High *Q* factor for mechanical resonances of batch-fabricated SiC nanowires

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The authors present here the measurements of high mechanical *Q* factors for singly clamped, batch-fabricated SiC nanowires measured by field emission (FE) in ultrahigh vacuum. The resonances of two nanowires, glued to the ends of tungsten support tips, were electrostatically excited and detected by the variation in the FE microscopy (FEM) images. Low amplitude oscillations were measured by numerical analysis of the FEM image blurring during frequency scans through the resonances. This avoided the artificial broadening of the resonances by nonlinear effects. A room temperature *Q* factor of 159 000 was achieved after high temperature *in situ* cleaning. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2432257]

The quality factor Q is an essential parameter in resonating nanoelectromechanical systems (NEMS).[1] It depends strongly on the different fabrication techniques employed which are adapted to specific excitation and detection strategies. Fabrication by top-down high resolution lithography on crystalline substrates and various bottom-up techniques such as the assembly of prefabricated nanotubes and nanowires are currently being exploited.[2] At present, top-down nanocantilevers have significantly higher Q's while the nanotubes and nanowires can have much smaller dimensions where higher sensitivity to external perturbations should be realizable.[1,3]

In this letter we describe the measurement of Q's of up to 159 000 at room temperature for a batch-fabricated SiC nanowire that was simply glued by a bottom-up approach to the end of a tungsten support tip (singly clamped). The nanowire resonances were excited capacitively and detected by the variation in field emission (FE) from its apex in ultrahigh vacuum (UHV) as the driving frequency was scanned through a mechanical resonance. Of note is that we have extended our original FE technique[4] to include an in-scan numerical analysis of the FE microscopy (FEM) images. This was essential because it permitted to measure resonances with $\simeq$100 times lower excitation voltage than previously in the same experimental geometry and thus to avoid artificial resonance broadening by nonlinear effects.

The samples studied here were monocrystalline SiC nanowires covered by nanometer-thick turbostratic amorphous carbon layers. They were produced by a commercially competitive process allowing fabrication of large amounts of SiC-based nanowires with tunable geometric features.[5] Details of the process and characterization of these nanowires have been reported elsewhere.[5,6]

Individual nanowires were glued using a three-dimensional micromanipulator to the apexes of etched W tips. Example scanning electron microscopy (SEM) images are shown in Fig. 1 where we have included images of a nanowire resonating in its first three fundamental modes for illustrative purposes. Two SiC nanowires were used in this study: (1) SiC with diameter ϕ=284 nm and length L=128 μm and (2) SiC with ϕ=206 nm and L=93 μm. The W tip/nanowires were mounted on heating loops and then inserted into an UHV-FEM system (10^{-10} Torr).

The samples were mounted in a triode configuration with an intermediary quadrupole extraction anode at a distance of $\simeq$2 mm.[4] A high enough voltage V_A is applied to the tip such that electrons are field emitted from the nanowire apex. The emission current in these experiments did not exceed several nanompere range for which heating effects for these fairly large cross-section nanowires are negligible. The electrons accelerate away from the apex, pass through the quadrupole, and form a FEM pattern on a phosphor screen placed at about 3 cm in front of the tip. The pattern is recorded by a digital video camera simultaneous to emission current measurements with a sensitive electrometer. In these experiments

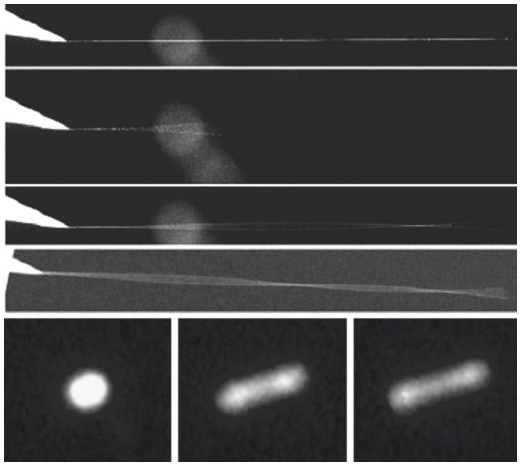

FIG. 1. SEM images of a SiC nanowire (L=243 μm, ϕ=250 nm) similar to the one used in the experiment mounted on a W tip. The nanowire is electrostatically excited in its first three modes. On the bottom are FEM patterns from a SiC nanowire at slightly different frequencies near a resonance. The pattern widens as the resonance maximum is approached.

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V_A was varied from −300 to −600 V for FE. The tips were regularly flashed to ≃1000 K during the experiments.

An additional variable frequency ac voltage V_{ac} is applied to the anodes to excite the resonances of the nanowire. The FEM pattern widens and the FE current varies during the resonances (Fig. 1). From the resonance frequencies Young's moduli for the nanowires were ≃260 GPa for both nanowires, almost independent of heat treatment. Both the FE current and the computer-processed video images are used to extract independently the relative oscillation amplitude. Since our camera is limited at 25 Hz, and our electrometer to 3 Hz, we only detect the time-averaged signals.

The FE current varies as the resonance is scanned because of the variation of the position of the nanowire apex and hence the field amplification factor.[4] This has been recently used to detect the resonances of top-down NEMS cantilevers.[7] However, the dependence of the field on the amplitude of oscillation is a second order effect (we are at an extremum) and as well in our present setup the measured current is averaged over the oscillation. These together mean that the total current measurement does not allow us to detect very small vibrations. For this reason we have turned to the analysis of the FEM images which improves enormously our signal to noise ratio.

To a first approximation the amplitude of the pattern oscillation A is proportional to the angle at the end of the nanowire by simple geometrical projection. A is accurately determined by calculating the variance of the light intensity distribution. (A fuller account of this method will be presented elsewhere.[8]) For the x direction and a distribution $I(x,y)$, the variance σ_x^2 is defined as

$$\sigma_x^2 = \frac{\int_{-\infty}^{\infty} x^2 I(x,y)dxdy}{\int_{-\infty}^{\infty} I(x,y)dxdy} - \left[\frac{\int_{-\infty}^{\infty} xI(x,y)dxdy}{\int_{-\infty}^{\infty} I(x,y)dxdy}\right]^2 \quad (1)$$

and in an analogous way for the y direction. The total variance is given by $\sigma^2=\sigma_x^2+\sigma_y^2$. It is easy to prove that relation between the in σ_{osc} and out σ_0 of oscillation variances and the amplitude is

$$\sigma_{osc}^2 = \sigma_0^2 + \frac{A^2}{2}. \quad (2)$$

The response curves for excitations of millivolt range measured by the variance for SiC(1) are shown in Figs. 2 and 3 after heat cleaning to about 1100 K. These low amplitudes could not be measured by the total FE current which was used for excitations in the volt range. In general the response curves for the nanotubes and nanowires we studied in FE show jumps and hysteresis between up and down scans[8] which is a signature of Duffing mode behavior of nonlinear driven systems.[9] As noted above these effects widen the response curves and thus mask the measurement of the true Q. In principle this may be avoided by going to very low amplitude. The response functions were not simple Lorentzians until the very low excitation of 1 mV. Nonlinear effects are enhanced in the FE configuration by the variation of the stress T and of the excitation force with the position of the nanowire apex and will be explored in a future publication. By using this technique in conjunction with averaging over 3 s per point we reached a linear response with 1 mV excitation with Q=36 000 for SiC(1) (see Fig. 3 inset). After 1100 K cleaning for SiC(2) we obtained Q=94 000, larger but in the same range as that of SiC(1). When SiC(2) was heated to even higher temperatures of 1350 K, Q=159 300 was obtained (see Fig. 3). These measures of Q are actually lower bounds for two reasons. Firstly some drifting of the resonance may occur because of adsorption or generation of defects over the measurement period of 10 min. Secondly the stability of the dc high voltage source plays a direct role because this voltage tunes the resonance frequency.[4]

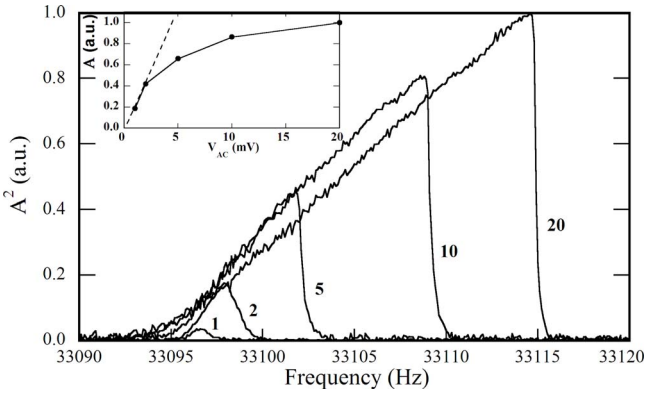

FIG. 2. Square of the amplitude as a function of the frequency for excitations V_{ac} of 1, 2, 5, 10, and 20 mV, for "up" frequency sweeps. The 2 mV curve is still asymmetric and thus nonlinear. The inset shows that the amplitude A is not close to linear in V_{ac} until the lowest voltages.

The derived value of Q is not very dependent on the image size, frequency step size, and averaging if these are chosen reasonably. The noise in the experimental curves comes from the instability in the FE current, setting a lower limit to the measurable amplitude at about ≃2 pixels. This is an experimental determination and depends on many factors. It corresponds to an amplitude at the nanowire apex of 600 nm or 2.5 times ϕ. Such low amplitude measurements can be achieved by long averaging times. The total measurement time, however, is limited by the stability of the oscillator to about 1 h after which thermal treatment must be made to clean the nanowire. Similarly the mechanical relaxation time is not negligible and sets a maximum for step size/step time. The gain in signal to noise ratio of the image method as opposed to the total emission current is ≃100. In fact, this has allowed us to observe and identify up to six of the harmonic resonances predicted by linear response theory.

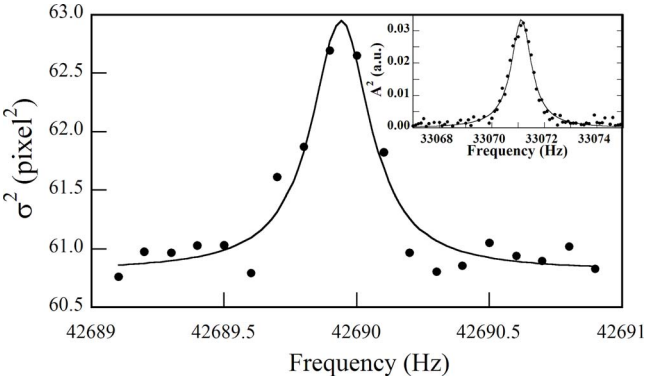

FIG. 3. Responses for 1 mV excitation. The fits to the square of a Lorentzian show that we have reached the linear regime with Q≃159 000 for SiC(2) and Q≃36 000 for SiC(1) (inset). No hysteresis was found.

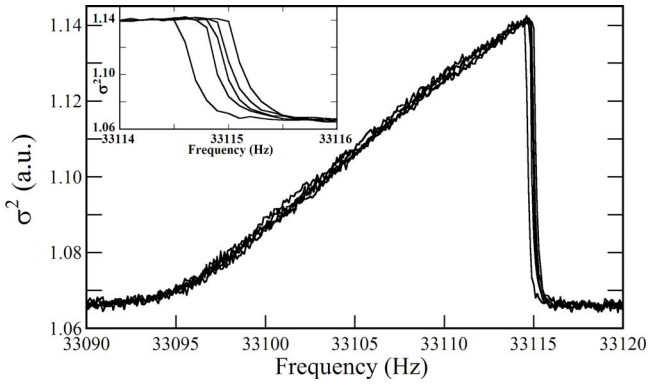

FIG. 4. Repetitive frequency scans at 20 mV excitation showing that the jumps are very reproducible in frequency. The inset is a zoom of the jump region.

Instead of using the linear response of a high Q resonator to measure a physical phenomenon by a frequency shift one could use the jumps in nonlinear response curves.[10] In Fig. 4 we show repetitive response curves for a 20 mV driving of SiC(1). The jumps for this and other millivolt driving frequencies are within a standard deviation of 0.2 Hz. This is equivalent to an effective Q of $\simeq 160\,000$ as opposed to the 36 000. Similarly the signal to noise ratio will be strongly enhanced by the very strong signal generated by the jump.

Comparing Q's from different authors must take into account their different physical and geometrical parameters as no authors measure exactly the same cantilever. In particular, one must scale to different cantilever volumes and temperatures. A literature survey shows that most published Q's for top-down fabricated cantilevers fall roughly linearly on $\log(Q) \simeq 0.3 \log(\text{volume}(\text{mm}^3)) + 6$.[1] The cantilevers measured in the same low volume range as ours were usually at low temperature. Q's scale against temperature with an empirical power law, e.g., $Q \alpha T^{-0.3}$.[11] Our Q value for SiC(2) would extrapolate to $Q(4\text{ K}) \simeq 600\,000$. For our volume $\log(\text{volume}(\text{mm}^{-3})) \simeq -8.5$ we are well above the top-down log plot for $Q(300\text{ K}) = 159\,000$ and very much above for the extrapolated low temperature value. A final remark is that Verbridge *et al.*[3] have very recently shown that double clamping can enormously increase the Q of top-down nanowires by introducing on-axis strains. Our nanowires were only singly clamped.

Damping factors include gas pressure viscosity, surface defects, mobile adsorbate surface layers, contact losses, and interactions with the transducer.[1,3] These intervene before the ultimate losses due to phonon generation and electron excitations can be reached. The high Q in our case can therefore be attributed to the high quality crystalline nature of our nanowire and the high temperature cleaning and UHV that remove mobile adsorbates, reduce reabsorption, completely remove gas viscosity, and finally crystallize the anchor glue and the nanowire itself.

In conclusion we have shown that nanometric-scale bottom-up fabricated resonators can have high quality factors that compete with those of top-down approaches. Similarly we have presented a sensitive detection technique for the mechanical resonances of nanotubes and nanowires. The technique may be useful in FE vacuum nanoelectronics devices where the use of spilt detection anodes would be similar to our image analysis technique. We are pursuing these measurements by going to lower temperatures, smaller SiC nanowires of the same fabrication, mounting, treatment and detection, and single wall carbon nanotubes.

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