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Tuning the emission of ZnO nanorods based light emitting diodes using Ag doping

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We have fabricated, characterized, and compared ZnO nanorods/p-GaN and n-Zn_{0.94}Ag_{0.06}O nanorods/p-GaN light emitting diodes (LEDs). Current-voltage measurement showed an obvious rectifying behaviour of both LEDs. A reduction of the optical band gap of the Zn_{0.94}Ag_{0.06}O nanorods compared to pure ZnO nanorods was observed. This reduction leads to decrease the valence band offset at n-Zn_{0.94}Ag_{0.06}O nanorods/p-GaN interface compared to n-ZnO nanorods/p-GaN heterojunction. Consequently, this reduction leads to increase the hole injection from the GaN to the ZnO. From electroluminescence measurement, white light was observed for the n-Zn_{0.94}Ag_{0.06}O nanorods/p-GaN heterojunction LEDs under forward bias, while for the reverse bias, blue light was observed. While for the n-ZnO nanorods/p-GaN blue light dominated the emission in both forward and reverse biases. Further, the LEDs exhibited a high sensitivity in responding to UV illumination. The results presented here indicate that doping ZnO nanorods might pave the way to tune the light emission from n-ZnO/p-GaN LEDs. © 2014 AIP Publishing LLC.

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I. INTRODUCTION

Zinc oxide (ZnO) due to its relatively large exciton binding energy of 60 meV, wide direct band gap (3.37 eV), and the possibility of growth in the nanostructure form using several techniques on any substrate has attracted considerable attention as a promising material for optoelectronic devices in the past few years.^{1–4} Since it is difficult to prepare stable p-type ZnO with high hole concentration,^{5,6} researchers have grown n-ZnO nanostructures on other p-type substrates such as GaN,^{6–9} SiC,^{10–12} GaAs,^{13,14} and NiO^{15–17} to provide another way to realize ZnO based p-n heterojunctions. GaN has the same crystal structure (wurtzite) with a small in plane lattice mismatch (1.8%) with ZnO, which makes it as one of the best p-type candidate substrate to fabricate ZnO based heterojunction light emission diodes (LEDs).^{18–21} Several studies have been reported about the electroluminescence (EL) from the n-ZnO/p-GaN heterojunction LEDs operated at forward and reverse biases,^{21–25} but the origin of the EL and the carrier transport mechanism are still under debate. Some researchers have reported that in n-ZnO/p-GaN heterojunction LEDs due to a prevailing electron injection from n-the ZnO towards the p-GaN, radiative recombination mainly originates from defect related states in the p-GaN.^{18,20,25} To use the advantages of the optical transitions of ZnO in order to improve the optoelectronic properties of n-ZnO/p-GaN heterojunction, it is necessary that the radiative recombination occurs in the n-ZnO. To overcome this problem and have more holes injection from the GaN towards the ZnO, the valence band offset (barrier for holes) should be

lowered to a value less than the conduction band offset (barrier for electrons). To the best of our knowledge, there have been few detailed investigations reported about use of doping to improve the optoelectronic properties of n-ZnO nanorods/p-GaN heterojunction based LEDs.^{26–28}

In the present work, we report on the structural, electrical, and optoelectronic properties of n-Zn_{0.94}Ag_{0.06}O nanorods/p-GaN heterojunction based LEDs under different forward and reverse biases and compared it to the case of n-ZnO nanorods/p-GaN heterojunction. Additionally, we investigate the influence of the UV illumination on the optoelectronic properties of the n-ZnO nanorods/p-GaN heterojunction LEDs. The aim of this study is to manipulate the band offsets at the n-ZnO nanorods/p-GaN heterojunction with the help of Ag doping to balance the carrier's injection over the heterojunction to enhance the defect assisted emission in ZnO.

II. EXPERIMENTAL

Commercially available p-GaN substrate was used in this study and all chemicals were purchased from Sigma Aldrich and were of analytical grade and used without further purification. At first, the p-GaN substrate was cleaned by sonication in acetone, deionized water, and isopropanol, respectively. Prior to the growth of the ZnO and the Zn_{0.94}Ag_{0.06}O nanorods on the p-GaN substrate, a 10 and 40 nm thickness of Ni and Au were deposited, respectively, using thermal evaporation on a small part of the p-GaN substrate to act as an ohmic contact. This was followed by annealing at 350 °C for 15 min. Then, the substrate preparation technique developed by Green *et al.*²⁹ was used to improve the quality of the grown nanorods. For the growth of the ZnO and the Zn_{0.94}Ag_{0.06}O nanorods, an equimolar concentration of hexamethylenetetramine

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FIG. 1. Top view and tilted SEM image of (a) and (c) ZnO and (b) $\text{Zn}_{0.94}\text{Ag}_{0.06}\text{O}$ nanorods.

(HMT), zinc nitrate hexahydrate (94%), and silver nitrate hexahydrate (6%) (0.075 M) solutions were prepared and mixed together. Then, the prepared solutions were poured in a beaker and the pre-treated substrates were immersed in the solution with the growth side facing downward. Then, the beaker was sealed and heated in a laboratory oven at 95°C for 5 h and, then, it was allowed to cool down to room temperature. After the growth process, and to remove possible residual salts, the samples were rinsed with deionized water and dried with flowing nitrogen. Then, an insulating layer of Shipley 1805 photo resist (Marlborough, Ma, USA) was spin-coated on samples for filling the spaces between the nanorods. Then, reactive ion etching was used to expose the tips of the nanorods before the deposition of Al top ohmic contact (50 nm).

The structural and morphological properties of the heterojunctions were studied by X-ray diffraction (XRD: Phillips PW 1729 powder diffractometer equipped with $\text{CuK}\alpha$ radiation) and field emission scanning electron microscope (FESEM: LEO 1550 Gemini). The optical characterization of the pure and Ag-doped ZnO nanorods was performed using a Perkin Elmer Lambda 900 UV-visible spectrophotometer. The electrical properties were investigated by semiconductor parameter analyzer (Agilent 4155B) and the EL measurement was performed using Keithley 2400 source to provide a fixed voltage and the emission spectra were

collected using a detector (SR-303i-B). The light emission features of the pure and Ag-doped ZnO nanorods and GaN were studied by micro-photoluminescence (μPL) setup at room temperature. The excitation was performed by a frequency doubled Nd:YVO laser as a continuous wave excitation source, giving a wavelength of $\lambda = 266\text{ nm}$.

III. RESULTS AND DISCUSSION

A. Morphological and structural properties

Figures 1(a)–1(c) show the SEM images of the pure ZnO and $\text{Zn}_{0.94}\text{Ag}_{0.06}\text{O}$ nanorods hydrothermally grown on the p-GaN substrate. It can be seen that relatively well aligned ZnO and $\text{Zn}_{0.94}\text{Ag}_{0.06}\text{O}$ nanorods with hexagonal faces and average diameter of about 50 nm were achieved. Almost no observable differences from the SEM images were recognized for the $\text{Zn}_{0.94}\text{Ag}_{0.06}\text{O}$ nanorods when compared to the ZnO nanorods. To characterize the structure of the n-ZnO nanorods/p-GaN and n- $\text{Zn}_{0.94}\text{Ag}_{0.06}\text{O}$ /p-GaN heterojunctions, the X-ray diffraction (XRD) patterns were taken as shown in Figure 2(a), which indicates that the ZnO and the $\text{Zn}_{0.94}\text{Ag}_{0.06}\text{O}$ nanorods were highly oriented along the c axis as the (002) diffraction peak is intense (JCPDS Card No. 36-1451). Moreover, these x-ray spectra indicate that both Ag-doped and pure ZnO nanorods have the same

FIG. 2. (a) XRD patterns of n-ZnO/p-GaN and n- $\text{Zn}_{0.94}\text{Ag}_{0.06}\text{O}$ /p-GaN heterojunction and (b) Plot of $(\alpha h\nu)^2$ versus $h\nu$ of the ZnO and $\text{Zn}_{0.94}\text{Ag}_{0.06}\text{O}$ nanorods.

out of plane orientation with respect to the GaN substrate. The observed (002) peak of the $\text{Zn}_{0.94}\text{Ag}_{0.06}\text{O}$ nanorods was found to be shifted a little bit towards a lower angle. This is ascribed to the fact that the substitution of the Ag ions with the Zn ions leads to expansion of the ZnO lattice. This is due to the larger ionic size of the Ag ion compared to the Zn ion. No additional peaks related to other impurities phases were observed.

B. Optical properties

The optical band gap of the ZnO and the $\text{Zn}_{0.94}\text{Ag}_{0.06}\text{O}$ nanorods were obtained from the $(\alpha h\nu)^2$ versus $h\nu$ plot shown in Figure 2(b), which was measured using the following equation:³⁰

$$(\alpha h\nu) = A (h\nu - E_g)^{1/2}, \quad (1)$$

where α is the optical absorption coefficient, $h\nu$ is the photon energy, A is a constant coefficient, and E_g is the optical band gap energy. The optical band gap values for the ZnO and the $\text{Zn}_{0.94}\text{Ag}_{0.06}\text{O}$ nanorods, obtained by the extrapolation method were 3.30 eV and 3.21 eV, respectively. So we can conclude that the interaction of Ag states with the ZnO host states resulted in creating an energy donor levels in the band gap that leads to reduce the optical band gap.

C. Electrical properties

Figure 3(a) demonstrates the current-voltage (I-V) characteristics of the n-ZnO nanorods/p-GaN and n- $\text{Zn}_{0.94}\text{Ag}_{0.06}\text{O}$ nanorods/p-GaN heterojunction LEDs. This figure shows an obvious rectifying behaviour with threshold voltages of 3.5 V and 2.0 V, respectively. The schematic diagram of the n-ZnO nanorods/p-GaN heterojunction LED is shown as an inset of Figure 3(a). The series resistance (R_s) of the n-ZnO nanorods/p-GaN and the n- $\text{Zn}_{0.94}\text{Ag}_{0.06}\text{O}$ nanorods/p-GaN heterojunction LEDs can be determined by calculate the slope of the curve of $I/(dI/dV)$ versus I as shown in the inset of Figure 3(b). The value for the pure ZnO nanorods was 244.37 Ω ,

while for the Ag-doped ZnO, it was reduced to 221.85 Ω . It can be seen that by doping ZnO with Ag, the R_s of the heterojunction is decreased, which leads to decrease the threshold voltage of the heterojunction. The thermionic emission current-voltage relationship of a p-n heterojunction is usually written as a function of the applied voltage as³¹

$$I = I_0(\exp(qV/nK_B T) - 1), \quad (2)$$

where I_0 is the saturation current, q is the electronic charge, V is the applied voltage, n is the ideality factor, K_B is Boltzmann's constant, and T is the temperature in Kelvin. The ideality factor (n) can be calculated from the slope of the straight line region of the forward bias $\ln(I)$ - V plot as shown in Figure 3(b). The experimental values of n were calculated 12.16 and 11.07 for the n-ZnO nanorods/p-GaN and n- $\text{Zn}_{0.94}\text{Ag}_{0.06}\text{O}$ nanorods/p-GaN heterojunction, respectively. The ideality factors of these heterojunctions are much larger than that of an ideal heterojunction ($n=1$). Such a high value of n suggests that the transport mechanism is not dominated by the thermionic emission, but consists of other mechanisms like, e.g., defect assisted tunnelling with conventional electron-hole recombination.³¹

D. Optoelectronic properties

1. Performance under forward bias

The EL spectra of the n-ZnO nanorods/p-GaN and n- $\text{Zn}_{0.94}\text{Ag}_{0.06}\text{O}$ nanorods/p-GaN heterojunction LEDs were measured under different forward biases (10–35 V). As shown in Figure 4(a), the EL spectrum of the n-ZnO/p-GaN heterojunction LED shows a violet-blue emission peak centred about 399 nm and a broad emission peak covering the range from 480 nm to 750 nm with low intensity. Figure 4(c) displays that the EL spectrum of the n- $\text{Zn}_{0.94}\text{Ag}_{0.06}\text{O}$ /p-GaN heterojunction LED consisted of a violet-blue emission peak centred about 404 nm and a broad emission peak with high intensity extended from 500 nm to 800 nm. Figures 4(b) and 4(d) demonstrate the integrated

FIG. 3. (a) Current-voltage (I-V) characteristic curve and (b) $\ln(I)$ vs. V plot for extraction n of the n-ZnO/p-GaN and n- $\text{Zn}_{0.94}\text{Ag}_{0.06}\text{O}$ /p-GaN heterojunction LEDs. Insets (a) and (b) show the Schematic diagram and curve of $I/(dI/dV)$ versus I of the n-ZnO nanorods/p-GaN heterojunction.

FIG. 4. EL spectra of the (a) n-ZnO/p-GaN and (c) n-Zn_{0.94}Ag_{0.06}O/p-GaN heterojunction LEDs under forward bias. The integrated emission bands intensity as a function of the forward bias voltage for (b) n-ZnO/p-GaN and (d) n-Zn_{0.94}Ag_{0.06}O/p-GaN heterojunction LEDs. (Inset) The chromaticity coordinate of the n-ZnO/p-GaN and n-Zn_{0.94}Ag_{0.06}O/p-GaN heterojunction LEDs under forward bias.

band intensity of emission peaks versus voltage and as it can be seen, by increasing the forward bias voltage from 10 to 35 V, the violet-blue emission peak was exponentially increased and a red shift in both the n-ZnO/p-GaN and n-Zn_{0.94}Ag_{0.06}O/p-GaN heterojunction LEDs was observed as shown in the inset of Figures 4(a) and 4(c). The integrated band intensity of the broad emission peak in the n-ZnO/p-GaN heterojunction did not increase dramatically but in the n-Zn_{0.94}Ag_{0.06}O/p-GaN heterojunction LED, it was significantly increased. The CIE 1931 colour coordinate measurement for the LEDs under forward bias of 35 V illustrated in the inset of Figures 4(b) and 4(d). As it can be seen the n-ZnO/p-GaN and n-Zn_{0.94}Ag_{0.06}O/p-GaN heterojunction LEDs show blue and relatively white emission light, respectively. To understand the origin and the mechanism of the emissions from the n-ZnO nanorods/p-GaN and the Zn_{0.94}Ag_{0.06}O nanorods/p-GaN heterojunction LEDs, we performed PL measurement and band diagram model. The

room temperature PL spectra of the pure ZnO, the Zn_{0.94}Ag_{0.06}O nanorods and the GaN substrate are shown in Figures 5(a)–5(c). All the spectra were taken at the same excitation power and integration time and are therefore comparable. It can be seen that the ultraviolet (UV) emission, which is called near band edge emission (NBE) and two broad deep level emission (DLE) peaks were observed for the ZnO nanorods and were centred approximately at 375 nm, 520 nm (DLE1, green emission), and 680 nm (DLE2, red emission), respectively. The UV emission is attributed to the recombination of free excitons and the green and red peaks are ascribed to the recombination between the conduction band and zinc interstitial (Zn_i) energy level to oxygen vacancy (V_O) and oxygen interstitial (O_i), respectively.³² The PL spectrum of the Zn_{0.94}Ag_{0.06}O nanorods indicated a red shift in the NBE as expected and it is consistent with the UV-vis data. The PL spectrum of the GaN showed a blue peak centred at 406 nm, which is known

FIG. 5. Room temperature photoluminescence spectra of (a) ZnO nanorods, (b) $\text{Zn}_{0.94}\text{Ag}_{0.06}\text{O}$ nanorods, and (c) GaN substrate.

and is attributed to transition from the conduction band to deep Mg acceptor levels in the p-GaN.²⁵ The band alignment of the n-ZnO/p-GaN heterojunction at zero, forward and reverse biases voltage was drawn with help of the Anderson model⁸ to understand the origins of the emissions, as shown in Figures 6(a)–6(c). Since the carrier mobility in the n-ZnO is higher than that of the p-GaN, electrons could not be blocked in the n-ZnO region and will be injected into the p-GaN site to recombine with holes. Under forward bias, electron and hole barriers are decreased and the electrons in the conduction band of the n-ZnO move towards the p-GaN and the holes in the valence band of p-GaN move towards the n-ZnO. The origin of the violet emission has been not fully understood and is still under debate, for example, Fu *et al.* suggested that this emission can be ascribed to the transition from the conduction band edge of the ZnO to the Mg acceptor level of GaN.^{33–35} According to the PL spectra, the blue emission can be attributed to the transition from the conduction band of the p-GaN to the deep Mg acceptor levels in the p-GaN²⁵ and the broad emission peak is attributed to deep defect states such as oxygen vacancy (V_O) and zinc vacancy (Zn_O) in n-ZnO site.³² It seems that increasing the forward bias voltage leads to increase the carriers and since ZnO has carrier with higher mobility than GaN, most of electron-hole recombination will occur in GaN site, which leads to blue emission for the n-ZnO/p-GaN heterojunction LED. The reduction of the optical band gap of the $\text{Zn}_{0.94}\text{Ag}_{0.06}\text{O}$ in comparison to ZnO, results in decrease of the valence band offset of the n- $\text{Zn}_{0.94}\text{Ag}_{0.06}\text{O}$ /p-GaN heterojunction LEDs compared to the n-ZnO/p-GaN heterojunction LED. This reduction will lead to more holes injection from the GaN towards ZnO and increase the electron-hole recombination in ZnO site. Hence, by increasing the forward bias voltage

FIG. 6. Band alignment of the n-ZnO/p-GaN heterojunction LED at (a) zero, (b) forward, and (c) reverse bias voltage.

the broad emission peak of the n-Zn_{0.94}Ag_{0.06}O/p-GaN heterojunction LED in the visible region is significantly increased.

2. Performance under reverse bias

Figures 7(a) and 7(c) shows the EL spectra of the n-ZnO/p-GaN and n-Zn_{0.94}Ag_{0.06}O/p-GaN heterojunction LEDs under various reverse bias from 15 V to 35 V. It can be seen that n-ZnO/p-GaN and n-Zn_{0.94}Ag_{0.06}O/p-GaN heterojunction LEDs spectra show the violet-blue emission centred at 409 nm and 403 nm, respectively. The integrated band intensity of violet-blue emission peak of the n-ZnO/p-GaN and n-Zn_{0.94}Ag_{0.06}O/p-GaN heterojunction LEDs versus voltage is demonstrated in Figures 7(b) and 7(d). This revealed that by increasing the reverse bias voltage the violet-blue emission peak was increased and it was blue shifted for the case of the n-ZnO/p-GaN and red shifted for n-Zn_{0.94}Ag_{0.06}O-pGaN heterojunction LED, as shown in the inset of Figures 7(a) and 7(b). The CIE 1931 colour coordinate measurements for the

LEDs under reverse bias of 35 V are illustrated in the inset of Figures 7(b) and 7(d). As it can be seen that both the n-ZnO/p-GaN and n-Zn_{0.94}Ag_{0.06}O/p-GaN heterojunction LEDs show blue emission light for this case. Figure 6(c) displays the band alignment of the n-ZnO/p-GaN heterojunction under the reverse bias voltage to illustrate the mechanism of EL. Under reverse bias, since large barriers are formed at the heterojunction, the occupied valence band maximum in the p-GaN would be higher than the unoccupied conduction band maximum of the n-ZnO and the n-Zn_{0.94}Ag_{0.06}O, which will results in decreasing the transport of holes from the p-GaN towards the n-ZnO and n-Zn_{0.94}Ag_{0.06}O, respectively. Therefore, most of the recombination are expected occur in the p-GaN site and this would leads to blue light emission and this is consistent with what we observed.

3. Performance under UV light

The response of the EL of the n-ZnO/p-GaN and the n-Zn_{0.94}Ag_{0.06}O/p-GaN heterojunction LEDs to UV light

FIG. 7. EL spectra of the (a) n-ZnO/p-GaN and (c) n-Zn_{0.94}Ag_{0.06}O/p-GaN heterojunction LEDs under reverse bias. The integrated emission bands intensity as a function of the reverse bias voltage for (b) n-ZnO/p-GaN and (d) n-Zn_{0.94}Ag_{0.06}O/p-GaN heterojunction LEDs. (Inset) The chromaticity coordinate of the n-ZnO/p-GaN and n-Zn_{0.94}Ag_{0.06}O/p-GaN heterojunction LEDs under reverse bias.

FIG. 8. EL spectra in dark and under UV light of (a) n-ZnO/p-GaN and (b) n-Zn_{0.94}Ag_{0.06}O/p-GaN heterojunction LEDs. (Inset) The chromaticity coordinate of the n-ZnO/p-GaN and n-Zn_{0.94}Ag_{0.06}O/p-GaN heterojunction LEDs under UV light.

illumination was investigated. We first illuminated the LEDs using UV lamp with a wavelength of 365 nm. Then, the EL output of the LEDs was measured immediately after turning off the UV light to avoid the interference of the UV light with our measurement because of the decay of UV conductance in ZnO lasts for up to several minutes.³⁶ Figures 8(a) and 8(b) show the EL spectra of the n-ZnO/p-GaN and n-Zn_{0.94}Ag_{0.06}O/p-GaN heterojunction LEDs under forward bias of 25 V in dark and under UV light. As it can be seen the EL intensity of the violet-blue emission of the n-ZnO/p-GaN heterojunction LED under UV light significantly increased but the broad emission peak almost did not changed. Also, the EL intensity of the violet-blue emission and broad emission peak of n-Zn_{0.94}Ag_{0.06}O/p-GaN heterojunction LED under UV light significantly increased. The CIE 1931 color coordinate measurement for the n-ZnO/p-GaN and n-Zn_{0.94}Ag_{0.06}O/p-GaN heterojunction LEDs under UV light display blue and white emission lights, respectively, as shown in the inset of Figures 8(a) and 8(b). It seems that the UV illumination can effectively create electron-hole pairs, which lead to increase the carrier's energy. Since electrons have more mobility than holes, in the n-ZnO/p-GaN heterojunction LED most of the electron-hole recombination will occur in the GaN site but in the n-Zn_{0.94}Ag_{0.06}O/p-GaN heterojunction LED and because of the reduction in the valence band offset, electron-hole recombination are expected to increase in both sites and this will lead to increase both the violet-blue emission and the visible broad emission band.

IV. CONCLUSION

In summary, we have fabricated the n-ZnO nanorods/p-GaN and n-Zn_{0.94}Ag_{0.06}O/p-GaN heterojunction LEDs. Doping the ZnO nanorods with Ag was found to reduce both the optical bandgap and series resistance. Consequently, the valence band offset at the n-Zn_{0.94}Ag_{0.06}O/p-GaN heterojunction interface is

reduced. White light emission was observed only in the case of n-Zn_{0.94}Ag_{0.06}O/p-GaN LED under forward bias, while in reverse bias, both heterojunctions emitted blue integrated light. The present results indicated that by doping the ZnO nanorods with Ag, the light emitted when forming a heterojunction with p-GaN can be tuned. Here, the Ag-doped n-ZnO/p-GaN LEDs results are shown for 6% case; nevertheless, increasing the Ag doping level is expected to further tune the emitted spectrum towards the centre of the white emission range. The EL intensity was found to be affected after UV illumination.

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- ¹X. Fang, X. Wang, D. Zhao, H. Zhao, F. Fang, Z. Wei, J. Li, X. Chu, F. Wang, D. D. Wang, and Y. S. Yan, *Physica E* **59**, 93 (2014).
- ²G. H. Nam, S. H. Baek, and I. K. Park, *J. Alloys Compd.* **613**, 37 (2014).
- ³D. Sahu, N. R. Panda, B. S. Acharya, and A. K. Panda, *Opt. Mater.* **36**, 1402 (2014).
- ⁴A. Echresh, M. Z. Shoushtari, and M. Farbod, *Mater. Lett.* **110**, 164 (2013).
- ⁵J. Bian, X. Kou, Z. Zhang, Y. Zhang, J. Sun, F. Qin, W. Liu, and Y. Luo, *Mater. Sci. Semicond. Process.* **16**, 1684 (2013).
- ⁶W. Z. Liu, H. Y. Xu, J. G. Ma, C. Y. Liu, Y. X. Liu, and Y. C. Liu, *Appl. Phys. Lett.* **100**, 203101 (2012).
- ⁷N. Yu, L. Du, H. Du, D. Hu, Z. Mao, Y. Wang, Y. Wu, and D. Liu, *Thin Solid Films* **550**, 206 (2014).
- ⁸M. A. Abbasi, Z. H. Ibupoto, M. Hussain, O. Nur, and M. Willander, *Nanoscale Res. Lett.* **8**, 320 (2013).
- ⁹J. R. Sadaf, M. Q. Israr, S. Kishwar, O. Nur, and M. Willander, *Nanoscale Res. Lett.* **5**, 957 (2010).
- ¹⁰I. Shteplyuk, V. Khranovskyy, G. Lashkarev, V. Khomyak, V. Lazorenko, A. Ievtushenko, M. Syvajarvi, V. Jokubavicius, and R. Yakimova, *Solid State Electronics* **72**, 81 (2013).
- ¹¹J. J. Hassan, M. A. Mahdi, A. Ramizy, H. A. Hassan, and Z. Hassan, *Superlattices Microstruct.* **53**, 31 (2013).
- ¹²I. Tsiaoussis, V. Khranovskyy, G. P. Dimitrakopoulos, J. Stoemenos, R. Yakimova, and B. Pecz, *J. Appl. Phys.* **109**, 043507 (2011).
- ¹³P. Koc, S. Tekmen, A. Baltakesmez, S. Tuzemen, K. Meral, and Y. Onganer, *AIP Adv.* **3**, 122107 (2013).

- ¹⁴S. Tekmen, E. Gur, H. Asil, K. Cinar, C. Coskun, and S. Tuzemen, *Phys. Status Solidi A* **207**, 1464 (2010).
- ¹⁵D. Ju, H. Xu, Z. Qiu, J. Guo, J. Zhang, and B. Cao, *Sens. Actuators, B* **200**, 288 (2014).
- ¹⁶L. T. Hoa, H. N. Tien, and S. H. Hur, *Sens. Actuators, A* **207**, 20 (2014).
- ¹⁷A. Echresh, M. A. Abbasi, M. Z. Shoushtari, M. Farbod, O. Nur, and M. Willander, *Semicond. Sci. Technol.* **29**, 115009 (2014).
- ¹⁸Y. Shen, X. Chen, X. Yan, F. Yi, Z. Bai, X. Zheng, P. Lin, and Y. Zhang, *Curr. Appl. Phys.* **14**, 345 (2014).
- ¹⁹J. J. Hassan, M. A. Mahdi, Y. Yusof, H. Abu-Hassan, Z. Hassan, H. A. Al-Attar, and A. P. Monkman, *Opt. Mater.* **35**, 1035 (2013).
- ²⁰X. Mo, G. Fang, H. Long, S. Li, H. Huang, H. Wang, Y. Liu, X. Meng, Y. Zhang, and C. Pan, *J. Lumin.* **137**, 116 (2013).
- ²¹X. Chen, A. M. C. Ng, F. Fang, Y. H. Ng, A. B. Djurisi, H. L. Tam, K. W. Cheah, S. Gwo, W. K. Chan, P. W. K. Fong, H. F. Lui, and C. Surya, *J. Appl. Phys.* **110**, 094513 (2011).
- ²²J. R. Sadaf, M. Q. Israr, S. Kishwar, O. Nur, and M. Willander, *Semicond. Sci. Technol.* **26**, 075003 (2011).
- ²³L. Zhang, Q. Li, C. Qu, Z. Zhang, R. Huang, and F. Zhao, *J. Opt.* **15**, 025003 (2013).
- ²⁴H. C. Chen, M. J. Chen, Y. H. Huang, W. C. Sun, W. C. Li, J. R. Yang, H. Kuan, and M. Shiojiri, *IEEE Trans. Electron Devices* **58**, 3970 (2011).
- ²⁵M. Q. Fu, W. Cao, G. Q. Li, Z. D. Lin, Z. Chen, C. B. Xu, Y. F. Tu, and Z. B. Ma, *Appl. Surf. Sci.* **293**, 225 (2014).
- ²⁶O. Lupan, T. Pauporte, L. Chow, G. Chai, B. Viana, V. V. Ursaki, E. Monaico, and I. M. Tiginyanu, *Appl. Surf. Sci.* **259**, 399 (2012).
- ²⁷O. Lupan, T. Pauporte, B. Viana, V. V. Ursaki, I. M. Tiginyanu, V. Sontea, and L. Chow, *J. Nanoelectron. Optoelectron.* **7**, 712 (2012).
- ²⁸F. Xian, X. Wang, L. Xu, X. Li, and W. Bai, *J. Lumin.* **144**, 154 (2013).
- ²⁹L. E. Greene, M. Law, D. H. Tan, M. Montano, J. Goldberger, and G. Somorjai, *Nano Lett.* **5**, 1231 (2005).
- ³⁰A. Echresh and M. Z. Shoushtari, *Mater. Lett.* **109**, 88 (2013).
- ³¹Z. Yuan, *Physica E* **56**, 160 (2014).
- ³²N. H. Alvi, M. Riaz, G. Tzamalidis, O. Nur, and M. Willander, *Semicond. Sci. Technol.* **25**, 065004 (2010).
- ³³H. K. Fu, C. L. Cheng, C. H. Wang, T. Y. Lin, and Y. F. Chen, *Adv. Funct. Mater.* **19**, 3471 (2009).
- ³⁴S. Dalui, C. C. Lin, H. Y. Lee, S. F. Yen, Y. J. Lee, and C. T. Lee, *J. Electrochem. Soc.* **157**, H516 (2010).
- ³⁵S. Xu, C. Xu, Y. Liu, Y. Hu, R. Yang, Q. Yang, J. H. Ryou, H. J. Kim, Z. Lochner, S. Choi, R. Dupuis, and Z. L. Wang, *Adv. Mater.* **22**, 4749 (2010).
- ³⁶X. M. Zhang, M. Y. Lu, Y. Zhang, L. J. Chen, and Z. L. Wang, *Adv. Mater.* **21**, 2767 (2009).