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Photoluminescence linewidth of self-organized $In_{0.4}Ga_{0.6}As/GaAs$ quantum dots grown on InGaAlAs stressor dots

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The molecular beam epitaxial growth of self-organized $In_{0.4}Ga_{0.6}As/GaAs$ quantum dots on buried InGaAsAs/GaAs stressor dots has been characterized by photoluminescence measurements and cross-sectional transmission electron microscopy. The presence of the stressor dots enhances the growth rate and spatial uniformity of the $In_{0.4}Ga_{0.6}As$ dots. The incorporation of Al in the stressor dots not only provides a strain field, but also inhibits carrier recombination therein. A low photoluminescence linewidth of 21 meV, almost invariant in the temperature range of 7–100 K was measured in a heterostructure with an optimal number of stressor and active dot layers. © *1999 American Institute of Physics.* [S0021-8979(99)05020-3]

Self-organized quantum dots (QDs), grown via the Stranski–Krastonow growth mode, have demonstrated characteristics favorable for their application to optoelectronic devices. Interband edge- and surface-emitting lasers,[1–7] intersubband long wavelength detectors,[8,9] and electro-optic modulators[10] have been demonstrated, sometimes with performance matching those of similar quantum well (QW) devices. However, it is expected, by virtue of the singular density of states of ideal QDs, that their characteristics should surpass those of QW devices.[11] The biggest hindrance to achieving this objective has been the growth mode itself $-a\sim 10\%$ inhomogeneity in size and associated fluctuations in shape and composition causes inhomogeneous broadening of the photoluminescence (PL) and severely limits the advantages of three dimensional confinement. For example, PL linewidths as narrow as 34 μeV have been observed for luminescence emission from single dots,[12] whereas in a large ensemble, typical linewidths are 30–60 meV, even at cryogenic temperatures. Additionally, the interplay of surface kinetics and energetics on the surface randomizes the positioning of the dots.[13,14]

Many techniques have been demonstrated to reduce the PL linewidth and spatial ordering of QDs, with reasonable success.[15,16] By using patterned substrates, uniform arrays of dots have been demonstrated, but the dot densities are much smaller than 10^{10} cm^{-2}.[17] Since the island growth mode is strain induced, it is evident that some kind of ''strain patterning'' might yield more favorable results than physical patterning, eliminating the complexities of epitaxial regrowth. Sopanen *et al.* have studied the strain field and luminescence characteristics produced by InP/GaAs stressor dots grown on a buried InGaAs/GaAs QW.[18] It has also been shown that the surface strain in a capping layer by an initial ensemble of buried dots perturbs the adatom migration rates during growth of a subsequent dot layer, thereby influencing their size, shape, and lateral ordering.[16,19] Such strain driven self-organized growth leads to spatial ordering and vertical coupling between dots in successive layers.[20–22] Vertical coupling of dots also reduces the PL linewidth—accompanied by a redshift of the emission wavelength—due to a size filtering effect.[23] PL linewidths as narrow as 25 meV have been reported for double layer InAs dots.[16] Recent theoretical calculations also confirm that it is possible to grow a more uniform and regular arrangement of islands even on a nonuniform set of buried islands.[24]

In the experiments reported to date, the stressor and overlying QDs, vertically coupled or otherwise, have the same composition. It would be more advantageous to have the two dot systems of different composition, providing the following advantages: (i) the choice of stressor dot and barrier material could prevent carrier injection in the stressor dots, so that only the overlying dot system emits light; (ii) the stressor dots could form a part of the doped layer in a device heterostructure; and (iii) the barrier layer thickness could be varied, so that ultimately the strain patterning could be engineered. In this communication we report the luminescence and structural characteristics of $In_{0.4}Ga_{0.6}As/GaAs$ QDs grown on a system of $In_{0.4}Ga_{0.3}Al_{0.3}As/GaAs$ stressor dots by molecular beam epitaxy (MBE). It is observed that the stressor dots influence the spatial ordering of the overlying dots. PL emission linewidths as low as 21 meV are measured.

The QD heterostructures were grown on (001) GaAs substrates in a Varian Gen II MBE system with an As_4 source providing an arsenic pressure of 1×10^{-5} Torr. A typical heterostructure in shown in Fig. 1(a). The number of stressor and active dot layers and spacer layer thicknesses have been varied to optimize the PL characteristics. A 0.5 μm GaAs buffer layer was first grown at 630 °C. The substrate temperature was then lowered to 530 °C and the system of $In_{0.4}Ga_{0.3}Al_{0.3}As$ stressor QD layers, with GaAs spacer layers were grown. This was followed by the growth of the active $In_{0.4}Ga_{0.6}As$ dot layers with GaAs spacer layers. Finally, a 0.1 μm GaAs cap layer was grown at 610 °C. After the deposition of dot material, a 10 s growth interruption was

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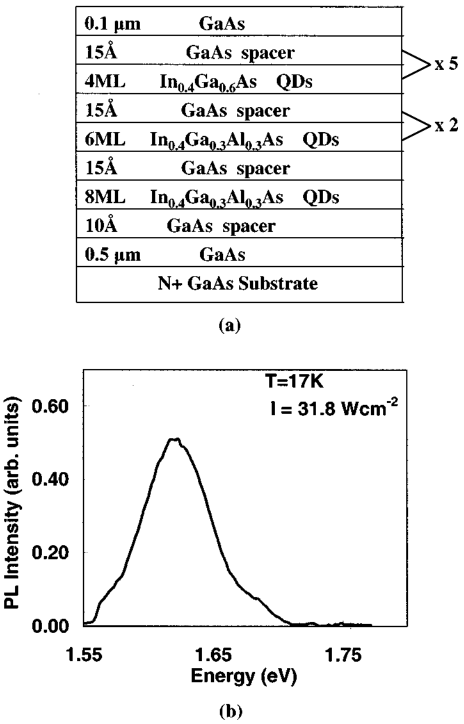

FIG. 1. (a) Typical InGaAs/GaAs quantum dot heterostructure with buried $In_{0.4}Ga_{0.3}Al_{0.3}As$ stressor dots and active $In_{0.4}Ga_{0.6}As$ dots grown by MBE. (b) Photoluminescence from a sample with only $In_{0.4}Ga_{0.3}Al_{0.3}As$ stressor dots confined between $Al_{0.18}Ga_{0.82}As$ barrier layers at $T=17$ K. The linewidth of the emission is 60 meV.

introduced, with As over pressure, to enable complete formation of the dots. The spacer layer was then grown. The entire heterostructure is undoped.

Variable temperature PL measurements were done with 632 nm light from a He–Ne laser. The luminescence was analyzed with a 1 m Jarrell–Ash spectrometer and detected with a liquid N_2-cooled photomultiplier tube after lock-in amplification. The alloy composition of the stressor dots is so chosen that the effective band gap off the dots is higher than that of the GaAs spacer layers. Thus all the photogenerated carriers in a PL experiment essentially relax into and recombine in the $In_{0.4}Ga_{0.6}As$ dots. This is confirmed by the absence of a PL signal from a heterostructure in which only the InGaAlAs/GaAs dots were present. However, a strong emission was observed from the stressor dots [Fig. 1(b)] when they were confined with an $Al_{0.18}Ga_{0.82}As$ barrier layer, instead of GaAs, confirming the high optical quality of the stressor dots.

It was found that the number of monolayers (MLs) of $In_{0.4}Ga_{0.6}As$ required for dot formation and the optimum thickness of the GaAs spacer layers depended on the built-in strain profile. For the heterostructure with no buried stressor InGaAlAs dots, the $In_{0.4}Ga_{0.6}As$ active dots in the first layer were formed after 7 ML of growth; on the other hand with a single buried layer of stressor dots, the active dots were formed after 5–6 ML of growth. This confirms the predicted role of the strain patterning provided by the stressor dots.[16] We next studied the effect of increasing the number of stressor dot layers on a single overgrown layer of active $In_{0.4}Ga_{0.6}As$ dots. The nominal thickness of the active dot remained fixed at 7 ML. The photoluminescence data are shown in Fig. 2(a). As the number of stressor dot layers is increased, the emission peak shifts progressively to lower energies. This can be understood on the basis of the built-in strain field due to the stressor dots. As the strain increases, the dots are formed at an enhanced rate with a thinner wetting layer and hence, for a fixed amount of charge (7 ML), larger dots are formed. At the same time, the full width at half maximum (FWHM) or PL linewidth, of the PL emission decreased significantly, from 55 meV for a sample with no stressor dots to 36 meV for a sample with three layers of buried stressor dots, as shown in Fig. 2(b). The redshift of the PL peak can be greatly reduced, at the same time maintaining the decrease in PL linewidth, if the first InGaAs dot layer is formed with 7–8 ML and subsequent dot layers are formed with 3–4 ML, in the absence of buried stressor dots. This is due to the vertical coupling of the layer dots in the subsequent dot layers with the initial one. Similar results have been reported by us earlier.[23] Furthermore, in the presence of the buried InGaAlAs stressor dots, even the first InGaAs dot layer can be formed with 3–4 ML of growth.

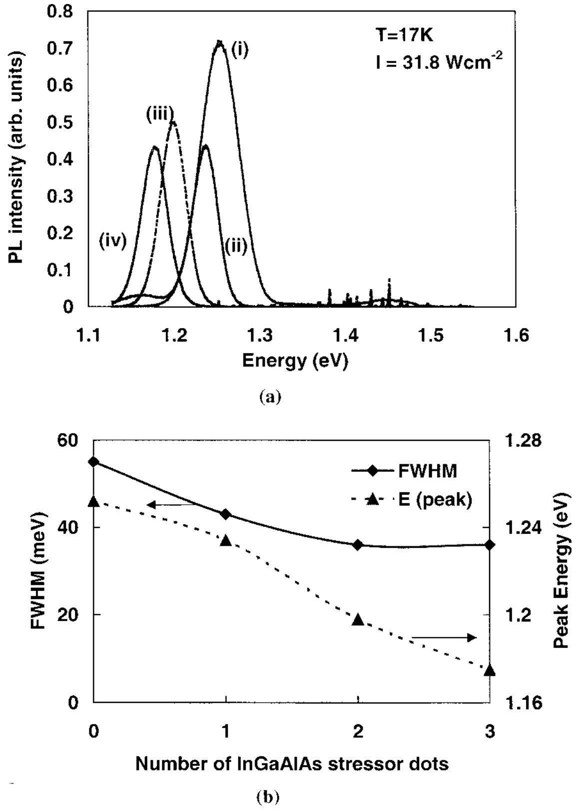

FIG. 2. (a) Effect of the number of buried $In_{0.4}Ga_{0.3}Al_{0.3}As$ stressor dots on the PL spectra of a single layer of 7 ML active $In_{0.4}Ga_{0.6}As$ at $T=17$ K: (i) no stressor dots; (ii) single layer of stressor dots; (iii) two layers of stressor dots separated by 15 Å GaAs spacer layer; (iv) three layers of stressor dots. The intensity of the structure in not to be compared directly; (b) variation of the peak energy and FWHM of $In_{0.4}Ga_{0.6}As$/GaAs dot luminescence with the number of buried stressor dot layers.

Taking all the above results into account, we grew an optimal structure with three layers of buried InGaAlAs stressor dots and five layers of $In_{0.4}Ga_{0.6}As$ active dots, as de-

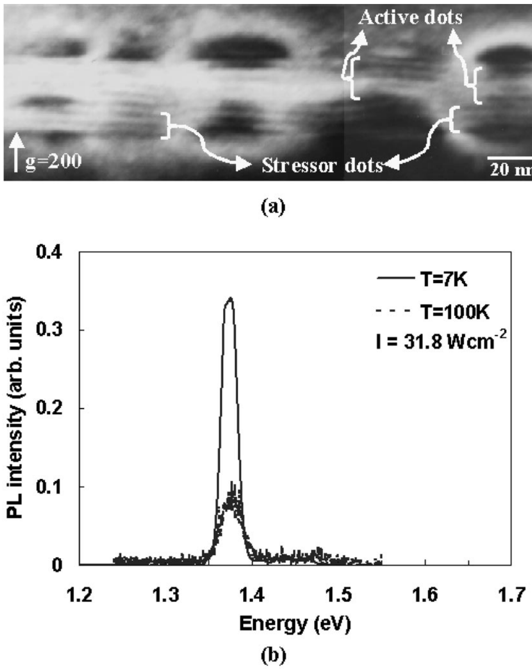

FIG. 3. (a) Cross-sectional TEM image of the heterostructure with five layers of active $In_{0.4}Ga_{0.6}As$ dots and five layers of $In_{0.4}Ga_{0.3}Al_{0.3}As$ stressor dots; (b) Photoluminescence emission measurements at $T=17$ K and $T=100$ K from this sample.

picted in Fig. 1(a). The first layer of buried dots were nominally 8 ML thick, with 15 Å GaAs spacers with the subsequent layers of stressor dots of thickness 6 ML. The nominal thickness of all the active dot layers was fixed at 4 ML, with 15 Å GaAs spacer layers between them. The formation of the dots was monitored by *in situ* RHEED and their presence and alignment was confirmed by cross-sectional transmission electron microscopy (XTEM). The XTEM data are shown in Fig. 3(a).

Temperature-dependent PL measurements in the range of 7–100 K yielded a strong emission peaking at 1.37 eV with a much weaker peak at 1.46 eV, the latter originating from the GaAs regions in the heterostructure. A linewidth (FWHM) of 21 meV was measured at 7 K for the 1.37 eV emission which remained virtually unchanged up to 100 K, indicating that the linewidth is principally determined by inhomogeneous broadening. The blueshift of the peak, relative to similar samples grown without stressor dots, could originate from several factors. The active dots are smaller, being grown to a nominal thickness of 4 ML. Moreover, a small amount of Al diffusion from the stressor dots into the GaAs spacer layer could increase the effective barrier seen by the dots. A similar blueshift has been observed by Garcia *et al.*[8] for InAs/AlAs dots.

In conclusion, we report a significant reduction in the PL linewidth of $In_{0.4}Ga_{0.6}As$/GaAs self-organized QDs, grown on buried InGaAlAs/GaAs stressor dots. By varying the nominal thickness and number of dots layers, we grew an optimal structure which exhibited an invariant PL linewidth (FWHM) of 21 meV in the temperature range of 7–100 K. A further reduction in linewidth may be possible by varying the composition of the stressor dots and by growing InAs active dots, which have an intrinsically larger compressive strain.

ACKNOWLEDGMENTS

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