a stacking fault in the InP and (c) two 60° misfit dislocations at the interface.
The structural quality of the layers was also investigated with XRD (004) rocking curves, as shown in Fig. 4. The two spectra are from M-HEMTs grown with [Fig. 4(a)] a graded InAlAs M-buffer and [Fig. 4(b)] a bulk InP M-buffer. The sharp peak at 33° is from the GaAs substrate. The spectra demonstrate the two different paths to relaxation. For the graded InAlAs M-buffer, the XRD confirms the gradual change in lattice constant from the GaAs to the InP-based alloys of the HEMT, seen as a peak at 31.6°. The inverse grade design is evident from the signal down to 31°. Previous x-ray reciprocal mapping has shown that the inverse grade results in nearly complete relaxation of the M-buffer. For the bulk InP M-buffer, there is no gradual change in lattice constant. The HEMT response at 31.6° is broadened by the thick defective M-buffer. The five-crystal x-ray technique does not have sufficient resolution to extract a reliable quantification of the percent relaxation in the metamorphic buffer. The (004) spectra are typical for these M-HEMT designs.

Another key structural aspect of the metamorphic epilayers is their flatness. The lattice mismatch can induce a distortion of the wafer contour. If excessive, this can cause problems with lithography and device processing. Substrate manufacturers typically specify wafer flatness in terms of warp (measured on a free-standing wafer) and TTV (measured with the wafer clamped to a reference surface). For 4 in. diameter GaAs and InP substrates, the warp and TTV specifications are typically less than 5–10 μm. Measurements on 4 in. GaAs pseudomorphic high electron mobility transistor (PHEMT) and InP HBT epilayers show no increase in warp or TTV above the substrate specification. For 4 in. M-HEMTs and M-HBTs, the TTV remains low, but the warp increases as shown in Fig. 5. For metamorphic wafers with either the InAlAs or InP M-buffers, the warp typically increases by a factor of 3. Limited measurements of 6 in. M-HEMT epilayers show an even larger increase in warp as well as in TTV, indicating the need to further optimize growth parameters. Growth temperature nonuniformity is a key issue in controlling the flatness of the 6 in. metamorphic wafers.

Hall measurements in the van der Pauw geometry were used to gauge the electrical transport properties of the M-HEMTs in comparison to baseline structures grown on InP substrates. Table I summarizes the various 300 and 77 K Hall data. For the baseline structure with a 200 Å InGaAs channel structure and a fixed Si delta-doping concentration, a channel charge around 3 \times 10^{12} \text{cm}^{-2} and mobility values of 10,000 and 40,000 cm^2/V s are typical for 300 and 77 K, respectively. M-HEMTs grown on the InAlAs M-buffer have similar charge and slightly higher mobility values. We find

<table>
<thead>
<tr>
<th>Structure</th>
<th>M-Buffer</th>
<th>( n_s ) at 300 K ( \times 10^{12} \text{cm}^{-2} )</th>
<th>( \mu ) at 300 K ( \text{cm}^2/\text{V s} )</th>
<th>( n_s ) at 77 K ( \times 10^{12} \text{cm}^{-2} )</th>
<th>( \mu ) at 77 K ( \text{cm}^2/\text{V s} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>LM-HEMT</td>
<td>N/A(^a)</td>
<td>2.9</td>
<td>10,400</td>
<td>2.9</td>
<td>40,200</td>
</tr>
<tr>
<td>M-HEMT</td>
<td>InAlAs</td>
<td>3.0</td>
<td>10,700</td>
<td>2.8</td>
<td>40,700</td>
</tr>
<tr>
<td>M-HEMT</td>
<td>InP</td>
<td>2.6</td>
<td>9140</td>
<td>2.8</td>
<td>27,600</td>
</tr>
</tbody>
</table>

\(^a\)N/A indicates not applicable.
TABLE II. Large-area dc device data for a DHBT structure grown LM on InP and with a graded InAlAs M-buffer on GaAs. The breakdowns are measured at a current of 0.5 mA.

<table>
<thead>
<tr>
<th>dc parameter</th>
<th>LM-HBT</th>
<th>M-HBT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain (β) at I_b = 1.2 mA</td>
<td>120</td>
<td>100</td>
</tr>
<tr>
<td>Base R_g (Ω)</td>
<td>785</td>
<td>728</td>
</tr>
<tr>
<td>β/R_{sh}</td>
<td>0.15</td>
<td>0.14</td>
</tr>
<tr>
<td>V_{offset} (V)</td>
<td>0.12</td>
<td>0.13</td>
</tr>
<tr>
<td>BV_{ceo} (V)</td>
<td>12.4</td>
<td>11.3</td>
</tr>
<tr>
<td>B−E junction V_j/V_r</td>
<td>0.55/2.9</td>
<td>0.54/2.6</td>
</tr>
<tr>
<td>B−C junction V_j/V_r</td>
<td>0.42/16.4</td>
<td>0.41/15.6</td>
</tr>
<tr>
<td>Ideality factors (n_c/n_b)</td>
<td>1.10/1.32</td>
<td>1.10/1.33</td>
</tr>
</tbody>
</table>

that the channel transport properties degrade to 9000 and 27 000 cm²/V s for the same HEMT grown on the InP M-buffer. Multiple growth temperatures have been used for the InP M-buffer, with the best transport properties seen around 460–500 °C. However, further investigation can be done with respect to P-flux and growth rate in order to further optimize this M-HEMT. Even though the transport properties are degraded, large-area device fabrication and testing show good pinch-off and transfer characteristics.

Large-area DHBT devices were fabricated for dc testing. Table II shows that the M-HBTs with the InAlAs M-buffer have similar properties to baseline LM-HBT structures grown on InP substrates. The DHBT structure contains a thick InP collector and is designed for high gain and breakdown. The figure of merit, β/R_{sh}, is very similar for the two structures, as are most of the other parameters. The most consistent difference is the ~10% degradation of the breakdown voltages in the InAlAs M-HBT, but they are still very good with a BV_{ceo} of 11.3 V. Our previous work on SHBTs shows no degradation in gain or breakdown between LM- or InAlAs M-SHBT structures, but breakdown for SHBTs are typically <5 V due to the InGaAs collector. The Gummel plots (Fig. 6) for the two HBTs also exhibit similar characteristics. However, M-HBTs grown on the InP M-buffers show more degradation in gain and breakdown, with values about half that of the LM-HBTs. This again may be related to the residual strain and dislocations propagating from the bulk M-buffer. This degradation may be characteristic of the high-power DHBT design, as published reports for high-speed devices designed for lower breakdown voltages do not note degradation compared to the identical structures grown LM on InP.8

IV. CONCLUSIONS

M-buffers consisting of graded InAlAs or bulk InP have been employed for the MBE production of InP-based epilayers on GaAs substrates. The graded InAlAs is the standard M-buffer used for production M-HEMTs. The bulk InP offers superior thermal properties for higher current density circuits of the future. The surface morphology and crystal structure of the two M-buffers are distinctly different and can be attributed to the difference in the underlying strain relaxation mechanism. The graded InAlAs resulted in a cross-hatched pattern with nearly full relaxation, while the bulk InP gave a uniform isotropic surface. Both types of M-buffers had similar AFM rms roughness values. The Hall transport properties of HEMTs grown on the InAlAs M-buffer were the same as the baseline LM-HEMT structure, while the InP M-buffer showed a decrease in the mobility. Similarly, the DHBT dc parameters on the InAlAs M-buffer were much closer to the LM-HBT than those measured on the InP M-buffer. The breakdown voltages on the M-DHBT were >11 V using the InAlAs M-buffer. The decrease in performance of the device on the InP M-buffer was attributed to the incomplete dislocation filtering in the bulk InP. Further work can be done to optimize the growth conditions, specifically P flux and InP growth rate, and should result in an improvement of the M-HEMT and M-HBT characteristics. Both M-buffers can provide access to the higher-speed performance of InP-based alloys grown on the larger diameter more mature GaAs substrates.