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1. 3μm InGaAs/ InAs/ GaAs Self-Assembled Quantum Dot Laser Diode Grown by Molecular Beam Epitaxy *

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Abstract: The growth of multi-layer InGaAs/ InAs/ GaAs self-assembled quantum dots (QDs) by molecular beam epitaxy (MBE) is investigated, and a QD laser diode lasing at 1. 33μm in continuous operation mode at room temperature is reported. The full width at half maximum of the band edge emitting peaks of the photoluminescence (PL) spectra at room temperature is less than 35meV for most of the multi-layer QD samples, revealing good, reproducible MBE growth conditions. Moreover, atomic force microscopy images show that the QD surface density can be controlled in the range from 1×10^{10} to $7 \times 10^{10} cm^{-2}$. The best PL properties are obtained at a QD surface density of about $4 \times 10^{10} cm^{-2}$. Edge emitting lasers containing 3 and 5 stacked QD layers as the active layer lasing at room temperature in continuous wave operation mode are reported.

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1 Introduction

InAs quantum dots (QDs) have been intensively studied in recent years because of their promising applications in 1. 3μm QD lasers for fiber-optic communication systems. InAs QD lasers are expected to have superior lasing properties, such as a low threshold current density and a high characteristic temperature, because of their delta-function-like density of states[1]. Thus, they are a promising alternative to commercial InGaAsP-based lasers, which have poor temperature characteristics because of insufficient carrier localization in their quantum wells. In addition, using GaAs substrate for the InAs QDs would make it possible to use AlGaAs alloys as cladding and waveguide layers and fabricate an AlGaAs/ GaAs Brag reflector in a single process at low cost.

In the past few years, much work has been done to improve and exploit the properties of self-assembled InAs QDs grown by molecular beam epitaxy (MBE)[2~7]. The emission wavelength of InAs QDs can be tuned in the 1. 1～1. 7μm region by varying the growth conditions[8,9]. Many high quality InAs QD lasers with low threshold current density and high characteristic temperature have been reported[10].

Although significant improvements in the growth of InAs QDs have been achieved, optical gain is still limited by relatively low dot density, which makes InAs QD lasers hard to lase at the ground state. There are two main effective ways to overcome this problem: one is to increase the QD density by optimising the growth conditions, and the other is to increase the effective number of QDs by using multi-layer QD structures. The InAs QD density has been increased to about $1 \times 10^{10} \sim 1 \times 10^{11} cm^{-2}$ by varying growth conditions[2~7,11]. However, at a high QD density, the QD size is small, and the emitting wavelength tends to be short[2~7,11]. In this paper, we present a detailed study of the growth conditions of InAs QDs by MBE. Relatively long emitting wavelengths of 1. 33～1. 35μm with a high density up to $4 \times 10^{10} cm^{-2}$ are achieved.

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Multi-layer structures are usually adopted to increase optical gain for QD laser devices[11~16]. However, the coupled QDs in the multi-layer structures are usually highly strained. In this work, thick GaAs spacer layers up to 50nm between the QD layers are adopted. We also take an in situ annealing treatment during the growth of the spacer layers to remove defects induced by the high stress. In addition, we have focused extensively on reducing the defects inside the QDs and narrowing the dot size distribution while keeping the density high. The density of the InAs QDs is increased, and the optical properties are improved by optimising growth conditions. InGaAs cap layers are employed to extend the wavelength of the InAs QDs to 1.35μm. High-performance InAs QD edge-emitting lasers lasing at room temperature in continuous wave operation mode are reported.

2 Experiment

The InAs QDs were grown on (001) GaAs substrate in a Veeco Mod Gen Ⅱ MBE system equipped with a reflection high-energy electron-diffraction (RHEED) instrument. The epitaxial structures contain a 300nm GaAs buffer layer, a QD active region, a 50nm GaAs capping layer, and a QD layer on top, which is for atomic force microscopy (AFM) measurement. The QD active region was formed by depositing 1.8~3.5 mono-layer (ML) InAs followed by a thin InGaAs covering layer. The InAs QDs were formed under a repeated growth sequence of a 0.1~0.15ML InAs growth (1~5s) and a 5s As exposure, which is known as the interruption growth mode. The growth interruption was introduced in order for the substrate to reach thermal equilibrium at the desired QD growth temperature. The growth temperatures were 580 ℃ for the buffer and 460~510 ℃ for the QDs and covering layers. A valved As cracker cell was used to supply the As_2 beam. The As/Ⅲ BEP ratio for all the layers was kept between 15 and 20. The transition of InAs growth mode from two to three dimensions was checked by the RHEED.

For laser structures, the QD active region is grown at the center of an undoped GaAs waveguide with n-type lower and p-type upper cladding layers of $Al_{0.5}Ga_{0.5}As$. The Be and Si doping level in the n- and p-type cladding layers is $2\times10^{18}cm^{-3}$. Device fabrication begins with the formation of 20μm ridges with reactive ion etching followed by the plasma-enhanced chemical-vapor deposition of a thin SiO_2 layer. The SiO_2 layer above the ridge is plasma-etched to enable electrical contact. The CrAu p-type contacts are e-beam deposited. Finally, Au-Ge-Ni n-type contacts are e-beam deposited after the substrate has been lapped down to a thickness of about 125μm. The wafer is then cleaved into laser bars with a cavity length of 3mm, without facet coating.

The variable temperature PL spectra were measured using the 632.8nm line of a He-Ne laser and dispersed using a Nicolet FTIR760 Fourier spectrometer. The signal was collected using a cooled Ge detector. The AFM measurements were carried out to study the QD morphology using a NanoScape Ⅲa (Digital Instruments) microscope in contact mode.

3 Results and discussion

3.1 Control of the morphology of the InAs QDs

The AFM images of InAs QDs of samples 1A, 1B, 1C, 1D, 1E, and 1F are shown in Fig. 1. The QDs were formed using the interruption mode at 480 ℃. The InAs deposition amounts for samples 1A~1F were 1.8, 2.2, 2.5, 3.0, 3.0, and 2.2ML, respectively. The InAs deposition rate was 0.1ML/s for samples 1A, 1B, 1C, 1D, and 1F and 0.15ML/s for sample 1E. The InAs QDs were formed under a repeated growth sequence of a 0.1ML InAs growth (1s) and a 5s As exposure for samples 1A~1E and a sequence of a 0.5ML InAs growth (5s) and a 5s As exposure for the sample 1F. For all samples, when 1.8~2.0ML was depo-sited, the RHEED pattern changed from streaky to spotty, indicating that InAs grows in a 3D mode. From the AFM images, it is clear that the QD density increases gradually to a maximum as the amount of InAs deposition increases. But further increasing the InAs deposition could decrease the QD density. For the sample 1A, the amount of InAs deposition lies just at the critical thickness for dot formation. Its QD density is only $7.1\times10^{9}cm^{-2}$. The QD density increases to about $4.2\times10^{10}cm^{-2}$ when the amount of InAs deposition increases to 2.5ML. This high

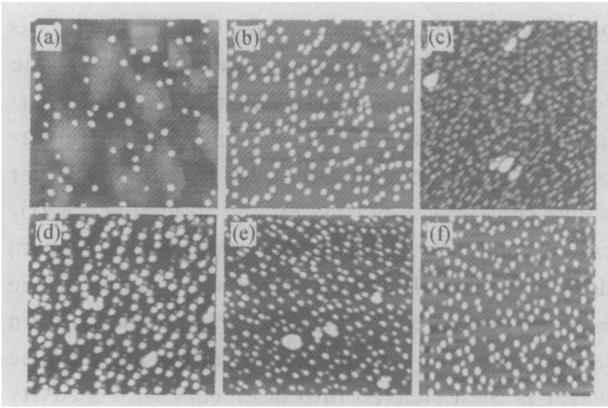

Fig. 1 AFM images (a)～(f) of InAs QDs of samples 1A～1F grown by MBE on GaAs (001) substrate (1μm ×1μm area for all images)

density is favorable for increasing the gain to make the InAs QD lasers lase at the ground state. The average QD diameter and the height of samples 1A, 1B, and 1C are similar, about 45 and 4.5nm, respectively. The distribution of their QDs size is narrow. But the QDs of sample 1D are of bimodal distribution. The average lateral diameter of the large QDs is about 51.3nm, and the height is about 10nm. The average lateral diameter of the small QDs is about 25nm, and the height is about 5nm. For samples 1A, 1B, and 1C, the QD density increases with InAs deposition while the average QD size actually remains constant. This is a little different from the phenomenon observed by Leonard[17] and Kobayashi[18], in which with InAs deposition, the average QD size decreases while the QD density increases, which has been explained in terms of the interaction between QDs and an attachment barrier around the QD edges. The explanation for our case could be that the interaction between the QDs and the attachment barrier around the QD edges prevents the QDs from growing up but is not strong enough to reduce the QD size. As more InAs is deposited, the size distribution of the QDs evolves into a bimodal distribution while the QD density decreases, which is just the case of sample 1D. The reason for this could be that the neighbouring QDs begin to coalesce to reduce the QD density as more InAs is deposited. As a consequence, the effect of the QD interactions is reduced, resulting in an increase in the average size of existing the QDs and formation of new, small QDs. The formation of this bimodal distribution indicates the coexistence of two metastable states and strongly supports the thermodynamic nature of the quantum dot growth[19]. Malachias has shown using X-ray diffraction that the small nanostructures are coherent (strained) and the large nanostructures are incoherent (relaxed)[19]. Since the bimodal distribution and incoherent structure are not favourable for QD lasers, they should be restrained during the growth.

The growth conditions of sample 1E are similar to 1D except for a higher growth rate of 0.15ML/s. In the AFM image of sample 1E, the bimodal distribution is not obvious. The density of the small QDs is low and the size of the large QDs is small compared to sample 1D. This means that a high growth rate could restrain the evolution of the bimodal distribution. A high growth rate could also increase the QD density. As a consequence, the amount of InAs deposition for sample 1E is not enough for the neighbouring QDs to coalesce as in sample 1D.

The amount of InAs deposition per pulse in the interruption mode also affects the morphology of the QDs. Sample 1F was grown in a sequence of a 0.5ML InAs growth (5s) and a 5s As exposure. Its other growth parameters are the same as that of sample 1B. From AFM images, it is clear that its QD density, $2.59\times10^{10}cm^{-2}$, is a lightly higher than that of sample 1B, which is $2.15\times10^{10}cm^{-2}$. Another important growth parameter for InAs QDs is temperature. It is known that the QD density could be increased noticeably by lowering the growth temperature. However, the low temperature could induce defects and poor optical properties, effects which will be discussed later.

3.2 Photoluminescence properties of the InAs QDs

PL spectra for samples 1A～1F are shown in Fig. 2. The InAs QDs of samples 1B～1F are covered with 6nm $In_{0.2}Ga_{0.8}As$, but sample 1A is capped by GaAs directly. From the above morphology studies, the QD size of sample 1A is similar to samples 1B, 1C, 1E, and 1F. But its emitting wavelength is noticeably shorter than the latter ones. This means that the QDs emit at a longer wavelength when the $In_{0.2}Ga_{0.8}As$ cover layer partially reduces the compressive stress and lowers the potential barriers.

The low QD density is subject to saturation of the ground state when excited intensely. Thus the

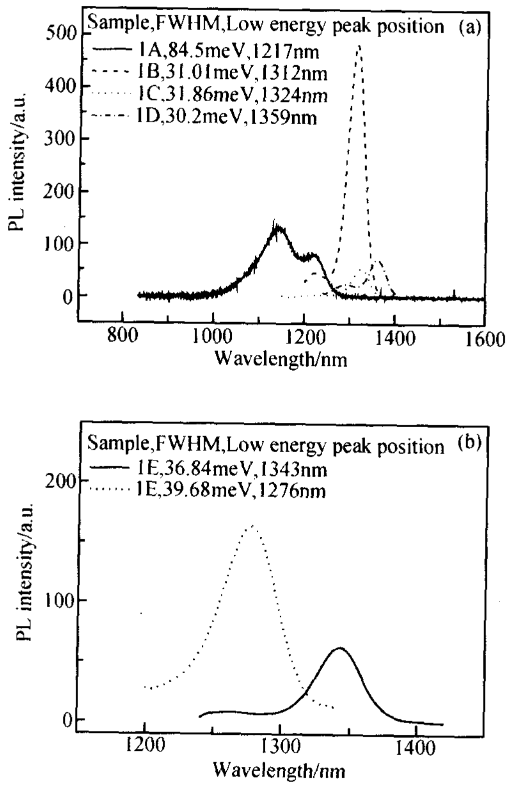

Fig. 2 PL spectra of samples 1A, 1B, 1C, and 1D (a), and 1E and 1F (b) at room temperature with an excitation power of 16mW

relative intensity of the emitting peak from the first excited state is inversely proportional to the QD density when excited with intense light. This is consistent with our case. From Fig. 2, it is clear that the relative peak intensity of the first excited state decreases as the QD density increases for samples 1A, 1B, 1D, and 1C. The peak intensity of the first excited state is even higher than the ground state for sample 1A, due to its very low QD density. For sample 1C, the peak of the first excited state is hard to recognize due to its very high QD density, which is very favourable for laser devices.

Figure 2 shows that the peak intensity of sample 1B is much higher than that of sample 1A. This could be explained by the different QD densities and covering layers between the samples. For the sample with a higher QD density, more QDs contribute to emission when excited with the same intensity. In addition, the $In_{0.2}Ga_{0.8}As$ covering layer could relax the compressive stress of the QDs partially and reduce the formation of the non-radiative defects. As a consequence, the emission intensity of sample 1B should be stronger than that of sample 1A. However, the emission of samples with even higher QD density, such as 1C, 1D, and 1E, is lower than that of sample 1B. This can be explained by the greater number of non-radiative defects formed during the QD growth due to the large compressive stress induced by the higher QD density. The growth conditions of sample 1F are almost the same as that of sample 1B except for the amount of the InAs deposition per interruption. But Figure 2 (b) shows that its emission is much shorter than sample 1B. A possible explanation for this could be that the substrate could not reach thermal equilibrium during the continuous deposition of the InAs in this case. The amount of InAs deposition per interruption also affects the PL pro-perties. As shown in Fig. 2(b), sample 1E shows a slight blue shift compared to the sample 1D due to the larger amount of InAs deposition per interruption.

The temperature dependence of the PL emission of sample 1C was investigated under the excitation power of 16mW from 8.3 to 300K, as shown in Fig. 3. To better illustrate the PL properties, we plot the temperature dependencies of the peak position, intensity, and FWHM of the low energy peak in Figs. 3(b)～(c). Up to 80K, the energy peak position shifts to a low energy monotonically. At about 100K, an anomalous decrease was observed. We explain this behaviour as being caused by a thermally activated electron transfer from the small dots to the larger ones. The temperature dependence of the FWHM of the peak better illustrates this behaviour, as shown in Fig. 3(c). We observe an anomalous decrease of the FWHM around 100K due to the thermally activated electron transfer.

In many previous reports, S-type curves were observed in the temperature dependent PL spectra of the InAs QDs[20～23]. The S-type curve at low temperatures is usually related to the high carrier localization inside the QDs. It is hard to observe the S-type curve in Fig. 3. This indicates that the density of the carrier localization inside the QDs in sample 1C is low, revealing a good MBE growth condition.

3.3 Properties of the InAs QD edge emitting lasers

From the above discussion, we know that sample 1C has a high QD density and good PL proper-

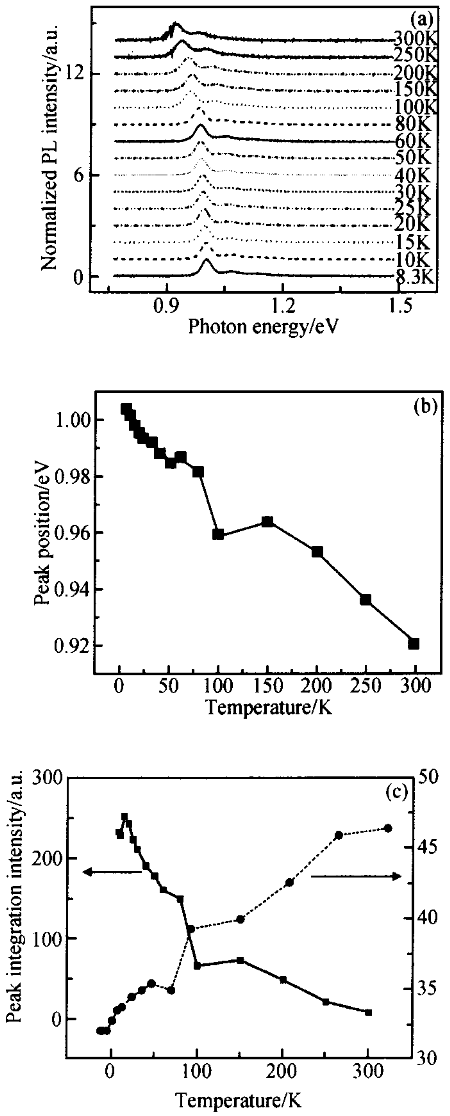

Fig. 3 Temperature dependent PL spectra of sample 1C with an excitation power of 16mW (a) Normalized intensity; (b) Peak position; (c) Integration intensity and FWHM of the low energy peak

ties for laser devices. Although the QD density has been increased to $4.2 \times 10^{10} cm^{-2}$ for sample 1C, it is still too low for the InAs QD lasers to lase at the ground state. We overcome this problem by increasing the effective number of QDs using multi-layer QD structures. Five layers of InAs QDs were grown with 50nm GaAs layers as barriers. The GaAs barriers are thick enough to decouple the neighbouring QD layers. The barriers were annealed during growth to eliminate non-radiative defects.

Figure 4 (a) shows the laser spectrum of an InAs QD laser with a 3mm-long cavity in continuous wave mode at room temperature. The lasing wavelength is 1.33μm, confirming that the device lases at the ground state. Our wavelength is comparable to the best reported RT CW quantum dot laser at 1.33μm with a much lower threshold current density of $19A/cm^2$[21]. Figure 4(b) shows the light output characteristics and bias voltage versus current of the laser. The threshold current and threshold current density are about 150mA and $250A/cm^2$, respectively. The average external differential quantum efficiency, η_{ext}, can be extracted from the slope of the L-I curve. The value is about 21.6%. The results indicate that the structure of the multi-layer of QDs separated by the annealed GaAs spacer layers prevents gain saturation, allowing us to achieve a long-wavelength laser operating at the ground state.

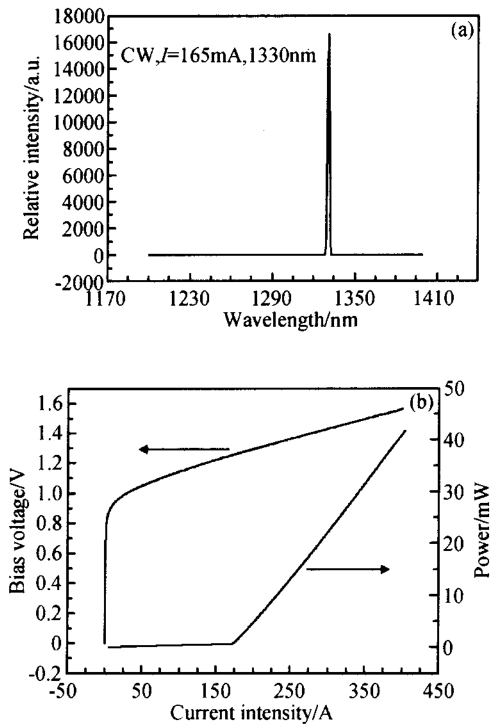

Fig. 4 (a) Laser spectrum of a 3mm-cavity-length InAs QD laser operating in CW mode measured at room temperature; (b) Light output characteristics and bias voltage versus current of the lasers

4 Conclusion

We have successfully grown multi-layer InGaAs/InAs/GaAs self-assembled quantum dot laser diodes emitting at 1.3μm. The morphology and surface density of the InAs QDs can be controlled by the MBE growth parameters. The QD layer, with a surface density of around (3～4) $\times 10^{10}$ cm^{-2}, shows good PL properties. The effects of QD morphology on PL properties are discussed; no S-type curve appeared in the temperature dependent PL spectra (from 8. 3 to 300 K), indicating that the density of the carrier localization inside the QDs is low. The edge emitting lasers containing 5 layers of QDs and lasing at room temperature in continuous wave operation mode are achieved.

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1.3μm 自组织 InGaAs/InAs/GaAs 量子点激光器分子束外延生长*

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摘要：报道了分子束外延生长的 1.3μm 多层 InGaAs/InAs/GaAs 自组织量子点及其室温连续激射激光器. 室温带边发射峰的半高宽小于 35meV，表明量子点大小比较均匀. 原子力显微镜图像显示，量子点密度可以控制在 $(1\sim7)\times10^{10}cm^{-2}$ 范围之内，而面密度处于 $4\times10^{10}cm^{-2}$ 时有良好的光致发光谱性能. 含有三到五层 1.3μm 量子点的激光器成功实现了室温连续激射.

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