RF Actuation of Capacitive MEMS Switches

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Abstract— **An analytical calculation of microwave actuation for shunt capacitive MEMS switches is presented. This calculation shows that the microwave signal deflects the beam according to the RMS voltage of the signal. In addition, heating of the beam due to dissipated microwave power is shown to play a significant role in microwave actuation**

I. Introduction

Several investigations of power handling of microwave shunt capacitive MEMS switches have recently been presented [1], [2]. This paper extends these previous works to show that microwave actuation of the switch is heavily dependent not only on the effective RMS voltage of the microwave signal, but also the heating of the switch due to dissipated microwave power. This effect must be considered in the design of high power MEMS switches.

The analytical model presented here provides a solution for the effective bias applied to a switch due to a combined microwave and DC drive signal. Using the basic model of Rizk [1], the temperature rise of the bridge is calculated as a function of the input microwave signal. The temperature rise results in thermal expansion of the bridge, thus changing the stress in the beam. The increased stress is calculated and used to calculate a modified pull-in voltage for the switch. Finally, the DC bias required to pull-in the bridge is calculated by including the effective biasing due to the microwave signal.

Calculations using this model show that thermal heating of the bridge dramatically lowers the pull-in voltage of the switch. Based on published information, a limited comparison with the data from Pillans, *et al.* is possible. This comparison shows that the low self actuation power found by Pillans is largely due to thermal heating of the switch. We have taken measurements at microwave powers up to 1 watt to verify this model.

II. Theory

Microwave power has a dual effect on RF MEMS switches. Consider the capacitive switch shown in Figure 1. First, the microwave power deflects the switch in a manner similar to an applied DC bias. Second, it induces current in the suspended bridge which results in ohmic heating. This heating causes the metal to expand, relaxing the bridge, and thus lowering the pull-in voltage. The following sections derive the effective voltage caused by the combined DC and RF biases, the pull-in voltage as a function of increased bridge temperature, the temperature rise in the bridge, and finally the measurable pull-in voltage.

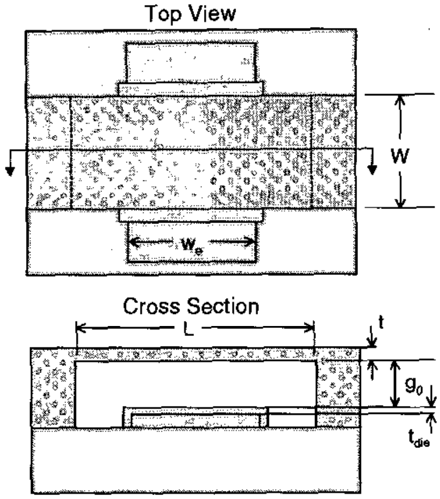

Fig. 1. Schematic picture of the capacitive switch.

A. Calculation of Effective Voltage

During operation, a capacitive microwave switch is subjected to the combination of a drive voltage, V_d and a microwave signal, $V_{RF} sin(2\pi f_{RF} t)$. Over a short interval, $\tau << 1/f_r$ where f_r is the mechanical resonant frequency of the switch, the switch will see this combined bias as if it were a constant voltage, V_{eff}. Typically, $f_r < 0.5$ MHz, so $\tau < 200$ ns can be considered short. V_{eff} can be calculated by equating the integrated force over a short time interval as:

$$\frac{1}{\tau}\int_0^{\tau} A_1 V_{eff}^2 dt = \frac{1}{\tau}\int_0^{\tau} A_1 \left(V_d + V_{RF} Sin(2\pi f_{RF} t)\right)^2 dt \quad (1)$$

where $A_1 = \epsilon_0 W w_e / 2g^2$ is a constant over the short time period and g is the gap between the bridge and the electrode. Setting $\tau = 1/f_{RF}$ (at 1 GHz, $\tau = 1$ ns), and evaluating Equation 1 results in the solution:

$$V_{eff} = \sqrt{V_d^2 + \frac{V_{RF}^2}{2}} \quad (2)$$

With no microwave power, V_{eff} is equal to the DC bias, V_d, while with no DC bias, V_{eff} is equal to the RMS voltage of the microwave signal, $V_{RF}/\sqrt{2}$. It should be noted however, that the combination of a DC bias and a microwave signal is not equivalent to the addition of the RMS voltage and the DC bias voltage.

The microwave power in the system is defined as

$$P_{RF} = \frac{V_{RMS,RF}^2}{Z_0} \tag{3}$$

where $V_{RMS,RF} = V_{RF}/\sqrt{2}$ is the RMS voltage of the microwave signal, and Z_0 is the characteristic impedance of the system. By combining Equation 2 and Equation 3, the effective voltage can be calculated as

$$V_{eff} = \sqrt{V_d^2 + Z_0 P_{RF}} \tag{4}$$

B. Calculating Pull-in Voltage

The pull-in voltage of the bridge is a function of the bridge design and materials and is calculated as [3]

$$V_{pi} = \sqrt{\frac{8k_{beam}g_0^3}{27\epsilon_0 W w_e}} \tag{5}$$

where ϵ_0 is the permittivity of free space, g_0 is the initial height of the beam, W and w_e are design parameters defined in Figure 1, and k_{beam} is the spring constant of the beam. The spring constant of the beam is calculated as [4]

$$k_{beam} = \frac{32EWt^3}{L^3\left[2(2-x)x^2\right]} + \frac{8\sigma(1-\nu)Wt}{L(2-x)} \tag{6}$$

where E and ν are the Young's modulus and Poisson's ratio for the bridge metal, $x = w_e/L$, and σ is the stress in the beam. The stress in the beam is calculated as

$$\sigma = \sigma_{res} - \alpha\delta TE\left[1 - \frac{L - w_e}{3L}\right] \tag{7}$$

where the σ_{res} is the residual stress in the bridge due to fabrication, and the second term of the equation is thermally induced stress due to the bridge heating up by a temperature δT and α is the coefficient of thermal expansion. The fraction $(L - w_e)/3L$ is used to compensate for the non-uniform temperature of the bridge. For any positive temperature increase in the beam relative to the substrate, the induced stress is compressive, and thus the spring constant is reduced.

C. Temperature Rise of the Bridge

As a microwave signal propagates through the switch, small coupling currents occur in the bridge. Some of these currents are dissipated due to the small, but finite, shunt resistance of the metal bridge, R_s. These dissipated currents cause the bridge to heat up. The temperature rise of the beam can be calculated using the thermal model shown in Figure 2, where I_{heat} is the microwave power dissipated in the beam as described by Rizk [1], R_{cond} is the thermal resistance due to conduction, and R_{conv} is the thermal resistance due to convection.

The power dissipated in the beam is calculated using the formulation of Rizk [1]

$$P_{Diss} = \frac{1}{2}(2\pi V_{RF} f_{RF} C_{pi})^2 R_s \tag{8}$$

where C_{pi} is the capacitance of the bridge just before it collapses. This is set to $1.4C_u$ where C_u is the undeflected

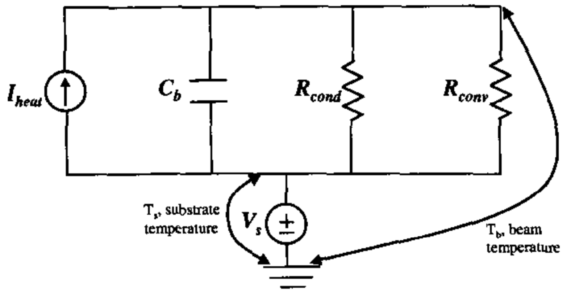

Fig. 2. Simplified equivalent thermal circuit for the capacitive shunt switch.

bridge capacitance. Substituting for V_{RF}, gives the dissipated power as a function of input microwave power, P_{RF}:

$$P_{Diss} = 39.48 Z_0 R_s (f_{RF} C_{pi})^2 P_{RF} \tag{9}$$

The thermal resistance due to conductivity is calculated as

$$R_{cond} = \frac{L - w_e}{6kWt} \tag{10}$$

where L, w_e, W, and t are defined in Figure 1, and k is the thermal conductivity of the bridge material. The factor of $1/6$ is obtained through the parallel combination of two equal resistors, each shortened to account for the expected thermal profile of the switch. Finally, the convection resistance is calculated as

$$R_{conv} = \frac{1}{2hLW} \tag{11}$$

where h is the convection heat transfer coefficient, and the factor of 2 accounts for heat loss from both of the beam surfaces. In general, the convection loss is negligible compared to the conductive loss.

For the calculation of the temperature, we are only concerned with the steady state temperature, and therefore the thermal capacitance, C_b, is ignored. The use of the steady state condition is valid as long as the RF signal is applied for much longer than the thermal time constant. For typical switches, this time constant is on the order of 100 μs [1]. The temperature rise in the beam can thus be calculated as

$$\Delta T = P_{Diss} R_T \tag{12}$$

where $R_T = R_{cond} \parallel R_{conv}$.

D. DC Pull-in Voltage

Given the derivation above, the pull-in voltage for a switch can be calculated as a function of the microwave power and frequency. The switch will actuate whenever the effective voltage applied to the switch is greater than the calculated pull-in voltage. However, the effective voltage is a function of both the microwave power and the DC bias. Using Equation 4 and Equation 5 the DC pull-in voltage can readily be calculated as

$$V_{pi,DC} = \sqrt{V_{pi}^2 - Z_0 P_{RF}} \tag{13}$$

TABLE I

RF MEMS SWITCH PARAMETERS.

Switch Parameter	Value	Switch Parameter	Value
Length	250.0 μm	Gap	2.0 μm
Width	100.0 μm	Up capacitance	70 fF
Electrode width	100.0 μm	Shunt resistance	0.5 Ω
Thickness	1.0 μm	Room Temperature	25 °C

III. RESULTS

For typical switch designs, the microwave power can result in significant heating of the bridge. As an example, Figure 3 shows the temperature rise in a beam having the same parameters as those simulated by Rizk [1]. For this simulation, C_{pi} ($= 1.4C_u$) is set to be 100 fF. At 1 W and 10 GHz, the power dissipated in the bridge is calculated to be 0.99 mW which results in the beam temperature rising from room temperature (25 °C) to 26.29 °C, while at 20 W and 10 GHz, the dissipated power rises to 20 mW and the temperature of the bridge climbs to 50.88 °C. For comparison, the simulations by Rizk [1] show a bridge temperature of $\approx$ 53 °C with a dissipated power of 20 mW. As shown in Figure 3, the temperature increases with both power and frequency.

Several pull-in simulations are presented using the switch parameters shown in Table I. The effect of thermal heating results in a reduction in the pull-in voltage as shown in Figures 4 and 5. Figure 4 shows several different plots of the various switch pull-in voltages. $V_{pi,0}$ is the pull-in voltage of the switch with no microwave signal applied. If thermal heating did not occur, then this value would remain constant irrespective of microwave power. However, as the bridge heats up, the metal expands and the stress becomes more compressive (or less tensile). This effect is shown by the $V_{pi}(P_{RF})$ profile. For comparison, the RMS voltage of the microwave signal is also plotted. When this value equals the

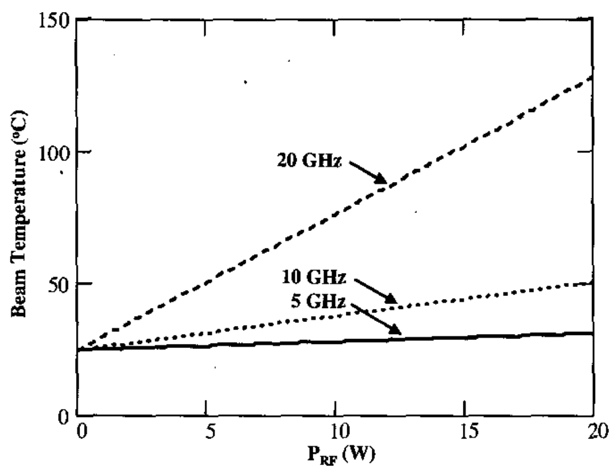

Fig. 3. Calculated temperature for a switch with design parameters: $L =$ 300 μm, $W =$ 80 μm wide, $T =$ 1 μm, $w_e =$ 100 μm, and $R_s = 0.5\Omega$.

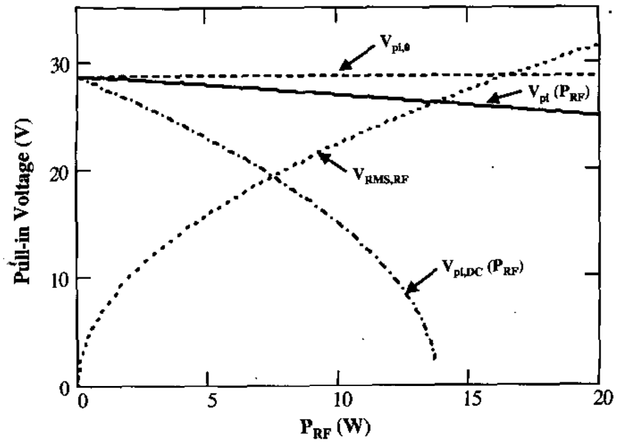

Fig. 4. The simulated pull-in voltages for a pure DC input voltage, a DC and RF combined input, and the measurable pull-in voltage are illustrated using a 14 GHz RF signal. The RMS value of the RF signal is plotted for comparison.

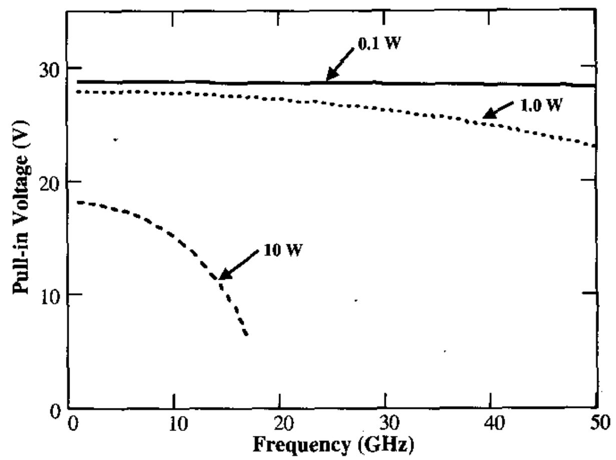

Fig. 5. The simulated pull-in voltages as a function of frequency for three different power levels.

thermally adjusted pull-in voltage, the switch will collapse. As shown, this occurs at approximately 14 W, below the $\approx$ 16 W that would have been required had no thermal heating occurred. The final line shown is the DC pull-in as a function of microwave power, $V_{pi,DC}$. This value goes to zero when microwave self actuation occurs. Figure 5 shows the variation in the pull-in voltage $V_{pi,DC}$ as a function of frequency at several power levels.

A. Measurements of DC Pull-in Voltage

Measurements were taken using a switch with the parameters shown in Table I. The measurements were taken with power levels of 1 mW to 1 W and frequencies from 8 to 18 GHz. The results of these measurements are shown in Figure 6 and Figure 7. In general, the measurements agree well with the calculated shifts.

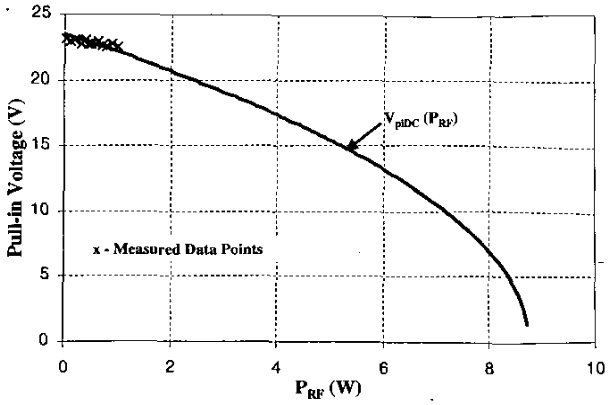

Fig. 6. A comparison of the measurable pull-in voltage to the measured pull-in data for input PRF levels up to one watt.

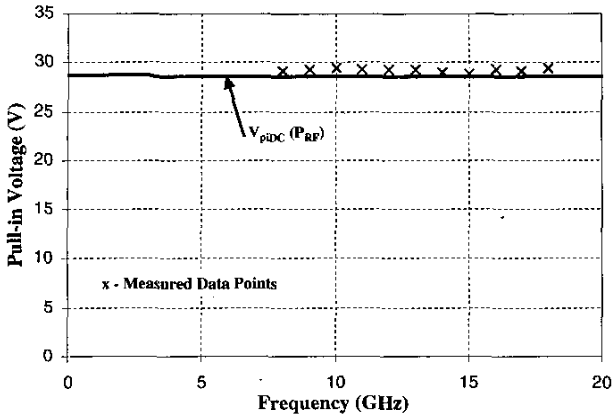

Fig. 7. A comparison of the modelled switch to the measured pull-in levels for a 0.1 watt input signal with the RF ranging from 8 to 18 GHz.

A calculation was also done based on the data presented by Pillans, *et al.* [2]. Since complete switch design values were not included in Pillans paper [2], values were estimated from one of Raytheon's earlier publications [5] with some modifications. The gap of the beam was set at 2.75 μm and the residual stress was set to 19 MPa to fit the 30-32 V pull-in reported by Pillans [2]. This is not considered a major change as the switch from Goldsmith [5] had a higher pull-in voltage and it is not clear how the pull-in voltage was reduced. Second, an up state capacitance of 70 fF was used instead of the 30 fF cited in [2]. This change is consistent with a lower gap. As shown in Figure 8, thermal heating reduces the microwave actuation voltage from approximately 19.5 W to 7.0 W. This is consistent with the actuation power values of 4 W measured by Pillans.

IV. Conclusion

A complete model of microwave actuation is presented. It is shown that thermal heating of the bridge in a shunt type capacitive MEMS switch can dramatically lower the pull-in

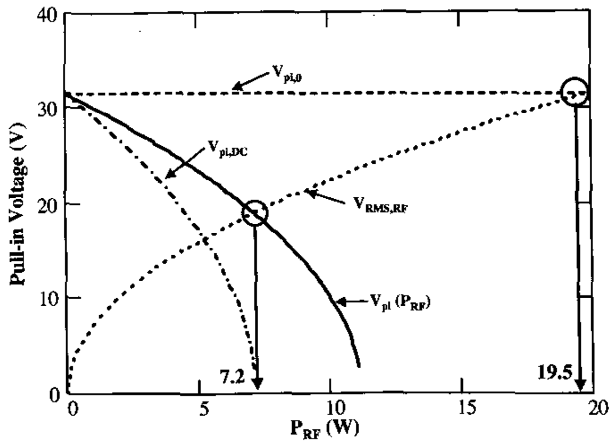

Fig. 8. Modelled pull-in voltages for the Raytheon aluminum capacitive RF MEMS switch. Switch dimensions used were: $L = 280\ \mu m$, $W = 80\ \mu m$, $w_e = 80\ \mu m$, and $t = 0.5\ \mu m$. The pull-in voltage is measured to be approximately 31 V and the RF power to initiate self actuation was measured to be between 3.0 to 4.9 W [2].

voltage of the switch. The lowered pull-in voltage directly impacts the power handling of the switch. Since the effect of the heating is also a function of frequency, it is anticipated that thermal lowering of the pull-in voltage will be the primary power handling limiter of the switch. However, the calculation presented here can greatly aid the design of switches with increased power handling capacity.

Acknowledgment

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