Operational Reliability of RF MEMS
Ohmic-Contact RF MEMS Relay Repeatability, Lifetime, and Environmental Test Methods

XCOM Wireless, Inc.
2815 Junipero Ave., Suite 110
Signal Hill, CA  90755
(562) 981-0077
www.xcomwireless.com
Overview

• **Component Application**

• **Test Methods & Data**
  – Performance Characterization
  – Environmental Reliability
  – Operational Lifetime
  – Operational Repeatability

• **Future Work**
RF MEMS Potential Insertions

Transmit

Receive

MEMS Components
- Compact Integration
- Better Signal Quality
- Power Savings

PA Tuning
Diplexer/Duplexer/Filtering
Tuning or Phasing Input
Tuning Antenna Element
SPXT
Tunable Filter
First Customers – Test Equipment

- Nearly all wireless products are rigorously tested
- Conventional test hardware slow and expensive
- Testing costs used to be 6-8%, now at 15-20%
- Industry needs fast, broadband, repeatable relays
- Longer life – larger product runs, adaptable load boards and interface racks

Testing wireless and high speed digital semiconductor products

Teradyne FLEX system example; image used without permission
Critical Component Goal

- RF MEMS relays at “attractive” size & cost vs. SAM
- Part must exist; supplier must exist; moderate volumes (100k/mo) must be supported
- Hermetic package for severe environments
- Lifetime must be 100M to compel change/savings
- Otherwise do everything “same or better”
Hybrid Architecture

- 1.7 mm Si MEMS die
- 3.8 mm Alumina leadless package w/Cu vias
- 3.7 mm stamped metal lid w/Au coating
- 25 um thick stamped Sn-Cu-Ag seal pre-form
Classic Microelectronic Assembly

- Stud bumped w/semi-auto ball bonder
- Thermosonic flip chip RF MEMS die
- Tack weld preforms to lids
- Align and seal in vac furnace in fixture
**XCOM Industrial Product – 2007**

**XW3000 SPDT Relay**

<table>
<thead>
<tr>
<th>Device</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEMS</td>
<td>Xipe MEMS die</td>
</tr>
<tr>
<td></td>
<td>• Surface-micromachined beam</td>
</tr>
<tr>
<td></td>
<td>• Repeatable gold alloy contacts</td>
</tr>
<tr>
<td></td>
<td>• Ultra high-repeatability device</td>
</tr>
<tr>
<td>Package</td>
<td>MPT QFN-like leadless carrier</td>
</tr>
<tr>
<td></td>
<td>• Ceramic Substrate</td>
</tr>
<tr>
<td></td>
<td>• Hermetic metal-filled vias</td>
</tr>
<tr>
<td>ASIC</td>
<td>None; future version adds drive and proprietary ESD protection</td>
</tr>
<tr>
<td>Seal</td>
<td>Near-Hermetic Glass</td>
</tr>
</tbody>
</table>

**Item** | **Description**
---|---
Foundry | Innovative Micro Tech (Dedicated MEMS Foundry)
Performance | **20 GHz bandwidth**
Ruggedness | MIL-STD thermal, vibration
Qualification | JEDEC RoHS solder reflow
Pricing | $50 to $10 ASP; SAM grows as price drops
XCOM Industrial Product – 2009

XW3100 SPDT Relay

<table>
<thead>
<tr>
<th>Device</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEMS</td>
<td>Xipe MEMS die</td>
</tr>
<tr>
<td></td>
<td>• Surface-micromachined beam</td>
</tr>
<tr>
<td></td>
<td>• Repeatable gold alloy contacts</td>
</tr>
<tr>
<td></td>
<td>• Ultra high-repeatability device</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Package</th>
<th>New QFN SMT substrate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>• Proprietary Substrate</td>
</tr>
<tr>
<td></td>
<td>• Hermetic metal-filled vias</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ASIC</th>
<th>None; separate drive circuit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seal</td>
<td>Hermetic Metal</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Foundry</th>
<th>Innovative Micro Tech (Dedicated MEMS Foundry)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance</td>
<td>12 GHz bandwidth</td>
</tr>
<tr>
<td></td>
<td>Near-perfect linearity</td>
</tr>
<tr>
<td>Ruggedness</td>
<td>MIL-STD thermal, vibration</td>
</tr>
<tr>
<td></td>
<td>JEDEC RoHS solder reflow</td>
</tr>
<tr>
<td>Qualified</td>
<td>Partial Q2 2009, hot-switch lifetime and ESD weakness!</td>
</tr>
<tr>
<td>Pricing</td>
<td>$20 to $3 ASP; SAM grows very rapidly as price drops</td>
</tr>
</tbody>
</table>

Item Description

3.8 mm

Relay Die

Hermetic Lid Seal

Lid and Label

SMT Package
XCOM Industrial Product – Today

**XW3200 SPDT Relay**

### MEMS
- Xipe MEMS die
  - Surface-micromachined beam
  - Repeatable gold alloy contacts
  - Ultra high-repeatability device

### Package
- Variant QFN SMT substrate
  - Proprietary Substrate
  - Hermetic metal-filled vias

### ASIC
- None; future version can add drive and further ESD protection

### Seal
- Hermetic Metal, cleaner and higher yielding process

### Table

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foundry</td>
<td>Innovative Micro Tech (Dedicated MEMS Foundry)</td>
</tr>
<tr>
<td>Performance</td>
<td>12 GHz bandwidth</td>
</tr>
<tr>
<td></td>
<td>Near-perfect linearity</td>
</tr>
<tr>
<td>Ruggedness</td>
<td>MIL-STD thermal, vibration</td>
</tr>
<tr>
<td></td>
<td>JEDEC RoHS solder reflow</td>
</tr>
<tr>
<td>Qualified</td>
<td>Q3 2010 Completed hot-switch, cold switch, RF, DC</td>
</tr>
<tr>
<td></td>
<td>repeatability, ruggedness</td>
</tr>
<tr>
<td>Pricing</td>
<td>$20 to $3 ASP</td>
</tr>
</tbody>
</table>

- **Relay Die**
- **LCC Package**
- **Lid and Labeling**
- **Lid and Labeling**
Overview

• Component Application

• Test Methods & Data
  – Performance Characterization
  – Environmental Reliability
  – Operational Lifetime
  – Operational Repeatability

• Future Work
RF MEMS Relay RF Performance

XCOM SPDT relay

As probed on SMT pads with wide CPW

Loss ~0.5 dB through 10 GHz

Input reflection good to 12 GHz

Isolation also good > 40 dB to 13 GHz

5W @50 Ohm rated

25W @50 Ohm, CW

30 MHz survival (limited testing)
Electromechanical Performance

- Failures of various types identified in 100% DC screening – typically high resistance
- Drive voltage 100V (~70-90V closure)
- Dielectric standoff 120-200V pin-pin
- Power consumption near-zero
- Switching speed
  - Predictive closure speed 6-8 us
  - Reactionary closure speed 30-40 us
  - Open 4V DC standoff ~200 ns
  - Open full RF rated isolation 1-2 us
Electrostatic Discharge (ESD)

• Do I have to test for ESD sensitivity?
• Yes, if you’re trying to assess vs:
  – ISO 10605/TR10605
  – EN 61000-4-2 (European electronics)
  – IEC 61340-3-1/2
  – MIL 883 (Defense)
  – MIL-STD-1512
  – Ford EMC
  – GR-78-CORE
  – RTCA DO 160
ESD Model Basics

• 3 Classifications based on JEDEC 22-A114-B

ESD association [http://esda.org/](http://esda.org/)

- Human body model (HBM) 100 pF@1.5 kOhm, ESD STM5.1 – 6 nsec pulse for a short, achieves peak 463 mA through 500 Ohm for 1kV charge
- Charge device model (CDM) 4 pF/30pF, DS5.3.1 item itself charges up to 2-30 A peak
- Machine model (MM) 200 pF@0 Ohms, STM5.2 – as if discharged through 500 nH inductor

• Each customer needs to know your ratings, typically HBM is biggest issue, but MM also critical for automated assembly.
Testing ESD

- Inexpensive simulator circuits available for ESD STM5.1 (HBM), 5.2 (MM), and 5.3.1 (CDM)
- If Defense part, just convert to MIL-STD 1686 section 5.2.1.1 classification, or you could start from MIL-STD-883 Method 3015
- EU uses IEC-61000-4-2 specification
- Most options available in higher end “ESD guns” ESD3000 for about $3-5k or $200 for 1 wk rental
- XCOM relay is a Class 1A. M2, C2 device
- You really should characterize all three models
Overview

• Component Application

• Test Methods & Data
  – Performance Characterization
  – Environmental Reliability
  – Operational Lifetime
  – Operational Repeatability

• Future Work
Environmental Categories – JAN vs. ER

• JAN tested to MIL-PRF-39016/28776
• ER $T^2R$ tested to Teledyne Established Reliability Program™ requirements (highly regarded relay industrial rating)
• Allowable reliability failure rates (high!)
  – $A = T^2R$ 1.5% per 10,000 unit cycles
  – $B = T^2R$ 0.75% per 10,000 unit cycles
  – $L = JAN$ 3% per 10,000 unit cycles
  – $M = JAN$ 1% per 10,000 unit cycles
## Industrial Relay Testing – Subgroup 1

<table>
<thead>
<tr>
<th>Inspection Type and Rating</th>
<th>T²R B 1.5%/10k</th>
<th>T²R B .75%/10k</th>
<th>JAN L 3%/10k</th>
<th>JAN M 1%/10k</th>
</tr>
</thead>
<tbody>
<tr>
<td>Screening, Internal Moisture (custom Acceptable Quality Level sampling)</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Vibration (Sinusoidal) AQL sampling</td>
<td></td>
<td>Yes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vibration (Sinusoidal) 100% test</td>
<td>Yes</td>
<td></td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Screening, Burn-In (No semiconductor switching device)</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Screening, Run-In (Room Temp) (1000 cycles @ 1mA)</td>
<td>Yes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Screening, Run-In (+125 &amp; -65C) 1000 cycles @ 1mA)</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
</tbody>
</table>
# Industrial Relay Testing – Subgroup 2

<table>
<thead>
<tr>
<th>Inspection Type and Rating</th>
<th>T²R B 15%/10k</th>
<th>T²R B 75%/10k</th>
<th>JAN L 3%/10k</th>
<th>JAN M 1%/10k</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drive Functionality (Coil Equiv.)</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>(test electrostatic drive open/close)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insulation Resistance</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>(&gt;1MOhm drive and load pins)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dielectric Withstand Voltage</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>(120 drive pins, 200 V load pins)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Static Contact Resistance</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>(&lt;2.5 Ohms at 1 mA &amp; 4V comp.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turn-On and Turn-Off Voltage</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>(drive voltage &lt;90V, release &gt;20V)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turn-On and Turn-Off Time (DC)</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>(react close &lt;50 usec, open &lt;1 usec)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## Subgroup 2 - Continued

<table>
<thead>
<tr>
<th>Inspection Type and Rating</th>
<th>T²R B 1.5%/10k</th>
<th>T²R B .75%/10k</th>
<th>JAN L 3%/10k</th>
<th>JAN M 1%/10k</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hold Current (equiv. EMR Voltage) (&lt;1 uA relay, &lt;20 mA driver)</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Contact Repeatability (&lt;0.1 Ohm @ 1mA, 2 Hz, 1k cycles)</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Contact Bounce Window (&lt;50 usec total from drive close)</td>
<td>Yes</td>
<td></td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Contact Stabilization Time (+/-0.040 Ohm, &lt;100 usec total)</td>
<td></td>
<td>Yes</td>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td>Set/Reset Time &amp; Voltage, Neutral Screen, Coil Transient Suppression, Diode Integrity, and Break-Before-Make Testing not relevant for MEMS</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>
# Industrial Relay Testing – Subgroup 3

<table>
<thead>
<tr>
<th>Inspection Type and Rating</th>
<th>T²R B 1.5%/10k</th>
<th>T²R B .75%/10k</th>
<th>JAN L 3%/10k</th>
<th>JAN M 1%/10k</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solderability</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>(2/Lot 30 sec @ 250C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leak Test</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>(2/Lot Fine He Leak)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature Cycle</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>(2/Lot 1011.9 Cond B –55 to 125°C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liquid-Liquid Thermal Shock</td>
<td>Yes</td>
<td></td>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td>(2/Lot 1011.9 Cond B –55 to 125°C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant Acceleration</td>
<td>Yes</td>
<td></td>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td>(2/Lot 2001.2 Cond A 5 kG 1 min)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concrete Drop Shock</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>(2/Lot)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Overview

• Component Application

• Test Methods & Data
  – Performance Characterization
  – Environmental Reliability
  – Operational Lifetime
  – Operational Repeatability

• Future Work
Operational Lifetime

• **Warning: This Takes Time!**
  - Only take data meaningful to customers – pick power levels, duty cycles, speeds etc. carefully
  - Perform **parallel testing**, 4x, 8x, 16x whatever
  - Automate as much as possible, capture more data than you need if you can glean other value

• **Data Collection Process**
  - For RF MEMS, we pick 5 mW and 2 W to cover common power levels used
  - Hot switch and cold switch, run to definition of failure (death or exceeding 3 dB from optimal)
  - **Stop when Weibull plots converge**
  - Get testing with the customer precisely as needed for their application, otherwise you waste time and money
Lifetime – Cold Switch 5 mW

- **Long data sets, no convergence**
  - Baseline many hundreds of millions typical
  - Modified process ran for 1B, single part, no lifetime issue
  - Would like to get converged plot in multi-part test
Lifetime – Cold Switch 2 W

- **2W CW 50 Ohm, 1 kHz, modifications improve**
  - Look for 10% and 62.5% points on 50% confidence line
  - Characteristic life 84M baseline, modified parts 135M!
  - Hit 100M point required by customer, so ready to sample
Lifetime – Hot Switch 5 mW

- 5 mW CW 50 Ohm, 1 kHz, modifications improve
  - Characteristic life 420k baseline
  - Modified process parts 700k, almost a 2x improvement!
Lifetime – Hot Switch 2 W

- **2W CW 50 Ohm, 1 kHz, mods show significant gain**
  - Characteristic life 51k baseline
  - modified parts 205k, a 4x improvement!
Overview

• Component Application

• Test Methods & Data
  – Performance Characterization
  – Environmental Reliability
  – Operational Lifetime
  – Operational Repeatability

• Future Work
Repeatability Is Critical!

- Repeatability most challenging ATE specification – #1 reason for design win failures of MEMS in past
- Mid/high load repeatability easy to achieve; higher power helps makes a clean contact!
  - Application-specific load, speed, lifetime tests
- Low-load repeatability critical due to importance of low-power testing of wireless systems
  - Standard 1 mA test from HP 4338 w/20mV @ 2Hz
  - Cannot have single event >5 Ohms in 1000 cycle screen
  - 100% of all parts must pass
  - Must have 90% DCRT <40 mOhms in 1000 cycle screen
  - 100% of eval boards & test coupons must pass
- Industry already uses many compensation techniques for macro relay weaknesses
RF Repeatability, 2/Lot Screen

• Full Sweep to 10 GHz, find worst point
  – Plot window min, mean, max, and climb
• Cycle 100x, plot every 10^{th} cycle
  – Must have <0.02 dB window, no climb
• Cycle 1Mx, plot every 100,000^{th} cycle
  – Must have <0.04 dB window, no climb
• Cycle 10Mx, plot every 1M^{th} cycle
  – Must have <0.08 dB window over life
  – Window climb should also be <0.08 dB
Repeatability - RF

- RF repeatability validated by Teledyne cycle-sweep method
  - As expected, only variance is due to DC resistance evolution

![Graph showing error bars denoting 95% probability threshold.](image-url)
Repeatability – DC (AC) Low Load

Typical 4338 test for build lot
- Purple part fails (contamination)
- Red part high but passes
Repeatability – 1000 Cycle Variance

XCOM SPDT relay in standard package as tested on 4338

Standard 100% part screen 1000 cycles

Take all data, report only 90% DCRT

Example 22.5 mOhm

If below 40, ship it!

Test is costly, so adds to price, but proves each part good for high sensitivity apps
What About Repeatability Over Time?
Bin Size 1M Cycles (1 Trace/Part)
Bin Size 10k Cycles (10 Traces/Part)
Bin Size 10k Cycles (100 Traces/Part)
Bin Size 5k Cycles (200 Traces/Part)
Bin Size 1k Cycles (1,000 Traces/Part)
Oh, We’re Not Done Yet . . .

90% mark for 1K, 5K, 10K, 100K and 1M groups
Plot The Bins! NOW It’s Characterized

100k bin 90% DCRTs well behaved. . . you only have to calibrate this part every 100k (!) times you use it.

1M bin not well behaved
The 10k Bins Look Even Better

10k bins < 150 mOhm
5k bins < 100 mOhm
1k bins < 50 mOhm

Tightest tolerance ever seen in an application can wait to recalibrate every 1,000 uses!
Overview

• Component Application

• Test Methods & Data
  – Performance Characterization
  – Environmental Reliability
  – Operational Lifetime
  – Operational Repeatability

• Future Work
## Industrial Relay Readiness

<table>
<thead>
<tr>
<th></th>
<th>MRL 1 (Proven Worth)</th>
<th>MRL 2 (Production Intent)</th>
<th>MRL 3 (Production Start)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology Level</td>
<td>4-5</td>
<td>6-7</td>
<td>8+</td>
</tr>
<tr>
<td>System Insertion</td>
<td>Demonstrated</td>
<td>Well Tested</td>
<td>Fully Tested</td>
</tr>
<tr>
<td>Specs Validated</td>
<td>50%</td>
<td>90%</td>
<td>100%</td>
</tr>
<tr>
<td>Interface Phy/Elec</td>
<td>50%</td>
<td>90%</td>
<td>100%</td>
</tr>
<tr>
<td>Cost Achieve/Plan</td>
<td>CKP1B, 80% CKP2</td>
<td>80% CKP3</td>
<td>At Cost</td>
</tr>
<tr>
<td>Manufacturing</td>
<td>Demo</td>
<td>Proven</td>
<td>Ready</td>
</tr>
<tr>
<td>Processes</td>
<td>Nearly Complete</td>
<td>Complete</td>
<td>Complete</td>
</tr>
<tr>
<td>Equipment</td>
<td>Cost Estimated</td>
<td>Cost/Plan Done</td>
<td>In Place</td>
</tr>
<tr>
<td>Reliability &amp; Char.</td>
<td>90% Part</td>
<td>90% System</td>
<td>100% System</td>
</tr>
<tr>
<td>Failure @ System</td>
<td>75% / 25%</td>
<td>100% / 75%</td>
<td>100% / 100%</td>
</tr>
<tr>
<td>Ops Test/Eval Plan</td>
<td>Considered</td>
<td>Initiated</td>
<td>Complete</td>
</tr>
</tbody>
</table>
Recap Product History

• Product looked great, but cost was too high
• Solved yield root cause over two years, modified packaging to accommodate
• Established characterization, testing, and screening requirements based on JEDEC, MILSTD, and relay industry standards
• Reliability qualification completed (twice)!
• Manufacturing qualification incomplete
• System-level assessment finally underway
RF MEMS Future

• Ramp Industrial Relays
  – XCOM sampling
  – OMRON starting ramp
  – Radant & others sampling

• High-End Circuit Products
  – Matrix & tuner development
  – Phase shifters qualifying

• Consumer Products?
  – EPCOS, WiSpry, Cavendish
  – New players? Consolidation?

• Activity & Excitement!

Simulation; No RF MEMS parts are presently incorporated into RFMD power amplifiers or used in Samsung handsets
P/A image used without permission