Study of electrical properties of single GaN nanowires grown by MOCVD with a Ti mask

A A Vasiliev¹,², A M Mozharov², M M Rozhavskaya³, V V Lundin³ and I S Mukhin²,⁴

¹ Experimental physics department, Peter the Great Saint-Petersburg Polytechnic University, Saint Petersburg 194021, Russia
² Renewable Energy Lab, St. Petersburg Academic University, St. Petersburg 194021, Russia
³ Physics of semiconductor heterostructures Lab, Ioffe Institute RAS, Saint Petersburg 194021, Russia
⁴ The metamaterial Lab, University ITMO, Saint-Petersburg 197101, Russia

Abstract. We researched electrical characteristics of GaN nanowires (NWs) grown by MOCVD through solid titanium film. The technology of creating the ohmic contacts and MESFET structure on single NWs has been developed. The optimal annealing temperature of contacts has been found and conductivity structure, the free carrier concentration and mobility has been evaluated.

1. Introduction
For the last few years the interest in new growth technologies of III-N structures has increased due to problems in planar technology, where appearing a lot of defects during the epitaxial growth is a main disadvantage. This relates to the large mismatch of the crystal lattice parameters of the substrate and growing layer. Therefore, this leads to researching new ways of organizing material, for example, an organization in the form of nanowires (NWs). The main advantages of the NWs structures is the ability to create an active region on side faces in the non-polar and semi-polar directions and it helps to reduce the stress caused by the mismatch of the crystal lattice parameters of the substrate and a growing nanostructure.

Different structures could be produced using NWs: transistors, light-emitting device with low power consumption, various types of sensors, single electron transistors, solar cells [1,2,3,4]. In this paper we investigate NWs nitride compounds (GaN, InGaN), produced by MOCVD and also consider the possibility of their use.
1.1. Growth technology

At present, the technology of metal-organic chemical vapor deposition (MOCVD) is widely used. MOCVD method has several advantages, such as: the possibility to use a large area substrates, relatively high rate of growth (in comparison it with other methods), good control of the growth parameters, high homogeneity and high crystal quality layers. In this paper GaN NWs were produced by the method of growth in which the sapphire substrate previously was coated with a solid Ti mask of 10-30 nm thickness\[5\].

Studied structure was synthesized on a sapphire substrate by MOCVD at a temperature of 1040 °C with a precipitated Ti layer (figure 1a). It is a core-shell structure of GaN / InGaN / GaN. The sizes of grown n-type NWs ensemble constituted about 100 microns in length and about 1 micron in diameter at the growth time about 15 minutes. For our research NWs less than 1 micron in diameter were used.

\[ \text{Figure 1(a,b). (a) SEM image of the grown nanowires array; (b) Measurement circuit layout;} \]

1.2. Measurements problem

Creating the devices based on III-nitride NWs there are several problems with the formation of ohmic contacts to the semiconductor structure. In particular, it is known that reduction of contact resistance increases intensity of radiation and efficiency of InGaN of light-emitting diodes. Since the low value of GaN electron affinity (about 3.8-4.1) eV, there are certain difficulties in the selection of materials to create an ohmic contact. One of the appropriate materials for producing ohmic contacts may be a pair of Ti / Al. [6].

Well known method for measurement electrical properties of semiconductors is the Hall method [7]. For using this method we need to make 4 contacts at least and the studied material should be isotropic. In our case we work with structure of InGaN, which is anisotropic material. Implementation the Hall method to anisotropic material can lead to increase an error.

In order to independently determine the mobility and free carrier concentration in the NWs it is necessary to make FET structure. Knowing the value of the carrier concentration it will be possible to make more accurate estimation of the carrier mobility, using the formula \( \rho = 1 / e n \mu \), where \( \rho \) - resistivity, \( e \) - electron charge, \( n \) - carrier concentration, \( \mu \) - mobility. Transistor MESFET structure (figure 1b) with Schottky barrier as the gate electrode and good ohmic contacts allows to estimate both parameters. As a material forming a high Schottky barrier to n-type GaN Au, Ni, Pd, Pt may be selected [8,9,10].
2. Experiment

The synthesized NWs with ultrasonic treatment method were separated from the substrate and transferred to the quartz substrate to form a contact to the single NWs. Using methods of the laser lithography and thermal evaporation in vacuum a group of drain / source contacts which based on materials Ti / Al / Ti / Ag (30/150/30/100 nm) was created (figure 2a). Annealing of contacts was performed at 710 ° C. In order to verify the ohmic properties of the produced contacts volt-ampere characteristics (VAC) was measured by using 2-terminal measurement method (figure 2b). From experiment data we calculated conductivity, which equal to 16 S/cm.

![Figure 2(a, b, c).](image)

(a) Optical image of the transistor structure. Annealed top and bottom contacts are drain and source. Central contact is a gate; (b) VAC of the drain-source contacts without gate contact; (c) Schottky VAC of the gate contact (Pd contact);

To form MESFET structure gate contact must be Schottky contact. We evaporated Pd (50nm), and after evaporation we measured VAC between source and gate to verify the presence of Schottky barrier (figure 2c).

The results of measurements of the transistor characteristic of our structure is shown on figure 3a. We changed gate voltage and measured drain-source VAC. It can be seen that applying negative gate voltage with higher values leads to increasing the nanowire resistance. It could be explained by the fact that applying the reverse bias leads to increasing the region of the depletion layer in NW. This causes to overlap the conduction channel and the decrease in the current.
3. Modeling
To estimate carrier concentration and mobility we calculated the electrical properties of our NW. The modeling solves symmetric problem, in which the gate contact is around the NW. We chose the such parameters for which the simulation results are similar to the results of the measurements (figure 3). From modeling we estimated that carrier concentration is about \((2-3) \cdot 10^{17} \text{cm}^{-3}\). Hence we could estimate a mobility value: \(330 \text{cm}^2/\text{Vs}\). We also found that the mobility has no affect the shape of the VAC curves but just scales it.

4. Summary
In this paper we have studied NWs which were grown by MOCVD method with Ti mask. We were able to move nanowires from the growth substrate to the quartz substrate and made ohmic contact to single NW. We found that optimum annealing temperature to form ohmic contacts is \(710^\circ \text{C}\). Also we formed MESFET structure and measured electrical characteristics of our NW. We found that concentration value is \((2-3) \cdot 10^{17} \text{cm}^{-3}\) and mobility is \(330 \text{cm}^2/\text{Vs}\).

The method of synthesizing the NWs using a solid titanium mask may be perspective due to the simplicity, the quality of the structures and their high growth rate.

References
[1] Dubrovskii V G, Cirlin G E, Ustinov V M 2009 *Semiconductor* **43-12** 1539-84
[2] Li S, Wang A 2012 *J. Appl. Phys.* **111** 071101
[3] Mozharov A, Bolshakov A, Cirlin G, Mukhin I 2015 *Physica status solidi* **9-9** 507-10
[4] Neplokh V, Ali A, Julien F H, Foldyna M, Mukhin I, Cirlin G, Harmand J-C, Gogneau N, Thernycheva M 2016 *Materia science in Semiconductor Processing*
[5] Rozhavskaya M M, Lundin V V, Lundina E, Davydov S, Troshkov S I, Vasilyev A A, Brunkov P, Baklanov A, Tsatsulnikov A F, Dubrovskii V G 2014 *J. Appl. Phys.* **11** 11399
[6] Blank T V, Gol’dberg Yu A 2007 *Semiconductors* **41-11** 1263-92
[7] Storm K, Halvardsson F, Heurlin M, Lindgren D, Gustafsson A, Wu P M, Monemar Bo, Lars Samuelson 2012 *NATURE NANOTECHNOLOGY* **7** 717-722
[8] Motayed A, Davydov A V, Mohammad S N, Melgailis J 2008 *J. Appl. Phys.* **104** 024302
[9] Kuykendall T, Pauzauskis P, Lee S, Zhang Y, Goldberger J, Yang P 2003 *Nanoletters* **3-8** 1063-66
[10] Blanchard P T, Bertness K A, Harvey T E, Mansfield L M, Sanders A W, Sanford N A 2008 *IEEE of Transactions of nanotechnology* **7-6** 760-65