Electrical Lasing in GaAs Quantum Dots Grown by Droplet Epitaxy

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Abstract: We have demonstrated electrically injected lasing in GaAs quantum dot grown by droplet epitaxy. High-quality QDs with superior uniformity were produced by employing improved growth procedures.

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1. Introduction

Quantum dot (QD) lasers have many advantages compared to existing solid-state lasers, such as high-speed modulation, low-threshold current, and high-temperature characteristics. GaAs/AlGaAs QDs emitting in the wavelength range of 600-800 nm are an attractive candidate for QD lasers for on-chip optical interconnect applications. To achieve the lasing, uniformly sized QDs with high density and high quality are desirable. So far, photopumped laser action was reported for GaAs quantum rings on (001) substrates and GaAs QDs on (311)A substrates [1,2]. The former improved the size uniformity using low As pressure, while the latter realized high density of 10^{11} cm^{-2} with good uniformity on (311)A. However, no electrically pumped lasing has been observed yet.

Here, we report electrically pumped laser action of self-assembled GaAs/AlGaAs QDs grown on (001) substrates by droplet epitaxy. High-quality GaAs QDs were fabricated by thin AlGaAs capping and subsequent *in-situ* annealing [3]. High-temperature annealing also flattened the top of the QDs, resulting in the formation of height-controlled QDs. Furthermore, a GaAs two-dimensional layer (2DL) of 2 nm was introduced to effectively enhance the dot volume as well as relieve the dot height fluctuations. All these improved growth techniques lead to electrically injected lasing in GaAs QDs.

2. Experimental

Samples were grown on GaAs(001) substrates by molecular beam epitaxy. The growth of high-quality GaAs QDs consists of several steps: insertion of an artificial wetting layer, control of As flux for GaAs crystallization, and thin AlGaAs capping with high-temperature annealing. The effectiveness of each of these processes is discussed later. First, a 100-nm AlGaAs buffer layer was deposited at a substrate temperature of 580°C. Next, a 2-nm GaAs layer was grown at 580°C as a two-dimensional layer before the formation of QDs. Then, droplet epitaxy of GaAs QDs was performed at 200°C. Five monolayers (MLs) of Ga were deposited to form Ga droplets at 0.5 ML s^{-1}, followed by crystallization into GaAs by irradiating As_4 flux of 5×10^{-5} Torr. Subsequently, the QDs were annealed at 400°C for 10 min under As_4 flux of 1×10^{-5} Torr without capping. The QDs were then covered with a 2-nm AlGaAs layer, and annealing was performed again at 640°C for 5 min. Finally, the QDs were capped with a 50-nm AlGaAs and a 10-nm GaAs coat. The surface morphology of the uncapped QDs was studied by atomic force microscopy (AFM). Photoluminescence (PL) spectra of the samples were taken at 6 K, using the 532-nm line of a frequency-doubled Nd:YAG laser. The PL signals were dispersed by a monochromator and detected by means of a cooled Si charge-coupled device array.

The laser structure was grown on an *n*-GaAs(001) substrate. The active layer contained fivefold stacked GaAs QD layers separated by 16-nm $Al_{0.3}Ga_{0.7}As$ barriers, which were embedded in a 200-nm $Al_{0.3}Ga_{0.7}As$ layer for separate confinement. The bottom and top cladding layers were 1300-nm n-$Al_{0.6}Ga_{0.4}As$ and 1300-nm p-$Al_{0.6}Ga_{0.4}As$ with a 100-nm p^+-GaAs contact, respectively. All separate-confinement and cladding layers were grown at 1 ML s^{-1} at 580°C. Once the entire growth sequence was completed, rapid thermal annealing (750°C, 4 min) was performed under N_2 ambient in order to improve the optical quality.

3. Results and discussion

Figure 1(a) shows a schematic illustration of a QD structure. Uniform-height-controlled QDs coupled with a 2DL were formed to achieve ultra-narrow emission. The controllability of a 2DL is one of the notable features of droplet epitaxy [4,5]. In the lattice-matched GaAs/AlGaAs system, we can grow a GaAs quantum well (QW) of arbitrary thickness. If we insert a GaAs QW below GaAs QDs, the QW can work as an artificial wetting layer for the QDs. This is in stark contrast to the SK QDs, in which the thickness of a wetting layer is fixed due to the strain balance. The additional 2DL has three main benefits for improving the optical quality of QDs. The first is the superior height uniformity of QDs. Since the 2DL thickness can be controlled within ML precision, the fluctuation in the total height of the coupled QD structure becomes small. The second is the improved dot quality. Possible degradation of crystal quality during low-temperature processes for the crystallization of droplets has been an issue in droplet epitaxy. In contrast, the 2DL grown at high temperature is of high quality, and thus raises the quality of the whole structure. The third benefit is the improved efficiency of capturing carriers into QDs due to the sufficient 2DL thickness.

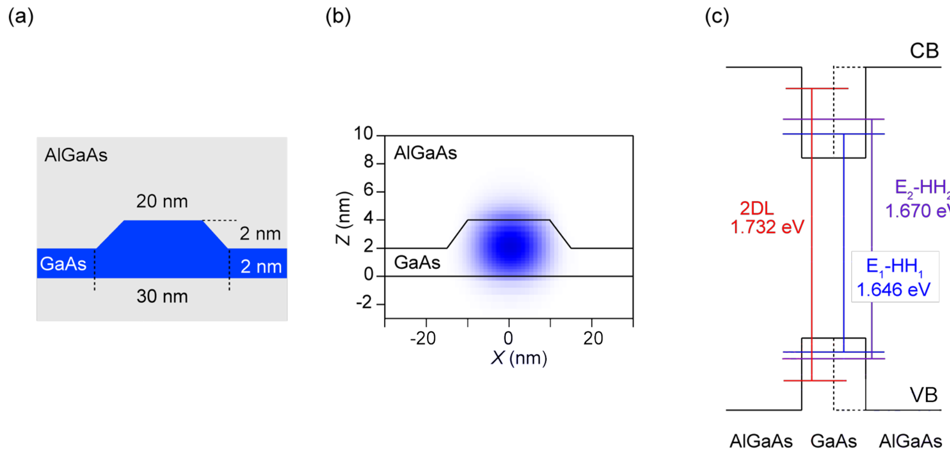

Fig. 1. (a) Schematic illustration of a QD coupled with a 2DL. (b) Electron probability density for the ground state of a QD. (c) Schematic band diagram of a QD structure. Solid (dotted) lines denote the potentials for a QD (2DL). Calculated transition energies for the ground state (E_1-HH_1) and the first excited state (E_2-HH_2) of the QD are shown along with that for the 2DL.

The coupled dot structure retains zero-dimensionality even when the 2DL thickness is comparable to the dot height: wavefunctions are localized within the dot, with the discrete density of states. To illustrate the zero-dimensionality of the coupled dot structure, we calculated the electronic states of the dot using nextnano[3], the device simulator which solves the Poisson-Shrödinger equation in terms of a finite difference method [23]. For the calculation we assume the QD has rotational symmetry along the growth (z) axis, and the composition of $Al_xGa_{1-x}As$ barrier was set to $x = 0.3$. Figure 1(b) shows the electron probability density for the ground state of the QD structure in Fig. 1(a). The localization of electrons within the dot region can be clearly seen. In Fig. 1(c), we show the band diagram of the QD along with the relevant transition energies. The transition energies of the ground and first excited state are 1.646 eV (753 nm) and 1.670 eV (742 nm), respectively. The energy difference of 24 meV between the ground and first excited state is only slightly smaller than that of 30 meV for the QD without a 2DL, indicating that the density of states remains discrete after introducing the 2DL.

The next step in the formation of high-quality QDs is the control of As_4 flux. In droplet epitaxy, the shape and size of GaAs QDs significantly depend on the As_4 flux for crystallizing Ga droplets. Specifically, the formation of monomodal QDs requires the supply of an intense As_4 flux of ~2×10^{-4} Torr on (001) substrates. However, quick crystallization of droplets under such a high As_4 flux causes large fluctuations in the dot size as well as the degradation of QDs. If we decrease the As_4 flux to slowly crystallize droplets, a morphological change from monomodal to ring-shaped QDs occurs simultaneously. To overcome this trade-off, Ga droplets were first crystallized under a moderate As_4 flux, and subsequently annealed without capping. Initially formed QDs are of double-dot shape due to the enhanced Ga diffusion under moderate As_4 flux. The peaks of these QDs, however, are susceptible to thermal annealing, and monomodal QDs with flat tops are obtained by uncapped annealing. Thus, standard (monomodal) QDs with good quality are obtained by using a moderate As_4 flux combined with uncapped annealing in droplet epitaxy.

The final step in the formation of highly uniform QDs is to perform thin AlGaAs capping followed by high-temperature annealing. Recently, we have reported the formation of height-controlled QDs using thin capping with high-temperature annealing [3]. In this process, annealing at 640°C on AlGaAs-capped QDs induces the redistribution of the dot apices, leading to the formation of QDs whose heights are controlled by the thickness of the AlGaAs capping layer. In the current study, the thickness of the AlGaAs layer was set to 2 nm so that the total dot height became 4 nm, as shown in Fig. 1(a).

As a result of the improved growth techniques, ultra-narrow emission from highly uniform QDs is achieved. Figure 2 shows a low-temperature PL spectrum of height-controlled QDs coupled with a WL. For reference, PL from *normal* QDs is also shown. The top spectrum shows the emission from GaAs QDs crystallized at 200°C and As_4 flux of 2×10^{-4} Torr. As mentioned above, large fluctuations caused by a high As_4 flux result in broad QD emission with the full width at half maximum (FWHM) of 157 meV. By decreasing the As flux to 5×10^{-5} Torr, the size uniformity improves and the FWHM is lowered to 67 meV (middle spectrum), which is still broad for laser applications. In contrast, PL from the height-controlled QDs coupled with a 2DL (bottom spectrum) shows ultra-narrow emission with the FWHM of 20 meV. The emission peak at 754 nm is very close to the calculated transition energy of 753 nm for the ground state, illustrating the formation of highly uniform QDs as designed.

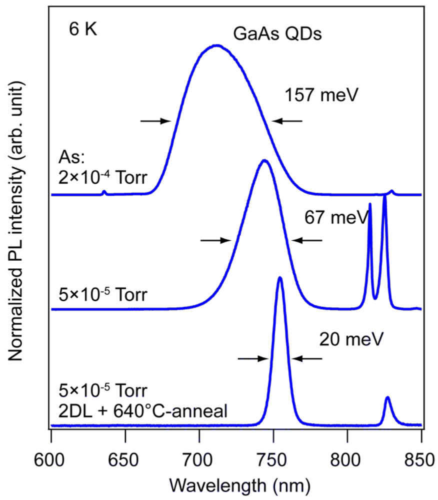

Fig. 2 6-K normalized PL spectra of GaAs QDs: (Top) 3.75 MLs of Ga crystallized under an As_4 flux of 2×10^{-4} Torr, (Middle) 5 MLs of Ga crystallized at 5×10^{-5} Torr, (Bottom) 5 MLs of Ga crystallized on a 2-nm GaAs 2DL at 5×10^{-5} Torr, followed by annealing at 640°C with a 2-nm AlGaAs cap. Ga droplets were formed and crystallized at 200°C for all samples. FWHM of each emission are 157, 67, and 20 meV, respectively.

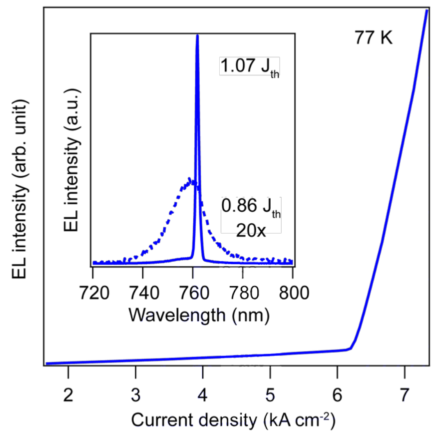

Fig. 3 *L-I* characteristics of the laser. The threshold current density is 6.2 kA cm^{-2}. The inset shows EL spectra of a GaAs QD laser diode under pulsed operation (0.02% duty cycle, pulse width of 0.2 µs) at 77 K.

Finally, a broad contact laser diode was fabricated employing high-quality and highly uniform QDs. The cavity length was 1500 µm with a stripe width of 10 µm, and both cleaved facets were uncoated. Figure 3 shows electroluminescence (EL) spectra for different current densities under pulsed operation (0.02% duty cycle, pulse width of 0.2 µs) at 77 K. For current densities lower than 6.2 kA cm^{-2}, the EL shows a relatively narrow spontaneous emission at 760 nm. At 6.2 kA cm^{-2}, a stimulated emission peak appears on top of the spontaneous EL peak. The lasing occurs at the wavelength of 761 nm, which is close to the spontaneous emission peak, indicating the high uniformity of the QDs. The light output versus current (*L-I*) characteristics of the QD laser yield the threshold current density of 6.2 kA cm^{-2} at 77 K.

4. Summary

We have reported the growth and fabrication of a GaAs/AlGaAs QD laser diode on GaAs(001) substrates grown by droplet epitaxy. High-quality QDs with superior uniformity were produced by employing improved growth procedures: insertion of a two-dimensional layer, control of As flux for GaAs crystallization, and thin AlGaAs capping with high-temperature annealing. Under pulsed excitation at 77 K, ground-state lasing with J_{th} = 6.2 kA cm^{-2} was observed for a GaAs/AlGaAs QD laser diode containing fivefold stacked QD layers.

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