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# Measurement of the bending of thin inclined nanowires as a method for determining elastic modulus

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**Abstract.** The method of measuring nanowires elastic modulus by scanning probe microscopy is presented. This method uses the measurement of nanowire bending profiles in the precise force control mode. The possibilities of the method are demonstrated by measuring the Young's modulus of thin tapered InP nanowires.

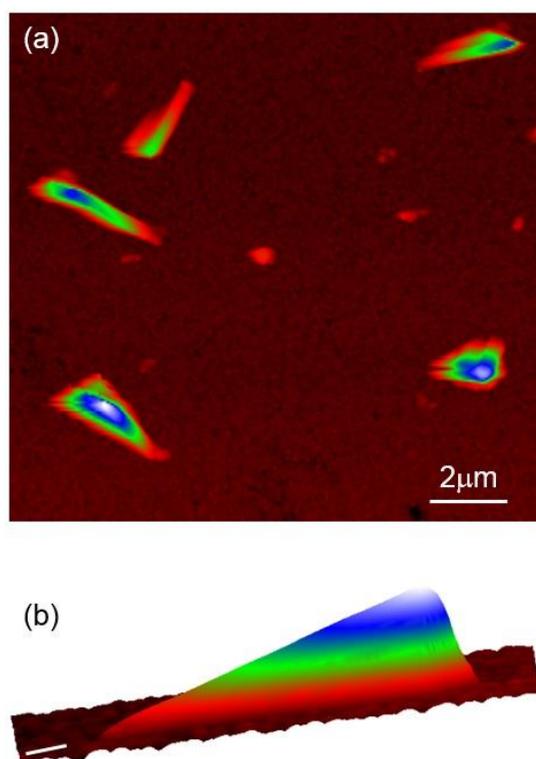
## 1. Introduction

Recently, the interest of various scientific groups has been attracted to studies of semiconductor nanowires (NW). On the basis of NW, it is planned to create advanced sensoric, nanoelectronic, and photovoltaic devices [1,2]. For producing the NW-based device structures it is important to know not only their electrophysical properties, but also their mechanical properties. Therefore, it is important to have information about the Young's modulus of NW. In a number of works it is shown that the Young's modulus of thin NW can differ from the tabulated values of the bulk materials [3]. The physical properties of a number of A<sup>III</sup>B<sup>V</sup> materials (GaAs, InP, InAs, etc.) with a zinc blende structure have been already thoroughly investigated. However, the properties of the same A<sup>III</sup>B<sup>V</sup> materials with the wurtzite structure have not been yet studied experimentally. For example, Young's moduli of wurtzite InP, InAs, and a number of other A<sup>III</sup>B<sup>V</sup> materials are still unknown. It is worth noting that in sufficiently thin NW the crystalline wurtzite structure may appear. In this work, we present scanning probe microscopy (SPM) method for determining the Young's modulus of sufficiently thin NW. The capabilities of the method are demonstrated by measuring the Young's modulus of thin tapered InP NW [4].

## 2. Experimental

Thin NW, due to the high length-to-radius ratio may have extremely small flexural stiffness coefficient. An experimental study of sufficiently thin NWs is a serious challenge. When studying thin NW by the SPM methods large bends of NW and even their breakage may occur. In order to prevent this, we used the method of precise force control – Peak Force Tapping (Bruker) [5]. This mode was specially designed to minimize the force of the probe's impact on the surface. Peak Force Tapping mode makes it possible to investigate "very soft media", including NWs with small flexural stiffness. We had the opportunity to reduce the probe's force acting on the surface down to 0.05 nN and maintain it during scanning with a high degree of accuracy. Scanning with ultra-small force allowed us to obtain noiseless images of inclined InP NWs without their deflection (Fig. 1). This was a very important step necessary to further accurately measure the NWs bending.

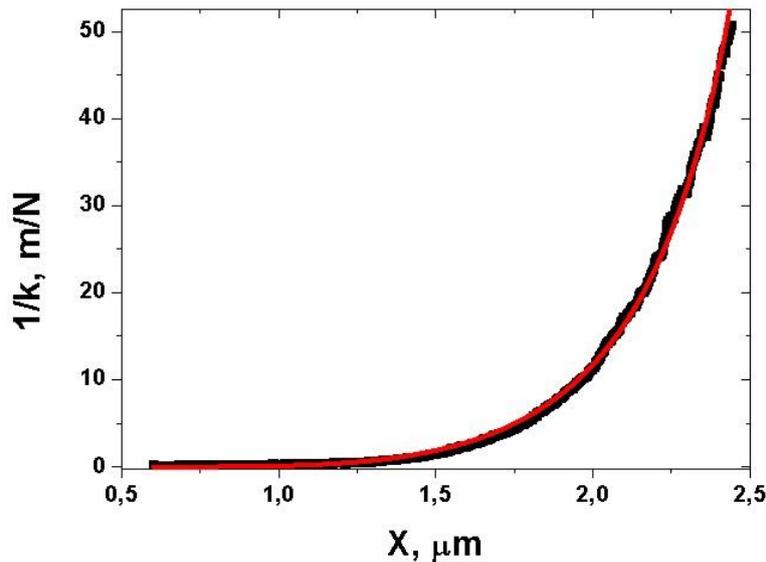




**Figure 1.** (a) SPM image of an array of inclined InP NW; (b) 3D SPM image of an individual InP NW (the scale bar corresponds to 200 nm).

In this paper, we investigated samples with tapered InP NWs differing both in geometric parameters and in the crystal structure. The length of the studied NWs was from 2 to 3 microns, the average radius was from 15 to 40 nanometres, and the cone angle was 1-1.5 degrees. The samples with NWs array were grown on the Si-substrate by metalorganic chemical vapour deposition method. The growth temperature was chosen so to realize the desired “vapour-liquid-solid” growth mechanism. The geometric parameters of the NW were determined by SPM and scanning electron microscopy (SEM). We used Multimode-8 (Bruker) microscope for SPM measurements. The type of crystal structure of InP NW was determined from electron diffraction data. An important property of the NW array was that a significant number of NW was inclined to the surface at a small angle of 15-20 degrees. This important circumstance made it possible to investigate the bending of these inclined NW by the SPM methods.

In this paper, we used the SPM method of measuring the bending profiles on inclined NW with different peak forces  $F_{\text{peak}}$  acting on the NW. It was found that with increasing values of the peak force, the deflection of the NW increased, which led to a change in the scanning topography of the inclined NW. It is reasonable to assume that the deflection of the NW is close to zero when working with near-zero forces. Therefore, if we subtract the profile of non-bent NW from the profile of the NW bended by the force  $F$ , then we will obtain the bending profile of the NW (for the given force  $F$ ). During our measurements, we observed a linear increase in the bending profiles  $w(x)$  with increasing values of the peak force  $F_{\text{peak}}$ . This means that in the range of applied forces there is a linear bending of the NW according to the Hooke's law. After the measurement of set of bending profiles measured along the NW with different forces, these profiles were divided by the values of the corresponding forces and thus the inverse stiffness profile was obtained. The resulting inverse stiffness profile is then analysed in accordance with the theoretical deflection model of the NW. In our case, the NW under study had a tapered shape, so we used the bending model from Ref. [4]. By fitting the experimental inverse stiffness profiles by theoretical bending model one can obtain the Young's modulus value of studied NW. It should also be emphasized that this method can be applied to any thin and flexible 1D object (nanoparticles, thin fibrils, asbestos tubes, nanotubes, etc.) as well as thin and flexible 2D membranes (graphene, transition metal dichalcogenide layers, etc.).



**Figure 2.** Inverse stiffness profile  $1/k(x)$  measured on the inclined InP NW. Fitting by Eq. (1).

### 3. Results

Figure 1 shows an image of an array of inclined NW (Fig. 1a), as well as 3D image of one of the NW (Fig. 1b) scanned with a near-zero force ( $F_{\text{peak}}=0.1\text{ nN}$ ). As it can be seen, the length of this inclined NW is about  $2\ \mu\text{m}$ . Figure 2 shows the inverse stiffness profile  $1/k(x)$  measured on this NW and a smooth fitting curve using bending profile formula for a tapered beam [4].

$$\frac{1}{k(x)} = \frac{4}{3\pi} \frac{1}{E} \frac{1}{R_{\text{mid}}^4} \frac{x^3}{(1+a(x-L/2))(1-aL/2)^3}, \quad (1)$$

where  $a=\alpha/R_{\text{mid}}$  ( $\alpha$  is the NW cone angle tangent),  $L$  – length of the NW. During the fitting one can get the value  $E \cdot R_{\text{mid}}^4$  ( $R_{\text{mid}}$  is the average radius of tapered NW and  $E$  is the Young's modulus). Knowing this value and measuring  $R_{\text{mid}}$  by SPM or SEM methods one can obtain the Young's modulus value.

In this work, using the above mentioned method, we calculated the Young's moduli for 17 NW of different radii and with different crystal structures (zinc blende (ZB) and wurtzite (WZ)). It was found that Young's modulus of NW of large radius ( $R_{\text{mid}} > 30\ \text{nm}$ ) was 65 GPa. With a decrease in the radius of the NW, the measured Young's modulus increased to 130 GPa. Apparently, the increase in the Young's modulus is due to the presence of a wurtzite crystal structure in thin NW. Indeed, this electron diffraction indicates that NW with radii less than 20 nanometres have a wurtzite structure, while larger NW have a mixed ZB/WZ structure. Thus, it is established that wurtzite InP nanoparticles have a Young's modulus of about 130 GPa.

### 4. Conclusion

Thus, in this work, special SPM procedure was presented for the measurement of Young's modulus of thin and flexible NW. The method consists in measuring the inverse stiffness profiles  $1/k(x)$  in the Peak Force Tapping precision force control mode. To analyse the bending profiles of thin InP NW of tapered shape, the formula was used that related the inverse stiffness  $1/k(x)$  of the tapered NW and the Young's modulus. Using this approach, it was possible to measure the Young's modulus of tapered InP NWs with a wurtzite and mixed ZB/WZ structure. Young's modulus value of mixed ZB/WZ NWs turned out to be close to 65 GPa, while the Young's modulus of wurtzite InP NW was approximately twice as large (130 GPa).

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