Design and technology optimization of SiC-based RF MEMS switch

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Abstract. This paper presents design and technology optimization of RF MEMS switch based on the silicon carbide film. The universal optimization criterion for electromechanical parameters was calculated. The experimental results of determination of the technological critical factors are discussed. Recommendations for the subsequent technology improvement are presented.

1. Introduction

Silicon, its compounds and metals are conventional materials to use as movable elements in RF MEMS switches [1]. At the same time, silicon carbide (SiC) is one of most challenging materials for various RF MEMS devices. The use of SiC film as a material for the movable MEMS element provides the following advantages:

- The higher vibration stability due to the great value of Young’s modulus.
- The lesser material density in comparison with metals ensures higher resonance frequency and speed of operation.
- The extended temperature operational range due to the low values of temperature coefficients of thermal expansion and Young’s modulus.

On the other hand, the technology of SiC film deposition by magnetron plant is not optimized to produce movable MEMS elements. One more problem is to determine the best design of a MEMS switch within the specified technology.

2. Design optimization

Main electromechanical parameters of RF MEMS switch are the driving voltage ($U_c$) and the resonance frequency ($f_0$), that determines the speed of device operation. A large quantity of researches are held at the present time. Some of them are directed to get lower driving voltage and others to heighten a device speed [2]. So, one could find a big amount of various switch designs.

Thus, the optimization criterion was derived to compare different switch designs. This criterion allows one to select the design with the most optimal ratio of the electromechanical parameters. The optimization criterion has the following form:

$$\frac{U_c^2}{f_0^2} = \frac{4\pi^2 C}{3} \frac{\gamma_0}{\varepsilon_0} \frac{\rho h}{\varepsilon_0}$$
where $y_0$, $\rho$, $h$ are the gap between driving electrodes, material density, film thickness. These quantities are defined by selected technology. The $C$ parameter is defined by the type of switch design. It was found during the calculations that the $C$ parameter is a constant with the value of $8/9$ for designs where bending deformation dominates ($C_k$). However, if one uses movable elements with torsion suspensions (figure 1), the $C$ parameter begins to depend on the length of the movable mass ($C_\alpha$) (figure 2):

$$C_\alpha = \left( \frac{1}{1 - \frac{l_2}{l_3}} - \frac{1}{1 - \frac{l_1}{l_3}} \right) + \ln \left( \frac{1 - \frac{l_2}{l_3}}{1 - \frac{l_1}{l_3}} \right).$$

Figure 1. Sketch of actuator with movable element based on torsions.

Figure 2. Parameter $C_\alpha$ vs geometrical dimensions.

Thus, the use of elements with torsions allow one to obtain the gain (region below dashed line on figure 2) according to the optimization criterion within the same technological process.

The use of a SiC film as a material for a movable element constrains the structure design. It is known that SiC film deposited by magnetron plant has compressive mechanical stresses [3]. So, the structure with interior mount of torsion suspensions was designed to compensate negative stresses (figure 3).
Figure 3. Sketch of actuator with interior mount of torsion suspensions.

The parameter $C$ for this design will be as follows:

$$C = \left[ \frac{1}{1-l_2 l_3^{3}} \right] - \frac{1}{1-l_1 l_3^{3}} + \ln \left[ \frac{1-l_2}{1-l_1} \left( \frac{l_2}{l_3} \right) \right]^{\frac{1}{3}} \left[ 1 - \left( \frac{l_1}{l_3} \right)^{3} \right]$$

Thus, moving the anchor inside the movable element allows one to obtain an additional gain of several percent order due to the term $1-\left( \frac{l_1}{l_3} \right)^{3}$.

3. **Technology optimization**

To implement designed structures, the basic technology was developed for manufacturing the RF MEMS switch based on a silicon carbide film.

The main features of the basic technology:

- isolating substrate with two-sided polishing;
- 4 photolithography operations;
- one two-level sacrificial layer;
- movable element based on SiC layer which is deposited by magnetron sputtering;
- dry etching of sacrificial layer;
- Au-Au contact area;
- vacuum sealing.

The main disadvantage that limits usage of SiC films in MEMS devices is the appearance of residual mechanical stresses. These stresses are non-uniformly distributed along the thickness of SiC film. As a result, undesirable bend of movable element occurs (figure 4). This leads to the increase of driving voltage, deterioration of operation speed and device reliability.
Figure 4. SEM image of RF MEMS switch with undesirable bend of movable element based on torsions.

To eliminate these defects, a number of technological experiments were held to determine the critical factor which has an influence on the magnitude of mechanical stresses in a silicon carbide film. The following critical factors of the technological process were picked out:

- substrate heating after shutter opening;
- difference between residual atmosphere pressures before and after the deposition process;
- surface charging;
- impurity diffusion into growing layer.

The experiments have shown that if one reduces the difference between residual atmosphere pressures before and after the deposition process by a factor of \( N \) times, the maximum gap also decreases \( N \) times and the radius of surface curvature increases \( N^{0.5} \) times. The experiments with other factors showed their minimum influence on the nonuniformity of mechanical stress distribution along the thickness of SiC film.

4. Conclusion

The universal optimization criterion for electromechanical parameters of RF MEMS switch was worked out. The use of this criterion allows one to choose optimal switch design within the same technological process.

It has been found experimentally that the difference between residual atmosphere pressures before and after the SiC film deposition process is the main critical factor. The reduction of this difference allows one to produce devices with a minimal deviation from the design parameters.

References

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