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SIMULTANEOUS ELECTRICAL AND THERMAL MODELING OF A CONTACT-TYPE RF MEMS SWITCH

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ABSTRACT

Improving the power handling capability of direct contact RF MEMS switches requires a knowledge of conditions at the contact. This paper models the temperature rise in a direct contact RF MEMS switch, including the effects of electrical and thermal contact resistance. The maximum temperature in the beam is found to depend strongly on the power dissipation at the contact, with almost no contribution from dissipation due to currents in the rest of the switch. Moreover, the maximum temperature is found to exceed the limit for metal softening for a significant range of values of thermal and electrical contact resistance. Since local contact asperity temperature can be hundreds of degrees higher than the bulk material temperature modeled here, these results underscore the importance of understanding and controlling thermal and electrical contact resistance in the switch.

INTRODUCTION

RF MEMS switches have been demonstrated with high isolation, low insertion loss, high bandwidth, and good linearity [1]-[4]. Their chief drawbacks include slow switching speed (compared to diodes or transistors), low power handling capability (generally much below 1 W), and difficult packaging [5]. This paper addresses the power handling capability of direct contact MEMS switches by modeling the switch temperature during operation.

Many of the possible failure mechanisms which limit power handling capability are related to the switch temperature. Examples include electromigration, creep, adhesion, welding, and surface degradation. Previous work in the thermal modeling of MEMS switches includes analysis of capacitive switches in both up and down states [6],[7] and modeling of a switch in the up state [8]. Notably, the researchers in [6] and [7] assumed that the temperature at the *capacitive* contact in the down state was equal to the ambient temperature, which is equivalent to assuming zero thermal contact resistance. This paper presents the analysis of down-state MEMS switches by modeling the temperature in a *direct contact* MEMS switch, including the effects of electrical and thermal contact resistance. The temperature is modeled using a coupled electrothermal FEM model.

INTEGRATED ELECTROTHERMAL MODELING

The switch analyzed in this paper is a simple direct contact switch, in which metal-to-metal contact allows current flow. As illustrated in Fig. 1, it consists of a metal cantilever beam inserted in a microstrip or other transmission line. When the beam is up, the line is open, and no signal propagates. When the beam is pulled down into contact with the lower electrode, current flows, and the signal propagates. The next sections describe the switch modeling, including electromagnetic modeling, thermal modeling, and the combination of the two into an integrated electrothermal model.

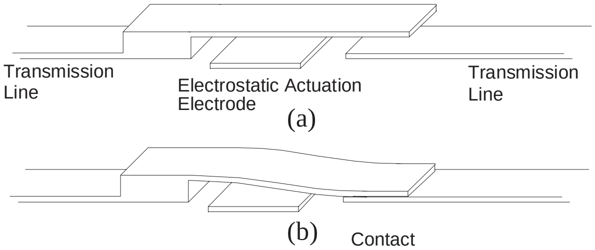

Figure 1: Illustration of the MEMS switch in (a) the upstate and (b) the downstate

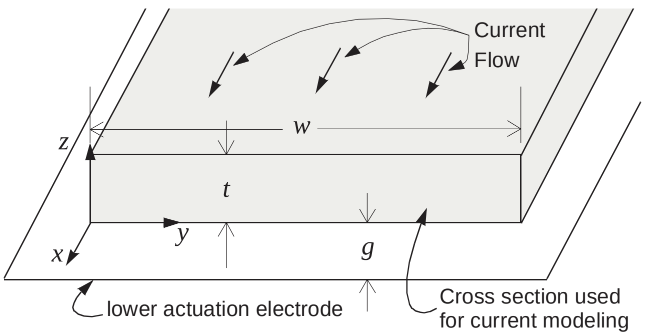

Figure 2: Beam cross-section used in electromagnetic modeling

Electromagnetic Modeling

For this paper, we model the beam in the down state shown in Fig. 1(b). The RF current flowing through the beam dissipates power, which generates heat. The average heat generated is equivalent to the electrical power loss,

$$p_{loss} = \|\boldsymbol{J}_{rms}\|^2 \rho \tag{1}$$

where p_{loss} is the average power loss per unit volume, $\boldsymbol{J}_{rms}$ is the rms current density in the beam, and ρ is the electrical resistivity. Hence, to calculate the heat generated in the beam, we first evaluate the current density for the beam geometry, and frequency. For a rectangular cross-section, this requires a numerical solution. The approach here is very similar to that used in [8] for up-state switch modeling.

A full-wave, 3D numerical simulation would allow the best accuracy. However, the time required for such a simulation is prohibitive. Three assumptions simplify the modeling:

- The electric field in the beam remains parallel to the beam's length. Thus, transverse current components can be ignored.
- The field variation along beam's length is very small. Consequently, fields may be modeled only in the transverse plane, corresponding to a beam cross section.
- The effects of capacitance between the actuation electrode and the beam are small, and are ignored.

These assumptions allow 2D modeling on a transverse cross-section normal to the beam's length, as illustrated in Fig. 2.

The fields on the cross-section are modeled using the finite element method. Within the beam, the electric field satisfies the wave equation

$$\nabla^2 E_x - \gamma^2 E_x = 0 \tag{2}$$

where γ is the complex propagation constant in the metal. However, the boundary conditions to be used for such a simulation are not well defined. Therefore, we generated one detailed solution for a micromachined beam at 2 GHz using full-wave analysis in Ansoft HFSS. We found that the electric field along the beam's length was nearly constant on the bottom of the beam, while it was nearly zero on the top of the beam. Therefore, in our 2D FEM, we applied this boundary condition, with linearly varying electric field along the sides of the beam. These simple boundary conditions most likely introduce significant error in the current density solution; however, we will show in the results section that this error has a very small effect on the final temperature. After calculating the electric field on the cross section, the current is obtained from $\boldsymbol{J} = \sigma \boldsymbol{E}$, where σ is the metal conductivity.

The electrical behavior at the contact obviously differs from that predicted by the 2D simulation. However, power dissipation at the contact can easily be calculated from

$$P_c = I_{rms}^2 R_c \tag{3}$$

where p_c is the power dissipated in the contact, I_{rms} is the total rms current flowing through the switch, and R_c is the total electrical contact resistance.

Thermal Modeling

Once the current density is known, Eq. (1) and Eq. (3) are used to find p_{loss} and P_c, which are treated as time-invariant heat sources. The temperature in the beam is obtained from the steady-state heat equation

$$\nabla(\kappa \nabla T) = -p_{loss} - \frac{p_c}{tA_c} \tag{4}$$

where κ is the thermal conductivity, T is the temperature, t is the beam thickness, and A_c is the apparent contact area. P_c is zero everywhere except at the beam contact, where it takes the value given by Eq. (3). Because the heat generation term p_{loss} is evaluated numerically, Eq. (4) is also most easily solved with numerical techniques. As with the electromagnetic fields, Eq. (4) was solved using the finite element method. The assumptions involved in the analysis are:

- The temperature is constant through the beam thickness because the thickness of micromachined beams is much smaller than their width.
- Heat lost due to convection or radiation is insignificant.
- The small deformations in the contacting beam are inconsequential for the thermal analysis.

This allows a 2-D FEM simulation in the plane of the beam's width and length, with only conduction modeled.

After discretizing, the left edge of the beam is set to ambient temperature to represent heat conduction into the substrate. All other edges are treated as adiabatic, since convection and radiation are ignored. A conceptual thermal resistance is placed between each element and the ground, which is at ambient temperature (25°C). For elements representing the contact, this resistance is the thermal contact resistance. For all other elements, it represents the volume thermal resistance due to conduction through the air under the beam into the substrate below, which is not negligible because of the small gap under the beam (typically about 2 μm or less).

Integrated Modeling

For accurate results, the electrothermal model requires iteration. This is because the electrical resistivity of the metal and the thermal conductivity of air under the beam vary with temperature. The electrical and thermal problems are coupled and solved together using the relaxation method of iteration.

ELECTRICAL AND THERMAL CONTACT RESISTANCE

Contact resistance is caused by roughness of contacting surfaces. When the surfaces are pushed together, contact occurs at asperities scattered across the surface. As a result, the surfaces have actual contact over a small portion of their apparent contact area. Hence, heat and current are restricted in flowing across the contact, creating a thermal or electrical contact resistance. This section summarizes relevant contact theory and describes how contact resistance values were chosen for the simulation.

Electrical Contact Resistance

In an electrical contact, current flows only through the contact asperities. Contact resistance theory predicts that the total electrical contact resistance (ECR) is independent of the apparent contact area. Instead, it depends only on contact force [10]. However, actual contact resistance also depends on other factors, including temperature and the presence of adsorbed materials on the contacting surface. Reported values of contact resistance vary, even for measurements made on the same switch after different numbers of cycles. Therefore, rather than choosing one value of contact resistance to use in the electrothermal simulation, we evaluated the simulation for a range of values. The chosen range was 0.2 Ω to 4 Ω, which is fairly representative of values reported in [1], [3], [4], and [11].

Thermal Contact Resistance

Heat can flow across the contact either through the contact asperities or through the air in the gap between non-contacting portions of the surfaces [12]. Therefore, thermal contact resistance (TCR) does depend on apparent contact area. As with ECR, it also varies with contact force, presence of adsorbed species, and temperature. While numerous models have been proposed for TCR (see, for example, [12]-[13]), none have addressed contact under the low forces available for MEMS switches. Moreover, no data has been reported in the literature for TCR of MEMS-scale metal contacts. Therefore, for our simulation, we estimated the likely range of TCR as between 1×10^{-7} and 1.25×10^{-6} $m^2 \cdot K/W$. This range is based on the authors' experience with thermal contacts and rough correlation with several models found in the literature.

MODELING RESULTS

The full electrothermal model was evaluated as described above using an example beam made of gold. The beam was 200 μm in length, 50 μm in width, and 2 μm in thickness, with a gap of 2 μm. The contact included the whole width of the beam for the last 20 μm of the length. All simulations were run at 2 GHz, with rms current of 0.2 A, corresponding to a power of 2 W assuming a 50 Ω load.

To test the dependence of temperature on any inaccuracies in the electromagnetic model, three simulations were run with ECR and TCR spanning the ranges given above. These were:

1. The electromagnetic model was evaluated as described.
2. The effect of current in the beam was ignored, so that only the heat dissipated in the contact was considered.
3. The electromagnetic model was evaluated, and the power dissipated by currents in the beam was doubled before being used in the thermal model.

It was found that for all values of TCR and ECR, the maximum temperature for simulations 2 and 3 was within 0.8°C of simulation 1. This is because the power dissipated due to current flow in the beam is small compared to the power dissipated in the contact. This is an important conclusion, allowing us to ignore power dissipation due to beam currents.

The simulation results were also studied to determine the beam location where thermal-related failure was most likely. For all cases of significant temperature rise, maximum temperature is at the beam contact. Fig. 3 illustrates the temperature along the beam for the worst case, with a maximum temperature of 139°C. Fig. 4 shows the simulated contact temperature over the range of thermal and electrical contact resistances outlined above. Based on this data, we conclude that the effects of both electrical and thermal contact resistance are significant and must be included in an accurate down-state model. Moreover, gold begins to soften and plastically deform at temperatures as low as 100°C [14]. Thus, based on our simulation, softening and eventual failure can occur in the beam if ECR is greater than 2.5 Ω and TCR is great than 6×10^{-7} $m^2 \cdot K/W$.

Note also that this simulation models the temperature in the bulk device, rather than at the individual asperities. Local temperature at the asperity could be much larger. For example, [10] predicts local asperity temperature as much as 400°C higher than bulk temperature for a contact resistance of only 1.0 Ω for

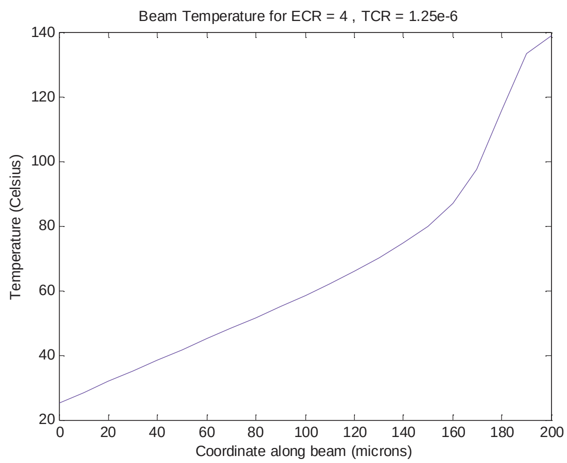

Figure 3: Temperature along the beam for the worst case, with ECR = 4 Ω and TCR = 1.25x10^{-6} m^2·K/W.

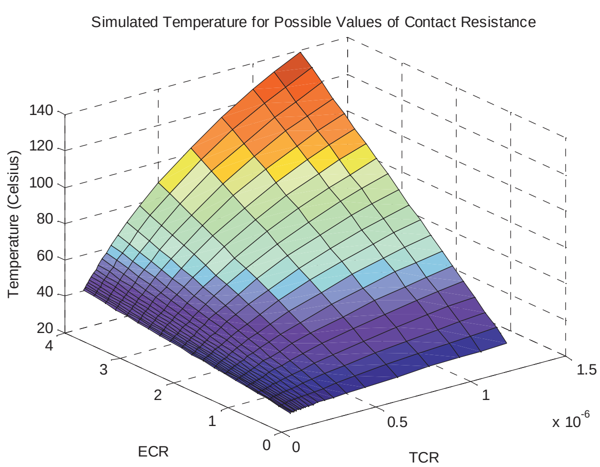

Figure 4: Simulated temperature at the contact for the range of thermal and electrical contact resistances.

the current used here. Therefore, the bulk contact temperatures predicted in Fig. 4 could easily lead to softening, cold working, or even welding of the asperities. This data underscores the importance of modeling asperity temperature rise in conjunction with the bulk beam temperature modeled here. Development of such a model is underway. We are also working on the design and testing of structures that will allow us to measure, for the first time, the thermal contact resistance in a MEMS switch.

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