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MEMS Resonance Test for Mechanical Characterization of Nano-Scale Thin Films

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1. Introduction

MEMS and electric devices include nanometer-thick film materials that have a variety of functions. For their reliable design and the improvement of their performance and lifetime, understanding of mechanical properties is significant. Especially Young's modulus is one of the most important material characteristics in order to carry out the structural design of devices. The basic material properties of materials are usually measured by tensile, bending, and nanoindentation tests. In the case of film specimens with a micrometer thickness, the tensile test is typical. To date lots of tensile test techniques have been developed for accurate material characteristics [1-2]. In the case that the target material is a film having a nanometer thickness, those testing techniques are hard to be employed because there are lots of technical difficulties, such as specimen preparation, handling, and force-displacement relation measurement. Therefore, a new material test technique for simply characterizing nanoscale films should be developed.

The purpose of this study is to develop a quantitative measurement method for the Young's modulus of nanometer- thick films. This paper focuses on developing the test technique using a MEMS resonator array and measuring the Young's moduli of Al and plasma-polymerization films made from CH_4 and CHF_3 gases.

2. Experimental Procedure

2-1 MEMS resonator array

Figure 1 shows the photograph of the produced MEMS resonator array that was made from a SOI wafer. The resonator consists of a fan-shape resonator with rotation angle measurement gauge, a rotation fulcrum, an electrostatic comb-drive actuator, and a capacitive sensor [3]. The resonant frequency, f, of the device is expressed as:

$$f = \frac{1}{2\pi}\sqrt{\frac{Ew^3}{6\ell\rho\theta R^4}} \tag{1}$$

where E, w, l, ρ, θ, and R are Young's modulus, width and length of fulcrum, density, rotation angle, and radius of resonator, respectively. The resonator was designed by finite element analysis to achieve proper vibration amplitude by resonance.

2-2 Derivation of Young's modulus

The resonant frequency of the device was firstly measured before film deposition. Then the Young's modulus, E_1, of a Si substrate was calculated as:

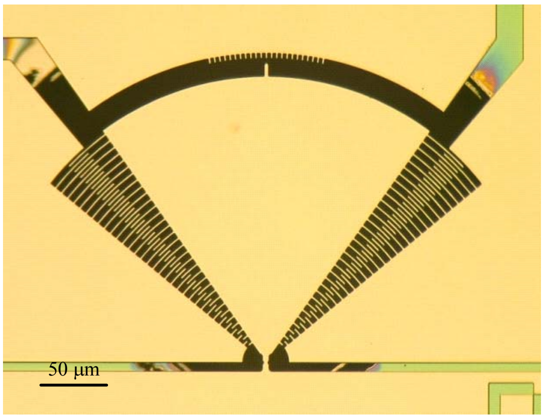


Figure 1 The fabricated MEMS rotational resonator.

$$E_1 = (2\pi f_1)^2 \frac{6\ell\rho\theta R^4}{w^3} \tag{2}$$

After that, a nanometer-thick film that is a target material was deposited onto the substrate, and the resonant frequency of the sum of the film and substrate was measured. After these measurements, the Young's modulus, E_2, of the deposited film can be simply given by:

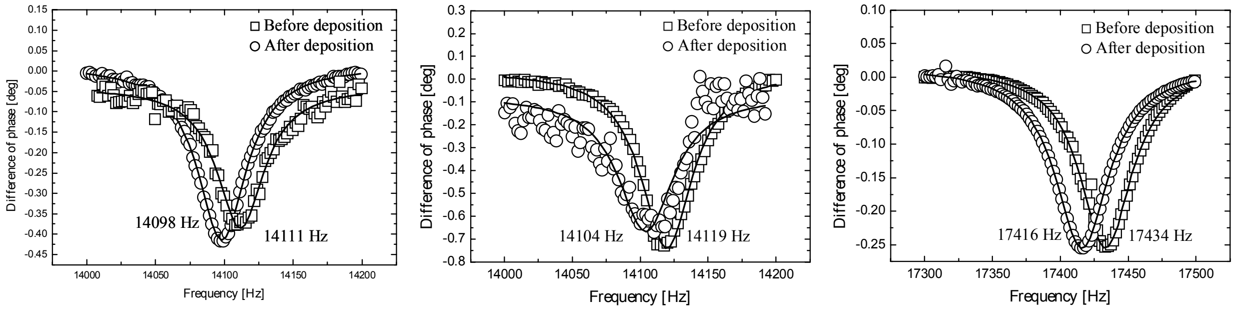
$$E_2 = E_1\left\{\left(\frac{f_{1+2}}{f_1}\right)^2\left(\frac{t_1}{t_2}+\frac{\rho_2}{\rho_1}\right)-\frac{t_1}{t_2}\right\} \tag{3}$$

where t_1 and t_2 are the thickness of substrate and film, and ρ_1 and ρ_2 are the density of substrate and film, respectively. Eq. (3) is obtained if the Poisson's ratio of deposited film is the same as that of substrate. In terms of its simplicity, we used Eq. (3) for Young's modulus derivation of thin films.

3. Results and Discussions

3-1 Resonance test results

Figures 2 show the phase curves of (a) Al, (b) CH_4-, and (c) CHF_3-derived polymer films obtained by frequency response analyzer (FRA) measurements. The square and circle plots indicate the phase curves before and after film deposition, respectively. In Fig. 2(a), before deposition of Al film, the phase curve has a downward sharp peak. The frequency at the peak position was calculated to be 14.111 kHz, which indicates the resonant frequency of the resonator used. By deposition of the film with 99.5 nm-thick, the resonant frequency shifted to 14.098 kHz because the mass



(a) Al film *(b) CH_4-derived polymer film* *(c) CHF_3-derived polymer film*

Figures 2 Results of resonance test: phase curves of resonator before and after deposition of nanometer-thick films.

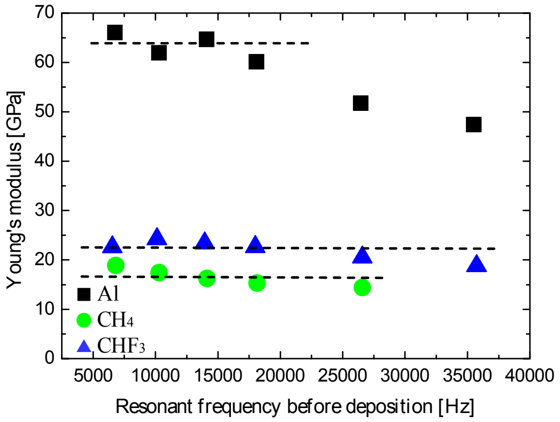


Figure 3 Resonant frequency and Young's modulus.

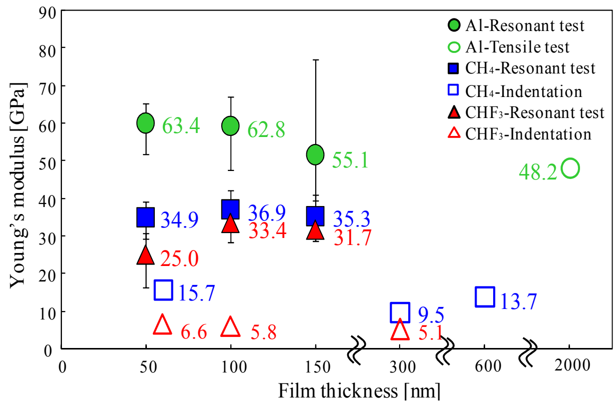


Figure 4 Young's modulus vs. film thickness.

of the resonator increased by the deposition. In Figs. 2(b) and (c), the resonant frequencies dropped by several Hz by depositions of CH_4- and CHF_3-derived polymer films with 85.1 and 159.4 nm-thick as with Al film. This indicates that the resonant frequency is sensitive to the change in the mass of resonator by film deposition.

3-2 Young's modulus measurement

Figures 3 show relation between the calculated Young's modulus and resonant frequency of a resonator before deposition. The mean Young's modulus of Al film is found to be 62 GPa, which is smaller by about 8 GPa than that of the bulk. The measured value stays constant throughout the resonant frequencies of resonators though the data derived from resonators with their resonant frequencies over 25 kHz deviate from the constant value. This would be caused by an experimental error in measuring film thickness. In the cases of CH_4- and CHF_3-derived polymer films, the measured Young's moduli are found to be 35.7 and 30.3 GPa on average, respectively, and shows no significant influence of resonant frequency.

Figure 4 represents the measured Young's modulus vs. film thickness. The closed plots of all the styles indicate the moduli derived from the resonance test, and the open plots are indicative of that from the tensile and nanoindentation tests. The mean Young's modulus of 50 nm-thick Al film is found to be 63.4 GPa, approximately 10 % smaller than the bulk value. The modulus gradually decreases with increasing film thickness. We consider the change of Young's modulus as not specimen size dependency but an experimental error. The Young's moduli of CH_4- and CHF_3-derived polymer films of 50 nm-thick are 34.9 and 25.0 GPa on average, respectively, which are kept almost constant in spite of a film thickness change ranging from 50 to 150 nm. The mean values are larger by 19.2 and 18.4 GPa than those by nanoindentation test. The smaller values by nanoindentation test would be caused by the tip-shape effect originating from very small penetration depth.

4. Conclusions

We proposed novel Young's modulus measurement method for nanometer-thick film materials. The Young's moduli of Al, CH_4- and CHF_3-derived polymer films could be measured from the resonant frequencies of a resonator before and after film deposition. The proposed technique would be useful for characterizing nanometer-thick film materials used in MEMS and electron devices.

Acknowledgements

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