Temperature Variation of Actuation Voltage in Capacitive MEMS Switches

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***Abstract*—A simple theoretical model for temperature variation of actuation voltage for fixed-fixed beam switches is developed and applied to model capacitive radio frequency microelectromechanical systems switches. Measured data from these switches fit very well with the model over a 120 °C operating temperature range, demonstrating an average 0.127 V/°C to 0.132 V/°C with less than 8% deviation between measured and modeled results. The proposed model provides valuable insight into the factors impacting variability of actuation voltage over broad temperature ranges.**

***Index Terms*—Actuation, capacitive switch, electrostatic, radio frequency microelectromechanical systems (RF MEMS), temperature.**

I. INTRODUCTION

ROBUST operation over temperature is a critical criterion for any electronics technology. The ability to maintain consistent device performance irrespective of temperature is a necessary ingredient for useful application of electronic devices. Fixed-fixed beam capacitive microelectromechanical systems (MEMS) switches commonly possess an actuation voltage that varies significantly over temperature. This is due to their inherent mechanical design which allows the substrate to induce changes in the stress state of the mechanical membrane over temperature. The sparse data that has been published on this topic demonstrates variations in the range of 0.3–0.5 V/°C [1], [2]. Over a broad temperature range, this can lead to excessively large supply voltage variations. Additionally, operation at high voltages (necessary for low temperatures) can also adversely impact device longevity [3]. Clearly, it is important to understand and control the mechanisms which determine the actuation voltage for a fixed-fixed beam MEMS switch. This article develops a simple analytical description of the mechanisms inducing change in pulldown voltage over temperature and compares them with experimental results. The result is an excellent fit between theory and experiment, and better insight into the factors affecting robust operation over temperature.

II. THEORY

Fixed-fixed beam micromechanical structures have been utilized to make RF MEMS capacitive switches [4] for more than a decade. A thin, flexible metal membrane is suspended across two support posts, and is electrostatically actuated via a lower electrode beneath the membrane. The pulldown voltage for this switch is a function of geometrical dimensions and material characteristics of the mechanical material. A simple, first-order model for the elastic deformation of the membrane gives an expression for the pulldown voltage of the membrane as [5]

$$V_P = \sqrt{\frac{8kg_o^3}{27\varepsilon_o A}} \tag{1}$$

where k is the linear spring constant of the membrane, g_o is the undeflected gap between the membrane and lower electrode, ε_o is the permittivity of free space, and A is the overlap area of the membrane and electrode. The spring constant of a membrane switch in the stress-dominated regime is given by [5] as

$$k \sim \frac{8\sigma(1-\nu)tw}{L} \cdot \gamma_g \tag{2}$$

where σ is the residual stress, ν is the Poisson ratio, and t, w, and L are the thickness, width, and length of the fixed-fixed beam. This equation is generally within 20% of a more detailed finite element simulation. Other geometrical factors may impact this model, including the finite width of the lower electrode beneath the membrane and the impact of a flared membrane shape rather than a rectangular shape. These are taken into account by the geometrical constant γ_g in the above equation.

The cause of pulldown voltage changes over temperature is due to strain caused by the difference in expansion coefficients between the mechanical membrane and the substrate. Often, the metal membrane and the insulating substrate possess a significant difference in expansion coefficients, on the order of 20 ppm/°C. This results in a situation where the substrate will force substantial changes in the membrane stress. At a deposition temperature, T_d, the membrane is deposited with a residual stress, σ_d, set by the deposition conditions. As the temperature decreases from the deposition temperature, the tensile stress linearly increases due to the strain induced by substrate expansion. This can be characterized by the simple relationship

$$\sigma(T) = \Delta\alpha E[T_{zs} - T] \tag{3}$$

where $\Delta\alpha$ is the difference in thermal expansion coefficient of the beam and substrate, T is temperature, and T_{zs} is the effective temperature of zero stress within the membrane, which is determined by

$$T_{ZS} = T_d - \frac{\sigma_d}{\Delta\alpha E}. \tag{4}$$

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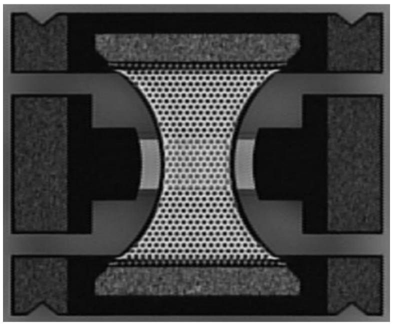

Fig. 1. Top view of a shunt MEMS capacitive switch.

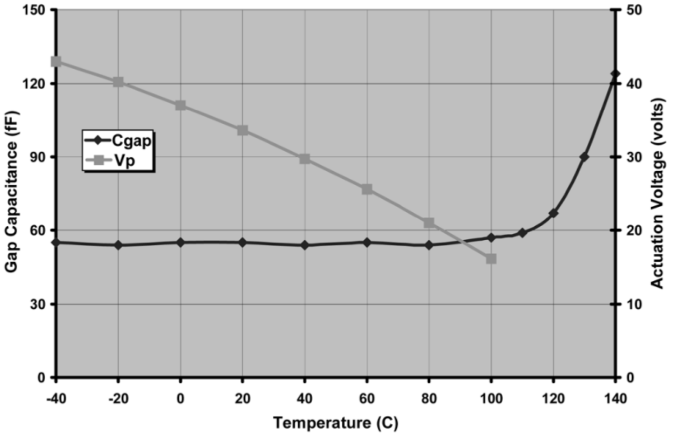

Fig. 2. Measurement of gap capacitance and actuation voltage over temperature.

This formulation makes obvious that a single variable, T_{zs}, accounts for the as-deposited stress and deposition temperature of the membrane.

Combining (1)–(3) yields an expression for the actuation voltage as a function of temperature caused by strain induced temperature variations

$$V_P(T) = \sqrt{\frac{64\gamma_g(1-\nu)tg_o^3}{27L^2\varepsilon_o}\left(\Delta\alpha E(T_{zs}-T)\right)}. \tag{5}$$

This equation expresses the fundamental relationship of the switch actuation voltage over temperature for a fixed-fixed beam MEMS switch. As will be evidenced in the measured data, practical values for switch parameters yield a relationship which is only mildly nonlinear over broad temperature ranges.

III. EXPERIMENT

Experimental verification of the proposed model was obtained using capacitive MEMS switches. These switches were fabricated on Pyrex glass substrates (Corning 7740) with copper posts, gold electrodes, and aluminum alloy membranes. A photograph of the top view of the switch is shown in Fig. 1. The CPW transmission lines have a 150-μm center linewidth and 35-μm spacing. These conductors are approximately 2.5-μm tall with a 300-μm ground-ground spacing. The lower electrode is constructed from gold, being approximately 0.3-μm tall and 80-μm wide. The center conductor is covered by 0.25 μm of silicon dioxide as the switch dielectric.

These RF MEMS switches were tested on a Cascade Microtech Attoguard test station outfitted with a Temptronic temperature controller capable of setting and controlling the chuck temperature over the $-50\,^\circ$C to $+100\,^\circ$C temperature range. The switches were actuated using an Agilent Model 33 220A arbitrary waveform generator driving a Tabor Electronics Model 9100 high voltage amplifier. The waveform was programmed to be a dual-pulse waveform similar to that described in [3] to minimize dielectric charging. The amplitude of the actuation pulse was variable over a 20–50 V actuation range. The duration of this peak voltage was approximately 500 μs. The holding voltage in the waveform was set to approximately 38% of the peak actuation voltage (i.e., a 15-V holding voltage for a 40-V actuation voltage). The repetition rate of the waveform was 10 Hz so that actuation was visible through the test station microscope. Voltage drive was initially set low and increased until the onset of switch actuation. The minimum actuation voltage was then recorded for each switch over the temperature range of $-50\,^\circ$C to $+100\,^\circ$C. Six MEMS switches were measured across the face of two different wafers and all results tabulated.

IV. RESULTS

Prior to the above described actuation voltage measurements, a measurement of switch off-capacitance was taken over temperature. This data was taken to investigate whether the height of the membrane changed appreciably over temperature. A graph of gap capacitance versus temperature is shown for one of the MEMS switches in Fig. 2. As can be seen from this figure, the off-capacitance is maintained constant until the "critical buckling stress" is reached at approximately 90 °C. This implies that the gap between the membrane and electrode remains constant until the onset of buckling. This data supports the validity of the model of (5), which would be incorrect if the membrane gap changed significantly over temperature. In order to avoid buckling of the membrane at the high temperatures, a maximum temperature of 70 °C was used for model fitting.

Graphs of actuation voltage for the six devices from each of two wafers are represented by individual datapoints in Fig. 3. The data from the first wafer, Wafer A, demonstrates an average actuation voltage at 25 °C of 32 V. Total variation over a 115 °C temperature range, from $-45\,^\circ$C to $+70\,^\circ$C, is approximately 14.5 V. This represents an average variation of 0.127 V/°C. Similarly for Wafer B, the average room temperature actuation voltage is approximately 24 V with a 16-V variation over a full 120 °C temperature range. This represents an average variation of 0.132 V/°C over the temperature range.

Next, the measured data was fitted to the model represented by (5). The data from six switches was fitted with individual values for the gap, g_o, and a common value of T_{zs} from each wafer. For the aluminum membrane, a Young's modulus of 70 GPa and Poisson ratio of 0.35 were used (those of bulk aluminum). The average thickness of the aluminum membranes are taken to be 2800 A. The difference in expansion coefficient between the aluminum membrane and glass substrate was taken as 20 ppm/°C. For the particular switch portrayed in Fig. 1, the geometrical constant γ_g in (2) is 1.1. This encompasses contributions from the finite width of the electrode beneath the

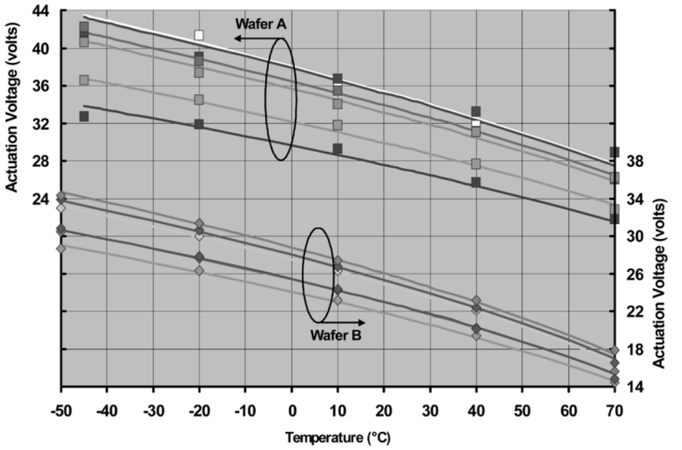

Fig. 3. Measured and modeled actuation voltage over temperature for Wafers A and B.

TABLE I
FITTING RESULTS OF T_{zs} AND SWITCH GAP TO ACHIEVE MODEL FIT GIVEN IN FIG. 3

Wafer A		Tzs	148.01	**Deg C**		
Device	**1**	**2**	**3**	**4**	**5**	**6**
Gap (µm)	1.92	2.27	2.26	2.21	2.03	2.18

Wafer B		Tzs	110.41	**Deg C**		
Device	**1**	**2**	**3**	**4**	**5**	**6**
Gap (µm)	2.02	2.04	2.08	1.91	1.85	1.92

membrane (approximately 0.53) and the flared shape of the membrane relative to a rectangular shape (approximately 2.1, as measured experimentally).

Fig. 3 displays the fitted models (solid lines) for Wafer A and B against the measured datapoints. As can be seen from the figure, the measured data and fitted models correlate very well. The resulting parameters from the model fit, the individual values of g_o and T_{zs} for each of the two wafers, is shown in Table I. Maximum deviation between fitted and measured data over temperature is less than 8%, or about 2.5 V maximum. In the specific case of Wafer B, the fit is better than 4% and 0.5 V over the temperature range. The gap values given in Table I are consistent with the measurements of switch dimensions and off-capacitances. Similarly, the derived values for T_{zs} are consistent with the general deposition conditions of the membranes. The data in Table I suggests that the roughly 8 V difference in actuation voltage at room temperature is mostly due to differences in residual stress of the membranes rather than the gaps between the membrane and lower electrode. The excellent fit between model and experimental results over temperature enables interesting insights into techniques which might lessen the actuation variation over temperature.

Despite the excellent fit between measured and modeled data, it should be noted that the actual mechanical structure of the fixed-fixed beam switch is far more complicated than the simple first-order model presented here. The actual as-deposited residual stress of the mechanical membranes is commonly monitored as part of the process flow and tends to be quite high. In the case of aluminum membranes, this stress is a function of the temperature history of the membrane as it undergoes inelastic deformation at elevated temperatures during sacrificial layer removal [6]. However, the presence of release holes in the membrane tends to allow stress relaxation of the residual stress [7] making the released stress significantly lower. In addition, developers of MEMS devices commonly incorporate three-dimensional features into the membrane [8] to reduce the final stress of the membrane. The impact of both of these features is to lower the effective residual stress on the membrane in order to maintain reasonable control voltages. With the theoretical basis for the variation in actuation voltage over temperature established, it is now possible to understand the impact of these features on actuation voltage variation over temperature.

V. CONCLUSION

A simple model for variation in actuation voltage over temperature has been put forth and experimentally verified for one particular design of fixed-fixed beam capacitive switches. This model provides insight into the parameters impacting this temperature variation, and allows simple design changes to minimize this undesired variation over temperature. The theoretical model fits very well with measured switch data over a broad temperature range. Measurements of switches from other wafers produce similar results. It is believed that this model will accurately represent the variation in actuation voltage over temperature for a variety of RF MEMS capacitive switches being designed and produced today.

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