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Near-field light detection by conservative and dissipative force modulation methods using a piezoelectric cantilever

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We demonstrated near-field light detection by dynamic force microscope using a self-sensing piezoelectric cantilever having a lead zirconate titanate thin film layer. The cantilever tip was brought close to a glass plate with a patterned chromium film on a right angle prism. The backside of the prism was irradiated by an intensity modulated laser light to create an evanescent field at the glass surface. We obtained near-field optical images of the patterned glass by detecting the frequency shift modulation or the amplitude modulation induced by the near-field light while the tip-sample distance was regulated by the frequency modulation method in ambient condition. © *2010 American Institute of Physics*. [doi:10.1063/1.3449131]

Scanning probe microscopy has become one of the most important research tools in the field of surface science, material science, and biology. We have been developing scanning near-field optical microscopy (SNOM) based on dynamic force microscopy (DFM), which is capable of mapping optical characteristics as well as surface topography.[1,2] In this system, we utilize a self-sensing piezoelectric cantilever having a lead zirconate titanate (PZT) thin film layer to avoid stray light from the optical displacement sensor which is required for conventional cantilevers. Since the pyramidal hollow of the tip in the self-sensing cantilever, which is referred to as the PZT cantilever hereinafter, is made of silicon nitride and PZT, which are transparent, the near-field optical images can be collected by an objective lens and a photomultiplier tube. However, the signal-to-noise ratio (SNR) of the collected optical image was not excellent because of the low collection efficiency of light even with a relatively large aperture. On the other hand, the apertureless SNOM has an advantage that the cantilever tip does not require an aperture and it has a high SNR as long as the scattered light was efficiently collected and the background light was sufficiently suppressed.[3,4]

Here we propose alternative apertureless SNOM based on the detection of the interaction force modulation induced by the intensity modulated near-field light. We utilized the frequency modulation (FM) detection method,[5] in which the conservative and dissipative interaction forces can be independently detected as the resonance frequency shift and the change in the oscillation amplitude, respectively.[6,7] Moreover, the dissipative interaction force can be efficiently detected by the dissipative force modulation (DM) method.[8] In this paper, we demonstrate apertureless SNOM based on near-field light detection using a self-sensing piezoelectric cantilever.

Figure 1 shows a schematic of an experimental setup for apertureless SNOM/DFM system. We used a lab-made atomic force microscope (AFM) apparatus. We used a PZT cantilever, whose fabrication process and specifications have been reported in Ref. 9. The spring constant of the PZT cantilever and the resonance frequency (f_r) were about 150 N/m and about 100 kHz, respectively. Mechanical Q-factor in the ambient conditions was about 700. The PZT cantilever was self-oscillated at the resonance frequency and the resonance frequency was detected by using the home-built electronics.[10] The distance between the tip and sample was regulated by keeping the resonance frequency shift constant to obtain topographic images.

We mounted a right angle prism on a tube scanner. The backside of the prism was irradiated by a laser light from a semiconductor laser (Hitachi: HL6312G, 635 nm). The incident angle of the laser light was adjusted to the critical angle for the total internal reflection (TIR) at the prism surface. The laser light was focused at the point of the TIR to produce a strong evanescent field. The intensity of the laser light was modulated by a laser driver circuit (Asahi Data Systems: ALP-6323LA), which is capable of controlling the laser current linearly to the modulation signal. The laser current was modulated with a square wave so that the intensity was modulated within the range of 0.5–4.5 mW. The average

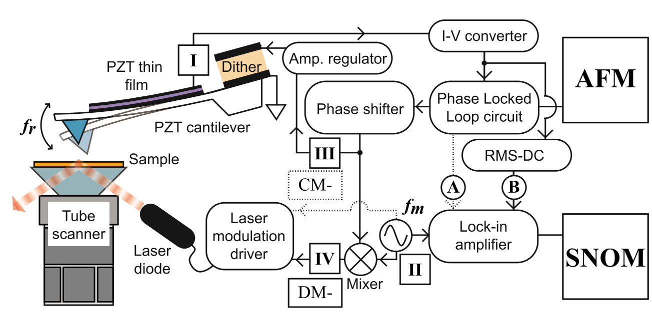

FIG. 1. (Color online) Schematic of experimental setup for apertureless SNOM/DFM system.

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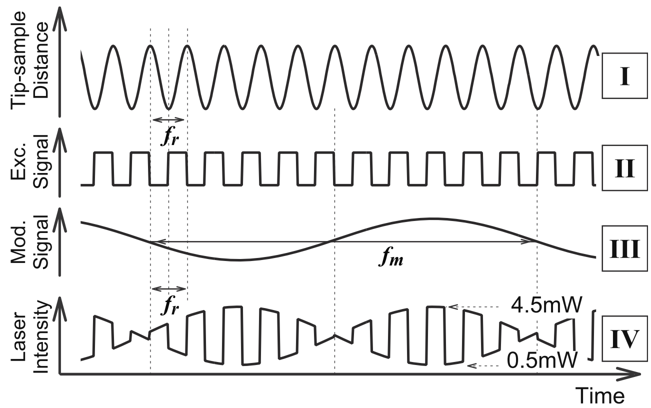

FIG. 2. Schematic of waveforms in DM method for detecting photoinduced dissipative interaction force.

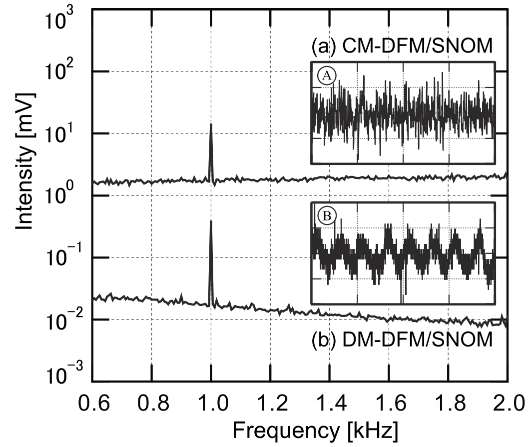

FIG. 3. Frequency spectra and signal waveforms of input signal to lock-in amplifier. (a) CM method. (b) DM method.

intensity of the laser light measured with the detector (Advantest: TQ8210) was 2.5 mW.

We employed two detection schemes in this study. First scheme is the conservative force modulation (CM) method, where the resonance frequency induced by the conservative interaction force is directly detected by a lock-in amplifier (NF Corporation: 5610B) as indicated by dotted arrows (A) in Fig. 1. Since the modulation frequency (f_m) should be lower than the bandwidth of the frequency shift detector, we set f_m at 1 kHz. On the other hand, in the DM method, the square wave for laser intensity modulation was derived from the same signal with the cantilever excitation signal sent to a piezoelectric dither plate. Therefore, the modulation frequency for the DM method was the same as f_r. Furthermore the square wave at f_r was modulated by an analog multiplier (Analog Devices: AD734) and then sent to the laser driver to modulate the dissipative interaction force.[8] The oscillation amplitude was detected by a root-mean-square-to-dc (rms-dc) circuit. The output of the rms-dc circuit was sent to the lock-in amplifier as indicated by solid arrows (B) in Fig. 1, instead of the dissipation signal, which is the control signal to keep the oscillation amplitude constant. We set f_m at 1 kHz so that the bandwidth of the rms-dc circuit is higher than f_m and the bandwidth of the amplitude feedback electronics is lower than f_m.

Figure 2 shows schematic waveforms in the DM method to detect photoinduced dissipative interaction force. Waveforms I, II, III, and IV correspond to those of the tip-sample distance, cantilever excitation signal, modulation signal, and intensity of the laser, which were indicated in Fig. 1. As the cantilever is self-oscillated at the resonance frequency, the intensity of the laser light is modulated. In a certain cycle, the intensity of the laser is high (4.5 mW) during the retraction of the cantilever away from the surface while it is low (0.5 mW) when the cantilever approaches to the surface. After a half-cycle of f_m (0.5 ms), the situation becomes opposite; the laser intensity is high during the retraction and low during approach. Due to the acceleration and deceleration by the photoinduced force in a cycle, the oscillation amplitude of the cantilever increases and decreases depending on the phase, and the oscillation amplitude is modulated at f_m accordingly.

We brought the cantilever tip in the proximity of the area on the sample with the evanescent illumination. The oscillation amplitude of the cantilever was about 20 nm peak-to-peak. The resonance frequency shift was set to about +10 Hz, therefore the average tip-sample interaction force was repulsive. Figure 3 shows frequency spectra and signal waveforms (insets) of the input signals to the lock-in amplifier in the CM method and the DM method, measured using a digital oscilloscope (softDSP: SDS-200) with a fast Fourier analysis function. The magnitude of the peaks in the two spectra correspond to the resonance frequency shift of about 2 Hz and the oscillation amplitude modulation of about 20 pm, respectively. The scales in the waveforms are 70 Hz/div and 50 pm/div for vertical axes, 2 ms/div for horizontal axes. SNR calculated as the ratio of the peak height to the background level was about 18 dB in the CM method while it was about 27 dB. The improvement of the detection sensitivity by a factor of about 3 (9 dB) was observed when the DM method was used. Since the magnitude of the light intensity modulation was 2 mW and the area with evanescent light illumination on the sample was about $8\times10^{-9}\ \text{m}^2$, the light intensity modulation per unit area was about $2.5\times10^5\ \text{W/m}^2$. Therefore the optical energy that the PZT cantilever received can be estimated as 2 nW by considering that the surface area of the lever tip was about $8\times10^{-15}\ \text{m}^2$.

We placed a sample on the prism and brought the cantilever tip again to the proximity of the area on the sample with the evanescent illumination. The sample used in this study was a glass plate with a checkerboard-patterned chromium film (25 nm thickness). The dimension of each transparent opening area was about $1\times1\ \mu\text{m}^2$. Topographic image and SNOM image were simultaneously obtained by each method. Figures 4(a) and 4(b) were obtained by the CM method while Figs. 4(c) and 4(d) were obtained by the DM method. The scanned area was $3.5\times3.5\ \mu\text{m}^2$. The cross-sectional line profiles measured on the white lines were shown under each figure.

In each method, we observed the photoinduced force modulation on the area in which the glass substrate was exposed and transparent. In contrast, the signal intensities were strongly attenuated on the area covered with the chromium film in each method. The line profiles show that the signals were attenuated roughly by a factor of 3 to 4. It is estimated that the evanescent light intensity is attenuated by a factor of 5 by the chromium film with the thickness of 25 nm,[11] which is almost consistent with the experimental results. Therefore it is considered that the force modulation on the glass area was induced by the photoinduced conservative and dissipa-

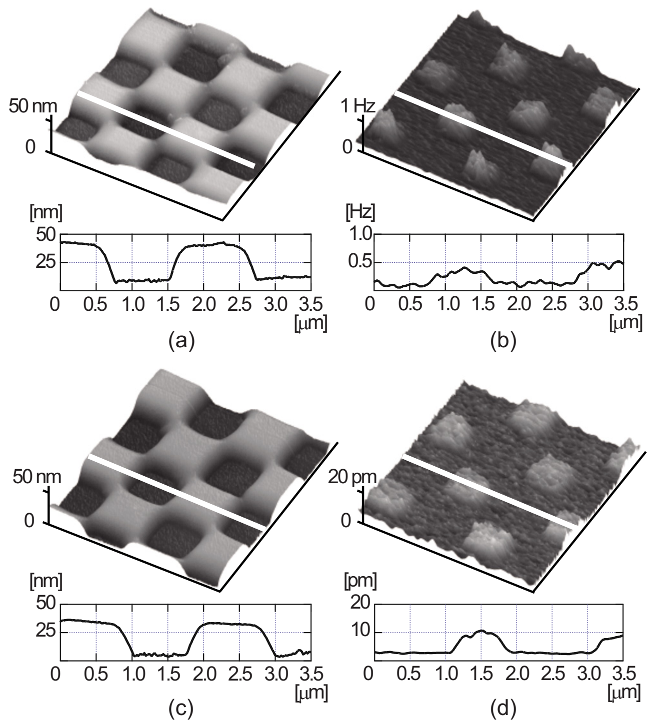

FIG. 4. (Color online) (a) Topographic AFM image and (b) SNOM image (magnitude of frequency shift modulation) of a patterned chromium film on glass taken by the conservative force modulation method. (c) and (d) are topographic AFM image and (b) SNOM image (magnitude of amplitude modulation) by the dissipative force method. Cross-sectional line profiles measured along the white lines were also shown below each image.

tive force, which was modulated by the light intensity modulation.

The possible mechanisms of the photoinduced forces are such as the optical radiation pressure, electrostatic force, thermal stress, etc. It has been reported by Abe *et al.*[12] that the near-field light can be detected as the modulation of the electrostatic force using the semiconductor tip because of the photovoltaic effect in an ultrahigh vacuum condition with a high SNR. In our experiments, the cantilever was insulating rather than semiconductor and we did not observe any force modulation on the chromium area. Therefore, we do not consider that the interaction force was caused by the photovoltaic effect. However, we still cannot neglect the possibility of the electrostatic force since we utilized the piezoelectric cantilever. It is possible that the additional electrostatic force was generated by the charges caused by the piezoelectric or pyroelectric properties of the PZT layer. Our future investigations will include simultaneous local surface potential measurement[13] and study on the influence of the light exposure on the surface charges. On the other hand, we also considered the effect of the thermal stress induced by the near-field light. As several researchers utilize the intensity modulated lasers for exciting cantilever oscillations at the frequency even up to 1 MHz,[14] it might be possible that the modulations in the frequency shift and oscillation amplitude were induced by the photothermal effect. However, they irradiate the cantilevers with lasers with an intensity of a few milliwatts or more to achieve the oscillation amplitude on the order of nanometers. In our case, the estimated optical power at the tip was about 2 nW, which we believe is insufficient to produce modulation in the oscillation amplitude as large as 10 pm, as shown in Fig. 4(d). Therefore we consider that it is less probable that the photothermal effect due to the local heating of the tip is the main imaging mechanism. The imaging mechanisms would be clarified by comparing the dependence of the photoinduced forces on the different experimental conditions such as the intensity of the incident laser light and the modulation depth, the relationship of the phase of the laser light modulation and the tip oscillation, the conductivity of the tip, etc. There is also a possibility that the similar experiments can be performed using conventional cantilevers with optical displacement sensors.

In summary, we demonstrated the possibility of the near-field optical imaging by the detection of the photoinduced conservative and dissipative forces by the self-sensing piezoelectric cantilevers. Since the optical power modulation is detected as the frequency shift modulation or the amplitude modulation of the cantilever, increasing the force sensitivity of the cantilever can increase the resolution limit in the optical detection, which can be advantageous compared to the conventional aperture-based SNOM.

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