Simulations Based Design for a Large Displacement Electrostatically Actuated Microrelay

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ABSTRACT

An electrostatically actuated microrelay with large displacement, small actuation voltage and limited plate surface dimensions is designed to meet stringent telecommunication switching requirements. Fabrication feasibility and performance characteristics of the device are evaluated using a commercial CAD for MEMS tool. Simulation results of the device performance including pull-in voltages for different suspension stiffness variations, natural frequencies, stresses and restoring forces are presented.

Keywords: microrelay, microswitch, electrostatic actuation, large displacement, CAD simulation, low actuation voltage, coil spring suspension

1. INTRODUCTION

A microelectromechanical system (MEMS) based relay manifests the combined attributes of a solid-state relay (i.e. fast switching time, small size, batch fabrication, low cost, etc.) and a traditional electromechanical relay (i.e. smaller on-state resistance, high off-state resistance). Three major types of actuation mechanisms extensively investigated in the past include electrostatic, magnetic and thermal.

Electrostatic actuation has been a mechanism of choice if low displacements are required. Electrostatically actuated microrelays have been reported in literature in as far back as 1979 [1]. The actuation principle and theory is well documented [2,3,4], and is based on the principle of charge attraction. Various types of electrostatically actuated microrelays have been demonstrated successfully on complimentary metal-oxide-semiconductor (CMOS) circuitry [5,6]. These devices had a carry current of approximately 10 mA. It was demonstrated that with a constant bias voltage applied to the microrelay, they devices could be actuated with net driving voltage of 1 to 10 V. The offset voltage was approximately 32 V. Switching was achieved at operation frequencies of 100 kHz, with contact voltage of 0.15VAC. Lifetimes of these devices have demonstrated in excess of 10^9 operations. Other versions of electrostatic microrelays have also been demonstrated and have shown lower contact resistance through the use of metallic contact materials [7,8,9,10,11,12,13,14]. Another device has been reported with actuation voltages from 30 to 400 V [15], and a switched current of 10 mA. One electrostatically actuated device has reported lifetimes in excess of 10^8 operations [8]. A recent microrelay [16] displayed the ability to actuate with less than 24V and was able to switch currents up to 200 mA. Various patents have been issued by the United States Patents and Trademarks Office (USPTO) [17] for electrostatic relays and switching. Electrostatic actuation in MEMS devices is commonly used because of its simplicity in design, fabrication and operation. However, for devices having a large gap between the electrostatic plates, the voltage required for actuation is usually too large for common applications. The range of travel is also limited by tilting instability. One of the approaches to overcome this limited travel is to use a series capacitor to provide stabilizing negative feedback [18].

Electromagnetic actuation is best suited when low voltages and high currents are used in switching. Applications for electromagnetic actuation are in integrated circuit test equipment or automotive environment where low noise is required. Previously manufactured electromagnetic microrelays include ones that do not have fully integrated coils or magnetic components [19,20,21]. These devices used either an external electromagnet [19,20] to actuate a movable member or an integrated heating element [21] to demagnetize a portion of magnetic circuit, thereby changing state towards another magnetized region and pulling the contacting elements apart. However, the use of external coils in these devices requires additional assembly and reduces the benefits of batch fabrication as the coils are wound using standard wiring techniques. This type of device (based on external coils) has shown to achieve contact resistances between 100 mΩ to 150 mΩ [22]. In the case of thermally controlled magnetic actuation, the forces are relatively large, but it does tend to increase the switching time and induce noise voltages because of thermal voltage generation effects (i.e. Seebeck effect). Using LIGA (a MEMS fabrication technique), a fully integrated device was designed that was able to switch 1 mA current between the contacts with

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an estimated 250 mN of force when applying 1A coil current [23]. Other reported work includes the use of a planar spiral electromagnet as the driving element of the micro relay [24]. Movements of about 40 microns at an applied current of 1 –2 A were achieved. Yet another technique uses a spiral electromagnet that actuates a cantilever beam created by combined bulk and surface micromachining techniques [25]. This device was reported to generate up to 200 μN forces at 80 mA coil current. Taylor [26] has designed and fabricated fully integrated magnetically actuated micromachined relays. Two different electromagnet designs were investigated (planar spiral and planar meander electromagnets). The reported values for planar meander microrelays were a minimum contact resistance of 30 mΩ, maximum switched current of 1.2A, minimum switching power of 33 mW and lifetime in excess of 850 operations. Numerous patents have been issued on the electromagnetic actuation mechanism [28]. These patents cover a broad area of magnetic actuation mechanism. However, none of these devices have been commercially viable so far, for various reasons such as fabrication costs compared to the mechanically actuated relays available in the market.

Thermal actuation has been used in a variety of MEMS applications. Previously reported relays include a thermally actuated beam that uses a polysilicon heater on top of a SiO_2-Si-SiO_2 clamped beam [29]. Deflections above 40 μm were achieved using an input voltage of approximately 45 V. The researchers indicated that for 15 μm displacement, a temperature increase of 90 K was required. The other parameters included an operation time of 5 ms, a force of 19.6 mN (2 gF) at 25 μm defection, 27 V voltage and 25 mW power. This indicates that reasonable deflections could be achieved with a thermal actuation mechanism. A thermally actuated relay that uses mercury contacts to reduce contact wear and arcing effects has also been reported [30]. The reported contact resistance is less than 1 ohm with a maximum carry current of 20 mA. Other reported thermally actuated devices include a temperature sensor [31] that uses the temperature sensitivity of micromechanical beams and switches. The switches close when heated, or if they are pre-latched with a microscope probe, they pull apart with decreased temperature. Tomonari et al. [32] designed a thermally actuated bimetal relay. This relay uses silicon bimetal materials to provide Type-A relay contact. The device had physical dimensions of 2 mm x 3 mm, control power of only 100 mW, contact forces of 3.4 mN and could achieve a breakdown capability of 500 V. The displacements achieved in this device were up to 30 microns, with switching times of 26 – 77 milliseconds. TiNi Alloy company [33] has also reported a shape memory microribbon based relay that is claimed to provide low-ohmic contact. This device is still in the development stages. Carlen et al. [34] designed a high actuation power, thermally activated paraffin microactuator. This actuator uses the phase change property of paraffin wax to generate a volumetric change and corresponding pressure increase on the silicon diaphragm. This actuation force could be harnessed for use as an actuation mechanism. The volumetric expansion is feasible when the device sizes are large so that the small displacement, large force could be converted to large displacement, small force. Various patents include Field et al. [35] using a thermally actuated element to make contact with another element and Dhuler et al. [36] using arched microelectromechanical beams, which are actuated by providing heating from separate heating elements. The arched beams get radiatively heated to provide the necessary displacement required for actuation. Thermal actuation can provide large forces and displacements. However, thermal cycling issues, response time and heat dissipation requirements must be considered carefully when using this mechanism. Also, for a thermally actuated device, the high temperature required to achieve high displacements also limits the choice of materials.

This research study focuses on the design of a relatively low voltage (50 volts) electrostatically actuated microrelay having a large air gap of 100μm with 1mm x 1mm plate surface dimensions. In the design analysis, research is focused on two main considerations. The first is to maintain plate parallelism during the entire 100μm travel, as this is critical in achieving the maximum electrostatic force required for the displacement. The second is that the stiffness of the suspension system for the moving electrostatic plate must be of an optimal value within the confines of a 1mm x 1mm footprint. A quad-supported, two-dimensional coil-spring suspension design was investigated and the device performances were characterized using IntelliSuite™ [39]. A detailed CAD simulation study is conducted for this microrelay using a simulated environment in the process simulation modules of IntelliSuite™. Using standard fabrication techniques, a three dimensional solid model is created and automatically meshed. A mesh convergence study was conducted to ensure result accuracy. The results obtained were compared against theoretical calculations and were found to be in good agreement. Results of the device performance including pull-in voltages for different suspension stiffness variation, natural frequencies, stresses and restoring forces are presented. This design study demonstrated that with the proper suspension system, electrostatic actuation is able to provide the required displacement over large gap with low actuation voltages applied to relatively small plate dimensions.

2. DEVICE SPECIFICATIONS AND DESIGN CHALLENGES

This microrelay application is targeted for the telecommunication industry, in which miniaturization is highly desired without sacrificing performance while achieving lower cost. Functioning as a switch in telecommunication equipment, a large gap of

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at least 100μm (operation in vacuum / nitrogen) between the electrostatic plates is required to prevent arcing during a possible high voltage surge on the order of 2000 volts [37]. This safety requirement poses a fundamental challenge to the electrostatic actuation principle that is usually applied to gaps in the region of few microns. In addition, the voltage for electrostatic actuation is limited to 50 volts. Furthermore, in order to be economically viable, the design constraint of maximum device size of 1mm x 1mm is imposed. This size constraint is based on economics of manufacturing. The combination of this large gap, relatively low actuation voltage and small surface area is detrimental to the strength of the electrostatic force present at its initial position. High current safety requires that the device withstand 3 Amps current for one second for the contact part of the relay. The temperature increase due to this current flow is targeted not to exceed 200^{O}C. The coupled requirements of low actuation voltage, large displacement gap for voltage surge protection, current and heat dissipation, size and cost make this an interesting design challenge.

3. DESIGN AND SIMULATION

Considering two parallel plates with an applied voltage (V); the capacitance (C) between the plates is given by (neglecting fringe field effects):

$$C = \varepsilon_O \varepsilon_r \frac{A}{g} \tag{1}$$

Where ε_o and ε_r are the free-space and relative permittivities respectively, A is the area of the parallel plates and g is the distance between the plates. When a voltage is applied between the two plates, the magnitude of the potential energy is given by [38]:

$$W_e = \frac{1}{2} C V^2 = \frac{\varepsilon_O \varepsilon_r A V^2}{2g} \tag{2}$$

Then the force generated between the two plates may be calculated by taking the derivative of the energy in the direction of the motion. Hence for z direction:

$$F_e = \frac{\partial W_e}{\partial z} = \frac{\varepsilon_O \varepsilon_r A V^2}{2g^2} \tag{3}$$

Figure 1 shows the theoretical plot of the above equation for actuation voltages of 40 volts to 55 volts. The theoretical electrostatic force existing between the parallel plates at an instantaneous displacement from its initial 100μm gap position can be determined from the respective constant voltage lines.

Superimposed in Figure 1 is a line whose gradient represents the stiffness, K_z, of a suspension system for the moving electrostatic plate. Assuming a linear relationship, the mechanical restoring force, F_m, from the suspension system is related to it displacement, Z, by the equation;

$$F_m = K_z Z \tag{4}$$

and the instantaneous gap between the two electrostatic plates is related to the displacement of the suspension system by;

$$g = (100 - Z) \tag{5}$$

This line shown in Figure 1 has a gradient of K_z=0.075μN/μm and is tangent to the constant actuation voltage line of 50V. This represents the minimum pull in voltage required for the electrostatic plates to snap across the 100μm gap. If an actuation voltage of 40V is applied, this suspension stiffness would result in a mechanical restoring force that equals to the electrostatic force at a displacement of 12μm or a gap of 88μm.

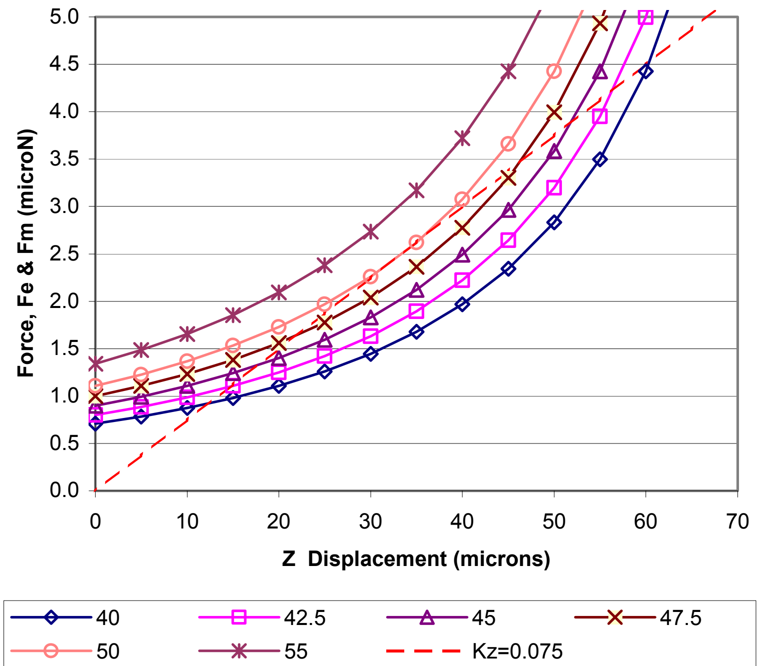

Figure 1 : Electrostatic and mechanical restoring forces at different displacement of the moving electrostatic plate

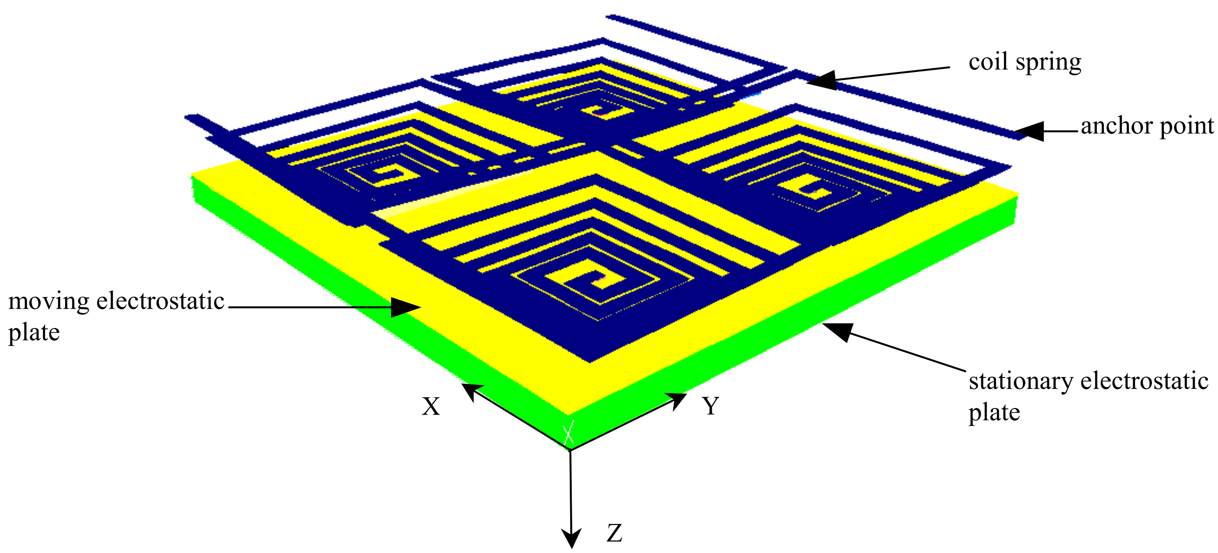

Figure 2 : A quad-support, two-dimensional coil spring suspension system

Using the same analogy, the suspension stiffness required for different pull in voltages can be determined. To fulfill these stiffness requirements within a confined footprint of 1mm x 1mm, a quad-supported, two-dimensional coil spring concept was implemented. Figure 2 shows this suspension system in its actuated mode. Each spring consists of 27 segments, each with lengths varying from 45µm to 490µm and width of 25µm. The gap between the segments is 10µm. The different stiffnesses are achieved through different deposition thicknesses, thus capitalizing on the advantages associated to using a common mask.

The fabrication feasibility of this design was evaluated in a detailed CAD simulation study using the process simulation modules of IntelliSuite™ [39,40]. Figure 3 shows the key fabrication steps as shown in IntelliFab™ process window. These

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key steps include thermal oxide growth on silicon substrate and addition of silicon nitride passivation layer. Then a doped polysilicon layer is deposited using LPCVD process for the lower stationary electrostatic plate (polysilicon). This is followed by a low temperature sacrificial oxide deposition. Next a polysilcon layer is used for upper plate, and finally another polysilicon layer is used for the quad springs. A different conductor layer can be used for top plate if an etch stop is needed for creation of polysilicon springs. The electrostatic plates are doped to attain a resistivity of 0.03 ohm-cm to accommodate the heat dissipation required during 3 Amps current surge for one second.

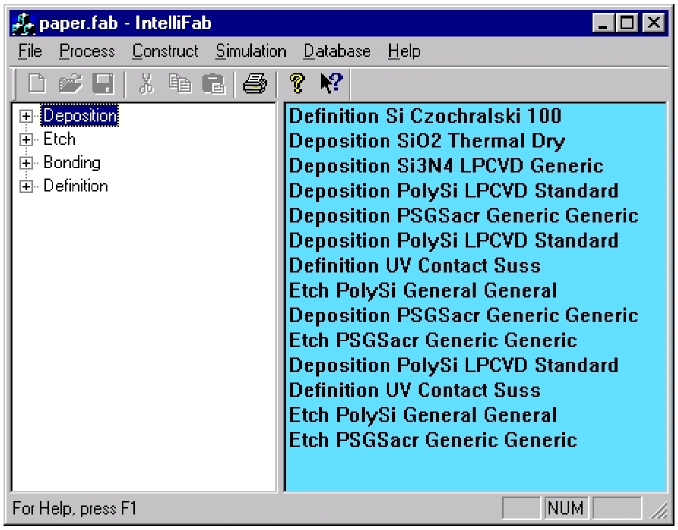
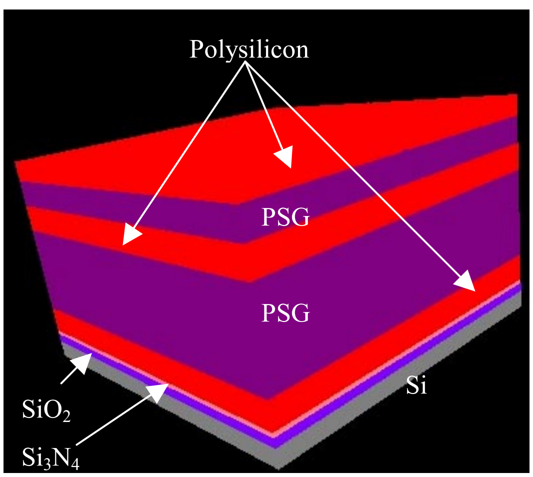


Figure 3: Process simulation window for device fabrication

Subsequent to the fabrication simulation, a three-dimensional solid model was created. Figure 4 shows the device solid model before removal of sacrificial layer. This model is then automatically meshed with mechanical and electrical mesh [41]. Coupled electromechanical analysis was carried out using the Electromechanical Analysis module of IntelliSuite™ . A mesh convergence study was also conducted to ensure result accuracy.



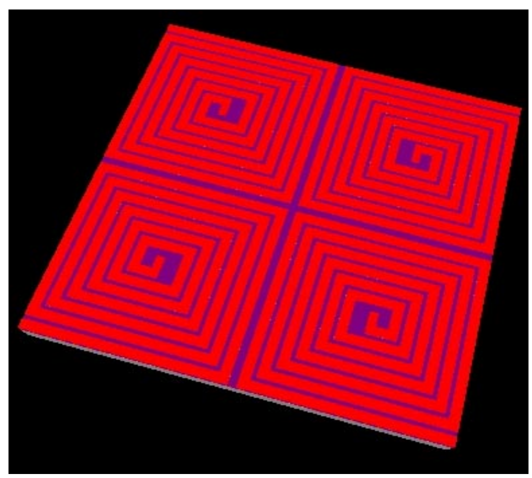


Figure 4: Solid model showing various fabrication layers (Sacrificial layer not removed) Side and top views

4. RESULTS AND DISCUSSIONS

Results from detailed CAD simulation studies revealed that device snapping is possible at different pull-in voltages by varying the suspension stiffness. The quad-suspension system is able to maintain plate parallelism during the entire 100µm travel. The electrostatic pressure on the plate surfaces is uniformly distributed throughout the entire surfaces and no tilting instability was manifested.

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Figure 5 shows the pull-in voltage of the microrelay with different suspension stiffnesses. The results are in good agreement with theoretical predictions, having a deviation of about 1%.

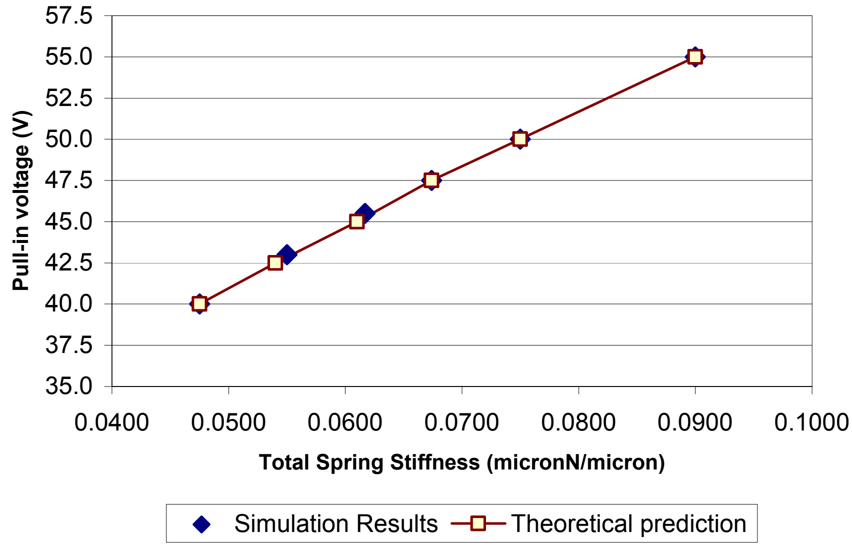

Figure 5: Simulation results of pull-in voltage for different coil spring stiffness

The natural frequencies of the device using different suspension stiffnesses are depicted in Figure 6. The first three modes of resonance were analyzed. The first mode represents Z-axis planar displacement of the moving electrostatic plate. The second and third mode represents the out-of-plane rotation of the plate about its axes of symmetry.

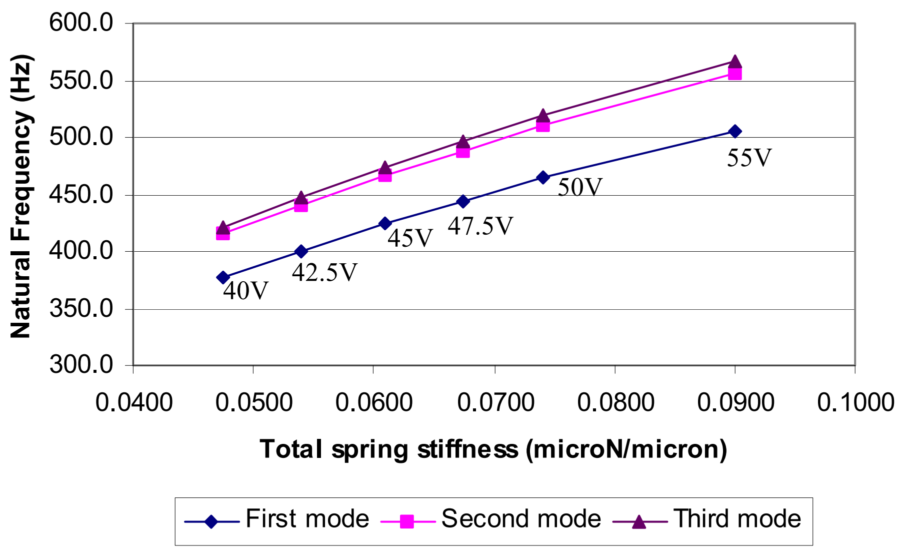

Figure 6: Natural Frequency for different coil spring stiffness

First mode resonance occurs at about 370 Hz to 500 Hz for suspension stiffnesses ranging from 0.0475 to 0.0900 µN/µm with a pull-in voltage range from 40 volts to 55 volts. Of particular interest, the 50 Volts pull-in voltage stiffness design resulted in a first mode natural frequency of about 460 Hz. The out-of-plane frequencies ranges from 410 Hz to 570 Hz. The slight difference of about 2% between the second and third mode frequency is related to the orientation of the coil spring anchor points. From the functional aspect of the microrelay, these frequencies are acceptable for its intended application. However, considerable emphasis must be placed on the package vibration isolation requirements if the relay is required to operate in an external environment having excitation frequency close to this range.

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Stress analysis shows that the maximum Von-Mises stress occurs near the turning point of each spring segment. These stresses with the corresponding restoring force of the coil spring suspension system are depicted in Figure 7. For the 50 Volts pull-in voltage design, the Von-Mises stress is about 40% of the yield strength of polysilicon (Figure 8). These stress values could be further reduced by reducing the stress concentration effect due to the sharp corners of the spring design through filleting.

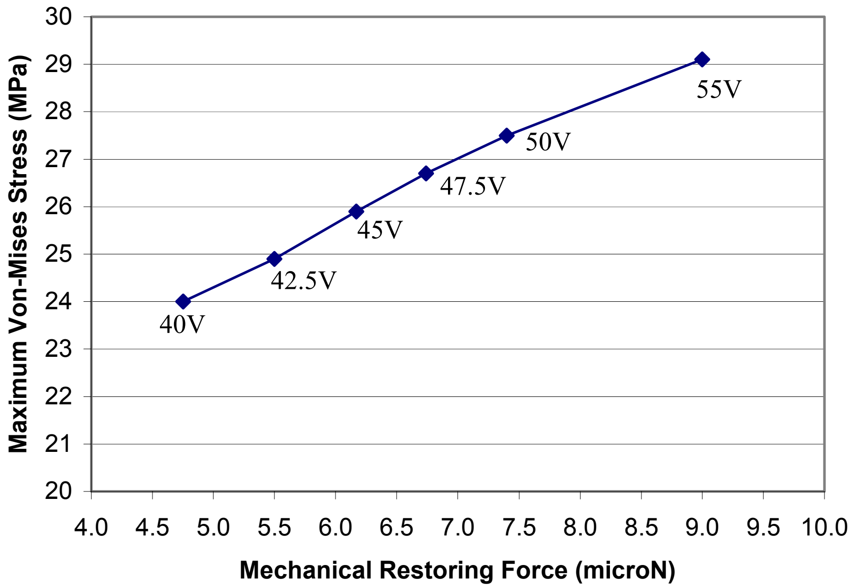

Figure 7: Maximum Von-Mises stress and restoring force of the coil springs

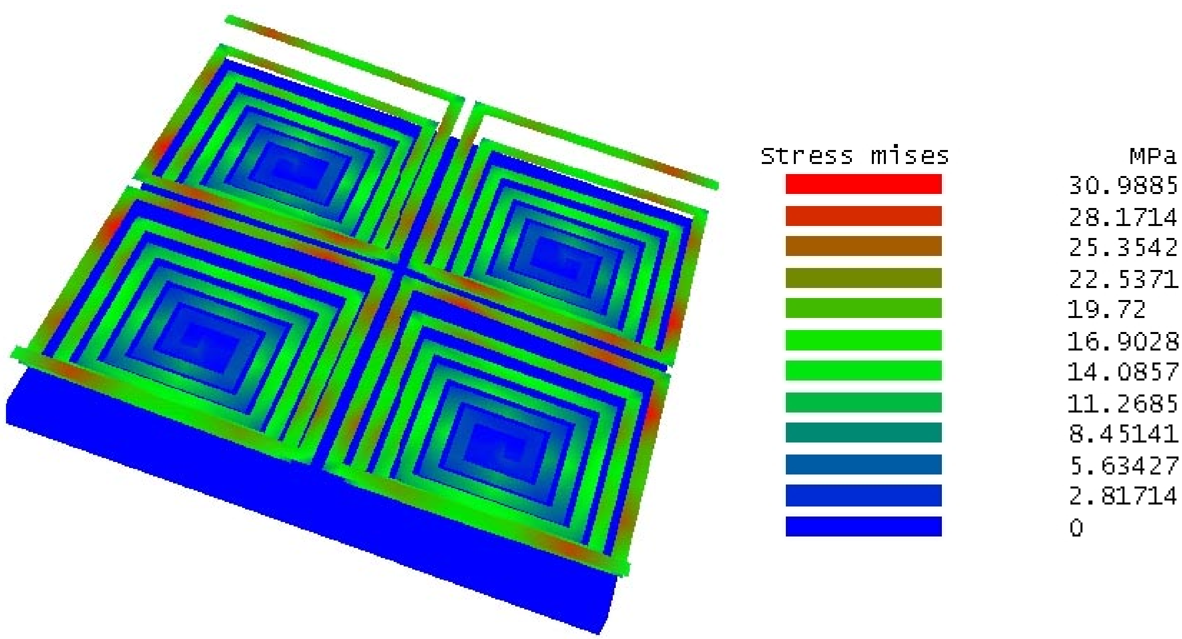

Figure 8: Von Mises Stress for the device at 50 Volts

It should be noted that in this design, the mechanical restoring force is the only mechanism to retrieve the moving plate back to its initial position. This type of relay (Type A- SPST) will work in condition when low contact force is required. If the environment has moisture and propagates stiction, it will be difficult to un-stick the relay due to microweld formation in high current switching applications. In this design analysis, squeeze film damping affects, which will be appreciable in a non-vacuum environment has not been accounted for. The settling time for the relay after it breaks the contact has not been investigated. If required, a physical breaking mechanism can be used to avoid the oscillatory motion that may result after the switch / contact breaks. Alternatively, a third electrode placed above the spring suspension can be used to attract the plate to its equilibrium position after the first break occurs. The contact materials (usually gold or gold-alloys) which significantly affect device operation and lifetime require investigations. This study has focused on a design and its variations and has shown that through proper design, relatively large displacements can be achieved using electrostatic actuation mechanism. More research involving practical aspects, and fabrication issues/requirements can be done in the areas mentioned above.

5. CONCLUSIONS

This simulation based design study has demonstrated that with a carefully designed suspension system, it is possible to achieve large displacement via electrostatic actuation using a relatively small actuation voltage over small surface dimensions. Its relevance has been demonstrated on a microrelay with device specifications meeting stringent telecommunication equipment requirements. The unique quad-supported, two-dimensional coil spring suspension system is the key principle of achieving the low stiffness required for the device to function over tight footprint size. The device mechanical characteristics are able to meet the device functional expectations. Improvement of the mechanical characteristics can be achieved through refining the surface geometry of the coil spring. A circular spiral coil spring design instead of a square coil spring would certainly improve the mechanical characteristics.

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