Journal of Applied Physics

RESEARCH ARTICLE | AUGUST 19 2010

Contact voltage-induced softening of RF microelectromechanical system gold-on-gold contacts at cryogenic temperatures

D. Berman; M. J. Walker; J. Krim

Journal of Applied Physics 108, 044307 (2010)
https://doi.org/10.1063/1.3459893

AIP Publishing

Contact voltage-induced softening of RF microelectromechanical system gold-on-gold contacts at cryogenic temperatures

D. Berman,[1,a)] M. J. Walker,[2] and J. Krim[1]
[1]*Department of Physics, North Carolina State University, Raleigh, North Carolina 26795, USA*
[2]*Department of Materials Science and Engineering, North Carolina State University, Raleigh, North Carolina 26795, USA*

(Received 21 March 2010; accepted 4 June 2010; published online 19 August 2010)

A series of experiments were performed in vacuum environments to investigate the impact of rf micromechanical system switch contact voltage versus resistance for gold-on-gold contacts at cryogenic temperatures. The purpose of this work was twofold as follows: (1) to examine whether asperity heating models already validated for high temperature contacts were also applicable at cryogenic temperatures and (2) to explore the implications and validity of prior suggestions that contact temperatures between 338 and 373 K are high enough to dissociate adsorbed film and/or push them aside but low enough to prevent asperities from becoming soft and adherent. Measurements on two distinct switch types, fabricated at independent laboratories, were performed in the temperature range 79–293 K and for contact voltages ranging from 0.01 to 0.13 V. Contact resistance values at all temperatures were observed to be lower for higher contact voltages, consistent with the aforementioned asperity heating models, whereby increased contact currents are associated with increased heating and softening effects. *In situ* removal of adsorbed species by oxygen plasma cleaning resulted in switch adhesive failure. Switches that had not been cleaned meanwhile exhibited distinct reductions in resistance at contact temperatures close to 338 K, consistent with suggestions that films begin to desorb, disassociate, and/or be pushed aside at that temperature. © *2010 American Institute of Physics*. [doi:10.1063/1.3459893]

I. INTRODUCTION

Present day radio frequency microelectromechanical system (RFMEMS) switches compare favorably, in terms of power consumption, size, and cost,[1] to existing semiconductor technology devices.[2–4] They are however inhibited by low operating lifetimes due to failure mechanisms associated with adhesion, material transport and surface contamination.[5,6] A fundamental understanding of these failure mechanisms requires a wide-range of studies to be performed with varying environments, temperatures, and materials[7,8] to reveal how the various failure mechanisms interrelate and give rise to overall system response. Prior literature reports have documented that interfacial creep rate elasticity,[9] contact melting,[10] friction,[11,12] and energy dissipation[13] are dominated by the more compliant material in contact.[14] The temperature of an electric contact has great influence on all of these, for both like and unlike contacts, and impacts whether catalysis is likely to occur for native surface contaminants.[15] We focus here on the impact of contact voltage on the contact temperature and heating effects for gold-on-gold RFMEMS switches, through controlled studies at varying cryogenic temperatures.

Studies of the physical properties of RFMEMS switches at cryogenic temperatures have increased in recent years, as they provide much insight on the degree to which a contact heats when an electrical current passes through it.[16,17]

Understanding the effects of cryogenic temperatures and large temperature variations on overall switch performance is also an area of increasing importance to switch designers as they integrate the switches into satellite, microwave, and space monitoring systems.[18,19] Other emerging applications of cryogenic RFMEMS include integration with materials that become superconducting at cryogenic temperatures.[2,3,20]

In the 1960s, Holm presented theoretical calculations of physical processes that impact contact temperature for macroscopic metal contact switches.[15] Holm's theory was later modified and investigated experimentally for RFMEMS switches at room temperature by Jensen *et al.*[21] and Kwon *et al.*[22] Jensen[21] assumed the contact size to be on the order of the electron mean free path, i.e., that relevant to MEMS devices, and established that contact heating decreases the resistance of contacts.[21] Kwon *et al.*[22] showed that high contact forces place limits on increases in the contact area, demonstrating that softening effects are more easily observed at lower loads, which corresponds to lower actuation voltages. Their results provide a strong motivation to examine contact heating effects at lower temperatures, to explore whether softening was inhibited by reducing the overall device temperature and to explore prior suggestions that contact temperatures between 338 and 373 K are high enough to dissociate adsorbed film and/or push them aside,[21] but low enough to keep asperities from softening.

The work reported here is a first-time study of contact softening effects at cryogenic temperatures. To examine whether asperity heating models already validated for high temperature contacts could also be applicable at cryogenic temperatures, measurements on two distinct switch types, fabricated at independent laboratories, were performed in the

[a)]Electronic mail: dyanchu@ncsu.edu.

temperature range 79–293 K and contact voltages range 0.01–0.13 V. Measurements were carried out in either high, or ultrahigh, vacuum to infer the effects of adsorbed contaminant species. Contact resistance values at all temperatures were observed to be lower in the "soft" contact regime (above 338 K) relative to that of the "hard" regime (below 338 K), consistent with the aforementioned asperity heating models, whereby increased contact currents are associated with increased heating and softening effects. *In situ* removal of adsorbed species by oxygen plasma cleaning resulted in switch adhesive failure, while switches that had not been cleaned exhibited distinct reductions in resistance at contact temperatures close to 338 K, consistent with suggestions that films begin to desorb, disassociate, and/or be pushed aside at that temperature.

The paper is divided into six sections. In Sec. II, a model of contact heating is reviewed. Section III presents information about the experimental setup and procedures for taking measurements. The results are shown in Sec. IV. Discussion is included in the Sec. V. Conclusions and summary are presented in Sec. VI.

II. THEORY

Contact surfaces roughness plays a key role in the contact resistance. Current is confined to flowing through the contacting asperities, and the flow is governed by the size and shape of those asperities. Only a few gold asperities come into contact when the switch is closed, so the area through which the current flows is initially small. After initially being cycled, up to thousands of times, the resistance is perceived to decrease because of the disruption of resistive films and the increase in the contact area. Changes in contact temperature also affect the contact resistance by softening the asperity contacts and increasing vacancy mobility to a greater degree at high temperature.[23,24]

Once the switch is closed, current flowing through contacts causes Joule heating. This heating causes an increase in temperature to tens or even hundreds of degrees higher than the temperature of the surrounding material. For metals, Jensen[21] obtained a relation between the temperature of the contact T_C and the ambient temperature T_0,

$$T_C = \sqrt{\frac{f(\lambda/a)R_M}{4LR_C}V_C^2 + T_0^2}, \quad (1)$$

where V_C is the contact voltage, $L=\rho\kappa/T=2.45 \times 10^{-8}$ W Ω/K^2, for electrical resistivity ρ and thermal conductivity κ, the contact resistance $R_C=f(\lambda/a)\ R_M+R_S$ for contact radius *a*, and electron mean free path, λ. The scaling factor $f[(\lambda/a)$ accounts for a transition between resistance regimes and the relative proportions of contact resistance that arise from lattice scattering (R_M) and boundary scattering (R_S) of electrons. It ranges from 0.624 for $a \ll \lambda$ to 1 for $a \gg \lambda$. Assuming that the contact radius is much larger than the mean free path in gold [approximately 38 nm (Ref. 21)], $R_M=R_C$ in Eq. (1), and the expression reduces to:[15]

$$T_C = \sqrt{\frac{V_C^2}{4L} + T_0^2}. \quad (2)$$

At sufficiently high contact temperature, annealing of the contact takes place which reduces the contact hardness; this phenomenon is known as "contact softening."[25]

Holms reported softening to be at $T=373$ K, the softening temperature of gold. Jensen[21] however later performed measurements on RFMEMS switch contacts between 273 and 373 K obtained a "softening temperature" value of 338 K. Jensen could not rule out the possibility of thermal breakdown of the bonds between the gold and the absorbed film layer at this temperature, which might be easily pushed aside. Therefore, this temperature of 338 K could be employed in Eq. (2) to obtain a voltage at which a reduction in contact resistance is expected to occur but the contacts remain hard.

$$V_C = \sqrt{4L(T_C^2 - T_0^2)}. \quad (3)$$

As mentioned already, the purpose of the present study is twofold as follows: (1) to examine whether asperity heating models already validated for high temperature contacts were also applicable at cryogenic temperatures and (2) to explore the implications and validity of prior suggestions that contact temperatures between 338 and 373 K are high enough to dissociate adsorbed film and/or push them aside but low enough to prevent asperities from becoming soft and adherent. By performing measurements in vacuum conditions and with *in situ* oxygen plasma cleaning capabilities, the impact of an adsorbed contaminant film on the "softening" temperature, and whether its physical origin is truly due to the presence of an adsorbed film, could be probed.

III. EXPERIMENTAL PROCEDURE

To study contact heating at different device temperatures, inline metal contacting switches provided by Northeastern University (NEU) (Ref. 26) and rf microdevices (RFMD) (Ref. 27) were employed. Both switches had similar cantilever designs, as shown in Fig. 1.

The NEU switch is an inline metal contacting switch [Fig. 1(a)].[26] The transmission signal enters at the anchor or fixed end, and travels the length of the cantilever beam and exits to the transmission line through the contacts at the end of the cantilever beam. Because the signal must travel through the cantilever beam and the beam must be stiff enough to overcome the force of adhesion at the contacts, the cantilever is fabricated using a thick layer of electroplated gold (~9 μm). The cantilever is 75 μm long by 30 μm wide. The pull-down electrode is 15×25 μm^2 and separated from the cantilever by 0.6–1.2 μm. The short, thick design results in a stiff structure and requires 60–80 V and a current of ~6–10 μA to actuate into the closed position. The switch has two contacts in parallel separated from the transmission line (drain) by 0.4–0.6 μm. The contact area is ~5 μm^2. Contact resistance is 2–3 Ω at 100 μN of contact force.

The RFMD switch is an inline metal contacting switch [Fig. 1(b)]. Like the NEU switch, the cantilever is con-

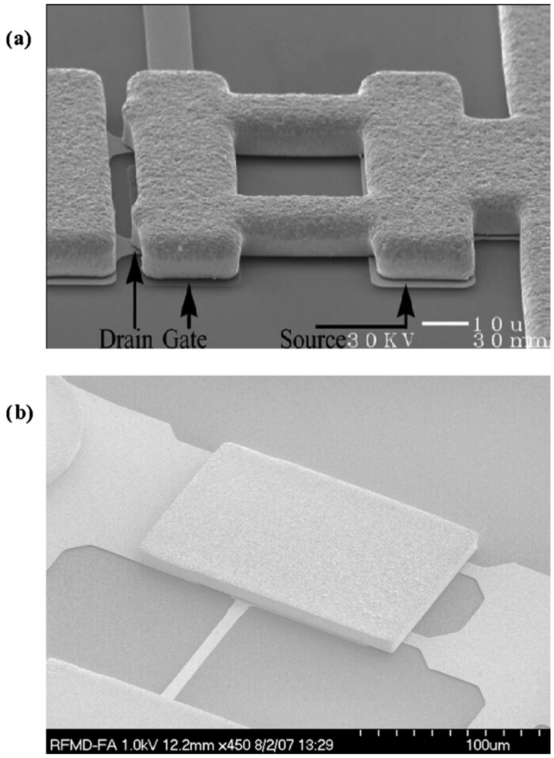

FIG. 1. RFMEMS Au/Au switches: (a) NEU and (b)rfMD.

structed of thick gold layer which allows the transmission signal to travel through the length of the beam and maintains the stiffness required to break contact. The pull-in voltage is less than 100 V with beam collapse and shorting at 150 V. The close time is approximately 5 μs. The contact resistance is approximately 1 Ω. The switch is designed to meet the power handling (>2 W) and frequency requirements of cellular communications systems and has been proven to 1×10^8 cycles.[28]

At room temperature, the RFMD switches required actuation voltages between approximately 60 to 120 V, while the NEU switches required approximately 60–80 V. (Actuation levels above 100 V causes the actuation lines to evaporate for the NEU switches.) Actuation voltage for cantilever beam switches are generally higher than those of capacitive switches,[29] which follows from the design parameters of the switches.[25] Based on the actuation voltages employed for the present experiments, the room temperature contact forces were estimated to be on the order of 70–100 μN.[30]

During the cooling process, the strain gradient in the switch cantilevers changed, resulting in an increase in the actuation voltages required to close the switches. The voltage needed to close a switch was a factor of one and a half, (NEU) or double (RFMD) at 87 K, compared to 293 K. (Fig. 2).

The actuation voltages returned to their initial value upon returning to room temperature, thus showing a reversible process. Moreover, when switches were held in closed position during cooling, the actuation voltage at some point would become too small to produce sufficient pull down force, causing switches to reopen. Such increases in actuation voltage were not observed for switches fabricated by

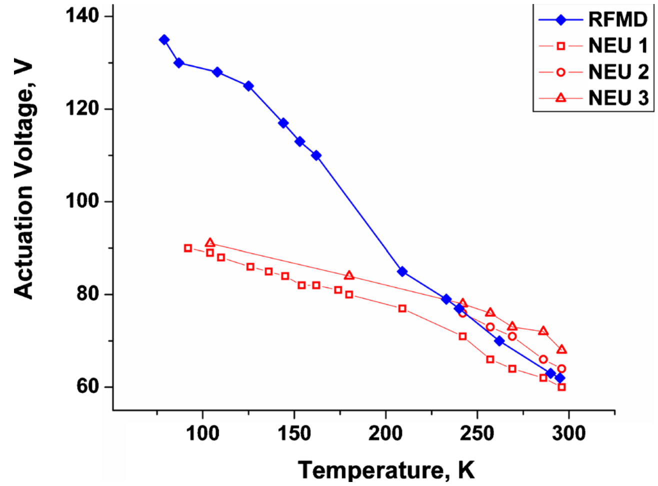

FIG. 2. (Color online) Voltage necessary to actuate RFMEMS Au/Au switch at different temperature.

WiSpry that were reported in an earlier publication.[16] This is attributed to a difference in the matching behaviors of the expansion properties of the cantilever mounting materials.

According to Bogozi *et al.*[31] the force necessary to actuate the switch greatly depends on the properties of material from which the cantilever beam is made and on the physical parameters of the switch. This dependence has not widely been studied but existing results prove that temperature should affect the switch actuation. The possible explanation of this effect is increasing strain gradient in the cantilever and Young's modulus of gold during cooling.[30] Previous measurements showed how temperature affects the actuation voltage for two-fixed end switches.[21,29]

The experimental setup (Fig. 3) consisted of an adaptation of a setup described earlier by Brown *et al.*[16] whereby the 20-pin electrical feedthrough was replaced with a 32-pin electrical feedthrough that supported a 24-pin ceramic dual inline package and a platinum resistance thermometer. A short description of the chamber is as follows. The test chamber consisted of a thin steel 3.75-in.-diameter cylinder fitted with a 32-pin electrical feedthrough at the lower end, allowing a four-point dc measurement of the device's contact resistance. A 28-in. extension arm was fitted to the top of the

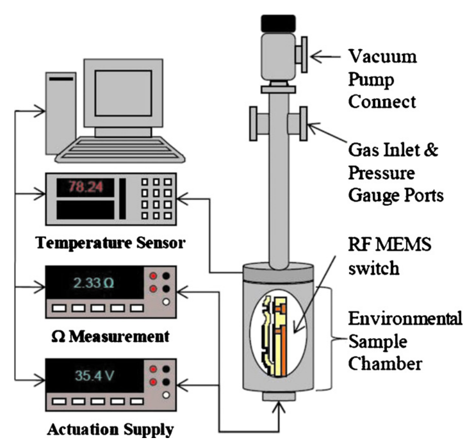

FIG. 3. (Color online) Experimental setup diagram (reprinted from Ref. 28, Fig. 3.1).

cylinder to ensure that the environmental chamber was as low as possible in the cryostat Dewar. The top of the transfer arm was attached to a four-way cross that allowed for pressure measurement, vacuum access, and ports for backfilling with different gases. Electrical connections inside the chamber were made with a standard braded copper vacuum wire between the feedthrough and a 24-pin socket. The die with switches were placed on the ceramic side braze package with gold leads. One mil (25 μm) gold wires were wirebonded between the device die and ceramic package. The packages were then inserted in the socket during testing. Electrical connections outside the chamber between the feedthrough and test circuitry were made using constantan wire to ensure that no additional resistance changes were measured as a result of thermal fluctuations from wire exposed to liquid nitrogen during testing.[16]

All experiments were performed in vacuum environment, to allow the results to be reproduced irrespective of the laboratory in which they are performed. Vacuum environments are moreover directly applicable to certain space applications that require open packaging. They also provide baseline data for studies of close packaging environments. Finally, they allow studies of the impact of adsorbed films in a controllable manner.

Two vacuum chambers were employed for data recording. The majority of the data were recorded in a high vacuum chamber which was pumped to 10^{-5} Torr pressure, as measured by cold cathode gauge. A second ultrahigh vacuum chamber, which was pumped to 5×10^{-9} Torr pressure, and equipped with *in situ* oxygen plasma cleaning capabilities, was used for additional data to examine the theory of lowering softening temperature due to the possible presence of a contamination layer.

Two Keithley 2400 source meters were used for actuating the switch and performing a four-point dc contact resistance measurement across the device contacts. During the measurements, actuation currents were limited to 10 μA. All instrumentation was controlled via LABVIEW. The chamber was cooled by submerging the entire sample cell in the liquid nitrogen (77.4 K). The temperature was measured with a platinum thermometer, and switches were actuated by applying an actuation voltage (i.e., the voltage necessary to close the switch) until stable contact resistance was achieved. Data presented herein show experimental results for one NEU and one RFMD switch. The actuation voltage was regulated to be low enough to allow softening effects to be seen clearly.[22] However, the load force on the switch was not controlled in between different device temperatures. Once at a given temperature, the actuation voltage remained the same during all measurements to perform the same load force. During experimental measurements, tests were performed with 5–10 min breaks between measurements.

IV. EXPERIMENTAL RESULTS

A. High vacuum chamber

1. Sourcing voltage dependence of the RFMD and NEU switches

Measurements of resistance versus time dependence were performed for different sourcing voltages and device temperatures. Using Eq. (3), sourcing voltages were applied in random order to have a contact temperatures T_C both below (in the hard regime) and above (in the soft regime) the predicted contact softening temperature. The applied (actuation) voltage, which determines the loading force, remained the same during all the measurements at the same temperature. However, the applied threshold actuation voltage changed during cooling down process, thus potentially causing variation in contact forces among three isotherms. The varying contact forces influence the magnitude of the contact resistance, thus producing a wide range of resistance values for the same switch at different temperatures but do not influence the observed performance trends in an isotherm. Figures 4(a)–4(c) present data for Au-Au contacts from RFMD switches, showing resistance as a function of time for a various contact voltages and for three different ambient temperatures: 87, 125, and 280 K. The most striking feature of the data sets is a relatively sudden drop in resistance when the contact voltage crosses a certain threshold. Similar features are observed for data recorded on the NEU switches (Fig. 5), which were recorded at 92, 178, and 293 K. The drop is not as abrupt for the 87 K(RFMD) and 92 K(NEU) data sets, which may be indicative of the larger temperature gradients present for switches undergoing softening at the colder ambient temperatures: Smaller regions of the switch will be above the softening temperature in these cases.

Figures 4(d) and 5(d) show that threshold for resistance reduction in both the NEU and RFMD switches occurs close to a temperature of 338 K. This can be observed by solving Eq. (3) for an assumed contact temperature of 338 K, which is represented by the solid line in Figs. 4(d) and 5(d). The regions below the curve then represent contact voltages and ambient temperatures where the system has not softened and any contaminant film present has not been displace. The area above this curve represents contact voltages and ambient temperature values consistent with either true softening and/or an initial disruption of a contaminant film that is manifested as a drop in resistance.

Having confirmed that Jensen's value of 338 K was also observed at cryogenic temperatures, we next performed a experiments to explore whether this feature corresponded to displacement of a contaminant film or in fact a true softening of the contact.

2. Control experiment no. 1: Resistance of a permanently closed switch

As a control experiment, permanently closed (fused) switches (adhered in the closed position with zero actuation voltage) were investigated in order to investigate the temperature dependence of gold resistivity with presumably constant contact area. Alternate methods for investigation the constant contact area, such as control of electric current flow,[32,33] have been reported in prior literature. The fused switch study proved to be a convenient approach for this work to perform the experiments with exactly the same parameters and in the same environment as working switch. The expectation here is that the resistance should track the known temperature dependence of the resistivity of gold and that any applied contacts voltage will impact the resistance

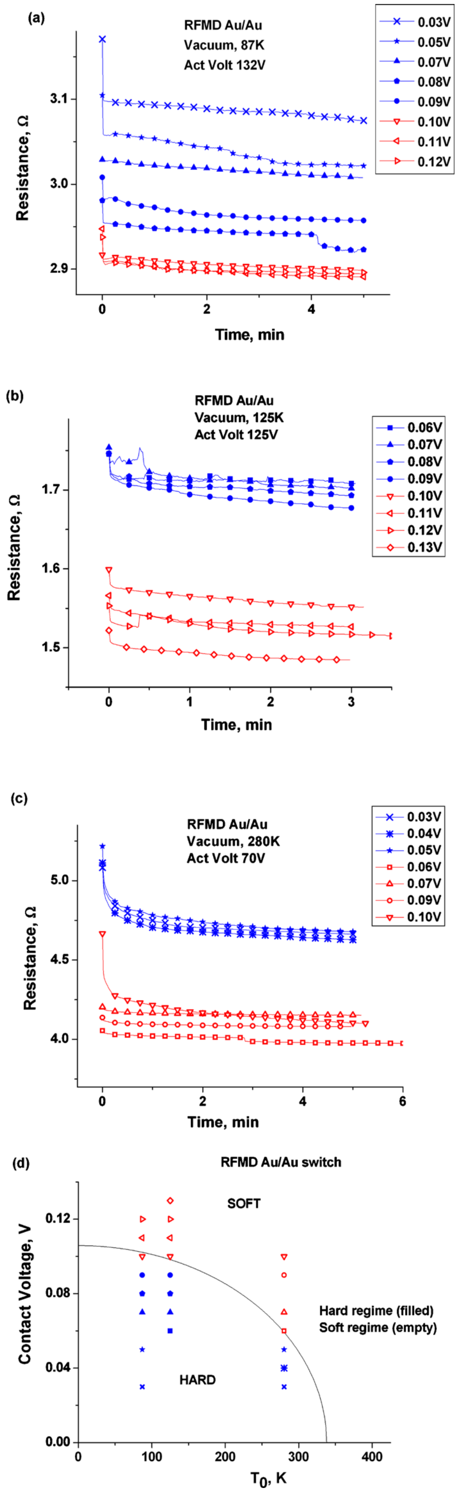

FIG. 4. (Color online) Resistance vs time for voltages above and below predicted values for the softening point via Eq. (3). for the rfMD Au/Au switch: (a) 87 K; (b) 125 K; (c) 280 K; (d) Eq. (3) with $Tc=338$ K compared to ambient temperatures T_0 and voltages at which data were recorded. Open points correspond to data points above the experimentally observed threshold where the resistance exhibited a sudden drop-off. Filled points depict data recorded at voltages below this threshold.

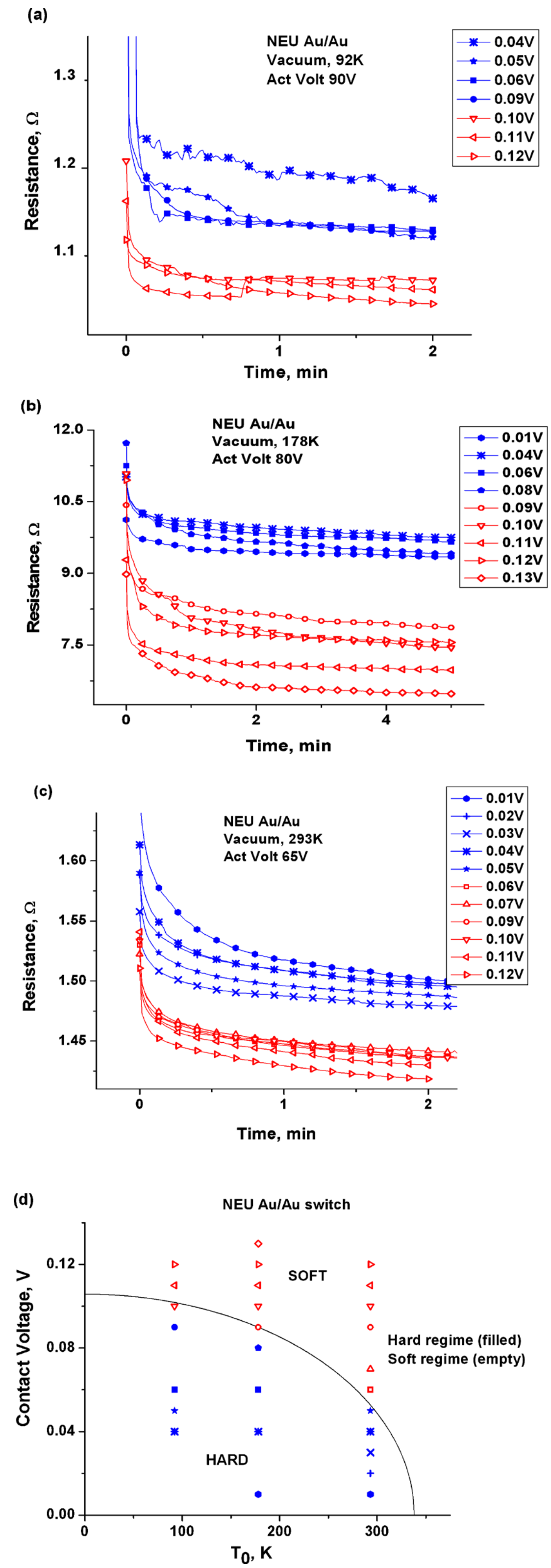

FIG. 5. (Color online) Resistance vs time for voltages above and below predicted values for the softening point via Eq. (3). for the NEU Au/Au switch: (a) 92 K; (b) 178 K; (c) 293 K; (d) Eq. (3) with $Tc=338$ K compared to ambient temperatures T_0 and voltages at which data were recorded. Open points correspond to data points above the experimentally observed threshold where the resistance exhibited a sudden drop-off. Filled points depict data recorded at voltages below this threshold.

only through changes in temperature but not through changes in contact area arising from the fact that the contact is softer (and thus increases in response to the applied load).

During this control experiment, no actuation voltage was applied and thus no external load impacted the area of the

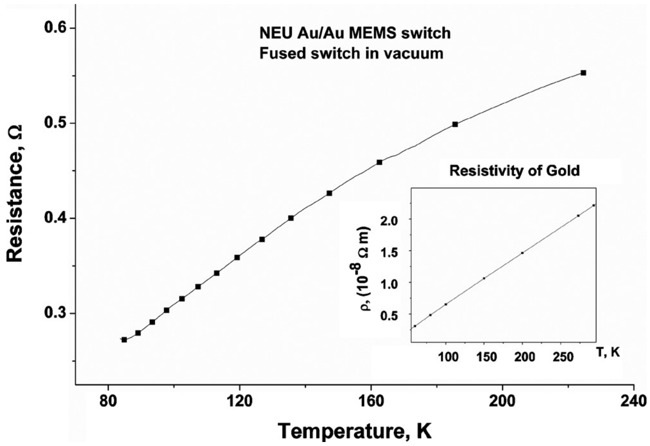

FIG. 6. NEU Au/Au fused switch. Resistance vs temperature dependence during cooling down process. Inset represents the resistivity of gold at different temperature (Ref. 34).

switch. The dependence of resistance on temperature during cooling for fused switches, which were permanently adhered, compares well with known values for resistivity (Fig. 6). Resistivity of the switch should decrease with temperature decrease, and previous measurements identified temperature dependence of gold resistivity to be almost linear[34] in the range of temperatures presented here.

Resistance measurements for varying contact voltages on fused devices are shown in Fig. 7. For permanently closed switches, contact area remains constant and resistance should be affected only by changes in resistivity. The change in resistance due to sourcing voltage heating of fused switch is less than 5%. Similar measurements for fused switches of different design were taken by Brown.[28] Brown's data also indicated a small percent change in overall resistance. However, Brown used a much lower compliance current, which restricted the current not to exceed a specific value, thus affecting the trend in resistance.

3. Measurements on "clean" switches in ultrahigh vacuum

Additional measurements of resistance versus time dependence for RFMD switch were performed for different

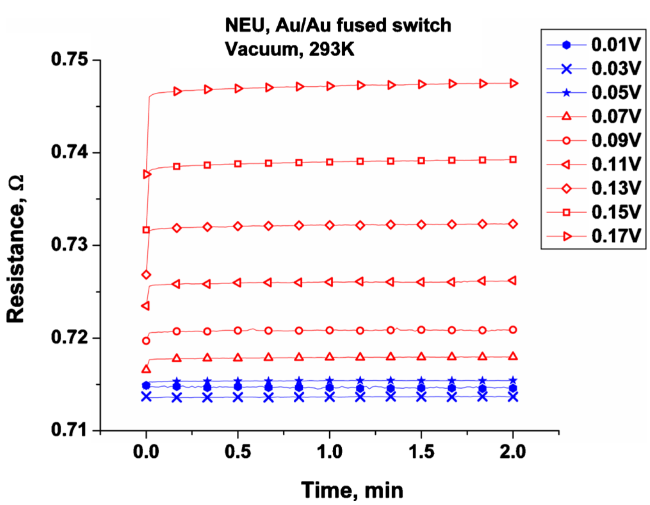

FIG. 7. (Color online) Closed switch resistance vs time dependence for different sourcing voltage. NEU Au/Au switch.

sourcing voltages in a UHV chamber. These measurements were performed to explore the hypothesis that the temperature at which a sudden drop in resistance is observed corresponds to adsorbed film effects and not actual softening. Cleaning of the switches to remove such layers should then result in an increase the softening temperature to its expected value of 373 K.

It is well known that physisorbed layers condense onto gold surfaces[35] in both vacuum and ambient conditions, that the coverage is determined by the pressure surrounding the surface[36,37] and the uniformity of the substrate.[38,39] At room temperature, the adsorbates are largely composed of hydrocarbon species and water vapor.[38,39] At cryogenic temperatures, both oxygen and nitrogen from residual ambient will also condense on gold.[36,40–42] Both the absolute temperature[35,42] as well as thermal fluctuations[37] have great impact on coverage levels for such thin adsorbed layers. Since such layers are not completely removed by UHV conditions alone, the UHV chamber was equipped with *in situ* oxygen plasma capabilities[43] capable of removing adsorbed contaminants. The switches however all adhered upon cleaning and no measurements could be performed on them to probe for an elevated softening temperature. We therefore looked for indirect evidence for such behavior, by comparing data for switches before and after measurements had been recorded at elevated contact temperatures.

In UHV conditions, Walker *et al.*[43] have reported that several days are required for contaminant films to reform once removed, in contrast to high vacuum conditions where residual films from the gas phase reform quickly. We therefore compared data sets before and after softening for switches that had not been exposed to the oxygen plasma cleaning treatment. Figures 8(a) and 8(b) show the data first set for such a switch [Fig. 8(a)] and second set of data for the same switch after it had undergone a softening measurement at elevated temperature and contact voltage[Fig. 8(b)].

Indeed, the voltage required for softening at the room temperature did move upward, from 0.05–0.06 V to 0.07–0.08 V, a clear indication of removal or partial removal of a contaminant species.

V. DISCUSSION

A. Sourcing voltage dependence on contact temperature

The impact of contact voltage on contact resistance at various cryogenic temperatures has been measured, and is displayed on Figs. 4 and 5. In Figs. 4(d) and 5(d), a theoretical line is drawn for an assumed $T_C = 338$ K, which is consistent with the resistance drop observed in the data sets. Using formula (1) from Nicolic *et al.*[44] and estimating the upper limit of contact resistance, the resistance change between the upper and lower regimes implies an approximate change in effective contact area to be 20%–40%. Alternatively, the resistance drops occurring at 338 K could be due to desorption and/or disruption of adsorbed films: when such films are pushed aside, the resistance will drop without any actual increase in contact area.[21,45,46] Overall, the data that we have collected here lends strong support to the suggestion

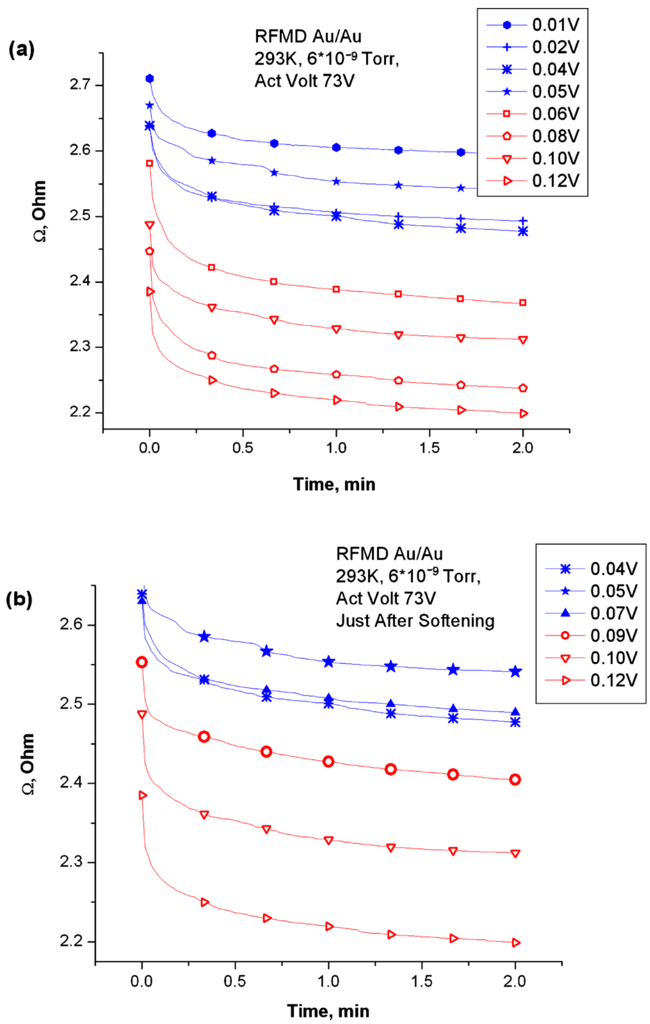

FIG. 8. (Color online) Contact heating effect for rfMD Au/Au switch at 293 K: (a) switch with residual adsorbed contamination layer; (b) switch after passing above elevated temperatures several times, the presumption being that the adsorbed film is disrupted and has not had time to reform in the UHV conditions. Data points for hard regime (filled symbols) and soft regime (empty symbols) are comparable to theoretical softening threshold at 338 K (0.052 V) and 373 K (0.072 V), respectively, for case (a) and case (b).

that the resistance drop observed at 338 K is associated with adsorbed film effects, and that actual softening occurs are higher temperature (Fig. 8).

The real contact area is not the only contributor to contact resistance. The resistivity of the materials also plays a role because of its dependence on temperature. As calculated in,[34] resistivity of gold should decrease by a factor of 2 in the temperature range from 100 to 200 K. Indeed, in Fig. 5, resistance of a fused NEU switch decreases by a factor of 2 when cooled over the same range. However, the contact temperature affects the resistivity in a different way when compared to the ambient temperature. For data recorded on a permanently closed switch (Fig. 7), it is assumed the contact area changes minimally, therefore any change in resistance is primarily due to the change in resistivity of the gold because of the contact temperature change. For contact voltages of 0.01 to 0.17 V we observe a slight rise in resistance, $\sim$0.04 Ω, which is explained by resistivity increase with higher temperature. This is a small change in resistance and it occurs in opposite direction to the resistance change for working switches. Therefore, we can neglect resistivity change during sourcing voltage experiments for working switches, thus the main mechanism of changes occurring in working switches belongs to changes in contact area and/or removal or changes in the adsorbed film species.

VI. CONCLUSIONS

A series of experiments were performed in vacuum environments to investigate the impact of RFMEMS switch contact voltage versus resistance for gold-on-gold contacts at cryogenic temperatures and to explore contact softening effects in such systems. Measurements on two distinct switch types, fabricated at independent laboratories, were performed in the temperature range 79–293 K and for contact voltages ranging from 0.01 to 0.13 V. Similar results were observed for both switches. The central results can be summarized as follows:

(1) Contact resistance values at all temperatures were observed to be lower for higher contact voltages, consistent with the aforementioned asperity heating models, whereby increased contact currents are associated with increased heating and softening effects.
(2) *In situ* removal of adsorbed species by oxygen plasma cleaning resulted in switch adhesive failure.
(3) Switches that were are not subjected to cleaning exhibit distinctive reductions in contact resistance at close to 338 K, consistent with suggestions that adsorbed films present on the surfaces begin to desorb, disassociate, and/or be pushed aside at that temperature.
(4) Therefore, contact temperatures between 338 and 373 K appear to be high enough to dissociate adsorbed contaminant films and/or push them aside but low enough to prevent asperities from becoming soft and adherent.
(5) Resistivity changes due to heating in contacts have only a slight effect on resistance. Therefore, the resistivity changes can be neglected for actual RFMEMS switches while the contact area variation and adsorbed film effects plays major roles.
(6) The actuation voltage necessary to close a switch is strongly influenced by the device temperature and design. Although some switch designs result in no dependence of the actuation voltage on temperature[10] the switches measured here required approximately double the actuation voltage at 90 K compared to room temperature.
(7) Low ambient temperature operation of a RFMEMS switch allows a wider range of contact voltages to be used without causing asperity softening and the associated detrimental effects of adhesion.

ACKNOWLEDGMENTS

This work was supported by AFOSR MURI Grant No. FA9550-04-1-0381 entitled “Multifunctional Extreme Environment Surfaces: Nanotribology for Air and Space” and DARPA S&T Fundamentals Program, “Center for RFMEMS Reliability and Design Fundamentals,” Grant No. HR0011-

06-1-0051. The authors would like to thank to Jonathan Hammond at rf Micro Devices and N. E. McGruer at Northeastern University for providing the experimental switches, Keeley Stevens at NCSU for valuable technical discussions, and G. M. Rebeiz at UCSD for both motivating discussions and vision in overall project direction of the DARPA RFMEMS Center.

[1]G. M. Rebeiz, *RF MEMS Theory, Design, and Technology* (Wiley, New York, 2003).
[2]J. Noel, Y. Hijazi, J. Martinez, Y. A. Vlasov, and G. L. Larkins, Jr., Supercond. Sci. Technol. **16**, 1438 (2003).
[3]E. M. Prophet, J. Musolf, B. F. Zuck, S. Jimenez, K. E. Kihlstrom, and B. A. Willemsen, IEEE Trans. Appl. Supercond. **15**, 956 (2005).
[4]J. Y. Park, G. H. Kim, K. W. Chung, and J. U. Bu, Sens. Actuators, A **89**, 88 (2001).
[5]D. J. Dickrell III and M. T. Dugger, Proceedings of the Fifty-First IEEE Holm Conference on Electrical Contacts, Vol. 255 (2005.
[6]W. M. van Spengen, R. Puers, and I. De Wolf, IEEE Trans. Device Mater. Reliab. **3**, 167 (2003).
[7]Z. J. Guo, N. E. McGruer, and G. G. Adams, J. Micromech. Microeng. **17**, 1899 (2007).
[8]J. Tringe, W. Wilson, and J. Houston, Proc. SPIE **4558**, 151 (2001).
[9]R. Holm, *Electric Contacts: Theory and Applications* (Springer, Berlin, Germany, 1969).
[10]B. Borovsky, J. Krim, S. A. Syed Asif, and K. J. Wahl, J. Appl. Phys. **90**, 6391 (2001).
[11]B. D. Dawson, S. M. Lee, and J. Krim, Phys. Rev. Lett. **103**, 205502 (2009).
[12]J. Krim, Am. J. Phys. **70**, 890 (2002).
[13]J. Krim, Langmuir **12**, 4564 (1996).
[14]M. O. Robbins and J. Krim, MRS Bull. **23**, 23 (1998).
[15]R. Holm, *Electric Contact*, 4th ed. (Springer-Verlag, Berlin, 1967).
[16]C. Brown, M. A. Zikry, and J. Krim, J. Microelectromech. Syst. **19**, 025006 (2009).
[17]S. B. Gong, H. Shen, and N. S. Barker, IEEE Trans. Microwave Theory Tech. **57**, 3442 (2009).
[18]Y. Zhu and H. Espinosa, J. Micromech. Microeng. **14**, 1270 (2004).
[19]H. T. Su, I. Llamas-Garro, M. J. Lancaster, M. Prest, J.-H. Park, J.-M. Kim, C.-W. Baek, and Y.-K. Kim, Electron. Lett. **42**, 1219 (2006).
[20]Y. Hijazi, A. Bogozi, M. Brzhezinskaya, J. Martinez, J. Burke, J. Noel, Y. A. Vlassov, and G. L. Larkins, Jr., IEEE Trans. Appl. Supercond. **15**, 952 (2005).
[21]B. Jensen, L. Chow, K. Huang, K. Saitou, J. Volakis, and K. Kurabayashi, J. Microelectromech. Syst. **14**, 935 (2005).
[22]H. Kwon, S. S. Jang, Y. H. Park, T. S. Kim, Y. D. Kim, H. J. Nam, and Y. C. Joo, J. Micromech. Microeng. **18**, 105010 (2008).
[23]O. Rezvanian, M. A. Zikry, C. Brown, and J. Krim, J. Micromech. Microeng. **17**, 2006 (2007).
[24]A. Fortini, M. I. Mendelev, S. Buldyrev, and D. Srolovitz, J. Appl. Phys. **104**, 074320 (2008).
[25]B. D. Jensen, Z. Wang, L. Chow, K. Saitou, K. Kurabayashi, and J. L. Volakis, Wireless Communication Technology, IEEE Topical Conference, Vol. 10 (2003).
[26]S. Majumder, N. E. McGruer, G. G. Adams, P. M. Zavracky, R. H. Morrison, and J. Krim, Sens. Actuators, A **93**, 19 (2001).
[27]RF Micro Devices, http://www.RFMD.com
[28]C. Brown, Ph.D. dissertation, NCSU, 2008.
[29]H. T. Su, I. Llamas-Garro, M. J. LancasterM. Prest, Electron. Lett. **42**, 165 (2006).
[30]P. M. Osterberg and S. D. Senturia, J. Microelectromech. Syst. **6**, 107 (1997).
[31]A. Bogozi, A. V. Datye, M. Brzhezinskaya, Y. S. Hijazi, J. Martinez, J. Noel, K. H. Wu, Y. A. Vlasov, and G. L. Larkins, Jr., IEEE Trans. Appl. Supercond. **15**, 980 (2005).
[32]C. L. Goldsmith, IEEE Microw. Wirel. Compon. Lett. **15**, 718 (2005).
[33]S. Patton and J. Zabinski, Tribol. Lett. **18**, 215 (2005).
[34]D. R. Lide, *Handbook of Chemistry and Physics*, 75th ed. (CRC, New York, 1996).
[35]J. Krim, J. G. Dash, and J. Suzanne, Phys. Rev. Lett. **52**, 640 (1984).
[36]V. Panella, R. Chiarello, and J. Krim, Phys. Rev. Lett. **76**, 3606 (1996).
[37]K. R. Mecke and J. Krim, Phys. Rev. B **53**, 2073 (1996).
[38]V. Panella and J. Krim, Phys. Rev. E **49**, 4179 (1994).
[39]C. Mak and J. Krim, Faraday Discuss. **107**, 389 (1997).
[40]J. Krim, E. T. Watts, and J. Digel, J. Vac. Sci. Technol. A **8**, 3417 (1990).
[41]R. P. Chiarello, J. Krim, and C. Thompson, Surf. Sci. **306**, 359 (1994).
[42]C. Brown, O. Rezvanian, M. Zikry, and J. Krim, J. Microelectromech. Syst. **17**, 1460 (2008).
[43]M. Walker, C. Nordquist, D. Czaplewski, G. Patrizi, N. McGruer, and J. Krim, J. Appl. Phys. **107**, 084509 (2010).
[44]B. Nikolić and P. B. Allen, Phys. Rev. B **60**, 3963 (1999).
[45]L. Kogut and K. Komvopoulos, J. Appl. Phys. **95**, 576 (2004).
[46]L. Kogut and K. Komvopoulos, J. Appl. Phys. **97**, 073701 (2005).