

ZnO nanorod arrays and direct wire bonding on GaN surfaces for rapid fabrication of antireflective, high-temperature ultraviolet sensors



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ABSTRACT

Rapid, cost-effective, and simple fabrication/package of microscale gallium nitride (GaN) ultraviolet (UV) sensors are demonstrated using zinc oxide nanorod arrays (ZnO NRAs) as an antireflective layer and direct bonding of aluminum wires to the GaN surface. The presence of the ZnO NRAs on the GaN surface significantly reduced the reflectance to less than 1% in the UV and 4% in the visible light region. As a result, the devices fabricated with ZnO NRAs and mechanically stable aluminum bonding wires (pull strength of 3–5 gf) showed higher sensitivity (136.3% at room temperature and 148.2% increase at 250 °C) when compared with devices with bare (uncoated) GaN surfaces. In addition, the devices demonstrated reliable operation at high temperatures up to 300 °C, supporting the feasibility of simple and cost-effective UV sensors operating with higher sensitivity in high-temperature conditions, such as in combustion, downhole, and space exploration applications.

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1. Introduction

Gallium nitride (GaN) has been widely used for high-temperature and high-power-density microelectronics because of its direct, wide bandgap properties [1–3]. In particular, GaN-based sensors have emerged for sensing within harsh environments such as combustion exhausts [4,5], radiation [6,7], and corrosive chemical conditions [8,9] due to their thermal, mechanical, and chemical stability. Among the many types of GaN-based sensors, ultraviolet (UV) photodetectors have especially attracted interest because GaN enables operation within high-radiative and high-temperature environments while absorbing a wide UV photon energy greater than the bandgap of GaN (3.4 eV for Wurtzite crystal structure) [10–14].

The epitaxial growth of GaN films is typically achieved on sapphire and silicon carbide (SiC) substrates using metal organic chemical vapor deposition [15,16], molecular beam epitaxy [17,18], or hydride vapor phase epitaxy [19,20] techniques to minimize lattice mismatch between substrates and grown films [21]. In general, photodetector sensitivity is enhanced using two types of surface modification techniques. One technique leverages surface topography modification (i.e., the shape change of sensor surface),

which increases the sensor surface area and induces multiple collisions of photons on the sensing area [22–24]. In other words, the shape of sensor surface needs to be physically changed by surface roughening or bulk micromachining techniques including photolithography, deposition, and etching processes, which are very challenging processes to implement using sapphire and SiC substrates [25]. The second surface modification architecture uses antireflective surface coatings (films and nanostructures), which have been shown to enhance the sensitivity of optical devices fabricated on planar substrates by reducing the reflectance of the sensing surface without sophisticated microfabrication techniques [26–29]. One well-known antireflective layer is zinc oxide (ZnO), which has been used to enhance devices using thin film or nanowire microstructures [28–34]. ZnO has a direct wide bandgap (~3.3 eV) that is very close to that of GaN and can efficiently absorb the UV photons in the short-wavelength region while simultaneously providing chemical and thermal stability for high-temperature applications [28–32]. Therefore, photodetectors with antireflective layers are able to trap more light and increase absorption of incident photons leading to enhanced optical sensitivity.

To fabricate and package practical optical sensors, metallization is essential for electrical connection between sensor chip and chip carrier. However, device metallization generally includes multiple processes such as photolithography, photoresist development, metal evaporation, and lift-off. In addition, expensive metal sources (e.g., Ti, Al, Pt, Ni, and Au) with specialized equipment (e.g., sputter,

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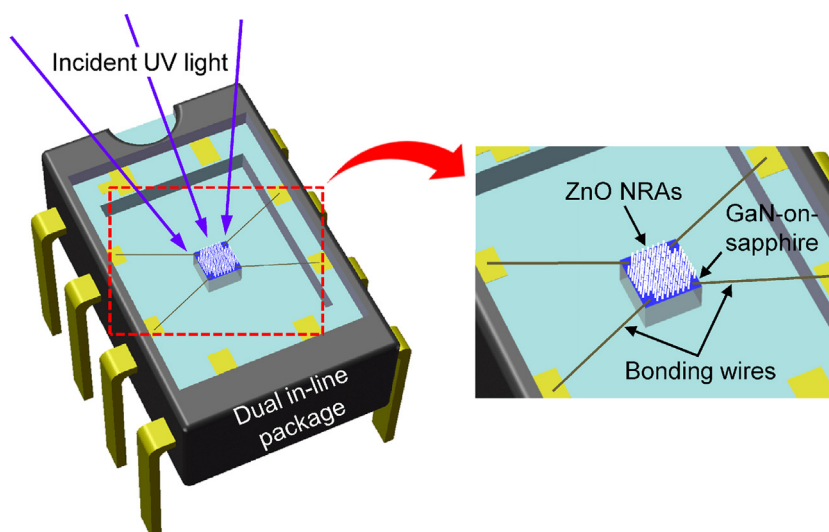


Fig. 1. Schematic of the GaN-on-sapphire (1 mm $\times$ 1 mm) ultraviolet sensor packaged in an 8-pin dual in-line package (DIP) with antireflective zinc oxide nanorod arrays (ZnO NRAs) and direct wire bonding of aluminum wires.

electron beam evaporator, and vacuum pump) are often required. In this study, enhanced optical sensitivity and rapid fabrication/packaging of UV photodetectors are demonstrated using a ZnO (nanorods) antireflective coating and direct bonding of aluminum wires (without intermediate metal contacts) on a GaN surface for high-temperature UV sensing applications. We show that ZnO nanorod arrays (NRAs) on the GaN surface enables enhanced UV sensing at high temperatures (up to 300 °C in air). In addition, the use of direct wire bonding of aluminum wires reported in our previous study [35] serves as a rapid device fabrication/packaging technique and eliminates the need for tedious metallization processes, typically used in traditional microfabrication processes, while maintaining robust high-temperature operation.

2. Experimental method

A schematic illustration of the GaN UV photodetectors with ZnO NRAs integrated into an 8-pin dual in-line package (DIP) is shown in Fig. 1. Unlike conventional devices that are metallized using costly microfabrication processes, the GaN-on-sapphire substrate was directly bonded to aluminum wires after synthesis of ZnO NRAs, allowing cost-effective, facile device fabrication and rapid packaging [35]. The fabrication of the ZnO NRA/GaN UV photodetector is composed of three main steps: hydrothermal synthesis of ZnO NRAs on a GaN-on-sapphire substrate to create antireflective coating layer, mechanical dicing (sawing) for singulating the ZnO-coated substrate into a desirable die size, and wire bonding of aluminum wires for interconnections between GaN dies and the DIP's lead frame, as shown in the closed-up view in Fig. 1. As a first step, vertical ZnO NRAs were synthesized on commercial n-type GaN-on-sapphire wafers with $<5 \Omega \text{ cm}$ resistivity (Kyma Technologies Inc.) using a solution-phase approach [36–40]. A clean GaN-on-sapphire wafer was wetted with 5 mM zinc acetate dihydrate ($\geq 99\%$, Sigma-Aldrich) in ethanol for 10 s, rinsed with clean ethanol, and dried, repeated three times [36]. The substrate was then placed on a hot plate and kept for 20 min at 350 °C in air to thermally decompose the coated ZnO layer and form ZnO islands (dots) on the substrate [36]. The synthesis of ZnO NRAs was carried out in an aqueous solution containing 10 mM zinc nitride hexahydrate (90%, Sigma-Aldrich) and 10 mM hexamethylenetetramine ($\geq 99\%$, Sigma-Aldrich) at 90 °C for 2.5 h [37,38]. To compare an optical property between the GaN surfaces with and without coated ZnO NRAs, the surface reflectance was characterized using a spec-

trophotometer (Cary 6000i UV-Vis-NIR, Agilent Technologies Inc.). The GaN wafer was then coated with a photoresist to protect the NRAs before dicing for singulation into 1 mm $\times$ 1 mm dies using a wafer saw (DAD3240, DISCO Corp.). After the protective photoresist was removed in acetone, the singulated dies were attached to the 8-pin DIP (CSB00815, Spectrum Semiconductor Materials Inc.) using double-sided polyimide tape (DuPont Inc.), followed by direct bonding of aluminum wires (ALW-29S, 1%Si, Heraeus Deutschland GmbH & Co. KG) between GaN surfaces and a lead frame using a wedge-wedge wire bonder (7476E, West Bond Inc.) [35]. The bonding process was performed using a two-step process: the first bonding step was carried out to remove ZnO NRAs by ultrasonic-induced shear forces, exposing a small area of bare GaN surface where aluminum wires would be firmly bonded during the second process. To evaluate pull strength of aluminum wires boned on a GaN surface, a manual pull test with destructive mode was conducted using a gram-force (gf) gauge with 0.2 gf resolution (GD-1, Jonard Tools). The current-voltage response and real-time current change at different temperatures were electrically and visually characterized using a semiconductor device analyzer (B1500A, Agilent Technologies Inc.), high-temperature probe station (S-1060, Signatone Corp.), and UV lamp (365 nm, UVLS-26 EL Series, UVP LLC).

3. Results and discussion

Fig. 2(a) shows the fabricated and packaged ZnO NRA/GaN UV photodetector bonded on the 8-pin DIP and its size in comparison to a U.S. dime. After growing the ZnO NRAs coating on the GaN film, a facile and rapid fabrication of the UV photodetector was achieved using direct aluminum wire bonding [35]. Fig. 2(b) shows the scanning electron microscope (SEM) top-view image of the fabricated sensor with four aluminum wires bonded on each corner of the ZnO NRA/GaN die using an ultrasonic power of 480 mW and bonding time of 30 ms [35]. Any two of these bonded wires can act as a source and drain electrode, eliminating complex metallization processes to create patterned source/drain electrodes. Because vertically-aligned ZnO NRAs prevent mechanically robust wire bonding on a flat GaN surface, a preliminary bonding process was performed as a first step to remove a portion of the ZnO NRAs and expose GaN film at desired locations where the aluminum wires would be securely bonded by the following bonding processes. Fig. 2(c) and (d) shows fallen ZnO NRAs along the

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