The study of ZnO MSM UV photodetector with Pd contact electrodes on (PPC) plastic

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In this paper, we report the fabrication and investigation of metal-semiconductor-metal UV photodetector (MSM UV PD) by deposition ZnO thin film on poly propylene carbonate (PPC) plastic substrate by direct current (DC) sputtering technique, using palladium (Pd) contact electrodes. The structural, optical and electrical properties of the ZnO thin film were studied by using X-Ray diffraction (XRD) measurement, and photoluminescence (PL). The electrical characteristics of the detector were investigated using the reverse biased current–voltage (I–V) measurements which show that the dark- and photo-currents were found to be 6.21 and 93.8 µA, respectively, Using forward dark conditions at 5 volt; the barrier height ϕ_B was calculated and it was found to be 0.70 eV. Under incident wavelength of 385 nm, the maximum responsivity (R) of the Pd/ZnO/Pd MSM PD was determined to be 1.473 A/W.

1. Introduction

Detection of ultraviolet (UV) radiation is becoming important in a number of areas, such as flame detection, water purification, UV astronomy, and UV radiation dosimetry [1, 2]. Recently, wide-bandgap materials are under intensive studies to improve the responsivity and stability of UV photodetectors [3]. Among them is zinc oxide (ZnO) which belongs to II–VI compound semiconductors, has been under extensive research in recent years for its wide technological applications [4]. ZnO has a wide bandgap of 3.37 eV and large exciton binding energy of 60 eV at room temperature, and these properties make ZnO a promising photonic material for many applications such as light-emitting diodes (LEDs) [5], laser diodes (LDs) and ultraviolet (UV) detecting devices [6–8]. Several deposition methods have been adopted for the growth of ZnO layers, including metal-organic chemical vapor deposition (MOCVD) [6], plasma-assisted molecular beam epitaxy (PA-MBE) [7], pulsed laser deposition (PLD) [8], and spray pyrolysis [9].

ZnO Schottky diodes and MSM PDs detecting in the UV region have also been investigated by Liang *et al*. by growing ZnO on R-plane sapphire substrates by MOCVD deposition [10]. MSM PDs consist of interdigitated Schottky contacts deposited on the top of the active layer, the device is two Schottky diodes in a back-to-back arrangement; since one electrode has a positive bias (anode) and the other a negative bias (cathode); this means, one contact is forward biased and the other reverse biased, leading to reduced dark current compared to a photoconductive detector. The dopant density of the semiconductor is usually low to achieve full depletion of majority carriers in the region between the contacts. When it is used as a photodetector, the incident photons with energy larger than the bandgap of the semiconductor strike the region of bare semiconductor and are absorbed resulting in the upward transition of a free electron from the valence band to the conduction band [11].

To produce high-performance MSM UV PDs, it is important to achieve a large Schottky barrier height at the metal–semiconductor interface that leads to a small leakage current and high breakdown voltage which could result in improving responsivity and photocurrent to dark current contrast ratio [12]. To achieve a large Schottky barrier height on ZnO, one can choose metals with high-work functions such as Pt, Ni and Pd. Pd is an interesting metal that has recently been used as a stable Schottky contact. Several investigations on the deposition of ZnO Schottky diodes with Pd contact electrodes on silicon, glass, sapphire substrates [4, 7, 13] or flexible substrates such as polyethylene terephthalate (PET) [14], polytetrafluoroethylene (Teflon) [15] have been reported. However, the deposition of ZnO thin film on PPC plastic substrate has not been reported in the literature. To the best of our knowledge, we are the first group to report the fabrication of ZnO MSM UV detector using PPC plastic as a substrate. PPC has been selected as a substrate in this study because it is cheap, has low chemical reactivity. In addition, it also has a high dielectric strength over wide frequencies and high surface resistivity. These properties

will make the PPC as a good substrate for a variety of microelectronic applications.

In this work, we report the deposition of ZnO thin film on the PPC plastic sheet, subsequently ZnO-based MSM PD with Pd electrodes is fabricated, and the responsivity of the detector is determined. The results obtained in this study by using PPC plastic as a substrate for ZnO UV detector are very encouraging.

2. Experimental details

The ZnO thin films were deposited on PPC plastic by sputtering system (model Edwards Auto 306). The sputtering system operated with base pressure of about 5×10^{-5} torr; the target material used in this work was ZnO disk having a diameter of about 76.2 mm; it is thickness was around 6.35 mm; with purity 99.99%. The distance between the target and the substrates was around 7 cm. Prior to the deposition, the plastic substrates were cleaned thoroughly. The cleaning procedures started by immersing the plastic sheets in the active cleaning liquid (DECON90) for 5 minutes, then rinsed with distilled water, after that they were dried by N_2 gas. Before the deposition process, the target was pre-sputtered for 20 min to remove any contamination from the target surface. After deposition, the thin film thickness was measured by using surface optical system Filmetric F20-VIS. The crystalline structure of the film was studied by XRD using High resolution (XRD (PANalytical X'pert Pro MRD)) with a Cu-Kα1 radiation source (λ = 1.5406Å), while the photoluminescence spectrum (PL) was recorded by using photoluminescence spectroscopy system Model: Jobin Yvon HR 800 UV, The line of He-Cd laser of 325 nm having a power of 20 mW is used to excite the sample. Finally ZnO MSM PD was fabricated by sputtering the Pd with a thickness of about 130 nm on the ZnO thin film by using a metal MSM mask, The structure of ZnO MSM PD consists of two interdigitated Schottky contact (electrodes) with finger width of 0.2 mm; the length of each electrode is about 5.4 mm and the spacing between the electrodes is 0.4 mm, each electrode has five fingers as shown in Fig. 1. As we mentioned before, typically, the device is biased such that one of the two contacts is grounded while the other is reversed biased. At sufficiently high bias the depletion regions beneath the Schottky gates can be connected. The MSM device can be used as a PD by shining light on the top surface of the structure [16].
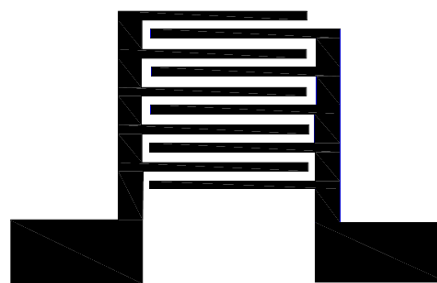

Fig.1 Schematic drawing of MSM interdigitated photodetector.

3. Results and discussion

The thickness of the prepared film was found to be about 1μm. Fig. 2 shows the XRD diffraction pattern of ZnO thin film deposited on PPC plastic substrate, with one sharp peak. Diffraction pattern was obtained with 2θ from 30° to 70°. The spectrum of XRD shows that the film is ZnO as compared to the (ICDD) library and it is oriented in C-axis which is the preferred orientation axis for such material. The strong peak was observed at 2θ= 34.25^{o}; in addition, a lower intensity peak was also found at 2θ = 52.7^{o}.
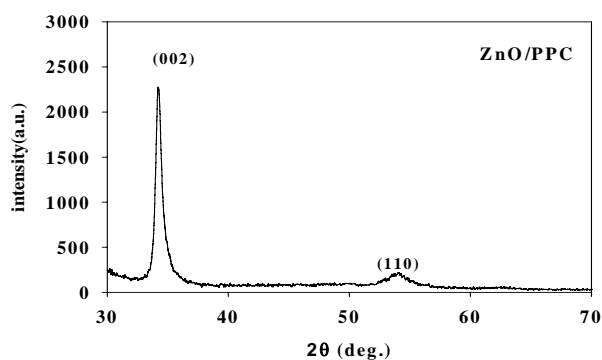

Fig. 2 X-ray diffraction for ZnO thin film on PPC substrate.

Fig. 3 shows the PL spectrum of the ZnO thin film with a high UV emission peak (379.5 nm) and a low and broad blue–green emission peak (490 nm).

The emission at 379.5 nm close to the bandgap of ZnO material according to Young *et al.* [17], and is assigned to the recombination of bound excitons of ZnO. The blue–green emission mechanism in ZnO which may be due to the defect related deep level emission [18]. It is well-known that the ultraviolet emission, which reflects the intrinsic property of ZnO, corresponds to the near band-edge (NBE) emission, namely the recombination of free excitons through an exciton-exciton collision process [19].
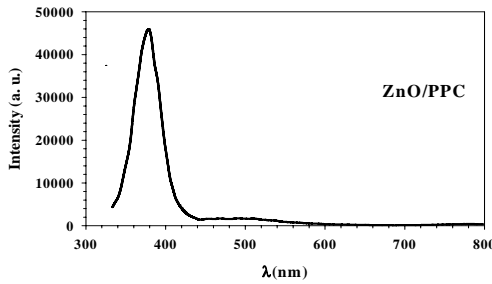

Fig. 3. Room temperature PL spectra of DC- sputtered ZnO on PPC substrate.

Fig. 4 shows the current–voltage (I–V) characteristics (under reverse biased) of the deposited ZnO with Pd contact on PPC plastic measured without and with UV illumination. Under dark environments, the current at 5 V was found to be 6.21 μA, on the other hand, when the sample was illuminated with UV lamp with power of 58.4 μW, the current (same voltage) was observed to be 93.8 μA. Under UV illumination, light impinges onto the thin film, the high-energy photons will be absorbed by the ZnO layer producing more electron–hole pairs, the application of a bias voltage to the Pd contact creates an electric field within the underlying ZnO thin film that sweeps the photogenerated carriers out of the depletion region resulting in the increase of the photocurrent. The contrast ratio of this photo to dark currents was 15.1 times. This electrical result is very encouraging for further study of photodetector.
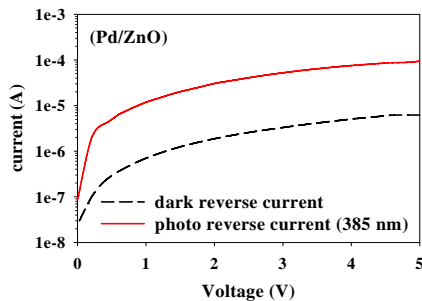

Fig. 4 I–V characteristics of the deposited ZnO with Pd electrodes on PPC substrate measured under reverse biased in dark- and photo-currents.

The MSM-PD performance is critically dependent on the quality of the Schottky contacts. Therefore, it is necessary to measure the Schottky barrier height of the actual contact, which is a constituent part of the MSM-PD under investigation. As we mentioned, the MSM- PD essentially consists of two Schottky contacts connected back-to-back. When a bias is applied, one of the Schottky contacts is forward-biased and the other is reverse-biased. Only the reverse current–voltage (I–V) characteristics of these Schottky contacts can be measured. The Schottky barrier height can be determined by using forward-biased I–V measurements as in Eq (1) [20].

$$I = I_o \exp(qV/\{nKT\})[1 - \exp(-qV/\{KT\})] \quad (1)$$

$$I_\circ = A^* A T^2 \exp\{-q\phi_B/(KT)\} \quad (2)$$

where I_o is the saturation current, n is the ideally factor, K is the Boltzmann's constant, T is the absolute temperature, ϕ_B is the barrier height, A is the area of the Schottky and A^* is the effective Richardson coefficient. The theoretical value of A^* can be calculated using Eq. (3) below:

$$A^* = 4\pi m^* qK^2 / h^3 \quad (3)$$

where h is Planck's constant and $m^* \sim 0.27m_o$ is the effective electron mass for n-type ZnO so that $A^* \sim 32A/cm^2K^2$ [10].

Based on equation (1), the plot of $\ln\{I \exp(qV/\{KT\})/[\exp(qV/\{KT\})-1]\}$ vs V will give a straight line; I_o is derived from the interception with y-axis when V =0, and from Eq. 2 we found that Schottky barrier height ϕ_B at the Pd/ZnO interface is equal to 0.70 eV.
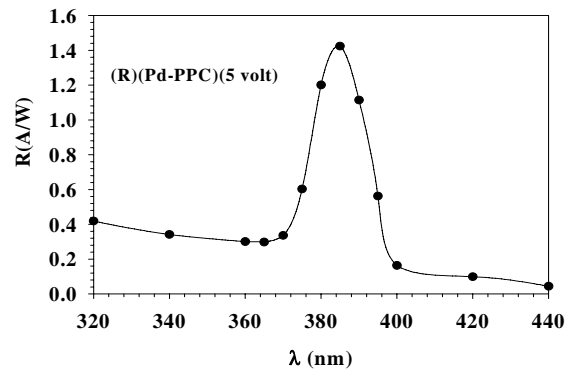

Fig. 5 The spectral responsivity of the fabricated Pd/ZnO/Pd MSM PD on PPC substrate.

One of the important parameters to evaluate a photodetector is the responsivity R, which is the ratio of the device photo-current to the incident optical power which is given by Eq. (4): [21]

$$R = \frac{I_p}{P_{inc}} (A / W) \qquad (4)$$

where I_p is the photocurrent and P_{inc} is the incident optical power.

Fig. 5 shows the measured spectral responsivity of the Pd/ZnO/Pd MSM PD fabricated on the PPC plastic. As shown in the figure, the photodetector responsivity was nearly constant in the region ∼ 320–365 nm; while it was an obvious response in the UV region, peaking at 385 nm. The UV light irradiated with energy which is higher than the bandgap (3.37 eV for ZnO) generates electron–hole pairs, these excess charge carriers contribute to photo current and result in the response to the UV light. The cut-off at wavelength of 385 nm close to the ZnO energy bandgap of 3.37 eV; the responsivity decreases at the shorter wavelength range due to the decrease of the penetrating depth of the light, resulting in an increase of the surface recombination [22].   With an incident wavelength of 385 nm and 5 V applied bias, it was found that the maximum responsivity of the fabricated Pd/ZnO/Pd MSM PD is 1.423 A/W. This high responsivity may be attributed to its high internal gain [23]. This indicates that with a Schottky barrier at the metal electrode-semiconductor interface, can exhibit hole-trapping in the reversed-bias junction that shrinks the depletion region and this allows tunneling of additional electrons into the photoconductor. When electrons pass multiple times, this mechanism yields photoconductive gain greater than 1. From the literature, similar ZnO MSM PD with responsivity 1.5 A/W has been reported by Liang et al [10] which is the performance of comparable to our result.

5. Conclusions

In summary, we have fabricated metal-semiconductor-metal UV photodetector by deposition ZnO thin film on PPC plastic substrate. The characteristics of ZnO thin film were investigated by various tools. XRD spectrum showed that ZnO has preferential orientation along the c-axis with dominant peak observed at 2θ= 34.25°. PL measurement exhibited a strong UV emission peak at 379.5 nm. I-V measurements showed that the dark- and photo-current were observed to be 6.11 and 89.3 μA at 5 V. In addition, the maximum responsivity of the Pd/ZnO/Pd (MSM) photodetector was determined to be 1.423 A/W. The results showed that the fabrication of ZnO MSM UV photodetector on PPC plastic by using DC-sputtering technique is possible.

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