Abstract—For the first time, both pull-in and release transients were characterized under high RF power levels on electrostatically actuated capacitive switches that exhibited little ambient temperature dependence under small-signal conditions. In spite of the complication of buckling, thermal resistances and time constants were extracted for both pull-in and released states. In the pulled-in state, the extracted thermal resistance and time constant were approximately 5000°C/W and 40µs, respectively. In the released state, the corresponding values were approximately 3000°C/W and 100µs, respectively. These extracted parameter values could serve as the foundation for physical understanding, as well as compact modeling of large-signal transients. They could also help improve the design of switches that are more robust against temperature change and RF loading.

Keywords—electromechanical effects, microwave devices, pulse measurement, switches, transient analysis.

I. INTRODUCTION

The RF power-handling capacity of electrostatically actuated MEMS capacitive switches can be limited by stiction in the pulled-in state or self-actuation in the released state [1]. Previously, we modeled [2] and characterized [3] pull-in transients under pulsed RF power. In this paper, we characterized release transients and extracted parameter values that can be used in the future for compact modeling. The extracted parameter values can also be used to gain physical understanding and to design more robust switches. Note that there had been only speculative data on thermal resistance or time constant of a switch in the pulled-in state [4].

II. EXPERIMENTAL

The present switch is based on a movable molybdenum membrane approximately 300µm-long, 100µm-wide, and 0.3µm-thick, which is anchored on both ends to the ground conductors of a 50Ω coplanar transmission line. The center conductor of the transmission line is made of 0.4µm-thick gold, which is coated with 0.25µm-thick silicon oxide to prevent shorting when the membrane is pulled in by electrostatic force to contact the center conductor. The transmission line is fabricated on a 650µm-thick sapphire substrate, which matches molybdenum in thermal expansion while providing high thermal conductivity [3]. Normally, without any DC bias, the membrane is suspended 2µm above the center conductor with approximately 50fF fringe capacitance, so that a 12GHz signal can propagate through the transmission line with less than 0.3dB insertion loss. When the DC bias applied to the center conductor exceeds a pull-in voltage \( V_p \), the membrane contacts the oxide-coated center conductor with a capacitance of approximately 1.2pF to shunt the RF signal to ground with more than 10dB isolation. Once the membrane is pulled in, a lower bias \( V_R \) is sufficient to hold the membrane in place. For the present switch, \( V_p \sim 25V \) and \( V_R \sim 10V \).

All tests were performed in dry air with precise temperature control. Fig. 1 illustrates the test setup and conditions. Steady-state \( V_p \) and \( V_R \) of the switch were characterized under constant incident RF power by ramping the DC bias up and down in 1ms while monitoring abrupt changes in transmitted or received power.
reflected RF power. Pull-in transients were characterized by using a microsecond solid-state switch to pulse the incident power at 12GHz to different levels without any DC bias. Typically, the pulse period is 5ms, which is much longer than the mechanical (~10μs) or thermal (~100μs) time constants of the MEMS switch, while the duty cycle is kept low at 0.05% to prevent any memory effect. Release transients were characterized by pulsing the RF incident power from 50mW to different levels while simultaneously pulsing the DC bias voltage to 30V to ensure the membrane is fully pulled in during the entire 5ms period. The constant 50mW base power is required for sensing the switch state and is provided by a separate RF power source. Such a low power level does not significantly perturb the thermal response of the switch as shown in Sec. IV and Sec. V.

III. STEADY-STATE ANALYSIS

Fig. 2 shows the measured temperature and power dependence of steady-state $V_P$ and $V_R$. As expected, the temperature dependence is very weak. It can be seen that $V_P$ and $V_R$ decrease steadily with increasing RF power, until the switch sticks ($V_R \approx 0$) around 1W or self-actuates ($V_P \approx 0$) around 2W. This power dependence is characteristic of a membrane with room-temperature residual stress of 37 MPa tensile [3].

IV. PULL-IN TRANSIENT

Fig. 3(a) shows the transient reflected power (relative to the power reflected in the fully-released state) when the incident power was pulsed to different levels. (The transmitted power shows similar but less obvious trend.) It can be seen that there is hardly any transient when the incident power was pulsed to 1W. However, at 1.6W and 2W, a transient on the order of 100μs occurs, which indicates that the membrane is heated, relaxed, and pulled closer to the stationary electrode by combined self-heating and self-biasing [3]. When the power exceeds 2W, the membrane eventually self-actuates, resulting in ~5dB abrupt increase of reflected power. However, this reflected power level is ~5dB lower than that of the switch fully pulled in by a DC bias. This is because the membrane buckles under such high RF power and is making only partial contact with the stationary electrode, as confirmed by inspection under a microscope.

Fig. 3(b) shows that the time it takes for the membrane to buckle depends weakly on the ambient temperature, but strongly on the RF incident power until it asymptotically approaches approximately 60μs. Under self-heating, the temperature increase required to reduce the residual stress to the critical level for buckling $\sigma_c$ is [5]

$$\Delta T = (\sigma_{300} - \sigma_c) / \alpha_M E = P_D \Theta$$

where $\alpha_M$ is the thermal expansion coefficient, $E$ is Young’s modulus, $P_D$ is the dissipated power, and $\Theta$ is the thermal resistance of the membrane. With $\sigma_c \approx 3$ MPa, $\alpha_M \approx 4.8$ ppm and $E \approx 329$ GPa, $\Delta T \approx 30^\circ$C. With $P_D$ estimated to be 10mW for an incident power of 2W, $\Theta \approx 3000^\circ$C/W. Note that $P_D$ is less than 1% of the incident power and cannot be estimated more accurately, so $\Theta$ cannot be extracted more accurately either.

V. RELEASE TRANSIENT

Fig. 4(a) shows the release transient in relative reflected power after a 5ms pulse of 30V and different RF power levels. At 1W or 1.3W, the membrane is released smoothly in approximately 10μs. For power levels 1.9W or higher, the initial ~25dB release step is followed by a ~5dB smoothing step, until the reflected power decreases to the same level as 10μs after the 1W pulse. The ringing after ~10μs confirms that the membrane is fully released. However, due to buckling, the fringe capacitance is higher than normal until the membrane cools off and smoothes out. Note that, although the temperature dependence of metal resistivity in the transmission line can also cause thermal transient [5], there is hardly any transient measured on a through line after a 4W pulse as shown on the bottom of Fig. 4(a).
Fig. 3. Measured (a) self-actuation transient in reflected power and (b) time it takes to buckle after the incident power is pulsed to different levels.

Fig. 4(b) shows that the full (release + smoothing) release time increases approximately exponentially with increasing power and exhibits weak temperature dependence between 25°C and 75°C. With $P_D$ estimated to be 20mW for an incident power of 2W, the thermal resistance and time constant are extracted to be approximately 5000°C/W and 40μs, respectively. These values are higher than that of the released state because in the pulled-in state, heat transfer involves not only the membrane, but also the oxide, stationary electrode, and substrate. Such a complicated heat-transfer process needs to be analyzed by 3D finite-element simulation.

VI. CONCLUSION

Both pull-in and release transients were characterized under high RF power on electrostatically actuated MEMS capacitive switches that exhibited little ambient temperature dependence under small-signal conditions. Under high RF power, both pull-in and release transients were complicated by buckling, but the buckling allowed thermal resistances and time constants to be extracted. In the pulled-in state, the extracted thermal resistance and time constant were approximately 5000°C/W and 40μs, respectively. In the released state, the corresponding values were approximately 3000°C/W and 100μs, respectively. These values were higher for the pulled-in state because, in this case, heat transfer involved not only the membrane, but also the oxide, stationary electrode, and substrate. Coupled with higher dissipated power in the pulled-in state, this is why the power-handling capacity of the present switch is currently limited by stiction instead of self-actuation. This also suggests that the thermal design of the stationary electrode needs to be improved so that stiction and self-actuation can occur at comparable RF power levels.

REFERENCES


