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A MODEL TO PREDICT TEMPERATURE ACCELERATION OF DIELECTRIC-CHARGING EFFECTS IN RF MEMS CAPACITIVE SWITCHES (PREPRINT)

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14. ABSTRACT

Temperature acceleration of dielectric-charging effects in state-of-the-art RF MEMS capacitive switches was characterized and modeled. From the measured charging and discharging transient currents across the switching dielectric, densities and time constants of traps in the dielectric were extracted under different temperatures. It was found that, while charging and discharging time constants are relatively independent of temperature, steady-state charge densities increase with temperature. A charging model was constructed to predict the amount of charge injected into the dielectric and the corresponding shift in actuation voltage under different temperatures. Good agreement was obtained between the model prediction and experimental data.

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A Model to Predict Temperature Acceleration of Dielectric-Charging Effects in RF MEMS Capacitive Switches

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***Abstract* — Temperature acceleration of dielectric-charging effects in state-of-the-art RF MEMS capacitive switches was characterized and modeled. From the measured charging and discharging transient currents across the switching dielectric, densities and time constants of traps in the dielectric were extracted under different temperatures. It was found that, while charging and discharging time constants are relatively independent of temperature, steady-state charge densities increase with temperature. A charging model was constructed to predict the amount of charge injected into the dielectric and the corresponding shift in actuation voltage under different temperatures. Good agreement was obtained between the model prediction and experimental data.**

***Index Terms* — RF, MEMS, switch, dielectric, charging, trap, temperature acceleration.**

I. INTRODUCTION

Despite their near-ideal high frequency characteristics, lifetime of electrostatically actuated RF MEMS capacitive switches is limited by dielectric-charging effects [1]. To date, dielectric-charging effects in RF MEMS devices have been studied by different research groups [2]-[4]. The authors have proposed an approach to characterize the switch dielectric and extracted a charge model to predict charge injection and actuation-voltage shift at room temperature [2]. However, for switch applications in harsh environment (e. g., military temperature range from -55 °C to 125 °C), temperature effects on the charging failure need to be understood. In this paper, we present the results on temperature acceleration of the dielectric-charging effects in state-of-the-art RF MEMS capacitive switches. By using the methodology proposed in [2], a temperature-dependent charging model was extracted to predict the actuation-voltage shift under different temperatures and found to be in good agreement with the experimental data.

II. EXPERIMENTAL

The device used in this study is a state-of-the-art metal-dielectric-metal RF MEMS capacitive switch fabricated on a glass substrate [2]. The dielectric is sputtered silicon dioxide with a thickness of 0.25 μm and a dielectric constant of 4.0. The top electrode is a 0.3-μm-thick flexible aluminum membrane that is grounded. The bottom chromium/gold electrode serves as the center conductor of a 50 Ω coplanar waveguide for the RF signal. Without any electrostatic force, the membrane is normally suspended in air 2.5 μm above the dielectric. Control voltage in the range of 25-35 V is applied to the bottom electrode, which brings the membrane in contact with the dielectric thus forming a 120 μm x 80 μm capacitor. The dielectric-charging effect was studied by applying a stress voltage (-30 V) on the bottom electrode of the switch for different time periods under different temperatures while measuring the corresponding actuation-voltage shift.

In order to extract the temperature-dependent charging model, charging and discharging transient currents [2] were measured under different temperatures on large metal-insulator-metal (MIM) capacitors (500 x 500 μm^2) with the same electrode and dielectric material as the switch. A precision semiconductor parameter analyzer (HP 4156C) was used to force a voltage pulse (-30 V) on the bottom electrode of the MIM capacitor while sensing the transient current. Well-guarded probe station and probes were used to suppress the capacitive and leakage currents in the measurement path, thus extending the transient current measurement range below pA level.

When a voltage pulse is applied to a MIM capacitor, the total current across the capacitor includes displacement current, trap charging current, and steady-state leakage current. Since the time constant for the displacement current is of the order of milliseconds, the transient currents measured in the seconds range comprise mainly trap charging and steady-state leakage currents. Similarly, transient currents measured after the voltage pulse is removed comprise mainly trap discharging currents [2]. In this case, trap densities, charging/discharging time constants, and steady-state

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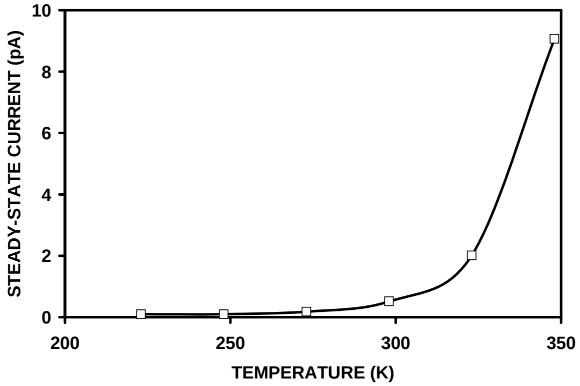


Fig. 1. Steady-state leakage current extracted from the measured transient currents on the 500 x 500 µm^2 capacitor under -30 V bias. Measurement temperatures are -50, -25, 0, 25, 50, and 75 °C.

leakage currents can be extracted from the measured transient currents under different temperatures.

III. MODEL EXTRACTION

The injected charge density in the dielectric can be modeled as [2]

$$Q=\sum_J Q^J[1-\exp(-t_{ON}/\tau_C^J)]\exp(-t_{OFF}/\tau_D^J), \qquad (1)$$

where Q^J is the steady-state charge density of the *Jth* species of trap, τ_C and τ_D are the charging and discharging time constants, t_{ON} and t_{OFF} are the on and off times of the switch corresponding to the charging and discharging times.

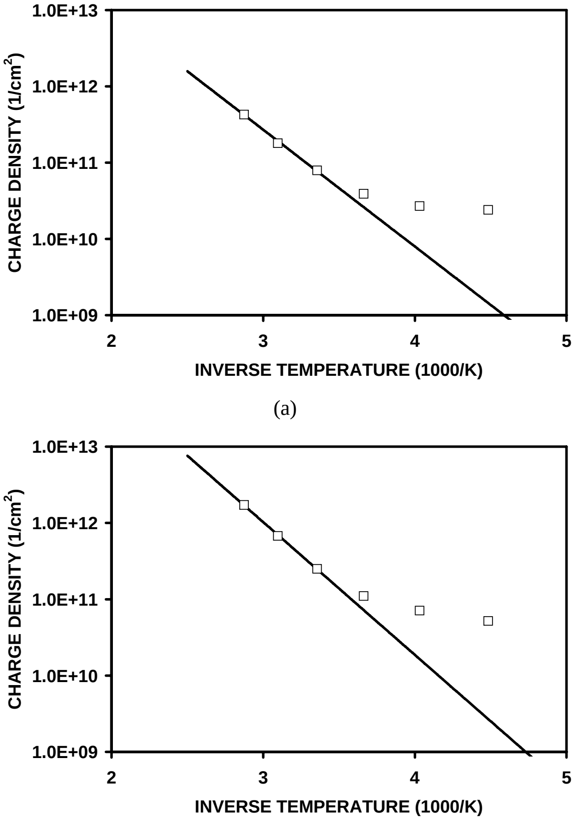
Assuming all traps are empty before applying the charging voltage pulse, transient current after the voltage is turned on is

$$I_C = qA\frac{dQ}{dt}+I_S = qA\sum_J \frac{Q^J}{\tau_C^J}\exp(-t_{ON}/\tau_C^J)+I_S, \qquad (2)$$

where q is the electron charge, A is the surface area of the dielectric, and I_S is the steady-state leakage current across the dielectric. This is a combination of transient trap-charging current and steady-state (DC) leakage current. Similarly, assuming the traps are all charged during the voltage pulse duration, transient current due to the discharging of the traps after removal of the voltage is

$$I_D = qA\frac{dQ}{dt} = -qA\sum_J\frac{Q^J}{\tau_D^J}\exp(-t_{OFF}/\tau_D^J). \qquad (3)$$

Charging model parameters (Q^J, τ_C, and τ_D) were extracted at each temperature (-50, -25, 0, 25, 50, and 75 °C) by fitting the measured transient currents under -30 V bias with exponential functions in (2) and (3). Two exponential functions, representing two trap species, were found to give good fit.



(a)

(b)

Fig. 2. Comparison of (symbols) extracted and (lines) fitted temperature dependence of steady-state charge densities for (a) trap 1 and (b) trap 2. Measurement temperatures are -50, -25, 0, 25, 50, and 75 °C.

As shown in Fig. 1, the extracted steady-state leakage current increases with temperature. Similarly, the extracted steady-state charge densities for trap 1 and trap 2 both increase with temperature as shown in Fig. 2. This indicates that a “leaky” dielectric might not be able to reduce the amount of charging. Instead, for the sputtered silicon dioxide that we characterized, the amount of charging increases when the dielectric conducts more steady-state leakage current at higher temperatures. Temperature dependence of the steady-state charge density for the *Jth* trap is modeled using the standard equation for a thermally activated process

$$Q^J = Q_0^J\exp(-Ea_J/kT), \qquad (4)$$

where *Ea* is the activation energy of the process while Q_0 is a fitting parameter. By using (4), temperature dependence of the steady-state charge density was fitted reasonably well for temperatures above 0 °C as shown in

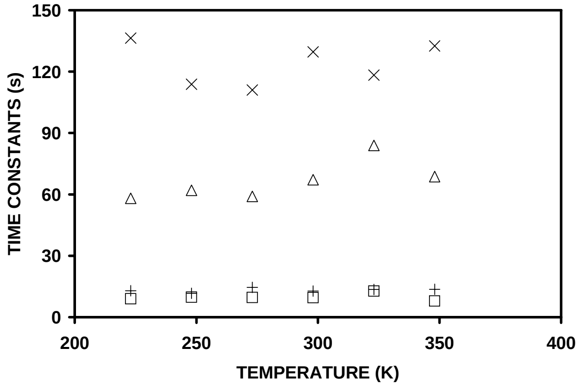


Fig. 3. Extracted (□) trap 1 charging, (+) trap1 discharging, (Δ) trap 2 charging, and (x) trap2 discharging time constants. Measurement temperatures are -50, -25, 0, 25, 50, and 75 °C.

Fig. 2. For temperatures below 0 °C, extracted data points deviate from the fitted line. However, since steady-state charge density is larger at higher temperatures while the membrane is more prone to charge-induced stiction (smaller spring constant at higher temperatures), it is more important to make the model work accurately at higher temperatures. In contrast, the extracted charging and discharging time constants are relatively independent of temperature as shown in Fig. 3. Therefore, τ_C and τ_D were taken as the average of the time constants extracted under different temperatures.

From the measured charging and discharging transient currents on the 500 x 500 μm^2 MIM capacitor, charging model parameters were extracted for -30 V bias using the above-described approach and were listed in Table I. This charging model was used to predict the measured actuation-voltage shift under different temperatures.

IV. MODEL VERIFICATION

The dielectric-charging effect on the state-of-the-art RF MEMS capacitive switch was measured by applying a stress voltage on the bottom electrode of the switch for different time periods while measuring the corresponding actuation-voltage shift. The stress voltage used in the experiment is −30 V, which is sufficient to actuate the switch at all measurement temperatures (0, 25, and 50 °C). The actuation voltage was shifted in the positive direction after the stress indicating injection of negative charges from the bottom electrode into the dielectric under all temperatures.

The actuation-voltage shift due to dielectric charging can be expressed as

$$\Delta V = qhQ / \varepsilon_0 \varepsilon_r , \qquad (5)$$

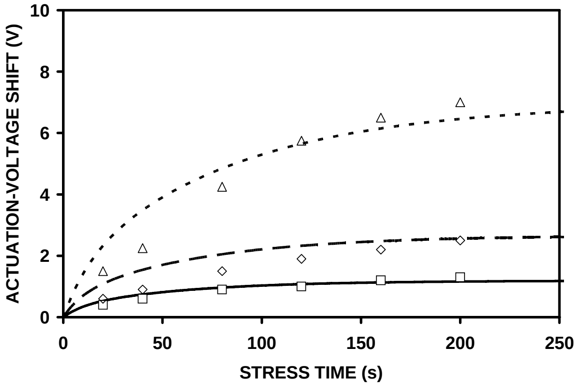


Fig. 4. Measured actuation-voltage shift for (□) 0 °C, (◊) 25 °C, and (Δ) 50 °C. Modeled actuation-voltage shift for (▬) 0 °C, (---) 25 °C, and (···) 50 °C. Measurement was taken after 20, 40, 80, 120, 160 and 200 s of -30 V stress on the bottom electrode of the switch. The sheet charge is assumed to be 180 nm away from the bottom switch electrode.

TABLE I
EXTRACTED MODEL PARAMETERS

J	τ_C (s)	τ_D (s)	Q_0 (cm^{-2})	E_a (eV)
1	9.8	13.2	1.07×10^{16}	0.30
2	66.5	123.6	1.71×10^{17}	0.35

where h is the distance between the bottom electrode and the trapped charge sheet, Q is the injected charge density predicted by (1), ε_0 is the permittivity of free space, and ε_r is relative dielectric constant of the switch dielectric.

Since h can not be directly measured, the actuation-voltage shift for a certain stress period is predicted by the charge model (1), (4), and (5) with h optimized to give the best fit between model prediction and experimental data at all temperatures. Fig. 4 shows the measured and modeled actuation-voltage shifts after different stress periods at different temperatures. Good agreement was obtained for all temperatures by using h = 180 nm, which is about two thirds of the dielectric thickness.

V. DISCUSSION

The extracted charging and discharging time constants are independent of temperature. This is because the extracted time constants are not the exact capture and emission times for the traps. (It is well known that trap emission time is temperature dependent.) Instead, charge tunneling injection, trap-to-trap hopping, and charge redistribution across the thick (250 nm) dielectric all contribute to the measured transient currents. Therefore, the extracted charging and discharging time constants should not be construed as capture and emission times.

The injected charges are most likely distributed across the thickness of the dielectric. Since their collective effect on the actuation voltage can be approximated by a sheet charge, it greatly simplifies the model by using the sheet-charge assumption. In addition, the difference between the MIM capacitor and the actual switch is also absorbed in the *h* parameter which defines the location of the sheet charge.

Dielectric with high leakage current is not necessarily desirable to reduce charge trapping. As shown in Fig. 1, 2, and 4, although the steady-state leakage current increases at elevated temperatures, the steady-state charge density and corresponding actuation-voltage shift also increase. On the other hand, the spring constant and restoring force of the membrane decrease at elevated temperatures; therefore, the switch is more prone to charge-induced stiction when temperature increases. Conversely, lowering the temperature will increase the membrane spring constant while reducing the charge injection, which will render a better switch lifetime.

VI. CONCLUSION

For the first time, temperature acceleration of dielectric-charging effects in state-of-the-art RF MEMS capacitive switches was characterized and modeled. It was found that, while charging and discharging time constants are relatively independent of temperature, steady-state charge densities increase with temperature. A temperature-dependent charging model was constructed to predict the amount of charge injected into the dielectric and the corresponding shift in actuation voltage. Good agreement was obtained between the modeled and measured actuation-voltage shift.

REFERENCES

[1] C. Goldsmith, J. Ehmke, A. Malczewski, B. Pillans, S. Eshelman, Z. Yao, J. Brank, and M. Eberly, "Lifetime characterization of capacitive RF MEMS switches," in *IEEE MTT-S Dig.*, 2001, pp. 227-230.

[2] X. Yuan, J. C. M. Hwang, D. Forehand, and C. L. Goldsmith, “Modeling and characterization of dielectric-charging effects in RF MEMS capacitive switches,” in IEEE MTT-S Int. Microwave Symp. Dig., June 2005

[3] J. R. Reid, and R. T. Webster, “Measurements of charging in capacitive microelectromechanical switches,” Electron. Lett., vol. 38, no. 24, pp. 1544-1545, Nov. 2002.

[4] W. M. van Spengen, R. Puers, R. Mertens, and I. De Wolf, “A comprehensive model to predict the charging and reliability of capacitive RF MEMS switches,” *J. Micromechanics Microengineering*, vol. 14, pp. 514-521, Jan. 2004.