Electrical properties of InGaN nanostructures with branched morphology synthesized via MBE on p-type Si(111)

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Abstract The work is devoted to the study of electrical properties of InGaN nanostructures with branched morphology (NSs) on p-type Si substrates. It was found that the IV curves between InGaN NSs and p-Si are close to linear, which could indicate a tunneling conductivity. Such unique structures as InGaN NSs on p-Si can be used as building blocks for water splitting devices and tandem solar cells.

1. Introduction

III-N semiconductors are paramount materials for applications in the solid-state lighting [1, 2] and renewable energy sources [3]. In particular, InGaN is a promising material since it has a direct band gap in the range from 0.7 to 3.43 eV achieved by tuning the alloy composition. However, the synthesis of high-quality InGaN epitaxial layers is difficult due to the lack of lattice-matched substrates and the different thermal expansion coefficients between InGaN and other materials. These problems can be solved via the synthesis of InGaN nanostructures with branched morphology. Due to a branched morphology of nanostructures, mechanical strains caused by the difference in lattice constants and thermal expansion coefficients between InGaN and substrates, effectively relax, leading to a significant decrease in the number of defects [4].

Several research groups [5,6] studied the electrical properties of InGaN layer/Si and InGaN nanowires/Si heterojunctions with different electrical conductivities of the materials in order to determine the prospects of their application in renewable energy sources. However, InGaN nanostructures with branched morphology (NSs) are unique objects that may have advantages over compact layers and nanowires. As previously shown [7,8], InGaN NSs have a complex structure with an inhomogeneous distribution of chemical composition over the height, «white» photoluminescence at room temperature, and high optical quality. The present work is dedicated to the study of the electrical properties (IV curves) of such InGaN NSs, grown on a p-type silicon substrate.

2. Samples and method

InGaN nanostructures were grown using Riber Compact 12 MBE system equipped with indium (In) and gallium (Ga) effusion cells and a nitrogen source. To grow the InGaN, we used a p-type Si (111) substrate with a carrier concentration of 10¹⁶ cm⁻³. Initially, the unprepared substrate was transferred
into the growth chamber and the substrate temperature was set to 950 °C for thermal treatment. Next, the substrate temperature was reduced to the actual growth temperature set to 600 °C. The nitrogen plasma source was ignited and the N flux was set to 0.4 sccm and 450 W. Finally, the Ga and In sources were opened. Ga and In partial pressures were equal and set to 10⁻⁷ Torr [7]. Morphological properties of the sample were investigated using a SUPRA 25 C. Zeiss scanning electron microscope (SEM). Figure 1 demonstrates the SEM images of (a) cross-section view and (b) plane view of the InGaN NSs.

![SEM images of InGaN NSs](image)

**Figure 1(a, b).** SEM images of InGaN NSs: (a) cross-section view [6] and (b) plane view (PV). The scale bars correspond to 1 µm.

As can be seen from Figure 2, InGaN NSs have a three-dimensional branched structure. Previously [8], it was demonstrated the grown structure consists of a nanotubes layer near the substrate and nanoflowers above. It should be noted, that sample has the high surface density of the nanostructures. The formation of the three-dimensional branched structure can be explained by the changing of an effective surface temperature during the growth process [9-11].

### 3. Postgrowth processing, measurements and discussion

The electrical properties of the grown structure were characterized by obtaining IV curves of InGaN NSs/p-Si heterojunction, measured in the dark and in the light conditions. Two approaches were applied. Firstly, the IV curves of a single InGaN NS on p-Si were measured. Then the IV curves of an InGaN NS array on p-Si were measured. To measure the IV curves, ohmic contacts (Al/Au) were formed on the back of the substrates by the BOC Edwards Auto 500 vacuum coating system. Further preparation of the samples will be described below.

#### 3.1 I-V curves measurement of a single InGaN NSs/Si structure

The IV curves of a single InGaN NS on the p-Si substrate were measured using the conductive atomic force microscopy (C-AFM) by contacting the probe with one NS [12]. The measurements were carried out on 10 single InGaN NS units at room temperature using NT-MDT Ntegra AURA setup with W₂C-coated probes having a tip curvature radius of 30 nm. To measure the IV curves in the light conditions, a laser with a wavelength of 690 nm was used. Figure 2 demonstrates: (a) scheme of the electrical properties investigation from a single InGaN NS by AFM; (b) averaged IV curves of a single InGaN NS.

As can be seen from Figure 2(b), the obtained IV curves of a single InGaN NS have characteristics that are close to ohmic ones. Such type of IV curves has previously been observed between n-type In₀.₄₆Ga₀.₅₄N and p-type Si. It can be explained by the electron tunneling through a narrow space charge region [5]. However, on the reverse branch of the IV curves, we can see some deviation from the ohmic behavior. Perhaps this is due to an increase in the space charge region and, as a consequence, the reduced efficiency of electron tunneling. It should be noted that the photoconductivity of InGaN NSs increased by light with a wavelength of 690 nm. It can be explained by fluctuations in the chemical composition along the nanostructure height and internal point defects [8].
Figure 2(a, b). Scheme of the electrical properties investigation from a single InGaN NS by AFM (a); averaged IV curves of a single InGaN NS (b).

3.2 I-V curve measurement of the InGaN NS array/Si structure
To measure the IV curves of the InGaN NS array/Si, a photodiode structure was created. Figure 3(a) demonstrates a corresponding scheme of the device structure. Figure 3(b-d) shows PV SEM images of the sample on each stage of a photodiode structure creation: (b) initial, (c) after polymer coating, (d) after ITO deposition. Firstly, the sample was covered by the SU-8 dielectric polymer layer. The dielectric polymer layer was used to planarizes the sample surface. Next, this polymer layer was etched with oxygen plasma to uncover the upper parts of the InGaN NSs. At the last stage, the ITO contacts were formed on the layer to the upper parts of the InGaN NSs through a mask with holes by RF magnetron sputtering method using BOC Edwards AUTO 500 vacuum coating system. The thickness of the ITO contacts and the surface area of them were about 100 nm and 12 mm², respectively. The ITO contacts and polymer layer SU-8 were used due to their transparency for the visible spectrum. The IV curves were measured by Keithley 2400 SourceMeter multimeter and SunLight Solar Simulator (ABET Technologies) providing AM1.5 G, 100 mW/cm² spectrum. Figure 3(e) shows the corresponding IV curves of the InGaN NS array/p-Si structure.

Figure 3(a, b, c, d, e). (a) Scheme of the photodiode structure based on InGaN NS array/p-Si heterostructure; PV SEM images of the sample: (b) initial, (c) after polymer coating, (d) after ITO deposition. The scale bar corresponds to 1 µm; (e) averaged IV curves of the sample.
Figure 3(e) shows the IV curves of the InGaN NS array/p-Si, which qualitatively coincide with the IV curves of single InGaN NS/p-Si. Some deviations of the IV curves of a single InGaN NS (figure 2(b)) and InGaN NS array (figure 3(e)) can be explained by the passivation of the structure by the SU-8 polymer [13].

4. Conclusion
The electrical properties (IV curves) of InGaN NSs on p-type silicon substrates were studied. The results show the IV curves of single InGaN NS and InGaN NS array are close to ohmic ones. Such dependencies indicate a possible tunnel junction between InGaN NSs and p-type Si substrate. Thus, we consider the InGaN nanostructures with branched morphology on Si substrates can be used for water splitting devices and tandem solar cells.

Acknowledgements
The samples were grown under support of Ministry of Science and Higher Education of the Russian Federation (state task № 0791-2020-0003). The electrical properties were studied under financial support of RSF grant (project № 18-02-40006 mega).

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