

Impact of Humidity on Dielectric Charging in RF MEMS Capacitive Switches

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Abstract—A novel technique is used to distinguish the charging of the surface from that of the bulk of the dielectrics of different types of RF MEMS capacitive switches under different electric fields and humidity levels. In general, bulk charging dominates in dry air, while surface charging increases linearly with increasing humidity. Under comparable electric fields and humidity levels, switches made of silicon dioxide are less susceptible to surface charging than switches made of silicon nitride. These quantitative results not only underscore the importance of packaging the switches in a dry ambient atmosphere, but also validate the novel technique for evaluating the effectiveness of dielectric preparation and packaging.

Index Terms—Charge injection, dielectric films, dielectric materials, humidity, microelectromechanical devices, microwave devices, switches.

I. INTRODUCTION

HUMIDITY is known to hinder the instantaneous performance of RF MEMS capacitive switches through stiction caused by the capillary force of water. Less is known about the impact of humidity on the long-term reliability of switches. Since the lifetime of switches is currently limited by dielectric charging [1], it is desirable to investigate its dependence on humidity. In particular, charging has been shown [2] to occur at both the surface and the bulk of the dielectric. While bulk charging is not expected to be sensitive to ambient atmospheric conditions, surface charging can be affected by humidity. Following standard microelectronics practices, the dielectric used

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TABLE I
TYPES OF RF MEMS CAPACITIVE SWITCHES

Type	Dielectric	Deposit Method	Deposit Temp.	Thickness	Membrane	Movable Contact	Stationary Contact
A	SiO ₂	sputter	150°C	250 nm	Al	Al	Cr
B	SiN _x	PECVD	250°C	280 nm	Al	Al	TiW
C	SiN _y	PECVD	150°C	200 nm	Au	Ti	Au

in RF MEMS switches is typically silicon dioxide or silicon nitride. Because in general silicon dioxide is hydrophilic and silicon nitride is hydrophobic, it is also desirable to compare the impact of humidity on surface charging of silicon dioxide with that of silicon nitride.

II. EXPERIMENTAL

Table I lists the dielectrics and metals used in the three types of switches investigated. Each switch contains a movable metal membrane fixed at both ends and a stationary electrode of dielectric-coated metal. The membrane and the stationary electrode are separated by an air gap of different humidity levels. With the membrane grounded, a positive or negative control voltage is applied to the stationary electrode to pull the membrane in by electrostatic force. When the magnitude of the control voltage exceeds a threshold, the membrane contacts the dielectric to form a metal-insulator-metal capacitor. The pull-in voltages are approximately 25, 30 and 15 V for Types A, B and C switches, respectively. Although all three types of switches are of similar design, due to processing variations, the residual stress in the membrane of Type C switches is much lower than that of Types A and B switches, which causes the pull-in voltage of Type C switches to be much lower than that of Types A and B switches. To investigate dielectric charging, switches are stressed with voltages up to twice the pull-in voltage. To facilitate comparison between different types of switches, stress voltages are converted to electric fields, assuming they are constant across the thickness of the dielectric. Similarly, the shift in the pull-in voltage is normalized to the pull-in voltage of the switch in its pristine state. To ensure the switch starts with a pristine charge state, it is annealed at 110 °C in dry air for one hour before each stress experiment. The stress experiments are repeated on several switches of each type, but only representative results are used to illustrate the differences between different types of switches.

To quantify the impact of humidity on dielectric charging, the switches are stressed under different electric fields and humidity levels for 5 min, with the relative humidity controlled to

within 1%. During and after stress, the pull-in voltage is periodically sampled by ramping the control voltage down and up within a few seconds. During stress, charge can be injected either from the membrane into the surface of the dielectric or from the stationary electrode into the bulk of the dielectric [2]. Regardless of the sign of the stress field, injected surface charge always increases the magnitude of the pull-in voltage, whereas injected bulk charge always decreases the magnitude of the pull-in voltage. The compensating effects of surface charge and bulk charge mean they cannot easily be separated from the net shift of the pull-in voltage during stress. Instead, they can be separated by analyzing the recovery of the pull-in voltage after stress. After stress, the membrane springs back to its suspended position and surface charge is forced to diffuse across the thickness or surface of the dielectric while bulk charge has a relatively short path to return to the stationary electrode. This is evidenced by the fact that bulk charge discharges in seconds or minutes, whereas surface charge discharges in hours or days. Therefore, surface charging can be quantified by analyzing the charge state after sufficient time (~ 20 min) is passed for the bulk charge to dissipate completely.

III. RESULTS AND DISCUSSION

Fig. 1(a) shows measured pull-in voltage shifts for a Type A switch when stressed under 1.2 MV/cm for 5 min with 0%–30% relative humidity. In the case of 0% humidity, the pull-in voltage decreases during stress and quickly recovers to its pristine value after stress, indicating that the change in the pull-in voltage is due to bulk charging and surface charging is negligible. With 5% humidity, the pull-in voltage behaves similarly, except that it recovers in 20 min to a value slightly higher than its pristine value, indicating a small amount of surface charging which is dominated by bulk charging. With 15% humidity, the pull-in voltage again behaves similarly to that with 0% humidity except that it recovers in 20 min to a still higher value than its pristine value, indicating increasing amount of surface charging. Finally, with 30% humidity, the pull-in voltage increases initially then decreases after 0.5 min, indicating that surface charging dominates initially but is soon overwhelmed by bulk charging. After stress, the pull-in voltage recovers in 20 min to the highest value of approximately 105% of the pristine value. In all cases, the pull-in voltage never shifts by more than $\pm 10\%$. Fig. 1(b) shows that the result under negative 1.2 MV/cm is similar to that under positive 1.2 MV/cm, except with slightly more bulk charging and slightly less surface charging. Such slight dependence on the sign of the stress voltage may be due to the different contacting metals above and below the dielectric [2].

Fig. 2 illustrates similar stress experiments of a Type B switch, which is similar to the Type A switch except the silicon dioxide dielectric is replaced by silicon nitride. It can be seen that although bulk charging still dominates with 0% humidity as in the case of the Type A switch, surface charging increases rapidly with increasing humidity. With 30% humidity, surface charging dominates from the beginning and the pull-in voltage shifts by more than 30% after stress, indicating that surface charging in this case is much more sensitive to humidity.

Fig. 3 illustrates the stress experiments of a Type C switch, which is similar to the Type B switch except that its silicon ni-

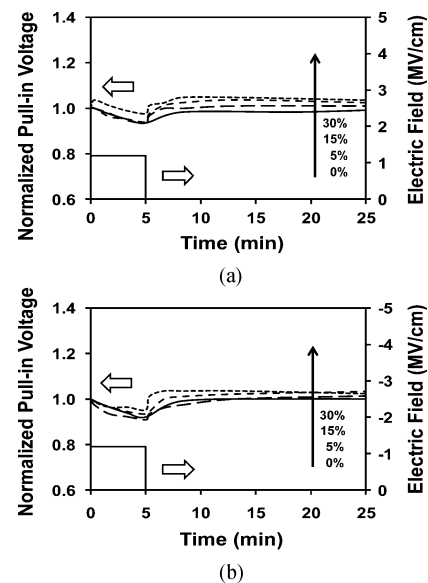


Fig. 1. Pull-in voltage shifts for a Type A switch with 150°C SiO₂ during and after a 5 min stress with (a) 1.2 MV/cm and (b) -1.2 MV/cm stresses with (—) 0%, (---) 5%, (-·-) 15%, and (···) 30% relative humidity. Lower-left rectangle indicates stress duration and magnitude.

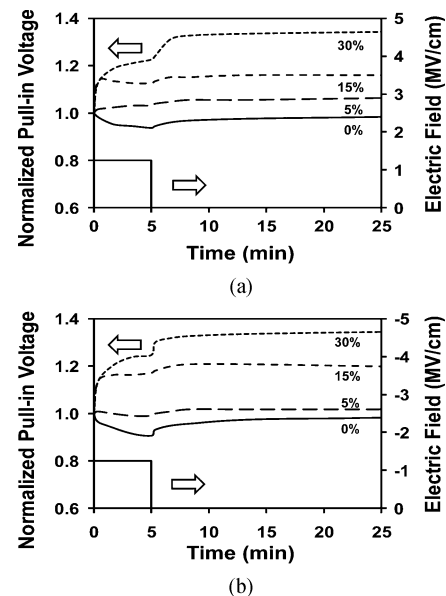


Fig. 2. Pull-in voltage shifts for a Type B switch with 250°C SiN_x during and after a 5 min stress with (a) 1.25 MV/cm and (b) -1.2 MV/cm stresses with (—) 0%, (---) 5%, (-·-) 15%, and (···) 30% relative humidity.

tride is deposited at 150 °C instead of 250 °C and it has much lower pull-in and release voltages. For this reason, the Type C switch was stressed with 0.75 MV/cm instead of 1.25 MV/cm. However, in spite of the lower field, its surface-charging behavior is as sensitive to humidity as that of the Type B switch. In addition, the low release voltage of the Type C switch makes it vulnerable to stiction after a few minutes of stress, although the switch usually unsticks soon after stress is removed.

Fig. 4 compares the surface-charging sensitivities of Types A, B and C switches by plotting their pull-in voltages 20 min after stress with different humidity levels. In general, surface charging increases linearly with humidity and Types B and C

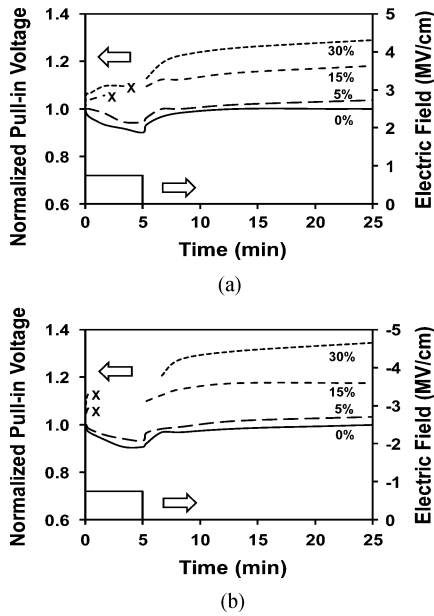


Fig. 3. Pull-in voltage shifts for a Type C switch with 150 °C SiN_Y during and after a 5 min stress with (a) 0.75 MV/cm and (b) -0.75 MV/cm stresses with (—) 0%, (- -) 5%, (- - -) 15%, and (- - -) 30% relative humidity. “X” indicates stiction.

switches are much more sensitive to humidity than the Type A switch under comparable fields. This is unexpected because in general silicon dioxide is hydrophilic whereas silicon nitride is hydrophobic. However, silicon dioxide can be made hydrophobic and silicon nitride can be made hydrophilic after different surface treatments, especially aggressive treatments such as oxygen plasma descum of photoresist residue [3]. Notice that, under a high field of 2 MV/cm, the Type A switch can be as sensitive to humidity as Types B and C switches under lower fields.

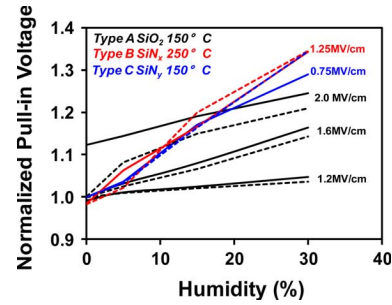


Fig. 4. Humidity dependence of pull-in voltage shifts for (—) Type A, (---) Type B, and (---) Type C switches under different positive electric fields. Corresponding shifts for negative electric fields are plotted together in dashed curves (---).

IV. CONCLUSION

By stressing RF MEMS capacitive switches under different electric fields and humidity levels, it was found that bulk charging dominates in dry air, while surface charging increases linearly with increasing humidity. Under a typical operating field in the order of MV/cm, switches made of silicon dioxide are much less susceptible to surface charging than switches made of silicon nitride. Since surface charge discharges very slowly and is detrimental to the lifetime of switches, it is critical to package switches in < 1% relative humidity.

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