Transactions of the Materials Research Society of Japan 31[1] 113-116 (2006)

Double Beam Laser Doppler Interferometer and FEM Analysis to Determine Piezoelectric Constants of Thick Film Actuators

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Double Beam Laser Doppler Interferometer (DB-LDI) and Finite Element Method (FEM) analysis were used to evaluate the piezoelectric constants of the film structure. Using DB-LDI, resonance frequency and displacements of both surfaces could be measured. The number of parameters of thick film should be reduced analyzing the dominant parameters of each measurable value through the FEM analysis. From these results, it was found that an energy-trapped structure is essential for measurements and the structure of top electrodes should be properly designed for the resonance frequency not to be shifted. By the FEM verification, the piezoelectric constants d_{31} and d_{33} could be evaluated within the accuracy of 5% by changing the thicknesses of substrates. In the measurement, one sample was obtained and the displacements of both surfaces were 4 and 3 nm and resonance frequency was 371.1 kHz. In this study, we propose the newly developed method to evaluate the piezoelectric constants of the film structure.

Keywords: piezoelectric constants, PZT, thick film, FEM, MEMS, aerosol deposition method

1. INTRODUCTION

Recently, piezoelectric thick films have been extensively studied for micro actuators in Micro Electro Mechanical System (MEMS) applications due to their large piezoelectric displacement and generative force. For the development of MEMS, it is very important to evaluate piezoelectric constants of films because it is one of important fundamental constants to design devices for MEMS. In general, the precise properties of piezoelectric thick films cannot be expected before the structure of devices is designed and behavior of their piezoelectric films is measured. So in this procedure, the time and cost are consumed. From the point of view, it is required that their properties should be able to be measured as a simple structure. However, the evaluation method of piezoelectric constants regarding the film structure has not been established yet because it is difficult to distinguish the displacement of their piezoelectric component itself from the total displacement. The reason is that the total displacement at the surface of the film is derived from the displacement of the film constants as well as the bending of the substrate. This means that the piezoelectric properties of a film on a substrate cannot be evaluated from the total displacement at the surface of the film since the bending of the substrate highly depends on its elastic properties and the thickness of the substrate.

In our research group, Double Beam Laser Doppler Interferometer (DB-LDI) system has been developed for a measurement of the difference in the displacements between at the surface of a film and at the back surface of a substrate, which enable us to evaluate the longitudinal strain of the film by eliminating the effect of the bending [1,2]. Moreover, the resonance frequency can be measured by measuring the displacement as a function of frequency by using DB-LDI. However, this longitudinal strain is still affected by the elastic property and the thickness of the substrate because the piezoelectric deformation of the film is restricted by the substrate. In order to solve this problem, we focused on a Finite Element Method (FEM) to analyze these complicated behaviors. The objective of this study is to propose a novel method to evaluate precisely the piezoelectric constants by DB-LDI and FEM taking the case of lead zirconate titanate (PZT) thick film.

2. EXPERIMENTAL

2.1 FEM Analysis

An energy-trapped structure for piezoelectric films is essential to measure the displacements of both surfaces and their resonance frequencies. When the vibration is not trapped, it spreads to films and substrates so that sympathetic vibrations with a sample holder are occur. We deigned the measuring sample structure for the energy trapping as shown in Fig. 1. A brass plate with a hole was attached to the back face of a substrate to restrict the vibration region in the film. The thickness of the substrate and the size of the hole of the brass plate were optimized by the commercialized FEM analysis software (ANSYS Inc.). Figure 2 illustrates the model used for the FEM analysis. Since the sample structure has a cylindrical symmetry, only a part 10° of the circumference 360° was calculated and analyzed. For the brass plate and the silicon substrate, parameters such as Young's modulus, Poisson ratio and density were referred from a paper [3]. The required parameters of the

PZT thick films were listed in Table 1. There were elastic compliance tensors, piezoelectric coefficient tensors, dielectric permittivity tensors and density. The following conditions are satisfied for these parameters.

$s_{22}=s_{11}$, $s_{23}=s_{13}$, $s_{44}=s_{55}=s_{66}$, $\varepsilon_{22}=\varepsilon_{11}$, $d_{31}=d_{32}$, $d_{24}=d_{15}$.

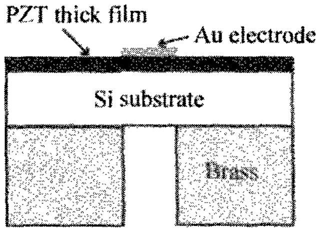


Fig. 1. Schematics of an energy-trapped structure.

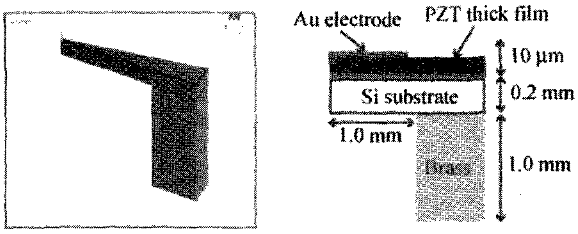


Fig. 2. Model for FEM analysis.

Table I. Parameters of PZT films required for analysis.

Elastic constants	s_{11}^{E} s_{33}^{E}	s_{12}^{E} s_{44}^{E}	s_{13}^{E} s_{66}^{E}
Density		ρ	
Dielectric permitivity	ε_{11}^{T}	ε_{33}^{T}	
Piezoelectric constants	d_{31}	d_{33}	d_{15}

2.2. Measurement of PZT thick films

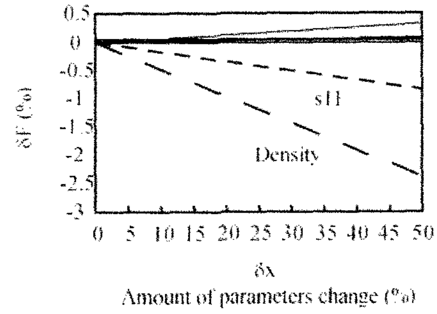
$Pb(Zr_{0.52}Ti_{0.48})O_3$ thick films were fabricated on $Pt/IrO_2/SiO_2/Si$ substrates at 600°C by Aerosol deposition method (ADM). The apparatus and mechanism of ADM have been reported elsewhere [4,5]. After deposition, the PZT films were annealed at 600°C for 1 hr in air. The piezoelectric displacements of the two faces were independently measured with two LDIs (Neoark, MLD-301A-TKD). The signal from LDI was amplified by a digital lock-in amplifier (NF, LI5640). The waveform of the signal was monitored with a digital oscilloscope (Agilent, 54624A). The displacement was calculated by integrating vibration velocity. For measurement of the resonance frequency, the sample was applied to AC voltage of 10 V at 5 kHz. The displacements of surfaces were measured by DB-LDI at 1 - 500 kHz.

3. RESULTS AND DISCUSSION

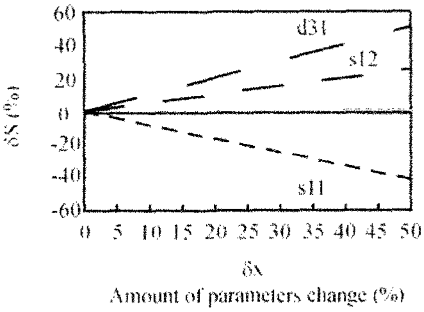
3.1 Simulation for evaluating piezoelectric constants of films by FEM

Taking DB-LDI into account, we could measure the resonance frequency and the piezoelectric displacements regarding the surface of a PZT thick film and the back surface of a Si substrate. At first, the number of parameters of PZT films required for analysis was tried to be reduced using FEM analysis since there are too many unknown parameters as shown in Table 1. In order to reduce the parameters, we calculated and analyzed the dominant parameters among each measurable value using FEM. Figure 3 shows the results of the simulation. There were two dominant parameters (*density*, s_{11}) affecting the resonance frequency, and three dominant parameters (d_{31}, s_{11}, s_{12}) affecting the displacement of the back surface of a Si substrate and four dominant parameters (d_{31}, d_{33}, s_{11}, s_{12}) affecting the displacement of the surface of PZT thick film.

(a) Resonance frequency.



(b) Displacement of back surface of Si substrate.



(c) Displacement of surface of PZT thick film.

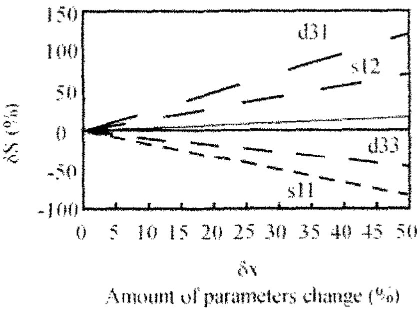


Fig. 3. Measurable value change as a function of amount of parameters change. (a) resonance frequency, (b) displacement of back surface of Si substrate, (c) displacement of surface of PZT thick film.

Consequently, the number of the required parameters of PZT thick film was reduced from 12 parameters to 2-4 parameters by FEM analysis. However, the piezoelectric constants of PZT thick films could not determined since it was impossible to determine more than two parameters from only one measurable value. Therefore, we performed many simulations to overcome the above problems, for instance, according to the change in the radius of top electrode, the thickness of PZT thick films, and the thickness of Si substrates. As a result, the only one method exhibited a possibility to solve the problem, which is just to change the thickness of Si substrates to determine the piezoelectric constants with a high accuracy.

We explain this calculation procedure in detail. First, we analyze the value of resonance frequency. There are two dominant parameters affecting the resonance frequency as shown in Fig. 3. When the thickness of a Si substrate is constant, we can choose some combinations of two parameters (*density*, s_{11}) to fit the one real resonance frequency. It means that it is impossible to determine two parameters from one value. When the thickness of Si substrates is changed, however, each combination had each own value of resonance frequency as shown in Fig. 4. Therefore, it is possible to determine the combination of two parameters, so that the value of *density* and s_{11} can be determined. Secondly, only two dominant parameters (d_{31}, s_{12}) remained from the displacement of the back surface of Si substrates by using two determined parameters from the analysis of the resonance frequency. As the previous analysis, these two parameters can be determined. Thirdly, using these determined parameters, there was only one dominant parameter (d_{33}) from the displacement of the surface of PZT thick films, so that d_{33} can be clearly determined from the one measurable value. By employing this method using the various thicknesses of Si substrates, we can determine the piezoelectric constants of the film structure from the dominant parameters of PZT thick films. Figure 5 shows the procedure of the method to determine piezoelectric constants of thick film. Finally, we tried to verify this method by FEM analysis. First of all, the parameters of thick film were given from the representative values of PZT parameters in a paper [3]. The values of resonance frequency and displacements of the surface of PZT thick films and the back surface of Si substrates were analyzed at same conditions as measurement. Regarding these values as measurement values, we fitted them using this newly developed method. As a result, the piezoelectric constants, d_{31} and d_{33}, could be determined with the deviation of less than 5% from the real measurement values.

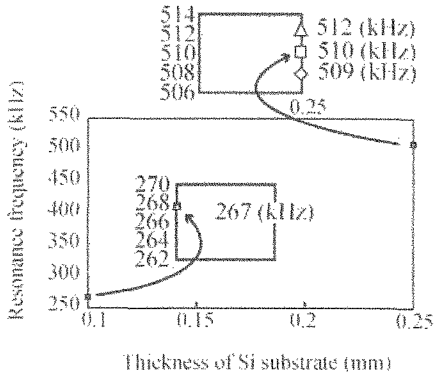


Fig. 4. Resonance frequency as a function of thickness of Si substrates.

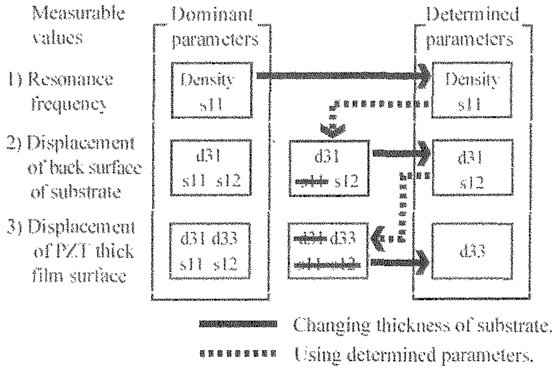


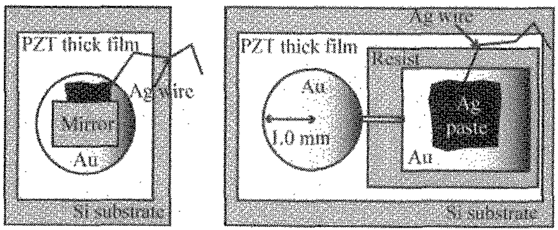
Fig. 5. Procedure of method to determine piezoelectric constants of thick films.

3.2 Sample structure for high precision measurement

For the measurement using DB-LDI, the top electrode of the sample should be satisfied with the following condition, which is that the reflection area for the laser beam is on the electrode for applying electric field. Taking into account of this condition, we checked the influence of the structure of top electrodes using FEM analysis as follows. In the previous study, the mirror was attached to a top electrode for getting the reflection from DB-LDI. And Ag paste was attached to the region of a top electrode as shown in Fig. 6(a). As a result of FEM analysis, it was confirmed Ag paste attached to the region of a top electrode affects the piezoelectric strain so that the resonance frequency is shifted from the real resonance frequency as shown in Fig. 7. As mentioned above, this resonance frequency value is very important to obtain the piezoelectric constants with a high accuracy when this evaluation method proposed in this study is used. Referring to this result, the electrode for wiring should be on the other places like an outer island for the measurement. However, when the outer island was fabricated directly on the PZT films, the piezoelectric deformation was occurred in this region, too. For the highest accuracy measurement, the electric field on the PZT film should be decreased as low as possible. Therefore, we designed the structure of the sample as shown in Fig. 6(b), in which a resist layer with low dielectric permittivity was deposited under this outer island electrode for wiring. It was confirmed that this structure does not shift the resonance frequency by the FEM analysis. Therefore, we adopted this sample structure for the accuracy measurement.

As for the sample, PZT thick films were prepared on Pt/IrO$_2$/SiO$_2$/Si substrates by the ADM. The Au electrode was sputtered on the surface of the PZT thick film. The PZT thick film was poled by applying a 60 kV/cm electrical field at 250°C for 1 hr. For the use of this newly developed method to evaluate the piezoelectric constants of thick films, the samples with various thicknesses of Si substrates are necessary. Simultaneously, it is required that the thicknesses of PZT thick films are same for the all samples. In order to satisfy these conditions, the back surfaces of Si substrates were grinded to be 0.10, 0.15, 0.20 and 0.25 mm of their thicknesses, respectively. The surfaces of PZT thick films were also grinded to be 10 μm exactly of their thicknesses. The same pattern shown in Fig. 6(b) was fabricated by the photolithography. In this process, resist coating, alignment and development were performed. After the formation of a gold electrode using the DC sputtering and the lift-off method, a brass plate with a hole of 2 mm in a diameter was attached to the back face of Si substrates for the energy-trapped structure.

During the preparation of these samples, however, many problems were arisen. Because the thicknesses of Si substrates were too thin, the samples were easily broken down. Moreover, some peeling occurred between the PZT thick films and Si substrates because the adhesion strength between them was too weak. At present, one sample was successfully prepared for the measurement due to these difficulties. However, it was enough to check the resonance frequency of the PZT thick films with a high accuracy using one sample by the DB-LDI, which is one of the most important parameters to be measured.



(a) (b)

Fig. 6. The sample structures for the measurement used (a) in the previous and (b) in this study.

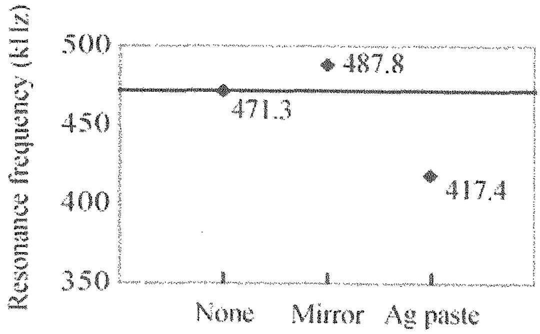


Fig. 7. Dependence of the resonance frequency according to the influence of a mirror and Ag paste on the top electrode.

As a result of the DB-LDI measurement, the displacement of the surface of the PZT thick film was 4 nm and the displacement of the back surface of the Si substrate was 3 nm. These values of displacements were too small in comparison to the values obtained from FEM analysis. It is considered that this discrepancy was caused by the insufficient poling state. Grinding the PZT thick film after poling had a possibility to destroy some poled regions. And the measured resonance frequency by the DB-LDI was 371.1 kHz from the displacement measurement of the surface of the PZT thick film as a function of frequency as shown in Fig. 8. This result was consistent with the value from the FEM analysis. Even though we could not obtained the piezoelectric constants of the PZT thick films in this study, it can be suggested that our method developed in this study will be useful for evaluating the piezoelectric constants regarding the film structure with the high accuracy.

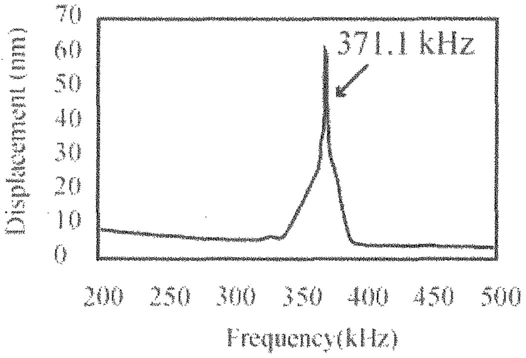


Fig. 8. Displacement of the surface of PZT thick films as a function of frequency.

4. CONCLUSIONS

As the results of FEM analysis, the number of required parameters was reduced and the dominant parameters in each measurement values were determined. By changing the thickness of Si substrates, it was found that two parameters in one measurable value could be determined. Using this result and combined analysis of the measurement of resonance frequency and displacements of both surfaces, the method to determine piezoelectric constants d_{31} and d_{33} of thick films was proposed. From the FEM analysis, these values had a deviation from real value of less than only 5%. If the samples with various thicknesses of substrates can be prepared, piezoelectric constants d_{31} and d_{33} of thick films which had a deviation from real value of less than only 5% could be determined using this method.

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(Received December 10, 2005; Accepted January 31, 2006)