

# Selective manipulation of InAs quantum dot electronic states using a lateral potential confinement layer

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To further the objective of controlled manipulation of the electronic states in epitaxial island quantum dots (QDs), we introduce the notion of a lateral potential confinement layer (LPCL) whose judicious placement during island capping allows selective impact on ground and excited electron and hole states. The energy states of InAs/In<sub>0.15</sub>Ga<sub>0.85</sub>As QDs are manipulated using 10-monolayer-thick In<sub>0.15</sub>Al<sub>0.25</sub>Ga<sub>0.60</sub>As LPCLs positioned at the bottom, upper, and top region of the QDs. The changes in the photoluminescence (PL) and PL excitation spectra reveal the nature of the electronic transitions impacted selectively through the spatial charge distributions of the states involved. © 2002 American Institute of Physics. [DOI: 10.1063/1.1517710]

Strain-driven In(Ga)As self-assembled quantum dots (QDs)<sup>1</sup> have been studied extensively for the physics and potential device applications of zero-dimensional semiconductor systems.<sup>2</sup> Understanding and manipulation of the electronic states of QDs are important issues for applications in electronics and optoelectronics. Tuning of the QD electronic structure can be achieved by varying QD size, QD capping layers,<sup>3-5</sup> or by thermal annealing.<sup>6,7</sup> Most such approaches affect the QD electronic structure as a whole and do not allow tuning primarily subsets of QD states. Calculations show that the charge centers of gravity of QD carrier wave functions can be located at different vertical positions inside the QD (i.e., in the growth direction).<sup>8-10</sup> Consequently, selective modification of the lateral confinement potential at various heights of the QDs offers a means of selectively tuning the energy levels and associated transitions. In this letter we report some results of the effect of inserting a 10 monolayer (ML)-thick In<sub>0.15</sub>Al<sub>0.25</sub>Ga<sub>0.60</sub>As layer as a lateral potential confinement layer (LPCL), positioned at different height of QDs, on the electronic states of otherwise In<sub>0.15</sub>Ga<sub>0.85</sub>As capped InAs QDs.

All samples were grown on undoped GaAs (001) substrates by solid-source molecular beam epitaxy (MBE). InAs QDs were formed at substrate temperature of 500 °C using 2.5 ML InAs delivery at a rate of 0.054 ML/s under As<sub>4</sub> partial pressure of  $7 \times 10^6$  Torr. Subsequently, the samples were cooled to 350 °C for the growth of capping layers deposited by migration enhanced epitaxy, which shows good optical characteristics. Such low temperature capping procedure minimizes both the degree of intermixing between InAs QDs and capping layers, and the decomposition of alloy In-(Al)GaAs capping layers. For photoluminescence (PL) and PL excitation (PLE) studies, the QD samples were excited by 514 nm Ar<sup>+</sup> laser and a quartz tungsten halogen lamp dispersed by 0.25 m monochromator with a triple grating turret, respectively. The emission was dispersed through 0.85 m double grating monochromator and detected with a liquid nitrogen cooled Ge detector.

In this study, InAs QDs capped by 30 ML In<sub>0.15</sub>Ga<sub>0.85</sub>As+140 ML GaAs (InGaAs capped sample) were used as a reference. To investigate the change in the electronic states of such QDs by LPCLs positioned at the bottom, upper, and top region of the QDs, 10 ML of the 30 ML In<sub>0.15</sub>Ga<sub>0.85</sub>As were replaced by In<sub>0.15</sub>Al<sub>0.25</sub>Ga<sub>0.60</sub>As, as shown in the inset of Fig. 1. Since the In<sub>0.15</sub>Al<sub>0.25</sub>Ga<sub>0.60</sub>As layer has the same In amount, it gives essentially the same strain relieving effect to QDs as does the In<sub>0.15</sub>Ga<sub>0.85</sub>As layer. However, having a larger band-gap energy (~1.606 eV at 300 K)<sup>11</sup> than that of In<sub>0.15</sub>Ga<sub>0.85</sub>As (~1.21 eV at 300 K),<sup>12</sup> it enhances the potential barrier in the lateral directions. Sample 1 has the LPCL located at the bottom of the InAs QDs. In samples 2 and 3, the LPCL is positioned 10 and 20 ML above the bottom of the QDs, respectively. Atomic force microscopy results obtained from uncapped 2.5 ML InAs QDs showed that QD density was ~400/μm<sup>2</sup>, the average width was ~20 nm, and the average height was ~6 nm.

Figure 1 shows PL spectra of InAs QDs capped by a 170 ML GaAs layer (called GaAs capped sample), the InGaAs capped sample, and samples 1, 2, and 3. The GaAs capped

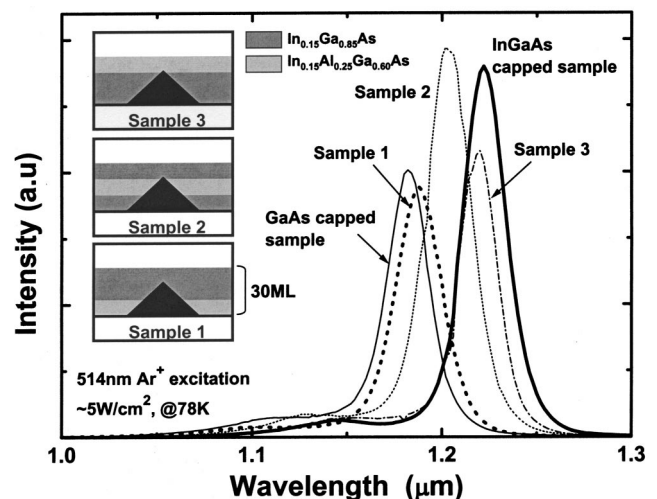


FIG. 1. PL spectra of the GaAs and the InGaAs capped reference samples, and samples 1, 2, and 3 at 78 K.

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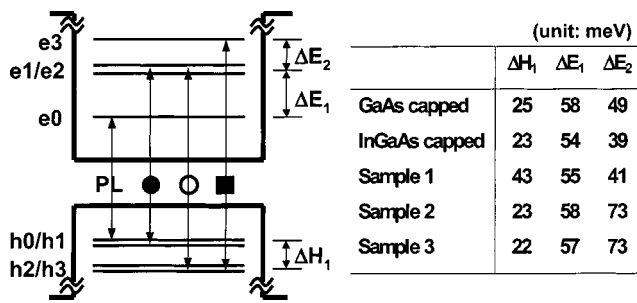


FIG. 4. Schematic of electron and hole energy levels and associated transitions of InAs QD.

the third PLE peaks in samples 1, 2, and 3 can be understood in terms of the varied impact of the LPCL ( $\text{In}_{0.15}\text{Al}_{0.25}\text{Ga}_{0.60}\text{As}$  layer) on different electron and hole states depending upon the nature of their spatial charge distributions. Indeed, these shifts can be viewed as the first direct experimental probing and confirmation of the nature of the calculated charge distributions of higher (excited) hole and electron states in pyramidal QDs.

In Fig. 4, we schematically summarize the types of transitions involved suggested by the comparison of the observed PLE peak positions and the calculated transition energies available in the literature.<sup>8,9,14,15</sup> The first PLE peak energy ( $\sim 54\text{--}58$  meV) of Fig. 3 is well established to represent the energy difference of the ground electron state ( $e_0$ ) and the first subset of excited electron states ( $e_1/e_2$ ).<sup>14,15</sup> The calculated  $e_0$  and the  $e_1/e_2$  wave functions are  $s$ -like and  $p$ -like, respectively, but the heights of the charge density iso-surfaces are reported to be very similar.<sup>8–10</sup> The observed insensitivity of the  $e_0\text{--}e_1/e_2$  transition ( $\Delta E_1$ ) to the different positions of the LPCL thus suggests that the  $e_0$  and  $e_1/e_2$  energy levels are shifted almost in parallel. By contrast, the second PLE peak (marked ○) is blueshifted by  $\sim 20$  meV only in sample 1 having the LPCL positioned at the bottom region of QDs. The energy difference of the first and the second PLE peaks represents the difference ( $\Delta H_1$ ) in excited hole energy levels ( $h_2/h_3$ ) and the ground hole levels ( $h_0/h_1$ ) (see Fig. 4). The hole states tend to be more confined inside dots than the electron states. A common finding<sup>8,9</sup> of the calculations is that the  $h_2/h_3$  charge distributions have lobes located near the bottom corners of QDs. As a result, the  $h_2/h_3$  states are more sensitive to the squeezing effect of the LPCL when positioned in the bottom region of QDs and contribute the  $\sim 20$  meV blueshift in the  $e_1/e_2\text{--}h_2/h_3$  transition energy. When the LPCL is located in the upper and top regions of QDs (samples 2 and 3), its effect on the  $h_2/h_3$  states essentially disappears, and the second PLE peak is back to that of the InGaAs capped sample. However, in these cases, the third PLE peak (marked ■) is maximally blueshifted by  $\sim 34$  meV. Attributing the third peak to the transi-

tions involving the second subset of excited electron states ( $e_3$  or higher states) and  $h_2/h_3$  hole states as indicated by (■) in Fig. 4 would be consistent with the blueshift arising from the increased lateral localization of the charge of the second subset of excited electron states if it were concentrated in the upper region of the QDs. The charge distribution of the potential electron states in the second subset calculated in Ref. 8 suggests that certain states have likely a significant part of their charge distribution in regions higher than the electron states of the first subset ( $e_1/e_2$ ). A more quantitative explanation must await appropriate theoretical analysis.

In conclusion, we have systematically investigated the effect of a LPCL, positioned at different heights of QDs, on the electronic states of the InAs/ $\text{In}_{0.15}\text{Ga}_{0.85}\text{As}$  QD system. The electron and hole ground states and the first subset of excited hole states are perturbed most effectively by the LPCL located in the bottom region of QDs, indicating that the charge center of gravity of these states resides near the QD bottom. Moreover, by positioning the LPCL in the upper region of the QDs, certain high excited electron energy levels could be tuned without significantly perturbing other states, thus indicating that these electron states have their charge distribution centers of gravity located in the upper regions of the QDs. Our findings open another path to manipulating intra- and interband transition energies for applications such as QD infrared photodetectors, lasers, and optical amplifiers.

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