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Self-powered GaN ultraviolet photodetectors with p-NiO electrode grown by thermal oxidation

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ABSTRACT

Self-powered ultraviolet photodetectors based on n-GaN and p-NiO were fabricated through thermal oxidation. The transparent NiO was mainly dominated by [111] texture with an optical band gap of approximately 3.69 eV. Compared with the conventional Ni/GaN photodetector, the p-NiO/GaN heterostructure photodetector possess a larger turn-on voltage and a smaller dark current because of the relatively higher effective barrier height. At an external bias of 0 V, the photo responsivity and the UV to visible rejection ratio of the NiO/GaN photodetector are enhanced to 0.15 A/W and 406, respectively. The improvement in UV photodetector performance is attributed to that the depletion region in NiO/GaN heterostructure can effectively eliminate the trapping charge carriers at the metal/semiconductor interface. The high-performance NiO/GaN photodetectors without driving power are potential for portable UV detectors application.

1. Introduction

GaN-based material with wide direct band gap, high saturation velocity and high thermal conductivity is believed to be the most promising candidate for solid-state lighting, high frequency and high power device [1–3]. Besides, the high UV/visible rejection ratio of GaN also makes it potentially useful in ultraviolet photodetectors (UV PDs). Recently, various types of GaN based PDs like p-n PDs [4], Schottky barrier PDs [5], metal semiconductor metal PDs [6], and metal insulator semiconductor PDs [7] have been investigated and applied in military and commercial areas, such as missile detection, flame warning and ozone detection. Among those, the p–n PDs or Schottky barrier PDs which possess built-in electric field (photovoltaic effect) is beneficial for exploiting self-powered UV PDs [8]. The spontaneous diffusion of free carrier generates the space charge region as well as the built-in electric field at the interface, which can separate the photogenerated electron–hole pair effectively and lead to the generation of photocurrent. Generally, the p–n PDs with a relatively wider depletion layer than the Schottky barrier PDs are preferable adopted to separate the electron–-hole pair. Besides, they are not affected by the interface state between metal and semiconductor observed in Schottky barrier PDs [9,10].

Recently, self-powered, visible-blind ultraviolet p–n PDs using GaN material have already been reported by some groups. However, they are mainly combining the n-ZnO nanorods or film with the p-GaN to overcome the difficulty in achieving good p-doped ZnO [11,12]. In fact, the achievement of high quality p-GaN is also a challenge because of the low solubility of Mg dopant (Cp2Mg), strong self-compensation effect as well as the high activation energy of Mg acceptor [13]. Therefore, it is important to develop a high performance PDs with n-GaN and p-type semiconductor.

Nickel oxide (NiO) behaves as a natural p-type semiconductor with excellent thermal stability and high transparency [14]. In our previous works, circular p-NiO/n-GaN heterojunction diode and p-NiO gated normally-off AlGaN/GaN transistor have been achieved by low temperature methods [15,16]. The good thermal stability, small leakage current and ignorable hysteresis imply the better interface quality and smaller interface state. Furthermore, the NiO/GaN heterojunction meet the requirement of forming type-II heterojunction (i.e., staggered gap) for PDs fabrication [17]. However, The NiO was only evaluated to alternate the Ni electrode for power device application, while the p–n PDs based on p-NiO and n-GaN is rarely reported so far. Herein, we fabricate self-powered GaN UV-PDs possess high stability and high UV/visible rejection ratio utilizing NiO as the electrode.

2. Experimental

The n-GaN wafer used for UV-PDs fabrication was grown by metal organic chemical vapor deposition on c-plane sapphire substrate. The

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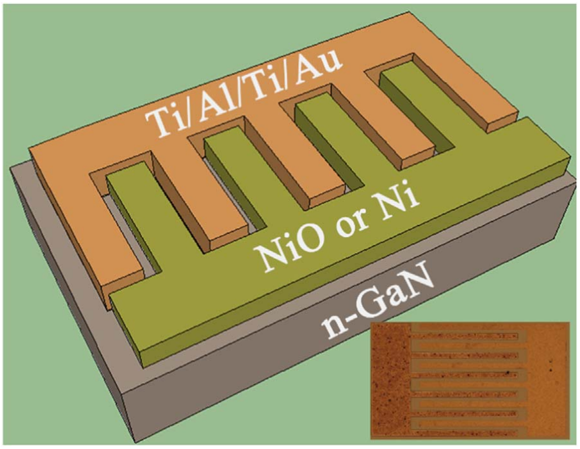

Fig. 1. Schematic structure of the Ni and NiO electrode UV PDs. Inset is the top-view optical image of the NiO PDs.

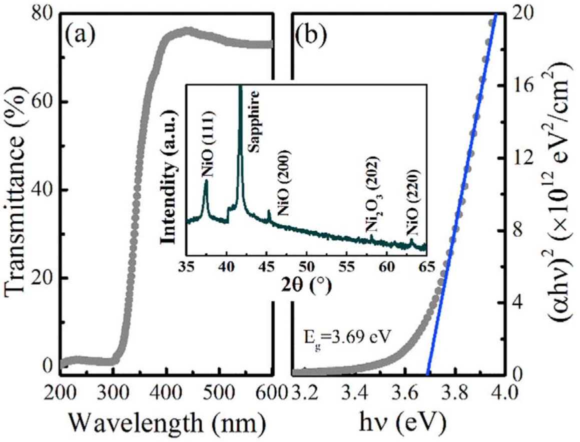

Fig. 2. Optical transmittance spectra (a) and the $(\alpha h\nu)^2$ versus hν plots (b) of the NiO film. Inset presents the corresponding XRD pattern.

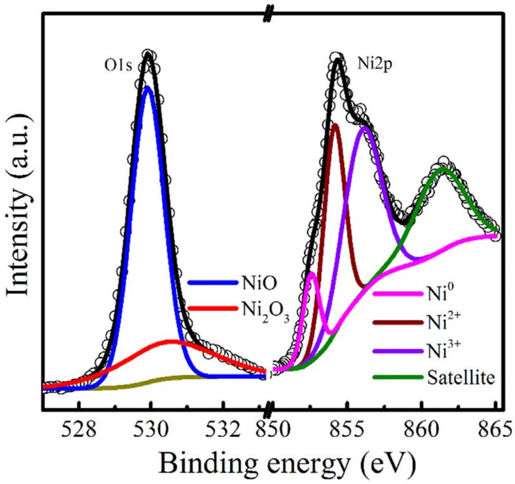

Fig. 3. Typical Ni2p and O1s spectra along with the fitting curves of NiO film after surface etching.

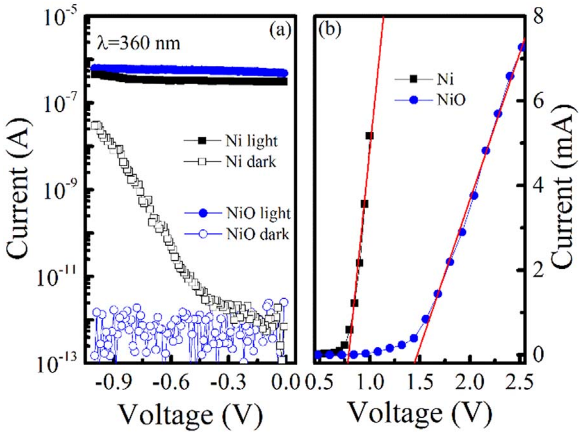

Fig. 4. The I-V characteristics of the circular Schottky diodes with logarithmic plot (a) and linear plot in the forward region (b).

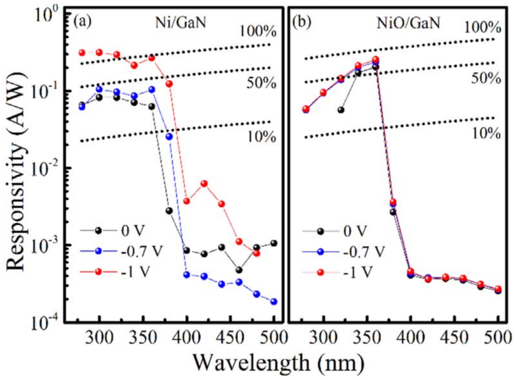

Fig. 5. Responsivity of Ni and NiO PDs as a function of incident wavelength at different applied bias of 0, −0.7, and −1 V.

wafer structure consists of a buffer layer (around 2.4 µm), an n^+-GaN access layer (around 3.6 µm with impurity density of 9.7×10^{18} cm^{-3}) and an n^--GaN drift layer (around 1.0 µm with impurity density of 1.6×10^{16} cm^{-3}) from bottom to top. The UV-PDs with interdigitated finger structure were fabricated using a standard lift-off technology (Fig. 1). Before device fabrication, the as-grown GaN material was cleaned by sulfuric peroxide mixture (H_2SO_4:H_2O_2 = 3:1) and diluted HCl solution (HCl:H_2O_2 = 1:1). Ohmic contact were formed by sputtering a multi-layers of Ti/Al/Ti/Au (50/200/40/40 nm) and annealed at 800 °C for 1 min in an N_2 ambient environment. This structure is commonly used as ohmic electrode for GaN-based devices. And the formation of good ohmic contact is also confirmed previously. Then, 40 nm Ni metal was sputtered on GaN as Schottky electrode in an Ar ambient environment. For comparison, the Ni electrode of one sample was transformed into NiO though oxidizing in oxygen ambient at 500 ℃ for 15 min. The finger length and width are 540 and 30 µm with a spacing of 10 µm. The electrical properties of the GaN UV PDs were investigated by Agilent B1505A analyzer. The spectral photoresponsivity was evaluated with a Keithley 6487 picoammeter/voltage source, a 500 W Xe lamp source and a monochromator.

3. Characteristics and discussion

To evaluate the crystalline structure and material properties of NiO, Ni metal was first deposit on double-polished sapphire and oxidized in oxygen ambient at 500 °C. After thermal oxidation, the optical transmittance of Ni is enhanced obviously, which is also confirmed from the transmission spectrum. The obtained NiO presents a high UV/visible rejection ratio. The transmittance in the visible range is approximately 76% while it decreases to approximately 0% drastically when the wavelength is smaller than 320 nm (Fig. 2a). The optical band gap value was determined to be approximately 3.69 eV applying the Tauc model, and the Davis and Mott model (Fig. 2b) [18]. Inset of Fig. 2 presents the X-ray diffraction (XRD) spectrum of NiO film, which was used to identify the crystalline structure and composition. The spectrum is

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