Effect of residual stress on resonant frequency in Nitinol based thin film resonator

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Abstract: This current work focuses on the study of residual stress introduced in thin surface micromachined films due to the thermal stress. A model is presented here to study the change in thermal residual stress as the temperature changes and in turn how this change affects the resonant frequency of the resonator. The model uses two design; a resonator with straight and folded cantilevers. This work also involves in analysing the resonator performance as the material properties are changed. The simulations are done on Nitinol which is a Shape Memory Alloy (SMA). The simulation is carried out on COMSOL Multiphysics.

Keywords: Residual stress, thermal stress, shape memory alloy, resonant frequency

1. INTRODUCTION

Microfabricated cantilevers are widely used as sensors and actuators as they have high sensitivity, fast switching speeds, small size and low cost[1]. These when used as transducers find a lot of applications in chemical and biological industries[2-5]. The techniques such as variation in deflection, resonant frequency or quality factor of the beam can be easily studied from these kind of sensing techniques. They can be used in finding the DNA properties [6-8], and detecting the mass of particles on the beam[9-15]. The surface stress is the principle factor in finding how the solids behave and in finding the structure equilibrium[16].

For resonators, resonant frequency and quality factors are the two important characteristics[17]. MEMS resonators are designed in such a way that the resonant frequency should be fixed and if there is any shift in the frequency of the final structure then it will have a adverse effect on a desired application. There are various aspects that change the designed frequency of the resonator. This includes the deposition of metal layers on the structural layer and when this fabricated structure has a presence of residual stresses[17]. These coating of metal which is also used as an electrode, adds the mass in the structure and the stiffness is increased[18]. There are many designs which are modelled to study the effect of residual stress on the resonant frequency of the used devices[17].

The thermal characteristics of the layers produces residual stresses for the high temperature deposition processes[20]. The deflections obtained due to resonant frequency change have a adverse effects on the sensitivity of the resonator[19]. The residual stress in the multilayer designs are mainly because of variation in coefficients of thermal expansion of the different layers[21]. When the solid- liquid interface is involved, the interface involves of stresses between the solid phase and that separated by the interface[16]. As the negative temperature varies, the residual stress changes and this in turn...
changes the first natural frequency [22]. It also means that the change in positive temperature changes the compressive residual stress. When the first resonant frequency changes, there is a change in axial stress and it is most effective when applied voltage is equal to the pull in voltage [22].

In this current work, we study the effects of residual stress on the resonant frequency by using a cantilever beam made up of the SMA material Nitinol.

2. MODEL GEOMETRY

2.1 Straight Cantilever

![Modelled Straight cantilever](image)

The modelled cantilever has a width of 250 μm and a height of 120 μm. This paper studies a resonator with two designs; one having straight cantilever as shown in Figure 1. And other with folded cantilevers (Figure 2).

![Modelled Folded cantilever](image)

The above Figure 2 has four cantilever folded beam springs. The current work investigates the resonant frequency for both the cases when the beam is not subjected to any stress and when it is under thermal stress.
Table 1 shows the structure dimensions for both the design choices.

| Parameter | Straight Cantilever | Folded Cantilever | Plates |
|-----------|---------------------|--------------------|--------|
| Length    | 200 μm              | 170 μm             | 10 μm  |
|           |                     | 146 μm             | 250 μm |
| Width     | 2 μm                | 2 μm               | 2 μm   |
|           |                     | 2 μm               | 120 μm |
| Thickness | 2.25 μm             | 2.25 μm            | 2.25 μm|
|           |                     | 2.25 μm            | 2.25 μm|

### 2.2 Shape Memory Alloy
The Shape Memory Alloy[19,23,25] such as Nitinol (Titanium Nitrate) is used to model the structure and simulate the results. Nitinol has excellent superelastic properties and SMA materials possess unique property of remembering their shape. SMA has martensite transformations at high temperatures and Austenite at low temperatures[24].

### 3. METHODOLOGY
The Eigen frequencies for the structure are subjected to residual stress. A Pre-stressed Eigen frequency study is used [26]. The thermal expansion is studied first to determine the residual stress. This solution is used to produce the shifts necessary to compute the Eigen frequencies in the linearization points. The effects of stress-stiffening is computed accurately.

For a resonator with the model used in this paper, the in plane bending is computed by using the equation 1.

$$f_0 = \frac{1}{2\pi} \sqrt{\frac{24\sigma_r t b}{5mL} + \frac{4Et b^3}{mL^3}} \quad (1)$$

E is the young’s Modulus, L is cantilever length, m is the resonator mass, $\sigma_r$ is the residual stress in the beam.

The material is assumed to be isotropic, that is the stress is uniform throughout the film. The relationship of stress-strain is given by the equation 2.

$$\sigma_r = \left(\frac{E}{1-\nu}\right)\varepsilon \quad (2)$$

The strain $\varepsilon = \alpha\Delta t$, $\alpha$ being the coefficient of thermal expansion of the material used for the beam. $\Delta t$ is the temperature difference the deposition and the operating temperature. $\nu$ is the Poisson’s ratio.

### 4. RESULTS AND DISCUSSIONS
The simulation for two design choices are carried out on Comsol Multiphysics and it is shown in below figures.

An initial Stationary study step is used to calculate the residual thermal stress due to the difference between the fabrication and operation temperatures; the solution to this step is then used to shift the linearization point around which the eigen frequencies are computed in a subsequent Eigen frequency study step. Eigen frequency, Prestressed studies are used as this study type contains the required study steps by default. The modelled straight and folded cantilever without stress is shown in figure 3 and figure 4.
Figure 3. Modelled Straight cantilever without Stress

Figure 4. Modelled Folded cantilever without Stress

Figure 5. Modelled Straight cantilever subjected to residual stress
The straight and folded cantilevers subjected to residual stress is shown in figure 5 and figure 6. The reduction in the stress is depicted in figure 7.

5. CONCLUSION

The resonant frequency for the straight cantilevers increases when the model has residual stress. This stress sensitivity of the resonant frequency is reduced by folding the cantilevers. Thermal residual stress is reduced in thin film springs by folding the flexures. The stress is reduced in the flexures as all the springs can expand or contract in the direction of its axis. The predefined study type used in this paper helps the static thermal expansion problem which computes the residual stress.

ACKNOWLEDGMENTS

We are thankful to IIT (BHU), Varanasi for providing access to Comsol Software.

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