STICTION AT HIGH TEMPERATURE (>250°C) IN ENCAPSULATED MEMS DEVICES FOR HARSH ENVIRONMENT APPLICATIONS

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ABSTRACT

We demonstrate the stiction properties of ultra-clean, wafer-scale, vacuum encapsulated MEMS devices at elevated temperatures from 30-325°C. A modest increase in the sidewall adhesion (stiction) force between the pure, single crystal silicon surfaces is observed as temperature is increased, but no fundamental change in behavior occurs. Repeated cycling at high temperature demonstrates that no additional degradation results from the high temperature conditions over thousands of contact impact cycles. This is indicative of the suitability of these encapsulated devices for harsh environment applications.

INTRODUCTION

Static surface adhesion (stiction) is a common problem and failure mode in MEMS/NEMS devices [1] due to the scaling of surface and volume forces. At the small length scales found in micro-sensors and devices, the magnitude of surface forces such as Van der Waals force, or capillary attraction can be of comparable magnitude to the mechanical, piezoelectric and electrostatic forces which permit the device to operate. The failures may occur either during fabrication (process stiction), or during use (in-use stiction). Harsh environment applications make additional demands on device design that can further complicate the problem posed by stiction.

As a result of the significant problem posed by stiction in MEMS devices, numerous methods of mitigating surface adhesion have been developed. By using strict design rules it is possible to design devices with sufficiently high restoring forces, or large gaps to prevent contact from occurring under any circumstances, but this often severely limits device performance [2]. Typical solutions to prevent device failure from adhesion during planned or unplanned surface contact include anti-stiction surface treatments [3], such as polymer self-assembled monolayers (SAMs) [4], and over travel stops to reduce contact area.

High temperature harsh environments present a particularly difficult challenge with regards to stiction. Typical anti-stiction SAMs are polymer based materials with limited thermal budgets. Decomposition of SAMs may begin at temperatures as low as 200°C [5], and few of the materials can withstand temperatures above 300°C for any extended period of time. In addition, critical stiction-related surface properties of silicon, such as roughness and asperity distribution can be modified by exposure to elevated temperatures for extended periods of time [6]. Additionally, harsh environments frequently involve vibration and shock events that make inadvertent surface contact more likely. Such environments include down-hole oil drill monitoring, and combustion engine measurement and control.

The epitaxial encapsulation process is natively high-temperature compatible due to the 1100°C encapsulation process step [7]. The completed device is finalized in an epitaxial furnace, so all aspects of the device are designed to withstand extreme temperatures. As a result, this process has unique implications regarding stiction. Use of polymer anti-stiction materials is impossible, and the sidewalls are smooth, pure silicon, but the environment is free of moisture and hydrogen bonding. Previous work has examined the stiction properties of encapsulated devices [8], and the possibility of mechanical anti-stiction solutions [9]. In addition, previous investigation has demonstrated devices fabricated in this process to be suitable for high temperature use in cases where the behavior is dominated by current flow through the contact [10]. Given the native high-temperature compatibility of these devices, they present an intriguing possibility for use in harsh environments, conditional upon successfully negligible stiction failure modes.

EXPERIMENT DESIGN

Fully encapsulated, electrostatic test structures were fabricated in the standard epitaxial process. The test structures were designed to have anti-stiction spring bump stops, guided by previously observed results [11]. These devices were mounted on polyimide printed circuit boards (PCBs) to allow for high temperature testing.

Device Design and Fabrication

The test structures were designed to allow for a precise and repeatable test of the surface adhesion properties under various conditions. In order to achieve this goal, the following specific features were prioritized in the design:

- Electrostatic pull-in actuation
- Capacitive position sensing
- Released mass, spring constant similar to typical inertial sensors
- Anti-stiction bump stops

A schematic of the final device design is shown in figure 1. Several variants of this device were fabricated with slightly different bump stop configuration, but the basic operation is identical.

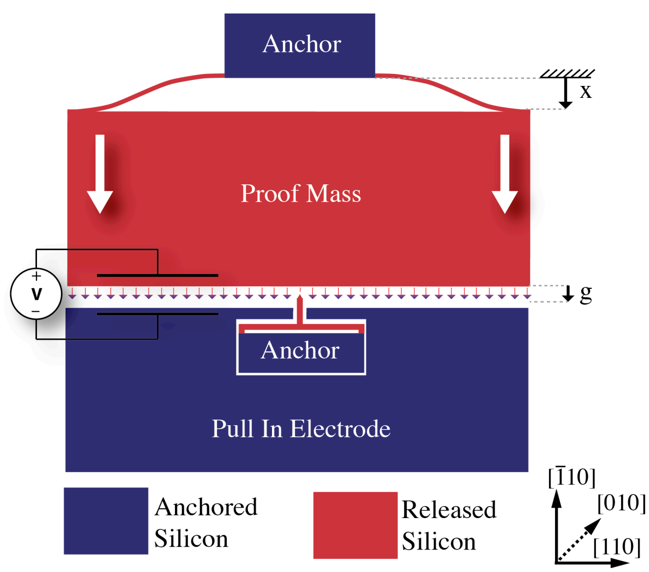

Figure 1 - Schematic of test structure device design

The devices were fabricated on 40μm heavily doped single crystal silicon (both n and p type), and encapsulated at the wafer level in a pure, native oxide-free environment. The encapsulation process which enables this environment was developed at Stanford University, in cooperation with Robert Bosch GmbH, and has been reported upon extensively in previous publications [7]. Over 100 devices were fabricated, with a yield of about ~75%.

Experimental Procedure

The finalized test structure dies were mounted and wire-bonded directly to a high-temperature compatible, polyimide PCB. The PCB was mechanically mounted to an aluminum block heater. This setup, shown in figure 2, avoided the use of solder and most polymer materials, thus allowing the devices to be heated to temperatures in excess of 300°C during long-term testing. A platinum resistive thermometer was used to monitor the temperature, and for the proportional-integral feedback controller, which maintained a desired temperature within ± 0.15°C. The maximum testing temperature of ~325°C was constrained by the PCB substrate material, but is still well within the range qualifying as a harsh environment.

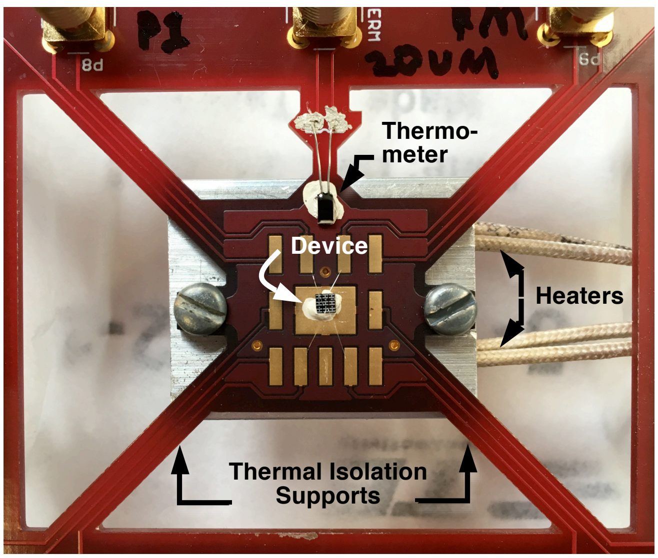

Figure 2 - High-temperature, long-term test set up

An LCR meter with a DC bias tee was used to simultaneously actuate surface contact and measure the behavior. This quasi-static process allows the proof mass to be pulled in to make contact with the bump stop and released by sweeping the bias voltage. The position of the proof mass may be calculated by measuring the parallel plate capacitance. An example measurement is presented in figure 3. Some fraction of the pull-in/pull-out hysteresis is accounted for by the non-linear nature of the electrostatic force. The remainder of that hysteresis is contributed by the stiction force between the bump stop and the proof mass.

Previous investigation has shown that this quasi-static testing does not utilize the stored energy in the bump stop spring to promote release from stiction [11]. In addition, this test method forces the contact to occur for at least one second on each cycle. For these reasons, this testing does not provide a "best-case" measurement, and is in fact quite conservative. Allowing the spring bump stops to be utilized to their full potential has been shown to improve stiction performance by >50% [11].

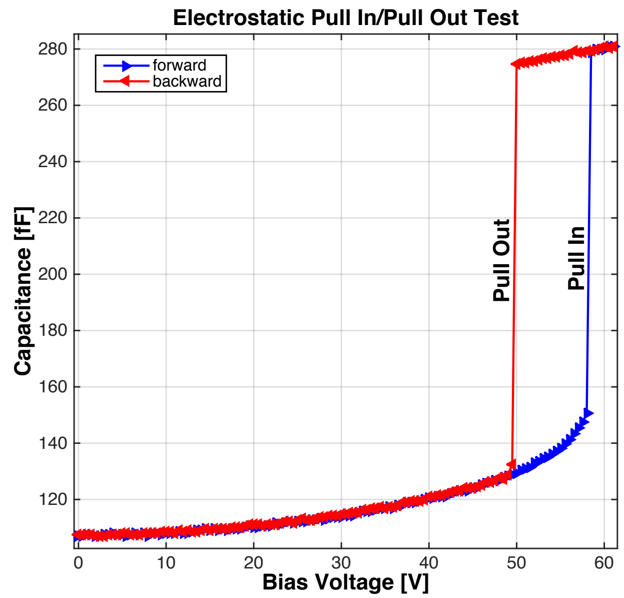

Figure 3 - Capacitive measurement of electrostatic pull-in test for a typical device

RESULTS AND DISCUSSION

By repeating the basic pull-in test at a series of elevated temperatures we were able to observe the temperature dependence of stiction. The pull-in and pull-out voltage results shown in figure 4 demonstrate that the stiction force increases modestly at high temperature. Assuming the bump stop deflection is small, we may calculate the stiction force, using the method reported previously [11]. At ambient temperature the measured force was 9 µN, and it increased to 19 µN at 250°C.

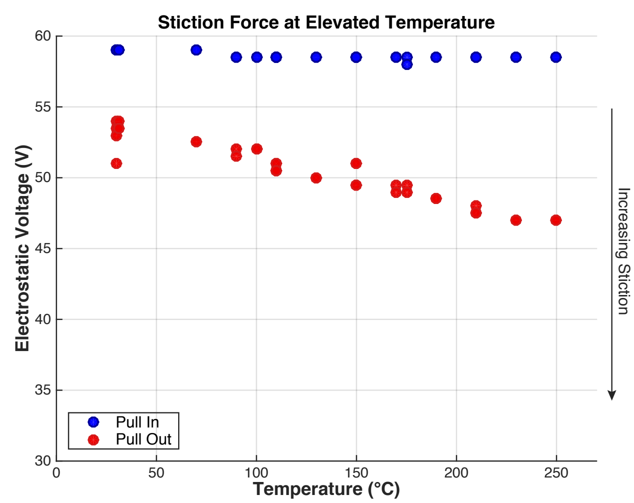

Figure 4 - The pull-out voltage decreases at higher temperature, indicating that the stiction force is stronger.

The data in figure 4 is assembled from several separate temperature sweeps on a single device. This indicates that the temperature dependence of stiction is both repeatable and reversible. In addition, this same behavior was repeated for all the tested devices.

The most important noteworthy feature of this result is the stable and smooth nature of the temperature dependence. As compared to devices utilizing a polymer anti-stiction coating, which may abruptly and irreversibly switch from relatively low stiction to much greater stiction, the epitaxially encapsulated devices display a monotonic, and approximately linear increase in stiction. In addition, the devices are not affected by repeated or extended exposure to high temperatures. This behavior imposes only simple design restrictions on devices intended for use in high temperature harsh environments.

The physical mechanism resulting in the increased stiction is likely to be the increased surface energy of silicon, which has been reported elsewhere [12] for bonding of silicon-on-insulator wafers. In addition, although 250°C still well below the brittle-to-ductile transition temperature of silicon [13], there may already be some slight softening of the silicon surfaces. This is additionally suggested by the slight decrease in pull in voltage, as the pull in voltage is entirely determined by the material properties and geometry of the device. It is important to remark that the larger change in observed stiction force cannot be accounted for solely by the reduced mechanical restoring force brought about by the softening of the suspension springs, as this is a much smaller change.

Repeated Cycle Testing

To ensure the results reported above are truly repeatable (and may thus form the basis for future design guidelines), it was necessary to perform the pull-in experiment repeatedly over hundreds or thousands of cycles at a constant high temperature. Subjecting the same test device from figure 4 to over 5,000 contact cycles produced the result shown in figure 5. The device continued to operate normally at the conclusion of the test, and the number of cycles was constrained only by the time required to perform the testing.

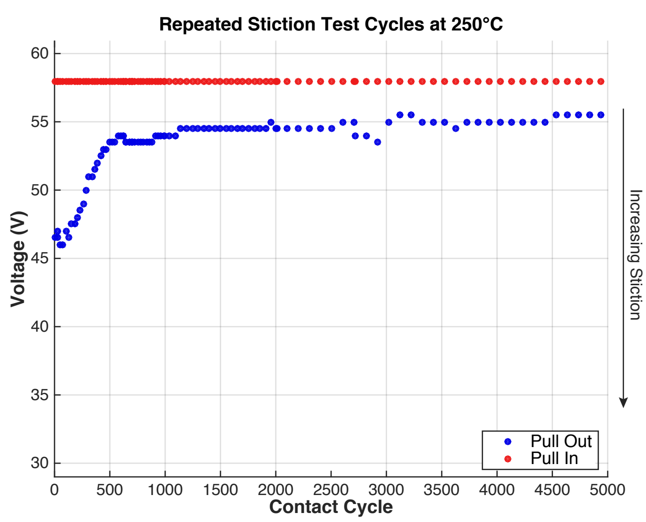

Figure 5 - Results of repeated stiction test cycles at 250°C, collected over 3 hours. The measurement was collected every 20 contact cycles for the first thousand cycles, and then with decreasing frequency for the remainder of the test.

The repeated cycling clearly does not cause significant degradation in the stiction behavior of the device. In addition, the non-contact behavior of the device does not change, as demonstrated by the constant pull-in voltage. Further, the data indicates that there is some initial "break-in" stiction force, which is reduced by the repeated cycling at elevated temperature. Before cycling, the stiction force was measured to be 19 μN, and after 5000 contact cycles, it was reduced to 7 μN. This same trend is reproduced across several similar devices with different spring bump stop variants.

There are several possible mechanisms for this improvement. A reduction in surface energy, or decrease in contact area could come about during the impacts, and the addition of more thermal energy at the contact could exaggerate these effects. This data alone, however, is insufficient to form a strong conclusion. Further investigation of the surface topology and bonding properties is required to definitively determine the mechanism.

Though the mechanism for the reduction in stiction force seen in figure 5 is not directly observable from this data, it is clear that the modification to the surface adhesion properties is permanent. After cycling, the devices were cooled, and allowed to rest for several days. The original temperature sweep experiment was subsequently repeated for several devices, with the result shown in figure 6.

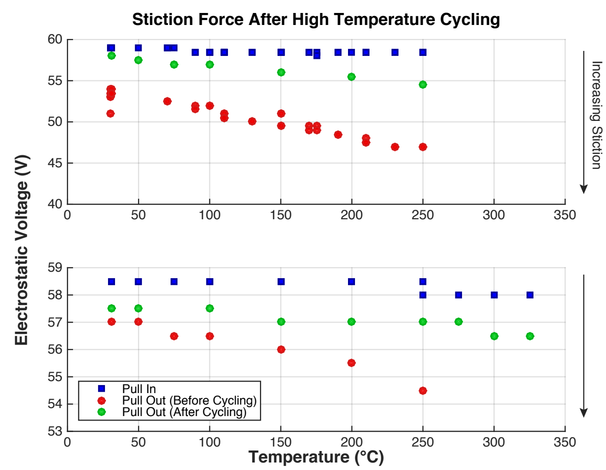

Figure 6 - Temperature dependence of stiction before and after high temperature cycling for devices A (upper) and B (lower), with slightly different bump stops

The improvement caused by the high temperature cycling process is seen to persist during subsequent testing once the device has cooled, and in additional high temperature sweeps. The base stiction force at ambient temperature is substantially reduced as a result of the cycling, and at 250°C, the stiction force was seen to decrease by as much as 55%. Repeating the measurement of stiction force at ambient temperature three weeks later revealed no change, further indicating that the modifications are permanent.

CONCLUSIONS

High temperature harsh environments present a unique series of challenges to reliable MEMS device design. Many of the basic materials used to construct MEMS devices, such as silicon and silicon dioxide, have high melting temperatures and are relatively insensitive to changes in temperature, which makes them promising candidates for this application. Unfortunately, nearly all of the self-assembled-monolayers and some of the chemical getters used to combat stiction are completely incompatible with high temperatures.

The wafer scale encapsulation process is natively compatible with high temperatures, as a result of the 1100°C encapsulation step. Since typical anti-stiction methods are unavailable, alternative, mechanical anti-stiction bump stops were previously developed. In this work we demonstrate that these anti-stiction bump stops perform well at high temperature. Though the effective stiction force does increase modestly with increasing temperature, the force remains manageable, and this increase is both predictable and reversible. Further, since no destructive processes occur at elevated temperature, the stiction performance does not degrade over time, and it appears that devices may be held at high temperature indefinitely with no negative consequence. Repeated contact cycles at high temperature do not damage the anti-stiction performance, and in fact may serve to reduce the stiction forces. These results demonstrate the suitability of epitaxially encapsulated MEMS devices for use in high temperature harsh environments.

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