Conductive AFM study of the electronic properties of individual epitaxial GaN nanowires

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Abstract. In this work, we use conductive atomic force microscopy (CAFM) to study the impact of substrate surface preparation and buffer layer composition on the electrical transport properties of GaN nanowires (NWs). I-V curves of single NWs from seven differently prepared samples were obtained. The tip of atomic force microscope (AFM) was used as a top conductive electrode to create stable electric contact to NW free upper grain, while the bottom contact was established between the highly doped Si substrate and a grounded sample holder of the AFM device. Single NW I-V curves were compared to those of NW arrays. The difference between them was discussed.

1. Introduction
Development of one dimensional semiconductor structures remains one of the most perspective directions in modern nanoelectronics. In particular, GaN nanowires (NWs) are important for the development of the light-emitting diodes and optoelectronic devices operating in the blue and near-ultraviolet range as well as for nanogenerators and piezoelectric devices. The combination of beneficial mechanical, optical, and transport properties of NWs makes them promising building blocks for the next generation of optoelectronic [1], photovoltaic [2], sensing, and energy harvesting devices [3]. Thus, the understanding of their electrical properties is crucial.

One of the problems that III-N-based devices fabrication technology is facing today is the high cost of Al2O3 or GaN substrates promoting researchers to develop the nitride compounds growth techniques on more accessible wafers, such as silicon, and find new approaches for the defect free epitaxial growth of highly lattice mismatched systems [4]. Fortunately, quasi one-dimensional NW geometry provides a unique possibility of high crystallinity nanostructures growth on lattice mismatched substrates due to more effective strain relaxation in comparison to the thin film heterostructures [5]. In this work, we study influence of the Si (111) substrate surface preparation and buffer layer composition on the GaN NW/Si heterojunction electronic properties.

2. Experimental
The investigated GaN NWs were grown on boron doped Si (111) wafers by plasma assisted molecular beam epitaxy (PA-MBE) using Veeco GEN-III machine. The experimental setup description can be found elsewhere [6]. Equivalent pressures of nitrogen and gallium molecular beam fluxes were kept at ~2×10−7 and ~1×10−8 Torr, correspondingly. Substrate temperature for the NWs growth was set to
760°C in all the experiments. We studied seven samples that had been grown using different substrate surface preparation techniques after the oxide removal.

In the first growth experiment, GaN deposition was initiated immediately after the oxide removal. In the second one, a thin amorphous SiNₓ layer was formed on the substrate surface as a result of exposition under activated nitrogen flux. In the third sample, thin AlN buffer layer was deposited on the substrate. The fourth sample was covered with ∼20 nm thick GaOₓ layer prepared by the plasma enhanced chemical vapour deposition (PECVD) prior to the placement into MBE growth chamber. In 5-7 samples, GaN seeding layer was obtained via nitridation of Ga predeposited on bare Si(111) surface with equivalent thicknesses of 0.3, 0.6, and 2 ML, respectively. All samples were Si-doped for the last two hours of the growth. More details about the growth process can be found in Ref. [7]. Figure 1 shows scanning electron microscopy (SEM) images of all the samples. Average length of NWs varied from 350 nm for the 1st and the 6th samples to 750 nm for the 3rd one, with typical diameter from 50 to 150 nm.

Electrical properties of grown structures were characterized by obtaining IV curves. Two approaches were used. Firstly, we measured the curves from individual NWs. Then the curves from the whole array were obtained and the results were compared. To obtain the IV curve from an individual freestanding NW, two electric contacts were required. The first one was created using conductive atomic force microscope (AFM) tip being a nanosized electrode accurately positioned on the NW top. The second one was formed between the highly doped Si growth substrate and an AFM sample holder. The principal scheme of the experiment is shown in Figure 2a. This technique proved its effectiveness in a number of researches [8,9]. The experiments were performed at room temperature using NT-MDT Ntegra AURA setup with W₂C-coated probes having tip curvature radius of 30 nm. The measurements were carried out in medium vacuum (around 1 Torr) in order to decrease the role of the surface water layer.

Figure 1. SEM images of the synthesized NW arrays: (a) NWs grown on Si without buffer layer, (b) SiN buffer, (c) AlN buffer, (d) GaO, buffer; (e)-(g) GaN seeding layer resulting from nitridation of (e) 0.3 ML Ga, (f) 0.6 ML Ga, (g) 2 ML Ga predeposited on bare Si. Scale bar is 400 nm.
3. Results and discussion

In case of n-GaN/p-Si heterojunction, the forward current is attributed to hot electrons passing through the barrier. The hot-holes current is negligible due to high potential barrier [2]. Reverse current may be connected with defect-related leakage mechanisms [10] and band-to-band tunnelling [11]. Figure 2b shows I-V curve series from individual NWs obtained with C-AFM. Several NWs were studied on each sample with subsequent averaging. Sample 3 (AlN) demonstrates the highest current values in both forward and reverse bias. It is also the only sample that does not show exponential behaviour of the I-V curve. It is known that Al is a good p-type dopant for Si and easily incorporates in its lattice. Thus, sample 3 represents n-GaN/p-Si heterojunction with highly doped p-type region at the interface. Higher values of the reverse current are observed for this sample in comparison with the others. It is typical for a tunnel or backward diode operating according to the BBT mechanism. However, knee voltage in the forward region is not pronounced, which indicates contribution of the SRH mechanism and high defect density at the heterointerface. Reverse current is rather high for the 7th sample (2 ML Ga) that corresponds to high recombination rate at the heterointerface. Thus, we assume that unintentional doping of Si substrate occurs for the samples grown on AlN or GaN seeds prepared by the droplet epitaxy. However, growth on the nitridated 0.3 ML thick Ga layer has a negligible effect on the reverse region of the I–V curve similar to the case of the nitridated Si surface. The lowest obtained leakage current value and the most rectifying behaviour were found for the sample with GaOx buffer layer indicating that this interlayer effectively suppresses the GaN/Si interface recombination.
Figure 3. (a) Averaged I-V curves from individual NWs, (b) current enhancement.

The I-V curves for the samples with ITO top contact pad and Al-back contact measured at 300K are presented in Figure 3a. Enhancement of the current density (Fig. 3b) was observed for the I-V curves obtained with C-AFM at both forward and reverse biases. The ratio was calculated as \( (I_{C-AFM} - I_{NW}) / I_{NW} \), where \( I_{C-AFM} \) is the current density from the C-AFM I-V curve measurement, and \( I_{NW} \) is the current density obtained from the I-V curves for the ITO-coated NWs. It can be seen that the C-AFM measurements with the use of conductive probe as a top contact demonstrates up to the 40 times current increase. We assume that such a phenomenon relates to only partial uncoverage of the NWs top facets after the epoxy etching resulted in lower effective contact area compared to the calculated value and, correspondingly, to a lower value of the calculated current density. Second, we assume that the current could be reduced due to the voltage drop in the ITO layer in the NWs array geometry. Third, the difference of the Schottky barrier for the different experiment geometries exists. That is clearly seen for the 6th sample (0.6 ML Ga) as the reverse current increased and for the 7th sample (2 ML Ga) as the curve behaviour changed from rectifying type (Fig. 2b) to Ohmic one (Fig. 3a). Taking into account abovementioned issues, we assume that for better understanding NW electronic properties, C-AFM measurements are preferable.

4. Conclusion

We investigated electrical properties of GaN NW/Si(111) heterostructures grown with various techniques of substrate surface preparation and buffer layer compositions. C-AFM measurements were carried out to compare the electrical transport properties of individual heterojunctions formed by a single NW on Si and that of NW arrays. Significant difference in the curves shape and the current density was observed. It was demonstrated that buffer layer preparation technique chosen for further GaN growth on Si(111) had an essential effect on the electronic transport properties of GaN/Si nanoheterostructures.

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References

[1] Zhao S, Nguyen H P, Kibria M G and Mi Z 2015 III-Nitride nanowire optoelectronics Prog. Quant. Electron. 44 14-68

[2] Mozharov A, Bolskakov A, Cirlin G and Mukhin I 2015 Numerical modeling of photovoltaic efficiency of n-type GaN nanowires on p-type Si heterojunction Phys. Stat. Sol. Rapid Res. Lett. 9 507-10
[3] Huang C-T, Song J, Lee W-F, Ding Y, Gao Z, Hao Y, Chen L-J and Wang Z L 2010 GaN nanowire arrays for high-output nanogenerators J. Am. Chem. Soc. 132 4766-71

[4] Bertness K A, Sanford N A and Davydov A V 2011 GaN nanowires grown by molecular beam epitaxy IEEE J. Sel. Top. Quant. 17 847-58

[5] Bertness K, Sanford N and Schlager J 2011 Gallium nitride nanowires achieve crystalline perfection SPIE Newsroom

[6] Fedorov V, Bolshakov A, Kirilenko D, Mozharov A, Sitnikova A, Sapunov G, Dvoretckaia L, Shtrom I, Cirlin G and Mukhin I 2018 Droplet epitaxy mediated growth of GaN nanostructures on Si (111) via plasma-assisted molecular beam epitaxy Cryst. Eng. Comm. 20 3370-80

[7] Bolshakov A D, Fedorov V V, Shugurov K Y, Mozharov A M, Sapunov G A, Shtrom I, Mukhin M S, Uvarov A V, Cirlin G E and Mukhin I S 2019 Effects of the surface preparation and buffer layer on the morphology, electronic and optical properties of the GaN nanowires on Si Nanotechnology 30 395602

[8] Alekseev P A, Sharov V A, Dunaevskiy M S, Kirilenko D A, Ilkiv I V, Reznik R R, Cirlin G E and Berkovits V L 2019 Control of conductivity of InxGa1-xAs nanowires by applied tension and surface states Nano Lett. 19 4463-9

[9] Alekseev P, Sharov V, Geydt P, Dunaevskii M, Soshnikov I, Reznik R, Lysak V, Lähderanta E and Cirlin G 2018 GaAs wurtzite nanowires for hybrid piezoelectric solar cells Semiconductors 52 609-11

[10] Bessire C D, Björk M T, Schmid H, Schenk A, Reuter K B and Riel H 2011 Trap-assisted tunneling in Si-InAs nanowire heterojunction tunnel diodes Nano Lett. 11 4195-9

[11] Nguyen H P T, Djavid M, Cui K and Mi Z 2012 Temperature-dependent nonradiative recombination processes in GaN-based nanowire white-light-emitting diodes on silicon Nanotechnology 23 194012