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Development of Gallium Nitride based Ultraviolet Photodetectors

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***Abstract**—Ultraviolet (UV) radiation photodetectors are of great importance due to their potential application in the field of modern world electronic devices, space-to-space communication and defense technologies. In this article, the fabrication of chemically etched porous gallium nitride (GaN) semiconductor based high efficiency UV photodetectors is reported. GaN thin film was subjected to KOH and* H_3PO_4 *chemical etching to develop porosity and thereafter the sample was used to fabricate UV photodetectors. Morphological, optical and electrical properties pristine (i.e. un-etched) and chemical etched GaN based photodetectors were analyzed and significant improvement in device parameters were perceived. It was observed that chemical etching modifies surface morphology from flat surface to porous structures and assists in higher photon absorption. Further, photoluminescence results divulged 6 fold reduction in the intensity of broad band related to defect states associated absorption in the energy spectrum. Finally, photodetection devices were fabricated using gold electrodes with a channel length of 500 μm, and the current-voltage curves were recorded using a 325 nm laser source. At a bias voltage of 1V, 8 fold increment in photocurrent of chemically etched photodetector along with a responsivity and detectivity of 45mA/W and 3.6 (x* 10^8*) Jones, respectively was observed. The fabricated devices showcased high switching rate with a response and recovery time of 6 & 4 sec for pristine and 1 & 2 sec for chemically etched GaN based photodetectors. The study concludes that surface modification offering higher surface areas facilitates optimum photon absorption and thereby improves the performance of a UV photodetector.*

Introduction

Ultraviolet (UV) is sub-visible range (< 380 nm) electromagnetic radiation that holds the potential to trigger chemical modifications and cause lethal impact on human health. Besides that, UV radiation also has a variety of applications in space-to-space communication, flame & ozone detection, biochemical sterilization, solar irradiance/industrial control and modern world military warfare equipment [1-3]. Such applications generate great demand for efficient sensing of UV radiation via fabrication of next generation optoelectronic devices. These optoelectronic devices that convert optical signals into measurable to electrical impulses are referred as Photodetectors [4]. A Photodetector (PD) may operate under photovoltaic or photoconductive mode depending upon the external bias, and its efficacy depends on collection of incident light photons generated electrical charge carriers. The Figure of merit parameters governing a PD's efficiency and performance are responsivity (response towards incident light), detectivity (ability to detect weak signals) and switching time (time taken by device to respond) [5].

Gallium Nitride (GaN) is a proven semiconducting material for photodetection application due to its high sensitivity towards UV radiation. The wide & direct bandgap, higher carrier mobility, high radiation hardness, strong temperature and chemical stability of GaN are best suited to serve as an ideal UV PD under extreme and adverse environmental conditions [6-8]. It has been witnessed that the performance of a GaN based UV PDs is affected by two major factors namely; aspect ratio (i.e., surface to volume ratio) and the density of defect states in the grown film [9]. High surface area (or aspect ratio) offers greater number of sites for incident photon absorption and thereby increases the photo-generated charges (i.e. electron-hole pair). The increased optical absorption provides high density of charge carriers with lower resistance which lead to enhancement in detection capabilities of the fabricated PDs. On the other hand, reduction in defect states facilitates lower dark current and thereby improves the responsivity as well as the switching time of the device. Besides that, processes like carrier recombination and series resistance which deteriorate the PD performance can also be minimized via reduction in defect states. Therefore, the present article reports the fabrication of GaN based efficient UV PDs via surface modification approach. The surface of GaN thin film was modified using a chemical etching process to synthesize porous GaN film offering higher surface area and lower defect densities. The morphological, optical and the electrical properties of the pristine and etched GaN were studied extensively. Further, UV PDs were fabricated on etched GaN film which showcased nearly 8 times higher responsivity and lower switching time.

Methodology

A commercially purchased high quality GaN thin film grown on c-plane sapphire substrate by Metal Organic Chemical Vapor Deposition (MOCVD) technique was used for experimental purposes. Prior to the experiment, the pristine (or un-etched) GaN film was pre-cleaned with isopropyl alcohol and device grade acetone followed by drying in nitrogen gas to remove the organic contaminants. The pristine GaN film was then etched in 1M KOH and 85% H_3PO_4 solution kept at 80ºC for 10 minutes to develop porous structures as shown in Figure 1. After the chemical treatment, the etched film was rinsed in deionized (DI) water and blown dried by pressurized nitrogen gas to perform various characterizations.

In order to probe the impact of chemical etching, the morphological and optical properties of the pristine and etched GaN were investigated via Field Emission Scanning Electron Microscopy (FESEM) and Photoluminescence (PL) Spectroscopy techniques. The device fabrication was processed via Metal-Semiconductor-Metal (MSM) approach using 200 nm thick gold electrodes deposited via thermal evaporation technique with a spacing of 500 µm. The current voltage and photodetection measurements were performed using a probe station setup connected to Keithley source meter equipped with a 325 nm focused laser source.

Results and Discussion

To perform the experiments, a commercially purchased high quality GaN film having a smooth surface morphology was used as shown in Figure 1(a). Thereafter, the procured GaN film was subjected to chemical etching in 1M KOH and 85% H_3PO_4 solutions under controlled environmental conditions. The temperature of both the solutions and the etching time was kept at 80ºC and 10 minutes as learned from a previous study [10]. The chemical etching treatment led to significant modification in the film surface morphology and development of porosity was witnessed. Field emission scanning electron microscopic (FESEM) images shown in Figures 1(a) and 1(b) represent that the flat surface of the pristine GaN film was converted into porous structures after the chemical etching treatment. The development of porous structures upon chemical etching displays substantial increment in the surface area (and aspect ratio) of the etched GaN film.

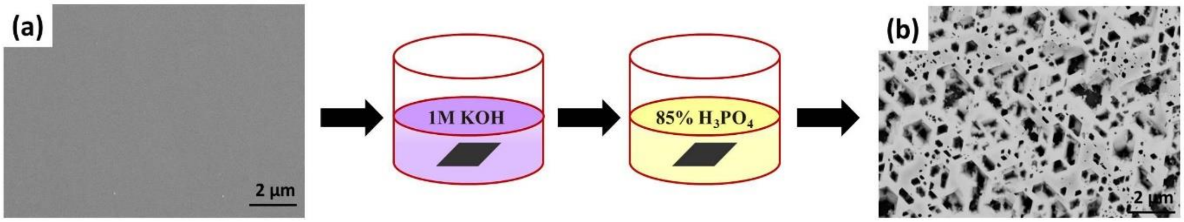

Figure 1: FESEM images showing surface morphology of (a) pristine and (b) etched GaN film.

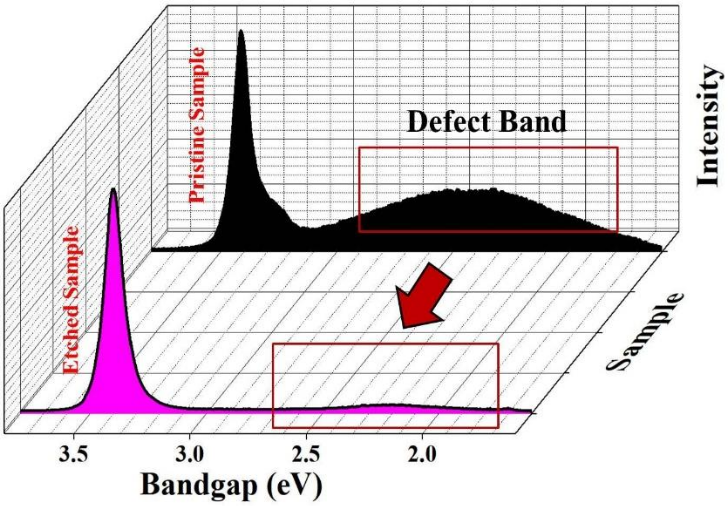

Figure 2: Photoluminescence spectra of the samples showing drastic reduction in the defect band of the etched GaN film.

Further, to explore the impact of chemical etching on the optical properties and defect states of the GaN films, Photoluminescence (PL) studies were performed. Figure 2 represents the PL spectrum of the pristine and chemically etched GaN film. The spectra consisted of a sharp peak located at 3.4 eV associated with the band gap of the GaN along with a broad band

(1.8 – 2.8 eV) related to defect states [10-12]. It is evident from the obtained PL spectra that intensity of the peak corresponding to the bandgap of GaN doesn't show any visible changes, though the intensity of defect band (marked as red box in Figure 2) decreased drastically. The PL analysis divulged that chemical etching led to ~ 5-fold reduction in the intensity of defect states of the etched film in companion with pristine GaN film. It indicates that etched GaN pursuing low defect density would be an ideal candidate for the fabrication of efficient UV PDs.

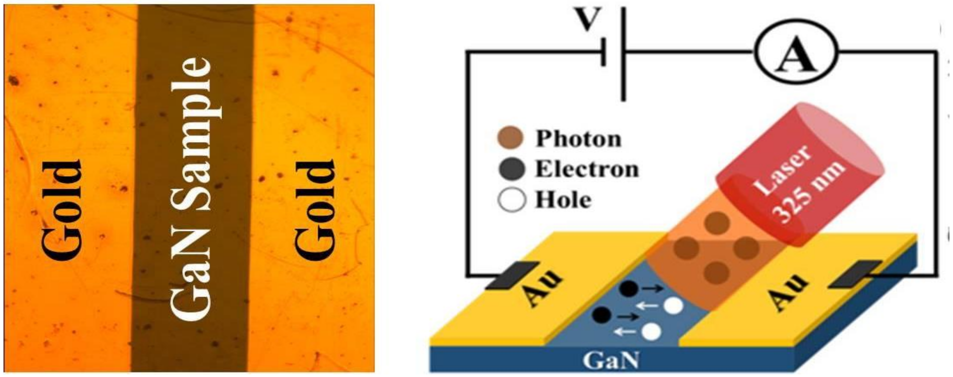

Figure 3: Optical image of the fabricated devices and the schematic representation of the photodetection measurement setup.

The optical microscopic (OM) image of the fabricated PD devices and the schematic representation of the photodetection measurement setup is shown in Figure 3. To perform current-voltage (I-V) and photodetection measurements, gold electrodes of 200 nm thickness and a spacing (i.e. channel length) of 500 µm were deposited on the GaN film. A focused He-Cd laser operating at a wavelength of 325 nm was employed as a UV radiation source for photodetection purposes. The fabricated devices were then connected to a probe station equipped with a source meter for providing external bias and the measurement of photogenerated current. The UV photon induced generation and collection of electrons and holes toward respective electrodes are represented in the figure and the experimentally obtained time dependent photo-response curves is shown in Figure 4.

Figure 4(a) displays the I-V curves of the fabricated devices under forward and reverse bias conditions, while the time dependent photo-response curves are shown in Figure 4(b). The room temperature I-V curves of pristine GaN based PD divulged Schottky nature with asymmetrical behavior under forward and reverse bias. On the other hand, symmetrical I-V curves (for both bias conditions) with Schottky nature were perceived for etched GaN based PD. The cause behind the asymmetrical nature I-V curves of pristine GaN is associated with high density of defect states which on reduction in etched GaN (as perceived from PL results) led to symmetrical I-V curves. However, the lower value of current in etched GaN was associated with the developed porosity and poor charge carrier collection.

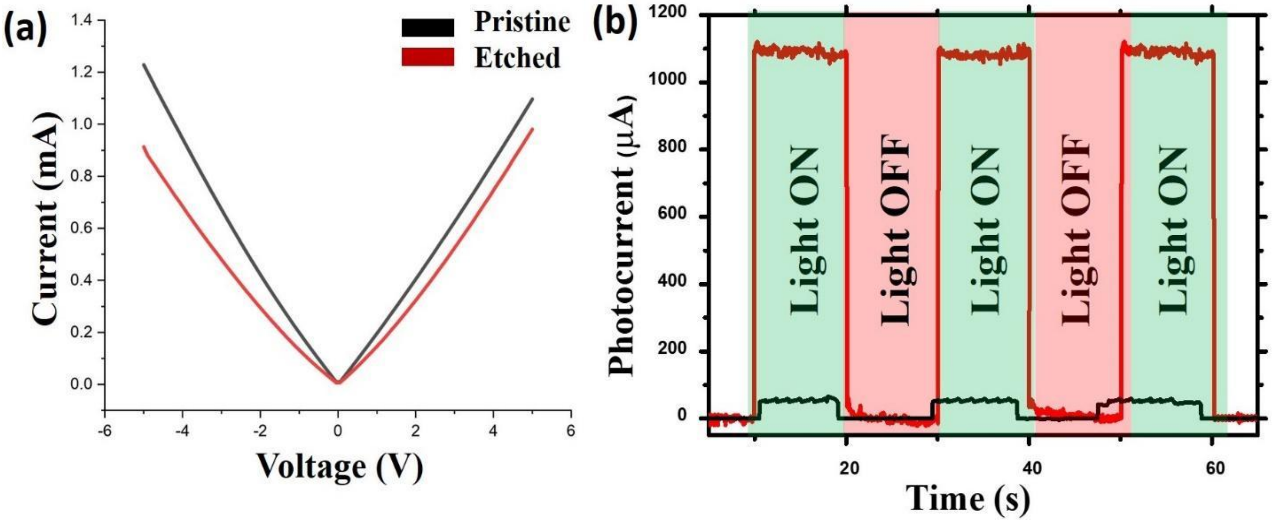

Figure 4: (a) Current-Voltage and (b) Time dependent photo-response curves of the pristine and etched GaN films.

Finally, UV photodetection measurements on both the fabricated PDs were performed as represented in Figure 4(b). The normalized time dependent photo-response of the fabricated UV PDs (at a bias voltage of 1V) are shown in Figure 4(b). The figure displays that incident UV photons create electron-hole pairs and increase the overall current which further drops to its original value when the laser source is switched off. It is evident from the measurements that the etched GaN based UV PD (red curves) pursue ~10 times higher photocurrent in comparison with pristine GaN based UV PD (black curves). Further, the state of art device parameters such as responsivity (R) and detectivity (D) were calculated from the photo-response curves using the following equations [11,12]:

$$R = \frac{qV_B\mu_e}{LP_{opt}}\,(S\Delta n + n\Delta S) \qquad \text{….. [1]}$$

$$NEP = \frac{\underline{i_n^2}^{1/2}}{R} \qquad \text{….. [2]}$$

$$D = \frac{(A\,\Delta f)^{\frac{1}{2}}}{NEP} \qquad \text{….. [3]}$$

Here, q is electrical charge, V_B is applied bias voltage, μ_e is electron mobility, L is the distance between the two electrodes (i.e., 500 µm), P_{opt} is optical power, $\underline{i_n^2}^{1/2}$ is the measured noise, Δf is the electrical bandwidth and NEP is the noise equivalent power. Using the aforementioned equations, a responsivity of 5.5 mA/W & 45 mA/W and detectivity of 2.5 & 3.6 (x 10^8) Jones for pristine and etched GaN based UV PDs was calculated respectively. The response and recovery time of the fabricated UV PDs to ensure switching performance of the fabricated devices was also calculated. To calculate the switching parameters, the photo-response curves were fitted using mathematical equations (using origin pro software) to calculate the response time (current increasing from 10 – 90%) and recovery time (current decreasing from 90 – 10%) of the fabricated UV PDs [13]. The photo-response curve fittings ensured fast switching rate with a response and recovery time of 6 & 4 sec for pristine and 1 & 2 sec for chemically etched GaN based photodetectors.

In Summary, it was observed that the surface modified chemically etched GaN based UV PDs display higher efficiency (8-fold increment in responsivity) and a fast-switching rate (3 times lower response time). Such enhancement in the device performance was ascribed to higher surface area and reduction in defect density of the surface modified chemically etched GaN films as perceived from FESEM and PL results. Though the fabricated devices show high efficiency of 45mA/W, it was emphasized to address more scientific attention for optimizing the device performance to match the international status as the recent studies report a peak responsivity, detectivity and response time values up to 695.3 A/W, 1.0 (x 10^{17}) Jones and 66 micro-seconds, respectively [14-17]. However, it is also noteworthy to mention that these research methodologies have utilized new and hybrid (ZnO and graphene) materials decorated on GaN nanostructures (channel length < 100 µm) which drastically increases the overall device performance. Therefore, it was concluded that the presented report opens avenues for developing high efficiency GaN based UV PDs via a simple surface modification approach.

Conclusion

A new approach was adopted for chemically modifying flat GaN surfaces to develop porous structures. Systematic chemical etching of GaN thin films with 1M KOH and 85% H_3PO_4 solution under controlled environmental conditions was performed. In comparison with the pristine films, the chemically etched porous GaN offered higher surface area and displayed significant reduction in the defect states. Standard gold electrodes with a channel length of 500 µm were deposited on both the films to ascertain their current-voltage characteristics and fabricate UV PDs. Room temperature I-V curves divulged the Schottky nature of the fabricated devices with asymmetrical/symmetrical behaviour for pristine/etched GaN films. Thereafter, photodetection measurements on the fabricated devices were performed using a 325 nm laser source at an external bias of 1V. The obtained results revealed 8 folds increment in the photocurrent of chemically etched photodetector along with a responsivity and detectivity of 45mA/W and 3.6 (x 10^8) Jones, respectively. The high switching rate of fabricated devices was ensured with a response and recovery time of 6 & 4 sec for pristine and 1 & 2 sec for chemically etched GaN based photodetectors.

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