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Fundamental study on optimization of microchannel structure with respect to wireless PDMS-QCM biosensor

無線 PDMS-QCM バイオセンサの微細流路構造最適化に関する基礎的研究

Yu Sato[1†], Noriyasu Masumoto[1], Fumihito Kato[1], and Hirotsugu Ogi[2] ([1]Fac. Fund. Eng., Nippon Inst. of Tech.; [2]Grad. Sch. Eng., Osaka Univ.)

佐藤 優 [1†]，増本 憲泰 [1]，加藤 史仁 [1]，荻 博次 [2] ([1] 日工大 基幹工, [2] 阪大院 工)

1. Introduction

Biosensors are effective tools for early detection of intractable diseases such as cancer and diabetes and for the development of new drugs with few side effects. One candidate for such a biosensor is quartz crystal microbalance (QCM) biosensor.[1)] The QCM biosensor is a mass detection sensor that detects mass loading of the quartz oscillator as the resonance frequency change when the target substance is adsorbed on the quartz surface which vibrates in thickness shear mode. The sensitivity of the QCM biosensor is inversely proportional to the square of the thickness of quartz oscillator, as can be derived from Sauerbrey equation.[2, 3)] However, because the inertial resistance of the metal electrode is relatively increased as the thickness of the quartz oscillator is reduced, it is impossible to increase the sensitivity because the excitation of the quartz oscillator is prevented. The wireless electrodeless QCM biosensor has been developed as a method to improve these issues.[4)] This sensor does not have the metal electrodes for excitation on the surfaces of a thin crystal oscillator. In addition, the quartz oscillator is not mechanically fixed, therefore it is not affected by ambient temperature changes due to differences in thermal expansion coefficient. Thereafter, in order to fabricate the sensor chip inexpensively, the wireless PDMS-QCM biosensor fabricated by nanoimprint lithography with poly(dimethylsiloxane) (PDMS) was developed.[5)] Because this sensor can package the quartz oscillator in the microchannel at room temperature, the organic sensitive film can be formed on the quartz oscillator surfaces. Because the PDMS-QCM biosensor supports the thin quartz crystal resonator by the micropillars in the microchannel, the structural damping of vibration energy can be reduced compared to the commercially available QCM in which the quartz oscillator is mechanically fixed. However, the optimum micropillars arrangement considering the structural damping has not been considered. In this study, we investigated the better arrangement of the micropillars through the piezoelectric analysis of AT-cut quartz oscillator by the finite element method.

E-mail: kato.fumihito@nit.ac.jp

2. Piezoelectric analysis

Using the finite element analysis software Femtet (Murata Software Co., Ltd.), piezoelectric analysis of AT-cut quartz oscillator was performed. AT-cut quartz oscillator is the thin quartz plate which is cut at an angle of 35.25° with respect to the optical axis of the artificial quartz crystal. Because it is necessary to convert real space to analysis space, the coordinates were converted using Euler angles (α, β, γ)=(0°, 35.25°+ 90°, 0°) as shown in Fig. 1.

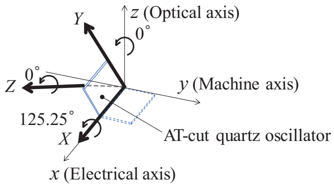

Fig. 1 Coordinate transformation from real space to analysis space.

The quartz oscillator of the PDMS-QCM biosensor is supported by the micropillars without mechanical fixing. Therefore, the quartz oscillator itself was used as a reference analysis model, and the positions of the micropillars were investigated as the parameter. Figure 2 shows the piezoelectric analysis models. The AT-cut quartz oscillator is 2.5 mm in width, 1.7 mm length and 30 µm thickness, respectively. The quartz oscillator and micoropillars were divided into four layers and one side of the mesh was set to 0.04 mm. The applied voltage was set to GND on the lower side of the quartz oscillator and 5 V on the upper side. The sweep frequency of harmonic analysis was performed from 54 MHz to 56 MHz, including the fundamental resonance frequency of 55.7 MHz. The micropillars have an outer diameter of 50 µm and a height of 50 µm, and the material is PDMS which is 0.75 MPa in Young's modulus and 0.48 in Poisson's ratio. The boundary surface between the quartz oscillator and the micropillars was in a bonded state due to the limitation of boundary condition setting of the software, and the bottom surfaces of the micropillars were in a completely fixed state.

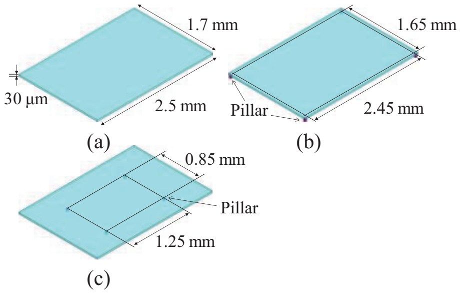

Fig. 2 Piezoelectric analysis models: (a) Blank quartz oscillator, (b) with pillars at four corners, and (c) with pillars placed near the center.

3. Results and discussion

Figure 3(a) shows the displacement in the x-axis direction at the fundamental resonance frequency in the thickness shear vibration of the quartz oscillator alone. The displacement in the x-axis direction is distributed near the central axis in the longitudinal direction of the quartz oscillator. From this result, the vibration energy of the AT-cut rectangular quartz oscillator is concentrated near the center, and in order to reduce the structural attenuation due to the micropillars, it is desirable to place them near both ends in the longitudinal direction of the quartz oscillator. Figure 3(b) shows the result of placing micropillars at the four corners of the quartz oscillator. Although the quartz oscillator is completely fixed by four micropillars, the displacement in the x-axis direction is concentrated near the center of the quartz oscillator. Compared to the crystal oscillator alone, the displacement distribution is slightly larger, however the displacement distribution is almost the same, therefore it can be found that the micropillars do not interfere with the vibration of the quartz oscillator. Figure 3 (c) shows the result of placing the micropillars near the center of the quartz oscillator. Four micropillars are arranged near the center where the vibration displacement is large, however the vibration of the displacement in the x-axis direction is concentrated near the center of the quartz oscillator. As in Fig. 3(b), it was found that the displacement distribution was larger than result of the quartz oscillator alone. However, this result is almost similar to the result shown in Fig. 3(a), so it is considered that the micropillars do not disturb the vibration. From these results, it is considered that the structure that supports the quartz oscillator with the micropillars with a diameter of 50 μm and a height of 50 μm does not contribute to the structural damping. The reason why the displacement distribution of the quartz oscillator with micropillars is larger than that of the quartz oscillator alone is considered to be due to superposition of other vibration modes (e.g., bending modes) in addition to the thickness shear vibration. This piezoelectric analysis was performed assuming a vacuum state. However, in actually, because the quartz oscillator vibrates in the solution, vibrations such as bending mode other than thickness shear vibration are attenuated by the viscosity of the solution and do not appear as vibration modes. Therefore, it is considered that the micropillar structure and the pillar position do not affect the thickness shear vibration of the quartz oscillator. However, in the future, it will be necessary to fabricate the devices and compare them with simulation results.

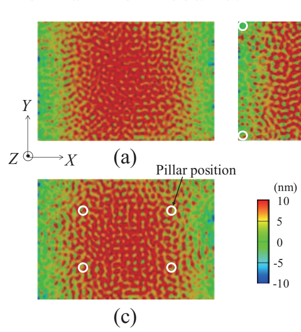

Fig. 3 Displacement of quartz surface in x-axis direction: (a) Blank quartz oscillator, (b) with pillars at four corners, and (c) with pillars placed near the center.

4. Conclusion

The thickness shear vibration distribution of the AT-cut rectangular quartz oscillator was investigated by piezoelectric analysis. It was found that there was a large displacement near the center of the quartz oscillator. It was also found that the micropillar structure and the position of the micropillars do not affect the structural damping. However, it will be necessary to compare actual devices with simulation results in the future.

Acknowledgment

This study is partially supported by SENTAN program from Japan Science and Technology Agency (JST) and Japan Society for the Promotion of Science (JSPS) KAKENHI Grant Number 17K01420.

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