Steady State Thermal Analysis and High-Power Reliability Considerations of RF MEMS Capacitive Switches

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Abstract— **This paper presents a detailed steady-state thermal analysis of RF MEMS capacitive switches. In the up-state position, the maximum temperature on the bridge occurs at the center and is only 50° and 70°C for 1 μm-thick gold and aluminum membranes, respectively, for a power dissipation *in the bridge* of 20 mW. This corresponds to an incident RF power of 10 W for C_u = 100 fF at 12 GHz (or C_u = 35 fF at 35 GHz) and R_s = 0.5 Ω. In the down-state position, it is shown that the bridge temperature does not increase considerably for an incident power of 1 W, and therefore, does not contribute to the reliability problems at high RF powers. On the other hand, it is our opinion that the RF current density on the leading edge of the bridge membrane is the main factor of the failure of MEMS capacitive switches at high RF powers. Two-dimensional temperature measurements are currently being done at Rockwell Scientific, and will be presented at the conference.**

Keywords— **MEMS Switches, Capacitive switches, High Power, Reliability**

I. Introduction

MEMS capacitive shunt switches have been demonstrated by several research groups with excellent results up to 120 GHz [1], [2], [3], [4]. They provide very low loss performance and are used in switched-line and distributed phase shifters up to 50 GHz [5], [6]. Recently, the reliability of MEMS capacitive switches was investigated, and it was shown that dielectric charging contributes to the failure of the bridge in the down-state position. This occurs independent of the RF power level and is solely due to the applied pull-down voltage [7], [8]. This paper investigates the effect of the RF power on the steady-state temperature and high-power reliability of a capacitive MEMS shunt switch, both in the up-state and down-state positions.

II. Coupled Electrical/Thermal Analysis of MEMS Capacitive Switches

RF Currents on the Switch: The RF currents on a capacitive shunt switch in a CPW configuration are calculated using Em-Sonnet [9] and are shown in Fig. 1 in the up-state and down-state positions. The MEMS bridge is 80 μm wide and is suspended 2.5 μm over the CPW t-line. In the up-state position, the current is concentrated along the edges of the bridge (or cantilever) in a $\sim$ 10 μm strip width. The total current and power dissipated in the shunt switch are given by:

$$I_{C_u} \simeq \frac{V_l}{Z_{C_u}} = V_l \omega C_u \qquad (1)$$
$$P_{C_u} = \frac{1}{2} I_{C_u}^2 R_s$$

where R_s is the resistance of the bridge. The rms current on the shunt switch is 53 mA for an up-state capacitance of 100 fF at 12 GHz (or 35 fF at 35 GHz) and an incident RF power of 1 W. The calculated dissipated power in the switch is only 1-2 mW for R_s = 0.25-0.5 Ω. Measurements on MEMS capacitive bridges on high-resistivity silicon substrate indicate a loss of around −0.04 dB per switch at 35 GHz, which is equivalent to 0.8% of the incident power (around 8 mW). However, most of this power is lost in the t-line underneath the MEMS switch, and the switch membrane dissipates around 2 mW (equivalent to a series resistance of 0.5 Ω). For the case mentioned above, the current density of the four strips is around 0.2 MA/cm^2 which is well below the critical current density in gold or aluminum.

In the down-state position, most of the current is carried along the leading edge of the capacitive switch, in a 10 μm wide strip (Fig. 1c). The strip width depends on the switch capacitance per unit length and the frequency of operation. The short-circuit current is 280 mA for an RF power of 1 W, and the current density on the leading edge of the bridge is around 4 MA/cm^2 (two strips are used). This is above the critical current density in gold or aluminum and limits the power handling of MEMS switches.

Thermal Properties and Thermal Solution of RF MEMS Switches: The steady-state temperature distribution on a rectangular MEMS bridge having a length l, width w, and thickness t is solved using the generalized steady state heat conduction equation with constant thermal conductivity, given by:

$$\nabla^2 T + \frac{\dot{g}}{k} = 0 \qquad (2)$$

where T is the temperature of the MEMS bridge (in K or °C), $\dot{g}$ is the rate of heat generated per unit volume (W/m^3), and k is the thermal conductivity of the bridge (W/mK). The entire system (bridge and wafer) is considered to be at an initial temperature of 25°C. For the physical bridge layer (Au or Al), the main mode of heat transfer is conduction; however, the boundaries are subjected to conduction, convection, and radiation as depicted

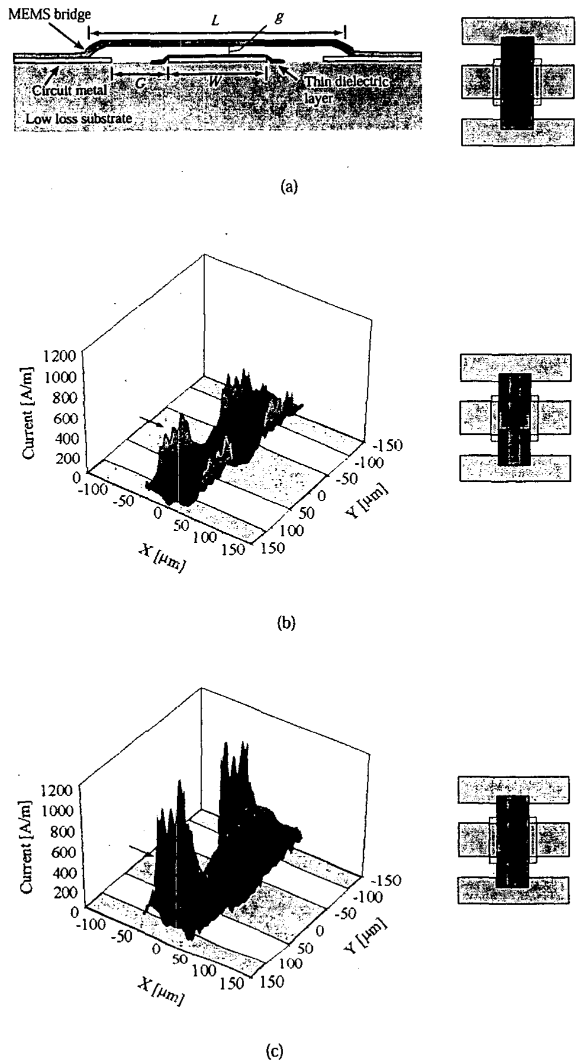


Fig. 1. Geometry of a MEMS switch (a), and currents on the MEMS switch in the up-state (b), and down-state (c) positions.

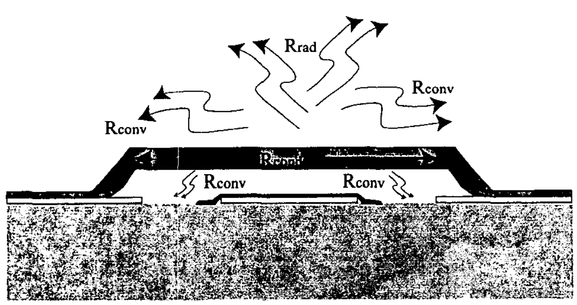


Fig. 2. Thermal model of a MEMS switch

in Fig. 2. The conduction and convection heat transfer modes can be described using a thermal resistance model $\dot{Q} = \Delta T/R$, where $\dot{Q}$ is the rate of heat transfer (W), ΔT is the temperature difference (K or °C), and R is the thermal resistance (K/W or °C/W). Using Fourier's Law of heat conduction:

$$\dot{Q}_{cond} = kA\frac{\Delta T}{l} \equiv \frac{\Delta T}{R_{cond}} \Rightarrow R_{cond} = \frac{l}{Ak} \qquad (3)$$

where l is the length of the heat conduction path (m), A is the cross-sectional area of conduction (m^2). Using Newton's Law of cooling:

$$\dot{Q}_{conv} = kA\Delta T \equiv \frac{\Delta T}{R_{conv}} \Rightarrow R_{conv} = \frac{1}{hA} \qquad (4)$$

where h is the convection heat transfer coefficient (W/m^{2}K) and A is the surface area subjected to convection (m^2). The net rate of radiation heat transfer between two surfaces is given by:

$$\dot{Q} = \epsilon\sigma A F_{12}(T_{s1}^4 - T_{s2}^4) \qquad (5)$$

where ϵ is the surface emissivity, σ is Stephan-Boltzman constant (W/m^{2}K^4), A is the radiation surface area (m^2), F_{12} is the view factor between surfaces 1 and 2 (it represents the fraction of radiation leaving surface 1 that strikes surface 2), and T_{s1}, T_{s2} are the temperatures in Kelvin of surfaces 1 and 2 respectively. $r = \epsilon\sigma AF_{12}$ is a number that gives an idea of the order of the radiation power.

The bridge dimensions are given by $l = 300$ μm, $w = 80$ μm, and $t = 1$ μm. The whole system, bridge and wafer, is surrounded by air at room temperature ($h_{air} = 40$ W/m^{2}K). The bridge is composed of either gold ($k_{Au} = 317$ W/mK, $\epsilon_{Au} = 0.03$) or aluminum ($k_{Al} = 237$ W/mK; $\epsilon_{Al} = 0.07$). For the case of a gold bridge, $R_{cond} = 5.9 \times 10^3$ K/W; $R_{conv} = 1.04 \times 10^6$ K/W and $r = 4.1 \times 10^{-17}$ W/K^{-4}. If we assume that $(T_{s1}^4 - T_{s2}^4) = (100)^4$, then $\dot{Q}_{rad} = 4.1 \times 10^{-9}$ W, which makes the radiation contribution to be completely negligible. Also, the thermal resistance values show that the effect of convection is negligible. The same analysis can be done for Aluminum bridges and yields the same conclusions. Therefore, for either gold or aluminum, the main mode of heat transfer on the bridge is conduction.

Problem Discretization: The thickness of the MEMS bridge ($t = 0.5$-3 μm) is small compared to the length and width of the bridge. Therefore we will consider the numerical formulation and solution of a two-dimensional steady state heat conduction in rectangular coordinates using the Finite Difference Method. The geometric model of the whole system, MEMS bridge and wafer, was built and meshed using RHINOceros [10]. The thermal numerical solution was done using RADTHERM [11]. RADTHERM is a finite difference program that solves the 3-D heat balance equation for both steady state and transient conditions with a finite difference numerical solution based on an implicit Crank-Nicholson technique. Thermal elements in RADTHERM have a node at the center of each face of an element (i.e. two nodes per element since each element has a front and a back face). The temperature distribution is determined from the solution of the system of governing equations, which is formed by writing the energy balance equation for each thermal node (conduction, convection and radiation). The system of equations is solved first using "Adaptive Successive Over Relaxation" and then by Gauss elimination with partial pivoting.

Coupling Electrical and Thermal Solutions: The RF current distributions shown in Fig. 1 are used to calculate the heat generator strips on the bridge surface, and this is fed to the thermal model presented above. The most important factor is the total power dissipated in the bridge, and not the exact current distribution. We have found that the calculated bridge temperature changes only by ±3°C if the current strip width is assumed to be 20 μm instead of 10 μm (for the same power in the bridge). This is due to the first-order thermal differential equation which has an averaging effect. Also, the height of the bridge has virtually no effect on the temperature solution. In fact, the temperature changed by ±3° for a bridge height of 1.5-3 μm. This proves that the conduction component dominates over the convection and radiation components.

III. Steady-State Temperature Simulation Results

The simulated bridge temperature distribution and peak temperature in the up-state position is shown in Fig. 3 for MEMS switches on a silicon wafer. The temperature peaks at the center of the bridge (as expected) and is highest for thin membranes. The temperature distribution is identical for 40 mW or 80 mW of absorbed power, and the only difference is the value of the peak temperature at the center of the bridge. It is seen that for a 1 μm-thick gold or aluminum membrane, one can dissipate 44 and 28 mW (*in the bridge*), respectively, and still keep the peak temperature below 80°C. This translates to approximately 22 and 14 W of incident RF power (assuming C_u = 100 fF at 12 GHz, or 35 fF at 35 GHz, and R_s = 0.5 Ω). However, if the up-state capacitance is 70 fF at 35 GHz, this translates to double the current and four times the power on the MEMS bridge. In this case, the RF power will drop to 5.5 and 3.5 W for Au and Al, respectively. In general, since the current on the MEMS switch increases as ωC_u, the MEMS switch power handling capabilities fall as f^{-2} for the same geometry and same up-state capacitance. Still, it is seen that in the up-state position, the MEMS bridge may fail by voltage self-actuation or current-density limitations before it fails due to thermal considerations.

Fig. 4 presents the thermal resistance and thermal time constant of Au and Al bridges in the up-state position (w = 80 μm, l = 300 μm). The thermal resistance is proportional to l/tw, and the thickness dependance is clearly seen in Fig. 4. The thermal capacity of the bridge is $C = V\rho C_p$, where V is the bridge volume, and ρ, C_p are

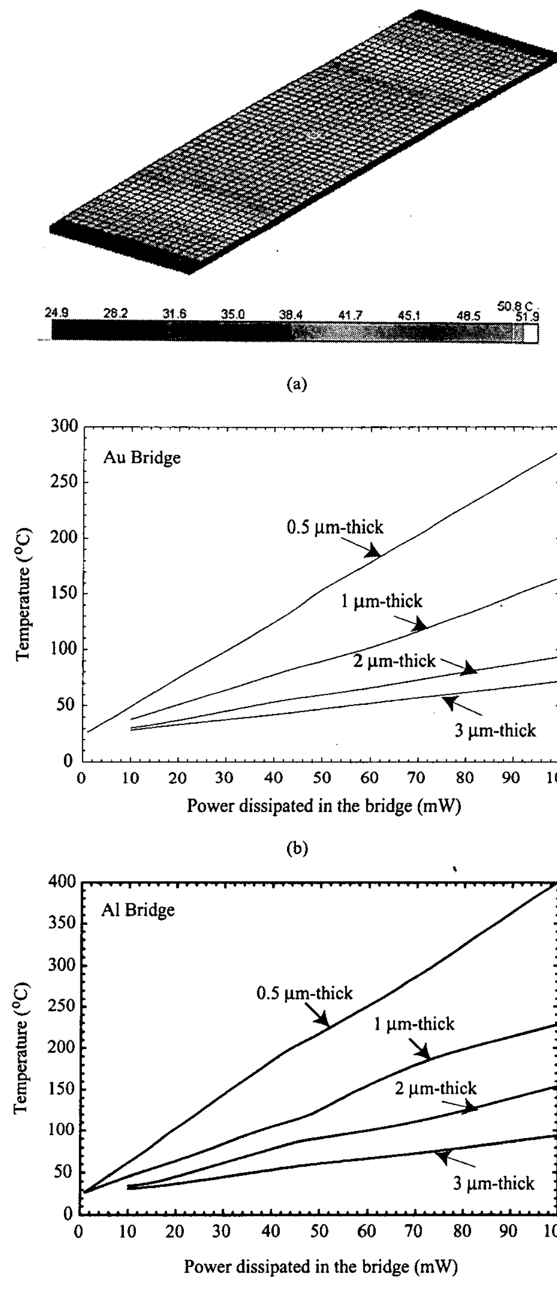


Fig. 3. Simulated two-dimensional temperature distribution (a) and peak temperature (b,c), for Au and Al bridges in the up-state position. The power dissipated in the MEMS bridge is 20 mW.

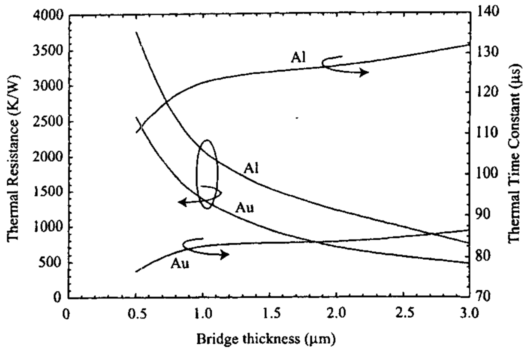


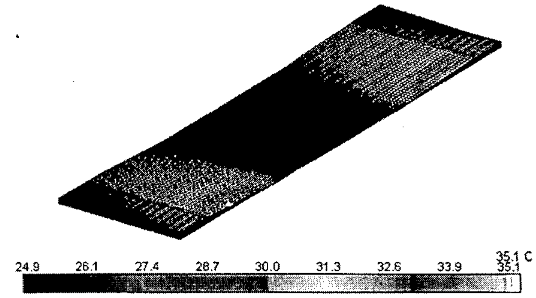
Fig. 4. Simulated thermal resistance and time constants for Au and Al bridges in the up-state position.

the density and specific heat of Au or Al, respectively. The thermal time constant is defined as $\tau = RC$, where R is the thermal resistance of the bridge. The thermal time constant is independent of the thickness or width of the switch since as these factors increase and the thermal resistance decreases, the thermal capacity of the bridge increases. A thermal time constant of 85 μs and 125 μs is found for Au and Al bridges, respectively. This means that the temperature of a MEMS bridge will not follow the time-domain RF current waveform, and steady-state analysis is a valid assumption at microwave frequencies.

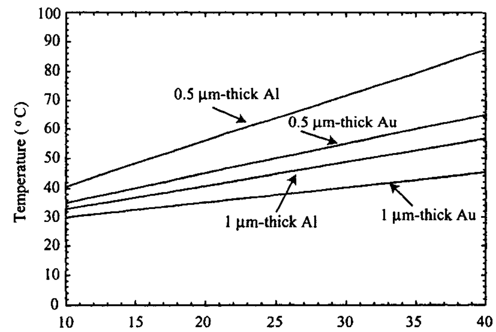
The temperature distribution and peak temperatures in the down-state position are shown in Fig. 5. The bridge is "cool" in the center since it is in intimate contact with 1500 Å of silicon nitride which rests above 4000 Å of gold. As seen in Fig. 5, the highest temperature occurs on the bridge portions which are elevated from the wafer. Still, the peak temperatures are only 45-55° for a power dissipation of 40 mW in the bridge (which translates to an incident RF power of 1W for $R_s = 0.5\ \Omega$). However, it is well known that 1 μm-thick Au or Al MEMS switches fail quickly for an incident power of 0.2-1 W. We believe that the reason of this failure is that the critical current density, which is of the order of 1 MA/cm^2 in gold, is greatly surpassed on the leading edge of the bridge (see Fig. 1). This results in electron migration, current bunching, and localized hot spots which greatly increase the temperature of the bridge and result in a quick thermal failure. It is clear to us that further study is needed on this aspect of failure in a MEMS capacitive switch.

IV. Conclusion

This paper presented a steady-state thermal model of MEMS capacitive switches. The thermal model is coupled to the RF current distribution and heating on the bridge in order to accurately predict the steady-state temperature of the bridge. It is found that a MEMS bridge can handle Watt-level RF powers in the up-state and down-state positions with no degradation due to thermal effects. However, the down-state current density on the leading edge of the MEMS bridge is higher than the critical current density in Au and Al, and is the probable cause of failure of MEMS shunt capacitive bridges.



(a)



(b)

Fig. 5. Simulated two-dimensional temperature distribution (a) and peak temperature (b), for Au and Al bridges in the down-state position. The power dissipated in the MEMS bridge is 20 mW.

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