Advanced RF MEMS Switch Devices using Glass Packaging

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Corning Precision Glass Solutions

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Outline

• Development of Glass as a Substrate and Packaging Material
  – Material properties
  – Supply Chain

• Evolution for Radio Frequency Front Ends

• RF Applications
  – LC-based Filters
  – MEMS Switches
The inherent properties of glass make it an excellent material of choice for RF and MEMS

<table>
<thead>
<tr>
<th>Properties of glass</th>
<th>MEMS and RF</th>
<th>Packaging</th>
<th>As a Carrier</th>
<th>MEMS Capping Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range of CTEs</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Optical transparency</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Low electrical loss</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flatness &amp; smoothness</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Stiffness</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Variety of thicknesses</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Scalability</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
</tbody>
</table>
Leveraging Material Properties into Performance Advantages

Glass wafers tailor-made to specific applications

Wafer w/TGV

RF Modules System
Glass’ low electrical loss enables integration for RF modules

MEMS capping
Glass caps create a strong seal which addresses hermeticity for MEMS

Glass wafer

Wafer w/ cavities

Glass window
Gap
MEMS
Corning’s Through Glass Via Capabilities
We’ve made significant investments in precise TGV manufacturing

<table>
<thead>
<tr>
<th>TGV (Glass + Vias)</th>
<th>Metallized TGV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td></td>
</tr>
<tr>
<td>Wafer: up to 300mm diameter</td>
<td></td>
</tr>
<tr>
<td>Panel: up to 500x500mm</td>
<td></td>
</tr>
<tr>
<td>Thickness</td>
<td>100µm - 500µm</td>
</tr>
<tr>
<td>Via Diameter</td>
<td>30µm - 100µm $\rightarrow$ &lt;30µm</td>
</tr>
<tr>
<td>Pitch</td>
<td>Min. 2x via diameter</td>
</tr>
<tr>
<td>Process Control</td>
<td>Positional accuracy: $&lt;\pm$ 10µm</td>
</tr>
<tr>
<td>Yield</td>
<td>42% improvement since '18</td>
</tr>
<tr>
<td>Metrology</td>
<td>26x faster throughput since '18</td>
</tr>
<tr>
<td>Volume</td>
<td>100s per month $\rightarrow$ 1000s in '19</td>
</tr>
<tr>
<td>Process Control</td>
<td>90% production grade selects</td>
</tr>
<tr>
<td>Partners</td>
<td>Multiple in Asia and US</td>
</tr>
<tr>
<td>Volume</td>
<td>100s per month</td>
</tr>
</tbody>
</table>

Precision via control at high throughput; Capabilities to make different via shapes
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• Use Cases
  – LC-based Filters
  – MEMS Switches
Handset RFFE evolution

4G → 5G is increasing demand for high performance substrates like glass with precision vias

4G/LTE Module

Example of 5G Module

- # of Frequency bands increasing
- Usage of MIMO increasing module count
- Integration and low loss instrumental for low cost

<table>
<thead>
<tr>
<th>Addressable with TGV</th>
<th>Potential for TGV</th>
</tr>
</thead>
</table>

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High Q inductors/capacitors have been demonstrated

- Completed LC Network
- High Q inductance from 3D Solenoid inductor
- Capacitance achieved through MIM structure

Source: Yun, Kuramochi, Shorey, “Through Glass Via (TGV) Technology for RF Applications”, IMAPS 2015, Orlando, FL
## Inductor Structures Compared

<table>
<thead>
<tr>
<th>Inductor type</th>
<th>Inductance@100MHz (nH)</th>
<th>Q&lt;sub&gt;PEAK&lt;/sub&gt;@F /GHz</th>
<th>Q @900MHz</th>
<th>SRF (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LTCC</td>
<td>2.0</td>
<td>80 @ 3.95</td>
<td>55</td>
<td>8.68</td>
</tr>
<tr>
<td>TGV (SG3)</td>
<td>2.0</td>
<td>108 @ 3.95</td>
<td>61</td>
<td>&gt;10</td>
</tr>
<tr>
<td>2D Glass</td>
<td>1.9</td>
<td>70 @ 5.94</td>
<td>27</td>
<td>&gt;10</td>
</tr>
<tr>
<td>HRS</td>
<td>1.9</td>
<td>64 @ 4.48</td>
<td>25</td>
<td>&gt;10</td>
</tr>
</tbody>
</table>

![2D HRS inductor](image1.png)

![2D Glass inductor](image2.png)

![TGV inductor](image3.png)

![LTCC inductor](image4.png)
Metal on glass achieves much smoother surfaces

Cu on glass

Source: U. of Florida

Ag on LTCC

Source: S. Rane et al Soldering and Surface Mount Technology
Handset RFFE evolution
TGV IPDs offer lower RF loss and small form factor

80% higher Q (lower RF loss) vs. Si
- Use same battery → Increase talk time
- Use smaller battery → Save space
- Use cheaper battery chemistry → Save up to ¥2/ phone

5-10X more components, same footprint
- Smaller thinner components → slim devices
TGV IPD prototypes show high Q and low capacitance, which validates our model

- First TGV IPD prototype designed at sub-3 GHz shows higher Q (peak 70) vs. Si (peak 60) → Next, we are developing sub-7 GHz bandpass filter
- Developed knowledge in TGV and metallization processes with fab partners
- We would like to propose jointly developing prototypes with your design
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**RF Switches**

Menlo Micro introduces an ideal switch enabled by Corning TGVs

- **Simple & Scalable**
  - Simple design lets us go very small (50μmx50μm unit cell)
  - Small → easy to scale power-handling through massive switch arrays
  - Small → easy to scale cost with volume: low-cost-roadmap

- **Unique glass packaging**
  - Better thermals & power handling
  - Improved RF performance

- **Through Glass Via**
  - Lower parasitics
  - Lower resistance
  - Smaller size package
  - Lower cost

- **Versatile**
  - Standard PDK to create many products
  - Shorter design cycles → Quicker to market

- **Reliable**
  - >3B cycles spec w/ roadmap to >20B
  - High-power capable
How is it made?

*Revolutionary materials & processing combined with standard, scalable semiconductor manufacturing techniques*

### Wafer-Level Manufacturing

- **Wafer-scale manufacturing on 8 inch (200mm) glass substrates**
- **Scalable series / parallel switch architecture: Design ability to scale up to 1000V+ and 10A+**
- **Through Glass Vias Miniaturized packaging with highest performance**
- **Wafer Level Chip-Scale-Package from 16mm² to < 1mm²**

### Application-Specific Configurations

- **Core Switch**
  - Simplest, smallest building block can be integrated into many power or RF applications.
- **Switch with integrated controls**
  - Simpler control for high channel counts, decrease need for external components
- **Multiple Switch die, w/routing & control**
  - For matrix and high-density switching systems.
- **System-on-Chip**
  - Integrate passives & other structures on die along with Menlo switches to create miniaturized RF & Power subsystems.

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**RF Switches**

Metal-on-glass platform creates ideal RF environment for low Ron*Coff

- For SOI, Ron*Coff is measured for **single transistor**
- Actual **switch product** needs transistor stacks for up to 80V

**Table:**

<table>
<thead>
<tr>
<th>Parallel</th>
<th>Series</th>
<th>$R_{On}$ (Ohms)</th>
<th>$C_{Off}$ (fF)</th>
<th>$S21$-on @ 6Ghz (dB)</th>
<th>$S21$-off @ 6Ghz (dB)</th>
<th>Power Handling</th>
<th>Standoff Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1.16</td>
<td>6.2</td>
<td>0.10</td>
<td>32.5</td>
<td>26 dBm (0.4W)</td>
<td>150 V</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>1.6</td>
<td>7.6</td>
<td>0.18</td>
<td>45.0</td>
<td>26 dBm (0.4W)</td>
<td>300 V</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>0.86</td>
<td>14.2</td>
<td>0.09</td>
<td>24.5</td>
<td>35.5 dBm (3.5W)</td>
<td>150 V</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>0.72</td>
<td>17.3</td>
<td>0.10</td>
<td>37.5</td>
<td>35.5 dBm (3.5W)</td>
<td>300 V</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>0.86</td>
<td>18.5</td>
<td>0.11</td>
<td>20.0</td>
<td>40 dBm (10W)</td>
<td>150 V</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>0.80</td>
<td>28.3</td>
<td>0.14</td>
<td>31.5</td>
<td>40 dBm (10W)</td>
<td>300 V</td>
</tr>
</tbody>
</table>

*Various DMS unit cell configs measured at RF probe

- Single series beam: Ron*Coff from **7 to 16fs**
- Dual series beam: Ron*Coff from **12 to 23fs**
- Significant margin for Vpeak, with power handling to go beyond UE

Source: Peregrine Semiconductor’s next-generation platform, UltraCMOS® 12 technology
RF Switches

Lowest Losses from DC to mmWave

Advances in wafer-level glass packaging show mmWave performance is achievable

Previous generation of packaging (2017/2018)

Current generation of packaging

With TGV, everything gets better from an RF point of view:
- Lower parasitics, Lower bulk resistance/IL
- Improved thermals, better power handling
- Smaller size, lower cost

0.7dB IL at 28GHz
Reliability Testing shows Stable Operation

Continuous reliability testing for accelerated life evaluation:

- Multiple parallel automated testers capable of 20 die evaluation
- 3 ovens in operation at 3 different acceleration temperatures
- >10,000 die evaluated

Stable resistance <0.4Ω for over 12 billion cycles
SPST 50W and 6GHz capability

- **Switch ON:**

<table>
<thead>
<tr>
<th>Freq</th>
<th>S11</th>
<th>S21</th>
<th>S12</th>
<th>S22</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Ghz</td>
<td>-32.48dB</td>
<td>-0.056dB</td>
<td>-0.061dB</td>
<td>-32.093dB</td>
</tr>
<tr>
<td>3 Ghz</td>
<td>-27.19dB</td>
<td>-0.100dB</td>
<td>-0.097dB</td>
<td>-33.716dB</td>
</tr>
<tr>
<td>6 Ghz</td>
<td>-19.00dB</td>
<td>-0.148dB</td>
<td>-0.156dB</td>
<td>-17.302dB</td>
</tr>
</tbody>
</table>

- **Switch OFF:**

<table>
<thead>
<tr>
<th>Freq</th>
<th>S11</th>
<th>S21</th>
<th>S12</th>
<th>S22</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Ghz</td>
<td>-0.058dB</td>
<td>-24.809dB</td>
<td>-24.920dB</td>
<td>-0.097dB</td>
</tr>
<tr>
<td>3 Ghz</td>
<td>-0.535dB</td>
<td>-16.256dB</td>
<td>-16.557dB</td>
<td>-0.644dB</td>
</tr>
<tr>
<td>6 Ghz</td>
<td>-0.647dB</td>
<td>-10.229dB</td>
<td>-10.634dB</td>
<td>-0.916dB</td>
</tr>
</tbody>
</table>
**RF Switches**

**Packaging evolution**

<table>
<thead>
<tr>
<th>Year</th>
<th>Part Number</th>
<th>Package Type</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>2017</td>
<td>MM7100</td>
<td>WL Glass w/TGV</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>9x9mm</td>
<td>Mems</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BGA w/SPI</td>
<td></td>
</tr>
<tr>
<td>2018</td>
<td>MM3100</td>
<td>WL Glass w/TGV</td>
<td>Mems</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6x6mm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>BGA w/SPI</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>+ Glass cap Mems</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>+ Package Substrate</td>
<td></td>
</tr>
<tr>
<td>2019</td>
<td>MM5120</td>
<td>WL Glass w/TGV</td>
<td>Mems</td>
</tr>
<tr>
<td></td>
<td>MM3100</td>
<td>4x4mm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>MM5130</td>
<td>2.6x2.6mm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>MM5130</td>
<td>1x1mm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>WL-BGA</td>
<td></td>
</tr>
</tbody>
</table>

Corning-Menlo partnership is enabling the scale-up of a low cost TGV supply chain
RF Tunable Filter – Size, Weight & Power for RF

MM3100 Replacing PIN diodes in tunable radios

Potential to enable high power handling (5W-20W) in a 2W form factor

<table>
<thead>
<tr>
<th>Benefits:</th>
</tr>
</thead>
<tbody>
<tr>
<td>• 10x increase in power handling</td>
</tr>
<tr>
<td>• 80%+ reduction in components</td>
</tr>
<tr>
<td>• 75% reduction in board size</td>
</tr>
<tr>
<td>• Reduced need for thermal management, smaller box</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>With PIN diode</th>
<th>With DMS Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max input:</td>
<td>&lt;2W</td>
<td>20W+</td>
</tr>
<tr>
<td>Size:</td>
<td>200+ components (2-sided board) 50% area for complex pin-diode switch biasing</td>
<td>~25 components No pin-diodes, single-sided board, simple bias scheme</td>
</tr>
<tr>
<td>Insertion Loss:</td>
<td>&gt; 3dB @ 500MHz</td>
<td>&lt; 2dB @ 500MHz</td>
</tr>
<tr>
<td>Power Consumption:</td>
<td>1.2W</td>
<td>&lt;100mW</td>
</tr>
<tr>
<td>Linearity:</td>
<td>IP3: ~40dBm</td>
<td>IP3: ~65dBm</td>
</tr>
</tbody>
</table>

Key metrics:
- Fast frequency tuning
- Lightweight
- Long battery life
- Reliability

Ex. Mil Radio

With PIN diode
UHF interstage (2W)

With DMS Technology
UHF interstage (20W)
Glass and Through Glass Vias (TGV)

Interposer (Photonics, High Performance Computing)

Radio Frequency Front End (RFFE)

High Performance Substrate Material

Filters, antennas, switches in mobile phones, telecom infrastructure, medical equipment

Re-routes connection between layers inside a semiconductor package (ie chip) using through vias (ie holes)
Summary

• Material properties being leveraged into device level performance benefits
• RF Front End Usage cases broadening into Filters, Switches, Antennas
• RF MEMS Switches gain on:
  – Insertion Loss
  – Figure of Merit
  – Harmonics
  – Packaging Footprint
  – Thermal/Power Handling