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A highly integrable p-GaN MSM photodetector with GaN n-channel MISFET for UV image sensor system

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Abstract

A metal-semiconductor-metal (MSM) ultraviolet (UV) photodetector (PD) is proposed as an effective UV sensing device for integration with a GaN n-channel MISFET on auto-doped p-type GaN grown on a silicon substrate. Due to the high hole barrier of the metal-p-GaN contact, the dark current density of the fabricated MSM PD was less than 3 nA/cm^2 at a bias of up to 5 V. Meanwhile, the UV/visible rejection ratio was 400 and the cutoff wavelength of the spectral responsivity was 365 nm. However, the UV/visible ratio was limited by the sub-bandgap response, which was attributed to defect-related deep traps in the p-GaN layer of the MSM PD. In conclusion, an MSM PD has a high process compatibility with the n-channel GaN Schottky barrier MISFET fabrication process and epitaxy on a silicon substrate.

Key Words : GaN, MSM, UV photodetector, UV image sensor

1. Introduction

The commercial applications of ultraviolet (UV) sensors are continuing to grow, especially in the areas of healthcare, ozone-layer monitoring, and fire alarms, and GaN-based III nitrides are well known as the key materials for high-response UV photodetectors (PDs), due to their wide and direct bandgap. Thus, several types of GaN-based PD have already been investigated, including a p-i-n diode[1,2], Schottky barrier PD[3,4], and metal-semiconductor-metal (MSM) PD[5,6]. However, despite a simple fabrication process and high responsivity, an MSM PD on n-GaN suffers from a high leakage current due to a low Schottky barrier of around 1 eV that is unavoidably limited by the work function of the metals and Fermi level pinning effect.

As an alternative, the hole barrier can be increased as high as 3 eV in a p-GaN Schottky junction, which allows suppression of the leakage current. Moreover, since an n-channel enhancement type Schottky barrier metal-insulator- semiconductor field effect transistor (SB-MISFET) can also be fabricated on the same p-GaN layer along with a p-GaN MSM PD, this enables the integration of an MSM PD with an n-MISFET circuit, thereby facilitating the commercialization of low-price UV image sensors, similarly in structure with the silicon CMOS image sensor (CIS).

Accordingly, this paper proposes and fabricates an MSM UV PD on auto-doped p-GaN[8], which is grown on a silicon substrate. The fabricated MSM PD is highly compatible with the fabrication process of a GaN n-channel SB-MISFET on a p-GaN substrate[7], which may allow the implementation of an integrated UV image system in the near future.

2. Experiment

The MSM PD was fabricated on a silicon-auto-doped p-type GaN epitaxial layer. First, p-GaN was grown on a (111)-oriented n-type silicon substrate by metal organic chemical vapor deposition (MOCVD) without the supply of any intentional dopant sources, yet with a high-temperature AlN buffer to induce tensile stress on the growth surface. The resulting 700 nm-thick p-GaN layer exhibited a hole concentration of 2.1×10^{17} cm^{-3} and hole mobility of 46 cm^2/Vs. The enhancement mode operation of the n-GaN SB-MISFET confirmed the p-type conduction of the GaN layer[7]. P-type conduction has already been explained as the preferred substitution of silicon into nitrogen sites due to tensile

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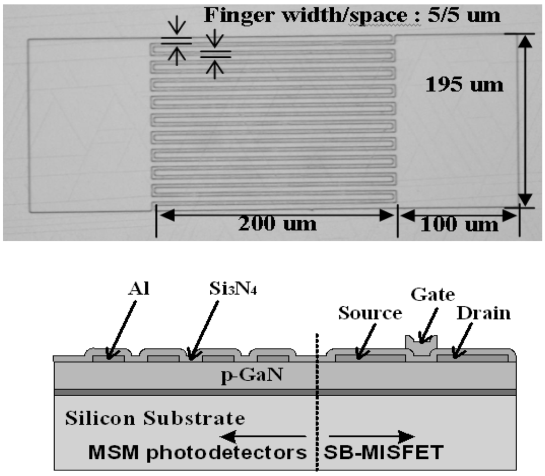

Fig. 1. Photomicrograph and schematic diagram of GaN MSM UV photodetector.

stress on the growth surface[8].

Fig. 1 shows a microphotograph (a) and schematic cross-sectional view (b) of the fabricated GaN MSM UV PD, which facilitates integration with an SB-MISFET based on gate metallization. The finger spacings and widths of the MSM PD ranged from 5 to 10 um, and the fabrication process flow is described below. The Schottky metal contacts were both formed on the p-GaN layer by depositing 500 Å-thick aluminum, then a 500 Å-thick Si_3N_4 layer was deposited on the p-GaN layer for passivation between the two electrodes using a plasma-enhanced chemical vapor deposition (PECVD) process at 300 °C. Thus, the high compatibility of an MSM PD with an SB-MISFET was confirmed as regards the fabrication process, as well as the p-GaN epitaxy on the silicon substrate. Furthermore, the source/drain of an SB-MISFET can be fabricated using the same Schottky metallization process as used for MSM, plus the gate dielectric of an SB-MISFET is the same as the passivation layer in an MSM PD. The electrical and optical properties of the MSM PDs were characterized using an HP4155 and optical set-up with a 150 W Xenon arc lamp.

3. Results and Discussion

Fig. 2(a) shows the statistical distribution of the dark current density of the fabricated MSM PDs with finger spaces and widths ranging from 5 to 10 μm. Over 90 percent of the 35 fabricated devices showed a dark current density of less than 3 nA/cm^2, which is very low compared to previous MSM or Schottky-type GaN PDs fabricated on n-GaN layers[3-6]. Fig. 2(b) shows the photocurrents of the MSM PDs that were measured under 340 nm wavelength UV light and 0.03 mW/cm^2 power. The photocurrents were enhanced by nearly five orders of magnitude compared to the dark current at a 5 V bias.

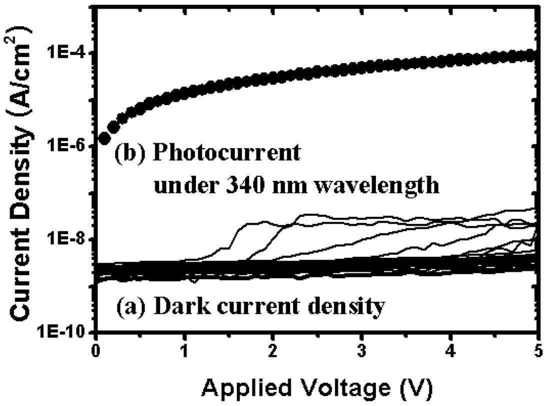

Fig. 2. Electrical properties of fabricated MSM photodetectors: (a) dark current densities of 35 MSM photodetectors and (b) I-V characteristics of MSM photodetector under 340 nm wavelength UV illumination.

The spectral responsivity of the fabricated p-GaN MSM PDs was also measured, as shown in Fig. 3, where the cutoff wavelength was about 365 nm. The UV responsivity was significantly enhanced by the

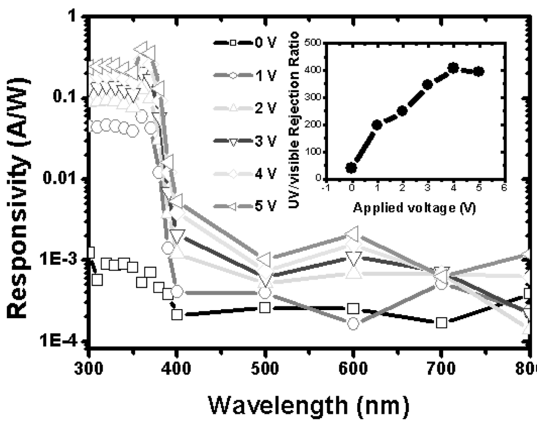

Fig. 3. Spectral responsivities according to bias conditions (inset is bias-dependent UV-to-visible rejection ratio).

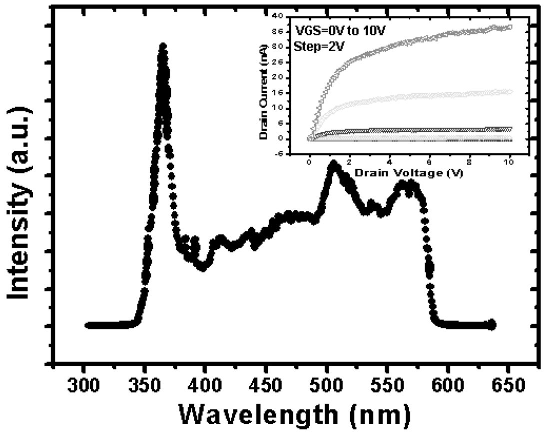

Fig. 4. Photoluminescence spectrum of p-type GaN epitaxial layer (inset is output characteristic of Schottky barrier MISFET).

applied biases, thereby enhancing the UV/visible rejection ratio from 10 to 400 under a 4 V bias, as shown in the inset. However, when considering the very low dark current mentioned above, the UV/visible rejection ratio was not high enough. The reason for this was because the visible wavelength responsivity was also increased due to absorption by sub-bandgaps, as implied by the photoluminescence spectrum of the p-type GaN layer used in this work, as shown in Fig. 4. The broad intensities above 365 nm were due to distributed mid-gap traps (Et), which originated from defects in the auto-doped p-GaN on the silicon substrate during the epitaxy process. Thus, to clarify the p-type conduction and evaluate the quality of the p-GaN layer, the output characteristics of an n-channel SB-MISFET fabricated on the same wafer is shown in the inset of Fig. 4, where the MISFET is in the enhancement mode operation by the channel inversion from p-GaN, yet the Id was only 0.3 μA/mm.

The low Id was mainly related to the quality of the Si_3N_4 gate dielectric and surface states of the p-GaN grown on the silicon substrate. The Si_3N_4 film available in this group has 7.5×10^12 cm^{-2} interface state density. The surface states of GaN epitaxial layer also has a variation in surface morphology. Therefore, if the epitaxial p-GaN film quality is improved and a high-quality dielectric film adopted, the characteristics of both the MISFET and the MSM PD will be greatly improved. Finally, an integrated UV image sensor system in the form of an active pixel sensor (APS), with four SB-

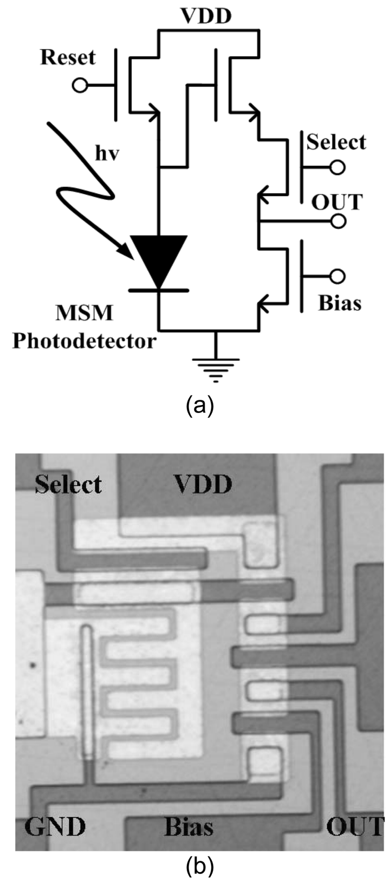

Fig. 5. Circuit schematic (a) and surface microphotograph (b) of fabricated active pixel sensor (APS) consisting of MSM photodetector integrated with four n-channel GaN MISFETs

MISFETs and one MSM PD, was implemented, as shown in Fig. 5(a). The active pixel operation will be presented later.

4. Conclusions

An MSM UV PD was fabricated on p-GaN grown on a silicon substrate. The resulting dark current density was 3 nA/cm^2 and the UV/visible ratio was 400 for a 4 V bias. However, the wavelength selectivity was limited by an increased visible responsivity due to mid-gap traps in the GaN layer. Therefore, optimizing the GaN growth and gate dielectric process will significantly improve the characteristics of the MSM PD, as well as the n-MISFET, while also facilitating the implementation of UV imaging systems.

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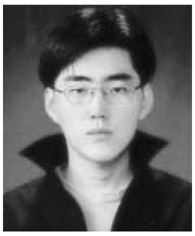

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