# III/V ratio based selectivity between strained Stranski-Krastanov and strain-free GaSb quantum dots on GaAs

G. Balakrishnan,[a] J. Tatebayashi, A. Khoshakhlagh, S. H. Huang, A. Jallipalli, L. R. Dawson, and D. L. Huffaker[b]
*Center for High Technology Materials, University of New Mexico, 1313 Goddard SE, Albuquerque, New Mexico 87106*

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The authors demonstrate and characterize type-II GaSb quantum dot (QD) formation on GaAs by either Stranski-Krastanov (SK) or interfacial misfit (IMF) growth mode. The growth mode selection is controlled by the gallium to antimony (III/V) ratio where a high III/V ratio produces IMF and a low ratio establishes the SK growth mode. The IMF growth mode produces strain-relaxed QDs, where the SK QDs remain highly strained. Both ensembles demonstrate strong room temperature photoluminescence (PL) with the SK QDs emitting at 1180 nm and the IMF QDs emitting at 1375 nm. Quantized energy levels along with a spectral blueshift are observed in 77 K PL. Transmission electron microscope images identify the IMF array and crystallographic shape for both types of QD formation. Atomic force microscope images characterize QD geometry and density. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2362999]

The Sb-bearing compounds offer a wide range of electronic band gaps, band gap offsets, and electronic barriers along with the extremely high electron mobility[1] to enable a variety of extremely fast, low power electronic devices and infrared light sources.[2,3] The ability to grow high quality Sb-bearing quantum dots (QDs) on GaAs provides an excellent alternative to the existing In(Ga)As QD technology and may extend the accessible wavelength of QD emitters. While GaSb on GaAs has a lattice-mismatched interface ($\Delta a_0/a_0=7.8\%$) similar to InAs on GaAs, the growth of GaSb Stranski-Krastanov (SK) QDs has not been as straightforward as that of InAs SK QDs because the GaSb/GaAs SK growth mode requires atypical growth conditions—a low III/V ratio. As a result, there have been no reports of fully quantized GaSb/GaAs QDs formed by the SK growth mode, despite several reports of emission from GaSb/GaAs QDs and their wetting layers.[4–7] The standard Sb-rich growth conditions result in a growth mode characterized by the laterally propagating (90°) interfacial misfit (IMF) dislocations confined to the episubstrate interface.[8–10]

In the following paragraphs, we demonstrate the ability to grow GaSb QDs in the SK growth mode as well as the IMF growth mode. The controlling growth parameter used for this selection is the Ga:Sb (III/V) ratio where a high III/V ratio of 1:10 produces IMF and a low ratio of 1:1 favors the SK growth mode. A similar, but not equivalent, situation exists in the InAs/GaAs material system where an In:As ratio of 1:6 produces SK QDs and a 1:1 ratio produces an IMF-based interface.[11,12] The III-V ratio requirements to achieve the two respective growth modes is exactly opposite in the InAs/GaAs compared to the GaSb/GaAs, since the larger atom in the case of InAs on GaAs is the group III atom. From these two cases, we can establish two primary requirements for the IMF growth mode to dominate over the SK growth mode. First, there must be sufficient size disparity between the constituent adatoms and second, the larger adatom must be in larger quantity on the growth surface compared to the small adatom. In contrast, when the larger atom is present in much reduced numbers the SK growth mode is observed.

In the GaSb/GaAs QD formation reported here, the growth conditions for both SK and IMF growth modes are identical with the exception of the III/V ratios during QD formation. Both samples are grown on a (100) GaAs substrate with a 1000 Å GaAs buffer followed by the QD ensemble. The QD ensembles are formed at 500 °C with a total coverage of 3 ML, a growth rate of 0.3 ML/s, and III/V ratios of 1:10 and 1:1 for the IMF and SK modes, respectively. The corresponding reflection high-energy electron diffraction (RHEED) patterns are described below. The samples

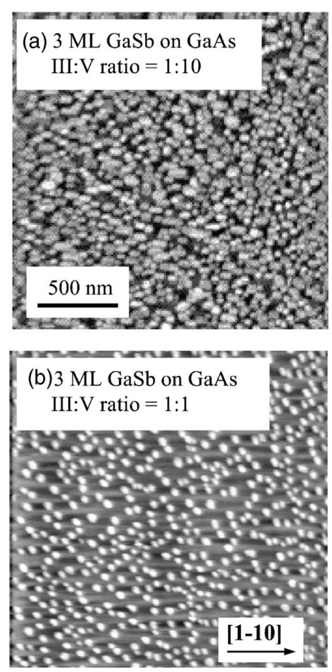


FIG. 1. AFM images of GaSb on GaAs after 3 ML deposition under (a) 1:10 III/V ratio resulting in IMF QDs and (b) 1:1 III/V ratio resulting in SK QDs.

[a]Electronic mail: gunny@unm.edu
[b]Electronic mail: huffaker@chtm.unm.edu

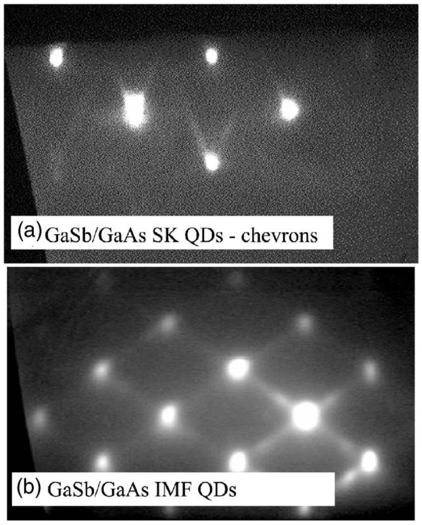


FIG. 2. RHEED images of the (a) SK and (b) IMF QDs. The SK QDs show "chevron" patterns while the IMF QDs show patterns corresponding to relaxed islands.

for microscopic characterization are immediately cooled to room temperature. The samples for photoluminescence (PL) characterization include an $Al_{0.9}Ga_{0.1}As/GaAs$ barrier surrounding the single QD layer active region and a GaAs cap.

Figures 1(a) and 1(b) show the atomic force microscopy (AFM) images of both GaSb QD ensembles on GaAs. The SK QD ensemble in Fig. 1(a) displays typical characteristics for SK QDs—a uniform size distribution with a slight elongation in the [110] direction. The average width and height are 10 and 5 nm, respectively, with QD density of $\sim 3 \times 10^{10}$ QDs/cm$^2$. The IMF QDs in Fig. 1(b) are somewhat elongated along the [1−10] direction in comparison with the [110] direction. The QD dimensions are widely varied with

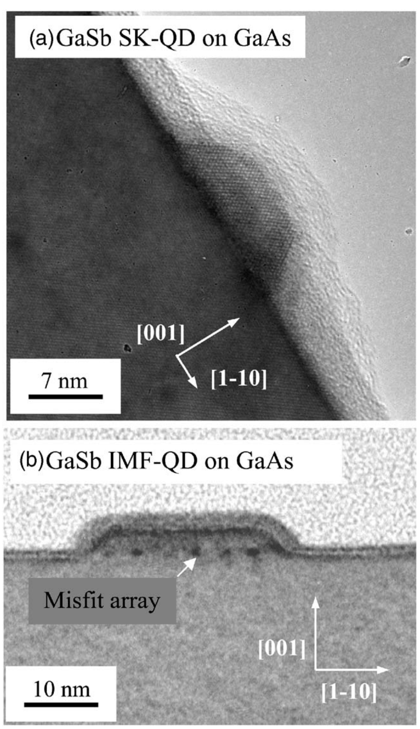


FIG. 3. Cross sectional TEM image of (a) GaSb SK QD on GaAs and (b) IMF QD with strain relieving misfit dislocations that can be observed at the interface.

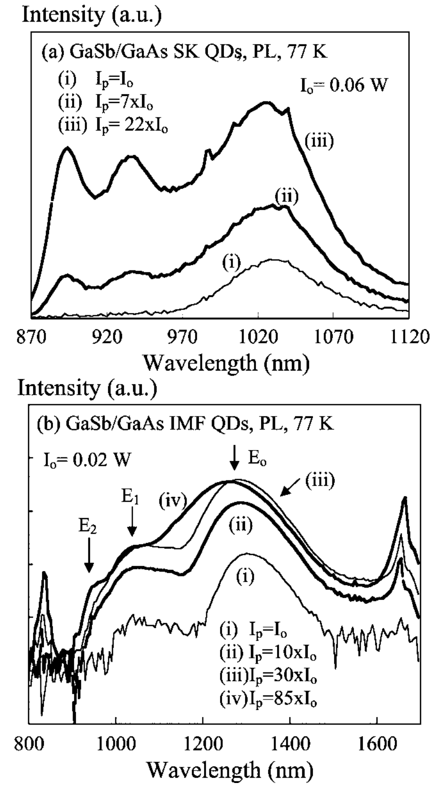


FIG. 4. PL from the QD samples at 77 K. The SK QDs have a ground state at 1022 nm with excited states at 930 and 890 nm showing intersubband energy spacings of 117.8 and 67.9 meV. The IMF QDs have a ground state at 1310 nm with weak excited states observed at 1060 and 960 nm.

average length along the [110], width along the [1−10], and heights of 50, 30, and 6 nm, respectively. The QD density is $\sim 6 \times 10^{10}$ QDs/cm$^2$. These SK QD data account for ~20% of the deposited material, which suggests the presence of a 2 ML thick wetting layer; however, some of the material could be used up by larger defective islands that are present on the sample. The IMF QD volume accounts for ~60% of the deposited material. In the case of IMF QDs, large defective islands sufficiently account for the rest of the material.

Figure 2 shows the RHEED patterns observed during the growth of the two QD ensembles. Both QDs are nucleated on a $2 \times 4$ reconstructed atomically smooth GaAs surface. Figure 2(a) shows the classical "chevron" pattern associated with strained SK QD formation. A comparison of the angles involved in the chevron pattern with those obtained from InAs QDs indicates a close match suggesting that the crystallographic planes enclosing the two ensembles may be very similar. A precise comparison of the chevron patterns was done using a KSA™ RHEED analysis system. The RHEED pattern associated with IMF formation, shown in Fig. 2(b), does not consist of chevrons, but instead show components that belong to the {111} and {100} planes, indicating a relaxed form.

Figures 3(a) and 3(b) show high-resolution transmission electron microscope (TEM) images of the IMF and SK QDs. Figure 3(a) shows a single IMF QD and the characteristic array of misfits at the GaSb interface. The QD shape is very flat and broad; QD height and width are 5 and 30 nm, respectively. The space between the misfit dislocations is ~5 nm or approximately eight lattice sites as expected from the $\Delta a_0/a_0 = 7.8\%$.[13] Figure 3(b) shows a highly crystalline SK QD with height and width of 7 and 10 nm, respectively, and a domelike shape typical of SK-formed QDs. The GaSb/GaAs interface is abrupt and shows no indication of misfit dislocations.

The PL spectra for both ensembles were collected under room temperature (RT) and 77 K [low temperature(LT)] conditions using a cw Ar+ laser at power levels ranging from 0.02 to 1.8 W, with a 2 mm spot size. The LT PL for the GaSb SK QDs and IMF QDs is shown in Figs. 4(a) and 4(b). The pump power ($I_p$) is referenced to $I_0=0.06$ W. As shown in Fig. 4(a) the ground state emission is peaked at $\lambda=1022$ nm. For pump powers $<0.2$ W, only a single peak is excited with a full width at half maximum (FWHM) of 77.3 meV. With increasing pump power, two excited states become evident at $\lambda=930$ nm and $\lambda=890$ nm. Thus, the intersubband energy spacings are 117.8 and 67.9 meV. An 11.8 meV blueshift in the peak wavelength is observed with increasing pump power from 0.156 to 1.3 W characteristic of a type II alignment.[14] Room temperature PL spectra (not shown) indicate a weak ground state emission near 1180 nm and much stronger emission from excited states at 960 and 910 nm. No blueshift is observed at room temperature.

Figure 4(b) shows the LT PL spectra for the IMF QDs plotted on a logarithmic scale to elucidate high-energy peaks. The LT PL ground state emission is peaked near 1310 nm with FWHM $\sim 101.2$ meV that is considerably broader than the SK QDs due to a much larger size distribution. The emission wavelength of the IMF QDs is longer than the SK QDs, but shorter than bulk GaSb ($\lambda=1660$ nm) due to the strain-relaxed lattice and quantized nature, respectively. Excited states are weakly observed at 1060 and 960 nm. The ground state and first excited state are both saturated at $I_p>0.60$ W or $\sim 30I_0$ as the second excited state begins to emerge. Along with the IMF QD peaks, a peak at 1660 nm is observed perhaps from larger bulklike islands. A 29.9 meV blueshift is observed within the pump power range. Room temperature PL emission (not shown) is peaked at $\lambda\sim 1350$ nm with FWHM $\sim 109.5$ meV. No blueshift is observed at room temperature. We believe that excited states seen in these spectra are a result of a quantization of holes within GaSb QDs. However, there is still much to be learned about details of the effects of strain and quantization on band structure and electron/hole recombination rates in type II QDs. Thus, theoretical modeling will be very useful in this area.

In summary, we have demonstrated the ability to access either a SK or an IMF growth mode to form GaSb QDs on GaAs substrates controlled by III/V ratio. In the case of GaSb on GaAs, a high III:V ratio of 1:10 produces IMF and a low ratio of 1:1 favors the SK growth mode. Both AFM and TEM verify the structural contrast in the two growth modes. Both QD ensembles produce strong RT PL with wavelengths indicative of strain content—i.e., the SK QDs are strained and emit at 1180 nm compared to the unstrained or strain-relaxed IMF QDs which emit at 1350 nm. Higher-energy peaks are strongly observable from the SK QDs under LT PL conditions, but only weak from the IMF QDs. We believe that excited states seen in these spectra are a result of a quantization of holes within GaSb QDs. However, the transition matrices of the two type II QD ensembles that determine relative PL intensity are not well understood and thus further investigation for these issues is required.

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