3P2-1

Evaluation of electrical conductivity of silicon using resonant vibration of piezoelectric material

Aya Yoshida‡, Kanta Adachi, and Nobutomo Nakamura*
(Grad. School Eng., Osaka Univ.)

1. Introduction

Piezoelectric materials are widely used as acoustic transducers and sensors because of their ability to transduce electrical and mechanical energy. For example, quartz crystal microbalance (QCM) evaluates the mass of substances attached on the quartz oscillator by measuring the change in the resonant frequency, and it has been used for detecting biomolecules.[1] The resonant vibration of the piezoelectric material is also used for detecting the hydrogen gas[2] and for evaluating changes in the morphology of the thin film deposited on the surface of the piezoelectric material.[3] In these conventional applications, the substance being measured is attached to the piezoelectric material and vibrated together with it.

In contrast to the above studies, recent research has shown that when a conductive material is present in the vicinity of a resonantly vibrating piezoelectric material, the resonant frequency of the piezoelectric material changes depending on the conductivity of the conductive material.[4] This phenomenon implies the possibility of noncontact resistance measurement based on the resonant response of the piezoelectric material, and it is expected to lead to a new research field in the resonance of piezoelectric materials. For these reasons, this study aims to verify whether it is possible to measure electrical resistance in a noncontact manner using the resonance of a piezoelectric material. By placing Si single crystals in the vicinity of the piezoelectric material and measuring the change in the resonant frequency, we evaluated the effect of the conductivity of Si on the resonant frequency.

2. Measurement principle

The measurement principle of the proposed method is based on the research on elastic waves propagating in piezoelectric semiconductors.[5] According to this research, the propagation velocity of elastic waves in piezoelectric semiconductors exhibits a frequency dependence, and it changes significantly around a frequency called the conduction frequency ω_c . The conduction frequency depends on the electrical conductivity σ and the dielectric constant ϵ of the semiconductor, and it is expressed as $\omega_c = \sigma/\epsilon$. Therefore, by measuring the frequency dependence of the propagation velocity and measuring the conduction frequency, the electrical conductivity can be evaluated.

In a recent study,[4] it was found that when a conductive material exists in the vicinity of a resonantly vibrating piezoelectric material, the resonant frequency of the piezoelectric material changes depending on the conductivity of the conductive material. This phenomenon is similar to that observed in the elastic waves propagating in the piezoelectric semiconductor. Therefore, by measuring the frequency dependence of the resonant vibration, the conductivity of the specimen will be measurable.

The resonant frequency f of a piezoelectric material depends on the elastic constant C, mass density ρ, piezoelectric constant e, and dielectric constant as follows:

$$f \propto \sqrt{C + \frac{e^2}{\epsilon}} \tag{1}$$

When a conductive material is present near the piezoelectric material, the oscillating electric field generated around the piezoelectric material weakens, and the electrical polarization in the piezoelectric material is reduced. This reduces the apparent piezoelectric constant, leading to a decrease in the resonant frequency. Similarly, when a semiconductor is placed instead of a conductive material and the resonant frequency is low, carriers in the semiconductor can move following the electric field, and it weakens the electric field as in the conductive material, thereby decreasing the resonant frequency. However, at a higher resonant frequency, the carriers cannot more following the electric field, and the semiconductor behaves like an insulator, and the resonant frequency barely decreases. Thus, the resonant frequency of a piezoelectric material changes depending on the electrical conductivity of the material placed near it, and the change ratio depends on the resonant frequency. Utilizing this relationship, resistance should be measurable.

E-mail: ‡yoshida@dfm.mech.eng.osaka-u.ac.jp,
*nakamura@mech.eng.osaka-u.ac.jp

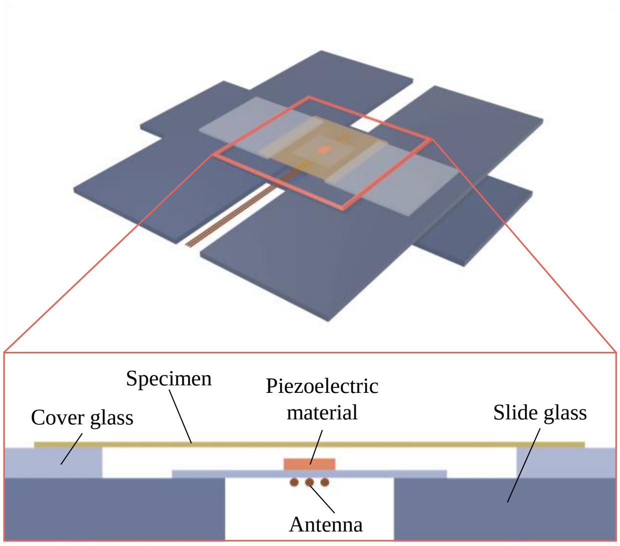


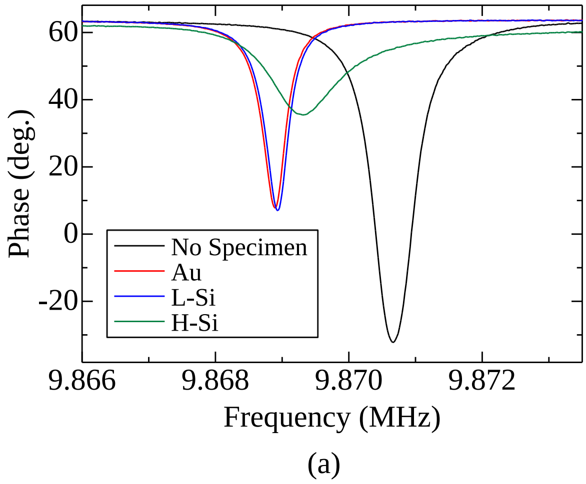
Fig.1 The schematic diagram of the experimental setup.

3. Experiments

We used lithium niobate as the piezoelectric material. Its dimension is 2.5 mm × 1.7 mm × 0.2 mm, and the free-resonance modes are measured. **Figure 1** shows the experimental setup for measuring the resonant frequencies of a piezoelectric material. The structure allows the specimens to be placed near the piezoelectric material without touching it. We used an Au thin film as a conductor and two Si single crystals as semiconductors. The Au thin film was sputtered on a cover glass measuring 18 mm × 18 mm × 0.1 mm. Electrical resistivity of Si was 1 ~ 3 Ω·cm and $8.4 \times 10^4 \sim 1.0 \times 10^5$ Ω·cm, and they were named L-Si and H-Si, respectively.

4. Results and Discussion

We repeatedly placed and removed the specimen above the piezoelectric material and measured the changes in the resonant frequency of the mode around 9.87 MHz. In **Fig. 2**, measured resonant spectra and the corresponding changes in the resonant frequency are shown. The specimens were placed above the piezoelectric material in the order of Au, L-Si, and H-Si. From the spectra, the lower the resistivity of the specimen, the lower the resonant frequency, indicating that the expected results were obtained. This means that the resonant frequency of the piezoelectric material depends on the resistivity of the specimen placed in the vicinity of the piezoelectric material. Therefore, it was confirmed that the piezoelectric resonance can be used to measure the resistivity of a specimen in a noncontact manner.



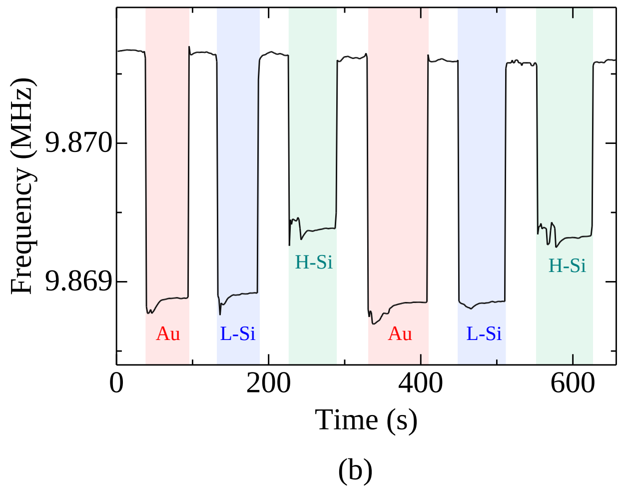


Fig.2 Experimental results for the resonant mode around 9.87 MHz. (a) Resonant spectra measured with different specimens. (b) Changes in the resonant frequency when specimens are placed above the piezoelectric material.

5. Conclusion

We measured the change in resonant frequency when the specimen was placed above the piezoelectric material. The lower the resistivity of the specimen, the lower the resonant frequency. These results suggest that it is possible to measure the resistivity of a specimen in a noncontact manner using the resonance of the piezoelectric material.

References

1) H. Ogi, Jpn. J. Appl. Phys. **63**, 040802 (2024).
2) L. Zhou, N. Nakamura, A. Nagakubo, and H. Ogi, Appl. Phys. Lett. **115**, 171901 (2019).
3) N. Nakamura, N. Yoshimura, H. Ogi, and M. Hirao, J. Appl. Phys. **118**, 085302 (2015).
4) N. Nakamura and H. Ogi, Appl. Phys. Lett. **111**, 101902 (2017).
5) A. R. Huston and D. L. White, J. Appl. Phys. **33**, 40 (1962).