Zero-Level Packaging for RF MEMS Switches

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Abstract: *A process has been developed to effectively package RF MEMS switches using a new technique called wafer-level micro-encapsulation (WLμE). This technology is designed to be completely compatible with high-performance RF MEMS capacitive switch fabrication. This zero-level packaging technique has demonstrated excellent package added insertion loss through 110 GHz and sufficient protection to humidity.*

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

Introduction

A promising process has been developed to effectively package RF MEMS switches using a new technique called wafer-level micro-encapsulation (WLμE) [1]. This technology is designed to be completely compatible with high-performance RF MEMS capacitive switch fabrication. This zero-level packaging technique has demonstrated excellent package added insertion loss through 110 GHz and sufficient protection to humidity.

This packaging concept creates a 1-2 nL 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.

The operation of RF MEMS capacitive switches is not adversely affected by oxygen, nitrogen, or helium. Instead, RF 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 create stiction. 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 were developed to investigate water diffusion into the micro-packages, utilizing dew point sensors and accelerated testing similar to [2].

Process and Process Design

Wafer-level micro-encapsulated humidity sensors and RF MEMS switches were fabricated on 150 mm Corning 7740 glass substrates and are shown in Figure 1. The dew point sensors consist of interdigitated electrodes in three size variations; 2.5 μm, 5 μm, and 10 μm lines and spaces. The mask set was designed to simultaneously build the sensors and RF MEMS switches on the same wafer. A schematic cross-section of a WLμE RF MEMS switch package is shown in Figure 2. A detailed microencapsulated switch process sequence was discussed in [3,4].

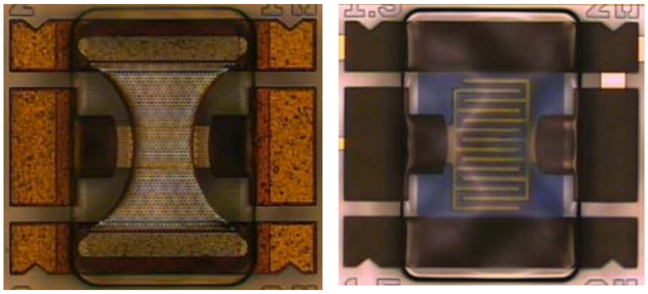


Figure 1. Photo of a microencapsulated RF MEMS switch and dew-point sensor.

Because of the newness of the micro-encapsualtion process, many packaging design variations have been investigated, as shown in Figure 3, to determine their effects on packaging yield. Numerous design variations can be cost-effectively investigated using a photo mask. We are currently utilizing a third generation mask-set. Other design parameters, such as cage material/thickness/stress, encapsulant, and sealant require significantly more resources to investigate. The third generation mask-set contains 18 different package variations. There are 6 replicates within each die, and 84 possible die on a wafer.

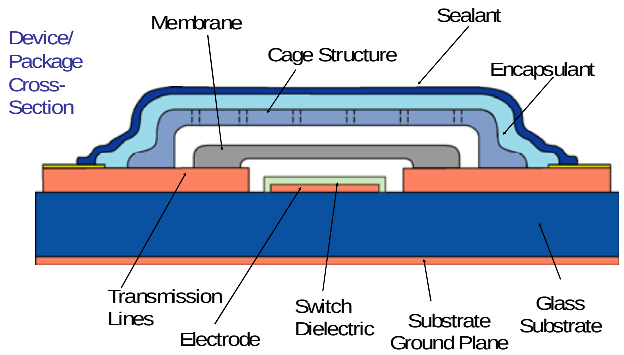
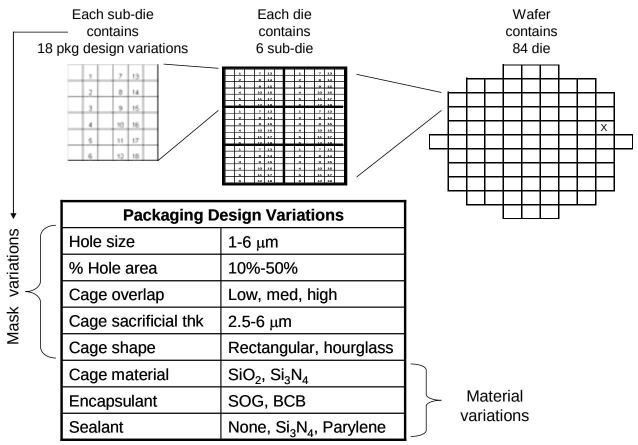


Figure 2. A cross-section of the microencapsulated package reveals a cage, encapsulation, and a sealant protecting the MEMS switch inside.



Packaging Design Variations	
Hole size	1-6 μm
% Hole area	10%-50%
Cage overlap	Low, med, high
Cage sacrificial thk	2.5-6 μm
Cage shape	Rectangular, hourglass
Cage material	SiO_2, Si_3N_4
Encapsulant	SOG, BCB
Sealant	None, Si_3N_4, Parylene

Figure 3 WLμE process design variables

Results

Yield – The two major causes of yield loss are incomplete removal of the sacrificial layers, and BCB wicking into the cage. The incomplete sacrificial layer removal is caused by the cage holes failing to open and subsequently blocking the release plasma etch. As one would expect, this type of failure primarily occurs with the small hole size variations not being opened up during wafer pattern. The BCB wicking is affected by hole size, hole placement, and BCB application technique.

These failure types are fairly easy to detect during optical inspect, but extremely time consuming to detect with 100% switch actuation testing. Therefore, the "good die" from optical inspect were verified by sample testing with RF MEMS switch actuation. Wafer maps of die-yield of three of the 18 mask variations are shown in Figure 4, along with the die yield of all 18 variations.

In order to obtain a better representation of the expected yield of a phase shifter, a die was considered good only if all 6 of 6 package replicates were good. As can be seen from the wafer maps, the die yield does not exhibit a Guassian distribution. The yield drop-out at the center of the wafer is because of BCB application method. Split 12 shows good promise having a 50% die yield with 6 of 6 good packages. A fourth generation mask set is being designed around split 12, and different BCB application techniques will be investigated to further optimize the package die yield.

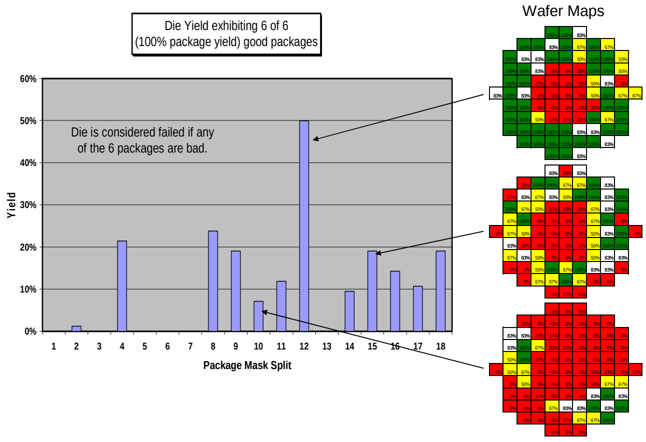


Figure 4 Wafer map of die yield of 3 representative micro encapsulation variations.

Results

RF Measurements - RF measurements up to W-band have been made on wafer-level micro-encapsulated transmission lines [3]. 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 5 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. 6. 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.

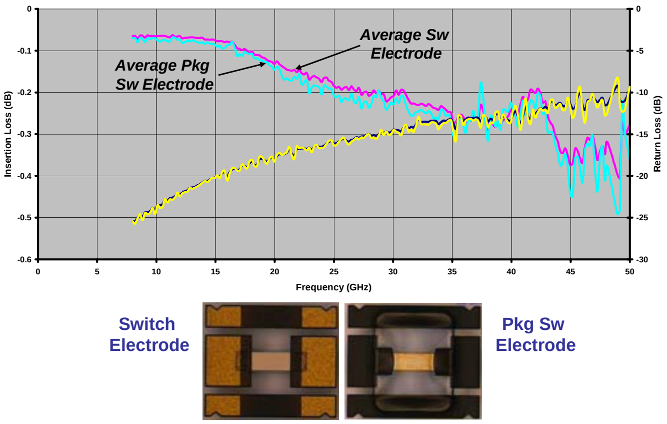


Figure 5 Comparison of losses for an unpackaged and packaged switch electrode through 50 GHz

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.

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.

Humiticity: Accelerated humidity test procedures were given in [3,4]. 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 to determine package lifetime, with 30 pA at 40V sensor current as the failure level.

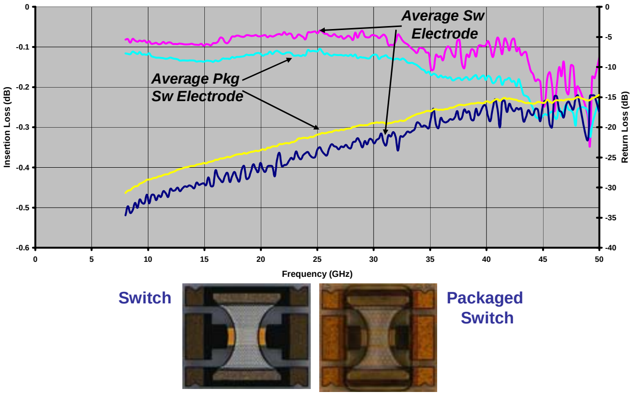


Figure 6 Comparison of losses for an unpackaged and packaged RF MEMS switch through 50 GHz

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. Each die includes twelve micro-packaged dew point sensors.

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.

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 test indicated that the thick BCB die showed significant delamination. The delamination occurs over copper structures, starting with the largest features.

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 7 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 the first accelerated test sequence.

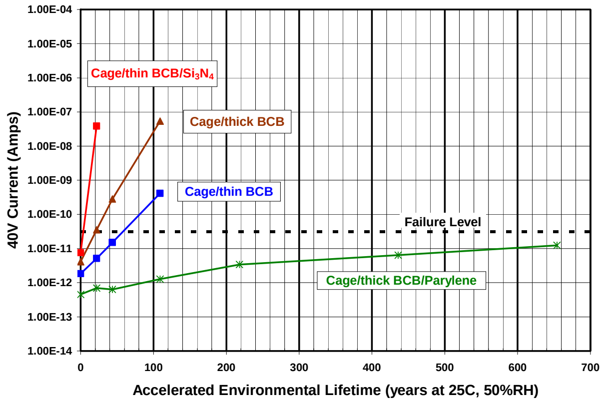


Figure 4 Sensor current at 40V versus lifetime.

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 and shows respectable die yield for early stage development. 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. 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. Development is ongoing to improve yield and repeatability, and continue investigating environmental robustness.

Acknowledgements

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