Broadband light emitting from multilayer-stacked InAs/GaAs quantum dots*

Liu Ning(刘 宁)[a)b)], Jin Peng(金 鹏)[a)†], and Wang Zhan-Guo (王占国)[a)]

[a)] *Key Laboratory of Semiconductor Materials Science and Beijing Key Laboratory of Low-Dimensional Semiconductor Materials and Devices, Institute of Semiconductors, Chinese Academy of Sciences, Beijing* 100083, *China*

[b)] *Electricity Examination Department, Patent Examination Cooperation Center of the Patent Office, State Intellectual Property Office, Beijing* 100190, *China*

(Received 5 June 2012; revised manuscript received 19 July 2012)

We report the effect of the GaAs spacer layer thickness on the photoluminescence (PL) spectral bandwidth of InAs/GaAs self-assembled quantum dots (QDs). A PL spectral bandwidth of 158 nm is achieved with a five-layer stack of InAs QDs which has a 11-nm thick GaAs spacer layer. We investigate the optical and the structural properties of the multilayer-stacked InAs/GaAs QDs with different GaAs spacer layer thicknesses. The results show that the spacer thickness is a key parameter affecting the multi-stacked InAs/GaAs QDs for wide-spectrum emission.

Keywords: quantum dots, broadband spectrum, superluminescent diode

PACS: 73.21.La, 78.67.Hc, 85.60.Jb **DOI:** 10.1088/1674-1056/21/11/117305

1. Introduction

Broadband light emission from a semiconductor active medium is required in many applications,[1] such as superluminescent diodes (SLDs),[2−9] broadband lasers,[10] semiconductor optical amplifiers (SOAs),[11] and external cavity tunable lasers.[12−15] It has been proposed that the non-uniform size distribution of self-assembled quantum dots (QDs) grown by the Stranski–Krastanow (SK) mode is beneficial in enhancing the spectral width of the device.[16] Some methods, including using double or multiple mode QDs and applying the ground-state and the excited-state transitions simultaneously, have been introduced to expand the full-width-at-half-maximum (FWHM) of the QD luminescence.[17,18] Other methods include using multiple-chirped structures, which focus on changing the matrix surrounding the QDs. The multi-dot-in-well structure with different compositions of indium in different wells has a multi-Gaussian emission characterized by about 50 nm-wide ground state emissions.[19] The gain and the spontaneous emission bandwidth can be enhanced by using a hybrid quantum well (QW)/QD structure.[20] By varying the indium composition of each InGaAs strain-reducing layer (SRL), a ground-state photoluminescence spectral width of 78 nm has been achieved.[21] The broadening of the optical gain spectrum can be achieved with InAs QDs in the AlGaAs matrix.[22] The bandwidths and the intensities of photoluminescence (PL) emission peaks of InAs QDs on GaAs substrates are closely related to the thickness of the thin AlAs layers.[23] By tuning the QD height in the active region, which can be achieved by using the In flush process, ultrawide bandwidth and broadband light emissions may be achieved.[24] Recently, multilayer vertically stacked and electronic state coupled InAs/GaAs quantum dots have attracted considerable attention.[25−27] The combined action of vertical stacking and electronic coupling effect on the PL line width and peak position is notable. The main attention focuses on the peak position shift and for long-wavelength applications.[25] However, for our practical applications, we would like to achieve broadband light emissions using multilayer-stacked QD structures. This is done by modifying the vertical stacking and the electronic coupling, which are altered by changing the thickness of the GaAs spacer layer between the InAs QD layers.[28,29]

In this work, we investigate the optical and structural properties of multilayer-stacked InAs/GaAs QDs

*Project supported by the National Basic Research Program of China (Grant No. 2006CB604904) and the National Natural Science Foundation of China (Grant Nos. 60976057, 61274072, and 60776037).

†Corresponding author. E-mail: pengjin@semi.ac.cn

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with different GaAs spacer layer thicknesses. A photoluminescence spectral bandwidth of 158 nm is achieved from a five-layer stack of self-assembled InAs QDs with an 11-nm thick GaAs spacer layer. The method is very simple and easily controllable to obtain a broadband light emitting. The results prove that the InAs/GaAs QDs can be a very promising active medium for wide-spectrum device applications.

2. Experiments

The experimental samples were grown in a RIBER 32p molecular beam epitaxy (MBE) system with As_2 source. A 200-nm GaAs buffer was first deposited on an Si-doped GaAs (100) substrate at 600 °C. After the substrate temperature cooled down to 510 °C, five periods of 2.0 monolayer (ML) InAs and GaAs spacer layers were grown. Finally, a ∼ 80-nm thick GaAs cap layer was grown at 600 °C. The 8-nm, 11-nm, 15-nm, 20-nm, and 22-nm GaAs spacer layers were grown for samples A, B, C, D, and E, respectively. A single QD-layer reference sample, which had the same growth parameters as the multi-layer samples, was also grown for comparison. The InAs layers were deposited with a growth rate of 0.1 ML/s. After the InAs deposition, a growth interruption of 30 s was introduced. We monitored the transition from two dimensions to three dimensions using the RHEED. The samples were characterized using photoluminescence measurements and transmission electron microscopy (TEM). The PL investigations were carried out at room temperature (RT) using an Ar^+ laser at the wavelength of 514.5 nm, a lock-in amplifier, and an InGaAs photodiode. The TEM analysis was carried out using a JEOL 200 kV JEM-2010 microscope.

3. Results and discussion

Figure 1 shows the $g = (002)$ dark field TEM cross-section images for the five samples. In Fig. 1(a), we can see the perfectly vertically aligned InAs dot columns in sample A. The dots regularly stack on the top of one another in many areas of this sample. In sample B, the dot positions also exhibit good correlation. For the two samples, it is shown that the InAs QDs are much larger in the upper layers, although the same amount of InAs is deposited in each layer. For samples C and D, the positions of the dots exhibit less correlation. For sample E, the dots in different layers do not exhibit any positional correlation. No dislocation is observed in all of the five samples.

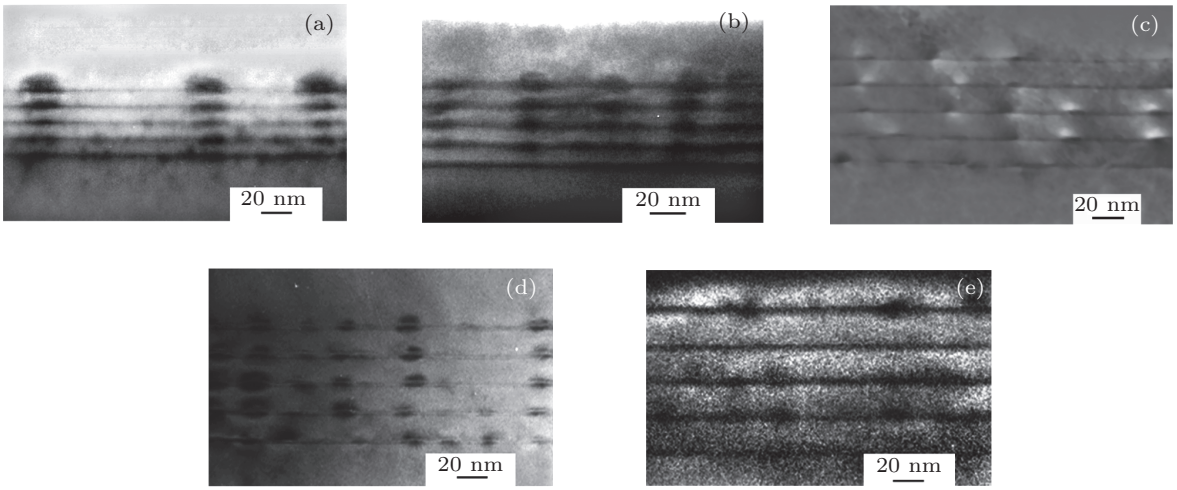


Fig. 1. Dark field ($g = 002$) cross section TEM images of (a) sample A with 8-nm GaAs spacer layers, (b) sample B with 11-nm GaAs spacer layers, (c) sample C with 15-nm GaAs spacer layers, (d) sample D with 20-nm GaAs spacer layers, and (e) sample E with 22-nm GaAs spacer layers.

The increased size for the vertically aligned QDs (samples A and B) can be explained as follows. The vertical alignment of the QDs in the upper layers is caused by the stress coupling of the buried dots in the underlying layer. The thinner the GaAs spacer layer, the more dramatic the coupling effect during the stacking process. Then the critical thickness of the transition from the two-dimensional plane to the three-dimensional islands decreases.[30] The QD density also decreases as the dot layers increase. There-

fore, the InAs QDs in the upper layers are much larger than those in the lower layers, although the same amount of InAs is deposited in each layer.

Figure 2 gives the room temperature PL spectra of the five multi-layer-QD samples and the reference single-layer QD sample. For the sample with a large spacer layer thickness (22 nm for sample E), the PL spectrum is similar in line shape to that of the single-layer reference sample. Moreover, there is a little enhancement in the PL FWHM of sample E compared with that of the single-layer-dot sample. However, when the spacer thickness is decreased, the FWHM of the spectrum is drastically increased. There are two peaks centered at 1.2 μm and 1.16 μm for sample D, 1.25 μm and 1.23 μm for sample C. A 158 nm PL bandwidth with Gaussian shape centered at 1.23 μm is achieved for sample B with a 11-nm GaAs spacer layer. The bandwidths of samples B, C, and D are larger than that of sample E. When the spacer layer is decreased to 8 nm (sample A), the spectrum can be decomposed into three Gaussian peaks. The strongest peak, with an FWHM of 28 eV, is centered at about 1.3 μm (0.95 eV). In comparison to the peak position of the reference sample, which is centered at 1.12 μm (1.1 eV), the spectral peak position red-shifts about 180 nm (160 meV). The PL linewidth and shape strongly depend on the space layer thickness. Moreover, for samples A–D, the PL peaks considerably red-shift as the spacer layer thickness decreases.

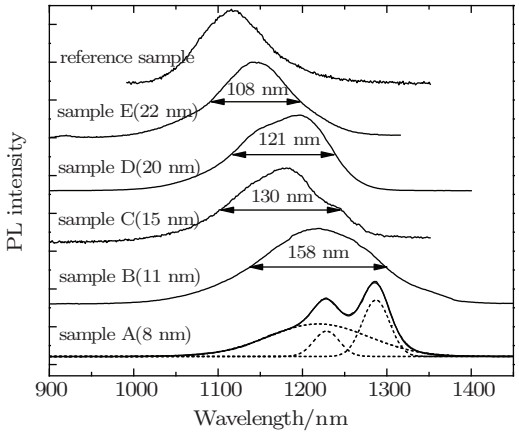


Fig. 2. RT PL spectra of the five-layer-stacked InAs/GaAs QD samples with different spacer layer thicknesses. The PL spectrum of the reference single-QD-layer sample is also shown for comparison.

Figure 3 shows the excitation power dependence of the PL spectrum of sample B at room temperature. A nearly power-independent PL line shape is found. A slight blue-shift as well as a slight spectral broadening is found with the increasing excitation power. It can be explained by the state-filling effect.

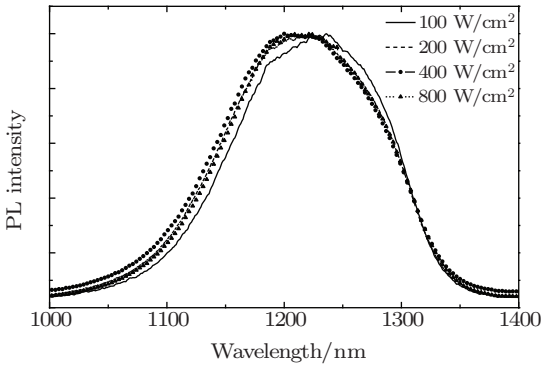


Fig. 3. Excitation power dependent PL spectra of sample B with 11-nm GaAs spacer layers. All the spectra are normalized to give the same maximum intensity.

We attribute the large red-shift of the spectral peaks and the linewidth narrowing to the co-action of the vertical stress coupling and the strong electronic state coupling in sample A, which is also observed in previous researches. The 8-nm GaAs spacer layer is thin enough so that the strong coupling of the energy states occurs within a vertical-aligned QD column. So the lower energy levels of the large QDs in the upper QD sheets contribute to the PL peak narrowing and red-shift. However, the 11-nm thick space layer in sample B seems to prevent sufficient electronic coupling of the QDs in the same vertical-aligned column. But strong stress coupling is still present for sample B. This causes the larger dispersion in the dot uniformity between the different QD layers. The increased spectral linewidth of sample B is derived mainly from the increased size fluctuation of the whole five-layer QDs assembly. In comparison with the reference sample, the PL red-shift of sample B is related to the larger proportion of large QDs in this sample. For samples C and D, as compared with sample B, thicker spacer layers lead to less stress couplings, then the PL FWHMs decrease, and the PL peak red-shifts diminish. We would like to compare our results with the previous reports on the properties of PL linewidth from multilayer-stacked InAs/GaAs QD structures. Generally, 100–120 nm PL FWHMs were obtained at similar wavelengths.[18,21] In this work, the ultrawide light emission is due to the QD size fluctuation from the strong stress coupling and the weak electronic coupling.

4. Conclusion

In conclusion, vertically stacked InAs/GaAs QD structures with varying GaAs spacer thicknesses have been characterized. PL properties are changed by modifying the spacer thickness. We have achieved an ultra-wide (158 nm) PL spectrum with a five-layer stacked QD structure. We present here a potential method to grow large-spectral-width QD materials by proper selection of the spacer thickness for multi-layer stacked self-assembled QDs.

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