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Low dark current and internal gain mechanism of GaN MSM photodetectors fabricated on bulk GaN substrate

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ABSTRACT

Metal-semiconductor–metal ultraviolet photodetectors are fabricated on low-defect-density homoepitaxial GaN layer on bulk GaN substrate. The dislocation density of the homoepitaxial layer characterized by cathodoluminescence mapping technique is $\sim 5 \times 10^6$ cm^{-2}. The photodetector with a high UV-to-visible rejection ratio of up to 1×10^5 exhibits a low dark current of <2 pA at room temperature under 10 V bias. The photo-responsivity of the photodetector gradually increases as a function of applied bias, resulting in a photodetector quantum efficiency exceeding 100% at above medium bias. The photo-responsivity also shows a dependence on the incident optical power density and illumination conditions. The internal gain mechanism of the photodetector is attributed to photo-generated holes trapped at the semiconductor/metal interface as well as high-field-induced image-force lowering effect.

1. Introduction

With large direct bandgap energy ($\sim$3.4 eV), high thermal conductivity and high electron saturation velocity, GaN-based materials are promising for highly sensitive ultraviolet (UV) photodetector applications. A variety of GaN-based UV-detectors, such as photoconductors [1], Schottky barrier photodiodes [2], *p*–*i*–*n* photodiodes [3], avalanche photodiodes [4] and metal-semiconductor–metal (MSM) photodetectors [5] have been reported. Among the above structures, MSM photodetectors have many attractive advantages for practical applications, such as low capacitance, intrinsic high speed, fabrication simplicity and compatibility with field effect transistor technology. To achieve a high-performance MSM photodetector, it is important to reduce dark current of the device which determines the lowest detectable optical signal strength. Although detailed reverse leakage mechanism of GaN-based Schottky contacts is still under debate, it is well accepted that structural defects, especially dislocations, within GaN epilayer play an important role in determining junction leakage. There is evidence suggesting that dislocations with a screw component are primary leakage path in GaN-based Schottky junctions [6]. However, due to the large lattice mismatch between GaN and its foreign substrate like sapphire, hetero-epitaxial GaN often suffer from a high dislocation density in the range of 10^8–10^{10} cm^{-2}. Thus, vastly reducing dislocation density in GaN epilayer is essential for fabricating low dark current GaN-based photodetectors.

In this work, we report fabrication and characterization of MSM photodetectors based on low-defect-density homoepitaxial GaN layer. By growing device structure on bulk GaN substrate, the photodetector shows very low dark current and high UV-to-visible rejection ratio. The device also exhibits an internal gain, resulting higher than 100% quantum efficiency. The gain mechanism of the photodetector is studied by varying applied bias and illumination conditions.

2. Experiment

The free-standing bulk GaN substrate used in this work is prepared by hydride vapor phase epitaxy with a thickness of $\sim$300 μm and a room-temperature (RT) carrier density of 2×10^{18} cm^{-3}. The epi-structure consists of a 1 μm silicon doped n^+ GaN ($\sim 3 \times 10^{18}$ cm^{-3}) transition layer followed by a 3 μm unintentionally doped GaN active layer. The homoepitaxial GaN layer is characterized by using cathodoluminescence (CL) mapping technique, high-resolution X-ray diffraction (XRD) and atomic force microscopy (AFM), respectively. In fabrication of the MSM photodetectors, Ni (30 nm)/Au (300 nm) metal stack is used as the Schottky contact metal. Standard photolithography and lift-off techniques are used to define interdigitated contact electrodes. The fingers of the contact electrodes are 15 μm wide and 300 μm

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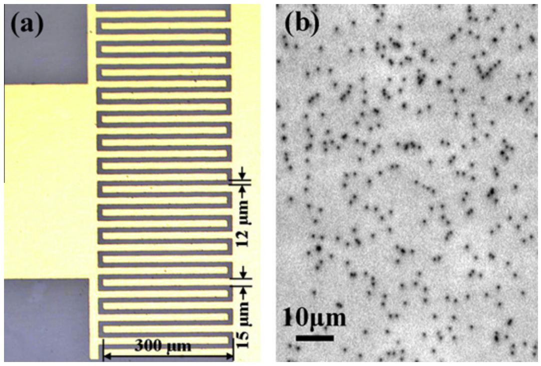

Fig. 1. (a) Photograph of an interdigitated GaN MSM photodetector and (b) panchromatic CL mapping image of the homoepitaxial GaN layer grown on bulk GaN substrate.

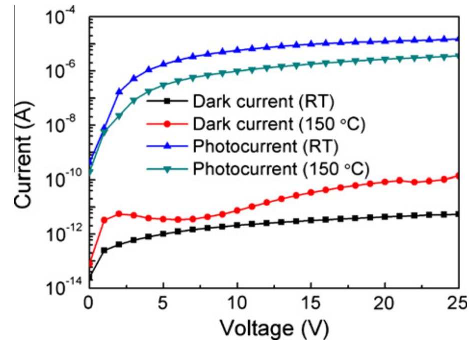

Fig. 2. *I–V* characteristics of the photodetector measured under dark and under 360 nm light illumination at RT and 150 °C, respectively.

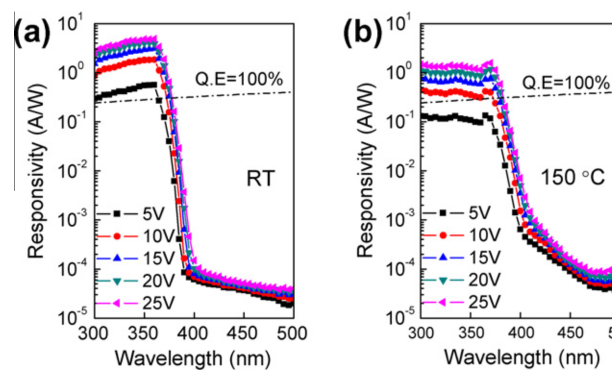

Fig. 3. Bias-dependent spectral response of the GaN MSM photodetector measured at: (a) RT and (b) 150 °C.

long with a spacing of 12 µm. Fig. 1a shows a top view image of one finished device.

The current–voltage (*I–V*) characteristics of the photodetectors are measured by using a Keithley 2636A sourcemeter both under dark and under illumination. The light output from a 350 W Xe lamp is directed into a monochromator for single wavelength selection. The photodetectors under test are illuminated by monochromic light transmitting through an optical fiber, which is coupled into the output port of the monochromator. The evolution of photo-responsivity as a function of optical power density is measured by pumping a commercial GaN-based 365 nm UV light emitting diode at different current levels. The incident optical power is calibrated by using a UV-enhanced Si photodiode.

3. Results and discussion

The dislocation density of the homoepitaxial GaN layer on bulk GaN substrate is measured by a CL mapping technique which has been confirmed to be a reliable method to count dislocations in low-dislocation-density GaN [7]. Fig. 1b shows a typical panchromatic CL mapping image of the homoepitaxial GaN layer examined over a large surface area, in which each dislocation is represented by a small dark spot resulting from strong local non-radiative recombinations. The dislocation density of the homoepitaxial GaN layer is estimated to be $\sim 5 \times 10^6\,cm^{-2}$ in average, which is about 2–3 orders lower than the typical dislocation density of hetero-epitaxial GaN. The corresponding full width at half maximum of the GaN (0002) XRD rocking curve is 80–100 arcsec, which agrees with the low dislocation density determined by CL mapping. The surface roughness of the GaN homo-epilayer measured by AFM over a $5 \times 5\,\mu m^2$ area is ~0.56 nm. The above analysis indicates that low-dislocation-density GaN epilayer with reasonable surface morphology has been obtained through the homoepitaxial growth process.

The dark and photocurrent curves of the MSM photodetector are shown in Fig. 2, in which the optical power density of the 360 nm UV illumination is $\sim 5.4\,\mu W/mm^2$. The photodetector exhibits a low RT dark current of less than 2 pA at 10 V bias, which can be attributed to the low dislocation density within the homoepitaxial GaN layer. Even at a high temperature of 150 °C, the dark current at 10 V is still below 10 pA, suggesting that the device is suitable for high temperature applications. The decrease of photocurrent with increasing temperature can be explained by thermal activation of trapped holes at the semiconductor/metal interface, which will be discussed later. In addition, enhanced recombination loss at high temperature can also reduce photocurrent.

Fig. 3a and b show the spectral response characteristics of the photodetector at RT and at 150 °C, respectively. A sharp cutoff in the photo-response curves occurs at approximately 365 nm, which corresponds to the bandgap energy of GaN. At above 10 V bias, the UV-to-visible rejection ratio of the photodetector could be as high as 1×10^5 at RT, and is still higher than 3×10^3 even at a high temperature of 150 °C. Here, the UV-to-visible rejection ratio is defined as the responsivity measured at 360 nm divided by that measured at 450 nm. The responsivity of the photodetector gradually increases as a function of bias and the corresponding photodetector quantum efficiency could well exceed 100%, indicating that an internal gain mechanism exists within the device.

Photocurrent gain has been widely observed in various MSM photodetectors, which is desirable for applications requiring high responsivity but could limit the detector bandwidth simultaneously [8]. It seems that the internal gain is not necessarily linked to the crystalline quality of the semiconductor, as it could also present in MSM photodetectors based on much maturer semiconductors like GaAs [9]. Several theories have been suggested to explain the gain mechanism, such as photoconductive gain [10], avalanche carrier multiplication [11], and trapping of photo-carriers at semiconductor/metal interface [12]. In addition, image-force lowering of Schottky barrier height should happen more or less in most Schottky-based photodetectors at high applied bias.

To understand the internal gain mechanism, photocurrent curves are measured under a specially-designed illumination condition, in which a 500 nm sub-bandgap light shines on the sample surface together with the original 365 nm UV light. A schematic of the experimental setup is shown in the inset of Fig. 4. Interestingly, compared to the control case with only UV illumination, the pho-