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Junction temperature in n-ZnO nanorods/(p-4H–SiC, p-GaN, and p-Si) heterojunction light emitting diodes

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ABSTRACT

The junction temperature of n-ZnO nanorods/(p-4H–SiC, p-GaN, and p-Si) heterojunction light emitting diodes (LEDs) at built-in potential was modeled and experiments were performed at various temperatures (15–65 °C) to validate the model. As the LEDs operate near the built-in potential that's why it is interesting to investigate the temperature coefficient of forward voltage near the built-in potential ($\sim V_o$). The model and experimental values of the temperature coefficient of forward voltage near the built-in potential ($\sim V_o$) were compared. We measured the experimental temperature coefficient of the series resistance. By including the temperature coefficient of the series resistance in the model, the theoretical and experimental values become very close to each other. It was found that the series resistance has the main contribution in the junction temperature of our devices. We also measured the junction temperature above the built-in potential and found that the model deviates at higher forward voltage. From this observation we concluded that the model is applicable for low power devices, operated near the built-in potential.

1. Introduction

Zinc oxide (ZnO) is a wide band gap semiconductor (3.37 eV) and has a relatively large exciton binding energy (60 meV) at room temperature. In addition deep level defects (intrinsic and extrinsic) and the different heterostructures fabrication of ZnO can lead to different emissions in the range of 380–750 nm which covers the whole visible range leading to the possibility of generating white light [1–4]. This implies that ZnO has interesting properties for many opto-electronic applications. As a stable reproducible p-type doping in ZnO is challenging, therefore the excellent optical properties of ZnO might be best utilized by constructing heterojunctions. In this way, the emission properties of LEDs can still be determined by the excellent optical properties of ZnO. ZnO thin film heterojunction have been reported by using various p-type materials like GaN, AlGaN, Si, CdTe, GaAs, diamond and SiC [5–12]. In most of these reports, the junction quality and the over grown ZnO films were of a quality that hindered the utilization of ZnO optical emissions. As ZnO has self organization growth property, ZnO nano-structures with very small footprint can be grown without the need of a special substrate. In addition, a general property of nanorods based LEDs is that each nanorod can act as a wave guide, minimizing side scattering of light, thus enhancing light emission efficiency [13]. This implies that ZnO nanorods grown on p-4H–SiC, p-GaN, and p-Si can lead to a better heterojunction compared to thin films. Solid state lightning technology is offering relatively high efficiency and long lifetime as compared to conventional light sources. It is expected to replace conventional inherently less efficient incandescent and fluorescent light sources [14,15]. The junction temperature is a critical parameter and affects the internal efficiency, the maximum output power and the reliability. It influences the chromaticity and the color-rendering properties of LEDs [16]. Different techniques, such as micro-Raman spectroscopy, electroluminescence, photoluminescence, thermal resistance, and threshold voltage, have been used to determine the junction temperature [17–19]. For homojunction GaN ultraviolet LEDs a relation for temperature dependent forward voltage was derived [20], but it gives an indication that there is an extension beyond the built-in potential V_o and the Shockley model which was used in the derivation has only a limited reliability regarding forward voltage (V_f).

Up till now no work has been done for the junction temperature measurement of heterojunction LEDs. In this report we investigate the influence of junction temperature dependence of the forward voltage for n-ZnO nanorods/(p-4H–SiC, p-GaN, and p-Si) heterojunction LEDs. A relationship for the temperature dependence of the forward voltage is modeled and derived from the energy band diagram of n-ZnO nanorods/p-4H–SiC heterojunction LEDs and then it was generalized for n-ZnO nanorods/(p-GaN and p-Si) LEDs. Theoretical and experimental results are compared and discussed at the built-in potential V_o.

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2. Mathematical modeling and device fabrication

2.1. Mathematical modeling

To derive the relation for the temperature dependent forward voltage, we consider the energy band diagram of n-ZnO nanorods/p-4H–SiC heterostructure as shown in Fig. 1b and generalize the result for n-ZnO nanorods/(p-GaN and p-Si) heterojunction LEDs. The band gap energies of ZnO and 4H–SiC are taken as 3.37 eV and 3.25 eV, respectively. We start by assuming an abrupt interface and ignore any effects due to interface states [21]. From the band energy diagram the equilibrium energy are given below,

$$eV_o = (E_{gp} + \chi_p) - \{(E_f - E_{VP}) + (E_{CN} - E_f) + \chi_n\}. \quad (1)$$

where, V_o is built-in potential, E_f is Fermi energy level, E_{gp}, χ_p, E_{VP}, are the energy band gap, electron affinity and effective densities of states in the valence band of p-4H–SiC, and χ_n, E_{CN} are electron affinity and effective densities of states in the conduction band of n-ZnO.

The difference in energy between the Fermi level and band edges can be taken from Boltzmann's statistics assuming that all dopants are fully ionized [21]. We have,

$$E_{CN} - E_f = -kT \ln \frac{N_D}{N_{CN}} \text{ for the n-type side} \quad (2)$$

$$E_f - E_{VP} = -kT \ln \frac{N_A}{N_{VP}} \text{ for the p- type side} \quad (3)$$

where k is Boltzmann constant and have a value 1.38×10^{-23} J/K, T is absolute temperature in Kelvin and N_D, N_A are donor and accepter concentrations. Now we can write Eq. (1) as follows,

$$eV_o = (E_{gp}) + (\chi_p - \chi_n) - \{(E_f - E_{VP}) + (E_{CN} - E_f)\} \quad (4)$$

As $\Delta E_C = \left|\chi_p - \chi_n\right|$ the value of ΔE_C is always positive. By using Eqs. (2) and (3) we can write Eq. (4) as:

$$V_o = \frac{E_{gp}}{e} + \frac{\Delta E_c}{e} + \frac{kT}{e} \ln \frac{N_D N_A}{N_{VP} N_{CN}} \quad (5)$$

Let the LED be operated in forward direction close to built-in voltage, i.e.

$$V_f = \frac{\Delta E_C}{e} + \frac{E_{gp}}{e} + \frac{kT}{e} \ln \left(\frac{N_D N_A}{N_{CN} N_{VP}}\right) \quad (6)$$

Differentiate Eq. (6) with respect to temperature (T) and assume $\frac{dV_f}{dT} = \frac{dV_o}{dT}$ we get

$$\frac{dV_f}{dT} = \left[\frac{1}{e}\frac{d\Delta E_C}{dT} + \frac{1}{e}\frac{dE_{gp}}{dT} + \frac{d}{dT}\left\{\frac{kT}{e} \ln \left(\frac{N_D N_A}{N_{VP} N_{CN}}\right)\right\}\right] \quad (7a)$$

where

$$\frac{d}{dT}\left\{\frac{kT}{e} \ln \left(\frac{N_D N_A}{N_{VP} N_{CN}}\right)\right\} = \frac{k}{e}\left(\ln \frac{N_D N_A}{N_{VP} N_{CN}}\right) + \frac{kT}{e}\frac{N_{VP} N_{CN}}{N_D N_A}\frac{d}{dT} \times \frac{N_D N_A}{N_{VP} N_{CN}} \quad (7b)$$

As all dopants are fully ionized N_D and N_A are independent of temperature and,

$$N_{CN} = 2\left(\frac{2\pi m_{de} kT}{h^2}\right)^{\frac{3}{2}} \text{ and } N_{VP} = 2\left(\frac{2\pi m_{dh} kT}{h^2}\right)^{\frac{3}{2}} \quad (8)$$

where m_{de} and m_{dh} are density-of-states effective mass for electrons and holes, respectively, h is the Planck's constant. By putting Eq. (8) in Eq. (7b) we get,

$$\frac{d}{dT}\left\{\frac{kT}{e} \ln \left(\frac{N_D N_A}{N_{VP} N_{CN}}\right)\right\} = \frac{k}{e}\left(\ln \frac{N_D N_A}{N_{VP} N_{CN}}\right) - \frac{3k}{e} \quad (9)$$

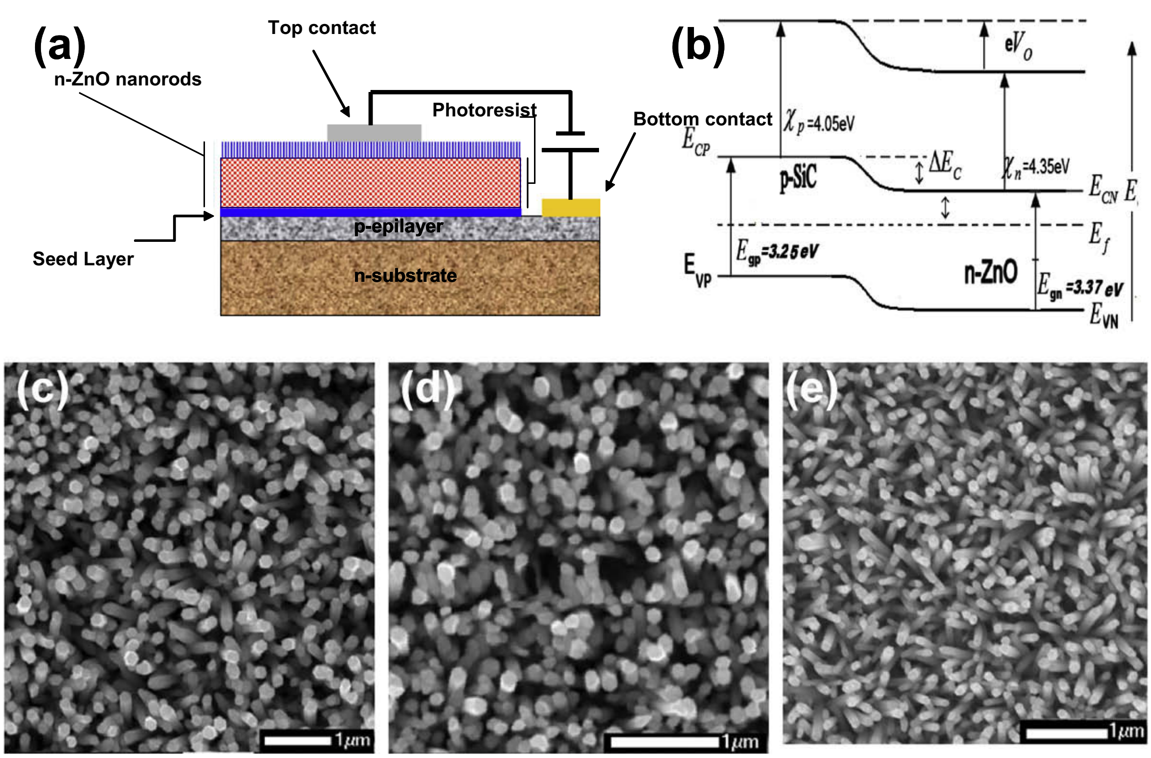

Fig. 1. (a) shows the schematic diagram of the fabricated LEDs, 1(b) shows a typical schematic equilibrium energy band diagram for n-ZnO nanorods/p-4H–SiC heterostructure, showing the band gap offset between the two materials, 1(c–e) shows the top SEM image of ZnO nanorods on p-4H–SiC, p-GaN and p-Si substrates respectively.