Effect of Frost Formation on Operation of GaN Ultraviolet Photodetectors at Low Temperatures

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***Abstract*— Effects of frost growth on the sensitivity of gallium nitride (GaN) photodetectors were investigated by characterizing electrical and optical properties under dark and 365-nm ultraviolet (UV) illumination from room temperature down to −100°C. The direct wire bonding architecture was used to create aluminum/GaN interdigitated devices for the microfabrication. As the operation temperature decreased below −5°C, the frost formed from humid air was observed on the GaN surface, and photo-to-dark current ratio (sensitivity factor) showed significant reduction (6.76 at room temperature and 2.73 at −100°C under 1 V-bias). The presence of frost on the device surface significantly reduced the absorption of incident UV light into the GaN surfaces (average 85.6% reduction from room temperature to −70°C). This paper supports the characterization of the GaN for UV detection within low-temperature environments, such as cryostats, Arctic research, and space exploration applications.**

***Index Terms*— Gallium nitride, photodetector, low-temperature environments, ultraviolet, frost formation.**

I. INTRODUCTION

OPTOELECTRONICS based on wide bandgap semiconductors, such as gallium nitride (GaN), aluminum nitride, zinc oxide, and silicon carbide, has been extensively developed for the detection of ultraviolet (UV) lights [1]–[7]. In particular, GaN-based photodetectors have gained considerable interest because GaN absorbs a wide range of UV wavelengths whose photon energy is larger than 3.4 eV (bandgap of wurtzite GaN) [8]–[10] while providing high tolerance of chemical corrosion [11], temperature [12]–[14], and radiation [15], [16]. GaN UV photodetectors can be achieved using various solid-state device architectures, such as Schottky photodiode [17], [18], photoconductor [19], [20], p-n junction [21], [22], metal-semiconductor-metal (MSM) [23], [24], and transistor types [25], [26]. Among such structures, photoconductor and MSM-type photodetectors have attracted interest because of their simple fabrication process, which requires only a pair of ohmic or Schottky metal contacts on a single semiconductor (active) layer [23], [24], [27], [28].

Although GaN-based optoelectronics have been widely investigated for high-temperature applications [19], [29]–[31], characterization under cold temperatures is also required for extreme low-temperature applications [32]. In particular, typical operation temperatures during space exploration significantly drop below around -150°C (e.g., Jupiter and Europa), even below -200°C when exploring Pluto [33]–[35]. To withstand these low-temperature conditions, electronics are typically packaged with thermal insulators or external heaters to maintain and control devices' operation temperature [36], [37]. However, these supporting materials and instruments increase the overall spacecraft weight, size, and cost. Consequentially, microscale GaN-based optical sensors are emerging as a promising candidate for the operation in a wide range of temperatures. In this work, effects of frost growth on operation and sensitivity of interdigitated MSM UV photodetector were experimentally investigated and characterized at low temperatures down to −100°C in air. We found that the optical sensitivity of GaN photodetectors kept decreasing as the operation temperature was dropped below −5°C due to the reduction in absorption ability by frost formation on sensor's surfaces. This work demonstrates the characterization of GaN surfaces for UV detection within extreme cold environments to support many applications (e.g., space exploration, Arctic research, and cryostat systems).

II. EXPERIMENT

Fig. 1(a) shows a schematic of the GaN-based interdigitated MSM UV photodetectors integrated into a 14-pin dual in-line package (DIP) within extreme low-temperature environments (e.g., snow and frost). In this study, for the facile and simple fabrication, the direct bonding of aluminum wires on GaN surfaces as reported in our previous study [29], [30] was used. In short, to create interdigitated MSM structure, a small piece of the GaN-on-sapphire substrate was first glued on the DIP, and aluminum bonding wires were bonded directly on the GaN surface to form interdigitated Schottky metal contacts. More specifically, the overall fabrication of interdigitated MSM UV photodetectors includes two main steps: mechanical dicing of the GaN-on-sapphire wafer to create a desirable substrate size (dies) and direct bonding of aluminum wires on top of the GaN surface using an ultrasonic power for electrical connection between the lead frame in the DIP and GaN layer (Fig. 1(b)). In this study, a commercially available n-type GaN-on-sapphire wafer (< 5Ω cm resistivity, Kyma Technologies Inc.) was cut into 1 mm × 1 mm dies using a wafer dicing saw

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Manuscript received April 20, 2017; revised May 30, 2017; accepted May 30, 2017. Date of publication June 6, 2017; date of current version July 10, 2017. This work was supported by NSF under Award ECCS-1542152. The associate editor coordinating the review of this paper and approving it for publication was Prof. Kazuaki Sawada. *(Corresponding author: Hongyun So.)*

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Digital Object Identifier 10.1109/JSEN.2017.2712639

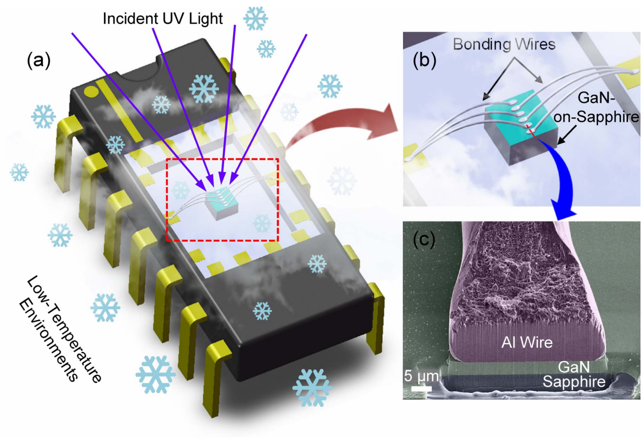

Fig. 1. (a) Schematic of the GaN interdigitated metal-semiconductor-metal ultraviolet photodetector integrated into a dual in-line package with direct bonding of aluminum wires and (b) zoomed-in view of three pairs of interdigitated metal electrodes and its operation under low-temperature environments. (c) SEM image of 45° tilted cross-sectional view of the bonding interface (cut through the focused ion beam) between the aluminum wire and the GaN surface (For visualization, aluminum wire, GaN, and sapphire overlaid with purple, green, and blue colors in the SEM image, respectively).

(DAD3240, DISCO Corp.). After the single die was fixed on the DIP, aluminum bonding wires (ALW-29S, 1%Si, Heraeus Deutschland GmbH & Co. KG) and a wedge-wedge wire bonder (7476E, West Bond Inc.) were used to electrically connect the GaN surface onto the lead frame in the DIP. For the qualitative characterization of fabricated devices, scanning electron microscope (SEM, XL30 Sirion, FEI Co.) and focused ion beam (FIB, Strata 235DB, FEI Co.) were used to observe the bonding interface between aluminum wires and GaN surface. To evaluate the device performance of the fabricated photodetectors, the current-voltage response was measured under the dark and UV illumination using a semiconductor device analyzer (B1500A, Agilent Technologies Inc.), UV lamp (365 nm, UVLS-26 EL Series, UVP LLC), light meter (UVA/B 850009, Sper Scientific Ltd.), and probe station (S-1060, Signatone Corp.), as shown in Fig. 2(a). The temperature controlled pressure chamber (THMS600-PS, Linkam Scientific Instruments Ltd.) and liquid nitrogen were used to characterize the device performance under low-temperature conditions. A humidity sensor (HIH-4030, Honeywell Inc.) was used for the measurement of relative humidity in air. A thermocouple was also glued on the GaN surface using a thermal grease to measure the actual devices temperature. For the characterization of optical property, the GaN surface reflectance and absorbance at both room and low temperature was measured using a spectrophotometer (Cary 6000i UV-Visible-NIR, Agilent Technologies Inc.).

III. RESULTS AND DISCUSSION

The SEM images of metal contacts, which are composed of aluminum wires (25.4 μm in diameter) bonded on the GaN film (approximate thickness of 4.2 μm), are shown in Fig. 1(c). An ultrasonic power of 480 mW and a bonding time of 30 ms were used to secure stable wire a bonding [29], [30]. Fig. 1(c) shows a 45° tilted cross-sectional view of the aluminum wire bonded on the GaN-on-sapphire substrate, which was cut through the FIB method. The smooth interface between the bonded aluminum wire and the GaN film indicates a stable contact, which is comparable with the metal-semiconductor interface through conventional metal deposition methods (i.e., electron-beam evaporation and sputtering). This result may be due to the fact that the ultrasonic power generates strong mechanical forces pushing the wires in the perpendicular direction (i.e., normal compressive force) to the GaN film [38]–[40], thereby resulting in a mechanically robust bonding interface between aluminum wires and GaN surface. Fig. 2(b) shows the image of experimental setup at room temperature that is composed of the temperature controlled pressure chamber in which the fabricated photodetectors are tested, two probe tips contacting interdigitated metal electrodes, thermocouple, and supply tubes for liquid nitrogen flow. The room temperature and relative humidity at ambient pressure were measured to be 21.7°C and 24−30%, respectively. Fig. 2(c) shows the image of experimental setup after the device temperature dropped to −100°C. The surface of devices was fully covered with frost which comes from humid air.

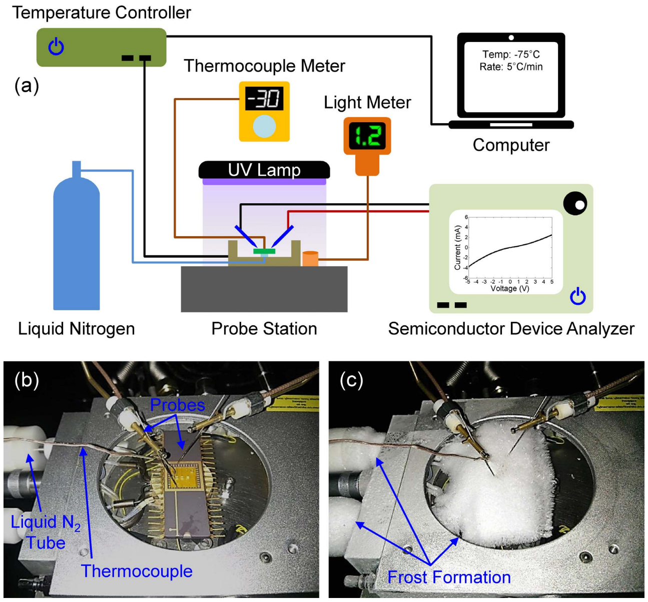

Fig. 2. (a) Schematic of the overall experimental setup to test the fabricated photodetectors under low-temperature conditions. Liquid nitrogen was used to cool down the temperature of devices. Images of the experimental setup during the test of photodetectors operation at (b) room temperature and (c) −100°C.

To characterize the operation of the fabricated photodetectors, the current-voltage response was measured under the dark and UV illumination (365 nm, approximate intensity of 1.2 mW/cm^2) at different operating temperatures from room temperature (21.7°C) down to −100°C. After measuring dark and photocurrents at room temperature, the chuck of the temperature controlled pressure chamber was cooled down using liquid nitrogen, and this temperature level was kept for about 15 min. The measurement was then performed again, and this procedure was continued down to −100°C. Fig. 3 shows the measured dark and photocurrents at different operation temperatures. The magnitude of dark current increased as the operation temperature decreased. This might

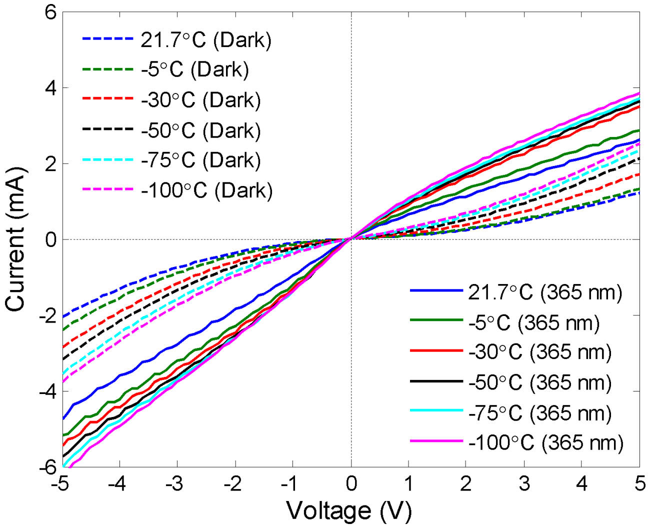

Fig. 3. Current-voltage response of the ultraviolet (UV) photodetectors using aluminum wires that directly bonded on GaN surfaces in dark condition (dashed lines) and under UV illumination (365-nm wavelength, solid lines) with intensity of ~1.2 mW/cm^2 at different low temperatures.

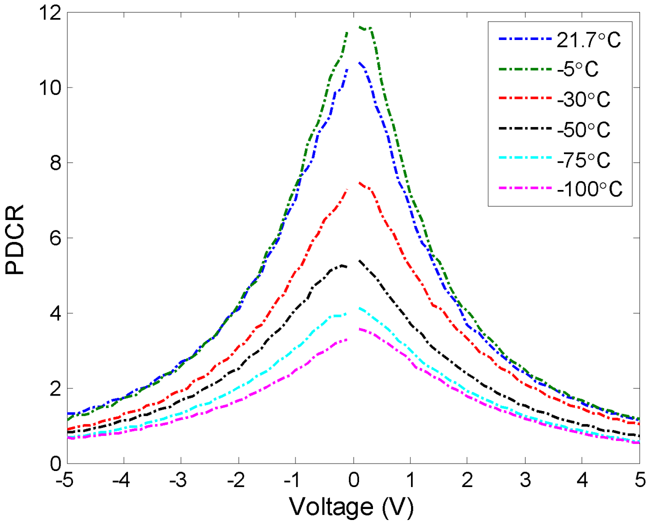

Fig. 4. Photo-to-dark current ratio (PDCR) of the interdigitated GaN photodetectors in an applied voltage range of −5 V to 5 V with respect to the operation temperature under ultraviolet illumination (~1.2 mW/cm^2).

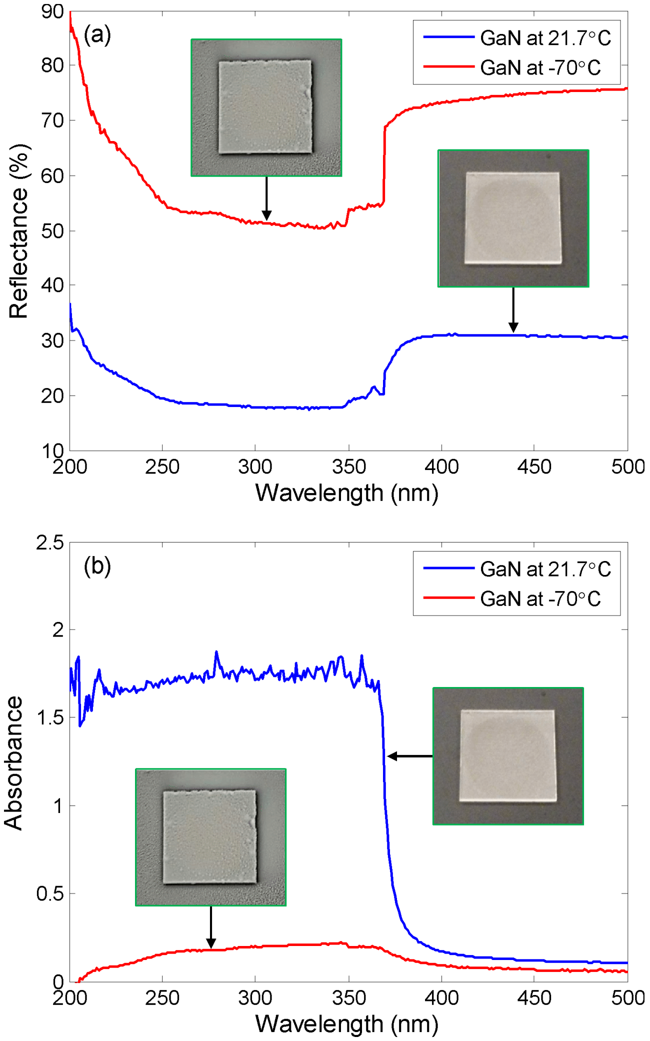

Fig. 5. Comparison of the (a) reflectance and (b) absorbance of bare GaN surface at room temperature (21.7°C) and low temperature (−70°C). Inset shows the optical images of 1 cm × 1 cm GaN-on-sapphire substrate before and after freezing using liquid nitrogen, indicating fully covered frost on the GaN surface after freezing.

be because the persistent photoconductivity in n-type GaN [41] was not completely removed (mitigated) at low temperatures during the 15 min period. The magnitude of photocurrent also increased as the operation temperature decreased, as shown in Fig. 3. It should be noted that the fabricated photodetectors showed almost same dark current and photocurrent levels after the operation temperature returned to the room temperature, demonstrating stable and reversible operation within the measured low temperature ranges.

To investigate the temperature-dependent sensitivity of the GaN UV photodetectors, the photo-to-dark current ratio (PDCR= $(I_p - I_d)/I_d$, where I_p and I_d are the current under UV illumination and dark conditions, respectively) [42], the sensitivity factor, was calculated based on the current-voltage response in Fig. 3. Fig. 4 shows the calculated PDCR values of the UV photodetectors in an applied voltage range of −5 V to 5 V under the different operation temperatures. The PDCR values exponentially decreased as the operating voltage increased. This reduction in PDCR with higher applied bias has also been observed in previously reported results [31], [43]. It is also noticeable that overall PDCR values for all bias ranges decreased as the temperature dropped below −5°C. This is because the condensation of moisture in air began and generated the frost at temperature below freezing point (0°C for water), thus started to cover the GaN surface (i.e., sensing area) with thin layer of ice. The frost became more severe as the temperature further deceased, and the GaN (sensing) surface became more opaque and invisible due to the completely covered thick layer of frost, as shown in Fig. 2(c). This severe frost (ice) that covered the GaN surface reflected a portion of incident UV light [44]–[46], thus making photodetectors absorb less UV light.

To demonstrate the reduced absorption through the GaN film because of the formed frost on the surface, reflection and absorbance spectra were characterized as shown in Fig. 5. For the low-temperature measurement, the GaN-on-sapphire

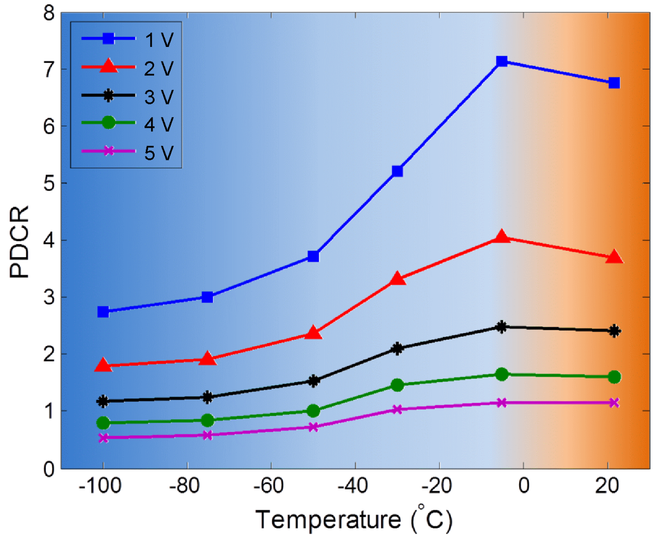

Fig. 6. Photo-to-dark current ratio (PDCR) of the GaN UV photodetectors in an operation temperature range of −100°C to 21.7°C (room temperature) with respect to the different applied voltages under 365-nm ultraviolet intensity of ~1.2 mW/cm^2.

substrate was frozen using liquid nitrogen and measurement was immediately performed. The frozen GaN substrate showed an approximate surface temperature of -70°C during the measurement. As a result, in the UV region (200−400 nm), the reflectance of the frozen GaN surface showed higher values (average 175.4% increase, 158.5% increase at 365 nm) than that of the room-temperature GaN, as shown in Fig. 5(a). This increased reflectance in the UV region eventually caused the significant reduction in absorption of incident UV light, as shown in Fig. 5(b). The average absorbance of GaN surface at low temperature was reduced by 85.6% (88.3% at 365 nm) compared with the values obtained at room temperature, demonstrating that the severe frost formed from the moisture in air significantly degraded optical properties of GaN surface, and thus decreased the photodetectors sensitivity.

To further investigate temperature-dependent sensitivity, PDCR values were calculated with respect to the operation temperature under different applied voltages, as shown in Fig. 6. For all applied voltages, the PDCR values showed approximately stable behavior until the operation temperature dropped below −5°C. However, the significant reduction in PDCR was observed when the temperature further decreased from −5°C to −100°C (i.e., approximately 52−61% decrease for all applied voltages). This might be because the thickness of frost became thicker as the temperature further decreased, thus reducing an opportunity for the incident photons to be absorbed into the GaN surface (i.e., sensing area), as shown in Fig. 5. In practical application, relatively lower voltage ranges between 1 V to 2 V can be used to obtain higher PDCR values with lower power consumption. To prevent the reduction in the photodetector sensitivity at low temperature, an on-chip heater or membrane-type photodetector with self-heating (via applied voltages) [47] could be used to melt and remove the frost from the sensors surface, thus maintaining a consistent absorption of incident UV light even at low-temperature environments. In addition, surface treatments such as super-hydrophobic surface [48], [49] or anti-frost coating [50] can be leveraged to delay the frost formation on GaN surface.

IV. CONCLUSIONS

In summary, the effects of frost formation on the optical sensitivity of GaN UV photodetectors were experimentally investigated by characterizing sensors electrical and optical properties under 365-nm UV illumination at low-temperature environments (from room temperature down to −100°C). To characterize the fabricated devices performance at low-temperature region, a temperature controlled pressure chamber was used and photo-to-dark current ratio (sensitivity factor) was measured under dark and 365-nm UV illumination. The bonded aluminum wires on the GaN surfaces showed a physically good metal contact, indicating a considerably smooth bonding interface between the aluminum (metal) and the GaN (semiconductor) film, and remained intact even at cold temperatures. However, the optical sensitivity of GaN showed both voltage- and temperature-dependent behavior (i.e., sensitivity decreased as applied voltage increased and as operation temperature decreased). At temperatures below −5°C, the sensitivity was continuously reduced because the frost (ice) formed from humid air started to cover GaN surface, leading to the reduction in absorption of incident UV light into the GaN surface (i.e., increase in reflectance of GaN surfaces). As the operation temperature further decreased, the sensitivity was significantly decreased because the thickness of frost became thicker, and thus completely covered the GaN surface. To enhance the GaN-based photodetectors sensitivity under low-temperature conditions, pulsed heating from external power (or built-in heater) or surface treatments can be leveraged to remove the frost on the sensing area. This study supports the characterization of wide bandgap semiconductor materials for UV detection within low-temperature environments, such as space and Arctic exploration applications, as well as cryostat designs.

ACKNOWLEDGMENT

This work was conducted in the Stanford Nanofabrication Facility (SNF) and Stanford Nano Shared Facilities (SNSF).

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