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High-performing transparent photodetectors based on Schottky contacts

Dipal B. Patel[a,b], Khushbu R. Chauhan[a,b], Sung-Ho Park[a], Joondong Kim[a,b,*]

[a] Department of Electrical Engineering, Incheon National University, 119 Academy Rd. Yeonsu, Incheon 406772, Republic of Korea
[b] Photoelectric and Energy Device Application Lab (PEDAL), Multidisciplinary Core Institute for Future Energies (MCIFE) Incheon National University, 119 Academy Rd. Yeonsu, Incheon 406772, Republic of Korea

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ABSTRACT

Transparent UV-photodetectors exhibiting very high responsivity and fast operation are discussed. Schottky contact photoelectric devices utilizing wide band gap TiO_2 absorber layer were evaluated for their performances as UV-photodetectors. Three different work function metals Cu, Mo and Ni were used to realize Schottky barrier with TiO_2. Ni Schottky contacts were found to be most suitable to fabricate high responsivity (2.034 A/W) photodetector with faster rise time (0.14 ms) and wide linear dynamic range (128 dB) operating at small applied reverse bias of −1 V. However, higher barrier height in the case of Mo/TiO_2 interface resulted in lowest dark current density of the value 2.21×10^{-8} A/cm^2 with quick fall time of 0.52 ms. The modulation of the barrier height would provide a route for designing fast and high responsive Schottky photodetector with broad linear dynamic range performance.

1. Introduction

UV-photodetectors have gained a lot attention due to their applications in source calibration, UV astronomy, sensors and space monitoring [1]. Wide bandgap materials, such as GaN, ZnO, AlN and ZnSe, are currently being used for developing such “Solar blind” photodetectors [2–5]. The advantage of low dark current, high responsivity, stable and faster operation can be exploited by using wide bandgap materials in UV-photodetection. Many different configurations like p-n junction, metal-semiconductor-metal and Schottky contact have been utilized to develop efficient photodetectors [6–13]. However, most of the wide bandgap materials exhibit many crystallographic imperfections which affect the mobility of charge carriers. Hence, optimum benefit of such wide bandgap materials can be extracted only if they are synthesized in form of pure or highly crystalline structures.

In this regard, materials other than III-V group (like TiO_2, ZnO, SnO_2) may also be suitable to provide the efficient photodetection and sensing properties. Amongst these materials, TiO_2 thin films with different structural properties have been widely used in UV-photodetectors. Two dimensional TiO_2 nanosheets were synthesized to obtain the high photocurrent and extremely low dark current values [14]. On the other hand, SnO_2/TiO_2 core shell structure was investigated for its performance as self-powered photodetector [15]. TiO_2 nanorod arrays have also been studied for quick response and highly sensitive UV-Photodetectors [16]. The advantage of TiO_2 material is that one can develop transparent Schottky photodetectors by interfacing an ultrathin active layer with metal contacts [17]. A recent report showed an improved responsivity and detectivity of TiO_2 based UV-photodetectors by utilizing monolayer graphene Schottky contact [18]. Extremely high responsivity of TiO_2 photodetector was demonstrated by using Ni electrodes [19]. However, current research in UV-photodetectors evolves in the direction of development of transparent thin films and front contacts for better responsivity [20]. A recent report demonstrated highly crystalline rutile TiO_2 nanocrystalline thin films with dual band gaps (3.45 eV, indirect bandgap) and 4.08 eV, direct bandgap)) which showed great potential to be used in UV-photodetection. The ultrathin film should have good crystallinity with very high absorption coefficient and transmittance. The motivation behind this work came due to the existence of all these important criteria in fabricated TiO_2 thin films.

In this manuscript, we demonstrate the operation of transparent photodetectors utilizing metal/TiO_2 configuration. Three different work function metals were used to understand the junction as well as photodetection properties by forming the Schottky contact to rectify the current flow. It will be shown that such simple configurations lead to efficient transparent photodetectors having high responsivity, faster response time, low dark current and wide linear dynamic range (*LDR*).

2. Experimental

Rutile-nanocrystalline (NC) TiO_2 thin films were prepared by D.C. sputtering of Ti metal followed by controlled oxidation in rapid thermal

* Corresponding author at: Department of Electrical Engineering, Incheon National University, 119 Academy Rd. Yeonsu, Incheon 406772, Republic of Korea.
E-mail address: joonkim@incheon.ac.kr (J. Kim).

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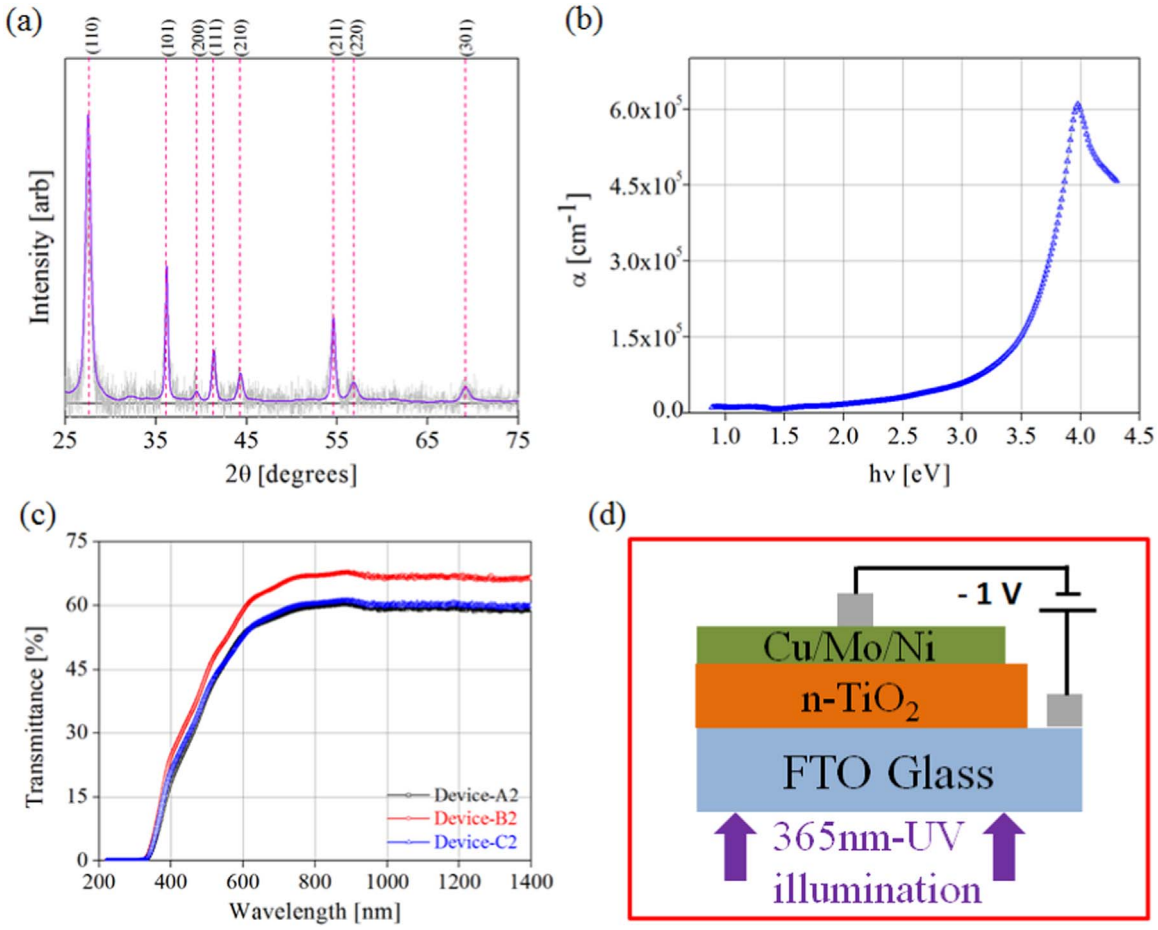

Fig. 1. (a) XRD spectrum of nanocrystalline TiO_2 thin film (b) Variation in absorption coefficient with photon energy for TiO2 thin film (c) Transmittance spectra of Cu/170 nm TiO_2/FTO, Mo/170 nm TiO_2/FTO and Ni/170 nm TiO_2/FTO photodetectors and (d) Schematic showing the device configuration under UV illumination and reverse bias conditions.

process (RTP) system. The substrates, F:SnO_2 (FTO) glasses were ultrasonically cleaned in methanol, acetone and deionized water after which they were dried through nitrogen jet stream. DC sputtering of high purity Ti target (99.99% pure, iTASCO) was done by applying a constant power of 300 W at 5 mT working pressure with continuous flow of Ar (30 sccm) at room temperature for 600 s. To assure the uniform deposition of Ti film, substrate stage was kept at 5 rotations per minute. Ti coated FTO samples were then thermally treated in RTP at 700 °C for 600 s to convert Ti thin films into titanium dioxide (TiO_2). High work function metals, Cu, Mo or Ni were D.C. sputtered on TiO_2 thin films to realize Schottky UV-photodetectors.

TiO_2 thin films were characterized for their structural, morphological and optical properties. Phase identification of the films was done by X-ray diffraction (Rigaku, SmartLab) using CuKα radiation with a characteristic wavelength λ = 1.5406 Å. Morphological analysis of the films was done by using field emission scanning electron microscope (FE-SEM) (JSM7800F, Jeol). A field-emission transmission electron microscope (FETEM, JEOL, JEM-2100F) was applied to observe the TiO_2 layer. Optical characterizations of the films were done by using UV–Vis spectrophotometer (Shimadzu-2600). The resistivity of TiO_2 thin films was measured by using four point probe technique (CMT-100S, Advanced Instrument Technology). The photoresponse and capacitance-voltage measurement of the photodetectors were recorded using Potentiostat/Galvanostat (Zive SP1, ZIVELAB, WonATech Co,. Ltd). Monochromatic UV LED (LEDENGIN, 365 nm) operated by constant power supply (MCH-305D11) and function generator (MFG-3013A) was used as light source for photoresponse measurements. The chopping frequency of 100 Hz was selected to accurately calculate the junction capacitance (C_j), rise time (τ_r) and fall time (τ_f) of the photodetectors. Intensity dependent I-V characteristics were recorded by using source measure unit (Keithley-2400) to determine the responsivity (R), detectivity (D^*) and LDR.

3. Results and discussions

The XRD spectrum of deposited NC-TiO_2 thin films has been presented in Fig. 1(a). It was found from the XRD pattern that all the major peaks correspond to the rutile-TiO_2 phase. The major peaks were found to be situated at 2θ values 27° 54′, 36° 20′ and 54° 60′ which correspond to (110), (101) and (211) planes of tetragonal rutile TiO_2 phase, respectively. The variation in absorption coefficient (α) of TiO_2 thin film with incident photon energy is presented in Fig. 1(b). The maximum value of α was found to be $6.1 \times 10^5\ cm^{-1}$ at the energy of 3.97 eV. It is noteworthy that NC-TiO_2 thin films possess very high absorption coefficient and hence even 100 nm thick films can be utilized for complete photoabsorption. However, for optimized performances of UV photodetectors, TiO_2 films with higher thicknesses (120 and 170 nm) were utilized. For simplicity, the device configurations Cu/120 nm TiO_2/FTO, Mo/120 nm TiO_2/FTO, Ni/120 nm TiO_2/FTO, Cu/170 nm TiO_2/FTO, Mo/170 nm TiO_2/FTO and Ni/170 nm TiO_2/FTO were designated as devices-A1, B1, C1, A2, B2 and C2, respectively. The device transmittance spectra (for Devices A2, B2 and C2) are shown in the Fig. 1(c). It can be seen that all the devices possess more than 55% transmittance above 600 nm. Fig. 1(d) shows the device schematic along with the illumination direction and polarity of applied bias. The morphologies and cross-sectional images of the devices are shown in Fig. 2 (Inset: actual device photographs). It was found that the metal layer was uniformly coated onto the NC-TiO_2 with small crystal-