



Analysis of static friction and elastic forces in a nanowire bent on a flat surface: A comparative study



Mikk Antsov^{a,b,*}, Leonid Dorogin^{a,b}, Sergei Vlassov^{a,b}, Boris Polyakov^{a,c}, Mikk Vahtrus^{a,b}, Karine Mougín^d, Rünno Lõhmus^{a,b}, Ilmar Kink^{a,b}

^a Institute of Physics, University of Tartu, Estonia, Riia 142, 51014 Tartu, Estonia

^b Estonian Nanotechnology Competence Centre, Riia 142, 51014 Tartu, Estonia

^c Institute of Solid State Physics, University of Latvia, Latvia

^d Institut de Science des Matériaux de Mulhouse, 15 rue Jean Starcky, 68057 Mulhouse, France

ARTICLE INFO

Article history:

Received 18 September 2013

Received in revised form

5 December 2013

Accepted 8 December 2013

Available online 17 December 2013

Keywords:

Nanomanipulation

ZnO nanowire

Static friction

Elasticity

ABSTRACT

ZnO nanowires bent to a complex shape and held in place by static friction force from supporting flat surface are investigated experimentally and theoretically. The complex shapes are obtained by bending the nanowires inside a scanning electron microscope with a sharp tip attached to a nanopositioner. Several methods previously described in the literature are applied along with author's original method to calculate the distributed friction force and stored elastic energy in the nanowires from the bending profile. This comparative study evidences the importance of the usage of appropriate models for accurate analysis of the nanowires profile. It is demonstrated that incomplete models can lead up to an order of magnitude error in the calculated friction force for complex profiles.

© 2013 Elsevier Ltd. All rights reserved.

1. Introduction

Nanowires (NWs) are known to have unique mechanical [1], optical [2] and electrical [3] properties in comparison to the bulk material and have a number of promising applications in nanoscale mechanics [4], electronics [5] and piezotronics [6]. The progress in miniaturisation and improving the efficiency of micro- and nano-electromechanical systems (MEMS, NEMS) demands accurate modelling of nanoscale phenomena [7]. In particular, adhesion and friction are crucial parameters for the operation of NEMS. Considering that fabrication of NW-based electromechanical devices requires precise control over positioning and subsequent behaviour of the NWs, as well as the fact that friction and adhesion can cause failures of NEMS, it is evident, that deeper understanding of NW-surface interaction mechanisms is essential from applicative point of view.

Friction between an elastically bent NW and a flat substrate has been studied by several authors using atomic force microscopy (AFM) [8–10]. It was shown that NWs possess enhanced flexibility compared to the bulk [11]. At the same time the NW-substrate adhesion and static friction can be high enough to preserve

the NW in the bent state. The equilibrium between elastic and friction forces can be utilised to analyse the distributed friction from the known NW bending profile and NW elastic modulus. Such approach was firstly described by Bordag et al. in [10] and further developed by other authors [8,9,12].

Bordag [10] assumed the most bent state of arc-shaped NW to be circular, which enabled to simply use the maximum curvature of such NW as a basis for the static friction calculation. Strus [9] introduced a method, where an AFM image of a bent CNT was used for determining the static friction and elastic stresses in the framework of the elastic beam theory. Stan [8] used parabolas to fit through a defined region of the NW centreline for the analysis with Strus' equilibrium expressions. The drawbacks of the named methods were the unconsidered boundary conditions and incomplete equilibrium equations.

An elaborated method for modelling the static friction force in the framework of the elastic beam theory was proposed and demonstrated for ZnO NWs on silicon substrate by Dorogin et al. [12,13]. The method benefits from fully satisfied boundary conditions and complete equilibrium equations. Although the applicability of the method was demonstrated on arc-shaped NWs, it is also suitable for more sophisticated profiles. The more complex the bending shape is, the more accurate method has to be applied due to high sensitivity of the equilibrium equations to curvature derivatives. Therefore the importance of proper skeletonization and equilibrium force analysis can be hardly overestimated.

* Corresponding author at: Institute of Physics, University of Tartu, Riia 142, 51014 Tartu, Estonia. Tel.: +372 58164820.

E-mail address: Mikk.Antsov@ut.ee (M. Antsov).

The aim of the present paper is to revise and compare three above-mentioned methods [8–10] in application to NWs bent to complex shapes and to propose a refined method based on Dorogin's original method [12]. ZnO NWs were deposited onto an oxidised silicon substrate and then bent using an AFM tip attached to a piezo-driven manipulator inside a scanning electron microscope (SEM) chamber like described in [13]. The SEM images of NWs were acquired and used for extracting NW-substrate static friction distribution by four above mentioned methods. The results are compared and analysed. Interpretation of the differences in the obtained quantities is given with a reference to physical and geometrical peculiarities of the problem.

2. Theoretical background: elastic beam theory for 1D nanostructures

Let us consider a prismatic NW elastically bent in a plane under external lateral forces, which may consist of uniformly distributed or point forces. As a result, the NW is kept in equilibrium due to the balance of intrinsic elastic forces and external forces. In this case the common elastic beam theory [14] can be employed to find the equilibrium equations for the NW. They include the force \mathbf{F} and momentum \mathbf{M} of the elastic stress defined as integrals of cross-section S at any given point l along the NW axis by components [14]

$$F_i = \int_S \sigma_{i\gamma} n_\gamma dS \quad (1)$$

$$M_i = \int_S e_{i\alpha\beta} r_\alpha \sigma_{\beta\gamma} n_\gamma dS \quad (2)$$

where $\sigma_{\beta\gamma}$ is the component of the stress tensor, n_γ is the component of the normal vector of the elements of the cross-section area dS , r_α is the component of the radius vector from the axial point l and $e_{i\alpha\beta}$ is the unit anti-symmetric tensor. Both the momentum \mathbf{M} and the elastic force \mathbf{F} are functions of the coordinate l along the axis of the NW.

For a NW at equilibrium, the equations of the full system between the force \mathbf{F} and the momentum \mathbf{M} are as follows:

$$\frac{d\mathbf{F}}{dl} = -\mathbf{f} \quad (3a)$$

$$\frac{d\mathbf{M}}{dl} = \mathbf{F} \times \mathbf{t} \quad (3b)$$

where \mathbf{f} is the external distributed force per unit length acting on the NW and \mathbf{t} is the tangent vector of the NW axis.

For the pure bending case of prismatic NWs we obtained the following equations:

$$\mathbf{M} = EI\mathbf{t} \times \frac{d\mathbf{t}}{dl} \quad (4)$$

where E is the Young modulus and I is the area moment of inertia of the NW. Since the NW deformation is in a plane, \mathbf{M} is always directed out of the plane and Eq. (4) can be rewritten as:

$$M = EI \frac{d\phi}{dl} = EI\kappa \quad (5)$$

where the curvature κ can be defined as $\kappa = d\phi/dl = 1/R$, where ϕ is the tangent angle along the NW in the point l , and R is the local radius of curvature.

In case of a NW bent on a surface, the distributed static friction force \mathbf{F}^{st} plays the role of an external force: $\mathbf{f} = \mathbf{F}^{st}$. In order to complete the equations of equilibrium, the tangential component of the static friction is assumed to be negligibly small $F_t^{st} = 0$. Solution of the Eqs. (3a), (3b) and (5) with respect to \mathbf{F}^{st} as a function of l was obtained by Strus [9] and then employed by Stan [8]. Independently the solution was obtained by Dorogin [12], which contained an additional term (as can be seen from Table 1). It must be noted that Bordag [10] had deduced the expression for \mathbf{F}^{st} directly from the integrated elastic energy of a circularly bent NW.

3. Experimental

ZnO NWs grown by the vapour transport method (VTM) [15] were chosen for manipulation experiments. NWs obtained by the VTM method have shown well-defined geometrical structure, with well-structured facets [16] and proper mechanical properties for manipulation experiments. The NWs obtained ranged from 10 to 20 μm in length and from 60 to 200 nm in diameter.

The manipulation experiments were conducted inside a SEM (Tescan VEGA II) using a contact AFM cantilever (Nanosensor ATEC-CONT cantilevers $C=0.2$ N/m) mounted onto a 3-dimensional nanomanipulator (SmarAct SLC-1720-S). The geometry of the cantilever provided tip visibility from the top. The NWs were mechanically transported from the VTM grown substrate by either scraping it with a sharp tip or using cleanroom wipes to pick up the wires by touching the substrate and moving them to a silicon surface. During the transport the NWs were broken into shorter pieces (1–10 μm). More details about the experimental nanomanipulation setup can be found in [13].

A single NW on a silicon surface was manipulated by the following procedure. The substrate with the deposited NWs was inspected in SEM and a single NW of appropriate aspect ratio in the range from 30 to 60 was selected. These NWs can be bent into complex shapes more easily. For lower aspect ratios the elastic forces in a bent NW tend to overcome the static friction force and arc-shapes can be obtained. Proper NW was chosen and gradually bent with the AFM tip on the surface of the substrate. After retraction of the tip the residual bent shape of the NW was determined by the balance between the elastic and the interfacial

Table 1
Analytical expressions and calculated values of static friction distribution between the complexly bent NW and substrate (for description see text).

| Authors | Static friction between the NW and substrate | | | |
|---------------------------------|--|-----------------------|-----------------------|-----------------------------------|
| | Analytical expression | Average value (nN/nm) | Maximal value (nN/nm) | Magnitude of the total force (nN) |
| Bordag et al. [10] ^a | $F_n^{st} = (EI/2)\kappa^3$ | 0.024 | 0.1 | 0.004 |
| Strus et al. [9] | $F_n^{st} = EI(d^2\kappa/dl^2)$ | 0.21 | 0.49 | 29 |
| Stan et al. [8] ^b | $F_n^{st} = -EI \frac{24A^3(16A^2x^2 + 16ABx + 4B^2 - 1)}{(4A^2x^2 + 4ABx + B^2 + 1)^{3/2}}$ | 0.19 | 1.4 | 9.5 |
| Dorogin et al. [12] | $F_n^{st} = EI(d^2\kappa/dl^2) + (\kappa^3/2)$ | 0.20 | 0.38 | 0 |

^a Modified Bordag using our skeleton as a basis.

^b x is the coordinate in the plane of the SEM image.

Download English Version:

<https://daneshyari.com/en/article/614777>

Download Persian Version:

<https://daneshyari.com/article/614777>

[Daneshyari.com](https://daneshyari.com)