

# Electrical Contact Resistance and Device Lifetime Measurements of Au-RuO<sub>2</sub>-Based RF MEMS Exposed to Hydrocarbons in Vacuum and Nitrogen Environments

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**Abstract** Electrical Contact Resistance (ECR) measurements are reported for RF micro-electromechanical switches with Au-RuO<sub>2</sub> contacts, situated within an ultrahigh vacuum system equipped with in situ oxygen plasma cleaning capabilities. Two studies are reported, each involving a comparison of the ECR in vacuum and nitrogen environments for measurements performed immediately after cleaning. The first study reports measurements of initial resistance (resistance measured upon first time closure) versus pressure as dodecane gas is admitted to the chamber. A significant increase is observed at pressures in vacuum as low as 10<sup>-5</sup> torr, ( $P/P_{\text{sat}} < 10^{-4}$ ) consistent with earlier reports involving repetitive cycling of macroscopic switches in partial pressures of hydrocarbons in nitrogen. Somewhat unexpectedly, however, the resistance only doubles, even for pressures sufficiently high as to result in full monolayer condensation. In a second study, switch lifetimes in vacuum (10<sup>-8</sup>–10<sup>-9</sup> torr) and nitrogen gas environments are compared, for switches operated immediately afterward, or alternatively left open for a number of days before operation. Although it was expected that vacuum would reduce and/or prevent contamination of the electrical contact surfaces, no

enhancement or extension of lifetime was observed: Continuous operation of a switch in a nitrogen environment immediately after plasma cleaning was in fact the only procedure observed to indefinitely prolong device lifetime. The results suggest that (1) Hydrocarbon reaction products, but not mobile physisorbed hydrocarbons themselves, are responsible for increasing ECR by orders of magnitude and (2) Repetitive cycling motion of a clean switch in nitrogen inhibits formation of physisorbed hydrocarbon contaminants on the contacts, while vacuum levels far superior to 10<sup>-9</sup> torr are required to prevent contamination.

**Keywords** MEMS devices · Contact mechanics · Adhesion · Stiction · Surface roughness

## 1 Introduction

Radio frequency microelectromechanical system (RF MEMS) switches have many promising advantages over solid-state switches, particularly with respect to cutoff frequency, insertion loss, linearity, and power consumption characteristics [1, 2]. They are, however, highly susceptible to a variety of different failure mechanisms associated with high resistivity and adhesive bonding [3, 4]. The uptake and control of hydrocarbon films adsorbed on their contacts are central to this [5, 7], since both the contact resistance [5–7] and contact adhesion [8, 9] are highly sensitive to the presence of thin adsorbed films. Studies of switch performance in varying environments may help to find the best conditions to improve switches characteristics and prolong their lifetime. Vacuum environments are, for example, directly applicable to certain space applications that require open packaging. Nitrogen environments are often used for MEMS transportation. Finally, dodecane environments

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allow studies of the impact of adsorbed films in a controllable manner.

It is well established that physisorbed layers condense onto gold and other noble metal contacts [10] in both vacuum and ambient conditions and that the coverage is determined by the pressure surrounding the surface [11, 12] and the uniformity of the substrate [13, 14]. At room temperature, the adsorbates are largely comprised of hydrocarbon species and water vapor [11, 15–17], and the coverage levels, especially for very thin films, are very sensitive to both temperature [10, 18, 19] and thermal fluctuations [12]. It is believed that residual hydrocarbon films at the surface lead to decomposition and then deposition of highly resistive carbon deposits [3, 4, 20–22]. The layers are extremely difficult to remove [8, 23], and even after in situ plasma cleaning in Ultra High Vacuum (UHV), they have been observed to readily reform. Walker et al. [8], for example, reported contaminant films to reform after several days in UHV, and almost immediately in high-vacuum conditions. Such contaminant layers are generally invoked whenever experimentally measured resistances are found to be higher than theoretical values for a clean contact [4, 8]. The situation is complicated, however, by the fact that actual contact occurs only at a limited number of small “contact spots” [24–26] that can exhibit asperity creep and grow larger in time [27–30]. This causes the contact resistance to decrease in time. Contact pressures may also squeeze part or all of the film out of the contact as time progresses. (The actual contact area can be as little as 1% or less of the apparent area after a closure time of 1 s and can increase to approximately 7% after a closure time of 40 h [30], depending on the physical properties of the materials in contact.) Realistic theoretical treatments of the topic must take these effects into account, as well as considering surface roughness and electron tunneling contributions through thin adsorbed layers and/or regions of both planar contact and nonplanar regions in close proximity [5, 31–36]. Well-controlled experimental studies of RFMEMS contacts in the presence and absence of adsorbed films are meanwhile in great demand: Such studies are exacerbated by the fact that removal of the films is both difficult to achieve and can also render the switches non-operational through adhesive bonding failure [19].

Contact resistance measurements are reported here for Au-RuO<sub>2</sub>-based RF MEMS switches operating within an UHV system. The system is equipped with in situ oxygen plasma cleaning capabilities and has the ability to immediately expose the samples to partial pressures of dodecane gas, or alternatively examine samples lifetimes in either vacuum or nitrogen environments. In this stringently controlled chamber, we have previously reported the baseline contact resistance values after cleaning to be close to those theoretically predicted for a contact with no adsorbed

contaminant film [8]. Au-RuO<sub>2</sub> contacts were selected for our studies, as they are a promising materials combination for RFMEMS devices [8, 37], and in particular remain operational in a wide range of conditions so as to allow controlled studies to be performed on them [8]. In contrast, Au–Au contacts cold-weld and become fused when contamination layers are removed from their surfaces, thus preventing meaningful studies to be performed [19]. Dodecane was selected for study based on its well-documented impact on macroscopic switches, [20, 21] and also on account of the well-documented nature of its surface adsorption [38] and reaction [39–41] properties in the surface science literature. To our knowledge, the only prior reports of contact resistance measurements during controlled exposures to hydrocarbons were performed on macroscale relays operating in synthetic air (80% nitrogen, 20% oxygen) or pure nitrogen environments where [20–22] it can be presumed that thin adsorbed contaminants were present from the outset. An interesting conclusion of the aforementioned studies was that oxygen-rich environments inhibit hydrocarbon surface contamination by enabling the formation of volatile oxides: Vacuum and pure nitrogen environments, by this argument, would thus result in similar sample behaviors as they are both oxygen deficient.

The focus of the work reported here is (1) to examine in a vacuum environment the pressure at which a hydrocarbon gas, namely dodecane, first causes an initial resistance increase (the resistance measured upon first time closure) for an RFMEMS device cleaned in situ, including comparison of the pressure and magnitude of the increase with that reported in the literature for macroscopic switch contacts operating continuously in nitrogen environments and (2) to compare lifetimes for initially clean devices operated, respectively, in nitrogen, and vacuum environments, to explore the common notion that vacuum conditions are superior to pure nitrogen in terms of switch degradation.

As described in the following sections, a significant increase in resistance is observed at dodecane pressures in vacuum as low as  $10^{-5}$  torr, ( $P/P_{\text{sat}} < 10^{-4}$ ) consistent with earlier reports involving repetitive cycling of macroscopic switches in partial pressures of hydrocarbons in nitrogen. Somewhat unexpectedly, however, the resistance only doubled, even for pressures sufficiently high as to result in full monolayer condensation. Lifetime measurements of the initially clean RF MEMS switches meanwhile revealed that vacuum levels on the order of  $10^{-8}$ – $10^{-9}$  torr failed in all cases to enhance or extend switch lifetimes: Continuous operation in nitrogen environments immediately after plasma cleaning was the only procedure observed to indefinitely prolong device lifetime. The results suggest that (1) although hydrocarbon reaction products can increase contact resistance by many orders of magnitude, the physisorbed hydrocarbon species, while intact, causes

an increase on the average of only a factor of two (the value of which remains largely unexplained) and (2) repetitive cycling motion of a clean switch in nitrogen inhibits the formation of physisorbed hydrocarbon contaminants on the contacts, while simply storing it in nitrogen or vacuum does not.

## 2 Experimental Setup and Data Collection

The switches were fabricated, released, and wire bonded at Sandia National Laboratories (SNL). The switches consist of a 7- $\mu\text{m}$ -thick gold mechanical beam separated from the substrate by approximately 4  $\mu\text{m}$ . The design contact dimple depth is 1.6  $\mu\text{m}$ , for a total travel of 2.4  $\mu\text{m}$ . The switch spring constant is approximately 80 N/m, resulting in total contact forces of 360  $\mu\text{N}$  at 120 V and restoring force of 200  $\mu\text{N}$ , spread across the four contacts. The switches were wire bonded with one mil (25  $\mu\text{m}$ ) Au wire to unlidded 24-pin or 40-pin side braze ceramic dual inline package (DIP) contact electrodes and then transported in ambient to North Carolina State University (NCSU) in Electrostatic Discharge (ED) protective packages, held in place by pressing the leads into an ED resistant form. At NCSU, they were stored for periods ranging from days to months, in a  $\text{N}_2$ -filled glove box in advance of the measurements. All top contacts consisted of Au, while the bottom contacts were either reactively sputtered  $\text{RuO}_2$  (“bulk  $\text{RuO}_2$ ”) or sputtered Ru that was oxidized after deposition (“surface  $\text{RuO}_2$ ”). The initial thicknesses of the Ru contact electrodes were 181 nm, and oxidation of the surface  $\text{RuO}_2$  added an additional 6 nm in thickness. Each die consisted of 12 switches, with at least four bulk and four surface  $\text{RuO}_2$  contacts, divided into three isolated banks of four. Each bank of four switches shared two common ground electrodes, one sense electrode, and one source electrode to enable four wire resistance measurements to be performed in close proximity to the switch. Each device also had a dedicated actuation electrode to close individual switches. All of the ground electrodes were wire bonded to the package ground to mitigate electrostatic discharge. All switches were completely exposed to the surrounding environment; their packaging did not include lids or encapsulation.

The ceramic package holding the samples was transferred to a stage within the vacuum chamber (evacuated to  $1 \times 10^{-9}$  torr) where the ECR measurements were performed. The stage consisted of two custom built rectangular machinable glass ceramic pieces with an array of holes drilled out to support 24, 40 and 64 pin side braze ceramic inline packages. The ceramic pieces were mounted on a piece of Oxygen-Free High-Conductivity (OFHC) Cu that was suspended inside the UHV chamber. All pin

sockets were connected to standard vacuum wires by spot welding, to reduce the possibility of outgassing within the vacuum and during plasma cleaning. Two Cu discs, 2.5” diameter and 1/4” thick, were mounted on either side of the MEMS stage and connected to a high voltage power supply for generating plasma in situ. Schematics and images of the apparatus are reported in [8].

Oxygen plasma cleaning treatments were performed as follows: all actuation voltage and four wire resistance connections outside the chamber were disconnected from the feedthroughs, and a gate valve connecting the sample chamber to the ion pump was closed. Research grade  $\text{O}_2$  was then leaked into the sample chamber until a capacitance manometer pressure gauge read approximately 150 mtorr. The system was then pumped with a turbo molecular pump, connected through a regulating valve adjusted to maintain a pressure of 150 mtorr. One Cu disc was then connected to a potential of 0.4 kV, while the other Cu disc was connected to both the grounded vacuum chamber and the ground of the power supply. Switches were exposed to oxygen plasma for 5 min. The power supply was then turned off and the chamber pumped immediately to  $10^{-8}$  torr with the turbomolecular pump followed by the ion pump. Only oil-free pumps were used in the experiments to prevent contamination of the experimental apparatus. Our previous work [8] revealed that oxygen plasma exposure reduces the contact resistance of Ru-based switches to values lower than obtained by operating the switches in UHV alone and that oxygen plasma exposure times longer than about 5 min do not result in further lowering of the resistance. The contact resistance of switches operated or simply left open in vacuum was always observed to increase, but subsequent exposure to oxygen plasma allowed the contact resistance to be returned to their original values. This reproducible contact resistance after oxygen plasma exposure served as the baseline for the experiments reported here. In the same study, we also observed that oxygen plasma induced thickening of oxide layers on the bulk sample caused the two samples to have very similar properties [8, 39, 41].

The pressure inside the experimental setup and gas composition were repeatedly checked with a Residual Gas Analyzer (SRS RGA 200). Gas composition analysis at low pressure showed that oxygen and water were at levels below  $10^{-8}$  torr.

Experimental resistance values were measured using a four probe resistance technique, with a source voltage of 0.02 V. The resistance included contributions from the device contact electrodes, which are estimated to be on the order of hundredths of an ohm [8]. The actuation voltage to close the switches ranged from 87 to 99 V, corresponding to 280–365  $\mu\text{N}$  [42, 43]. Once a device was closed, the actuation voltage was held constant for over 30 min to

allow the time dependence of the contact resistance to be documented. The switch was then reopened and exposed to a higher dodecane pressure. The actuation voltage itself was supplied by a waveform generator through a high voltage amplifier to the appropriate actuation switch electrode and monitored with a multimeter. The contact resistance was recorded by means of a Labview program, and its time dependence while held in the closed position was analyzed according to the power law relation [28],

$$R(t) = A t^{-\alpha} + B \quad (1)$$

where  $A$  is reflective of the topography of the contacts,  $\alpha$  is an intrinsic material property related to material creep properties [28], and  $B$  is the theoretical limiting resistance at  $t = \infty$ .

In order to estimate gas uptake on the samples, a polished QCM with gold electrodes was situated close to the RFMEMS samples, and its frequency was recorded simultaneously. The measured drift of the QCM was 0.1 Hz/h or less, and all measurements were recorded in 15 min or less. This compares favorably with the  $\delta f = 3.78$  Hz shift expected for one monolayer of uptake, estimated as follows: The Sauerbrey equation for uptake onto two sides of an AT-cut (AT is a transverse shear mode) QCM is [44]

$$(2.21 \times 10^5) \delta f = \sigma f_0^2, \quad (2)$$

where the resonant frequency  $f_0$  is in Hz, and the mass per unit area of the adsorbed film  $\sigma$  is in  $\text{g}/\text{cm}^2$ . The mass per unit area of an adsorbed dodecane ( $\text{CH}_3(10\text{CH}_2)\text{CH}_3$ ) monolayer is well documented for the case up uptake on a gold surface [38]. For molecules oriented with their hydrocarbon backbones parallel to the surface, each molecule ( $2.839 \times 10^{-22}$  g; or molecular weight 170) can be assumed to occupy a  $1.73 \text{ nm} \times 0.5 \text{ nm}$  rectangle area on the surface, corresponding to  $\sigma = 33 \text{ ng}/\text{cm}^2$ . For a 5 MHz resonant frequency QCM, this corresponds to a 3.78 Hz frequency shift per monolayer. Clearly, this is an estimate, as only one of the contacts is Au, and the geometry is far from planar, but the information is nonetheless very useful to document that uptake is indeed occurring.

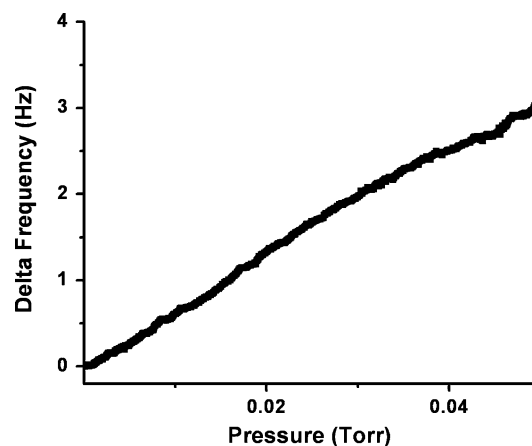
### 3 Results

Two distinct studies were performed on the initially clean switches, each involving a comparison of properties of the contact resistance in vacuum and nitrogen environments. The first involved measurements of initial resistance (the resistance measured upon first time closure) versus pressure as dodecane gas were admitted to the chamber. The second study examined switch lifetimes in vacuum ( $10^{-8}$ – $10^{-9}$  torr) and nitrogen gas environments for switches

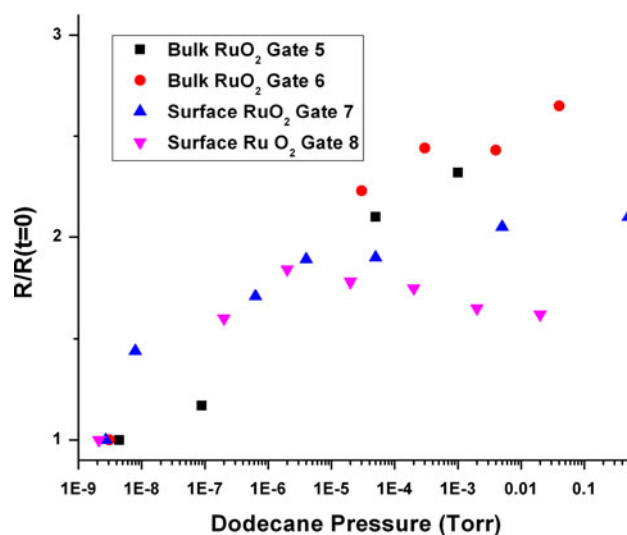
operated immediately after cleaning, or alternatively left open for a number of days before operation.

#### 3.1 Dodecane Uptake Studies

QCM frequency shift and initial contact resistance (the resistance measured upon first time closure) divided by its value at  $10^{-9}$  torr are presented, respectively, in Figs. 1 and 2 as a function of dodecane pressure surrounding the sample. The switches were cleaned once at the beginning



**Fig. 1** Frequency shift versus dodecane pressure for a quartz crystal microbalance with gold electrodes situated near the RFMEMS switches. The bulk vapor pressure at room temperature is 0.3 torr, and one monolayer of dodecane adsorbed on the electrodes corresponds to a 3.8 Hz shift



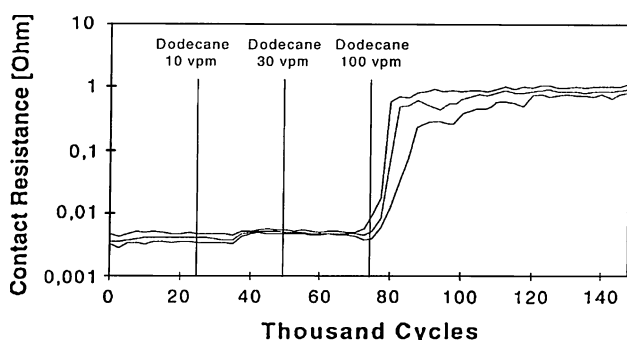
**Fig. 2** Initial contact resistance (the resistance measured upon first time closure at  $t = 0$ ) divided by its value at  $10^{-9}$  torr versus surrounding dodecane pressure for four switches. Contact resistance doubles for all devices for pressures of  $10^{-5}$  torr, where uptake on the QCM is negligible. They fail to increase significantly thereafter, even for full monolayer coverages of dodecane. The bulk vapor pressure of dodecane at room temperature is 0.3 torr

of the sequence, and then, the pressure surrounding them was raised while they were held in the closed position. They were briefly re-opened at progressively higher pressures and then held in the closed position to obtain the time dependence resistance values.

In all cases, the switch resistances have doubled by the point at which the surrounding pressure reaches  $5 \times 10^{-5}$  torr, which is well below the detection level of the microbalance, or hundredths of a monolayer. The best explanation for this is the fact that the binding energy for adsorption close to the contact is expected to be substantially greater than that of the open geometry of the QCM electrode: in short, the adsorbed particles close to the switch contact are coming into contact with multiple surfaces. The QCM measurements of coverage remain relevant, however, as an important reference point for comparison purposes [13].

Resistance versus pressure changes have also been reported by Koidl et al. [20, 21]. This is displayed in Fig. 3, for adsorption uptake in synthetic air (20% oxygen, 80% nitrogen). Koidl et al. observed the resistance to increase during repeated cycling of the switches, while in experiments presented in this paper, the increase occurs after the first closure of the switches. Moreover, the change in resistance during dodecane adsorption in experiments presented here occurs at pressures that are orders of magnitude lower. This result is consistent with Koidl et al.'s observation that hydrocarbon contamination produces resistance increases at partial pressures that are orders of magnitude higher when oxygen is present.

The data in Fig. 2 represent the initial resistance upon first time closure of the switch. As mentioned earlier, the contact area increases in time as a switch is held in the closed position. The resistance measurements were



**Fig. 3** Contact resistance versus cycles and time (1,000 cycles = 1,000 s) for a macroscopic Au contact switch operated at 1 Hz and exposed to increasing levels of dodecane gas as a partial pressure in synthetic air (80% nitrogen, 20% oxygen) The critical concentration of 100 vpm, or parts per million volume, corresponds to a partial pressure of  $7.6 \times 10^{-2}$  torr. The authors suggest an oxygen deficient environment should lower the critical concentration by more than 2 orders of magnitude, consistent with our observation of a critical concentration near  $10^{-5}$  torr. (Reprinted from [20], Fig. 4)

**Table 1** Average resistance at time 0 and 30 min, as well as fit values to Eq. 1 for the four switches displayed in Fig. 2

Pressure (torr)	$R_{ave}$ ( $\Omega$ , $t = 0$ )	$R_{ave}$ ( $\Omega$ , $t = 30$ min)	$A_{ave}$	$\alpha_{ave}$	$B_{ave}$ ( $\Omega$ )
5e-9 (initially clean)	14.6	12.9	13.3	0.018	0.05
5e-5 (resistance doubles)	32.1	25.5	25.9	0.035	0.05
5e-2 (one monolayer)	40.3	25.5	28.7	0.031	0.04

therefore also recorded as a function of time held in the closed position after exposure to various levels of dodecane partial pressures and analyzed according to the power law relation, Eq. 1 [28]. The average fit parameters and average resistance values at times 0 and 30 min are reported in Table 1.

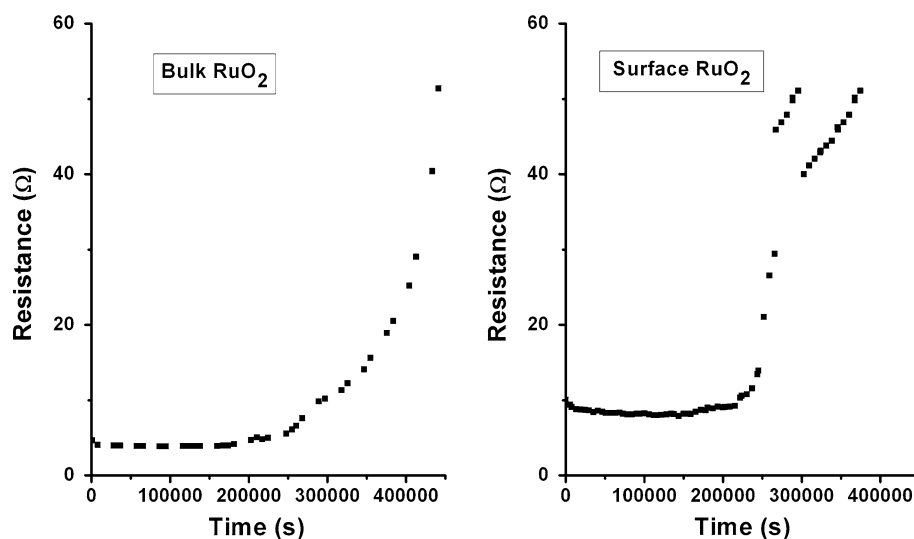
The values are reported for  $10^{-9}$  torr after in situ cleaning but before dodecane was admitted to the chamber, at  $5 \times 10^{-5}$  torr, the pressure by which the switch values had doubled but no measurable uptake on the QCM had been detected, and at 0.05 torr, where a full monolayer or more had condensed on the surface of the nearby QCM. Changes in the contact resistance values are dominated by very low levels of adsorbed dodecane, and level off at higher coverages. It is clear that monolayer uptake does not increase the switch resistance by orders of magnitude, as is generally observed for switch degradation during repetitive cycling of both RFMEMS and macroscale switches (Fig. 3).

### 3.2 Switch Lifetime Measurements

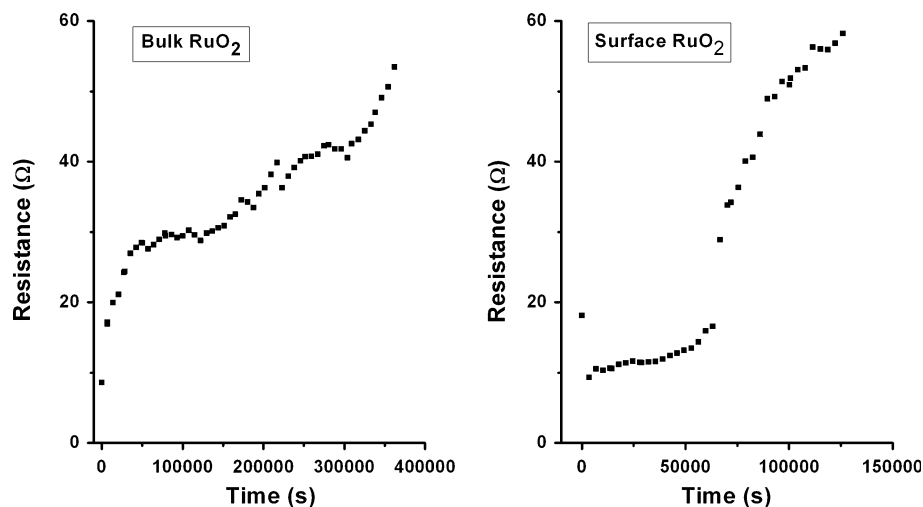
Switch lifetime measurements involving repetitive cycling of bulk and surface Au-RuO<sub>2</sub> switches in vacuum and nitrogen environments were also performed. In general, switch lifetime measurements must be performed on a large number of samples to be statistically relevant. However, the in situ cleaning capabilities of our setup allow lifetime studies to be performed repeatedly on the same switch, which allows for an element of control. Switch lifetimes in vacuum ( $10^{-8}$ – $10^{-9}$  torr) and nitrogen gas environments were compared, for switches operated immediately after cleaning, or alternatively left open for a number of days before operation. In the latter case, the samples were stored either in vacuum or in nitrogen environments. It is commonly assumed that vacuum environments reduce and/or prevent switch contamination. We observed, however, no indication whatsoever that vacuum at the level of  $10^{-8}$ – $10^{-9}$  torr preserved switches any better than pure nitrogen alone. Indeed in one case, we observed just the opposite.



**Fig. 4** Bulk RuO<sub>2</sub> (*left*) and Surface RuO<sub>2</sub> (*right*) switches operated in vacuum immediately after cleaning. Significant increase in contact resistance is observed after approximately 3 days, or ~250 k cycles



**Fig. 5** Bulk RuO<sub>2</sub> (*left*) and Surface RuO<sub>2</sub> (*right*) switches operated in vacuum after being left open in vacuum for 5 days



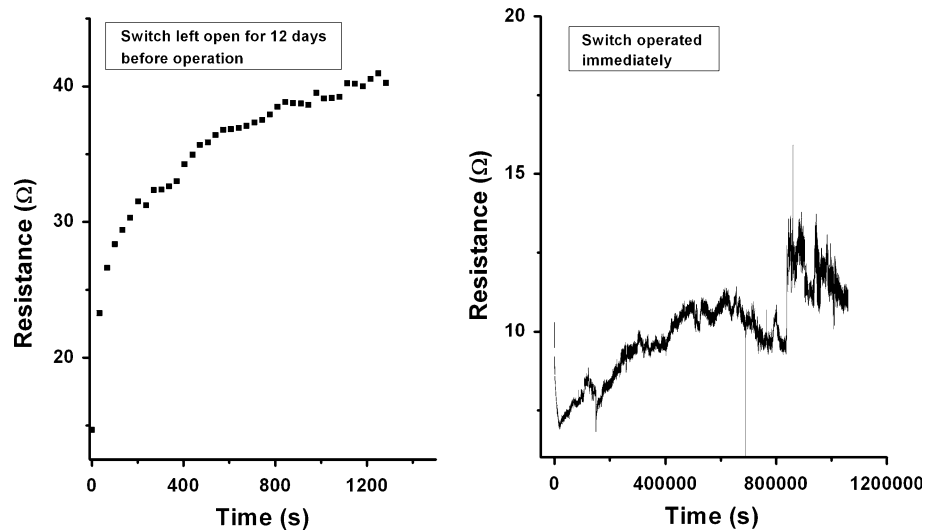
Contact resistance data for bulk and surface RuO<sub>2</sub> switches that began repetitive cycling in vacuum at 1 Hz immediately after oxygen plasma exposure are presented in Fig. 4. In both cases, the resistances remained at their original values for about  $2 \times 10^4$  cycles and then increased dramatically near 250 k. They subsequently exhibited progressive increases with no signs of leveling off. In terms of actual time elapsed, the switches exhibited the rapid rise in resistance approximately 3 days after in situ cleaning.

We next recleaned both samples and then stored them in  $10^{-8}$ – $10^{-9}$  torr vacuum for 5 days before performing sample lifetime studies. The bulk RuO<sub>2</sub> exhibited an immediate increase in resistance (Fig. 5, left). The surface RuO<sub>2</sub> displayed a slow increase in contact resistance and then an abrupt increase after only 50 k cycles, on the order of just a few hours (Fig. 5, right). Given that contaminants are expected to reform on the surfaces held in this level of vacuum for several days, the results are perhaps not

unexpected. But they do reveal that vacuum at the level of  $10^{-8}$ – $10^{-9}$  torr failed to preserve cleanliness of the samples and fail to enhance longevity in any of the samples that we studied. These results are consistent with prior lifetime measurements performed by Patton et al. for self-assembled monolayer (SAM)-coated MEMS switches [15]. An initial decrease in the resistance of surface RuO<sub>2</sub> (Fig. 5, right) switches may follow from thinning of hydrocarbon layer formed during storing the switches for 5 days. Moreover, initial higher values of switches on Fig. 5 comparing to experiments performed immediately after cleaning (Fig. 4) indicate the presence of adsorbed contamination layer after storing the switches in vacuum.

To compare sample lifetimes in vacuum to that of nitrogen, we recleaned the switches with oxygen plasma and then backfilled it with 760 torr of nitrogen gas (99.999%) after having pumped out the oxygen in the chamber to a level of  $10^{-8}$  torr. Contact resistance data for

**Fig. 6** Bulk RuO<sub>2</sub> (*left*) switch left open in 760 torr of nitrogen and then operated in nitrogen. Immediate failure is observed. Surface RuO<sub>2</sub> (*right*) switch operated in 760 torr immediately after being cleaned. After more than a million cycles and 12 days, the switch resistance remained low



**Table 2** Summary of switch lifetime measurements

	Number of cycle before failure			Number of cycle before failure		
	Initial contact resistance	10 <sup>-9</sup> torr	Final contact resistance	Initial contact resistance	760 torr of nitrogen	Final contact resistance
Cycled immediately after cleaning	7	250k–300k	50	7	>1 M	13
Cycled after being stored in open position for days	9	10k–75k	60	14	~0–12 days storage	40

The failure criteria is defined as the point where the resistance has approximately doubled

the surface RuO<sub>2</sub> sample are presented Fig. 6. The sample resistance remained relatively low for one million cycles (12 days), after which the test was discontinued. A bulk RuO<sub>2</sub> sample nearby that had been left open for 12 days in the nitrogen failed almost immediately, indicating that contamination had clearly formed on that switch while being stored in the open position in nitrogen. The results suggest that repetitive cycling motion of a clean switch in nitrogen can inhibit reformation of the physisorbed hydrocarbon contaminants on the contacts, while simply storing it in nitrogen or vacuum does not. Patton et al. [3] reported an increase in the switch resistance during cycling in a nitrogen environment due to carbon products from a SAM layer decomposition. In the experiments presented here, the only source of contamination during the 12 days of storage is residual contaminants in the nitrogen gas, since a SAM is not present. The results of the various lifetime studies are summarized in Table 2. One issue that must be considered carefully when comparing data recorded in vacuum to data recorded at atmospheric pressure is the lack of gas damping, which can result in switch bounce [42] and accelerated contact damage. For cycling at a low frequency with a slow rise-time signal, as is the case here,

this mechanism is not likely to be a major factor. If there is a sharp rise-time and a fast cycle rate, the impact forces at closure are, however, much less controlled.

#### 4 Discussion

In order to interpret these results, we first compare our dodecane uptake data to that reported by Koidl, Rieder and coworkers in Ref. [20, 21] as displayed in Fig. 3. The authors monitored contact resistance versus cycles and time (1000 cycles = 1000 s) for a macroscopic Au contact switch operated at 1 Hz that was exposed to increasing levels of dodecane gas as a partial pressure in synthetic air (80% nitrogen and 20% oxygen). The resistance increased abruptly by about 2.5 orders of magnitude for partial pressures in excess of 100 vpm (ppm volume), which the authors refer to as the “critical concentration”. The authors reported that the critical concentration dropped by orders of magnitude, in some cases below experimental resolution, when the measurements were repeated in pure nitrogen environments. Koidl et al. [20, 21] as well as others, [22] interpreted this as a protective property of oxygen, given

that carbon deposits in an oxygen deficient environment are inhibited from forming a volatile oxide. Critical concentrations by this argument are then expected to be extremely low in vacuum environments, since perfect vacuum is completely depleted of oxygen. From this perspective, our observation of an abrupt increase in resistance at a very low partial pressure of dodecane in vacuum is entirely consistent with the prior reports.

The partial pressure at which we observe an abrupt increase in resistance occurs, however, several orders of magnitude in pressure below that where the QCM registers a definite uptake in gas adsorption. The pressure at which adsorption occurs on an oxide compared with gold may account for some of the difference, but it is more plausible that adsorbed dodecane is accumulating close to the regions of true contact, even though adsorption levels in unconfined regions may be exceptionally low. Alternatively, the plasma cleaning process may be producing high binding defect sites on the switch surfaces, in which case uptake would occur at much lower pressures. Similar behavior has been reported for the case of ethanol lubrication of silicon MEMS, where indefinite lubrication was reported at coverage levels below that which a QCM could detect [45].

Assuming that dodecane is accumulating close to or within the regions of true contact, it is interesting to note that the resistance exhibits only a weak dependence on coverage after the initial rise at very low pressures. This raises the question of the possible physical origins of the factor of the approximate doubling in the resistance: A dielectric material (for dodecane,  $K = 2$ ) confined within the contact is expected to raise the resistance by many orders of magnitude [6, 31] and depend closely on the number of molecules confined within. It is possible that the molecules, being physisorbed and mobile, are not actually within the contacts but squeezed out into the regions immediately outside of them [46–51]. Indeed, Patton et al. [3] reported that contact force of 200  $\mu\text{N}$  is high enough to remove SAM molecules outside of MEMS contacts. This would help explain the lack of sensitivity to surface coverage but would then raise the important question of how adsorbates could be influencing the electrical resistance of the contact. One possible explanation, which will be discussed at length in a separate publication [52], could be that vacuum tunneling currents present in the nearby regions are suppressed upon uptake of adsorbed films [31–36]. This scenario, which theoretically would increase the resistance by levels that are consistent with the experiment [52], is also consistent with the fact that the change in resistance is constant after the switch remains closed for 30 min with a contact force of  $\sim 300 \mu\text{N}$  [42, 43]. Alternatively, the molecules may in fact be confined to within the contacts or subsurface defects and exhibit far more

conductive behavior than might first be expected [31–36]. Switch failure then occurs when, upon repetitive contact, the hydrocarbons disassociate and cause carbon deposits to form. The carbon remains on the surface in the absence of oxygen, as volatile compounds are not able to form. A detailed study of the molecular effects that may double the resistance of RuO<sub>2</sub> switches after dodecane adsorption on this topic will be reported in a separate publication [52].

The aforementioned interpretation also provides an explanation for the majority of the lifetime tests that we have performed: If a hydrocarbon species adsorbs on a contact surface (through direct deposition or alternatively prolonged exposure to trace levels in vacuum or nitrogen), then the species remains there until it eventually degrades upon repeated switching events. This explanation would be consistent with all of the lifetime results obtained if repetitive operation of a switch in nitrogen inhibited condensation of physisorbed hydrocarbon contaminants on the contacts. Given that operating it immediately in vacuum, or simply storing it in the same nitrogen or vacuum does not inhibit condensation, we infer that the mechanical motion may somehow favor nitrogen to be closer to the contacts than the hydrocarbon molecules.

Our explanation for the indefinite lifetime of the switch in nitrogen is far from complete and based on very few statistics. The result, however, points to a wealth of interesting future studies that could be performed in various gas environments. For example, one could operate the switches in pure oxygen, argon, CO, or CO<sub>2</sub> environments. With proper proportions, the mixtures might provide cleaning action for hydrocarbon products that are demonstrated to have great impact even at trace levels. Given that Ru does not react readily with oxygen at room temperature unless exposed to oxygen plasma, the reaction products might well be volatile. Also, Ru contacts with Au are far less adhesive than Au–Au contacts. It therefore may be possible to store a Au–RuO<sub>2</sub> contact in the closed position to inhibit contamination from the surrounding environments.

## 5 Summary

Contact resistance measurements as a function of dodecane gas exposure have been reported here for RF micro-electromechanical switches with Au–RuO<sub>2</sub> contacts. The switches were situated within an ultrahigh vacuum system equipped with in situ oxygen plasma cleaning capabilities so that measurements could be performed immediately after cleaning. Two studies were performed on the switches, each involving a comparison of the electrical contact resistance in vacuum and nitrogen environments for measurements. The first study involved measurements of initial resistance (the resistance measured upon first time



closure) versus pressure as dodecane gas was admitted to the chamber. The second study compared switch lifetimes in vacuum ( $10^{-8}$ – $10^{-9}$  torr) and nitrogen gas environments, for switches operated immediately after cleaning, or alternatively left open for a number of days before operation. The primary observations are summarized as follows:

- A significant increase in initial contact resistance measured for first time switch closure was observed for trace levels of dodecane in vacuum, as low as  $10^{-5}$  torr, ( $P/P_{\text{sat}} < 10^{-4}$ ). The pressure at which this was observed to occur is consistent with earlier reports involving repetitive cycling of macroscopic switches in partial pressures of nitrogen.
- The initial contact resistance unexpectedly only doubled on average, even for dodecane pressures sufficiently high as to result in full monolayer condensation.
- Given that physisorbed dodecane monolayers alone did not increase resistance by more than an approximate factor of two, the results suggest that hydrocarbon reaction products, but not the physisorbed hydrocarbon itself, are responsible for the common observation of the contact resistance increase by orders of magnitude.
- Vacuum in all cases failed to enhance or extend switch lifetime: Continuous operation of a switch in a nitrogen environment immediately after plasma cleaning was the only procedure observed to indefinitely prolong device lifetime. The repetitive cycling motion of a clean switch in nitrogen may inhibit uptake of physisorbed hydrocarbon contaminants on the contacts.
- Vacuum levels far superior to  $10^{-9}$  torr are required to prevent contamination.

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