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Compact microdisk cavity laser with type-II GaSb/GaAs quantum dots

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Microdisk lasers with active region made of type-II GaSb/GaAs quantum dots on the GaAs substrate have been demonstrated. A microdisk cavity with diameter of 3.9 μm was fabricated from a 225-nm-thick GaAs layer filled with GaSb quantum dots. Lasing at wavelengths near 1000 nm at 150 K was achieved for this microdisk. A high threshold characteristic temperature of 77 K was also observed. It is found that the lasing wavelength matches closely with the first-order whispering-gallery mode of the cavity as obtained from the finite-element method simulation. © *2011 American Institute of Physics*. [doi:10.1063/1.3543839]

In recent years, the GaSb/GaAs quantum dot (QD) structures have attracted great interest due to their type-II band alignment and intrinsically different properties compared to the well known InAs/GaAs QD system.[1–3] There are several studies of the type-II GaSb/GaAs QDs for understanding their optical properties and carrier dynamics.[4–6] The type-II band alignment accommodates spatially indirect transitions in which the interface properties will drastically influence the optical and electrical properties. Meanwhile, the type-II band-alignment heterojunctions have been widely studied for semiconductor lasers,[7–9] memories,[10,11] and light emitting diodes.[12,13] Besides the emission at the near-infrared or mid-infrared regimes, the light sources with type-II QDs might also have advantages in photon stability, thermal stability, and an extra parameter to fine tune wavelength.[8] These advantages will benefit many applications such as optical integrated circuits, flexible optoelectronics,[14] or bioimage.[15]

In this study, we demonstrated a compact microdisk cavity laser[16] made of type-II GaSb/GaAs QDs on GaAs substrate. The GaSb/GaAs QD epitaxial wafer was prepared for optical emission around 1 μm wavelength. Microdisk cavities were fabricated in the GaSb/GaAs QD membrane by electron-beam lithography and several etching steps. The observed blueshift in photoluminescence (PL) spectrum is one of the key characteristics and indications for type-II QD heterostructure.[6,12,17] The lasing action was obtained from a 3.9 μm diameter microdisk with a low threshold. The high quality factor first-order whispering-gallery lasing mode was verified with three-dimensional finite-element method (FEM) simulation.

The microdisk cavities were fabricated from a 225-nm-thick GaSb/GaAs QD layer. This GaSb/GaAs QD layer contains three monolayer thick GaSb QD sublayers separated by GaAs barriers, which forms the active region for the QD heterostructure laser. Figure 1(a) shows the layer structures of the GaSb/GaAs QD epiwafer. The first half of the wafer includes 2.0-μm-thick AlGaAs layer grown by metal-organic chemical vapor deposition, followed by the active GaSb/GaAs QD region grown by molecular beam epitaxy. Figure 1(b) shows the atomic force microscopy surface image of the GaSb/GaAs QD layer prior to encapsulation by GaAs. The area density of GaSb QDs is around 4.53×10^{10} cm^{-2}.

For fabrication of microdisk cavities on the wafer, a silicon nitride (SiN_x) layer and a polymethylmethacrylate layer are deposited for the dry etching processes and electron-beam lithography. The microdisk patterns were defined by electron-beam lithography followed by two dry etching steps with CHF_3/O_2 mixture and $Ar/SiCl_4$ mixture gas in the inductive couple plasma system. From the suspended membrane structure, the $Al_{0.6}Ga_{0.4}As$ sacrificed layer was removed by HF solution with $HF:H_2O=1:1$. Figure 2(a) shows the scanning electron microscopy (SEM) image of a microdisk cavity with diameter of 3.9 μm and Fig. 2(b) shows the angle view.

The microdisk cavities were then optically pumped in the cryostat by using an 850 nm wavelength diode laser at normal incidence with a 1.5% duty cycle and a 30 ns pulse width. The pump beam was focused on the devices by a 100× objective lens. The pumped beam spot size is approximately 2 μm in diameter. The output power from the lasers was collected by a multimode fiber connected to an optical spectrum analyzer.

Before measuring the optical properties of microdisk cavities, the PL from the GaSb/GaAs QD wafer was first characterized. Figure 3(a) shows the PL spectrum from QD wafer under different incident pump powers. The PL spectra show good optical response form the GaSb/GaAs QD wafer for the wavelength region from 950 to 1100 nm. Three main peaks were observed. They could correspond to lowest unoccupied molecular orbital–highest occupied molecular orbital emissions from QDs of different sizes or from emis-

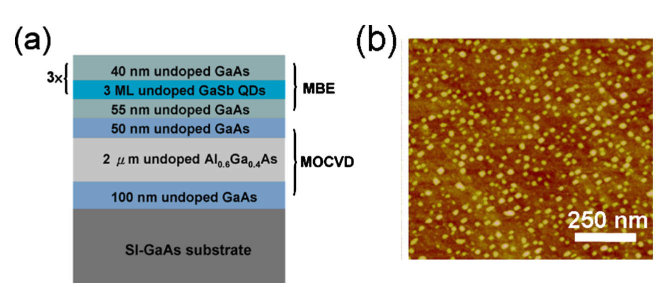

FIG. 1. (Color online) (a) The illustration of a layer structure with the GaSb/GaAs QD epiwafer and (b) the atomic force microscopy image of the GaSb/GaAs QD epiwafer.

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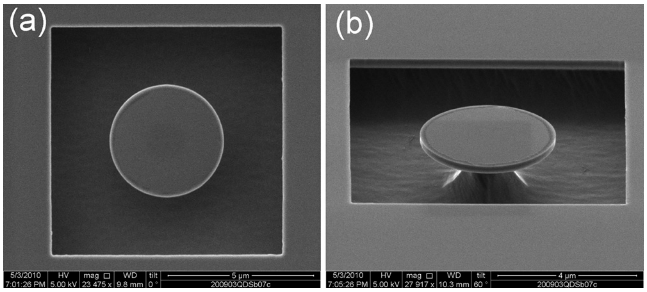

FIG. 2. The SEM image of a microdisk cavity with a diameter of 3.9 μm. (a) Top view and (b) angle view.

sions involving excited states of QDs (which are populated at high pump power). The emission associated with the GaSb wetting layer was observed for other samples and it is much weaker than the QD emissions shown here. The PL spectrum also shows a blueshift as the pump power increases, which is one of the key characteristics of type-II gain material, which had been studied widely.[17–19] Time-resolved PL spectra characterization is our current work, and we will investigate more details of carrier dynamics in the type-II QD system.[19–21] The peak position for the principal PL peak of this QD wafer versus the pump power density is shown in Fig. 3(b). As shown in Fig. 3(b), the principal PL peak is shifted from 1.2424 to 1.2523 eV with increasing pump power density. The black curve in Fig. 3(b) is a fitting curve based on the following relation: (PL peak energy) $=1.299\,12+0.000\,23$ (power density)$^{1/3}$. This relation between energy and power density can be explained by the band bending effect due to excited carriers and had been reported.[6,17] We obtained a good agreement between fitting curve and measured results.

The lasing action of the microdisk cavities was observed during the characterization. The blue curve in Fig. 4(a) illustrates the lasing spectrum from a microdisk laser with 3.9 μm diameter at 150 K temperature. The lasing peak appears at a wavelength of 968.2 nm. The light-in-light-out (L-L) characteristics of this laser are shown with a red curve in Fig. 4(b). It was found that the laser has a low threshold power of 450 pJ/pulse. The linewidths of the lasing mode at various pump powers are also marked with blue circles in Fig. 4(b). A linewidth narrowing was observed as the incident pump power increases, confirming the lasing action from the GaSb/GaAs QD microdisk. The quality factor of the microdisk cavity is approximately 5300, which was estimated from the ratio of resonant peak wavelength to linewidth at transparence (i.e., $Q \sim \lambda/\Delta\lambda$). The temperature dependence in lasing threshold was also studied. The device

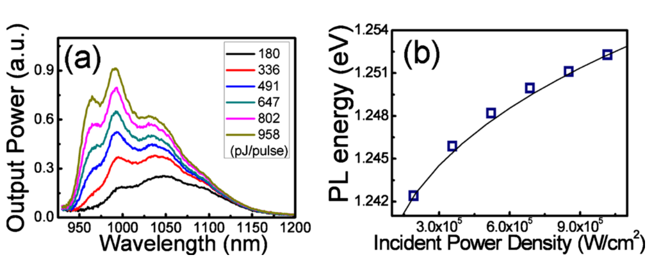

FIG. 3. (Color online) (a) The PL spectrum from the GaSb/GaAs QD layer on a GaAs substrate with different incident pump powers at temperature of 150 K. (b) The measured PL peak energy (squares) and the fitting curve for PL peak energy with a cube-root dependence of the power density.

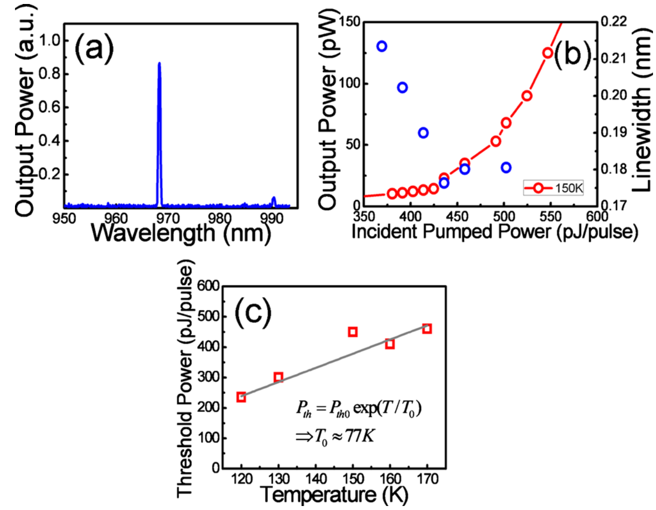

FIG. 4. (Color online) (a) The lasing spectrum from a microdisk laser at 150 K and its lasing wavelength is 968.2 nm. (b) The L-L curve, the linewidth (circles) of the laser, and its threshold behavior were observed at an incident power of 450 pJ/pulse. (c) The measured threshold power of the GaSb QD microdisk laser at different temperatures.

was characterized at different temperatures under similar pumping conditions. Figure 4(c) shows the threshold power versus operating temperature. The threshold power of the microdisk laser rises from 235 to 465 pJ/pulse as the temperature increases form 120 to 170 K. The temperature dependence of lasing threshold (I_{th}) can be described the empirical form,

$$I_{th}(T) = I_{th}(T_0)e^{(-T/T_0)}, \quad (1)$$

where T_0 is the characteristic temperature of threshold for the laser. By fitting experimental data to this formula, we obtained a threshold characteristic temperature of 77 K for the GaSb QD microdisk laser. This value is higher than reported values for similar-size lasers made of InGaAsP quantum wells[22] and InAs QDs.[23] A high threshold characteristic temperature indicates high thermal stability of this microdisk laser, which is one of the advantages of the Type-II QD lasers.

In order to understand the optical mode of this microdisk cavity, the three-dimensional FEM was used to perform the simulation for the 3.9 μm microdisk. A whispering-gallery mode (WGM) was observed at 961 nm in the FEM simulation, which is close to the lasing mode observed at 968.2 nm from the measurement. Figure 5 shows the simulated H_z mode profile for the lasing mode: (a) top view and (b) cross-section view. The results indicate the behavior of the first-order WGM lasing mode in the microdisk cavity. The small wavelength shift ($<1\%$) between simulation and measurement is attributed to the imperfection of fabrication. Another WGM resonant mode was also observed at 991 nm wavelength in the lasing spectrum of Fig. 4(a). Other modes were not observed because they are outside the strong optical gain region of GaSb/GaAs QDs.

In summary, a GaSb/GaAs QD microdisk laser with 3.9 μm diameter has been demonstrated. The high-Q microdisk cavity was fabricated in a 225-nm-thick type-II GaSb/GaAs QD layer on the GaAs substrate. The blueshift in PL peak with increasing pump power was observed for the type-II QD structure. The lasing at 968.2 nm wavelength with a low threshold was achieved at 150 K. The resonance

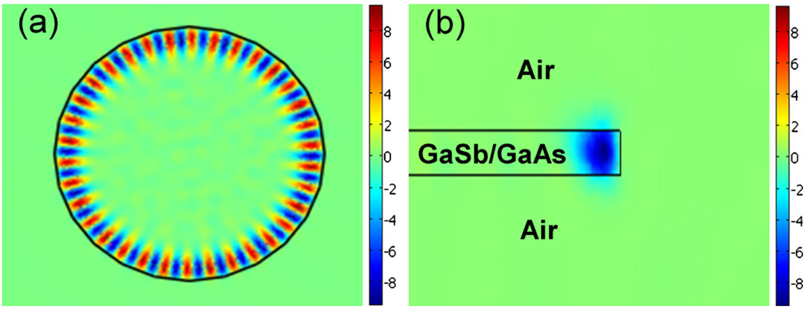

FIG. 5. (Color online) (a) The top view of H_z mode profile for a 3.9 μm microdisk cavity at 961 nm from the FEM simulation. (b) The cross-section view of the calculated H_z profile around the edge of a microdisk cavity.

wavelength of the first-order whispering-gallery lasing mode was also verified by the three-dimensional FEM simulation.

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