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Strain-induced quantum dots by self-organized stressors

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Novel *in situ* method to produce quantum dots is reported. Three-dimensional confinement of carriers to a GaInAs/GaAs quantum well dots is observed by photoluminescence. The confinement potential is induced by stressors, formed by self-organizing growth of InP nanoscale islands on top barrier GaAs surface. Two transitions arising from the strain-induced quantum dots produced by two types of InP islands are identified. The luminescence from higher electronic states of the quantum dots having a level splitting of 8 meV is also observed. © *1995 American Institute of Physics.*

Lattice-mismatch induced growth of nanoscale islands is a promising candidate for the fabrication of quantum dot structures with good optical quality. For example, InAs, GaInAs, and InP nanoclusters have been formed using growth techniques such as hydride vapor phase epitaxy (VPE),[1] metalorganic vapor phase epitaxy (MOVPE),[2] and molecular beam epitaxy (MBE).[3] An other method to achieve three-dimensional confinement is lateral modulation of a quantum well (QW) band gap with local strain.[4] In previous studies the strain field has been introduced by defining stressors on the surface of the sample by lithographic means.[5–7] In this letter, the use of nanoscale islands as stressors to create three-dimensional quantum confinement is reported. The advantage of this approach is the capability of making the stressors *in situ* without lithography and etching. Additionally, in three-dimensional growth the dislocation-free islands can be thicker than the critical thickness of the two-dimensional pseudomorphic layer,[8] resulting in a larger local strain compared to etched stressors.

The samples were grown in a horizontal MOVPE reactor at atmospheric pressure. The details of the growth system are described elsewhere.[9] The source materials were trimethylgallium (TMGa), trimethylindium (TMIn), tertiarybutylarsine (TBAs), and tertiarybutylphosphine (TBP). The semi-insulating (100)±0.5° GaAs were used as substrate and the growth temperature was 650 °C. A 125 nm thick GaAs buffer layer was deposited before the growth of a 7 nm $Ga_{0.75}In_{0.25}As$ quantum well and a 29 nm GaAs barrier layer. InP islands were grown on the top GaAs barrier layer using TMIn molar flow of 7.9 μmol/min, V/III ratio of 100 and growth time of 5 s. Figure 1(a) shows the structure of the sample. As a reference a similar sample containing only the quantum well without the InP islands was grown.

The deposition of InP on GaAs results in formation of islands. The growth mechanism has been described as coherent Stranski–Krastanow growth.[8] The island structure of the sample was examined by a scanning electron microscope. Using the growth parameters above, two types of islands with different sizes are formed. Smaller islands have a relatively homogeneous size distribution (±10%) with a base diameter of 100 nm and a height of 20 nm.[10] The larger islands are 50–80 nm high with a base width of 200–300 nm. With similar growth parameters coherently strained and partially relaxed island types were observed when depositing InP on $Ga_{0.51}In_{0.49}P$/GaAs by MOVPE.[11] The critical island dimensions for dislocation formation were reported to be 120 nm in width and 22.5 nm in height. The formation of dislocations accelerates the growth of an island, producing large, partially relaxed islands. Our smaller and larger islands correspond to these coherently strained and partially relaxed types, respectively.

The strain induced by an InP island on the QW is tensile below the island and compressive under the edges of the island. The strain-induced modulation of the conduction band of the QW, shown schematically in Fig. 1(b), creates a two-dimensional, nearly parabolic potential well.[4] The modification of the valence band can be neglected as a first approximation. The modulation of the QW band gap by the InP

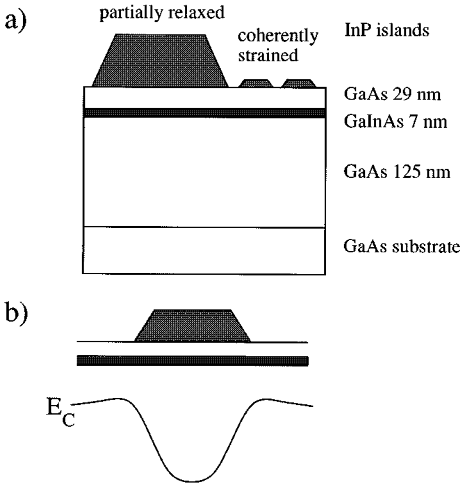

FIG. 1. (a) Schematic structure of the as-grown sample. Deposition of InP on a GaAs surface results in formation of islands, which act as stressors on the GaInAs quantum well. (b) Strain-induced conduction band modulation of the GaInAs well under an InP island shown schematically.

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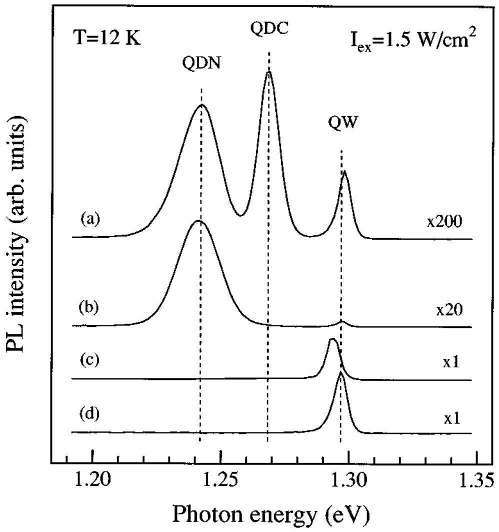

FIG. 2. Photoluminescence spectra of the as-grown sample (a), sample etched for 20 s in diluted HCl (b), sample etched for 3 min in fuming HCl (c), and the reference quantum well (d). The QW peak originates from the undisturbed part of the quantum well. The QDC and QDN peaks are related to quantum dots produced by a strong field of the coherent islands and the larger, partially relaxed islands, respectively.

stressors results in three-dimensional carrier confinement, forming quantum dots (QD) under the islands.

To investigate the strain field produced by the InP islands in the quantum well the samples were characterized by photoluminescence (PL) measurements. The PL spectra were measured by a liquid-nitrogen-cooled germanium detector using standard lock-in techniques. The 488.0 nm line of an Ar^+-ion laser was used for excitation. The laser beam was focused into a spot having a diameter of 200 μm. The PL spectrum from the as-grown stressor sample in Fig. 2(a) shows three distinct peaks at 1.297 eV (labeled QW), 1.268 eV (QDC), and 1.242 eV (QDN). The QW peak, which also can be seen in the PL spectrum of the reference QW sample (d), results from excitonic recombination in the undisturbed part of the quantum well.

To identify the origin of the other transitions (QDC and QDN), one part of the stressor sample was etched for 20 s in diluted HCl. The smaller islands were completely etched away, whereas the size of the larger islands was not significantly reduced. The PL spectrum of the etched sample in Fig. 2(b) shows only two peaks, the QW and QDN transitions. The absence of the smaller, coherently strained islands has resulted in the disappearance of the QDC peak. This indicates that the QDC peak originates from quantum dots produced by the strain field of the smaller islands. The redshift of 29 meV of the QDC peak from the QW peak corresponds approximately to the depth of the strain-induced potential well. The full width at half-maximum (FWHM) of only 10 meV confirms that the island size distribution is homogeneous.

Another part of the as-grown sample was etched for 3 min in fuming HCl. In this sample both types of islands were removed. The PL spectrum of this sample in Fig. 2(c) contains only the QW transition. Therefore, the QDN peak in the as-grown sample is related to quantum dots produced by the larger islands. The redshift of the QDN peak relative to the QW peak is 55 meV and FWHM is 18 meV.

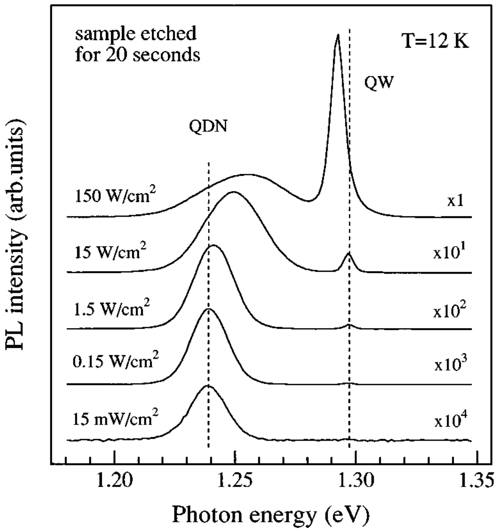

FIG. 3. Photoluminescence at various excitation intensities of the sample etched for 20 s, containing only partially relaxed islands. The blueshift of the QDN peak is 16 meV and the redshift of the QW peak is 6 meV at the excitation intensity of 150 W/cm^2.

The total luminescence intensity of the as-grown stressor sample relative to the reference sample is 6%. The absorption of excitation light in InP decreases the PL intensity. Moreover, the strain-induced gradient in the conduction band of the top GaAs barrier layer enhances the drift of electrons to surface. When the smaller islands are etched away, the total luminescence intensity increases to 28% of the reference. The absorption in larger InP islands and carrier drift to these partially relaxed islands still occurs. The intensity of the QDN peak has increased tenfold compared to the as-grown sample due to absence of the smaller quantum dots and subsequent diffusion of the carriers along the quantum well to larger QDs. The intensity of the QW peak from the sample etched for 3 min relative to the reference sample has been reduced only by 22%, indicating that the total dislocation density of the quantum well area is low. Some dislocations are present, indicated by the reduced luminescence intensity along with broadening and redshift of the QW peak.

To show, that stressors form three-dimensional confinement, photoluminescence was measured as a function of excitation intensity. The PL intensity of the QW transition from the reference QW sample and the sample etched for 3 min varies approximately linearly with the excitation intensity. To investigate the behavior of the QDN peak explicitly the PL spectra of the sample etched for 20 s is discussed first (see Fig. 3). The intensity of the QDN transition increases linearly with the excitation intensity and the peak position has a maximum blueshift of 16 meV at the excitation intensity of 150 W/cm^2, indicating significant state filling in the strain-induced quantum dot.[12] At this excitation level the QW peak has a redshift of 6 meV due to band-gap renormalization.[13] The intensity of the QW transition increases superlinearly due to the filling of the states in the QDs, resulting in enhanced recombination of carriers in the undisturbed part of the QW.

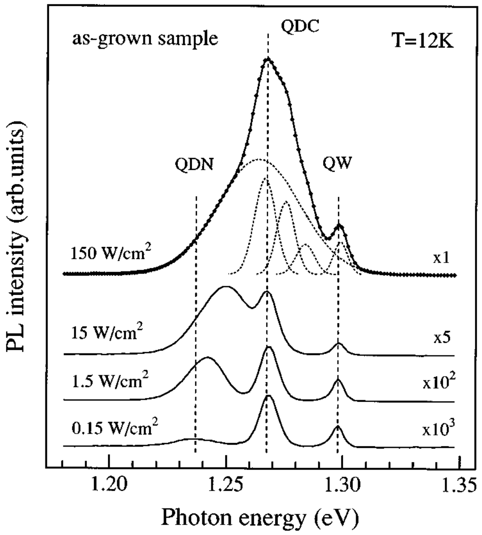

FIG. 4. Photoluminescence spectra of the as-grown sample as a function of excitation intensity. The dashed curves show peaks fitted to the spectrum measured with the excitation intensity of 150 W/cm^{-2} and diamonds represent their sum curve. Two additional peaks in the high-energy side of the QDC peak appear due to luminescence from higher electronic states in the nearly parabolic well having a level splitting of 8 meV.

Figure 4 shows the PL spectra of the as-grown sample with different excitation intensities. The QDN peak has a strong blueshift of 26 meV at the excitation intensity of 150 W/cm^2. After the lower-laying states of the larger dots are filled, the state filling occurs in the smaller dots as well. The maximum of the QDC peak is not shifted to blue, but the derivative of the spectrum reveals the appearance of new peaks on the high-energy side of the QDC peak. To resolve the overlapping peaks, Gaussian profiles were fitted to the PL spectrum. The fitted peaks together with their sum curve are shown in Fig. 4. The two additional peaks together with the QDC peak are separated equally by 8 meV from each other. We believe this is due to the filling of the ground state in the smaller dots and consequent luminescence from higher electronic states. The level splitting of 8 meV agrees with a simple model of a two-dimensional parabolic well having a depth of 30 meV and a width of 70 nm.

In summary, the use of self-organized growth to form stressors is demonstrated. In the photoluminescence spectra two peaks arising from the strain-induced quantum dots produced by two types of InP islands with different sizes are identified. The luminescence from higher electronic states of the quantum dots having a level splitting of 8 meV is also observed. The dislocation density in the quantum well area is low, because the PL intensity of the QW peak is almost restored after the removal of the islands by wet etching.

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