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ROBUST, RELIABLE, RADIO FREQUENCY (RF) MICROELECTROMECHANICAL SYSTEMS (MEMS) CAPACITIVE SWITCHES

Charles L. Goldsmith
MEMtronics Corporation
3000 Custer Road, Suite 270-400
Plano, TX 75075

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STINFO INTERIM REPORT

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/s/

JOHN L. EBEL
Electron Devices Branch
Aerospace Components Division

/s/

KENICHI NAKANO, Chief
Electron Devices Branch
Aerospace Components Division

/s/

ROBERT T. KEMERLEY, Chief
Aerospace Components Division
Sensors Directorate

This report is published in the interest of scientific and technical information exchange and does not constitute approval or disapproval of its ideas or findings.
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 < 0.1 dB package insertion loss up through 110 GHz and accounts for only 28% of the total packaged RF MEMS circuit cost. This article overviews the processes, measurements, and testing methods used for determining the integrity and performance of individual encapsulated RF MEMS packages.
Robust, Reliable RF MEMS Capacitive Switches

RF Switch Characterization

RF Performance vs. Voltage

Insertion Loss, Return Loss (dB)

Frequency (GHz)

$V_P \sim 32$ volts
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RF Capacitive Switch Model

Summary

Insertion Loss @ 35 GHz  ~0.06 dB
Isolation @ 35 GHz  15 dB

Model Values

Rse  0.18 Ohms
Rsh  0.24 Ohms
Coff  0.015 pF
Con  0.73 pF
Ron  0.25 Ohms

Capacitance Ratio  50
Cutoff Frequency  >2,000 GHz
Switching Speed  < 40 μs
Intercept Point  TBD dBm
Switching Voltage  25-35 volts
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**Dielectric Charging Characterization**

- Uses transient current spectroscopy to measure charging and discharging of carriers within capacitor dielectrics.
- Requires measurement of very small currents, ~femtoamps.
- Use measurements to extract carrier densities and time constants as a function of applied voltage.

**Dielectric Charging Characterization**

**Charging Measurements**

**Charging Characterization**

![Graphs showing charging and discharging currents as a function of time and applied voltage.](image)
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Modeling of Dielectric Charging

Charging Model

\[ \Delta Q = \sum J \Delta Q_j^0(V) \left[ 1 - \exp\left(-t_{ON}/\tau_C^j\right) \right] \exp\left(-t_{OFF}/\tau_D^j\right) \]

Extracted Model Parameters

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<th>( t_c (s) )</th>
<th>( t_D (s) )</th>
<th>( Q_o (\text{cm}^2) )</th>
<th>( V_o (V) )</th>
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<th>( J )</th>
<th>( t_c (s) )</th>
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Results

- Measurements demonstrate two carrier types contributing to charging
- One has a short time constant, 6-7s, and the other long, 50-75s.
- Exponential dependence on control voltage
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**Proximity Switch**

- Initial design shows good capacitance ratio (~10:1)
- Very low insertion loss
- Switches tend to burn out due to shorting of the membrane and electrode
- Characterization ongoing at a low level
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Reducing Variation in Actuation Voltage

$$V_p(T) = \sqrt{\frac{64 \gamma_s (1 - \nu) t g_s^3}{27 L^2 \varepsilon_o}} \left( \Delta \alpha E (T_{zs} - T) \right)$$

Membrane gap constant over temp

Critical buckling temp

Prior publications showed 36 volts to 60 volts variation over -50°C to +70°C

Assumed linear relationship

This project demonstrated 21 volts to 22 volts variation over temperature

Demonstrated correlation between theory and measured data to square-root relationship
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RF MEMS Micro-Encapsulation

Process:
Prior to membrane release, add a second sacrificial layer on top of switch.
Deposit/pattern/etch an insulating cage structure on top of sacrificial layer.
Release both sacrificial layers.
Apply spin-on glass to encapsulate switches (surface tension restricts flow of encapsulant).

Advantages (beyond wafer-level pkg):
- Lower temperature processing.
- No wafer bonding or alignment required.
- No significant packaging loss or parasitics!
- No separate seal ring or interconnect area required, ~85% more die for a 4 x 6 mm IC.
- No expensive thru-wafer vias required.
- CMOS compatible, an excellent way to seal RF MEMS co-integrated with GaAs or SiGe MMICs.
- Package cost ~30% of total die cost.
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Wafer-Level Microencapsulation

"Nanoliter Packaging"

Packaged Capacitive Switch

Device/Package Cross-Section

Membrane

Cage Structure

Encapsulant

Electrode

Switch Dielectric

Transmission Lines

Substrate Ground Plane

Glass Substrate

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Packages work to 110 GHz+!!

- Packages exhibit excellent measured performance to 110 GHz!
- Full package loss < 0.1 dB to 110 GHz with > 20 dB return loss
- Losses very difficult to measure as they are on same order as measurement uncertainty

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Insertion Loss

Return Loss

Thanks to Prof. Papapolymerou and student Matt Morton

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RF Loss Comparisons – Packaged Structures

Packaged Switch Electrode

Packaged Switch
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Total Package Loss

Results of Packaging Comparisons

- Excellent performance measured through 110 GHz with < 0.1 dB loss
- No significant degradation in return loss
- Absolutely no package resonances
- Package loss is approximately 0.02-0.06 dB at 35 GHz
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Package Humidity Sensors

Failure Criteria
- Failure criteria taken to be equivalent moisture of 25°C at 30-50% humidity
- Moisture has sufficient surface adhesion to impede operation of a membrane switch
- Failure level ~50 10⁻¹² amps

Humidity sensor consists of interdigitated capacitor with 2.5μm lines/spaces
- Fits into same area/volume as MEMS switch
- Measures surface conductivity due to adsorbed moisture

Sensor Calibration Data

Microencapsulated Dew Point Sensor

0°C Dry
25°C Dry
50°C Dry
75°C Dry
100°C Dry

25°C Humid
0°C Humid
Condensation Event

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**Microencapsulation Humidity Measurements**

**Procedure**
- Select 12 packaged sensors for accelerated testing
- Subject packages to accelerated test sequences of 130°C/100% humidity for 1.5 hours
- Characterize sensor I-V curve to determine adsorbed moisture

**Results**
- Initial encapsulation layer withstands 2 ATSs before defined failure level is reached
- This is equivalent to 42 years at 25°C/50% humidity or 2 years of jungle conditions at 35°C/85% humidity
- Additional sealant layers will increase humidity

![Graph showing Humidity/ Temperature Accelerated Test Sequence (ATS)]