Effect of Packaging on Dielectric Charging in RF MEMS Capacitive Switches

Zhen Peng[1], Cristiano Palego[1], James C. M. Hwang[1], Cody Moody[2], Andrew Malczewski[2], Brandon W. Pillans[2], David I. Forehand[3], and Charles L. Goldsmith[3]

[1]Lehigh University, Bethlehem, PA 18015, USA.
[2]Raytheon Co., Dallas, TX 75243, USA.
[3]MEMtronics Corp. Plano, TX 75075, USA

***Abstract* — A novel technique was used to evaluate the effectiveness of packaging in maintaining a dry ambient atmosphere for electrostatically actuated RF MEMS capacitive switches and in preventing the charging of the dielectric surface after prolonged operation. It was found that as-packaged switches exhibited different degrees of surface charging, probably due to different amounts of moisture inadvertently sealed in the essentially hermetic packages. However, after the switches were delidded and baked dry, all switches showed minimum surface charging. The results imply that the switches can have consistently long lifetimes by improving the yield of the packaging process.**

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

I. Introduction

Intertwined packaging and reliability issues have prevented widespread use of RF MEMS capacitive switches. For example, the switch lifetime can be limited by dielectric charging [1], while dielectric charging can in turn be aggravated by humidity [2]. Using a novel technique [3] to distinguish the charging of the surface from that of the bulk of the dielectrics of different types of *unpackaged* switches under different humidity levels, we found that bulk charging dominates in dry air, while surface charging increases linearly with increasing humidity. Under comparable humidity levels and electric fields, switches made of silicon dioxide are less susceptible to surface charging than switches made of silicon nitride. Since surface charging is more detrimental to switch lifetime than bulk charging [3], this paper reports the application of the same technique on *packaged* switches to evaluate the effectiveness of packaging in maintaining a dry ambient atmosphere and in preventing surface charging.

II. Experimental

Two types of state-of-the-art RF MEMS capacitive switches, both employing a movable aluminum membrane, were investigated. One type [1] contains silicon dioxide; the other type [4] contains silicon nitride. The silicon dioxide was sputtered at 150°C to a thickness of 250 nm on top a Cr-Au stationary electrode and a glass substrate. The silicon nitride was deposited by plasma-enhanced chemical vapor deposition at 250°C to a thickness of 280 nm on top of a Ti-W stationary electrode and an alumina substrate. The pull-in voltages are approximately 25 V and 30 V for the silicon-dioxide and silicon-nitride switches, respectively.

With proper dielectric preparation and packaging, surface charging is negligible and bulk charging is minimized so that selected samples of both silicon-dioxide and silicon-nitride switches exhibited excellent lifetimes beyond 250 billion operation cycles [1], [4]. Nearly hermetic wafer-level packaging was used for both types of switches. The silicon-dioxide switches were packaged by a benzocyclobutene spin-on microencapsulation technique [5]. The silicon-nitride switches were packaged by a glass lid wafer using liquid-crystal polymer adhesive [6]. While both packaging methods are not truly hermetic, they were nevertheless proven effective in preventing moisture ingression during accelerated life tests in humid ambient.

To investigate dielectric charging, the switches are stressed with approximately 10^6 V/cm for 5 min, assuming the field is constant across the thickness of the dielectric. To ensure the switches start in pristine charging state, they are annealed at 110°C in dry air for one hour before each stress experiment. The stress experiments are repeated on several switches on each wafer. Data from representative switches are presented below.

During and after stress, the pull-in voltage is periodically sampled by ramping the control voltage down and up within one second. 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, assuming polarization charge and dielectric leakage are negligible. Assuming further that the injected charge is uniformly distributed across the surface of the dielectric, the charge injected from the membrane always increases the magnitude of the pull-in voltage, whereas the charge injected from the stationary electrode always decreases the magnitude of the pull-in voltage. The shift in the pull-in voltage is [3]

$$\Delta V = \left(hQ_S - h_B Q_B \right) / \varepsilon \tag{1}$$

where h is the dielectric thickness, Q_S is the sheet density of surface charge, Q_B is the equivalent sheet density of bulk charge situated at a height h_B above the stationary electrode,

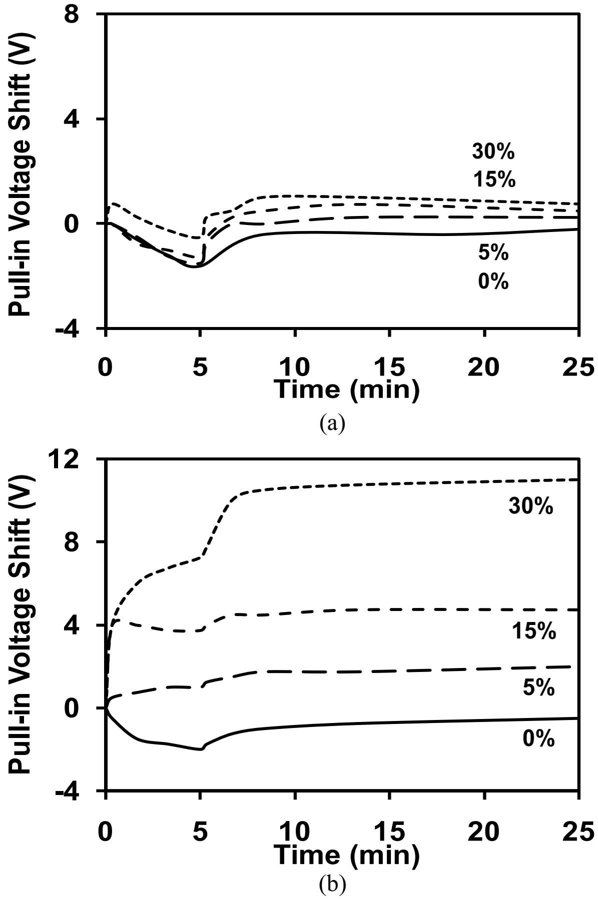

Fig. 1. Pull-in voltage shifts during and after 5 min 10^6 V/cm stress of *unpackaged* (a) silicon-dioxide and (b) silicon-nitride switches under (——) 0%, (— —) 5%, (—–) 15%, and (– – –) 30% relative humidity.

and ε is the dielectric permittivity. Experimentally it has been found that $h_B \approx h/2$.

The compensating effects of surface charge and bulk charge means 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 of the dielectric while bulk charge can readily discharge through 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 pull-in voltage shift after allowing sufficient time (~20 minutes) for the bulk charge to dissipate and before a significant amount of surface charge is dissipated.

III. Results and Discussion

Figs. 1, 2 and 3 compare the stress results of unpackaged, properly packaged, and improperly packaged switches, respectively, with each switch representing the typical behavior of a different wafer. Notice that with wafer-level packaging, all switches of the same wafer are packaged and diced together and it is impossible to simultaneously compare packaged and unpackaged switches from the same wafer.

Fig. 1 focuses on the stress experiments of *unpackaged* switches with the relative humidity controlled within 1% of 0%, 5%, 15% and 30%. It can be seen from Fig. 1(a) that in the case of a silicon-nitride switch under 0% humidity, the pull-in voltage decreases monotonically during stress then recovers quickly to its pristine value after stress, indicating that the pull-in voltage shift is due to bulk charging and surface charging is negligible. Under 5% humidity, the pull-in voltage behaves similarly, except that it recovers to a value slightly higher than its pristine value, indicating a small amount of surface charging. Under 15% humidity, the pull-in voltage again behaves similarly to that under 0% humidity except that it recovers to a still higher value than its pristine value, indicating increasing amount of surface charging. Finally, under 30% humidity, the pull-in voltage increases initially then decreases after 0.5 min, indicating that surface charging dominates initially but is soon overtaken by bulk charging. After stress, the pull-in voltage recovers to the highest value approximately 1 V above the pristine value.

Fig. 1(b) shows that although bulk charging of a silicon-nitride switch still dominates under 0% humidity as in the case of a silicon-nitride switch, surface charging increases rapidly with increasing humidity. Under 30% humidity, surface charging dominates during stress and the pull-in voltage shifts by more than 10 V after stress. According to (1), since the silicon nitride has approximately the same thickness but twice the dielectric constant as that of the silicon dioxide, the surface charge in this case is actually more than twenty times that of the comparable case of the silicon-dioxide switch.

Fig. 2 compares measured pull-in voltage shifts of *properly packaged* switches during and after stress. It can be seen that both silicon-dioxide and silicon-nitride switches exhibited negligible surface charging as packaged. However, after the switches are intentionally delidded, exposed to room air with 30-40% relative humidity, and stressed again, they showed surface charging as in the case of unpackaged switches stressed under humid air. Again, the silicon-nitride switch is more susceptible to surface charging than the silicon-dioxide switch. Finally, when the delidded switches are baked at 110°C for one hour and restressed in 0% humidity, surface charging is again negligible. These results suggest that although the silicon-dioxide and silicon-nitride switches are packaged differently, both packaging approaches can provide dry ambient atmosphere to minimize surface charging.

Fig. 3 compares measured pull-in voltage shifts of *improperly packaged* switches during and after stress. Unlike properly packaged switches, these switches exhibited surface charging as packaged, and even more surface charging after delidding. However, after baking they exhibited negligible

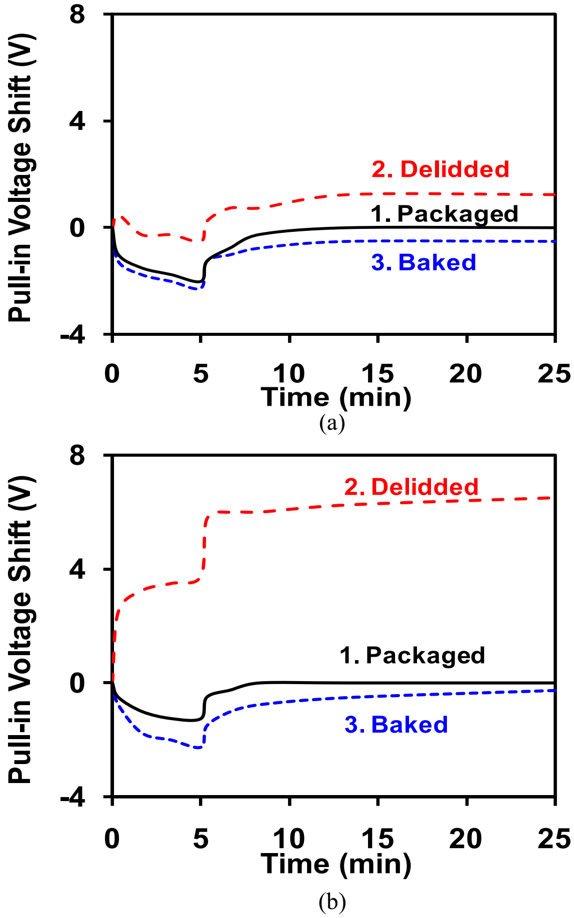

Fig. 2. Pull-in voltage shifts during and after 5 min 10^6 V/cm stress of *properly packaged* (a) silicon-dioxide and (b) silicon-nitride switches (——) as packaged, (— —) after delidding, and (– – –) after baking under 0% relative humidity.

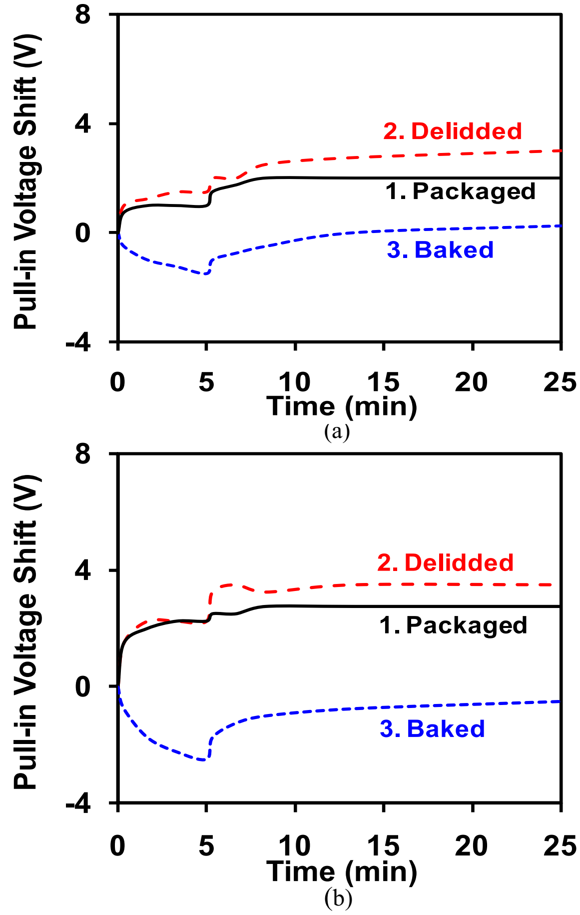

Fig. 3. Pull-in voltage shifts during and after 5 min 10^6 V/cm stress of *improperly packaged* (a) silicon-dioxide and (b) silicon-nitride switches (——) as packaged, (— —) after delidding, and (– – –) after baking under 0% relative humidity.

surface charging as the properly packaged switches. These results suggest that had the moisture not been inadvertently sealed in the packages, the switches would have not suffered from surface charging. On the other hand, without delidding, these improperly packaged switches showed the same surface charging tendency before and after baking, confirming that the packages were nearly hermetic to moisture retention as well as moisture ingression.

Fig. 4 summarizes the stress results of *packaged* switches from a dozen silicon-nitride wafers, using the pull-in voltage shift 20 min after stress as a measure of surface charging. It can be seen that as-packaged switches had a wide range of charging tendency, suggesting inconsistent packaging. The spread remains wide after delidding, confirming that the variation is caused by different amounts of moisture inadvertently sealed in the packages. Lastly, the distribution is much tighter after baking, confirming that the wafer fabrication yield is much higher than that of packaging.

IV. Conclusion

Using a novel stress technique and a delid-and-bake sequence, we have shown that with proper dielectric preparation and packaging, surface charging can be negligible and bulk charging can be minimized so that both silicon-dioxide and silicon-nitride switches can exhibit excellent lifetimes. Currently, the wafer yield is inherently good and the packaging is nearly hermetic, but different amounts of moisture may be inadvertently sealed in the packages to impact the switch lifetime differently. Improvement is being made to the packaging process and more consistent yield is expected in the near future.

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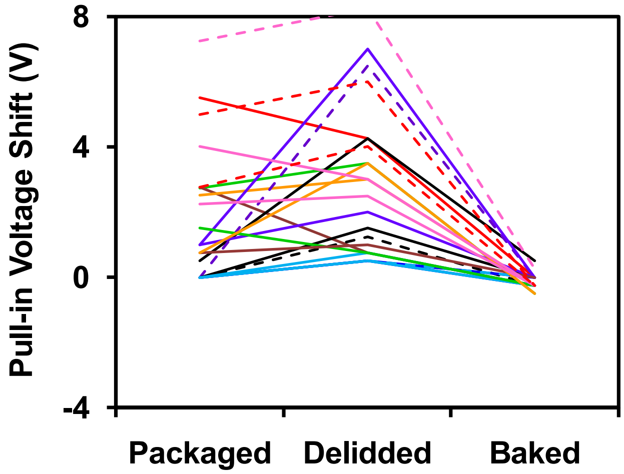

Fig. 4. Pull-in voltage shifts 20 min after 5 min 10^{6} V/cm stress of silicon-nitride switches from a dozen different packaged wafers stressed and tested after packaging, after delidding, and after backing.

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References

[1] C. L. Goldsmith, D. I. Forehand, Z. Peng, J. C. M. Hwang, and J. L. Ebel, "High-cycle life testing of RF MEMS switches," *IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 1805-1808, June 2007.

[2] Z. Peng, C. Palego, J. C. M. Hwang, D. I. Forehand, C. L. Goldsmith, C. Moody, A. Malczewski, B. W. Pillans, R. Daigler, and J. Papapolymerou, "Impact of humidity on dielectric charging in RF MEMS capacitive switches," *IEEE Microwave Wireless Components Lett.,* accepted for publication.

[3] Z. Peng, X. Yuan, J. C. M. Hwang, D. Forehand, and C. L. Goldsmith, "Top vs. bottom charging of dielectric in RF MEMS capacitive switches," *Proc. Asia Pacific Microwave Conf.,* Dec. 2006.

[4] B. Pillans, L. Coryell, A. Malczewski, C. Moody, F. Morris, and V. Pillai, "RF MEMS phase shifters manufacturing technology," *Proc. Defense Manufacturing Conf.*, Dec. 2008.

[5] D.I. Forehand and C.L. Goldsmith, "Zero-level packaging for RF MEMS Switches," *Proc. Government Microcircuit Applications Critical Technologies Conf.*, pp. 36-39, Mar. 2006.

[6] C. Moody, B. Pillans, A. Malczewski, and F. Morris, "Near hermetic wafer level packaging using LCP adhesive layer," *Proc. IMAPS Int. Conf. Device Packaging*, Mar. 2009.