DOI: 10.1017/S143192760344169X
Microsc Microanal 9(Suppl 2), 2003

Dual-Mode Elecromechanical Resonance of Nanobelts Observed by In-situ TEM

Z.L. Wang[*, +], X.D. Bai[*, **], P.X. Gao [*] and E.G. Wang[**]

[*] School of Materials Science and Engineering, Georgia Institute of Technology, Atlanta, Georgia 30332-0245
[**] International Center for Quantum Structures and State Key Laboratory for Surface Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100080, China

+ e-mail: zhong.wang@mse.gatech.edu

Semiconducting oxide nanobelts [1] and nanowires [2] have shown novel electronic, chemical and optical properties [3,4]. 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) [5,6] (Fig. 1A). A key phenomenon for applying nanobelts in NEMS technology is their electromechanical resonance behavior, and an important physical quantity for cantilever applications is their bending modulus. In this paper, the electromechanical resonance of a single ZnO nanobelt, induced by an alternative electric field, was studied by *in-situ* transmission electron microscopy (TEM). Due to the rectangular cross-section of the nanobelt, two fundamental resonance modes have been observed in corresponding to the two orthogonal transverse vibration directions. The electromechanical resonant behavior of the nanobelts is directly correlated with their distinct structural feature, showing a possibility for versatile applications as nanoresonators and nanocantilevers.

A new experimental approach, based on the electric-field-induced resonant excitation, has been developed for direct measurement the mechanical properties of individual nanowire-like structures by *in-situ* TEM [7,8]. Using this method, mechanical properties of carbon nanotubes [7], silicon nanowires [9], and silicon carbide-silica composite nanowires [10] have been investigated. This is the technique that will be applied to study the resonance behavior of individual ZnO nanobelts. From the classical elasticity theory for a rectangular beam [11], the fundamental resonance frequencies corresponding to the thickness direction (x-axis) and width direction (y-axis) (Fig. 1B), respectively, are

$$\nu_{xi} = \frac{\beta_i^2 T}{4\pi L^2}\sqrt{\frac{E_x}{3\rho}} \qquad \text{and} \qquad \nu_{yi} = \frac{\beta_i^2 W}{4\pi L^2}\sqrt{\frac{E_y}{3\rho}},$$

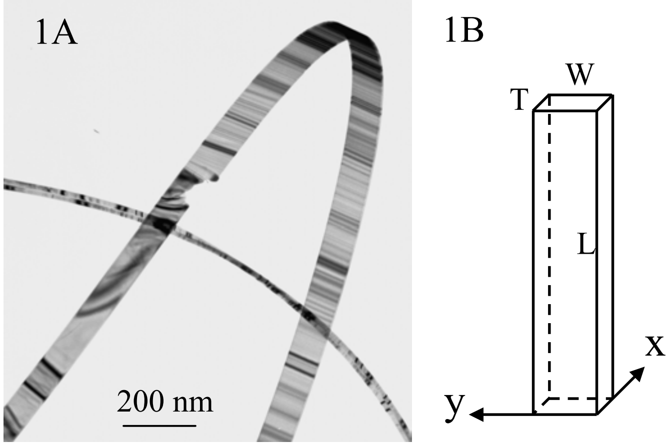
where β_i is a constant for the ith harmonic: $\beta_1 = 1.875$ and $\beta_2 = 4.694$, E_x is the bending modulus for the vibration along the x-axis, L is length of the nanobelt, ρ is mass density; and E the corresponding resonance frequency. The ratio of the two fundamental frequencies is directly related to the aspect ratio of the nanobelt by $\nu_{y1}/\nu_{x1} = W/T\,(E_y/E_x)^{1/2}$.

Due to the rectangular cross-section of the nanobelt, two fundamental resonance modes have been observed in corresponding to two orthogonal transverse vibration directions (Fig. 2), showing the versatile applications of nanobelts as nanocantilevers and nanoresonators. The bending modulus of the ZnO nanobelts was measured to be ~52 GPa (Table I). The two resonance modes just correspond to the two modes of the tip operation when the nanobelt-base cantilever is used as a force sensor: one is the tapping mode, and the other is the non-contact mode. Thus, the force sensor fabricated using the ZnO nanobelts is versatile for applications on hard and soft surfaces [12].

[1] Z.W. Pan, Z.R. Dai, and Z.L. Wang, Science 291, 1947 (2001).
[2] M.H. Huang, S. Mao, H. Feick, H. Yan, Y. Wu, H. Kind, E. Weber, R. Russo, and P. Yang, Science 292, 1897 (2001).
[3] M.S. Arnold, P. Avouris, Z.W. Pan, and Z.L. Wang, *J. Phys. Chem*. B 107, 659 (2002).
[4] E. Comini, G. Faglia, G. Sberveglieri, Zhengwei Pan, and Zhong L. Wang, Appl. Phys. Lett. 81, 1869 (2002).
[5] H.G. Craighead, Science 290, 1532 (2000).
[6] W. Hughes and Z.L. Wang, Appl. Phys. Letts. submitted (2002).
[7] P. Poncharal, Z.L. Wang, D. Ugarte, and W.A. de Heer, Science 283, 1513 (1999).
[8] Z.L. Wang, P. Poncharal, and W.A. de Heer, Pure Appl. Chem.72, 209 (2000).
[9] Z.L. Wang, Adv. Mater. 12, 1295 (2000).
[10] Z.L. Wang, Z.R. Dai, Z.G. Bai, R.P. Gao, and J. Gole, Appl. Phys. Lett. 77, 3349 (2000).
[11] L. Meirovich, *Elements of Vibration Analysis*, (McGraw-Hill, New York, 1986).
[12] We acknowledge support from the NASA URETI program (E-16-V14), China NSF, International Center for Quantum Structures (CAS) and Georgia Tech.

Table I. Bending modulus of the ZnO nanobelts. E_x and E_y represents the bending modulus corresponding the resonance along the thickness and width directions, respectively.

	Length L (μm)	Width W (nm)	Thickness T (nm)	Resonance Fequency (kHz)		Bending Modulus (GPa)	
Nanobelt	(±0.05)	(±1)	(±1)	ν_{x1}	ν_{y1}	E_x	E_y
1	8.25	55	33	232	373	46.6 ± 0.6	50.1 ± 0.6
2	4.73	28	19	396	576	44.3 ± 1.3	45.5 ± 2.9
3	4.07	31	20	662	958	56.3 ± 0.9	64.6 ± 2.3
4	8.90	44	39	210	231	37.9 ± 0.6	39.9 ± 1.2



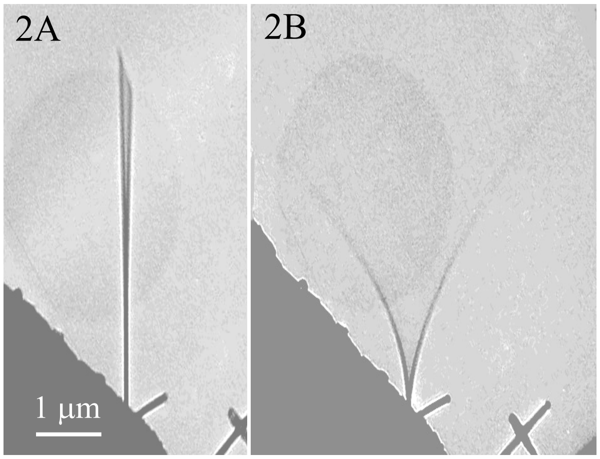


FIG. 1. (A) A typical TEM image of a ZnO nanobelt. (B) Geometrical shape of a nanobelt.
FIG. 2. A selected ZnO nanobelt at (A) the first harmonic resonance in x direction, ν_{x1} = 622 kHz, and (B) the first harmonic resonance in y direction, ν_{y1} = 691 kHz.