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Evaluation the effect of aspect ratio for Young's modulus of nanobelt using finite element method

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ABSTRACT

The traditional nanoindentation method provides experimental data for the calibrating mechanical parameters of nanobelt through semi-empirical formulae. In this paper, a technique to identify Young's modulus of nanobelts with different aspect ratios is introduced combining finite element method (FEM) and nanoindentation test. For the nanobelt on the substrate, the power function relationship is used to describe the loading curve of the nanobelt indentation behavior. The loading curve exponent of the power function which is the fitting parameter can reflect the influence of aspect ratio of nanobelt on Young's modulus of nanobelts as well as the maximum indentation load. In the forward analysis, considering the substrate effect and the size effect, the numerical loading responses are simulated at the appropriate penetration depth, and then the dimensionless equations between the parameters characterizing the indentation loading curve and the properties of nanobelt/substrate system can be established via extensive FEM simulation. In the reverse analysis, the nanoindentation tests were performed on ZnO and ZnS nanobelts, and the experimental indentation loading curves can be fitted as power function. The maximum indentation loads and the loading curve exponents are extracted from two experimental loading curves, and then they are substituted into the dimensionless equations to solve the Young's moduli of ZnO and ZnS nanobelts. The results show the Young's moduli solved are close to previous values, indicating that the Young's moduli are reasonable. This developed method is effective to identify the Young's modulus of nanobelt and it can be applied to identify the Young's modulus of other nanobelts in practice.

1. Introduction

Nanobelts are the fundamental building blocks for fabricating nanoscale sensors and logic circuits. The nanobelts have a distinct structural morphology, characterized by a rectangular cross section and a uniform structure, which could be directly used as nanocantilevers and nanoresonators in nanoelectromechanical systems (NEMS). The mechanical properties of nanobelts are of critical importance to integrate them into functional nanodevices, because the mechanical failure of these nanobelts may lead to the malfunction or even failure of the entire devices. Several techniques have been developed to measure the mechanical properties of nanobelts. For instance, Bai et al. used an electric-field-induced resonant excitation method to measure directly the mechanical properties of ZnO nanobelts [1]. Techniques based on atomic force microscopy (AFM) and nanoindenter have gained wide applications in measuring the mechanical properties of nanobelts. Li et al. and Mao et al. used the combined AFM/nanoindenter technique to measure the mechanical properties of ZnS nanobelts [2], ZnO nanobelts [3] and SnO_2 nanobelts [3], by *in situ* nanoindentation. In a nanoindentation test, a hard indenter is pressed into nanobelts shown in the inset of Fig. 1, in which a sharp rigid conical indenter with half apex angle 70.3° is taken as the Berkovich indenter [4]. The indentation load (F) and indentation depth (h) are continuously recorded as Fig. 1. According to Oliver and Pharr method, the elastic modulus can be obtained from $F-h$ data and through the equations.

$$\frac{1}{E_r} = \frac{(1-\nu^2)}{E} + \frac{(1-\nu_i^2)}{E_i} \quad (1)$$

$$S = \frac{dF}{dh} = \frac{2}{\sqrt{\pi}} E_r \sqrt{A} \quad (2)$$

where E_r is defined as reduced modulus, and E and ν are Young's modulus and Poisson's ratio for the nanobelt, and E_i and ν_i are the same parameters for the indenter. Here, $S = dF/dh$ is the experimentally measured stiffness of the upper portion of the unloading data,

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