Sensitivity of a miniaturized touch probe sensor using PZT thin film vibrator

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Abstract

In this paper, an improved touch probe sensor device for higher sensitivity and low contact force is reported. In order to improve the resolution, we have evaluated the sensitivity and fabricated a miniaturized sensor. The sensor transducer was 3 mm long and had higher resonance frequency. The resonance frequency of the vibrator was 937 kHz. Evaluated sensitivity was $1 \times 10^{-11}$ mV/nm. This value equals five times larger than that of a previous sensor. Miniaturization of the sensor device carried smaller vibration operation and higher sensitivity. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Touch probe sensor; PZT thin film; Hydrothermal method; Surface profile measurement

1. Introduction

It has been receiving increasing attention to measure surface profile of a nanostructure, for example, submicron rule VLSI or micro-electro-mechanical systems. For surface profile measuring tools or scanning probe microscopes, some kinds of longitudinally vibrating touch probe sensors [1–4] have been fabricated. Although bending vibration is used as to such kind of sensor probe, especially, most atomic force microscopes, the longitudinally vibration was used for our sensor. This is due to maintain high mechanical $Q$ value for high resolution and high resonance frequency. Therefore this sensor is also useful in liquid, and can realize quick scanning. These features are advantageous for measuring nanostructures.

Fig. 1 shows the schematic view of the surface profile measurement by the longitudinally vibrating touch probe sensor. The sensor consists of a part longitudinal vibrating and an exponential horn, which enlarges the amplitude at the contact point. By detecting the contact and scanning along the surface of an object, the surface profile of the object can be obtained. We use piezoelectric film to oscillate the vibrator and to detect the vibration. As to the piezoelectric film we use PZT film, which was deposited by a hydrothermal method [7–9].

The goal of our study is to realize high resolution more than 0.5 nm, and low contact force under 500 nN. It was also expected to realize a wide scanning range in mm scale square, and quick scanning surface profile measurement. In order to realize such a measuring instrument, to achieve a sensor, which has high sensitivity for detection of the contact is important. It can be considered to miniaturize the sensor vibrator is effective to obtain higher sensitivity. We have fabricated a miniaturized sensor, and evaluated the features.

2. Principle

2.1. Resolution and sensitivity

We have reported some kind of longitudinally vibrating touch probe sensor. Our first probe sensor was rod-shaped and its resonance frequency was 116 kHz [3]. We also reported much smaller and flat-type sensor [4]. When the driving voltage was $3 V_{pp}$, the resonance frequency, vibration amplitude at the resonance, and
mechanical $Q$ value of the flat-type sensor were 304.4 kHz, 126 nm, and 705, respectively. The sensitivity and resolution were $2 \times 10^{-2}$ mV/nm and 2.4 nm. This resolution depends on the noise level of the pickup signal [4].

In addition, the sensitivity will be improved by the larger piezoelectric constant of PZT film. The sensitivity of the sensor is proportional to the piezoelectric constant $e_{31}$ of the piezoelectric film when the piezoelectric constant $e_{31}$ is smaller than 6 C/m² [5]. From the calculation based on the experimental data, the piezoelectric coefficient of $e_{31}$ of the longitudinal transducer was estimated to be $-0.2$ C/m² [4]. This value is one tenth of that of bulk materials of $3.1$ C/m² (calculated from the constants in Ref. [6]). When the larger piezoelectric coefficient of the PZT thin film is obtained, the sensitivity will be improved.

2.2. Miniaturization

The miniaturization of the sensor vibrator is also effective to obtain higher sensitivity. To estimate the dependence on the dimensions of the vibrator, we estimated the sensitivity of a quarter wavelength longitudinal vibrator sensor as shown in Fig. 2. Electrodes are on each side, one is for driving, and the other is for pickup. The length, width, and thickness of the Ti substrate and those of the PZT film are $l$, $b$, $t_1$, and $t_2$, respectively. PZT thin film layers are present on both surfaces of the Ti substrate. The ratio between $l$, $b$, and $t_1$ is 40:10:1. The thickness of the PZT film, $t_2$, was constant at 3 μm, since the thickness of the film was kept constant at about 3 μm when the PZT thin film was deposited using the hydrothermal method [7–10]. Fig. 3 shows the relationship between the sensitivity of the sensor and the vibrator length when the ratio of dimensions of the vibrator was fixed. Fig. 3 reveals that the sensitivity of the sensor is improved when the dimensions are miniaturized.

3. Experiments

3.1. Structure

The structure of the sensor is shown in Figs. 4 and 5. The sensor element has a half wavelength of the longitudinal vibration. The element is supported at the nodal point of its longitudinal vibration mode. The length of the sensor vibrator was 3.0 mm and the width was 0.3 mm. The thickness of the Ti substrate was 0.1 mm. The previous sensor whose resonance frequency was about 300 kHz was 9.8 mm long and 1.0 mm wide [4].

PZT thin film was deposited by a hydrothermal method [7–10] on the titanium substrate. The thickness of the film was about 3 μm each side [10]. The width at the tip of the vibrator was 0.1 mm. The vibration...
amplitude at the tip of the vibrator was enlarged by the exponential horn. The step-up ratio of the exponential horn was 1.7 from the ratio of the width of the both end of the vibrator. The vibration was excited and detected by PZT thin film on each side of the vibrator.

3.2. Vibration amplitude

To estimate the vibration amplitude, the vibration velocity was measured. Fig. 6 shows the vibration amplitude at the tip of the vibrator. When the driving voltage was 1.0 V<sub>p-p</sub>, the resonance frequency, vibration velocity at the resonance frequency and mechanical Q value were 937 kHz, 2.4 × 10<sup>-2</sup> m/s and 394. From these experimental results, the vibration amplitude at the resonance frequency was 4.1 nmo<sub>p</sub>. Fig. 7 indicates the relationship between the driving voltage and the vibration amplitude. The relationship has good linearity.

3.3. Sensitivity

The sensitivity is obtained by using an equivalent circuit [4]. Fig. 8 shows the equivalent circuit of the...
sensor. Lump element circuit components of $L$, $1/C$, $R$, $A_1$ and $A_2$ are equivalent mass, equivalent elasticity modules, equivalent viscosity coefficient, and force factors in the driving piezoelectric element and that in the pickup piezoelectric element. $C_{d1}$ and $C_{d2}$ indicate the capacitance in the driving element and that in the pickup element due to the PZT film’s ferroelectricity. By using these parameters, the sensitivity $P$ can be described as [4]

$$P = \frac{A_1}{C_{d2} \sqrt{1 + \left( \frac{d_1^2}{mR_{d1}} \right)^2}}. \quad (1)$$

The estimated equivalent circuit elements are summarized in Table 1. From these elements, the sensitivity of the sensor was $1.0 \times 10^{-1} \text{ mV/nm}$. This value equals 5.0 times larger than that of the previous sensor, $2.0 \times 10^{-2} \text{ mV/nm}$ [4].

### 3.4. Pickup voltage

The pickup voltage of the sensor can be estimated from the equivalent circuit using parameters on Table 1. Fig. 9 shows the calculated results about the vibration amplitude using the equivalent circuit of Fig. 8. When the driving voltage was $1.0 \text{ V}_{\text{p-p}}$, the resonance frequency and vibration amplitude were 937 kHz and 4.1 nm, respectively. These values are as same as the experimental results as indicated in Fig. 6. The calculated results about the pickup voltage are shown in

### Table 1

<table>
<thead>
<tr>
<th></th>
<th>Previous [4]</th>
<th>Miniaturized</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resonance frequency (kHz)</td>
<td>304</td>
<td>937</td>
</tr>
<tr>
<td>$L_m$ Equivalent mass (kg)</td>
<td>$2.0 \times 10^{-4}$</td>
<td>$1.9 \times 10^{-7}$</td>
</tr>
<tr>
<td>$R_m$ Equivalent viscoelastic loss (N s/m)</td>
<td>$5.4 \times 10^{-3}$</td>
<td>$2.7 \times 10^{-3}$</td>
</tr>
<tr>
<td>$C_m$ Equivalent compliance (m/N)</td>
<td>$1.4 \times 10^{-3}$</td>
<td>$1.5 \times 10^{-7}$</td>
</tr>
<tr>
<td>$A_1$ Force factor (N/V)</td>
<td>$8.7 \times 10^{-3}$</td>
<td>$1.3 \times 10^{-4}$</td>
</tr>
<tr>
<td>$C_{d2}$ Damped capacitance (F)</td>
<td>$5.5 \times 10^{-9}$</td>
<td>$1.1 \times 10^{-9}$</td>
</tr>
</tbody>
</table>

Fig. 10. As a result of the calculation, the pickup voltage is $0.3 \text{ mV}_{\text{rms}}$ at the resonance frequency of 937 kHz.

From the measurement, the pickup voltage of the sensor was about $0.2 \text{ mV}_{\text{rms}}$. This difference between the calculation and the measurement would be caused by the error in estimation of the equivalent mass. This is because the shape of the exponential horn and supporting part will lead to an error.

### 4. Conclusion

In order to realize higher resolution, we have evaluated the sensitivity and fabricated the miniaturized sensor. The length and the resonance frequency of the sensor vibrator were 3 mm and 937 kHz, respectively. The vibration amplitude at the resonance was 4.1 nm when the driving voltage was $1.0 \text{ V}_{\text{p-p}}$. Evaluated sensitivity was $1.0 \times 10^{-1} \text{ mV/nm}$. This value equals 5.0 times larger than that of the previous sensor. Miniaturization of the sensor device carried small vibration operation and higher resolution.

### Acknowledgements

This work was supported by the Grant-in-aid for general scientific research of the Ministry of Education, Culture, Sports, Science and Technology, and by the Proposal-Based New Industry Creative Type Technology R & D Promotion Program from the New Energy and Industrial Technology Development Organization (NEDO) of Japan, and by the Grant-in-aid for Research Fellowship for Young Scientists of the Japan Society for the Promotion of Science.

The authors would like to thank Mr. Yasui of The University of Tokyo for valuable advice on and his assistance with the hydrothermal method of depositing the PZT thin film.
References