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The effect of the dielectric SiO_2 layer on the characteristics of visible-blind ultraviolet photodetectors based on ultrathin GaN epitaxial layers grown on c-Al_2O_3 substrates

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Abstract. In this work ultraviolet metal-semiconductor-metal and metal-insulator-semiconductor photodetectors based on GaN epitaxial layers were fabricated. N-polar GaN epitaxial layers were synthesized by plasma-assisted molecular beam epitaxy on nitrided sapphire substrates. To form Schottky barrier contacts a Ni/Au metallization was chosen. SiO_2 layers were deposited by plasma enhanced chemical vapor deposition. I—V characteristics of fabricated photodetectors were studied. It was found that the dark current of the photodetectors decreased by 49 times after introducing a 20 nm thick SiO_2 dielectric layer, and the photocurrent to dark current ratio increased by a maximum of 35 times.

Keywords: GaN, SiO_2, ultraviolet photodetector, metal-semiconductor-metal, metal-insulator-semiconductor

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Материалы конференции
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Влияние диэлектрического слоя SiO_2 на характеристики видимо-слепых ультрафиолетовых фотодетекторов на основе ультратонких эпитаксиальных слоев GaN, выращенных на подложках c-Al_2O_3

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Аннотация. В данной работе были изготовлены ультрафиолетовые фотодетекторы металл-полупроводник-металл и металл-диэлектрик-полупроводник на основе эпитаксиальных слоев GaN, и исследованы их вольт-амперные характеристики. Было обнаружено, что темновой ток фотодетекторов уменьшился в 49 раз после введения диэлектрического слоя SiO_2 толщиной 20 нм, а отношение фототока к темновому току увеличилось максимум в 35 раз.

Ключевые слова: GaN, SiO_2, ультрафиолетовый фотодетектор, металл-полупроводник-металл, металл-диэлектрик-полупроводник

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Introduction

Nowadays visible-blind and solar-blind ultraviolet photodetectors (UV PDs) are in demand for a wide range of commercial applications such as flame detection for fire alarms, engine control, environmental monitoring, UV calibration and detection of toxic substances [1–3].

One of the most promising materials for the fabrication of semiconductor UV PDs is (Al)GaN. The bandgap width of (Al)GaN can be varied between 3.4 and 6.2 eV depending on the composition, corresponding to the wavelength range of 365 to 200 nm, respectively [4]. In addition, the great mechanical, thermal and chemical stability of these semiconductors gives the potential for stable operation of the devices based on them in harsh environments [5].

There are several basic types of UV PD structure designs, among which metal-semiconductor-metal (MSM) PDs attract great attention owing to the ease of fabrication, low intrinsic capacitance, high response speed, and low noise level [6]. At the same time, due to the high dislocation density in GaN epitaxial layers, MSM PDs based on them suffer from high dark current, as it was shown in our previous work [7]. The use of SiO_2 layer (i.e., the conversion of MSM PDs to metal-insulator-semiconductor (MIS) PDs) can provide semiconductor surface passivation to reduce the dark current [8]. In this work, the devices of both types were fabricated and their characteristics were studied and compared.

Materials and Methods

In this work the two-dimensional 2D GaN epitaxial layers with thickness not exceeding 150–200 nm were grown by plasma-assisted molecular beam epitaxy (PA MBE) on annealed and nitrided c-Al_2O_3 substrates using Veeco GEN 200 MBE system. The surface morphology of the synthesized samples was analyzed using a scanning electron microscope (SEM) Supra 25 Zeiss. Crystallographic polarity was determined by etching for 5 minutes in aqueous KOH solution (1:5) heated up to 40 °C. The conductivity type, concentration and mobility of charge carriers in GaN epitaxial layers were determined by Hall effect measurements based on the Van der Pauw four-point probe method using the Ecopia HMS-3000 system.

Then, the MSM PDs as well as MIS PDs using a 10 and 20 nm thick SiO_2 layer were fabricated. SiO_2 layers were deposited by plasma enhanced chemical vapor deposition using Oxford PlasmaLab System 100. Ni/Au (15/15 nm) interdigitated electrodes were formed by e-beam evaporation, resistive thermal evaporation and standard lift-off lithography. The I-V characteristics of the formed PDs were measured in the dark and under 365 nm UV light-emitting diode (LED) illumination using an Agilent B1500A semiconductor device parameter analyzer.

Results and Discussion

The characteristic SEM images of GaN/c-Al_2O_3 epitaxial structure are shown in Fig. 1. It can be seen that the ultrathin GaN layer grown on sapphire substrate has a relatively smooth surface with a high density of V-defects, which arise, for the most part, due to a strong lattice mismatch between the GaN layer and substrate. In this case the nucleation of GaN by a Volmer-Weber

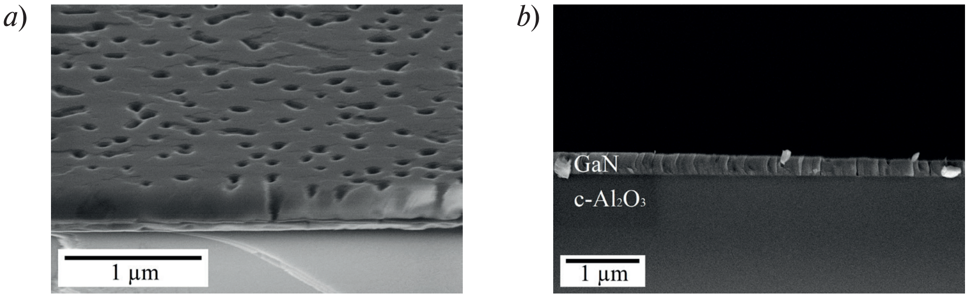

Fig. 1. SEM image of the GaN/c-Al_2O_3 epitaxial structure: isometry (*a*) and cross-section (*b*)

growth mode [9] may be caused by the presence of the elastic stress, which arises from the large lattice mismatch between GaN and c-Al_2O_3 (about 16% [10]).

As it was mentioned above, crystallographic polarity of the GaN layers was determined by etching in KOH solution. Fig. 2 shows the SEM image of the plan view of GaN/c-Al_2O_3 epitaxial structure after etching in KOH for 5 minutes. It can be clearly seen that the epitaxial layer of GaN is N-polar, as the etching in alkali resulted in the formation of a characteristic relief of hexagonal pyramids on the sample surface.

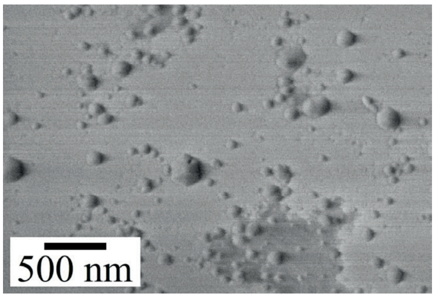

Fig. 2. SEM image of the plan view of GaN/c-Al_2O_3 epitaxial structure after etching in KOH

In addition, it was determined by the Hall effect measurements that undoped GaN epitaxial layer has n-type conductivity, which is typical for III-nitrides [11, 12]. The concentration of charge carriers was about $n \approx 1 \cdot 10^{18}$ cm^{-3} and the mobility about $\mu \approx 25$ cm^2/(V·s). This value of charge carrier concentration can be related to the presence of deep defect levels [11]. However, up to now there is no consensus on which type of defects or impurities in GaN epitaxial layers makes the main contribution in electronic type of conductivity [12]. The obtained value of carrier mobility is below the typical value for ultrathin GaN epitaxial layers at room temperature [5]. This may be due to the fact that the ultrathin GaN epitaxial layer grown on sapphire substrate has larger defect density near the GaN/substrate heterointerface.

The image of the fabricated PDs is shown in Fig. 3, *a*. The analysis of the I-V characteristics of the formed photosensitive elements showed that the introduction of a 10 nm and 20 nm thick dielectric layer led to decrease in the dark current (I_d) by almost 25 and 49 times respectively at an applied bias of 3 V (Fig. 3, *b*).

The reduced dark current for MIS PDs can be explained by the role of the dielectric layer as a passivation layer, which isolates surface defects thus decreasing the recombination events occurring at the metal-semiconductor interface during light illumination [13]. In addition, by using an insulating SiO_2 layer, a greater height and width of the potential barrier at the metal-semiconductor interface can be achieved, which can lead to a lower dark current and higher breakdown voltage [8, 14]. In this work the potential barrier height and ideality factor was calculated by Rhoderick's method [15]. It was found that the MIS structure has a higher potential barrier when the MSM structure (Table), as expected. It can also be seen from the table that the calculated values of the ideality factor are greater than 1, which may indicate a high inhomogeneity of the contact coating.

It is worth noting that by introducing a dielectric layer, the photocurrent decreases as well, which also noted in the [13]. However, the photocurrent to dark current ratio (I_{ph}/I_d) increases. It was found that the maximum I_{ph}/I_d for MSM PDs was 2.5. At the same time, the use of a 10 and 20 nm thick SiO_2 layer resulted in an increase in this ratio to a maximum of 4 and 35 respectively (Fig. 3, *c*).

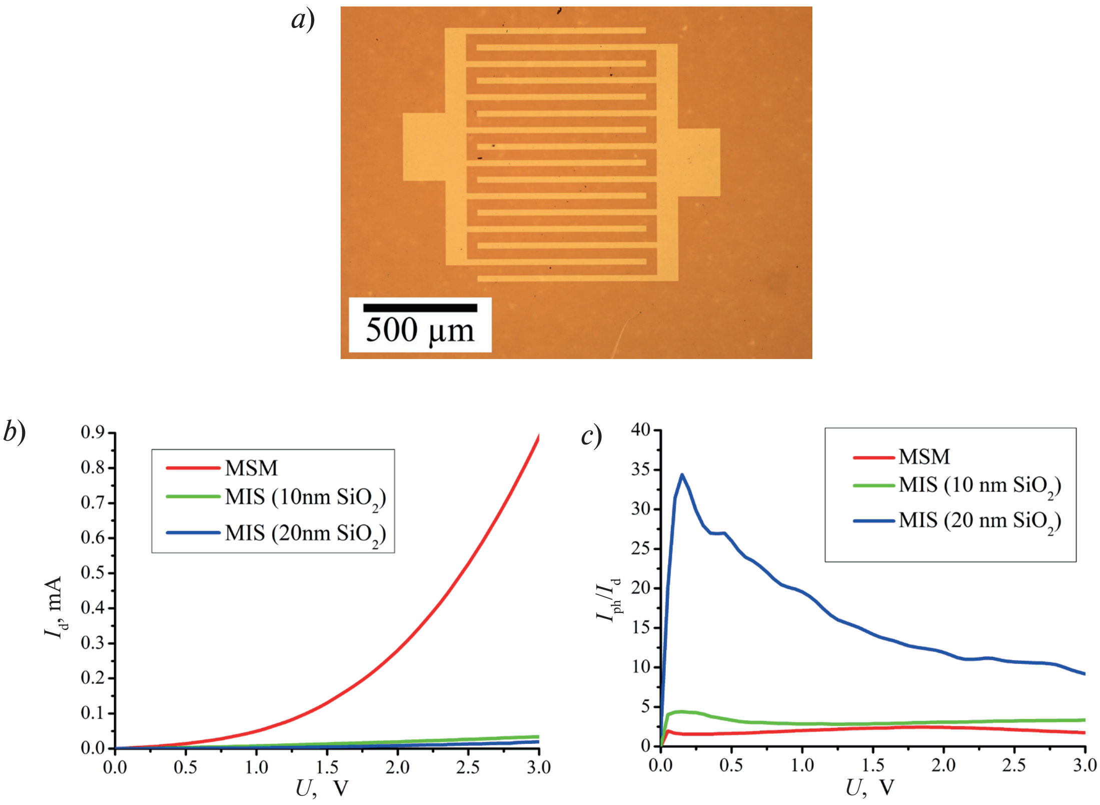

Fig. 3. Photomicrograph of metal electrodes (*a*), dark current (*b*) and photocurrent to dark current ratio (*c*) of the obtained PDs

Table

Photovoltaic characteristics of the solar cells based on black silicon

Structure	Ideality factor	Height of the potential barrier, eV
MSM	2.76	1.11
MIS (10 nm SiO_2)	2.56	1.14
MIS (20 nm SiO_2)	2.30	1.26

Thus, the results obtained in this work have confirmed that the introduction of a SiO_2 layer in PDs based on GaN ultrathin epitaxial layers can increase the potential barrier, which in turn reduces the dark current of these devices and therefore increases their sensitivity.

Conclusion

In this work ultrathin GaN epitaxial layers were synthesized by PA MBE. Their morphology, crystallographic polarity, and electrophysical characteristics were investigated. These ultrathin GaN epitaxial layers were used to fabricate MSM and MIS PDs. It was shown that MIS PDs based on ultrathin GaN epitaxial layers have a lower dark current and a higher photocurrent to dark current ratio compared to MSM PDs based on the same epitaxial structures. Thus, the introduction of a dielectric layer can be a promising approach to increase the sensitivity of the UV PDs based on ultrathin GaN epitaxial layers. The results obtained in this work can be used to develop and improve the technology for fabrication of UV PDs based on GaN epitaxial layers. In addition, the technology for producing GaN-based PDs is the foundation for the development of technology for producing solar-blind AlGaN-based PDs.

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