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# Monolayer-by-monolayer compositional analysis of InAs/InAsSb superlattices with cross-sectional STM

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ABSTRACT

We use cross-sectional scanning tunneling microscopy (STM) to reconstruct the monolayer-by-monolayer composition profile across a representative subset of MBE-grown InAs/InAsSb superlattice layers and find that antimony segregation frustrates the intended compositional discontinuities across both antimonide-on-arsenide and arsenide-on-antimonide heterojunctions. Graded, rather than abrupt, interfaces are formed in either case. We likewise find that the incorporated antimony per superlattice period varies measurably from beginning to end of the multilayer stack. Although the intended antimony discontinuities predict significant discrepancies with respect to the experimentally observed high-resolution x-ray diffraction spectrum, dynamical simulations based on the STM-derived profiles provide an excellent quantitative match to all important aspects of the x-ray data.



## 1. Introduction

It has been recognized for some time that type-II superlattices based on the GaSb/InAs system might hold distinct advantages over HgCdTe in long-wave-infrared detector applications [1]. For many years, research attention focused largely on the non-common-atom binary materials, and their closely-related, ternary variant InAs/Ga(In)Sb, despite early recognition of the potential offered by a simpler, common-atom analog, namely InAs/InAsSb [2]. With the recent demonstration that InAs/InAsSb superlattices exhibit minority carrier lifetimes up to two orders of magnitude greater [3,4] than those observed in InAs/Ga(In)Sb [5,6], there has been renewed interest in the prospects for competitive devices built from this material.

The deliberate tailoring of optical transitions in these, and similar, quantum-confined structures typically relies on theoretical or empirical paradigms whose predictive utility is judged against assumed (intended) rather than empirically determined (as-grown) constituent-layer sequences. Accurate knowledge concerning the as-grown atomic arrangements responsible for the confining potentials that make these structures unique is rarely available.

Here, we show how atomic-resolution scanning tunneling microscopy (STM) may be used to reconstruct the monolayer-by-monolayer composition profile throughout one such structure, an $InAs_{0.67}Sb_{0.33}$ strained-layer superlattice (Fig. 1), following cleavage in ultra-high vacuum (UHV). We also show how STM may be used to quantify the changes in superlattice composition as growth progresses from beginning to end by selectively examining a subset of periods at various points along the multilayer stack. Finally we demonstrate these results are globally representative by comparing x-ray simulations based on the STM findings to high-resolution x-ray diffraction (HRXRD) data from the same wafer.

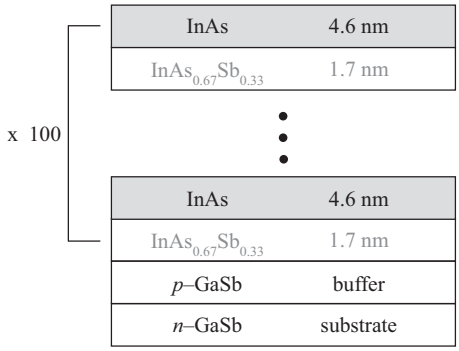


**Fig. 1.** Intended superlattice layer sequence. Growth direction is from bottom to top.

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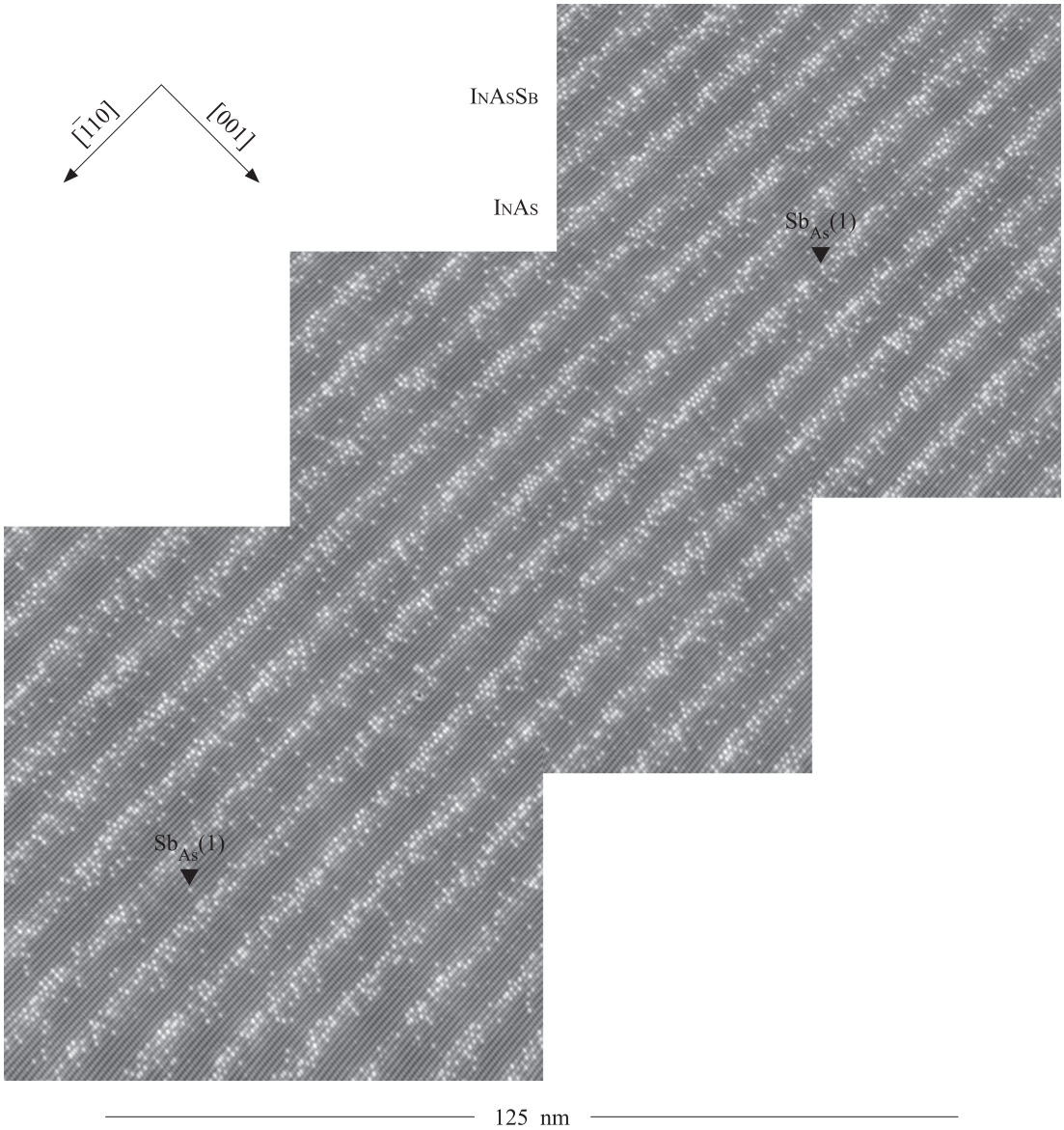


**Fig. 2.** Anion images from a large-area STM survey of superlattice periods 73–84. Antimony-for-arsenic replacement within the top-layer, cleavage-exposed plane is identified by carets. Growth direction is from top left to bottom right.

## 2. Experimental details

Epitaxial growth of the superlattice shown in Fig. 1 was carried out by solid-source molecular beam epitaxy at Sandia National Laboratories. The layers were deposited on a (001)–oriented GaSb substrate under an anion overpressure[1] of ~1.5:1 and growth rate of 0.9 monolayers/s (ML/s). The substrate was held at approximately 420 °C and rotated continuously throughout deposition. Subsequent HRXRD examination of the (004) reflections in a triple-axis configuration revealed a period of 6.28 nm (corresponding to 20.6 ML) and substrate mismatch of −0.05% following analysis of nine superlattice satellite orders.

Select dies from this wafer were transferred to a dedicated UHV–STM system, with base pressures below 1E-13 Torr for all reactive species save hydrogen (at the 1E-11 Torr level), where the completed structure was exposed in cross section by cleavage along $(1\bar{1}0)$ or (110) planes. Precise position control allowed placement of an STM tip above any desired subset of layers from the 100-period stack as well as navigation across the entire structure in the [001] growth direction and up to a micron in the orthogonal ⟨110⟩ direction.

Large-area surveys were assembled from overlapping atomic-resolution images along periods near the initiation and completion of growth for multiple locations on the substrate wafer. Fig. 2 shows a representative portion of one such survey, obtained with negative sample bias to image the filled-state densities associated with As and Sb. Isovalent replacement of arsenic with antimony at the cleavage-exposed surface is unmistakably pinpointed here by the change in covalent radius and back-bond length attending any such non-native, InSb-like pairing. As we will see shortly, the evident intermixing along each and every interface is due to segregation of vapor-deposited antimony atoms.

To facilitate compilation of the requisite bulk antimony profile, a counting window extending 62 surface monolayers in the growth direction, thus encompassing 6 repeats of the bulk superlattice period, was overlaid on each image of the survey. The ⟨110⟩ width of these

[1] The quoted anion overpressure represents a sum of As:In of ~1.2 and Sb:In of ~0.3.