2006

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Ya. I. Alivov
Virginia Commonwealth University, yialivov@vcu.edu

Bo Xiao
Virginia Commonwealth University, xiaob@vcu.edu

Q. Fan
Virginia Commonwealth University

Hadis Morkoç
Virginia Commonwealth University, hmorkoc@vcu.edu

D. Johnstone
SEMETROL

Alivov, Ya.I., Xiao, B., Fan, Q., et al. Band offset measurements of ZnO/6H-SiC heterostructure system. Applied Physics Letters, 89, 152115 (2006). Copyright © 2006 AIP Publishing LLC.

APPLIED PHYSICS LETTERS **89**, 152115 (2006)

Band offset measurements of ZnO/6*H*-SiC heterostructure system

Ya. I. Alivov,[a] B. Xiao, Q. Fan, and H. Morkoç
Department of Electrical Engineering, Virginia Commonwealth University, Richmond, Virginia 23284

D. Johnstone
SEMETROL, Chesterfield, Virginia 23838

(Received 19 May 2006; accepted 30 August 2006; published online 11 October 2006)

The conduction band offset of *n*-ZnO/*n*-6*H*-SiC heterostructures fabricated by rf-sputtered ZnO on commercial *n*-type 6*H*-SiC substrates has been measured by a variety of methods. Temperature dependent current-voltage characteristic, photocapacitance, and deep level transient spectroscopy measurements showed the conduction band offsets to be 1.25, 1.1, and 1.22 eV, respectively. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2360924]

ZnO is under consideration for a variety of optical devices owing to its large exciton binding energy (60 meV), relative ease of bulk material growth, and the possibility of growing highly conductive layers. Because high quality, reproducible *p*-type ZnO layers are not yet available, *p*-*n* junctions are fabricated that take advantage of heteroepitaxy.[1] Heteroepitaxial structures are also of interest on their own merits because of advantages provided by the valence and conduction band offsets.[2] Various heteroepitaxial structures have been used as the *p*-type layer for device fabrication. For example, ZnO has been used as a channel for high quality field-effect transistors by several groups.[1,3,4] The component materials of the heterojunction can have a large impact on device performance.

One of the vital criteria in heteroepitaxial based devices is to match the lattice parameters, and from this point of view GaN and its alloys with aluminum have been considered by many authors as one of the best candidates for such device fabrication.[5–9] Another good candidate for ZnO based heterostructure devices is SiC, which matches the wurtzite crystal structure and has a relatively small lattice mismatch of ~4% with ZnO.[10–13] Recently, we demonstrated high quality and highly reproducible *n*-ZnO/*p*-6*H*-SiC heterojunction diodes with a very good rectifying behavior and with a leakage current less than $1\times10^{-4}\,\mathrm{A/cm^2}$ at −10 V, a forward current of 4 $\mathrm{A/cm^2}$ at 8 V, and a breakdown voltage greater than 20 V.[10,11] In Ref. 11 it was shown from electroluminescence measurements that electron injection takes place primarily from ZnO into SiC without substantial hole injection into the ZnO. Although this is not beneficial for light-emitting diode applications (because ZnO would not be the active photon emission layer in this case), it would be of interest for applications in which ZnO would serve as the emitter, such as photodiodes and *n*-*p*-*n*-type heterostructure bipolar transistors.

To better understand heterostructure device performance, knowledge of the band offset between materials forming the heterostructure is necessary. No report on the band offset in ZnO/SiC heterostructure is available. In this letter we have measured the conduction band offset of this material system by studying *n*-ZnO/*n*-6*H*-SiC isotype heterodiodes with Ohmic contacts by temperature dependent current-voltage characteristic (*I*-*V*-*T*), photocapacitance, and deep level transient spectroscopy (DLTS) measurements.

The *n*-ZnO/*n*-SiC heterostructure samples were fabricated by growing 0.3 μm thick undoped ZnO film by rf sputtering on 300 μm commercial *n*-type 6*H*-SiC substrates. ZnO layers were deposited directly on 6*H*-SiC substrates at 750 °C by rf magnetron sputtering in an $\mathrm{Ar}+\mathrm{O_2}$ ambient atmosphere. Electron concentration of *n*-6*H*-SiC was $2.6\times10^{17}\,\mathrm{cm^{-3}}$. The chamber process pressure and plasma power were 4.20 mTorr and 100 W, respectively. After growth ZnO layers were annealed at 950 °C for 1 h to improve film crystal quality. It should be noted that we observed earlier that such treatment of ZnO on SiC leads to significant improvement of ZnO crystal quality.[12] The 250 μm diameter mesa structures were fabricated by conventional photolithography method. The Ohmic contacts to *n*-ZnO and *n*-SiC were formed by depositing Au/Al (300/300 Å) and Au/Ti/Ni (300/300/300 Å) metal layers, respectively, with subsequent rapid temperature annealing at 800 °C for 2 min. The *I*-*V*-*T* and DLTS measurements were performed in the temperature range of 80–700 K. The photocapacitance spectroscopy was taken at 80 K using a xenon lamp and monochromator.

In Fig. 1 the typical *I*-*V* characteristics of the diodes at 300 and 80 K are shown. As seen from the figure, the *I*-*V* characteristic exhibits a clear rectifying behavior, and at room temperature the forward current at 3 V is 1×10^{-2} A while the reverse current at −3 V is 1×10^{-7} A. Both reverse

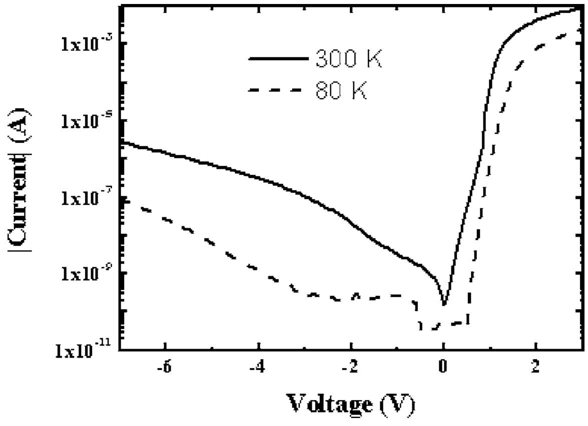

FIG. 1. Typical current-voltage characteristics for a *n*-ZnO/*n*-6*H*-SiC isotype heterojunction diode at 300 K (solid line) and at 80 K (dotted line).

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[a] Electronic mail: yialivov@vcu.edu

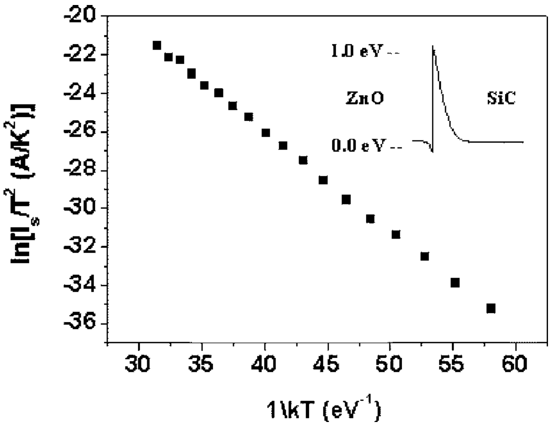

FIG. 2. Arrhenius plot of the saturation current for a n-ZnO/n-6H-SiC diode vs the inverse temperature. The slope leads to a barrier height of 1.25 eV. The inset shows the expected band bending.

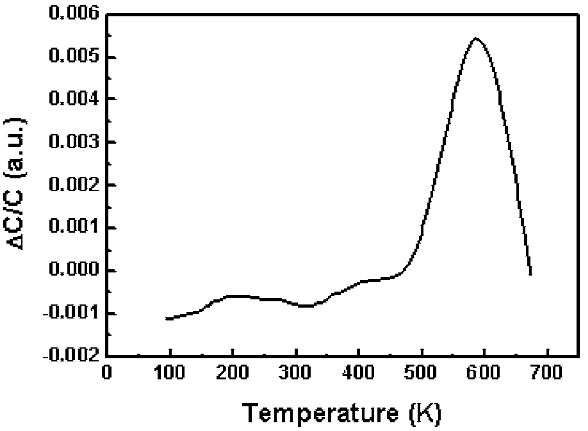

FIG. 4. DLTS rate window plot of the n-ZnO/n-SiC heterojunction diode. The rate window is 278/s. The filling pulse is 1 V, and the measurement bias is 3 V.

and forward currents decrease with decreasing temperature, and at 80 K the values are 2.84×10^{-10} and 2.4×10^{-3} A at −3 and +3 V, respectively.

The I-V-T results are summarized in Fig. 2, where the Arrhenius plot of the saturation current of n-ZnO/n-6H-SiC diode versus inverse temperature is shown. For thermionic emission, the diode equation is expressed as

$$I = I_S\left[\exp\left(\frac{qV}{nkT}\right) - 1\right], \tag{1}$$

where I_s is the saturation current, n the ideality factor, k the Boltzmann constant, and T the absolute temperature. The saturation current in Eq. (1) is given by

$$I_s = A^*T^2\exp\left(\frac{-\phi_B}{kT}\right), \tag{2}$$

where A^* is the effective Richardson constant and ϕ_B the barrier height.[14] The forward bias current from Eq. (1) was fitted for the saturation current at each temperature. A plot of $\ln(I_s/T^2)$ vs $1/kT$ has a slope of $-\phi_B$, which is 1.25 eV.

Adjustments can be made to account for the position of the Fermi level relative to the conduction band in each component material, but the shallow carrier activation energy in each is similar and small compared to the band offset. The band offset in a n-n heterojunction is

$$\Delta E_c = qV_D - \delta_1 + \delta_2. \tag{3}$$

V_D is the sum of the band bending in each material, and δ_1 and δ_2 are the Fermi level positions with respect to the conduction band in each material. The band bending in the ZnO will also be very small compared to the band bending in the SiC, proportional to the ratio of dopant in SiC to conduction band density of states in ZnO. A calculation of the band bending based on a band offset of 1.25 eV and carrier concentrations of $6\times10^{17}/\text{cm}^3$ in ZnO and $1\times10^{18}/\text{cm}^3$ in SiC is shown in the inset of Fig. 2.

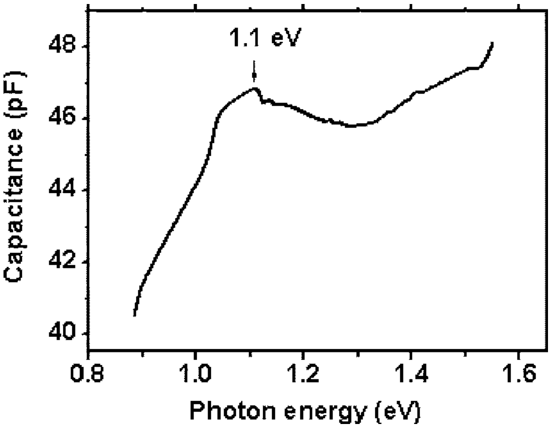

FIG. 3. Photocapacitance spectroscopy of a n-ZnO/n-6H-SiC diode.

Photocapacitance measures the change in capacitance when monochromatic light with energy near the barrier height is incident on the diode. Figure 3 presents the results of photocapacitance measurements for a n-ZnO/n-6H-SiC diode as a function of photon energy taken at 80 K. As seen from the figure, the spectrum has a peak at 1.1 eV, which corresponds to the energy necessary to overcome the energetic barrier due to the band offset at the n-ZnO/n-6H-SiC interface.

The temperature dependence of thermionic emission over the barrier was also measured using DLTS to determine the band offset. The filling pulse was 1 V for 100 ms, and the measurement bias was −3 V. The filling pulse bias required to bring the Fermi level above the bottom of the triangular well at the heterojunction was determined from an abrupt increase in the emission amplitude as the filling pulse was increased. The spectrum for a rate window of 278/s is shown in Fig. 4. A conventional rate window analysis was performed to obtain the energy.[15] The energy from a rate window analysis is 1.2 eV. This is the thermionic emission energy over the heterojunction barrier.

In conclusion, the conduction band offset of n-ZnO/n-6H-SiC diode with Ohmic contacts has been measured by three different methods: I-V-T, photocapacitance, and DLTS. The measured band offsets using each method are 1.25, 1.1, and 1.2 eV, respectively.

This research has been funded by AFOSR under the direction of G. L. Witt and K. Reinhardt.

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