InP nanowires on Si(111) for piezotronic applications

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Abstract. III-V nanowires (NWs) are a promising technology for piezotronic and nanooptoelectronic applications. In this work, we investigate the processes of fabricating a structure with InP NW arrays on a silicon substrate for piezotronic applications. The coating of the NW array with a polymer and the fabrication of a transparent electrical contact to NWs is studied. The piezoelectric effect for the structures with a nonzero piezoelectric modulus $d_{33}$ is demonstrated in an oil environment at voltage amplitudes of about 100 mV. The experimental electromechanical coupling is about 0.049, which is close to the theoretical estimate of 0.053.

1. Introduction

Several areas related to the production and application of piezoelectric nanosensors and nanogenerators are currently being intensively developed [1-3]. The investigation of the use of III-V semiconductor nanowires (NWs) is of particular interest due to the potential growth of the material in the wurtzite phase [4-6] with a nontrivial piezoelectric modulus $d_{33}$ [7-9]. Previously, the piezoelectric effect was investigated for GaAs NWs [2,7-9]. The investigation showed an abnormally strong piezoelectric effect. In particular, the piezoelectric modulus $d_{33}$ in GaAs NWs with a crystal lattice of the wurtzite type can achieve 29 nCl/N. Unfortunately, the parameters of the piezoelectric coupling are unstable and strongly dependent on the specifics of the crystal structure and measurement methods (including technological design). The piezoelectric effect in InP NWs is poorly studied. In this work, we develop a method for fabricating a structure of a measuring device based on InP NW arrays grown on Si(111).

2. Experiments and results

2.1. Fabrication structure of piezosensor device

InP NW arrays are grown on Si(111) $p$-type substrates by molecular beam epitaxy (MBE) using a Riber Compact 21TM MBE machine. The growth of InP NWs was described earlier [10]. Figure 1 shows scanning electron microscope (SEM) images of the InP NW array grown on Si(111) $p$-type substrates. The average length and diameter of the NW array are about 5500 nm and 60 nm, respectively. The average density of the array is $1.7 \times 10^7$ cm$^{-2}$. The technological design of piezosensors with InP NWs includes the processes of polymer/dielectric coating, removing the polymer overlay by plasma etching before opening top NWs, and fabrication of contact layers. The bottom Al/Au contact (40/60 nm thick) to the silicon substrate is deposited by vacuum evaporation using a BOC Edwards AUTO 500 evaporation system. The following NW array is coated with a layer of AZ9260 polymer using a spinner at 4000 rpm. The layer polymerization process is realized at 110°C for 1 min (figure 2). The excess
polymer is etched using a V55-G plasma reactor until the appearance of the NW top. The surface is shown in figure 3. The contact to the NW top is realized by an indium tin oxide (ITO In$_2$O$_3$:Sn) layer at a thickness of about 100-200 nm. The ITO layer is deposited using a BOC Edwards AUTO 500 RF magnetron sputtering system.

**Figure 1.** SEM images of the InP NW array on a Si(111) substrate

(a) – Cross-section  (b) – Plane view

**Figure 2.** SEM images of the cross section of samples with an InP NW array after coating with a polymer layer of low(a) and high(b) viscosity
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Figure 3. The result of plasma-chemical etching of InP NWs:
(a) – InP NWs after plasma etching of the polymer layer
(b) – etching depth vs etching time

2.2. Characterization
The surface morphology is characterized by a Zeiss Supra 25 C scanning electron microscope. The current-voltage ($I$-$V$) curves of the samples with InP NW arrays are measured using a Keithley 2400 source meter and an electrode manipulator. Measurements are performed in the dark and under illumination by a SunLight Solar Simulator (ABET Technologies) at AM 1.5 G, 100 mW/cm².

The piezoelectric effect for the tensor component $d_{33}$ is investigated by special equipment with an ultrasonic sound source at 40 kHz frequency and measuring the potential in a dielectric medium. This approach makes it possible to increase the signal amplitude relative to the air medium and modulate longitudinal waves propagating in the structure along the NWs growth axis, which corresponds to the tensor component $d_{33}$. The signal detected by the oscilloscope gives a picture of the response impulse from the signal source. The scheme of the equipment is presented in figure 4.

Figure 4. The scheme for studying the piezoelectric effect
2.3. Results

The coating of a dielectric layer and electrical transparent contacts to InP NW arrays on a silicon substrate is studied. In particular, figure 2 shows the effect of viscosity and composition on the morphology of the polymer coating layer. It can be seen that at low viscosity the fabricated layer is not planar, and NWs are formed in groups. The use of a high-viscosity polymer can cause porosity between NWs, which negatively affects the results. Both morphologies are likely explained by the effect of surface tension.

$I-V$ curves of the structures with InP NW arrays in the dark and under illumination are given in figure 5(a). The $I-V$ curves are of a diode type with an open-circuit voltage of about 0.3 V and a short-circuit current of about -0.5 mA at 1-sun illumination. A special investigation of the photovoltaic effect will be presented in the following manuscript. In the experiments, we measured the dependence of the voltage on the intensity of ultrasonic generation and the shift time vs the source – receiver distance. Figure 5(b) shows the time dependence of the voltage in a liquid dielectric medium. The maximal voltage is about 100 mV. The output signal at the ultrasonic source was 1.5 V. Theoretical calculations of the electromechanical coupling factor were carried out using the formulas of hydro and electroacoustics [11]. The volume level near the source in a dielectric oil medium was 90 dB.

$$L_s = 20 \times \log \frac{P_s}{P_0} \rightarrow P_s = P_0 \times 10^{\frac{L_s}{20}} = 0.625 \text{ (Pa)}$$

(1)

The power of the received signal and the coefficient were estimated taking into account the correction for the distance to the receiver ($r = 0.2$ m):

$$P = \frac{P_{\text{acoustic}}}{r_s^2} = 3.125 \text{ (Pa)}$$

(2)

$$K = \sqrt{\frac{W_{\text{acoustic}}}{W_{\text{electric}}}} = 0.053$$

(3)

The experimental electromechanical coupling factor for the structure with an InP NW array is estimated at 0.049. This estimate is based on the efficiency of charge distribution near the NW tops, taking into account the density of the NWs array and the area of the contact pad. The experimental and theoretical values are approximately in the same range. These values are not large compared to the existing complex compounds of piezomaterials, but they are already at the level of crystalline quartz (quartz coefficient between 0.05 and 0.1).

**Figure 5.** (a) $I-V$ curves of the structures with an InP NW array in the dark and under illumination; (b) Detected piezo-response at an ultrasonic power of about 90 dB
3. Conclusion
In the work, we studied the features of the main processes of fabricating a piezotronic structure with an InP NW array: deposition of a dielectric layer and electrical transparent contacts to an InP NW array. We obtained the optimal coating structure using AZ9260 polymer while spinning at 4000 rpm. The etching process is controlled at 50 nm/min until the appearance of the NW top. The layer polymerization process is realized at 110°C for 1 min duration. The 100-200 nm ITO layer is deposited by a magnetron sputtering system. The fabricated structures demonstrate diode-type current-voltage characteristics. The piezoelectric response at ultrasonic generation of a structure in a liquid dielectric medium is up to 100 mV. The experimental value for electromechanical coupling is about 0.049, which is close to the theoretical value of 0.053.

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