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Erratum

ZnO-based MIS photodetectors

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Abstract

We report the fabrication of ZnO-based metal–insulator–semiconductor (MIS) and metal–semiconductor–metal (MSM) photodetectors. With 5 V applied bias, it was found that photocurrent to dark current contrast ratios of the ZnO MSM and MIS photodetectors were \(2.9 \times 10^2\) and \(3.2 \times 10^4\), respectively. It was also found that measured responsivities were 0.089 and 0.0083 A/W for the ZnO MSM and MIS photodetectors, respectively, when the incident light wavelength was 370 nm. Furthermore, it was found that UV to visible rejection ratios for the fabricated ZnO MSM and MIS photodetectors were \(2.4 \times 10^2\) and \(3.8 \times 10^3\), respectively.

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1. Introduction

In recent years, much research has been focused on high performance solid-state ultraviolet (UV) photodetectors [1]. Photodetectors operating in the UV region are important devices that can be used in various commercial and military applications. For example, visible-blind UV photodetectors can be used in space communications, ozone layer monitoring and flame detection. Currently, light detection in the UV spectral range still uses Si-based optical photodiodes. Although Si-based photodiodes are sensitive to visible and infrared radiation, the sensitivity in the UV region is low since the room temperature bandgap energy of Si is only 1.2 eV. With the advent of optoelectronic devices fabricated on wide direct bandgap materials, it becomes possible to produce high performance solid-state photodetectors that are sensitive in the UV region. For example, GaN-based UV photodetectors are already commercially available [2,3]. ZnSe-based UV photodetectors have also been demonstrated [4].

ZnO is another wide direct bandgap material that is sensitive in the UV region [5,6]. The large exciton binding energy of 60 meV and wide bandgap energy of 3.37 eV at room temperature make ZnO a promising photonic material for applications such as light emitting diodes, laser diodes and UV photodetectors. Indeed, ZnO has attracted much attention in recent years [7–9]. High quality ZnO epitaxial layers can be grown by metalorganic chemical vapor deposition [5], molecular beam epitaxy (MBE) [10] and pulsed laser deposition [11] on top of ZnO substrates [6], sapphire substrates [12] and epitaxial GaN layers [13]. ZnO Schottky diodes and metal–semiconductor–metal (MSM) photodetectors detecting in the UV region have also been demonstrated [8]. MSM photodetectors consist of two interdigitated Schottky contacts deposited on top of an active layer. The reduced parasitic capacitance of this structure, as well as the low dark current and noise values, and its linearity with optical power, make MSM detectors the most promising candidates...
for high-speed photodetection [14–16]. To achieve high performance MSM UV photodetectors, it is important to improve crystal quality and to achieve large Schottky barrier height at metal–semiconductor interface. A large barrier height leads to small leakage current and high breakdown voltage which could result in improved responsivity and photocurrent to dark current contrast ratio. To achieve a large Schottky barrier height on ZnO, one can choose metals with high work functions [17]. However, many of the high work function metals are not stable. In other words, severe inter-diffusion might occur at metal–ZnO interface. To solve this problem, one can insert an insulating layer between metal and the underneath ZnO [18]. With the insulating layer, we can also effectively suppress leakage current of the photodetectors. In this paper, we report the fabrication of ZnO-based metal–insulator–semiconductor (MIS) UV photodetectors. Optical and electrical properties of the fabricated photodetectors will also be discussed.

2. Experiments

ZnO samples used in this study were all grown by radio frequency (rf) plasma-assisted MBE (Omni Vac) on sapphire (0 0 0 1) substrates. The base pressure in the growth chamber was \( \sim 3.0 \times 10^{-10} \) mbar. The elemental source materials of Zn (6N) and Mg (5N) were evaporated from commercial Knudsen cells (Crea Tech). Active oxygen radicals were produced by rf-plasma system (SVTA). The flow rate of oxygen gas was controlled by a mass flow controller (ROD-4, Aera). Prior to the growth, we first degreased sapphire substrates in trichloroethylene and acetone. These substrates were then etched in \( \text{H}_2\text{SO}_4: \text{H}_3\text{PO}_4 = 3:1 \) at 130°C for 20 min followed by rinsing in de-ionized water. After loading into the growth chamber, they were thermally cleaned at 700°C for 30 min, and then exposed to oxygen radicals for 30 min at 100°C with 400 W rf power and 2 sccm oxygen flux so as to form oxygen-terminated sapphire surface. After this treatment, a thin Mg layer was predeposited on the substrates at 80°C and then re-evaporated while the temperature ramped up. It should be noted here that after the processing, the substrates were covered with a uniform Mg wetting layer, which can be verified from the absence of rotation domains and the achievements of unipolar ZnO growth. We subsequently grew a 1000 nm thick unintentionally doped ZnO epitaxial layer with conventional two-step growth method, i.e., a low temperature buffer layer grown at 260°C and a high temperature layer grown at 670°C. After the growth, we in situ annealed the ZnO epitaxial layer at 750°C. It is well-known that interface engineering is essential for hetero-epitaxy of high quality ZnO films on sapphire substrates in terms of rotation domain elimination and polarity control [19–22]. It was revealed that the interface control by using oxygen radicals pretreatment and Mg predeposition is very effective on property improvement and defect density reduction of ZnO film, which was confirmed with Hall, photoluminescence (PL) and X-ray diffraction (XRD) measurements. The carrier concentration of the as-grown ZnO films was \( 2.8 \times 10^{16} \text{ cm}^{-3} \) at room temperature.

ZnO MSM and MIS photodetectors were then fabricated. Prior to metal deposition, we cleaned the ZnO samples by acetone and methanol. For MSM photodetectors, we deposited 100 nm thick Pt film onto the sample surface by electron beam evaporation to serve as metal contacts. Standard lithography and etching were then performed to define the interdigitated contact pattern. For MIS photodetectors, we first deposited 5 nm thick SiO\(_2\) by plasma-enhanced chemical vapor deposition (PECVD) followed by the same Pt film deposition and photolithography. The fingers of the Pt contact electrodes were 10 \( \mu \)m wide and 180 \( \mu \)m long with a spacing of 10 \( \mu \)m. The active areas of the fabricated MSM and MIS photodetectors were all kept at 200 \( \mu \)m \( \times \) 200 \( \mu \)m. The schematic structures of the MSM and MIS photodetectors fabricated in this study were shown in Fig. 1(a) and (b), respectively. Room temperature current–voltage (I–V) characteristics of the devices were then measured by an HP 4145 semiconductor parameter analyzer under both dark and illumination. The top-illuminated spectral responsivity of these devices was also quantified using a 250 W Xe arc lamp with a calibrated monochromator as the light source. The monochromatic light, calibrated with UV-enhanced Si photodetectors and an optical power meter, was collimated onto each photodetector via an optical fiber.

3. Results and discussion

Fig. 2 shows room temperature PL spectrum of our ZnO epitaxial films. It was found that we observed a strong excitonic related PL peak at 379 nm (3.27 eV). It was also found that full-width half-maximum (FWHM) of the excitonic related PL peak was only 74 meV. It should be noted that no oxygen vacancy related defect peaks could be found in the spectrum [12]. These results all indicate good crystal quality of our ZnO epitaxial layers. The inset of Fig. 2 shows measured XRD spectrum of the 1000 nm thick ZnO epitaxial film prepared on sapphire substrate. The peak located at \( 2\theta = 41.9^\circ \) in the spectrum was originated from the (0 0 6) plane of sapphire substrate. We also observed a ZnO (0 0 2) XRD peak at \( 2\theta = 34.3^\circ \) with a FWHM of 0.11°. Such a result indicates that the ZnO film was preferen-
Fig. 2. Room temperature PL spectrum of epitaxial ZnO films. The inset shows XRD spectrum of the epitaxial ZnO films prepared on sapphire substrate.

tially grown in c-axis direction. The small FWHM of the ZnO (002) XRD peak again indicates good crystal quality of our samples.

Fig. 3 shows I–V characteristics of the two fabricated ZnO photodetectors measured in dark (dark current) and under 370 nm illumination (photocurrent). The dark current is originated from thermionic emission of carriers. It can be seen clearly that dark currents measured from MIS photodetector were much smaller than that measured from MSM photodetector. With 5 V applied bias, it was found that measured dark currents were $4.11 \times 10^{-7}$ and $2.22 \times 10^{-10}$ A for the fabricated MSM and MIS photodetectors, respectively. In other words, we can reduce dark current by more than three orders of magnitude by inserting the 5 nm thick SiO$_2$. Such a significant reduction could be attributed partially to the insulating nature of SiO$_2$ and partially to the effective passivation of ZnO surface states by the SiO$_2$ layer. Compared with the photocurrent of ZnO MSM photodetector, it was found that photocurrent measured from ZnO MIS photodetector was small. With 5 V applied bias, it was also found that measured photocurrents were $1.2 \times 10^{-4}$ and $7.12 \times 10^{-6}$ A for the ZnO MSM and MIS photodetectors, respectively. Furthermore, photocurrent to dark current contrast ratios for these two photodetectors can be determined from the measured dark currents and photocurrents which were shown in Fig. 4. With 5 V applied bias, it was found that photocurrent to dark current contrast ratios of the ZnO MSM and MIS photodetectors were $2.9 \times 10^2$ and $3.2 \times 10^4$, respectively. In other words, we can achieve much larger photocurrent to dark current contrast ratio from the ZnO MIS photodetector.

Fig. 5(a) and (b) shows measured optical responsivities of the ZnO MSM and MIS photodetectors, respectively. It was found that sharp cutoff occurred at around 370 nm for both detectors. With incident light wavelength of 370 nm and 5 V applied bias, the measured responsivities were 0.089 and 0.0083 A/W for the ZnO MSM and MIS photodetectors, respectively. The smaller responsivity observed from ZnO MIS photodetector can again be attributed to the insertion of highly resistive SiO$_2$ layer. It was found that responsivity in the long wavelength stop band was also smaller for ZnO MIS photodetector, as compared to that measured from ZnO MSM photodetector. This agrees well with the smaller dark current for ZnO MIS photodetector. Here, we define UV to visible rejection ratio as the responsivity mea-
sured at 370 nm divided by the responsivity measured at 450 nm. With such definition and 5 V applied bias, it was found that UV to visible rejection ratios for the fabricated ZnO MSM and MIS photodetectors were 2.4 × 10^2 and 3.8 × 10^3, respectively. These values indicate that we can also significantly enhance UV to visible rejection ratio by inserting a SiO2 into our ZnO photodetectors. The large 3.8 × 10^3 UV to visible rejection ratio also suggests ZnO MIS photodetectors are potentially useful for practical applications.

4. Summary

In summary, ZnO epitaxial films were grown on sapphire (0 0 0 1) substrates by MBE. ZnO MSM and MIS UV photodetectors were fabricated. It was found that we can achieve smaller dark current, larger photocurrent to dark current contrast ratio and larger UV to visible rejection ratio from the ZnO MIS UV photodetector.

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References

[1] M. Razeghi, A. Rogalski, Semiconductor ultraviolet detectors, J. Appl. Phys. 79 (1996) 7433–7477.
[2] C.H. Chen, S.J. Chang, Y.K. Su, G.C. Chi, J.Y. Chi, C.A. Chang, J.K. Sheu, J.F. Chen, GaN metal–semiconductor–metal ultraviolet photodetectors with transparent indium–tin-oxide Schottky Contacts, IEEE Photon. Technol. Lett. 13 (2001) 848–850.
[3] D.V. Kuksenkov, H. Temkin, A. Osinsky, R. Gaska, M.A. Khan, Low-frequency noise and performance of GaN p–n junction photodetectors, J. Appl. Phys. 83 (1998) 2142–2146.
[4] S.J. Chang, T.K. Lin, Y.K. Su, Y.Z. Chiu, C.K. Wang, S.P. Chang, C.M. Chang, J.J. Tang, B.R. Huang, Homoepitaxial ZnSe MSM photodetectors with various transparent electrodes, Mater. Sci. Eng. B 127 (2006) 164–168.
[5] T.M. Barnes, J. Leaf, S. Hand, C. Fry, C.A. Wolden, A comparison of plasma-activated N2O2 and N2O2 mixtures for use in ZnO:N synthesis by chemical vapor deposition, J. Appl. Phys. 96 (2004) 7036–7044.
[6] H. Kato, M. Sano, K. Miyamoto, T. Yao, Homoepitaxial growth of high-quality Zn-polar ZnO films by plasma-assisted molecular beam epitaxy, Jpn. J. Appl. Phys. 42 (2003) L1002–L1005.
[7] Y.I. Alivov, E.V. Kalinina, A.E. Cherenkov, D.C. Look, B.M. Ataev, A.K. Omaev, M.V. Chukichev, D.M. Bagnall, Fabrication and characterization of n-ZnO/p-AlGaN heterojunction light-emitting diodes on 6H-SiC substrates, Appl. Phys. Lett. 83 (2003) 4719–4721.
[8] S.J. Young, L.W. Ji, S.J. Chang, Y.K. Su, ZnO metal–semiconductor–metal ultraviolet sensors with various contact electrodes, J. Crystal Growth 293 (2006) 43–47.
[9] A. Mang, K. Reiman, St. Rubenacke, Band gaps, crystal-field splitting, spin–orbit coupling, and exciton binding energies in ZnO under hydrostatic pressure, Solid State Commun. 94 (1995) 251–254.
[10] A. Setiawan, Z. Vashaei, M.W. Cho, T. Yao, H. Kato, M. Sano, K. Miyamoto, I. Yonenaga, H.J. Ko, Characteristics of dislocations in ZnO layers grown by plasma-assisted molecular beam epitaxy under different ZnO flux ratios, J. Appl. Phys. 96 (2004) 3763–3768.
[11] E.M. Kaidashev, M. Lorenz, H. von Wencckstern, A. Rahm, H.C. Semmelhack, K.H. Han, G. Benndorf, C. Bundemann, H. Hochmuth, M. Grundmann, High electron mobility of epitaxial ZnO thin films on c-plane sapphire grown by multistep pulsed-laser deposition, Appl. Phys. Lett. 82 (2003) 3901–3903.
[12] D.C. Reynolds, D.C. Look, B. Jogai, H. Morkoc, Similarities in the band-edge and deep-centre photoluminescence mechanisms of ZnO and GaN, Solid State Commun. 101 (1997) 643–646.
[13] H.J. Ko, Y.F. Chen, S.K. Hong, T. Yao, MBE growth of high-quality ZnO films on epi-GaN, J. Crystal Growth 209 (2000) 816–821.
[14] R.P. Joshi, A.N. Dharmasi, J. McAdoo, Simulation for the high-speed response of GaN metal–semiconductor–metal photodetectors, Appl. Phys. Lett. 64 (1994) 3611–3613.
[15] E. Monroy, F. Calle, J.L. Pau, E. Munoz, F. Omnes, B. Beaumont, P. Gibart, Application and performance of GaN-based UV detectors, Phys. Stat. Sol. A 185 (2001) 91–97.
[16] J.C. Carrano, T. Li, P.A. Grudowski, C.J. Eiting, R.D. Dupuis, J.C. Campbell, Comprehensive characterization of metal–semiconductor–metal ultraviolet photodetectors fabricated on single-crystal GaN, J. Appl. Phys. 83 (1998) 6148–6160.
[17] F.D. Auret, S.A. Goodman, M. Hughes, M.J. Legodi, H.A. van Laarhoven, D.C. Look, Electrical characterization of 1.8 MeV proton-bombarded ZnO, Appl. Phys. Lett. 79 (2001) 3074–3076.
[18] A. Chini, J. Wittsch, S. Heitkam, S. Keller, S.P. DenBaars, U.K. Mishra, Power and linearity characteristics of GaN MISFETs on sapphire substrate, IEEE Electron Device Lett. 25 (2004) 55–57.
[19] Z.X. Mei, X.L. Du, Y. Wang, Z.Q. Zeng, H. Zheng, J.F. Jia, Q.K. Xue, Z. Zhang, Controlled growth of Zn-polar ZnO epitaxial film by nitridation of sapphire substrate, Appl. Phys. Lett. 86 (2005) 112111.
[20] Z.X. Mei, Y. Wang, X.L. Du, M.J. Ying, Z.Q. Zeng, H. Zheng, J.F. Jia, Q.K. Xue, Z. Zhang, Controlled growth of O-polar ZnO epitaxial film by oxygen radical preconditioning of sapphire substrate, J. Appl. Phys. 96 (2004) 7108–7111.
[21] Y.F. Chen, H.J. Ko, S.K. Hong, T. Yao, Layer-by-layer growth of ZnO epilayer on Al2O3 (0 0 0 1) by using a MgO buffer layer, Appl. Phys. Lett. 76 (2000) 559–561.
[22] X.L. Du, M. Murakami, H. Iwaki, I. Ishitani, A. Yoshikawa, Effects of sapphire (0 0 0 1) surface modification by Ga pre-exposure on the growth of high-quality epitaxial ZnO film, Jpn. J. Appl. Phys. 41 (2002) L1043–L1045.

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Erratum

Erratum to “ZnO-based MIS photodetectors”
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The publisher deeply regrets that some errors occurred in the printed version of the above article in Sensors and Actuators A: Physical, pages 529–533. Please see the corrected article over.

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