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Properties of isotype n-ZnO/n-GaN heterostructures studied by *I*–*V*–*T* and electron beam induced current methods

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Abstract
Electrical properties of isotype n-ZnO/n-GaN heterostructures obtained by radio-frequency sputtering of ZnO films on GaN layers are studied by means of temperature dependent current–voltage (I–V–T) characterization and electron beam induced current (EBIC) measurements. The n-ZnO/n-GaN diodes showed highly rectifying behavior with a forward and reverse current ratio of about 10^6 at ± 5 V. From the analysis of I–V–T measurements, a conduction band offset of $\sim$0.62 eV was derived. From EBIC measurements, the minority carrier diffusion length of ZnO was estimated to lie in the range 0.125–0.175 μm, while an activation energy was derived as 0.462 ± 0.073 V and was attributed to the traps.

Devices capable of functioning in harsh environments are desirable. From this point of view ZnO, a wide band gap semiconductor ($E_g = 3.3$ eV, $T = 300$ K), is a very promising material due to e.g. large exciton binding energy ($\sim$60 meV), radiation hardness, availability of bulk crystal and ease of ZnO film growth [1]. Although p-ZnO growth technology is still a hotly debated issue, development of ZnO heterojunction based devices is of interest nonetheless because such devices have advantages over the homojunction devices owing to carrier and optical confinement, lower diffraction losses, and reduction of threshold current in injection devices. A number of reports are available on the anisotype ZnO heterostructures prepared by growing n-type ZnO films on different p-type materials [2]. N-ZnO/p-(Al)GaN heterostructures have been of particular interest because ZnO and GaN have relatively close lattice parameters and physical properties [3–10]. A study of the properties of isotype n-ZnO/n-(Al)GaN type heterostructures is also important because, in particular, isotype heterostructures (depending on their band alignment) can also have strong diode-like rectifying behavior comparable to that of anisotype p–n heterojunctions. In addition, highly doped ZnO layers with electron concentration higher than 10^{19} cm^{-3} were used as transparent ohmic contacts to GaN in many reports, for example [11–13]. An n-ZnO/n-GaN being a part of the p-GaN/n-ZnO/n-GaN double heterostructure may be of interest for high efficiency optoelectronics devices. Therefore, investigation of the current transport mechanisms in n-ZnO/n-GaN heterostructures is warranted. In this work we report on the electrical properties of n-ZnO/n-GaN heterostructures studied using temperature dependent current–voltage (I–V–T) measurements, and electron beam induced current (EBIC). The EBIC technique is known to be an effective method to measure the minority carrier diffusion length and the barrier height [14, 15]. The electron beam current density and spot diameter were 9.6×10^{-4} A cm^{-2} and 10 nm, respectively.

The structure was fabricated on *rf* sputtered of 0.3 μm thick ZnO layers on as grown n-type GaN films grown by metal–organic chemical vapor deposition (MOCVD) on sapphire. After growth, the ZnO films were annealed at 900 °C for 30 min to improve crystal quality [16]. As grown ZnO films had n-type conductivity with electron concentration

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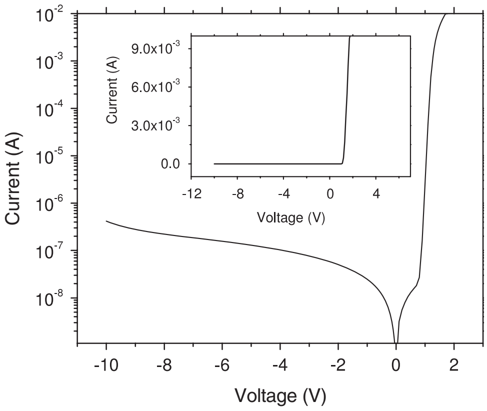

Figure 1. Typical room temperature I–V characteristics of the n-ZnO/n-GaN heterostructures in logarithmic and linear (inset) scales.

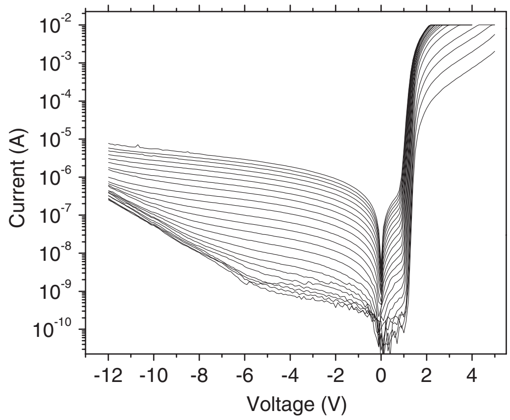

Figure 2. I–V–T characteristics of the n-ZnO/n-GaN structure; temperature was varied from 80 to 570 K.

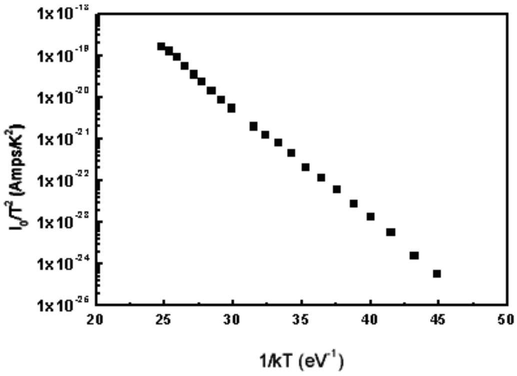

Figure 3. Arrhenius plot of the saturation current for a n-ZnO/n-GaN diode versus the inverse temperature. The slope leads to a barrier height of 0.62 eV.

about 10^{18} cm^{-3} as determined by C–V measurements. The carrier concentration of the as grown MOCVD n-GaN used was about 10^{17} cm^{-3}. The ZnO and GaN mesa structures of 250 μm diameter size were fabricated using conventional photolithography. Ohmic contacts to ZnO and GaN were formed using Au/Al (300/300 Å) for both.

A typical room temperature I–V is shown in figure 1. As seen from this figure this curve has a very pronounced diode-like rectifying behavior with forward and reverse currents $\sim 7 \times 10^{-2}$ A and $\sim 10^{-7}$ at ± 5 V, respectively, with a rectification factor $I_{\rm fow}/I_{\rm rev}$ about $\sim 7 \times 10^5$. The breakdown and turn-on threshold voltages were ~ -10 and ~ 1 V, respectively. The ideality factor n was temperature dependent and decreased from 3 to 1.25 as temperature increased from 100 to 500 K indicating increasing dominance of thermionic emission. Above 2 an ideality factor is indicative of some sort of tunneling component being present. As seen from these data the properties of the diode studied in this work are comparable to the best reported ZnO/GaN type p–n heterojunction diodes so far [2, 3, 7, 17]. It should be noted that the properties of the diodes are very reproducible.

I–V–T measurements were performed in the temperature range 80–570 K and the set of curves is shown in figure 2. The reverse current increases much faster with temperature than forward current indicative of that current having a more predominant thermionic emission component. As seen from the figure, at low temperatures and higher voltages (>6 V) the reverse current increases that may result from tunneling current, as indicated by the relatively temperature insensitive current, as well as from Frenkel–Poole emission. The Arrhenius plot simulating the thermionic emission current was generated using the I–V–T data and plotted as shown in figure 3 for -2 V bias. An activation energy of 0.125 eV was deduced at -2 V reverse bias in the figure which was mainly constant over a wide range of biases, but was dependent on the temperature region used for the fit. The Arrhenius plot is somewhat s-shaped—exhibiting relatively lower energies at low and high temperatures and higher energies at mid-range temperatures. The barrier height of 0.125 derived from the Arrhenius plot in this work is the activation energy of the dominant current leakage path. The forward bias current was also measured and a fit was attained for the saturation current. The temperature dependence was then used to construct an Arrhenius plot. The activation energy obtained from the slope of the plot is 0.62 eV. This is the effective conduction band offset, in terms of the thermionic emission current conduction, between GaN and ZnO [18]. This value is slightly less than the value reported previously for ZnO/GaN heterostructure [19]. Hong *et al* estimated the conduction band offset at the ZnO/GaN(0001) heterojunction with Zn pre-exposure to be 0.82 eV with a type-II band alignment. The band offset was determined in this work by ultraviolet and x-ray photoelectron spectroscopy, and the layers ZnO on GaN were grown by plasma assisted MBE [19]. This difference between conduction band offset values may be due to different growth methods since this physical parameter is very sensitive to the quality of the interface. In figure 4 a schematic energy band diagram of the isotype n-ZnO/n-GaN heterostructure studied in this work has been presented. This diagram was built considering ideal n-ZnO/n-GaN heterojunction without any interface states. Corresponding to electron concentrations of ZnO and GaN, which are respectively, $\sim 10^{18}$ cm^{-3} and $\sim 10^{17}$ cm^{-3}, band bending is also shown.

Minority carrier diffusion length, L, and the activation energy of traps in the ZnO layer was studied by EBIC. The

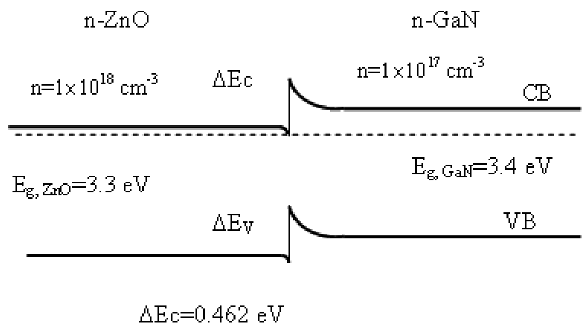

Figure 4. Schematic energy band diagram of the isotype n-ZnO/n-GaN heterostructure at equilibrium.

measurements were conducted at low e-beam accelerating voltage of 5 kV corresponding to electron penetration depth of about 100 nm, so that almost all excess carries were generated in the ZnO layer. The EBIC measurements were carried out laterally, and the EBIC signal was measured as the electron beam was moving from the edge of the mesa structure. The effect of irradiation with electron beam of the scanning electron microscope was studied using EBIC at temperatures 25, 50, and 75 °C. The results are shown in figure 5 in which the room temperature EBIC signal decay in ZnO as a function of distance from the edge of the mesa in the ZnO layer is presented. Curve 1 corresponds to the initial line-scan; curves 2 and 3 correspond to $t = 330$ s and 554 s, respectively. The minority carrier diffusion length, L, was extracted using the following expression

$$I = kd^{\alpha} \exp(-d/L)$$

where I is the EBIC signal, d—distance between e-beam and junction, k—constant, α—coefficient lying between $-1/2$ and $-3/2$ dependent on surface recombination velocity. In the present work $\alpha = 1/2$ was used, which corresponds to the negligible surface recombination velocity. The extracted values for L are plotted in the insets of figure 5 for each temperature. Depending on excitation conditions diffusion lengths in the range 0.125–0.175 μm were measured from EBIC[6]. It is seen that the diffusion length L varies linearly with duration of irradiation, t. The observed irradiation induced increase in diffusion length is supposed to be caused by the trapping of non-equilibrium electrons on deep acceptor levels [20–22]. The L value measured in this work is much smaller than that for bulk ZnO measured previously 2–3 μm [23] that can be explained by higher electron recombination rate in thin films rate due to free surface.

The increase of the diffusion length with duration of irradiation was also observed at elevated temperatures. The insets of figure 5 demonstrate that this increase is linear and that its rate, R_L, diminishes with increasing measurement temperature. Temperature dependence of R_L was used to

[6] It should be noted that 'radiation hardness' usually refers to irreversible changes of the crystal physical properties and is associated with radiation-induced structural defects. Diffusion length changes described here are due only to the re-distribution of non-equilibrium minority carriers and are spontaneously reversible.

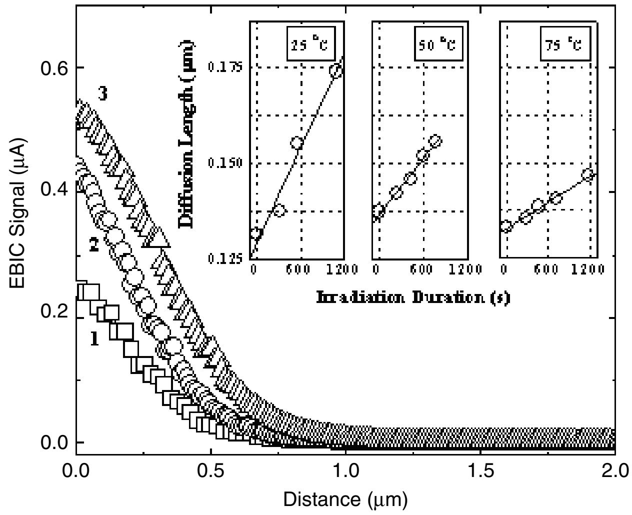

Figure 5. Room temperature EBIC signal decay in the ZnO layer as a function of distance from the edge of the mesa in the ZnO layer at different irradiation times. The inset: the diffusion length L versus t experimental dependence and the linear fit at variable temperatures.

estimate the activation energy for the electron irradiation effect according to the expression of the form [14, 24]

$$R = R_0 \exp\left(\frac{\Delta E_A}{2kT}\right)$$

where R_0 is a scaling constant and ΔE_A is the activation energy. The fit yielded an activation energy of 0.462 ± 0.073 V, which is most likely activation energy of acceptor-like traps. There have been several reports on deep levels in ZnO films grown by magnetron sputtering [25] and by molecular-beam epitaxy [26] and no traps with activation energy around 0.462 eV were reported in these studies. Nakano *et al* [25] observed deep levels located at 0.98, 1.20, and 2.21 eV below the conduction band in ZnO films grown by magnetron sputtering. Oh *et al* [26] reported on electron traps with energy 0.12–0.15 eV in ZnO films grown by molecular-beam epitaxy. However, defect structure of the films depends on many factors as growth conditions, substrate, post-growth treatments, so our films may contain defects with activation energy around 0.462 ± 0.073 eV.

In conclusion, n-ZnO/n-GaN type isotype heterostructures were fabricated by rf-sputtering of ZnO films on GaN layers grown by MOCVD and their electrical properties have been studied. I–V characteristics of the n-ZnO/n-GaN diodes showed rectifying behavior with forward and reverse currents $\sim 7 \times 10^{-2}$ A and $\sim 10^{-7}$, respectively, at ± 5 V. An activation energy ~ 0.62 eV was deduced for the band offset from the Arrhenius plot. An activation energy 0.462 ± 0.073 eV was derived from the temperature dependent EBIC measurements which was attributed to donor-like traps. A minority carrier diffusion length in the range of 0.125–0.175 μm, depending on the excitation conditions, was deduced from EBIC measurements.

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