Molecular Beam Epitaxy Growth-Space Investigation of InAsBi and InGaAsBi on InAs

S. J. Maddox*, H. P. Nair, V. D. Dasika, E. M. Krivoy, R. Salas, and S. R. Bank

ECE Department, The University of Texas at Austin, Austin, Texas 78758

Highly mismatched alloys (HMA) have garnered increasing interest over the past few decades due to the promise of increased engineering flexibility in the design of advanced compound semiconductor heterostructure devices. Increased control over key device parameters such as lattice constant, bandgap, and band offsets opens the door to improved performance for a wide range of electronic and optoelectronic devices. However, the large miscibility gaps characteristic of HMA's make these materials far more difficult to grow than traditional III-V alloys. Growth of dilute-bismuthides, in particular, has historically been plagued by bismuth surface segregation, resulting in droplet and alternate phase formation. However, if these growth challenges can be overcome, InAsBi, and its lattice-matched cousin, InGaAsBi, hold great promise for InAs-based mid-to-long wavelength infrared photodetectors; this material system benefits from having a controllable bandgap, a strong absorption coefficient, lattice-matched and super-lattice-free growth, and mature III-V processing, making it a significant competitor to the more established InSb, HgCdTe, and type-II GaSb/InAs material systems. By applying recent advances from molecular beam epitaxy (MBE) growth of GaAsBi [1] to the growth of InAsBi and InGaAsBi on InAs, we map out a growth space free of droplet and alternate phase formation in which the optical quality is significantly enhanced.

Samples were grown by solid-source MBE in an EPI Mod. Gen. II system on n-type, sulfur doped (100) InAs substrates. A range of substrate temperatures from 305°C to 355°C, bismuth beam equivalent pressures (BEP) from 2.0E-8 Torr to 1.1E-7 Torr, and stoichiometric (V/III) flux ratios from approximately 0.95 to 1.35 were explored. Bi incorporation was found to dramatically decrease above substrate temperatures of ~330°C (Figure 1) and stoichiometric (V/III) flux ratios of ~1.15 (Figure 2); below these temperatures and flux ratios, incorporation was found to be linear with Bi BEP (Figure 3), signifying near-unity sticking of Bi. InAsBi layers 150 nm thick with Bi concentrations up to 5.25%, as determined by X-ray diffraction (XRD) rocking curves using an InBi lattice constant of 6.686Å, were grown without droplet formation, as confirmed by Nomarski phase contrast microscopy. InGaAsBi layers 200 nm thick with Bi concentrations ranging from 1.3% to 5.25% were grown lattice matched to InAs, with strained mismatch repeatedly below 300 parts per million.

Optical quality of the as-grown layers was studied using room temperature and 77K photoluminescence (PL). InAsBi PL intensity was found to improve at colder growth temperatures (Figure 4); however, significant degradation to the PL intensity as compared to an InAs control grown under similar conditions suggests the presence of a significant interstitial Bi component or, alternatively, some other degradation mechanism. Rutherford backscatter spectrometry (RBS) studies are underway to quantitatively investigate this possibility, and we expect further optimization of the growth parameters and controlled annealing to improve the material quality to the level required for optoelectronic device applications.

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*Corresp. Author: smaddox@utexas.edu, Phone: 1-512-471-5383, Fax: 1-512-471-9674

[1] A. J. Ptak, et al., Journal of Crystal Growth **338**, 107-110 (2012).

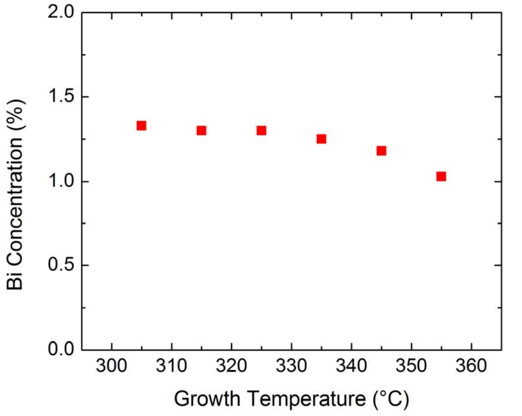

Figure 1. Bi concentration as a function of growth temperature. All samples were grown with a Bi BEP of 2E-8 Torr at a growth rate of 0.9 µm/hr and with a V/III flux ratio of ~1.05. The weak temperature dependence below 330°C signifies that the Bi sticking coefficient is near unity in this growth regime.

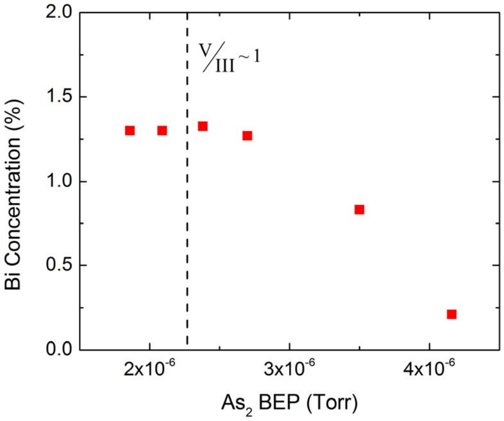

Figure 2. Bi concentration as a function of As_2 BEP. All samples were grown at 325°C with a Bi BEP of 2E-8 Torr at a growth rate of 0.9 µm/hr. The dashed line corresponds approximately to a stoichiometric flux ratio, as determined by group-V limited RHEED oscillations.

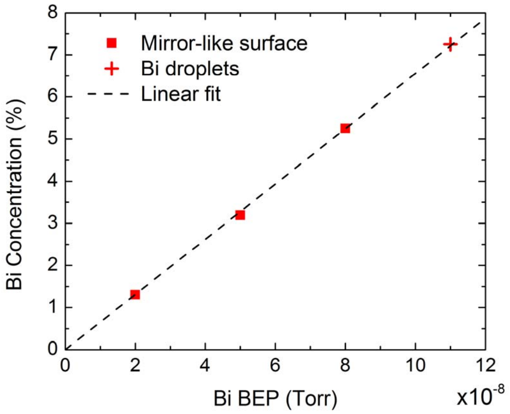

Figure 3. Bi concentration, as determined by X-ray diffraction rocking curves, as a function of Bi BEP. All samples were grown at 325°C, with a growth rate of 0.9 µm/hr, and with a V/III flux ratio of ~1.05. The highly linear dependence in this growth regime indicates near-unity sticking of Bi, while the onset of droplet formation at higher Bi BEP's is consistent with previous reports.

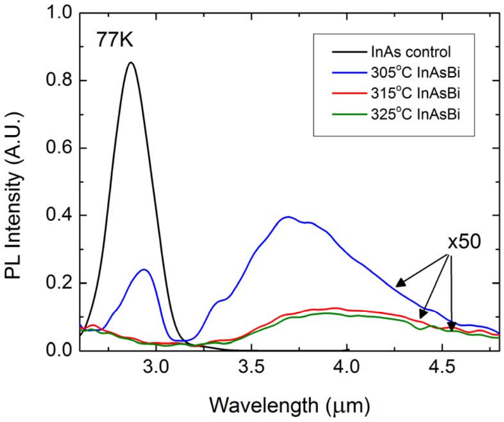

Figure 2. 77K Photoluminescence (PL) intensity for samples grown at various temperatures. All samples were grown at a growth rate of 0.9 µm/hr and with a V/III flux ratio of ~1.05. The InAsBi samples were grown with a Bi BEP of 2E-8 Torr and contain ~1.3% Bi. PL intensity from the InAsBi samples improves significantly at lower growth temperatures, but remains ~100x weaker than the InAs control, suggesting a significant interstitial Bi concentration, or some other degradation mechanism caused by Bi incorporation.