Self-Powered Fast-Response X-Ray Detectors Based on Vertical GaN p-n Diodes

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***Abstract*— GaN offers an excellent potential for fabricating X-ray detectors, taking advantage of its superior material properties and well-developed manufacturing technologies. In this letter, we demonstrated a self-powered fast-response X-ray detection using GaN-based vertical p-n diodes grown on a bulk GaN substrate. Attributed to the high crystalline quality achieved by homoepitaxy, the fabricated photodiodes exhibited an excellent rectification behavior, and therefore, a strong photovoltaic response to X-ray illumination when biased at 0 V. The transient X-ray detection analysis revealed that the self-powered detectors have a relatively short response time (< 20 ms) and a good linear response to the X-ray incident dose rate with a high specific sensitivity of 170 nC·Gy^{-1}·cm^{-2}.**

***Index Terms*— GaN, p-n diode, self-powered, X-ray detectors.**

I. Introduction

DIRECT-CONVERSION semiconductor X-ray detectors have received remarkable research interests in recent years because of their superior properties, such as high energy resolution, small system volume, low cost, and suitability for mass production. They can benefit a range of applications including medical diagnostics, security systems, and aerospace and nuclear industries [1]–[4]. To obtain a reasonable detectivity, the X-ray detectors generally require a relatively large size external power supply, which makes the overall circuitry bulky and uneconomical in the current low-carbon scenario [5], [6]. Thus, X-ray detectors which are able to detect at a zero-volt bias, namely self-powered, can be an energy-efficient solution [7]–[9].

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GaN is a commercial semiconductor that has been extensively used for both optoelectronic and electronic devices [10], such as light-emitting diodes (LEDs) [11], laser diodes (LDs) [12], photodetectors [13], sensors [14] and high-speed high-power field-effect transistors (FETs) [15]–[17]. The wide bandgap (4.3 eV), large density (6.09 g·cm-3), relatively large atomic number of Ga (31) and excellent chemical and thermal stability also make GaN a promising candidate for X-ray and particle detection [18]–[24], particularly in high temperature and radiation environments. The availability of high quality bulk GaN substrate enables the fabrication of high performance vertical GaN radiation detectors, since a much thicker sensitive region is essential to collect the high-energy radiation photons and charged particles. Furthermore, GaN-based detectors can be potentially integrated with a wide range of well-developed GaN-based electronics and circuits to yield a compact radiation detection system [25]–[28].

In this letter, GaN-based vertical p-n diodes have been fabricated on a bulk GaN substrate and tested as X-ray detectors. The device exhibited a low reverse leakage current density of $\sim 10^{-1}$ A/cm^2 at -300 V. When biased at 0 V, the detector showed a fast and stable transient response to the switching of X-ray illumination using internal photovoltaic effect, demonstrating the great potential of using GaN p-n diodes as self-powered X-ray detectors or X-ray photocells.

II. Experiments

The GaN p-n structure used in this study was grown on a 2-inch bulk GaN substrate by metal organic chemical vapor deposition (MOCVD). The n-type GaN substrate was of 350 μm thick, with a resistivity of $\sim$ 0.05 Ω·cm and a dislocation density of $\sim 5 \times 10^5$ cm^{-2}. The epilayers included a 200-nm thick Si-doped n$^+$-GaN layer ($\sim$ n $= 2 \times 10^{18}$ cm^{-3}), a 5-μm thick unintentionally doped n$^-$-GaN layer (carrier concentration at the order of 10^{16} cm^{-3}), and a 500-nm Mg-doped p-type GaN ($\sim$ p $= 2 \times 10^{17}$ cm^{-3}). Trimethylgallium (TMGa) and ammonia (NH_3) were used as precursors for Ga and N, respectively. Fig. 1(a) shows the atomic force microscopy (AFM) image of the as-grown sample. The root mean square (RMS) roughness was slightly high, 1.9 nm for a scanned area of 10×10 μm^2, which could be related to the low temperature growth of the upmost p-GaN layer. The fabrication of the vertical p-n diodes started with mesa isolation etching using a BCl_3/Cl_2-based inductively coupled plasma (ICP) etch process. Following that, the sample was immersed into a 25% tetramethylammonium hydroxide (TMAH) solution

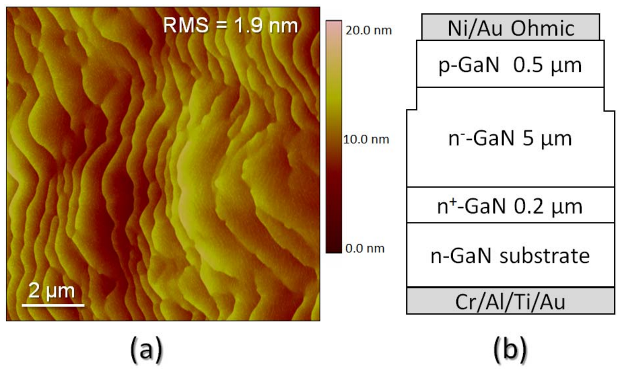

Fig. 1. (a) AFM image of the as-grown GaN p-n structure ON a bulk substrate. (b) Schematic cross-section of the vertical GaN p-n diode.

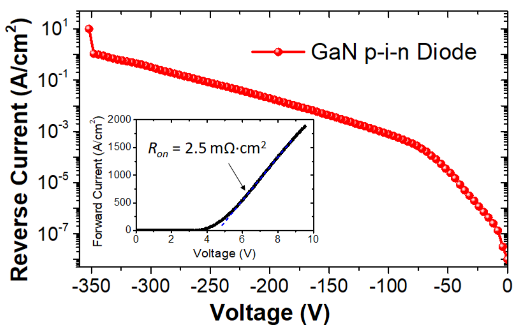

Fig. 2. Reverse I-V characteristics of the vertical GaN p-n diode. The inset shows the forward current of the device.

at 75 °C for 60 minutes. The TMAH treatment was found effective in suppression of leakage current by removing etch damages from the mesa sidewall [29]. Then, the p-electrode was formed by e-beam evaporation of a Ni/Au (30/30 nm) metal stack and a liftoff process. A rapid thermal annealing (RTA) at 570 °C was performed in an atmospheric ambient for 5 minutes to facilitate the formation of a good Ohmic contact between Ni and p-GaN. Subsequently, a Cr/Al/Ti/Au metal stack was deposited on the backside of the sample by e-beam evaporation, serving as n-electrode. Fig. 1(b) shows the cross-sectional schematic of the fabricated vertical GaN p-n diode. The diode was in circular shape with a diameter of 560 μm.

III. Results and Discussion

Fig. 2 shows the reverse current-voltage (I-V) characteristics of the fabricated vertical GaN p-n diode in dark condition, with a breakdown voltage (V_{br}) of $\sim$ 350 V. The reverse leakage current density of the vertical GaN p-n diode at -300 V is $\sim 10^{-1}$ A/cm^2. The forward I-V characteristics of the device was shown in the inset of Fig. 2. The turn-on voltage ($V_{\rm ON}$) extracted at the current density of 10 A/cm^2 was 3.8 V, close to the bandgap of GaN. The high $V_{\rm ON}$ and low leakage current correspond to a high barrier height, i.e. a high built-in potential in the p-n junction, which is essential for a self-powered photodetector using photovoltaic effect. A larger built-in electric field will provide better separation of photo-excited electron-hole pairs. Moreover, the fabricated diode exhibited a low on-state resistance ($R_{\rm ON}$) of 2.5 m$\Omega$$\cdot$cm^2, indicating a greatly suppressed parasitic resistance in the device.

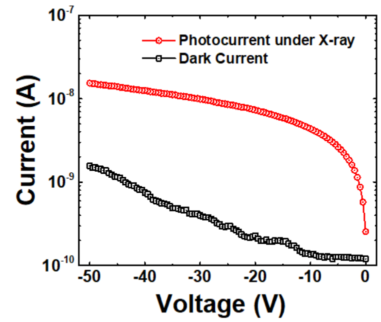

Fig. 3. Comparison of the photocurrent and dark current of the GaN p-n diode to X-ray illumination as a function of reverse bias voltage.

The fabricated diodes were mounted onto a conductive holder and wire bonded for the X-ray detection tests. A miniature X-ray source (60 kV, 12 W X-ray source, Moxtek, USA) was used in the experiments. When the X-ray tube accelerating voltage is set at 30 kV, a wide continuous spectrum of X-ray beam with a peak photon energy at around 24 keV can be generated. According to the calibration using a commercial Si X-ray detector, the X-ray dose rate at a distance of 1 cm from the source is 1.532 Gy/s when the X-ray tube current is set at 100 μA. The X-ray flux is proportional to the X-ray tube current, which can be tuned from 1 μA to 400 μA, when its accelerating voltage is fixed. All the X-ray detection measurements were conducted at RT in this study, and the detector was illuminated by X-ray from the front side perpendicularly with a distance to the X-ray source of 1 cm.

In order to demonstrate the X-ray detection capability, the reverse I-V characterization of the fabricated diode was performed under X-ray exposure with an incident dose rate of 1.532 Gy/s. As shown in Fig. 3, the photocurrent (I_p) of the GaN p-n detector increases dramatically when compared with its dark current (I_d).

The transient response of the GaN p-n detector to the switching of X-ray illumination was characterized and plotted in Fig. 4(a). The X-ray switching period was set to be 60 s, and the sampling frequency of the measurement was 50 Hz. When biased at 0 V, the detector exhibited a good and stable transient response. The dark current of the detector was well below the measurement limit of the equipment owing to its passive operation mode, which is one of the important advantages in terms of signal-to-noise ratio (SNR) and power consumption. Fig. 4(b) shows the enlarged plot of the rise and decay process of the photocurrent for the GaN p-n detector when the X-ray source was turned on and off. The switching time of the X-ray source is negligible. Both the rise time (t_r, 10% to 90%) and decay time (t_d, 90% to 10%) of the transient photocurrent were very short ($<$ 20 ms, the time resolution of the equipment in our experiments). The result was benchmarked with other reported X-ray detectors in the literature using different wide bandgap semiconductors, as listed in Table I. Our device exhibited a competitively fast response speed, which could be attributed to the high build-in electric field within the GaN p-n junction. According to photovoltaic mechanism, electron-hole pairs were excited by the X-ray photons in the space-charge region of the zero-volt

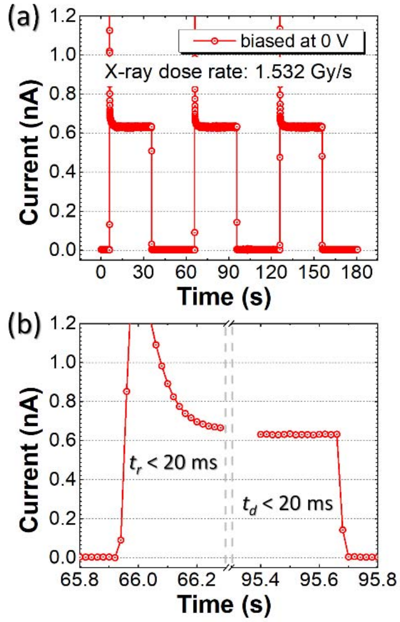

Fig. 4. (a) The transient responses of the GaN p-n detector to the switching of X-ray illumination at biases of 0 V. (b) The enlarged plots of the rise and decay process of the photocurrent when the X-ray source was turned on and OFF.

TABLE I
BENCHMARK OF RESPONSE SPEED OF THE WBG SEMICONDUCTOR X-RAY DETECTORS

Detectors	Bias voltage	Response time
GaN p-i-n Diode [21]	200 V	15 s
GaN Schottky Barrier Diode [30]	4 V	10 s
	0 V	< 1 s
GaN MSM [31]	200 V	28 s
Ga_2O_3 Schottky Barrier Diode [3]	15 V	20.9 s
	0 V	< 20 ms
$MAPbBr_3$ MSM [32]	N/A	~ 10 s
Diamond MSM [6]	> 150 V	< 8 ms
This work	0 V	< 20 ms

biased diode, and then swept out rapidly by the built-in electric field to produce photocurrent. The favorable high build-in electric field in the junction helps to efficiently collect the photo-generated carriers. Therefore, the self-powered GaN p-n detector in this study operated as a current source. Similar to most of other X-ray semiconductor detectors, the photocurrent in our device can be processed using either a charge sensitive amplifier for spectroscopy or a transimpedance amplifier for dosimetry. Fig. 5 (a) shows the transient response of the zero-volt biased GaN p-n diode to X-ray illumination with different incident flux. The X-ray tube current was set to 50 μ A, 100 μA, 200 μA, and 300 μA, corresponding to X-ray dose rates of 0.766 Gy/s, 1.532 Gy/s, 3.064 Gy/s and 4.596 Gy/s, respectively. Even with different X-ray incident dose rates, the zero-volt biased GaN p-n detector showed stable and repeatable transient response. The net photocurrents (I_p - I_d) of the detector under illumination were plotted as a function of the X-ray dose rate in Fig. 5(b) and a good linear relationship was derived. The specific sensitivity (R_s, defined

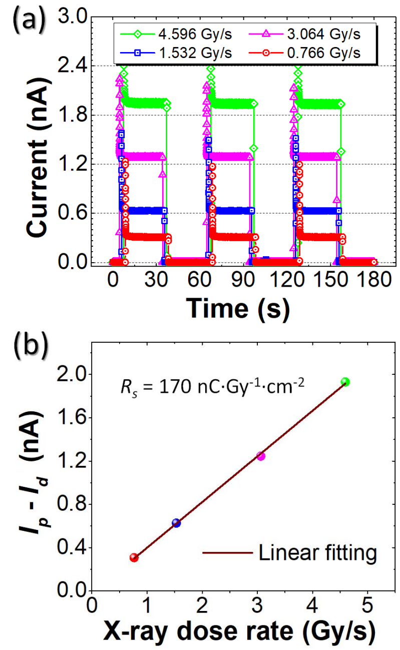

Fig. 5. (a) The transient response of the GaN p-n detector to the switching of X-ray illumination with different incident dose rates. (b) The photocurrent of the GaN p-n detector under X-ray illumination as a function of the X-ray incident dose rate.

as the ratio between net photocurrent and radiation dose rate per device unit active area [6]) of the self-powered GaN X-ray detector was calculated to be as high as 170 nC·Gy^{-1}·cm^{-2}.

IV. CONCLUSION

In conclusion, self-powered fast-response X-ray detectors based on GaN p-n diodes have been developed on a bulk GaN substrate. Attributed to its low leakage current and high build-in electric field, the fabricated devices exhibited an excellent photovoltaic behavior to X-ray illumination when biased at 0 V. The transient X-ray detection characterization for the detectors revealed a sensitive, fast and stable response, as well as a linear response to the X-ray incident dose rate. These results suggested that the GaN p-n diodes are promising for passive X-ray detection when the power consumption is crucial.

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