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Fabrication and investigation of UV photodiode based on *n*-GaN / *p*-NiO heterojunction

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Abstract. This paper presents the experimental results of the study of *n*-GaN/*p*-NiO heterojunction for application as a selective UV photodetector. Synthesis of *n*-type GaN layers was carried out by plasma-assisted molecular beam epitaxy (PA MBE) on GaN/c-Al_2O_3 template substrates. The *p*-type layers were formed by reactive DC magnetron sputtering of NiO films followed by annealing. Post-annealing in an oxygen atmosphere at a temperature of 550 °C was used to improve the crystallinity of the deposited NiO films. The optical and electrical characteristics of individual semiconductor layers and *n*-GaN/*p*-NiO diode structure were studied. Photoluminescence spectra of GaN layers showed the presence of a narrow peak near 3.43 eV. The optical band gap of the NiO layers, determined by the edge of optical absorption, was 3.35 eV. The study of the *n*-GaN/*p*-NiO heterojunction current-voltage characteristics under light and dark conditions showed the selective sensitivity of the diode structure to UV radiation. Furthermore, the manufactured structure demonstrated the behavior of a self-powered photodiode. At a wavelength of 365 nm, the detectivity of the photodiode was $6.8 \cdot 10^9$ Jones and the photoresponsivity was 3.64 mA/W.

Keywords: UV photodiode, gallium nitride, oxide semiconductors, DC magnetron sputtering, molecular beam epitaxy

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Изготовление и исследование УФ – фотодиода на основе гетероперехода *n*-GaN/*p*-NiO

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Аннотация. В данной работе представлены экспериментальные результаты исследования гетероперехода *n*-GaN/*p*-NiO для УФ фотодиода. Синтез монокристаллических пленок нитрида галлия *n*-типа проводимости осуществлялся методом молекулярно-лучевой эпитаксии с плазменной активацией азотом на темплатных подложках GaN/c-Al_2O_3. Слои p-типа проводимости формировались методом реактивного магнетронного напыления на постоянном токе пленок полупроводникового оксида никеля. Последующий отжиг в кислородной среде при 550 °C использовался для улучшения кристалличности осажденных пленок NiO. Проведены исследования оптических и электрических характеристик отдельных полупроводниковых слоев и диодных структур на их основе. Спектральная зависимость фотолюминесценции GaN показала наличие узкого пика в области энергии 3.43 эВ. Оптическая ширина запрещенной зоны NiO, измеренная по краю оптического поглощения, составила 3.35 эВ. Исследование вольт-амперных характеристик *n*-GaN/*p*-NiO гетероперехода при его облучении светом в видимой и ультрафиолетовой области спектра показало избирательную чувствительность фотодиодной структуры к УФ излучению. При этом изготовленная структура продемонстрировала работу в режиме фотоэлемента. На длине волны 365 нм удельная обнаружительная способность гетероструктуры составила $6.8 \cdot 10^9$ см·Гц$^{0.5}$·Вт$^{-1}$, а величина фоточувствительности составила 3.64 мА/Вт.

Ключевые слова: УФ-фотодиод, нитрид галлия, оксидные полупроводники, магнетронное напыление на постоянном токе, молекулярно-лучевая эпитаксия

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Introduction

Improvement in technologies for the epitaxial growth of gallium nitride (GaN) contributed to the successful application of this material in high-frequency electronics and optoelectronic devices, such as light-emitting diodes and lasers [1, 2]. In addition, the high band gap of GaN makes this material promising for the development of selective UV photodetectors (wavelength $\lambda < 400$ nm). To create such devices, various photodiode structures based on homo- or heterojunctions can be used [3, 4]. However, due to numerous technological difficulties that arise during the synthesis of high-quality *p*-type GaN epitaxial layers [5], the use of homojunctions for UV photodiodes is less preferable compared to heterojunctions based on *n*-type GaN and another wide-gap *p*-type semiconductor. Among various *p*-type materials, nickel oxide (NiO) is most compatible with GaN in terms of such parameters as band gap and lattice parameter [6]. In addition, NiO is a direct gap semiconductor, has excellent chemical stability, and is easy to deposit with current microelectronics technologies. Therefore, the *n*-GaN/*p*-NiO heterostructure can be used in the future to create cheap and efficient UV photodiodes.

In this work, we analyze the possibility of creating a selective UV photodetector based on the *n*-GaN/*p*-NiO heterojunction.

Materials and Methods

The design of the manufactured photosensitive sample is a planar structure with layers of GaN and NiO, which form a heterojunction, and metal layers, which form contact pads. Figure 1 shows the test sample design and the stages of fabrication process.

The synthesis of GaN layers was carried out on a Veeco Gen 200 industrial equipment by the PA MBE method [7]. The growth of the epitaxial layer was carried out on GaN/c-Al_2O_3 template substrates, where 2 μm thick GaN sublayer was obtained by metal-organic vapor phase epitaxy. The subsequent growth of Si-doped GaN layers was carried out at constant substrate temperatures T_s = 700°C, a gallium flow of ~0.25 μm/h, and an activated nitrogen flow of ~0.05 μm/h. The silicon doping used in the experiments made it possible to obtain an electron concentration in the GaN layers of $\sim 3.7 \times 10^{18}$ cm^{-2}.

The formation of NiO films was carried out using DC magnetron sputtering from a nickel target Ni (99.95%) in a mixture of working gases 30% O_2 / 70% Ar at a working pressure of 3 mTorr and magnetron power of 100 W. The deposition was carried out both on the surface of

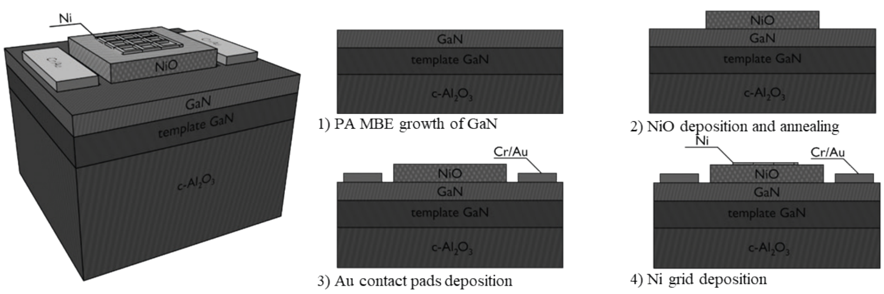

Fig. 1. Design and process flow of *n*-GaN/*p*-NiO photodetector

the GaN epitaxial film and on the glass (Corning 0211) for optical and electrical measurements of the obtained layer. Film thicknesses were determined using an Ambios XP-1 contact profilometer. Subsequent annealing of the NiO films at a temperature of 550°C and duration of 60 min was applied to improve the films quality, increase the resistivity and optical transmission of the films.

To form non-rectifying (ohmic) contacts, Cr/Au and Ni layers were used for contact to GaN and NiO, respectively. Contact metallization to the NiO layer was made in the form of a grid structure with an aperture of 3 mm, where the width of the grid band was 5 μm with a period of 100 μm.

In this work, optical transmission and reflection spectra of GaN and NiO layers were obtained using an AvaSpec-ULS2048XL-EVO-RS spectrometer and a xenon radiation source. The photoluminescence (PL) spectra of the structures were measured using an Accent RPM Sigma setup with 266 nm lasers. Based on the measurement results, the values of the optical band gap for semiconductor layers were obtained.

Measurement of dark and light current-voltage characteristics was carried out using a halogen radiation source and UV LEDs with a wavelength of 365 nm. The power density of the incident light of the UV LEDs (365 nm) was 2.3 mW.

Results and Discussion

The thickness of the high-doped epitaxial GaN layers, measured using scanning electron microscopy, was about 300 nm. A detailed study of the morphology of the surface, composition and inner structure of the synthesized GaN layers is given in the article [7]. The epitaxial GaN layers on a sapphire substrate had a high transparency in the visible part of the spectrum, more than 90%. However, the spectral characteristics in the UV region showed a sharp drop in transmittance at a wavelength of 400 nm. This drop in transmission is probably due to the absorption of radiation by the substrate, which does not allow measurements to be made near the edge of GaN optical absorption. Figure 2, *a* shows the results of measuring the photoluminescence spectra of the synthesized layers. The main peak of photoluminescence lies near the energy of 3.43 eV and has an FWHM equal to 0.097 eV, as shown in the inset in figure 2, *a*.

The thickness of the NiO layer was about 300 nm. The as-deposited NiO films had high conductivity and low transparency. The resistivity of the film was 0.04 Ω·cm. At the same time, the optical transmission of the film did not exceed 5%, as shown in figure 2, *b*. Subsequent annealing of the films at a temperature of 550°C and duration of 60 min led to an increase in the resistivity and optical transmission of the film. Figure 2, *b* shows that after annealing, the transmission of the film increased to 80% and has a sharp absorption edge. The optical band gap of NiO was 3.35 eV, as shown in the inset in figure 2, *b*. The value of film resistivity after annealing was 1460 Ω·cm. An increase in the transparency and resistivity of NiO films after high-temperature annealing is due to a decrease in the concentration of intrinsic defects, which play the role of an acceptor impurity (nickel vacancies and interstitial oxygen atoms).

The current-voltage characteristics of *n*-GaN/*p*-NiO heterojunctions had the form of typical diode dependences, as shown in figure 3. Exposure of the samples to radiation in the visible region of the spectrum did not lead to a change in electrical characteristics. However, when the samples were irradiated with an LED with a wavelength of 365 nm, a shift of the I-V characteristic due to the occurrence of a photocurrent was recorded. Furthermore, the *n*-GaN/*p*-NiO heterojunction demonstrated the behavior of a self-powered photodiode. The dark current and photocurrent

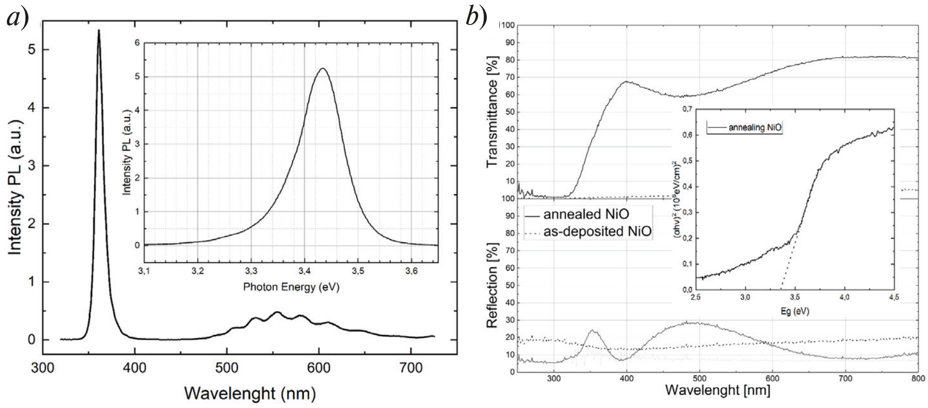

Fig. 2. Photoluminescence spectra of GaN (*a*); NiO optical transmittance, reflection spectra and (*inset*) the plot of $(\alpha h\nu)^2$ versus photon energy $h\nu$ (*b*)

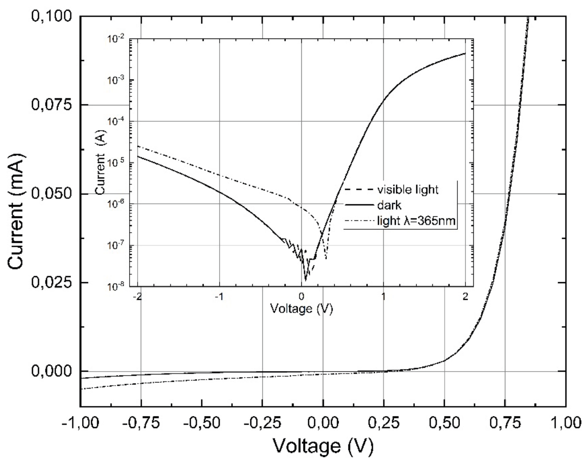

Fig. 3. I-V plot of the NiO/GaN photodetector on a linear scale and (*inset*) on a semi-log scale

were 0.08 μA and 0.84 μA, respectively. Open-circuit voltage was 0.29 V. (It is worth noting that even in the dark condition, a slight open-circuit voltage was also observed. Its value was about 0.05 V and changed slightly for different samples, which may be due to the presence of a built-in charge at the boundary of the GaN and NiO layers or the excess of the depletion region width over the NiO layer thickness.)

To quantify the sensitivity of our UV PDs compared to other ones, we used parameters such as photoresponsivity and detectivity. Photoresponsivity is defined as the photocurrent generated per unit power of incident light on the effective area of a photodiode. Detectivity (D*) of a UV PD is another parameter, meaning its ability to detect weak signals from noise environment. Both of these parameters can be calculated as in the article [8]. The photoresponsivity of the fabricated *n*-GaN/*p*-NiO photodetector at zero voltage was 3.64 mA/W, its detectivity was $6.8 \cdot 10^9$ Jones.

Conclusion

In summary, we fabricated self-powered photodetector based on *n*-GaN/*p*-NiO heterojunction structure on c-Al_2O_3 substrate. The photodetector exhibits a responsivity of 3.64 mA/W and detectivity of $6.8 \cdot 10^9$ Jones, when exposed to a light with a wavelength of 365 nm at zero voltage. The NiO film as a p-type semiconductor layer for GaN-based diode was synthesized by a simple, scalable, and low-cost method. The study of the diode current-voltage characteristics under light and dark conditions showed the selective sensitivity of the diode structure to UV radiation. These results demonstrate the high quality of NiO/GaN heterojunction diodes and its great potential for future GaN based power electronics.

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