ZnO random laser diode arrays for stable single-mode operation at high power

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(Received 30 September 2010; accepted 25 November 2010; published online 16 December 2010)

An array of highly disordered *i*-ZnO:Al(3%) random cavities, which have 1 μm width, 150 nm thickness, and 2 mm length, is sandwiched between *n*-ZnO:Al(5%) and *p*-GaN/sapphire substrate to form an array of heterojunctions. The random cavities, which are electrically isolated and optically coupled with the adjacent random cavities, are laterally separated by a 1 μm wide Al_2O_3 dielectric insulator. Stable single-mode operation is observed from the laser diode array under high electrical pumping (i.e., $>6\times$ threshold current) at room temperature. © *2010 American Institute of Physics*. [doi:10.1063/1.3527922]

Significant efforts have been made to achieve electrically pumped random lasers using ZnO as the lasing media.[1–5] This is because ZnO (1) exhibits high excitonic gain at room temperature and (2) can realize highly scattered random media to support coherent optical feedback.[6] For example, patterned ZnO nanoclusters were used as the intrinsic layer of a *p-i-n* heterojunction to sustain random lasing action.[1,2] Highly disordered ZnO thin films were also utilized as the random cavities of metal-oxide-semiconductor[3] and semiconductor-oxide-semiconductor heterostructures[4] as well as embedded MgZnO/ZnO/MgZnO quantum well[5] to achieve coherent random lasing under electrical excitation. Nevertheless, due to the lack of control of the random modes, electrically pumped ZnO random lasers still suffered from the problems of poor directionality and multiple-mode operation. These will definitely impair the usefulness of random lasers in practical applications. In this letter, we propose to realize an array of ZnO random laser diodes, which has a strong interelement coupling of random modes, to achieve stable single-mode operation at high output power.

Figure 1(a) shows a schematic of the proposed *n*-ZnO:Al(5%)/*i*-ZnO:Al(3%)/*p*-GaN heterojunction laser array. An ~150 nm thick *i*-ZnO:Al(3%) thin film was deposited on a *p*-GaN:Mg/sapphire substrate (purchase from Semiconductor Wafer Inc., Taiwan) by filtered cathodic vacuum arc (FCVA) technique at a substrate temperature of 150 °C.[7] The *p*-GaN:Mg layer is also used as a hole injection layer of the heterojunction. The sample was annealed at 900 °C in open air for 20 min to obtain grains and voids inside the *i*-ZnO:Al(3%) layer to support coherent random lasing. An array of photoresist line-mask, which has a 1 μm width and an 800 nm thickness as well as a 1 μm separation, was coated onto the *i*-ZnO:Al(3%) thin film. This is the smallest line-mask that can be formed by photolithography to fabricate the laser diode array. The sample underwent ion-beam etching for 15 min at an etching rate of ~10 nm/min to form an array of highly disordered random cavities. An ~120 nm thick Al_2O_3 was chosen as an isolation layer to deposit onto the etched surface by electron-beam evaporation. This is because the wide bandgap (~6.0 eV) and large refractive index (~1.78) of Al_2O_3 can maximize the interelement coupling of the laser diode array. After the removal of photoresist, a strip of ZnO:Al(5%) with length, width, and thickness of 2 mm, 20 μm, and 100 nm, respectively, was deposited by the FCVA technique onto the sample as an electron injection layer. Hence, a heterojunction array of ten highly disordered ZnO:Al(3%) random

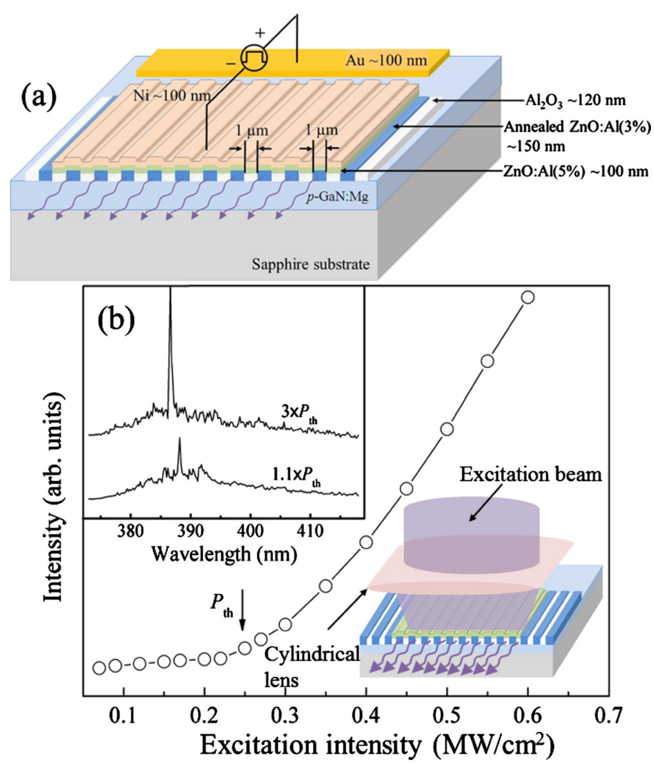

FIG. 1. (Color online) (a) Schematic of a ZnO random laser diode array. (b) Light-light curve and emission spectra measured from the edge of the ZnO random laser array under optical excitation. Metal contacts have not been deposited to the sample for this optical experiment.

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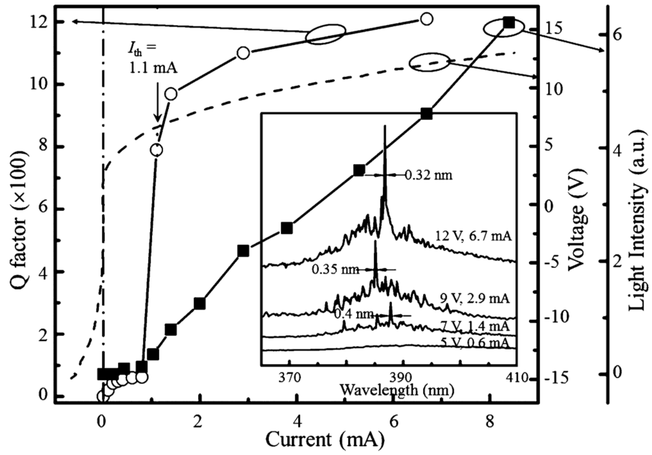

FIG. 2. Voltage-current curve, light-current curve, and Q-factor vs injection current of the ZnO random laser diode array. The insert plots the EL spectra measured from the edge of the laser diode array at different bias conditions.

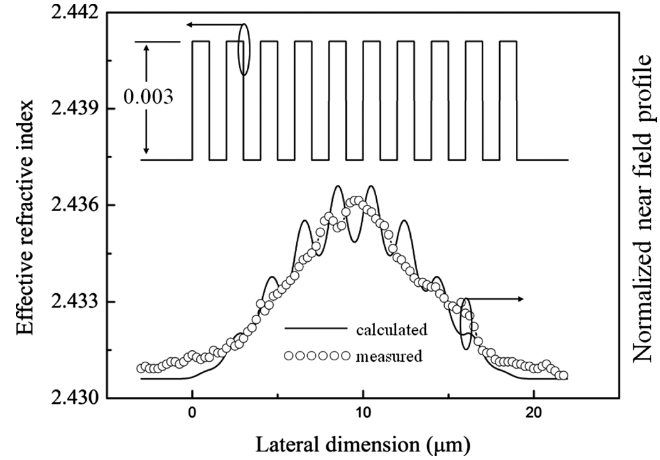

FIG. 3. Measured (circles) and calculated (solid-line) near-field patterns from the edge of the laser diode array biased at $6\times I_{th}$. Lateral distribution of effective refractive index used for the calculation is also shown in the figure.

cavities was formed. The number of random cavities can also be increased with the width of the ZnO:Al(5%) stripe. It can be shown that the effective refractive indices of n-ZnO:Al(5%)(100 nm)/i-ZnO:Al(3%) ×(150 nm)/p-GaN:Mg and ZnO:Al(5%) ×(100 nm)/Al_2O_3(150 nm)/p-GaN:Mg dielectric layers are 2.4411 and 2.4374, respectively, at an operating wavelength of ~385 nm. In this case, the penetration length of the evanescent wave into the isolation layer can be estimated to be ~0.8 μm. As the random cavities have a separation of 1 μm, strong interelement coupling should be obtained from this design of laser diode array. Subsequently, an ~100 nm thick Ni and an ~100 nm thick Au were coated onto the n-ZnO:Al(5%) strip and p-GaN:Mg substrate, respectively, by electron-beam evaporation.

Figure 1(b) shows the light-light curve and photoluminescence spectra of the sample without the deposition of metal contacts. The sample was excited by a 355 nm pulsed (10 Hz, 6 ns) Nd:YAG (yttrium aluminum garnet) laser at room temperature. The laser beam was focused to a strip with ~20 μm width by a cylindrical lens, and the lasing emission was collected from the edge of the sample. It is observed that a kink appears in the light-light curve for pump intensity P equal to a threshold value of P_{th} ~0.26 MW/cm^2. Furthermore, a single peak is emerged from the broadened emission spectrum for P larger than P_{th}. These imply that the sample exhibits random lasing action under optical excitation.[8] For P increases to $\sim 3\times P_{th}$, which is the maximum damage power of the sample, a stable single-mode operation can still be maintained. The emission spectra of the sample at $P\sim 1.1\times P_{th}$ and $\sim 3\times P_{th}$ are also shown in the inset of the figure. Stable single-mode operation of the laser array at a large value of P has indicated that (1) only one dominant random mode is excited from each of the random cavities, and (2) the dominant random modes supported by the random cavities have the same wavelength due to the strong interelement coupling of the laser array.[9]

Figure 2 plots the voltage-current and light-current curves as well as Q-factor versus current of the ZnO laser diode array. The diode array was driven by a rectangular pulse voltage source with repetition rate and pulse width of 7.5 Hz and 80 ms, respectively. The diode array exhibits a diodelike rectifying current-voltage characteristic with a turn-on voltage of ~5 V. It is also observed that a kink appears in the light-current curve for injection current I equal to a threshold value of I_{th} ~1.1 mA. This is consistent with the measured Q-factor of the heterojunction as for $I\sim I_{th}$, the value of Q-factor jumps from ~40 to ~1000 and reaches ~1200 at $I\sim 6.7$ mA. Figure 2 also shows the electroluminescence (EL) spectra of the diode array. There is only one dominant peak emerged from the EL spectra at I equal to or larger than I_{th}. In addition, full-width at half-maximum (FWHM) of the lasing peak $\Delta\lambda$ decreases from 0.4 nm at I ~1.4 mA to 0.32 nm at $I\sim 6.7$ mA. This implies that the electrical energy is only channeled to the dominant random mode so that $\Delta\lambda$ decreases with the increase in I. On the other hand, although the position of the dominant mode is stable (i.e., the corresponding value of $\Delta\lambda$ approaching the noise limit) at a value of I, hopping of dominant mode is observed for the change in I. This may be due to the carrier induced refractive index change inside the random cavities as the thermal effect is less significant for the laser diode array under pulsed operation.

Near-field pattern (circle) measured from the edge of the ten ZnO:Al(3%) highly disordered random cavities under electrical pumping at $I\sim 6\times I_{th}$ is plotted in Fig. 3. The near-field pattern, which has a single-lateral-mode profile with a FWHM of ~10 μm, was recorded from an Olympus BH2-UMA microscope with 1000× magnification. The near-field pattern reveals no fine structure that could be used to identify the individual random cavities. Figure 3 also shows the calculated fundamental near-field pattern (solid-line) by using effective index method[10] and the effective refractive index profile of the laser diode array used in the calculation. It is noted that envelope of the calculated near-field pattern is roughly matched with the measured near-field pattern. Hence, the array of ten highly disordered random cavities supports stable fundamental-lateral-mode operation, and the design of laser diode array has substantial interelement coupling. Figure 4 plots the normalized far-field emission patterns versus different bias conditions. A single-lobed far-field pattern is maintained over the operation conditions, and the variation of the FWHM of the far-field pattern is less than 1°. Hence, we have proved that the proposed ZnO laser diode

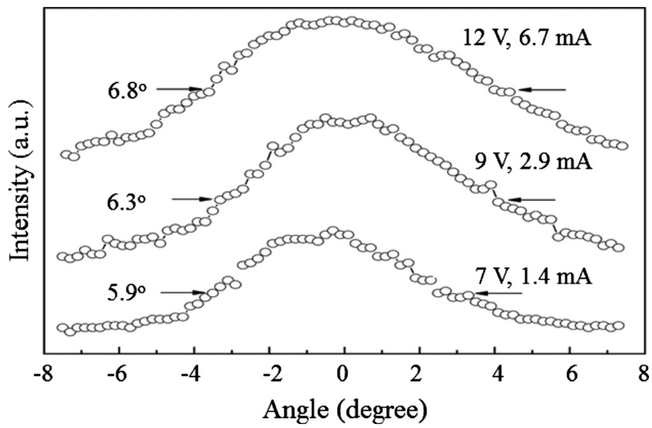

FIG. 4. Normalized far-field patterns measured from the edge of the laser diode array under different bias conditions.

array can sustain a stable single-mode operation at high power.

It is expected that the lasing spectra observed from the laser diode array are arisen from the strong interelement coupling of the dominant random modes. The dominant random modes, which are generated from the ten individual highly disordered ZnO:Al(3%) random cavities, should have the same wavelength and closed-loop cavity length L to achieve a stable single-mode operation. Hence, it is possible to deduce the value of L by power Fourier transform (FT).[7] Figure 5 shows the power FT of the laser diode array versus bias voltage. It is observed that L reduces with the increase in bias voltage and is saturated at ~ 4.1 μm. If we assume that the closed-loop random modes have a two-dimensional circular shape located inside the plane of the heterojunctions, the shortest diameter $d(=L/\pi)$ will be ~ 1.3 μm wide; see also the insert of Fig. 5. This value of d, which is close to the width of the random cavities, represents a closed-loop random mode with the highest modal gain. However, the excitation of side modes with L larger than 4.1 μm will not be obtained due to their relatively low modal gain.[8] This finding of d from the laser diode array is consistent with the assumptions that the ten individual random cavities have the same wavelength and L. Otherwise, if L is smaller than 4.1 μm, excitation of side modes can be observed due to the (1) increase in the modal gain of the side modes and (2) reduction in interelement coupling. Furthermore, if L is larger than 4.1 μm, the threshold of the laser diode array can be significantly increased.

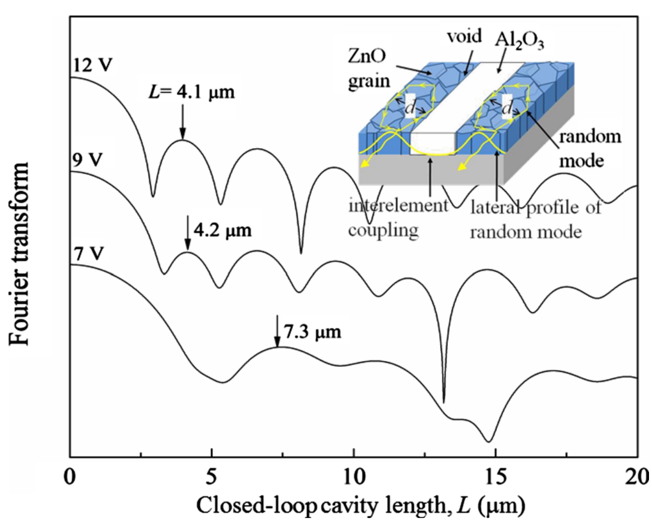

FIG. 5. (Color online) Power FT of the edge emission spectra of the laser diode array at different bias conditions. The inset diagram explains the interelement coupling of closed-loop random modes between adjacent random cavities.

Laser diode arrays with 14, 20, and 25 random cavities were also fabricated for comparison. It can be shown that all the laser diode arrays sustain a stable single-mode operation at high power (i.e., $I > 6 \times I_{th}$). However, the wavelength of the dominant random mode is less controllable due to the (1) nonuniform distribution of optical gain across the laser array and the (2) variation of interelement coupling between the adjacent random cavities. In conclusion, we have fabricated arrays of n-ZnO:Al(5%)/i-ZnO:Al(3%) random cavities/p-GaN:Mg heterojunctions. Al_2O_3 was selected as the dielectric insulator in order to achieve large electrical isolation and strong optical interelement coupling between the adjacent random cavities. Room-temperature stable single-mode operation has been obtained from the proposed laser diode arrays under high electrical excitation (i.e., $> 6 \times I_{th}$).

This work was supported by the HK PolyU grant (Grant No. 1-ZV6X), SUTD grant (Grant No. SRG EPD 2010-003), and Loreal Singapore for Women in Science National fellowship.

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