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# Photoluminescence and lasing properties of InAs/GaAs quantum dots grown by metal-organic chemical vapour deposition*

Liang Song(梁 松)†, Zhu Hong-Liang(朱洪亮), Pan Jiao-Qing(潘教青), Zhao Ling-Juan(赵玲娟), Wang Lu-Feng(王鲁峰), Zhou Fan(周 帆), Shu Hui-Yun(舒惠云), Bian Jing(边 静), An Xin(安 欣), and Wang Wei(王 圩)

*Key Laboratory of Semiconductor Materials Science, Institute of Semiconductors, Chinese Academy of Sciences, Beijing* 100083, *China*

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Photoluminescence (PL) and lasing properties of InAs/GaAs quantum dots (QDs) with different growth procedures prepared by metalorganic chemical vapour deposition are studied. PL measurements show that the low growth rate QD sample has a larger PL intensity and a narrower PL line width than the high growth rate sample. During rapid thermal annealing, however, the low growth rate sample shows a greater blueshift of PL peak wavelength. This is caused by the larger InAs layer thickness which results from the larger 2–3 dimensional transition critical layer thickness for the QDs in the low-growth-rate sample. A growth technique including growth interruption and in-situ annealing, named indium flush method, is used during the growth of GaAs cap layer, which can flatten the GaAs surface effectively. Though the method results in a blueshift of PL peak wavelength and a broadening of PL line width, it is essential for the fabrication of room temperature working QD lasers.

**Keywords:** metal-organic chemical vapour deposition, InAs/GaAs quantum dots, laser
**PACC:** 7320D, 7280E, 7820

## 1. Introduction

In recent years, there has been considerable interest in the fabrication of self-assembled InAs/GaAs quantum dots (QDs) because of their potential in extending emission wavelength of GaAs-based devices to the important optical-fibre communication wavelengths of 1.3 and 1.55 $\mu$m.[1−4] Due to QD's $\delta$-like density of states, InAs/GaAs 1.3$\mu$m QD lasers grown by molecular beam epitaxy (MBE) have been shown to possess impressive characteristics such as low threshold current[5] and high characteristic temperature.[6] It is known that, compared with QD devices prepared by MBE technique, QD devices grown by metal-organic chemical vapour deposition (MOCVD) have many practical advantages, such as high growth rate in volume production, application to distributed feedback lasers, and optically integrated devices for which selective area growth or regrowth is needed. However, long wavelength QD lasers grown by MOCVD progress slowly and the properties of long wavelength InAs/GaAs QD laser are far worse than QD lasers by MBE.[7] It is relatively difficult to obtain long wavelength MOCVD grown QDs with good material quality due to the defects formed with increasing strain and the complicated surface environment.[8] The MOCVD growth of the InAs/GaAs QDs and their lasers are still challenging and more research works are needed.

In this paper, the effects of MOCVD growth conditions on the optical properties of InAs/GaAs QDs are studied and long wavelength InAs/GaAs QD laser which can work at room temperature under pulse conditions is fabricated.

## 2. Experimental

The samples were grown by MOCVD (8000 Pa) using trimethylgallium (TMGa), trimethylindium (TMIn), arsine ($AsH_3$) and phosphine ($PH_3$) with Pd-

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†E-mail: liangsong@red.semi.ac.cn

diffused $H_2$ as carrier gas. A 200 nm GaAs buffer layer was first grown at 600°C and then the InAs QDs were deposited at 507°C with a V–III ratio of 5. Growth interruptions with (as specified) or without As supply were introduced after the QD deposition. A 2nm InGaAs strain cap layer (SCL) was inserted between the QDs and the GaAs cap layers. The growth conditions of two samples designated as A and B are shown in Table 1. The GaAs cap layers of the samples were grown at 507°C with a thickness and growth rate (Gr) of 80 nm and 10nm/min, respectively. Under the cover of $SiO_2$ grown at 300°C, the QD samples were subjected to rapid thermal annealing (RTA) in nitrogen ambient at temperatures ranging from 650 to 800°C for 40 s. To obtain a flat QD GaAs cap layer, an indium flush method[9] was used, which includes growth interruption and in-situ annealing. After the formation of InAs QDs, they were firstly capped at 495°C by a 2 nm GaAs. Then the wafer was annealed under the protection of $AsH_3$ at 595°C for 300 s, before the growth of the remaining GaAs interlayer. The atomic force microscope (AFM) measurements were performed with a tapping mode in air. The PL measurements were carried out in closed-cycle He cryostat under the excitation of 514.5 nm line of $Ar^+$ laser focused onto a 0.5 $mm^2$ spot. The PL spectra were detected with a Fourier transform infrared spectrometer operating with an InGaAs photodetector.

**Table 1.** Growth conditions of samples A and B. GIT in the table designates growth interruption time.

| | Gr/(ML/s) | InAs (ML) | GIT/s | $In_xGa_{1-x}As$ |
|---|---|---|---|---|
| A | 0.034 | 1.7 | 8(As) | 0.25 |
| B | 0.02 | 2.6 | 30 | 0.18 |

## 3. Results and discussion

Figure 1 shows the room temperature PL spectra of the samples. The emission wavelengths of samples A and B are 1368 and 1369 nm, respectively. Compared with the PL spectrum of sample A with a full width at half maximum (FWHM) of 63 nm, the PL spectrum of sample B has a larger intensity and its line width is as narrow as 40 nm (27 meV). The better optical properties of sample B originate first from the introduction of growth interruption without $AsH_3$ flow. The pause of $AsH_3$ for a few seconds after the QD nucleation allows surface adatoms to migrate from the polycrystalline defect, which leads to the reduction of defect density.[10] Then, lowering the QD growth rate from 0.032ML/s to 0.02ML/s leads to both the decrease of PL line width and the increase of PL intensity.[11]

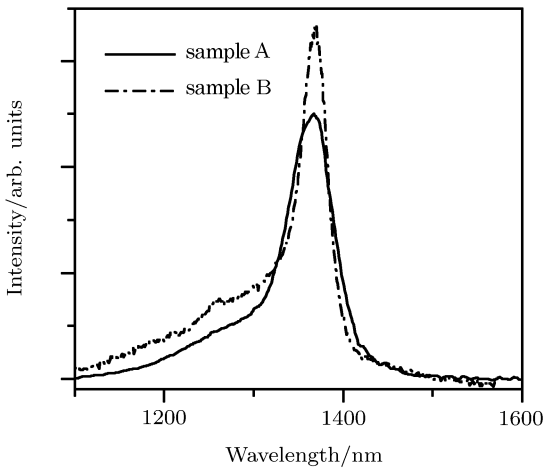



**Fig.1.** Room temperature PL spectra of sample A and B.

Figure 2 shows the RTA temperature dependence of 77 K PL peak wavelength. As can be seen, the emission wavelengths of both the QD samples shift toward shorter wavelengths due to the In/Ga intermixing induced by annealing. As shown in Table 1, the SCL of sample A contains more indium than that of sample B, which would lead to an enhanced QD intermixing and thus more RTA induced wavelength blueshift for sample A than that for sample B.[12] Figure 2 shows, however, the amount of blueshift for sample B is larger than that for sample A. This observation can be considered to be caused by sample B's larger InAs layer thickness which is related to the larger QD 2 dimensional–3 dimensional transition critical layer thickness (CLT) resulting from its low growth rate.

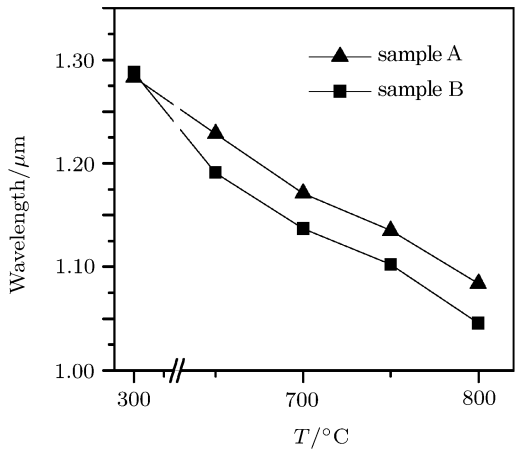



**Fig.2.** RTA temperature dependence of 77K PL peak wavelength.

Figure 3 shows the room temperature PL spectra of QD samples with different InAs layer thicknesses at a growth rate of 0.02ML/s. For comparison, PL spectrum from a 0.034ML/s sample with 1.7ML InAs is also shown. The SCL of the samples is $In_{0.16}Ga_{0.84}As$ with all the other growth conditions being the same as those of samples A. As can be seen, the PL spectrum of the 0.034ML/s sample shows only one narrow peak which is attributed to the well developed QDs. This is a clear contrast to the QDs grown at a deposition rate of 0.02ML/s with other growth conditions unchanged, whose PL has a broad peak centred around 1280 nm with a shoulder at around 1350nm. While the long wavelength shoulder is attributed to the full developed QDs, the shorter peak can be attributed to the many developing QDs which are much smaller and

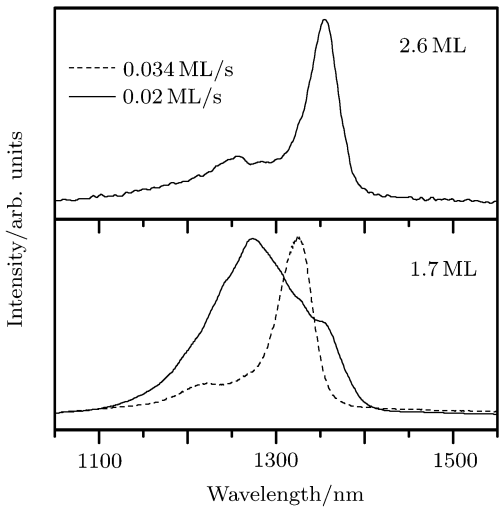



**Fig.3.** Room temperature PL spectra of QD samples with different InAs layer thickness grown at a growth rate of 0.02ML/s. For comparison, PL spectrum from a 0.034ML/s sample with 1.7ML InAs is also shown.

are still accepting the deposited InAs.[13] AFM studies[1] have suggested that the decrease of the InAs growth rate would lead to the increase of CLT. Here with PL measurements, our results show a similar trend, that is, at a lower growth rate more deposited InAs is needed to gain fully developed QDs and high quality PL emission. At the growth rate of 0.02ML/s, the QDs are not fully developed until a layer thickness of 2.4ML as shown in Fig.3. Theoretical studies show that the stress in the QD material system increases with the increase of the coverage of QD material.[14] Due to the larger InAs layer thickness, more stress is accumulated in sample B, which greatly accelerates the blue shift of its PL wavelength during RTA and leads to its larger blueshift of wavelength despite that there is less indium in its SCL. It should be noted that both the low growth rate and the growth interruption without As supply of sample B will lead to the formation of larger QDs.[10,11] This, however, will further solid our discussions above, because the annealing induced wavelength blueshift of large dots is shown to be smaller than that of small dots under the same conditions.[15]

The InAs QDs are usually grown at around 500°C, however, the optimum growth temperature of GaAs is over 600°C. At QD growth temperatures, surface corrugations of the GaAs cap layer are often caused by the underlying QDs (sample B) as shown in Fig.4(a). To obtain flat GaAs cap layer, an indium flush method[9] was used with its effects shown as follows. By the indium flush method, the root mean square (RMS) roughness of the cap layer of a single QD layer being reduced from 2.76 to 0.5 nm (for a $2\mu m \times 2\,\mu m$ region). The room temperature PL spectra of single layer and multi-layer QD samples obtained with indium flush method are shown in Fig.6. The multi layer sample consists of 4 layers of InAs QD layers grown under the same condition as for sample B and separated with each other by a 50nm GaAs interlayer. Compared with the PL spectrum of sample B shown in Fig.1, the peak wavelength of the QD sample grown by using indium flush method is blueshifted to 1320 nm with a FWHM of 84 nm. The effective flattening of the surface of the GaAs cap layer as shown in Fig.4(b) is a result of the enhanced mobility of the GaAs adatoms. The significant broadening of QD PL linewidth is different from the results in Ref.[9] and probably results from the inhomogeneous diffusion of In/Ga during the annealing.[16] Compared with the single layer QD sample, the stacking of QDs has only a little influence on the optical properties of QD materials treated with indium flush method. This means that the material properties of the upper QD layers are not affected by the ones beneath, which is desirable for utilization of device.

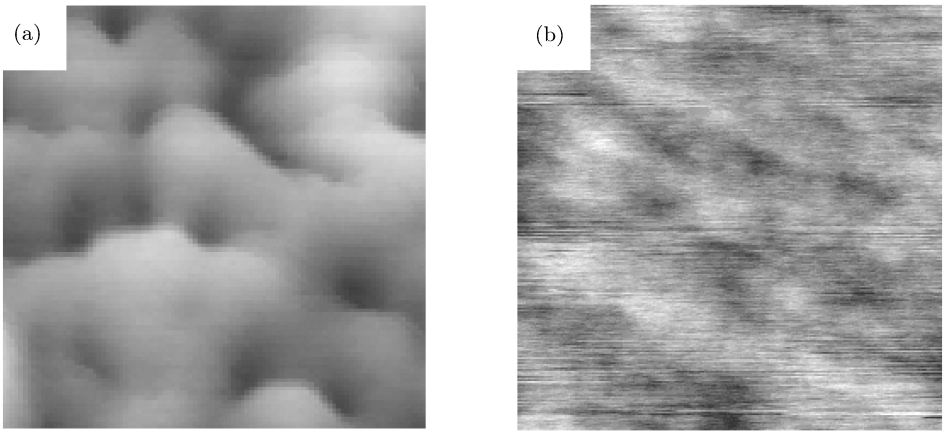



**Fig.4.** The 2$\mu$m×2 $\mu$m AFM images of GaAs cap of a single layer InAs/GaAs QDs grown without (a) and with (b) the use of indium flush method.

Laser structure was grown on an n-GaAs (100) substrate, followed by a 1.2$\mu$m n-InGaP (lattice match to GaAs) lower cladding layer (LCL), the InAs/GaAs active region, a 1.2$\mu$m p-InGaP upper cladding layer (UCL), and a 200 nm $P^+$ GaAs contact layer. Both the LCL and the UCL were grown at 560°C. The active layer obtained was the same as the above multilayer in QDs. The 25-$\mu$m-wide ridge waveguide lasers were fabricated by using standard photolithography and wet chemical etching. Ti/Au and AuGeNi were deposited for the p and n contacts, respectively. The laser was measured under pulsed conditions with a pulse width of 10 $\mu$s and a repetition rate of 1000 Hz.

Despite that the indium flush method can lead to the blueshift and the broadening of PL spectrum, it is essential for the fabrication of MOCVD grown laser structure with multi layer QDs as active material. Figure 6 shows the output power–current ($L-I$) characteristics and the electroluminescence (EL) lasing spectra of a 2 mm long cavity InAs QD lasers with indium flush method used at different temperatures. The threshold current is 213, 800 and 1860 mA for temperatures of 80, 220, and 300 K, respectively. As shown in Fig.6, from 80 to 220 K the lasing wavelength is tuned from 1.16 to 1.22 $\mu$m. Lasing occurs at the wavelength of 1.256 $\mu$m at 300K, which corresponds to the first excited state QD emission, as shown in Fig.5. While QD lasers fabricated using indium flush method can operate at room temperature (300K), the QD lasers grown without using indium flush method can only work at below 150K. The corrugations as shown in Fig.4(a) for the GaAs cap layer surface can seriously degrade the material qualities of stacked QDs. What is more, in QD devices, corrugated interfaces between the GaAs wave guide and the cladding layer will lead to waveguide loss due to scattering. These effects inhibit the lasing of QD laser at high temperatures.

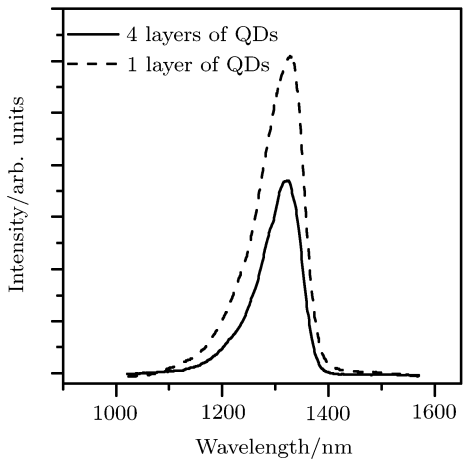



**Fig.5.** Room temperature PL spectra of one layer and four-layer QD samples grown using indium flush method.

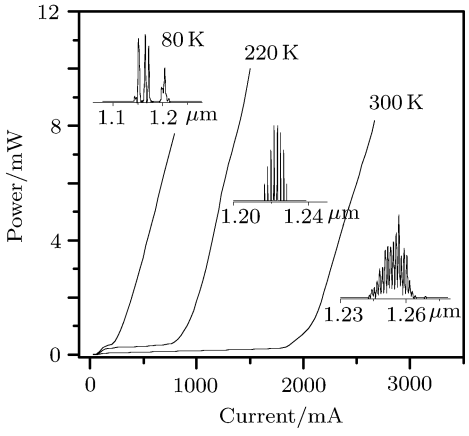



**Fig.6.** $L-I$ characteristics and EL spectra of the InAs/GaAs QD laser under pulsed operation (10 $\mu$s pulse width and 1000 Hz repetition rate). The EL spectrum at each temperature is measured at 1.2 $I_{\rm th}$.

# 4. Conclusion

The influences of different growth procedures in metalorganic chemical vapour deposition on the optical and the lasing properties of InAs/GaAs QDs have been studied. It is found that the low-growth-rate sample has larger PL intensity and narrower PL line width than the high-growth-rate sample. During rapid thermal annealing, the low-growth-rate sample shows greater blueshift of PL wavelength. This is caused by the larger thickness of InAs layer which results from the larger QD 2D–3D transition critical layer thickness of the low-growth-rate sample. The indium flush method can flatten the GaAs surface effectively. Although the method results in a blueshift of PL peak wavelength and a broadening of PL line width, it is essential for the fabrication of QD lasers working at room temperature. Long wavelength InAs/GaAs QD lasers grown using the indium flush method can work at room temperature under pulse condition, while QD lasers without using the method can only work at below 150 K.

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