ZnO–ZnMgO Multiple Quantum-Well Ridge Waveguide Lasers

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***Abstract*—ZnO–ZnMgO multiple quantum-well (MQW) thin-film waveguides with ridge structures have been fabricated on quartz substrates. Low-temperature deposition of high-quality ZnO–ZnMgO MQW thin films was achieved by filtered cathodic vacuum arc technique. A ridge is defined on the thin film by plasma etching. Room-temperature lasing with a peak wavelength at 378 nm of 1.5-nm well width was observed under 355-nm optical excitation. Exciton–exciton scattering was attributed to the amplified spontaneous emission observed from the MQW waveguide. The net optical gain can be larger than 80 cm^{-1} at a pump intensity of 2 MW/cm^2.**

***Index Terms*—Filtered cathodic vacuum arc (FCVA) deposition technique, quantum wells (QWs), ridge waveguide lasers, ZnO.**

I. Introduction

ULTRAVIOLET (UV) quantum-well (QW) semiconductor lasers are of immense technological interest due to their potential applications in optical storage and optical data processing. ZnO, being a large bandgap (3.37 eV) material with high exciton binding energy (60 meV), has become an excellent candidate to realize UV QW lasers. ZnO-based QW semiconductor lasers have been fabricated by pulsed laser deposition [1], [2] and molcular beam epitaxy [3], [4] techniques. Although very high-quality QW samples can be assured from these deposition methods, the stringent requirement of lattices matching substrate and high substrate temperature (>500 °C) have refrained the mass production of ZnO QW lasers at low cost. In this letter, filtered cathodic vacuum arc (FCVA) technique is proposed to fabricate ZnO-based QW semiconductor lasers. This technique allows the deposition of ZnO–ZnMgO QWs on quartz substrate at a substrate temperature of 200 °C. It can be shown that the room-temperature optical characteristics of ZnO QW lasers can be comparable with those obtained from the mainstream fabrication methods [3], [4].

II. Fabrication Procedures

Fig. 1 shows the schematic diagram of a ZnO–ZnMgO multiple quantum-well (MQW) structure. The MQW consists of ten ZnO wells with thickness varying from 1.5 to 5 nm and the ZnMgO barrier thickness of 10 nm. ZnO and ZnMgO were deposited separately on a quartz substrate from two independent cathodic arc sources from a modified FCVA system [5]. Zn and Zn : Mg (with 15 at% of Mg) metal targets, both with purity of 99.99%, were used to form Zn and Zn : Mg plasmas, respectively, from the two cathodic arc sources. Oxygen gas was introduced from an outlet which was 2 cm above the surface of the substrate. The gas was mixed with the metal plasmas to form metal–oxide thin films. The thickness of the metal–oxide thin films can be controlled by a gold crystal thickness monitor. In the studies, the oxygen flow rate was set to 160 sccm and the oxygen partial pressure was maintained at 5×10^{-4} torr. The arc currents for the Zn and Zn : Mg cathodic arc sources were both kept at 70 A. The substrate was set to 200 °C with a rotational speed of 30 rev/min. The deposition rate of the ZnO and ZnMgO were found to be 1.0 nm/min.

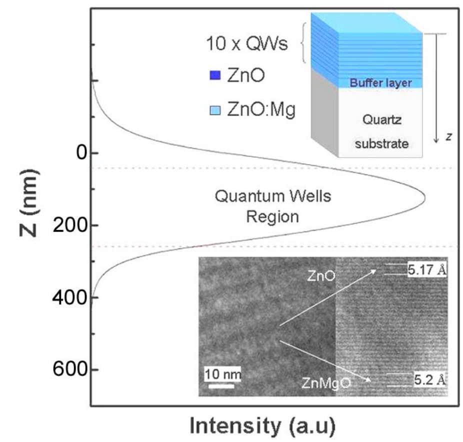

Fig. 1. Schematic of the ZnO–ZnMgO MQWs and the calculated intensity profile of the confined light along the growth direction of the MQWs. The inset shows the TEM image of the ZnO–ZnMgO MQWs.

The MQW was designed and fabricated to confine light along the growth direction of the QW region. A 50-nm $Zn_{0.85}Mg_{0.15}O$ buffer layer was first grown on the quartz substrate and followed by ten periods of ZnO–ZnMgO MQWs. A capped layer of ZnMgO was then deposited on the top of MQWs to provide a further confinement of light. The calculated intensity profile of the confined light along the growth direction of the MQWs is also plotted in Fig. 1. The inset of Fig. 1 shows the transmission electron microscope (TEM) image of the ZnO–ZnMgO MQWs with a well width of 5 nm. As the concentration of Mg is only 15%, the MQWs structure is barely observed from the TEM image. Lattice constant along c axis of ZnO well and ZnMgO barrier were found to be 0.517 and 0.52 nm, respectively.

Manuscript received July 27, 2009. First published September 09, 2009; current version published October 14, 2009. This work was supported by Singapore Ministry of Education Academic Research Fund Tier 2 under Grant ARC 2/06.

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Digital Object Identifier 10.1109/LPT.2009.2031089

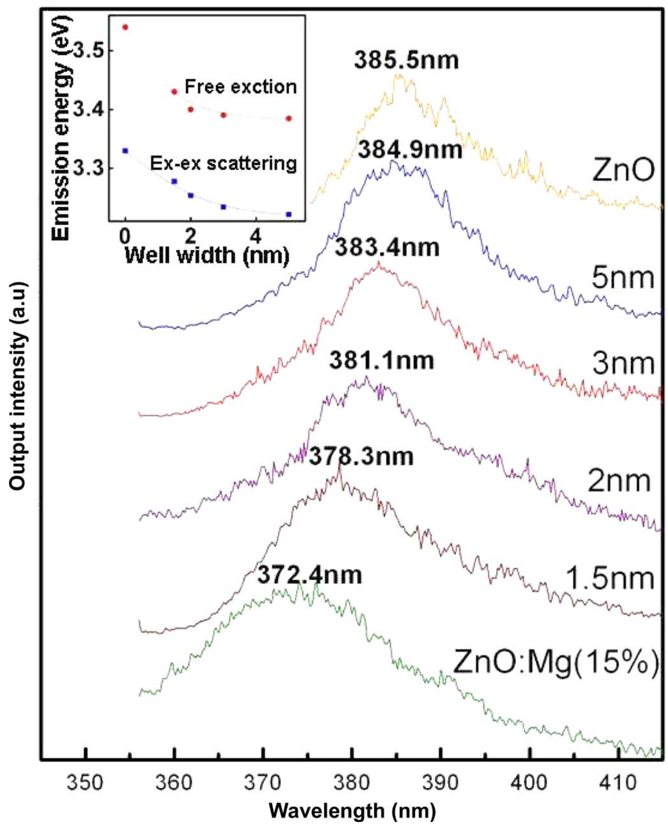

Fig. 2. Emission spectra of the ZnO–ZnMgO MQWs with various well widths. The inset shows the calculated and measured emission energies of ZnO–ZnMgO MQWs versus well widths.

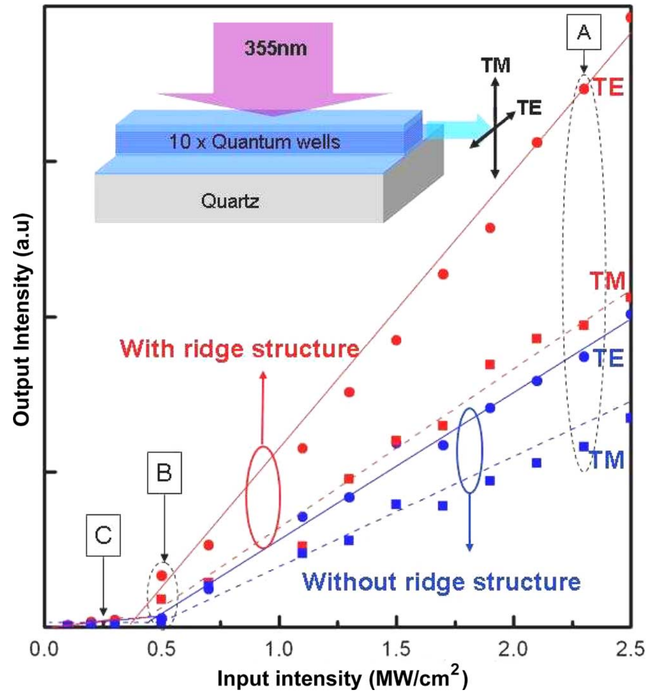

Fig. 3. Light–light curves of the ZnO–ZnMgO MQWs with and without ridge waveguide structure. The samples were excited normal to the surface of the quartz substrates and the emission light was measured perpendicular from the surface of the ZnO–ZnMgO MQWs.

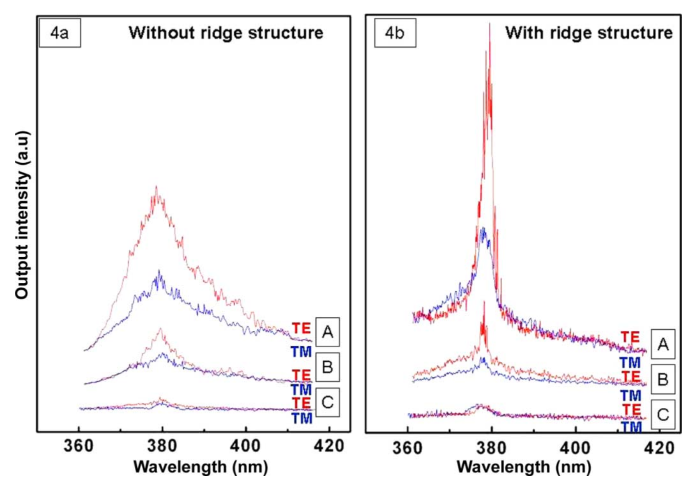

Fig. 4. Emission spectra of the ZnO–ZnMgO MQWs with and without ridge waveguide structure.

III. Experimental Results

The room-temperature optical characteristics of the ZnO–ZnMgO MQWs were studied under optical excitation by a frequency-tripled Nd : YAG (yttrium aluminum garnet) laser (355 nm) at pulsed operation (120 ps, 10 Hz). Optical pumping was achieved by using a cylindrical lens to focus a 1×0.5 mm^2 pump stripe on the surface of the MQWs. Fig. 2 shows the normalized emission spectra measured from the edge of the MQWs with different well widths. The corresponding excitation power was maintained at $\sim$ 0.4 MW/cm^2. The normalized emission spectra of ZnO and ZnMgO thin films were also plotted in the figure for comparison. As expected, the emission peak is blue shifting with the reduction of well width. The inset of Fig. 2 plots the measured emission energy versus well width of the MQWs. The calculated free exciton recombination energy versus well width of the MQWs [6], [7] is also plotted in the inset of Fig. 2. It is observed that the two curves show the same trend except they are different by $\sim$0.15 eV. This indicated that the recombination mechanism of the MQWs is mainly due to exciton–exciton scattering recombination [8].

To fabricate the ridge waveguide structure, photoresist stripes with a width of 2 μm were formed on the MQWs by photolithography technique. The unmasked region of the MQW is etched away by the Ar^+ ion beam sputtering system at a rate of 10 nm/min. Fig. 3 shows the light-light curves of the ZnO–ZnMgO MQWs ridge waveguide with 1.5-nm well width for both TE and TM modes. The light–light curves from the MQWs thin films are also plotted for comparison. It is observed that the TE mode is stronger than the TM modes from both samples. This is expected as the ridge and planar waveguides are both favored TE modes. Furthermore, the confinement of TE mode is improved with the ridge structure so that the emission intensity of ridge waveguide is higher than that of the planar waveguide. In fact, the slope efficiency of TE modes of the ridge guided structure is double to that of the planar structure. Kinks were also observed at about 0.5 MW/cm^2 (0.4 MW/cm^2) for the sample without (with) ridge waveguide structure. Fig. 4(a) and (b) shows the emission spectra from the MQWs without and with the ridge waveguide structure, respectively. For the pump intensities exceeding threshold, a

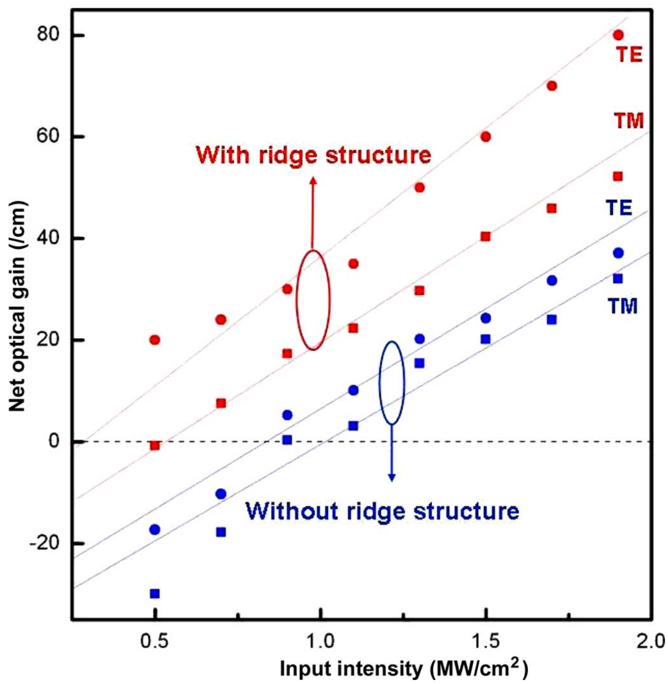

Fig. 5. Net optical gain of the ZnO–ZnMgO MQW thin films with and without distributed Bragg reflector (DBR) structure.

narrowing of emission spectra is observed. The narrowing of emission spectra and the presence of the kink in the light–light curves suggested that the lasing process is due to amplified spontaneous emission.

Fig. 5 shows the effect of the ridge waveguide structure on the optical gain of MQWs. The net optical gain was measured by the variable stripe length method [9]. It is observed that both TE and TM net optical gains of the MQWs with a ridge waveguide structure are almost two times larger than those without the ridge waveguide structure. The maximum gain of the TE emission from the ridge waveguide was measured to be about 80 cm^{-1} at 2 MW/cm^2.

IV. Conclusion

We have demonstrated the deposition of high-quality ZnO–ZnMgO MQWs thin films on quartz substrates by the FCVA technique at 200 °C. High-intensity UV lasing is observed from the devices at room temperature due to amplified spontaneous emission. Furthermore, a ridge waveguide structure is proposed to improve the lasing performance of the MQWs. It was shown that the ridge waveguide structure can maintain stable TE mode emission at high pump intensity and the corresponding laser threshold (slope efficiency) can be reduced (increased) by 1.25 times (doubled). The corresponding net optical gain can be as high as 80 cm^{-1} at pump intensity of 2 MW/cm^2.

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