Performance of Molybdenum as a Mechanical Membrane for RF MEMS Switches

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Abstract — **This article details the construction and measurement of RF MEMS capacitive switches using molybdenum as the mechanical material. The resulting switches exhibit a significantly reduced rate of change in actuation voltage over temperature, with rates less than 0.03 V/°C up to 150°C. Resistivity of the molybdenum membranes averaged 10-11 μΩ-cm, yielding an effective shunt resistance of less than 0.25 Ω. Initial cycling measurements were made which show that the resulting membranes were capable of at least 20 billion cycles without failure, indicating that molybdenum is a promising mechanical material for constructing RF MEMS switches.**

Index Terms — microelectromechanical systems, RF MEMS, MEMS switch, molybdenum, capacitive switch, temperature.

I. INTRODUCTION

As RF MEMS switch technology continues to mature, much of the development has focused on packaging, reliability, and environmental robustness. To date, many innovative ideas have been presented for RF MEMS packaging, and the reliability of the devices has seen much improvement [1]. Now, increasingly more attention is being focused on device performance over temperature. While the electrical/RF performance of MEMS switches is usually very stable with temperature, the mechanics of the device are more variable. Often, RF MEMS switches and capacitors are commonly fabricated with fixed-fixed beams, where two ends of the mechanical beam are fastened to the substrate. One of the detractors to this arrangement is that changes in temperature modify the residual stress of the beam, which changes the operating pull-in and release voltages for the switch. Little data is published on this effect, but depending on the materials and design, the rate of change can be as large as 0.5 volts/°C.

The root cause of this change in operating voltage is due to the difference in thermal expansion coefficient between the mechanical beam and the substrate [2]. Changes in temperature cause the two materials to expand, but at different rates, which induces a change in the residual stress of the MEMS beam. The beam's residual stress changes by

$$\Delta\sigma = \Delta\alpha E \cdot \Delta T$$

where $\Delta\alpha$ is the difference in thermal expansion coefficient, E is the Young's modulus of the beam material, and ΔT is the change in temperature. This change in stress impacts the spring constant of the beam, which in turn influences the switch pull-in voltage. Almost all MEMS switches are fabricated out of metal for low RF loss, but metals generally have a thermal expansion much higher than that of commonly used substrate materials. Thus, the devices exhibit significant changes in operating voltages over temperature.

One innovative method to mitigate this problem is to modify the geometry of the switch to compensate for these changes in stress over temperature [3]. In this technique, the geometry of the switch suspensions are designed to eliminate thermal stress at the anchor points of the switch. The resulting structure shows stable operation over temperature, with operating voltages changing less than 5% over 100°C temperature excursions. This technique works well for thicker beams where the impact of stress gradients can be minimized. Further development has extended the concept of using switch geometry to mitigate stress changes over temperature, as was recently demonstrated in [4].

An alternative method towards minimizing changes in stress on the fixed-fixed beam is to pick a mechanical material which has an expansion coefficient much closer to that of the substrate material. In RF MEMS switches, the range of choices is not particularly broad, as other considerations such as resistivity of the films directly impact the RF performance of the switch. Figure 1 summarizes a number of metals commonly used in semiconductor processing, listing their coefficient of thermal expansion, Young's modulus, and resistivity.

			Substrate	**Pyrex**	**Glass**
			α	3.25	ppm/°C
Metal (units)	**E** (Gpa)	α (ppm/°C)	ρ (μohm-cm)	Δα (ppm/°C)	**ΔαE** (MPa/°C)
Ag	83	18.9	1.6	-15.65	-1.30
Cu	130	16.5	1.7	-13.25	-1.72
Au	78	14.2	2.2	-10.95	-0.85
Al	70	23.1	2.65	-19.85	-1.39
W	411	4.5	5	-1.25	-0.51
Mo	329	4.8	5	-1.55	-0.51
Ni	200	13.4	7	-10.15	-2.03
Cr	279	4.9	12.7	-1.65	-0.46
Ti	116	8.6	40	-5.35	-0.62

Figure 1 - Mechanical properties (bulk) of selected metals and substrates [5] (E=Young's modulus, α= coefficient of thermal expansion, and ρ=resistivity)

Aluminum alloys have been used as a mechanical material for RF MEMS switches for over a decade, dating back to the early days of MEMS for television displays. While the resistivity of aluminum is quite good (yielding a distinct performance advantage in MEMS switches), its expansion coefficient with temperature is very high. Compared to a silicon or glass substrate, aluminum's expansion over temperature can be quite significant. Refractory metals such as chrome, molybdenum, and tungsten provide much less change over temperature. However, this improved thermal performance comes at the expense of increased resistance. For well designed MEMS switches, this increase is justified by more robust operation over temperature. Additional benefits ensue as well. Aluminum has strict temperature limits before release, while it is still bound to the sacrificial layer. Prior to release, temperature excursions above 150°C can cause plastic deformation of the beam material which permanently increases the stress and operating voltage of the device [6]. This places restrictions on several processing operations to keep the temperature within reason, especially the release process itself (which releases much faster and cleaner at higher temperatures). Utilizing a refractory metal for the MEMS switch allows for a more temperature robust process, which can reduce costs and improve yields.

In order to investigate the potential improvements over temperature, molybdenum was chosen to replace aluminum as the mechanical material in MEMS capacitive switches. Some data already exists demonstrating that molybdenum is suitable for MEMS applications [7], and molybdenum provides a reasonable balance between thermal expansion coefficient and film resistivity. The results of this research are detailed below.

II. DEVICE CONSTRUCTION/PROCESSING

The micromechanical switches utilized in this article consist of low-loss MEMS capacitive switches which operate at microwave and millimeter-wave frequencies, and are similar in construction to those previously reported [8]. The mechanical membrane is constructed with 0.28 μm thick molybdenum, with planar dimensions of approximately 320 μm in length and 100 μm in width. The molybdenum was deposited on a CVC cluster tool using DC magnetron sputtering. Plasma power, argon flow, plasma pressure, and substrate bias were adjusted to achieve stress in the range of 50-150 MPa tensile. The maximum temperature during deposition was approximately 90°C. The mechanical beam is suspended approximately 2.5 μm above a Pyrex 7740 glass substrate. The lower electrode consists of 0.4 μm of gold with 0.25 μm of sputtered silicon dioxide as the switch insulator. The mechanical posts supporting the membrane consist of plated copper. A photo of the switch is shown in Figure 2.

Figure 2 - MEMS capacitive switch fabricated with a molybdenum metal membrane.

III. RESULTS

The goal of this research was to develop a metallic membrane much less subject to residual stress changes over temperature. Three important characteristics of the mechanical material used in an RF switch are 1) voltage change over temperature, 2) film resistivity, and 3) mechanical reliability. The metal film must have a resistivity that is commensurate with the ultra-low loss requirements for MEMS switches at microwave and millimeter-wave frequencies. The residual stress must be sufficiently low to enable the switches to operate with low voltages, the lower the better with respect to dielectric charging. Lastly, the mechanical reliability of the switch should be such that the switch can cycle for long periods without mechanical degradation. If these three criteria are sufficiently satisfied, then the material is a suitable candidate.

A. Voltage Change over Temperature

To demonstrate the change in actuation voltage over temperature, a representative sampling of devices was chosen with actuation voltages over the 30 volt to 45 volt range. The characteristics curves of these devices were measured from 20°C (the lower limit of the test station) up to 150°C. The resulting change in actuation voltages are shown in Figure 3. Over the 130 degree temperature change, the switch actuation voltages varied between +1.2 volts and -4.5 volts, or equivalently +0.002 V/°C and -0.032 V/°C. This change is far less than the typical -0.1 V/°C to -0.3 V/°C experienced with aluminum membranes. The specific voltage variation over temperature is also dependent on the specific 3-D shape of the membrane. Some of the variation in these results may be due to small differences in the curling of the switch membrane (as evidenced by the dark contour on the left side of the switch photo in Figure 2). To ensure that the switches were stable over temperature, the off-capacitance of the switches was monitored over the same temperature range. In all cases, the off-capacitance of these switches was invariant over temperature. This verifies that there was no buckling of the membranes over the investigated temperature range. In aluminum switches, zero residual stress is reached somewhere around 80°C – 90°C, at which point the membrane buckles and changes its position relative to the lower electrode, increasing its off-capacitance. This was not evident up to 150°C in the molybdenum switches shown in Figure 3.

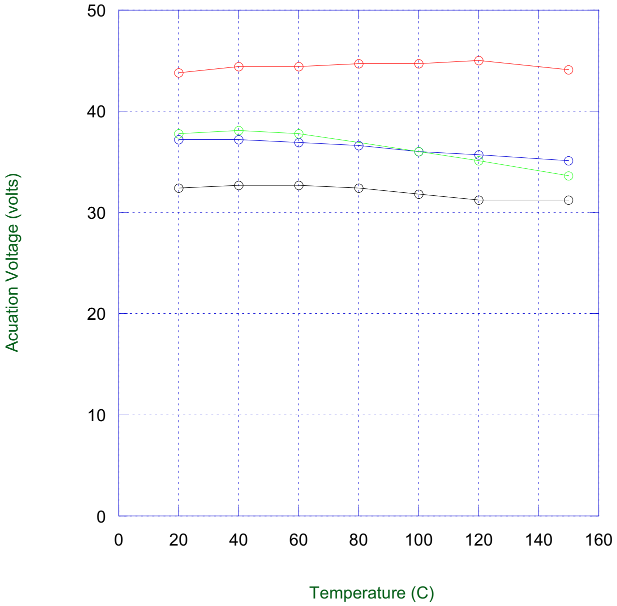

Figure 3 - Variation in actuation voltage for molybdenum membranes ranges from +0.002 to -0.03 V/°C (four representative devices shown)

B. Resistivity

The resistivity of sputtered metals is typically 2x-3x that of bulk values. Measurement of film resistivity can be accomplished with four-point probes or suitable test structures. In this case, long meandering lines of molybdenum were measured and resistivity computed. The resulting values of resistivity were 0.4 Ω/□, with a standard deviation of 0.06 Ω/□. With a 0.28 µm thick membrane, this is equivalent to approximately 11 µΩ-cm, just over twice the bulk resistivity. All wafers in this lot had similar results, with the resistivity averaging 10 µΩ-cm to 11 µΩ-cm. The total resistance from end-to-end of the switch membrane is approximately R_M =1.0 +/- 0.1 Ω. The effective shunt resistance of the switch to ground, R_{SH}, equates to $R_M/4$ (two halves of the membrane in parallel to ground), or 0.25 Ω. The ultimate isolation from a single shunt switch is determined by the shunt resistance to ground

$$ISO = 20\log\left(\frac{R_{SH}}{R_{SH} + \frac{R_o}{2}}\right)$$

where R_{SH} is the shunt resistance and R_o is the system impedance. This means that the use of a molybdenum membrane limits the ultimate switch isolation of a single MEMS switch to at most 40 dB (ignoring capacitive reactance). This is a reasonable tradeoff for greatly improved robustness over temperature.

B. Reliability

Detailed qualification of mechanical reliability is an extensive process. To demonstrate the initial viability of molybdenum as a mechanical material, a switch was actuated for 20 billion cycles without failure. The test station used for this cycling test was previously described [9]. The drive waveform consisted of a square wave with a peak actuation

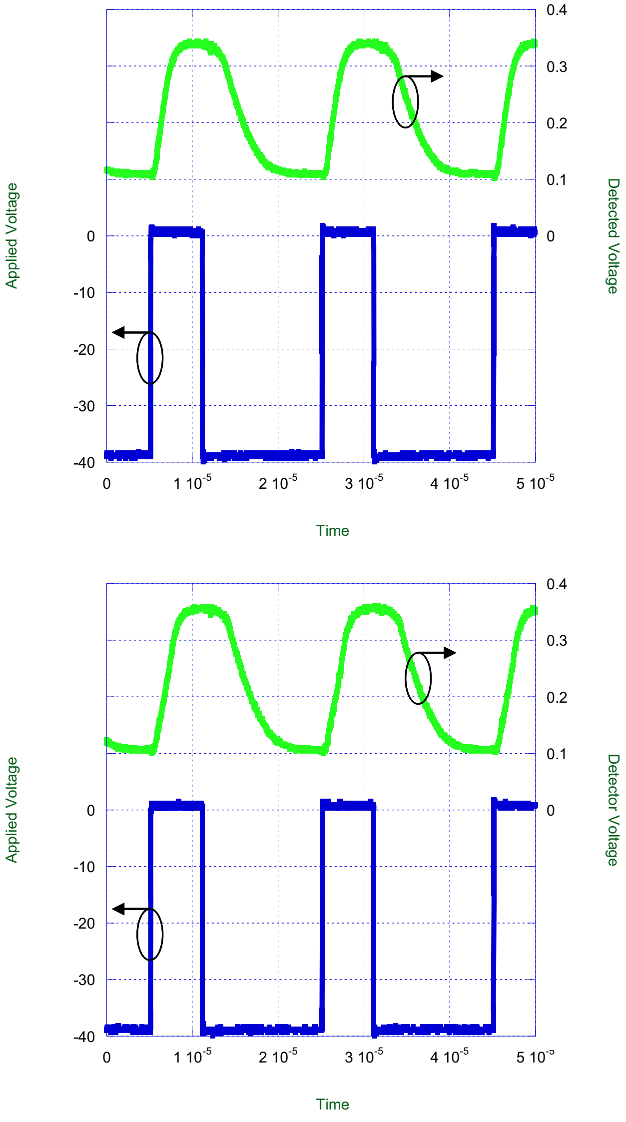

Figure 4 - Drive and monitor waveforms for a molybdenum RF MEMS switch at the beginning of a cycling test (upper graph) and after 20 billion cycles (lower graph).

voltage of -39 volts and a repetition frequency of 50 kHz. The duty cycle was set to 35% to yield approximately equal on- and off-times of 5-7 μS. On-off and off-on transition times accounted for the remainder of the 20 μS period. The device was hot-switched with approximately 0 dBm of RF at 35 GHz. The pull-in voltage of the switch was approximately 30 volts. The cycling test was stopped after 20 billion cycles without failure. The graphs of Figure 4 depict the high-speed switching waveform of the switch in a virgin state (no significant cycles) and after 20 billion cycles, with very little difference between the two waveforms. Full characterization of more switches over longer cycle times and environmental conditions is on-going, but these results give an optimistic indication that molybdenum is a suitable material for mechanical operation of MEMS capacitive switches.

IV. CHALLENGES

Any new metal deposition process has challenges, especially if one is concerned about both mechanical and electrical properties; using molybdenum for MEMS capacitive switches is no different. One challenge encountered in using molybdenum for the mechanical material is achieving the desired residual stress. Though parameterized characterization of the deposition system has been completed, achieving consistency of the desired stress state in the metal is difficult. The resulting stress tends to be close to zero stress, or heavily tensile. Though it is generally desirable to have switches with low residual stress, switches with almost zero stress are much more subject to curling and buckling, which can be problematic. Achieving a moderate tensile stress on a repeatable basis will require further development.

During fabrication and testing of multiple wafers using molybdenum it was observed that, if the temperature of the plasma release (with oxygen) is too high, significant oxidation occurs on the surface of the molybdenum. This oxidation does not hinder or degrade switch operation in any significant way. However, the oxidation does prevent measuring the resistivity of the deposited films.

V. CONCLUSION

Significant improvements have been demonstrated in the operation of fixed-fixed beam capacitive switches over temperature. Utilizing molybdenum as the mechanical material reduced the rate of change in actuation voltage from 0.1-0.3 V/°C for aluminum to less than 0.03 V/°C. The switches also operate up to at least 150°C without any evidence of buckling. The resistivity of the molybdenum films is 10-11 μm-cm yielding membrane resistances of approximately 1 Ω. Initial cycling tests show that the membrane material can operate a significant number of cycles (20 billion cycles) without mechanical failure. Further development is required to make this process production worthy, but all indications show that molybdenum is a good candidate material for building RF MEMS capacitive switches which exhibit robust operation over broad temperature ranges.

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