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Analysis of high-Q, gallium nitride nanowire resonators in response to deposited thin films

J.R. Montague[a,*], M. Dalberth[b], J.M. Gray[a], D. Seghete[c], K.A. Bertness[d], S.M. George[c], V.M. Bright[e], C.T. Rogers[a], N.A. Sanford[d]

[a] University of Colorado, Dept. of Physics, 390 UCB, Boulder, CO 80309, USA
[b] Cambridge NanoTech Inc., 68 Rogers St., Cambridge, MA 02142, USA
[c] University of Colorado, Dept. of Chemistry and Biochemistry, Boulder, CO 80309, USA
[d] Optoelectronics Division, NIST, Mailstop 815.04, 325 Broadway, Boulder, CO 80305-3328, USA
[e] University of Colorado, Dept. of Mechanical Engineering, Boulder, CO 80309, USA

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ABSTRACT

Gallium nitride nanowires (GaN-NWs) are systems of interest for mechanical resonance-based sensors due to their small mass and, in the case of *c*-axis NWs, high mechanical quality (*Q*) factors of 10,000–100,000. We report on singly-clamped NW mechanical cantilevers of roughly 100 nm diameter and 15 μm length that resonate near 1 MHz and describe the behavior of GaN-NW resonant frequencies and *Q* factors following coating with various materials deposited by atomic layer deposition (ALD), including alumina (Al_2O_3), ruthenium (Ru), and platinum (Pt). Changes in the GaN-NW resonant frequencies with ALD deposition clearly distinguish conformal film growth versus island film growth. Conformal films lead to a stiffening of the NW and typically increase resonant frequency, whereas island films simply increase the NW mass and cause decreased resonant frequencies. We find that conformal growth of ALD alumina leads to stiffening of ~4 kHz per nm of alumina, in agreement with previously measured material properties. Conformal growth of Ru and Pt, respectively, qualitatively confirm our analytical predictions of positive and negative resonant frequency shifts. Island growth of ALD Ru has demonstrated a decrease in resonant frequency consistent with mass loading of ~0.2 fg for a 150 ALD-cycle film, also consistent with analytical predictions. Resonant *Q* factors are found to decrease with ALD film growth, offering the additional possibility of studying mechanical dissipation processes associated with the ALD-NW composite structures.

1. Introduction

Gallium nitride (GaN) nanowires (NWs) are being intensively studied for possible applications in such areas as gas sensing [1], signal processing [2,3], electronic circuitry [4], and light emitting diode (LED) structures [5,6]. In this paper, we investigate the possible use of GaN-NWs in resonant mass sensor applications. NWs are strong candidates for resonant mass sensors, due to the benefits provided by small sensor mass, and high mechanical quality factors [7–11], both of which are provided in the GaN-NW system. Examples of as-grown nanowires are shown in Fig. 1. Briefly, the GaN-NWs investigated here are grown, catalyst free, via gas source molecular beam epitaxy on Si (1 1 1) substrates [12]. The NWs have a defect-free, wurtzite crystal structure with their *c*-axis along the long axis of the NW, have diameters approximately 200 nm, and overall lengths from 15 μm to 20 μm. The average total NW mass is roughly 2 pg and their lowest, singly-clamped, mechanical resonance frequencies are near 1 MHz. The quality (*Q*) factor (defined as the ratio of the resonant frequency to the resonance full width at half maximum power, or FWHM) is in the range 10^4 to 10^5 and has been measured as high as 10^6 [13]. In this paper, we describe the use of GaN-NWs to study ALD film deposition through the shifts in nanowire resonant frequency and *Q* factors. Our results show that NW vibrational frequencies can readily distinguish conformal film growth from island growth, and mode *Q* factors are sensitive to mechanical dissipation losses in the ALD films. Thus, GaN-NW mechanical resonators have great potential for monitoring ALD film growth mechanisms.

2. Resonance theory and measurements

A simple picture of how NW mechanical resonators are sensitive to thin film properties is provided by beam theory for the cantilever flexural resonant modes of a singly-clamped beam [14]. Eq. (1) gives

* Corresponding author. Tel.: +1 303 492 7940; fax: +1 303 492 3352.
E-mail address: Joshua.Montague@Colorado.edu (J.R. Montague).

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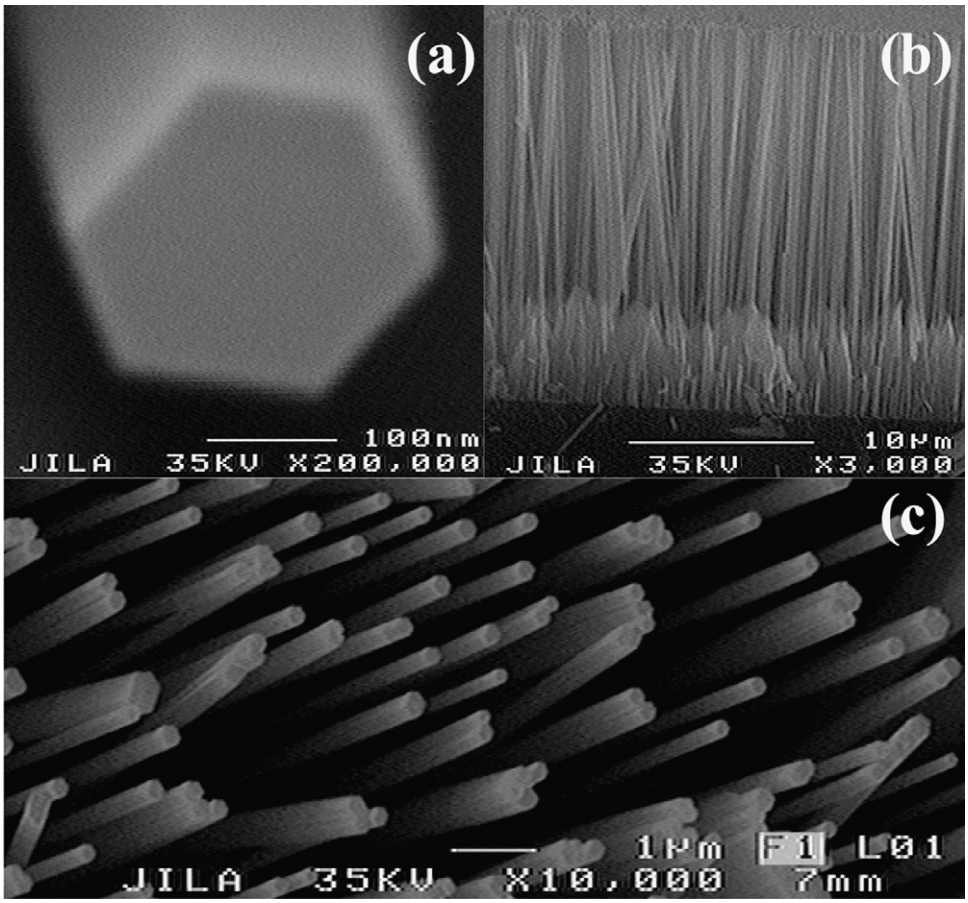

Fig. 1. Electron micrographs of as-grown GaN-NWs [12]. (a) Typical hexagonal cross-section of *c*-axis, wurtzite crystal structure. (b) Side view of nanowire growth from GaN matrix layer to 15–20 μm. (c) Angled plan view of as-grown nanowires.

the resonant frequency for the *n*th mode of such a beam:

$$f_o = \frac{1}{2\pi}\sqrt{\frac{\kappa}{\mu}}\frac{\alpha_n^2}{L^2}. \quad (1)$$

Here, κ and μ are, respectively an effective stiffness and effective mass per unit length, α_n is a dimensionless number determined by the boundary conditions, and L is the beam length. For the lowest-order, fundamental frequency of a singly-clamped beam, $\alpha_o = 1.875$. For simple geometries, $\kappa = EI_2$, where E is the Young's modulus, I_2 is the second moment of the beam (e.g. $\pi r^4/4$ for a circular cross-section with radius r, $5\sqrt{3}a^4/16$ for a hexagonal cross-section with side length a) and $\mu = \rho A$, where ρ is the density and A is the beam's cross-sectional area. Depositing a film on such a beam can change the resonant frequency by two competing effects. First, the added mass of the film increases the total mass per unit length, and thereby can cause a decrease in resonant frequency. Second, the combination of film Young's modulus and degree of continuity can increase the stiffness of the beam and lead to an associated increase in resonant frequency. We find that both of these effects may occur with different ALD coating materials.

As an illustrative example, useful for comparison to our data, consider a cylindrical beam of material 1 (density ρ_1, Young's modulus E_1) and initial radius, r, with an additional uniform thickness, t, of material 2 (ρ_2, E_2). The lowest-order resonant frequency is found within Euler–Bernoulli beam theory to be

$$f_o = \frac{1}{4\pi}\left[\frac{E_1 r^4 + E_2((r+t)^4 - r^4)}{\rho_1 r^2 + \rho_2((r+t)^2 - r^2)}\right]^{1/2}\left(\frac{1.875}{L}\right)^2. \quad (2)$$

Fig. 2 shows the predicted resonant frequency versus ALD film thickness starting with an initial resonant mode at 1 MHz, for the three ALD materials studied in this work: Al_2O_3 (alumina), ruthenium (Ru), and platinum (Pt). The calculated resonant frequencies using a cylindrical cross-section overestimate those of the hexagonal cross-section by approximately 9%.

In the limit $t \ll r$ appropriate for thin layers, we find a first-order shift in the resonant frequency, δf, from the $t = 0$

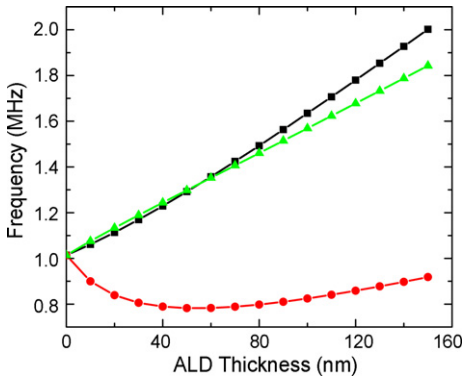

Fig. 2. Predicted resonant frequency shifts for the three ALD materials studied in this work, assuming conformal growth. Squares, triangles, and circles correspond, respectively, to alumina, Ru, and Pt. The initial, bare GaN-NW resonance is set to 1 MHz. The ALD material properties used are described in the text. With alumina and Ru, stiffening of the nanowire dominates the mass loading, causing an overall increase in resonant frequency. For high-density Pt, mass loading dominates initially, followed by stiffening for thicker films. Our experimental results qualitatively confirm these trends.