Nanomechanical Tuning Forks Fabricated by Focused-ion-beam Chemical Vapor Deposition

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Numbers of researchers have been working on nanomechanical resonators to realize various novel devices including sensors of ultra-high sensitivity. Quality factor ($Q$-factor) enhancement of the nanomechanical resonators is of great interest to the researchers because the resolution of the resonator sensors is determined by the $Q$-factors. In this paper, we employed tuning forks, which are schematically depicted in Fig. 1, to achieve high-$Q$ on the nanomechanical resonators. Although tuning forks are known as a traditional high-$Q$ mechanical resonator, they have rarely been employed for the $Q$-enhancement of the nanomechanical resonators. The nanomechanical tuning forks were fabricated by focused-ion-beam chemical vapor deposition (FIB-CVD). A schematic of the fabrication is shown in Fig. 2. A focused gallium ion beam was irradiated on a silicon substrate in the phenanthrene ($C_{14}H_{10}$) atmosphere of $10^{-4}$ Pa. By controlling the irradiation point of the FIB, nanomechanical tuning forks made of diamond-like carbon (DLC) were fabricated perpendicular to the silicon surface. A scanning electron microscope image of the nanomechanical tuning forks is shown in Fig. 3. The arms of the tuning forks were 3.6–6.9 $\mu$m long, 1.1 $\mu$m wide, and 0.3 $\mu$m thick. For the vibration characteristics comparison, DLC cantilevers of the same size order were also fabricated by FIB-CVD.

Vibration characteristics of the nanomechanical tuning forks were investigated with a laser-Doppler vibration measurement system. An oscillation laser was irradiated around the base of the tuning forks and a measurement laser was irradiated around the tip of the tuning fork arms. A network analyzer was used to obtain resonant curves from the laser-Doppler measurement. The resonant frequencies and $Q$-factors of the tuning forks and cantilevers measured at 10 Pa and room temperature are plotted in Fig. 4(a). Comparing the cantilevers and the in- and anti-phase mode of the tuning forks, the anti-phase mode represented the highest $Q$-factor. The result proved that the tuning forks possess the superiority of $Q$-factor even in the nanometer-order scale. Subsequently, the same samples were measured in the air. As shown in Fig. 4(b), in contrast to the measurement in the vacuum, the anti-phase mode represented the lowest $Q$-factors. On the nanomechanical tuning forks, since the distances between the arms are too small (below 2 $\mu$m in our sample), the motion of the arm is considered to affect each other through the air between the arms. Detailed theoretical discussion about the resonant frequency and $Q$-factor of the tuning forks will be provided in the paper.

**Figure 1**: Tuning forks and its primal resonant modes: Since the anchoring loss is decreased, the anti-phase mode represents higher $Q$-factors.

**Figure 2**: Schematics of tuning fork fabrication by FIB-CVD: The irradiation point of the FIB was controlled by a function generator.

**Figure 3**: Scanning electron image of nanomechanical tuning forks fabricated by FIB-CVD: An acceleration voltage and a beam current of the FIB used in the fabrication were 30 kV and 7 pA, respectively. Fabrication time of the tuning forks shown in this image was 4 minutes per sample.

**Figure 4**: Experimentally measured resonant frequencies and $Q$-factors of nanomechanical tuning forks and cantilevers: (a) Measurement at 10 Pa. (b) Measurement in the air.