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Room-temperature 1.6 μm light emission from InAs/GaAs quantum dots with a thin GaAsSb cap layer

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It is demonstrated that the emission of InAs quantum dots (QDs) capped with GaAsSb can be extended from 1.28 to 1.6 μm by increasing the Sb composition of the capping layer from 14% to 26%. Photoluminescence excitation spectroscopy is applied to investigate the nature of this large redshift. The dominant mechanism is shown to be the formation of a type-II transition between an electron state in the InAs QDs and a hole state in the GaAsSb capping layer. The prospects for using these structures to fabricate 1.55 μm injection lasers are discussed. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2173188]

Self-assembled InAs/GaAs quantum dots (QDs) are of considerable interest due to their physical properties and potential applications, for example, long wavelength GaAs-based QD lasers operating in the 1.3–1.6 μm telecommunications wavelength range.[1] High-performance InAs/GaAs QD lasers, with emission close to 1.3 μm, have been demonstrated using InGaAs, InAl(Ga)As, and GaAsSb capping layers (CLs) to directly cover the InAs QDs.[2–6] In addition, there have been a number of attempts to extend the emission wavelength beyond 1.5 μm, with room-temperature (RT) photoluminescence (PL) above 1.5 μm having been demonstrated for large InAs/GaAs QDs,[7] GaInNAs/GaAs QDs,[8] InAs QDs with an $In_{0.45}Ga_{0.55}As$ CL,[9] InAs QDs with InGaNAs CL,[10] and InAs QDs grown on InGaAs or GaAsSb metamorphic buffer layers.[11,12] In a previous letter, we reported ~1.3 μm emission from InAs QDs with a GaAsSb CL.[6] Evidence for a type-II system for Sb compositions >14% was obtained, and a 1.3 μm laser was fabricated. In the present letter we show that RT emission at 1.6 μm may be obtained by increasing the Sb composition to 26%. The compositional dependence of the electronic band structure is probed using a combination of PL and PL excitation (PLE).

The samples were grown in a V80H molecular beam epitaxy system equipped with conventional solid sources for group-III elements and EPI cracker sources for As and Sb. The QDs were formed by depositing 2.8 monolayers (MLs) of InAs at a rate of ~0.1 ML/s on GaAs and were subsequently capped with 6 nm of $GaAs_{1-x}Sb_x$. Four samples were grown with Sb compositions (x) of approximately 14%, 18%, 22%, and 26%. The InAs QDs and GaAsSb CL were embedded between 100 nm GaAs layers and further confined by 50 nm AlGaAs layers. PL was excited using either a 532 nm solid-state laser or light from a tungsten-halogen lamp dispersed by a 0.25 m monochromator. The latter system was also used to excite the PLE. PL emission was detected with a cooled Ge detector.

Figure 1 shows 10 K PL spectra of the structures. The InAs QD emission wavelength increases from 1190 to 1460 nm as the Sb composition increases from 14% to 26%, with the full width at half maximum increasing from 19 to 40 meV. The intensity of the PL also weakens slightly. The emission from the 18%, 22%, and 26% samples exhibits a strong blueshift with increasing excitation power, consistent with a type-II transition believed to originate between an electron state in the QDs and a hole state in the GaAsSb. In contrast, the emission wavelength of the 14% sample is power independent, consistent with a type-I system and

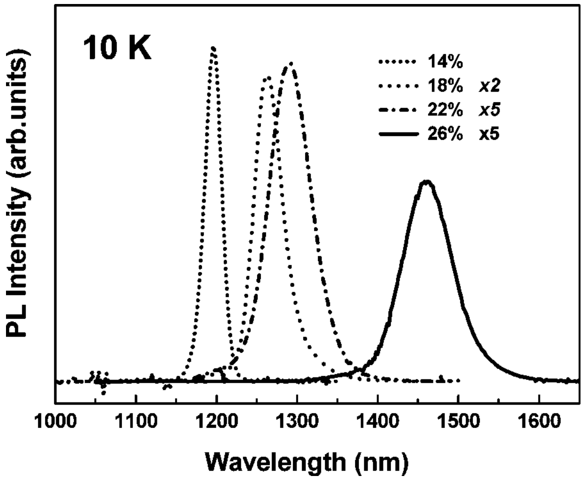

FIG. 1. 10 K PL spectra of the $GaAs_{1-x}Sb_x$ (x=14%, 18%, 22%, and 26%) capped InAs QDs.

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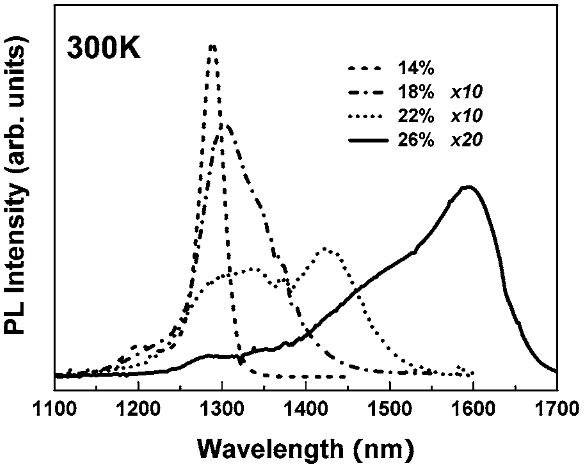

FIG. 2. RT PL spectra of the $GaAs_{1-x}Sb_x$ (x=14%, 18%, 22%, and 26%) capped InAs QDs.

hence a type-I/type-II transition for Sb compositions $\gtrsim 14\%$, in agreement with our previous findings.[6]

Figure 2 shows RT PL spectra of the structures. As observed at low temperatures, increasing the Sb composition of the capping layer results in a significant redshift of the dominant emission, with 1.6 μm emission obtained for the highest composition of 26%. The emission from the higher Sb composition structures is now relatively broad, extending from the long wavelength emission down to a weaker feature at ~1300 nm. It is believed that the former represents the type-II transition and the latter a type-I transition internal to the QDs. This attribution is supported by power dependent PL measurements, which reveal a strong blueshift with increasing power for the long wavelength emission but power independent emission at 1300 nm, and PLE measurements described below.

There are two possible contributions to the redshift of the emission with increasing Sb composition of the GaAsSb CL: a modified strain[2] and/or size of the QDs, or the development of a type-II system which pushes the hole states in the GaAsSb layer closer to the electron states of the QD. However, the fact that the energy of the type-I transition is relatively independent of Sb composition indicates that the physical structure of the QDs remains approximately constant, and hence that it is the formation of a type-II system which accounts for the large redshift. A type-II system for both GaAsSb/GaAs and GaAsSb/InGaAs quantum wells has been previously reported, in both cases the lowest hole state occurring in the GaAsSb.[13]

Figure 3 shows PL and PLE spectra of the samples recorded at a temperature of 4.2 K. For the 14% sample a number of features are observed in PLE between ~950 and 1150 nm, the absolute energies of which shift rigidly with the detection energy. These features correspond to the multiple-LO phonon carrier relaxation processes previously reported for InAs/GaAs QDs.[14,15] Such features are absent from the PLE spectra of the higher Sb compositions, consistent with a different emission mechanism in these structures.

In addition to the LO phonon features, which are specific to the 14% sample, the PL and PLE spectra exhibit three main features. The emission in the region of 1200–1500nm, which redshifts strongly with increasing Sb composition, is attributed to the type-II transition, occurring between the QD electron state and hole states in the GaAsSb layer. The absorption at ~1200 nm for the three highest Sb samples, with corresponding emission for the 14% sample, is attributed to the type-I QD transition. Finally, the absorption in the region of ~900–1050 nm, which redshifts relatively weakly with increasing Sb composition, is attributed to a type-I transition within the GaAsSb layer. Figure 4 shows schematic band diagrams for the 14% and 26% samples based on the PL and PLE results. It is believed that the 14% sample is close to the type-I/type-II crossover so that the lowest hole state may be extended throughout both the QD and GaAsSb layer in this structure.

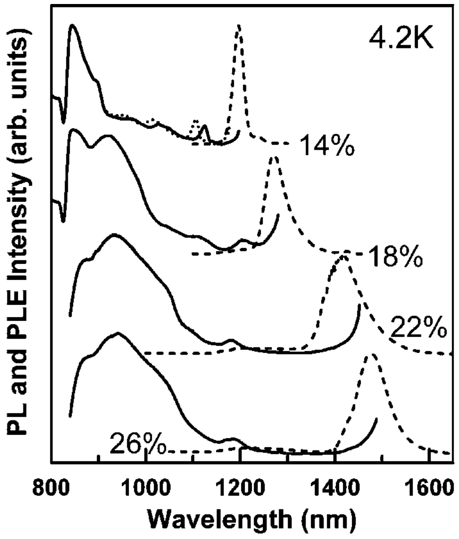

FIG. 3. 4.2 K PL (dashed line) and PLE (solid line) spectra. Two PLE spectra are shown for the 14% sample corresponding to different detection energies. The intensities of the spectra have been normalized.

A number of points can be deduced from the PL and PLE spectra. First, although the energy of the type-I transition is relatively constant it varies slightly by ~12 meV between the 14% and 26% samples. This small variation may arise from a number of causes, including changes in the confinement potential, the dot strain, and hole confinement width. However, the fact that this variation is small in comparison to the redshift of the PL (196 meV between the 14%

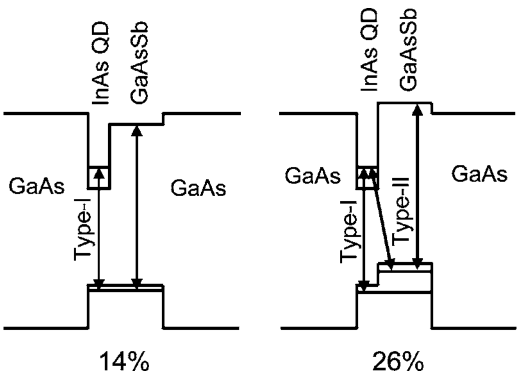

FIG. 4. Schematic band diagrams of the 14% and 26% structures. The 26% structure is type II. The 14% structure is believed to be close to the type-I to type-II crossover.

and 26% samples) indicates that the dominant contribution to the latter is the formation of a type-II system. Second, the significantly larger redshift of the type-II transition compared to that of the GaAsSb band gap with increasing Sb composition indicates that the GaAsSb conduction band edge moves upwards relatively to that of the QDs and GaAs with increasing Sb. This is indicated in Fig. 4. Finally, there is little absorption below the type-I transition in the 22% and 26% samples, suggesting that the type-II transition is relatively weak. This would be consistent with the RT PL where the type-I transitions are observed, in addition to the type-II transitions, even though the thermal population of the underlying states will be relatively small. The observation of both type-I and type-II emissions, despite a low carrier population for the former, implies significantly different oscillator strengths.

Although the present structures achieve >1.5 μm emission via a type-II transition this may not preclude the attainment of a laser device. We note that RT lasing near 1.3 μm has been successfully demonstrated for GaAsSb/GaAs quantum-well structures despite their probable type-II nature.[16,17] In the present 26% Sb structure the long wavelength emission continues to dominate even at very high excitation powers suggesting that a >1.5 μm laser may be possible with this GaAs-based system. Finally we note that a 1.6 μm emission at RT has also recently been observed by Ripalda *et al.*[18] from GaAsSb capped InAs QDs.

In conclusion, InAs QDs capped with GaAsSb exhibit room-temperature emission at wavelengths as long as 1.6 μm. A detailed optical spectroscopic study provides strong evidence for a type-II transition which redshifts rapidly with increasing Sb composition.

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