Reliability Without Hermeticity: Commercial Vapor Deposited Coatings for High-Frequency RF Micro-Electronics

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Trends in Electronics

• Higher performance, lighter, smaller footprint, lower cost
• Packaging has a significant impact on size, weight and cost (SWAP-C)
Industry Status Quo for Environmental Protection

- Digital and low RF frequency (<8 GHz)
  - PCB Design
  - Environmental housing (non-hermetic)
  - Conformal Coatings (100’s of μm)
    - Wet applied polymers (polyurethanes, silicones)
    - Thicker, vapor applied polymers (parylene)

- RF and Microwave frequency (>8 GHz)
  - Module Design
  - Metal or Ceramic Hermetic Packaging
Why is the Status Quo an Issue?

- Hermetic packaging is expensive (custom-made), heavy, requires significant space.
- Conventional conformal coating’s dielectric constant severely impacts RF circuit performance (can’t be applied directly to active components).
- High frequency RF and microwave devices are compatible only with hermetic packaging or no protection at all.
- **No viable alternative** as a replacement for hermetic packaging.
- Critical Concerns:
  - RF compatibility
  - Environmental protection
  - Cost-efficiency
  - Scalability
Solution: Ultra-Thin Vapor Deposited Conformal Coatings

A low-temperature coating process which produces thin polymer coatings on almost any material.

- “Gentle” application
- low temperature (20-100°C)
- dry process (no solvents)
- single-step (no drying/annealing)
- nano- to micro- meter thickness control (1-3 µm typical)
- conformal on nano- and micro- structures
- minimal/no RF impact
C. Coating Enables Packaging Design Improvements

RF-compatible ultra-thin vapor deposited coatings allows RF systems designers to use printed circuit board technology

- Reduced packaging material cost (>50%)
- Reduced design lead time (20%)
- Reduced material lead time (>60%)
Hermetic Protection vs. Conformal Coating

• Hermetic Packaging seals electronics within impermeable housing
  – Validated with leak-rate tests
  – Low-permeability, inorganic materials required

• Conventional (polymer) conformal coatings are not impermeable
  – **No polymer is hermetic** – many coatings act as pseudo-barriers via sheer thickness

• Ultra-thin conformal coatings
  – **Adhesion** is critical to environmental protection, not low permeability
In High Relative Humidity

Well Adhered Polymer
• Molecular-level coverage of surface
• No room for condensation
• Stable in presence of water molecules

Poorly Adhered Polymer
• Regions of poor adhesion
• Readily displaced by water molecules
• Open surface sites allow for condensation, resulting in conductive pathways

(surface conductivity (S/cm))

(Wet)

(Polymer Coating)

Magnified View of PCB Surface

RF Performance Measurements

- Conformal coating causes no measurable increase in insertion loss up to 50GHz on 50ohm transmission lines. (Testing carried out by Rogers Corp.)

- Conformal coatings show negligible impact on S-parameters, gain, isolation, return loss before and after 8 days environmental exposure at 85°C/85%RH. Samples tested to 20GHz. (Testing carried out by major defense contractor)

Insertion Loss of 50 Ω Microstrip on 0.0047” Rogers RO4350B Laminate
(Red lines show approx. limits of reproducibility in RF measurement)
## Summary of RF Data

<table>
<thead>
<tr>
<th>Feature</th>
<th>Test Freq. (GHz)</th>
<th>Performance Degradation</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>MMIC SPDT Switch</td>
<td>100</td>
<td>0.7 dB</td>
<td>Minor degradation</td>
</tr>
<tr>
<td>MMIC LNA</td>
<td>100</td>
<td>1.3 dB</td>
<td>Minor gain degradation</td>
</tr>
<tr>
<td>Balanced Ampl. Config.</td>
<td>35</td>
<td>2.9 dB</td>
<td>Moderate gain degradation</td>
</tr>
<tr>
<td>MMIC SPDT Switch</td>
<td>37</td>
<td>0.2 dB</td>
<td>Minor degradation</td>
</tr>
<tr>
<td>Coupled line band pass filter</td>
<td>35</td>
<td>0.2 dB</td>
<td>Minor degradation in bandwidth and insertion loss</td>
</tr>
<tr>
<td>Coupled line band pass filter</td>
<td>17.6</td>
<td>0.5 dB</td>
<td>Minor degradation in bandwidth and insertion loss</td>
</tr>
<tr>
<td>Branchline Couplers back to back</td>
<td>35</td>
<td>0.07 dB</td>
<td>No degradation in bandwidth and insertion loss</td>
</tr>
<tr>
<td>2-inch 50 Ω microstrip line</td>
<td>40</td>
<td>0.01 dB</td>
<td>No degradation in bandwidth and insertion loss</td>
</tr>
</tbody>
</table>
## Results of Environmental Exposure

<table>
<thead>
<tr>
<th>Test</th>
<th>Method</th>
<th>Description</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salt Fog</td>
<td>ASTM B117</td>
<td>500 hours of exposure</td>
<td>PCB covered in salt crystals; PCB operational with no signs of metal corrosion</td>
</tr>
<tr>
<td>Humidity</td>
<td>JESD22-A101C (not biased)</td>
<td>1,000 hours of exposure</td>
<td>PCB operational with no signs of metal corrosion</td>
</tr>
<tr>
<td>Immersion</td>
<td>N/A</td>
<td>Electrode soaked for 7 years in salt water under sweeping +/- 5V bias</td>
<td>No drop in resistance across the coating, indicating no degradation</td>
</tr>
</tbody>
</table>

Images of coated board (1 µm thick coating) with lower contacts masked and an uncoated board after Salt Fog testing per MIL-STD-810G Method 509.5
Coating Advantages – Avoiding Hydrogen Poisoning

- **Hermetic Packaging**
  - Metal components used in manufacture can outgas hydrogen
  - Sealed environment results in hydrogen build-up
  - Results in ‘poisoning’ of GaAs and InP devices

- **Conformal Coating**
  - Open (non-sealed) environment over coating does not allow hydrogen build-up

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**Protective Coating: Not a Sealed Environment, Partial Pressure of Hydrogen Kept <0.1%**
Multiple Levels of Protection

- **Level 1: Chip-Level Protection**
  - Protects bare die from Foreign Object Debris
  - Provides Structural Support for air bridges without significant RF impact
  - Last Line of Defense of reliability w/o hermeticity

- **Level 2: Package-Level Protection**
  - Non-Hermetic seals and materials reduce weight/cost of packaging
  - Exilis Protective Layer to provide extra reliability w/o hermeticity
  - Can coat Individual or Board-Mounted Packages
  - Hydrophobic Layer to reduce impact of condensed moisture

- **Level 3: Board-Level Protection**
  - Exilis Protective Layer for environmental protection of board traces (RF and otherwise)
  - Improved Rework compared to hermetic packaging, Parylene, and other coatings
**Other Conformal Coating Requirements:**

<table>
<thead>
<tr>
<th>Area of Need</th>
<th>Ideal Coating Behavior</th>
</tr>
</thead>
<tbody>
<tr>
<td>Connector Masking</td>
<td>Easy to Mask and does not require painstaking coverage to prevent coating of connecting pins/surfaces</td>
</tr>
<tr>
<td>Demasking</td>
<td>Easy demasking with no coating peelback or delamination</td>
</tr>
<tr>
<td>Handle-ability</td>
<td>Coating withstands normal handling</td>
</tr>
<tr>
<td>Rework</td>
<td>Coating easily removed using standard processes (microparticle abrasion, reactive ion etch)</td>
</tr>
<tr>
<td>Touch-Up</td>
<td>Coating easily redeposits to both coated and uncoated regions with good adhesion</td>
</tr>
<tr>
<td>Coating Time</td>
<td>&lt;2-4 hrs for 1 to 3 µm thick coating. Shorter deposition time = lower chamber maintenance costs.</td>
</tr>
<tr>
<td>Thermal stability</td>
<td>Able to withstand contact with high temperature devices during operation.</td>
</tr>
</tbody>
</table>
Reworkability: Other Protective Solutions

Hermetic Packaging
- Defective small packages rarely repaired
- Requires the welded lid of larger units to be milled away
  - Time-consuming and expensive
- Rework introduces conductive foreign debris to sensitive electronics

Parylene and other conventional coatings
- Major bottleneck due to labor-intensive processing
- Reduced system reliability due to:
  - Poor adhesion increases risk of moisture ingress
  - Challenging masking/demask increases risk of localized failure
Reworkability: Optimally Designed Conformal Coating

Conformal Coating (<2 µm) applied to B-25A IPC Test Board

- **Processing:** Masking and demasking are easy processes, do not require scoring, result in a clean de-masking line.
- **Rework of a faulty component:** Remove the component as if the coating were not present. Replaced components demonstrated to pass solder joint life testing.
- **Coating reapplication:** Can be reapplied to the entire PCB or selectively applied via masking methods.
Compatible with Board Cooling Techniques

- Thin (≤ 1 μm) coatings do not impede cooling
- No need to mask high-power, hot-running chips reduces masking preparation prior to coating
- Thermally stable to 200°C, can be treated to be stable up to 250°C
Commercial Coating Systems

- Small facility footprint
  - 14’ x 28’
- Vapor Coating System:
  - Dimensions:
    - Length: 40”
    - Width: 20”
    - Height: 12”
  - Recipe-driven controls
  - Automated for repeatability and ease for production
Summary

• Ultra-Thin, Conformal Polymer coatings are a viable method for achieving Reliability Without Hermeticity
• Compatible with RF microelectronics
• Can be applied on multiple levels (wafer, package, and board)
• No impact on thermal control
• Enables new types of combined RF-Digital boards