Optically pumped ultraviolet microdisk laser on a silicon substrate

X. Liu, W. Fang, Y. Huang, X. H. Wu, S. T. Ho, H. Cao,[a] and R. P. H. Chang
Materials Research Center, Northwestern University, Evanston, Illinois 60208

(Received 24 September 2003; accepted 6 February 2004)

We have fabricated ultraviolet microdisk lasers on silicon substrates. A thin layer of zinc oxide is grown on top of the silica microdisks and serves as the gain medium. Under optical pumping, lasing occurs in the whispering gallery modes of the hybrid microdisks at room temperature. Above the lasing threshold, a drastic increase of emission intensity is accompanied by a decrease of spectral width of the lasing modes. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1695090]

As optoelectronics becomes increasingly important for information and communication technologies, there is a need to develop optoelectronic devices that can be integrated with standard silicon microelectronics.[1] Over the past decade, there has been much progress in developing silicon-based optoelectronic devices such as waveguides, tunable optical filters, add/drop switches, optical modulators, CMOS photodetectors, photonic crystals, and microelectromechanical systems. In addition to these devices, light sources such as lasers and light-emitting diodes are also important components of integrated optoelectronic circuits. Despite the recent development of efficient silicon light-emitting diodes[2–4] and report of optical gain in silicon nanocrystals,[5] a silicon-based laser has not yet been realized. We take a different approach in fabricating silicon-based laser: instead of extracting optical gain from silicon, we grow other gain materials on top of silicon substrates. Usually the lattice mismatch between the silicon substrate and the grown material reduces the optical quality of the gain material. However, we demonstrated a few years ago that zinc oxide (ZnO) thin films grown on amorphous fused silica (SiO_2) substrates exhibit high optical gain.[6] Based on this observation, we report in this letter the fabrication of ultraviolet microdisk lasers on silicon substrates. Microdisks sustain whispering gallery (WG) modes that are confined by total internal reflection. The high quality factor of WG modes would enhance the spontaneous emission coupling efficiency and reduce the lasing threshold.[7] We fabricated the microdisks with SiO_2 instead of ZnO, because SiO_2 disks can have very high quality factor as demonstrated recently by Armani *et al.*[8] A thin layer of ZnO is deposited on top of the SiO_2 disks and serves as the gain medium. As compared to the vertical cavities made of distributed Bragg reflectors, microdisks not only have higher quality factor, but also are much easier to fabricate. The main disadvantage of microdisk cavities is lack of directional output. However, recent studies show that deformed microdisks can provide directional output while maintaining high quality factor.[9–12]

We have fabricated SiO_2 microdisks on a commercial silicon (Si) wafer. The thickness of SiO_2 layer is 320 nm. The wafer is spin-coated with 1.1-μm-thick photoresist. Disk patterns are defined by optical lithography. The disk diameter varies from 2 to 20 μm. Then the pattern is transferred from the photoresist to the SiO_2 layer by reactive ion etching. The dry etching consists of two steps. First, a radio-frequency plasma of carbon tetrafluoride and hydrogen is employed for the highly selective etching of SiO_2 over photoresist. Second, a short time etching with a plasma of carbon tetrafluoride and oxygen is used to fully expose the silicon surface and facilitate the subsequent wet etching. A selective wet etching of silicon by tetramethyl ammonium hydroxide solution is followed, and the Si pedestal is formed underneath each SiO_2 disk. Figure 1 is the scanning electron micrograph (SEM) of a SiO_2 microdisk on top of a Si pedestal. The disk diameter is about 10 μm. The disk periphery is very smooth. The edge of SiO_2 disk is uniformly undercut by the selective wet etching. The top of the Si pedestal is shown as the dark circle in the middle of the SiO_2 disk in the top view of SEM.

After the SiO_2 microdisks are formed on the Si wafer, a thin layer of ZnO is grown on top of the disks as the gain medium. The ZnO film is deposited by metalorganic chemical vapor deposition in a pulsed organometallic beam epitaxy system. The growth apparatus has been described elsewhere.[13] Diethylzinc is used as the zinc precursor. It is stored in a liquid bubbler and cooled down to $-26\,°C$ during ZnO growth. Helium gas passes through the bubbler and carries diethylzinc vapor to reaction chamber. Oxygen is introduced into the chamber via a separated line to prevent premature reaction. The flow rates of helium carrier gas and oxygen are both controlled by mass flow controller to 1 standard cubic centimeter per minute(sccm) and 30 sccm, respectively. During the growth of ZnO film, the sample is immersed in an oxygen plasma excited by microwave energy at frequency 2.45 GHz. The sample is heated to $600\,°C$ by resistive heating of sample holder. Figure 2 is the SEM of the microdisk structure after ZnO deposition. A close-up view in the inset shows that the disk surface is uniformly covered by ZnO nanocrystals whose size is around 30 nm. The ZnO

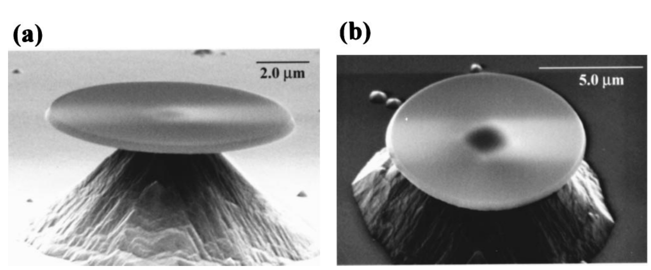

FIG. 1. Scanning electron micrographs of a SiO_2 disk: (a) side view, (b) tilt view. The disk diameter is about 10 μm.

[a]Electronic mail: h-cao@northwestern.edu

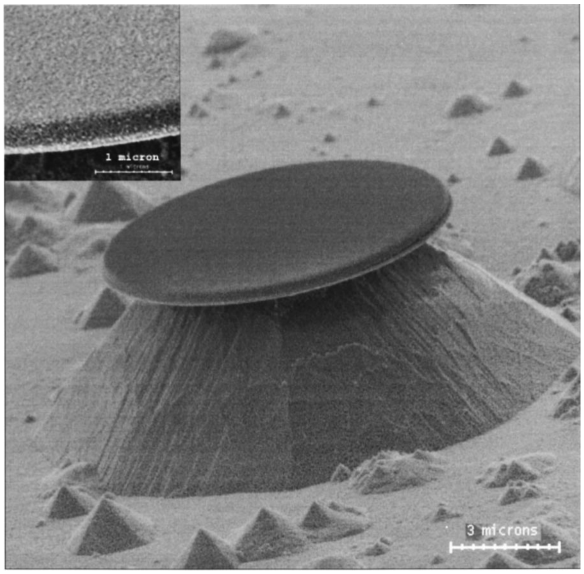

FIG. 2. Scanning electron micrograph of a 10 μm disk after the deposition of ZnO film. The inset is a close-up view.

layer on top of the SiO_2 disk is $\sim$55 nm thick. The side view SEM of some broken disks reveals a very thin layer of ZnO ($\sim$25 nm thick) on the back side of the SiO_2 disks. Note that we have to etch the disks before ZnO deposition, because ZnO can be easily removed during the wet etching process.

The hybrid ZnO/SiO_2 microdisk is optically pumped by the third harmonics ($\lambda = 355$ nm) of a mode-locked Nd:YAG laser (10 Hz repetition rate, 20 ps pulse width). A microscope objective lens is used to focus the pump beam onto a single disk. Part of the emission from the WG modes is scattered into the normal direction and collected by the same objective lens. The emission spectrum is measured by a 0.5 m spectrometer with a liquid nitrogen cooled charge-coupled-device array detector. The sample is at the room temperature.

Figure 3 shows the spectra of emission from a 10 μm disk at low and high pumping. The emission peaks correspond to the cavity modes. As the pumping intensity increases, the peaks shift to longer wavelength. This redshift is caused by the increase of ZnO refractive index with the carrier density. The intensities of some peaks increase much more rapidly with the pumping than the others. Their linewidth is also reduced significantly. Figure 4 is a plot of the emission intensity integrated over a spectral peak versus the incident pump pulse energy. We can see that the emission intensity increases dramatically above a pumping threshold, and eventually saturates. The spectral width of an emission peak is plotted as a function of the incident pump pulse energy in Fig. 5. The linewidth is decreased from 0.36 to 0.17 nm with increasing pumping. A sudden drop of the mode linewidth is observed across the pump threshold $\sim$0.85 nJ/pulse. These data clearly illustrate that lasing occurs in the hybrid ZnO/SiO_2 microdisks.

The commercial silicon wafer that we used is not designed for microdisk structure. The oxide layer thickness is not optimized for single guided mode operation. In fact the ZnO/SiO_2 disk layer supports three transverse electric modes (TE0, TE1, TE2) and three transverse magnetic modes (TM0, TM1, TM2). For the TE modes, the electric field is parallel to the disk plane; while for the TM modes, the electric field is perpendicular to the disk plane. To identify the lasing modes, we calculate the effective index of refraction n_{eff} for the guided modes at the ZnO emission frequency. $n_{\mathrm{eff}}=1.76$, 1.50, 1.27 for TE0, TE1, TE2 modes, and $n_{\mathrm{eff}}=1.50$, 1.35, 1.07 for TM0, TM1, TM2 modes. From the effective index of refraction, we find the frequencies of WG modes in a microdisk. The radial variation of the mode field is given by the mth order Bessel function $J_m(2\pi n_{\mathrm{eff}} r/\lambda)$, where r is the radial coordinate, and m is the azimuthal number. The boundary condition is that the field is zero at the disk edge: $J_m(2\pi n_{\mathrm{eff}} R/\lambda)=0$, where R is the disk radius. By solving for the zero points of J_m, we obtain the wavelength $\lambda_{m,n}$ of the WG modes. n represents the order of the zero points of J_m, and it is called the radial number. Thus a WG

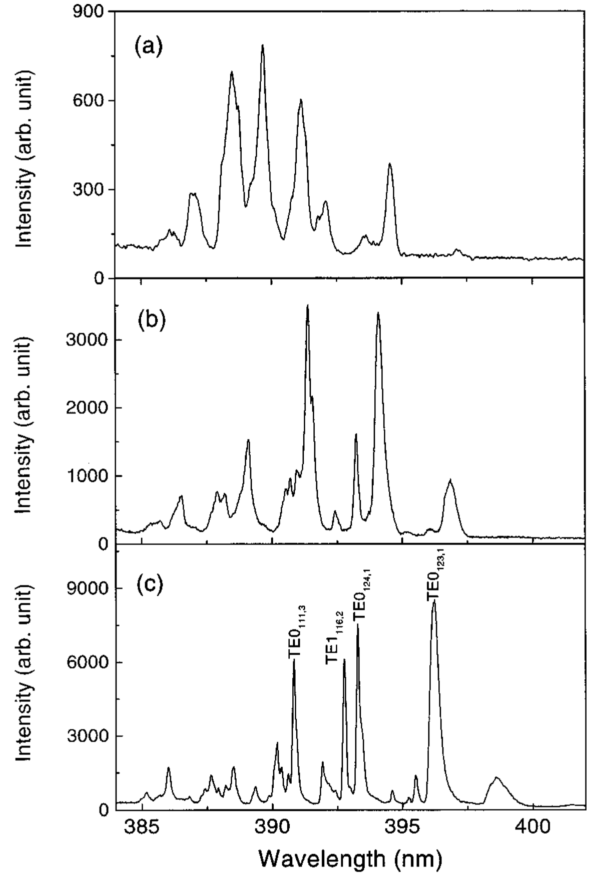

FIG. 3. Spectra of emission from a 10 μm disk. The incident pump pulse energy is (a) 0.42 nJ, (b) 0.95 nJ, (c) 1.8 nJ.

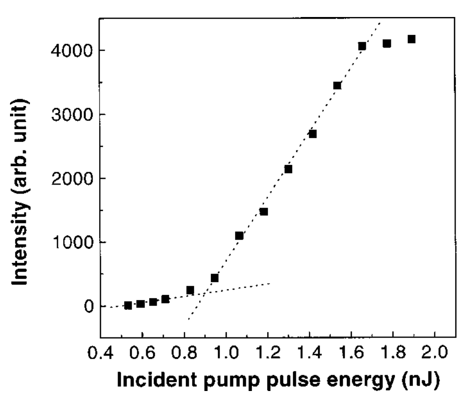

FIG. 4. Spectrally integrated emission intensity of a WG mode as a function of incident pump pulse energy.

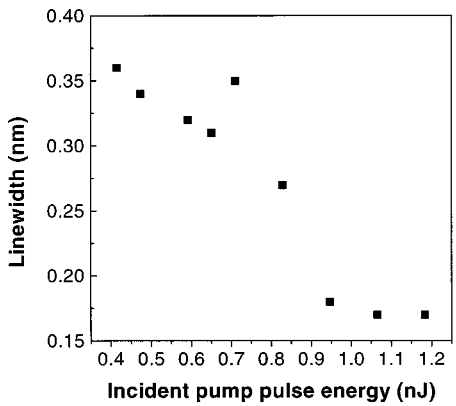

FIG. 5. The full width at half maximum of a WG mode vs the incident pump pulse energy.

mode is labeled as $TEX_{m,n}$ or $TMX_{m,n}$, where X is the order of the guided mode. For our disks, X can be 0, 1, or 2. In a 10 μm disk, there are many WG modes within the ZnO gain spectrum. The frequency spacing between some WG modes is so small that the modes cannot be resolved. Instead they appear to be one relatively broad peak. Although there are six guided modes, the lasing modes are mainly the fundamental transverse electric mode TE0 as indicated in Fig. 3(b). To understand this phenomenon, we calculate the spatial profiles of the six guided modes. We find the TE0 mode has the largest spatial overlap with the ZnO layer (gain medium). Hence, it experiences the highest gain. We also notice that the lasing modes have small radial number n. This is because a WG mode with smaller n has larger effective radius. Its wave function has less extension to the disk center, thus the scattering loss caused by the pedestal is minimized.

Although we have realized ultraviolet lasing in the hybrid ZnO/SiO_2 microdisks, the lasing threshold is still quite high. The high lasing threshold result from several factors. (i) Most incident pump light is not absorbed by the thin ZnO layer. (ii) Higher-order guided modes compete for gain. (iii) Impurities in the SiO_2 layer absorb laser emission. (iv) ZnO nanocrystals induce scattering loss. Therefore, we believe the lasing threshold can be significantly reduced by decreasing the SiO_2 layer thickness to suppress the higher-order guided modes, using pure SiO_2 to eliminate absorption, and reducing the size of ZnO nanocrystals to minimize the scattering loss.

This work is supported by the MRSEC program of the National Science Foundation (DMR-00706097) at the Materials Science Center of Northwestern University.

[1] A. Himeno, K. Kato, and T. Miya, IEEE J. Sel. Top. Quantum Electron. **4**, 913 (1998).
[2] K. D. Kirschman, L. Tsybeskov, S. P. Duttagupta, and P. M. Fauchet, Nature (London) **384**, 338 (1996).
[3] W. L. Ng, M. A. Loureno, R. M. Gwilliam, S. Ledain, G. Shao, and K. P. Homewood, Nature (London) **410**, 192 (2001).
[4] M. A. Green, J. Zhao, A. Wang, P. J. Reece, and M. Gal, Nature (London) **412**, 805 (2001).
[5] L. Pavesi, L. Dal Negro, C. Mazzoleni, G. Franz, and F. Priolo, Nature (London) **408**, 440 (2000).
[6] H. Cao, Y. G. Zhao, H. C. Ong, S. T. Ho, J. Y. Dai, J. Y. Wu, and R. P. H. Chang, Appl. Phys. Lett. **73**, 3656 (1998).
[7] T. Baba, IEEE J. Sel. Top. Quantum Electron. **3**, 808 (1997), and references therein.
[8] D. K. Armani, T. J. Kippenberg, S. M. Spillane, and K. J. Vahala, Nature (London) **421**, 925 (2003).
[9] C. Gmachl, F. Capasso, E. E. Narimanov, J. U. Nöckel, A. D. Stone, J. Faist, D. L. Sivco, and A. Y. Cho, Science **280**, 1556 (1998).
[10] S. Lacey and H. Wang, Opt. Lett. **26**, 1943 (2001).
[11] S.-B. Lee, J.-H. Lee, J.-S. Chang, H.-J. Moon, S. W. Kim, and K. An, Phys. Rev. Lett. **88**, 033903 (2002).
[12] N. B. Rex, H. E. Tureci, H. G. L. Schwefel, R. K. Chang, and A. D. Stone, Phys. Rev. Lett. **88**, 094102 (2002).
[13] S. J. Duray, D. B. Buchholz, S. N. Song, D. S. Richeson, J. B. Ketterson, T. J. Marks, and R. P. H. Chang, Appl. Phys. Lett. **59**, 1503 (1991).