Influence of interface layer preparation on the electrical and spectral characteristics of GaN/Si solar cells

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Abstract. Volt-ampere and spectral characteristics of GaN/Si solar cell samples differing in interface layer preparation are obtained and analyzed. External quantum efficiency curves are experimentally determined via excitation with a 532 nm incident radiation wavelength. It is demonstrated that interface preparation has a significant influence on photovoltaic characteristics of the studied samples.

1. Introduction

The amount of electricity being annually consumed constantly increases with time. Since the main energy resources are currently exhaustible, there is a severe need for the development of alternative energy sources, and solar energy conversion is known to be the most promising approach. The development of photovoltaic devices is usually realized through improvement of the characteristics and efficiency of photoconverters (solar cells). The most effective solar radiation converters at the moment are multijunction cells based on A\textsubscript{II}B\textsubscript{V} [1] compounds, which have several advantages over other compounds due to a combination of crucial properties. Today, particular attention is focused on compounds of the A\textsubscript{III}N type. It is related to good electronic, structural and other properties of these materials [2].

First of all, most A\textsubscript{III}N compounds are wide-band semiconductors with high electron mobility [3], which allows to use them in solar cells (SCs) as a wide-gap window, and as a material for an antireflection coating to improve SC efficiency through light absorption enhancement. Secondly, Group III nitrides such as GaN are capable of operating at higher temperatures [3] compared to other compounds. As a consequence, this material can be used in the development of cost-effective photoconverters with solar concentrators. Thirdly, on an industrial scale, the devices based on A\textsubscript{III}N compounds on silicon substrates are economically more profitable than their nearest competitors.

The characteristics and efficiency of SCs are influenced by many factors, and among them interface layer passivating properties are important ones [4]. Characteristics of similar SCs can differ significantly due to distinctive interface preparation and, as a consequence, different surface recombination rates. For SCs based on indirect-band materials (silicon, germanium), recombination through surface states and volume recombination through impurity levels are the main limiting factors affecting the SC efficiency.
Our work is devoted to studying the electrical and spectral characteristics of SCs based on n-GaN / p-Si heterojunctions obtained with various types of interface layer preparation.

2. Experiment
Specially fabricated heterostructures based on arrays of n-GaN nanowires (NWs) grown on p-type silicon substrates using plasma-assisted molecular beam epitaxy were studied. The presence of an emitter layer in the form of an n-GaN NWs array is a distinctive feature of the SCs design. It is supposed to lead to an increase in the efficiency of silicon SCs and also to provide good antireflection properties without the use of expensive special multilayer antireflection coatings [5].

The synthesized heterostructures differed in the interface layer preparation process, which affects both the morphological properties of NWs (their diameter and density) and semiconductor properties of the heterointerface. There are three structure types considered in this paper. Structure 1 (sample 1): after thermal silicon oxide removal, the substrate was cooled down to a temperature of 810 °C (according to thermocouple measurements), and growth of NWs was initiated. Structure 2 (sample 2): after oxide removal, the hot substrate was treated with atomic nitrogen, cooled down to a temperature of 630 °C and exposed under gallium flow, and then the growth of NWs was initiated. Structure 3 (sample 3): before loading the substrate into a growth chamber, a GaO_x layer was deposited in a plasma-activated vapor deposition machine using the layer-by-layer deposition method, then the substrate was annealed at 850 °C under an atomic nitrogen flux, and NWs growth was initiated at a temperature of 800 °C.

At the next technological step, a back Al contact was fabricated on each of the synthesized GaN/Si heterostructures by thermal vacuum deposition of metals and further thermal annealing. Using various methods of post-growth treatment, a dielectric insulating layer was deposited over the emitter layer, while the tips of the NWs were left uncovered. Then a conductive transparent indium-tin oxide (ITO) coating was applied via magnetron sputtering. These heterostructures were used as the basis for fabricating solar photoconverters with a photoactive region in the form of a circular maze (2 mm in diameter).

Measurement of the current-voltage characteristics (I - V characteristics) was performed using a Keithley 2400 SourceMeter multimeter and a thermo-stabilized stage under illumination conditions of the AM 1.5G solar spectrum. The temperature was maintained at 25 °C during the measurements.

The spectral dependence of external quantum efficiency (EQE) was measured in the 350 – 1200 nm wavelength range using a M266 (Laser Solar) monochromator and a calibrated silicon photodiode with known spectral characteristics.

The study of EQE dependence on the incident radiation intensity was performed using a table with temperature stabilization over a wide intensity range from $10^2$ to $10^3$ mW/cm². The radiation source was a laser with a wavelength of 532 nm. A laser beam was transmitted through an aperture of 1 mm in diameter. The power of the laser beam applied to the photoactive region of the SCs was adjusted by a set of optical filters and was measured by a calibrated laser power meter PM100D (THORLABS).

3. Experimental results and discussion
The measured I - V characteristics of the SC samples with different interface layers are shown in figure 1(a). A distinguishable influence of the interface treatment on the SCs main characteristics, namely open-circuit voltage ($U_{oc}$) and short-circuit current ($I_{sc}$), was detected. Relatively low values of $U_{oc}$ and $I_{sc}$ are presumably related to an intensive radiative recombination process. By analyzing the difference between the light and dark I - V characteristics (figure 1 (b)) at large negative bias voltages, we can conclude that the dominant contribution to the recombination process is provided with surface recombination (on the substrate surface free of NWs and on the GaN/Si heterointerface).
Figure 1. Light $I$ - $V$ characteristics (a) and the difference between light and dark $I$ - $V$ characteristics (b).

Figure 2 shows dependencies of the EQE spectra of the studied SCs. It is clear that the method of preparation of the GaN/Si heterointerface has a significant influence on the spectral characteristics of the solar cell.

EQE was calculated using the following formula:

$$EQE = \frac{hc}{\lambda e} \cdot \frac{I}{P},$$

where $h$ is the Planck constant, $c$ is the speed of light in vacuum, $\lambda$ is the wavelength of the incident radiation, $e$ is the electron charge, $P$ is the power of the incident radiation, and $I$ is the current flowing through the solar cell under illumination.

Figure 2. Experimental spectral characteristics.
We assume that the characteristic oscillations of the EQE spectrum in the range from 400 to 900 nm in sample 3 are related to the presence of an NWs array with an optimal morphology providing antireflective properties.

The experimental results on the calculation of the EQE dependence on the incident radiation intensity for the SCs are shown in figure 3.

![EQE experimental dependence on incident radiation intensity with a wavelength of 532 nm.](image)

It was found that the EQE of sample 3 drops almost twofold from its maximum level at a light intensity of 100 mW/cm², which corresponds to the solar radiation intensity at the Earth's surface (see figure 3). This phenomenon relates to a high value of parasitic series resistance of the SCs. At low radiation intensities, the EQE does not change sufficiently, which is consistent with numerical modeling results not presented in this paper. We should also mention here that the rate of EQE decrease with the radiation intensity is subject to change by the surface passivation technique.

4. Summary
In our paper, we studied electrical and spectral characteristics of the SCs series based on GaN/Si heterostructures. We investigated the devices characterized by three different methods of the interface preparation. Volt-ampere characteristics of the samples were obtained using a solar spectrum simulator. EQE dependencies were calculated in the 350 – 1200 nm region of the incident light wavelength. We then carried out analysis of the obtained experimental data to compare the characteristics of the fabricated SCs. We also carried out experimental measurements of the EQE dependencies on the intensity of the 532 nm wavelength incident light. According to the results, the characteristics of GaN/Si SCs change sufficiently depending on the method of substrate treatment prior to GaN deposition.

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