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Lasing Oscillation of Vertical Microcavity Quantum Dot Lasers

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Abstract: We achieved lasing oscillation in a vertical microcavity quantum dot laser at 77 K for the first time by an optical pumping. The λ-microcavity ($\lambda = 985$ nm) consists of an InGaAs quantum dot layer formed by the Stranski-Krastanow growth mode and GaAs layers, located between two $AlAs/Al_{0.2}Ga_{0.8}As$ distributed Bragg reflector mirrors. The lasing oscillation was obtained at the energy corresponding to the lowest subband of the quantum dots.

1. Introduction

Since the utilization of quantum dots as an active layer of a semiconductor laser promises significant improvements of lasing characteristics[1,2], various activities have been devoted to the fabrication of quantum dot (QD) structures. These include selective growth technique, self-assembling growth technique, and etching technique[3-6]. In particular, recent progress of the self-assembling technique with the Stranski-Krastanow (SK) growth mode for fabricating the QDs is remarkable. A few trials for the lasing from InGaAs quantum dot Fabry-Perot type laser structures have been already investigated.[13,14] On the other hand, the microcavity structures are also expected to substantially reduce the threshold current owing to the control of the spontaneous emission.[7-11]. The control of both electron modes and photon modes in confined structures should play an important role in the optical devices for future communication systems. Therefore, the fabrication of a microcavity laser with an active layer of the nanostructures is a substantial step towards meeting those demands. [12]

In this paper, we report the first fabrication of a vertical microcavity quantum dot laser with lasing oscillation at 77 K. The InGaAs quantum dots were grown by the SK growth mode with the Metal Organic Chemical Vapor Deposition (MOCVD). We achieved the lasing oscillation at the first subband of the quantum dots by tuning the resonant wavelength of the microcavity to the corresponding photon energy.

2. Fabrication Procedure

The device structure was grown by the MOCVD growth technique, which was carried out on a GaAs substrate in a low-pressure (76 torr) horizontal quartz reactor. The total gas flow rate was 9 liter/min. using hydrogen as a carrier gas. Arsine (AsH3), trimethylgarllium (TMG), trimethylalminium (TMA) and trimethylindium (TMI) were used as source materials. The details of the technique for growing the self-assembling quantum dots by the SK growth mode

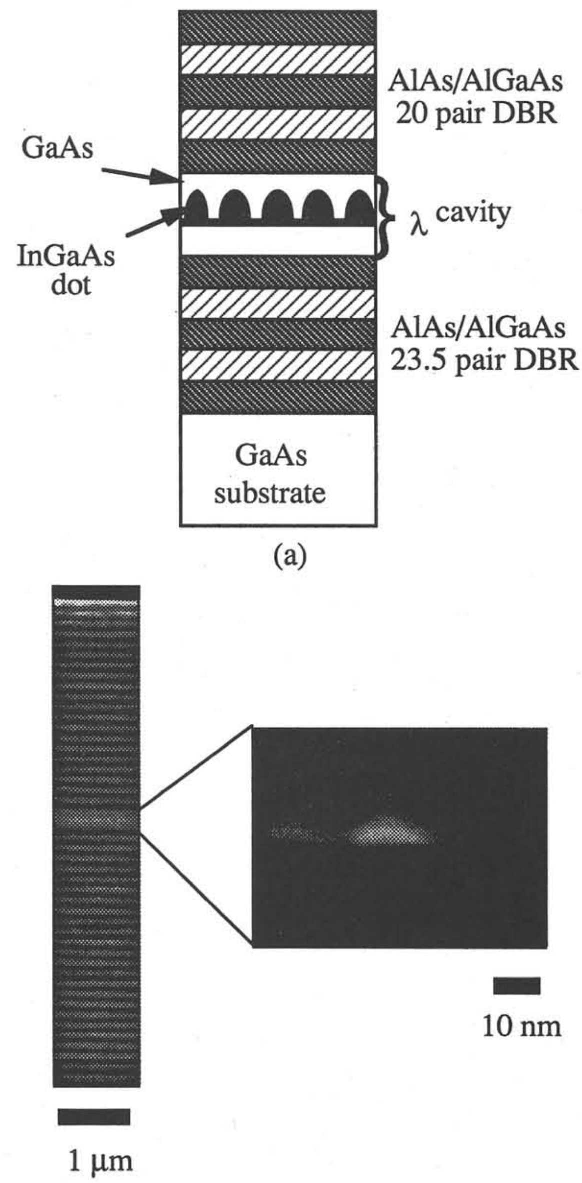

Fig. 1: Schematic illustration (a) and SEM image (b) of a laser structure. The active layer, consisting of InGaAs quantum dots, is embedded in a spacer layer. This structure is sandwiched between $Al_{0.2}Ga_{0.8}As$/ AlAs distributed Bragg reflectors.

was described elsewhere[5]. Figure 1 shows schematic illustration and cross sectional SEM image of the laser structure. The microcavity consists of an InGaAs quantum dot layer sandwiched by GaAs layers, located between two $AlAs/Al_{0.2}Ga_{0.8}As$ distributed Bragg-reflector (DBR) mirrors. The number of layer pairs is 20 in the upper mirror and 23.5 in the lower one. The partial pressure of AsH_3, TMG, and TMA were $2.2x10^{-4}$, $8.8x10^{-6}$, and $2.2x10^{-6}$ atm, respectively, for the growth of $Al_{0.2}Ga_{0.8}As$. The growth temperature was 700 °C.

InGaAs QDs were embedded in GaAs at the antinode of the cavity. When growth of the first GaAs layer in the cavity was started, the growth temperature was gradually decreased from 700 °C to 500 °C. Then the InGaAs quantum dots was formed by the SK growth mode at 500 °C. After the deposition of the InGaAs was finished, the growth was interrupted for 10 min. and the temperature was simultaneously lowered to 450 °C. The upper GaAs cap layer was grown while raising the growth temperature from 450 °C to 700 °C so that the sample's surface becomes smooth. It should be noted that the problem with the fabrication of the quantum dot structures with a cap layer in the SK growth mode is to obtain smooth cap layer surfaces. The increase of the temperature leads to enhanced diffusion of the material and therefore allows for a smoothing out of the structure. However, the enhanced diffusion also leads to a degradation of the QDs and to an associated degradation of the optical characteristics. In order to maintain both the structure of the QDs and obtain a smooth cap layer surface, the GaAs upper layers started to be grown at a low temperature of 450 °C, and then the temperature was gradually increased up to 700 °C at which the upper DBR mirror was grown.

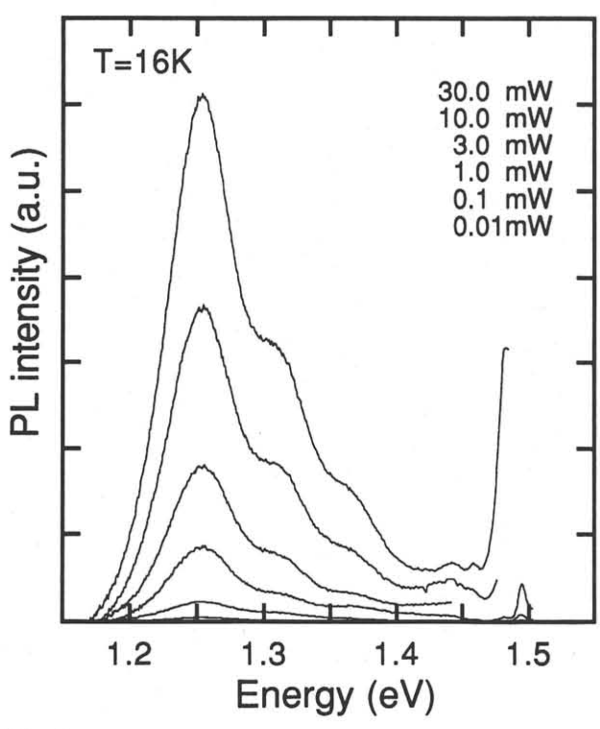

Fig. 2 : PL spectra of quantum dots without DBR mirrors

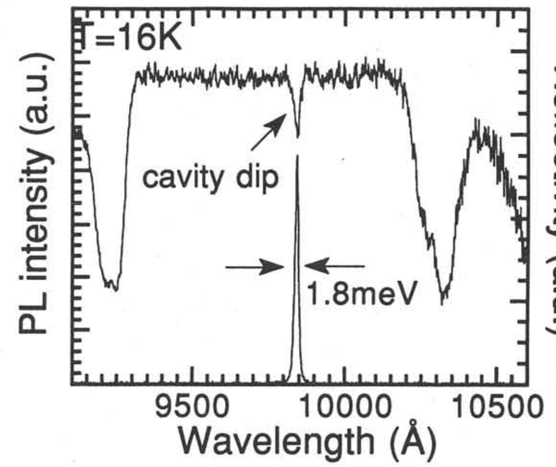

Fig. 3: The upper curve shows the reflectivity spectrum of a microcavity. It displays a 90 nm wide stop band. The narrowing of the PL emission peak in the lower curve clearly indicates the cavity effect.

3. Optical and Lasing Properties

In order to investigate optical properties of the QDs, we first measured PL from QDs without the DBR mirrors using He-Ne laser with a wavelength of 632.8 nm. Figure 2 shows the photoluminescence (PL) spectrum of quantum dots without the DBR mirrors. At low excitation intensity a single PL peak appears at 1.255eV (988 nm), while with the increase of the excitation power other peaks also appear at 1.315 eV (943 nm) and 1.365 eV (908 nm). These peaks can be attributed to higher subbands of the QDs. This excitation-intensity dependence of the PL spectra clearly indicates existence of the quantum dot effect.

Optical properties of the vertical microcavity quantum dot laser structure was measured by an optical pumping at 77 K. The resonance energy of the microcavity structures was tuned to coincide with the ground state of the PL peak. To measure the reflection characteristics of the cavity structures, an external source of collimated white light was used. This light was superimposed on the laser beam, using a beam splitter. Figure 3 shows spectra of both the reflected white light of a cavity structure and PL. The reflectivity spectrum displays a 90 nm wide stop band. The asymmetry of the spectrum is probably due to the wavelength dependence of the response characteristics of the measurement systems. Since the wavelength of the pumping laser light corresponds to a energy lower than that of the band gaps of the used GaAs and AlGaAs, no serious losses occur in the DBR structures. The cavity resonance was tuned to the PL peak of the lowest subband of the quantum dot structures. It should be noted that the lasing wavelength was clamped at this wavelength owing to the cavity effect even when higher subbands are excited. As shown in the diagram, a sharp PL linewidth with a full width at half maximum (FWHM) of less then 1.8 meV

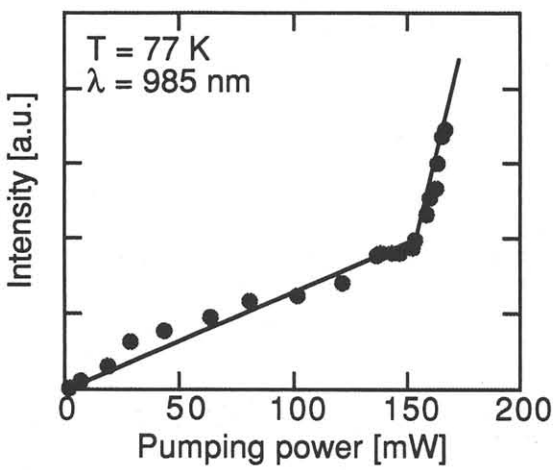

Fig. 4: Lasing oscillation of vertical microcavity quantum dot laser by an optical pumping method.

was observed. By comparing spectral broadening with and without the DBR structures, the cavity effect was clearly demonstrated.

The vertical microcavity quantum dot laser was operated by a optical pumping method at 77 K. The light input-output characteristics was shown in Fig.4, which indicates the lasing oscillation. We believe this is the first demonstration of quantum dot laser at the first subband energy level.

4. conclusion

We demonstrate the fabrication of microcavity structures with an active layer of quantum dots grown with the SK growth mode by MOCVD. Measurement of the PL clearly shows excitation-intensity dependence of the PL spectra, which can be attributed higher subband effects of the QDs. Lasing oscillation at 77 K in a vertical microcavity quantum dot laser by an optical pumping was observed at the lowest subband for the first time.

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