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Comparison of mixed anion, InAsP and mixed cation, InAlAs metamorphic buffers grown by MBE on InP substrates

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The structural, morphological and defect properties of $InAs_yP_{1-y}$ and $In_xAl_{1-x}As$ metamorphic step-graded buffers grown on InP substrates using solid source molecular beam epitaxy, out to a total mismatch of ~1.2%, were investigated. Symmetric relaxation with minimal lattice tilt for the final $InAs_{0.4}P_{0.6}$, $In_{0.7}Al_{0.3}As$ overlayers along with ordered crosshatch morphology with very low rms roughness of~2.2 nm for $InAs_yP_{1-y}$ graded buffers compared to $In_xAl_{1-x}As$ graded buffers (~7.3 nm) were achieved. High-quality InAsP buffers were achieved with a low threading dislocation density, while InAlAs graded buffers showed evidence for phase decomposition, which was related to the more pronounced surface roughness. The minority carrier lifetime in $In_{0.69}Ga_{0.31}As$ layers grown on InAsP step-graded buffer was 6 times higher than on InAlAs graded buffer, correlating with the different structural quality of the two buffer types.

I. INTRODUCTION

Compositionally graded metamorphic buffers grown on InP substrates to increase the InP substrate lattice constant are of interest to support a range of high-speed electronic and infrared optoelectronic devices based on the InGaAsP material system. Graded buffers have been utilized to produce relaxed, "virtual" substrates for many applications, including SiGe-based heterojunction field effect transistors, $In_xGa_{1-x}As/GaAs$ light emitting diodes (LEDs), $In_xGa_{1-x}P/GaP$ LEDs, $In_xGa_{1-x}P/GaAs$ metamorphic heterojunctions bipolar transistors (HBTs), $In_xGa_{1-x}P/GaAs$, $InAs_yP_{1-y}/InP$, $In_xAl_{1-x}As/In_xGa_{1-x}As$ high electron mobility transistors (HEMTs) on GaAs and $GaAs/Ge/Si_{1-x}Ge_x/Si$ solar cells [1-4]. Here, we investigate the structural, morphological and defect properties of mixed anion, $InAs_yP_{1-y}$ and mixed cation, $In_xAl_{1-x}As$ metamorphic step-graded buffers grown by molecular beam epitaxy (MBE) on InP substrates, out to a total mismatch of ~1.2%. An additional, far more fundamentally motivating factor for this study stems from the use of a group-V, anion-based graded alloy, $InAs_yP_{1-y}$, as opposed to a group-III graded cation alloy, $In_xAl_{1-x}As$, for the purpose of grading the substrate lattice constant. The use of a graded anion buffer for MBE growth offers a potential advantage compared with more common graded buffers choices such as $In_xGa_{1-x}As$ and $In_xAl_{1-x}As$ on InP, since control of the growth rate (Indium flux) for the former is decoupled from control of the layer composition and hence lattice constant.

II. EXPERIMENTAL

$InAs_yP_{1-y}$ and $In_xAl_{1-x}As$ step-graded buffers were grown to span the identical range of lattice constants and mismatch on semi-insulating (001) InP substrates. Growth was monitored by reflection high-energy electron diffraction (RHEED). The initial (2x4) symmetry of the InP surface observed by RHEED became blurry, but still observable, as a function of InAlAs growth time, which was minimized by reducing the exposure of the InP surface to an As flux prior to InAlAs growth. However, for InAsP growth, which is initiated under a P flux, a strong (2x4) RHEED pattern was consistently observed, indicating the problem of As replacing P on the InP surface under As exposure during InAlAs nucleation. The first three, undoped step-graded layers were grown to a thickness of 0.4 µm in each case, followed by a final 1.5 µm thick cap of either $InAs_{0.4}P_{0.6}$ or $In_{0.7}Al_{0.3}As$. The growth rate and the growth temperature for all $InAs_yP_{1-y}$ layers were kept constant at 0.75 ML/s, as determined by RHEED intensity oscillations and ~ 485°C, respectively. Similarly, $In_xAl_{1-x}As$ layers (x = 0.52-0.70) were grown on (001) InP substrates starting with a lattice-matched composition of $In_{0.52}Al_{0.48}As$ and subsequent grading to higher In content. The In and Al fluxes were independently varied to achieve the step grade while maintaining a constant growth rate of 3.28 Å/sec throughout the growth. The growth temperature was monotonically reduced from 520°C to 505°C in order to suppress In droplets for the high In content layers and a spotty RHEED pattern. For cross-sectional transmission electron microscopic studies, a final $In_{0.69}Ga_{0.31}As$ overlayer was grown to be lattice-matched to the final $In_{0.7}Al_{0.3}As$ layer, resulting in a total lattice mismatch of ~1.1-1.2%. The strain relaxation, surface morphology, and defect properties of the step-graded buffers were characterized using triple axis x-ray diffraction (TAXRD), atomic force microscopy (AFM), plan-view transmission electron microscopy (TEM) and cross-sectional TEM (XTEM). TEM samples were prepared by a conventional mechano-chemical thinning procedure followed by Ar ion milling. The lifetime was measured using photoconductive decay (PCD) with an excitation wavelength of 2000 nm.

III. RESULTS AND DISCUSSION

Figures 1 (a) and 1 (b) show reciprocal space maps (RSMs) using TA-XRD obtained for a 1.5 µm thick $InAs_{0.4}P_{0.6}$ and $In_{0.7}Al_{0.3}As$ epitaxial layers on 4-step $InAs_yP_{1-y}$ and $In_xAl_{1-x}As$ buffers with the incident beam along the $[110]$ and $[\bar{1}10]$ direction, respectively. Symmetric relaxation of ~90% in the two orthogonal <110> directions with minimal lattice tilt was observed for the terminal $InAs_{0.4}P_{0.6}$ and $In_{0.7}Al_{0.3}As$ overlayers of each graded buffer type, indicating nearly equal numbers of α and β dislocations were formed during the relaxation process and that the relaxation is near equilibrium and hence insensitive to asymmetric dislocation kinetics.

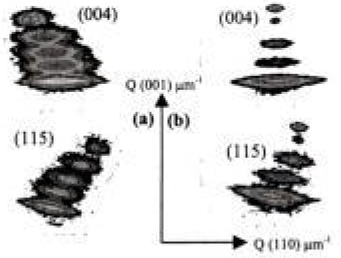

Fig. 1: RSMs of (a) InAsP and (b) InAlAs step-graded buffers

AFM revealed extremely ordered crosshatch morphology and very low rms roughness of ~2.2 nm for the InAsP relaxed buffers compared to the InAlAs relaxed buffers (~7.3 nm) at the same degree of lattice-mismatch with respect to the InP substrates and is clearly seen in Figure 2. This is consistent with RHEED observation during growth, which displayed much sharper (2x4) surface reconstruction patterns for InAsP. Further insight into the structural differences between cation-graded InAlAs versus anion-graded InAsP buffers are revealed by TEM.

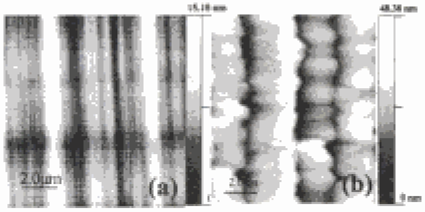

Fig. 2: Surface morphology of (a) $InAs_{0.4}P_{0.6}$ and (b) $In_{0.7}Al_{0.3}As$ layers by AFM

Fig. 3 (a) shows a representative XTEM image of a relaxed $InAs_{0.4}P_{0.6}$ layer grown on InP using $InAs_yP_{1-y}$ graded buffers. The high contrast at the graded buffer layer interfaces is due to misfit dislocations (MDs) with no threading dislocations (TDs) observable in the $InAs_{0.4}P_{0.6}$ cap layer at this scale. This conservatively indicates that the threading dislocation density (TDD) in this $InAs_{0.4}P_{0.6}$ layer is below $10^7 cm^{-2}$. More accurate TD counting has been performed using plan-view TEM, which shows an average TDD of ~ $4x10^6$ cm^{-2} for this film [3]. In contrast, XTEM images of a representative InAlAs-based graded structure, Fig. 3 (b), show clearly observable defects at this scale that are not simple threading dislocations and instead appear to be the onset of phase (spinodal) decomposition taking place in the final $In_{0.68}Al_{0.32}As$ buffer layer, consistent with the increased roughness for this layer as noted earlier by RHEED and AFM measurements. However, defects are also within the $In_{0.69}Ga_{0.31}As$ layer grown on the $In_xAl_{1-x}As$ buffers, in addition to the presence of surface roughening. Spinodal decomposition of ternary III-V semiconductor alloys during lattice-matched and lattice-mismatched heteroepitaxy using MBE has been observed by many groups, and is reported to be enhanced by surface roughness [5,6], consistent with our observations. The roughness observed for graded InAlAs can be understood by considering the difference between the bond strengths of In-As (1.41 eV) and Al-As (1.98 eV). This disparity leads to a higher In adatom mobility than for Al, In segregation, and ultimately phase decomposition. This correlates with the observed defect evolution as a function of layer thickness and increasing In content, where phase decomposition is more apparent in the higher In content InAlAs layers, Fig. 3 (b).

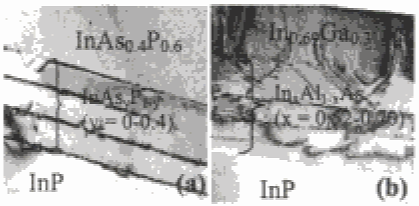

Fig. 3: Cross-section TEM images of (a) InAsP and (b) InAlAs step-graded buffers

Finally, the minority carrier lifetime in $In_{0.69}Ga_{0.31}As$ layer using InAsP step-graded buffer was 6 times higher than on InAlAs graded buffer as measured by PCD of InAsP/InGaAs/InAsP double heterostructures, the increased surface roughness consistent with of InAlAs. These results and the self-consistency between electrical, structural and growth properties indicate that III-V graded buffers grown by MBE that utilize the anion sublattice for controlling the lattice constant may be superior for III-V metamorphic devices grown on InP.

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