Experiment of Polarization Forces in Scanning Electrostatic Force Microscopy for Measuring Surface Profile of Dielectric

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Abstract: For measuring the surface profile of many micro-optical components with complicated shapes, which are made of non-conductive material, the electrostatic force microscopy (EFM) was recommended. The relationship between the polarization force and the tip-to-sample distance was analyzed based on dielectric polarization theory. The prototype of the scanning electrostatic force microscopy was built. The force curves of different samples with different materials and surface shapes were detected by the EFM prototype. Both theoretical analysis and the experimental results demonstrated that the EFM system can be used to measure the surface profile of non-conductor.

1. INTRODUCTION

For measuring the three-dimensional (3D) microstructures surfaces profile, scanning probe microscopy (SPM) is one of the most powerful tools [1, 2]. The representative SPM are scanning tunneling microscopy (STM) and atomic force microscopy (AFM). However, the STM can only be used for measuring the surface of conductor [3]. When the AFM works at the contact mode and the tapping mode, the large contact stress will damage the sample surface because of the sharp tip of the scanning probe [4]. Although the contact force can be reduced and the damage of the sample surface can be avoided by the use of the noncontact mode AFM (NC-AFM), it is necessary to maintain a very small tip to sample separation, less than 5 nm, so that the weak interactions of atomic force between the tip and the sample, which is only effective in a short tip to sample separation, can be detected [5]. This makes the probe tip of the NC-AFM scans over the sample surface with a slow speed for avoiding the tip from colliding with the surface. For conventional SPM, both STM and AFM, it is difficult to measure surface profiles of microstructures with steep local slopes and large amplitudes, such as diffraction gratings, micro-lens arrays and micro-prism sheets.

Recently, the electrostatic force microscopy (EFM) was also proposed for the measurement of the microstructure surface profile [6]. This EFM system, which can scan over the surface with a large tip to sample separation of up to several hundreds of nanometers by utilizing the long range electrostatic force, was built to measure the surface profiles for these micro-optical components. In that paper, it only discussed the measurement method about the conductive

surface. In this paper, the EFM system for non-conducting surface profile measurement was proposed. The measuring principle is discussed in theory and a prototype EFM measurement system was built for demonstrating the feasibility of the proposed method.

2. MEASUREMENT PRINCIPLE

A conducting probe tip is oscillated with small amplitude in the order of 10 nm by a tuning fork quartz crystal resonator at their resonance frequency of the oscillation system. The sample is attached on the back electrode as shown in Fig. (**1**) and the distance between the probe tip and the sample surface is denoted by d. The oscillation amplitude is set to be smaller than d so that the tip will not contact with the surface. When a bias voltage V_{dc} is applied on the probe tip and the electrode, the sample which is set in the electrical field will be polarized and the polarization charge will be produced on the sample surface [7]. The electrostatic force F between the probe tip and the sample surface can be expressed. The value of electrostatic force depends on d and voltage (V_{dc}) between the tip and sample surface. Because the electrostatic force acts as an external force to the oscillation system which consisting of the resonator and the probe tip, the effective resonance frequency of the system will be changed by the electrostatic force. Then the relationship between the frequency shift of the oscillation system Δf and the tip-sample distance d can be obtained. If the Δf is detected, d can be gotten. So, according to the frequency shifting value the profile of the sample surface can be acquired.

When the dielectric is put in an electrical field, polarization charges will emerge on the sample surface. So, the electrostatic force will be loaded on the probe tip, which can be calculated according to polarization theory. As shown in Fig. (**1**), when a bias voltage is loaded on the back electrode, the positive charges will be produced on the surface of the elec-
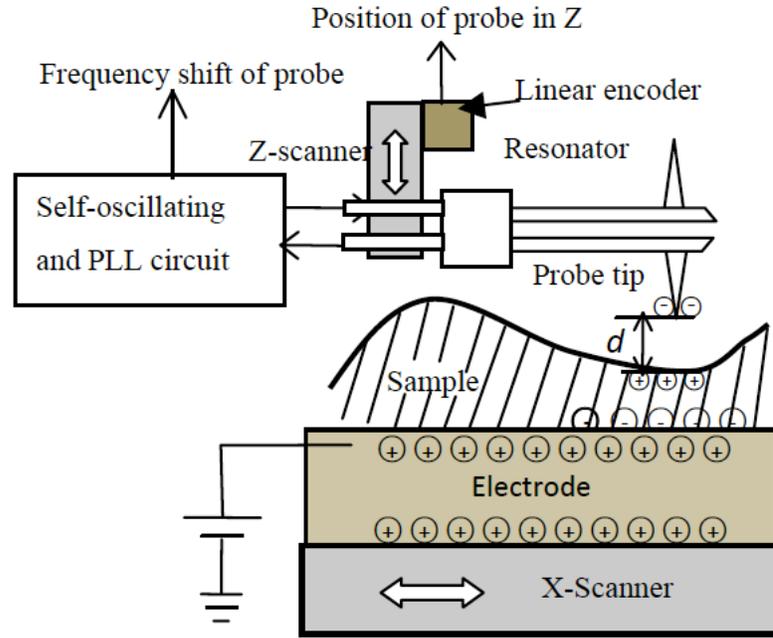
Fig. (1). Principle of EFM.

trode. Then, on the upper surface and the under surface of the sample positive charges and negative charges will emerge, respectively, and the image charges also will be produced on the tip of probe.

The electric susceptibility of the sample, the dielectric constant of vacuum and the permittivity of the sample is denoted by χ, ε_0, and ε_r respectively. U_{bt} is the potential difference between the back electrode and the probe tip.

The force between the tip and the sample can be calculated as:

$$F = \frac{\varepsilon_0}{2}\left[1 - \frac{h}{\varepsilon_r\left(h+d\right)}\right]^2 U_{bt}^2 \frac{A}{d^2} \tag{1}$$

where A is the area of the half sphere of probe apex, d is the tip-sample distance and h is the thickness of the sample.

The resonance frequency f_0 of the resonator will be changed by the force shown in Eq. (1). The frequency shift Δf can be written as [6]:

$$\Delta F = \frac{f_0}{2k} F' \tag{2}$$

where, k is the spring constant of the oscillation system, and the F', which means the electrostatic force gradient, is defined as: $F' = \partial F / \partial d$.

If the thickness of the sample h is far greater than the distance d, Eq. (1) can be written as:

$$F = \frac{\varepsilon_0}{2}\left(1 - \frac{1}{\varepsilon_r}\right)^2 U_{bt}^2 \frac{A}{d^2} \tag{3}$$

Thus,

$$F' = \frac{\partial F}{\partial d} = -\varepsilon_0\left(1 - \frac{1}{\varepsilon_r}\right)^2 U_{bt}^2 \frac{A}{d^3} \tag{4}$$

Combining the Eqs. (2) and (4), the frequency shift can be expressed as:

$$\Delta f = -\frac{\varepsilon_0}{2}\left(1 - \frac{1}{\varepsilon_r}\right)^2 U_{bt}^2 \frac{A}{d^3} \frac{f_0}{k} \tag{5}$$

As can be seen in Eq. (5), the frequency shift value Δf is a function of d, which is related to the surface profile.

3. PROTOTYPE EFM MEASUREMENT SYSTEM

With the similar principle of the frequency modulation (FM) AFM, the prototype of a scanning electrostatic force microscopy for profile measurement was built. The prototype system will be used for measuring the frequency shift with the distance between the tip and the sample surface. According to the frequency shift of the tuning fork resonator, the electrostatic force between tip and sample can be calculated and then the surface profile can be imaged. Fig. (**2**) shows a schematic of the prototype EFM measurement system. The EFM probe unit was mounted on a Z scanner which was driven by piezoelectric actuators. The Z scanner employed a linear encoder for accurate measurement of the probe displacement along the Z direction over a range of 50 μm with a nonlinear error of less than 10 nm. The sample and the back electrode were mounted on an XY scanner which was also driven by piezoelectric actuators. The commercial XY scanner was feedback controlled by using capacitive displacement sensors over a travel stroke of 100 μm with a nonlinear error of approximately 40 nm in each of the X and Y directions [6].
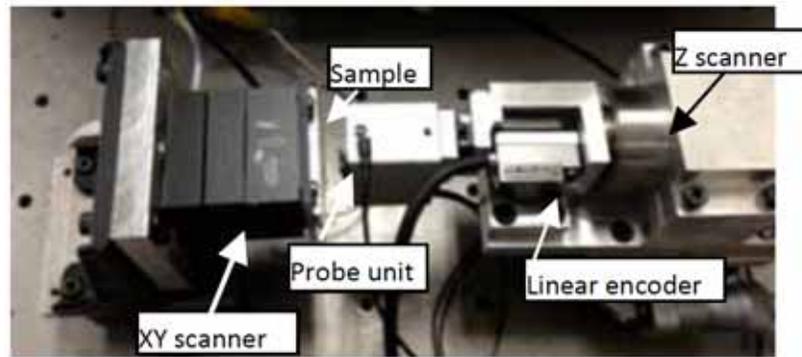
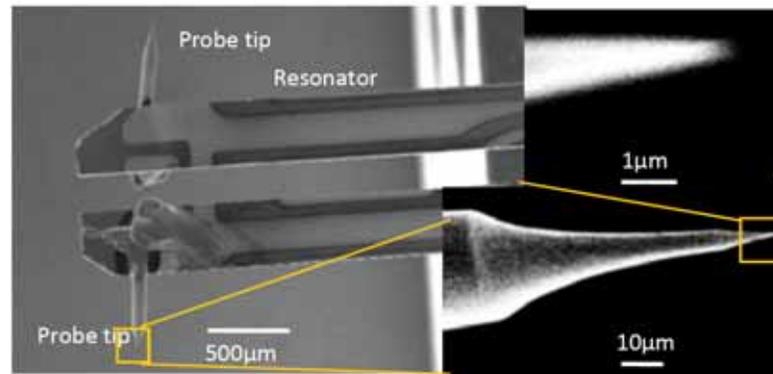**Fig. (2).** Schematic of the prototype EFM.

Fig. (3). SEM image of probe tip.

Fig. (**3**) shows the image of the probe unit. Two pieces of tungsten probe tip which were made by electrochemically polishing method were glued on a tuning fork quartz crystal resonator with conductive epoxy. One of the probe tips is utilized as a counterweight for balance, and the other tip is employed for detecting the electrostatic force. The probe tips were oscillated with the resonator at the fundamental resonance frequency of the resonator by using a self-oscillating circuit. With regard to the variation of the resonance frequency, the frequency shift signal was detected by using the phase locked loop (PLL) circuit and then the signal is fed into the computer for profile exploring and also sent to the proportional integral (PI) controller for controlling the probe tip to scan the sample surface with constant force mode.

4. EXPERIMENT

4.1. Experiment on Different Material

Form the Eq. (5), it can be seen that the frequency shift value Δf is also a function of the permittivity of the sample ε_r,. That means the frequency shift is affected by material. To confirm the feasibility of using the EFM system to measure surface profile of the dielectric, the frequency of the resonator shifting changes with different distances between the probe tip and sample surface on different dielectrics were tested. Firstly, a glass plate was employed as the sample and an aluminum alloy plate was used as the back electrode. The bias voltage applied between the probe tip and the back electrode was set to be 100 V. The probe was oscillated at the fundamental frequency of resonator which was about 26546Hz in this experiment. The quality factor of oscillation system was 2832. The sample was kept stationary and the probe tip was moved by the Z scanner to approach to the sample surface for investigating the relationship between the frequency shift and the tip to sample distance. The result is shown in Fig. (**4**). The vertical axis shows the corresponding frequency shifts. The bottom horizontal axis shows the outputs of the linear encoder of the Z scanner, which represents the relative displacement of the Z scanner. The results can be well fitted by an inverse cubic function by using the least squares method, which reflects the relationship shown in Eq. (5). The inverse cubic fitting curve can be used to estimate the absolute tip to sample distance based on Eq. (5). In Fig. (**4**), the upper horizontal axis is the estimated absolute tip to sample distance fitted by least squares method.

Then, with the same procedure, a silicon slice and a PVC film were taken as the sample and tested respectively. Fig. (**5**) and Fig. (**6**) are the test results. The three figures show that these materials can be test by the EFM system; and the signal when the sample is PVC is weakest because of its least ε_r.

4.2. Experiment on Different Position

According to the polarization theory, the topology of the sample surface will effect on the electrostatics force. For researching the effect by the topology of the surface, a
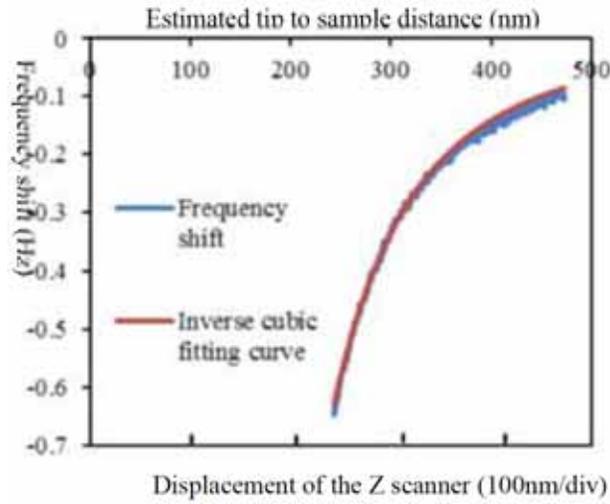
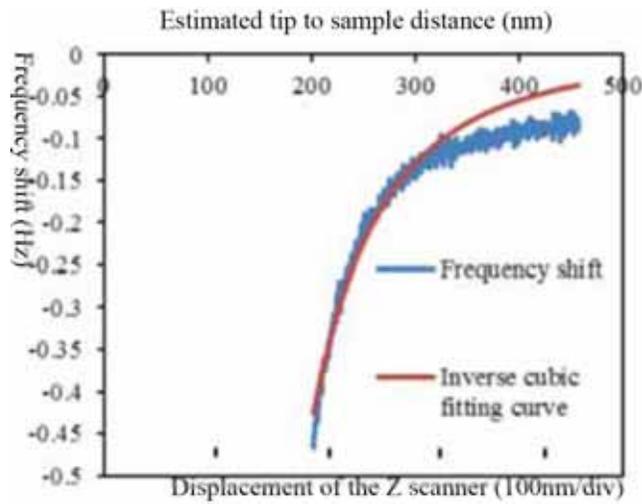**Fig. (4).** Relationship between d and Δf on glass plate.

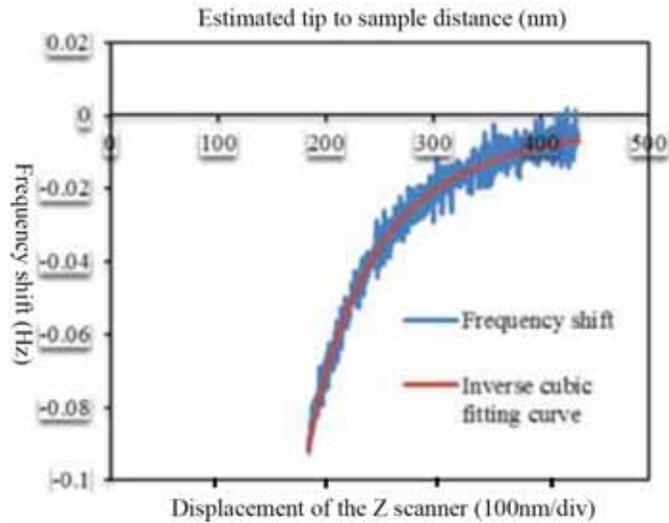**Fig. (5).** Relationship between d and Δf on silicon slice.

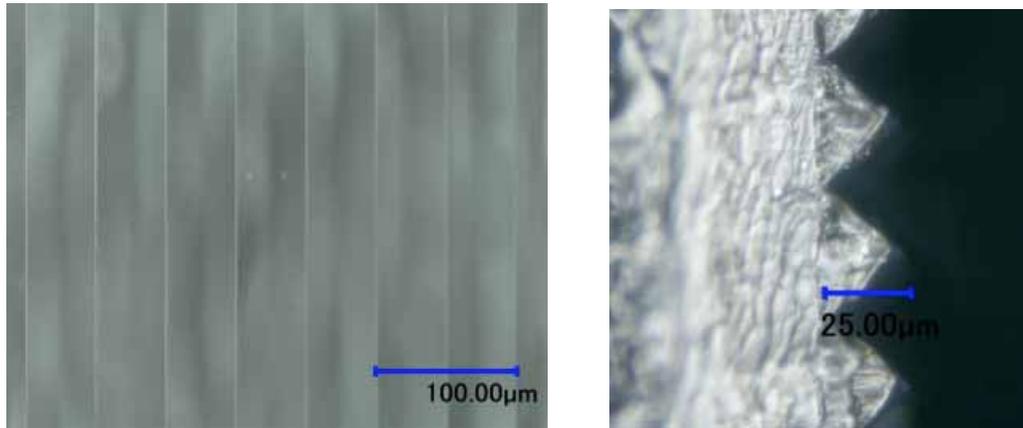**Fig. (6).** Relationship between d and Δf on PVC film.

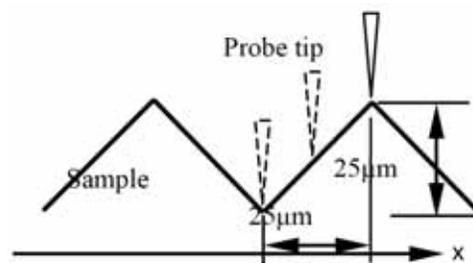**Fig. (7).** Image of the sample with 25μm- high ridge.

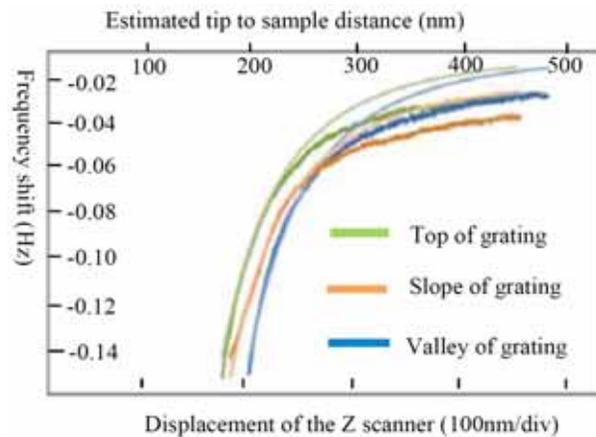**Fig. (8).** Testing method of force curve on grating.

Fig. (9). Relationship between d and Δf on grating.

diffraction grating with 25μm-high ridges was employed as the testing sample. Fig. (**7**) shows the topography of the sample surface. The right image is the section form of the ridges.

Along X direction within 50μm-length, the force curves at 50 points were tested by X-scanner moved with 1μm step, in order to insure that the top and the valley points on the ridge can be tested (shown as in Fig. (**8**)). Force curve at each point was obtained. Fig. (**9**) shows three of them.

They are the force curves on the top, the slope and the valley of the ridge respectively. In Fig. (**9**), the smooth curves are the fitted curves and the crude curves are the tested curves.

CONCLUSION AND FUTURE WORKS

Some of optical components, such as diffraction gratings, micro-lens arrays and micro-prism sheets etc., are made of non-conductive material. On the surface of these components, there are many complicated shapes with steep slopes and large amplitudes. The electrostatic force microscopy (EFM) was proposed to measure surface profiles of microstructure. For confirming the feasibility, according to the polarization theory, the electrostatic force between the conductive probe tip and the non-conductive sample was calculated. The result shows that the relationship between the electrostatic force and the distance from probe tip to sample surface is inverse square function.

A prototype of EFM has been developed for measuring the surface profile of non-conductor in noncontact condition.

Experiments have also been carried out by using the prototype EFM system to demonstrate the feasibility of the electrostatic force calculation by the analytic method. A glass plant, a silicon slice and a PVC film was employed as the sample respectively. The bias voltage applied between the probe tip and the back electrode was set to be 100 V. The fundamental frequency and the quality factor of the probe unit were tested. The values of them are 26546Hz and 2832, respectively. The samples were kept stationary and the probe tip was moved by the Z scanner to approach to the sample surface for investigating the relationship between the frequency shift and the tip-to-sample distance. The test result shows that the frequency shifts with the tip-sample distance changes as the analytic result in theory. Then, a diffraction grating with 25μm high ridge was employed as the sample to test the effect of the topography. All results indicate that the EFM system can be used to measure the microstructure surface profile of dielectric.

About the future works, firstly, the accurate relationship between the electrostatic force and the tip-sample distance should be investigated by using the other method. Then, according to the force curve, scanning measurement along X and Y direction will be done for imaging the surface profile.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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