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Effect of Residual Stress on CSRR Based RF MEMS Filter

Buddhadev Pradhan* and Bhaskar Gupta
Department of Electronics and Tele-communication Engineering, Jadavpur University, Kolkata: 700032, West Bengal, India.
Email: pradhanbuddha123@gmail.com*, gupta_bh@yahoo.com

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ABSTRACT
Effects of residual stress on the electromechanical characteristic of a CSRRs based band reject filter are presented. Realization of such a filter has previously been reported by the authors, [1] neglecting the effect of residual stress on MEMS beam. This paper presents electromechanical simulated results as well as theoretically calculated results with consideration of residual stress effect. Residual stress performance is calculated with respect to actuation voltage and spring constant of fixed-fixed gold metallic beam. It is apparent that the effects of residual stress are quite significant which should be taken into account for all such analysis.

Keywords: CSRRs Filter, MEMS, Residual Stress, Electro- mechanical analysis

1. Introduction

Thin metal films are applied in many MEMS devices for high frequency microwave application, because of their miniature size and single architecture [2]. To reduce the actuation voltage of RF MEMS beam, metallic thin film with holes may be used in tuned filters or the anchor height between the beam and bottom pull-down electrode may be reduced [3-4]. One of the reasons for change in the actuation voltage is due to the presence of residual stress on metallic beam, generated during the metal deposition [5]. The nature of it is either compressive or tensile. Thus presence of residual stress is an important issue for successful operation of RF MEMS device and its reliability.

Despite the significance of residual stress in gold line coatings, quantitative measurement of these stresses is experimentally challenging due to the complexities arising from their deposited structure and processing history [6-9]. The gold layers deposited in cyanide bath have predominantly the compressive residual stresses. Using Potassium gold cyanide salt the gold electroplating process is done. With other gold plating processes, like when gold layers are deposited by sulphite bath, the residual stress will vary between tensile to compressive in nature depending upon the plating condition [10-12]. The study of residual stress changes on fixed-fixed gold beams are analyzed in details [6]. In this paper, effects of such residual stress variation on filter electro-mechanical properties are presented.

2. Filter Design and Characterization

A CSRR based CPW transmission line with S/W/S of 30/200/30 has been designed for gold on silicon substrate. The CSRR structures on signal line and ground plane are different, which is shown in fig.1 (a). Dimensions of the gold beams length, width and thickness are given by *l*, *w* and *t* respectively. The length and width of the CSRR for central line are given by ‘h’ and ‘a’ respectively. ‘c’, ‘e’ and ‘f’, ‘d’ are the width & spacing of the split rings respectively, while ‘g’ and ‘t’ are the gaps between the split rings. The ground plane CSRR length and width are ‘L’ and ‘A’ respectively. The width & spacing of the split rings are ‘R’, ‘N’ and ‘k’, ‘Q’ respectively. The gaps between the split rings are ‘M’ and ‘V’. The CSRR based band reject filter shows up & down state notch frequencies of 33.17 GHz and 29.71 GHz [13]. Here, MEMS based varactors are employed along with the metamaterials to realize tunability over a wide range of frequencies depending on the different beam gap heights of MEMS beam. Cross section view of the proposed device is also shown in fig.1(b).

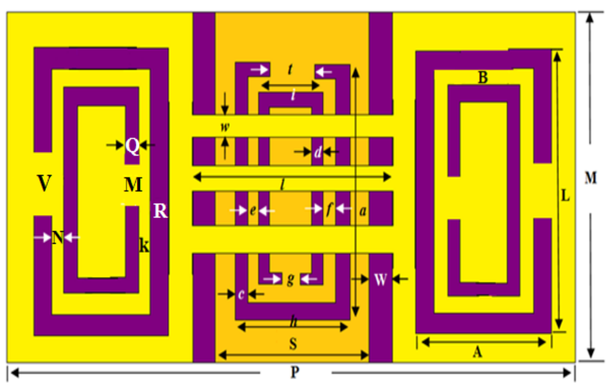

Figure 1(a): Top view of the RF MEMS bridge with CSRRs loaded CPW transmission line.

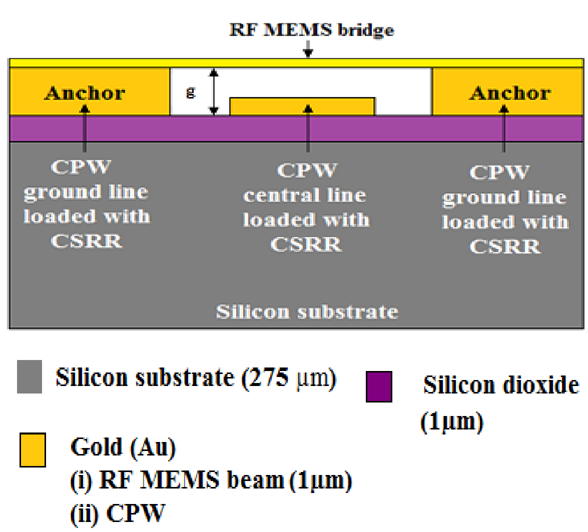

Figure 1(b): RF MEMS bridge with CSRRs loaded CPW transmission line.

RF characteristics of the optimally designed filter are shown in fig.1(c). The up and down state rejection of stop bands are around -18.10dB and -20.05dB respectively. The tunability of CSRR band reject filter is achieved when applied voltage is varied between the MEMS bridge and the CPW ground plane. Due to change of capacitance value of the bridge in its up & down states, we observe tunability of CSRR filter rejection frequency band.

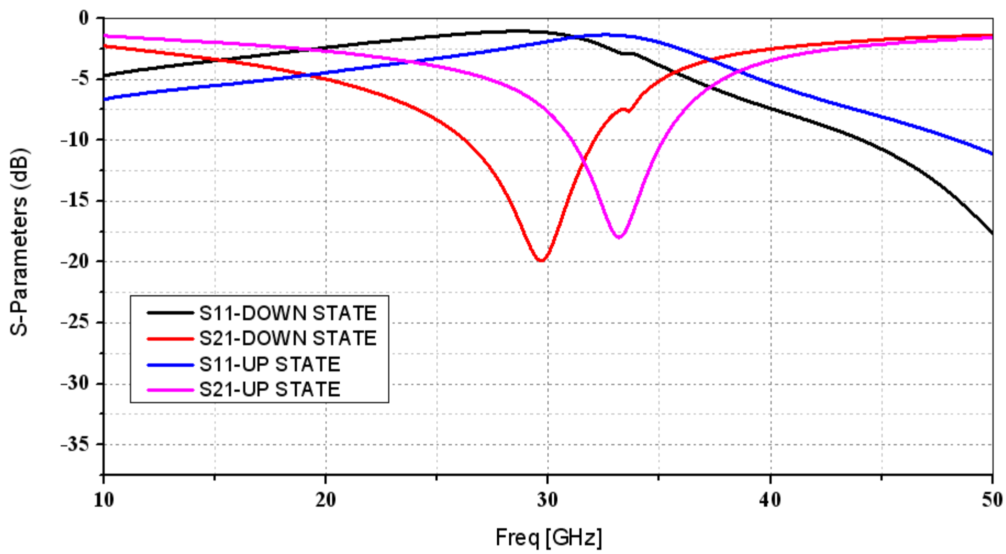

Figure 1(c): CSRR filter optimized 'S-Parameters' result.

3. Mechanical and Electromechanical Analysis

i) Effect of tensile residual stress on spring constant :

Electro-mechanical performance of the CSRR filter is done through analysis of the MEMS beam. The beam can be modelled using a linear spring constant, k (N/m) [14]. Change of the spring constant happens with deflection of the fixed-fixed beam due to an external force F(N). Therefore the applied voltage (V) between CPW signal line and ground plane is acted upon by electrostatic deflection force (F) and by an equal and opposite mechanical restoring force, which leads to

$$\frac{1}{2}\frac{\varepsilon_0 bwV^2}{g^2} = k(g_0 - g) \tag{1}$$

where

$$k = 32Ew\left(\frac{t}{l}\right)^3 \frac{1}{8\left(\frac{x}{l}\right)^3 - 20\left(\frac{x}{l}\right)^2 + 14\left(\frac{x}{l}\right) - 1} + 8\sigma(1-\nu)w(t/l)\frac{1}{3-2(x/l)} \tag{2}$$

TABLE 1: CHANGE OF THE SPRING CONSTANT DUE TO TENSILE RESIDUAL STRESS

Tensile Residual stress (MPa)	Spring constant for fixed-fixed beam(N/m)
0 [No residual stress]	3.9063
2	5.3563
4	6.8063
8	9.7063

k- is the spring constant of the MEMS beam and *l* is the length and *w and t* are the width and thickness of the MEMS beam respectively. 'E' is the Young's modulus, 'σ' is the biaxial tensile residual stress and 'ν' is Poisson's ratio of the MEMS beam [15-16]. Summarization of the spring constant values for the two cases with and without considering tensile residual stress are shown in Table -1. Change of spring constant due to increase in the residual stress value is also shown graphically in fig.(2).

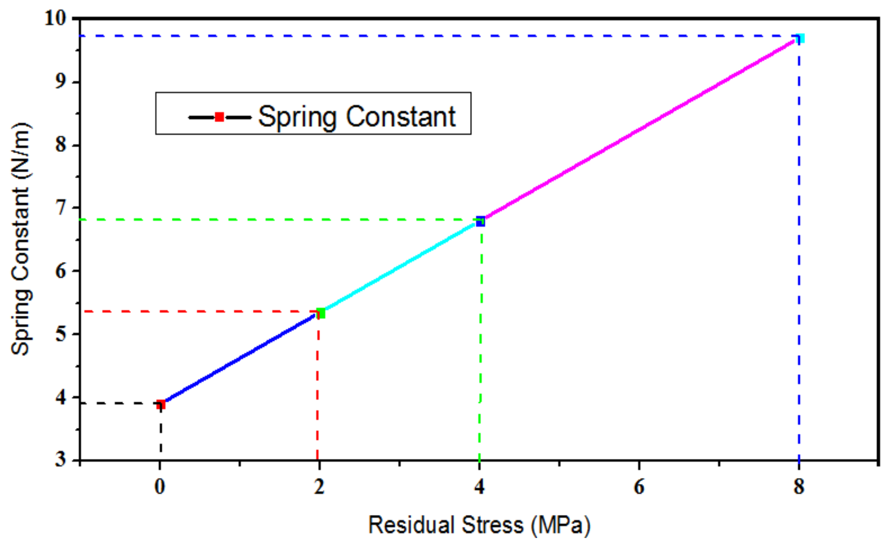

Figure 2: Change of Mechanical Spring constant with respect to Residual Stress.

ii) Effect of tensile residual stress on actuation voltage :-

When a bias voltage is applied across the MEMS beam and the lower electrode repeatedly, actuation voltage is increased due to residual stress. The fixed–fixed beam buckles due to sufficient uniform residual stress and the buckling direction is governed by gradient stresses. Therefore, the gap between the MEMS beam and lower electrode is dramatically reduced, resulting in significant decrease of actuation voltage [17]. We may equate these two forces, electrostatic force and mechanical restoring force analytically due to the stiffness of the beam, as shown below.

$$F = \frac{1}{2}\frac{\varepsilon_0 bwV^2}{g^2} \qquad (3)$$

$$\frac{1}{2}\frac{\varepsilon_0 bwV^2}{g^2} = k(g_0 - g) \qquad (4)$$

$$V = \sqrt{\frac{2k}{\varepsilon_0 bw} g^2(g_0 - g)} \qquad (5)$$

$$V_p = V(2g_0/3) \qquad (6)$$

$$V_p = \sqrt{\frac{8k}{27\varepsilon_0 bw} g_0^3} \qquad (7)$$

where, V_p is the actuation voltage, k= spring constant, g_0= air gap, ε_0= permittivity of air, *b*= width of the central line of the CPW t-line for dielectric layer, *w*= width of the bridge. Table-2 shown changes of actuation voltage due to change of tensile residual stress.

TABLE 2: CHANGE OF ACTUATION VOLTAGE DUE TO TENSILE RESIDUAL STRESS

Tensile Residual stress (MPa)	Actuation voltage (Volt)
0 [No residual stress]	18.79
2	22.0
4	24.8
8	29.61

Fig. 3 shows the variation in the actuation voltage of the MEMS bridge for biaxial tensile residual stresses of 0 MPa, 2 MPa, 4 MPa and 8 MPa respectively using equation (2). It is seen that the tensile residual stress increases the beam stiffness leading to an increase in the pull down voltage.

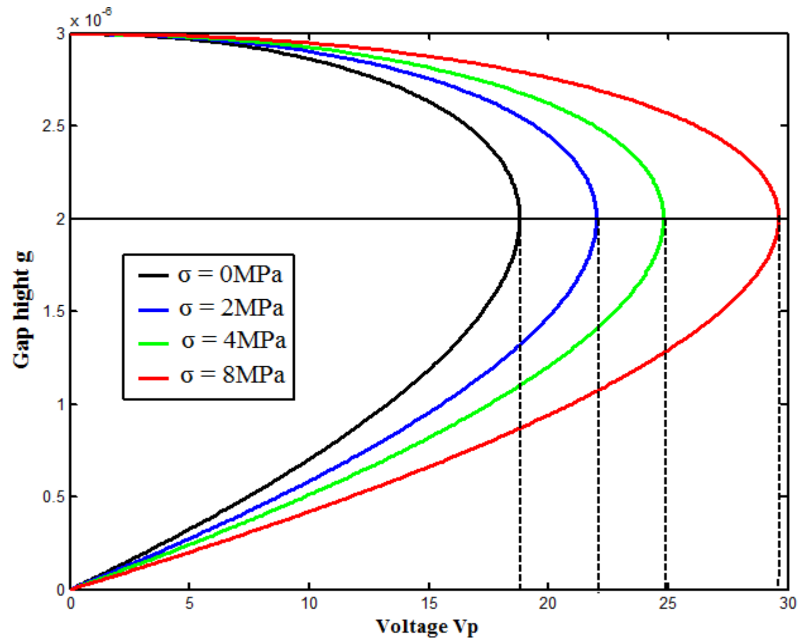

Figure 3: Variation in the actuation voltage for different values of mean biaxial tensile residual stresses.

3. Conclusions

Increase in actuation voltage for RF MEMS filters has been successfully demonstrated here due to residual stress which leads to buckling and bending effects. Gradient stress causes bending moment on the fixed-fixed MEMS beam, resulting in enhanced RF isolation. A knowledge of tensile residual stress on spring constant and actuation voltage in fixed-fixed beam is useful for design of the proposed device.

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