Optical properties of 1.3-μm InAs/GaAs quantum dots grown by metal organic chemical vapor deposition

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The optical properties of self-assembled InAs quantum dots (QDs) on GaAs substrate grown by metal-organic chemical vapor deposition (MOCVD) are reported. Photoluminescence (PL) measurements prove the good optical quality of InAs QDs, which are achieved using lower growth temperature and higher InAs coverage. At room temperature, the ground state peak wavelength of PL spectrum and full-width at half-maximum (FWHM) are 1305 nm and 30 meV, respectively, which are obtained as the QDs are finally capped with 5-nm $In_{0.06}Ga_{0.94}As$ strain-reducing layer (SRL). The PL spectra exhibit two emission peaks at 1305 and 1198 nm, which correspond to the ground state (GS) and the excited state (ES) of the QDs, respectively.

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Due to the low cost of GaAs substrate, associated with its compatibility with other semiconductor technologies, the InAs/GaAs quantum dots (QDs) have been the subject of intensive research in the past few years, since these structures provide the prospect of temperature-independent low threshold lasers. Due to the three-dimensional (3D) confinement of carriers, QDs are expected to improve the performance of semiconductor lasers compared with quantum well, and GaAs-based InAs QD lasers emitting at 1.3 μm with low thresholds have already been demonstrated[1−3]. However, a large photoluminescence (PL) linewidth, which results from size, shape, and composition variation in QDs, is one of the main obstacles limiting them from practical applications. Much effort has been made to improve the optical properties by using various special growth techniques such as a low InAs growth rate[4,5], an InGaAs strain-reducing layer (SRL)[6−8], and a low V/III ratio[9,10]. High density InAs QDs on GaAs exhibit intense pholuminescence in the region of 1.3 μm at room temperature, obtained by molecular beam epitaxy (MBE)[1−8]. Compared with the MBE system, the QDs grown by metal-organic chemical vapour deposition (MOVCD) has been limited due to the fundamental differences in growth mechanism. So far, there are very few reports on InAs/GaAs QDs grown by MOVCD with photoluminescence band in the 1.3-μm region[9−12]. The progress in this direction is slow since it is difficult to reach 1.3-μm emission wavelength due to the difficulty of growing sufficiently larger QDs with good optical performance.

In this letter, we present a method to obtain high density InAs quantum dots ($\sim 3\times10^{10}$ cm^{-2}) and the ground state emission beyond 1.3 μm at room temperature (300 K) using low-In composition strain-reducing layer.

All samples used in the study were grown on GaAs (001) by low-pressure MOCVD system, using trimethylindium (TMI) and trimethylgallium (TMG) as the group III sources, and tertiallybutylarsine (TBA) as the group V source. The total background pressure during the growth was 76 Torr. After oxide desorption at 800 °C, a 200-nm GaAs layer was deposited at 700 °C using TMG and TBA. Then substrate was cooled down and the subsequent InAs QDs were deposited at 490 °C using TMI and TBA, with InAs coverage of 2.9 ML. The growth rate for InAs was 0.025 ML/s. To achieve long wavelength emission beyond 1.3 μm, the QDs were finally capped with 5-nm $In_{0.06}Ga_{0.94}As$ strain-reducing layer and 100-nm-thick GaAs at 520 °C.

In order to obtain QDs with high density and long emission wavelength, we optimized the QDs growth conditions such as growth temperature and growth rate. As is acknowledged that the island size and density strongly depends on the growth temperature and growth rate. With a reduction in the growth rate, the island size increases and the light emission wavelength correspondingly shifts to the longer side[4,13]. A reduction in the growth rate enhances the migration length of the In adatoms. In order to minimize strain and surface energy, In atoms incorporate into existing dots instead of forming new dots. Thus, a reduction in the growth rate leads to a decrease in island density and a corresponding increase in size[14]. Therefore, we optimize the growth condition using lower growth temperature and higher growth rate to obtain high density of InAs QDs. The density of InAs QDs in the samples was characterized by measuring uncapped samples with an atomic force microscope (AFM). Figure 1 shows an AFM image of 1×1 (μm) size, and the density is $\sim 3\times10^{10}$ cm^{-2}, with an average height of ∼9 nm, and an average diameter of ∼24 nm. We also note the coalescence of dots ($\sim 3\times10^{8}$ cm^{-2}) with height up to ∼30 nm and diameter up to ∼80 nm.

To investigate the optical properties of InAs/GaAs QDs, PL characteristics were measured with a semiconductor laser as excitation source with wavelength of 670 nm and detected by a liquid-nitrogen cooled InGaAs

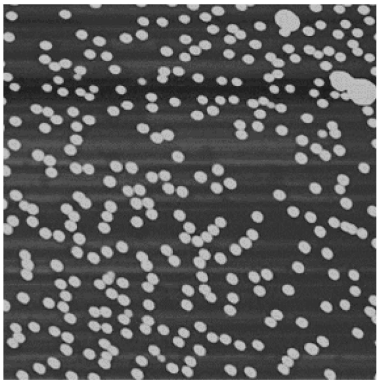

Fig. 1. 1×1 (μm) AFM image of InAs QDs.

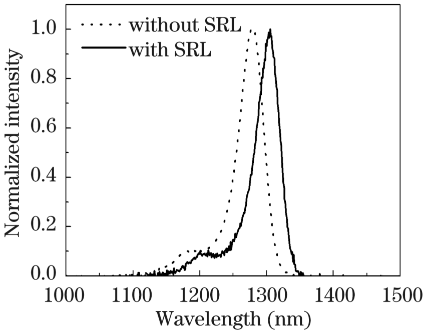

Fig. 2. PL spectra of the sample measured with and without SRL.

photodiode array. Figure 2 shows the PL spectra of InAs QDs grown on GaAs substrate with lower excitation powers at room temperature. For the samples, with and without using SRL, the peak emission wavelength (300 K) from InAs QDs are 1.305 and 1.279 μm, respectively. The linewidth (full-width at half-maximum, FWHM) of the QDs with and without SRL are about 30 and 34 meV, respectively. The achievement of the emission beyond 1.3 μm can be attributed to the SRL, which suppresses the size reduction and shape change of QDs and In/Ga intermixing that can occur during capping.

Figure 3 shows the PL spectra of InAs QDs sample with SRL measured at different excitation powers. PL spectra are measured at 300 K with a much higher excitation power, where emission from the first excited states of the QDs can be clearly recognized. The PL spectra exhibit two emission peaks at 1305 and 1198 nm, corresponding to the ground state (GS) and the excited state (ES) of the QDs, respectively. Figure 4 shows clearly that QD PL can be observed up to 300 K and the PL spectrum obtained with lower excitation density at 300 K shows a sharp peak similar to that observed at 10 K.

We also investigated temperature-dependent optical properties of the QDs under lower excitation density, measured from 10 to 300 K. Figure 5(a) shows the change of the FWHM with temperature. The linewidth of the QDs firstly increases and then decreases with temperature increasing. Similar behaviors about the dependence of linewidth on temperature have been reported[15], however, the mechanism of linewidth as a function of temperature is still poorly understood. It is commonly considered that the increase in the linewidth is a consequence of the broadening of carrier distribution function with temperature increasing, the linewidth reduction with temperature results from an increase of the carrier thermal emission from smaller QDs into nearby larger QDs[16]. The larger results of FWHM from the

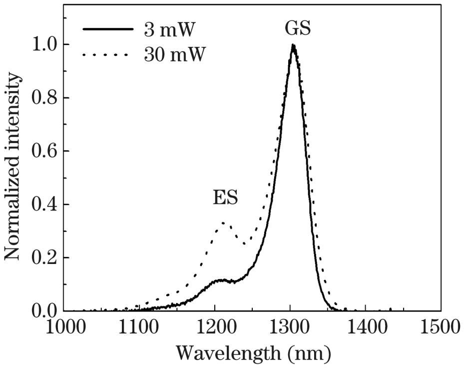

Fig. 3. PL spectra of the high density InAs QD sample at different excitation powers.

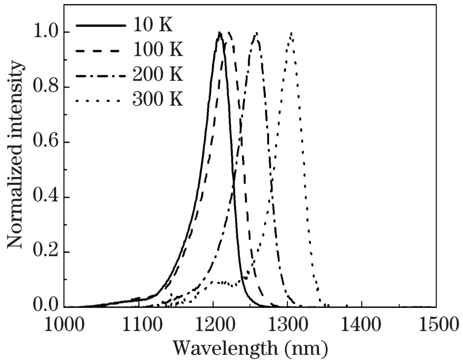

Fig. 4. PL spectra of the InAs QD sample measured at different temperatures.

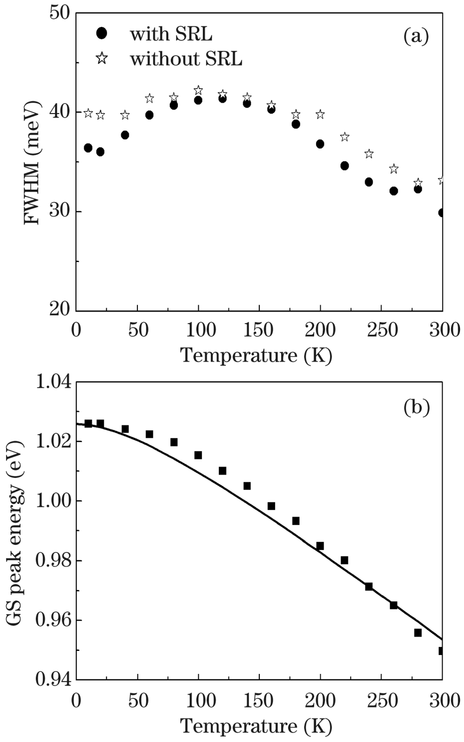

Fig. 5. Temperature dependence of the FWHM and GS peak energy of the InAs QD samples.

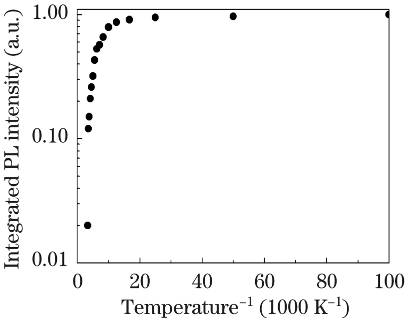

Fig. 6. Temperature dependence of the integrated PL intensity of the InAs QD sample with SRL.

dots without SRL are due to inhomogeneous broadening, induced from the finite-size distribution of the dots. The PL peak energy shift with temperature is plotted in Fig. 5(b), and the GS peak energy follows the expected dependence of the bulk InAs band gap energy (solid line). This temperature-independent behavior is distinctly different from that reported previously. Previous reports[17,18] show an abnormal decrease of PL linewidth with increasing temperature, which mainly results from thermal transfer of carriers from smaller QDs into nearby larger QDs with smaller ground-state energies.

Figure 6 shows the integrated PL intensity dependence on temperature. For temperature from 10 to 160 K, the PL intensity decreases slightly, and for temperatures greater than 160 K, the PL intensity decreases quickly. This is usually attributed to thermal escape of carriers at higher temperatures, when the thermal escape becomes dominant. The decrease in the integrated PL intensity results from the defect and nonradiative recombination centers in the quantum dot. As the temperature increases, the PL intensity corresponding to the bound electron peak is given by[19]

$$I(T) = A/[1 + \mathrm{B}\exp(E_{\mathrm{a}}/KT)], \tag{1}$$

where I is the integrated PL intensity, A and B are two fitting constants, E_{a} is the activation energy, and K is the Boltzmann constant. E_{a}, extrapolated from the PL quenching regime, is estimated to be 453 meV. At a low temperature of 10 K, the PL peaks originating from the GaAs barrier layer and the InAs QD ground state are observed at 1.490 and 1.026 eV, respectively. The PL peak energy difference between the InAs ground state and the GaAs barrier layer is 464 meV, which is consistent with the estimated E_{a} value of 453 meV. This indicates that the thermal escape of carriers into the barrier and subsequent nonradiative recombination center is the dominant quenching mechanism[16].

In summary, we show that it is possible to reach high density InAs QDs ($\sim 3\times 10^{10}$ cm^{-2}) with a light emission wavelength in the 1.3-μm region, grown by low-pressure MOCVD. PL measurements prove the good optical quality of high density InAs QDs grown on GaAs substrate using low-In composition InGaAs as SRL. Furthermore, the QDs exhibit less dependence of PL integrated intensity, linewidth, peak position of the sample with SRL on temperature. The results obtained have significant implications for the realization of high-performance QD lasers for applications in optical communication systems.

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