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Demonstration of a ZnO/MgZnO-based one-dimensional photonic crystal multiquantum well laser

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A ZnO/MgZnO-based one-dimensional photonic crystal multiquantum well laser operating at an emission wavelength of 360.7 nm is demonstrated. The photonic crystal providing optical feedback was fabricated in the form of parallel grooves with a period of 277.3 nm and a depth of 100 nm in a Si_3N_4 layer deposited directly on the epitaxial material. At a temperature of 11 K, 16 mW peak power is emitted from the laser surface, and the threshold intensity amounts to 0.33 MW/cm^2. From temperature-dependent output power versus pump intensity curves, we deduced a T_0 of 60 K and a maximal operating temperature of 135 K.

Very intense research on ZnO and its ternary alloys with CdO and MgO has recently led to various reports on optical light emitters such as light emitting diodes,[1] optically pumped lasers,[2–6] and random lasers.[7,8] Unfortunately, most of these reports are somewhat vague concerning the amount of emitted light, as well as on the temperature dependence of important device parameters such as pump threshold or spectral linewidth of the emission. In order to close this gap, we fabricated a laser which operates intrinsically single mode, and whose emission characteristics can be easily recorded as a function of pump intensity and temperature. Consequently, we present here a one-dimensional photonic crystal (PC) laser,[9] where optical feedback is provided via a photonic bandgap in a Si_3N_4 layer deposited on top of the active region of the device. This method allows at the same time for great design flexibility in terms of optical coupling, overlap factor, and periodicity; but it results also in an extremely well-defined lasing behavior. The finalized device was characterized at temperatures ranging up to 135 K, where it stopped lasing due to a too large mismatch between the photonic bandgap and the center of the gain peak.

Crystal growth of the layers relied on the molecular beam epitaxy on a *C*-face sapphire substrate using metallic Zn and Mg sources and an O_2 plasma cell. The layer structure consists of a 20 nm ZnO buffer layer, followed by a 400 nm thick $Mg_{0.3}Zn_{0.7}O$ lower cladding, a 30 nm thick $Mg_{0.2}Zn_{0.8}O$ waveguide layer, a nominally 93 nm thick $ZnO/Mg_{0.2}Zn_{0.8}O$-based multiquantum well (multi-QW) active region, another 30 nm $Mg_{0.2}Zn_{0.8}O$ waveguide layer, and a 50 nm thick $Mg_{0.3}Zn_{0.7}O$ top cladding layer. The active region itself consists of ten ZnO QWs with a thickness of 3 nm separated by 7 nm thick $Mg_{0.2}Zn_{0.8}O$ barrier layers. Additional details on the fabrication and the basic luminescence characterization on such multi-QW material can be found in Ref. 10. The entire layer stack was then covered with a plasma-enhanced chemical vapor deposited 150 nm thick Si_3N_4 host layer for the PC. Figure 1 shows refractive index profiles through all layers including the Si_3N_4. Refractive index values were taken from Schmidt *et al.*[11] and—where necessary—extrapolated to a photon energy of 3.43 eV (361 nm). Waveguide simulations with (red triangles) and without (blue circles) the PC layer are also presented. Taking an average refractive index for the PC layer $[n_{PC} = \frac{1}{2}(n_{air}+n_{Si_3N_4})]$ showed that the overlap with the QWs is sufficiently high (10% in average) so that propagation takes place mainly in the QW region. However, there is also a substantial optical overlap with the PC layer, namely, of the order of 25%. Since this layer provides the wavelength selection, this is a crucial feature for single-mode operation of the laser. After deposition of the Si_3N_4 layer, a one-dimensional PC consisting of parallel grooves with a period of 277.3 nm (third photonic bandgap) and 100 nm depth was holographically defined using a Kr^+ laser ($\lambda = 413.1$ nm). In order to improve the stability of the corrugation pattern written in the photoresist, a 10 nm thick Ge layer was evaporated from both sides under a shallow angle of 20°. Transfer into the Si_3N_4 layer was accomplished via reactive ion etching using first an O_2 plasma for the resist and, subsequently, a CHF_3 plasma for the Si_3N_4 layer. The desired period of the

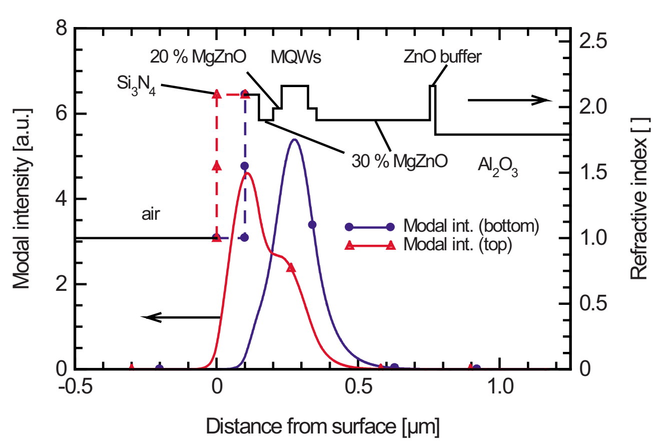

FIG. 1. (Color online) Refractive index profiles of the sample with (red dashed, triangles) and without (blue dashed, circles) the PC layer. The corresponding mode profiles for top and bottom of the PC layer are shown as continuous red (triangles) and blue lines (circles), respectively.

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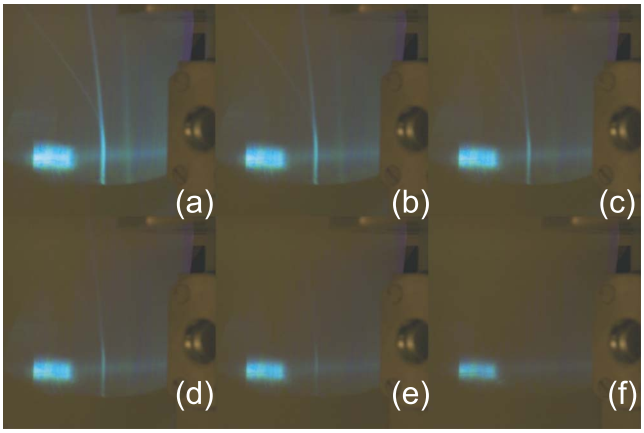

FIG. 2. (Color online) [(a)–(f)] Picture series showing the laser's far field at six different levels of optical pumping; namely, at (a) 1.2 MW/cm^2, (b) 1.0 MW/cm^2, (c) 0.8 MW/cm^2, (d) 0.6 MW/cm^2, (e) 0.4 MW/cm^2, and (f) 0.2 MW/cm^2.

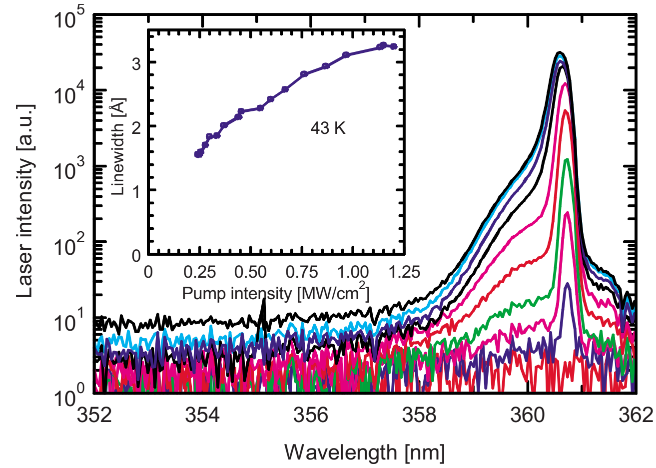

FIG. 3. (Color online) Surface emitted laser spectra vs optical pump power at ten representative pump intensities between 0.3 and 1.2 MW/cm^2 in steps of roughly 0.1 MW/cm^2. The inset shows laser linewidth as a function of pump power. A minimal linewidth of 1.5 Å was observed.

PC was verified by measuring the diffraction angle of a green HeNe laser at 543.5 nm.

Characterization of the devices relied on optical pumping using a pulsed N_2 laser (VSL-337i) at a wavelength of 337.1 nm, a peak power of 36 kW, and a pulse repetition rate of 8 Hz. The typical pulse length of such a laser is 4 ns, giving rise to a duty cycle of 3.2×10^{-8}. An adjustable neutral density filter for varying the pump intensity and a parabolic mirror to focalize the beam into a narrow stripe of roughly 3.6×0.1 mm^2 resulted in maximal pump intensities of the order of 10 MW/cm^2. The sample was mounted directly on the cold finger of a liquid He flow cryostat and held under an angle of roughly 50° between the incoming N_2 laser beam and the sample's surface normal, similar as in Ref. 6. Through Lambert's cosine law and the limited transmission of the quartz windows in the cryostat, we lost about another factor of 8 in pump intensity, so that the actually achieved maximal value dropped from 10 down to 1.25 MW/cm^2. As shown in Figs. 2(a)–2(f), we observed on a fluorescent screen the reflected pump beam at the left (big rectangular spot) and the single-mode laser emission as a sharp, nearly vertical line on the right. For decreasing pump intensity, the sharp line started to dim while only a small intensity difference was observed for the pump beam. Finally, the line disappeared completely at the lasing threshold while the pump beam, although becoming weaker too, was still relatively well visible.

For a quantitative analysis, the surface emission of the PC laser was directed to a quartz lens and focalized onto the 20 μm wide entrance slit of a grating spectrometer (Jobin Yvon HR460). Data acquisition was accomplished via a liquid N_2-cooled 1024 element Si photodiode array placed at the output of the spectrometer. The spectral resolution of this setup is of the order of 0.5 Å. In Fig. 3, we present emission spectra as a function of pump intensity ranging from below threshold to the maximal value. The laser, which was held at a temperature of 43 K, emits at a center wavelength of 360.7 nm. At high pump intensity, a small broadening toward shorter wavelengths is clearly seen; it can be explained by band filling effects which overcompensate the expected redshift due to device heating. The inset shows linewidth versus pump intensity data. The minimum linewidth of this particular device just above threshold is 1.5 Å. This value increases to roughly 3.3 Å at the highest possible pump intensity. Together with the stripe-shaped and very sharp far field distribution, the narrowness of the laser line shown in Fig. 3 is a clear proof for the single-mode operation of this device. We investigated also the temperature dependence of the emission. Surprisingly, only a very small wavelength change could be observed between 11 and 135 K. This is in contrast to what was observed in our earlier publication using a third order distributed feedback ZnO laser: in that case, we had measured a wavelength shift of roughly 3 Å between these two temperatures. One has to take into account, however, that the active region of that earlier device used a single ZnO thin film having an optical overlap of 80%. That laser was therefore strongly affected by the high dispersion right at the bandgap of the ZnO active region. In the present multi-QW laser containing large amounts of high bandgap MgZnO alloys and having an emission at 3.43 eV, all relevant bandgap energies ($Mg_{0.3}Zn_{0.7}O$:3.9 eV, $Mg_{0.2}Zn_{0.8}O$:3.7 eV) are relatively far away and the optical overlap with the ZnO QWs is only 10%, so that temperature-dependent dispersive effects are much smaller.[12] Finally, a substantial fraction of the optical mode (27% in average) propagates in the Si_3N_4 layer having an even larger bandgap of ~5 eV and showing practically zero dispersion.

Figure 4 shows the temperature dependence of the integrated laser power as a function of pump intensity between 11 and 135 K. The curves show a linear dependence without any kinks, thus following the textbook behavior of a single-mode device. At low temperature, an average optical power of 0.52 nW was measured with a thermopile detector. Taking into consideration the duty cycle of the pump laser (3.2×10^{-8}), an optical peak power of 16 mW was deduced. The threshold intensity for 11 K was of the order of 0.33 MW/cm^2 and increased gradually to 1.05 MW/cm^2 at 135 K. Most of the temperature behavior revealed in these measurements is dominated by the slight wavelength mismatch between the photonic bandgap and the gain peak. Such a mismatch is already present at 11 K and becomes increasingly large when going toward 135 K. This is also well reflected by the dependence of the threshold intensity as a function of temperature: there is a relatively small change

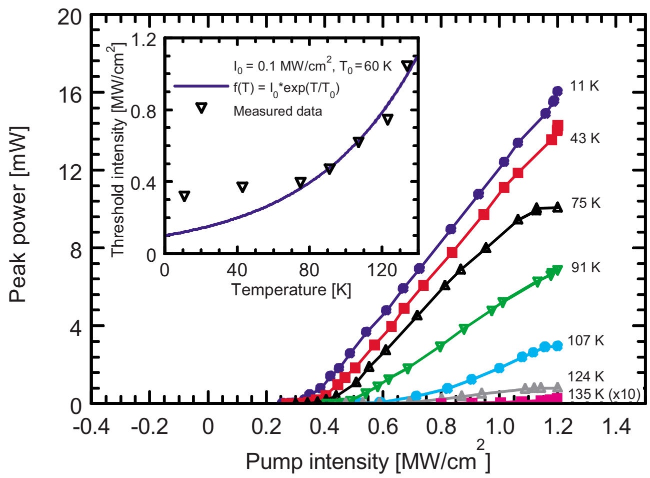

FIG. 4. (Color online) Integrated optical output power as a function of optical pump intensity for temperatures of 11, 43, 75, 91, 107, 124, and 135 K (×10). The inset shows threshold intensity vs temperature and a fit to an exponential function (only points between 75 and 135 K taken into account) resulting in T_0=60 K.

until 75 K; then an increasingly rapid increase in the lasing threshold accompanied by a decrease in the slope efficiency follows. The inset of Fig. 4 shows the measured threshold values as a function of temperature and a fit for the points above 75 K, revealing a T_0 value of 60 K. For the temperature range below 75 K, a much larger (and thus more favorable) value for T_0 would have been found. This is in line with the temperature tuning of the gain peak, which starts to accelerate at about this critical temperature. For this particular PC laser, T_0 is therefore a figure of merit for the (mis-) match between photonic bandgap and gain peak rather than for the design or quality of the epitaxial layers.

The pump intensity dependence of the gain peak at 11 K is displayed in Fig. 5. These data were measured at a spot with comparable quality of the PC but lower luminescence efficiency than the lasing spectra. Especially, the high pump power peaks show a pronounced dip around 360 nm, which we attribute to the third photonic bandgap of the PC. Its estimated width of 2 nm (coupling constant κ_{meas} $=600$ cm^{-1}) agrees well with the expected theoretical value (κ_{th}=550 cm^{-1}, resulting in 1.7 nm) based on refractive index calculations ($\Delta n_{eff}=3.67\times10^{-2}$) and effective third order Fourier components of the PC. Similar to the behavior of the gain maximum in a ZnO thin film distributed feedback laser, a pronounced acceleration of the temperature tuning was observed for temperatures above 75 K.[6]

In conclusion, we have presented an optically pumped ZnO/$Mg_{0.2}Zn_{0.8}O$-based PC surface emitting laser with a peak output power of 16 mW at 11 K and a minimal pump threshold intensity of 0.33 MW/cm^2. The device lased in a single mode up to 135 K and revealed a characteristic temperature of T_0=60 K. Its spectral linewidth could be lowered to a recorded small value of 1.5 Å at low pump intensity. Due to a strong diffraction at the PC, the far field distribution showed a very sharp vertical line.

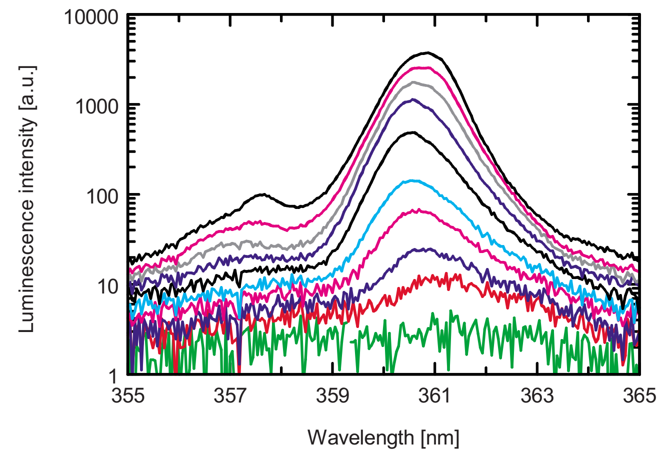

FIG. 5. (Color online) Pump intensity dependence of the luminescence spectrum at 11 K (from 0.3 to 1.2 MW/cm^2 in steps of about 0.1 MW/cm^2).

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