Quantitative Study of Sb Segregation in InAs/InAs$_{1-x}$Sb$_x$ Type-II Superlattices for IR Photodetectors

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Mercury cadmium telluride (MCT) semiconductor alloys remain the most widely used material system for infrared photo-detection in mid-wavelength and long-wavelength ranges despite major disadvantages of intrinsic Auger recombination and small effective mass [1]. Type-II superlattices (T2SL) have been proposed as possible alternatives because they may overcome these MCT problems, with flexible and more controllable band-gap engineering through SL layer thickness/composition and coherency strain, and additional benefits such as higher mechanical strength and lower cost [1, 2]. The most studied III-V T2SL system, InAs/Ga$_{1-x}$In$_x$Sb, suffers from short minority carrier lifetimes, possibly due to Shockley-Reed-Hall recombination induced by Ga-related native defects [3]. Ga-free InAs/InAs$_{1-x}$Sb$_x$ T2SL have demonstrated significantly improved minority carrier lifetimes, up to and exceeding an order of magnitude longer depending on wavelength [4, 5]. Ga-free InAs/InAs$_{1-x}$Sb$_x$ T2SLs grown with careful design of strain balance and choice/control of growth conditions have very low densities of extended defects [6]. Nevertheless, asymmetric SL peaks in high-resolution X-ray diffraction suggest the possibility of non-uniform SL layer thickness during growth, and interface roughness is inferred using transmission electron microscopy [6, 7]: either type of disorder could introduce perturbation to the superlattice band structure, and cause deterioration of the optoelectronic response and deviation from design.

Here we present a quantitative characterization of the interface abruptness of Ga-free InAs/InAs$_{1-x}$Sb$_x$ T2SLs using two independent electron-microscopy techniques: 002 dark-field (DF) imaging, and electron energy-loss spectroscopy (EELS) operated in scanning mode. Careful experimental design and data analysis were carried out for the purpose of quantification. For 002 DF imaging, contrast calibration was performed using the characteristic dark-line feature at the AlSb/InAsSb interface. For EELS, the closely positioned signals of Sb M$_{4,5}$ edge (onset at 528eV) and In M$_{4,5}$ edge (edge onset at 443eV) were extracted using multiple linear least-square fitting, and an accelerating voltage of 80 kV was used to reduce any beam-induced damage. Both 002 DF imaging and EELS probed the Sb compositional variation along the growth direction, and revealed asymmetric interfaces due to Sb segregation. Fitting of the Sb segregation profiles obtained by 002 DF and EELS to theoretical models demonstrated a remarkable quantitative agreement between the two independent techniques. The fitting parameters obtained from both techniques agreed very well within experimental errors, yielding a segregation efficiency of 0.81±0.01, and revealing very strong Sb segregation at the InAs-on-InAsSb interface [8, 9].

References:
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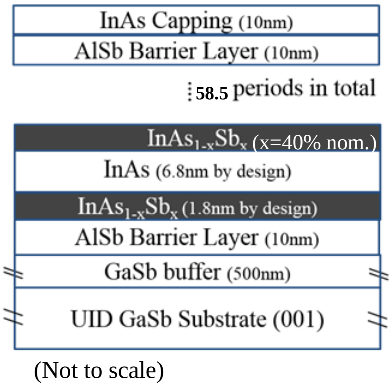


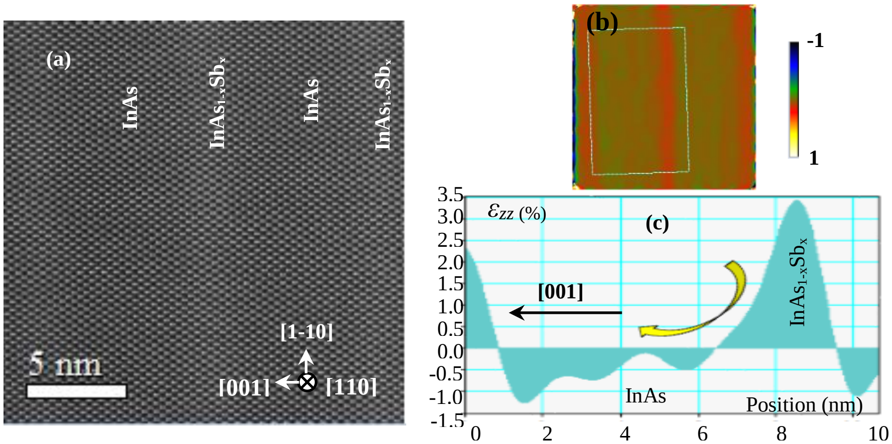
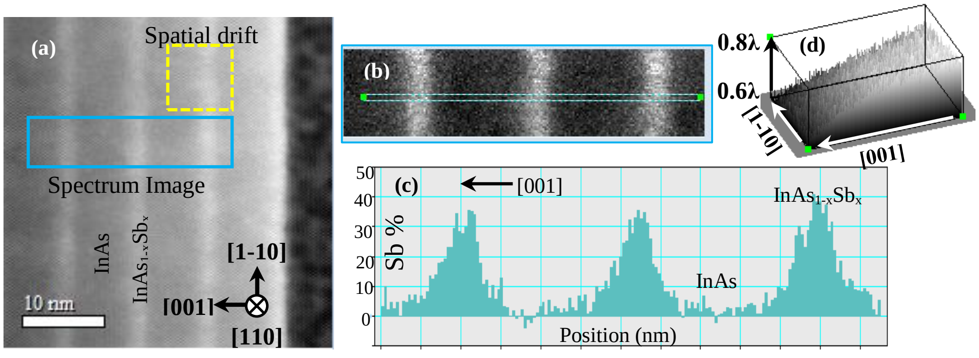


Figure 1. (top left) Schematic of the InAs/InAs$_{1-x}$Sb$_x$ T2SL specimen under study (not to scale).
Figure 2. (top right) (a) Aberration-corrected HAADF image; (b) out-of-plane strain map & (c) profile.



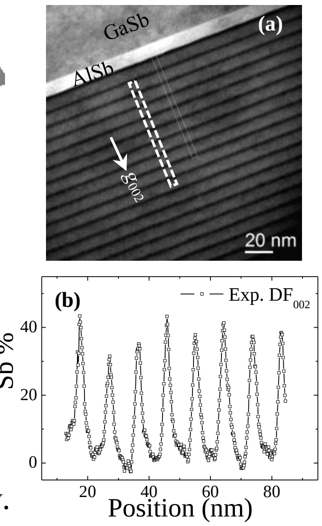


Figure 3. (middle left) (a) Survey image for EELS spectrum acquisition; (b) ratio map of MLLS fitting coefficients of Sb/In; (c) Sb composition profile across the superlattices; (d) relative thickness map of ROI.
Figure 4. (middle right) (a) Representative 002 dark-field image; (b) Experimental Sb composition profile from analyzing diffraction intensity.

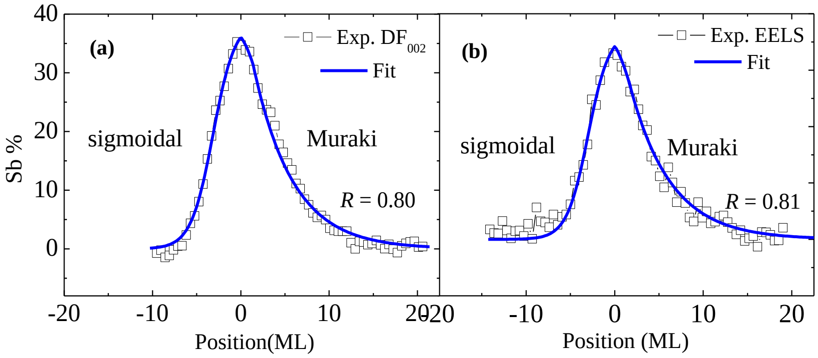


Figure 5. (bottom left) Experimental Sb composition profiles and the corresponding fitting curves using combination of sigmoidal function for InAsSb-on-InAs interface and Muraki's segregation model for InAs-on-InAsSb interface, as obtained from: (a) 002 DF imaging; and (b) STEM EELS.