A REVIEW REPORT ON RECENT ADVANCED IN ZnO BASED LED LASERS

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Abstract

The unique and fascinating properties of II-VI compound semiconductors have triggered tremendous motivation among the scientists to explore the possibilities of using them in industrial applications. ZnO p-n intersection diode was effectively developed on Si substrate by involving Sb and Ga for p-type and n-type dopants individually. The diode gadget was created by utilizing standard photolithography process. Because of the superior material quality, prevailing bright light outflow from ZnO homojunction diode was first and foremost noticed and the discharge properties were examined with expanded infusion flows. To work on the proficiency, A MgZnO/ZnO twofold heterojunction structure was acknowledged by sub-atomic pillar epitaxy development on Si substrate. Contrasted with homojunction structure, the transporter restriction impact in twofold heterojunction structure led to bigger result power at same infusion current. With more modest heterojunction well size, ZnO based random laser diode was created. A meager MgZnO/ZnO/MgZnO all around implanted in a ZnO p-n intersection was acknowledged by sub-atomic pillar epitaxy development. Random lasing discharges were seen at various infusion flows at room temperature. Lasing instrument was examined and demonstrated by profound examination of its nano-structure. Fabry-perot type laser was likewise evolved in our lab, to bring down lasing edge, conveyed Bragg reflector was proposed. In an upward direction adjusted ZnO nanowires were initially effectively developed on disseminated Bragg reflectors made of SiO2/SiNx elective layers. Through optical excitation, Fabry-Perot type lasing was noticed and described. Contrasted with a similar length nanowires without conveyed Bragg reflectors, better lasing execution was accomplished. The conversation of lasing component uncovered the capacity of dispersed Bragg reflectors in improving lasing execution.

Keywords- semiconductors, diode, ZnO homojunction, heterojunction, sub-atomic pillar, Bragg reflectors

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INTRODUCTION

Zinc oxide is an inorganic compound with the formula ZnO. ZnO is a white powder that is insoluble in water. It is used as an additive in numerous materials and products including cosmetics, food supplements, rubbers, plastics, ceramics, glass, cement, lubricants, paints, ointments, adhesives, sealants, pigments, foods, batteries, ferrites, fire retardants, and first-aid tapes. Although it occurs naturally as the mineral zincite, most zinc oxide is produced synthetically. ZnO is a wide-band gap semiconductor of the II-VI semiconductor group. The native doping of the semiconductor due to oxygen vacancies or zinc interstitials is n-type. Other favorable properties include good transparency, high electron mobility, wide band gap, and strong room-temperature luminescence. Those properties make ZnO valuable for a variety of emerging applications: transparent electrodes in liquid crystal displays, energy-saving or heat-protecting windows, and electronics as thin-film transistors and light-emitting diodes.

In the impending data, computerized, and sight and sound age, light-discharging diodes (LEDs) in light of wide-bandgap semi-directors stand out enough to be noticed. The high efficiency, fast exchanging time, high shading range, low power consump-tion, semipermanence, and low hotness result of the LED haveled to numerous new applications. The backdrop illumination units in fluid precious stone presentations have been supplanted by high-efficiency LEDs.As the efficiency of LEDs was additionally improved; many push ucts outfitted with LEDs have been accounted for. To meet the requirement of high-brilliance LEDs for brightening, mobile appliances, auto, and showcases, it is important to de-velop new wide-bandgap semiconductors like ZnO, whichhas magnificent underlying and actual properties analyzed toGaN. ZnO, besides, is economical, somewhat abundant, chemically steady, simple to plan, and nontoxic. We already reviewed ZnO development and doping, metal ohmic contacts, carving of ZnO, and ZnO-based LEDs in a past report. In this paper, we sum up ongoing aftereffects of ZnO-based LEDs, which were for the most part distributed after the past report .The association of this audit is given as follows. To begin with, ZnO materials properties, for example, physical and electrical properties and bandgap designing are portrayed in Section II. This is followed by the development of n-and p-type ZnO slim films inSection III. Area IV is given to late reports of ZnO-based LEDs.

Amplifying Random medium

The mention of the tenn laser evokes the picture of a highly ordered system. But the conjunction of la sing and disorder has been of interest for a long time. It was Letokhov who first proposed in 1968, the theory of self-generation of light in an active medium filled with scatterers. But only much later an experimental verification came when Lawandy et al made the discovery that placing random scatterers in a gain medium could enhance the frequency stability of laser emission. The observation of lasing action in rare earth doped powders and in colloidal suspensions of submicron Titania particles in dye solutions have renewed interest in amplifying random media. A dramatic narrowing of spectrum and shortening of emission time is observed above a threshold in pumping energy. These results have raised the prospects of utilizing the phenomenon for a variety of display, sensing and switching applications.

Random Lasers - basic mechanism

A random laser is a non-conventional laser whose feedback mechanism is based on disorder induced light scattering. Light scattering was traditionally considered detrimental to laser action because such scattering removes photons from the lasing mode of a conventional laser cavity. However, in a strongly scattering gain medium, light scattering plays a positive role (i) Multiple scattering increases the path length or dwell time of light in the active medium, thus enhancing light amplification by stimulated emission; (ii) recurrent light scattering provides coherent feedback for lasing. There are two kinds of feedback: one is intensity or energy feedback; the other is field or amplitude feedback. The former feedback is incoherent and non-resonant, while the latter is coherent and resonant. Based on the feedback mechanisms, random lasers are classified into two categories: (1) random lasers with non-resonant feedback, (also called incoherent random lasers) (2) random lasers with resonant feedback (also called coherent random lasers)

Random lasing in ZnO

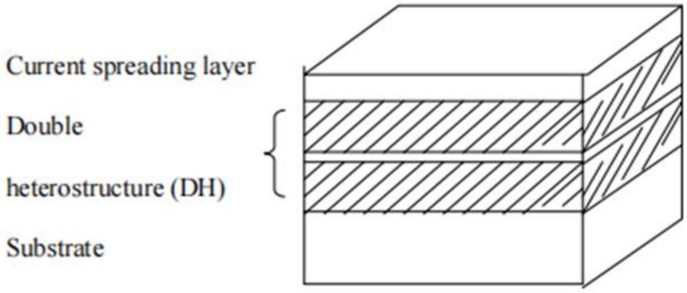
It was Cao et. Al. who first t demonstrated laser like emission in a 1 micron sized cluster of ZnO, thereby earning the name of first powder laser. Here they called it a microlaser because they individually pumped 1 J1 m sized ZnO clusters consisting of several 10000 of nanosized crystals. The term micro laser means to confine light in a small volume with dimensions of the order of wavelength of light. The same group also has observed random lasing with resonant feedback in ZnO films on silica substrates and powder films of ZnO which is electrophoretically deposited. They have also studied gradual transition from incoherent to coherent type of lasing in ZnO nanoparticles suspended in dye solutions.

ZnO homojunction light emitting diode

ZnO is considered to be a promising material for ultraviolet (UV) light emitting diodes (LEDs) and laser diodes (LDs) due to its direct band gap of 3.37 eV and large exciton binding energy of 60 meV. Nevertheless, unlike n-type ZnO, reliable p-type doping is difficult to achieve due to the possibility of holes getting compensated by the intrinsic donors such as zinc interstitials and oxygen vacancies. Therefore, previous efforts on ZnO p-n junctions are mostly made from n-type ZnO and other p-type semiconductors such as Si, SiC, GaN, SrCu2O2and so on. The benefit of making those heterojunction LEDs is that it is easy to obtain a device, however, the chemical and crystallographic differences between ZnO and dissimilar materials give rise to the formation of interfacial defects, which makes negative impact on optical and electrical properties of diodes. There arethree main disadvantages of heterojunction structure. UV ZnO light-emitting diode on Si (100) substrate has been understood. Solid p-type ZnO is framed and minutely the p-n homojunction comprises of section nanostructures. Au/NiO and Au/Ti make great Ohmic contacts to p-type and n-type segments of the ZnO nano sections for the arrangement of LED gadgets. I-V and C-V estimations show great correction conduct and EL tests exhibit predominant UV discharges, attributable to better p-type quality. Driven execution was described at both room temperature and 17 K, showing that outflow top redshift and effectiveness drop were incited by heat.

ZnO double heterojunction LED

The most straightforward sort of p-n LED plan is the initial step and is not generally utilized in current LED innovation since there are a few disadvantages which could bring down the proficiency in the lighting and enlightenment applications. First, electron infusion into the p-type locale is wanted for accomplishing high inside quantum proficiency, accordingly, a low infusion level of openings into the n-locale is required. The lifetimes got from the bimolecular rate condition show that the radiative rate increments with the free-transporter fixation for both the low excitation limit as well as the high excitation limit. It is consequently critical that the area in which recombination happens has a high transporter focus. Twofold heterojunction is elective method for accomplishing such high transporter focuses. Second, narcissism of the produced light is high because of the whole structure has same organization; this decreases the light extraction efficiency. Third, the radiative recombination in such LEDs is monomolecular, so that as it were expanding the doping can build the emanation rate.



Development of Zno based laser diodes

Bringing down threshold current is a vital objective on which researchers , scientists and engineers put a extraordinary arrangement of endeavors in the past 50 years, since the principal LD in light of GaAs p-n intersection structure was reported. A forward leap in electrically siphoned gadgets came from twofold heterojunction structure, which acknowledges happenstance and centralization of recombination, light outflow and populace reversal in a similar increase layer, subsequently the sensational lessening of limit current, notwithstanding, it is still excessively high for numerous applications. Notwithstanding, in some semiconductor materials like III-V nitride and GaAs, the exciton restricting energies are too little to even think about supporting warm interference, so excitonic emanation was just seen in the low-layered structures. Interestingly, ZnO has a local exciton restricting energy of 60 meV, which empowers excitonic gain even without low layered quantum confinement.

Despite the fact that ZnO has potential as an option in contrast to III-V nitride, it is still immature because of the trouble of p-type doping, which obstructs the acknowledgment of electrically siphoned LDs. Contrasted with electrically siphoned divided gem GaN diode.

Method of Synthesis

ZnO nanowires can be either developed freely or developed on specific substrates. Notwithstanding, an upward adjusted development on a substrate enjoys more benefits in photocatalytic applications. The anisotropy of the ZnO precious stone construction helps the development of nanowires. The most widely recognized polar surface is the basal plane (0 0 1) with one finish of the basal polar plane ending in somewhat sure Zn cross section focuses and the opposite end ending in to some degree negative oxygen grid focuses. The anisotropic development of the nanowires happens along the c-hub in the 0 0 2] direction. The growth velocities under hydrothermal conditions along the different directions are following the pattern (0001)>(1011)>V(1010) . The relative growth rate of these crystal faces will analysis the final shape and aspect ratio of the ZnO nanostructures.

The synthesis methods of ZnO nanowires could mainly be classified as vapor phase and solution phase synthesis.

a. Doping of ZnO Nanowires

Doping is the primary method of controlling semiconductor properties such as the band gap, electrical conductivity, and ferromagnetism. Many metals and nonmetals have been successfully used to dope ZnO nanowires by various synthesis methods. ZnO nanowire metal doping includes Ni, Co , Ga, Eu, Al, and Cu , and nonmetal doping includes C 111], N [112], P [113], and Cl [114]. Two different element codoped nanowires such as Mn + Co [115], Mn + Li [116], and Li + N [117], have also been studied by some research groups.

b. The Vapor Phase Synthesis

Vapor phase synthesis is the most extensively explored approach in the formation of 1D nanostructures. A typical vapor phase synthesis method takes place in a closed area with a gaseous surround. Vapor species are first produced by evaporation, chemical reduction, and gaseous reaction. After that, the species are transferred and condensed onto the surface of a solid substrate. Generally, the vapor phase synthesis process is carried out at high temperatures from 500°C to 1500°C and produces high-quality nanowires. The mainly vapor phase synthesis method includes vapor liquid solid (VLS) growth , chemical vapor deposition (CVD), metal organic chemical vapor deposition (MOCVD) , physical vapor deposition (PVD) , molecular beam epitaxy (MBE) , pulsed laser deposition (PLD), and metal organic vapor phase epitaxy (MOVPE) . Among the vapor phase synthesis methods, VLS and MOCVD are two of the most important methods for the ZnO nanowires synthesis.

Related to other vapor phase techniques, VLS method is a simpler and cheaper process, and is advantageous for growing ZnO on large wafers . The VLS process has been widely used for the growth of 1D nanowires and nanorods. A typical VLS process is used with nanosized liquid metal droplets as catalysts. The gaseous reactants interact with the nanosized liquid facilitating nucleation and growth of single crystalline rods and wires under the metal catalyst. Typical metal catalysts in the VLS process are Au, Cu, Ni, Sn, and so forth. ZnO nanowires have been successfully grown on sapphire, GaN, AlGaN, and ALN substrates through the VLS process . The quality and growth behavior of the ZnO nanowires are strongly affected by the chamber pressure, oxygen partial pressure, and thickness of the catalyst layer.

Catalyst-free metal-organic chemical vapor deposition (MOCVD) is another important synthesis method for ZnO nanowires. The catalyst-free method eliminates the possible incorporation of catalytic impurities and produces high-purity ZnO nanowires. Moreover, the growth temperature of catalyst-free MOCVD is lower than a typical VLS growth temperature. The ability to grow high-purity ZnO nanowires at low temperatures is expected to greatly increase the versatility and power of these building blocks for nanoscale photonic and electronic device applications

Physical vapor deposition (PVD) technique has also been used to fabricate ZnO nanowires. The advantages of PVD technique are the following: (1) composition of products can be controlled, (2) there is no pollution such as drain water, discharge gas, and waste slag, and (3) simple process of making samples. The process of PVD usually is direct thermal evaporation and oxidation of Zn powder at a high temperature and then deposition on the substrate to form the final product.

c. Solution Phase Synthesis

Solution phase synthesis has many advantages when compared to vapor phase synthesis, such as low cost, low temperature, scalability, and ease of handling. Generally, solution phase reactions occur at relatively low temperatures (<200°C) compared to vapor phase synthesis methods. Thus, solution synthesis methods allow for a greater choice of substrates including inorganic and organic substrates. Due to the many advantages, solution phase synthesis methods have attracted increasing interest.

Hydrothermal Method

Hydrothermal methods have received a lot of attention and have been widely used for synthesis of 1D nanomaterials. In addition, hydrothermally grown ZnO nanowires have more crystalline defects than others primarily due to oxygen vacancies . The general process for vertically aligned ZnO nanowires grown on a substrate by the hydrothermal method is the following.

a) A thin layer of ZnO nanoparticles is seeded on a certain substrate. The seeding layer promotes nucleation for the growth of nanowires due to the lowering of the thermodynamic barrier.
b) An alkaline reagent (such as NaOH or hexamethylenetetramine) and Zn2+ salt (Zn(NO3)2, ZnCl2, etc.) mixture aqueous solution is used as a precursor (or growth solution).
c) The ZnO seeded substrate is kept in the growth solution at a certain temperature and a certain period of time.
d) The resultant substrate and growth layer is washed and dried.

When hexamethylenetetramine ((CH2)6N4, or HTMA) and Zn(NO3)2 are chosen as precursor, the chemical reactions can be summarized in the following equations

$$(CH_2)_6N_4 + 6H_2O \longrightarrow 6HCHO + 4NH_3 \qquad (1)$$

Hydroxyl supply reaction:

$$NH_3 + H_2O \longleftrightarrow NH_4^+ + OH^- \qquad (2)$$

Supersaturation reaction:

$$2OH^- + Zn^{2+} \longrightarrow Zn(OH)_2 \qquad (3)$$

ZnO nanowire growth reaction:

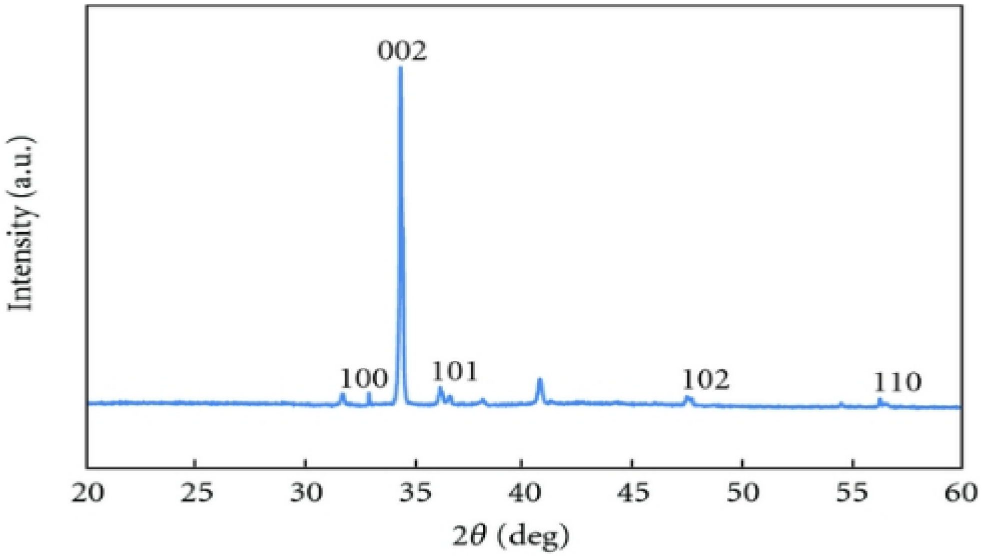
$$Zn(OH)_2 \longrightarrow ZnO + H_2O \qquad (4)$$

One of the key parameters for the growth of ZnO nanowires is controlling the supersaturation of the reactants. It is believed that high supersaturation levels favor nucleation and low supersaturation levels favor crystal growth . If a lot of OH− is produced in a short period, the Zn2+ ions in the solution will precipitate out quickly due to the high pH environment, and, therefore, Zn2+ would contribute little to the ZnO nanowire growth and eventually result in the fast consumption of the nutrient and prohibit further growth of the ZnO nanowires.

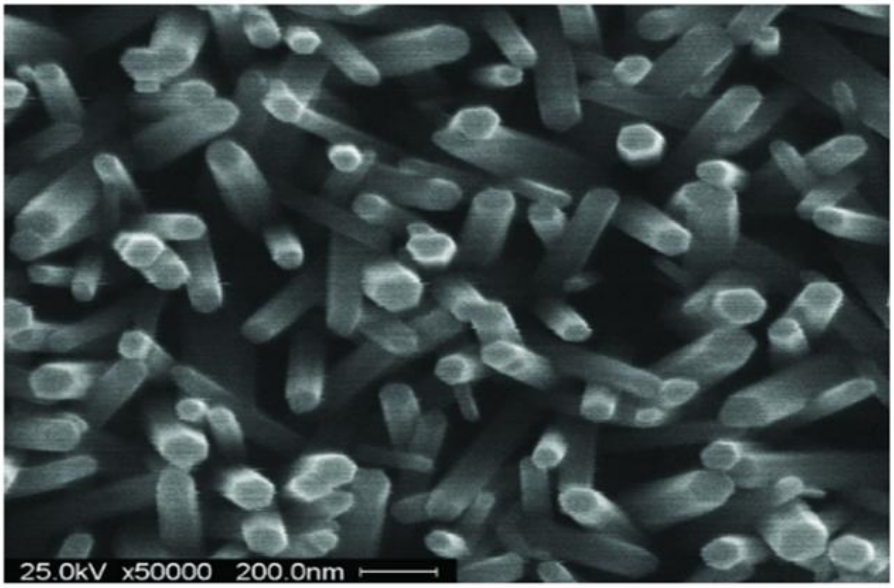
Properties of ZnO based led lasers

Commonly ZnO is single crystalline and exhibits a hexagonal wurtzite structure. The structure of ZnO nanowires could be revealed by X-ray diffraction (XRD) and scanning electron microscopy (SEM). Figure 1 shows the XRD pattern of the ZnO nanowire growth on a silicon substrate by using the hydrothermal synthesis method. A dominant diffraction peak for (002) indicates a high degree of orientation with the c-axis vertical to the substrate surface. Figure 2 shows a top down image of ZnO nanowires. Both XRD and SEM demonstrate the hexagonal wurtzite structure of the ZnO nanowires.

1. XRD of ZnO nanowires on a silicon substrate growth by the hydrothermal synthesis method



2. SEM image of the ZnO nanorods array on glass substrate by hydrothermal method



Further structural characterizations can be carried out by transmission electron microscopy (TEM) and high-resolution transmission electron microscopy (HRTEM).

The peaks of the ZnO nanowires at 327, 378, 437, 537, and 1090 cm−1 were observed in all the samples. A narrow strong band at 437 cm−1 has been assigned to E2 modes involving mainly a Zn motion corresponding to the band characteristic of the wurtzite phase. The band at 378 cm−1 (A1T mode) indicates the presence of some degree of structural order-disorder in the ZnO lattice. The band bands at 327 cm−1 should be assigned to the second-order Raman spectrum. A band at 537 cm−1 is the contribution of the E1 (LO) mode of ZnO associated with oxygen deficiency. The envelope of bands above 1090 cm− 1 can be attributed to overtones and/or combination bands.

3. Raman spectra of the ZnO structures obtained by the hydrothermal method at 130°C

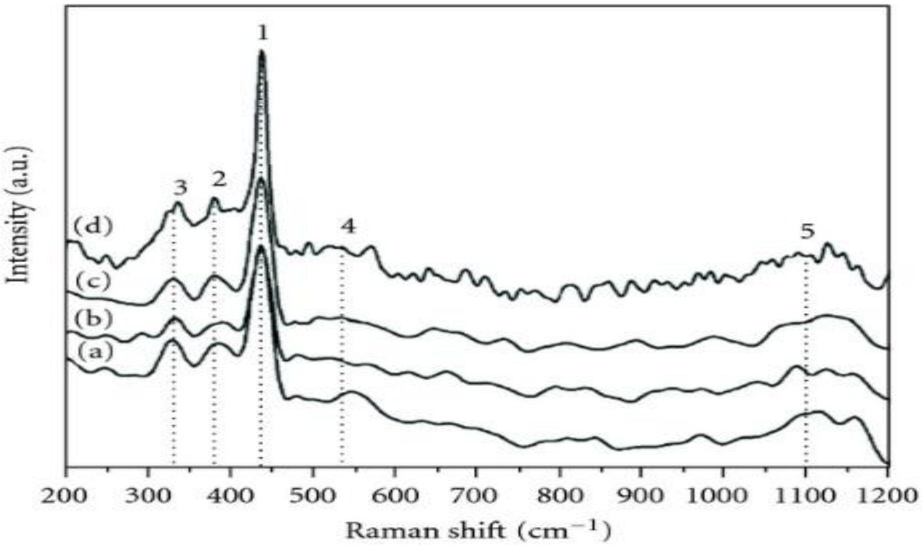


Figure 3 shows the UV-Visible absorption spectra of ZnO nanoparticles, ZnO nanowires, and ZnO/Fe nanowires. ZnO nanowires showed a larger enhancement absorption in the visible range as compared to ZnO nanoparticles. The ZnO/Fe nanowires exhibit even stronger absorption than the ZnO nanowires and nanoparticles in both the UV and the visible range implying that ZnO/Fe nanowires could more fully utilize most of the UV and visible light than the other two.

4. UV-Visible absorption spectra of ZnO nanoparticle, ZnO and ZnO/Fe nanowires

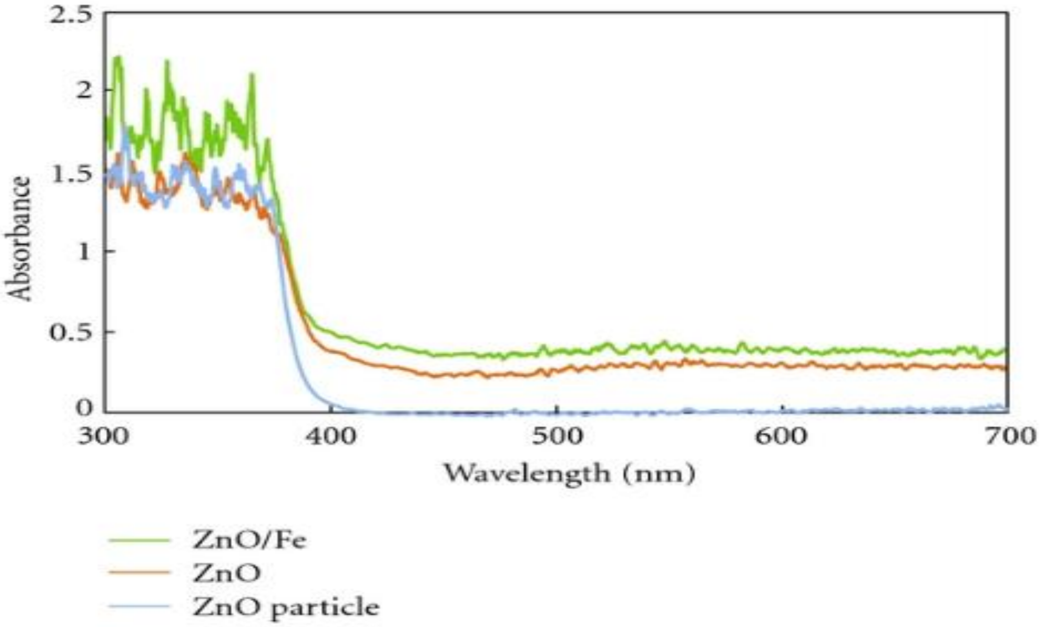


Figure 4 shows the FTIR spectrum of ZnO nanorods in the range of 2000–300 cm−1. There is only one significant spectroscopic band around 417 cm−1 associated with the characteristic vibrational mode of Zn–O bonding.

5. FTIR spectrum of ZnO nanorods prepared at 200°C for 20 h using NaOH

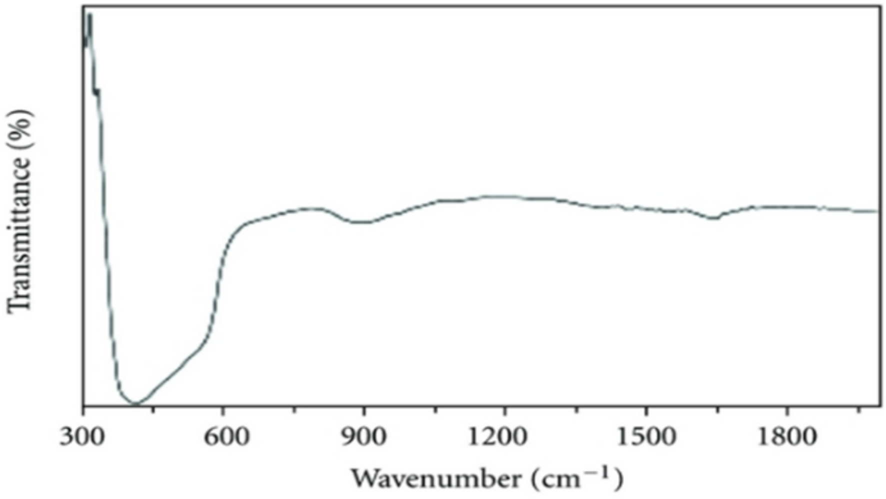
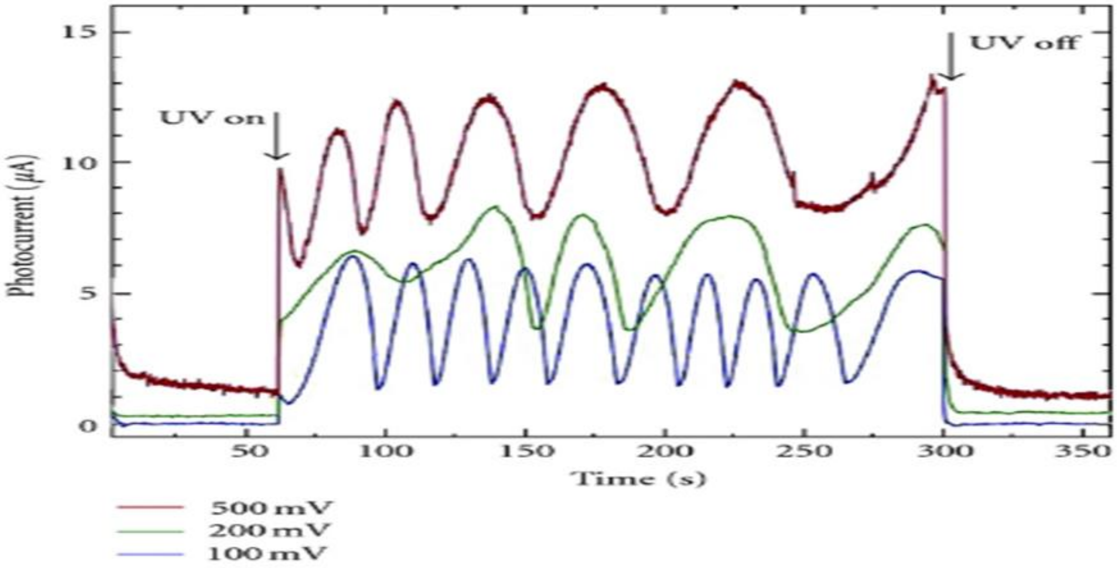


Figure 5 shows the photopotential response of a ZnO nanowire electrode under UV irradiation. When the UV light is switched on, electron-hole pairs are generated and produce a photocurrent. The UV irradiation changes the current abruptly with some variation, and the photo-potential is sharply reduced when the light is switched off.



In addition to the above properties, ZnO based led lasers also exhibit many other unique chemical and physical properties for many applications such as large surface areas, piezoelectric, piezotronic, and optical.

Applications of ZnO based led lasers

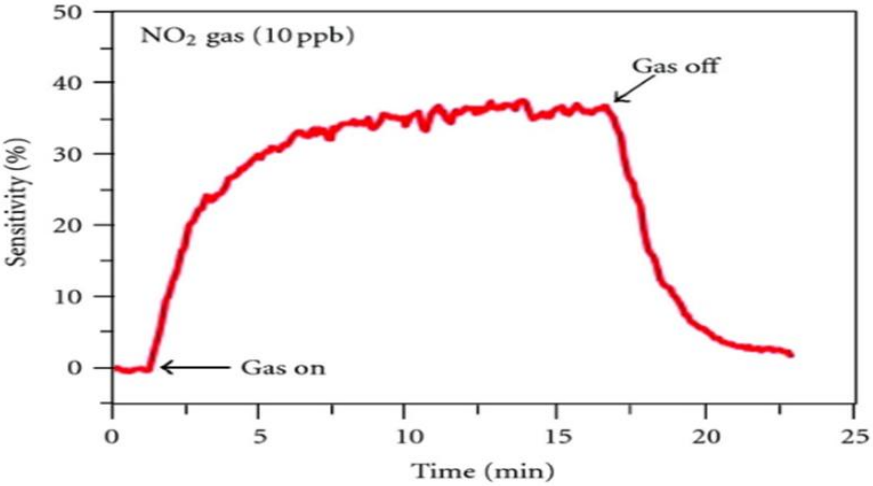
ZnO based led lasers can be used for a number of applications in different fields due to the unique electrical, optical, and mechanical properties.

A. SENSOR

a. Gas Sensor

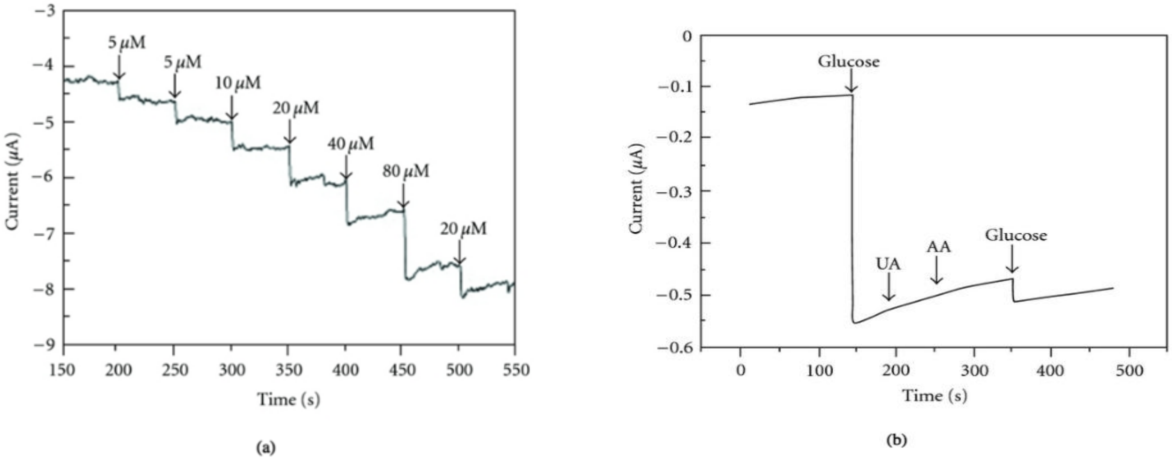
ZnO is one of the earliest discovered and freely used oxide gas sensing materials. ZnO functions as a gas sensitive material due to its electrical conductivity that can be dramatically affected by the adsorption or desorption of gas molecules on its surface. A room temperature NH3 gas sensor based on a CO sensors based on aligned ZnO nanorods on a substrate and exhibited high sensitivity to CO gas with the low detection limit of 1 ppm at 350°C.

Response curve of a ZnO gas sensor exposed to 10 ppb NO2 gas at 250°C



b. Biosensor

Recently, ZnO nanostructures have attracted interest in biosensor applications due to many advantages, including nontoxicity, biosafety, bio-compatibility, high electron-transfer rates, and combination with immobilized enzymes . The high isoelectric point (IEP) of ZnO (IEP 9.5) makes it a good matrix for immobilizing low IEP acidic proteins or DNA by electrostatic interactions with high binding stability. In addition, ZnO has high ionic bonding (60%), and it dissolves very slowly at normal biological pH environments. Liu et al. have constructed an ampere-metric glucose biosensor based on aligned ZnO nanorod films formed directly on the surface of ITO glass. The biosensor exhibited a linear response to glucose from 5 µM to 300 µM and a limit of detection of 3 µM (Figure 7). The biosensor also showed good selectivity for glucose. In an air-saturated and stirred 0.01 M PBS containing 5 µM glucose, there was no significant change of the ampere-metric response by the injection of 10 µM UA and AA, respectively



(a)

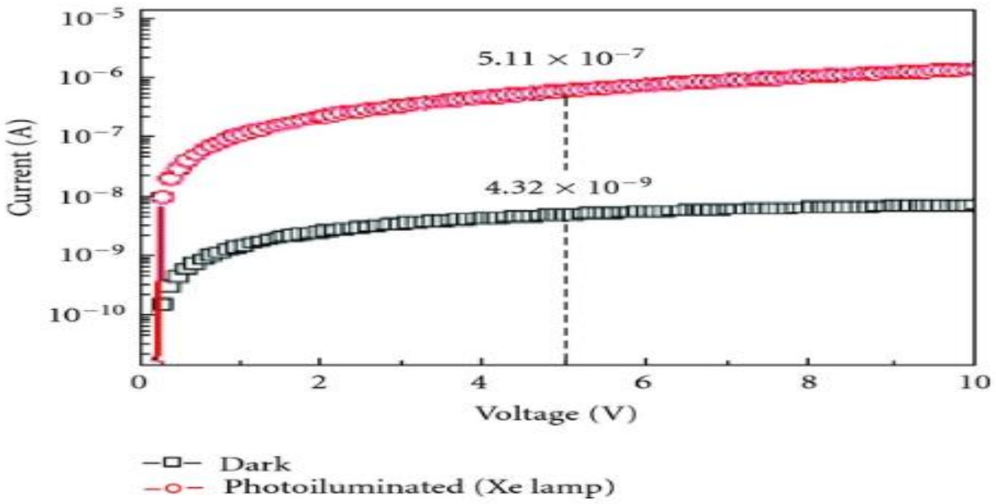
(b)

ZnO-nanorod-based biosensor with good reproducibility and selectivity for the quick monitoring of penicillin with the immobilization of the penicillinase enzyme by the simple physical adsorption method. The authors showed that the potentiometric response of the sensor configuration revealed good linearity over a large concentration range from 100 µM to 100 mM. ZnO nanowire field-effect-transistor- (FET-) based biosensor for the detection of low level biomolecular interactions. The ZnO nanowire biosensor could detect as low as 2.5 nM of the streptavidin with a current increase of 7.5 nA.

B. UV Detector

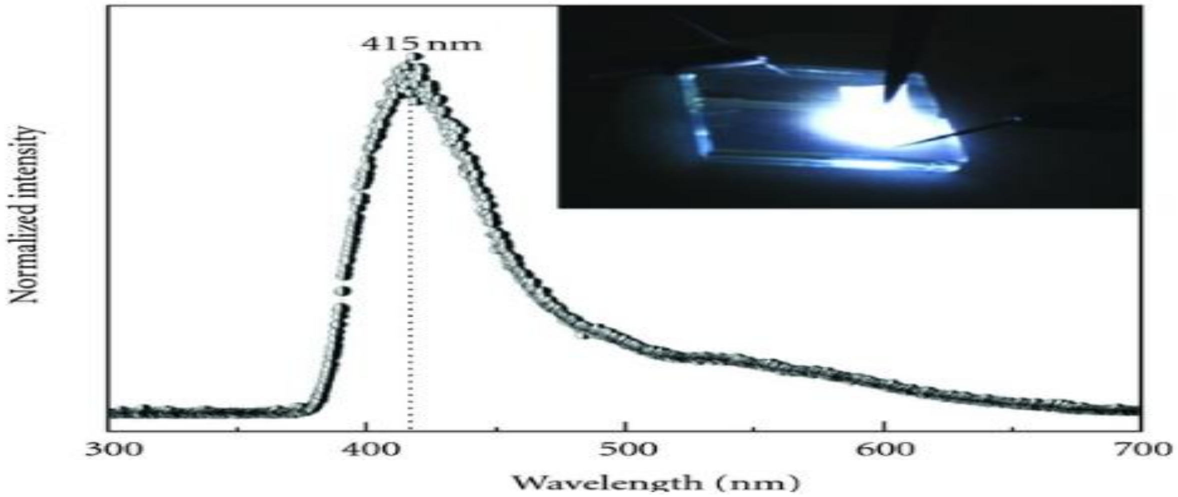
UV detection is another promising optical application of ZnO nanowires. The UV detector utilizes the electric potential of the ZnO nanowires changed under UV irradiation. A UV photodetector by contacting a circular spiral structure ZnO nanowire with 30 nm IrO2 electrodes. The I-V measurement showed that the curve corresponded to the Schottky metal-semiconductor contacts with the photo-generated current reaching 5.11 × 10−7 A, under a bias voltage of 5 V, and the photocurrent being 2 orders of magnitude larger than the dark current (Figure 8). A ZnO bridging nanowire structure exhibiting nanowatt UV detection. The electrodes were formed by the thick ZnO layers covering the Au-catalyst-patterned areas on the substrate, and the sensing elements consisted of the ultralong ZnO nanowires bridging the electrodes. The device exhibited drastic changes (10–105 times) in current under a wide range of UV irradiance (10−8–10−2 W cm−2). Moreover, the detector showed fast response (rise and decay times of the order of 1 s) to UV illumination in air. ZnO nanorods with graphene enabling the UV sensor to reach 22.7 A/W.

I-V characteristics of a ZnO photodetector in the dark and under Xe illumination



C. Light-Emitting Diode

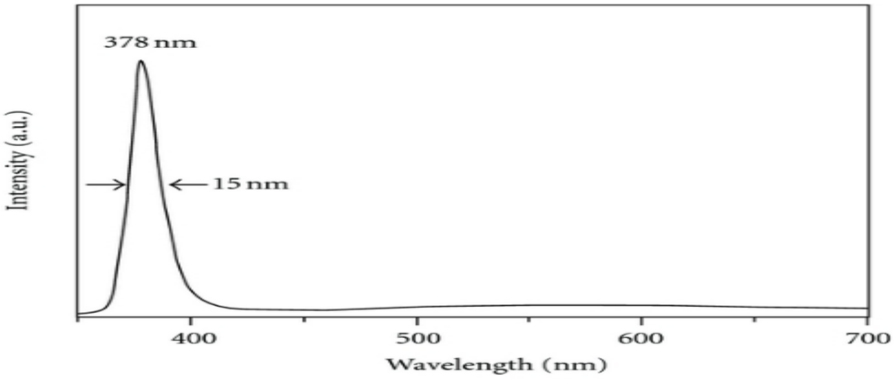
The output power of GaN LEDs with ZnO nanotip arrays can be enhanced by up to 50% times. A heterojunction LED could be fabricated by the growth of vertically aligned ZnO nanowires on a p-GaN substrate and employed indium tin oxide (ITO)/glass to combine and package. Figure 9 shows the electroluminescence (EL) spectra of ZnO NWs/p-GaN/ZnO nanowire heterostructure at a DC current of 20 mA. A UV-blue electroluminescence (EL) emission was observed from the nanowire-film heterojunction diodes. Most of the currently developed ZnO LEDs are based on heterojunctions. However, a ZnO rod p-n homojunction LED with an ion-implanted P-doped p-type ZnO



D. UV Laser

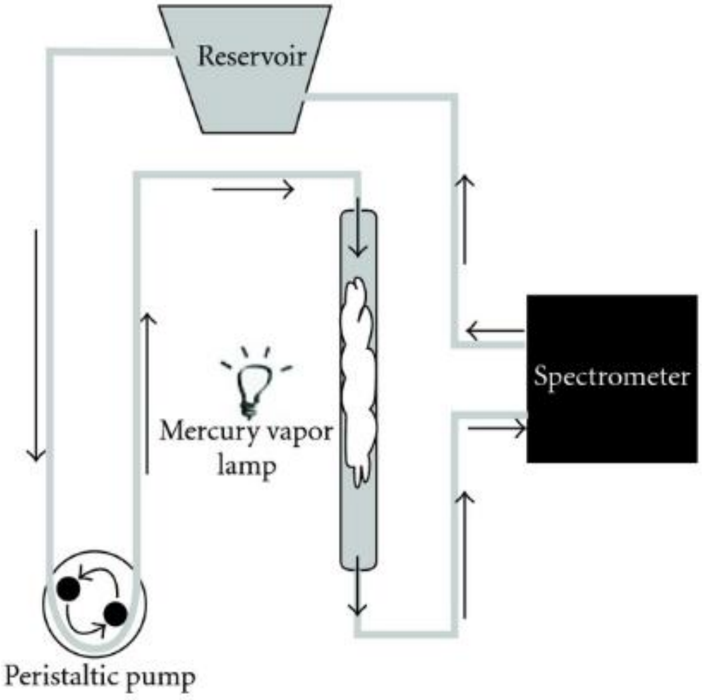
Room temperature of ZnO-nanowire-based UV lasing has been recently demonstrated. Figure 10 shows a typical room temperature photoluminescence (PL) spectrum of ZnO nanorods with an excitation wavelength of 325 nm at room temperature. The spectrum exhibits two bands including a strong ultraviolet emission at 378 nm (or 3.28 eV) and a weak spectral band in the visible region. The UV emission was contributed to the near band edge emission of the wide band gap of ZnO. Visible emission is due to the presence of various point defects such as oxygen vacancies.

Room temperature PL spectra of ZnO nanorods (λe x c= 3 2 5 nm)



E. Photocatalysis

ZnO nanowires used as photocatalysts have been recently reported by many research groups. A continuous flow water purification system by the fabrication of ZnO nanowires grown on flexible poly-L-lactide nanofibers. The continuous flow photocatalytic decomposition of organic compounds in water has no need for separation of the photochemically active material from the reservoir, and the purified water can be directly collected from the reservoir (Figure 11). The various organic pollutants that have been tested and removed under UV light illumination include methylene blue, monocrotophos, and diphenylamine. The results demonstrated that simultaneous photocatalytic decomposition of more than one organic contaminant is possible by using the polymer-ZnO nanostructure. The authors also stated that the fabrication can be easily scaled up and the whole photocatalytic water treatment setup can easily be adapted either as a point-of-use system or centralized large-scale water purification system.



To further increase the photoactivity of ZnO nanowires, our group has synthesized ZnO/Fe nanowires by the growth of ZnO nanowires on the Fe-doped ZnO seeding layer using the hydrothermal method. The photocatalytic activity was evaluated by photodegradation of dichlorobenzene (DCB) and methyl orange (MO) in water. The experiments were carried out under white light (60 W/m2 in visible plus 2 W/m2 in UV) or UV light (30 W/m2) irradiation. The results showed that the ZnO/Fe nanowires exhibited enhanced photocatalytic activity as compared with pure ZnO nanowires under different light irradiation as well as different contaminants.

Conclusion and future scope

This paper provides an overview of the synthesis Recent advanced in ZnO based led lasers. To develop ZnO nanowire laser, 10-period DBR structure was designed using SiO_2 and SiN_x. Vertically aligned ZnO nanowires were achieved by CVD growth, on a ZnO polycrystalline seed layer deposited on DBR by MBE. Fabry-Perot type lasing was observed with optical pumping and a lower threshold excitation power was achieved due to the lower cavity loss with the DBR structure. The cavity finesses is improved and the FWHM of lasing mode is reduced The hydrothermal synthesis method is simple and efficient and it has received increased attention. A mixture of zinc nitrate and hexamine as precursor is the most popular. Due to the unique properties of the material, ZnO nanowires are attractive for a number of potential applications such as photocatalysis, solar cells, sensors, and generators. Among the applications of ZnO nanowires, photocatalysis is being increasingly used for environmental protection. Further research is needed to improve the quality of ZnO nanowires and large-scale produce ZnO nanowires for practical industrial applications. Based on this paper, ZnO nanowires promise to be one of the most important materials in photocatalytic as well as others applications. ZnO-based LEDs show great promise for the future, however, there are some severe issues that are in need of further investigation to transition ZnO-based LEDs to commercial use from the current stage. One problem is that the usable, reproducible p-type ZnO are not easy to fabricate, although some researchers have been successful. Another is the achievement of high quality p-n junction based ZnO. The p-n junction with good threshold and breakdown voltages is necessary for the LEDs. In addition, diode-like behavior and light emission have been observed, however, the mechanism of the properties remain unclear.

References

1) Imamoglu, R. J. Ram, S. Pau and Y. Yamamoto, Physical Rev. A, 53, 4250 (1996).
2) R. Brown, D. D. C. Bradley, J. H. Burroughes, R. H. Friend, N. C. Greenham, P. L. Burn, A. B. Holmes, and A. Kraft, Appl. Phys. Lett. 61, 2793 (1992)
3) Zukauskas, M.S. Shur and R. Gaska, Introduction to Solid-State Lighting, Wiley, New York (2002)
4) Klingshirn, J. Cryst. Growth 117, 753 (1992).
5) Ren, B. Yang, M. Wu et al., “Synthesis of Ag/ZnO nanorods array with enhanced photocatalytic performance,” Journal of Hazardous Materials, vol. 182, no. 1–3, pp. 123–129, 2010.
6) W. Zou, L. X. Shao, L. P. Guo, D. J. Fu, and T. W. Kang, “Ferromagnetism and ferroelectric properties of (Mn, Li) co-doped ZnO nanorods arrays deposited by electrodeposition,” Journal of Crystal Growth, vol. 331, pp. 44–48, 2011
7) Fred Schubert, Light-Emitting Diodes, New York (2006)
8) K. Yam, Z. Hassan, Microelectronics Journal 36, 129 (2005)
9) X. Xiu, Z. Yang, L. J. Mandalapu, D. T. Zhao, J. L. Liu, and W. P. Beyermann, Appl. Phys. Lett. 87, 152101 (2005)
10) Frank M. Steranka, AlGaAs red light-emitting diodes, in: G.B. Stringfellow, M. G. Craford, (Eds.), Hight Brightness Light Emitting Diodes, in: R. K. Willardson, E. R. Weber, (Eds.) Semiconductors and Semimetals, vol. 48, Academic Press, New York, 1997, p.65.
11) J. Y. Kong, S. Chu, M. Olmedo, L. Li, Z. Yang and J. L. Liu, Appl. Phys. Lett. 93, 132113 (2008)
12) L. J. Mandalapu, F. X. Xiu, Z. Yang, and J. L. Liu, Appl. Phys. Lett. 88, 112108 (2006).
13) M. Zamfirescu, A. Kavokin, B. Gil, G. Malpuech, and M. Kaliteevski, Phys. Rev. B 65, 161205(R) (2002)
14) R. N. Hall, G. E. Fenner, J. D. Kingsley, T. J. Soltys, and R. O. Carlson, Phys. Rev. Lett. 9,366 (1962).
15) S. F. Chichibu, T. Azuhata, T. Sota and T Mukai, Appl. Phys. Lett. 79, 341 (2001).
16) W. Wegscheider, L. N. Pfeiffer, M. M. Dignam, A. Pinczuk, K. W. West, S. L. McCall, and R. Hull, Phys. Rev. Lett, 71, 4071 (1993).
17) Z. Dai, A. Nurbawono, A. Zhang et al., “C-doped ZnO nanowires: electronic structures, magnetic properties, and a possible spintronic device,” Journal of Chemical Physics, vol. 134, no. 10, Article ID 104706, 2011.
18) Zh. I. Alferov and R. F. Kazarinov, Inventor’s Certificate No. 181737 (in Russian) H. Kroemer, Proc. IEEE 51, 1782 (1963).