DRIE 식각을 이용한 대면적 실리콘 미세 구조물 부유 시 발생하는 열고립 현상 해석

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Numerical Analysis for Thermal Isolation on Plasma Etched silicon micro-structures

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Abstract - This paper presents a theoretical and numerical analysis for thermal isolation of silicon micro-structures, especially for a large size with poor thermal conductivity, as well as straightforward solution for such an issue. Additional metal patterns underneath the silicon structures effectively reduces the thermal isolation. Heat transfer mechanism is analyzed using an equivalent circuit of thermal network including plasma, a heat source, heat capacitors, and thermal resistances. The FEM simulation was carried out to investigate the temperature change of silicon micro-structures according to process time. The temperature of silicon micro-structures with 2 µm thick chrome layer at a steady state is 86 ℃, an approximately 40 % decrease from the silicon microstructure without thin metal (122 ℃)

1. Introduction

For several decades, microelectromechanical systems (MEMS) have been intensively studied and developed in order to be applied to the microsensors such as micro-inertial sensors, micro-optical sensors and micro-RF sensors [1-3]. Among various materials for micromachining, single crystalline silicon (SCS) is widely used for MEMS due to a structural stability and a simple fabrication process. Anodic bonding of silicon to a glass substrate has further facilitated silicon as a popular material in MEMS. In some MEMS applications, a low actuation voltage and large displacement are important to obtain high tunability or long operational range. We can easily realize the low actuation voltage and the large displacement of MEMS actuators by simply reducing a spring constant, i.e. a narrow and long spring.

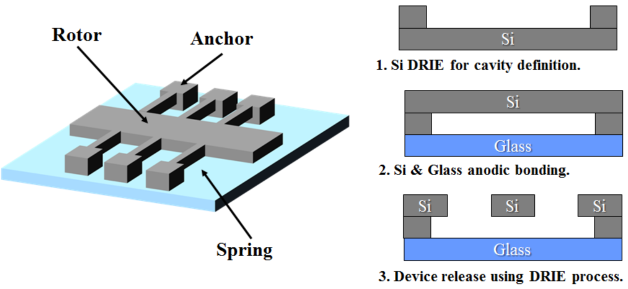
Usually deep reactive ion etching (DRIE) is used when the silicon structures on the glass substrate are released. In plasma enhanced etching systems, silicon micro-structures are exposed to large thermal flux from the plasma so that effective cooling is required to obtain well-defined structures. However a large area of the device and poor thermal conductivity from the device to a substrate hinders proper thermal release and causes structure deformation. As the spring constant decreases for the low actuation voltage and large displacement, the thermal conductance of spring also decrease. This decreasing thermal conductance eventually results in a thermal isolation, leading to an abrupt temperature rise of silicon structures. In addition, increased temperature causes an isotropic etching in the DRIE. In an extreme case, fine patterns such as comb electrodes or springs can be severly deformed or disconnected due to the accelerated isotropic etching at high temperature.

A few researches have been carried out to analyze and overcome this fabrication failure during DRIE process [2-4]. Hongwei Qu *et al* ,analyzed the temperature variation during DRIE process and suggested the solution to reduce the temperature rise by depositing 50-µm-thick photoresist (PR) as an additional heat transfer path [2]. However, the footing effect cause by charge accumulation was inevitable since PR was non-conducting material. S. E. Alper *et al*, suggested stepped-etching method by introducing 10 min etching and 20 min interrupt periods [3]. However the stepped-etching method extended process time too long, therefore process conditions should be optimized in terms of structure geometry and etching equipment.

In this paper, the heat transfer mechanism of silicon resonator is analyzed when the silicon structure is released using DRIE process. Based on the analysis of heat transfer mechanism, we propose an additional metal layer between the rotor and the anchor to reduce the temperature rise. The feasibility of the metal patterning is verified using the equivalent circuital modeling and FEM simulation.

2. Analysis

The proposed MEMS resonator has a long and narrow spring compared to the rotor size for a low actuation. The conceptual view and fabrication process are shown in Fig. 1. The rotor size was 3000 (l) x 1000 (w) x 50 (t) μm^3 and the spring size was 1000 (l) x 4 (w) x 50 (t) μm^3.



<Fig. 1> Schematic view of the MEMS resonator (left) and fabrication process (right)

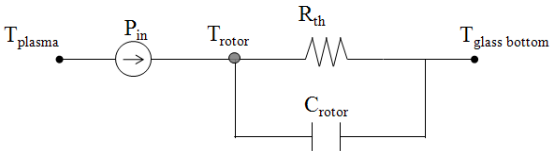
As can be seen from Fig. 1, at first the silicon was etched using DRIE process and the glass and the silicon substrate were bonded using anodic bonding. Finally the silicon device was released using DRIE process.

In general, heat transfer mechanism consists of conduction, convection, and radiation. These mechanisms are also applied to the proposed device when the structure is released using DRIE process. However, the heat transfer via convection is negligible because the pressure inside an etching chamber is maintained under a few mTorr. It is well-known that the incident heat source is an ion bombardment and it is expressed as [2],

$$P = n_i \sqrt{\frac{qT_e}{M}}\, qV_{bias} \qquad (1)$$

(n_i: ion density, q: charge, T_e :electron temperature, M: ion mass, V_{bias}: DC bias)

Here, most of the incident heat is accumulated on the rotor which plays role of heat capacitor. The thermal energy on the rotor is transferred to spring via conduction, radiation to surrounding, and convection by molecules, where each mechanism can be replaced equivalent thermal resistance. Based upon incident heat source, heat capacitor, and thermal resistance, we set the equivalent thermal circuit modeling as shown in Fig. 2.

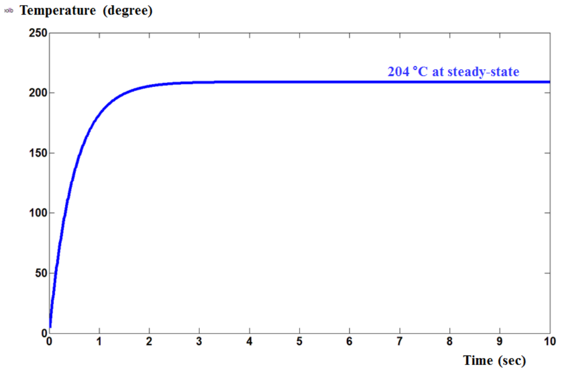


<Fig. 2> Equivalent thermal circuit using heat source, heat capacitor, and thermal resistance.

Then, the temperature on the silicon rotor can be expressed as

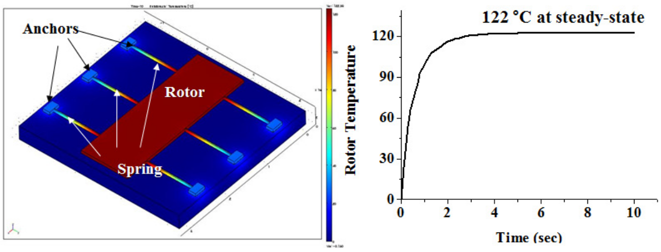
$$T(t) = T_0 + P \cdot A \cdot R_{th} \cdot (1 - \exp(-\frac{t}{R_{th} C})) \qquad (2)$$

the Fig. 3 shows the calculated temperature of rotor, where the temperature increased up to 204 ℃.



<Fig. 3> Calculated rotor temperature using thermal network method.

FEM simulation was also carried out to investigate temperature change precisely and the simulated results are shown in Fig. 4.

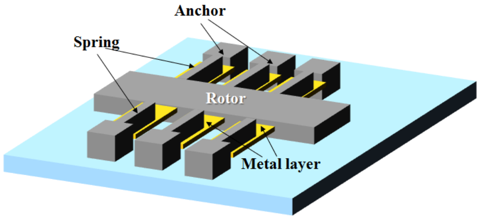


<Fig. 4> FEM simulation results of MEMS resonator.

Temperature of the rotor was 122 ℃ at the steady-state, which was 82 ℃ lower than the calculated value. The calculated value does not consider a geometry complexity. This seems to lead the difference between calculation and simulation. Both two results, calculation and simulation, indicated high temperature rise during DRIE process higher than 100 ℃. We expect, consequently, this high temperature would lead to a severe thermal isolation effect meaning the increase of isotropic etching. Fine patterns such as a few μm silicon springs can be distorted or vanished.

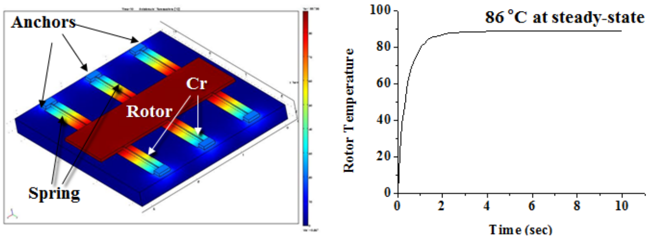
3. Simulation Results

A high temperature at steady state is inevitable in case of the MEMS devices which has large moving part comparing to the spring. As analyzed above, MEMS devices with a large heat capacity and resistance should be designed in the view of heat transfer to reduce an isotropic etching. Herein, we proposed the metal patterning beneath the silicon spring, which is connected with rotor and anchors to reduce the thermal resistance as shown Fig. 5.



<Fig. 5> Schematic view of the proposed MEMS resonator which has thin metal layer underneath the spring.

Total thermal resistance of the proposed design was effectively reduced due to the deposited metal layer. In this design, it is important to design appropriate geometric variables such as the width and thickness of metal layer because each variable determine not only thermal resistance but fabrication complexity. FEM simulation was carried out to prove the proposed method as shown Fig. 6.



<Fig. 6> FEM simulation results of MEMS resonator which has 2 μm thick chrome layer underneath the spring.

Temperature is decreased from 122 ℃ to 87 ℃ because of the deposited 2 μm-thick chrome layer. These results indicated that the accumulated heat energy can be effectively transferred to anchors via chrome layer beneath the silicon spring. Consequently, the thermal isolation effect can be suppressed and fine patterns would be possible.

4. Conclusion

Thermal isolation effect was demonstrated using a thermal equivalent circuit modeling and FEM simulation. The thin and wide metal patterning underneath silicon springs, which is connected with a rotor and anchors, leads to the reduce of a total heat resistance. A thermal isolation problem on a plasma etched silicon micro-structures can be solved by a thin metal patterning, and it is analyzed using FEM. We expect that the proposed method can be used for MEMS devices with a low actuation voltage. We are working on extracting the dominant parameters for thermal isolation effects.

[References]

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