Investigation of a Vacuum Encapsulated Si-to-Si Contact Microswitch Operated From −60 °C to 400 °C

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***Abstract*— We report on characterization of Si-to-Si contact microswitches fabricated in an ultraclean encapsulation process. This three-terminal microswitch relies on a curved beam (source) that actuates toward the contact terminal (drain) by charging the control terminal (gate). The operation range of this switch from −60 °C to 300 °C is investigated, which approximately yields a resistance drift of −200 Ω/K. Our experiments include tests of the high-temperature lifetime during continuous ON–OFF cycles. By reducing Joule heating at the contact, preliminary results demonstrate at least 10^6 cycles longer lifetime at 400 °C. Subsequently, the failure mode is investigated and reported. The study of ultraclean Si-to-Si contact-based microswitches provides a crucial guideline to the field of mechanical and electrical failure mechanisms for harsh environment applications. [2014-0373]**

***Index Terms*— Reliability, rugged electronics, electrostatic switch, relay, switch.**

I. Introduction

MICRO/NANO-ELECTROMECHANICAL(MEM/NEMS) switches have been shown to possess superior harsh environment reliability over the state-of-art complementary metal-oxide-semiconductor (CMOS) transistor technology [1]–[3]. Together with other mechanical switch advantages such as zero off-state power consumption and a steep sub-threshold slope, MEMS/NEMS switches could possibly be suitable for rugged electronic applications [4]–[7]. The investigation of such Si-to-Si based contact in a wide temperature range is especially interesting for harsh environment MEMS sensors. This is reinforced by recent report of a high resolution MEMS inclinometer based on the pull-in voltage [9].

In this work, the temperature stability and reliability of an ultra-clean, vacuum encapsulated (*epi-seal*) Si-to-Si MEMS switch are characterized from −60 °C to 400 °C. The temperature stability below 0 °C provides crucial information for outer space application, e.g. satellites. The *epi-seal* wafer-level encapsulation process used in this work was developed in collaboration between Bosch and Stanford University, and is the basis for stable time references made for commercial applications by SiTime [12]–[14].

Fig. 1(a) shows the exploded view of the vacuum encapsulated microswitch. In the bottom layer, the MEMS switch consists of three terminals: source (movable curved beam, fixed at one end), gate (fixed) and drain (fixed) defined on silicon-on-insulator (SOI) wafer. Above that is the capping layer with release holes and silicon sealing layer. In the sealing process, the ultra-clean environment is created for the active part of the device during the encapsulation as part of the epi-seal process, when the wafer is sealed with epitaxy Si at temperature >1100 °C with hydrogen, dichlorosilane and hydrogen chloride in an epi-reactor. This process eliminates residual oxygen, hydrocarbons and water, leaving behind only hydrogen molecules in the cavity at a sub-Pa pressure. Note that the epitaxy Si is also in-situ doped with a resistivity of 5-20 mohm-cm. At the same time, the sealing layer also acts as a contact via to the device's terminals. An isolation trench etches followed by dielectric fill and contact metallization is performed to create the top metal pads and interconnects. The X-ray image of the encapsulated device is shown in Fig. 1(b) with the top view shown in inset. This image is taken with an X-ray inspection system (DAGE XD 6500). The image reveals the encapsulated microswitch under the epitaxy seal. The contact area is better represented in Fig. 1(c) where the SEM image is taken before the encapsulation process. The electrical setup is also shown in Fig. 1(c). In our previous report, we have demonstrated near zero off-state power consumption and at least 10^3 cycles at temperature of 300 °C [18]. In this report, the temperature stability and failure mechanism with reference to Joule heating and contact degradation is demonstrated.

The curved beam (source terminal) can be electrostatically pulled in to contact the drain terminal by applying a gate voltage (V_G) between the gate and source terminal.

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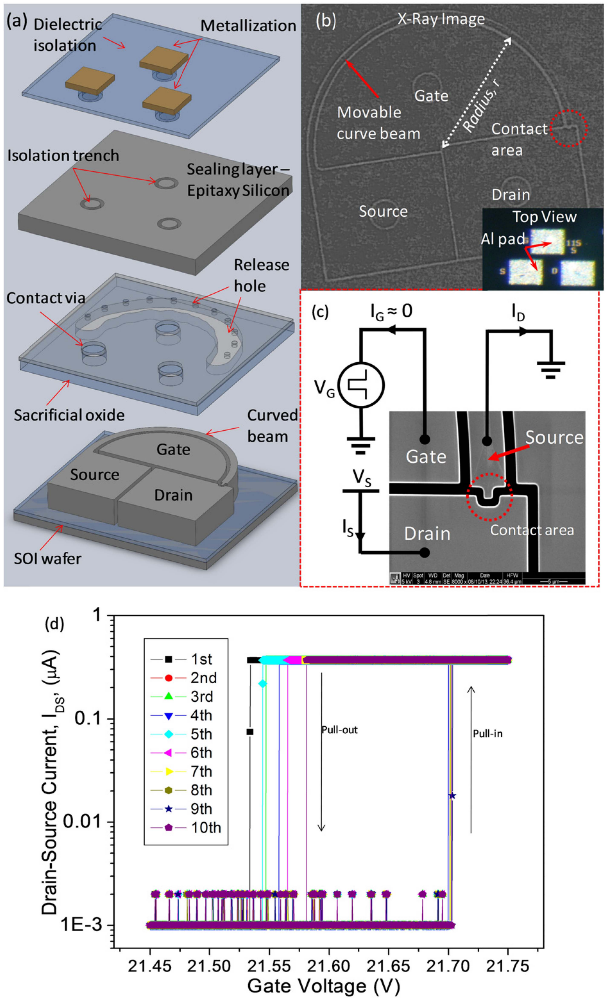

Fig. 1. (a) Exploded view of the Si-to-Si MEMS switch with encapsulation layers (b) X-Ray image showing the encapsulated three terminal microswitch comprised of a movable curve beam (Source), control terminal (Gate) and contact terminal (Drain). (Inset) Top view of the finished chip with metalized aluminium pad. The encapsulated device is flat with minimal topology. (c) Experimental set-up for the cycle testing with the SEM showing the switch's contact area before encapsulation. (d) High resolution pull-in voltage at 21.7 V, and variation in pull-out voltage.

Subsequently, electrical signals can pass from source to drain. The drain current (I_D) and source current (I_S) can flow due to drain-source voltage (V_{DS}). Both currents (I_{DS}, I_G) can be measured simultaneously to characterize the MEMS/NEMS switch as shown in Fig. 1(d). The pull-in and pull-out events are represented by abrupt increases and decreases in drain-source current (I_{DS}) respectively, usually within adjacent voltage steps. Multiple high-resolution gate voltage sweep measurements at room temperature show a consistent pull-in voltage at 21.7 V. In relevant comparison to a transistor, result from Fig. 1(d) is used obtained average subthreshold swing between two switching states including both on and off pull-in and pull-out voltage. This is approximately 0.06 V/decade, This property is at least comparable to the current transistor technology. Further improvement to the beam's stiffness may reduce adhesion hysteresis and lower the subthreshold swing. There is a small evolution of the pull-out voltage due to the modifications of the contact asperities after each cycle. The window between the pull-in and pull-out voltage, also known as the hysteresis width, is affected by electrostatic force, elastic force and adhesion arising from micro-welding between the contacts [19]–[21]. These microswitches are shown to operate through at least 5×10^6 cycles at room temperature.

II. Testing Set-Up

The temperature dependency of the microswitch is characterized with the minimum and maximum range from −60 °C to 300 °C in a chamber with temperature controller (Cascade Microtech PMV200). Nonetheless, the microswitches reliability on-off cycling test is performed up to 400 °C using a calibrated temperature chuck in a different test chamber (Cascade Microtech Microchamber RBL-6100). The electrical characterization is performed using Agilent semiconductor analyzer B1500 equipped with two medium-power source monitor units (MPSMU) and one high resolution source monitoring unit (HRSMU). Overall, the experiment set-up for testing of a three-terminal device, namely, gate, drain and source is used in all the experiments where the gate is used to control the on-off state of the microswitch, the source is designated as the curved beam which is ground, and the drain is the stopper with signal bias.

III. Operation Range

A. Contact Resistance VS Temperature

First, the device's operation range is investigated from −60 °C to 300 °C, while 400 °C is investigated later in the reliability testing. This study is performed by testing the device in a vacuum (10^{-6} Torr range) probe station (Cascade Microtech PMV200) with a temperature controlled stage. The vacuum provides protection to the tools in the chamber from condensation and oxidation. The convective heat loss from the device is considered negligible under the vacuum condition so that the calibrated temperature is accurate. The gate voltage, V_G is swept from 0 to 20 V, while the drain-source voltage, V_{DS} is set to 2 V. As the curved beam (source) pulled in to the drain terminal, the drain-source current I_{DS} rise is detected and measured. In contrast to the result from Fig. 1(d), the pull-in voltage varies slightly with increasing temperature. This is due to thermal expansion and the dependency of the Young's Modulus of Si to temperature, The Young's modulus thermal coefficient of Si, $\beta = -67 \times 10^{-6}\mathrm{K}^{-1}$, since the pull-in voltage is proportional to the $\mathrm{E}^{1/2}$, the pull-in voltage reduces as temperature increases. A finite element model of the microswitch is simulated with Coventorware Multiphysics to investigate the pull-in voltage under the effect of thermal expansion and Young's modulus dependency on temperature. This model is shown in Fig. 2(a). In the 3D model, the Si device layer is sandwiched between two SiO_2 layers, on the top and the bottom of the device. The entire device is anchored except the curved beam and the device is subjected to a uniform temperature varies from −60 °C to 400 °C. This causes the curved beam to deform due to expansion and difference in thermal coefficient of expansion of Si and SiO_2. After that, a voltage

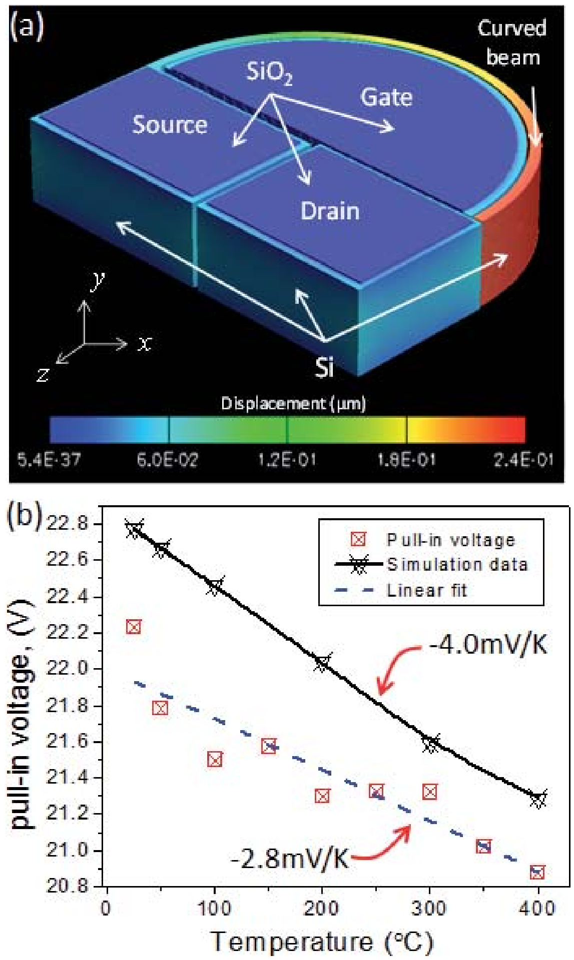

Fig. 2. (a) Finite element model of curved beam microswitch at 400°C. (b) Comparison between experimental pull-in voltage and FEM simulation versus temperature.

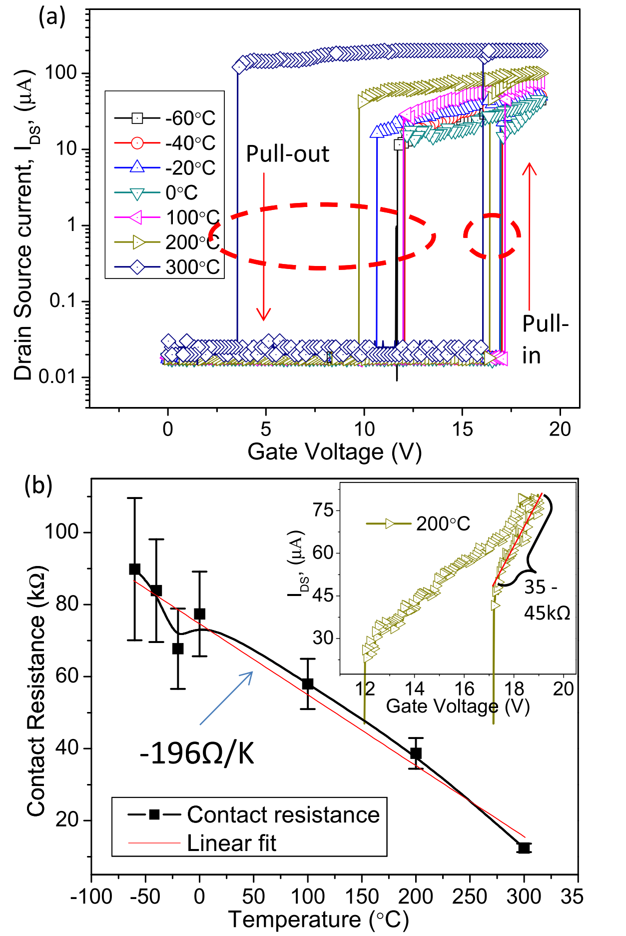

Fig. 3. Temperature stability of the microswitch's contact resistance from −60 °C to 300 °C. (a) Multiple pull-in I_{DS}- V_G at different temperatures. (b) Extracted mean contact resistance drift (35 measurements) of −196Ω/K. (Inset) Zoom in of linear rise in I_{DS} due to contact resistance for a microswitch operated at 200 °C.

sweep on the gate and the the pull-in voltage is evaluated. Note that the Young's Modulus dependency on temperature is included in the simulation. In this model, the Co-solve simulation, simultaneous thermo-mechanical deformation with the evaluation of the capacitive force between the gate and the curved beam is performed to investigate the effect to the pull-in voltage at different temperatures. The results are shown in Fig. 2(b). The simulation result is compared to the experiment result, which is also linearly fitted. Both results show negative pull-in voltage drift with increase temperature, the simulation data shows −4.0 mV/K while the experiment data shows −2.8 mV/K. The pull-in voltage drift due to the effect of thermal expansion and dependency of Young's modulus is confirmed by the result obtained from FEM simulation.

Next, the pull-in voltage measurement results at different temperatures are shown in Fig. 3(a). The pull-in voltage drift observed is in agreement with the explained behavior [22]. The contact resistance can be extracted from the linear increment in drain-source current, I_{DS} right after the curved beam is pulled in. This current flow is due to the 2 V potential applied across drain and source terminal. An example is shown by a device operated at 200°C in the inset of Fig. 3(b). The drain-source current continues to rise after pull in due to the change in contact area. As gate voltage continues to increase, a higher electrostatic force is induced by the increasing gate voltage after pull-in. Approximately 35 – 45 kΩ is extracted for this device. Note that the contact resistance in this device is typically in the range of tenths of kilo ohms. The contact resistance is usually higher than that of the bulk Si and the terminating resistor of the testing set up, which is in few kilo ohms and 50 Ω respectively. The mean contact resistance is extracted from 35 devices and we found that the contact resistance decreases with temperature from −60 °C to 300 °C. This is shown in Fig. 3(b), the fitted mean variation in contact resistance from −60 °C to 300 °C is approximately −200 Ω/K. The overall decrease in contact resistance is also related to the contact area dependency on temperature. As hardness of silicon decreases at elevated temperature, higher contact area is expected [23], [24]. As a result, a larger drain-source current, I_{DS} can flow through the contact, therefore reducing the resistance. This combination of effects may also lead to a faster surface degradation due to increased Joule heating and additional material softening.

Under these circumstances, there could be an adverse effect of increased probability of micro-welding at the contact interface, especially at higher temperature. This hypothesis is consistent with the observation of increased adhesion hysteresis between pull-in and pull-out voltages, as the pull-out voltage gradually decreases with each higher temperature step. The electrical conductivity is largely unaffected by temperature since the measured resistance of shorted test structure is approximately 4 kΩ and the temperature drift about 6 $\mu\Omega$/K. This means changes in the hysteresis width may indicate growth in contact area. This hypothesis is also supported by the observation that the "on voltage" remains constant while the "off voltage" is reduced as the number of cycle increases. The microswitch operates well below 200 °C but the reliability drops significantly at temperatures at and above 300 °C. As contact resistance decreases at higher temperature, a higher drain-source current, I_{DS} may flow through the contact. Therefore, it is important to limit the current through the microswitch to prevent excessive joule heating and acceleration of failure mechanisms.

B. Contact Resistance VS Drain-Source Voltage, V_{DS}

The role of self-heating at the contact due to drain-source voltage is further investigated. As higher voltage leads to higher current flows through the contact, this may cause excessive Joule heating that result in catastrophic failure in the microswitch.

In this study, the gate voltage sweep experiment is repeated with drain-source voltage, V_{DS} steps at 0.5 V until device failure is observed at room temperature. With constant room temperature, self-heating effect is observed by the non-linear drain-source current increase at different drain-source voltage step. At V_{DS} of 4.5 V, the drain and source are found to be permanently fused in contact and no pull-out voltage is observed as shown in Fig. 4(a). The self-heating has drastically reduced the contact resistance from 150 kΩ to near zero in just few voltage steps as shown in Fig. 4(b). The amount of current flow is higher compared to that caused by varying the environment temperature. The decrease in contact resistance with increases in drain-source voltage, V_{DS} is a result of Si softening at higher temperature, which induces larger contact area and higher flow of current, which is similar to the effect of increasing temperature. To confirm the phenomenon, the contact resistance related to asperities, contact force and elastic-plastic deformations of MEMS switches can be solved as demonstrated by Majumd *et al.* [25], [26]. Here, the loading phase of the MEMS switch is emphasized as contact resistance softening during the operation in high temperature is of much interest. The Derjaguin, Muller and Toporov (DMT) model is suitable here due to stiff material and smaller radius of asperity in contact [27]. This is further confirmed by evaluating the Tabor coefficient, μ_T shown in the equation below.

$$\mu_T = \left(\frac{R\gamma^2}{E_c^2 z_0^3}\right)^{\frac{1}{3}} \tag{1}$$

where R is the radius of the asperity, γ is the work of adhesion (1.4 mJm^{-2} for Si [28]), E_c is the effective elastic modulus, z_0 is the characteristic atom-atom distance. The result is closed to zero due to the low work of adhesion of Si compared

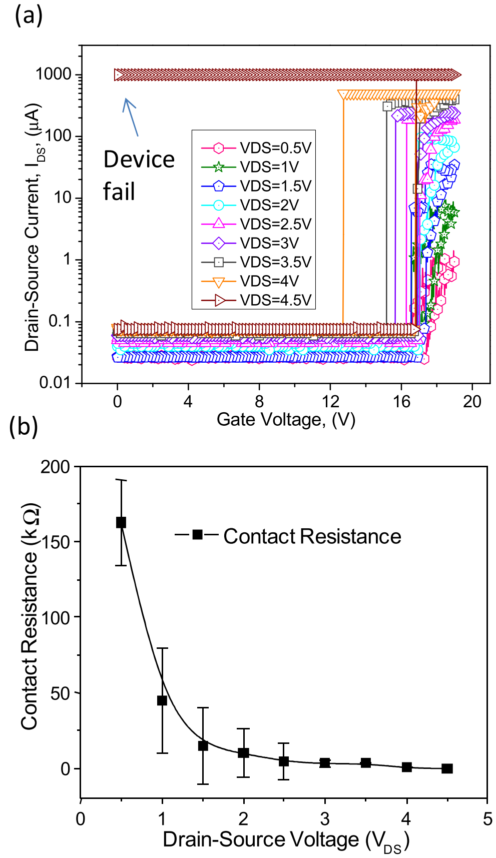

Fig. 4. Dependency of the contact resistance on V_{DS} bias from 0.5 V to 4.5 V. (a) I_{DS}-V_G at different V_{DS} where device failed at V_{DS} = 4.5V. (b) Contact resistance (45 measurements) versus drain source voltage, R_C- V_{DS}.

to metal. The DMT model as shown below can be fitted into the curved beam switch's effective contact area radius and the contact resistance can be determined.

$$a^3 = \frac{3R}{4E_c}\left(F + 2\gamma\pi R\right) \tag{2}$$

where F is the contact force. Additionally, reported Si's hardness decrement with temperature is evaluated [29]. The process is complex but can be predicted by incorporating the Si hardness's dependency on temperature in the estimation of contact area. Fig. 5(a) shows the hardness of Si at different temperature [23], [24]. The contact resistance of the MEMS switch is then predicted by upper bound and lower bound, as a result of the Wexler's solution [30] and Fig. 5(b) shows the mean modeled contact resistance versus contact force at different hardness due to increasing temperature. The contact resistance is evaluated based on 50 asperities in the contact in our device. As temperature increases, the hardness of Si decreases as a result of material softening. The hardness decreases significantly after 600 °C. This results in higher contact radius and higher current flow. At 800 °C, the contact resistance is decrease to the level of below 1 kΩ. From both the measured and the modeled contact resistance, we know that the temperature near the contact can be as high as 800 to 1000 °C when the applied drain-source voltage is increased beyond 2 V. At 4.5 V, the device fails to disconnect eventually given the

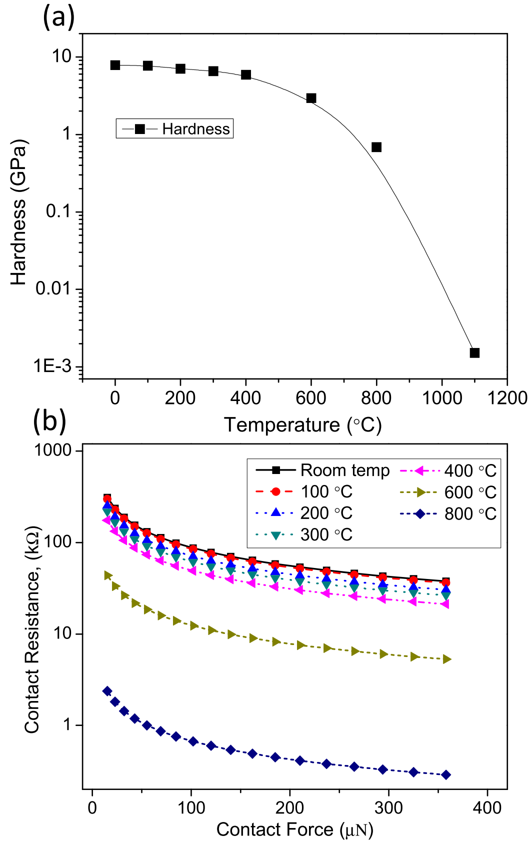

Fig. 5. (a) Si hardness dependency on temperature. (b) Modeled contact resistance versus contact force.

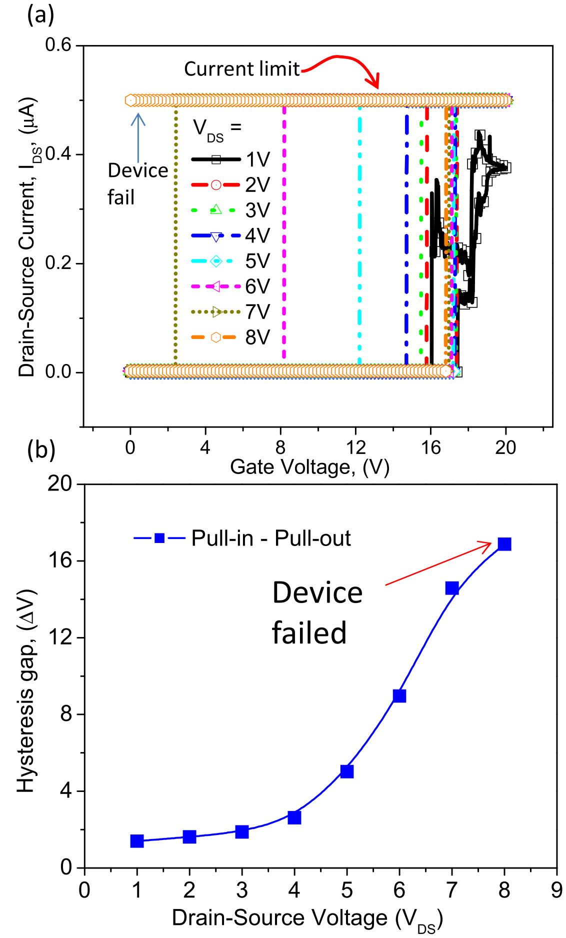

Fig. 6. (a) I_{DS}-V_G at different V_{DS} with I_{DS} limited to 0.5 μA. The device fails to pull out at $V_{DS} = 8$ V. (b) The hysteresis gap increases as drain-source voltage increases.

lowest measured resistance. This is shown in the experiment in Fig. 4(a). In these microswitches, Breakdown of the native oxide insulation during testing is not observed as the native oxide is removed in high temperature H_2 environment before sealing.

In these tests, the effect may be more severe as the drain-source current flow, I_{DS} is constricted through A-spots. “A-spots” are modeled as tiny contact areas on the surfaces between a pair of solid electrodes through which almost all of the electric current flows. The current density flowing through these A-spots can be a few orders higher than the average current density between contacts [31], [32]. Additional heating, softening and localized micro-welding may arise as a result of higher temperature near the contact [33]. At least ten devices were tested and all devices show the same failure at drain-source voltage, V_{DS} between 4 and 5 V. To improve the surface condition of microswitch, surface coating materials such as amorphous carbon, TiO_2 and RuO_2 have been demonstrated to harden the surface and improve the overall performance [1], [34], [35].

C. Limiting Drain-Source Current, I_{DS}

By understanding the temperature near the contact interface, the reliability of the device can be improved by limiting the current that flows through the contact. In this way, the contact degradation in high temperature can be lowered by reducing undesired excessive Joule heating. Fig. 6(a) shows sweeps of the gate voltage with drain-source current, I_{DS}, limited to 0.5 μA. The drain-source voltage is increased in 1 V steps until the device fails. We show that a higher drain-source voltage, V_{DS}, of up to 7 V can be accomplished before the device fails at 8 V. In this test, as the drain-source current limit is reached, the current output is limited; this is compensated by switching resistor in the tester to complement the input voltage. The source monitoring unit circuitry has to switch in and out different resistor values in order to handle the maximum expected current value based on compliance setting specified. In other words, the potential across the contact is still valid with the circuitry resistor. The hysteresis width ΔV is shown in Fig. 6(b). As the drain-source voltage increases, the width between pull-in and pull-out voltage widens. The increase in the hysteresis width shows that a larger adhesion force is present. The microswitch fails when it does not pull out even when the gate voltage is zero. Here, the largest hysteresis gap of 14.1 V is achieved at 7 V before the device fails at 8 V. It is reported that surface damage in hot switching consistently increase with the potential applied between the contacts. At higher voltage, hot switching regularly leads to large amount of material transfer [36]. Nonetheless, within the same voltage range from 0.5 to 4 V as shown in Fig 4, Joule heating can be reduced by setting

TABLE I
COMPARISON OF CONTACT RELIABILITY AND TEMPERATURE STUDY

Contact	Testing environment	Lifetime	Temperature stability
RuO_2 – Au [1]	N_2/O_2 chamber, RT	10^{10}	No data
W – W [8]	N_2 chamber, RT	10^9	No data
TiO_2 – TiO_2 [10]	N_2 chamber, RT	10^9	No data
W – TiN [11]	In air, RT	<1k	No data
Pt – Pt [15]	N_2 chamber, RT	10^7	No data
A-C – A-C [16]	NR, RT	10^8	No data
SiC – SiC [17]	Vacuum, 500 °C	2×10^9	No data
Si – Si (this work)	Vacuum encapsulated, 400 °C	$> 5 \times 10^6$@RT 10^6@400°C	-200 Ω/K (-60 °C to 300 °C)

MEMS/NEMS switch testing environment, reliability and temperature stability study.

a current that limits the flow of drain-source current. This is especially important as the microswitch is operating in high temperature.

IV. RELIABILITY TESTING

The reliability and temperature stability of these devices at high temperature is yet to be fully understood, where the mechanical contact interface is prone to failure by contact oxidation and material degradation [37]–[39]. The comparison in Table 1 shows different MEMS/NEMS switch's contact materials along with their reported reliability and temperature stability. The device reliability is related to the testing conditions such as the composition of the gas, the pressure and temperature. These environmental factors are important in enhancing the lifetime. For example, tungsten-to-titanium nitride (W – TiN) microswitches operated in air only achieved less than one thousand on/off cycles whereas the other micro microswitches tested in vacuum or and nitrogen environments have achieved higher numbers of operating cycles before microswitch failure. A ruthenium dioxide-to-gold (RuO_2 – Au) contact is found to work well under oxygenated environment too. While clean environment is preferred, vacuum encapsulation is a necessary process in Si contact microswitches due to formation of insulating oxide after cycles of on-off operation. Some vacuum encapsulated devices have been investigated but the information under high temperature operation is limited [28], [40], [41].

The curved beam design is a good candidate to test the reliability because the structure is unlikely to break-down via secondary pull-in [42], [43]. The results from tests of the curved beam design are shown in Fig 7. As the gate voltage sweeps from 0 to 100 V, no visible breakdown in gate current is observed.

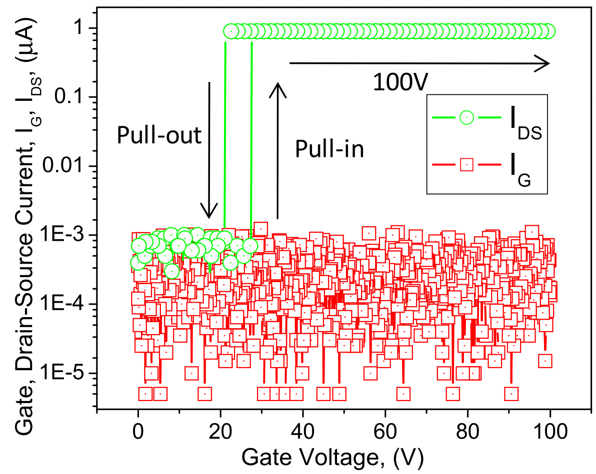

Fig. 7. Drain-source and gate currents, I_{DS} and I_G versus gate voltage, V_G. Noise level I_G measurements indicate a high tolerance to secondary breakdown despite gate voltage sweeps up to 100V.

A. Maximum Drain-Source Current = 1 A, Drain-Source Voltage, $V_{DS} = 2$ V

In the reliability test experiments, the drain-source voltage, V_{DS} is set to 2 V, the drain-source current, I_{DS} is limited to 1A, and continuous on-off cycling of the microswitch is explored at a high temperature of 400 °C. In this experiment, the microswitch operated up to 923 cycles before failure as shown in Fig. 8(a). A zoom-in of the plot in Fig. 8(b) shows that the microswitch failed to disconnect during the off cycle. This failure mode indicates that the beam is permanently in contact with drain. We also note that, in these high-temperature Si-to-Si contact tests, the contact resistance rises gradually with number of cycles and then, this resistance falls and gradually rise intermittently, which could arise from contact modification and roughening of the contact surface.

B. Limiting Drain-Source Current = 0.5 μA, Drain-Source Voltage, $V_{DS} = 2$ V

In order to improve the device's lifetime, the experiment is repeated with the drain-source current, I_{DS} current limited to 0.5 μA, instead of a maximum current of 1A. In this test, the probability for Joule heating is reduced and the surface degradation at the contact should be slowed, hence achieving higher reliability. Using this current-limited configuration, we observe that the lifetime of the contact microswitch can be extended to over 10^6 cycles at 400 °C. This result is shown in Fig. 8(c). As the maximum drain-source current is reached in every on cycle, a quasi-stable threshold can be represented by the compliance resistance. This representation is important as some threshold which is useful in especially computing application. Fig. 8(d) shows the higher-resolution observation of seven on-off cycles observed as a function of the gate voltage. Although the current is limited to 0.5 μA, we are still able to obtain three orders difference from on to off in every cycle.

Further investigation of the microswitch failure mechanism is performed from room temperature to 400 °C. The statistical

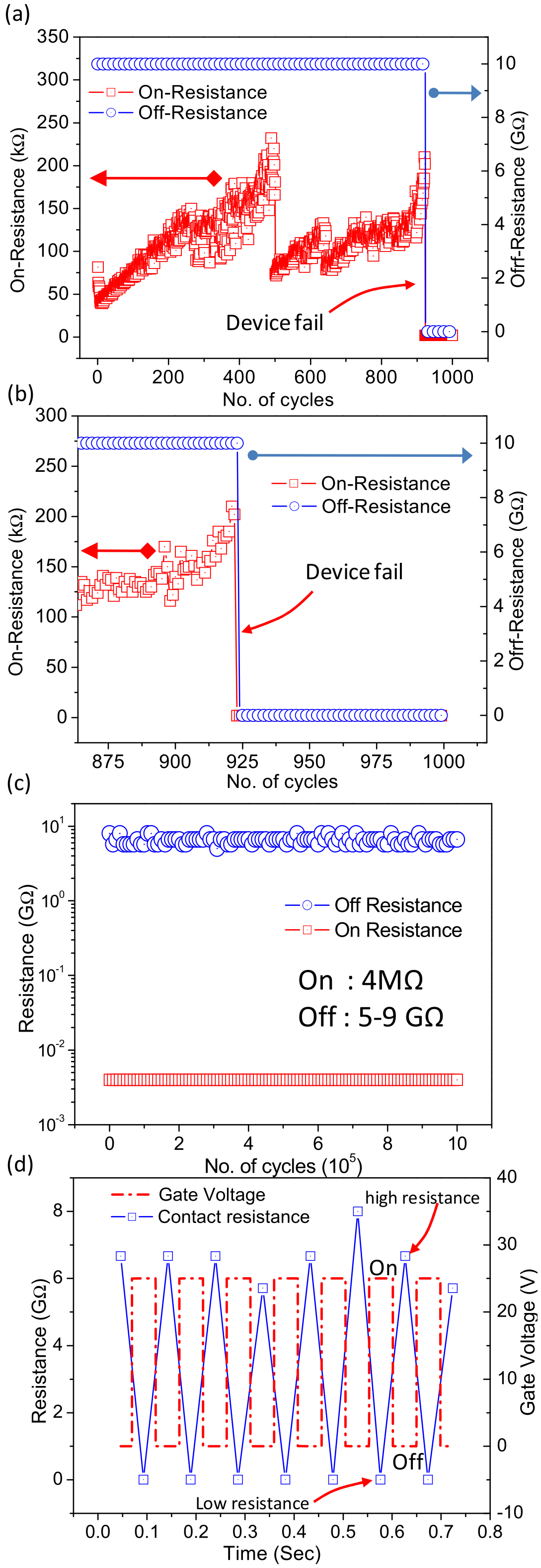

Fig. 8. Contact resistance versus number of cycles at 400 °C. (a) Contact resistance versus number of cycles at 400 °C without current compliance. (b) Zoomed-in view of device that failed abruptly at 923 cycles. (c) One million cycles with I_{DS} current limited to 0.5 μA in log scale. (d) Zoomed-in of device showing seven repeated on-off cycle with respect to gate voltage.

result in Fig. 9 shows twenty five devices (D1 - D25) tested at room temperature, 100 °C, 200 °C, 300 °C and 400 °C. These devices are tested at maximum drain-source current,

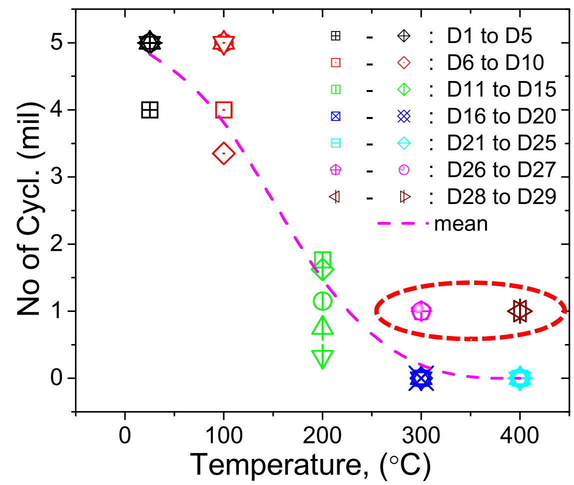

Fig. 9. Reliability statistics of twenty-five devices with maximum current flow (1A) . By limiting the current to 0.5 μA (highlighted), the reliability is enhanced – a lifetime of one million cycles is achieved at 300 °C and 400 °C.

I_{DS} (1A) except for the device (D27 - D29) highlighted with a dotted line. The lifetime of these Si-to-Si microswitches decreases with higher temperature as expected. The lifetime drops drastically above 200 °C and beyond that, the microswitch fails after just a few thousand cycles or less at 300 °C and 400 °C under maximum drain-source current flow. However, by limiting the current to 0.5 μA, device D27 – D29 can be cycled for at least 10^6 cycles at high temperatures of 300 °C and 400 °C without failure, as shown by the highlighted measurement. With this result, we have demonstrated that the reliability of ultra-clean Si-to-Si microswitches can be enhanced by limiting the current flowing between the contacts. This result also indicates that, in some way, the probability of the defective occurrence may be reduced due to the limited drain-source current, I_{DS}. In general, the measurement shows that the microswitch lifetime is highly dependent on the surrounding temperature, drain-source voltage, V_{DS} and besides that, prolonged lifetime at high temperature can be achieved by limiting drain-source current, I_{DS}.

V. Failure Mechanisms

Contact degradation has been explained by other researchers as shown in Fig. 10(a) where the contact material transfer and contact damage can lead to permanent bridging at the contact interface [44], [45]. This effect should be enhanced by elevated temperature. To further investigate the failure of Si-Si contact microswitches sealed with the epi-polysilicon encapsulation process, a focused ion beam is used to mill through the cap and device layer to a depth of nearly 100 μm, and cross-section scanning electron microscopy is used to inspect the interfaces in search for the failure mechanism. Fig. 10(b) shows one of the device's contact area failures at five million cycles. It is observed that contact roughening and bridging is formed on the contact surface. It is well understood that these defects may eventually lead to catastrophic failure in the device. The failure mode is further elaborated by a device

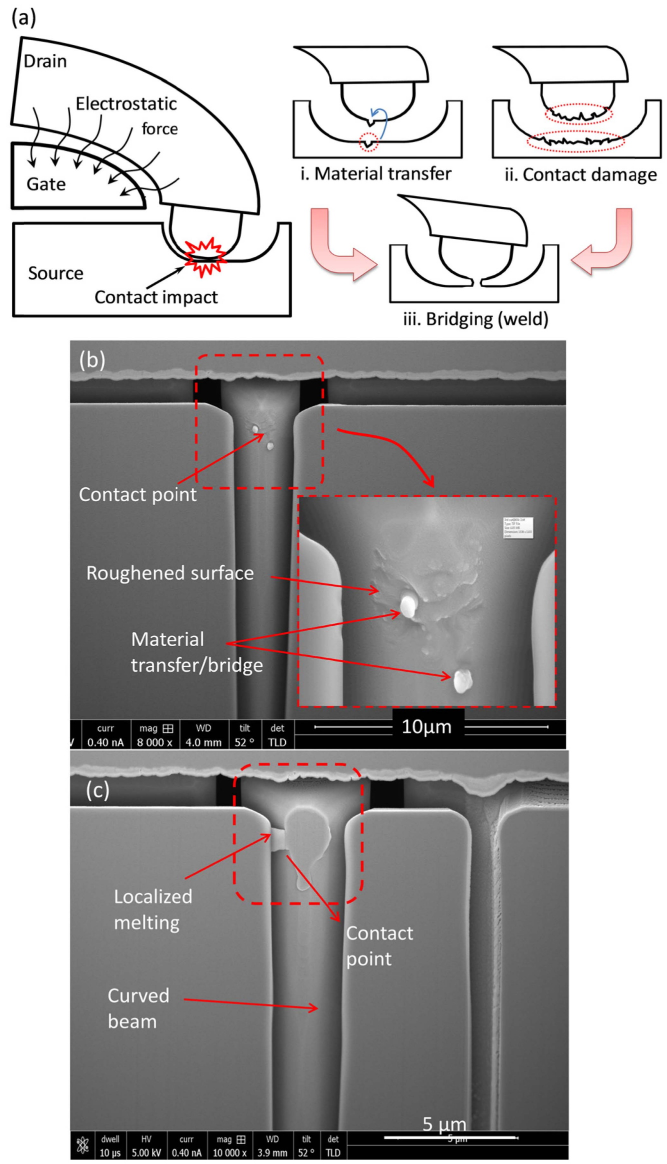

Fig. 10. (a) Illustration of failure mechanics due to contact degradation. (b) Focus ion beam milling reveals cross-sectional view of a failed device after ∼5 million cycling test. (c) Bridge formation due to localized melting near the contact.

deliberately shorted with high drain-source voltage of 8 V. This microswitch only operated for once and we found that a bridge has permanently formed, causing short circuit failure to the device. This phenomenon is clearly showing device failure can be caused by self-heating and localized melting, which is a failure mechanism when high drain-source voltage without current control is applied as source to the microswitch.

VI. Conclusion

In summary, we have presented the temperature-dependent behavior of a Si-to-Si contact microswitch, sealed in an ultra-clean vacuum environment. Our measurements show the device contact resistance dependence on temperature and the potential difference across the contact, drain-source voltage, V_{DS}. In order to prevent excessive Joule heating, limiting the drain-source current, I_{DS} current is shown to prolong the lifetime of such switches at high temperature. At least 10^6 cycles at 300 °C and 400 °C have been successfully demonstrated, and the high reliability could be valuable for harsh environment electronics such as automotive, aerospace and down-hole applications.

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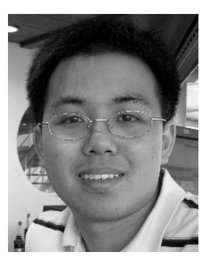

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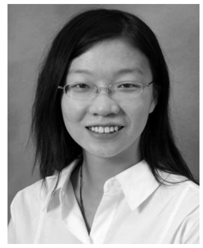

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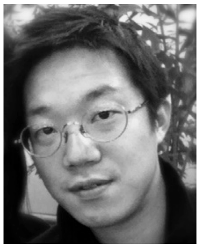

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