MICROELECTROMECHANICAL SYSTEM (MEMS) COMPONENTS
VARIABLE CAPACITOR DESIGN EFFECTIVENESS AND RELIABILITY

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ABSTRACT

Millimeter-waves are suitable for satellite communications because of their wide bandwidths and suitable for air-/space-borne radar as well as remote sensing due to their ability to penetrate clouds, fog, and smoke [1]. However, the use of smaller wavelengths requires proportional size reduction of devices and components. MEMS (Microelectromechanical System) technology overcomes this problem by using existing monolithic silicon micromachining techniques to create high-frequency components in micrometer dimensions with microactuators to achieve dynamic reconfigurability [2]. MEMS variable capacitors can be used for any RF, wireless, or high-speed application and feature low insertion losses at high frequencies. They are especially appropriate for space-borne and air-borne applications since MEMS devices are small, light-weight, robust and have low losses, high breakdown voltages and broad bandwidths. Currently, fixed integrated-circuit capacitors and varactor diodes suffer from high insertion losses and operation-frequency limitations. They are costly for space applications operating in the millimeterwave frequencies since the systems require extra amplifiers to compensate losses.

Three MEMS variable capacitor designs created by graduate students had previously undergone design analysis, fabrication, and post-fabrication. Valuable lessons learned during the design analysis/fabrication process were applied to new MEMS variable capacitor designs created by the author. Easier assembly procedures with the possibility of full self-assembly make the new designs more promising for industry applications and reduce production costs and time. New individual components, such as the self-locking hinge, have the potential to be more reliable, more efficient in their use of production area, and more flexible to meet variations in design requirements. These components also have the potential to replace their counterparts in our optical MEMS devices as well as our other RF MEMS devices.
INTRODUCTION

Variable capacitors are essential for communications and radar applications because of their ability to tune into and filter frequencies. However, as higher frequencies (microwaves and millimeterwaves) are being used to supply broader bandwidths, wavelengths become smaller resulting in the proportional decrease in the sizes of devices and components. MicroElectroMechanical System (MEMS) technology miniaturizes conventional components to the order of micrometers and uses microactuators to drive movable parts on the same chips. The miniaturization, using monolithic batch fabrication on wafer scales [3], makes MEMS structures very small and light weight; therefore, the actuators need only voltages and very little currents to provide the necessary force for movement. This increases the driving-power consumption efficiency, which is a major advantage for battery-operated or low-voltage power-supply applications such space and mobile uses.

In a previous report, a horizontal parallel-plate variable capacitor, designed by a graduate student, was analyzed, fabricated, and tested. The horizontal parallel-plate variable capacitor used actuators to power support arms up and down, raising and lowering the top plate to change the device’s capacitance. A circular variable capacitor, designed by another graduate student, was also analyzed and fabricated. Actuators rotate the top plate over the bottom plate, adjusting the amount of coupled surface area that produces capacitance.

Design reliability issues turned our attention from designing electrical components to the study of mechanical engineering. Stress, friction, wear, etc. must be taken into consideration during the design process to ensure design reliability. However, traditional physics cannot be used to describe the properties of MEMS devices. A hinge fabricated for an ordinary door consists of more than a billion atoms whereas a MEMS hinge may consist of a few hundred or a few thousand. Therefore, intermolecular interactions have a great affect on MEMS devices.

METHODS

Reliability Issues

Although the parallel-plate and circular variable capacitor performed well conceptually, fabrication errors and reliability issues limited the design’s potential. Stiction was a major concern because a small amount of water would cause atomic bonding between device parts, rendering them incapable of performing their intended function. Water was used during the post-fabrication procedures performed in the Physical Electronics Laboratory (PEL) located at the University of Hawaii. In order to prevent electrical shorts of actuator signals and capacitance generating surfaces, non-conducting positive photoresist was used as a connection between several key device components. However, positive photoresist is weakened by the acetone and methanol used to clean the device after post-fabrication so water was used. In order to prevent stiction, research associate Junichi Hayasaka decided to use negative photoresist that permits acetone and methanol washes, thus eliminating water from the process.

Research indicates that another major reliability concern is the amount of wear on moving parts. Bill Miller of Sandia National Laboratories, the leader in MEMS technology, stated that “one of the greatest challenges for the successful commercialization of this new technology is in proving its reliability [6].” Miller’s research team found that MEMS parts fail
by wear that involves parts rubbing and causing small pieces to rip off, Figure 1. These pieces attract and stick to each other, potentially causing damage to additional MEMS components [6].

![Figure 1: Sandia photograph of a pinhole joint before and after operation proving wear can cause damage to MEMS components](image)

In our devices, the components most susceptible to wear and friction are the hinges, actuators, and actuator railings. Obviously, components that feature moving parts will be at risk but the fact that the key part of the hinge is a mere 3 microns wide (3x10^-6 m) causes extra concern, Figure 2. Hinges, actuators, and actuator railings are common components used in many of our MEMS devices, including variable capacitors, so it is imperative that these components operate correctly. The photoresist layer also has the potential to weaken, sag, and possibly block a moving part. Reliability research has enabled our group to focus on possible problem areas and make informed decisions regarding design tradeoffs and functionality.

![Figure 2: Scanning electron microscope (SEM) picture of two separate hinges. At left, forces are concentrated on the 3 micron section of the hinge. At right, the identical 3 micron section has much less room to rotate, which increases the amount of friction and wear.](image)

**Design**

New variable capacitor designs and individual components were created to address reliability issues as discussed in the previous section. MEMS designs were composed using a software program, L-Edit, which eased the construction process because of its Microsoft Windows based point-and-click interface. In L-Edit, layers of 2-dimensional geometric shapes were manipulated into 3-dimensional structures. MEMS devices are composed of three polysilicon layers mounted on a substrate. Every facet of a MEMS device (hinges, actuator arms, etc.) must be composed of these three principle layers.

Only through comprehensive understanding of the fabrication process can one design a properly functioning device. The first layer, poly0, bonds to the substrate and thus cannot be used to form moving parts. After patterning the poly0 layer, phosphosilicate glass (PSG) is then deposited over the entire device, coating any poly0 surfaces in the design. PSG is a sacrificial layer that will be removed at the end of the fabrication process but currently serves to isolate the next polysilicon layer from device beneath. The use of PSG is essential to the formation of moving parts because it separates the polysilicon layers that would bond together with contact. By patterning the PSG, some areas of the substrate or poly0 will be exposed while the rest of the area remains covered by PSG. When poly1 is deposited over the entire device, poly1 will bond with either exposed substrate or poly0 and rest on top of the remaining PSG layer. A second layer of PSG is deposited over the device to separate the existing layers from the next layer, poly2. After patterning the second layer of PSG, poly2 is deposited over the entire device and
patterned as well. At this point, the design has been completed but the remaining PSG layers continue separate the individual layers. In Figure 3, the PSG has been removed and the patterned polysilicon layers that have no contact with the substrate or poly0 are now free to move.

![PSG](image)

Figure 3: At right, cross section drawing of a rail and its guide posts. Note that the layers of PSG (shown in light gray) affect the height and shape of the MEMS parts. At left, the final product after the PSG has been etched away.

An important fact to consider is that deposited layers of polysilicon or PSG will not necessarily be flat. Instead, the deposition process blankets the entire device with fixed height of polysilicon or PSG, filling any holes or vacant areas. Therefore, the deposited layer will have bumps and indentations that follow the shape of the layers below. This fact makes design work difficult because fabricated device will not necessarily be the same as the device layout. In our device layout, it is shown that poly2 is above poly1 and poly1 is above poly0. However, in reality, the height of each layer is variable. The layer being deposited will fill in vacant areas so, for example, poly2 can be at the same height as poly0 if all other layers were etched away in that particular area. Thus, moving parts that require a certain amount of height clearance might find their paths blocked. Also, bumps in guide railings might impede moving parts.

Additional limitations are imposed by design rules that must be followed in ensure successful fabrication. These rules account for the resolution and mask alignment capabilities of the fabrication equipment [5]. Minimum line/spacing rules must be followed else missing, undersize, oversized or fused components will result [5].

![Model](image)

Figure 4: At left, the scale model of one section of the vertical variable capacitor is shown at its rest position. At right, the model shows the process of lifting the plate up to create capacitance with a second plate (not shown).

Due to the complexity of the MEMS variable capacitor design, several scale models were built to ensure that there were no design errors, Figure 4. Design errors can be catastrophic to the design process because the time, money, and materials used to make the defective product will all have been wasted. Also, because a change to a single component will result in the change of all similar components in L-Edit, one design error can be magnified into a hundred.

**DISCUSSION**

The new MEMS vertical parallel-plate variable capacitor was designed in L-Edit (Figure 5) and has several advantages over previous designs. The horizontal parallel-plate variable capacitor performance suffered from parasitic capacitance generated by the coupling of the
support arms with the bottom plate. Parasitic capacitance is undesirable because it decreases the percentage range of variable capacitance a device is capable of generating and makes design capacitance specifications inaccurate. The vertical parallel-plate design separates the components supporting each plate such that the vertical plates are the only major coupling surfaces. This permits the design capacitance specification to be obtained with a higher degree of accuracy. The horizontal parallel-plate design also has the potential of having the bottom plate stuck to the top plate. This scenario is possible due to broken parts or other debris that settle between the two plates. In addition, the two plates are already very close together when in the rest position. The vertical parallel-plate design has the two plates initially flat and far apart until the actuators drive the plates up to their vertical position. The actuator's range of motion is designed to prevent the possibility of contact between the two plates and small debris should not affect the movement of the vertical plates. Thus, the vertical parallel-plate design has the potential to be more reliable than the horizontal design.

The vertical parallel-plate design also has potential to be more reliable than the circular variable capacitor design because of the affect wear has on the circular design's parts. The circular design depends on the pivoting center stub that will be subject to wear during operation. Wear on the center stub will not only shorten the stub and damage the top plate, but will also create debris that could short circuit the two plates and eliminate generated capacitance. The vertical parallel-plate design's weakness lies in its hinges but multiple and improved hinges can be used to ensure proper functioning.

Figure 5: L-Edit layout view of the MEMS vertical parallel-plate variable capacitor. Two plates will be lifted by the actuators and be separated by a 20 micron gap

Figure 6: Diagrams showing the step-by-step motion of the self-locking hinge. The spring-mounted clasp becomes compressed while moving through the guide railings and locks into place in the guide rail opening.

An additional component designed in L-Edit is the self-locking hinge. The key part in this component is the spring-mounted clasp. The clasp is compressed as actuators push the support arm that lifts the plate to its vertical position. Once the desired angle of plate elevation is reached, the clasp simultaneously reaches an opening in the guide rail and locks into position. The clasp prevents the plate from returning to the rest position and a barrier can be placed to prevent the plate from elevating further, Figure 6. Other locking hinges use “V-shaped” claps (Figure 7) that must be manually lifted into place after the fabrication process. This is undesirable because of the time and costs involved with the difficult process of
lifting/holding the plate in position and carefully sliding the “V-shaped” clasps over the plate without causing damage to the device. The self-locking hinge design has the potential to be self-assembled by using actuators to power the device into place or can be simply lifted and locked into position with one easy motion. In either case, time and money has been saved and the risk of damage to the device during assembly is minimized.

Fabrication work has not been performed by the author due to safety concerns that arose after the departure of Professor Kim, director of the Physical Electronics Laboratory (PEL) and person responsible for the safety of the laboratory personnel. In addition, life cycle testing could not be performed on fabricated designs due to the limited number of fabricated devices and the author’s inability to work in PEL.

CONCLUSION

Several MEMS variable capacitors have been designed and analyzed and both the parallel-plate and the circular variable capacitors have gone through fabrication and post-fabrication. While the design concepts have been proven successful in the fabricated devices, post-fabrication and assembly errors have limited their reliability. Lessons learned have been applied to the new designs, increasing their reliability and bringing them closer to the goal of self-assembly. These more reliable components also impact MEMS designs in optics and other RF components as well as variable capacitors. Work needs to be done to fabricate and test the improved designs and research on reliability issues needs to be continued and applied to current designs.

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REFERENCES