Young's Modulus and Size-Dependent Mechanical Quality Factor of Nanoelectromechanical Germanium Nanowire Resonators

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Supporting Information

Ge Nanowire Synthesis. Ge nanowires were synthesized by the supercritical fluid-liquid-solid (SFLS) approach[1-5] in a continuously-stirred 250 mL PARR reactor. This procedure yields ~1 g of crystalline Ge nanowires in a single reaction, with little particulate byproduct. Anhydrous hexane with 34.8 mM diphenylgermane (DPG, Geleste) and 3 nm diameter dodecanethiol-coated gold nanocrystals (prepared by arrested precipitation as described in the literature[6]) are fed into the reactor at the Au/Ge molar ratio of 1:1200 at 380 ºC and 800psi. The flow rate for the reaction was 7 mL/min (a residence time of 35 min). The total volume of hexane, DGP and Au nanocrystals are 500 mL, 3.25 mL and 1.25 mL, respectively. Before removing the nanowires from the reactor, they are exposed to isoprene for surface passivation. The reactor is cooled to 250 ºC and the pressure is increased to 1100 psi with the addition of hexane. Then 25 mL of isoprene is added to the reactor while the temperature was maintained at 250 ºC, which increased the pressure to 2300 psi. The reactor was then cooled to 145 ºC, flushed with hexane at 5 mL/min for 25 min, and then further cooled to 75 ºC and flushed again with hexane at 5 mL/min for 10 min. The reactor was finally cooled to room temperature and the wires were removed from the reactor. The Ge nanowires ranged from approximately 10 nm to 200 nm in diameter with predominantly a [110] growth direction with few extended defects. Surface passivation using isoprene was verified by X-ray photoelectron spectroscopy (XPS) and Fourier transform infrared (FTIR) spectroscopy, as described in detail in Ref. 3.

Error Propagation. Error in the calculation of the Young's modulus of the fabricated nanoelectromechanical germanium nanowire resonantors in this study was determined from the propagation of the measured quantities in the expression

$$E = 64\rho\left(\frac{\pi f_1}{d}\right)^2\left(\frac{L}{\beta_1}\right)^4 \quad , \tag{1}$$

where E is the Young's modulus, ρ is the density of Ge, f_1 is the resonant frequency of the first eigenmode, d is the nanowire diameter, L is the cantilever length, and $\beta_1 = 1.875$ for the first eigenmode. The error in the diameter and length were based on the clarity of TEM and SEM images and were estimated at 5 nm and 100 nm, respectively. Error in f_1 was determined from the Lorentzian fits to the measured frequency-dependent amplitudes of vibration of the nanowire resonators. The error was propagated as

$$\Delta E = E\sqrt{\left(\frac{\Delta f_1}{f_1}\right)^2 + \left(\frac{2\Delta d}{d}\right)^2 + \left(\frac{4\Delta L}{L}\right)^2} \quad , \tag{2}$$

and ranged from 3-35 GPa (8-19 %).

The error propagated in the calculation of the mechanical quality factors

$$Q = \frac{f_1}{\Delta f_1} \quad , \tag{3}$$

resulted from the error in the resonant frequency, f_1, and the FWHM, Δf_1, extracted from the Lorentzian fits to the data. This was propagated as

$$\Delta Q = Q\sqrt{\left(\frac{\Delta f_1}{f_1}\right)^2 + \left(\frac{\Delta(\Delta f)_1}{\Delta f_1}\right)^2} \quad , \qquad (4)$$

and ranged from 16 to 128 (3 to 41 %).

Movie of a Ge Nanowire Flexed Between Two STM Probes. The movie ("Flexed Ge nanowire movie") demonstrates the enhanced elasticity of a Ge nanowire as it is flexed between two tungsten probe tips. The wire was welded to the larger probe tip by electron beam-induced deposition of platinum.

Movie of an Oscillating Nanoelectromechanical Ge Nanowire Resonator. The movie ("Oscillating Ge nanowire cantilever") shows a Ge nanowire oscillating as the applied sinusoidal AC field nears the resonance frequency of the cantilever. The AC voltage is being swept from 143-145 kHz in 100 Hz steps. The resonant frequency of this 135 nm diameter resonantor was 144 kHz.

References

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