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Multiple quantum wells and laser structures containing InAs quantum dots grown by molecular-beam epitaxy

Chin-An Chang[a,*], Cheng-Zu Wu[a], Pai-Yong Wang[a], Xing-Jian Guo[a], Yi-Tsuo Wu[a], Chiu-Yueh Liang[a], Fei-Chang Hwang[a], Wen-Chang Jiang[a], Ferng-Jye Lay[a], Li-Wei Sung[b], Hao-Hsiung Lin[b]

[a] *Opto-Electronics & Systems Laboratories, Industrial Technology Research Institute, Hsinchu, Taiwan, Republic of China*
[b] *Department of Electrical Engineering, National Taiwan University, Taipei, Taiwan, Republic of China*

Abstract

InAs quantum dots were formed by depositing monolayers of InAs on GaAs, covered with InGaAs, and flanged with GaAs barriers. This formed a single quantum well in the present study, as grown by molecular-beam epitaxy. Both multiple quantum wells (MQW) and lasers containing such layers were studied. For the MQW structure, the InAs layer thickness affected both the wavelength and intensity of the photoluminescence measured. With increasing InAs thickness, the wavelength changed from about 1.0 to 1.3 μm, with an increasing photoluminescence intensity. The dot size also depended on the InAs layer thickness, ranging from 5 to 20 nm as analyzed by cross-sectional transmission electron microscopy. The photoluminescence intensity showed different dependence on n- and p-dopants, being reduced by the Si doping, but enhanced by the Be-doping. Pulsed lasing at room temperature was observed for the broad area laser fabricated, with a threshold current density of 2 kA cm^{-2}, at an emission wavelength of 1.06 μm. The effect of growth conditions on the lasing characteristics is also discussed. © 2001 Published by Elsevier Science B.V.

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1. Introduction

Materials with decreased dimension, or increased quantization, have been shown to be advantageous to lasers due to the reduced temperature sensitivity. Among such materials, the quantum dot has been of special interest ever since its proposal for such an application [1]. Research on quantum dot structures has since been active worldwide. One application is the long wavelength laser for optical communication. Reports in this area included growth, photoluminescence, electroluminescence, and lasers at wavelength near 1.3 μm [2–6]. To further realize the potential of quantum dots for laser application, the fundamental properties of quantum dots need to be fully explored. These include, the origin of luminescence, factors that affect the emission properties, and growth conditions that control size and distribution of dots for narrow laser linewidth.

In this paper, we report the growth by molecular-beam epitaxy (MBE) of multiple quantum wells (MQW) and laser structures containing InAs

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*Corresponding author.
E-mail address: changca@itri.org.tw (C.-A. Chang).

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quantum dots. Each quantum well consisted of monolayers of InAs covered with InGaAs, with GaAs forming the barrier layers. The photoluminescence of MQW was studied for its dependence on the InAs thickness and doping. Broad area lasers containing similar quantum wells were processed to study their lasing characteristics. The effect of growth conditions on the quality and emission wavelength of the lasers grown was also explored.

2. Experiment and results

Structures containing InAs quantum dots were grown by MBE using the Riber Epineat system. Two structures containing InAs quantum dots were studied, MQW and lasers. The schematics of the MQW and laser studied are shown in Fig. 1. Each quantum well consisted of monolayers of InAs covered with $In_{0.15}Ga_{0.85}As$ to form the wells, with GaAs as the barriers. The thickness of the individual layer was: 0.38–1.3 nm for InAs, 5 nm for $In_{0.15}Ga_{0.85}As$, and 50 nm for GaAs. The MQW structures contained ten quantum wells of the above composition while the laser structures contained three such quantum wells. The MBE growth proceeded as follows: A GaAs buffer layer of 200 nm thickness was first grown on the epi-ready GaAs wafers to smooth out the surface, followed by the growth of MQW structures and another GaAs cap layer of 200 nm thickness. The samples were analyzed by X-ray diffraction, photoluminescence and transmission electron microscopy. The laser structures contained, in addition, bottom and top cladding layers of AlGaAs, doped to n- and p-type using Si and Be, respectively, to mid-$10^{18}\,cm^{-3}$, with similarly doped GaAs bottom and top layers for contact purposes. Broad area lasers with a cavity length of 700 μm and varying widths were processed and fabricated, and their electrical and optical properties analyzed.

The photoluminescence spectra of several MQW structures are shown in Fig. 2, for three InAs thicknesses: 0.38, 0.58 and 0.76 nm. The sample with the thinnest InAs layer has an emission peak less than 1.0 μm. That is close to the emission wavelength of $In_{0.15}Ga_{0.85}As$ [7]. The other two structures have an emission at much longer wavelengths. Fig. 3 shows the bright field cross-sectional transmission electron micrographic (TEM) pattern of the MQW structure containing a 0.76 nm InAs layer. Clearly resolved images with strain field are manifested in areas around the quantum dots that consist of both InAs and the covering InGaAs layer. The high-resolution TEM image revealed dots with a horizontal dimension

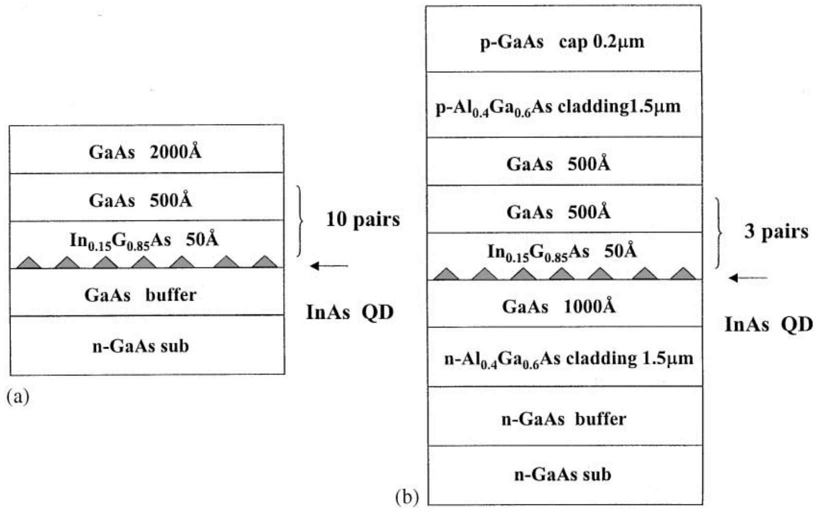

Fig. 1. Schematics of (a) multiple quantum wells, and (b) laser containing InAs quantum dots.

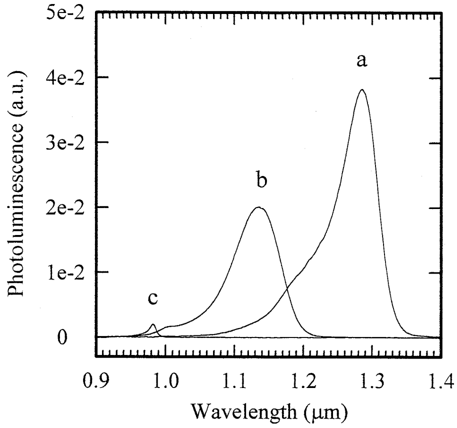

Fig. 2. Photoluminescence spectra of multiple quantum wells containing InAs of different thickness. (a) 0.76 nm InAs, (b) 0.58 nm InAs, and (c) 0.38 nm InAs. Both emission wavelength and intensity show strong dependence on the InAs layer thickness in the wells.

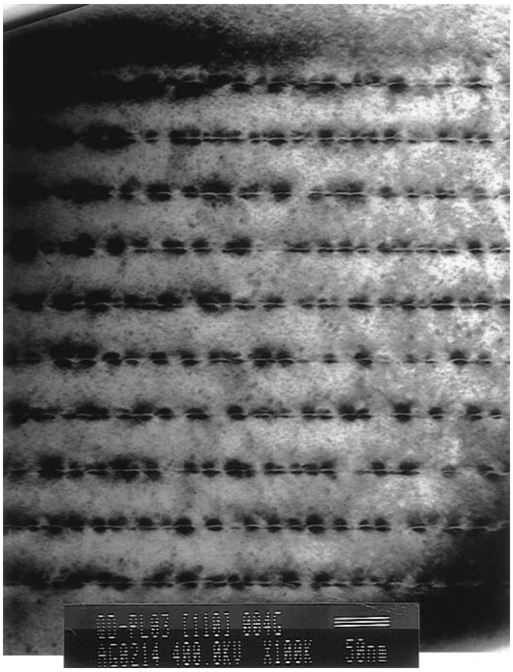

Fig. 3. Bright-field cross-sectional transmission electron micrograph of multiple quantum wells containing 0.76 nm InAs layer. Contrast due to strain shows the dot formation.

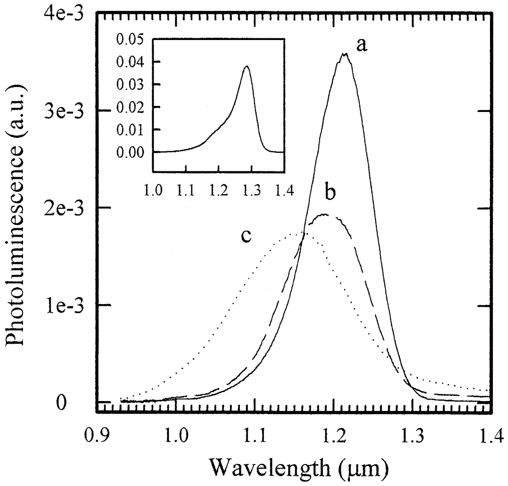

Fig. 4. Effect of Si-doping on the photoluminescence intensity of multiple quantum wells containing InAs quantum dots. (a) $1 \times 10^{16}\,\mathrm{cm}^{-3}$, (b) $1 \times 10^{17}\,\mathrm{cm}^{-3}$, (c) $1 \times 10^{18}\,\mathrm{cm}^{-3}$, and (inset) undoped sample.

of 15–20 nm and vertical dimension of about 5 nm. The periodic structure of the MQW is highly reproducible as the TEM graphs show. X-ray diffraction analysis of such structures also showed numerous satellite peaks with narrow half width, a further proof of the successful fabrication of the highly repeatable periodic structure grown.

The effect of doping of the wells on the photoluminescence intensity of the MQW structures was studied using Si and Be for n- and p-doping, respectively. Doping with Si resulted in significantly reduced photoluminescence intensity with increased dopant concentration, as shown in Fig. 4. Be-doping, on the other hand, led to increased photoluminescence intensity at dopant concentration up to $10^{17}\,\mathrm{cm}^{-3}$, and reduced intensity at higher dopant concentration. This is shown in Fig. 5. The results on doping will be discussed later.

For the laser structures, the same growth conditions were used for the MQW region and the two neighboring GaAs layers as those for the MQW structures shown above. The AlGaAs cladding layers were grown at higher temperatures around 700°C to achieve a better crystalline quality for an enhanced optical confinement. The thickness for the n- and p-GaAs layer was 0.2 μm, doped to mid-$10^{18}\,\mathrm{cm}^{-3}$ with Si and Be, respectively. The thickness for the n- and p-$\mathrm{Al}_{0.15}$-$\mathrm{Ga}_{0.85}\mathrm{As}$ cladding layers was 1.5 μm, also doped to mid-$10^{18}\,\mathrm{cm}^{-3}$ with Si and Be, respectively.

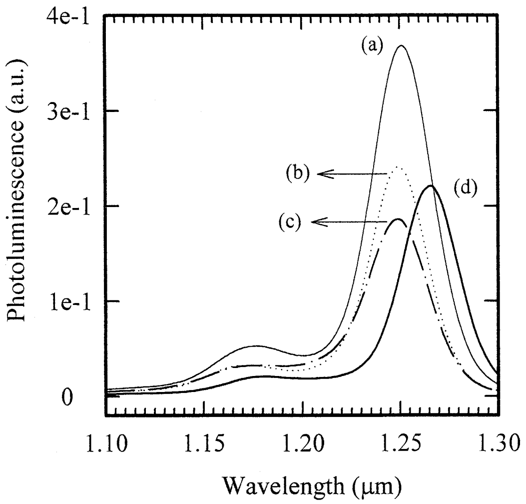

Fig. 5. Effect of Be-doping on the photoluminescence intensity of multiple quantum wells containing InAs quantum dots. (a) $5\times10^{16}\,\mathrm{cm}^{-3}$, (b) $1\times10^{17}\,\mathrm{cm}^{-3}$, (c) $1\times10^{18}\,\mathrm{cm}^{-3}$, and (d) undoped sample.

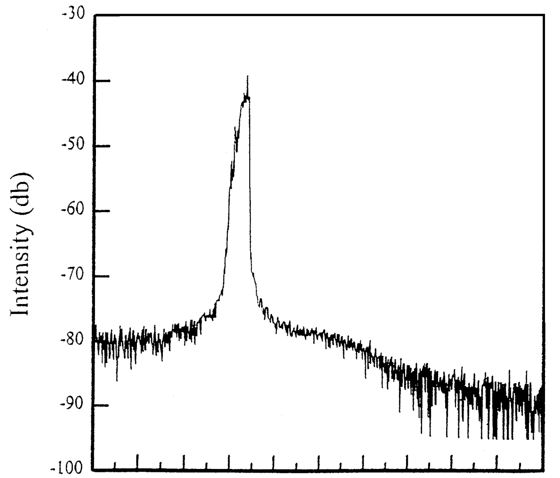

Fig. 6. Emission spectrum of a laser with pulsed lasing at room temperature, showing the blue shift in wavelength due to the growth of AlGaAs cladding layers at high temperature.

The $I-V$ characteristic showed a forward turn-on voltage of 1.08 V and a low reverse leakage current. The electroluminescence of the same structure had a peak wavelength of 1.06–1.07 μm. Fig. 6 shows the lasing spectrum of one such laser.

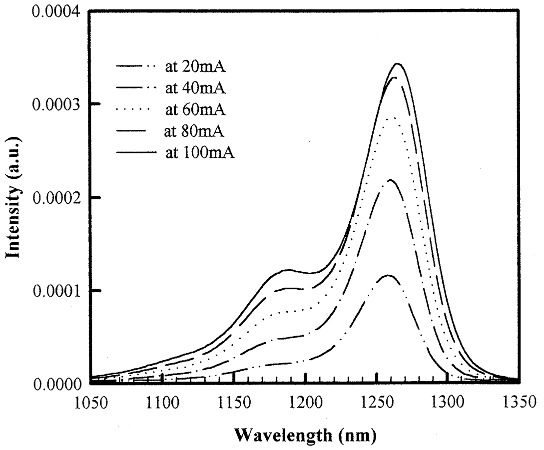

Fig. 7. Electroluminescence spectra of a homojunction laser without the high temperature grown cladding layers. Changes in injection currents allowed the ground and excited states to be explored.

The wavelength is shorter than the photoluminescence wavelength of identical MQW layers reported above. This is attributed to changes of the InAs quantum dots due to the high temperature annealing during the growth of the top AlGaAs cladding layer. To prove this point, a homojunction laser structure containing similar MQW layers without the AlGaAs cladding layers was also grown and its electroluminescence measured. The electroluminescence spectra at different injection currents are shown in Fig. 7. The electroluminescence had peaks near 1.28 μm, similar to the photoluminescence of the same laser structure and that of the MQW structure shown in Fig. 2. Both the ground and excited states were resolved in these spectra, with different responses to current changes. The excited state continued to increase in intensity at higher currents while the ground state became saturated. A detailed analysis of the relative changes in intensity with currents between the two states is underway, and will be reported at a later date.

For the laser structures with the AlGaAs cladding layers grown at high temperatures, it is interesting to note that, although the peak wavelength was blue shifted, the electroluminescence intensity was much higher than the homojunction structures. This indicated an enhanced optical confinement by the AlGaAs cladding layers that was vital to the successful fabrication of lasers. The broad area laser thus processed showed pulsed lasing at room temperature. The threshold current measured was 690 mA, corresponding to a threshold current density of 2 kA cm^{-2}, with an internal quantum efficiency of 40%.

3. Discussion

We have grown MQW and laser structures containing InAs quantum dots and studied their optical and electrical properties. Changes in structures, doping, and growth conditions were employed to study the effect on both the wavelength and intensity of the photoluminescence and electroluminescence of such structures. The observed pulsed lasing at room temperature was an encouraging sign of the quality of the quantum dots grown.

It was noted that different thicknesses of InAs led to the formation of quantum dots of different sizes, as revealed by our TEM analysis. Using monolayers of InAs and 5 nm $In_{0.15}Ga_{0.85}As$ for the wells in the MQW structure, the formation of dots with a photoluminescence wavelength longer than that of $In_{0.15}Ga_{0.85}As$ required an InAs layer of thickness greater than 0.38 nm. The photoluminescence spectrum of the sample containing 0.38 nm InAs layer differed from those of the samples with thicker InAs layers. The emission wavelength was the shortest among all the structures studied here. The observed emission at 0.98 μm was close to that of $In_{0.15}Ga_{0.85}As$ [7]. From the TEM analysis of this sample, the dots formed had smaller sizes than those in samples with thicker InAs layers. Based on the photoluminescence wavelength observed for this sample, the dots formed apparently had properties very different from those in the structures with thicker InAs layers. Using in situ reflection high-energy electron diffraction (RHEED) during the growth, a streaky RHEED pattern was observed throughout the growth of the wells and barriers for the structure with 0.38 nm InAs layer. The structure with 0.76 nm InAs layer, however, showed spotty RHEED pattern at the end of the deposition of InAs. The RHEED and TEM results thus showed a region with elastic strain in the wells for the structure with 0.38 nm InAs layer. With a thicker InAs layer, however, the strain was relaxed, resulting in a three-dimensional growth that was responsible for the dot formation. Thus, the RHEED and TEM analyses provided valuable information regarding the onset of InAs dot formation in the MQW structures studied here. The presence of $In_{0.15}Ga_{0.85}As$ in the wells also contributed to a very weak photoluminescence peak near 1.0 μm for the MQW structures containing 0.58 and 0.76 nm InAs layers.

The different effects of n- and p-doping on the photoluminescence intensity of the MQW layers grown are interesting. A rapidly reduced intensity was observed using Si doping in the range of low-10^{16} to mid-10^{18} cm^{-3}. A similar effect was also reported by other workers [8]. Be-doping, on the other hand, increased the photoluminescence intensity in the range of mid-10^{16} to mid-10^{17} cm^{-3} before reducing it at higher dopant concentration. The dopant effect could be related to the filling of the defects in the InAs-InGaAs dots that were caused by the large lattice mismatch with the GaAs barriers. The mismatch is 7% between InAs and GaAs, with a much smaller one of 1% between $In_{0.15}Ga_{0.85}As$ and GaAs. Be, being smaller in size than Si, is likely to fit in the defects better than Si, resulting in the improved photoluminescence intensity observed. Further studies are in progress to understand the relation between the doping and photoluminescence of the MQW structures.

Laser structures containing InAs quantum dots allowed several properties to be explored. When the top cladding layers were removed by etching, the same photoluminescence intensity as those of MQW structures was observed. This confirmed that the property of the quantum dots in the MQW was preserved in the growth of the laser structures without the annealing effect mentioned before. The comparison between electroluminescence and photoluminescence then allowed an evaluation of the laser structures fabricated. In general, similar wavelengths were observed for the laser structures containing MQW layers grown at the same temperatures. This served to check the integrity of the laser structures with additional GaAs and AlGaAs layers doped to different levels.

When the cladding AlGaAs layers were grown at a higher temperature than normally used for the MQW layers, both the photoluminescence and electroluminescence spectra shifted to shorter wavelengths. Mixing of InAs with the InGaAs matrix, and mixing of the original dots into the GaAs barrier layer can both lead to a blue shift of the photoluminescence wavelength. In the present study, the growth of AlGaAs cladding layers at high temperatures resulted in a much enhanced intensity of the electroluminescence regardless of the shift to shorter wavelength. This indicated an effective optical confinement in the lasers grown. The observed pulsed lasing at room temperature thus served to indicate good optical and electrical qualities of the multiple quantum wells grown.

4. Summary

InAs quantum dots were grown into multiple quantum well structures for the purpose of making quantum dot lasers. A minimal layer thickness of more than 0.38 nm InAs was found necessary for the formation of InAs quantum dots with a photoluminescence wavelength beyond that of $In_{0.15}Ga_{0.85}As$, when the quantum wells consisted of InAs and $In_{0.15}Ga_{0.85}As$ with barriers being GaAs. The photoluminescence intensity increased rapidly with increasing InAs thickness, with the emission shifting toward longer wavelength also. Doping of the quantum wells resulted in different effects on the photoluminescence intensity. A reduced intensity was observed on using Si, while an enhanced intensity was seen on using Be. Possible filling of the defects by dopants is suggested, with the different effects seen attributed to the size difference of the two dopants.

Lasers employing MQW layers of InAs quantum dots showed pulsed lasing at room temperature. The emission was shifted to a shorter wavelength due to the thermal annealing of quantum dots during the high temperature growth of the AlGaAs cladding layers. Work is in progress to make lasers with an emission near 1.3 μm for use in optical communication.

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