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High frequency torsional-mode nanomechanical resonators enabled by very thin nanocrystalline diamond diaphragms

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ABSTRACT

We report an experimental demonstration of high-frequency (HF) torsional-mode nanomechanical resonators based on nanocrystalline diamond films as thin as 50 nm. Devices axially supported by pairs of tethers as small as 90 nm × 50 nm in cross section are fabricated from suspended diaphragms by using focused ion beam (FIB), showing multi-mode resonances with frequencies (f_{res}) into the HF band (up to ~10 MHz, while most existing sensitive torsional devices are at kHz or low-MHz), and quality (Q) factors exceeding 1800 at room temperature in moderate vacuum (~20 mTorr). This fabrication process evades the conventional electron-beam lithography and etching steps that are destructive for very thin diaphragms. From the torsional and flexural modes of device resonances, we calculate Young's modulus (E_Y) to be as high as 977 GPa, which is almost comparable to the known value of 1220GPa for single-crystal diamond.

1. Introduction

Diamond has been a particularly attractive and interesting material for constructing micro/nanoelectromechanical systems (MEMS/NEMS) because of its exceptional mechanical properties (Young's modulus up to 1220 GPa), and relatively low mass density (3500 kg/m^3), which provides a high acoustic velocity resulting in high frequency mechanical resonators [1–3]. Its very high thermal conductivity (22 W/(cm·K)), and excellent wear/corrosion resistivity make diamond suitable for sensing, signal processing and communication in harsh environments [4]. As device dimensions scale down for applications that require higher sensitivity or higher speed, thin films of diamond have been grown by techniques such as microwave plasma chemical vapor deposition (MPCVD) [5,6], or hot filament chemical vapor deposition (HFCVD) [7,8], showing material properties comparable to single crystal diamond. Resonant structures based on polycrystalline, nanocrystalline, and ultrananocrystalline diamond films have been explored [8–17], demonstrating both high frequency (HF) and high quality (Q) factor resonators.

Torsional resonators are usually composed of a pair of tethers that support a paddle, with the paddle rotating with respect to the center line defined by the tethers. These devices are particularly interesting for sensing applications because high frequency can be achieved by the miniaturized tethers, while adequate capturing area can be realized by the rotating paddles [18,19]. Various sensing applications have been demonstrated based on torsional resonators [20–31], demonstrating the capability of this type of device design. These devices are mainly built on Si and SiN layers and fabricated by electron-beam lithography or photolithography, or with carbon nanotubes grown by bottom-up synthesis, which require careful chemical processing or etching. It would be desirable to explore torsional devices beyond these materials that are compatible with sensing in harsh environments. Towards this goal, we have explored torsional resonators using a 'smart-cut' 1.2 μm-thick 6H-SiC film [32] that is suitable for harsh environment applications, and demonstrated photon sensing with these devices [33]. Now we extend the technology to diamond thin films grown by CVD that are as thin as 50 nm while maintaining desirable material properties. Torsional resonators based on polycrystalline diamond have been demonstrated [11]; however, torsional devices based on diamond thin films showing resonances in the HF band have not yet been developed.

In this work, we demonstrate the first double-tether-supported nanocrystalline diamond torsional resonators with high resonance frequencies. We fabricate torsional resonators on 50 to 100 nm thin nanocrystalline diamond films with tether dimensions as small as 50 nm × 90 nm in cross section, and torsional paddles typically 5 μm × 2 μm in area. Focused ion beam (FIB) is carefully adjusted to fabricate the devices on suspended diaphragms, avoiding several challenging chemical processing steps that can adversely affect fabrication yield. Raman spectroscopy is performed on both suspended and non-suspended areas for films with different thicknesses to assess the quality of the diamond films. We measure multimode resonances of both undriven thermomechanical motions and the optically driven vibrations of these devices with laser interferometry, which show torsional resonances up to 8.4 MHz and Q's over 1800. From the resonance frequency of the torsional mode, we estimate Young's modulus $E_Y \approx 977$GPa which is close to single crystal diamond. We also calibrate the device performance at different pressures from 25 mTorr to atmosphere pressure, and observe the effect of air damping at pressure higher than 1 Torr.

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2. Device design and basic theory

The device has a torsional paddle supported by a pair of thin parallel tethers. For torsional motion, the tethers and the torsional paddles rotate around the axis defined by the two tethers, as shown in Fig. 1(a). Figure 1(b) illustrates the simulation result of the torsional mode shape by finite element modeling (FEM), which is consistent with Fig. 1(a): as one side of the paddle rotates up, the other side moves down, and the center of the paddle in line with the tethers does not move. The governing differential equation for torsional resonance is expressed as

$$\rho\frac{\partial^2\theta}{\partial t^2} = G\frac{\partial^2\theta}{\partial x^2}, \tag{1}$$

where ρ is the mass density, $G = E_Y/2(\gamma_P + 1)$, and γ_P is Poisson's ratio [34]. The equation can be rewritten as

$$\frac{\partial^2\theta}{\partial t^2} = a^2\frac{\partial^2\theta}{\partial x^2}, \tag{2}$$

where $a = \sqrt{G/\rho}$, which is similar to the case of the flexural mode. The resonance frequency of a torsional resonator can be expressed as

$$f_{res} = \frac{1}{2\pi}\sqrt{\frac{2J_TG}{L_TI}}, \tag{3}$$

where L_T is the tether length and J_T is the torsional area moment of inertia, which for rectangular cross section is

$$J_T = w_Tt^3 \times \left(\frac{1}{3} - 0.21 \times \frac{t}{w_T} \times \left(1 - \frac{{w_T}^4}{12 \times t^4}\right)\right), \tag{4}$$

where w_T is the tether width, t is the film thickness. I is the total mass moment of inertia from both the tethers and the paddle which is given by:

$$I = I_{tether} + I_{paddle} = \frac{1}{6}\rho tL_Tw_T\left({w_T}^2 + t^2\right) + \frac{1}{12}\rho twL^3, \tag{5}$$

where w is the paddle width and L is the paddle length [35,36].

According to the above Eq. (4), for the thickness range we consider (1-50nm), J_T increases with increasing t, while from Eq. (5) I also increases with t. Since the resonance frequency increases with higher J_T, but decreases with higher I, there is a tradeoff. As shown in Fig. 1(c), the torsional-mode resonance frequency (f_{res}) of this particular device we choose does not change monotonically with film thickness; instead, only at thickness greater than ~15 nm, f_{res} increases with increasing t, while for films thinner than ~15 nm, f_{res} increases with lowering thickness. Meantime, f_{res} is also related to multiple device parameters, such as Young's modulus (E_Y) of the material, the tether width w_T, tether length L_T, and paddle size L and w. Diamond has very high Young's modulus and low mass density, thus it has interesting potential for high frequency and high quality (Q) factor devices. Further, thinner devices are desirable for achieving better sensitivity when we use the device as force, torque or inertia sensors [32]. Therefore here we use very thin nanocrystalline diamond films for fabricating the devices.

3. Experiments

3.1. Device fabrication processes

Fabrication of the torsional resonators starts from nanocrystalline diamond films provided by Applied Diamond Inc.™ that were deposited by a MPCVD technique on Si substrates [37]. The suspended diaphragms are obtained by attaching a plastic etch mask on the back side of Si and performing isotropic wet etching with a HF/HNO_3 mixture (Fig. 2). Then FIB is performed with 30 kV and 10pA Ga^+ ions to pattern the devices. Compared to electron-beam lithography that requires patterning on the substrate-supported film and then releasing the device with etching, this technique has a higher likelihood of obtaining suspended structures once FIB parameters are properly determined. Even if the fragile diaphragms are broken due to handling or previous etching steps, suspended devices can still be fabricated on patches of the broken diamond diaphragms with careful FIB processing. This high-resolution FIB method avoids many of the chemical processes associated with electron-beam lithography, enabling rapid prototyping of device structures with small dimensions. Torsional devices are fabricated on both 50 nm thick and 100 nm thick broken nanocrystalline diamond diaphragms.

The FIB process requires careful engineering to successfully fabricate suspended torsional devices with thin tethers (Fig. 3). Low ion beam current is necessary so that in the milling process the ion beam pressure on the film does not easily tilt or twist the device since the broken films are quite pliable. Furthermore, optimizing the sequence of patterning is required so that the pressure on the film or stress in the film is more evenly distributed to prevent the FIB area from moving relative to the desired location of the device being fabricated. Fig. 3(a) shows our initial attempt in milling all the parts enclosed in the orange border in a single FIB sequence using a beam current of ~50 pA. The resulting device is pictured in Fig. 3(b), showing that the initial fabrication approach is not successful because the entire device is twisted and the tethers are malformed. We improve the process by performing FIB sequentially with the individual steps indicated by the numbers 1–10 in Fig. 3(c). Process steps 5–8 are repeated several times to gradually narrow the tethers, which induces minimal stress on the film because only a small amount of the film is milled away during each step. This method efficiently yields torsional diamond resonators with very thin tethers (Fig. 3(d)). We could also add more FIB steps to mill away the surrounding area

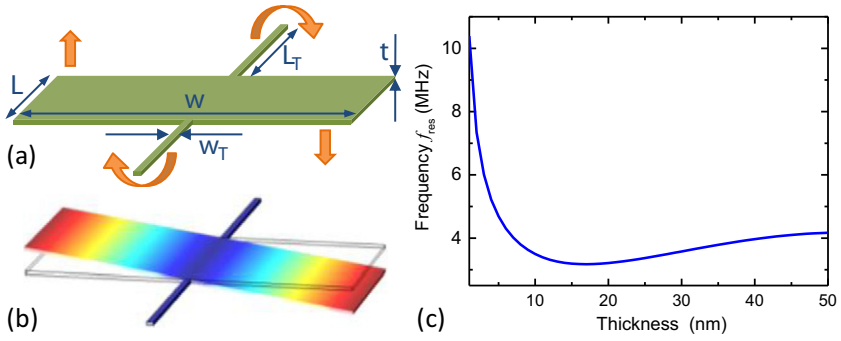

Fig. 1. Conceptual renderings of the diamond torsional resonators. (a) Illustration of the designed torsional resonator, with arrows showing the tether and paddle rotation. (b) FEM simulation of the torsional mode shape using COMSOL. (c) Dependence of the torsional mode resonance frequency on the film thickness. The parameters used are: $E_Y = 977$ GPa, Poisson ratio $\nu_P = 0.069$, $L_T = 2$ μm, $w_T = 50$ nm, $L = 2$ μm, $w = 5$ μm.