PIEZOELECTRIC ROTATIONAL MODE DISK RESONATORS FOR LIQUID VISCOSITY MONITORING

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ABSTRACT

This work reports on piezoelectric rotational mode disk resonators capable of operation in liquid and their performance as viscosity sensors. Piezoelectrically transduced rotational mode silicon disk resonators with resonant frequencies in the 1.0-4.0MHz range were fabricated and operated in five different liquid alcohols (Methyl, Ethyl, Allyl, Isopropyl and Butyl). A quality factor of up to ~54 was measured for such devices when immersed in liquid. It is shown through measurements that, as expected by fluid mechanics and vibrations theoretical analysis, both resonant frequency and quality factor of the resonators decrease as the viscosity of surrounding liquid increases. Frequency-viscosity sensitivity in the order of 40KHz/cP has been measured for such devices.

INTRODUCTION

Dynamic viscosity, simply known as viscosity, is one of the most important parameters describing fluid characteristics. Viscosity measurements are needed in various industrial, biomedical, and laboratory applications. In automobile industry, the viscosity of oil which is used as an engine lubricant should fall in a specific range to provide the normal operation. In petroleum industry, viscosity measurements are crucial for effective exploration and design/optimization of production strategies especially in biodegraded heavy oil. Viscosity measurement is also one of the steps in quality control of most liquid products such as pharmaceutical drugs, paints, cosmetics, and food. In addition, it can be used as a diagnostic tool to characterize human blood.

Conventional viscosity measurement techniques typically involve complex large machines that require continuous calibration in a laboratory environment. Measurement of viscosity by means of a resonating MEMS structure immersed in a fluid is an interesting alternative gaining attention in recent years. Immersing the resonator in a fluid dampens the resonance which leads to a shift in resonant frequency and quality factor of the device. This technique is beneficial as it only requires a tiny amount of sample liquid for measurement and involves a very straightforward and simple process. It also has the capability of quick and online measurement of viscosity in many complex systems. Li et al. introduced a viscosity sensor using resonant torsional micro-paddles with magnetic actuation. Such devices exhibit very low quality factors (in the order of 2-3) in liquid due to their out of plane vibration causing significant damping. Using such devices also involves a complex sensing and actuation mechanism [1]. Puchades and Fuller introduced a thermally actuated resonating plate which senses kinematic viscosity (the ratio of dynamic viscosity and density) [2]. It involves not only a complex procedure to measure viscosity but also relatively low quality factors (less than 18). Etchart et al. used resonating beams with millimetre-scale lengths and micron-scale cross-sections to measure fluid viscosity. They also couldn't achieve quality factors higher than 10 in low viscosity fluids [3].

In order to achieve higher resonator quality factors, thermally actuated rotational mode disk resonators have been previously demonstrated to operate in liquid media with quality factors as high as 300 [4]. Since all the surfaces of such structures in the

resonant mode of interest slide in parallel to the liquid interface, it has minimal interaction with the surrounding liquid. Moreover, unlike the previous resonating devices reported in the literature, only viscosity (not the density of fluid) would have an influence on the measured data. That is basically because shear stress, the main factor in rotating devices, merely involves the effect of viscosity while the normal stress involves the effect of fluid density. However, the heat generated by such devices increases the temperature in their surrounding liquid and as a result a precise measurement of the viscosity will not be possible. This is mainly because the viscosity itself is a function of temperature. To avoid this problem, in this work similar resonant disk structures were implemented in a thin-film piezoelectric on silicon (TPoS) technology [5].

RESONATOR FABRICATION

A TPoS resonator consists of a thin piezoelectric aluminum nitride film which is sandwiched between two metal electrodes. All three layers are deposited on top of the device layer of a silicon-on-insulator (SOI) substrate (Figure 1a). The top metal layer is dry etched to define the top electrodes and signal pads. The Aluminum Nitride is wet etched to reach the bottom ground electrode (Figure 1b). The resonant structure is defined in a stack dry etch (Figure 1c). Backside handle layer of silicon beneath the resonator body is etched and the buried oxide layer of SOI wafer is removed in HF to create free-standing resonant structures (Figure 1d).

Figure 1: Process flow for TPoS resonators starting with a) thin-film deposition, b) a top metal etch followed by an aluminum nitride etch, c) device silicon anisotropic dry etch d) and finally handle silicon dry etch with silicon dioxide wet etch release.

Figure 2 shows a scanning electron microscope view of a 3.44MHz piezoelectric resonator implemented using the TPoS technology. The fabricated disk resonator is comprised of a central circular mass and two support beams. Resonator actuation and sensing is performed by metal coated aluminum nitride films on the disk support beams. The resonator transduction is performed piezoelectrically. Upon application of an alternating voltage at the right frequency to the metal electrode on one of the support beams, the support beams start vibrating in their first longitudinal mode while the disk vibrates in its rotational mode. The vibration amplitude is sensed through the metal electrode on the second support beam. In TPoS devices, piezoelectric transduction is used to excite the resonant mode of a structure made from a substrate material such as single crystalline silicon. The low-loss single crystalline material provides an improved quality factor over a purely piezoelectric resonator.

Figure 2: Scanning electron microscope view of a 3.44MHz thin-film piezoelectric on silicon (TPoS) rotational mode disk resonator.

Figure 3: a) Schematic view of the disk resonator rotating in fluid b) Velocity profile of fluid between two plates. c) Forces acting on upper plate.

ANALYSIS

To analyze the interaction of the resonating element with the surrounding liquid, the basic theory of fluid mechanics is used. Viscosity which is the most important parameter for characterizing specific fluid mechanical behavior, relates the local stress in a moving fluid to the strain of the fluid element. When a fluid is sheared, it begins to move at a strain rate (equal to velocity gradient) inversely proportional to coefficient of viscosity (μ). For Newtonian fluids (common linear fluids such as water, oil, and alcohols) this shear stress (τ) can be expressed as:

$$\tau = \mu \frac{\partial u}{\partial y} \quad (1)$$

where u and y are fluid velocity and distance vertical to the flow of fluid, respectively.

When the flow is induced by relative motion between a fixed lower plate and a moving upper plate at velocity U (Figure 3a), the velocity distribution for every instant can be assumed to be linear (as shown Figure 3b). It should be noted that velocity of the fluid layer being in contact with the moving plate is the same as velocity of the plate itself. And as a result, equation (1) can be formulated as [6]:

$$\tau = \mu \frac{U}{Y} \quad (2)$$

where Y is the distance between two plates.

Neglecting the shear applied on top surface and side walls of the disk, a fluid element just below the disk surface (as shown in Figure 3a) can be considered to find the torque applied to the disk from the surrounding fluid shear. Thus:

$$dT = r dF \quad (3)$$

where dT and dF are the infinitesimal torque and force applied to the element from the liquid. r is the distance between the element and the center of the disk. The force applied to the element can be expressed as below:

$$dF = \tau dA \quad (4)$$

where dA is the area of the element which is as follows:

$$dA = r dr d\theta \quad (5)$$

where $d\theta$ and dr are infinitely small angle and distance, respectively. Combining equations (2)-(4), and using the relationship between the linear velocity of the element and the angular velocity of the disk:

$$U = r\omega \quad (6)$$

where ω is the angular velocity of each element at a specific instant. The torque applied from the fluid to the small disk element is therefore obtained as:

$$dT = \mu \frac{r^3 \omega}{Y} dr d\theta \quad (7)$$

Integrating this equation over the whole disk, the equation for damping torque applied from the fluid to the disk is obtained:

$$T = \frac{\pi \mu R^4}{2Y} \omega \quad (8)$$

where R is the disk radius. Allowing for this equation to be the damping torque applied to the disk, the system damping coefficient can be easily derived as:

$$b = \frac{\pi R^4}{2Y} \mu \quad (9)$$

Considering a resonant damped system, its resonance frequency is as follows:

$$f_r = f_n \sqrt{1 - 2\xi^2} \quad (10)$$

where f_r is the resonant frequency of the damped system, f_n is the natural frequency and ξ is the damping ratio of the system which can be defined as:

$$\xi = \frac{b}{2\sqrt{KJ}} \quad (11)$$

where K and J are the stiffness of the supporting beams and the disk moment of inertia, respectively. Combining equations (9)-(11), the relationship between viscosity coefficient and resonance frequency can be obtained as:

$$f_r = \frac{f_n}{A} \sqrt{C^2 - \mu^2} \quad (12)$$

in which C is the following constant:

$$C = \frac{2y}{\pi R^4} \sqrt{2KJ} \quad (13).$$

Quality factor also could be determined as a function of viscosity coefficient:

$$Q = \frac{1}{2\xi} = \frac{B}{\mu} \quad (14)$$

in which B is the following constant:

$$B = 2y \frac{\sqrt{KJ}}{\pi R^4} \quad (15).$$

As it can be seen, quality factor is inversely proportional to coefficient of viscosity.

MEASUREMENT RESULTS

When immersed in liquid, damping of the vibrating structure changes as a function of fluid viscosity. This simple principle is used here to measure liquid viscosity based on the change of quality factor and consequently resonant frequency of the piezoelectric resonators. Table 1 shows the viscosity of five different alcohols used in measurements.

Table 1: Viscosity of used liquids in the experiments [7]

Fluid	Viscosity (mPa s)
Methyl Alcohol	0.55
Ethyl Alcohol	1.06
Allyl Alcohol	1.30
Isopropyl Alcohol	1.95
Butyl Alcohol	2.60

The fabricated resonators were tested in a two-port configuration and the transmission data were recorded using a network analyzer. The silicon chip containing the resonators was placed on a printed board circuit board (PCB) and electrical connections to the resonators were provided by wedge-bonded aluminum wires.

The PCB was then placed in small containers containing different alcohols successively. Data were recorded at 25 °C after

immersion in each of alcohols when the frequency response got stable after a couple of seconds. Similar set of measurements were performed on different resonators with different dimensions. Table 2 summarizes the measurement results for these resonators operating in different liquids. As expected, with the increase in viscosity of the surrounding liquid, both the quality factor and resonant frequency decrease. Figure 4 shows the frequency response of the device#1 in five different alcohols.

Figure 5 depicts the changes in quality factor as a function of liquid viscosity for three different devices. The changes in the resonant frequency of the resonators working in liquids with various viscosities are also shown in Figure 6. As it is clearly shown by immersing the resonators in more viscous fluids, their quality factor and resonant frequency further decreases. This is mainly due to the effect of the shear applied from the surrounding fluid to the disk resonator, dampening its vibration.

Figure 4: Measured frequency responses for the 4.15MHz piezoelectric disk resonator operating in different liquids.

Figure 5: Measured quality factor of the rotational mode disk resonators as a function of liquid viscosity at 25 °C.

Frequency-viscosity sensitivities of 35, 40 and 15 kHz/cP, and quality factor-viscosity sensitivities of 5, 15 and 17cP⁻¹ were measured for the devices#1-3, respectively.

Table 2: Summary of measurement results obtained from piezoelectric disk resonators in different liquids.

	Plate Diameter (μm)	Support Beam Width (μm)	Support Beam Length (μm)	Liquid/Air	Quality Factor	Frequency (MHz)	Freq. Shift with Respect to Ethyl Alcohol (PPM)
Device#1	100	16	50	Air	80	4.15	
				Methyl	26.4	4.0486	2402
				Ethyl	19.5	4.0389	-
				Allyl	18.7	4.0226	-4036
				Isopropyl	16.7	4.005	-8393
				Buthyl	15.2	3.9816	-14187
Device#2	200	16	100	Air	243	3.44	
				Methyl	46.7	3.3967	4584
				Ethyl	37.4	3.3812	-
				Allyl	31.9	3.3692	-3549
				Isopropyl	23.2	3.3586	-6684
				Buthyl	17.9	3.3236	-17035
Device#3	500	40	300	Air	278	1.39	
				Methyl	54	1.3808	870
				Ethyl	45.9	1.3796	-
				Allyl	40.7	1.3758	-2754
				Isopropyl	27.3	1.3643	-11090
				Buthyl	21	1.3552	-17686

Figure 6: Measured resonant frequency of the rotational mode disk resonators as a function of liquid viscosity at 25 °C.

CONCLUSION

TPoS rotational mode disk resonators were introduced and utilized as viscosity sensing devices. Due to the minimum interaction with the surrounding liquid and the fact that they do not produce heat during operation, such devices were shown to be capable of reliable viscosity measurements. The frequency response of the fabricated resonators was monitored and recorded in five different liquids using a network analyzer. Quality factors as high as 54 were measured in liquids for such devices. As expected from the formulation, both quality factor and resonant frequency decreased as the viscosity of surrounding fluids was increased. The results show a relatively high frequency-viscosity sensitivity of up to ~40kHz/cP for the fabricated resonators.

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