Highly Uniform Quantum Dots with Near-Perfect Size Distribution

To enable ultrahigh capacity optical communication under extreme power/size/weight constraints, CONSRT researchers are developing high quality, multiple layer InAs/InGaAs quantum dot (QD) material for applications in next generation ultra-dense optical interconnects employing vertical cavity surface emitting lasers (VCSEL), micro-cavity lasers and amplifiers.

As QD uniformity is critical for realizing optical devices operated at room temperature, we have investigated several techniques to increase the dot uniformity. Recently, we have successfully demonstrated growth of a 3-dimensional QD array by Molecular Beam Epitaxy (MBE) using strain layer templates patterned with nano-scale structures. We have shown that by adding stressor dots before growing the QDs in the active region, the size uniformity of QDs can be significantly improved and the photoluminescence (PL) linewidth of the dot ensemble was found to reduce to that of a single dot. To our knowledge, this is the best linewidth measured from any self-organized QD structures to date.

Self-organized quantum dots, formed in the Stranski-Krastanow growth mode during epitaxy of strained In(Ga)As/GaAs heterostructures (emitting at 1.3-to-1.55 µm wavelengths) are currently used as the active region of lasers, amplifiers, infrared detectors and in other novel device applications. The size and shape of the coherently strained islands, which enable three-dimensional quantum confinement, depend on the heterostructure and the conditions for epitaxy. Island formation is kinetically controlled, based on arguments of minimization of crystal free energy by the growth front. There is therefore a distribution in the size of the islands in a given layer and also randomness in their spatial ordering.

It is imperative to control QDs size uniformity because the size variation gives rise to an inhomogeneous broadening of optical transitions resulting from carrier recombination or generation. Linewidths (full width at half maximum – FWHM) in the range of 30 – 60 meV are commonly measured in the photoluminescence spectra of In(Ga)As/GaAs quantum dots. The gain of a laser is inversely proportional to the linewidth of the spontaneous emission spectrum. Similarly, the intersubband absorption coefficient, which becomes relevant in intersubband quantum dot infrared detectors, is also inversely proportional to the transition linewidth.

The technique of “strain patterning” relies on the fact that the strain field around the quantum dots in one layer alters the adatom migration rates of subsequent dot layers such that larger and more uniform dots are formed on these layers. The “stressor dots” in the first layer act as a template which influences the growth kinetics, formation and characteristics of the second layer of “active dots”. For the growth of In(Ga)As/GaAs quantum dots, there is a tensile strain field in the GaAs barrier above the dots in the first layer, which influences adatom migration and induces a vertical coupling of the second layer of dots. By tuning the growth parameters used to form the first layer of stressor dots (which influence their size, shape and density) and by carefully adjusting the thickness of the GaAs barrier layer in between, the size non-uniformity of the second layer of active dots can be minimized.

The quantum dot heterostructures investigated in this work consist of two layers of InAs/GaAs QDs separated by 100 Å GaAs spacer layer (see Figure 1). These structures were grown on (001) n+-GaAs substrates by MBE. The first QD layer was grown at relatively high temperature (535 °C) and low InAs growth rates <0.01 monolayer (ML) per sec. After the deposition of 2.4 ML of InAs, a 100 Å GaAs cap layer was grown. The substrate temperature was raised and the sample was annealed at 600 °C for 10 minutes. The substrate temperature was then lowered to 480 °C and 3.1 ML of InAs was deposited to form the second (or active) QD layer with the same growth rate as that for the first QD layer. An additional 0.1 µm GaAs was grown as the cap layer.

Figure 2 shows a bright-field transmission electron microscopy (TEM) image of the sample. The perfect vertical coupling of the dots in the two layers and the increase in size of the dots in the second layer are evident. The PL linewidth (FWHM) of the ground state transitions are 10.6 meV and 17.5 meV at 20 K and 300 K, respectively, as shown in Figure 3. These are the smallest linewidths measured in InAs or InGaAs self-organized quantum dots. The PL linewidth of 17.5 meV at 300 K is almost identical to that measured in the emission from a single dot, indicating that the linewidth is determined by homogeneous broadening. The linewidth of 10.6 meV at 20 K is limited by inhomogeneous broadening.

Work is in progress to fabricate and characterize lasers with these homogeneous dots in the active region. Quantum dots with such narrow PL linewidth will also be immensely useful for the realization of slow light devices.

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