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Resonant Silicon Mass Sensor with Capacitive Readout

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1. Introduction

Mass sensor with a miniaturized resonator have attracted much attention due to the possibility to measure an extremely small mass [1-3], which is achieved by recent development of Micro/Nanofabrication technologies. These resonating sensors have the fundamental issue that environment has largely influence on the performance of sensor. Especially, in atmospheric pressure, the quality factor (*Q* factor) declines and the detectable minimum mass increases. Various noises including thermomechanical noise and temperature fluctuation noise limit the resolution of mass detection. Miniaturization can improve the influence of the thermomechanical noise. However, the temperature fluctuation noise increases by the miniaturization if its measurement method such as an optical sensing generates a heat and heat conduction. Capacitive sensing is less affected to temperature fluctuation noise than other detection methods. This paper reports a capacitive mass sensor with a very thin single crystalline silicon resonator.

2. Principle and Fabrication of Mass Sensor

Figure 1 shows the schematic illustration of the mass sensor. A thin single crystalline silicon cantilever is used as a resonator with capabilities of capacitive readout and electrostatic actuation. For operating in various environments, a heater element is integrated in this sensor, which can change the temperature of the cantilever, as required. The mass sensor consists of two cantilevers. One is the mass-sensing element and the other is the reference cantilever that compensates temperature variation on mass sensing. The opposite electrodes were fabricated on a Pyrex glass substrate that is chosen to reduce a parasitic capacitance. The electrical capacitance between the cantilever and the detection electrode is employed as the component of an electric LC oscillator with a high resonant frequency. Its oscillation frequency of the LC oscillator varies by the change of the sensor capacitance. Under the self-oscillation of the sensor, the resonant frequency of the LC oscillator is modulated in frequency. The vibration signal of the cantilever is obtained using a FM demodulator, and its frequency change due to a mass loading is determined by a frequency counter or another FM demodulator. Figure 2 shows the typical SEM images of the fabricated mass sensor.

3. Experiments

The capacitive readout of the mass sensor was demonstrated, and the detectable minimum mass

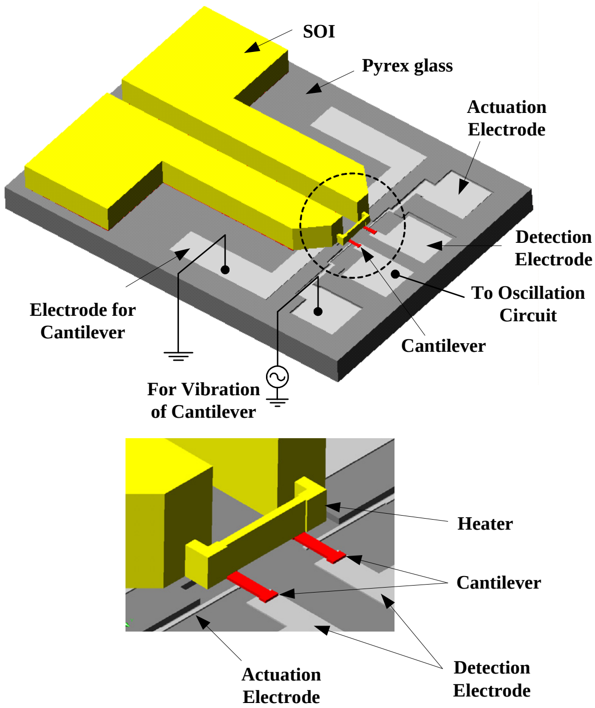

Figure 1. Schematic figure of mass sensor.

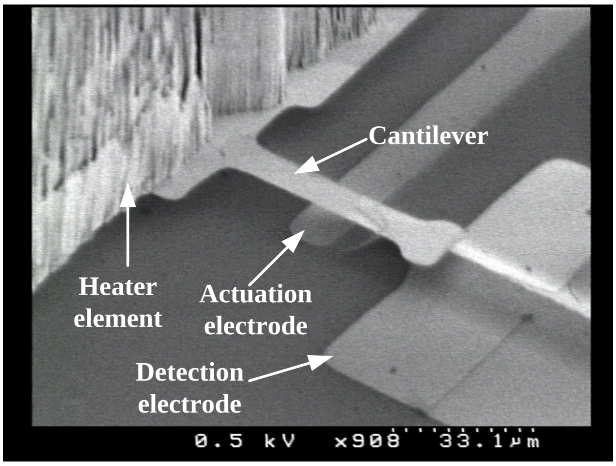

Figure 2. Magnified SEM image of the sensor after bonding.

in self-oscillation was investigated. The length, width, and thickness of the cantilever were 67 μm, 8 μm and 250 nm, respectively. The sensing electrode opposite to the cantilever with a 7 μm gap distance was 18 μm ×18 μm in size. The experimental setup is shown in Fig.3. As the oscillation circuit, Clapp oscillator was adopted and the mass sensor was replaced with the capacitor of the oscillation circuit. The capacitance variation of the sensor, which modulates the resonant frequency of the oscillator circuit, was detected using the FM demodulator and frequency counter. The output signal of the FM demodulator corresponds to the vibration signal of the cantilever. The self-oscillation of the cantilever was achieved by the positive feedback of vibration signal via a phase and gain adjuster. For the vibration of cantilever, piezoelectric actuator was adopted in this experiment. The resonant frequency (RF) from oscillation circuit was approximately 1 GHz, and the frequency (IF) converted from RF signal by mixer was adjusted to be approximately 500 kHz. Figure 4 shows the Fourier Transform results of the demodulated signal, in the cases of applied actuation voltages of 0 V and 10 V. It can be observed that the center frequency shifted to right side by the change of the average capacitance in vibration. The frequency width of the FM modulation signal was 100 kHz at 10 V of actuation voltage.

Figure 5 shows the detectable minimum mass of the self-oscillated cantilever measured using the frequency counter as a function of the signal integrating time. With a 250-nm-thick cantilever, the detectable minimum mass of 1×10^{-14} g was obtained. The noise amplitude of the sensor output corresponds to vibration amplitude of 0.05 nm/(Hz)$^{0.5}$ in a frequency domain in comparison with the actuation signal, which is equivalent to the detectable minimum capacitance variation of 2.9×10^{-21} F. Obtained values seem to be very close to that of calculated result at the short integration time. As the signal integration time increase, the difference between experimental and theoretical values increases. This is possibly caused by low frequency noise originated in gas adsorption and desorption.

Above experimental results show the high potential ability of capacitive silicon resonator for high sensitive, mass sensor.

4. Conclusions

The single crystalline silicon resonator as a mass sensor with capabilities of capacitive readout and electrostatic actuation was designed and fabricated. The sensor employed an electrical LC oscillator and the capacitance of the sensor served as a component of LC oscillator. Using the FM demodulator, the vibration of the cantilever could be measured with a high sensitivity in

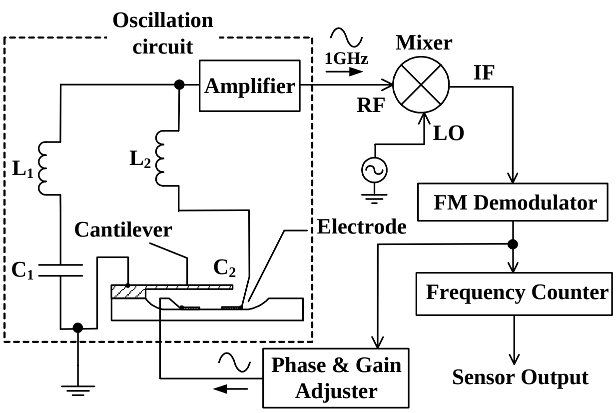

Figure 3. Capacitance measurement system of sensor

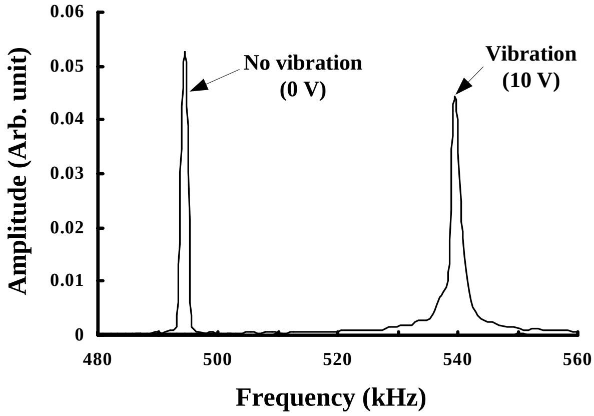

Figure 4. Fourier-transformed spectra of demodulated signal of IF signal with and without vibrating the cantilever.

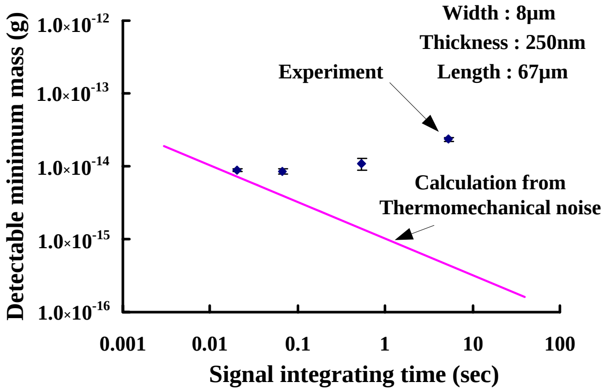

Figure 5. Detectable minimum mass of sensor when the signal integrating time is changed.

vibration amplitude. In the self-oscillated cantilever with a thickness of 250 nm, the detectable minimum mass of 1×10^{-14} g was obtained using the capacitive detection method. The noise amplitude of the sensor output corresponds to vibration amplitude of 0.05 nm/(Hz)$^{0.5}$ in a frequency domain in comparison with the actuation signal, which is equivalent to the detectable minimum capacitance variation of 2.9×10^{-21} F. These results show the high potential ability of capacitive silicon resonator for high sensitive and low noise mass sensor.

Acknowledgements

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