Tunable MEMS Capacitor for RF Applications

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Abstract: Radio Frequency MEMS devices have emerged to overcome the problem of high losses associated with semiconductors at high frequencies. A tunable MEMS capacitor is a micrometre-scale electronic device whose capacitance is controlled through different actuation mechanisms which govern the moving parts. It can have electrostatic or electrothermal actuators depending on the functional complexity and requires a predictable behavior over a continuous range of inputs. This work proposes an electrothermally actuated tunable MEMS capacitor suitable for filters, oscillators, phase shifters and impedance matching networks. The design utilizes bimetallic strip actuators instead of conventional asymmetric arm actuators. The model simulation using COMSOL Multiphysics has been able to provide surface deformation, temperature distribution, stress distribution and current density distribution results, and has indicated that the capacitance can be varied up to a tenth of its initial value.

Keywords: RF MEMS, Tunable Capacitor, MEMS Varcap, Electrothermal Actuation, Bimetallic Strip.

1. Introduction

Radio Frequency (RF) devices are those that are engineered to work in the radio wave spectrum of about 3 kHz up to 300 GHz. The functionality can be implemented using a variety of technologies including silicon-based or compound semiconductor, ferroelectric, vacuum tube or RF MEMS. Every one of these, bears specifications such as operating frequency range, gain, large-scale integration, lifetime, linearity, noise margin, power consumption, power rating, manufacturing price, packaging, reliability, ruggedness, size, supply voltage and switching time. Microelectromechanical Systems (MEMS) based RF components have emerged to overcome the limitation of high losses associated with semiconductors at high frequencies. There are various RF MEMS devices available, including switches, resonators, tunable inductors, varactors and tunable capacitors. Most RF MEMS devices involve the manipulation of air as the dielectric material. This is because losses associated with air as a dielectric is extremely small at microwave and millimeter-wave frequencies. Thus, the quality factor (Q) of RF MEMS devices can be very high.

RF MEMS varcaps have shown possibilities as the active elements of tunable filters, impedance matching networks, and phase shifters. Because of the high losses associated with semiconductors at high frequencies, high Q-factor capacitors are needed in microwave systems to replace the semiconductor varactors. The common structural materials used for fabrication is polysilicon and gold, as well as the use of air instead of other dielectric materials, make high-Q capacitors possible. Also, the linear movement of actuators with respect to the control voltage, achievable using MEMS design methodologies, allows linear tuning of RF components.

The functional complexity requirement is very important to the design because of the suitability of the device for a specific application. For example, different actuation schemes may be necessary, depending on the application. For slow, low voltage, high amplitude tuning, electrothermal actuators might be best. But for very fast, high voltage tuning, electrostatic actuation may be better. Electrostatic actuation is the preferred means of MEMS control due to its near-zero DC power consumption. Electrostatic actuation naturally results in a bistable response and is a well-suited actuation mechanism for switched capacitors. Variable capacitors with this actuation mechanism have the advantage of a more compact implementation and finer capacitance control but are more difficult to control.

Electrothermal actuators are preferable in case of low power, slow switching applications. The conventional method of actuation is based on the asymmetric arm or a structure with non-symmetrically placed arms with different rates of thermal expansion, which results in a desired deformed state on electrothermal heating. The other actuation mechanism is the bimetallic strip actuation, which is less frequently used. A bimetallic actuator essentially consists of two metal strips fixed together. If the two metals have different rates of expansion, then as the temperature of the actuator changes, one element will expand more than the other, causing the device to bend out of the plane. This work proposes a tunable capacitor design based on bimetallic strip actuation, for the design goals including, finer and stable control mechanism, lesser capacitor plate deformation and easier fabrication. Asymmetric arm actuation has been used to evaluate the performance of the proposed design.

Section 2 introduces the research background and previous work. Section 3 elaborates on the use of COMSOL Multiphysics software. Section 4 describes the proposed work and methodology. Section 5 summarizes the results and inferences.

2. Literature Survey

Research on MEMS tunable capacitors has mostly focused on electrothermal actuation mechanisms. Varactor performance parameters like tuning ratio (Cmax/Cmin), quality factor (Q), absolute capacity value CV characteristic, self resonance frequency are discussed by Maxim V. Shakhrai [1]. Dec and Suynama [2] have reported a MEMS tunable parallel plane capacitor using, again, an electrostatic actuator. A Q-factor of 9.6 at 1 GHz for a 4-pF capacitor has been reported. The capacitance value changed from 4.0 to 4.4 pF for bias voltage 0 to 0.8 V. Young and Boser [3] have described a MEMS tunable capacitor with electrostatic actuators using aluminum as structure material and obtained a Q value of 62 at 1 GHz for 2.11 pF of four shunt capacitors from the measured S-parameter up to 1.2 GHz. The design of flip-chip integrated MEMS tunable capacitor was design by Kevin F. Harsh, Bingzhi Su et al. [4]. Using the transfer process and design considerations, there is an opportunity to integrate complex MEMS onto any RF compatible substrate without the silicon semiconductor effects. The simple parallel-plate model described by Nino Zahirovic, Raafat R. Mansour [5] suggests that there are two potential capacitance states for a given bias voltage within the hysteresis window.
Yaping Liang, C. W. Domier et. all designed a RF MEMS Extended Tuning Range Varactor and Varactor Based True Time Delay Line [6].In that they discuss a problem of using shunt capacitor. In order to eliminate the Pull-In effect, one approach is to employ the so-called MEMS extended tuning range structure is discussed by Zou, J [7]. José Mireles et.al[8] proved that the more flexible springs used in the suspension system, the more capacitance variation obtained (due to the increment in plate separation between plates.) There are three mechanisms of heat flow: conduction, convection and radiation. According to previous research [9], the heat dissipation through radiation to the ambient can be neglected in comparison with the heat losses through conduction to the anchors which are considered as heat sinks and the heat losses through air to the substrate due to convection. The maximal temperature that polysilicon can handle is around 900K [10] and its melting point is 1685K. The temperature of the actuator should definitely remain under the glass transition temperature that is around 1000K. Furthermore, the temperature dependence of the elastic modulus also should be considered while including the load arising from the capacitor plate and the springs into the model. Thermal actuation using cold and hot arm is studied in [11]. This study developed a theoretical model for an electrothermal actuator structure. The analytical results are compared with the Finite Element Method (FEM) results which show a reasonable agreement. The model based on asymmetric arm electrothermal actuator suggested in [12]. This work is a varcap using bimetallic strip as a thermal actuator. The primary advantage is that, it is easier to fabricate. Lower supply voltage (in terms of mV) is required for actuation. Figure 1 represents the conventional asymmetric arm actuator.

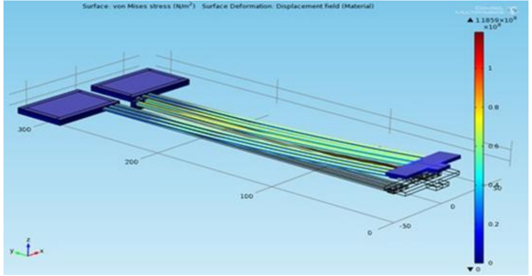

Figure 1. Asymmetric Arm Structure

3. Use of COMSOL Multiphysics

MEMS fabrication imposes design constraints on the structure and composition of any micro device. This work has required trials with different materials and specification of material properties during simulation. The asymmetric arm model requires the full characterization of polysilicon used and the bimetallic strip model requires the pertinent parameters of aluminium with the COMSOL Multiphysics tool to specify boundary conditions including fixed surfaces and voltages. The simulation has been able to provide surface deformation, temperature distribution, stress distribution and current density distribution results.

4. Bimetallic Strip Actuation Design

The whole assembly of suspension structure top plate needs to be manufactured in one single process. Thus a spring mould is necessary for patterning the springs when preparing this layer after combining. Figure 2 shows a spring mould. Figure 3 shows the construction of capacitor plate before removing material and final layer of capacitor plate after removing material

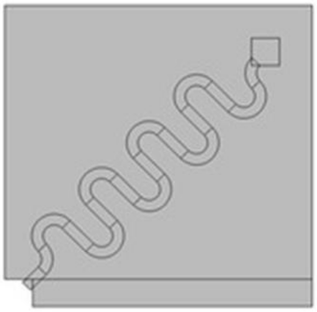

Figure 2. Spring Mould for Suspension

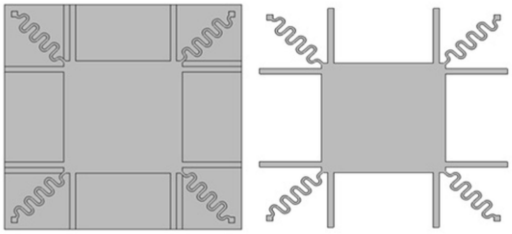

Figure 3. Capacitor Plate before and after Material Removal

The capacitor plate, mechanical suspension and first layer of bimetallic strip are built in the single layer of aluminium. The second layer of bimetallic strip is tungsten. The contact pads are provided in bimetallic strip to apply different voltage conditions. Thickness of both layer of bimetallic strip is of 1 µm. Bimetallic arms are attached in four corners of the capacitor plate to have equal displacement of plate and in order to avoid the unwanted bending of capacitor plate. The more flexible the springs used in the suspension system, the more is the capacitance variation obtained. Figure 4 shows the bottom view of designed capacitor.

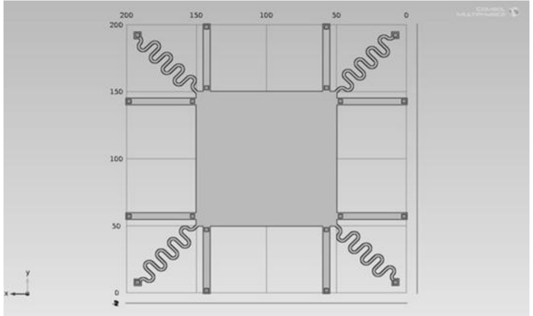

Figure 4. Bottom View of Capacitor highlighting Substrate Contacts

On the application of different voltages (50 mV, 100 mV, 200 mV etc.), a deflection is observed in the capacitor plate. Here a lesser voltage is needed compared to replicate models to get the same temperature variation. Figure 5 shows stress distribution at 50 mV and figure 6 shows temperature distribution at 50 mV. Figure 7 shows current density distribution in one arm at 50 mV. It can be noticed that in the inner strip the temperature is slightly higher. It is because the current is slightly higher in this region. Here one more advantage is that there is less distortion of capacitor plate plane after actuation. In electrothermal actuation design, slightly curved capacitor plate is formed after actuation.

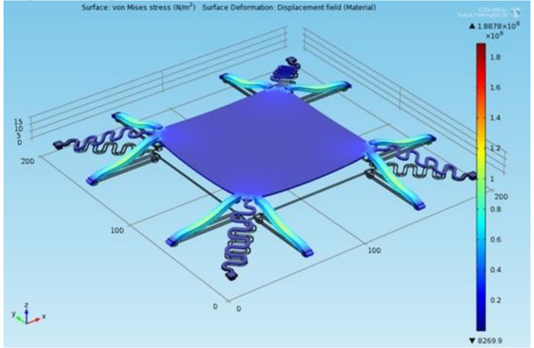

Figure 5. Stress Distribution at 50 mv

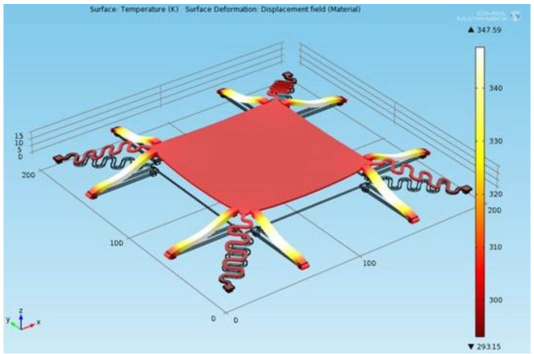

Figure 6. Temperature Distribution at 50 mv

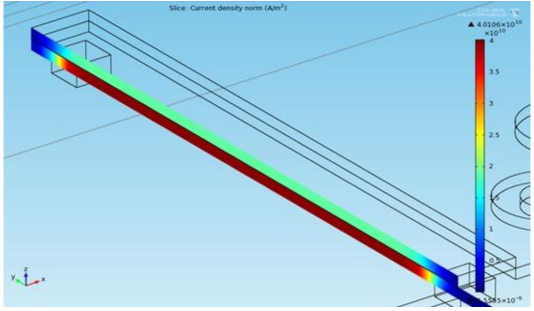

Figure 7. Current Density Distribution at 50 mv

5. Results and Conclusion

Figure 8 shows the comparison between the two electrothermal actuation schemes. Figure 9 represents the deflection characteristics of the bimetallic strip actuation mechanism. The primary advantage is that, it is easier to fabricate. Lower supply voltage (in terms of mv) is required for actuation. To get a better profile of the upper capacitor plate compared to previous models and to avoid the unequal bending of capacitor plate, 8 bimetallic arms at the corners of the upper plate have been used. From the results, it has been deduced that both the models yield the property of increase in deflection of the capacitor plate with increase in voltage as determined theoretically. The disadvantage of bimetallic strip actuator compared to electrothermal actuator is that due to the lower melting point of aluminium, a lesser variation in output capacitance is obtained leading to reduced tuning ratio. However, an accurate and stable actuation mechanism follows from the design of the proposed bilayer thermal actuator.

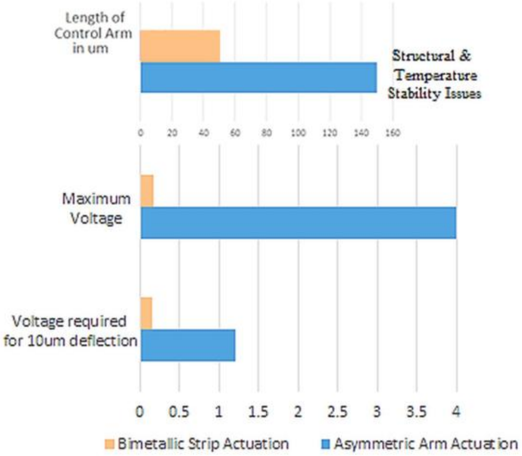

Figure 8. A Comparison between Actuation Schemes

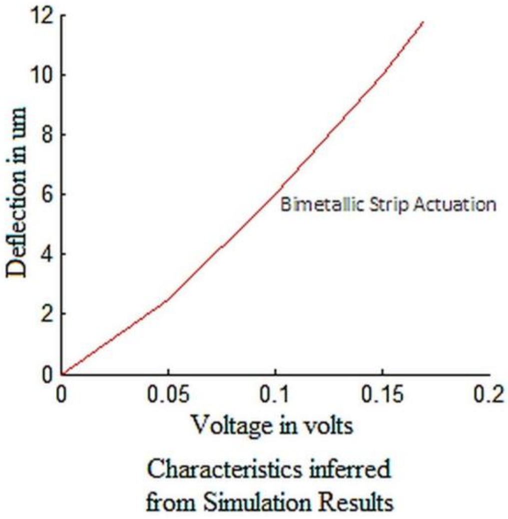

Figure 9. Deflection Characteristics

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