Extended Abstracts of the 1995 International Conference on Solid State Devices and Materials, Osaka, 1995, pp. 674-676

Low Threshold and Low Divergence Blue Vertical-Cavity Surface-Emitting Laser Diodes

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We demonstrate a low threshold and low divergence blue vertical-cavity surface-emitting laser (VCSEL) diodes with a SiO_2/TiO_2 dielectric multilayer mirror. Electrically pumped lasing was achieved at 77 K with a threshold current of 3 mA (pulsed). A low far-field radiation angle of 7° was observed above the threshold in a 10-μm-diameter device, which indicates the spatial coherence expected for lasing.

1. INTRODUCTION

Vertical-cavity surface-emitting lasers (VCSELs) have recently attracted much attention because of their surface-normal operation, potential for extremely low threshold currents, and the ease with which they may be fabricated in closely spaced and two-dimensional arrays and integrated with other devices such as transistors for photonic switching applications[1-5]. Output characteristics such as narrow divergence beams and operation in a single longitudinal mode, due to the large mode spacing in a short cavity, are additional advantages.

ZnSe-based wide-band-gap II-VIs are promising materials for use in blue laser diodes. Starting with the first demonstration of blue-green laser diodes, further developments have led to continuous-wave operation at room temperature and low-threshold-current pulsed operation[6-9]. Recently, fabrication of a ZnSe-based vertical cavity using SiO_2/TiO_2 reflectors was reported[10]. Optically pumped operation of the blue VCSEL has also been achieved[11], but current injection has not been reported. In this paper, we report the first results of the characterization of blue-green II-VI VCSELs by electrical pumping techniques.

2. DEVICE FABRICATION

The VCSEL structures were composed of a CdZnSe/ZnSe multi-quantum-well (MQW) active layer, n- and p-ZnSe cladding layers and two SiO_2/TiO_2 distributed Bragg reflectors (DBRs). The detailed schematic diagram of the fabricated VCSEL structure is shown in Figure 1. The CdZnSe/ZnSe epitaxial layers were grown by molecular beam epitaxy. The II-VI heterostructures were grown on a (100) n-GaAs substrate and consisted of a n-ZnSe cladding layer (1.5 μm), a MQW of four 6-nm-thick $Cd_xZn_{1-x}Se$ (x=0.2) quantum wells and 50-nm-thick ZnSe barriers, and a p-ZnSe cladding layer (1.5 μm). Nitrogen radical doping and Cl doping were employed to obtain p- and n-ZnSe layers, respectively. Carrier concentrations of both p- and n-ZnSe layers are about $2X10^{17}$ cm^{-2}. The growth temperature was 270 °C. The composition x of the $Cd_xZn_{1-x}Se$ alloy was determined by assuming a linear variation of the lattice constant with x (Vegard's law).

The DBRs were fabricated from SiO_2/TiO_2 quarter-wave (l/4) layers by reactive sputtering. The SiO_2/TiO_2 multilayers were deposited on both the light output and opposite sides. The first circular DBR (8 periods, 10 μm in diameter) was deposited on the top p-ZnSe layer using lift-off. Next, an insulator was used to define the annulus contact area of Pd/Au evaporated on the top p-ZnSe layer. The outer diameter of the annulus Pd/Au p-contact around the circular DBR was 14 μm. Since the GaAs substrate is only transparent for wavelengths longer than 900 nm, the light output windows were opened in the GaAs substrate side by selective wet etching using $NH_4OH-H_2O_2$ solution with approximately 20:1 selectivity between GaAs and ZnSe. After the n-GaAs substrate side was polished and etched to 150 μm thickness, the circular light output windows (100 μm in diameter) were formed by this selective wet etching technique and photolithography. Then, a second SiO_2/TiO_2 DBR (5 periods) mirror was deposited on the n-ZnSe layer through the windows. In/Sn was used as the n-metal contact to the n-GaAs substrate. Finally, the wafer was diced to form the laser chips.

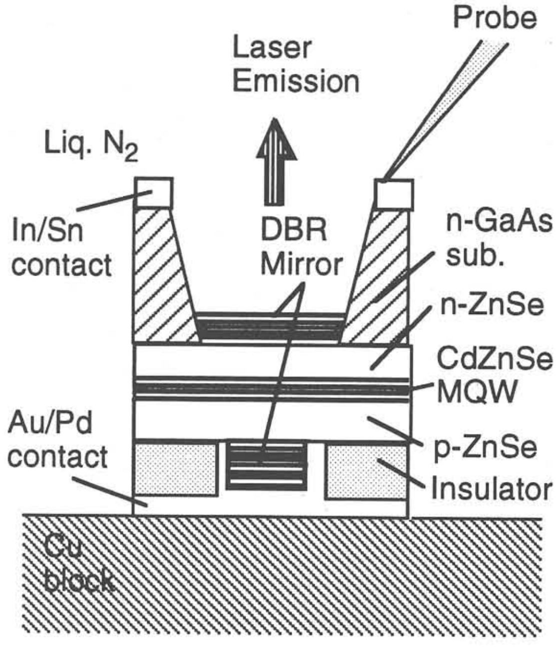

Fig. 1. Schematic diagram of CdZnSe/ZnSe blue vertical-cavity surface-emitting laser structure.

The reflectance spectra were measured in the DBR structure. The measured reflectivity of the SiO_2/TiO_2 dielectric mirrors with 8 pairs was greater than 99 %. The measured mirror center near 480 nm and the Fabry-Perot resonance were in good agreement with the calculated results assuming that the refractive indexes of SiO_2 and TiO_2 are 1.46 and 2.73, respectively.

3. CHARACTERISTICS

The VCSEL devices were characterized at 77 K under pulsed operation. The devices were tested by clamping the p-side down samples to a copper heat sink and directly probing the laser chips. The pulse width was 0.5 μs with a repetition rate of 1 kHz. The current-versus-light-output (I-L) and current-versus-voltage (I-V) characteristics are shown in Fig. 2. The steep rise of the emission indicates lasing. A very low threshold current of 3 mA was obtained in the VCSEL. The threshold current density of these devices is 3.9 kA/cm^2, which is as low as the value for the edge-emitting CdZnSe/ZnSe laser. The operating voltage is 17 V, which should be greatly improved with an optimized contact structure. In Fig. 3 are shown the emission spectra obtained in the vertical direction below and above the threshold at 77 K. Spectral narrowing was observed due to lasing. The FWHM of the lasing spectrum is about 9 Å above the threshold. The lasing wavelength is 484 nm under pulsed operation.

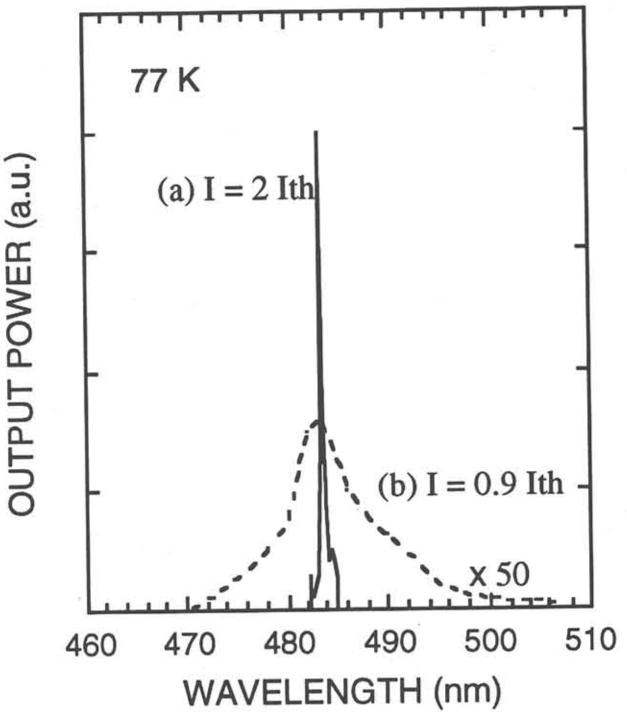

Fig. 3. (a) Lasing and (b) spontaneous emission spectra at 77 K under pulsed operation.

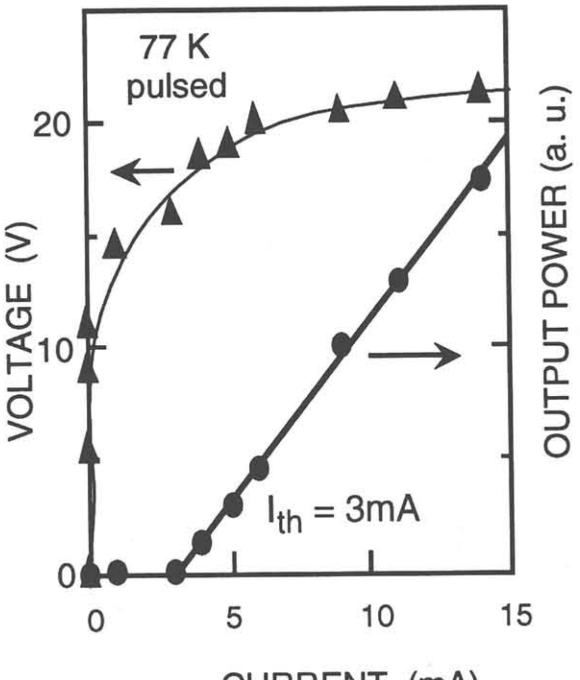

Fig. 2. Current-versus-light-output and current-versus-voltage characteristics for the blue vertical-cavity surface-emitting laser at 77 K under pulsed operation.

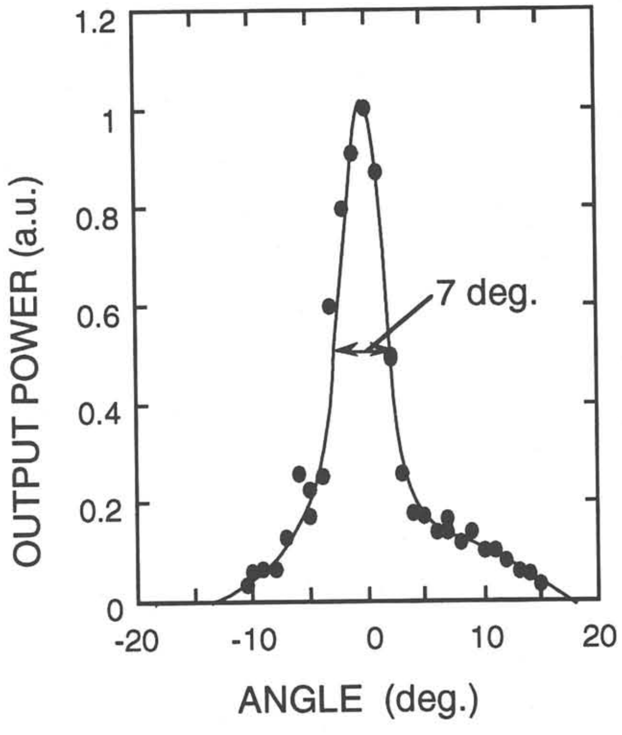

Fig. 4. Far-field pattern of the 10-μm-diameter blue vertical-cavity surface-emitting laser.

The far-field pattern of the lasing mode obtained at 77 K is shown in Fig. 4. The far-field radiation angle is as narrow as 7° above the threshold, which is in good agreement with the calculated result[5] and indicates the spatial coherence expected for VCSEL emission.

We investigated a polarization of the output light in the blue VCSEL diodes using Glan-Thomson prism. The dependence of the output power on the rotation angle is shown in Fig. 5. The large variation of the output power indicates a linear polarization and a laser operation in blue VCSEL diodes although the extinction ratio was about 50 % due to a multi-transverse-mode.

4. CONCLUSIONS

In conclusion, we have reported the demonstration of electrically pumped lasing from a CdZnSe/ZnSe blue vertical-cavity surface-emitting laser. Lasing was achieved at the wavelength of 484 nm at 77 K with a very low-threshold current of 3 mA. The far-field radiation angle was as narrow as 7° above threshold, which indicates the spatial coherence expected for VCSEL emission. This work opens the door to a broad range of new device applications of II-VI materials.

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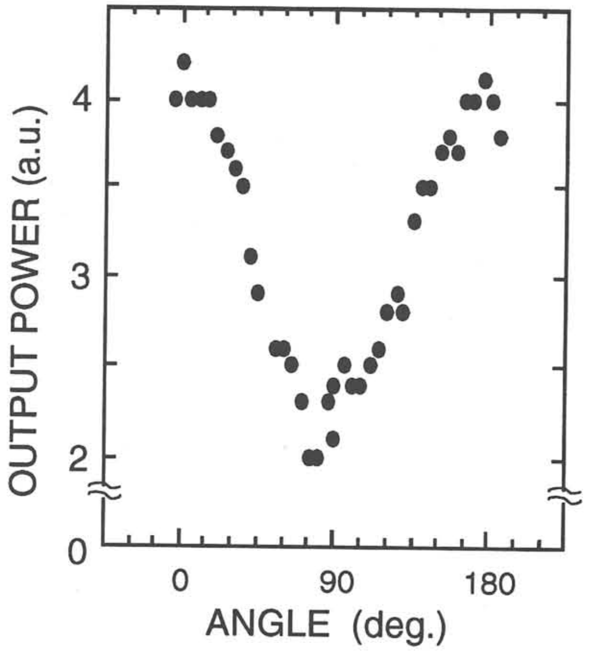

Fig. 5. The polarization of the blue vertical-cavity surface-emitting laser