Highly Symmetric GaAs/AlGaAs Quantum Dots on (111)A GaAs Using Droplet Epitaxy

Brian McSkimming

Electrical Engineering and Mathematics, University at Buffalo, State University of New York

NNIN iREU Site: National Institute of Material Sciences, Tsukuba, Japan

NNIN iREU Principal Investigator and Mentor: Dr. Takaaki Mano, Quantum Dot Research Center, National Institute of Material Sciences, Tsukuba, Japan

Contact: mcskimming@gmail.com, MANO.Takaaki@nims.go.jp

Abstract:

We report the successful growth of highly symmetric GaAs/AlGaAs quantum dots (QDs) on the (111)A surface of a GaAs substrate using modified droplet epitaxy. A growth recipe was optimized in order to attain samples with small, low density QDs as well as small, high density QDs and those parameters are reported here. The QD samples were characterized with macro and micro photoluminescence to determine their optical properties as well as possible size distributions.

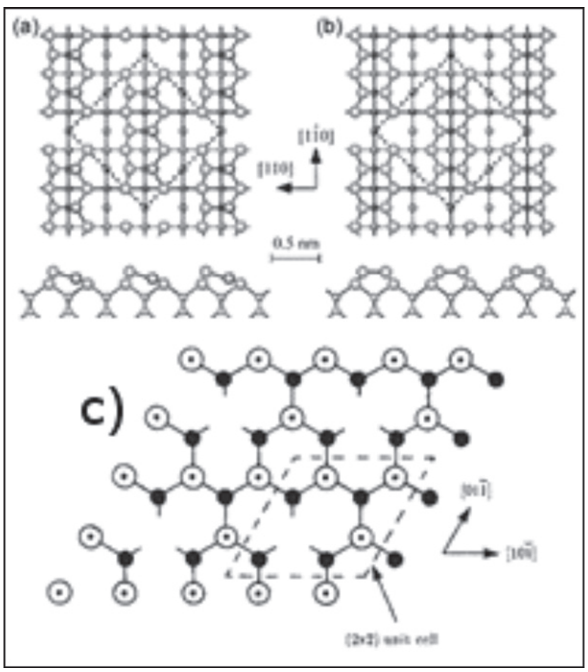


Figure 1: (a) & (b) GaAs (100) surface reconstruction; (c) GaAs (111)A surface reconstruction.

Introduction:

As the semiconductor industry continues to progress towards new and novel devices and structures the quantum dot (QD) continues to assert itself as one of the more promising and flexible nanostructures. One example of this flexibility is demonstrated in the capability of the QD to emit not only single photons, but an entangled photon pair. To date, entangled photon emission has been coaxed out of QDs through the use of external electric and/or magnetic fields as the fine structure splitting of the QD energy levels otherwise results in a lack of photon energy degeneracy. In order to eliminate this fine structure splitting, we utilized the following techniques: 1) QD growth using modified droplet epitaxy as opposed to Stranski-Krastanov (SK) growth which eliminates strain inherent and necessary in SK growth; and 2) QD growth on (111)A GaAs as opposed to the more standard (100) GaAs substrate with the expectation that the three-fold symmetry of the (111)A surface reconstruction as opposed to the two-fold symmetry of the (100) surface reconstruction will enforce greater symmetry and reduced anisotropy in the QDs themselves (Figure 1).

Experimental Procedure:

All of our samples were grown in a standard Riber molecular beam epitaxy (MBE) machine and characterized using atomic force microscopy (AFM) measurements to determine size and density/distribution, and photoluminescence measurements to determine the sample's emission spectrum. In order to be able to test and characterize individual QDs, it was necessary to grow our sample with a density lower than 10^9 QDs/cm^2, something that had not been published before utilizing the (111)A substrate. Further, in order to achieve what was believed to be optimum emission spectra, we desired the QDs to have a width of approximately 30-40 nm and a height of less than 4 nm.

All QD samples were grown utilizing a technique known as modified droplet epitaxy (MDE), in which gallium (Ga) is first deposited on the substrate alone, forming Ga droplets on the substrate surface, and then arsenide (As) is introduced into the growth chamber crystallizing the Ga droplets into GaAs QDs. It is these Ga droplets which we initially optimized for density and droplet size through a variance of three growth parameters, namely substrate temperature (T_c), Ga deposition rate and total amount of Ga deposited. Ga droplet samples were grown in three stages, each varying one of our growth parameters. The T_c was varied from 200°C through 500°C in increments of 100°C, while the deposition rate and deposition amount were held constant at 0.1 monolayer (ML)/s and 2 ML respectively. The second set of Ga droplet growths varied the deposition rate with growths at 0.1 ML/s, 0.05 ML/s and 0.01 ML/s while holding T_c constant at the optimized temperature and holding the deposition amount at 2 ML. Our third set of growths varied the deposition amount (2 ML, 0.1 ML and 0.05 ML) while holding the other two parameters constant.

Once we had achieved our desired density and size distribution we then grew crystallized GaAs samples with both low and high QD densities in order to measure the optical emission properties of our samples through photoluminescence. Macro photoluminescence was utilized to determine the emission spectrum of the overall quantum dot sample. From the sample's emission spectrum, there could be some estimations made with regard to quality and size of the quantum dots within the sample. Micro photoluminescence would then be used to characterize and determine the properties of individual nanostructures with specific attention paid towards attempting to determine the fine structure splitting of the quantum dot's energy levels.

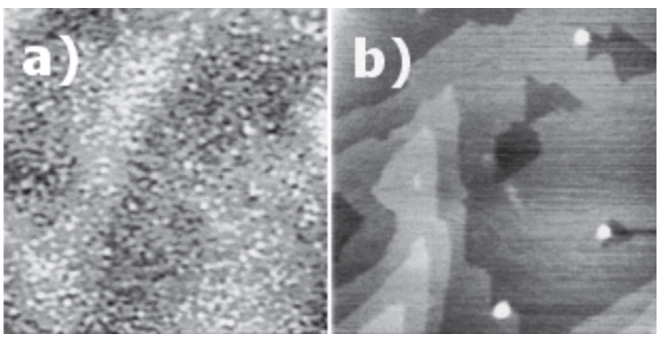
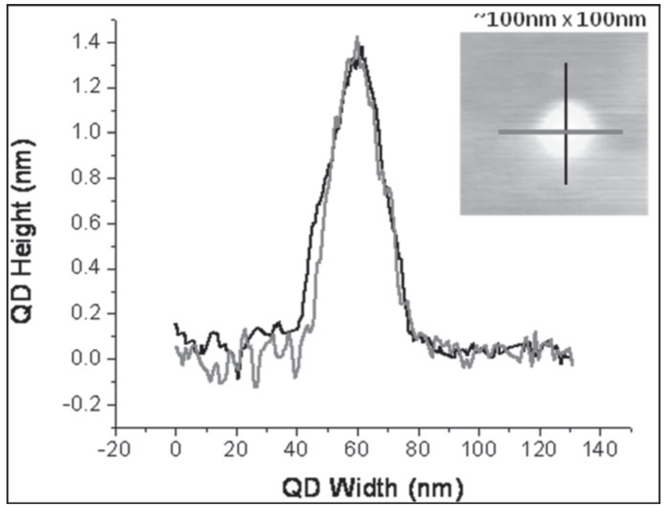


Figure 2: (a) Non-optimized Ga droplet sample; (b) Optimized Ga droplet sample.



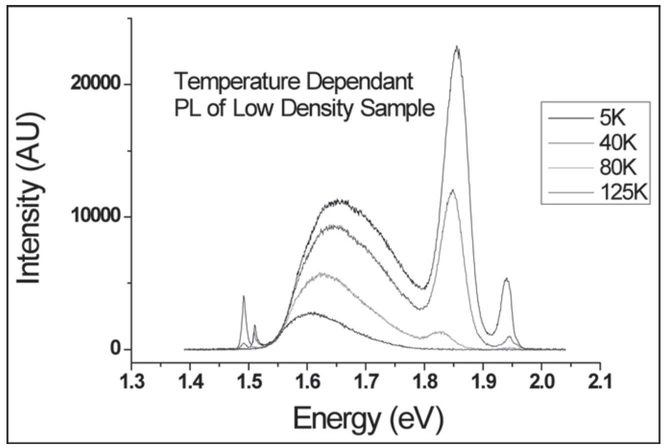


Figure 3, top: Cross-sectional profile of a single QD taken from two different orthogonal directions and overlaid on top of each other.

Figure 4, bottom: Temperature dependent photoluminescence emission of a low-density quantum dot sample.

Results and Conclusions:

Substrate temperature (T_c) and deposition rate had the greatest effect on droplet density reducing it from 2.8×10^{11} cm^{-2} (with T_c of 200°C and deposition rate of 0.1 ML/s) to 7.1×10^{8} cm^{-2} (with T_c of 500°C and deposition rate of 0.01 ML/s). The droplet size was able to be reduced from a maximum size distribution with a mean of ~ 100.0 nm wide by 21.8 nm high to a distribution with mean of 43.9 nm wide by 4.14 nm high. This reduction corresponds to a total volume decrease of more than a factor of ten. These drastic reductions in droplet density and size distribution can be seen in Figure 2. Macro photoluminescence results from one of the low density QD samples demonstrate something which was initially unexpected (Figure 3), that being a double peak in the optical emission spectrum. This double peak suggests that there is a certain point at which small Ga droplets coalesce into larger droplets, thus creating a vacancy in the photoluminescence plot where the emission from these midsized QDs would appear. The QDs grown demonstrate the isotropy and symmetry that we desired, as can be seen in Figure 4 where a cross-sectional profile was taken of the AFM image across two orthogonal directions.

Future Work:

Future work will include additional micro photoluminescence characterization intended to verify the emission of entangled photons from these QDs, as well as detailed characterization of the properties of these QDs.

Acknowledgements:

Many thanks to the National Nanotechnology Infrastructure Network for providing this opportunity, NSF for funding and to Japan's National Institute for Materials Science for everything.