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Low-roughness active microdisk resonators fabricated by focused ion beam

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The authors present a new approach for the fabrication of active microdisk resonators using focused ion beam (FIB) followed by selective wet-chemical etching. This efficient technique enables the placement of the devices at any region of a sample and facilitates prototyping of monolithical integration. Also, it allows the production of very smooth walls required by the resonators. High-quality resonators with an active region based on high-gain InGaAsP/InP quantum wells are demonstrated using this technique. Emission in the C-band at whispering-gallery modes is observed. © *2009 American Vacuum Society.* [DOI: 10.1116/1.3264481]

I. INTRODUCTION

Microresonators of various forms and material compositions have been studied over the years due to their potential applications in optical-communication systems. High-quality-factor microresonators are important in applications such as laser cavities,[1–3] spectral filters,[4] spatial switching,[5] modulators,[6] add/drop multiplexers and demultiplexers,[7] biosensors,[8,9] and others. More recently, microdisk resonators have been used for generating high-photonic-density structures to enhance four-wave mixing that is used for frequency-comb generation.[10]

Active microdisk resonators offer a great advantage in obtaining stimulated emission in small volume since they support whispering-gallery modes (WGMs), which are very confined resonances with maximum intensity near the disk edge.[11] A high photonic lifetime can be achieved without complex systems for optical feedback. Moreover, its planar structure, with planar emission without the need of cleaved mirrors, allows easy integration with other optoelectronic devices. Two factors are fundamental for the performance of active microdisk resonators: low roughness of the walls of the disk to reduce optical scattering losses[12] and low surface recombination velocity to increase internal quantum efficiency.

We have developed an efficient fabrication technique using a focused-ion beam (FIB) followed by wet-chemical etching, which allows the placement of devices anywhere in the sample, facilitating their monolithic integration with other optoelectronic devices. This technique also is very interesting for research and prototyping new devices or simply to modify devices already fabricated.[13–15] Moreover, this technique allows the fabrication of microdisks with walls of excellent quality and of any size. In this work, we present our recent results of fabricating microdisk resonators using this technique. Electrical and optical characterization of the resonator is presented.

II. FABRICATION

The epitaxial layers grown on a *n*-type (001) InP substrate were Si-doped (5×10^{17} cm^{-3}) InP lower cladding layer, undoped InGaAsP multiquantum well active region within a 300 nm InGaAsP waveguide layer, followed by a 1.9-μm-thick Zn-doped top *p*-type cladding layer. The doping concentration increased from low 10^{17} cm^{-3} to mid-10^{18} cm^{-3} with the growth. A highly Zn-doped *p*-InGaAs top contact layer of 200 nm was employed for *p*-contact.

In order to help the visualization, a flow with the microresonator-fabrication steps is outlined together with scanning electron microscope (SEM) micrographs in Fig. 1. Step (a) shows the planar sample with a Ti/Pt/Au microdisk obtained by conventional liftoff and electron-beam evaporation. The sample was alloyed in forming gas for 30 s at 420 °C. Subsequently, in step (b), the sample is taken to the ion-milling system. The milling was done with Ga$^+$ ions us-

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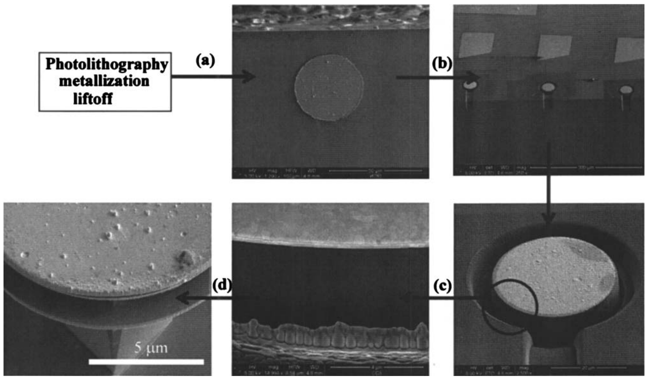

FIG. 1. Outline of the microresonator-fabrication process. (a) Metallization of contacts and liftoff; (b) focused ion beam milling of disks using 30 keV, 20 nA for 5 min; (c) smoothing process with FIB using 30 keV, 1 nA for 6 min resulting in vertical and very smooth walls; (d) InP selective etching using $3HCl:1H_2O$ for 40 s.

ing a dual-beam FIB/SEM. The milling was done with an emission current of 20 nA and 30 keV for about 5 min to reach a depth of 6 μm, which was well within the InP substrate. In this step, we removed the field around the microdisk, obtaining several pillars, all with the top metallization material. Step (c) consists of a polishing milling obtained by a reduced emission current of 1 nA, 30 keV for about 6 min. As a result, we obtained pillars with very smooth walls. The final step, step (d), was performed with a wet-chemical etching with H_2O and HCl to selectively remove InP material, leaving suspended disk structures of the InGaAs contact layer and the InGaAsP active region/waveguide. The finalized microdisk resonator is shown in the last image of Fig. 1. Figure 2 shows two SEM micrographs obtained for disks fabricated without (left) and with (right) the polishing milling step. We clearly see that polishing allows a smooth disk to be obtained that should result in minimized photon scattering.

III. CHARACTERIZATION

The experimental setup used for the characterization is shown in Fig. 3. The sample was mounted on a stage with a Peltier cooler. All measurements were performed at 18 °C. A probe tip placed on the microdisk and the back of the substrate were the anode and common cathode for all disks. The electrical characterization was done with a power source meter (Keithley 2400). For the electroluminescence characterization, a current source (ILX Lightwave LDC-3724) was used. The microresonator emission was collected by a single-mode fiber placed perpendicular to the active region of the device. The collected light was brought to an optical-spectrum analyzer, model (HP 70950B). All spectra were averaged ten times. Figure 3 also shows an infrared camera micrograph with the isotropic light emission from the microdisk.

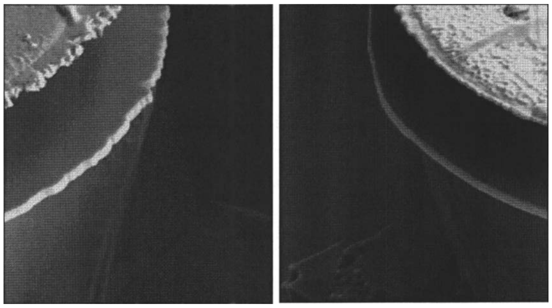

FIG. 2. Detail of the standing disk after the selective wet-chemical etching. Left: without polishing milling; right: with polishing milling.

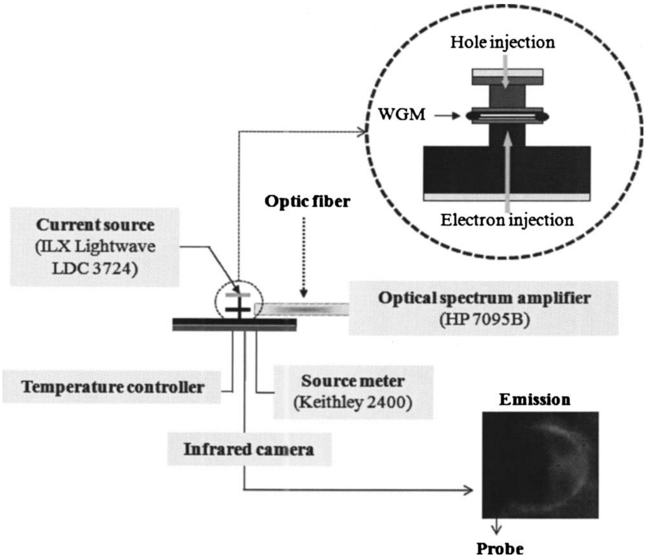

FIG. 3. Experimental setup used for the characterization of the disk. The image is an infrared-camera image of the disk emission.

The solid line in Fig. 4 shows the current-versus-voltage ($I\times V$) curve for a microdisk with a 5 μm radius. A typical diode behavior was obtained. The measured ideality factor was 2, which is expected for a diode with large recombination in the depletion region. The dashed line shows the dynamic resistance of this diode. The reverse-bias resistance was approximately 1 kΩ. This is a reasonably high value,

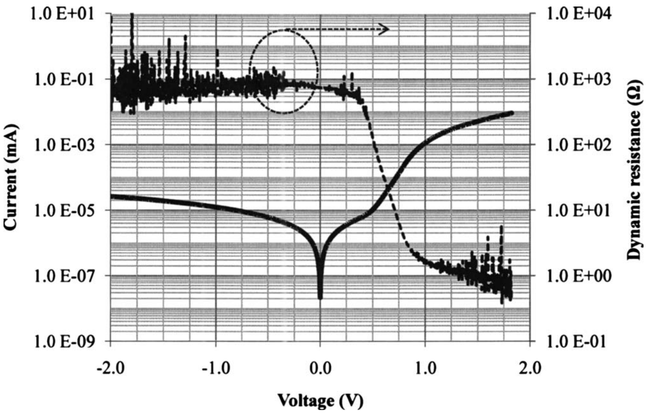

FIG. 4. Electrical characterization of a 5 μm radius microdisk resonator. Solid line: current vs voltage; dashed line (left axis): dynamic resistance vs voltage.

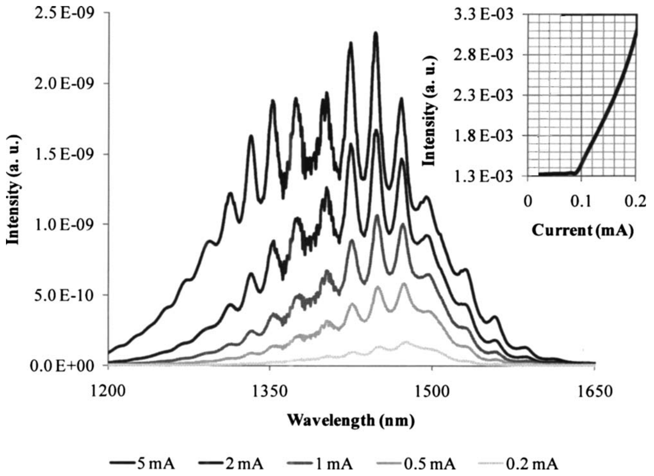

FIG. 5. Emission spectra obtained for applied continuous current varying from 0.2 to 5.0 mA for a 5 μm radius microdisk resonator. All spectra were averaged ten times. Inset: integrated light output power vs applied current for the same resonator.

however, allowing a small leakage of 20 μA. The series resistance approached 1 Ω. Therefore, minimized Joule heating was expected.

Figure 5 shows the measured emission spectra for a 5 μm microdisk for injection current varying from 0.2 to 5.0 mA. Several resonant modes with average spacing of $\Delta\lambda = 21$ nm were observed. This value is in good agreement with the calculated free spectral range $\Delta\lambda = \lambda^2/2\pi R\eta_{\text{eff}} = 26$ nm for whispering-gallery modes. In the above equation, R is the disk radius and n_{eff} is the effective index of refraction. As the microdisk walls were not so far from the pedestal, only first-order radial ($N=1$) modes, i.e., WGMs were observed, as demonstrated by Refs. 3 and 16. The WGMs expected for this microdisk ranged from $M=36$ to $M=62$ azimuthal modes with corresponding emission between 1200 and 1650 nm. The two highest intensity modes were probably $M=51$ ($\lambda_{51}=1446$ nm) and $M=52$ ($\lambda_{52}=1423$ nm). The inset in Fig. 5 shows the integrated emission power versus the current injection. A threshold current for emission near 80 μA, 102 A/cm^2 was obtained. This threshold current is calculated assuming a uniform current distribution from the post to the disk edge. The mode linewidth is approximately 10 nm, indicating that a large amount of stimulated emission was present. This result was achieved due to the very good morphology of the walls obtained with our process. Although there is little indication of induced damage by the Ga$^+$ ions, it is important to address this issue. Postmilling annealing has been proposed for reducing these damages.[17–19] We are investigating the use of annealing to improve the performance of our resonator. This study is ongoing.

IV. CONCLUSION

In this work, we present a new approach for the fabrication of microdisk resonators using focused ion beam and conventional chemical etching. This technique proved to be very efficient, enabling the placement of the devices at any region of a sample. The electrical characterization of the device is presented, showing a low leakage current. The optical characterization shows the presence of whispering-gallery modes, with a threshold current of 80 μA for the onset of the modes.

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