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Basic characteristics of quartz crystal sensor with interdigitated electrodes

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ABSTRACT

This paper describes basic characteristics of the quartz crystal sensor with interdigitated electrodes (IDE quartz crystal sensor) which is for simultaneous monitoring of mass, viscosity, conductivity and dielectric changes of liquids or thin films. As the IDE quartz crystal sensor has three terminals for a pair of IDEs on the one side and a counter electrode on the other side, the resonance properties have been analyzed using the electrical equivalent circuit models and measured experimentally for all connecting types of electrode pairs. The IDE quartz crystal has shown clear resonance curves for calculating the resonance frequency and resonance resistance values as well as normal quartz crystal in the air and in contact with liquid. Small shifts in the resonance frequency and resonance resistance depending on the connecting types have been obtained and analyzed using the equivalent circuit models. We have found the integrated quartz crystal and IDE sensors could be monitored simultaneously by only one impedance analyzer. Finally, two types of measuring systems have been demonstrated for continuous measuring methods.

1. Introduction

AT-cut quartz crystal has been used for a mass sensor with nanogram sensitivity [1] and applied to gas sensors [2,3]. When the quartz crystal is used in a liquid, the resonance frequency changes with the viscosity of the liquid [4–7]. Resonance resistance, which is the resistance in the electrical equivalent circuit of the quartz crystal, has been shown to reflect the viscosity change of the contacting liquid or thin films [8,9]. The resonance resistance measurement was applied to monitoring a viscosity of liquid, evaluating a property of thin films, and detecting a phase transition and coagulation in bio-reactions [9–17]. Additionally, dumping-factor of the quartz crystal is used for similar analysis [18].

Interdigitated electrodes (IDEs) have been used for analytical chemistry. For electrochemical analysis, cycling oxidation and reduction reaction between the IDEs increase the sensitivity of detection. Impedance measurement between the IDEs has also been applied for biological analysis [19,20]. Using the colloidal gold particles, high sensitive DNA detection method has been reported [21]. There are some studies modifying the electrode of the quartz crystal. One of the studies modifying the electrodes of the quartz crystal has clarified the mass sensitivity of radial dependence [22]. It showed that the center of the quartz crystal has higher sensitivity rather than the periphery.

The combination of the quartz crystal and IDE has been studied. In one of the studies, the IDEs were used to induce adsorption of protein by the electric field to enhance the sensor sensitivity [23]. Another study applied the IDEs to measure electric resistance of the polymer films simultaneously to monitor the mass increase with gas phase water and adsorption of organic molecules [24]. As the combined sensor can monitor mass, viscosity, conductivity and dielectric changes of liquids or thin films simultaneously, it can be used for many applications, and the basic characteristics should be analyzed for future applications.

In this study, we analyze the resonance characteristics of IDE quartz crystal in the air and in contact with liquids. The analysis is performed theoretically and experimentally using equivalent circuit models and a fabricated IDE quartz crystal. Two types of continuous measuring systems are demonstrated for applying the sensor to advanced chemical and bio-sensors.

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2. Theoretical section

Fig. 1(a, b) shows the design of the IDE quartz crystal. The IDEs were formed as one of the sides of the quartz crystal. On the backside, a normal circular electrode was formed. A size of the circular electrodes is same as a normal quartz crystal (Fig. 1(c)) used for a comparison. For using the IDE quartz crystal, four types of electrical connections were selected from the IDEs (E_1 and E_2) and the backside electrode (E_b). The illustrations are shown in Fig. 2 with a normal quartz crystal (Type 0). The first type (Type 1) was analyzed between the connected-IDEs ($E_1 + E_2$) and the backside electrode (E_b). The second type (Type 2) was analyzed between one IDE and the backside electrode. In this case, two patterns (Type 2(a) and 2(b)) can be selected in selecting IDEs (E_1 and E_2). Type 2(a) and 2(b) represent patterns using the electrode of E_1 and E_2, respectively. The third type (Type 3) was analyzed between one IDE and a set of the connected another IDE and the backside electrode. This type also has two patterns by selecting IDEs (Type 3(a) and 3(b)). Type 3(a) and 3(b) represent patterns using the electrode of E_1 and E_2, respectively. The fourth type (Type 4) was analyzed between one IDE (E_1) and another IDE (E_2).

Fig. 3(a) shows the electrical equivalent circuit of the normal quartz crystal resonator. The admittance of the normal quartz crystal can be written as:

$$Y_{type0} = 1/(R_1 + j\omega L_1 + 1/j\omega C_1) + j\omega C_0 \quad (1)$$

In the case of the IDE quartz crystal, the electrical equivalent circuit can be shown as in Fig. 3(b) where the impedance between the IDEs is defined as a parallel circuit of R_2 and C_2. For the IDE quartz crystal, the admittance can be treated as a total of the three admittance parts of Y_1, Y_2, and Y_3. The admittance equations for each part of the equivalent circuits are written as:

$$Y_1 = 1/(R_1 + j\omega L_1 + 1/j\omega C_1) + j\omega C_0 \quad (2)$$

$$Y_2 = 1/(R_1' + j\omega L_1' + 1/j\omega C_1') + j\omega C_0' \quad (3)$$

$$Y_3 = 1/R_2 + j\omega C_2 \quad (4)$$

When each IDE is treated as equivalent, the relation of $Y_1 = Y_2$ can be assumed.

For the four types of connections, the equivalent circuits are reformed as Fig. 3(c) to 3(f). The equivalent circuit form for type 1 connection (Fig. 3(c)) is a parallel circuit of the normal quartz crystal. The admittance equation can be written as:

$$Y_{type1} = Y_1 + Y_2 = 2Y_1 \quad (5)$$

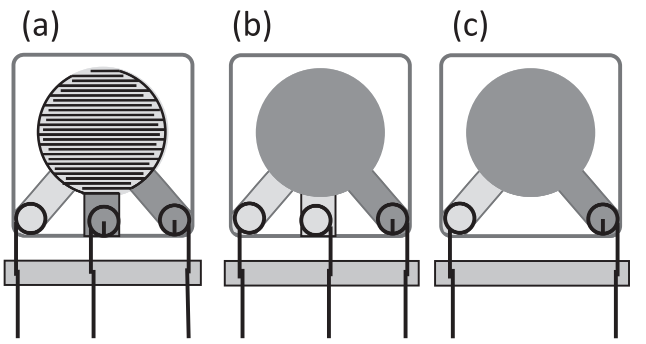

Fig. 1. (a–b) Design of the IDE quartz crystal. IDEs were designed to cover whole circular area of one of the sides of the quartz crystal (a), and a plane circular electrode was covered the other side (b). (c) Design of the normal quartz crystal. Plane circular electrodes were formed both sides.

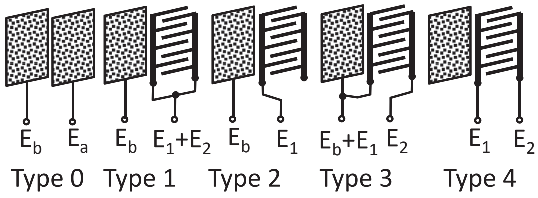

Fig. 2. Four connection types of the IDE for characterizing the resonance property of the IDE quartz crystal (Type 1–4) comparing with the normal quartz crystal (Type 0). E_1 and E_2 show the IDEs, and E_b shows the backside electrode. E_a shows the front electrode of the normal quartz crystal.

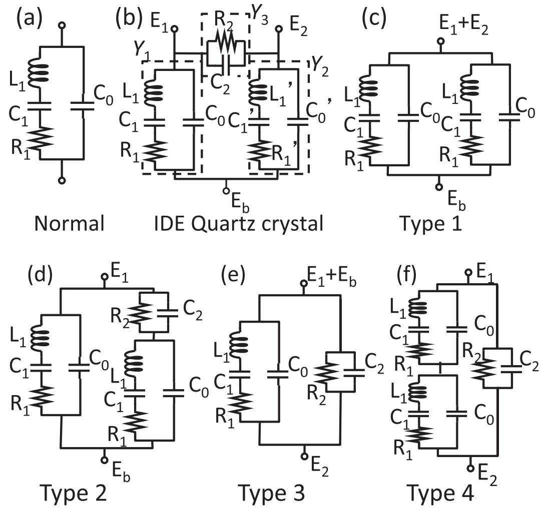

Fig. 3. Electrical equivalent circuit models for the normal quartz crystal and IDE quartz crystal. Types 1–4 show the equivalent circuit when the electrodes were connected as shown in Fig. 2. R_2 and C_2 mean the resistance and capacitance between the IDEs.

For type 2 connection, the admittance equation can be written according to the equivalent circuit (Fig. 3(d)):

$$Y_{type2} = Y_1 + Y_2Y_3/(Y_2 + Y_3) = Y_1 + Y_1Y_3/(Y_1 + Y_3) \quad (6)$$

In this case, two admittance components (Y_1 vs. $Y_1Y_3/(Y_1 + Y_3)$) have different resonance frequencies by the effect of the series capacitor C_2 in one of the components. For comparing the resonance frequency of two components, conductance curves for Y_1 and $Y_1Y_3/(Y_1 + Y_3)$ were calculated and shown in Fig. 4. For the component values for the calculation, the values of $R_1 = 600\ \Omega$, $L_1 = 0.014$ H, $C_1 = 2.23 \times 10^{-14}$ F, $C_0 = 2.0 \times 10^{-12}$ F were used as typical values of equivalent circuits. For the value of C_2 and R_2, $C_2 = 2 \times 10^{-12}$ to 2×10^{-10} F and $R_2 = 1 \times 10^3$ to $1 \times 10^7\ \Omega$ were used.

Fig. 4(a) shows the calculated conductance curve for $G_1 = \text{Realpart}(Y_1)$ and $G_{2\text{ for C1 to C3}} = \text{Realpart}(Y_1Y_3/(Y_1 + Y_3))$ for $C_2 = 2 \times 10^{-12}$ to 2×10^{-10} F and $R_2 = 1 \times 10^3 \Omega$. The resonance peaks in the calculated conductance curves shifted with the change of C_2 values. Lower C_2 value makes the peak frequency higher and more distance from the peak frequency for G_1.

For type 2 connection, the total conductance G is addition of G_1 and G_2 ($G = G_1 + G_2$); therefore, the peaks of G curves shifted with the peak shift of G_2. When the peak frequency of G_2 has enough distance from the peak frequency of G_1, the peak frequency of G does not change, but when the peak frequencies of G_1 and G_2 are