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Development of visible-blind ultraviolet photodetectors based on ultrathin GaN epitaxial layers grown on c-Al_2O_3 substrates

O. A. Sinitskaya [1]✉, K. Yu. Shubina [1], D. V. Mokhov [1], A. V. Uvarov [1], V. V. Filatov [1], A. M. Mizerov [1], S. N. Timoshnev [1], E. V. Nikitina [1,2]

[1] Alferov University, St. Petersburg, Russia;

[2] Ioffe Institute, St. Petersburg, Russia

✉ olesia-sova@mail.ru

Abstract. In this work, the prototypes of visible-blind ultraviolet metal-semiconductor-metal photodetectors based on GaN epitaxial layers were implemented. For this purpose, ultrathin GaN epitaxial layers were synthesized by plasma assisted molecular beam epitaxy on sapphire substrates. The morphology and electrical properties of the obtained samples were studied. To form electric contacts with the Schottky barrier, an interdigitated electrode design with Ni/Au metallization was chosen and standard lift-off laser lithography procedure was used. It has been established that the formed photodetectors have the highest sensitivity to radiation with a wavelength of 350–360 nm. It was found that rapid thermal annealing of photodetector structures at a temperature of 500 °C made possible to reduce the dark current by a maximum of 30 times. In addition, it was shown that high temperature annealing led to the increase in Schottky barrier height and decrease in the ideality factor. Thus, it was confirmed that use rapid thermal annealing method can improve the characteristics of metal-semiconductor-metal visible-blind ultraviolet photodetectors based on GaN.

Keywords: GaN, molecular beam epitaxy, ultraviolet range, photodetector, metal-semiconductor-metal, annealing

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Материалы конференции
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Разработка видимослепых ультрафиолетовых фотодетекторов на основе ультратонких эпитаксиальных слоев GaN выращенных на подложках c-Al_2O_3

О. А. Синицкая [1]✉, К. Ю. Шубина [1], Д. В. Мохов [1], А. В. Уваров [1], В. В. Филатов [1], А. М. Мизеров [1], С. Н. Тимошнев [1], Е. В. Никитина [1,2]

[1] Санкт-Петербургский национальный исследовательский Академический университет имени Ж. И. Алферова Российской академии наук, Санкт-Петербург, Россия;

[2] Физико-технический институт имени А. Ф. Иоффе, Санкт-Петербург, Россия
✉ olesia-sova@mail.ru

Аннотация. В данной работе были изготовлены прототипы видимослепых ультрафиолетовых фотодетекторов конструкции металл-полупроводник-металл (МРМ) на основе эпитаксиальных слоев GaN, которые были синтезированы методом молекулярно-пучковой эпитаксии с плазменной активацией азота на сапфировых подложках. Для формирования контактов с барьером Шоттки была выбрана встречно-штыревая геометрия контактных площадок с металлизацией Ni/Au. Было показано, что сформированные фотодетекторы имеют максимальную чувствительность к излучению с длиной волны 350–360 нм. Было обнаружено, что быстрый термический отжиг структур со сформированными МПМ фотодетекторами при температуре 500 °С позволяет уменьшить темновой ток максимум в 30 раз. Кроме того, было показано, что высокотемпературный отжиг привел к увеличению высоты барьера Шоттки и уменьшению коэффициента неидеальности. Таким образом, было продемонстрировано, что данный метод может использоваться для улучшения характеристик видимослепых ультрафиолетовых фотодетекторов типа металл-полупроводник-металл на основе GaN.

Ключевые слова: GaN, молекулярно-пучковая эпитаксия, ультрафиолетовый диапазон, фотодетектор, металл-полупроводник-металл, отжиг

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Introduction

In recent years, the development of visible-blind ultraviolet (UV) photodetector (PD) technology has sparked interest in generating innovative ideas to improve these devices and create efficient visible-blind UV PDs. There is a wide range of UV PD applications. These devices are used in environmental, industrial, military, biological and medical fields [1]. One of the most popular PD designs is metal-semiconductor-metal (MSM) structure due to the ease of fabrication, low noise level and high detection capability [2]. UV PDs can be fabricated based on various semiconductor materials, such as Si, SiC, ZnO and others. Among them, wide bandgap semiconductors, especially (Al,Ga)N, are one of the most prospective materials for this purpose. The advantages of (Al,Ga)N are: a wide band gap corresponding to the UV spectral range (Eg ~ 3.4 – 6.2 eV), high mobility of charge carriers, high breakdown voltage, as well as excellent mechanical, thermal and chemical stability [3]. In this work, the prototypes of MSM UV photodetectors based on epitaxially grown on c-Al_2O_3 substrates undoped GaN layers were developed and their characteristics were studied.

Materials and Methods

The 300 nm thick GaN layers were grown by plasma-assisted molecular-beam epitaxy (PA MBE) using Veeco GEN 200 industrial type MBE setup on annealed and nitrided c-Al_2O_3 substrates. The morphology of synthesized GaN epitaxial layers was studied using scanning electron microscope (SEM) (see Fig. 1, *a*, *b*). Using Hall measurements, it was found that the undoped GaN epitaxial layers have n-type conductivity, which is typical for III-N materials [4, 5], with a carrier concentration of $n \sim 1.5\times10^{18}$ cm^{-3} and mobility of $\mu \sim 40$ $cm^2/(V\times s)$.

The MSM structure with semitransparent Ni/Au (15 nm thick) interdigitated electrodes (see Fig. 1, *c*) was formed using standard laser lithography technique, e-beam and thermal vacuum evaporation, and standard lift-off process. The Ni/Au contact metallization was chosen because of its low ideality factor, large Schottky barrier height (SBH, 1.04 eV [6]), and simple fabrication process.

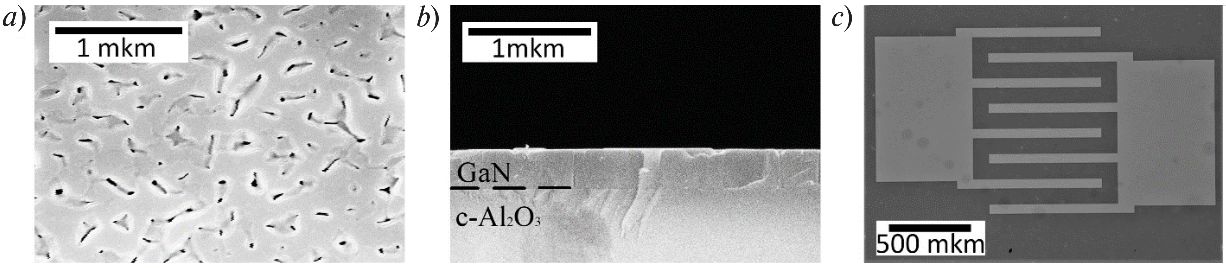

Fig. 1. SEM image of the GaN/c-Al_2O_3 epitaxial structure: plan view (*a*) and cross-section (*b*), photomicrograph of metal electrodes (*c*)

Results and Discussion

The UV PD I—V characteristics were obtained both in the dark, under visible range and 365 nm UV LED illumination (see Fig. 2, *a*). As can be seen, the I—V curves almost coincided for the measurements in dark and under normal illumination. Thus, visible radiation indeed has little effect on the operation of the fabricated UV PD. The appearance of additional photocurrent was observed under 365 nm LED illumination. At the same time, as can be seen from spectral characteristic (Fig. 2, *b*) the highest photoresponse was observed at wavelength range of 350—60 nm, that corresponds to GaN bandgap (3.4 eV) and confirms the reliability of the obtained I-V curves. However, as can be seen from Fig. 2, *a*, obtained photodetectors have a high dark current (6 mA at a bias of 2 V). It can be explained by both high dislocation density in the ultrathin epitaxial GaN layer grown on mismatched c-Al_2O_3 substrate and imperfection of contact formation procedure. It can be noted, that the dark current largely determines the sensitivity of the photodetector and depends on the parameters of the Schottky barrier [7]. In a number of works, photodetectors based on GaN with Ni/Au contacts were subjected to high-temperature annealing (400—700 °C) [8—12], which led to an increase in the height of the Schottky barrier, as well as to a decrease in the level of dark current. Therefore, it was decided to carry out a series of experiments with rapid thermal annealing (RTA) of the samples using Jipelec Jetfirst 100 system. PDs based on GaN/c-Al_2O_3 epitaxial structures were annealed for 90 seconds at 400, 500 and 600 °C in the N_2 atmosphere. As expected, this resulted in a decrease in the dark current (see Fig. 3, *a*). It was found that the smallest dark current and the highest I_{ph}/I_d ratio consequently (see Fig. 3, *b*) was achieved with annealing temperature of 500 °C.

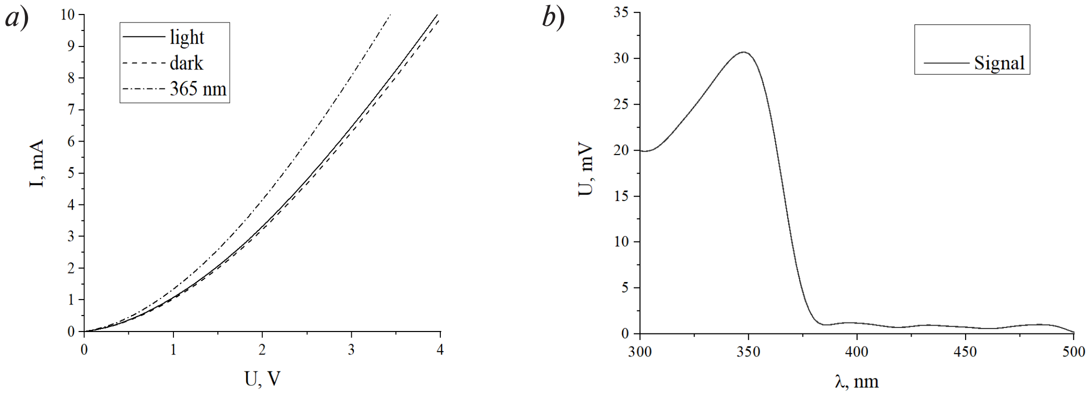

Fig. 2. I—V characteristics (*a*) and spectral response (*b*) of the formed PDs based on GaN/c-Al_2O_3

At the same time, as can be seen from Fig. 3, *a*, after annealing of PD structures at 600 °C, the dark current increased compared to the sample annealed at 500 °C. It can be the result of mixing Ni and Au or the Ga-Ni intermetallic formation [15—17]. Moreover, the SEM studies of the samples after annealing showed that the annealing at 600 °C leads to the formation of metal islands in the contact pad area (Fig. 3, *c, d*). Such phenomenon is usually observed at the interface between thin metal films and ceramics [18]. This can be explained by the fact that ceramics has very low surface energy, while the metal is quite high. To minimize the total surface energy of the system, the metal is collected in droplets to minimize the surface area and expose a large area of the ceramic surface. From this we can conclude that GaN has low surface energy, as also reported in the literature [18].

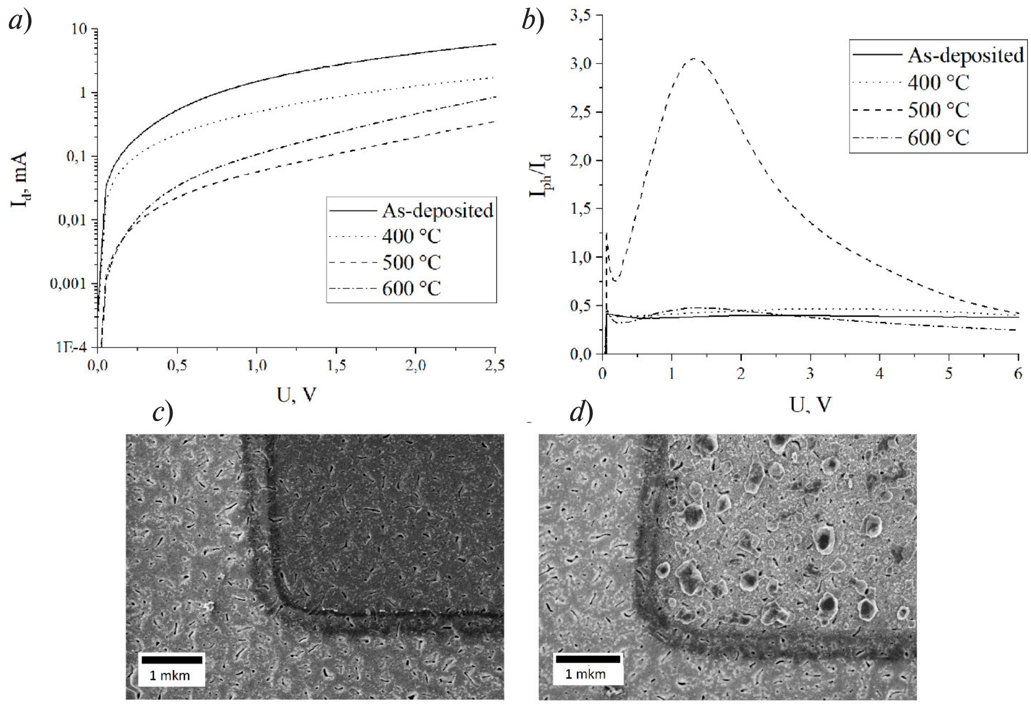

Fig. 3. Dark current of the obtained PDs before and after annealing at different temperatures (*a*), SEM image of the contact Ni/Au before (*b*) and after annealing (*c*)

From the I–V data for annealed and non-annealed samples, the ideality factor and the height of the Schottky barrier were determined by the Rhoderick method (Table 1) [19]. It was found that RTA actually led to an increase in the height of the Schottky barrier. An increase in the height of the Schottky barrier at higher annealing temperatures may be associated with the interfacial reactions between the metals and the semiconductor and phase transition [9]. In addition, RTA can lead to the accumulation of Ga vacancies near the metal/GaN interface which can contribute to an increase in the height of the Schottky barrier [8]. The last always corresponds to a decrease in the reverse leakage current [13, 14].

Table 1

Calculated ideality factor and height of the Schottky barrier of Ni/Au contacts for the obtained PDs

Annealing temperature, °C	Ideality factor	Height of the Schottky barrier, eV
Without annealing	2.8	0.85
400	2.7	0.88
500	2.2	1.12
600	2.1	1.16

According to the results of the study, it was found that RTA leads to a decrease in a dark current (by a maximum of 30 times). Nevertheless, its value remains relatively high. To further reduce the dark current, it is necessary to improve the crystalline quality of GaN and reduce the dislocation density in the epitaxial layers, for example, by use of various buffer layers or different types of templates for epitaxial growth of ultrathin GaN layers (SiC/substrate, GaN/substrate etc.). At the same time, the use of dielectric surface passivation (with SiO_2, Al_2O_3, etc.) and mesa etching also can provide the improvement of the characteristics of the proposed MSM PDs (including significant dark current reduce) and requires further investigation.

Conclusion

In this work, it was shown that wide-bandgap semiconductors (Al)GaN are promising materials for the creation of UV PDs due to their insensitivity to visible spectrum and sunlight, as well as high mobility of the charge carriers, and high resistance to harsh environments. UV MSM PDs were implemented based on the ultrathin GaN epitaxial layers synthesized by the PA MBE. Interdigitated semitransparent Ni/Au Schottky contacts were formed. It was found that the RTA of the MSM PD structures at a temperature of 500 °C allows to reduce the dark current by a maximum of 30 times and to achieve significant increase in I_{ph}/I_d ratio. In addition, it was shown that high temperature annealing led to the increase in Schottky barrier height and decrease in the ideality factor. Thus, RTA can be used to improve the characteristics of the PD. However, the level of dark current in comparison with the photocurrent remains quite high. Therefore, it is necessary to improve the technology of the epitaxial synthesis of the III-N layers, as well as to use additional post-growth methods, such as the mesa structures etching and the use of surface passivation coatings.

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THE AUTHORS

SINITSKAYA Olesya A.
olesia-sova@mail.ru
ORCID: 0000-0001-6561-0334

SHUBINA Kseniia Yu.
rein.raus.2010@gmail.com
ORCID: 0000-0003-1835-1629

MOKHOV Dmitry V.
mokhov@spbau.ru
ORCID: 0000-0002-7201-0713

UVAROV Alexander V.
lumenlight@mail.ru
ORCID: 0000-0002-0061-6687

FILATOV Vladimir V.
filatovbigfan@icloud.com
ORCID: 0000-0002-7495-1269

MIZEROV Andrey M.
andreymizerov@rambler.ru
ORCID: 0000-0002-9125-6452

TIMOSHNEV Sergey N.
timoshnev@mail.ru
ORCID: 0000-0002-9294-3342

NIKITINA Ekaterina V.
mail.nikitina@mail.ru
ORCID: 0000-0002-6800-9218

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