TEMPERATURE-COMPENSATED PURE SILICON CANTILEVER RESONATOR WITH COUPLED TORSIONAL STRUCTURE AT ANCHOR

Shunsuke Yamada, and Shuji Tanaka[1]
[1]Tohoku University, JAPAN

ABSTRACT

Combined with a coupled torsional structure at the anchor, a temperature compensated cantilever resonator was developed to reduce frequency dependence. The device shows the frequency dependence of 856 ppm with the temperature ranging from 25˚C to 80˚C. The FEM simulation indicates that the coupled torsional structure at the anchor allows us to reduce temperature dependence of resonators to be 170 ppm with temperature ranging from −40˚C to 80˚C, optimizing wafer dopant, density, and mode.

KEYWORDS

Resonator, temperature compensation, MEMS.

INTRODUCTION

Background

Temperature compensated resonators are crucial to achieve precise timing devices and sensors. The temperature coefficient of frequency (TCF) depends on dopant types, dopant densities, the structure of resonators, and vibration modes. To date, researchers demonstrated low TCF of Lamé mode and length extensional resonators by optimizing the design parameters. On the other hand, there is no report on low TCF of a pure silicon cantilever resonator, which is the most fundamental MEMS element. Although wafer dopants and density are optimized, a pure silicon cantilever resonator is unable to reduce the TCF less than 500 ppm. Silicon dioxide is effective to reduce TCF, but it has a significantly negative impact on Q factor and is not compatible with hydrofluoric acid etching. Herein, we first report a pure silicon cantilever resonator with TCF as low as 200 ppm/K.

Device Design

Figure 1 shows the structure of the cantilever with coupled torsional structure at the anchor (torsional cantilever). The idea of this new structure is based on the fact that the TCF of cantilever and torsional resonators increase and decrease, respectively, with a temperature ranging from −40˚C to 80˚C and dopant of 7.5×10^{19} cm^{-3} phosphorous as shown in Fig. 2. In such a case, the cantilever in Fig. 1 may exhibit low TCF by cancelling the TCF of the cantilever and torsional parts. Figure 3 shows frequency variation of the torsional cantilever calculated by the finite element method using data obtained by other groups [1, 2]. The characteristics exhibits dependence on dopant density, and the temperature variation of the resonator with phosphorous 7.5×10^{19} cm^{-3} is 600 ppm with the temperature range. The torsional cantilever successfully offset frequency variations of cantilever and show small frequency variation.

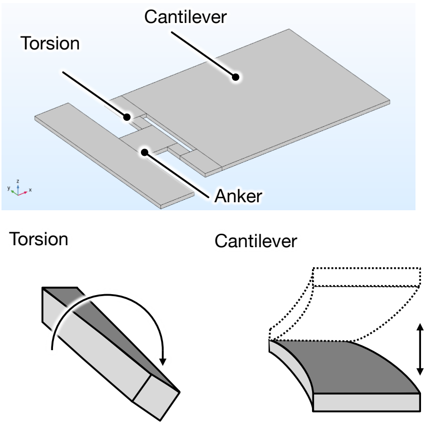

Figure 1: Schematic of a resonator with a coupled torsional structure at the anchor (torsion and cantilever).

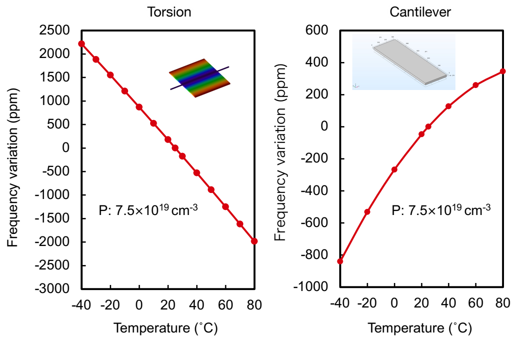

Figure 2: Temperature dependence of torsional and cantilever resonators.

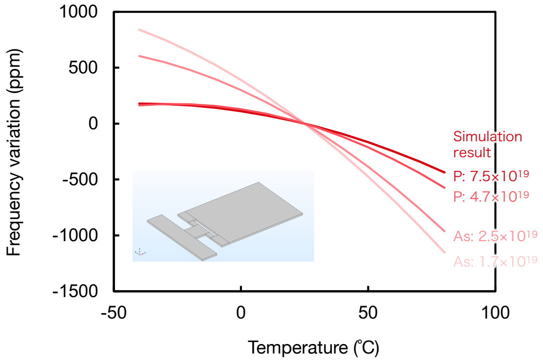

Figure 3: Simulation results of temperature dependence of torsional cantilever using p-type wafers.

EXPERIMENTS AND RESULTS

Device Fabrication

We, then, fabricated the torsional cantilever with a resonant frequency of 31 600 Hz. The resistivity and dopant of the wafer is of 0.001 Ω cm ~ 0.005 Ω cm and phosphorus, which correspond to the dopant densities of 1.0×10^{19} cm^{-3} ~ 1.0×10^{20} cm^{-3}. The fabrication started with cleaning the wafer with acetone, ethanol, and deionized water, followed by further cleaning with a piranha and HF solution. The Cr/Au = 20 nm/200 nm were deposited on the wafer, and photolithography and wet etching yielded contact pads. Deep-RIE patterned the device layer and made holes on the backside, and the diluted HF released the structure. Figure 4 shows the scanning electron microscope image of the completed resonator. The resonator and a temperature sensor were mounted on a ceramic package as shown in Fig.5, where the sensor monitored the temperature of the resonator.

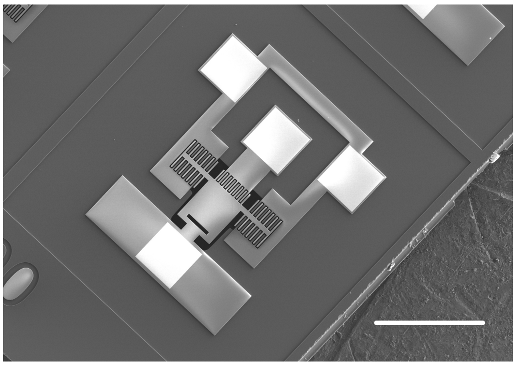

Figure 4: Photograph of the developed torsional cantilever (Scale bar 300 µm).

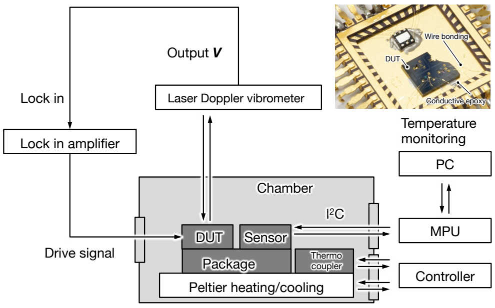

Figure 5: Experimental setup for temperature dependence measurement. Photograph shows the resonator and temperature sensor.

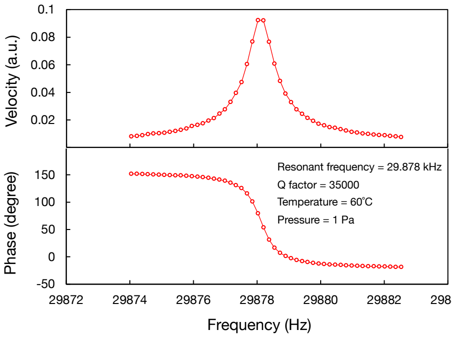

Figure 6: Velocity and phase of the resonator. The resonant frequency, Q factor, temperature, and pressure are of 29.878 kHz, 35 000, 60°C, and 1 Pa, respectively.

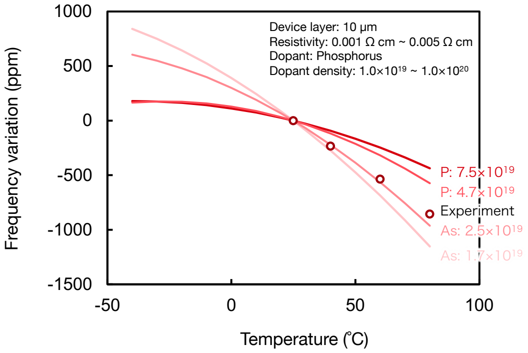

Figure 7: Comparison of temperature dependence in simulation and experimental results.

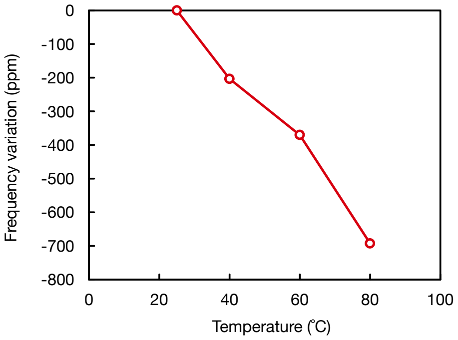

Figure 8: Latest result of frequency variation with respect to temperature.

Measurement of Resonant Characteristics

As shown in Fig 5, The resonator was settled into a vacuum chamber on a Peltier element to change the temperature of the resonator from 25°C to 80°C. The resonant characteristics are investigated with a laser Doppler vibrometer and lock-in amplifier. Figure 6 shows response of the resonator at 60°C and 1 Pa, and the resonant frequency and Q factor are of 29.878 kHz and 35 000, respectively. Figure 7 shows the frequency variation of the developed resonator and simulation results whose wafer are p-type and dopant densities of 1.7×10^{19} cm^{-3} ~ 7.5×10^{19} cm^{-3}. The frequency variation of the resonator is of 856 ppm with a temperature ranging from 25°C to 80°C, and the experimental result well agrees with the simulation result of 2.5×10^{19} cm^{-3} arsenic. To date, we have achieved the lowest temperature variation of 692 ppm with highly doped Si more than 5.0×10^{19} cm^{-3} and a temaprture ranging from 25˚C to 80 ˚C. We demonstrated the resonator with the coupled torsional structure at the anchor to achieve low frequency variation, which shows a potential to minimize frequency variation of MEMS devices including sensors, timing devices, and actuators.

CONCLUSION

We have developed a temperature-compensated resonator coupling the torsional and bending deformations to cancel their frequency variations. The device was designed using a FEM simulation that finds a structure and dopant density to reduce the frequency variation. The frequency variation of the developed resonator is 856 ppm with a temperature ranging from 25˚C to 80˚C, and the experimental result well agrees with the simulation result of 2.5×10^{19} cm^{-3} arsenic. The result offers an opportunity to develop a resonator that made of pure Si for temperature stable MEMS devices including timing device, sensors, and mirrors.

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CONTACT

* S. Yamada; santa@tohoku.ac.jp