ABSTRACT

WALKER, MATTHEW JAMES. Impact of Stringently Controlled Vacuum Environments with \textit{in situ} Surface Cleaning on Contact Resistance of Au and Ru Based Radio Frequency Microelectromechanical Switches. (Under the direction of Professor Jacqueline Krim).

Radio frequency microelectromechanical system (RF MEMS) switches have many promising advantages over solid state switches, particularly with respect to signal stability, cutoff frequency, insertion loss and power consumption characteristics. While gold has traditionally been employed for RF MEMS contacts on account of its chemical inertness and low resistivity, its softness has proven problematic in terms of reliability for commercial applications. The use of materials other than gold appears to be necessary, and a better understanding of the mechanisms causing premature failure has become increasingly necessary. Prior studies of RF MEMS contacts have been performed in air, nitrogen and vacuum environments that ranged in pressure from $10^{-3}$ to $10^{-7}$ torr. Since these studies were performed in conditions where condensation of contaminants can easily occur, their reproducibility is uncertain. The studies performed for this dissertation involved operation of switches in a stringently controlled vacuum environment, with \textit{in situ} oxygen plasma surface cleaning and controlled hydrocarbon gas exposure. Three primary topics were studied, and are reported on herein: 1) The impact of \textit{in situ} oxygen plasma cleaning on the resistance of Ru and Au-Ru based RF MEMS contacts in vacuum, 2) documentation of pentane and dodecane exposure levels that result in an increase in contact resistance for Ru and Au-Ru based contacts, and 3) switch lifetime measurements as a function of surrounding gas environment.
Impact of Stringently Controlled Vacuum Environments with \textit{in situ} Surface Cleaning on Contact Resistance of Au and Ru Based Radio Frequency Microelectromechanical Switches

by
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DEDICATION

To all the influential people in my life, especially HGB, who taught me to be a better person, persevere, and work hard for the things that matter most in your life
BIOGRAPHY

Matthew Walker was born in western Pennsylvania but lived in southeast Michigan most of his life. Regardless of where he was born or lived both places could be categorized as country or farming communities. Even with a reading disability Matt was able be in the National Honor Society in high school, mostly because he was able to excel in mathematics. For extracurricular activities Matt was usually good but never great when participating in sports, which interestingly matches his academic activities (gpa of approximately 3.3 in high school, undergrad, and graduate school).

Matthew Walker earned the B.S. in Engineering Physics, Computer Aided Design and a minor in Mathematics in 2001 from Eastern Michigan University and a M.S. in Physics in 2005 from North Carolina State University. He joined the Department of Materials Science and Engineering at North Carolina State University in 2005. His research interests lie in taking technological problems and developing control experiments to create solutions in the field of nanotechnology. His research focuses on studying metal contacts for RF MEMS switches in controlled environments to fundamentally understand sources of premature failures. Matt has been an active member of the on campus Materials Research Society and Graduate Physics Student Association during his tenure at North Carolina State University. Even at his age he is still active in sports.
ACKNOWLEDGMENTS

Achieving a doctorate in philosophy takes sacrifice on ones behalf but is only possible with the help of others. I will never be able to name them all here, however, I would like to note the following people and groups whose help made this possible.

My advisor, Dr. Jacqueline Krim, yes, she funded my work, but more importantly, she believed in me and guided me through this process. Along with her, comes a dynamic and knowledgeable nanotribology group.

To my collaborator in the DARPA and MURI RF MEMS teams, you pushed me to think about my results and helped shape the direction of experiments.

Since my preliminary examination, Dr C. Lewis Reynolds has been monumentally important to my work by guiding me though my research from a materials science point of view. Dr Reynolds is readily accessible, and, along with answering question, he asked questions. For me, this kind of interaction is what makes science worth doing.

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1. Introduction to RF MEMS
1.1 RF MEMS and Their Applications

Radio frequency microelectromechanical systems (RF MEMS) switches refer to components that are microscale and have moving parts to provide RF functionality. RF MEMS switches contain metal contact switches, capacitive sensing switches, varactors, resonators, and tunable inductors. The following chapters of this dissertation focus on metal-metal contact switches in stringently controlled environments to select contact materials and operational environments to optimize switch lifetime.

Interest in RF MEMS devices lies in their advantageous properties over conventional macroscale relays and solid state devices, particularly with respect to signal stability, cutoff frequency, insertion loss and power consumption characteristics (Table 1.1) [1, 2]. These devices are small, have very low mass, and are insensitive to acceleration. Fabrication of MEMS devices is usually performed below 350°C because of temperature sensitive components and mechanical structures [3, 4]. In addition, RF MEMS are surface micromachined on silicon and glass substrates, which allows for integration with semiconductors with similar low fabrication temperatures, e.g., complementary metal oxide semiconductor (CMOS). RF MEMS have lower on-resistance and parasitic capacitances than transistor switches. The properties of RF MEMS devices illustrates in Table 1.1 has drawn interest from military and industry sectors over the past twenty years [5, 6].

RF MEMS switches are fabricated in a variety of configurations and designs that can often be miniaturized macroscale mechanical devices. All RF MEMS contain both mechanical and electrical components. The mechanical component is the moveable portion
of the device that opens or closes to create an electrical connection. A device can be actuated by several different mechanisms: electrostatic, magnetostatic, piezoelectric, and thermal.

The second component of a device is electrical. The electrical aspect of a RF MEMS switch occurs once the mechanical component has been actuated, thereby completing the circuit, and allowing an electrical signal to be sent in series or shunt configurations with other devices.

Figure 1.1 shows the two types of contacts: metal-metal switch in a cantilever configuration and a capacitive switch in a bridge configuration. The work presented here focuses on electrostatic actuated devices with metal-metal contacts in both cantilever and bridge configurations.

**Figure 1.1.** a) SEM image and b) schematic of a cantilever configured metal-metal contact switch [7]. c) Optical image and d) schematic of a bridge configured capacitance contact switch from Raytheon [8].
The multitude of applications for RF MEMS devices includes tunable filters, phase shifters, antenna tuners, and reconfigurable amplifiers [5, 6]. These components are vital to satellites, RF instrumentation, microwave communications, and mobile phones. One prevalent example where RF MEMS devices can improve a current technology is mobile phones and their usage time. Here RF MEMS devices with their low power consumption would increase usage times of mobile phones. One component in a mobile phone that can use RF MEMS devices is the tunable filter that receives signals. Entesari et al. demonstrated a single pole, single throw metal contact RF MEMS switch, from Radant MEMS, in a circuit for a tunable filter spanning 25 to 75 MHz, depending on the combination of closed RF MEMS switches in the RLC circuit [9]. Also, with countries using different combinations of wireless bandwidths, digitally changed filter combinations allow for spanning a wide range

Table 1.1. Performance comparison of FET, PIN Diode, and RF MEMS electrostatic switches [1].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>RF MEMS</th>
<th>PIN</th>
<th>FET</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actuation Voltage (V)</td>
<td>20-80</td>
<td>3-5</td>
<td>3-5</td>
</tr>
<tr>
<td>Current (mA)</td>
<td>0</td>
<td>3-20</td>
<td>0</td>
</tr>
<tr>
<td>Power consumption* (mW)</td>
<td>0.05-0.1</td>
<td>5-100</td>
<td>0.05-0.1</td>
</tr>
<tr>
<td>Switching time</td>
<td>1-200 µs</td>
<td>1-100 ns</td>
<td>1-100 ns</td>
</tr>
<tr>
<td>$C_{eq}$ (series) (fF)</td>
<td>1-6</td>
<td>40-80</td>
<td>70-140</td>
</tr>
<tr>
<td>$R_s$ (Series) (Ω)</td>
<td>0.5-2</td>
<td>2-4</td>
<td>4-6</td>
</tr>
<tr>
<td>Cutoff frequency (THz)</td>
<td>20-80</td>
<td>1-4</td>
<td>0.5-2</td>
</tr>
<tr>
<td>Isolation (1-10 GHz)</td>
<td>Very high</td>
<td>High</td>
<td>Medium</td>
</tr>
<tr>
<td>Isolation (10-40 GHz)</td>
<td>Very high</td>
<td>Medium</td>
<td>Low</td>
</tr>
<tr>
<td>Isolation (60-100 GHz)</td>
<td>High</td>
<td>Medium</td>
<td>None</td>
</tr>
<tr>
<td>Loss (1-100 GHz) (dB)</td>
<td>0.05-0.2</td>
<td>0.3-1.2</td>
<td>0.4-2.5</td>
</tr>
<tr>
<td>Power handling (W)</td>
<td>&lt; 1</td>
<td>&lt; 10</td>
<td>&lt; 10</td>
</tr>
</tbody>
</table>

* Including voltage up-converter or drive circuitry
of bandwidths so that for mobile phones can be used internationally. Other wireless communications (Wi-Fi, digital TV, GPS) are subject to the same interference effects, which additionally reduce performance, voice quality, and data transmission rate. These sectors would also benefit from reliable RF MEMS devices.

1.2 RF MEMS Metal-Metal Contact Failure Modes

Today’s RF MEMS switches have not reached commercial markets to the extent predicted in the 1990s. What is inhibiting this technology are the devices inherently short operating lifetimes that come from multiple failure modes: adhesion, material transport, interfacial topography because of creep, contact heating, and hydrocarbon contaminations [10-19]. Below is a brief description of the primary failure mechanisms.

- **Adhesion**, which causes contacts to be permanently closed, removes the functionality of a switch. Often devices are operated in humid environments, which cause water films to condense on the contact surfaces and produce capillary forces that are greater than the restoring forces of the MEMS device [13, 14].

- **Material transfer**, either from one contact to the other or to a location that is completely removed from the contact. The initial engineered contact then changes shape, which causes unpredictable and uncontrollable changes in contact resistance. The type of operation, which is discussed in Chapter 2, has been shown to influence the severity and speed of this mechanism [10, 12, 20].

- **Creep** associated with changes in the interfacial topography, which occurs when the real area of contact increases with device actuation time. This lowers the contact
resistance, but may ultimately result in permanent adhesion if the contact area grows too large. It is thus important to optimize the contact area to minimize contact resistance without permanent adhesion [17, 21, 22].

- **Contact heating**, due to Joule heating of a contact when an electrical current is present. Increases in temperature have strong impact on interfacial creep, and may also cause adsorbed hydrocarbons on the surface to change chemical composition, thereby increasing contact resistance, or migrate rapidly to the surface[18, 19].

- **Hydrocarbon contamination**, which arises from adsorption of native molecules in the environment surrounding the device contacts, by surface migration of such contaminants, or through bulk migration to the surface from within the interior regions of the devices. This causes an increase in contact resistance by both adding an additional resistive layer between the contacts or by decreasing the number of metal-metal contacts [15, 16, 23].

These failure modes are convoluted and can lead to confusion when designing proper surface materials. Successfully understanding these failure modes provides insight on how to design RF MEMS devices in terms of the ideal contact materials and ideal packaging environments and operating conditions.

### 1.3 Brief Overview of Objectives for This Dissertation

To date, there have been no studies of RF MEMS switches in ultra high vacuum chambers with *in situ* surface cleaning. This lack of experimental work has limited comparisons between simulations and experimentation. The primary objective of this work
was to understand the change in contact resistance of RF MEMS devices through careful environmental control, particularly through measurements of the contributions of adsorbed films to switch failure modes. A better understanding of failure modes when operated under different environmental conditions will allow for better material selection of contacts. This will help optimize device lifetimes by selecting appropriate post fabrication packaging of devices, thereby minimizing contact resistance. The UHV chamber employed for the measurements reported in this dissertation and the in situ oxygen plasma cleaning of devices allowed measurements to be performed in a reproducible manner from one location to another. The chamber employed for this work also had gas dosing capabilities, which allowed MEMS switches to be operated in a range of partial pressures for “controlled” contamination to observe effects to contact resistance.
2. Literature Review
2.1 Overview

MEMS devices were first manufactured in the 1970s for pressure, temperature, and accelerometer sensors [24]. These are passive devices, meaning they change properties because of their surrounding environment. An example of this is a bulk micromachined pressure sensor that has a thin silicon diaphragm that is incorporated with an area of doped silicon, which is a piezoresistive transducer [25]. The deformation of the silicon diaphragm causes a change in the integrated piezoresistive transducer values. These values are measured and calibrated for pressure measurements. Passive devices are commonly exposed to the surrounding environment and have become readily used in the automotive, military, and laboratory sectors today [6].

It was not until the early 1990s that an active MEMS device was first demonstrated for microwave applications [26]. Active MEMS switches use controlled movements to perform a function. Unfortunately for this new technology, the reliability and yield of devices were poor. Improvements in the semiconductor micromanufacturing sector allowed the increase in yield for MEMS mechanical structures. This allowed for novel device configurations and the miniaturization of macroscale components. The miniaturization of these devices also increased resonance frequencies and quality factors over their macroscale counterparts and allowed for integration on semiconductor wafers when applicably advantageous [2]. Reliability of moving components has currently lagged behind standards for commercial uses, though the military has niche uses for RF MEMS devices [27]. Reliability issues are the focus of this dissertation, with a particular focus on the role of
adsorbed films in the deterioration of surface contact resistance. The following sections of this chapter describe prior computational and experimental studies on this topic.

### 2.2 Contact Materials and Fabrication

The following sections discuss current and possible contact materials and fabrication methods used in RF MEMS devices. Traditionally Au has been used but with the lack of commercial applications other materials are being investigated. The fabrication of MEMS devices come from the semiconductor micromachining industry. These methods are discussed for the uses of MEMS devices.

#### 2.2.1 Contact Materials

Materials for MEMS contacts need to be chosen carefully to have low resistivity, low reactivity to adsorbates, and good wear resistance [8]. Ag and Ag alloys have traditionally been used for macroscopic relays, selected for their desirable electrical and mechanical properties. Contact forces for macroscopic switches are on the order of Newton’s, and are generally large enough to penetrate most nonconductive insulting layers on the contact surface. The contact forces for MEMS switches are, however, on the order to 10 µN, and are generally not sufficient to penetrate insulting layers on Ag contact surfaces. Au is a viable alternative in that it has low resistivity and is inert. It is, however, highly prone to wear and material transfer, [7, 28, 29] which has promoted investigations of alternative materials [8, 30].
Chen et al. employed a scanning probe microscope test station to evaluate Au, Pt, Rh, Ru, and alloys for these transitions metal with Au [30]. They reported contact resistance, resistivity, hardness and modulus. The experiments were conducted in ambient conditions, where contact resistance for harder materials was closer to predicted values. The influence of contamination resistance for harder materials was thought to be less because the contact resistance was closer to the predicted values. Unfortunately, harder materials have greater contact resistance than Au. These experiments show quantitative values for different contact materials, thus, influencing proper selection for contacts depending on their uses. Figure 2.1 shows the general trend of alloy hardness and resistivity decreasing with increased Au composition.

![Graph showing hardness versus electrical resistivity for multiple metal films 300 nm and 1500 nm thick on silicon substrates [31].](image)

**Figure 2.1** – Hardness versus electrical resistivity for multiple metal films 300 nm and 1500 nm thick on silicon substrates [31].
2.2.2 Fabrication

Development of MEMS dimensional tolerances have been improved greatly by the mature manufacturing technologies of the semiconductor industry. There are two methods for MEMS fabrication: bulk micromachining and surface micromachining. Bulk micromachining involves removal of materials from a silicon wafer and generally employs wet etching techniques. MEMS devices that are made with bulk micromachining have typically been passive devices, e.g., pressure sensors and accelerometers. Surface micromachining leaves the substrate, silicon or glass, unaltered, but adds and/or removes additional layers above the substrate surface through sequences of photolithography processes. MEMS with more complex structures, e.g. RF MEMS are made with surface micromachining. An additional advantage of surface micromachining is the ability to integrate the devices with post-complementary metal oxide semiconductors (CMOS). RF MEMS are fabricated at low temperatures and can only be integrated with processes that do not change the mechanical stresses of the devices. This integration allows for the elimination of multichip components, which decreases parasitic capacitance and resistance of interconnects, eliminates bond pads and wire bonds attenuation of signal, and increases operation frequency [32, 33].

2.3 MEMS Operation

Metal contacts are operated either by hot switching or cold switching. Hot switching is the term used when a potential is continuously applied to the contacts, irrespective of whether the switch is open or closed. Hot switching is how switches would ideally be
operated, as it is simpler to leave the contact potential on continuously and transmit the signal when the switch is closed. Unfortunately, this expedites the contact resistance deterioration over the cycle lifetime [20]. Cold switching is therefore more commonly used. It differs from hot switching in that the potential across the contact is only on when the contact is closed. This requires more control of the electrical process, but the contact resistance change does not increase as quickly in this scenario.

Yang et al. demonstrated hot and cold switching in a test facility using an actual RF MEMS cantilever that was mounted on an AFM tip holder [20]. This allowed multiple contact materials to be quickly tested and screened. In this study, cantilevers were brought into contact with patterned lower electrodes formed from either pure Au or Au-Ni alloys. Switches were operated under both cold and hot switched conditions. As a result of hot switching conditions, contact resistance increased with a relatively smaller number of cycles than cold switching conditions. The contacts were examined post cycling, where it was shown that material transfer occurred from one contact to the other in hot switching more than in cold switching. Figure 2.2 a) shows results from their work in hot switching conditions, where an increase in resistance occurred after about 110 cycles. In contrast, cold switching conditions resulted in an increase in resistance after $10^9$ cycles, as shown in Figure 2.2 b).
Figure 2.2 – Contact resistance of sputter Au patterned substrate and Au contact cantilever pad operated by a) hot switching and b) cold switching [20].

Once the type of operation of a device is chosen, the force applied to close the switch is considered. The force applied when a switch is closed by an actuation voltage is referred to as “contact force.” It can range from 10 to 1000 µN [1]. The actuating voltage is applied to the gate of the switch, which is labeled in Figure 1.1 b). The contact force can be inferred from the gate voltage through modeling of the mechanical structure and composition [34]. For example, Majumder et al. applied Euler-Bernoulli beam equations to determine the beam
deflection and contact force for a given actuation voltage. Dimensions for this beam are
given in Figure 2.3 a) and the calibration curve corresponding to contact forces for applied
actuation voltages is shown in Figure 2.3 b) [34, 35]. This geometry, with an actuation
voltage between 80 and 100 V, corresponds to contact forces of 50 to 100 µN. This MEMS
design is one of the devices used in this dissertation and will be referred to in later chapters.

![Figure 2.3](image)

**Figure 2.3** – a) Dimensions of a Northeastern University switch (in µm) and b) the calculated
contact force for an applied actuation voltage [34, 35].

A representative plot of resistance versus applied actuation voltage has been reported
by Coutu et al. in Figure 2.4 [8]. Here, the minimum actuation voltage required to overcome
the restoring force of a switch beam was the pull-in voltage $V_{pi}$. As the actuation voltage
increased, the contact force rose, at first, causing the contact resistance to be high and
unstable. However, as the actuation voltage continued to increase, the contact resistance
decreased in a linear fashion. This decrease in resistance was attributed to the increase in
real contact area, which will be discussed in detail in the sections that follow. In this figure, an actuation voltage above 60 V caused an infinite resistance. This abrupt change in contact resistance was explained by the cantilever mechanically braking or the cantilever beams coming in connect with the gate pad. The latter causes electrical lines to evaporate. It is also possible to increase the contact area to the point where van der Waals and adhesion forces are larger than the restoring forces on the cantilever beam. In this case, the switch would become permanently closed, even when the actuation voltage is removed.

Figure 2.4 – A representation of how contact resistance changes as a function of actuation voltage [8, 36].
2.4.1 Contact Mechanics

To obtain reliable values of contact resistance, it is necessary to characterize the interface of the contacts pads. Asperity dimensions are critical in determining contact behavior. Analytical and numerical methods have been employed to study different length scales of contact mechanics [15]. Heinrich Hertz, in 1882, originally worked in the field of contact mechanics to understand how optical properties of stacked lenses change with varying forces being applied [37]. Hertz assumed elastic contact and ignored surface roughness. Because of its simplicity and relative reliability, his theory of contact mechanics is commonly used today in tribological contact theory.

In the 1960s, Holm developed a completely plastic model for macroscale electronic contacts with surface roughness, where local contacts, or asperities, are introduced to much larger stresses [15]. Here contact area is calculated by \( A = \frac{F}{H} \), where \( F \) is the contact force and \( H \) is the contact hardness. Surface contamination was acknowledged, but at sufficient contact forces, contacts were assumed to break through any contamination films, which are indicated by the contact resistance decreasing. This basic approach is used regularly today for RF MEMS devices to gauge approximate contact areas.

Greenwood and Williamson introduced a very well known asperity contact model in 1966 [38]. They assumed spherical asperities with a varying height distribution over the contact area and showed that contacts between surfaces are mostly plastically deformed. Their work provided the basis for a model by Chang et al., or CEB model, which assumed a
multi asperity rough surface for elastic-plastic deformation [39]. All of the models provide a good estimate of contact area. RF MEMS devices however have such low contact forces and variations in contact topography that a more accurate approach would consist of atomic force microscopy direct measurement of the contact topography in conjunction with simulations of the interfacial contact. Rezvanian et al. recently used AFM topography scans of Au RF MEMS contacts in a contact mechanics model to calculate the change in contact area for a range of realistic applied loads [27]. They showed the real contact area initially is 1% of the apparent contact and after 40 hours the real contact area is 7% of the apparent contact area.

2.4.3 Contact Resistance

In the 1930s and 1940s, work was performed that showed that the electrical resistance of a contact can be used to calculate the area of the interface [40, 41]. These calculations were developed for macroscale switches that were assumed to be free of contamination and where the contact area was assumed to be a single asperity with radius $r$. The contact resistance was expressed as [42]:

$$R_m = \frac{\rho_1}{4r} + \frac{\rho_2}{4r}$$

(2.1)

where $\rho_1$ and $\rho_2$ are the resistivity of either contact. If the contacts are made from the same material, Equation 2.1 reduces to $R_m = \frac{\rho}{2r}$ [15]. This is true for contact radii larger than the electron mean free path $\lambda$ of the material, a regime where resistance is dominated by a diffuse scattering mechanism. This is often referred to as the Maxwell Resistance. If the contact
radius is small compared with the electron mean free path of the contact material, then the contact resistance is expressed by a Sharvin mechanism term. In this regime, electrons ballistically travel through the contact. The Sharvin resistance $R_S$ is expressed as [43, 44].

$$R_S = \frac{4 \rho \lambda}{3 \pi a^2}$$  \hspace{1cm} (2.2)

The overall contact resistance $R_C$ for an RF MEMS contact can be written as:

$$R_C = f\left(\frac{\lambda}{r}\right)R_{\text{tr}} + R_S = \frac{1 + 0.83\left(\frac{\lambda}{r}\right)\rho}{1 + 1.33\left(\frac{\lambda}{r}\right)} \frac{\rho}{2r} + \frac{4 \rho \lambda}{3 \pi r^2}$$  \hspace{1cm} (2.3)

where $f\left(\frac{\lambda}{r}\right)$, shown in Figure 2.5, is an interpolation function, that allows for a smooth transition between resistance regimes [45].
2.4.3 Contact Heating

In reality for a closed switch, macroscale or microscale, multiple asperities with varying contact areas are in contact. As mentioned previously, there is some amount of roughness of a given surface, and when two surfaces come into contact, high points on each surface make contact, producing a real contact area at a finite number of points. In the presence of electrical current, these asperities cause restriction and increase the resistance across the contact. Figure 2.6 shows current flow lines from the contact pads through a single asperity. The asperity contact constricts the flow because only a finite amount of flow...
lines may pass through a given asperity. As electrical current flows though an asperity, heating occurs. If the temperature rises sufficiently, softening or annealing of the asperity will occur. For Au contacts, the softening temperature has been reported to be in the range of 60°C to 100°C [15, 18]. This corresponds to values of 0.25 T_m and 0.28 T_m, respectively, where T_m is the melting temperature in Kelvin [15, 18]. Usually softening temperature for bulk Au is 0.5 T_m. The reduced softening temperature observed in RF MEMS metal contacts is contributed to the nanocrystalline structure of asperity contact points [46].

![Figure 2.6](image)

Figure 2.6 – Current flow lines from a contact pad through an asperity. An insulating film is also present to show the possible inhibiting properties to electrical current flow [18].

Jensen et al. derived a relation between contact voltage and contact asperity temperature [18]. The contact resistance in Equation 2.3 is used for the potential drop across
an asperity. The contact heat generated is then expressed as \( IV_m = I^2 f \left( \frac{\lambda}{r} \right) R_m \). In an independent derivation, Holm obtained the expression [40]:

\[
f \left( \frac{\lambda}{r} \right) R_m \frac{V_c^2}{R_c} = 8 \int_{T_o}^{T_c} \rho_e \kappa_e dT
\]

(2.4)

where \( \rho_e \) and \( \kappa_e \) are the effective electrical resistivity and thermal conductivity for the transition region for electron transport, respectively, \( T_C \) and \( T_O \) are the contact temperature and ambient temperature, respectively, and \( V_c \) is the contact voltage. The Wiedemann-Franz law, \( \lambda \rho = LT \), where \( L \) is the Lorentz contact \( 2.45 \times 10^{-8} \text{ V}^2\text{K}^{-2} \), has been shown to apply at atomistic length scales [47]. The contact voltage is then related to the contact temperature by [48]:

\[
V_c^2 = \frac{4LR_c}{f \left( \frac{\lambda}{r} \right) R_m} \left( T_c^2 - T_o^2 \right)
\]

(2.5)

For asperity contact areas larger than the electron mean free path, the Maxwell resistance dominates in Equation 2.3, reducing Equation 2.5 to:

\[
V_c^2 = 4L \left( T_c^2 - T_o^2 \right)
\]

(2.6)

Therefore, the contact voltages needed for contact temperatures, \( T_C \), of 60°C and 100°C in a 20°C room, \( T_O \), are expected to range from 50 mV to 72 mV, respectively. Note that Equation 2.6 is a lower limit to the contact voltage for a given contact temperature because it does not account for Sharvin resistance.
2.4.4 Contact Creep Theory

It has been shown both experimentally and computationally that the time dependence of resistance follows a power law relation [17, 21, 22, 27]:

\[ R(t) = At^{-\alpha} + B \]  \hspace{1cm} (2.7)

where \( A \) reflects the topography of the contacts and increases with roughness, \( \alpha \) is an intrinsic material property related to material creep, and \( B \) is a theoretical limiting resistance as time goes to infinity. Rezvanian et al. analytically derived these values using single asperity geometry and strain rate formulas that assume creep with a power law dependence [17]. The following is how \( A \), and \( \alpha \) are equated to the canonical asperity in their model. Also included is the power law creep equation.

\[ A = \frac{\rho}{2} \left( \frac{LCe^{-Qc/kt}F^p(1+2p)}{\pi^p \tan(\beta)} \right)^{(1+2p)} \]  \hspace{1cm} (2.8)

\[ \alpha = \frac{1}{1+2p} \]  \hspace{1cm} (2.9)

\[ \dot{\epsilon} = C\sigma^p e^{-Qc/kt} \]  \hspace{1cm} (2.10)

where \( \rho \) is the contact resistivity, \( L \) is the initial asperity height, \( C \) is constant, which depends on the material and creep mechanism, \( Q_c \) is the activation energy for creep, \( k \) is the Boltzmann constant, \( T \) is the contact temperature, \( F \) is the load on the asperity, \( \beta \) is the angle of the side of the asperity with respect to the surface plane, \( p \) is the stress exponent, \( \dot{\epsilon} \) is the creep rate, and \( \sigma \) is the applied stress. This work assumed the contacts are contamination free and canonical in nature, as depicted in Figure 2.7.
2.5 Impact of Adsorbates on Contact Resistance

Experiments studying MEMS contact resistance to date have been performed in ambient, dry nitrogen, or low vacuum environments [7, 18, 28]. Brown et al. operated Au RF MEMS devices in air, nitrogen, helium, and vacuum pressures as low as $10^{-7}$ Torr [21, 22, 49]. At high vacuum pressures, the devices were cooled with liquid nitrogen or liquid helium and then operated. Once actuated at low temperature, the contamination layer on the contact surface was thought to be pushed out of the way, allowing for only metal-metal contact resistance measurements. Adsorbed films on contacts are often commented on in the literature as a source of higher than expected resistance measurements, but they have proven exceptionally difficult to control, remove and/or characterize.
In one particularly careful macroscopic experiment, Koidl et al. studied resistance changes due to adsorbed hydrocarbons onto commercial relays with different contact materials. The purpose of this study was to quantify the contact compatibility of numerous vapors and to develop general rules predating the contact compatibility [50, 51]. The experiments mixed synthetic air 80% nitrogen and 20% oxygen with different aliphatic and aromatic hydrocarbons and introduced different concentrations (in vpm = ppm volume) to contacts while operated. Figure 2.8 a) shows data for different concentrations of dodecane exposed to operating Ag relays. At 100 vpm the contact resistance was observed to increase by a factor of 2.5, and was considered, therefore, a “critical concentration” of dodecane.

Figure 2.8 b) shows data related to the adsorption of pentane, nonane, and dodecane on relay contacts of Pd, Au, and Ag. The black areas of the bar graphs indicate the range of critical concentrations for each molecule on the different relay materials. The increases in contact resistances for the macroscale relays were detrimental to the performance by inhibiting signal propagation. This also implies that, depending on where the relays are operated, the optimized relay lifetime should be chosen.
Figure 2.8 – a) dodecane uptake on relays at 10, 30, and 100 vpm concentrations. An increase in contact resistance is observed after 100 vpm concentration of dodecane is exposed to the Au contact surface. b) Critical concentrations of pentane, nonane, and dodecane on Pd, Au, and Ag contact surfaces [51].
2.6 Focus of Dissertations Work

The goals of the measurements performed for this dissertation are (1) document the impact of UHV environments on contact resistance of Au and Ru based contacts; (2) document the impact of UHV with in situ oxygen plasma cleaning of contact surfaces of Au and Ru based contacts; (3) compare the properties of soft, hard, and combined soft-hard contacts for Au-Au, Ru-Ru and Au-Ru-based contacts; (4) compare contact resistance in controlled partial pressures of hydrocarbons; (5) compare contact resistance changes when cycled in vacuum and inert gas; and (6) operate devices in the most stringently controlled environments for reproducibility.

The materials for study were selected as follows: Au has traditionally been employed for RF MEMS contacts because of its chemical inertness and low resistivity, but its softness has proved to be problematic in terms of reliability for commercial applications [28]. Prior studies of Au contacts have been performed in air, nitrogen and vacuum environments that range in pressure from $10^{-3}$ to $10^{-7}$ Torr [18, 21, 22]. Because these studies were performed in conditions where condensation of contaminants can easily occur, their reproducibility was uncertain. Therefore, if the operating conditions are sufficiently controlled and monitored, as is the case in this dissertation, the results should be reproducible, irrespective of the location where the measurements are performed.

The use of materials other than Au appears to be necessary, and a better understanding of the mechanisms causing premature failure is becoming increasingly
necessary. Molecular dynamic simulations of both Au and Ru contacts have been carried out to understand the ductile and brittle nature of these contacts at different operating temperatures [52]. Ru contacts are promising alternatives to Au [28, 31, 52, 53], but the conditions under which Ru can be meaningfully studied are more stringent than those required for Au. In particular, Ru is more sensitive to surface contamination by oxygen and hydrocarbon film species than Au [54]. When Ru is oxidized, it is a stable conducting oxide [55]. Iwashki et al. have reported that Ru becomes RuO₂ when exposed to O₂ plasma at room temperature for sufficiently long periods [56]. In addition, they reported that RuO₂ is less conductive than Ru, with bulk resistivity values for Ru and RuO₂ of 12.3 and 45.0 μΩ*cm, respectively [56].

Oxygen plasma has been used since the 1950s to remove organics from flat exposed surfaces [57-60]. More recently, oxygen plasma has been demonstrated to be far more effective at cleaning occluded areas and high aspect ratio regions than UV ozone [61]. It is thus well suited for cleaning the overhangs and non line-of-sight regions that are characteristics of RF MEMS switch contacts. It does, however, expose the surface to “oxygen contamination” so that an oxide rather than pure Ru, is expected at the surface [62-64]. To compare resistance data for various material combinations, time dependent resistance measurements were performed for close contacts for 30 minute periods both before and after cleaning. The data were fitted to power law extrapolations to infer contact creep properties and $t=\infty$ resistance values. The time-dependent creep properties of mixed Au-Ru contacts were observed to be close to those of Au-Au contacts, while the absolute value of the resistance of such contacts was more comparable to that of Ru-Ru contacts.
Contacts used were initially Au-Au to independently verify previous power law creep relations. This gave a baseline for Au, Ru, RuO₂, and mismatch combinations studied here. Studying how the resistance changes over time allowed for a better understanding of how to construct the composition of contact materials. The stringent vacuum environment in this dissertation allowed for the investigation of the cycling lifetime of contacts that were far superior to current work because the contact surface was initially cleaner than any other contact surface. This gave insight into how best to package RF MEMS devices, meaning whether it was better that devices be hermetically sealed in vacuum or was it better to package devices in an inert gas to optimize their lifetime.

In the following chapters, experimental setup, data, and explanations of results will be presented. Chapter 3 will cover all aspects of the experimental setup and electronics used to operate MEMS devices.

Chapter 4 will discuss data collection. Here properties of the different contact materials were compared in vacuum and after in situ oxygen plasma exposures using a theoretical power law relationship. How the contact resistance changes over time for closed switches were compared. In addition, the magnitude of the contact resistances for the different contact materials was compared. Oxygen plasma exposures are shown to initially increase contact resistance but after sufficiently long exposure times the contact resistance decreased. These longer exposures to oxygen plasma were shown to return contacts with increased resistance to reproduce initial values used in this dissertation.

Chapter 5 and 6 investigate the adsorption of pentane and dodecane, respectively, on clean contact surfaces. This work investigated the amount of hydrocarbons needed to
increase the contact resistance. The increase in resistance was then compared with resistance changes of contacts left in vacuum in the open state for extended periods of time along with a comparison to macroscale relay critical contact resistances.

Chapter 7 discusses the operational lifetimes of switches cycled for days in well known and controlled environments. All contacts had similar initial resistance values and then were operated in vacuum and inert gas environments. This investigation looked at what environments were best for a switch to be operated.

Finally, Chapter 8 covers conclusions of the work in this dissertation and suggests future experiments.
3. Experimental Details
3.1 Experimental Apparatus

Devices studied in this dissertation work were tested in a custom designed and built vacuum chamber constructed from UHV compatible machined components. The following subsections describe the mechanical design of the chamber, the wire connections leading from the ceramic dual inline package (DIP) packages to the electrical feedthroughs, the operation of the oxygen plasma, and the procedure for hydrocarbon dosing.

3.1.1 Vacuum Test Chamber

A schematic of the sample chamber, which was constructed entirely from ultra-high vacuum compatible components, is shown in Figure 3.1 a). The exterior sample chamber is a 6” CF flange full nipple [65] connected to a spherical square [66]. Both sides of the nipple are connected to 6” to 2.75” reducers. The 2.75” reducers are connected to 2.75” CF flanges with a 12 kV, 150 A nickel feedthrough. The spherical square has 4 x 2.75” CF flanges, 2 x 1 1/3” CF flanges, and 2 x 6” flanges. The 4 x 2.75” CF flanges are connected to a 19 pin feedthrough, a 32 pin feedthrough, a view port and bellows, leading to a right angle valve connected to a central chamber where ion pumps are housed. The 6” to 2.75” reducer, connected to the spherical square, has two ¼” stainless steel tubes welded below the 2.75” CF flange that forms a U-shape inside the sample that is fed through the OFHC Cu MEMS stage. The technical drawings for the OFHC Cu MEMS stage are shown in Figure 3.2. The stainless steel tubing mechanically suspends the MEMS stage inside the chamber and
provides means for cryogenic cooling of MEMS devices, as shown in Figure 3.1 b) and c). The MEMS stage consisted of two custom built rectangular machinable glass ceramic (Macor) pieces with an array of holes drilled out to support up to a 64-pin side braze DIP [67]. The Macor ceramic pieces are attached to a cylindrical Cu block so that the ceramic DIP package underside rests on the Cu block, but allows all electrical connections from the ceramic package to be electrically insulated from the Cu block. 2.5” diameter, ¼” thick Cu discs are mounted inside the chamber on both sides of the MEMS stage and are connected to nickel feedthroughs. Outside of the chamber is an Acopian power supply [68], that is connected to the 2.75” CF flange electrical feedthroughs.
Figure 3.1 – a) Schematic and photos of the b) outside and c) inside of experimental chamber
3.1.2 Wiring Configuration

All pin sockets were connected to standard vacuum wires by spot welding to reduce the possibility of outgassing in vacuum and during plasma cleaning. Wires connecting the pin sockets to the electrical feedthroughs are UHV compatible and covered with Kapton Type F insulation sheath to prevent grounding [69]. Figure 3.3 shows the technical drawing of the Macor ceramic with an array of holes that will accommodate a 24, 40, or 64 DIP ceramic packages. Additional holes are for electrical connections to a quartz crystal.
microbalance, thermal couple, and any additional accessories that might be needed in the future.

Figure 3.3 – Technical drawing of the Macor ceramic piece that holds the DIP ceramic device packages.

3.1.3 $O_2$ Plasma Conditions

The oxygen used to create plasma was a research grade gas supplied by Machine Welders. After the chamber was pumped to a base pressures of $10^{-9}$ Torr, the oxygen was leaked into the sample areas from the gas dosing lines depicted in Figure 3.1 a). The amount of gas allowed into the chamber was controlled by a leak valve, and the pressure was
measured with two MKS Baratron type 628B manometer pressure gauges (0.1 and 100 Torr). The high potential and ground from an Acopian power supply were connected to two Ni high voltage feedthroughs on both sides of the chamber, shown in Figure 3.1 a). The gas dosing lines were baked and evacuated with a diffusion pumping system before being filled with oxygen.

3.1.4 Hydrocarbon Dosing

The hydrocarbons used for controlled film dosing were obtained from Fluka in liquid form, 99.0% (pentane) and 98.0% (dodecane) free of olefins. Both were stored in a nitrogen filled glove box and were poured into separate vacuum compatible stainless steel vials, while in the glove box. Valves connected to each stainless steel vial were closed while in the glove box to prevent interaction with ambient contaminates. The vial for each hydrocarbon was attached to a separate gas dosing connection line. After being attached to the dosing lines, additional purification was performed separately via a freeze pump thaw process. Pentane and dodecane freezing points are 143.3 K and 263.4 K, respectively. Therefore, when either vial was submerged in liquid nitrogen and then exposed to vacuum, the majority of species pumped out from the vial were ambient species with lower freezing points, eg. O₂, N₂, and CO. After this additional purification, each hydrocarbon species was leaked separately into the chamber to provide controlled exposure to MEMS contacts.
3.2 RF MEMS Test Devices

Data were collected on RFMEMS switches fabricated at both Northeastern University (NEU) and Sandia National Laboratory (SNL). The contact materials for NEU devices were Au-Au and Ru-Ru. The contact materials for the SNL switches were Au-RuO$_2$, where RuO$_2$ was made in two ways that will be discussed in Section 3.2.2. All switches were operated to observe the power law creep trend. In addition, SNL switches were operated when exposed to hydrocarbons at different partial pressures and exposed to vacuum and nitrogen environments for lifetime experiments.

3.2.1 Northeastern University RF MEMS Switch

NEU devices consisted of 32 switches around the perimeter of a square, with eight switches per side. Ground lines had at least two wires wirebonded onto the die. The sense pads were not large enough to support two wirebonds. Therefore, one wire was wirebonded to the sense pad for each switch. This connection led to one feedthrough on the outside of the chamber. Here, two wires were connected to a single feedthrough for the sense and source connections, to complete the four wire resistance measurements. Therefore, the resistance measurements for NEU switches were slightly larger because the four wire resistance probes were not completely on the die. Resistance measurements of the two ground leads were taken during a separate measurement to account for this additional resistance of the contact. It was assumed that the sense and source lines had the same resistance. Figure 2.3 a) is a technical drawing of the NEU switch, and Figure 3.4 a) and b)
are SEM images of a single NEU device and an overview of the multiple devices on the perimeter of the die. The NEU and SNL devices were both wirebonded with one mil (25µm) Au wires to unlidded 24-pin or 40-pin side braze ceramic DIP contact pads. The NEU dies were attached to the DIP ceramic package with only the wire from wirebonding. No adhesives were used to attach the die to the DIP ceramic package to minimize contamination from outgassing adhesives.

**Figure 3.4** – a) SEM image of a NEU configured switch. b) Zoomed out SEM of large areas on the NEU die.
3.2.2 Sandia National Laboratory RF MEMS Switch

The SNL devices were patterned, released and wirebonded at SNL. The package consisted of 14 switches that were divided into three isolated banks of four plus two additional individual switches that were not used for the present study. Each bank of four switches shares two common ground pads, one sense pad and one source pad to allowed for four wire resistance measurements on the device die. Each device had a dedicated actuation pad to close specific switches. Each ground pad was wirebonded to the package bottom to mitigate electrostatic discharge. All top contacts were Au, while the bottom contacts were reactivly sputtered RuO\(_2\) ("bulk RuO\(_2\)”) or sputtered Ru that was oxidized after deposition ("surface RuO\(_2\)”). Figure 3.5 shows SEM images of a) a single switch and b) multiple switches on a die. In Figure 3.5 b), the two wirebond pads were not shown which allowed four wire resistance measurements to be performed on the die.
3.3 Data Taking Procedures

How the devices were handled in transit to NCSU, stored when not in use, and operated once inside the vacuum chamber is discussed in the following sections. Because devices were cleaned in situ, storing devices compared with operating immediately are not considered to influence experimental results.
3.3.1 Device Handling and Storage

Devices were transported in ambient by parcel services or hand carried on a flight to NCSU in electrostatic discharge (ESD) protective packages and held in place by pressing the leads into an ESD resistant form. Once at NCSU, the devices were stored for periods ranging from days to months in a nitrogen filled glove box in advance of the measurements. The studies reported do not rule out the possibility that thicker contamination films were present on devices stored for longer periods of time. No evidence for this intuitive possibility was noted, however, in the course of the measurements.

Devices were mounted into the chamber on a bench top in ambient lab environment. Because a small dust particle could land on a switch or across voltage supply lines and destroy all functionality on the die, exposures to the lab environment was minimized. It is worth noting that the work in this dissertation had a much higher yield of working devices than predecessor’s devices and is attributed to the fact that devices were placed into the enclosed chamber as quickly as possible to avoid any interactions with the ambient lab environment.

3.3.2 Electronics

The different MEMS switches were connected to a number of instruments and the operating conditions were controlled, and measurement values were collected with LabView. The actuation voltage to close NEU switches ranged from 85 to 95V, corresponding to 50 to 100 µN, and, for SNL, switches ranged from 87 to 99 V, corresponding to 280 to 365 µN.
Once any device was closed the actuation voltage remain constant until the switch was
opened by turning the actuation voltage off. The actuation voltages were sent from an
Agilent waveform generator [68] through a TEGAM high voltage amplifier [70] to the
appropriate actuation switch pad. To verify the actuation voltage, a monitoring output from
the TEGAM was sent to a Keithley [71] multimeter.

The experimental resistance values reported here were measured across the four
probe resistance contact points. This includes resistance from the wire bond connections,
signal lines, the device contact pads, and any additional resistances from contaminants that
were potentially present on the contact pads. To quantify the additional resistance in the
connection lines for NEU switches, the four wire resistance of the ground connections was
measured, assuming the sense and source connections were similar. Values reported here
have been corrected for the resistance in the connection lines. Once the switch was closed, a
four wire DC contact resistance measurement was performed across the contact with a
Keithley source meter [72].

### 3.4 Characterization of Contact Surfaces

Contact surface characterization was extremely important to understand how different
materials respond to device operations. Unfortunately, it was not possible in this dissertation
to study the contact surface between each cycle, because it required the destruction of a
device. Instead, after all experiments were done in all the varying operating environments
and operating conditions, contacts were then characterized in order to understand the material response.

### 3.4.1 Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS)

All SEM images were taken with a variable pressure Hitachi S3200 at the Analytical Instrumentation Facility at NCSU. This SEM was equipped with an Oxford Isis EDS system that allowed for elemental analysis of elements above Boron. The acceleration voltage could range from 0.3 to 30 kV. Images in this dissertation were taken at either 5 or 25 kV. The sample stage allowed for 360° rotation and 20 to 90° tilt. The tilt was important for the SNL devices because of the charging that occurred on the base substrate. Magnification of the SEM was 20x to 300,000x, but work here ranged from 100x to 25,000x. All images used the Everhart-Thornley secondary electron detector. SEM was used as an initial surface characterization technique to see damage to contact surfaces. The *in situ* ability with EDS was incorporated to observe if there was any material transfer or unusual materials on the contact surface other than what was initially reported from collaborators making the devices.

Figure 3.6 a) and b) are representative of bottom electrodes from SNL and NEU, respectively. SNL bottom electrodes all had dimples in the same proximity. It is unclear if this was the contact area from the top electrode or a product of the microfabrication process. Regardless, multiple EDS measurement were taken on this dimple and off this dimple to
measure surface composition. All spectrums are similar to Figure 3.6 a), which indicates the contacts are Ru on a Si substrate.

An abnormal contact for a SNL switch is shown in Figure 3.7. This switch was operated from gate 5 and initial experiments from this gate along with the other three gates were used to collect data. After many experiments and oxygen plasma exposures a pre-experimental test measurement of contact resistance with an actuation voltage of 0 V indicated a switch was closed in the bank of switches with gate 5. The extreme damage in Figure 3.7 indicates this switch was the cause of the short in the bank of switches. No abnormal operational parameters were indicated before this short circuit was measured.
Figure 3.6— a) EDS and SEM image of a SNL RuO$_2$ contact. b) EDS and SEM image of a NEU Ru contact.
Figure 3.7 – An abnormal SNL bottom RuO$_3$ contact showing an evaporated area that is thought to be the cause of a pre-experimental test measuring contact resistance with an actuation of 0 V.

3.4.2 Atomic Force Microscopy (AFM)

An ambient Thermomicroscopes Autoprobe CP-Research AFM was used to scan contact surfaces in contact mode. The main two components of the AFM are the probe head and the sample stage. The probe head consists of a laser diode, mirror, position sensitive photo detector, and chip carrier that holds AFM cantilevers. The laser was manually positioned onto the back side of the AFM cantilever to be reflected onto the detector. The stage below the probe head is equipped with a magnetic sample holder. The samples were adhered to a magnetic disc with silver paint, which was then placed on the sample holder. In
this AFM, the sample stage was rastered in the x, y plane, and the AFM tip was held stationary.

Quantitative measures were performed with AFM to measure surface roughness and to approximate the sharpness of asperities. Figure 3.8 a) and b) are representative of the SNL bottom contacts of both bulk and surface RuO₂. Figure 3.8 a) displays two of the dimples on a 100 x 100 µm scan and Figure 3.8 b) is a 5 x 5 µm scan of the lower dimple. Surface analysis was performed with IP AutoProbe Image software version 2.1.15, by ThermoMicroscopes. Roughness measurements were taken from multiple 2 x 2 µm areas in Figure 3.8 b) and other scan on other contact dimples. The rms roughness for RuO₂ was 10.834 ± 0.541 nm. The top electrode was not imaged, but there were two bottom electrode Au switches that were not wirebonded. AFM scan of these contacts had rms roughness of 1.717 ± 0.189 nm.

Using the line scan in Figure 3.9 and approximating each asperity as an isosceles triangle the height and width have average values of 0.29 µm and 0.21 µm. Superimposing this average values isosceles triangle onto Figure 2.7 gives a calculated value of β = 70.1°. This angle along with calculating the effective radius of $r_1$ and $r(t)$ allowed for the calculation of strain, $\varepsilon = x(t) / L$. 
Figure 3.8 – a) 100 x 100µm AFM scan of two RuO₂ contacts on a SNL die. b) 5 x 5 µm AFM scan of a dimple on the SNL bottom electrode.
3.4.3 X-ray Diffraction

X-ray diffraction (XRD) analysis was performed with a Rigaku X-ray diffractometer, using Cu Kα, $\lambda=0.1542$ nm, radiation in order to study the lattice parameters and microstructures of RuO$_2$ films. XRD uses x-rays to determine the lattice spacing of atomic planes of crystalline materials using Bragg’s Law

$$n\lambda = 2d \sin \theta$$  \hspace{1cm} (3.1)

where $n$ is the order of the peak, $\lambda$ is the wavelength of the x-ray, $d$ is the mean lattice spacing, and $\theta$ is the angle between the x-ray and the sample surface. If the lattice parameter
and unit cell structure are known, the mean lattice spacing can also be determined. Equations for the six crystal systems differ but the relation for HCP is as follows:

\[
\frac{1}{d^2} = \frac{4}{3} \left( \frac{h^2 + hk + l^2}{a^2} \right) + \frac{l^2}{c^2}
\]

(3.2)

where the Miller index is \((h,k,l)\), \(a\) and \(c\) are the lattice parameters. XRD patterns for polycrystalline materials could have multiple peaks. From these peaks the grains size can be determined by:

\[
D = \frac{K \lambda}{B \cos \theta}
\]

(3.3)

where \(K\) is a calibration constant equal to 0.9 and \(B\) is the full width at half maximum of a peak in radians. Typically, nanocrystalline materials are characterized by a grain size in the range of 1-100 nm [46].

A blanket surface RuO2 on Si sample was sent from SNL for XRD measurements. Figure 3.10 is the XRD data and shows a (110) orientation that agrees with other XRD measurements in the literature [73-75]. From this data, \(\theta=14.475^\circ\) and the full width at half maximum was \(B=0.00336\) rad. Using Equation 3.3, \(D=42.66\) nm corresponding to a grain size in the nanocrystalline range.
Figure 3.10 – XRD measurement of a blanket surface RuO$_2$ on Si substrate from SNL.
4. Impact of UHV and \textit{in situ} Oxygen Plasma Cleaning on Contact Resistance
4.1 Introduction

The following data was submitted to the Journal of Applied Physics [76]. Contact resistance measurements were reported for RF MEMS, operating within an ultrahigh vacuum system, equipped with in situ oxygen plasma cleaning capabilities. The measurements reported here were performed to (1) compare the properties of soft, hard and combined soft-hard, contacts for Au-Au, Ru-Ru, and Au-Ru-based contacts and to (2) document the impact of oxygen plasma on the resistance of Ru-based contacts. Ru-based contacts from SNL were prepared by using standard sputtering techniques, sputtering followed by post-deposition oxidation, (“surface RuO₂”) or reactive sputtering in the presence of oxygen (“bulk RuO₂”). A more complete description of these devices is in Section 3.2.2. To compare resistance data for various material combinations, time dependent resistance measurements were performed for closed contacts for 30 minute periods, both before and after cleaning. Data were fitted to power law extrapolations, Equation 2.7, to infer contact creep properties, \( A \) and \( \alpha \), and \( t=\infty \) resistance values, \( B \). To gauge the creep rate, normalized resistance changes over time will be shown.

4.2 Data Collection

The experimental resistance values reported here were measured across four wire resistance probes. For the NEU devices, this includes resistance from the wire bond connections, signal lines, the device contact pads, and any additional resistances from contaminants that were potentially present on the contact pads. For the SNL devices, the
four wire resistance probes were all attached on the die; therefore, signal lines from the DIP package to the electric feedthroughs were not contributing to the resistance measurements. To quantify the additional resistance in the connection lines for NEU switches, the four wire resistance of the ground connections was measured, and it was then assumed the sense and source connections contributed similar resistances. Values reported here were corrected for the resistance in the connection lines. Once the switch was closed, a four wire DC contact resistance measurement was performed across the contact with a Keithley [72] source meter.

The actuation voltage to close NEU switches ranged from 85 to 95V, and for SNL switches, it ranged from 87 to 99 V. Once any device was closed, the actuation voltage remained constant until the switch was opened by turning the actuation voltage off. The actuation voltage was sent from an Agilent waveform generator [70] through a TEGAM high voltage amplifier [71] to the appropriate actuation switch pad. To verify the actuation voltage, a monitoring output from the TEGAM was sent to a Keithley [77] multimeter. LabVIEW was employed to collect the actuation voltage, contact sourcing voltage, contact current, contact resistance, and time.

After mounting the devices within the vacuum chamber, the chamber was evacuated to a base pressure of $1 \times 10^{-9}$ Torr. Oxygen plasma cleaning treatments were performed as follows: all actuation voltages and four wire resistance connections outside the chamber were disconnected from the feedthroughs and a gate valve, which connected the sample chamber to the ion pump, was then closed. Research grade oxygen was leaked into the sample chamber until the Baratron capacitance manometer pressure gauge read approximately 150 mTorr. One Cu disc was connected to a potential of 0.4 kV, while the remaining Cu disc was
connected to the ground of the power supply. The body of the vacuum chamber was connected to the buildings power ground. To maintain 150 mTorr pressure, the system was simultaneously pumped with a turbo molecular pump through a valve that was regulated to maintain 150 mTorr.

4.3 Data Results

Initial measurements of the overall impact of oxygen plasma on Ru-Ru switches were first performed via comparisons of NEU Ru-Ru and Au-Au resistance data. Since the Ru surfaces, while being cleaned by the oxygen plasma, were also oxidized by it, more extensive studies of switch response were reserved for the combined Au-RuO2 SNL switches.

4.3.1 NEU Au-Au and Ru-Ru Contacts

Figure 4.1 a) and b) presents resistance versus time data for NEU Ru-Ru devices held closed for 30 minutes before and after one minute of exposure to O2 plasma. Both the switch and contact were composed of sputtered Ru. The base pressure in the chamber before cleaning was 1 x 10^-9 Torr. Data were recorded at a chamber pressure of 10^-8 Torr after cleaning. Cleaning the Ru contacts lowered the resistance by a factor of 20 and was attributed to the removal of hydrocarbons from the surface. For comparison purposes, data for NEU Au-Au devices held closed in 10^-9 Torr with no cleaning treatment are presented in Figure 4.1 c). Resistance values, recorded on the NEU Au contacts, were similar to those reported in Ref. [22] and fit well to the power law relation, expressed in Equation 2.7, albeit with different power law parameters. The difference may be attributed to the superior
vacuum conditions at which the present studies were performed or a difference in the nanocrystalline structure of the different Au contacts. Because the base pressure was $10^{-9}$ Torr there was more desorption of surface contamination and the strike rate of native hydrocarbons on the surface was an order of magnitude less than compared to the next best MEMS vacuum experiment in the literature [22]. Despite the fact that *in situ* oxygen plasma cleaning dramatically lowered the resistance of Ru contacts, it did not lower the resistance to values lower than those characteristic of Au contacts, irrespective of whether the Au contacts were cleaned. The power law fit parameters for Figure 4.1 data are presented in the upper three rows of Table 4.1.

![Figure 4.1](image-url)

**Figure 4.1** – Resistance versus time for switches held closed for 30 minutes. a) NEU Ru-Ru switch in $10^{-9}$ Torr and b) after exposure to O₂ plasma for one minute. c) NEU Au-Au switch in $10^{-9}$ Torr. Resistance values for cleaned Ru-Ru switches remain higher than Au switches that have not been cleaned.
**Table 4.1.** Fit parameters for equation (3), the power law fit and the error of the line to data.

<table>
<thead>
<tr>
<th>Contacts</th>
<th>$\alpha$</th>
<th>$A$ (Ω/min$^\alpha$)</th>
<th>$B$ (Ω)</th>
<th>Line Fit Error $R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Au-Au</td>
<td>0.0351</td>
<td>1.01</td>
<td>0.01091</td>
<td>0.99286</td>
</tr>
<tr>
<td>Ru-Ru Pre O$_2$ Cleaning</td>
<td>0.08758</td>
<td>197.61</td>
<td>3.00372</td>
<td>0.99658</td>
</tr>
<tr>
<td>Ru-Ru Post O$_2$ Cleaning</td>
<td>0.01312</td>
<td>6.53</td>
<td>0.62073</td>
<td>0.97697</td>
</tr>
<tr>
<td>Au-RuO$_2$</td>
<td>0.01946</td>
<td>8.87</td>
<td>0.04489</td>
<td>0.98769</td>
</tr>
</tbody>
</table>

4.3.2 **SNL Au-RuO$_2$ Contacts**

An extensive study of the impact of in situ cleaning on SNL Au-RuO$_2$ switches was performed next to compare oxygen plasma exposure for “bulk” and “surface” RuO$_2$ in controlled conditions and to document the impact of a mixed soft-hard Au-Ru contact. Data were recorded on numerous “surface” and “bulk” RuO$_2$ switches as a function of oxygen plasma exposure periods. In addition, baseline measurements on the same switches were performed in air and in base level vacuum before the oxygen plasma treatment and in vacuum 8 days after the treatment. Figures 4.2 and 4.3 present representative data for an individual switch, and the average results with error bars for the entire collection studied, respectively.

Figure 4.2 presents typical data for a Au “surface” Ru oxide switch that was held closed for 30 minutes. The measurements were recorded after 15s, 45s, 90s, and 8 minutes of O$_2$ plasma exposure on six different Bulk RuO$_2$ switches and four different surface RuO$_2$
switches. The base pressure in the chamber before cleaning was $1 \times 10^{-9}$ Torr and data were recorded at a chamber pressure of $10^{-8}$ Torr. The resistance measurements increased for contacts exposed to O$_2$ plasma for 45 s compared with 15 s but, for longer O$_2$ plasma exposure times (90 s and 8 min), the resistance dropped below initial values. The change in contact resistance, depending on the amount of oxygen plasma exposure, was a convolution of partial removal of hydrocarbons on the surface with initial stages of an oxide layer forming on the surface and a roughening on the surface. These contributions to contact resistance are discussed further in Section 4.4.

Figure 4.3 presents collective data for many switches and runs. In particular, it shows the average values for initial and $t=\infty$ resistance values as a function of oxygen plasma exposure time. The data reflect multiple “surface” and “bulk” RuO$_2$ switches. Overall, while a variability was present in the data at the initial times, after about five minutes of exposure to oxygen plasma, the data sets converge at both b) initial and a) $t=\infty$ time periods. There were no values for bulk RuO$_2$ for the 15 s O$_2$ plasma exposures since collected initially for these samples could not be fitted by a power law relation. Initial resistance values were on the order of 100’s of k$\Omega$ for these samples and they exhibited far more variability in their initial values than the “surface” Ru samples. As the devices were exposed to longer O$_2$ plasma times, all resistance measurements exhibited power law trends and both initial and infinity contact resistance values decreased. The power law fit parameters for Au-RuO$_2$ contacts from Figure 4.2 after exposure to O$_2$ plasma for 8 minutes are presented in the fourth row of Table 4.1.
The last set of data points in Figure 4.3 represents measurements of contact resistance after the switches were left for 8 days in vacuum at $10^{-8}$ Torr in the open state. The increase in both initial and limiting resistance can be attributed to slowly forming surface contamination. At $10^{-8}$ Torr, approximately 0.01 monolayer/s could strike the surfaces, some of which may eventually adsorb and cause an increase in resistance.

**Figure 4.2** – Au-surface RuO$_2$ contacts from SNL operated in air and after O$_2$ plasma exposures of 45 s, 90 s and 8 min.
Figure 4.3 – Resistance measurements versus variable exposure times showing that longer exposure times decreases both a) $t=\infty$ resistance and b) initial resistance values. The solid black line represents a break in the time axis in order to show switch closures after 8 days. During the 8 days the switches were left in the open position in $10^{-8}$ Torr vacuum.
4.4 Discussion

Figure 4.4 displays normalized resistance changes recorded for Au-Au, Ru-Ru and Au-RuO₂, where it is clear that the time evolution of the Au-RuO₂ contact is very similar to that of the Au-Au contacts. This is consistent with prior literature reports that creep rate is dominated by the more compliant contact material, in this case Au [15]. A slower rate of contact resistance change was anticipated for the Ru-Ru combination, as Ru resists deformation more than Au, as is observed here. The absolute value of the resistance for the mixed material contact, meanwhile, remains closer to that of the higher resistance material, in this case, Ru.

The schematic in Figure 4.5 depicts how the SNL surface and bulk RuO₂ films are thought to evolve and converge as a function of oxygen plasma exposure time. The NEU Ru-Ru contacts would be represented by Figure 4.6(b), but with a thinner oxide layer than SNL surface RuO₂. Using this schematic as a guide, tabulated calculations are presented in Table 4.2 for ideal contact resistance of Au, Ru, and RuO₂ contacts. Two resistance measurements were calculated; contact area with radius \( a \) and the thickness of the material with length \( l \). The values for \( l \) were taken from SNL contact deposition parameters, while \( a \) was taken from approximations based on computational values of apparent areas [17]. Under these assumptions, Table 4.2 shows resistance values for ideal contacts that are lower than experimental resistance values.

Fortini et al. [52] used molecular dynamic simulations to study contact closure and opening of Au-Au and Ru-Ru at different temperatures. At their respective elevated temperatures, 300 K for Au and 600 K for Ru, contacts were more ductile and show necking
when pulled apart. At their respective lower temperatures, 150 K for Au and 300 K for Ru, both contacts are brittle and form more dislocations and cracking formation when pulled apart. Using Wiedemann-Franz principle to estimate experimental contact temperatures at voltage values of 0.02 V, the contacts were assumed to be \(~300\, \text{K}\). At this temperature, the Au-RuO\(_2\) contact had a ductile Au contact with a brittle RuO\(_2\) contact, assuming RuO\(_2\) responded similarly as Ru. It was also assumed that RuO\(_2\) would not crack when in contact with Au, because Au would deform more easily when pulled apart from RuO\(_2\). Figure 4.4 shows this with Au-Au and Au-RuO\(_2\) contacts having similar normalized resistance changes over time. Here the change in Au was much faster than Ru, as shown by Fortini as being more ductile, so that faster resistance change was dominated by the material that had an increased contact area.

This work has shown that for a long enough O\(_2\) plasma exposure time the contact resistance can decrease by a factor of 20. It also shows that the resistance values of clean Ru-Ru contacts are slightly lower than those for Au-RuO\(_2\) contacts. Many variables can be attributed to the magnitude of contact resistance, i.e., contact force, thickness of an oxide layer, and surface roughness. Also exposing contacts to \(10^{-8}\) Torr vacuum environments for several days causes the contact resistance to increase 10’s of ohms. Measurements of contact resistances do not show any increase after being left in the open state in \(10^{-8}\) Torr vacuum for hours or 1 day. This leads to questions about how to keep the contact resistance minimal. One suggestion would be after cleaning the contacts, backfill and seal a non reactive gas into the packaging of the device. This could limit reactive hydrocarbons from interacting with the contacts, thereby keeping the contact resistance low.
Figure 4.4 – Normalized resistance change of Au-Au, Ru-Ru and RuO$_2$-Au contacts. Symbols match prior figures: Ru-Ru (Fig. 4.1b) and Au-Au (Fig. 4.1c). The Au-Au contacts were not exposed to O$_2$ plasma. Ru-Ru contacts were exposed to O$_2$ plasma for 1 minute. Au-RuO$_2$ contacts were exposed to O$_2$ plasma for 8 minutes. Au-RuO$_2$ contacts have similar resistance changes as Au-Au contacts and faster than Ru-Ru contact resistance changes.
Figure 4.5 – A representation of the bulk and surface RuO₂ initially and when exposed to O₂ plasma for short and long periods of time. Note this is not to scale.

Table 4.2 – Resistance for Au-Au, Ru-Ru, and RuO₂-RuO₂ contacts using equation (2) and using the equation for resistance through a wire, \( R = \rho l / (\pi a^2) \)

<table>
<thead>
<tr>
<th>Contact Material</th>
<th>Bulk Resistivity, ( \rho ) (µΩ·cm)</th>
<th>( R = \rho / (2a) ), (Ω) ( a = 0.098 \mu m )</th>
<th>( R = \rho / (2a) ), (Ω) ( a = 0.68 \mu m )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Au-Au</td>
<td>2.44</td>
<td>0.124</td>
<td>0.018</td>
</tr>
<tr>
<td>Ru-Ru</td>
<td>12.3</td>
<td>0.628</td>
<td>0.090</td>
</tr>
<tr>
<td>RuO₂</td>
<td>45</td>
<td>2.296</td>
<td>0.331</td>
</tr>
</tbody>
</table>

Film Thickness

<table>
<thead>
<tr>
<th>Material</th>
<th>( R = \rho l / (\pi a^2) ) (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ru</td>
<td>0.738</td>
</tr>
<tr>
<td>RuO₂</td>
<td>0.0895</td>
</tr>
</tbody>
</table>

Oxide Thickness

<table>
<thead>
<tr>
<th>Material</th>
<th>( R = \rho l / (\pi a^2) ) (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RuO₂</td>
<td>0.0895</td>
</tr>
<tr>
<td>RuO₂</td>
<td>2.796</td>
</tr>
</tbody>
</table>
5. Contact Resistance Change Due to the Adsorption of Pentane
5.1 Introduction

Contact resistance measurements were reported here for RF MEMS switches operating within an UHV system, equipped with *in situ* oxygen plasma cleaning capabilities, followed by exposures to partial pressures of pentane gas. The measurements reported here were performed (1) to compare critical concentrations of pentane on surfaces for microscale contacts with previously published work of pentane on macroscale relays [50, 51] and (2) to compare the change in the magnitude of contact resistance at critical concentrations with contact resistance changes seen in Chapter 4, when devices were stored in the open state in a 10⁻⁸ Torr vacuum environment. Contacts were still distinguished with “surface” and “bulk” RuO₂ naming schemes but they appear to have similar contact resistance values after both were exposed to oxygen plasma multiple times. Contacts were closed for 30 minute periods, and fitted to power law extrapolations, Equation 2.7.

Previous experiments measuring changes in contact resistance due to exposures to hydrocarbons have been investigated for macroscale relays [50, 51]. Two of the hydrocarbons used were pentane and dodecane, which have the same end groups but have different carbon backbone chain lengths. This chapter investigates the change in contact resistances for different partial pressure exposures of pentane. Chapter 6 investigates dodecane and compares those results with pentane. As seen in Table 5.1, the vapor pressure of pentane was high enough to evaporate from a liquid when exposed to an evacuated sample cell. A comparative study was performed to observe which hydrocarbon, pentane, or dodecane contributes a larger contact resistance at their respective partial pressures and surface coverage. By exposing contacts to oxygen plasma for five minutes, initial contact
resistances were shown to be reproducible. In this stringently controlled chamber, controlled pentane and dodecane at discrete partial pressures were exposed to microscale contacts. Initial contact resistance measurements were taken, normalized, and graphed with respect to the pressure of the exposed hydrocarbon. Using a quartz crystal microbalance (QCM) the amount of hydrocarbons on the surface was measured.

5.2 Data Collection

Experimental resistance values reported here were measured across four wire resistance probes that were all on the SNL die. Therefore, resistance contributions can only come from wire bond connections, signal lines on the die, switch contact pads, and the contamination purposefully adsorbed to the switch contact pads. The chamber was pumped to a base pressure of $10^{-9}$ Torr. The procedures for making oxygen plasma were the same as in Chapter 4 with the devices in all cases exposed to oxygen plasma for five minutes. Chapter 4 showed that oxygen plasma exposures of five minutes minimized the contact resistance (in Figure 4.3). After oxygen plasma exposure, the chamber was immediately pumped to $10^{-8}$ Torr. Switches were closed for 30 minutes and a four wire DC resistance was measured across a given switch. The succeeding closures of a switch were introduced to increasing pressures of pentane, followed by pumping out pentane once the device was closed.

The actuation voltage to close any given switch ranged from 97 to 99 V. Each switch was actuated at the same voltage for each closure to maintain the same approximate contact
force. The actuation voltage was sent from an Agilent waveform generator [70] through a TEGAM high voltage amplifier [71] to the appropriate actuation switch pad. To verify the actuation voltage, a monitoring output from the TEGAM was sent to a Keithley [77] multimeter. A LabVIEW program was made to operate switches by “cold switching” all devices and collected the actuation voltage, contact sourcing voltage, contact current, contact resistance, and time values.

5.3 Data Results

In Chapter 4 it was shown that post oxygen plasma exposure reduced the contact resistance of Ru based switches compared with operating switches in UHV alone. Once operated or left in vacuum in an open state for several days, the contact resistance increased. Exposure to oxygen plasma would, again, lower the contact resistance. This reproducible decrease in contact resistance, post oxygen plasma exposure, served as the baseline for the experiments reported here and in Chapter 6. Initial contact resistances were seen to increase with larger pressures of pentane being leaked into the sample cell as shown in Figure 5.1. Here, normalized initial resistances of a given switch are shown with increasing pressures of pentane. For a given contact, the resistance increased by a factor of 2.0 ± 0.2. Often times, an increased contact resistance of a factor of 2.0 was detrimental to the performance of a switch. This factor of 2.0 was observed at 0.1 Torr of pentane leaked into the chamber. The contact pad, actuated by gate 5, showed contact resistance leveling off at 0.5 Torr. This shape was similar to that reported by Koidl et al. for “critical concentration” adsorption
uptakes in Figure 2.8 a). Table 5.1 tabulates the critical concentrations for both Koidl et al.’s work and Figure 5.1 values for pentane adsorptions.

![Pentane Normalized Initial Resistance](image)

**Figure 5.1** – Normalized resistance change for four contacts exposed to pressure of pentane ranging from $\sim 10^{-6}$ Torr to 0.1 Torr. Contact resistance increased by a factor of 2 ±0.2 for each device, which can cause failure.

**Table 5.1.** Critical concentration and vapor pressure values for pentane

<table>
<thead>
<tr>
<th>Pentane</th>
<th>Critical Concentration</th>
<th>Vapor Pressure at RT</th>
<th>Schematic ($C_5H_{12}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Referenced</td>
<td>&gt; 7.600 Torr [51]</td>
<td>418.62 [78]</td>
<td></td>
</tr>
<tr>
<td>Our Work</td>
<td>0.05 -0.1 Torr</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A critical concentration, 0.1 Torr, of dodecane was measured to correspond to a contact resistance value of $27.38 \pm 12.47 \, \Omega$. This contact resistance was superimposed onto
Figure 4.3. The increase in contact resistance at the critical concentration for pentane was similar to that of a switch left in the open state at $10^{-8}$ Torr environment for eight days.

![Graph](image)

**Figure 5.2** – Contact resistance of pentane and dodecane at the critical concentration of hydrocarbon exposure, superimposed on Figure 4.3 in order to compare with contacts left in the open state in $10^{-8}$ Torr for eight days.

Using a QCM the amount of pentane was measured to approximate the coverage on the contact pads [79]. The QCM used was polished with a silver electrode. When adsorbing gases onto both sides of an AT-cut QCM the change in frequency can be calculated by:

$$\delta f = \frac{4f^2 \rho_{area}}{\rho_q \nu_q}$$  \hspace{1cm} (5.1)

where $f$ is the frequency of the QCM, $\rho_{area}$ is the area density of pentane, $\rho_q = 2.648$ g/cm$^3$ is the density of quartz, and $\nu_q = 3.338 \times 10^5$ cm/s is the speed of sound in quartz. Using the
schematic in Table 5.1 and assuming the bond lengths were 0.2 nm and the angle was 109°, the approximate surface area for one pentane molecule equals \( A_P = 2.62 \times 10^{-16} \text{ cm}^2 \). Using the atomic weight of 72.15 g/mol and Avogadro’s number gives an area density for pentane of \( \rho_{\text{area}} = 4.57 \times 10^{-7} \text{ g/cm}^2 \). For one monolayer of pentane on a 5 MHz QCM, the frequency shift equals \( \delta f = 51.7 \text{ Hz} \). Figure 5.3 shows the frequency shift of a QCM as pentane was leaked into a chamber initially at 10\(^{-9}\) Torr. The manometer pressure gauge was not accurate after 100 Torr; therefore, pressure measurements were stopped at 50 Torr. Using the vapor pressure at room temperature from Table 5.1, the partial pressure at 0.1 Torr was 2.39 \( \times 10^{-4} \) and for Koidl the partial pressure was 0.0185. The frequency shift at 0.1 Torr was approximately 0.05 Hz, which corresponds to a surface coverage of 9.67 \( \times 10^{-4} \) monolayer.
The drift of the QCM was measured in Figure 5.4 over an 18,000 s time span in a $10^{-9}$ Torr environment. Figure 5.4 shows the mixed frequency, which means the difference between the sample frequency of a QCM inside the chamber and reference frequency of a QCM outside the chamber. Each QCM was approximately 5 MHz and oscillated by separate Pierce circuits in a grounded metal box to avoid radio frequency interference from other electronic components [80]. Both signals were sent to a low pass filter, which was then sent to a Phillips Model 6673 frequency counter [81]. The mixed frequency signal gave an accuracy of 0.01 Hz compared with an unmixed frequency signal of ~10s of Hz. This accuracy was needed because the frequency change could be on the order of 0.05 Hz. Using

Figure 5.3 – Pentane uptake on a 5 MHz quartz crystal microbalance.
the change in frequency in Figure 5.4 gave a drift frequency of 0.005 Hz/min. For pentane, uptake shown in Figure 5.3, took 15 minutes corresponding to 0.075 Hz error.

![Graph of QCM frequency change](image)

**Figure 5.4** – The change in the mixed frequency of the QCM inside the UHV chamber at 10^{-9} Torr and a reference QCM outside the chamber. The drift of this QCM is shown to be approximately 0.005 Hz/min.

### 5.4 Discussion

Adsorption of pentane on clean microscale metal contacts indicated a critical surface coverage that increased the contact resistance. Controlled amounts of pentane were introduced to the MEMS switches and were monitored by manometer pressure gauges and a QCM mass uptake technique. Observations of pentane at partial pressures of 2.39 x 10^{-4}
increased the contact resistance by a factor of 2.0, which was detrimental to the performance of a switch. The contact resistance increase was similar in magnitude to the switch left in the open state for eight days in $10^{-8}$ Torr. This magnitude increase in contact resistance suggested native hydrocarbon adsorption to the contact surface in vacuum environments poses the same decrease in operational performance as small surface coverage from exposures to hydrocarbons. Measurements of pentane adsorption onto a QCM indicated a surface coverage of $9.67 \times 10^{-4}$ monolayer is needed to increase the contact resistance.

Comparing to macroscale contacts the partial pressure needed to increase the contact resistance is $>0.0185$, which is a factor of 77 larger than the partial pressure needed in this work. The larger amount of contamination to increase the contact resistance for macroscale switches was reasonable because macroscale contacts have much larger contact forces than microscale switches. The larger contact forces were able to penetrate and/or move contamination away from the contact asperities, creating more metal-metal contact area thereby lowering the contact resistance.
6. Contact Resistance Change Due to the Adsorption of Dodecane
6.1 Introduction

Contact resistance measurements are reported in this chapter for RF MEMS switches operating within an UHV vacuum system equipped with in situ oxygen plasma cleaning capabilities followed by varying exposure to partial pressures of dodecane. The measurements reported here were performed (1) to compare critical concentrations of dodecane on surfaces for microscale contacts with previous published work of dodecane on macroscale contacts [50, 51] (2) to compare the change in the magnitude of contact resistance at critical concentrations to contact resistance changes seen in Chapter 4, when devices were stored in the open position in $10^{-8}$ Torr vacuum environment, and (3) to compare dodecane, a longer hydrocarbon chain, to pentane, a similar shorter hydrocarbon chain. Contacts used here were the same as in Chapter 5, SNL Au-RuO$_2$ switches, both surface and bulk RuO$_2$. Contacts were still distinguished with “surface” and “bulk” RuO$_2$ naming schemes but they appear to have similar contact resistance values after both were exposed to oxygen plasma multiple times. Contacts were closed for 30 minute periods then fitted to power law extrapolations, Equation 2.7.

The vapor pressure of dodecane shown in Table 6.1 was found in the literature to be larger than pentane. Koidl et al. showed lower critical concentration values for dodecane on metal surfaces than for pentane. Dodecane has a chain length over twice the length of pentane; therefore a similar molecule of different size will be presented to compare the critical concentration needed to increase the contact resistance. A lower critical concentration would be expected for dodecane for microscale contacts used here because of
Koidl et al.’s observations of dodecane on macroscale contacts. Since critical concentrations of hydrocarbons were expected to be different because of the different vapor pressures, interest in the surface coverage causing an increase in contact resistance was investigated. A QCM mass uptake measurement used in chapter 5 for pentane was incorporated for mass uptake for dodecane to quantify the area density on the switch surfaces. This allowed for a comparison of the amount of coverage needed for each hydrocarbons adsorption corresponding to the critical concentration causing an increase in contact resistance.

6.2 Data Collection

Data collection was the same as Section 5.2, except dodecane was substituted for pentane. Dodecane was replaced with pentane to measure the contact resistance change of clean contacts. The contacts used here were the same as the ones used for pentane. The initial contact resistances after oxygen plasma exposures were the same as for the initial contact resistance values of pentane. Refer to Section 4.2 for details of the electronics used for the collection of data.

6.3 Data Results

In Chapter 4 it was shown that post oxygen plasma exposures reduced the contact resistance of Ru based switches compared with operating switches in UHV alone. Once operated or even left in vacuum in an open state, the contact resistance increased. Exposure to oxygen plasma would again lower the contact resistance. This reproducible decrease in contact resistance, post oxygen plasma exposure, was the baseline for the following
experiments. Because similar contact resistance values were achieved after exposure to oxygen plasma, oxides and roughening of the surface were not consider contributing factors to the contact resistance increase when contacts were exposed to varying amounts of dodecane. Initial contact resistances were seen to increase with larger pressures of dodecane being leaked into the sample cell shown in Figure 6.1. Here, normalized initial resistances of a given switch were shown with increasing pressures of dodecane. For a given contact the resistance increased by a factor of $2.1 \pm 0.1$. This factor of 2.1 was observed at $5 \times 10^{-5}$ Torr of dodecane leaked into the chamber. All contact pads showed contact resistance leveling off at $5 \times 10^{-4}$ Torr. This shape was similar to what Koidl et al. showed for their critical concentration adsorption uptakes, which was shown for dodecane in Figure 2.8 a). Table 6.1 tabulates the critical concentrations for both Koidl et al.’s work, and Figure 6.1 shows values for dodecane adsorptions. The critical concentration for Koidl et al.’s work was shown to be 0.266 Torr, but for this work, the critical concentration was shown to be $\sim 5 \times 10^{-5}$ Torr.
Figure 6.1 – Normalized resistance change for four contacts exposed to pressure of pentane ranging from $10^{-8}$ Torr to 0.05 Torr. Contact resistance increased by a factor of 2.1 ±0.1 for each device, which can be enough to cause failure due to too large of a resistance.

Table 6.1. Critical concentration and vapor pressure of dodecane

<table>
<thead>
<tr>
<th>Dodecane</th>
<th>Critical Concentration</th>
<th>Vapor Pressure at RT</th>
<th>Schematic $(\text{CH}_3(\text{CH}_2)_10\text{CH}_3)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Referenced</td>
<td>0.266 Torr [51]</td>
<td>0.3 [82]</td>
<td></td>
</tr>
<tr>
<td>Our Work</td>
<td>$5 \times 10^{-5}$ Torr</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A critical concentration, $5 \times 10^{-5}$ Torr of dodecane was measured to correspond to a contact resistance value of $30.66 \pm 13.69 \Omega$. This contact resistance was superimposed onto Figure 5.2. The critical concentration of dodecane caused the same increase in contact resistance as pentane at its respective critical concentration. These values also correspond to similar contact resistance values for switches left in the open state at $10^{-8}$ Torr environment for eight days.
A QCM was used to measure the amount of mass uptake by Equation 5.1 for dodecane. Using the schematic in Table 6.1 and assuming the bond lengths of 0.2 nm and an angle of 109° the approximate surface area for one dodecane molecule is $A_p = 2.08 \times 10^{-15}$ cm². Using with atomic weight of dodecane, 170.34 g/mol, and Avogadro’s number, the area density for one monolayer of dodecane is $\rho_{area} = 1.36 \times 10^{-7}$ g/cm². A monolayer of dodecane using a 5 MHz QCM corresponded to a frequency shift of $\delta f = 15.5$ Hz. Figure 6.2 shows the frequency shift of a 5 MHz QCM as dodecane was leaked into a chamber initially at $10^{-9}$ Torr. Using the vapor pressure at room temperature from Table 6.1, the partial pressure at $5 \times 10^{-5}$ Torr was $1.67 \times 10^{-4}$ and the work done by Koidl et al. showed a partial pressure of 0.887. The frequency shift at $5 \times 10^{-5}$ Torr was approximately 0.01 Hz which corresponds to surface coverage of $6.45 \times 10^{-4}$ monolayer.
The same drift from Chapter 5 was used for dodecane, ~0.005 Hz/min. Dodecane uptake shown in Figure 6.2 took 25 minutes, which corresponds to 0.125 Hz error.

6.4 Discussion

Dodecane was adsorbed onto clean microscale metal contacts to quantify the resistance changes. Controlled amounts of dodecane were introduced to the MEMS switches and were monitored by manometer pressure gauges and a QCM mass uptake technique. Dodecane partial pressures of 1.25 x 10^-4 were observed to increase the contact resistance by a factor of 2.1 which is detrimental to the performance of a switch. The contact resistance increase was similar in magnitude to a switch left in the open state for eight days in 10^-8 Torr.
The magnitude increase in contact resistance suggested native hydrocarbon adsorption to the contact surface in vacuum environments poses the same decrease in operational performance as small amounts of hydrocarbon covered purposefully contaminated contacts. In addition these results show that a small surface coverage of $6.45 \times 10^{-4}$ monolayers is needed to increase the contact resistance.

Comparing to macroscale contacts the partial pressure needed to increase the contact resistance is a factor of 5320 larger than the partial pressure needed in this work. The larger amount of contamination to increase the contact resistance for macroscale switches was expected because macroscale contacts have much larger contact forces than microscale devices. These larger contact forces for macroscale contacts allow for penetrating and moving of contamination layer(s) away from the contact asperities, thereby creating more metal-metal contact area and lowering the contact resistance.

The absolute pressures at which contact resistances increased for pentane and dodecane are orders of magnitude different, yet the measured amount of coverage on the surfaces is similar for the two hydrocarbons here. The small coverage causing this increase in contact resistance can be attributed to the small contact forces. Small contact forces limit the asperities from pushing contamination films. Table 6.2 compares the critical concentration values for the work presented here and by Koidl et al.,
Table 6.2. Summarizing pentane and dodecane values from Chapter 5 and 6 at critical concentrations of SNL switches

<table>
<thead>
<tr>
<th></th>
<th>Our Work</th>
<th>Koidl</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pentane</td>
<td>Dodecane</td>
</tr>
<tr>
<td>Critical concentration (Torr)</td>
<td>0.1</td>
<td>$5 \times 10^{-5}$</td>
</tr>
<tr>
<td>Partial pressure</td>
<td>$2.39 \times 10^{-4}$</td>
<td>$1.25 \times 10^{-4}$</td>
</tr>
<tr>
<td>Area density (ng/cm²)</td>
<td>0.442</td>
<td>0.088</td>
</tr>
<tr>
<td>Coverage of a monolayer</td>
<td>$9.67 \times 10^{-4}$</td>
<td>$6.45 \times 10^{-4}$</td>
</tr>
</tbody>
</table>
7. Impact of Surrounding Gas Environment on Switch Lifetime
7.1 Introduction

A fundamental understanding of the factors controlling RF MEMS switch lifetime was the ultimate goal of the present research. Measurements of device lifetimes were thus performed on devices with initially clean contacts, with a particular emphasis on the impact of the surrounding gas environment. Switches were operated (1) in $10^{-8}$ Torr vacuum immediately after oxygen plasma exposure, (2) left in the open state in $10^{-8}$ Torr vacuum for some time period, on the order of days, (3) in 760 Torr of dry nitrogen immediately after oxygen plasma exposure and pumping to $10^{-8}$ Torr, and (4) left in the open state in 760 Torr of nitrogen for days.

The SNL switches were shown to be reliable for the experiments performed in this dissertation in that the contact resistance returns to reproducible initial values after five minute exposures to oxygen plasma. Contacts were cycled until failure or to $1 \times 10^6$ cycles, where failure was defined as an increase in contact resistance above 40 Ω. Contact resistance of 40 Ω corresponded to an increase of approximately a factor of four in contact resistance. This factor of four was well above the factor of two that causes operational degradation. Contact materials used in the SNL switches were both surface and bulk RuO$_2$. Both fabricated contact materials, after multiple exposures to oxygen plasma, showed reproducible initial contact resistance values. Regardless of the similarities in initial contact resistance, distinctions of the contact materials were still made for thoroughness.
7.2 Data Collection

The base pressure of the chamber was $10^{-9}$ Torr. Research grade $O_2$ was leaked into the chamber to 150 mTorr. A 0.4 kV potential was turned on to create plasma. The die was exposed to oxygen plasma for five minutes. After the potential was turned off, the chamber was immediately pumped to $10^{-8}$ Torr with a turbomolecular pump, followed by an ion pump. One switch was cycled at ~1 Hz for ~14,000 cycles followed by another switch being cycled. The time from when the die was exposed to oxygen plasma to when the second switch was cycled was approximately four hours. Switches were operated for 14,000 cycles to verify the initial contact resistance was similar for both contacts. Once the initial contact resistance was verified, a switch was cycled until failure, while the other switches were left in the open state. Once the first switch failed the second switch was cycled until failure. The die was then exposed to five minutes of oxygen plasma, followed by switches being operated again, but in the reverse order.

Switches were cycled in two different environments: $10^{-8}$ Torr post oxygen plasma exposure and 760 Torr of nitrogen post oxygen plasma exposures. Testing in 760 Torr of nitrogen was similar to testing in vacuum. The die was exposed to five minutes of oxygen plasma, then immediately pumped to $10^{-8}$ Torr vacuum. Both switches were cycled in vacuum at ~1 Hz for ~14,000 cycles. This again shows the similar initial contact resistance values. At this point the chamber was vented with nitrogen. Gas nitrogen was leaked into the chamber from a tube submerged in a dewar of liquid nitrogen. Before venting to the sample cell area, the venting area was evacuated by a diffusion pump backed by a mechanical rotary vane pump. This prevented any ambient air in the venting tube from going
into the sample cell area. After the sample cell was vented to 760 Torr of nitrogen, the first switch was cycled, while the second switch was left in the open state. When the first switch failed or cycled to $1 \times 10^6$, the second switch was cycled.

### 7.3 Data Results

Figures a) through d) show control experiments of contact resistance measurements after baking the chamber in $10^{-9}$ Torr vacuum and after five minute oxygen plasma exposure, followed by pumping immediately to $10^{-8}$ Torr vacuum. Both gate five and gate seven (or the surface and bulk RuO$_2$) switches were shown to drop in resistance once exposed to oxygen plasma. After oxygen plasma exposures, the contact resistance for each switch was ~5 to 10 $\Omega$. Two effects may have been present for lowering the contact resistance when exposing contacts to oxygen plasma. First, oxygen molecules have enough energy to sputter contact surfaces. This removes contaminates from the surface, thereby reducing the contact resistance. Second, oxygen molecules can react with surface contamination to create byproducts such as CO. The reverse effect can influence the contact resistance, thereby increasing the contact resistance. When the oxygen sputters, the metal contact on the surface can roughen. A rough surface has less contact area, which increases contact resistance. Oxygen reacting with the metal surface creates an oxide surface that increases contact resistance. Because the contact resistance decreases after oxygen plasma exposures, these increased contact resistance contributions are thought to be negligible compared with the contributions decreasing contact resistance for long enough plasma exposure times.
Figure 7.1 – a) Surface RuO₂ switch operated after the chamber was baked and in 10⁻⁹ Torr. b) Same switch, but after exposure to oxygen plasma for 5 minutes. c) Bulk RuO₂ switch operated after the chamber was baked and in 10⁻⁹ Torr. d) Same switch, but after exposure to oxygen plasma for 5 minutes.

7.3.1 Cycling in Vacuum

Figure 7.1 a) and b) shows that the contact resistance was elevated after baking the sample cell and in 10⁻⁹ Torr vacuum. Contacts were then exposed to oxygen plasma for five minutes followed by cycling, at 1Hz, immediately after oxygen plasma exposure or after several days, with the switch being stored in 10⁻⁹ Torr vacuum in the open position. Both
surface and bulk RuO₂ contacts, operated immediately after oxygen plasma exposures, were cycled and it was observed that an increase in contact resistance occurred between 250k and 300k cycles. Switches stored in 10⁻⁹ Torr vacuum for 5 days showed an increase in contact resistance between 10k and 75k cycles once operated.

**Figure 7.2** – a) Surface RuO₂ (gate 5) switch operated after five minutes of oxygen plasma exposure until an increase in contact resistance was observed at ~250k cycles. b) gate 5 operated until an increase in contact resistance was observed at ~75k cycles. Before operation of gate 5 the contacts were exposed to oxygen plasma for 5 minutes, then left in the open state in 10⁻⁹ Torr vacuum for 5 days. c) Bulk RuO₂ (gate 7) switch operated after five minutes of oxygen plasma exposure until an increase in contact resistance was observed at ~300k cycles. b) gate 7 operated until an increase in contact resistance was observed at ~10k cycles. Before operation of gate 7, the contacts were exposed to oxygen plasma for 5 minutes, then left in the open state in 10⁻⁹ Torr vacuum for 5 days.
7.3.2 Cycling in Nitrogen

After oxygen plasma exposure the chamber was immediately evacuated to $10^{-8}$ Torr and then filled with nitrogen. Approximately 14,000 cycles were performed at 1 Hz to observe the initial contact resistance of switches, shown in Figures 7.3 a) and b). Comparing these graphs to Figure 7.1 b) and d), the contact resistance was comparable regardless of $10^{-8}$ Torr or nitrogen environments. Recalling one Langmuir of molecules striking the surface corresponds to 1 monolayer/s in $10^{-6}$ Torr vacuum, an approximation can be made that at $10^{-8}$ Torr 0.01 monolayers/s strike the contact surface and at 760 Torr ~1 x $10^{8}$ monolayers/s strike the contact surface.

A cycle lifetime test of bulk RuO$_2$ contacts shown in Figure 7.3 c) and d) were cycled over 1x$10^6$ with marginal contact resistance increases. The number of cycles here increased by a factor of 3 compared to cycling in $10^{-9}$ Torr vacuum. Surface RuO$_2$ contacts in Figure 7.3 d), left in the open state for 12 days in 760 Torr of nitrogen, and were operated, show an immediate increase in contact resistance.
Figure 7.3 – a) and b) Surface RuO$_2$ (gate 5) and bulk RuO$_2$ (gate 7), respectively, operated after exposure to oxygen plasma for five minutes, then back filled with nitrogen gas to 760 Torr. c) Gate 7 operated in 760 Torr for 1M cycles at 1 Hz. d) Gate 5 left in the open state for 12 days in 760 Torr followed by operating at 1 Hz.

7.4 Discussion

Table 7.1 summarizes the number of cycles before the contact resistance started to increase in both 10$^{-9}$ Torr vacuum and 760 Torr nitrogen gas. The data present here indicates that the cycle lifetime increases when in a nitrogen gas environment compared with a 10$^{-9}$ Torr vacuum environment. The increase in lifetime was attributed to the nitrogen gas.
interacting with the switch contacts and limiting the hydrocarbon interactions. Nitrogen was one of the strongest bonded molecules and was assumed to not break down and bond with the contact surface, thereby not increasing the contact resistance. Switches left open in 760 Torr of nitrogen for twelve days and then operated, had a contact resistance that increased immediately. The partial pressure of native hydrocarbons in $10^{-9}$ Torr vacuum could interact with the contact surface to produce as much as $1 \times 10^{-3}$ monolayers/s. Over a twelve day period, this could be as much as 1037 monolayers. When the contacts were not operated, there was no active component removing any adsorption of hydrocarbons compared with the physical component of an operated switch that pushed hydrocarbons off the contact surface.

Table 7.1. The number cycles before contact resistance starts to increase in $10^{-9}$ Torr and 760 Torr of nitrogen gas environments

<table>
<thead>
<tr>
<th></th>
<th>Number of Cycle Before Failure</th>
<th>Number of Cycle Before Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Initial Contact Resistance</td>
<td>109 Torr</td>
</tr>
<tr>
<td>Cycled immediately after plasma exposure</td>
<td>7</td>
<td>250k-300k</td>
</tr>
<tr>
<td>Left open for (#) days</td>
<td>9</td>
<td>10k-75k (5)</td>
</tr>
</tbody>
</table>
8. Conclusions and Future Work
8.1 Conclusions and Future Work

The motivation of this work was to gain a fundamental understanding of the contact failure mechanisms of RF MEMS switches in reproducible environments and apply this knowledge to a range of MEMS switches to ensure that findings are not device specific. The main conclusions and possible follow up studies are as follows:

**Topic 1: Cleaning and operating switches in reproducible environments**

1. Stringently controlled environments with active surface cleaning capabilities are needed to understand contributions to contact resistances of MEMS switches.

2. Short oxygen plasma exposure increases contact resistance but longer oxygen plasma exposure decreases contact resistance for Ru and Au-Ru based switches. For the present work, five minutes of oxygen plasma exposure was sufficient to minimize the contact resistance of switches from differing manufacturers. Each manufacturer will however need to calibrate their plasma exposures to their specific contact material to minimize contact resistance. Observations of a power law fit parameter B, or \(t=∞\) resistance, interestingly show similar trends as initial contact resistance measurements. The B parameter is a limiting value of the contact resistance which is close to the theoretical value. Changes in this B parameter indicate that adsorbates on the contact surface can influence the lower limit of the contact resistance.

3. When contacts are exposed to longer oxygen plasma times, alpha and B values from the power law fit equation are approximately \(\sim 0.019\) and 0.04 ohms, receptively. The
alpha value corresponds to the creep coefficient value of P=25.1. This is much larger than creep coefficients for polycrystalline grain boundaries. This can potentially be attributed to the fact that the power law equation does not take into account the threshold or internal stress of the contacts. Another potential explanation is that the oxide layer may no longer be polycrystalline after long exposure times to oxygen plasma. An amorphous contact surface would have larger creep rates, and thus larger creep coefficients.

4. Future suggested work would be to expose the same contacts to Ar plasma in order to observe if contact resistance decreases. Oxygen plasma removes hydrocarbon contamination from the contact surface but oxidizes the Ru surface, which in turn increases the contact resistance. If Ar plasma removes hydrocarbons from the surface, then the magnitude of the contact resistance should be lower than oxygen plasma because Ar plasma cannot create an oxide layer on the contact surface.

**Topic 2: Exposing contacts to partial pressures of dodecane and pentane in a controllable manner.**

1. Two hydrocarbons with the same end groups but with different backbone lengths have similar surface coverage that causes an increase in contact resistance. Because their respective vapor pressures are different, the increase in contact resistance occurs at different pressures. Comparing these partial pressures to macroscale contact experiments, the contact resistance increases at a much lower partial pressure for microscale contacts. Because macroscale contact forces are orders of magnitude
greater than microscale contact forces, thereby more readily able to move contami-
nations away from asperity contacts, it is not surprising macroscale contacts have an increase in contact resistance at greater partial pressures of contamination. In this dissertation, the uptake data shows that the coverage is only thousandths of a monolayer. Macroscale experiments did not indicate the surface coverage but it is assumed to be above a monolayer because of the partial pressures reported for the critical concentration.

2. The increase in contact resistance in advance of the measurements was expected to occur at a lower partial pressure than macroscale contacts because of the smaller contact forces in microscale contacts. The actual increase in contact resistance occurs at different partial pressures depending on the hydrocarbon, which is in fact expected since their respective vapor pressures differ. The coverage of the two hydrocarbons that causes an increase in contact resistance is approximately the same. This shows that there is a critical coverage that influences the contact resistance. Since the hydrocarbons have the same end groups but different backbone chain lengths, it is reasonable that they influence the contact resistance at the same coverage since they interact with the contact surface in similar ways. If the hydrocarbons are structurally different, the surface interactions will change, which could cause an increase in contact resistance to occur at a different coverage.

3. Future suggested work would be to expose clean contacts to common atmospheric contaminates to observe the surface coverage that corresponds to an increase in contact resistance. These contaminates can be common molecules in air; e.g. water,
CO, and CO₂. Other contaminates could be inert gases which could instead of contaminating a surface could service as a surface protector. If an inert gas adsorbs more readily to the contact surface it could serve as a protective barrier for switches in transit. When operating the switch, the gas is less likely to dissociate from itself because of the stronger bond compared to hydrocarbons. Here presumably the molecule would be pushed out of the way allowing for metal-metal contact.

**Topic 3: Lifetime tests in different ambient environments**

1. To increase cycle lifetimes, it is clear that the correct environment must be chosen for packaging post-fabrication. The last step of the manufacturing process can include a surface cleaning process, similar to that presented in this dissertation, following a hermetical sealing in some inert environment. Two environments, vacuum and nitrogen were studied here, and nitrogen clearly increased the switch cycle lifetime relative to vacuum. Nitrogen is a straightforward choice, but not necessarily the best choice. In this dissertation, the data indicate that an inert environment increases the cycle lifetime of a switch operated immediately after cleaning. Yet for switches stored in nitrogen for some period of time and then operated, resistance increases occurred rapidly. This leads to question how to store a switch. A possible solution is to close the switch when not in use. This would avoid adsorption on the asperity contacts.

2. The fact that a nitrogen fill environment slows the increase in contact resistance is expected. The nitrogen will impede smaller partial pressures of hydrocarbons from
interacting with the contact surface or saturate the contact surface thereby blocking hydrocarbons from interacting with the contact surface. The latter is discounted since data shows an immediate increase in contact resistance after being stored in nitrogen for days followed by operating.

3. Future suggested work would be to operate switches in other gas environments, e.g. argon, CO, or CO₂. The previous topic describes using CO and CO₂ as contamination materials. This is true from the point of view of pollution. But these molecules are strongly bonded together therefore are less likely to break apart and contaminate the contact surface. Even if they break apart, Ru does not react readily with oxygen at room temperature unless exposed to oxygen plasma. Also, when closing a switch with Ru contacts, the contact area increases more slowly than for Au contacts, thereby having a weaker metal-metal adhesion force. Therefore, closing a Ru contact while storing it would prevent contamination from adsorbing onto the asperity surface. Whether the switch would reopen after the closure for days, months, or even years would then become the main concern.
References


[81] Phillips, "PM 6673 Universal Frequency Counter."

[82] M. S. D. Sheet, "Dodecane 99%."