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Surface effects and high quality factors in ultrathin single-crystal silicon cantilevers

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Surface effects in ultrathin single-crystal silicon cantilevers of 170 nm thickness, which are optically actuated mainly by the light pressure effect, are investigated under ultrahigh vacuum (UHV) condition. Annealing the cantilevers at 1000 °C for 30 s in UHV results in an over 1 order of magnitude increase of the quality factor (Q factor), up to about 2.5×10^5 for cantilevers of 30–90 μm in length. The improvement of Q factor was found to be associated with the deoxidization of the surface, as determined by x-ray photoelectron spectroscopy. These results suggest that the surface effects in the ultrathin cantilevers dominate their mechanical behavior. With the promising mechanical behavior, the cantilever can be easily actuated by a laser beam (beam size: about $300 \times 100 \mu\text{m}^2$) with power down to less than 40 μW at a wavelength of 680 nm, corresponding to 480 nW, i.e., 1.64×10^{12} photons/s, irradiated on the cantilever surface ($60 \times 6 \mu\text{m}^2$). This provides a rather simple way to operate the ultrathin cantilevers dynamically in UHV. Atomic scale force resolution (4.8×10^{-17} N) at 300 K is also expected with these cantilevers. © 2000 American Institute of Physics. [S0003-6951(00)03749-9]

Ultrahigh force sensitivity and fast response of the cantilever are crucial points for the achievement of atomic scale force resolution in scanning probe microscopy (SPM), force-detected nuclear magnetic resonance (NMR), and electron spin resonance (ESR).^{1–3} The force resolution achievable for a freely vibrating cantilever is limited by the thermomechanical noise in the mechanical system. Setting the minimum detectable force δF_{\min} equal to the effective noise force δF_{noise} can be described as⁴

$$\delta F_{\min} = \sqrt{\frac{4kk_BTB}{\omega_0 Q}}, \quad (1)$$

where k is the spring constant, k_B the Boltzmann constant, T the temperature, B the bandwidth, ω_0 the resonance frequency, and Q the quality factor (Q factor). Equation (1) indicates that a low spring constant, a high resonance frequency, and a high Q value are essential for measuring an ultrasmall force at a given temperature. For cantilevers of rectangular shape, scaling down the thickness and length are favorable for the former two demands, respectively, but it seems not to be advantageous for the Q factor. Recent articles^{5–8} have suggested that the Q factor decreases proportionally to the cantilever thickness because the surface-to-volume ratio increases, therefore the surface loss becomes dominant in a thinner cantilever. Thus stronger efforts should be made to clarify the role of the surface effects. This is

important not only for the improvement of the Q factor, but also for a stable operation of the cantilever dynamically under a certain environment. In this letter, we actuate 170 nm thick single-crystal Si cantilevers by a laser beam with a power less than 40 μW at a wavelength of 680 nm, and measure the Q factor under various surface conditions of the cantilevers. High Q factors up to the 10^5 range with corresponding ultrahigh force sensitivity of about 4.8×10^{-17} N at room temperature can be achieved by our ultrathin cantilevers with clean and stable surfaces.

With the above considerations in mind, first an ultrahigh vacuum (UHV) system with a preparation chamber for surface treatment and a laser Doppler chamber for *in situ* mechanical properties measurement of the cantilevers was built up, as shown in Fig. 1. The vacuum is maintained at $(1-2) \times 10^{-10}$ mbar, while it is lower than 1×10^{-8} mbar during sample treatment. The good vacuum condition enables the clean surfaces of the cantilevers to be preserved during measurement. After annealing at 600 or 1000 °C in the preparation chamber, the sample was transferred to the laser Doppler chamber by a linear motion transfer. A 680 nm laser beam emitted from a laser diode (LD) was reflected by a mirror before impinging on the cantilever through an optical window of the UHV system. The mechanical resonance of the actuated cantilever is detected by the laser Doppler system and analyzed by a network analyzer, which also outputs a drive signal to modulate the pump frequency of the LD and thereby drives the cantilever into oscillation. Compared to other experimental arrangements, e.g., piezo actuation, the optical actuation simplifies the dynamic operation for cantilevers in UHV condition. The output power of the

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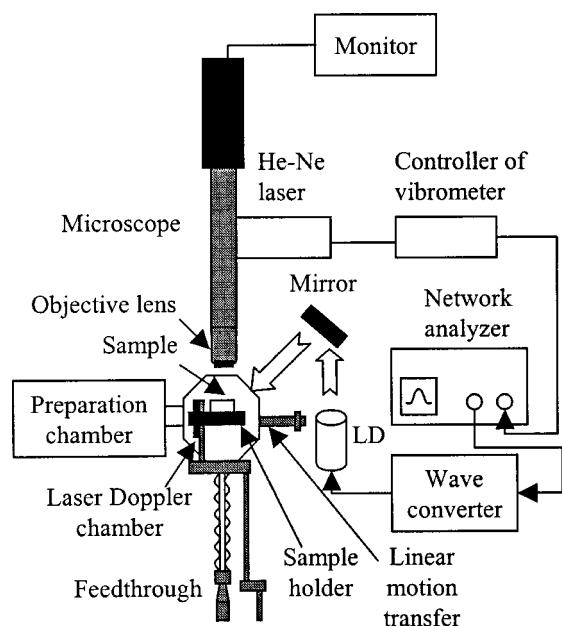


FIG. 1. Schematic diagram of UHV system consisting of a preparation chamber, a measurement chamber, and laser Doppler measurement loop.

LD was calibrated versus input pump current by using a GaAs power meter located in front of the window of the UHV system. The calibration result is given in Fig. 2.

Cantilevers 13–90 μm long and 170 nm thick have been fabricated on Si (100)-oriented [separated by implanted oxygen (SIMOX)] wafers. Length to width ratio for all the cantilevers studied is about 10:1. Details of the fabrication process have been described in Ref. 5. This fabrication process resulted in cantilevers without any observable curvature under optical microscope.

The laser power dependence of the resonance frequency

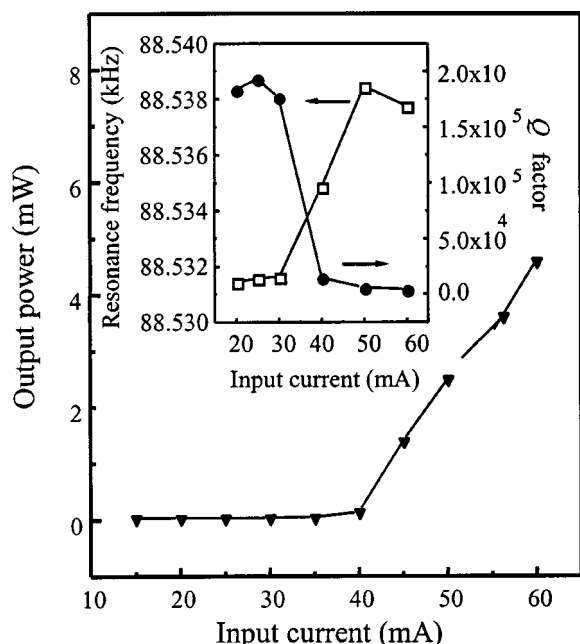


FIG. 2. Input pump current dependence of laser power before the UHV optical window. Inset shows resonance frequency and Q factor of a 48 μm long, 5 μm wide, and 170 nm thick cantilever as a function of input pump current of LD. The “soft spring” effect induces sharp changes in resonance frequency and the Q factor, as can be clearly seen at 30–40 mA.

and Q factor of a 48 μm long cantilever annealed at 1000 °C for 30 s was investigated and is shown in the inset of Fig. 2. By increasing the LD output power, the measured Q value and vibration amplitude (not shown here) decrease sharply, while resonance frequency increases slightly. This observation indicates that the “soft spring” effect⁹ occurs when the ultrathin cantilever is irradiated with a higher laser power, that is, actuated by a stronger actuation force. In order to ensure that the measurements were undisturbed by the soft spring effect, we limited our experiments to a laser output power of approximately 40 μW. The corresponding input pump current for the LD is 20–30 mA, close to the minimum threshold (~15 mA) of the LD. For all cantilevers with different lengths, the laser output power of about 40 μW is enough to excite and maintain a stable resonant vibration, revealing good mechanical properties of the cantilevers. Considering the laser beam size of about 300 × 100 μm², such a power level indicates that the laser power distributed on one 60 μm long and 6 μm wide cantilever is about 480 nW. Thus, the number of photons incident on this cantilever surface per unit time can be estimated as $n = p\lambda/hc = 1.64 \times 10^{12}$ photons/s, where $p = 480$ nW, $\lambda = 680$ nm, h is Planck’s constant, and $c = 3 \times 10^8$ m/s.

The feasibility of optically actuating the Si₃N₄ cantilever has been demonstrated, and the result suggests that a light pressure effect rather than photothermal effect plays a major role at room temperature.¹⁰ We found that our cantilevers can be actuated optically even when the temperature is raised up to about 780 °C. In this case, the temperature gradient along the cantilever thickness direction induced by the photothermal effect could be very small compared to the sample temperature. This fact suggests that the photothermal effect contributes much less to the actuation of Si cantilevers than the light pressure effect. Thus, we think that the cantilevers are mainly driven by the light pressure effect. Assuming that the momentum transfer of the absorbed photons can be neglected in comparison with the contribution of the reflected photons, for the above-mentioned 60 μm long and 6 μm wide cantilever, the light pressure force could be roughly estimated by $F = ((1 + R)hn/\lambda) \times \cos \alpha = 1.07 \times 10^{-15}$ N, where $R = 0.34$ is the reflectance of Si at a wavelength of 680 nm, $\alpha \approx 60^\circ$ the light incident angle, h is the Planck’s constant, and n the incident photon number per second.

Figure 3 shows the length dependence of Q factor for cantilevers under different treatments in the UHV chamber. The freshly fabricated cantilevers have Q factors around 10⁴, with little dependence on their length. This result is consistent with our previous study.⁵ For the ultrathin single-crystal silicon cantilevers operated in UHV or high vacuum condition (~10⁻⁶ Torr), air damping and internal friction are negligible. The shorter the cantilevers (<30 μm), the lower the Q factors due to obvious support loss.⁵ The Q values are independent of cantilever width, but proportional to the thickness because of the dominant surface dissipation. For cantilevers 30–90 μm long, annealing at 600 °C for 30 min in UHV increases the Q factor by 1 order of magnitude (into the 10⁵ range). Subsequent annealing at 1000 °C for 30 s causes a further increase of the Q values by a factor of 2–3. Keeping the sample in UHV for about 24 h after annealing at 1000 °C obviously reduces the Q factors of all the cantile-

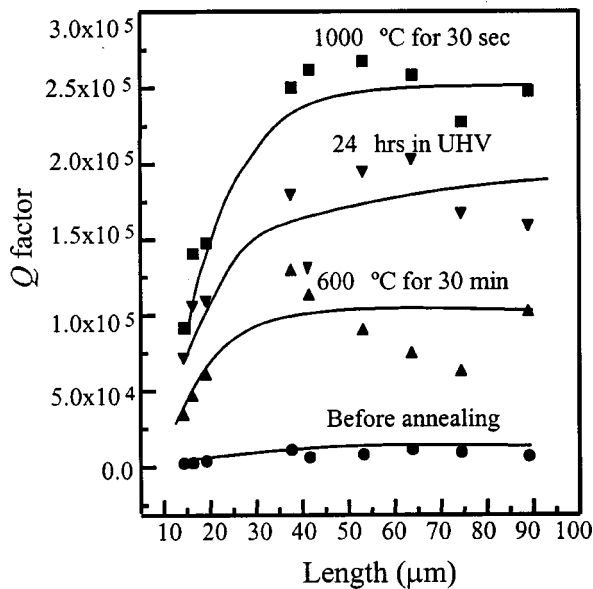


FIG. 3. Q factor of a set of cantilevers, 170 nm thick and 13–90 μm long (length to width ratio of 10:1) on one chip. UHV annealing leads to significant increase of Q factor, up to about 2.5×10^5 for 30–90 μm long cantilevers annealed at 1000 $^{\circ}\text{C}$ for 30 s.

vers, which suggests that the change in Q factor is caused by surface modification rather than annealing effect. These results indicate that the ultrathin cantilever is seriously subjected to the surface effect. According to the reports on the cleaning of the Si(100) surface in UHV,^{11,12} annealing at 600 $^{\circ}\text{C}$ in UHV could remove some adsorbates on the cantilever surface, e.g., H_2O and some organics. Flashing at 1000 $^{\circ}\text{C}$ for a short time will further clean the surface by desorbing most of the organics and some SiO_2 , modify the surface structure and thus the surface stress, which could be related to the surface energy dissipation.

Moreover, in order to get further insight into the surface modification during annealing of the samples, one large pattern of 400 $\mu\text{m} \times 400 \mu\text{m}$ plus several microcantilevers of 170 nm thick and several tens of micrometers long were fabricated on another chip by the same process. This patterned chip was annealed in UHV at 1000 $^{\circ}\text{C}$ for 15 s four times in a sequence. After each annealing, the surface of this square pattern was monitored by x-ray photoelectron spectroscopy (XPS) while the mechanical properties of the microcantilevers were examined. After annealing at 1000 $^{\circ}\text{C}$ for the first 15 s, no carbon peak can be detected, only photoelectron peaks of Si_{2S} , Si_{2P} , and O_{1S} , and an Auger peak of O_{KLL} are observed. As shown in Fig. 4 for cantilevers of 16, 56, and 80 μm long, annealing at 1000 $^{\circ}\text{C}$ in UHV reduces oxygen concentration on the surface and simultaneously enhances the Q values.

Our present study demonstrates that the surface effect plays an important role in the mechanical behavior of the ultrathin single-crystal silicon cantilever. Treatment under different conditions in the UHV chamber was able to clean the surface, thus modifying the surface stress condition, improving the Q values beyond 10^5 . According to Eq. (1), for a cantilever with length $L=60 \mu\text{m}$, in terms of our previous

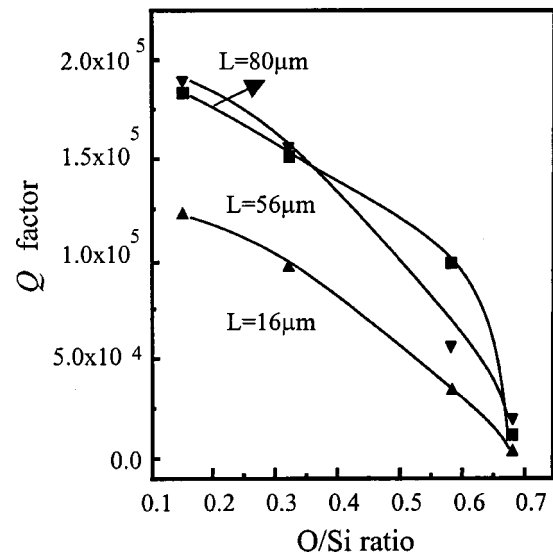


FIG. 4. Monotonic dependence of Q factor on O/Si ratio for three 170 nm thick cantilevers with lengths of 16, 56, and 80 μm (length to width ratio 10:1), respectively. Q factor and O/Si ratio were determined by *in situ* laser Doppler measurement and XPS, respectively, after annealing at 1000 $^{\circ}\text{C}$ for 15, 30, 45, and 60 s.

data in Ref. 5, $\omega_0 = 2\pi \times 50 \text{ kHz}$, $k = 4.4 \times 10^{-3} \text{ N/m}$, and $B = 1 \text{ Hz}$, the minimum detectable force is $4.8 \times 10^{-17} \text{ N}$ at room temperature, which is suitable for the ultrasensitive applications in SPM, NMR, and ESR. Our present research reveals that scaling down the size of the cantilever does not necessarily mean suppression of the Q factor, and that a higher Q factor and thus higher force sensitivity are achievable if the proper surface treatment and passivation process such as H termination⁶ are adopted for the ultrathin microcantilever.

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