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Numerical Modeling and Analytical Verification for Evaluating Performance of RF-Microelectromechanical Switches

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Abstract – In this paper, we report numerical modeling with analytical verification of Radio Frequency Micro-Electro Mechanical Systems (RF-MEMS) switch consisting of micro cantilevers which are actuated electrostatically. During the micro-fabrication process of the RF-MEMS switch, various stresses are induced within the micro-structure thereby deteriorating its static and dynamic performance. First analytical modelling of cantilever micro-beams is presented with varying geometrical parameters. The important design variables affecting the RF-MEMS switch are the length, width, and thickness of micro-cantilever beam with output as deflection, natural frequency and quality factor. After evaluating both analytical and simulated results, a good conformity is found between them for the micro-cantilever type of switch specimens. The modelling of device performance, based on the effects of device geometry would help in providing valuable insights into micro-fabrication process.

Keywords— RF MEMS Switch, Modeling, Performance

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INTRODUCTION

MEMS radio Frequency (RF) switches are being studied extensively and are widely in use as primary movers in a variety of MEMS applications. They include automated test equipment, advanced telecommunication systems, wireless communication (satellite communication, aerospace, defence applications), mobile phones, high frequency signal processing applications, environmental surveillance, patient surveillance and medical implants, etc. [1-2]. These switches are designed to operate in frequencies (0.1-100 GHz) and provide low power consumption, very high isolation, very low insertion loss and low cost which enables them to be used in high frequency applications [3]. These switches are being fabricated using MEMS fabrication technologies. Geometrical parameters of MEMS based switches are very important in their stability and reliable operations.

RF MEMS switch (shunt and series type) research has evolved over the last decade. Some of the developments include geometrical design optimization, redesign, and new materials to achieve better performances. Further new processes for fabrication and novel sensing mechanisms are available with us for implementation [4-6]. Various research groups have investigated design, analysis, optimization; redesign and fabrication of RF MEMS switches by using different geometrical models, minimization/maximization of critical parameters under considerations and materials such as Au, Al etc. as bridge with contact materials like Au, Pt, Au/Pt/Au, etc., were used. In this work the dependence of geometrical parameters of switch on its performance is investigated. Further we have presented this analytically and numerically for consideration of a good design of MEMS cantilever switch to give better insights on the role of switch dimensions and its performance parameters such as tip deflection, natural frequency, pull-in voltage and quality factor.

SWITCH DESCRIPTION

We have considered cantilever type RF MEMS switch consisting of a coplanar waveguide (CPW), as shown in Fig. 1, which is fixed at one end and separated from the bottom electrode by the air- gap (g_{air}).

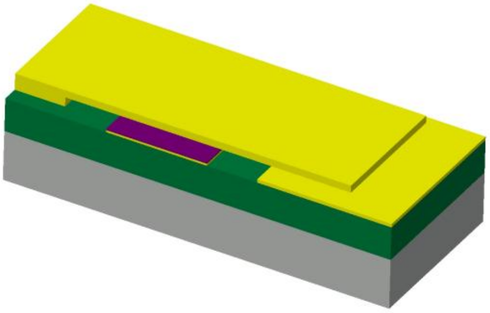


Fig. 1 **Schematic of RF MEMS switch.**

The relevant dimensions of the switch are shown in Table I. A dielectric layer is deposited on Cr/Au layer and patterned on the signal line. The signal line transmits RF signal and helps in actuating the beam. The two metal electrodes, namely the beam and the signal line, separated by the air gap g_{air} and the dielectric layer, introduce two capacitors in series resulting in a low capacitance in the up-state condition of the beam. In this state of the switch, the signal is transmitted with low loss (ON-state). A DC voltage is applied on the signal line to actuate the beam. Two dimples are used to reduce the overall contact resistance of the switch and to divide the RF/DC current. The dimple eliminates the beam shape dependency to gradient residual stress variations, thus preventing the unwanted curling. Front tip contact area is small as compared to conventional cantilever beams because of following reasons. Firstly small contact points will reduce the metal to metal striction and will increase the contact force. Secondly it gives better isolation. Dimples will help in reducing the gradient residual stress effect thus making the beam stiffer.

TABLE I Geometrical Dimensions of Switch

Specification	Value
Length of the cantilever beam, L	200
Thickness of beam, t	2
Width of cantilever, w	60
Thickness and width of dielectric **(HfO_2)**, t_d	0.1x60
Air gap, g_{air}	1.5
Length of the contact area electrode, L_c	60
Dimension of slot, d	60
Distance from start of beam to dielectric	50
Anchor length, A_L	30
Dimple-diameter X depth (2 Nos.)	20x1
Sacrificial layer thickness Min-Max	1.5-1.8

ANALYTICAL MODELING

The cantilever type DC contact in-line series switch can be modelled by treating it as a parallel plate capacitor using lumped mass and spring system. For this system it could be easily shown that the pull-in voltage is given by [1],

$$V_{pi} = \sqrt{\frac{8k}{27\varepsilon_0 Ww}\left(g_{air} + \frac{t_d}{\varepsilon_r}\right)^3} \qquad (1)$$

where, g_{air} is the air gap between the top and bottom electrode, ε_o is the free space permittivity, w is width of cantilever, W is length of bottom electrode, t_d is the thickness of dielectric layer, ε_r is the relative dielectric constant of dielectric layer, and k is the cantilever stiffness determined by the switch dimensions and Young's modulus of beam material given by [1],

$$k = \frac{Ew}{4}\left(\frac{t}{L}\right)^3 \qquad (2)$$

where, E is the Young's modulus of the beam material, and L, w, t is the cantilever length, width and thickness respectively. From eqn. (1) and (2) it is clear that the dependence of pull-in voltage on the switch geometry is only on the cantilever length and thickness. Hence fig. 2 shows the variation in pull-in voltage as a function of micro-beam length and thickness.

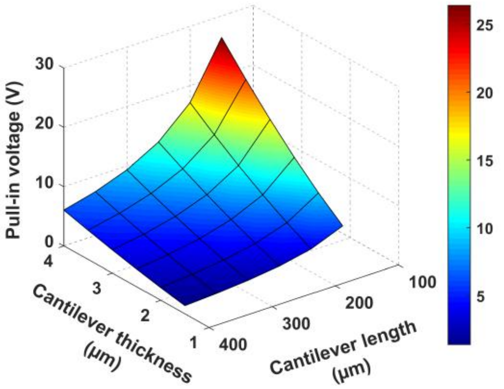


Fig.2 Variation of pull-in voltage as a function of micro-beam length and thickness.

It is seen from fig. 2 that the switch thickness has greater effect on the pull-in voltage as compared to the length, as lengths are almost 100 times the thicknesses. It is well understood from fig. 2 that as the length increases, the pull-in voltage decreases and as the thickness increases, the pull-in voltage increases due to the fact that the cantilever length is inversely and cantilever thickness is directly, proportional to the pull-in voltage. It is found out that for a given length with the increase in thickness the pull-in voltage increases but this percentage of increase reduces considerably after 3 μm thickness, remaining constant at about 23-26% and the percentage of increase in V_{pi} for 0.5 μm increase in thickness is in the range of 54 – 22%. Similarly, for given thickness with increase in length it is determined that for increase of 50 μm length the percentage of reduction in pull-in voltage is about 35 -

18%. This confirms that the cantilever thickness has a greater impact on the pull-in voltage parameter of switch. The frequency is given by eq.(3), quality factor by eq.(4) and µ is dynamic viscosity with varying temperature as given in eq.(5).

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \qquad (3)$$

$$Q = \frac{\sqrt{E\rho}t^2}{\mu(w \cdot L)^2} g_o^3 \qquad (4)$$

$$\mu = 1.2566 \times 10^{-6}\sqrt{T}\left(1 + \frac{110.33}{T}\right)^{-1} \qquad (5)$$

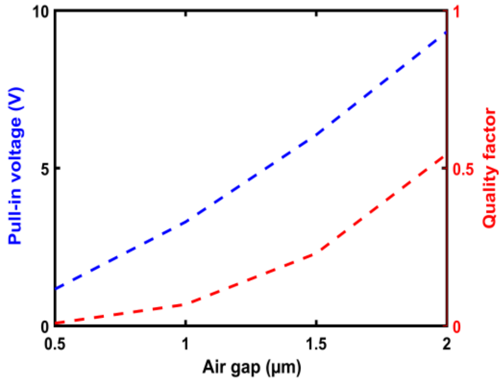


Fig.3 Variation of pull-in voltage and quality factor with air-gap.

NUMERICAL MODELLING

Numerical simulations are performed using ANSYS for the switch configurations. The beam is modeled using 20 noded 186 solid elements. In this study, we begin with a numerical solution of the beam equation using ANSYS. The numerical solutions provide insights into the geometric distributions of deflection, natural frequency. SOLID186 is a higher order 3-D 20-node solid element that exhibits quadratic displacement behaviour. The element is defined by 20 nodes having three degrees of freedom per node: translations in the nodal x, y, and z directions. The element supports plasticity, hyper elasticity, creep, stress stiffening, large deflection, and large strain capabilities. In the following section results are discussed in details.

Important **RESULTS AND DISCUSSION**

MEMS switch performance parameters are pull-in voltage, hold-on voltage, switching frequency, and contact force/area. These parameters are controlled using dimensional parameters of the switch such as length, width, and thickness of cantilever. This makes the need for study of the dependence of these parameters and finding out the optimum set of parameters for fabrication purpose. In an effort to study the effect of various geometric parameters such as length, width, and thickness of the micro-cantilever beam on the RF-MEMS switch performance, a 3-D parametric structure was modelled and simulated using ANSYS Mechanical APDL.

The cantilever length between 150 and 400 µm; cantilever width between 40 and 140 µm and cantilever thickness between 1.5 and 4 µm were selected for detailed simulations. In this work, three control factors were selected for analysis and their ranges are as follows: cantilever length from 150 to 400 µm, cantilever width from 40 to 140 µm, cantilever thickness from 1.5 to 4 µm. In an attempt to study the effect of cantilever beam length, width, and thickness variations, the simulations of resonant frequency and deflection of cantilever beam were carried out. Each geometrical parameter of the micro-structure is varied one at a time in order to interpret its effect on the frequency and deflection of cantilever beam.

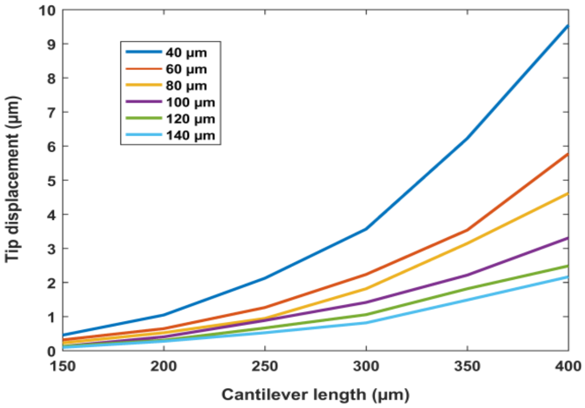
Detailed analyses of the deflection of the cantilever for different dimensional parameters reveal some interesting facts. In Fig. 4, the effect of varying length, width, and thickness of the micro- beam is simulated to obtain the maximum tip deflection of the micro-beam. At low temperatures the cantilever tip has minimum tip deflection; thereby it results in very less contact area, and in turn less or no contact force. Furthermore the high temperature produces a large deflection of the cantilever tip. It is observed that for a given length, the increase in temperature effectively varies the tip deflection compared to the other dimensional parameters of the structure. The results show that the micro-beams' maximum tip deflection for a constant thickness is less sensitive to the temperature variations but for varying thickness along with the temperature variation there is considerable maximum tip deflection as compared to the length and width. It was also observed that for a varying width at a constant temperature, there was an effective tip deflection. It is clear that for an increase in length, the maximum tip deflection increases considerably while for an increase in the width and thickness of the beam, the maximum tip deflection decreases.

Modal analysis gives the resonant frequencies of the cantilever beam for the first few modes of the switch structure. Resonant frequency is the maximum frequency at which the structure can operate, beyond which the structure will fail. Fig. 5, shows the simulated natural frequencies (first mode) for the varying temperature and the geometrical parameters.

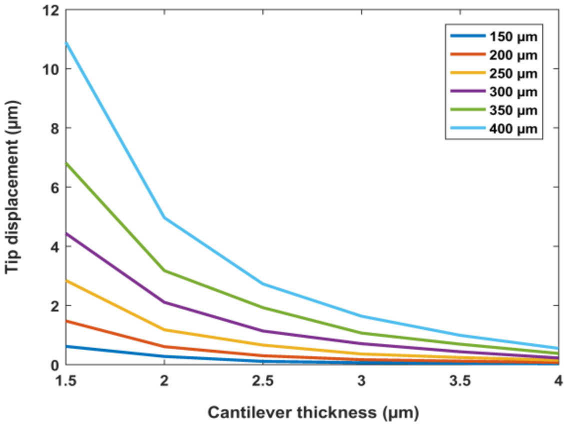
On the basis of the observations from the figures for the variation of the frequency with temperature for differing cantilever beam length, width, and thickness it is seen that the variation of width together with temperature has greater effect on frequency than the variation of other two dimensions of beam. It could also be seen that for a given length or thickness with the increase in temperature, the natural frequency almost remains constant. The results also show that the increase in length causes the natural frequency to decrease for the given temperature whereas for the increase in width and thickness of the micro-beam, the natural frequency tends to increase along with the increase in the temperature but for the higher increase in width, the increase in frequency is considerable.

As the quality factor of the MEMS switch depends upon the cantilever length, width, thickness and temperature, in Fig. 6, the effect of geometric dimensions on quality factor of the RF-MEMS switch is plotted with the micro cantilever length, width and thickness as the variables. The results show that the quality factor decreases at an elevated temperatures for a given micro-cantilever length, width and thickness. It can be seen that for a given temperature the quality factor decreases with the increase in cantilever length and width whereas for the increasing cantilever thickness at a given temperature the quality factor increases.

The results shows that the variation in the micro-cantilever width combined with a temperature changes have comparatively greater effect on the quality factor of the switch than the cantilever length and thickness. The quality factor almost remains constant for above 200 µm cantilever length and 60 µm cantilever width whereas for less than 3 µm cantilever thickness quality factor remains constant with temperature variations.



(a)



(b)

Fig. 4 Tip displacement of beam as a function of varying (a) length & width, and (b) thickness & length of micro-cantilever.

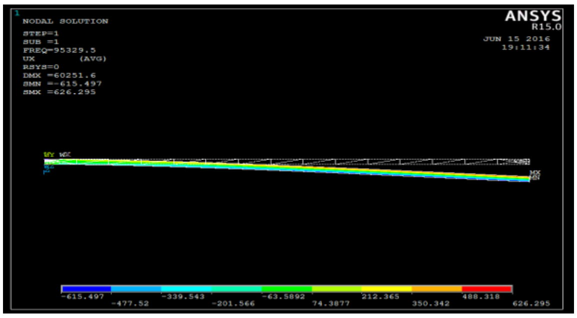
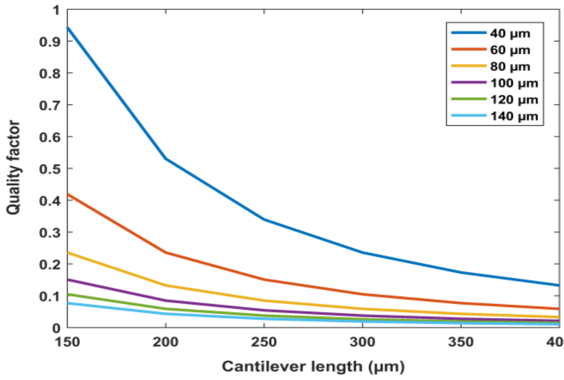
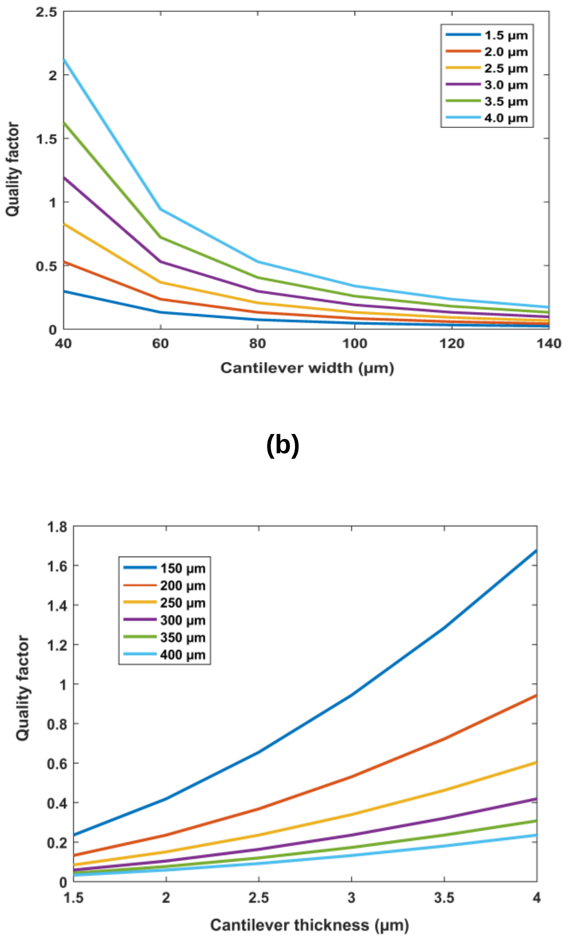


Fig. 5 Modal patterns of the beam structure for first mode.



(a)



(b)

(c)

Fig. 6 Quality factor of beam as a function of (a) length and width, (b) width and thickness, and (c) thickness and length of micro-cantilever.

In the following section the fabrication process of MEMS switch is described in details.

Fabrication

The RF MEMS micro cantilever switch for the surface micromachining procedure on a 300 μm thick P type SSP <100> oriented silicon wafer. This micro-fabrication process is a combination of different material deposition and etching techniques using sacrificial layer of PVDF-TrFE as shown in Fig. 7. The process can utilize the isolation and metallization layers available on CMOS process wafer and permit us to attain the suspended micro-cantilever beam using a sacrificial layer of 1.5 μm. The fabrication process requires six masks and the steps followed for the deposition and patterning of different layers. The steps for micro-fabrication of RF switch can be briefly outlined as follows:

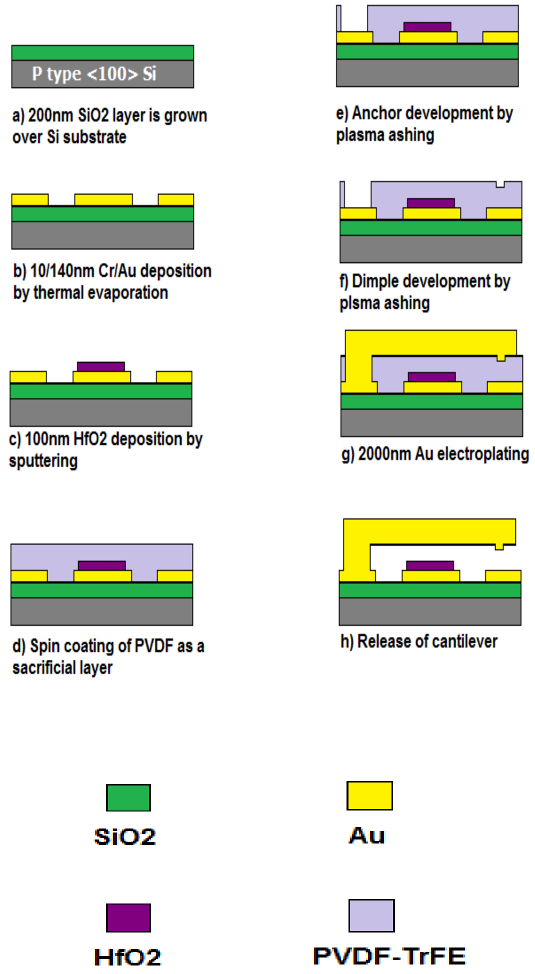


Fig. 7 Fabrication steps for micro-fabricated RF switch (not to scale).

(a) A SiO_2 film of 200 nm thickness is first grown on a silicon substrate using dry thermal oxidation process.

(b) A 10/140 nm thick Au bottom electrode is first patterned by lift off and Cr is used as adhesion layer.

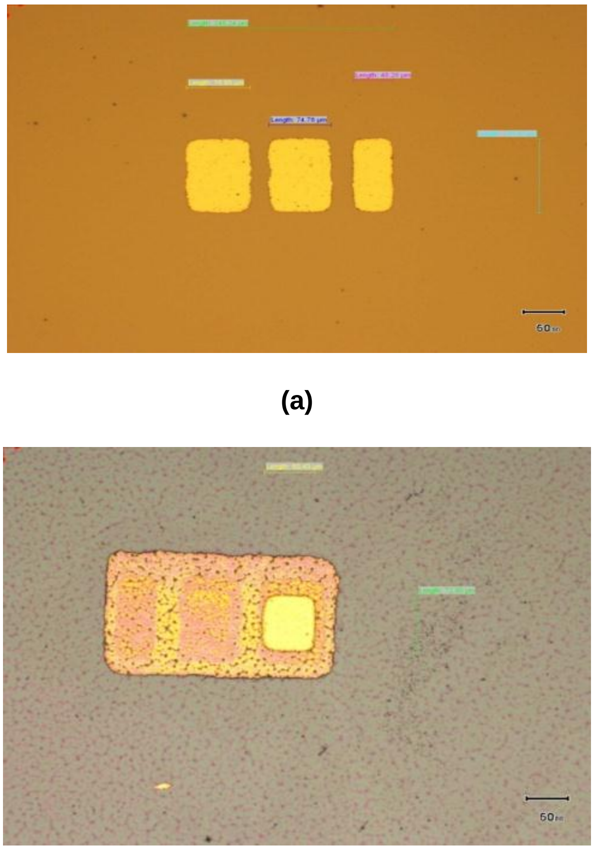
(c) A dielectric layer of 100 nm thickness of HfO_2 is deposited by sputtering on the bottom electrode and patterned by lift off.

(d) A 1.5 micron thick PVDF sacrificial layer is spin and annealed for 2 hours at 120 degree Celsius and Cr/Au (10/50nm) layer is deposited as hard mask for dry etching.

(e) Anchor and dimples are developed by patterning followed by etching of Cr/Au in respective etchants and PVDF in plasma asher for different time intervals for anchor and dimple.

(e) A 200 nm thick Au seed layer is deposited for subsequent electroplating.

(f) A cantilever is then electroplated to 2µm. A positive photo resist is spin coated to 1.4µm thickness and electroplated gold layer is patterned and etches out unwanted gold in gold etchant and cantilever is released in Acetone as PVDF dissolved in acetone. Microscope image after deposit of contact electrode with gold thin film of 140nm and high K dielectric HfO2 with thickness of 100nm is shown in Fig.8. The surface features of the evaporated gold thin films, (see, Fig. 9) these high energetic projectile ions seem to create grains with well-developed boundaries. This may occur due to thermal spike induced dewetting. The high local field generated by the surface features with high curvature is known to further amplify the surface enhanced Raman scattering signal.



(a)

(b)

Fig. 8 (a) Microscope image after depositing of contact electrode with gold thin film of 140nm., (b) microscope image after Anchor development by plasma asher.

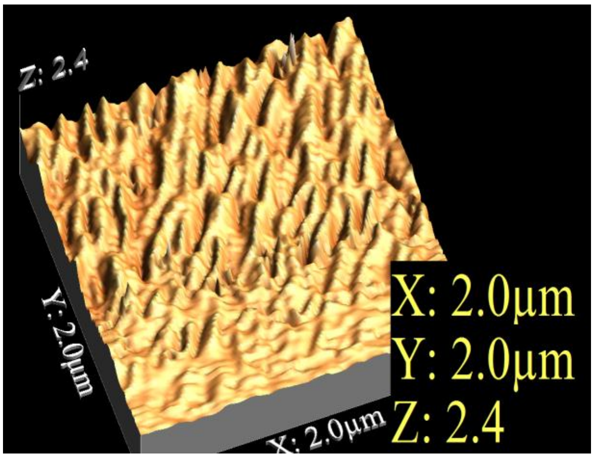


Fig. 9 Surface roughness of contact electrode (gold) having Ra value of 2.4nm using AFM.

CONCLUSIONS

Analytical and numerical solutions have been developed to predict the deflection, natural frequency and quality factor for RF MEMS switch. To enhance the device performance, we have considered the effect of dimensional variations on mechanical performance of switch. The results suggest that the geometric dimensions of switch should be selected optimally so that there is reduction in induced residual stresses and to improve the planarity in microstructures. Further the results obtained serve as a useful tool during fabrication of the switch.

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