AIP Applied Physics Letters

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Citation: Applied Physics Letters **107**, 231108 (2015); doi: 10.1063/1.4937472
View online: http://dx.doi.org/10.1063/1.4937472
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/107/23?ver=pdfcov
Published by the AIP Publishing

APPLIED PHYSICS LETTERS **107**, 231108 (2015)

Fabry-Perot resonance enhanced electrically pumped random lasing from ZnO films

P. N. Ni,[1,2] C. X. Shan,[1,3,a)] S. P. Wang,[1] Y. J. Lu,[3] B. H. Li,[1] and D. Z. Shen[1,a)]
[1]*State Key Laboratory of Luminescence and Applications, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 130033, China*
[2]*OPTIMUS, School of Electrical and Electronic Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798*
[3]*School of Physical Engineering, Zhengzhou University, Zhengzhou 450052, China*

(Received 17 September 2015; accepted 27 November 2015; published online 10 December 2015)

Fabry-Perot (F-P) resonance has been introduced into Au/MgO/ZnO structure in order to improve the performance of electrically pumped random lasing in this structure. It is found that the lasing threshold of this structure is significantly reduced by introducing the F-P resonance due to the better optical confinement. Meanwhile, this structure shows improved random lasing output characteristics with less random lasing modes and strong dominant output mode due to the gain competition process. The results demonstrate that introducing F-P resonance into the random media provides an effective strategy towards controllable, high performance electrically pumped random lasers. © *2015 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4937472]

During the past decades, random lasers have received extensive research interest both in theory and in experiment owing to their rich underlying physics as well as various potential applications in imaging, sensing, display, medical diagnostics, etc.[1–4] So far, random lasing has been widely observed and studied in many kinds of materials including semiconductors, dye molecules, rare-earth ions, biological tissues, and optical fibers.[5–9] Moreover, random lasers have covered a broad emitting wavelength bands from ultraviolet to middle-infrared region.[10–13] In contrast to the conventional laser, the optical feedback inside the random laser system is provided by multiple scattering rather than a mirror-based cavity. This feature makes random laser an attractive stimulated emission source with simple structure, small volume, and low fabrication cost.[14–16] However, due to the considerable scattering loss and the absence of a well-defined cavity, random lasers usually show relatively high threshold, multiple emission modes with poor directionality, which impair their practical usefulness greatly. To address these problems, various kinds of techniques have been proposed and employed to reduce the threshold of the random lasers as well as to control their spectral and spatial output characteristics, such as using metal plasmonic enhancement, increasing optical confinement by introducing waveguide structures or external mirrors, optimizing the optical pump profile, etc.[17–20] Among those pioneering works, introducing F-P resonance in random laser system has been demonstrated to be a simple and effective method to reduce its threshold, suppress the lasing modes, and improve its directionality,[21–23] which shows a promising way towards controllable random lasers. However, up to now, this strategy is only proved effective in optically pumped random lasers. As for the electrically pumped random laser, which is of more practical application importance, very few reports can be found.[19]

In this paper, F-P resonance has been introduced into ZnO-based metal-insulator-semiconductor (MIS) structure, and the electrically pumped random lasing characteristics of this structure have been studied. It is found that introducing F-P resonance into the electrically pumped random laser system can effectively improve the lasing performance by reducing the lasing threshold and improving the lasing output characteristics.

To fabricate the ZnO-based MIS structures, a 550 nm ZnO film was first grown on a double polished *a*-plane sapphire substrate using a VG V80H plasma-assisted molecular-beam epitaxy (MBE) technique. 99.9999% elemental zinc and 99.999% O_2 gas were used as the precursors for the growth. The O_2 gas was activated in an Oxford Applied Research plasma cell (Model HD25) with radio frequency operating at 13.56 MHz at a fixed power of 300 W. The chamber pressure was fixed at 2.5×10^{-5} mbar during the growth process. The as-grown ZnO film shows *n*-type conductivity with an electron concentration of $3.2 \times 10^{18}\,cm^{-3}$ and a Hall mobility of $65\,cm^2\,V^{-1}\,s^{-1}$. Then, a 100 nm MgO layer, of which the resistivity is too high to be measured by our Hall measurement system, was deposited onto the ZnO film in a reactive radio-frequency magnetron sputtering technique. The details of the deposition conditions can be found elsewhere.[24] Finally, an Au layer and In layer were deposited onto the MgO and ZnO layer by vacuum evaporation acting as electrodes, respectively.

The electrical properties of these films were characterized in a LakeShore 7707 Hall measurement system. The reflectance spectra were measured in a Perkin Elmer Lambda-1050 spectrophotometer. The current-voltage (*I*– *V*) characteristics of the structures were measured using a Keithley 2611 A SourceMeter, and the electroluminescence (EL) characteristics were recorded in a Hitachi F4500 spectrometer with a continuous power source at room temperature.

The inset of Fig. 1 shows the schematic diagram and emission recording geometry of the Au/MgO/ZnO structure.

[a)]Authors to whom correspondence should be addressed. Electronic addresses: shancx@ciomp.ac.cn and shendz@ciomp.ac.cn

The *I-V* characteristics of the structure are shown in Fig. 1, in which the forward bias is defined as the situation that a positive voltage is applied onto the Au electrode. As can be seen, this structure exhibits an obvious rectifying behavior. The emission spectra of this structure under different injection currents are shown in Fig. 2. Under the injection current of 24 mA, a broad emission band at around 390 nm, which is the typical near-band-edge (NBE) emission of ZnO, can be observed. When the injection current is increased to 38 mA, the intensity of this NBE emission increases significantly, meanwhile, some sharp peaks superposed on the broad emission band appear. Further increasing the injection current, more sharp peaks can be observed, and their intensity increases greatly. Moreover, both the intensity and the positions of these sharp peaks change randomly between different measurements. The above phenomenon is the typical random lasing characteristic, which has been widely observed from ZnO MIS structures and *p-n* structures.[18,25–27]

The mechanism of random lasing in the ZnO MIS structures under forward bias has been explained in details in our previous publications.[28,29] Under forward bias conditions, electrons will be blocked and accumulated at the MgO/ZnO interface due to the large conduction band offset between these two layers. In the meantime, optical gain will be provided, while non-equilibrium holes generated in the MgO layer via an impact-ionization process are injected into the ZnO layer under the drive of the bias voltage, and then recombine radiatively with the accumulated electrons. Moreover, closed-loop cavities can be formed randomly through the multiple strong scattering in this structure. The optical gain increases with increasing the injection current, and random lasing will take place once the optical gain is larger than the total loss in the close loops.

To form the F-P resonance in this structure, an Ag reflector employed as the high reflecting mirror of the F-P cavity was bonded onto the surface of the Au electrode, given that the reflectivity of Ag in the range from 375 nm to 400 nm is much larger than that of Au, as shown in Fig. 3. The Ag reflector was fabricated by depositing a 1000 nm thick Ag onto 1 cm × 1 cm glass substrate via thermal

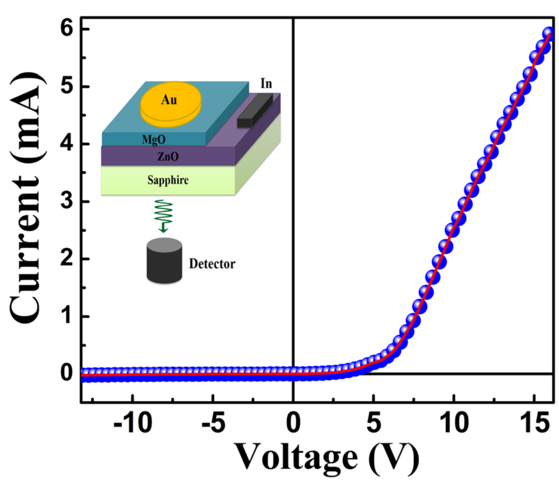

FIG. 1. Current-voltage characteristics of the Au/MgO/ZnO structure, and the inset shows the schematic diagram and emission recording geometry of this structure.

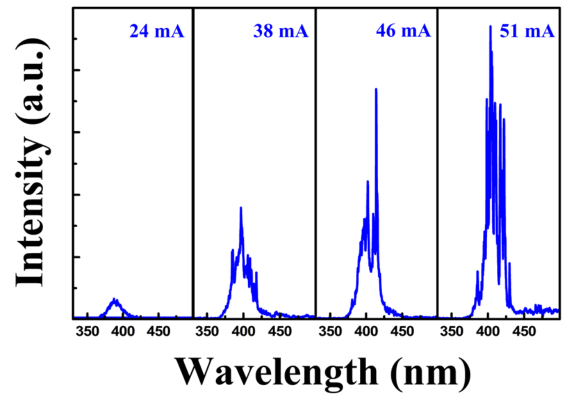

FIG. 2. Emission spectra of the Au/MgO/ZnO structure under different injection currents.

evaporation. Since the refractive index of Al_2O_3 that acts as the substrate is smaller than that of ZnO, the interface between these two layers could provide optical confinement within the ZnO side. Meanwhile, part of the emission light could also be reflected back into the ZnO layer by the interface between the sapphire substrate and the air. Therefore, the ZnO/sapphire interface or the sapphire/air interface could act as one of the F-P cavity facets with a relatively low reflectivity. The optical field distribution of the emission light in the MIS structures both with and without the Ag reflector at the same excitation conditions has been simulated and shown in Figs. 3(c) and 3(d). One can see that the optical field in the ZnO film has been enhanced greatly after introducing the Ag reflector, which means that the optical confinement in this structure has been improved significantly. Meanwhile, obvious standing-wave pattern can be observed in the ZnO film with the Ag reflector, as shown in Fig. 3(d), which verifies the occurrence of the F-P resonance in this structure.

The emission spectra of the Au/MgO/ZnO MIS structure with the F-P cavity are shown in Fig. 4. It can be seen that the MIS structure with the F-P cavity shows much less lasing modes than the structure without the F-P cavity. Moreover, obvious dominant peaks can be observed under different injection currents. These improvements of the output spectral characteristics are due to the facts that the F-P cavity will introduce F-P modes into the MIS structure and then modulate the random lasing action in this structure. To be specific, as soon as these F-P modes spatially overlap with the original random modes, some of the random modes will be suppressed significantly through the gain competition mechanism. In this way, the number of the lasing modes in the MIS structure with the F-P cavity is dramatically reduced, and accordingly some modes are enhanced, giving rise to the dominant lasing modes. The effect of the F-P cavity on the output performance of the random laser can be further demonstrated by the emission spectra taken from the same device by successive measurements, as shown in Fig. 5. It can be seen that only one dominant emission peak can be observed under low injection current, and it hardly changes with time. Furthermore, under higher injection current, although more strong emission peaks can be found, it is worth noting that one of the dominant peaks repeats itself very well between the successive measurements. On the contrary, one also can

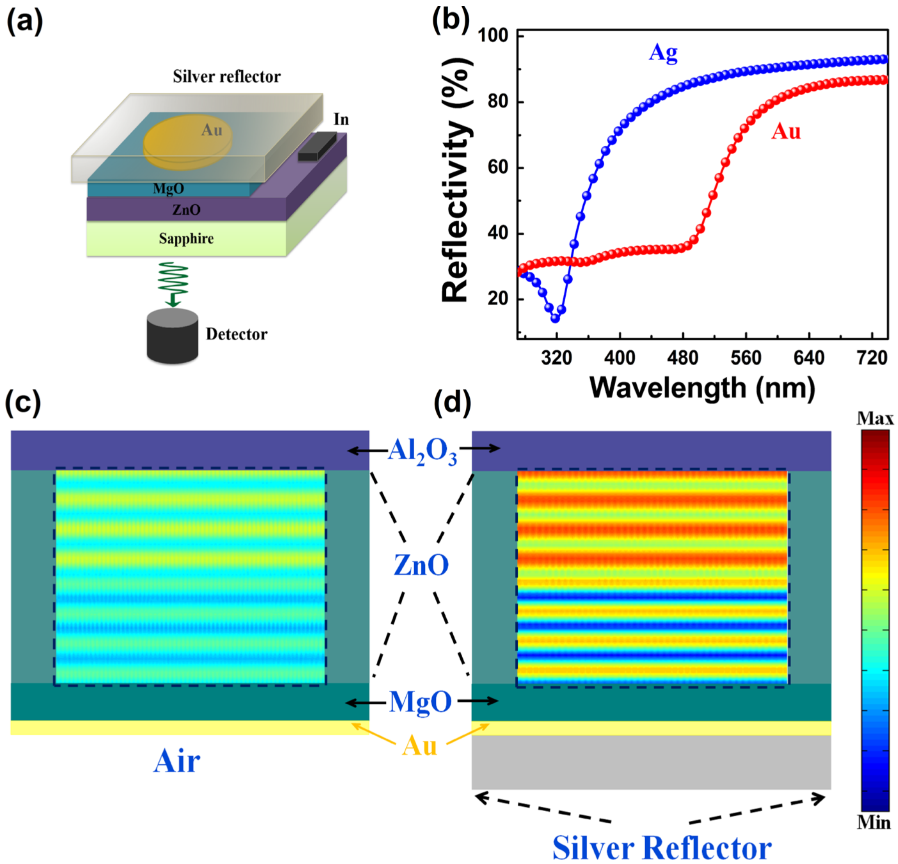

FIG. 3. (a) The schematic diagram and emission recording geometry of the Au/MgO/ZnO structure with the Ag reflector. (b) Reflectance spectra of the Ag reflector and the Au layer; the optical field distribution in the MIS structure without the Ag reflector (c) and with the Ag reflector (d).

see that there are many small emitting peaks, of which both the intensity and the position randomly change from one measurement to another. This temporal chaotic behavior is the typical feature of random lasers, which has been widely observed both in optically pumped and electrically pumped random laser systems.[30–32] Considering that the F-P modes brought in this structure by introducing the F-P cavity will not change from one shot to another, the good repeatability of the dominant emitting peaks from this structure is believed to result from the gain competition process between the random modes and the F-P modes, which further confirm the effect of the F-P cavity on the improvement of the random laser output characteristics. Moreover, after introducing the F-P cavity, the threshold current of the random lasing in the MIS structure has been reduced from ∼29 mA to ∼10.5 mA. This is because the Ag reflector helps to improve the optical confinement within the random gain media, that is, the total optical loss of the random cavities is reduced, which will lead to the reduced threshold of the random lasing.

The controllability over the emission directionality of the random lasers is highly desired in view of many practical applications. Angle-dependent EL spectra of the Au/MgO/ZnO structures under the injection current of 11 mA have been investigated to examine the effect of the F-P cavity on its emission directionality, as shown in Fig. 6. Although this structure still shows multi-directional lasing emitting characteristics, dominant lasing modes can only be observed in the direction perpendicular to the cavity surface. This is because the F-P modes introduced by the F-P cavity exist only in the

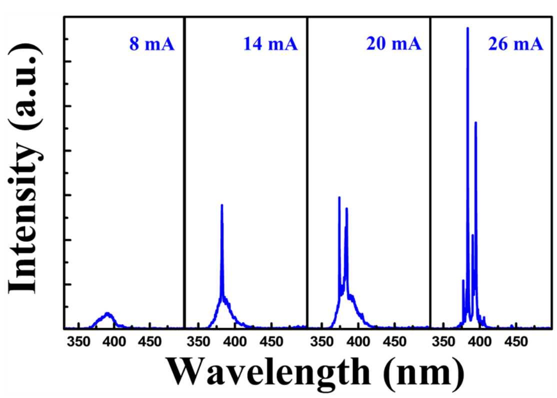

FIG. 4. Emission spectra of the Au/MgO/ZnO structure with F-P cavity under different injection currents.

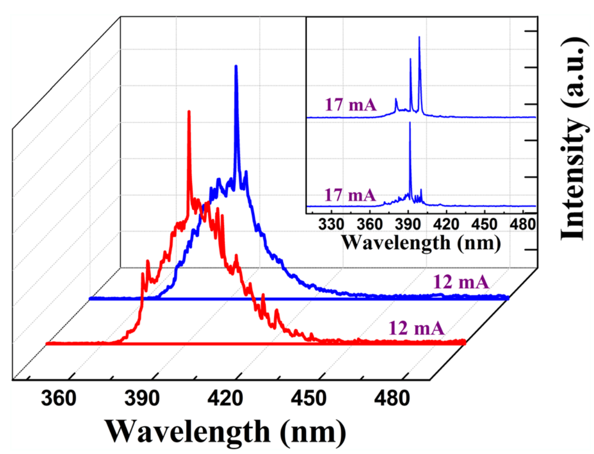

FIG. 5. Emission spectra of the Au/MgO/ZnO structure with F-P cavity under the injection current of 12 mA obtained in two successive measurements, and the inset shows two successive emission spectra of the same device under the injection current of 17 mA.

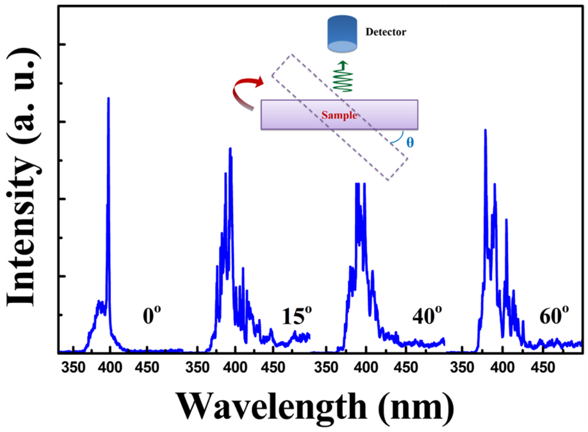

FIG. 6. Emission spectra of the Au/MgO/ZnO structure with F-P cavity under the injection current of 11 mA taken from different recording angles, the inset shows a schematic illustration of the recording configuration.

vertical direction inside this random media. Therefore, some of the random modes in the vertical direction will be enhanced. According to Song *et al.*, the planar cavity helps to improve the directionality of the random lasing, due to the fact that it can provide a large optical wave vector in the vertical direction.[22] Considering that the reflectivity of the F-P cavity facets in this structure has not been optimized, we believe that the directionality of the electrically pumped random lasing in this structure can be further improved by using higher reflecting mirrors to provide stronger F-P resonance.

In conclusion, the performance of electrically pumped random lasers from the Au/MgO/ZnO structure has been improved by introducing the F-P resonance into this structure. Due to the enhancement of the optical confinement caused by the F-P cavity, the random lasing threshold of this structure has been reduced. Moreover, the number of the lasing modes has been reduced resulting from the gain competition process. It is also found that the effect of the F-P cavity on the lasing characteristics is angle-dependent, and dominant lasing modes can only be observed in the vertical direction. The above results demonstrate that introducing F-P resonance into the random media may step forward towards controllable electrically pumped random lasers.

This work was financially supported by the National Basic Research Program of China (No. 2011CB302005), the National Science Foundation for Distinguished Young Scholars of China (No. 61425021), and the Natural Science Foundation of China (Nos. 11374296, 61376054, 61475153, and 61177040).

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