Ultraviolet amplified spontaneous emission from zinc oxide ridge waveguides on silicon substrate

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Zinc oxide (ZnO) thin-film waveguides with ridge structures have been fabricated on *n*-type (100) silicon substrates. The deposition of high-crystal-quality ZnO thin films on the lattice-mismatched silicon substrate was achieved by using the filtered cathodic vacuum arc technique. A ridge structure is defined on the ZnO thin film by plasma etching. Room temperature amplified spontaneous emission with peak wavelength at 385 nm is observed under 355 nm optical excitation. The pump threshold is found to be around $0.45\ \mathrm{MW/cm^2}$. The maximum net optical gain of the ZnO waveguide is larger than $120\ \mathrm{cm^{-1}}$ at a pump intensity of $1.9\ \mathrm{MW/cm^2}$. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1629784]

Zinc oxide (ZnO), which has a wide band gap (~3.37 eV) and a large exciton binding energy (~60 meV),[1] is one of the most promising candidates for the development of ultra-violet (UV) optoelectronics at room temperature. Recently, high-crystal-quality ZnO thin films have been fabricated using pulsed laser deposition,[2] metalorganic chemical vapor deposition,[3,4] and laser molecular beam epitaxy.[5] Room temperature amplified spontaneous emission (ASE) and lasing characteristics have also been demonstrated in self-assembled ZnO microcrystallite thin films.[6] However, the formation of high-crystal-quality thin films, which generates high intensity UV stimulated emission at room temperature, requires the deposition of ZnO thin films on (0001) sapphire substrates at temperatures greater than 500 °C.

Extensive studies have also concentrated on the growth of ZnO thin films on silicon substrates.[7–9] This is because the use of silicon substrates allows the integration of II-VI optoelectonics with silicon-based electronics. In addition, a silicon substrate is cheaper and easier to cleave than that of sapphire. Therefore, the successful deposition of device-quality ZnO thin films on silicon substrates might lead to the mass production of UV integrated optoelectronics. Recently, photoluminescence at room temperature with a strong exciton transition at 3.37 eV has been observed from ZnO thin films on silicon substrates prepared by the filtered cathodic vacuum arc (FCVA) at temperatures below 250 °C.[10] This implies that, if the structure of ZnO epitaxial thin films is carefully designed, it may be possible to realize high intensity UV light-emitting devices on silicon. In this letter, the design, fabrication, and characterization of ZnO thin-film ridge waveguides on lattice-mismatched silicon substrates are reported.

Figure 1 shows the schematic of the proposed ZnO thin-film ridge waveguide. A buffer layer is inserted between the ZnO thin film and the silicon substrate. This is required because the refractive index of silicon (~3.45) is higher than that of ZnO (~2.1). Silicon dioxide (SiO_2) is selected as the buffer layer because it has a refractive index (~1.45) lower than that of ZnO and exhibits a wide energy band gap of 9 eV so that transverse optical confinement can be achieved in a ZnO thin film with minimum absorption loss.[11] More importantly, SiO_2 can be easily obtained on the silicon surface by thermal oxidation. Furthermore, a ridge structure can be defined on the surface of a ZnO thin film by plasma etching in order to obtain optical confinement in the lateral direction. Hence, the pump and signal intensities can strongly interact inside the ZnO thin film so that the corresponding coupling efficiency can be maximized. In addition, the high absorption from the silicon substrate can be minimized.

In the fabrication of the ZnO thin-film ridge waveguides, *n*-type (100) silicon substrate underwent thermal dry oxidation to form a SiO_2 buffer layer 420 nm thick. A layer of 160 nm thick ZnO was then deposited on top of the SiO_2 buffer layer by the FCVA technique with the substrate temperature and oxygen partial pressure set to 230 °C and 2×10^{-4} Torr, respectively. Although the substrate temperature in the FCVA system can reach more than 400 °C, a substrate temperature of 230 °C is sufficient to produce high-crystal-quality ZnO thin films. Furthermore, photoresist stripes were coated on the sample using the photolithography technique. Finally, the unmasked region of the ZnO thin film was etched by the plasma-enhanced chemical vapor deposition (PECVD) technique at a working pressure of 45×10^{-4} Torr and exposed to $10H_2/30CH_4/5Ar$ plasma, where

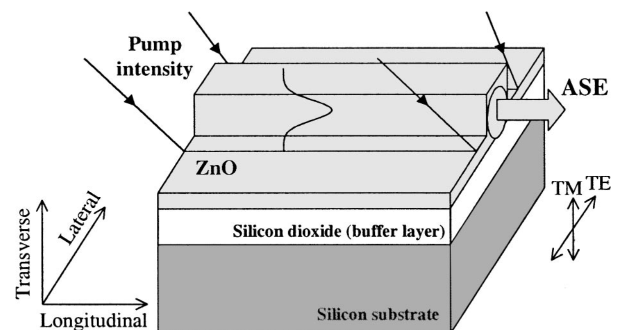

FIG. 1. Schematic of the ZnO thin-film ridge waveguide using silicon as the substrate.

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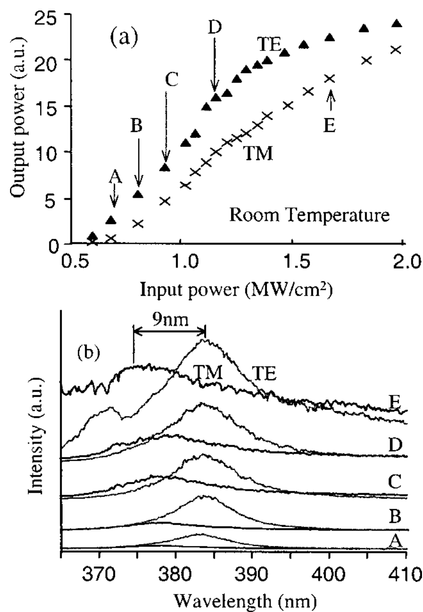

FIG. 2. (a) Light-light curves for the two polarizations of the ZnO thin-film ridge waveguide and (b) the corresponding emission spectra of the two polarizations at different pump intensities.

the numbers represent the gas flow in standard cubic centimeters per minute (SCCM).[12] The substrate was self-biased to -300 V and the corresponding radio frequency power was held constant at 120 W. A magnetic field was also applied perpendicular to the ZnO thin film in order to increase the surface plasma density. PECVD was used because the corresponding etch rate could be as low as ~ 6 nm/min so that the etching depth could then be carefully controlled. As a result, ridges with height, width, and separation of 100 nm, 2 μm, and 500 μm, respectively, were obtained on the ZnO thin film. The dimensions of the ridge waveguide were selected in order to maximize the optical gain of the fundamental TE mode.

The optical characteristics of the ZnO ridge waveguide at room temperature were studied under optical excitation by a frequency-tripled Nd:YAG (yttrium aluminum garnet) laser (355 nm) at pulsed operation (6 ns, 10 Hz). Optical pump was achieved by using a cylindrical lens to focus a pumping stripe of length 0.9 mm and width of 8 μm on to the ridge structure. The polarized emission from the edge of the ridge waveguide was analyzed, using a polarizer in the directions perpendicular (TE) and parallel (TM) to the lateral direction. The light-light curves and the emission spectra of both TE and TM modes at various pump intensities are given in Fig. 2. The output power increases linearly with the input power. This implies that both TE and TM modes are well confined inside the ridge structure. It is also noted that the strong optical confinement of the ridge waveguide has caused the two polarizations to have a 9 nm wavelength difference at the peak intensities under high pump intensities. The pump thresholds of the TE and TM modes are equal to ~ 0.45 and ~ 0.6 MW/cm^2, respectively. Figure 3 shows the cross-sectional scanning electron microscope image of the ZnO thin-film waveguide. It is shown that the interface between ZnO and SiO_2 is quite smooth and this implies that the FCVA technique is good enough to fabricate device-quality thin films on silicon. The corresponding far-field profile of

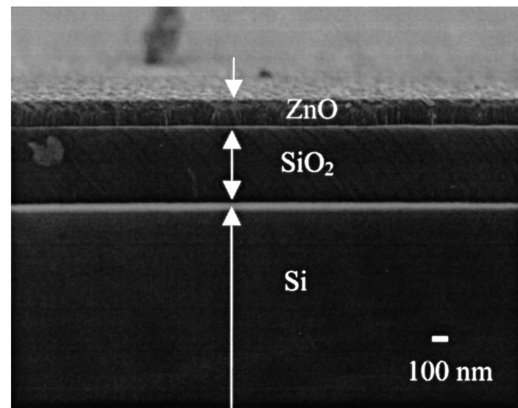

FIG. 3. Scanning electron microscope image of the cross-sectional $ZnO/SiO_2/Si$ interfaces.

the TE polarization at pump intensity equal to 1 MW/cm^2 is also shown in Fig. 4. It is clearly observed that only one bright spot is excited, which implies that the ridge waveguides can suppress high order TE modes. Hence, it is proved that high quality ZnO thin-film ridge waveguides can be formed on silicon using SiO_2 as a buffer layer.

As shown in Fig. 2(b), the two polarizations span the range 370 and 395 nm in the emission spectrum. This indicates that both exciton-exciton scattering and electron-hole plasma recombination contribute to the optical gain in the ZnO thin film, but electron-hole plasma recombination is the dominant process.[11] The plot of peak net optical gain, which was measured by the variable stripe length method, versus pump optical intensity for both polarizations is shown in Fig. 5. It is observed that the net optical gain for both polarizations increases with increase of pump intensities, and the thresholds for positive net optical gain of the TE and TM modes are 0.43 and 0.59 MW/cm^2, respectively. Furthermore, the net optical gain of the TE mode is larger than that of the TM mode over the range of pump intensities. This implies that suppression of TM modes by the ridge waveguide design has been achieved, and the maximum net gain difference between TE and TM modes can be as large as 20 cm^{-1}. The maximum net optical gain of the TE mode is 120 cm^{-1} at a pump intensity of 1.9 MW/cm^2, but any further increase in pump intensity may cause optical damage to the ridge waveguides.

The round-trip gain condition for Fabry-Pérot-type lasers can be written as $g-\alpha=(2L)^{-1}\ln(r^{-1})$, where g is the op-

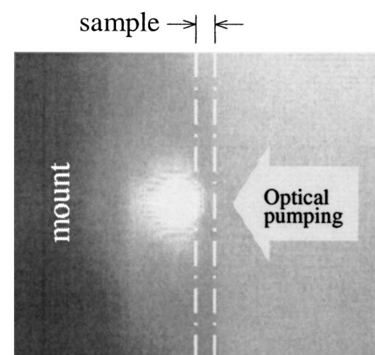

FIG. 4. Far-field profile of the TE fundamental mode at pump intensity of 1 MW/cm^2. The dot-dashed lines indicate the location of the sample.

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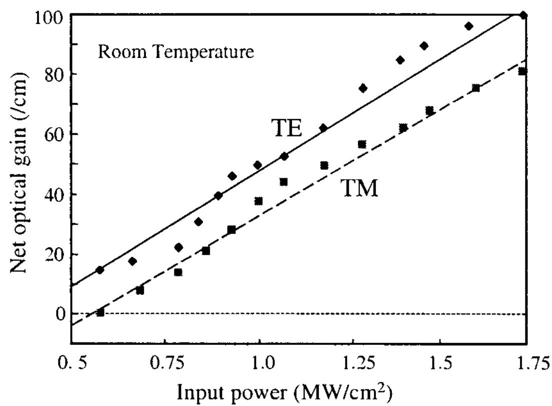

FIG. 5. Net optical gain versus pump intensities for TE and TM polarizations.

tical gain, α is the total absorption loss, L is the cavity length, and r is the field reflectivity at the end facets. In this equation, the expression $g-\alpha$ can be considered as the net optical gain of the laser. If the edges of our proposed ridge waveguide can form perfect reflectors (i.e., for a perfect air/ZnO interface, $r\sim 0.355$), then a Fabry-Pérot cavity can be obtained. In this case, the required net optical gain to sustain lasing is $26\,\mathrm{cm}^{-1}$, which can easily be realized in the proposed ZnO ridge waveguides, for $L\sim 200\,\mu\mathrm{m}$. However, our devices can exhibit high intensity ASE only at room temperature. This is due to the fact that natural facets required to provide positive optical feedback cannot be obtained in ZnO thin films by cleaving as in the case of (100) GaAs or InP semiconductor materials. Furthermore, our ZnO thin films have no self-assembled hexagonal microcrystallites to provide distributed feedback of light.[6] Other approaches are currently underway to realize optical feedback in our devices and the results will be published elsewhere.

In conclusion, we have demonstrated the deposition of device-quality ZnO thin films on lattice-mismatched silicon substrate by the FCVA technique. High intensity UV ASE is observed from our devices at room temperature. A stable fundamental TE mode is maintained inside the ridge waveguide at high pump intensity, and the corresponding maximum net optical gain is found to be $120\,\mathrm{cm}^{-1}$ at $1.9\,\mathrm{MW/cm}^2$ pump intensity. Such high pump intensity also indicates that our ZnO thin films on silicon substrate can withstand catastrophic optical damage at very high pump (lasing) intensities, so that they are a durable active medium to realize lasers. Hence, the proposed technique to fabricate ZnO thin-film waveguides on silicon could lead to the realization of low cost UV optoelectronics and their integration with silicon-based electronics.

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