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Analysis of doping distribution in horizontal GaAs nanowires with axial p-n junction by the conductive atomic force microscopy

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Abstract. This work presents the results of an investigation of in plane horizontal GaAs nanowires by Scanning Probe Microscopy (SPM) methods. Topography and a local conductivity map of the horizontal nanowire with axial p-n junction are obtained. The distribution of doping and position of p-n junctions in nanowires are visualized. The I-V curves of differently doped parts of nanowires were measured. These data can be important for the understanding of the doping incorporation mechanism of GaAs nanowires.

1. Introduction

Semiconductor nanowires (NWs) draw attention due to the possibility of their application in many nanoelectronics and photonics devices. Nanowires have already been used as photodetectors[1,2], lasers[3], biosensors[4] and solar cells[5,6]. Particular attention is paid to planar NWs. This is due to the lack of some disadvantages of an out-plane nanowires. For example, it is known that III-V out-plane semiconductor nanowires have a large number of twin-plane defects[7]. Additionally, integration of out-plane nanowires into the traditional planar technological process is a considerable problem. In-plane nanowires do not have these disadvantages. Such nanowires can be integrated into the traditional planar technological process. Twin-defects free in-plane nanowires can be obtained by the MOVPE[8]. Thus in-plane nanowires are the structures combining useful properties of nanowires and practical manufacturability. Of particular interest for electronics are NWs with p-n junction. Formation of a p-n junction can be done by switching the doping precursor during the growth. Nanowires with axial p-n junctions were obtained by this way can be used as diodes, detectors, solar cells, and logic elements. However, the distribution of doping and the position of p-n junction are important parameters for devices based on nanowires. Due to the small size of the structure, the analysis of the distribution of doping and the position of p-n junctions can be a non-trivial task. For example, such task can be solved by the Atomic Probe Tomography (APT)[9]. This method has high sensitivity and spatial resolution, but its practical implementation is very difficult. The experiment must be performed in ultra-high vacuum and samples must be prepared by special methods[10]. In some cases when there is no necessary in an accurate elemental analysis (for example as in this work), APT can be the overly complex and excess method. To solve it, we used the conductive atomic force microscopy (C-AFM). C-AFM is one of the standards and widely used AFM modes. Measurements



can be performed in room conditions and there is no necessary in any specific sample preparation[11]. The aim of this work was to study the topography characteristics of horizontal in plane GaAs nanowires with p-n junction grown by MOVPE on a GaAs (100) substrate, as well as detection of the p-n junction position and the doping distribution.

2. Samples and methods

2.1. Samples

The sample consists of the n-doped GaAs (100) substrate on which horizontal nanowires were grown by the MOVPE method. The p-n junction was created during the growth process by switching the doping precursor. At the start of the growth, a p-type (Zn) doping precursor was fed, and then approximately in the middle of the growth process, the doping precursor was switched to an n-type (Sn). Gold particles were served as a catalyst. Figure 1 shows the SEM image of the grown sample.

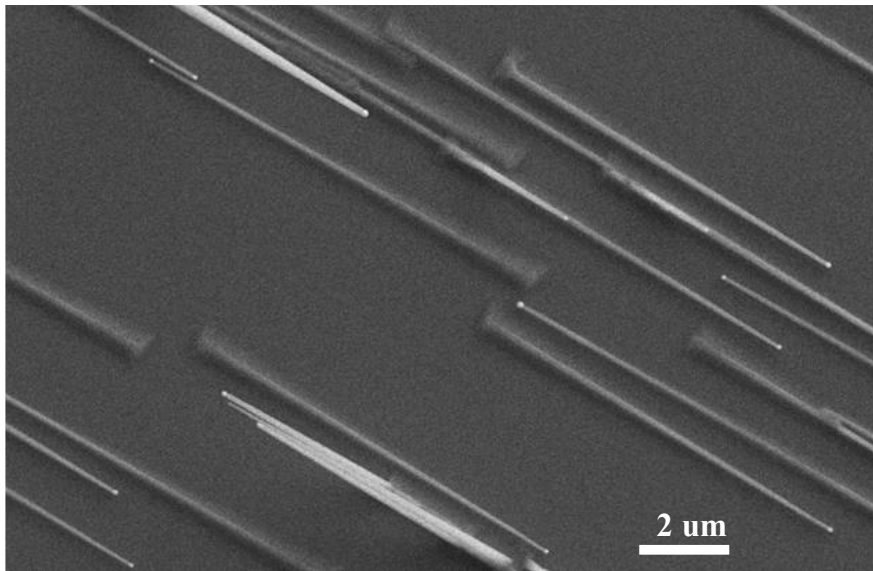


Figure 1. SEM image of the sample.

As can be seen from figure 1, the surface of the sample is covered in nanowires. The average length of nanowires is about 13 μm . Almost all nanowires have grown in the plane, but some of them have deviated from in-plane growth and switched to inclined growth (in 111 direction).

2.2. Methods

The experiment was performed on the Ntegra Aura (NT-MDT) scanning probe microscope using a DCP (NT-MDT) probes. The scheme of measurement is shown in figure 2.

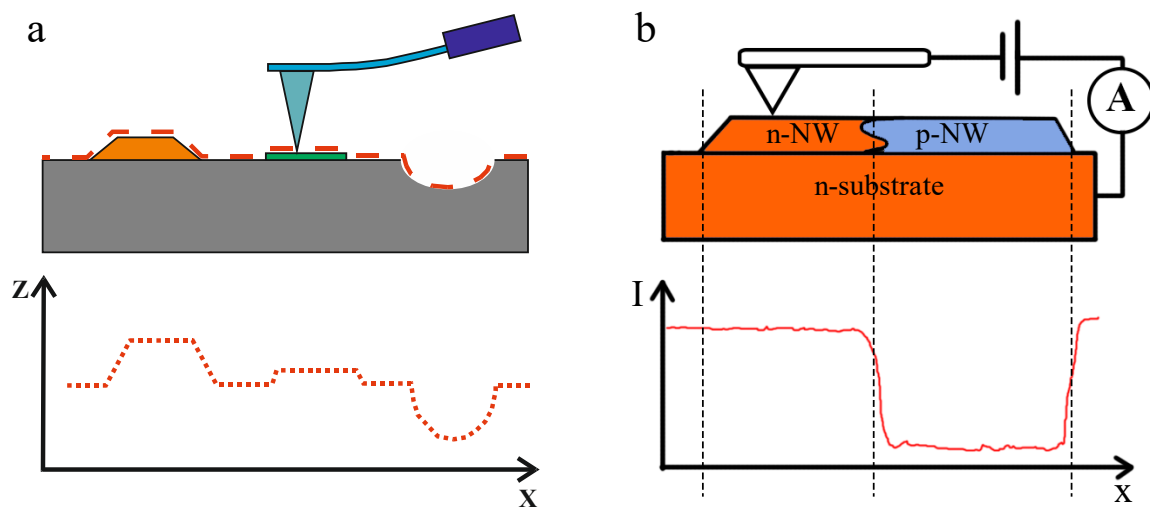


Figure 2(a, b). (a) The scheme of measurement of topography in contact mode; (b) The scheme of measurement of conductivity distribution.

The topography of nanowire was obtained in contact mode (figure 2a). The pressure force of the probe on the surface was set so as not to destroy the nanowire, but to be in electrical contact with the surface. In the process of obtaining the topography, a small voltage (1-2 V) was applied to the probe. Holder with a gold coating which pins the substrate was used as a second contact. The current flowing through the structure was measured. It depends on the place of contact with the surface. As can be seen from figure 2b, if the probe is in contact with the surface of the same type of doping as the substrate, a p-n junction will not be on the path of electrical current and its value will be large. But if the surface has the opposite doping type, a p-n junction will be on the path of electrical current and its value will be small. Thus, a local conductivity map was obtained.

3. Results and discussion

Figure 3 (a) shows the topography of a nanowire obtained by atomic force microscopy in contact mode. The local conductivity map is shown in figure 3 (b).

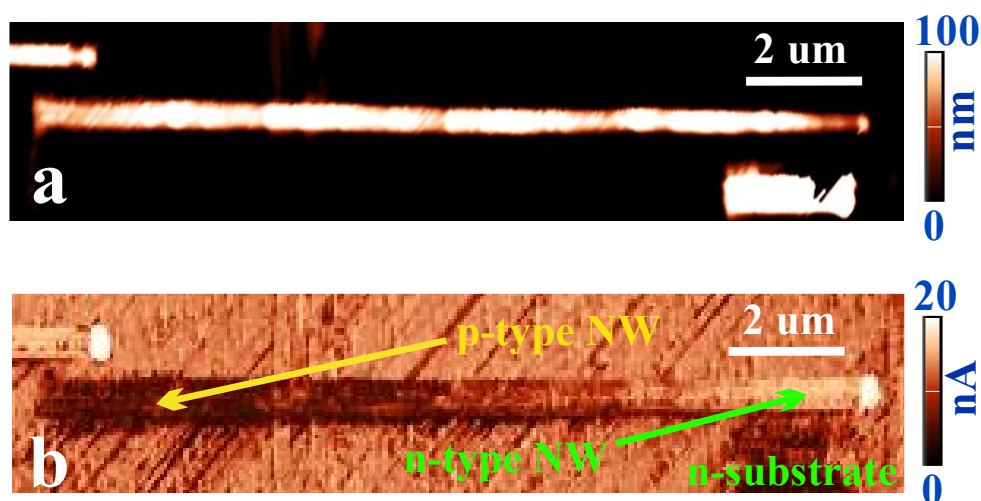


Figure 3(a, b). (a) AFM topography of the horizontal GaAs NW with axial p-n junction; (b) Local conductivity map of nanowire.

As can be seen from figure 3 (a), a nanowire about $\sim 13 \mu\text{m}$ long lies on the substrate surface. The nanowire has the same height along the entire length about $\sim 75 \text{ nm}$ and tapers toward the end. There are several small pieces of other nanowires around the nanowire. This is due to the method of investigation. It was said before, the topography was obtained by the contact atomic force microscopy, as well as not every nanowire grew in the plane of the surface. Thus, nanowires that deviated during the growth were broken by the probe during the scanning process. Vertical parts of nanowires were moved to the boundaries of the scanning area by the probe, but horizontal parts remained in its places. Figure 3 (b) shows a local conductivity map of the nanowire. The scheme of measurement of conductivity distribution is shown in figure 2 (b). One can see conductive (bright) and non-conductive (dark) areas. Conductivity shows the presence or absence of p-n junctions with the substrate in the contact point. As can be seen, the nanowire consists of two parts. P-doped part (dark) grew in the first stage with a p-doping precursor. After switching the precursor, the n-doped part (bright) began to grow. Thus, the p-n junction is localized in the second half of the nanowire. Such pictures may be important for understanding the growth mechanism of nanowires and the process of embedding the dopant. Thus, the distribution of doping and the p-n junction position were determined in horizontal nanowires with axial p-n junction by using the conductive atomic force microscopy. I-V curves in conductive and non-conductive areas were also measured (figure 4).

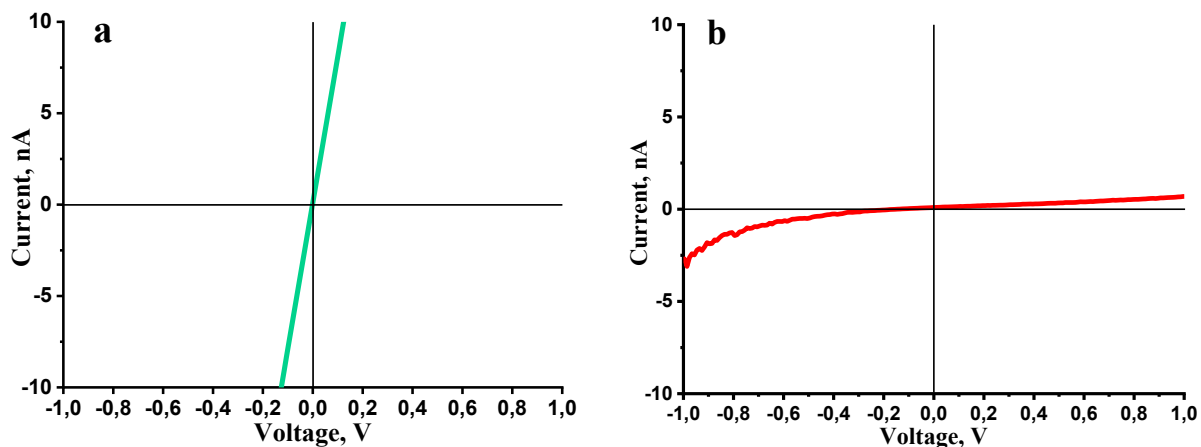


Figure 4(a, b). I-V curves in high conductive (a) and low conductive (b) areas.

As can be seen from figure 4 (a), the I-V curve in the high conductive area exhibits a clearly ohmic shape, indicating absence of the p-n junction. While the I-V curve in the low conductive area exhibits a rectifying (diode) shape (figure 4b).

4. Conclusion

To conclude, GaAs nanowires with axial p-n junction were studied by the scanning probe microscopy. Local conductivity map was obtained by using C-AFM. I-V curves of high conductive and low conductive areas were obtained. Based on the conductivity map, the doping distribution and the position of the p-n junctions were determined. The results of the work allow to consider the SPM as an effective method of analysis of horizontal nanowires.

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