Tensile-strained InGaAs quantum dots with interband emission in the mid-infrared

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Novel tunable light sources operating in the mid-infrared are desirable for a wide range of applications. Quantum cascade approaches produce devices with excellent performance but these structures are complex and time consuming to create. An alternative could be to use tensile strain as a way to reduce the band gap energy of semiconductors such as InGaAs, and push their emission deeper into the IR. We will discuss our efforts to use tensile-strain to drive the self-assembly of $In_{1-x}Ga_xAs$ quantum dot (QD) nanostructures on GaSb(111)A surfaces. The highly localized tensile strain stored in these QDs modifies the InGaAs band structure to red-shift the photon emission wavelength by ~2000 nm. We have determined a robust set of growth conditions for the self-assembly of the tensile-strained InGaAs QDs. During molecular beam epitaxy (MBE), InGaAs QDs form spontaneously on GaSb(111)A with less than 1 ML deposited, indicating a Volmer-Weber growth mode. We characterized these nanostructures using atomic force microscopy (AFM), transmission electron microscopy (TEM) and energy-dispersive X-ray spectroscopy (EDS) to understand InGaAs/GaSb(111)A QD structure as a function of the MBE growth conditions. A combination of photoluminescence (PL) spectroscopy and computational modeling shows that residual tensile strain in the QDs reduces the InGaAs band gap energy, to produce band-to-band light emission at 3.2–3.9 μm (Figure 1). When coupled with quantum size effects, the use of tensile strain to red-shift QD emission offers an attractive way to create highly tunable mid-IR light sources. This work is supported by the National Science Foundation under NSF CAREER Grant No. 1555270.

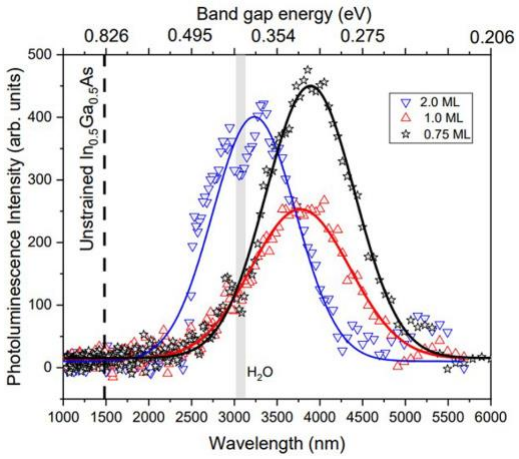

Figure 1. PL spectra at 77 K from InGaAs/GaSb(111)A samples containing a single layer of 0.75, 1.0, and 2.0 ML QDs. The continuous lines are Gaussian fits to each spectrum. The gray line highlights the position of a water absorption feature present in all three spectra at ~3000 nm.[1]

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Supplementary Pages

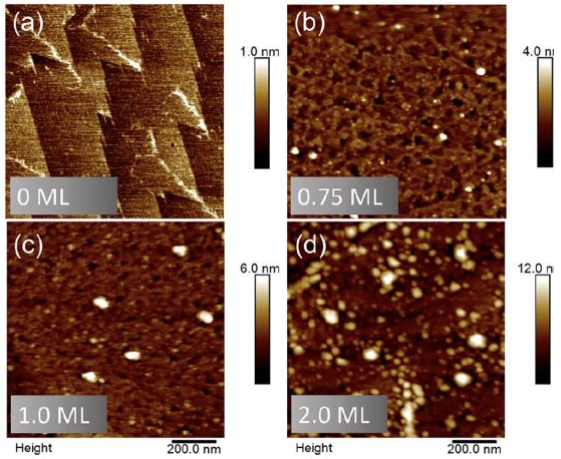

Figure S1. (a–d) 1 × 1 μm^2 atomic force microscope images showing the surface morphology of 0–2 ML InGaAs deposited on GaSb(111)A at 450 ºC, at 0.4 ML/s.

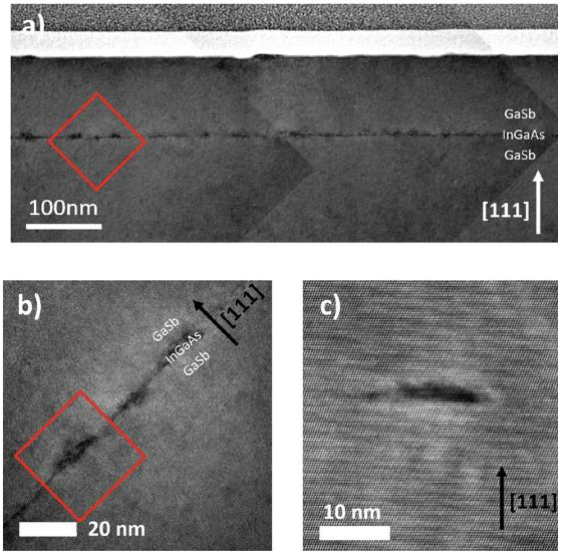

Figure S2. (a) Bright-field transmission electron microscope (BF TEM) image montage of a 1 ML InGaAs QD layer surrounded by GaSb(111)A barriers, with a second layer of identical InGaAs QDs at the surface. (b) BF TEM image of several buried 1 ML InGaAs QDs corresponding to the red square in (a). (c) High-angle annular dark-field scanning TEM image of the buried 1 ML InGaAs QD enclosed by the red square in (b).

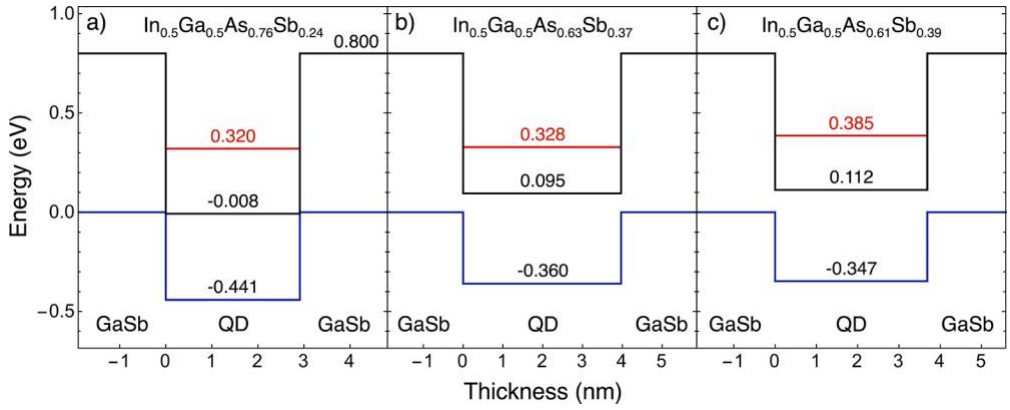

Figure S3. Calculated band alignments at 77 K for (a) 0.75 ML, (b) 1.0 ML, and (c) 2.0 ML InGaAs/GaSb(111)A QDs. A type-III band alignment exists for the 0.75 ML QDs, with a type-II alignment for the 1.0 and 2.0 ML QDs. The conduction band minimum is shown in black and the valence band maximum in blue. Red lines indicate the electron ground state energies. Comparison between this model and our experimental PL data reveals the unintentional incorporation of Sb into the InGaAs QDs from the surrounding GaSb barriers.