Composition-dependent conductivity of In\textsubscript{x}Ga\textsubscript{1-x}As nanowires

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Abstract. Using the methods of scanning probe microscopy, I-V characteristics of individual In\textsubscript{x}Ga\textsubscript{1-x}As nanowires with different In content (x) were measured. A sharp decrease in the conductivity was observed at x=0.7. It is shown that type of contact between nanowire and probe changes from ohmic at x=1 to Schottky at x=0.85. These changes were explained by the formation of surface conductive channel, induced by surface Fermi level pinning in conduction band for x>0.85.

1. Introduction
GaAs, InAs, and InGaAs nanowires each exhibit significant potential to drive new applications in electronic and optoelectronic devices due to direct bandgap, high electron mobility and compatibility with silicon-based device structures [1]. Semiconductor conductivity is usually controlled by doping. However, electronic properties of nanowires strongly depend on surface properties due to high surface/volume ratio [2] (see figure 1). In InGaAs semiconductors surface states density can reach \(10^{13}\) cm\(^{-2}\) [3]. It is known that in InAs the Fermi level on the surface is pinned in the conduction band [4] (Figure 1, a) and in GaAs is approximately in the middle of the energy gap [5] (see Figure 1, b). Recently it was shown that in In\textsubscript{0.8}Ga\textsubscript{0.2}As the surface position of the Fermi level coincides with the bottom of the conduction band [6] (figure 1, c).

![Band diagrams for n-type InGaAs nanowires. Formation of: (a) Surface conduction channel in InAs; (b) Depleted GaAs; (c) Flatband In\textsubscript{0.8}Ga\textsubscript{0.2}As.](image)

Figure 1. Band diagrams for n-type InGaAs nanowires. Formation of: (a) Surface conduction channel in InAs; (b) Depleted GaAs; (c) Flatband In\textsubscript{0.8}Ga\textsubscript{0.2}As.
It is known that for In$_x$Ga$_{1-x}$As the pinning position is equidistant from the vacuum level for all $x$ in metal-semiconductor interface [7]. Recently, we have shown a validity of this model for III-As nanowires surface with native oxide [8]. III-V nanowires can be grown with wurtzite crystal structure [9]. Conductivity of InAs nanowires depends on the crystal structure[10]. These effects are less studied for InGaAs nanowires. The aim of this work was to study a conductivity of the nanowires with wurtzite crystal structure using scanning probe microscopy. We measured I-V curves of single undoped oxidized In$_x$Ga$_{1-x}$As nanowires with different $x$.

2. Experiment

Scanning probe microscopy (SPM) was used for measuring of I-V curves[11]. Measurements were performed in ambient conditions on the Ntegra Aura (NT-MDT) microscope using the FM-W$_2$C probes with a conductive W$_2$C coating. Scheme of the experiment is presented in figure 2, a. For measuring of I-V curves of the NW two electrical contacts were created. One contact was connected to the surface of the substrate with nanowires array, and the second contact was created by SPM probe. In$_x$Ga$_{1-x}$As nanowires were grown by VLS technique using an Au as a catalyst in a molecular beam epitaxy chamber. NWs were grown on high doped n$^+$-Si substrates. A series of four samples with an In content ($x$) ranging from 0.7 to 1 was fabricated. Lengths of NWs were of 1-3 µm and diameters were of 20-40 nm (see figure 2, b). NWs exhibit a wurtzite crystal structure confirmed by transmission electron microscopy.

3. Results and discussion

Figure 3 shows I-V curves of In$_x$Ga$_{1-x}$As nanowires with different indium composition. At $x=1$ (pure InAs) the curve represents ohmic behavior with resistance of 50 MΩ (typical resistance of the probe), while at $x=0.85-0.8$ the contact switches to Schottky. At $x=0.7$ the resistance of NW sharply increases to 100 GΩ.

![Figure 2.](image)

To analyse measured I-V curves it is necessary to consider equivalent electrical scheme of the measurement setup (see inset in the figure 2, a). During the measurement an electrical current pass through a barrier between the probe and NW, then through the NW itself and then through the barrier between NW and substrate. The last barrier has a zero-height due to linear shape of the I-V curve measured for InAs NW. Thus, the barrier between NW and the substrate can be neglected in the analysis [12]. Resistance of the nanowire and height of the Schottky barrier probe-NW strongly depend on the surface Fermi level pinning (see figure 1). Indeed, for the InAs NW the Schottky barrier height is zero and the resistance of the NW is low due to surface conduction channel. For the GaAs
NW the Schottky barrier height is about 0.6 eV [5] and the NW resistance is very high due to full depletion of the conductivity channel. For the detailed explanation one should consider the In$_x$Ga$_{1-x}$As band diagram from [8] which is shown in figure 3, b. It is worthy to note, that the band structure of the wurtzite In$_x$Ga$_{1-x}$As alloys is poor studied. Recently, it was shown that conduction band offset between zinc blende and wurtzite InAs is in a range of 30-80 meV, depending on the crystal orientation of the wurtzite surface [13]. Position of the CBM for wurtzite In$_x$Ga$_{1-x}$As alloy is shown as grey band in figure 3, b. For x=0.7 the surface Fermi level (red line) is pinned in the band gap and the NW is fully depleted by charge carriers due to a high surface states density. In this case an electrical scheme of the experiment represents two Schottky barriers connected in opposite direction. This leads to reducing of the current down to the sensitivity of our device (30 pA). With the increasing of indium content the height of Schottky barrier is reduced with simultaneous increasing of the electrical current. For the x>0.85 the Fermi level is pinned in the conduction band that leads to the formation of surface conduction channel.

![Figure 3. (a) I-V curves of InGaAs NWs; (b) Fermi level surface positions of InGaAs depending on indium content x.](image)

4. Conclusion

Thus, a measurement of the I-V curves of undoped wurtzite In$_x$Ga$_{1-x}$As nanowires with 0.7<x<1 reveal a surface states-controlled conductivity of the nanowires. For x>0.85 an electronic surface conductive channel is formed. With a decreasing of indium content the conductivity of the nanowires is reduced by 4 orders of magnitude due to the formation of Schottky barrier to the depleted nanowire.

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