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Study of Electro-Optical Properties of ZnO Nanostructures

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ABSTRACT *It is worth noting that as the dimension of the semiconductor materials continuously shrinks down to nanometer or even smaller scale, some of their physical properties undergo changes known as the "quantum size effects". Understanding the fundamental physical properties is crucial to the rational design of functional devices. Investigation of the properties of individual ZnO nanostructures is essential for developing their potential as the building blocks for future nanoscale devices. This section will review the up-to-date research progress on the physical properties of ZnO nanostructures, such as piezoelectric, electrical and optical properties.*

KEYWORDS: ZnO, nanostructure, UV emission, nanowires.

I. Introduction

Nanostructured materials have attracted a great deal of attention in the last few years for their unique characteristics that cannot be obtained from conventional macroscopic materials. Owing to quantum size effects and surface effects, nanoparticles can display novel optical, electronic and structural properties that might find many important technological applications. An extremely active and prolific field in nanomaterial's is finding ways to control size and morphology of the nanoparticles since the properties and applications of the nanoparticles are largely dependent on their size and morphology [1]. Among various semiconducting materials, zinc oxide (ZnO) is a distinctive electronic and photonic wurtzite n-type semiconductor with a wide direct band gap of 3.37 eV and a high exciton binding energy (60meV) at room temperature[2]. In the past decade, II-VI semiconductor nanoparticles attract much attention because of their size-dependent (and thus tuneable) photo- and electro- luminescence properties and promising applications in optoelectronics. Among the family of II–VI semiconductors, ZnS, CdS, ZnO, CdTe, etc. are the foremost candidates because of their favorable electronic and Optical properties for optoelectronic applications. Among those ZnO is a commercially important II–VI semiconductor having a wide optical band gap, rendering it a very attractive material for optical application especially in Nano crystalline form. The optical properties of this material are currently the subject of tremendous investigations, in response to the industrial demand for optoelectronic devices that could operate at short wavelengths. There is a significant demand for high nonlinear optical materials, which can be integrated into an optoelectronic device. With many advantages such as low cost, nontoxicity, and stability, ZnO is becoming a very promising n-type oxide semiconductor.[3]

Electrical Properties of ZnO Nanostructures

The fundamental study of the electrical properties of ZnO nanostructures is crucial for developing their future applications in nanoelectronics.

The CVD grown ZnO nanostructures are single crystalline, rendering them superior electrical property than polycrystalline thin film. For example, an electric field effect mobility of 7 cm2/V-s is regarded quite high for ZnO thin film transistors. However, single crystalline ZnO nanowires show mobility as high as 80 cm2/V·s. Due to the native defects such as oxygen vacancies and zinc interstitials, ZnO nanowires are reported to show n-type semiconductor behavior. These results indicate that the ZnO nanostructure based device can achieve a faster operation speed than their thin film counterpart. Point defect concentrations in ZnO nanowires can be modified depending on growth conditions without any intentional doping. ZnO nanowires with a higher density of oxygen (O) vacancies showed higher on-state current in FET devices for which one possible explanation is the higher carrier concentration in the wires.[18] Furthermore, using a uniquely designed synthesis setup, one can tune the carrier concentration and mobility of the nanowires, providing a way to modify the electrical property. The major impediment of ZnO for wide-ranging applications in electronics and photonics rests with the difficulty of p-type doping. Several p-type doping efforts have been reported, with a Ga and N codoping method, low resistivity (0.5 Ω·cm) p-type ZnO thin film was obtained [4]. Successful p-type doping for ZnO nanostructures will greatly enhance their future applications in nanoscale electronics and optoelectronics. P-type and n-type ZnO nanowires can serve as p-n junction diodes and light emitting diodes (LED). And field effect transistors (FET) fabricated from them can constitute complementary logic circuits. Combined with their optical cavity effect, electrically driven nanowire laser can be potentially implemented.

Piezoelectric effect and polar surfaces

As one of the important properties of ZnO, its piezoelectricity has been extensively studied for various applications in force sensing, acoustic wave resonator, acousto-optic modulator, etc.[14,15,16] The origin of the piezoelectricity lies in its crystal structure, in which the oxygen atoms and zinc atoms are tetrahedrally bonded. In such a non-centrosymmetric structure, the center of positive charge and negative charge can be displaced due to external pressure induced lattice distortion (Fig. 1). This displacement results in local dipole moments, thus a macroscopic dipole moments appears over the whole crystal. In fact, among the tetrahedrally bonded semiconductors, ZnO has the highest piezoelectric tensor which provides a large electro-mechanical coupling. Another interesting result of the non-centrosymmetric ZnO crystal structure is its spontaneous polarization and polar face dominated nanostructures.

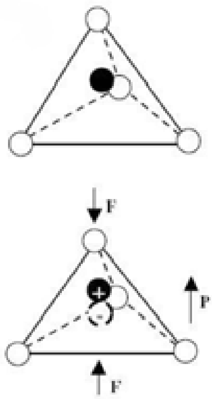

Figure 1 Schematics showing the piezoelectric effect in a tetrahedrally coordinated cation-anion unit.

Optical properties

Intrinsic optical properties of ZnO nanostructures are being intensively studied for implementing photonic devices. Photoluminescence (PL) spectra of ZnO nanostructures have been extensively reported.[5,6,10] Excitonic emissions have been observed from the photoluminescence spectra of ZnO nanorods.[7] The spectrum exhibits two emission peaks, one

is located at around 392nm (UV region) corresponding to the near band gap excitonic emission and the other is located at around 520nm attributed to the presence of singly ionized oxygen vacancies as shown in the fig 2 [17]. It is shown that quantum size confinement can significantly enhance the exciton binding energy. Furthermore the high exciton binding energy (~60meV) makes ZnO a good candidate to even brighter light emission then the well known GaN photonics[8]. The well-facetted nanowires also form promising optical resonance cavities which greatly facilitate highly directional lasing at room temperature in well aligned ZnO nanowires. Lasing power threshold of 40 kW/cm2 ~ 100 kW/cm2 was reported and it was suggested that higher crystal quality confers lower threshold. The additional advantages of ZnO nanowire lasers are that the excitonic recombination lowers the threshold of lasing, and quantum confinement yields a substantial density of states at the band edges and enhances radiative efficiency.

Optical waveguiding using dielectric nanowire also achieved considerable progress. These findings show that ZnO nanostructures can be potential building blocks for integrated optoelectronic circuits.

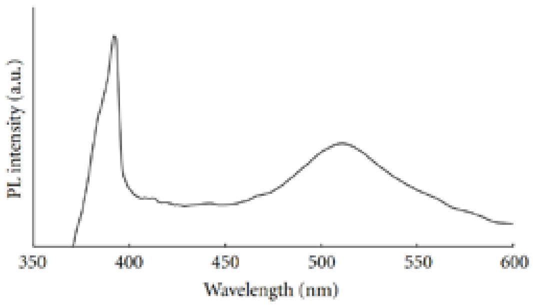

Figure 2: Photoluminescence spectrumof ZnO nanopar-ticles (λexc =320nm).[17]

Besides UV emitting and lasing, effort on utilizing ZnO nanowires for UV photo detection and optical switching have been reported by Kind et al.[9] Photocurrent is maximized when the electric field component of the incident light is polarized parallel to the nanowire long axis. This behavior is one of the characteristics of Q1D systems and renders them promising application in high contrast polarizer. From the photoconductivity measurements of ZnO nanowires, it is found that the presence of O_2 has an important effect on the photoresponse[11,12,13] i.e.O2 surface adsorption on the nanowires could significantly expedite the photocurrent relaxation rate. As shown in Fig. 3, the photocurrent relaxation time is around 8 s in air but hours in vacuum. It was found that the disportion-adsorption process of O_2 affects the photo response of ZnO nanowire. Upon illumination, photo generated holes discharge surface chemisorbed O_2 through surface electron-hole recombination, while the photo generated electrons significantly increase the conductivity. When illumination is switched off, O_2 molecules re-adsorb onto nanowire surface and reduce the conductivity.

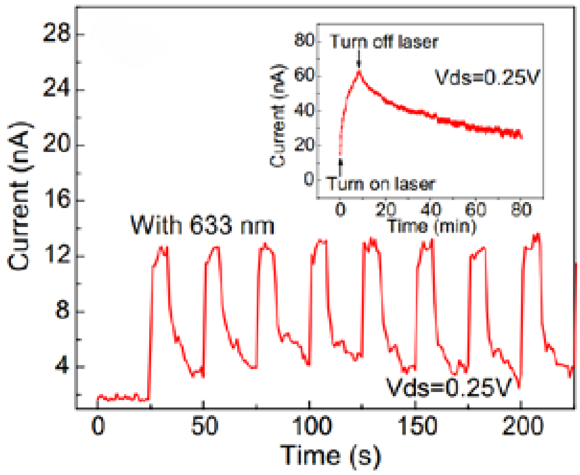

Figure 3 Nanowire photoresponse to 633 nm laser in air compared to that in vacuum [12]

Conclusion

ZnO offers tremendous potential in future applications of electronic and optoelectronic devices. Encouraging progress on the research of nanostructured ZnO materials have been accomplished as reviewed in this article. There are still important issues waiting to be further investigated. One key area is the growth of p-type ZnO nanowires and fabrication of nanoscale p-n junctions for electrically driven nano LED or laser. Integration of ZnO nanostructure building blocks for large scale device applications is another important issue. Continuous effort is dedicated to achieve large arrays of programmable structures for building reconfigurable architectures.

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