The Ideal Switch®: Glass-based device with demonstrated reliability

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Abstract
Menlo Microsystems has introduced a MEMS switch that utilizes both a glass substrate and a glass cap with through glass via (TGV) technology to provide an all-glass packaging solution. The MEMS switch technology, created in the R&D labs at GE, combined with an all-glass packaging solution, has resulted in the Ideal Switch®. It is the world's smallest, most reliable, and efficient micro-mechanical switch that has been used in numerous RF and power applications. The Ideal Switch® gains superior performance as well as mechanical, electrical and thermal reliability from several aspects of the MEMS and glass packaging design including robust electrical contacts, low electrical loss of glass, and hermetic TGVs which provide a well-controlled environment. This controlled environment is crucial for attaining reliable performance over billions of cycles. In addition to long lifetimes, parasitic are reduced by >75% vs. Si based RF devices enabling the devices to have a wide operational bandwidth from DC to > 50 GHz.

To enable the volume manufacture of this device Menlo has driven advancements in the glass supply chain, leveraging mostly standard semiconductor manufacturing processes for use on glass substrates (with and without TGV). The device contains multi-layer plated and deposited structures, hermetic wafer level glass to glass bonding, post-bond die singulation and device packaging in multiple formats. These devices pass standard JEDEC reliability testing and have operational lifetime in excess of 3 billion cycles. In this presentation we will discuss a number of advanced packaging processes employed by Menlo in the volume manufacturing process as well as key performance metrics of the Ideal Switch®. Early failure modes seen from this glass-based device are also discussed as well as solutions Menlo has established. Reliable performance relative to JEDEC standards is demonstrated.

Key words
MEMS, Ideal Switch, Glass, TGV, Reliability, Switch

I. Introduction
There has been a lot of progress in establishing glass-based microelectronics solutions over the past several years. [1-5] The advantages include low electrical loss, ability to provide thin and large format (panel-based) solutions by leveraging capabilities enabled by the Display industry, as well as ability to tailor material properties by adjusting the glass composition. Furthermore, there have been numerous demonstrators and prototype devices that have been fabricated showing the advantages provided by glass-based devices. However, there have been some hurdles to overcome in the transition of proof-of-concept devices into reliable volume manufacturing environments. Over the past few years, the supply chain gaps have started to close or have closed, making volume manufacture of glass-based devices a reality. This has facilitated the advancement of the ability to handle glass thus allowing for process demonstration and product reliability to be tested. Menlo has demonstrated the ability to process glass through assembly, test, final package and industry standard reliability testing.

The combination of glass, an excellent electrical insulator, and metal, an excellent electrical conductor, in a MEMS device platform enables next generation DC to RF switching technology. This electrostatically actuated cantilever-based MEMS device represents an important advancement in MEMS switching technology, providing state of the art contact/electrical reliability, robust package reliability and stable RF performance across a range of temperatures.

II. Glass Technology

Significant progress in the manufacturability of glass vias (TGV) has been made over the past decade. Examples of this are shown in Fig. 1. Furthermore, we have seen a lot of advances from the glass companies [6-8], vertically integrated TGV solutions provided by suppliers such as Samtec [9], 3DGS [10], Mosaic Microsystems [11], as well as companies with associated metrology and handling solutions. While TGV in early demonstrators were often susceptible to cracking (e.g. see Fig. 2), development over the past several years has led to the capability to avoid TGV cracking and maintain hermetic TGV performance after large thermal excursions in excess 300°C and thermal shock tests. These improvements have allowed Menlo Microsystems to develop their glass-based Ideal Switch® which benefits from the advantages offered by utilizing glass packaging.

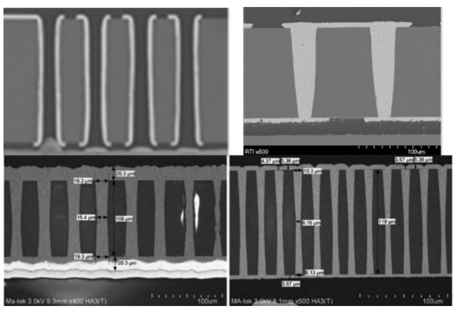

Fig. 1: Cross-section images of various forms of TGVs. [1, 2, 6]

Fig. 2: Example of a circumferential crack around a TGV. Processes have been developed to avoid this crack formation.

III. The Ideal Switch® - Glass based MEMS Device

Menlo Microsystems has introduced a glass-based MEMS switch that utilizes through glass via (TGV) technology to provide an all-glass packaging solution. Created in the R&D labs at GE, these MEMS solutions combined with the utilization of glass packaging have enabled the creation of the highly reliable Ideal Switch®. It is the world's smallest, most reliable, and efficient micro-mechanical switch that can be used for numerous RF and power applications.

As described above, leveraging the insulating properties of glass along with the highly conductive metal beams provides performance characteristics not available in other relay switch technology. An example of the 2-layer glass-device is shown in Fig. 3. An image of one die is shown in Fig. 3a and the cross-section shown in Fig. 3b. The top glass layer contains TGVs that allow for electrical connection to actuate the beams, which are enclosed in a cavity between the two glass layers. The TGV and the metallic bonds between the glass layers provide a hermetically sealed structure that leads to stable performance and long lifetimes. Devices can have dozens of switches in a small form factor that give reliable performance over billions of cycles. Fig. 4 shows an example of the low insertion loss over a range of frequencies up to 20 GHz in this case.

The TGV technology utilized in Menlo's design provides further advantages in conjunction with the glass packaging solution. [7] Namely:

- >60% smaller package size relative to wire bond. (die size as low as 2.5 mm)
- >75% reduction in parasitic
- Devices with a wide operational bandwidth - from DC to > 50 GHz.

A. B.

Fig. 3: All glass 2-layer design of Menlo Microsystems' Ideal Switch®. A. Image of the device and B. schematic of the cross-section showing the MEMS beam and TGV arrangement.

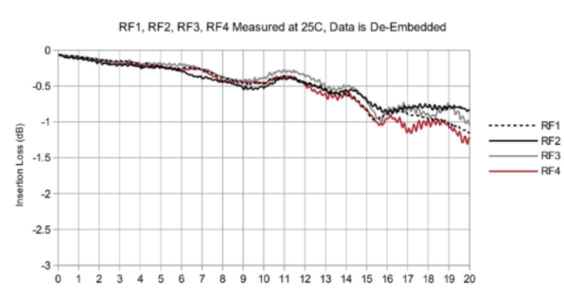

Fig. 4: Example of insertion loss measured on glass-packaged MEMS Ideal Switch®

Another advantage of the Menlo Micro's Ideal Switch® is that it is manufactured in a wafer format using processes consistent with those used to produce silicon-based devices. This is important for manufacturability and scalability. Over the past several years, Menlo has matured a nascent glass supply chain and driven significant advancements in manufacturability and reliability from everything from glass wafer supply through final package and test. This includes a range of different operating environments from room temperature operating lifetime (RTOL), high temperature operating lifetime (HTOL). Most recently reliable performance has been demonstrated at cryogenic temperatures for quantum computing applications, as well as in vacuum environments for space-based applications.

IV. Reliability Testing

A. Test Conditions

When testing MEMS switches, it is important to ensure that the test systems and protocols are not, in themselves, causing failures. Most importantly, it is critical that there is no hot switching occurring during cycling of the switch. [12].

To ensure the test system is not hot switching, the contact and beam terminals should be grounded whenever the gate terminal is transitioning. Because it is easy to make a logic or timing error in the test program, it is critical to verify this grounding with an oscilloscope.

Another potential source of hot switching is capacitive coupling between the gate line and the contact or beam nodes. Any parasitic capacitance in these paths allows a C*(dv/dt) current to flow when the gate is switched. If the contact or beam nodes have high resistance, the resulting voltage spike on those nodes can be significant, causing hot switching and shortening device lifetime. This issue can be mitigated by shielding the gate line or reducing both the parasitic capacitance and the resistance of the beam and contact nodes. As mentioned previously, it is always good practice to verify the absence of hot switching with an oscilloscope.

B. Electrical/Mechanical Reliability

Some common electrical/mechanical failure modes that can plague MEMS switches are beam creep, fatigue and contact degradation. [13, 14] Beam creep occurs when a constant load is applied which results in plastic deformation of the beam structure over time while fatigue occurs when a repeating load is applied which eventually reduces the strength at the load point, leading to damage. In operation, this is seen as unstable actuating voltage, reduced restoring force or pull-off voltage and, eventually, complete failure

Key innovations in cantilever metallurgy utilized in the Ideal Switch® (Fig. 5) result in structures that give increased strength, creep resistance and stable actuation voltage. The alloy's compositions were engineered to maintain both grain stability and minimal strain rate for typical MEMS loads. [15] The plot demonstrates that beams made with the Ni alloy withstand higher temperature and stresses than more typical Au alloys. Functionally, this leads to longer life performance. This data was used to identify compositions suitable for the Ideal Switch®.

The standoff lifetime of a metal MEMS switch can be predicted by measuring the change in actuation pull-in voltage (VPI) due to beam creep occurring from extended hold down tests at different conditions. [16] Since creep is permanent and irreversible deformation of the beam, it impacts the lifetime of the device. As the gap decreases due to beam creep, the VPI will also decrease in a predictable fashion so that the change in VPI over time can be used to predict when the gap has fallen below a critical value required for the specified standoff voltage. Fig. 6 shows modeled and measured change in VPI for the Ideal Switch® beam alloy material over 1000 hours and modeled values beyond 10 years for various operating temperatures. This beam alloy material is predicted to exhibit less than 10V change in VPI at temperatures of 85 ^{O}C and below over 10 years. This means that the Ideal Switch® has a predicted standoff lifetime of greater than 10 years.

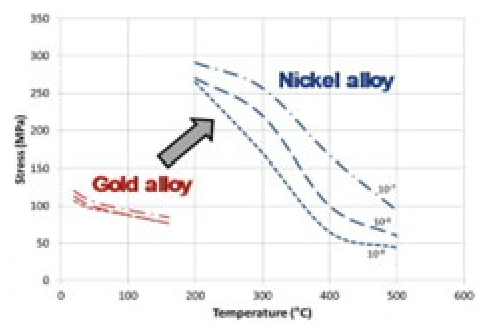

Fig. 5: Strain rate curves as a function of applied stress (derived from load time data)

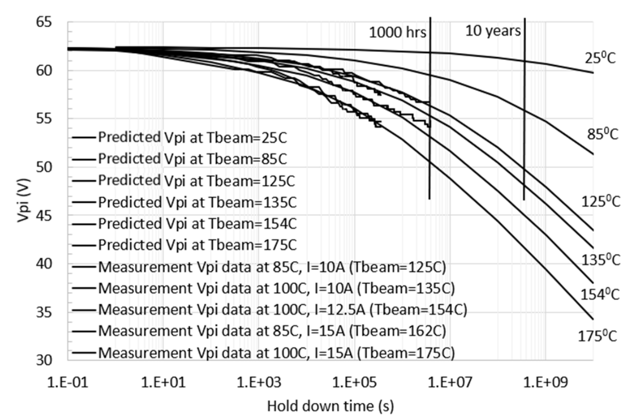

Fig. 6: MEMS switch creep lifetime prediction curves against measurement of VPI droop data at different conditions.

Contact degradation with cycling occurs when the switch contact surfaces become damaged or deformed with repeated direct contact. This can result in failures due to material transfer, contact breakdown or asperity flattening, the latter increasing contact surface area which can, in turn, cause the contacts to stick closed. To prevent these failure mechanisms, material selection and surface preparation of the contacts become critical in the MEMS design. For example, pure metal contacts can become "sticky" over cycles, resulting in the switch staying closed for longer after reducing the gate voltage. The effect is that the voltage at which the beam releases, the pull-off voltage (VPO), is reduced over cycles. This "VPO droop" is a clear indication that the contacts are "sticky" and will eventually result in a stuck-closed failure. Depending on the nature of the contact damage, this stuck-closed failure may or may not be reversible. Fig. 7A shows an example of a device with a VPO droop, indicating sticky contacts, and an example of a device with a metal oxide, such as RuO_2, contact which does not become sticky with cycles (Fig. 7B).

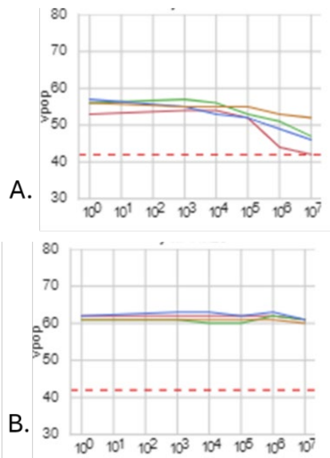

Fig. 7: Example of pull-off voltage over cycles for a device with (A) VPO droop and (B) flat VPO over cycles. Each line in the plot is for each of the 4 channels on the device.

Another contact related failure mode is the contamination of the contacts with a frictional polymer which can result in high resistance or stuck open fails (Fig. 8). Ru based contacts are particularly susceptible to this failure mode because of the tendency of ruthenium to catalyze the formation of carbon films on the contact surface [17]. The source of the organic contamination can stem from organic contamination on the MEMS itself, (i.e. residual photoresist) and/or non-hermetic packaging. It is critical to minimize the exposure to organic compounds, such as photoresist, during processing post beam release. In addition, ensuring a hermetically sealed environment for the switch, with well controlled gas composition, helps to minimize this organic buildup on the contacts by minimizing the available carbon species in the gas within the device cavity. It has been demonstrated that when cycled in open air, or a non-hermetic package, the carbon-based film that collects on the contact points results in a rapid increase in the measured resistance causing failures significantly earlier than normal. Typically, this resistance signature is seen as an exponential increase in this measured resistance over cycles that continues until the resistance is high enough that it results in a stuck open failure (Fig. 9). When cycling in a clean, well-controlled environment, the resistance should be flat over millions and even billions of cycles (Fig. 9B).

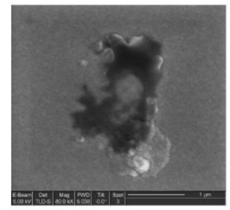

Fig. 8: Localized carbon contamination identified during post-cycling contact evaluation.

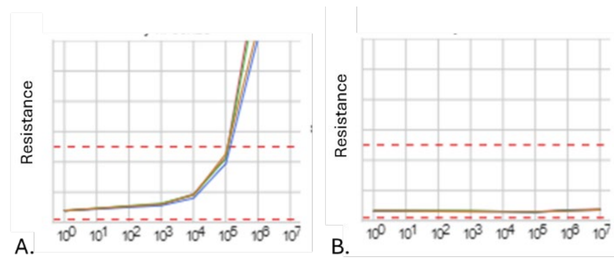

Fig. 9: Examples of Electrical Resistance measurements over cycles for a device with (A) exponential resistance rise due to contamination and (B) flat resistance over cycles (plots show up to 10^7 cycles). Each line in the plot is for each of the 4 channels on the device.

C. Package Reliability

A well-controlled environment is important for optimal operation of the MEMS switch. The Ideal Switch's glass packaging solution provides a robust, hermetic package that has a long storage life and thermal cycling reliability, retaining hermeticity with cycling across the -40 ºC to 125 ºC temperature range. The package consists of a glass cap with TGVs which is adhered to the MEMS device with Au-Au thermocompression bond. The TGVs in the cap provide the electrical connection between the MEMS and the RDL metal outside the package. These TGVs have leak rates better than 5E-6 atm-cc/s and are highly conductive, with resistivities <0.1 Ohm. These properties of the TGVs allow stable environmental control while not degrading the performance and lifetime of the switch.

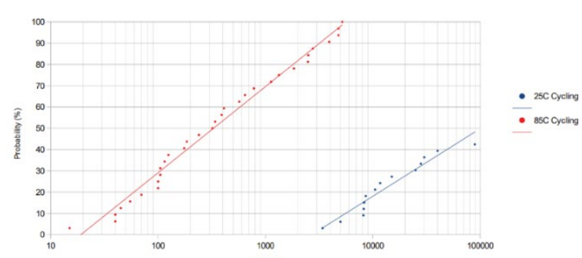

Fig. 10: Example of Reliability tests showing room temperature operating lifetime (RTOL) >3B cycles with <20% probability to fail to 10B cycles as well as high temperature operating lifetime (HTOL) at 85 ◦C with shorter lifetime.

III. Conclusion

Menlo Microsystems has developed the Ideal Switch®, with a lifetime of billions of cycles, by designing the device and test methods with common switch failure modes in mind. We have demonstrated the ability to detect and eliminate standoff, stuck closed, high resistance and stuck open fails that have traditionally plagued MEMS switch devices. Material selection for the beam and contacts, using engineered beam alloy and Ru based contacts, minimizes beam creep and contact adhesion issues. Glass packaged devices with hermetic through vias and capping methods ensure a well-controlled environment which allows billions of cycles with minimal polymer formation which provides low resistance operation over the lifetime of the device. Menlo Microsystems has demonstrated the ability to manufacture MEMS devices with all glass packaging utilizing the advances in through glass via technology and scalable volume manufacturing processes.

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