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MOVPE Prepared ZnO/Si Heterojunction Diodes with Dual Functions: Light-Emission and UV Photo-Detection

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1. INTRODUCTION

ZnO has been attracting much attention for optoelectronics applications. Particularly, fabricating ZnO-based *p-n* hetero-junctions has received extensive studies [1]. Meanwhile, integration of Si technology with UV optoelectronics devices based on III-nitrides or oxides, has been investigated as a key technology overcoming communication bottlenecks in electrical interconnects. Moreover, Si has an existing, mature and cost effective CMOS manufacturing support. ZnO/Si heterojunctions have been employed in the applications of solar cells and photodetectors where ZnO just acts as the transparent conducting window [1]. ***So far, few efforts were made on light-emitting and UV photo-detecting from ZnO/Si heterojunctions.***

In this work, we present a ZnO/Si heterojunction diode with dual functions of light emission and UV photodetection by MOVPE technique. The origin of electroluminescence and UV photoresponse and the carrier transport mechanisms are discussed with the aid of energy band diagram.

2. EXPERIMENTS

In this study, ZnO epilayers of 450nm were deposited on p^+-Si (100) ($2\times10^{18}cm^{-3}$) substrates by a MOVPE system. ZnO buffer layer ~25nm was deposited at 350°C. The growth temperature of epilayer was varied from 500 to 650°C. **Fig. 1** shows a schematic diagram of the n-ZnO/p-Si heterojunction. The films showed n-type of ~8.6×10^{16}-$5.3\times10^{17}cm^{-3}$. Circular Ag electrode contacts were thermally deposited on ZnO epilayer and underwent rapid thermal annealing (RTA) process at 600°C for 20 s [2]. Al electrodes were thermal deposited on the backside of Si. XRD, AFM, AES, photoluminescence, electroluminescence, I-V, and photoresponse were used to characterize the material quality and device performance.

3. RESULTS AND DISCUSS

Material Characterization The XRD pattern (**Fig. 2**) shows that the epilayer grown at 600°C exhibited only (0002) peak at 2θ=34.46º for wurtzite structure ZnO with its small FWHM of 0.24°, indicative of single crystalline quality. The regular hexagonal ZnO grains larger than 500nm dominated the surface morphology. Photoluminescence spectra (**Fig. 3)** show that the deep-level emission has a red shift as growth temperature increased, besides the sharp UV band-edge emission around ~3.28eV. Compared to the PL of buffer layer, the orange emission at ~2.1eV mainly comes from defects formed by Si diffusion into ZnO buffer layer [2-3]. The green emissions at ~2.5eV are attributed to native defects such oxygen vacancies [4]. It is noted that ZnO epilayer grown at 600°C exhibits best optical properties.

Diode performance and carrier transport mechanism The I-V characteristics (**Fig. 4)** show a rectifying behavior with an I_F/I_R value of 77 and 970 at 4V for ZnO/Si prepared at 500 and 600°C respectively, and the latter is comparable to previously reported values of ZnO/Si heterojunctions [5-6]. The turn-on voltage in **Fig. 4(a)** is less than the electron barrier, indicative of the dominant tunneling recombination processes due to more defects existed in ZnO epilayer deposited at low temperature. In comparison, ZnO/Si grown at 600°C shows better performance, attributed to re-crystallization of buffer layer and better quality of the epilayer. AES depth profile (**Fig. 5)** also shows that growth at higher temperature has a sharp interface between ZnO and Si, thus leading to the low interface states and small reverse current.

The log-log plot of dark I-V curve in **Fig. 6** exhibits three regimes. For V<1.4V, the current increased in the relation of I ~ exp (αV), which can be attributed to the recombination- tunneling mechanism [7]. For 1.5<V<2.8V, the I-V curve was dominated by space-charge-limited current (SCLC) conduction effect in relation of I ~ $(V-V_0)^2$. It is a typical feature in wide bandgap semiconductors due to single-carrier injection [8]. Only electron can cross the depletion region below 2.8V due to higher energy potential barrier for holes (**Fig. 7**). For V≥2.9V, this behavior disappeared due to the hole injection into ZnO side.

Light-emitting and UV photoresponse With a forward bias applied, distinct yellow EL emissions were observed by naked eyes (**Fig. 8**). As shown in **Fig. 9**, the coincidence of PL and EL spectra strongly suggests that the radiative recombination path of EL is mainly via deep-level states within ZnO buffer layer. The weak UV EL emission was due to the self-absorption effect and/or field-induced exciton nonradiative annihilation. The EL emission shifted to higher energy with the increase of injection current, possibly caused by the band filling effect or photon-assisted tunneling processes [9]. The L-V plot in **Fig. 10** shows that the ZnO/Si diode fabricated at 600°C has higher EL intensity with the same injection current due to high quality of ZnO material and sharp interface. Furthermore, the inset showed a larger turn on voltage than that in I-V curve, indicating that EL process was dominated by hole injection, as the nature of hole transport process. The small slope in the low voltage range of log-log L-V curve is due to the shunt path of current via tunneling recombination in nonradiative defect centers in ZnO depleted region [10]. High bias causes high carrier injection across the potential barrier and the nonradiative centers are saturated, the electrical-to-optical conversion efficiency increased greatly.

Fig. 11 shows the photoresponse spectra of ZnO/Si. The maximum photoresponse is in UV region due to the absorption of ZnO surface layer and the maximum value of 0.032A/W at -1.1V shows high performance for this p-n heterojunction photodetector, comparable to other reports [5, 11]. The photoresponse dependence on bias (**Fig. 11 inset)** shows that the photoresponse at 375nm becomes saturated when the bias is ≥1V, while photo-response at 765nm increases slowly over 1V. The difference is related to the drift speed of minor carrier (hole in ZnO and electron in Si) in the electrical field [1].

4. CONCLUSION

High-quality ZnO epilayer deposited on Si (111) substrate at 600°C by MOVPE technique shows the best material quality and device performance. The distinct EL emission was observed and attributed to the radiative recombination through deep-level defects in depleted ZnO layer. The distinct UV photoresponse was also investigated with a maximum value of 0.032A/W at 375nm for small bias of -1.1V. *I-V* and *L-V* characteristics were quantitatively discussed with the aid of energy band diagram.

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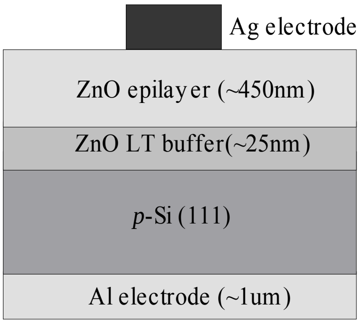

Fig.1 A schematic diagram of the n-ZnO/p-Si heterojunction

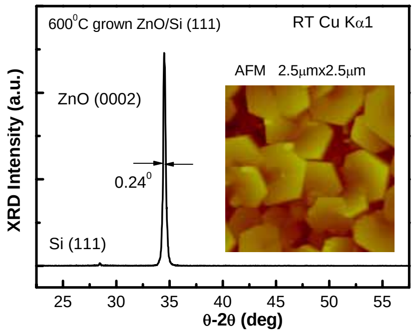

Fig.2 XRD pattern and AFM image of ZnO epilayer grown at 600^0C

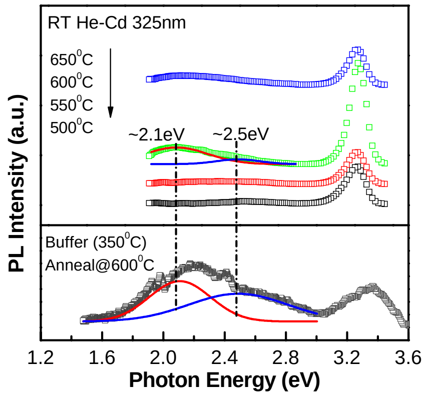

Fig.3 Room temperature photoluminescence of ZnO epilayer grown at room temperature and ZnO buffer layer annealed at 600^0C

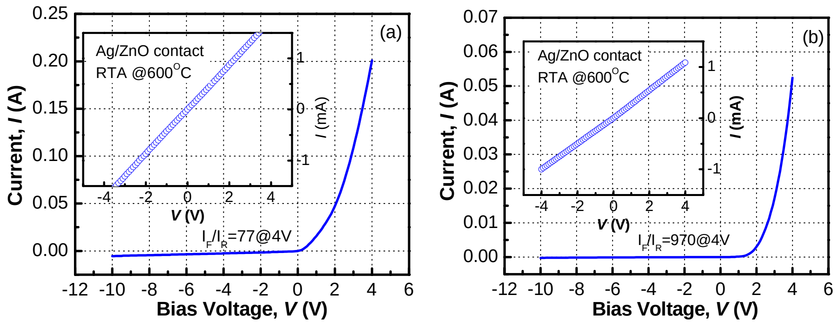

Fig.4 I-V characterization of ZnO/Si fabricated at 500^0C (a) and 600^0C (b), respectively. The inset shows I-V curve of two Ag points on ZnO

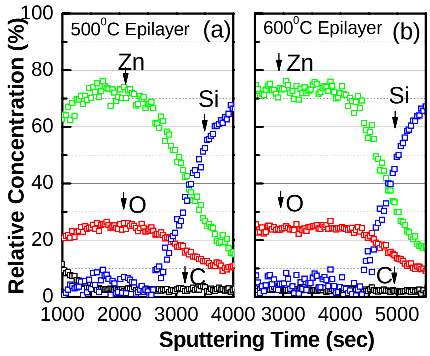

Fig.5 AES depth profile of ZnO/Si prepared at 500^0C (a) and 600^0C (b), respectively.

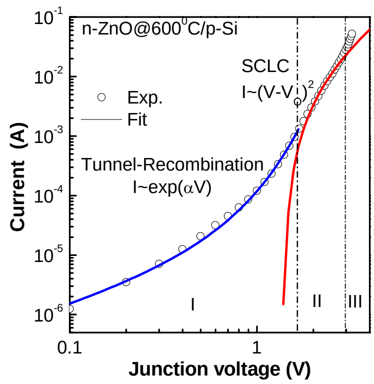

Fig.6 Injection current as a function voltage for ZnO/Si grown at 600^0C

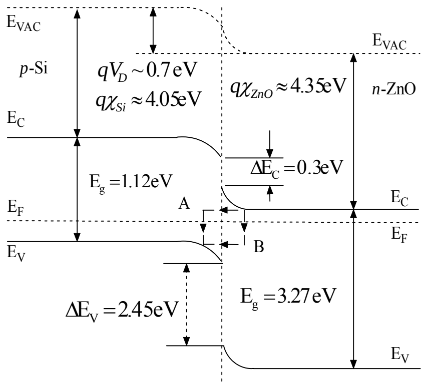

Fig.7 The energy band diagram of n-ZnO/p-Si heterojunction at zero bias

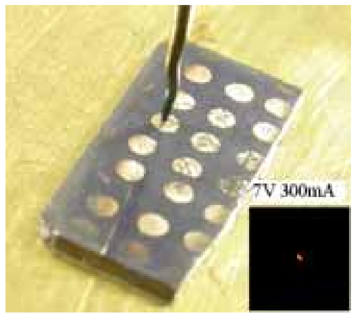

Fig.8 Photograph of device structure and orange EL emission taken in dark room

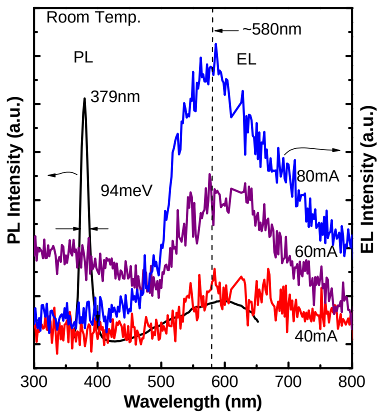

Fig.9 Room Temperature EL spectra of n-ZnO/p-Si heterojunction at various injection current

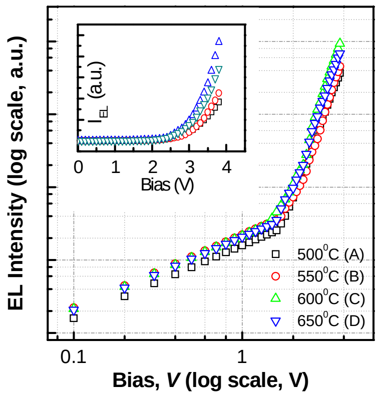

Fig.10 EL Intensity as a function of bias for ZnO/Si heterojunction prepared at various temperatures. The inset figure exhibits the rectifying-like characteristics

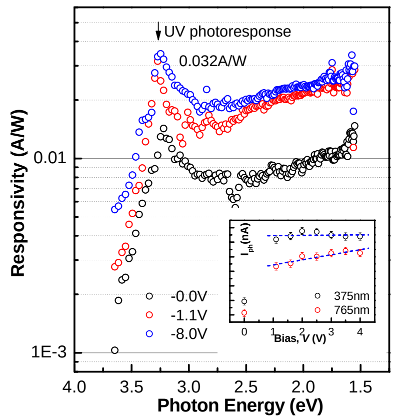

Fig.11 Photoresponse spectra of ZnO/Si heterojunction at various reverse biases, and the inset shows the photocurrent as a function of bias