DOMINATED ENERGY DISSIPATION IN ULTRATHIN SINGLE CRYSTAL SILICON CANTILEVER: SURFACE LOSS

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ABSTRACT

The effect of surface treatment in UHV chamber on Q factor of cantilevers with different thickness (60nm, 170nm and 500nm) and different surface orientation was investigated. When length L>30μm, Q factor is proportional to thickness, surface loss dominates. While L<30μm, support loss surpasses the surface loss. Heating can remove SiO_2 layer and absorbates, and result in an increase of Q factor. Hydrogen termination leads to a larger relative increase of Q factor in thinner structure than in thicker ones. Heating and H exposure improve Q values of Si(100) oriented cantilevers more than Si(110) oriented ones and result in the contrary resonance frequency response for these two surfaces.

INTRODUCTION

As a force sensor in SPM, micromachined cantilever is required to have a high quality factor (Q factor), a high resonant frequency and a small spring constant for achieving ultrahigh sensitivity. Miniaturization of the sensor is an effective routine for the later two factors, but it seems not to be advantageous for Q-factor. Recent researches have suggested that Q factor decreases with the size[1,2]. When the cantilever thickness scales down, the surface-to-volume ratio increases, the surface loss becomes dominated. The surface loss is mostly caused by surface stress which could significantly be modified by absorbates on the surface or surface defect[3,4]. When absorbate exists on the surface, the charge transfer between the surface and the absorbate, the Coulomb repulsion of the dipole moments associated with the adsorbate atoms and the overlap of the wave function of absorbates atoms orbits at a close distance would modify the surface stress, and lead to surface loss. Moreover this modification is different with crystallographic orientation[3]. The surface dissipation is proportional to the square of the peak strain integrated over the surface area of the beam. For the fundamental flexural mode of the cantilever, Q factor would be proportional to the thickness. Therefore, in the high surface-to-volume ratio structure, surface effect has become a crucial restriction for resonator device miniaturization. However, despite of its signification, little knowledge is understood for the surface loss mechanism in these ultrathin microstructures. To gain deep insight of this dissipation behavior and its relation to the sizes of devices, the present work focuses on studying the effect of surface treatment in Ultra-High-Vacuum(UHV) chamber on Q factor of microcantilevers with different thickness and crystallographic orientations.

It is well know that, the clean Si(100) and Si(110) surface usually display 2×1 and 2×16 reconstructure, respectively[5]. On these bulk-terminated surface each Si atom has one or two dangling bonds(dbs), which determines the initial reactivity of the surface and a final surface structure. In addition, hydrogen plays an important role in silicon surface chemistry, for instance, the stability and destabilization of one surface structure with different surface stress[6-8]. Thus the surface stress could be modified by hydrogen dose under various conditions. On the other hand, hydrogen terminated surface is chemically inert and is not easily oxidized in atmosphere, which is of importance for our present analysis. Having these insights in mind, we arranged the following treatment process: firstly the sample is flash-annealed in UHV chamber according to the usual condition to obtain a clean surface; Then exposure to atomic hydrogen is done to further modify the surface stress. Finally the modification is estimated by the response of Q factor and resonance frequency of cantilevers.

EXPERIMENTAL PROCEDURES

The cantilevers with length of 5–100μm have been fabricated from (100) oriented SIMOX (Separated by IMplanted OXygen) wafer with 60nm and 170nm thick top Si layer, SOI wafer with a 500nm thick top Si layer (Fig.1) and (110) oriented SIMOX wafer with a 160nm thick top Si layer. The details of the fabrication process and the measurement setup for mechanical properties of the cantilevers were described in [1]. The

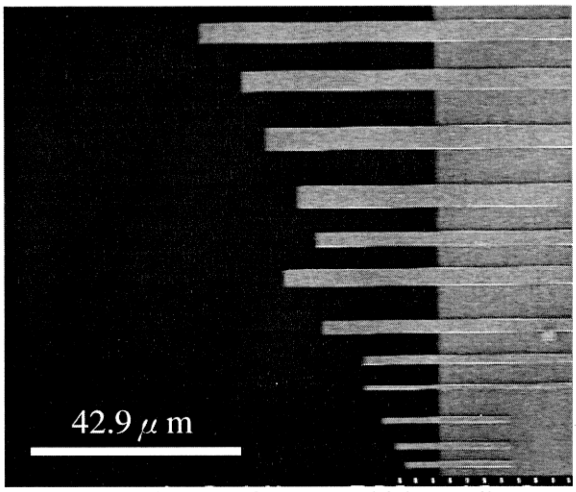

Fig.1: SEM image of 500nm thick cantilevers with length of 5-100μm.

surface treatment was performed in an UHV chamber with a base pressure of 10^{-10} torr. The sample temperature was measured by a calibrated pyrometer. Firstly the cantilevers were outgassed at 600°C for 30min-1hr, then quickly flashed at 900-1000°C for three times to remove SiO_2. During the treatment, the vacuum level is kept in the order of 10^{-9} torr. Atomic hydrogen was produced by the decomposition of molecule hydrogen on a 1500°C tungsten filament. Exposure to atomic hydrogen with a pressure around 5×10^{-8} torr was accomplished at room temperature and above 300°C for 30sec to 2min. After cooled down to room temperature in the UHV chamber, the cantilevers are transferred to a laser doppler system for measurement. The time interval for this transference was kept below 15min in order to reduce the atmosphere effect on the surface to as little as possible [9].

RESULTS AND DISCUSSION

As discussed in ref. [1], the last step of the fabrication process (O_2 asher) of cantilevers could lead to formation of thin SiO_2 layer on the surface[10]. For 170nm thick Si (100) cantilever, after heating at 1000°C, Q factors of all cantilevers increase clearly (as shown in Fig.2, (b)) due to the removal of the SiO_2 layer and surface absorbates. After exposing to atomic hydrogen, the surface could be modified further by hydrogen termination, the effect of native SiO_2 and the absorbates from atmosphere during sample transference was further reduced. As a result more increase of Q factor was obtained (Fig.2, (c)). However, the prolonged exposure to atomic hydrogen for 2min at room temperature (RT) results in serious etching of cantilever (Fig.3) and deteriorates Q factor very much (Fig.2, (d)). It is well established in ref. [7] that, saturation exposure of a clean Si(100) 2×1 surface to

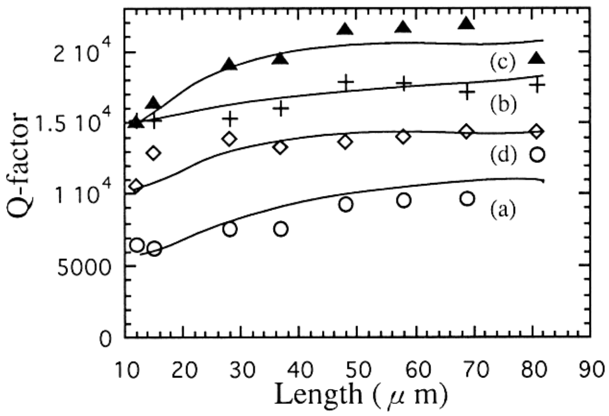

Fig.2: Length dependence of Q factors for 170nm thick cantilevers before (a) and after (b) heating at 600°C for 1hr and flashing at 1000°C for three times, after exposure to atomic hydrogen above 300°C for 30sec (c) and at RT for 2min (d).

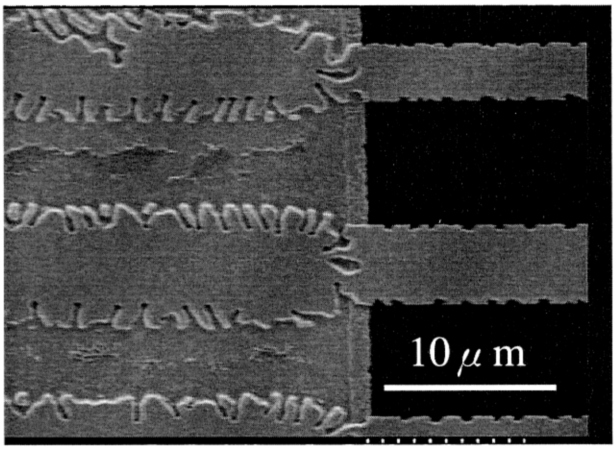

Fig.3: SEM image of 170nm thick cantilevers after exposure to atomic hydrogen at RT for 2 min.

atomic hydrogen at 300°C results in the formation of a monohydride surface. Hydrogen reacts with dbs on the Si dimer atoms while the dimer bonds and the associated 2×1 surface periodicity remains intact. Saturation exposure at lower temperature (room temperature (RT)) results in the 1×1 dihydride surface structure. The steric interaction between the neighboring dihydride units on the 1×1 surface produces strain which weaken the bonds within the units, as a result these bonds are susceptible to further attack and etching by hydrogen atoms.

In contrast to above result, exposing the slightly bent, 170nm thick cantilever to atmosphere for one month reduces the Q factor obviously (Fig.4, (b)). However, exposure to atomic hydrogen can still recover the Q factors of these cantilevers to 20000 (Fig.4, (c)). Comparing the results for flat cantilevers in Fig.2 with those for slightly bent cantilevers in Fig.4, we can infer that the surface dissipation is more serious than that caused by bending.

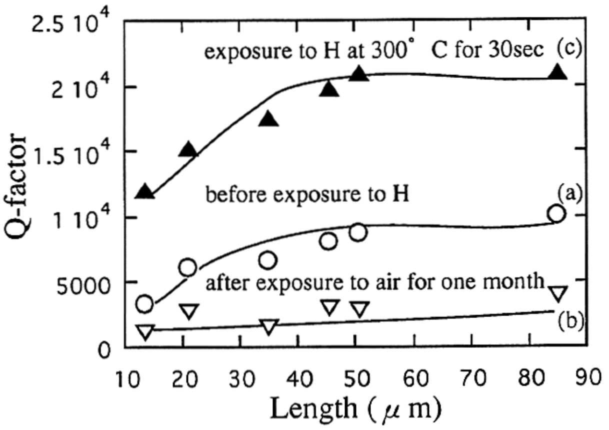

Fig.4: Q-factor vs length for slightly bent cantilevers before (a) and after (b) exposure to atmosphere for one month, and (c) to atomic hydrogen.

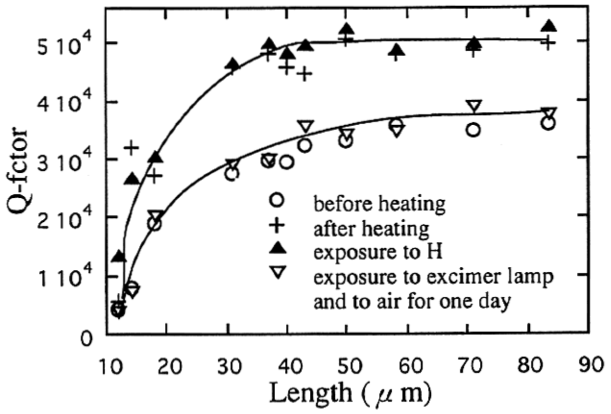

Fig.5: Q-factor vs length for 500nm thick cantilevers before and after heating, after exposure to atomic hydrogen, to excimer lamp and atmosphere.

When the thickness of cantilevers rise up to 500nm, the Q values of the cantilevers increase to around three times of the corresponding ones for 170nm thick cantilevers. Heating at 900-1000°C in UHV enhances the Q values a lot (Fig.5). However, exposure to atomic hydrogen did not make much change, probably since the thick cantilevers are not so sensitive to the effect of short-time exposure to air during transference between two chambers and to the surface modification by hydrogen termination. During the treatment in UHV chamber, another possible factor for improving Q factor is thermal effect. In order to testify if the heat treatment contributes to the increase of Q factor. The cantilever were exposed to an excimer lamp (USH10 co.) with wavelength of 172nm and total exposure energy of 180mJ/cm^2 for breaking Si-H bond, then to atmosphere for one day. As shown in Fig.5, the Q factors decrease to the similar level to those before treatment, from which, we can come to the conclusion that the improvement of the Q factor mainly originates from the surface modification, not thermal effect.

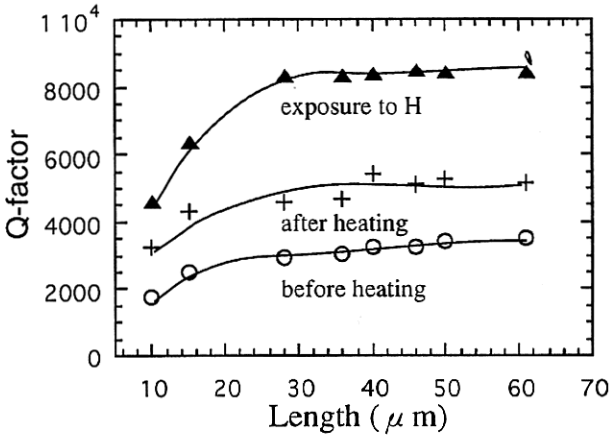

Fig.6: Q-factor vs length for 60nm thick cantilevers before and after heating, and after exposure to atomic hydrogen

When the thickness of cantilevers is reduced to 60nm, the Q values scale down correspondingly. As shown in Fig. 6, the thin cantilevers are more sensitive to the effect of short-time exposure to atmosphere during transference, as a result heating in UHV improves the Q factor a little (Fig.6, after heating). Hydrogen termination passivates the surface more effectively from air exposure [9], and results in more increase of the Q factors (Fig.6, exposure to H)

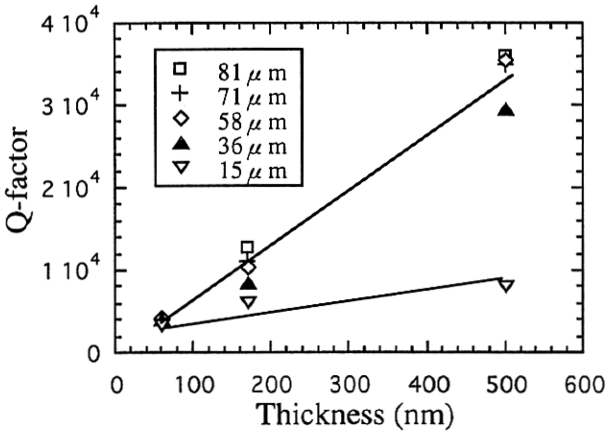

Fig.7: Q-factor vs. thickness for cantilevers with different length

Fig.7 shows the thickness dependence of Q factors for cantilevers with different length. For cantilevers with L>30μm, Q factor is almost proportional to the thickness, which indicates the surface loss dominates in these structures. But the thickness dependence of Q values for cantilevers with L<30µm deviates this relationship, suggesting that support loss play a more important role than surface loss in the shorter cantilevers (also see Figs.2, 4, 5, 6&11) [1]. As shown in Fig.8, surface modification has more influence on Q factors of the thinner structures than of the thicker ones. Due to the difficulty for analyzing the cantilever surface, at this moment, we can not definitely describe how heating and exposure to atomic hydrogen have modified the surface. With reference to the previous work by other researchers [6-8], the possible surface modification process is outlined in Fig.9. During heating at 600°C, some absorbates can be removed; heating at 900-1000°C can remove SiO_2 and most absorbates, result in a nearly clean surface except for SiC remaining locally on the surface, the removal of carbon requires a high temperature up to 1250°C. At such a high temperature, step flow occurs within very short time (<5 sec), leads to serious structure damage and low Q factor, especially for 60nm thick cantilever. At this process step, some of the surface structure may convert to Si (100) 2x1 with one dangling bond on each dimer atom (Fig.9, (b)). During transference from the UHV chamber to the laser doppler system, very thin native oxide and absorbate layer might be formed on the clean surface (Fig.9, (c)) and modify the surface stress, produce various effects on the Q factors for three differently thick cantilevers. Exposure to atomic hydrogen at above 300°C is favorable for formation of Si(100) 2x1:H monohydride surface structure with high stability and less stress (Fig.9, (d)). The considerable increase of the Q factor after exposure to atomic hydrogen could be a consequence of both surface modifications by this monohydride structure and the passivation effect. Another thing worthy noting is the resonance frequency response to the treatment: during adsorption and desorption, both mass loading and change of surface stress could induce a change of the resonance frequency [11]. As shown in the inset of Fig.10, heating and hydrogen termination decrease the resonance frequency. This result is counter to that anticipated only due to mass loading, suggests that the resonance frequency be mainly determined by surface stress. And this tendency is typical for adsorption and

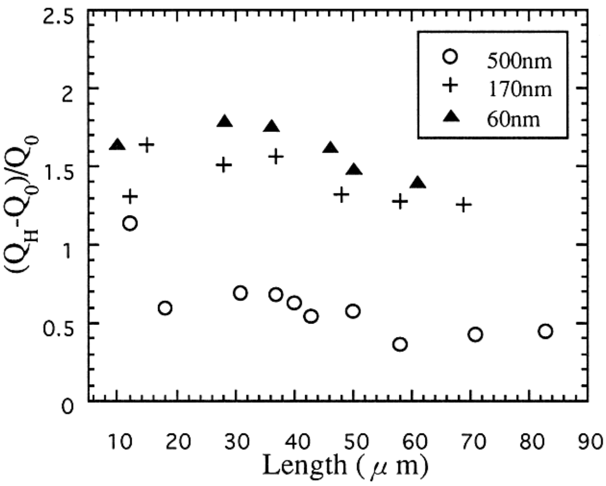

Fig. 8: Length dependence of relative change of Q factor before (Q_0) and after (Q_H) exposure to atomic hydrogen for cantilevers with different thickness

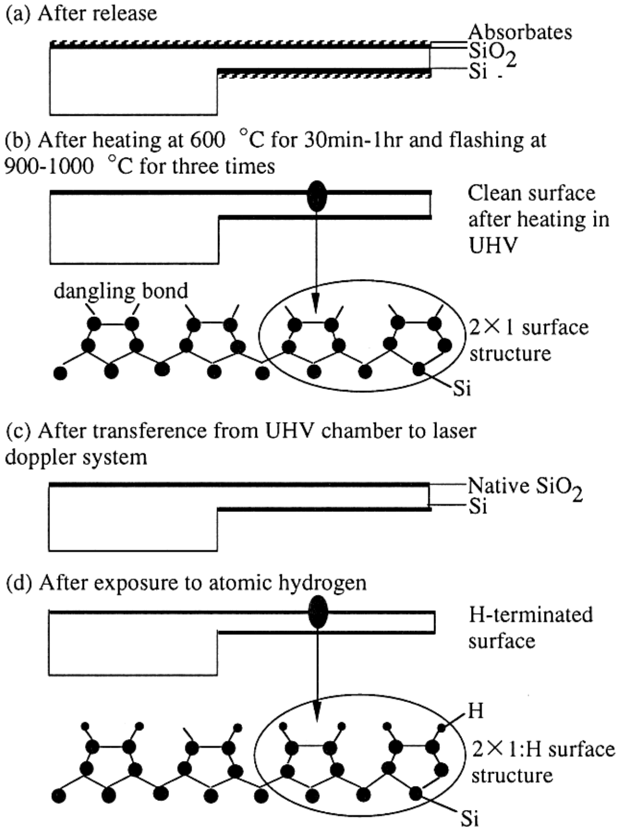

Fig.9: Skeleton diagram of surface treatment process

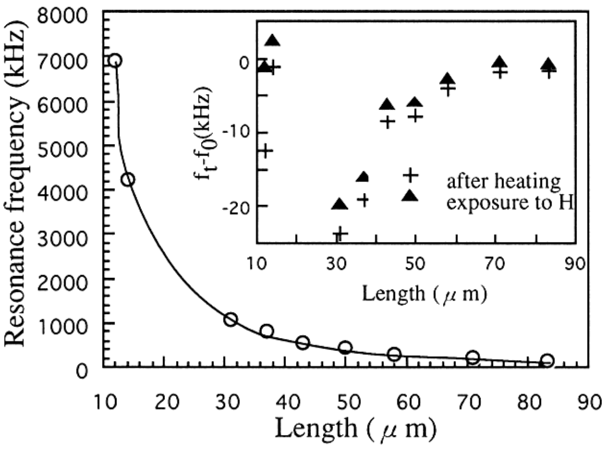

Fig.10: Length dependence of resonance frequency before treatment and their response to treatment for Si(100) oriented, 500nm thick cantilevers. f_0 and f_t: resonance frequency before and after treatment.

desorption on semiconductor surface[12]. But how these processes modify the surface stress is still unclear.

As mentioned in previous section, surface stress is closely related to the crystallographic orientation. In order to testify the different surface modification by treatment on differently oriented surface, cantilevers with similar sizes were fabricated from (110) oriented SIMOX wafer with 160nm thick top Si layer. As shown in Fig.11, Q factors of untreated cantilevers are comparable to the corresponding values of (100) oriented 170nm thick cantilevers. However, heating and exposure to atomic hydrogen increases the Q values much less than the (100) oriented cantilevers. This difference could be attributed to the different surface structure. Under the present treatment condition, after heating at 1000°C, clean Si(110) surface could reconstruct into 2×16 structure, hydrogen exposure would rearrange the surface atoms to bulk-like structure site, and form 2×16:H surface structure [13]. Compared to Si(100) structure, the surface modification on Si(110) by heating and exposure to atomic hydrogen is far different. As shown in Fig.12, the resonance frequency response to heating and hydrogen exposure on Si(110) surface are contrary to that on Si(100) surface (inset of Fig.10). At present, we can not give reasonable explanation about this result. More analytic investigation is needed to clarify this surface modification mechanism.

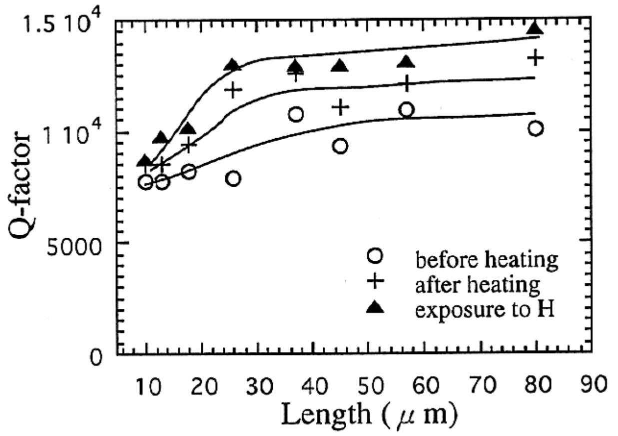

Fig.11: Q-factor vs. length for (110) oriented cantilevers before and after heating, and after exposure to atomic hydrogen

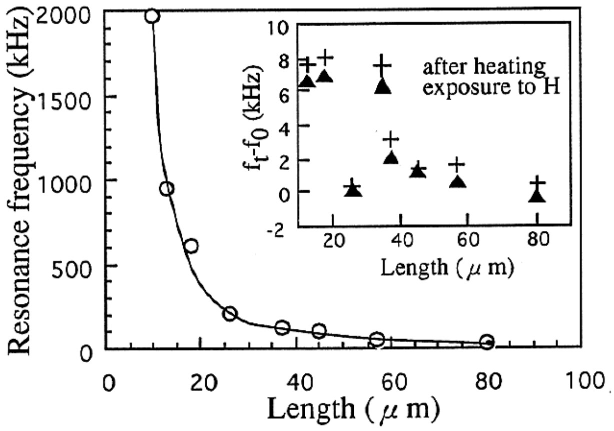

Fig.12: Length dependence of resonance frequency before treatment and their response to treatment for Si(100) oriented, 160nm thick cantilevers. f_0 and f_t: resonance frequency before and after treatment.

CONCLUSIONS

This aim of this work is to investigate the effect of surface modification on Q factors of cantilevers with different thickness (60nm, 170nm and 500nm) and different surface orientation. For cantilever with length L>30μm, Q factor is proportional to the thickness, surface loss dominates. For cantilevers with L<30μm, support loss overshadows the surface loss. Heating can remove SiO_2 layer and absorbates, obviously modify the surface structure and results in an increase of Q factor. Exposure to atomic hydrogen leads to a larger relative increase of Q factor in thinner structure than in thicker ones. The thinner cantilevers are more sensitive to the effect of atmosphere. Heating and exposure to atomic hydrogen improve Q values of (100) oriented cantilevers more than (110) oriented ones. On the other hand, the contrary resonance frequency response was observed for these two surfaces, probably due to the different surface structure. In order to better control the surface characteristics, next step the laser doppler system and UHV system will be combined. Thus systematic investigation of surface modification, for example, by one monolayer, could be performed by well controlling the vacuum level. With these promising properties of the microcantilever (high resonance frequency, low spring constant and high Q factor), the goal of atomic force resolution could be achieved ultimately.

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