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Wafer Level Micropackaging for RF MEMS Switches

David I. Forehand and Charles L. Goldsmith
MEMtronics Corporation
Plano, Texas, USA 75075
dforehand@memtronics.com

Abstract: *Wafer-level micro-encapsulation is an innovative, low-cost, wafer-level packaging method for encapsulating RF MEMS switches. This zero-level packaging technique has demonstrated 0.04 dB package added insertion loss at 35 GHz. This article overviews the processes, measurements, and testing methods used for determining the integrity and performance of individual encapsulated RF MEMS packages.*

Keywords: RF MEMS; low loss; packaging; wafer-level; hermeticity; humiticity.

Introduction

In the past decades, many advances have been made in the fabrication of miniaturized mechanical structures. Yet the application of this technology is hampered by the lack of production-worthy packages. MEMS packages must not only protect the often-fragile mechanical structures and provide the interface to the next level in the packaging hierarchy, they must also be fabricated in a cost effective manner to allow for affordable mass-produced devices. Since several thousand RF switches are simultaneously fabricated on a single substrate, a cost effective packaging process should perform most of the packaging steps at the wafer level, before separation into discrete devices.

There are several wafer-level packaging (WLP) techniques widely used with silicon micromachining: fusion bonding, anodic bonding, eutectic bonding, thermal compression bonding, and glass-frit bonding. While some of these packaging techniques have been demonstrated with non-RF MEMS devices, their use for RF MEMS is in its infancy. The ideal bonding technique would possess few, if any, RF parasitics, be processed at low temperatures, and tolerate a large degree of non-planarity and roughness.

Description - One disadvantage of present wafer-level packaging techniques is the requirement for a seal ring. The inclusion of a seal ring and the appropriate bonding pads outside the ring significantly increases the area of an RF MEMS switch or circuit. However, an innovative approach to packaging called wafer-level micro-encapsulation (WLμE) [1] eliminates the seal ring, which gives the potential payoff of much smaller, lower cost circuits. Instead of bonding a separate lid wafer to the RF MEMS wafer, an open cage-like structure is first built around the switch, and then a layer of spin-on enscapsulant is applied to the RF MEMS wafers to enclose an extremely small volume immediately surrounding each switch. A cross-section of this encapsulation technique is shown in Figure 1.

Advantages - This packaging concept creates a micro-encapsulation around each MEMS switch utilizing standard wafer processing techniques. The packaging possesses a low dielectric constant, requires only moderate temperature (200^oC – 275^oC), and tolerates non-planarity and roughness. Some of the advantages of this unique WLμE technology are:

- No seal ring
- Extremely small volume cavity
- No requirement for a package lid
- No requirement for hermetic thru wafer vias
- No double-wafer alignment required
- Requires only standard MEMS processing
- Substantial increase in the number of devices per wafer
- Packaged devices are thinner/lighter than any existing packaging technique
- Extremely low insertion loss
- No added parasitics
- RF circuit design transparent.

Challenge - A key challenge with the ~1 nL cavities of WLμE is to demonstrate good switch lifetimes in harsh environments. Fabricating and measuring the desired environment in nL-scale packages poses unique challenges. The helium fine leak testing of MIL-883D is not fully applicable for cavity volumes <1,000 nL [2]. Fortunately, unlike resonators, the operation of RF MEMS capacitive switches is not adversely affected by oxygen, nitrogen, or helium. Instead, capacitive MEMS switch operation is very sensitive to humidity levels because the surface tension of adsorbed water molecules is sufficient to overcome the membrane restoring force and cause stiction.

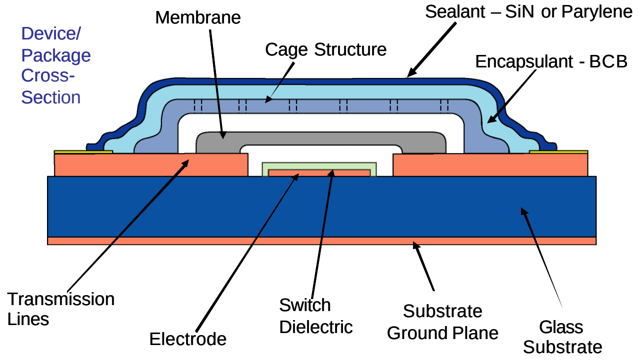

Figure 1 Schematic cross-section of the microencapsulation reveals a cage, encapsulant, and a sealant protecting the MEMS switch.

For a switch design with a spring constant of 5-10 N/m, water vapor induced stiction at room temperature occurs between 30-50% RH. Therefore, *humiticity* test procedures have been developed to investigate water diffusion into the micro-packages, utilizing dew point sensors and accelerated testing similar to [3].

Process

Wafer-level micro-encapsulated transmission lines, switch electrodes, humidity sensors, and RF MEMS switches have all been fabricated on 150 mm Corning 7740 glass substrates. Figure 2 shows a packaged RF MEMS switch and packaged dew-point sensor with 10 µm lines and spaces.

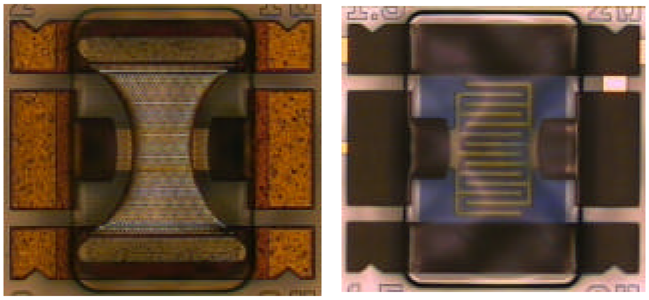

Figure 2 Photos of a microencapsulated RF MEMS capacitive switch and a dew point sensor.

The mask set was designed to simultaneously build the sensors and RF MEMS switches on the same wafer. A conventional switch process sequence through membrane pattern was utilized as: 1) wafer clean, 2) deposit/pattern/etch (D/P/E) 300 nm gold electrode, 3) D/P/E 250 nm SiO_2 switch dielectric, 4) electroplate 2.5 µm copper transmission lines, 5) pattern organic sacrificial layer, and 6) D/P/E 350 nm aluminum alloy membrane

Instead of releasing the membrane at this point in the process flow, as would occur for unpackaged switches or other packaging schemes, an additional cage sacrificial layer was applied over the unreleased switch membrane. This cage sacrificial layer creates the desired separation between the membrane and packaging cage. Next a dielectric cage was deposited.

Holes were patterned and etched into the cage and the sacrificial layers were plasma etched to create a released switch with a packaging superstructure above it. After release, a liquid encapsulant, such as spin-on-glass (SOG) or Cyclotene series 4000 benzocyclobutene (BCB), was applied over the entire wafer while in a dry nitrogen atmosphere. The surface tension of the SOG or BCB ensures that it covers the cage structure but does not wick *through* the cage holes to encroach onto the switch. The SOG or BCB was then cured at 250°C to form a closed seal over the switch. At this point in the process flow, the micro-encapsulation provides the lowest level of protection from humidity, which may be sufficient depending on the application. However, additional sealant overcoats can be applied to increase the level of protection.

Results

RF Measurements - RF measurements up to W-band have been made on wafer-level micro-encapsulated transmission lines [4]. That data showed < 0.10 dB packaged-added insertion loss up to 110 GHz. This work uses more detailed measurements over the 8-50 GHz range with a single-delay TRL calibration to de-embed all but the package performance.

Figure 3 demonstrates the insertion loss and return loss through 50 GHz for a simple unpackaged and packaged switch electrode. The data is an average of 6 devices. The difference in insertion loss is barely discernable in these measurements, ~0.02 dB at 35 GHz. The return loss measurements show no difference between packaged and unpackaged structures.

RF measurements were repeated for unpackaged and micro-packaged RF MEMS switches, shown in Fig. 4. The package-added insertion loss, based on the switch data, is ~0.06 dB at 35 GHz. The total packaged switch insertion loss is a very respectable 0.12 dB at 35 GHz. This micro-packaged switch insertion loss will be lower in a phase shifter because the off-capacitance will be impedence matched.

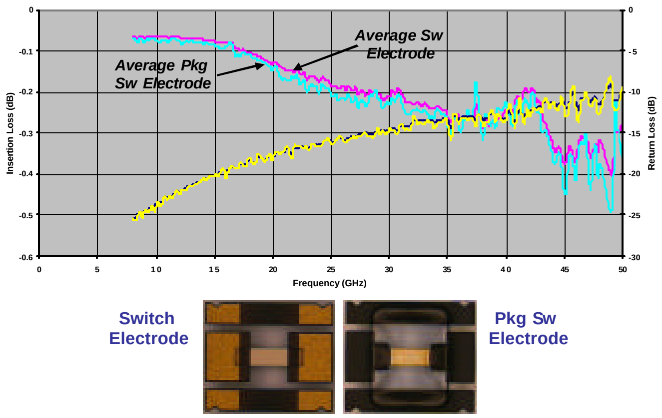

Figure 3 Comparison of losses for an unpackaged and packaged switch electrode through 50 GHz

It is also apparent that the difference in the return loss is more pronounced. This can be explained by the fact that these measurements were performed on separate wafers from different lots. Hence, there is more wafer-to-wafer variation in the membrane gap than in the electrode dimensions. Therefore, the switch RF data is expected to have more variation.

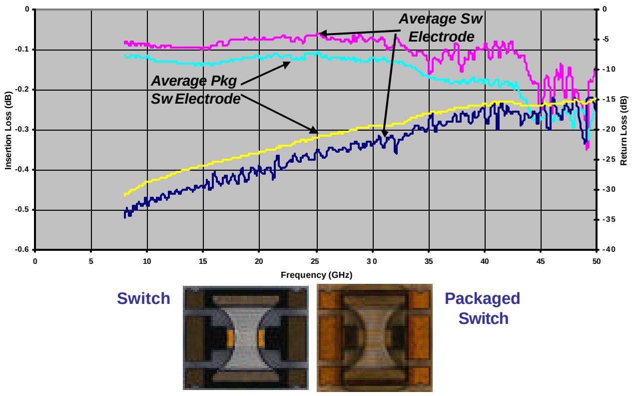

Figure 5 Comparison of losses for an unpackaged and packaged RF MEMS switch through 50 GHz

The total package added insertion loss versus frequency, shown in Fig. 5, is determined by taking the difference between the packaged and unpackaged data. At 35 GHz the package adds between 0.02 dB and 0.06 dB of insertion loss for the switch electrode and RF MEMS switch data, respectively. It is believed that the switch electrode data more accurately portrays the added insertion loss, but to be conservative, 0.04 dB is used.

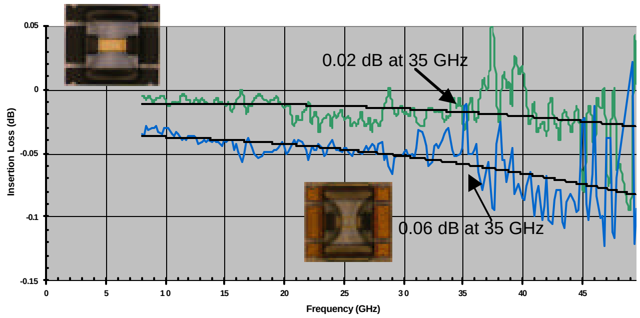

Figure 4 Total package added insertion loss versus frequency for the switch electrode and RF MEMS switch..

Humiticity: Dew point sensors were used to measure water diffusion into the micropackage. The sensors consist of interdigitated fingers in three size variations; 2.5, 5, and 10 µm lines and spaces. These comb structures were fabricated in the switch electrode layer and are not covered with dielectric.

The dew point sensors were tested by measuring current versus voltage in a Cascade Attoguard test station with a Keithley S4200 semiconductor parameter analyzer. The testing methodology was: 1) measure I-V curves of sensors in a dry environment; 2) measure I-V curves with the same sensors in humid conditions equivalent to where RF MEMS capacitive switches usually start to fail because of stiction; 3) perform accelerated environmental lifetime testing on packaged sensors and compare the resulting I-V data with baseline sensor data under humid conditions.

To characterize the 2.5 µm sensor baseline operation, several micro-packages were pierced to allow either dry nitrogen or humid cleanroom air (20°C, 45% RH, dew point ~7°C) to contact the sensor. The baseline sensors were baked out in dry nitrogen at 115°C for 10 minutes in the test station. Current-voltage measurements were taken in dry nitrogen with chuck temperatures of 100°C, 75°C, 50°C, 25°C, and 0°C. The current decreases with decreasing temperature. To determine the noise floor, I-V measurements were taken with the probes in the up/open position. The noise floor was $10^{-14} – 10^{-15}$ A.

The dry nitrogen was turned off and the front panel of the test station was opened to allow the environment to reach equilibrium with the cleanroom air. The resulting humid I-V data for chuck temperatures of 25°C and 2°C are shown in Fig. 6; along with the 25°C dry nitrogen data. As expected, the 2°C data shows a 10^6 increase in current, indicating the sensor is very sensitive to condensation when the temperature is below the dew point. Comparing the 25°C dry nitrogen to humid cleanroom air data, the average current at 40V of the dew point sensors increases from $6.5x10^{-13}$ A to $3.1 x10^{-11}$ A. This 50x increase in current is caused by the thin adsorbed water layer, again indicting that the sensor is very sensitive to surface moisture. The humid cleanroom air approximates the conditions where RF MEMS capacitive switches have been observed to exhibit water-related stiction failure. Therefore, a dew point sensor current of 30 pA at 40V is used to approximate this condition and the package will be classified has having failed.

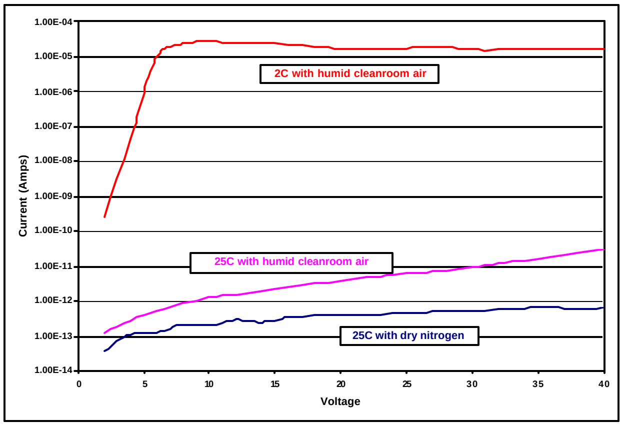

Figure 6 I-V calibration curves for dew point sensors under dry and humid conditions.

Fully packaged sensors were subjected to accelerated lifetime cycles and then I-Vs measured. The acceleration factor (AF), which relates the desired operating conditions to the accelerated test conditions, is based on the two-stress Eyring model [5] and modified by Halliberg and Peck [6] for humid environments,

$$AF = \frac{\left(RH^{-n} e^{\Delta E_a / kT}\right)_{operating\,conditions}}{\left(RH^{-n} e^{\Delta E_a / kT}\right)_{accelerated\ \ conditions}}$$

where RH is relative humidity, ΔE_a is the activation energy, k is Boltzman's constant, and T is absolute temperature. The recommended values for ΔE_a and n are 0.9eV and 3, respectively.

In this experiment, samples were subjected to very aggressive accelerated temperature and humidity conditions. The acceleration factor between standard room conditions (25°C, 50% RH) and the accelerated conditions (135°C, 100% RH) is ~10^5. Twelve micro-packaged dew point sensors on a single die received sequential accelerated test sequences (ATSs). Integrating the AF over a single ATS profile gives an equivalent time of 21.8 years at room conditions, shown in Fig. 7.

Initially, accelerated environmental testing was performed on sensors that received only a BCB encapsulation, to determine the BCB-only level of protection to humidity. Thick and thin BCB thicknesses were tested which were processed on separate wafers. Figure 8 shows the average I-V curve of 12 packaged dew point sensors for a thin BCB wafer after 0, 1, 2, and 5 ATSs, (0, 21.8, 43.6, and 109 years at standard room conditions). The micro-packaged sensor data indicates increasing adsorbed water inside the package with increasing accelerated test time, which is to be expected for a diffusion related phenomenon. Using 30 pA as the threshold of package failure for an RF MEMS switch, the 50% failure rate would occur around 55 years at standard room conditions.

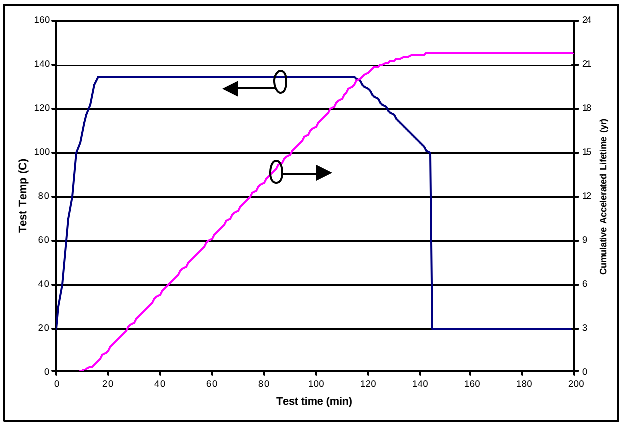

Figure 7 Temperature profile and cumulative room condition lifetime for an accelerated test sequence.

The data from the micro-packaged sensors that received thick BCB encapsulation actually failed earlier, ~20 years at room conditions. This was quite unexpected. Visual inspection of both test die after each ATS indicated that the thick BCB die showed significant delamination. The delamination occurs over copper structures, starting with the largest features.

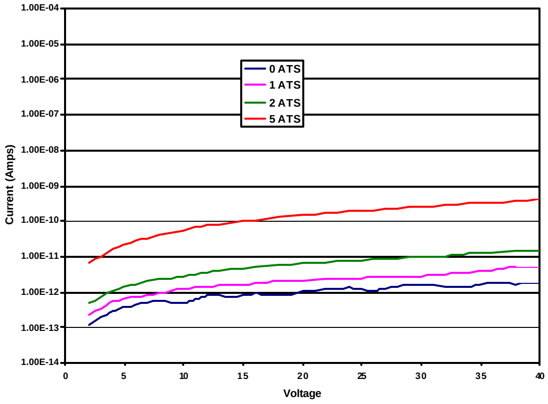

Figure 8 I-V data for thin BCB encapsulant after various accelerated test sequences.

To investigate the effect of adding a sealant, two different sealant films were applied over the BCB. The resulting package structures were either silicon nitride over BCB or parylene over BCB. These sensors were subjected to the same environmental lifetime testing as above. Figure 9 shows the resulting current at 40V versus the equivalent years at room conditions for all the packaging variations. The 30 pA package failure line is also included. It was interesting that the nitride overcoat performance was much worse than BCB-only. Visual inspection confirmed that the degree of delamination was quite severe after just one ATS.

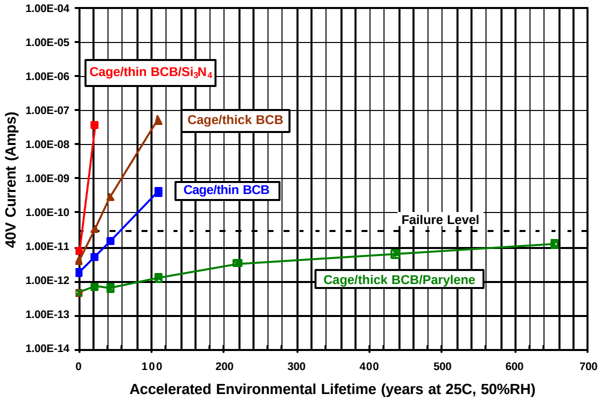

Figure 9 Sensor current at 40V versus lifetime.

The parylene overcoat data was a pleasant surprise. After over 600 equivalent room condition years, these packages still have not failed. Visual inspection during the testing showed virtually no delamination present on these parylene overcoated packaged sensors.

Measurement of the micro-encapsulated dew point sensors at lower temperatures did not indicate an abrupt current increase at the anticipated dew point temperature as was observed with unpackaged dew point sensors during baseline testing. This may be explained by the fact that the baseline sensors were exposed to an essentially infinite source of water vapor which would continue to condense onto the sensor as long as the temperature is below the dew point. In contrast, a 2 nL package contains an extremely small volume of water vapor that can condense. If all the water vapor in a 2 nL package with an environment of 25°C, 50% RH, adsorbed onto the inside package surfaces, then the increased thickness of H_2O would be < 1 angstrom. According to Freund [7], the adsorbed water thickness on gold for 50% RH is 100-200 angstroms. It has been observed that an unpackaged RF MEMS switch will fail from moisture stiction between 30-50% RH, which should correspond to ~100 angstroms adsorbed water. As a 2 nL package is cooled below dew point, the adsorbed water thickness would insignificantly increase, and no abrupt dew point sensor current increase would occur. In this situation, these micropackaged dew point sensors behave more like relative humidity sensors.

Conclusion

A process has been developed to effectively package RF MEMS switches using a new technique called wafer-level micro-encapsulation. This technology is designed to be completely compatible with high-performance RF MEMS capacitive switch fabrication. The packages created with this technology exhibit extremely low package-added insertion loss of 0.04 dB at 35 GHz, and < 0.10 dB for frequencies up to 110 GHz. Thorough lifetime characterization of these packages is an on-going activity, but initial results are promising. Preliminary accelerated lifetime data of wafer level micro-encapsulation indicates an RF MEMS lifetime of ~55 years at room conditions using BCB spin-on encapsulation. Additional sealant layers have shown very good promise by increasing the lifetime by an order of magnitude (>600 years). The compatibility of this package with MEMS switch processing, the extremely low loss and RF parasitics, and the potential for near-hermetic encapsulation makes this technology a promising solution for packaging and protecting a variety of MEMS devices, including RF MEMS switches.

Acknowledgements

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