1.5-μm InGaAs/InAlGaAs Quantum-Well Microdisk Lasers

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***Abstract*—Microdisk lasers with three InGaAs/InAlGaAs quantum wells were demonstrated for the first time. The selective etching method to fabricate the InGaAs/InAlGaAs microdisk laser structure is discussed. The lasers with 20 μm in diameter lase with single mode at 1.5-μm wavelength when optically pumped with pulsed Argon-ion laser at 80 K.**

INTRODUCTION

FOR THE VAST majority of semiconductor lasers, the need for cleaved facets to form a Fabry–Perot cavity is a limitation for large-scale planar integration. Lasers using distributed feedback grating or vertical cavity quarter-wave mirrors are difficult to fabricate. An alternative, simple, but compact laser structure that may be useful for future microphotonic integration is either the microdisk laser or the related pillbox-shaped ring laser. These lasers are based on a circular waveguide resonator that completely eliminates the need for a facet. Microdisk lasers have been demonstrated by McCall *et al.* in the InGaAs/InGaAsP quantum-well (QW) material system [1], [2], while ring lasers of about 80-μm diameter have been demonstrated in GaAs/AlGaAs material [3]. In these structures, light is guided in the form of whispering-gallery modes due to the high reflectivity at the semiconductor–air interface. In the case of a microdisk laser, the optical mode is also strongly confined in the vertical direction, because the disk is supported in air above the substrate through a small pillar. Because of this guiding action and the optical confinement, sufficient optical gain can be produced to support lasing action, provided that all of the losses can be kept small. Because of the small active volume, the transparency current or power may be very small. More significantly, the spontaneous emission coupling factor (β) for these microcavity lasers may be substantially larger, potentially leading to very small threshold power [4], [5]. In fact, we have estimated the β value of microdisk lasers to be around 0.1–0.2. This is a large value compared to $\beta \sim 10^{-5}$ of a conventional semiconductor laser structure [6].

In this letter, we report the demonstration, for the first time, of a microdisk laser in the InAlGaAs–InGaAs QW material system. The selective etching method to form microdisk laser with this material system is discussed. This material system, like InP/InGaAsP, is one whose bandgap energy is widely tunable over the technologically important "optical window" for fiber-optic communications. As such, the achievement of microdisk lasers in these material systems has potential application for optical communication systems.

LASER FABRICATION

The layer structure grown by molecular beam epitaxy used in our experiments is shown in Fig. 1. On top of the InP substrate an InGaAs etch stop layer was grown. Then a 1-μm InAlAs pillar layer was grown above the etch stop layer and followed by the disk laser. The 1900-Å thick disk layer consists of three 100-Å InGaAs QW's separated by 100-Å InAlGaAs barriers with 700-Å end caps on both sides. The thickness of the disk is chosen so that it is just below the cutoff thickness for the second-order planar waveguide mode [7]. At this thickness, our theory indicates that the gain for modes with polarization perpendicular to the disk is highly suppressed and that only modes with polarization parallel to the plane of the disk will lase [7]. This design approximately optimizes the β value for the microdisk lasers [5].

Photolithographic techniques were used to fabricate 20-μm diameter microdisk lasers [8]. First, the circular microdisks were patterned using AZ-1350J positive photoresist. A nonselective etchant ($H_3PO_4 : H_2O_2 : 35\ H_2O$, etching rate $\sim 0.1\ \mu$m/min) was used to remove the top disk layer into the pillar layer. Then a highly selective etchant (3 $HCl : H_2O$, etching rate $\sim$ 108 Å/s) was used to etch the remaining InAlAs layer down to the etch-stop layer as well as inward under the disk layer to form the supporting pillar. The degree of undercut was monitored with a microscope, which revealed the pillar in contrasting color. Scanning electron microscope photos of a resulting disk structure are shown in Fig. 2. The InAlAs pillar is rhombus-shaped because of the anisotropic etch.

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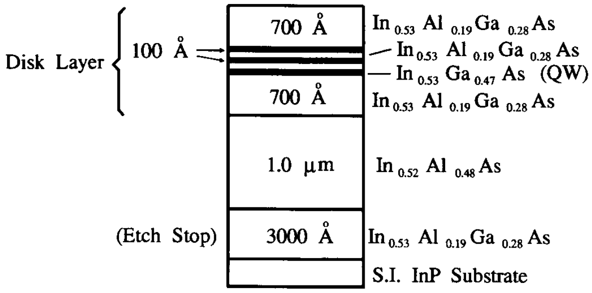

Fig. 1. Schematic of the layer structure of the microdisk laser.

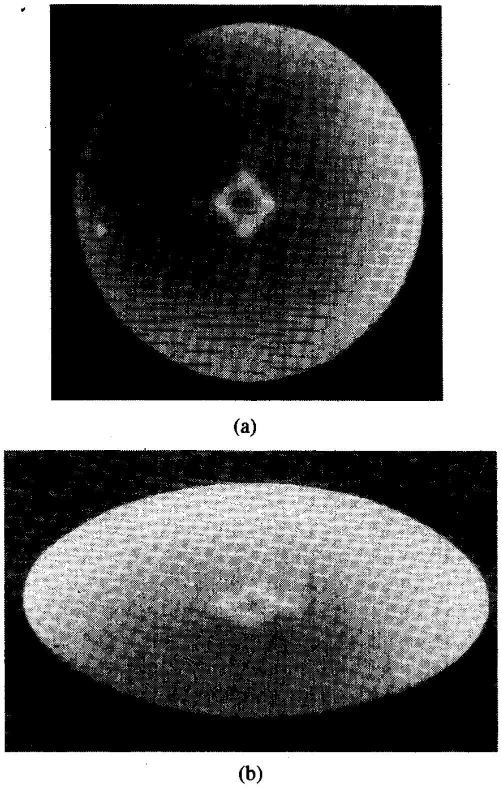

Fig. 2. Scanning electron microscope photos of a microdisk laser with 20-μm diameter. (a) Top view. (b) Oblique view.

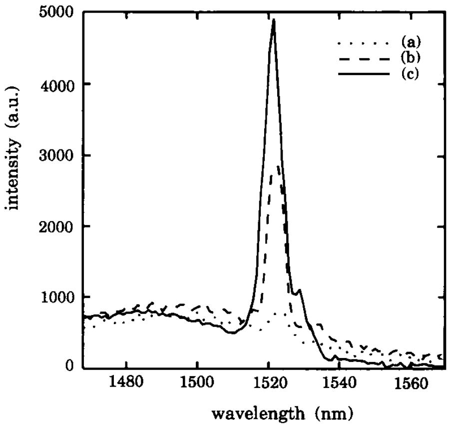

Fig. 3. Spectra of lasing lines for the 20-μm diameter microdisk at 80 K. Curve (*a*) was measured at threshold, and curves (*b*) and (*c*) were measured above threshold.

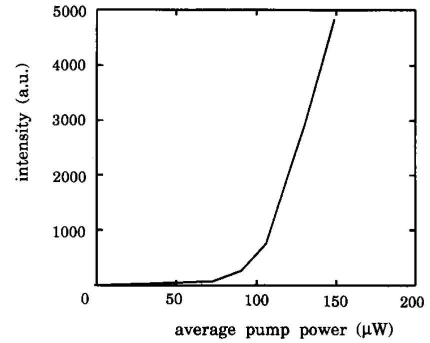

Fig. 4. The light intensity versus the average pump power for 20-μm microdisks.

Results and Discussion

The microdisk lasers were optically pumped with a 518-nm Argon-ion laser in a vacuum-assisted Joule–Thomson refrigerator at 80 K. The pump laser was modulated with a varying duty cycle by an acousto-optic modulator. The beam was focused with a 40 × microscope objective lens (1-cm working distance) to a spot size matching the size of the microdisk monitored via an infrared camera. Output of the microdisk laser was collected from top of the disk via the objective lens. The emission spectrum was detected and measured with a spectrometer, a liquid-nitrogen-cooled germanium detector, and a lock-in amplifier.

Fig. 3 shows the single-mode lasing spectra of microdisks with 20-μm diameter at and above threshold. In Fig. 3, the curve (*a*), represented by the dotted line, is the spectrum measured at threshold where the peak pump power incident on the microdisk is approximately 11 mW, while the average power is 110 μW with 400-ns pump pulse width and 1% duty cycle. The threshold power corresponds to an incident threshold intensity of 3.5 kW/cm^2. Curves (*b*) and (*c*) in Fig. 3 (dashed and solid lines) are the emission spectra above threshold where the average pump powers are 130 and 150 μW, respectively. We also plot out the emission light intensity versus the average pump power shown in Fig. 4. Lasing ceased above 100 K or an average power of more than 1 mW because of excessive heating.

A few of the microdisk lasers showed two modes lasing, which can be seen from the spectrum given in Fig. 5. The wavelength difference between two lasing modes is about 10 nm, which corresponds to the intermode frequency spacing $c/2n\pi r$, where r is the microdisk radius (~ 10 μm) and n is the refractive index (~ 3.4).

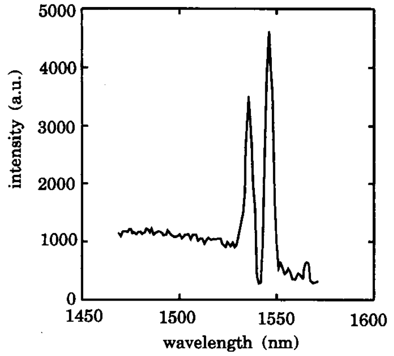

Fig. 5. Two modes lasing spectrum for some 20-μm microdisk laser. The intermode spacing is 10 nm.

SUMMARY

In conclusion, we have demonstrated lasing under pulsed excitation at low temperature for microdisk lasers fabricated from InGaAs/InAlGaAs/InAlAs material system. Similar experiments done with the InP/InGaAsP material system [1] give a laser threshold intensity about four times lower than ours (consider 25% of incident power excites the lasing and our mode area is 12 times larger). We believe that the higher-threshold intensity of the InGaAs/InAlGaAs material system could be due to the higher trap density and surface recombination in this material system. These properties will be further studied.

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Mode-Locked Multisegment Resonant-Optical-Waveguide Diode Laser Arrays

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***Abstract*—We report the first mode-locked operation of resonant optical waveguide (ROW) semiconductor laser arrays. The well-behaved emission patterns of such arrays allow coupling to external cavities with efficiencies comparable to those achieved by using single-element lasers. Single and multisegment lasers are employed to achieve active, passive, and hybrid mode-locking. The use of an arrayed gain region is effective in increasing the saturation energies of gain and absorber segments, resulting in high pulse energies. Pulses are generated that have well-suppressed secondary pulsations, with pulsewidths as short as 5.6 ps and peak powers of over 3 W in a collimated beam with a single main lobe.**

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I. INTRODUCTION

MODE-LOCKED semiconductor lasers are attractive as compact sources of short optical pulses for

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