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Spurious-free cantilever excitation in liquid by piezoactuator with flexure drive mechanism

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We have developed a cantilever holder for spurious-free cantilever excitation in liquid by piezoactuator. In the holder, generation and propagation of an acoustic wave are suppressed by "acoustic barriers," i.e., boundaries between two materials having significantly different acoustic impedance while cantilever vibration is excited by "flexure drive mechanism" utilizing elastic deformation of a flexure hinge made of a material having a low elastic modulus. The holder enables to obtain amplitude and phase curves without spurious peaks in liquid using a piezoactuator, which ensures stability and accuracy of dynamic-mode atomic force microscopy in liquid. © *2009 American Institute of Physics.* [doi:10.1063/1.3238484]

I. INTRODUCTION

Dynamic-mode atomic force microscopy (AFM) (Ref. 1) has been widely used for imaging nanoscale surface structures of various materials. In dynamic-mode AFM, a cantilever is mechanically oscillated at a frequency near the resonance. The amplitude, phase, or frequency of the cantilever oscillation is detected and used for the tip-sample distance regulation. The cantilever oscillation is typically excited by shaking a piezoactuator (PZT) integrated in a cantilever holder (i.e., piezoelectric excitation). However, the amplitude and phase curves obtained by piezoelectric excitation often show distortions due to an excitation of spurious resonances of the cantilever holder by acoustic waves generated by the PZT. This problem is particularly evident in AFM applications in liquid owing to an increase in propagation paths through liquid[2] and a low Q factor of the cantilever resonance.

In order to avoid the influence of spurious resonances, other methods such as magnetic[3] and photothermal[4,5] excitations have been developed. In addition to experimental studies, theoretical studies have been carried out to investigate the difference in cantilever dynamics between these excitation methods.[6] Although these methods enabled spurious-free cantilever excitation in liquid, piezoelectric excitation has still been the most widely used owing to its simplicity and usability. Thus, considerable efforts have been made for suppressing the influence of spurious resonances in piezoelectric excitation.[7–10] These efforts mainly focus on improving the efficiency of the cantilever excitation through an acoustic wave by controlling its propagation from a PZT to a cantilever as well as to the other mechanical components constituting the cantilever holder.

In contrast, here we present a method referred to as "flexure drive mechanism," where cantilever vibration is excited through elastic deformation of a flexure hinge induced by vibration of a PZT. Meanwhile, the generation and propagation of an acoustic wave are suppressed by "acoustic barriers," i.e., boundaries between two materials having significantly different acoustic impedance (Z_a). This method has distinctive advantages over the previous methods using piezoelectric excitation. The method enables spurious-free cantilever excitation without using special components such as an ultrasonic transducer or a Fresnel lens.[7,8] In addition, the method provides complete isolation of a PZT from liquid.

II. DESIGN DETAILS

Figure 1 shows schematic illustrations of the cantilever holder consisting of four major parts: a holder body (plastic: PEEK), a PZT, an optical window (glass: BK7), and a base support (stainless steel: SS316). For comparison, we also prepared another cantilever holder having the same design except that the holder body is made of SS316. SS316 and PEEK are widely used as materials of a cantilever holder for liquid-environment AFM because of their chemical resistance and machinability. The PZT is attached to the upper side of the holder body, providing a complete isolation from the liquid. The optical window is fit into a hole prepared in the holder body for providing a laser beam path for the cantilever deflection measurement. A Si cantilever is fastened onto the base support with a metal fitting made of SS316 (not shown here).

A. Acoustic barriers

Application of an excitation voltage to the PZT induces its mechanical vibration, giving a stress on the holder body at their boundary. The stress gives rise to an acoustic wave which propagates through the holder body to the boundaries with the optical window and the base support. If the major part of this acoustic wave is transmitted through these boundaries to reach the cantilever and to excite its vibration, amplitude and phase curves will show multiple peaks owing to the influence from the spurious resonances.

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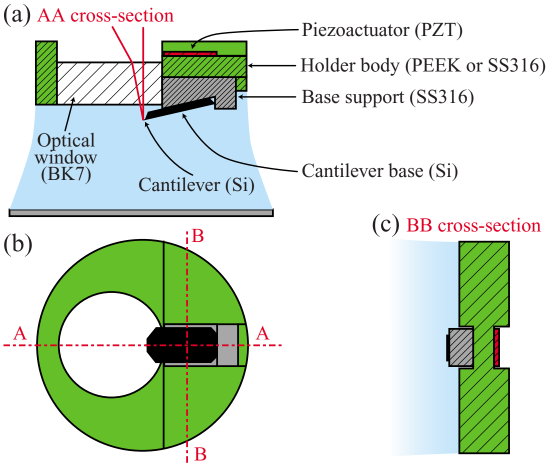

FIG. 1. (Color online) Schematic illustration of the developed cantilever holder. (a) AA cross section. (b) Bottom view. (c) BB cross section.

In order to suppress such influence, the generation and propagation of the acoustic wave are suppressed in the developed cantilever holder [Fig. 2(a)]. At the boundary between the PZT and the holder body, the efficiency of the acoustic wave generation decreases with increasing the mismatch of their Z_a values. Thus, we used PEEK having a much lower Z_a value (3.3×10^6 kg/m^2 s) than that of PZT ($Z_a=33\times 10^6$ kg/m^2 s) for suppressing the acoustic wave generation [Fig. 2(a)]. In contrast, if we use SS316 as the material of the holder body [Fig. 2(b)], the acoustic wave is efficiently generated owing to the close impedance matching between SS316 ($Z_a=36\times 10^6$ kg/m^2 s) and PZT.

In addition to the generation of the acoustic wave, we also suppressed its propagation at the boundaries between the holder body and the adjacent components. Assuming that a plane acoustic wave is transmitted through a boundary between two materials having acoustic impedances of Z_{a1} and Z_{a2} with an incident angle of 90°, the energy transmittance (T_e) of the acoustic wave is given by[11]

$$T_e = \frac{4Z_{a1}Z_{a2}}{(Z_{a1}+Z_{a2})^2}. \tag{1}$$

The equation shows that T_e decreases with increasing the impedance mismatch between the two materials.

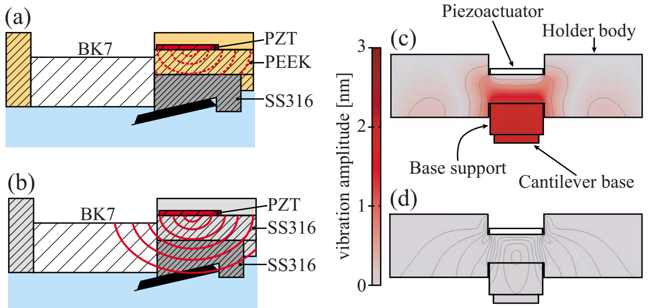

FIG. 2. (Color online) Schematic illustrations of acoustic wave propagation in the cantilever holder with a holder body made of (a) PEEK and (b) SS316. Two-dimensional distribution of vibration amplitude in the simplified model of the flexure hinge made of (c) PEEK and (d) SS316 simulated by FEM (COMSOL MULTIPHYSICS 3.5A, COMSOL Ltd.). The PZT was driven with an ac voltage having an amplitude of 1 V_{p-p} and a frequency of 148 kHz which corresponds to the resonance frequency of the cantilever used in the experiment shown in Fig. 3.

To suppress the propagation of the acoustic wave, we used PEEK as the material of the holder body as it has a relatively low Z_a value compared to that of the surrounding components such as the optical window (BK7: $Z_a=11\times 10^6$ kg/m^2 s) and the base support (SS316). Owing to the large impedance mismatch, the transmissions through the PEEK/BK7 ($T_e=0.71$) and PEEK/SS316 ($T_e=0.31$) boundaries are greatly reduced [Fig. 2(a)]. The effect of such "acoustic barriers" is highlighted, when we consider the case where SS316 is used instead of PEEK. As both of the holder body and the base support are made of SS316, the acoustic wave is transmitted through the boundary without reflection as schematically shown in Fig. 2(b). Note that the propagation of an acoustic wave through liquid is negligible as the cantilever is surrounded by the bottom of the optical window and the side of the base support (Fig. 1).

B. Flexure drive mechanism

While the generation and propagation of the acoustic wave are restricted by the acoustic barriers, cantilever vibration is excited by the "flexure drive mechanism." In our design, the PZT and the base support are fixed on the both sides of a flexure hinge as shown in Fig. 1(c). An impulsive force generated by the vibration of the PZT gives rise to an elastic deformation of the flexure hinge. This deformation is directly translated as the displacement of the cantilever base, which excites the cantilever vibration.

In the flexure drive mechanism, elasticity of the material used for the flexure hinge significantly influences the efficiency of the cantilever excitation. To investigate such an influence of the elasticity, we performed a two-dimensional simulation of a simplified model of the flexure hinge made of PEEK and SS316 using finite element method (FEM) as shown in Figs. 2(c) and 2(d), respectively. The model has the same cross section as the developed cantilever holder [Fig. 1(c)] and a depth equal to the length of the PZT. Figures 2(c) and 2(d) show the distribution of the vibration amplitude in the vertical direction of the figures. Owing to the low elastic modulus of PEEK (Young's modulus: $E_Y=4.2$ GPa), the flexure hinge made of PEEK shows much larger vibration amplitude than that for the one made of SS316 ($E_Y=193$ GPa). The result reveals that the use of a compliant material such as PEEK is vital for the cantilever excitation by the flexure drive mechanism.

III. RESULTS AND DISCUSSION

To confirm the effect of the flexure drive mechanism and the acoustic barriers, we measured amplitude and phase curves using each of the developed cantilever holders with a holder body made of SS316 or PEEK (Fig. 3). The amplitude curves in Fig. 3(a) show several peaks around the resonance frequency while those in Fig. 3(b) present a single peak at the true resonance frequency of the cantilever. The phase curves in Fig. 3(c) show nonmonotonic frequency dependence with irregular peaks. In contrast, the phase curves in Fig. 3(d) show monotonic frequency dependence without significant peaks around the resonance frequency. The results

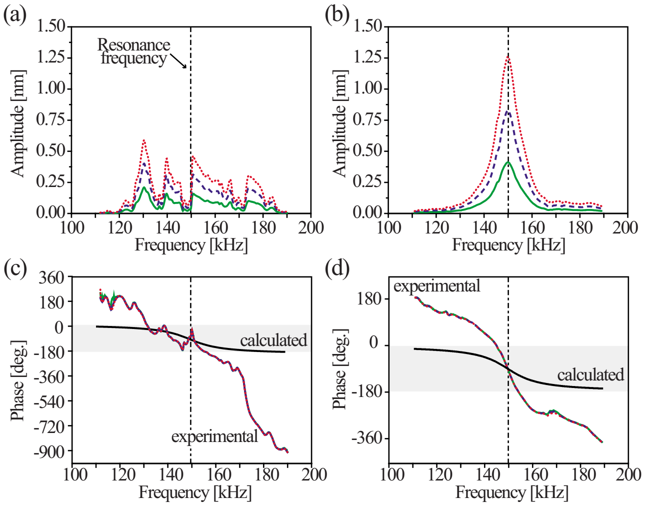

FIG. 3. (Color online) Amplitude and phase curves obtained by the developed cantilever holder with the holder body made of SS316 [(a) and (c)] and PEEK [(b) and (d)]. All the measurements were performed in pure water with a Si cantilever (PPP-NCH, Nanoworld) having a resonance frequency of 148 kHz and Q factor of 7.6 in water. These parameters were determined by fitting a thermal vibration spectrum of the cantilever and used for calculating the ideal phase curve as shown in (c) and (d). The cantilever was driven with an excitation signal having amplitude of 50, 100, or 150 mV. Note that the measured phase curves in (c) and (d) appear as a single curve due to their small dependence on the excitation amplitude.

reveal that the spurious resonances in amplitude and phase curves are greatly suppressed by using PEEK as the holder body to form the acoustic barriers.

The peak amplitude at the resonance frequency in Fig. 3(b) is much higher than the amplitude of the spurious peaks in Fig. 3(a). The phase curves in Fig. 3(c) show a larger deviation from the calculated phase curve than the curves in Fig. 3(d). These results suggest that the flexure drive mechanism has a higher efficiency and causes a smaller phase delay than the acoustic wave excitation does.

The improvements achieved by using the acoustic barrier and the flexure drive mechanism lead to several advantages in dynamic-mode AFM. The elimination of the spurious peaks in the amplitude and phase curves makes it possible to stably oscillate a cantilever at the true resonance frequency, which gives a higher force sensitivity, stability, and accuracy in dynamic-mode AFM. Although the remaining phase delay caused by the flexure drive mechanism may give an error in force measurements by frequency modulation AFM or in phase imaging by amplitude modulation AFM, the linear frequency dependence of the phase error around the resonance frequency [Fig. 3(d)] allows us to apply a simple linear compensation to recover the true phase information. This has been impossible with the acoustic wave excitation due to the influence of spurious resonances [Fig. 3(c)].

In general, compliant materials tend to have a higher thermal expansion coefficient (α_{th}) than rigid materials. For example, α_{th} values of PEEK and SS316 are 4.8×10^{-5} and $1.6\times 10^{-5}\ \mathrm{K}^{-1}$, respectively. However, the typical drift rate achieved by our setup using the developed cantilever holder made of PEEK is approximately 1 nm/min, which is sufficiently low for subnanometer-resolution imaging as experimentally demonstrated.[12] Thus, the increase in α_{th} is not a serious problem even in high-resolution imaging.

The flexure drive mechanism utilizes elastic deformation of the flexure hinge with a millimeter scale dimension. The maximum driving frequency should be determined by the resonance frequency of the hinge. In our setup, the resonance frequency is estimated to be a few hundreds of kilohertz. Since the resonance frequency used in this study (148 kHz) is relatively high for a cantilever used in the liquid-environment AFM, the developed cantilever holder is applicable to most of the practical experiments in liquid. It is likely that the maximum frequency can be enhanced by optimizing the design parameters in the flexure drive mechanism.

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