Quasi electrical contact behaviors of metal micro-contacts for micro/nano-electromechanical systems (MEMS/NEMS)

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**Quasi Electrical Contact Behaviors of Metal Micro-
contacts for Micro/Nano-electromechanical Systems
(MEMS/NEMS)**

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2014

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Abstract

The electrical contact behavior of metal micro-contacts is of significant importance in various fields of science and engineering, and it has not yet been adequately understood compared to the bulk metal contacts. Specifically, in DC contact type of microelectromechanical (MEMS) or nanoelectromechanical (NEMS) devices, the metal contact is one of the most crucial parts, as it determines the device performance and is closely related to the reliability issues. In order to investigate the degradation mechanism of the metal contacts under different testing conditions, load cycling tests have been performed using MEMS switches. The micro-contact behavior during a single load test has also been intensively studied. The electrical contact resistance (R_c) as a key parameter was characterized and analyzed to understand the contact behavior.

In general, the relation between R_c and contact force F_c can be divided into three regions for a typical contact cycle. It starts from an unstable contact region (Region I) with drastic fluctuations of R_c , followed by a stable but gradual reduction of R_c in Region II and reaches a steady state with low R_c in Region III. A minimum contact force $F_{\min}$ is required to establish the stable electrical contact. When the contact force exceeds $F_{\min}$ (in Region II), the gradual reduction of R_c could be attributed to plastic deformation of surface asperities until the high force region (Region III), in which R_c is determined by film thickness effects on a macroscopic scale. The metal-to-metal contact behaviors have been widely studied by many different research groups. However, the unstable electrical contact behavior under low contact force (Region I) remains unexamined. In conventional MEMS switches, the

contact force is believed to be larger than $F_{\min}$ for most cases. Therefore, past studies of contact behavior mainly focused on the stable region, including the load cycling tests. On the other hand, there is an ongoing demand to scale down the MEMS components towards sub-micrometer and nanometer dimensions, in which the contact force could be drastically reduced. Therefore, it becomes necessary to look into the unstable contact region of metal micro-contacts.

In this thesis, the electrical contact instability is investigated. A nanoindentation stage was utilized for the contact tests under precisely controlled experiential conditions (various combinations of applied voltage, contact material, surface treatment, etc.). X-ray photoelectron spectroscopy (XPS) techniques were used to characterize the sample surface. The results reveal that the contamination film on the metal contact surface, which may originate from the residues of microfabrication process or absorption of air-borne species such as hydrocarbons and carbon dioxide, plays a critical role in determining the micro-contact behavior under low contact force. The rapid fluctuations of contact resistance in the unstable region could be explained under the framework of electron tunneling through the alien contamination film. The asperity deformation process, which was conventionally observed in the stable region, is also observed at the initial stage of contact formation.

To better understand the unstable contact behavior, the electrical conduction noise of DC contact type MEMS switches has been analyzed. In the power spectral density (PSD) curve of the electrical conduction noise, Lorentzian and $1/f^2$ components are clearly identified. The $1/f^2$ noise can be attributed to the inhomogeneous local conductivity of the thin gold film, while the Lorentzian spectrum is closely related to the electrical contact instability in the unstable contact

region. The contact voltage fluctuation shows a typical two-level RTS behavior with “on” and “off” states, which could be caused by the trapping and detrapping of electrons in the alien film. This is in good agreement with the Lorentzian component in the low frequency noise (LFN) spectrum. Moreover, the relaxation time extracted from the Lorentzian component is used to determine the trap density.

The electrical contact formation process between metal contacts with an alien film was further investigated in detail with statistical means. It is unveiled that the electrical conduction in the contamination film follows the weakest-link principle. The occurrence of the switching event (fluctuation between “on” and “off” states) has an independent character, till the generation of certain “weak” spots close to the end of the unstable region. The electrical contact formation process is found to be electrical field enhanced and sensitive to the thickness of the contamination film by Weibull analysis. A geometrical picture could be used to describe the breakdown of the insulating alien film, in which the stable electrical contact is eventually established by overlapping “weak” spots that form a percolation path between the micro-contacts. The results provide further insights into the contact formation process in the MEMS/NEMS devices.

In addition, a comparative contact study was conducted between Au-to-Au and Ru-to-Ru contacts, to investigate the effects of various stressing conditions on the quasi electrical contact behaviors. Time-to-stable contact formation t_{SCF} is shown to be an effective indicator of the surface conditions. It is found that Au-to-Au contact is relatively stable upon cycling under the force level of conventional MEMS switches, as the contamination film on the contact surface is rather persistent. On the other hand,

Ru-to-Ru contact is sensitive to the loading cycles as well as the applied voltage during cycling, which could be due to the partially filled *d*-band electron structures of Ru, and the surface chemical reactions related to localized joule heating at the contact spot. A new and effective *in situ* approach is demonstrated to study the degradation of metal contact surface during cycling, which is of great importance for the reliability of DC type of MEMS/NEMS devices.

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List of Acronyms

μTAS	Micrototal Analysis System
AES	Auger Electron Spectroscopy
AFM	Atomic Force Microscope
ATE	Automated Test Equipment
Bio-MEMS	Biomedical (or Biological) Microelectromechanical System
CAGR	Compound Annual Growth Rate
CMOS	Complementary Metal–Oxide–Semiconductor
DFT	Discrete Fourier Transform
FET	Field-Effect Transistor
FFT	Fast Fourier Transform
IC	Integrated Circuit
LFN	Low Frequency Noise
LIGA	Lithography Electroplating Moulding
LPCVD	Low Pressure Chemical Vapour Deposition
MEMS	Microelectromechanical System
NEMS	Nanoelectromechanical System
PIN	Positive-Intrinsic-Negative
Poly-Si	Polycrystalline Silicon
PSD	Power Spectral Density
RF	Radio Frequency
RF MEMS	Radio Frequency Microelectromechanical System
RMS	Root Mean Square

RTS	Random Telegraph Signal
TOF-SIMS	Time-of-Flight Secondary Ion Mass Spectroscopy
VCO	Voltage-Controlled Oscillator
VLSI	Very-Large-Scale Integration
XPS	X-ray Photoelectron Spectroscopy

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Chapter 1

Introduction

1.1 Miniaturization and MEMS – “Plenty of Room at the Bottom”

In 1959, Richard Feynman gave his famous “There’s plenty of room at the bottom” lecture at the annual meeting of the American Physical Society, in which he proposed the possibility of direct manipulation of individual atoms and fabrication of nanoscale machines. Several years later, this lecture became to be regarded as a seminal event for micro/nano-technology proponents. It inspired a few immediate works; for instance, William McLellan constructed a tiny yet operational motor using existing methods and tools within months and claimed the \$1000 award offered by Feynman. However, the technology to build submicron machines was not ready at that time. The field of microelectromechanical systems (MEMS) evolves from the integrated circuit (IC) industry, while development of the microfabrication technology is the key driving force behind. Several pioneering researchers started to transfer the process technology from integrated circuit to micromechanical devices from the mid-1960s, including cantilevers, membranes, etc. Since the 1980s, the rapidly maturing surface/bulk micromachining technologies have enabled the constructions of various types of MEMS devices, such as microrotary motors [1, 2], accelerometers [3, 4], gyroscopes [5], digital micromirrors (DMD) [6, 7] and so on.

Ever improving microfabrication process capabilities together with the advancing simulation and characterization techniques open up a wide range of MEMS applications in the past three decades. For example, optical MEMS components have been deployed in optical display, adaptive optics, tunable filters, network routers, etc. [8] Bio-MEMS could be integrated with minimally invasive medical devices for implants and surgical procedures [9, 10]. Microfluidics systems promise major changes in point-of-care medical diagnosis and distributed environmental monitoring [11, 12]. Meanwhile, MEMS switches have been drawing tremendous research interest as another important branch of MEMS technology. Compared to conventional positive-intrinsic-negative (PIN) diode and field-effect transistor (FET) based semiconductor switches, they provide better isolation, lower insertion loss, excellent linearity, and there is virtually no power consumption. These advantages make MEMS switches an attractive alternative in automated test equipment (ATE), telecommunication, remote sensing and radar systems.

Predicted, or in certain sense, driven by the Moore's Law, the down-scaling trend has been going for half a century [13]. Nanoelectromechanical system (NEMS) with characteristic dimensions between 1 nm and 100 nm were investigated in recent years, to explore the scaling possibilities of MEMS. NEMS components for radio frequency (RF) applications have been actively studied due to favorable scaling laws. NEMS resonators and filters with high frequency and high quality factor were fabricated using lithography patterned nanomechanical cantilevers [14-16]. In addition, NEMS switches were built in several research institutes for integration with CMOS logic and memory applications [17-19].

1.2 DC MEMS/NEMS Devices and the Metal Contacts

From MEMS/NEMS technology development to realization of its enormous commercial potential in those application areas, performance is an essential criterion but always not the only one. Since the first viable MEMS switch was introduced in 1991 at the Hughes Research Labs [20], intensive research efforts have been put into the reliability matters. The switch robustness was tested by cycling under various operation conditions that can be summarized into two categories, cold switching mode and hot switching mode. In cold switching mode, the DC current or RF signal is applied only when the switch is at “on” state, and removed before the switch is “off”; while in hot switching mode, the potential difference across the contacts exists continuously, regardless of the “on” and “off” states of the switch during operation. To meet the market demands, the cold and hot switching lifetimes have to be higher than 100 billion cycles and 100 million cycles accordingly. It was soon realized that the reliability of MEMS switches fell well short of the expectations. The longest lasting switch till 2008 survived around 10 billion cycles under cold switching condition.

To improve the lifetime of MEMS switches and the devices that incorporate MEMS switch structures such as phase shifters [21], tunable filters [22], reconfigurable antennas [23], etc., there have been attempts focusing on the structural design, process optimization, dynamic modeling, selection and characterization of beam and contact materials and so on. There are two kinds of MEMS switches in terms of contact type, the capacitive switch and the DC contact switch. In general, the mechanical failure (metal fatigue or fracture) could be avoided by well-designed

micromachined structure, and a number of MEMS switches (including both types) have been demonstrated to be free of mechanical failure around the anchors with maximum strain level up to 50 billion cycles [24]. The reliability of capacitive MEMS switch is mainly limited by the charge injection and charge trapping in the dielectric layer, which could be mitigated by different actuation schemes, such as bipolar actuation voltage and use of side pull-down electrodes, etc. [25-28] On the other hand, for the DC contact type of MEMS switch, it is closely related to the metal contact [28-30]. However, compared to the bulk metal contacts, the micro-contact behavior of miniaturized MEMS/NEMS switches remains not fully understood.

For micro-contacts, the surface roughness has to be taken into consideration. When two rough surfaces are brought close to each other, the outmost asperities start to interact and form contact. Various analytical and numerical methods have been applied to estimate the real contact area under a compressive force, following elastic, elastic-plastic or plastic asperity deformation models (Hertzian [31], Greenwood-Williamson [32], Chang-Etison-Bogy [33], etc.). With an applied bias voltage, the current is confined to flow through those interacting asperities. The electrical contact resistance is determined by different transport mechanisms (diffusive, ballistic, and quasi-ballistic), which are closely related to the radius of the contact spot [34]. Therefore, there have been substantial efforts to correlate the contact resistance with the contact load in the MEMS or microsystem community. These modeling works showed reasonable agreement with the experimental measurements over the force range of several hundred micronewtons and above. Under lower contact forces, the experimental results were widely scattered and could no longer match the predictions of the conventional models [35-37].

The discrepancies between modeling work and measurements at a low contact load could be associated with the contamination film on the metal contact surface. It is believed that there is an insulating film on gold and other noble contact materials (Pt, Ru, etc.), which could originate from several sources, including absorption of airborne organic molecules and residue of the microfabrication process, and the coverage is determined by the uniformity of the substrate and the ambient pressure in the proximity of the contact surface [38-41]. It has also been reported that this contamination layer is rather persistent. To alleviate the effects of the surface contamination, Jensen *et al.* used the “burn-in” process under a contact voltage of 2-3 mV to get the appropriate electrical contact resistance values [42], and Schimkat applied the “Schaltreinigung” procedure with bias voltage of 50 V and DC current of 50 mA in nitrogen [43]. However, for miniature MEMS and NEMS components, these methods can be destructive due to the high current or voltage level. Most of the time, the contact load and electrical current are ineffective to remove the contamination layer in normal operations of MEMS and NEMS switches.

1.3 Objectives

It is of paramount importance to understand the micro-contact behavior in the MEMS/NEMS components and devices, as the metal contact determines the performance (insertion loss in RF applications, signal to noise ratio in memory applications, etc.) and is closely related to the reliability matters. The purpose of this work is to have an in-depth investigation of the micro-contact behavior under the contact force level of miniature MEMS and NEMS in various aspects.

Although the instability of micro-contact behavior under a low contact load has been reported by a few researchers [28-30, 35-37], it was observed rather than studied. The mechanism behind the fluctuations of contact resistance remains unclear. The first objective of this research is to explore the physical origin of the contact instability and the role of the alien contamination film on the contact surface, by comparing the quasi electrical contact behaviors between two groups of samples that underwent different surface treatments. A nanoindentation stage was utilized for the contact tests under precisely controlled experimental conditions.

Noise in MEMS has also been drawing increasing research interest in the past decades, as the close coupling of electrical, mechanical, optical, thermal and other mechanisms raises a primary challenge in the simulation, design and optimization of MEMS devices [44-49]. However, the electrical conduction noise of DC contact MEMS/NEMS has not received much attention so far. Therefore, the second objective of this study is to analyze the noise components in the unstable contact region, and to discuss the physical mechanisms behind.

Due to the nondeterministic nature of the unstable contact behavior, as well as the difficulties in quantifying the properties of the alien insulating film on the contact surface, there is a knowledge gap in understanding the overall contact formation process in one contact cycle with increasing contact load [17, 28, 50]. The third objective is thus to examine the establishment of electrical contact from the initial unstable contact region to formation of stable contact.

Lastly, the load cycling tests have been extensively performed in the reliability studies of MEMS switches, to evaluate the lifetime under various conditions. The

contact performance during cycling tests was discussed in the stable contact region, using the electrical contact resistance as a primary indicator [21, 51-53]. Nevertheless, it will be interesting to see how the contact cycling affects the quasi electrical contact behaviors in the unstable region, which is the fourth objective of this research.

1.4 Thesis Outline

The work described in this thesis was motivated by the desire to better understand the micro-contact behaviors for micro/nano-electromechanical systems in various aspects. This thesis comprises 7 chapters, and chapter 3-6 cover the main contributions made. The organization of this thesis is as follows:

Chapter 1 serves as the introductory chapter, including a brief introduction of the background and objectives of this research work.

Chapter 2 presents an overview of the MEMS technology, followed by the fundamentals of MEMS switches, including fabrication techniques and processes, mechanical modeling as well electrical contact modeling. Several important contact issues such as selection of contact material, arcing and field evaporation, and contamination on the contact surface are reviewed.

Chapter 3 investigates the quasi electrical contact behaviors at the initialization stage of contact formation. Au-to-Au contact scheme is used a test vehicle. The results reveal that the alien contamination film on the contact surface plays an important role in determining the micro-contact behavior under low contact load. The mechanism

behind the instability of electrical contact resistance is explored under a framework of trap-assisted electron tunneling.

Chapter 4 analyzes the noise behavior of Au-to-Au micro-contact in the unstable contact region of MEMS/NEMS switches. Lorentzian and $1/f^2$ components are identified in the power spectral density (PSD) of the electrical conduction noise, and the physical mechanisms of both noise components are discussed.

Chapter 5 applies statistical means to further look into the establishment of electrical contact from unstable region to formation of stable contact. The impacts of electrical field and thickness of the contamination film are studied under a framework of Weibull distribution. The results suggest that the establishment of electrical contact is inherent to the dielectric breakdown of the thin alien contamination film, and triggered by overlapping of the electric stress induced defects that form a percolation path between the metal electrodes.

Chapter 6 is a comparative study on the effects of mechanical and hot switching stresses on quasi contact behaviors of Au-to-Au and Ru-to-Ru contacts. The results demonstrate a new and effective *in situ* approach to investigate the micro-contact surfaces under various cycling conditions from a microscopic point of view, which provides insight to understand the degradation of metal contact surface during operations of DC contact type MEMS/NEMS devices.

Finally, Chapter 7 concludes this thesis with a summary of the research work and achievements that have been accomplished, and recommendations for future research efforts.

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Chapter 2

Literature Review

2.1 Overview of MEMS Technology

MEMS, the abbreviation of microelectromechanical systems, refer to a collection of devices and systems with combined electrical and mechanical components that are created using the microfabrication techniques. The critical dimension of MEMS elements can vary from millimetres to sub microns, depending on particular designs and applications. The first batch-fabricated MEMS device (a resonant gate transistor) was produced by Nathanson and his colleagues at Westinghouse in 1967, and computational modelling played an important part in the development [1]. The invention of microprocessor in the early 1970s, which is not a technical contribution to MEMS itself, sparked interests in lithography processes that become crucial in microfabrication [2]. The first MEMS accelerometer was developed at Stanford University in 1979, and it continues to become the first commercial MEMS device [2]. Meanwhile, a micromachined sensor was fabricated at the IBM research laboratory, using bulk micromachining to make the thin silicon diaphragms [3]. In the 1980s, there were remarkable achievements in nanotechnology, for example, the development of the scanning tunnelling microprobe (STM) and atomic force microscope (AFM) in 1982 and 1986 respectively, which are powerful characterization tools and also can be used for manipulations of nano-structures. The Polycrystalline silicon (poly-Si) surface micromachining process was successfully developed at the University of California at Berkeley in 1984, leading to a boost in the

MEMS field [1]. Five years later, the first silicon microrotary motor driven by electrostatic forces was demonstrated, which was capable of rotating at a maximum speed of 500 rpm under a three-phase, 350 V driving voltage [4]. The MEMS field has entered a period of rapid and dynamic growth since the 1990s. MEMS research activities on various areas have been supported worldwide by both government and private funding agencies, and there have been fruitful results. Besides the commercialization of a few less integrated MEMS devices, such as ink-jet printer heads [5] and digital micromirrors [6, 7], the ideas and practicability of more complex MEMS components and devices have been proposed and demonstrated for a wide spectrum of application fields, including adaptive optics, tunable filter, biomedicine, microfluidics and so on [8-11].

The total market of MEMS has been expanding quickly since the last decade, and it is expected to maintain the strong growth in the 2010s as shown in Fig. 2.1 [12]. In several sectors, a mature and stable state is reached, for example, the ink-jet heads. On the other hand, there are some emerging “hot” sectors, driven by the demand of advanced sensing and actuating applications in sectors such as communication system and micrototal analysis system (μ TAS), etc. Figure 2.2 provides a zoom-in at the market of MEMS switches [13]. The mobile device is identified as a key driving portion, due to its strong demand for the tunable module, which is built from a switch multiplexer connected to inductors and capacitors.

Figure 2.1: MEMS market forecast values in US dollars (2012 – 2018), with a compound annual growth rate (CAGR) of ~ 13% [12].

Figure 2.2: Market forecast values of MEMS switches in US dollars (2012 – 2018) [13].

2.2 Fabrication of MEMS

Si micromachining has been the essential factor for the enormous progress of the MEMS field [14]. There are two types of Si micromachining technologies: bulk micromachining and surface micromachining. Bulk micromachining is a “subtractive” process that is used to etch MEMS structures into the bulk substrate, while surface micromachining is more like an “additive” process, which is used to construct MEMS structures from films and layers deposited onto the substrate. Beside micromachining, micromolding is another basic technology in MEMS fabrication. It uses electroplated materials to make MEMS devices with high aspect ratios [15].

2.2.1 Bulk Micromachining

In Si bulk micromachining process, a portion of the Si substrate is removed in order to create freestanding mechanical structures (e.g. beams and membranes), or unique three-dimensional features (e.g. cavities and mesas). There are two major categories of processes according to the medium of the etchants: wet etching and dry etching. Wet etching uses aqueous chemicals, and dry etching uses plasma (high-energy gas containing ionized radicals) or vapour-phase etchants for material removal.

The three-dimensional distribution of etch rates results in the surface profiles of microstructures. The etch rate of wet bulk etching may depend on crystal orientation, while the etch rate of dry bulk etching may depend on the directions in a wafer. Isotropic etching is defined when the etch rate is identical in all directions, as shown in Fig. 2.3. In anisotropic etching, the etch rate is orientation dependent.

Figure 2.3: Illustration of isotropic and anisotropic etching.

It should be noted that in both cases, etching action is not confined in the open areas of mask. Material removal in the lateral direction can occur underneath the masked areas, which is generally known as undercut. Undercut is more significant in isotropic etching. In certain circumstances, it is desired to create suspended structures, and in some other applications, it becomes undesirable and needs to be minimized by careful mask design and process control [16].

When applying bulk micromachining processes, several important issues should be considered, including etch rate, etch rate selectivity, processing temperature, etch uniformity across a wafer, sensitivity to over etch, safety and cost of etchants. Table 3.1 summarizes the relevant properties of some common etchants for bulk micromachining and related etching methods [14].

	EDP	Alkali-OH	TMAH	Gas Phase	Plasma Etch
Dry/Wet	Wet	Wet	Wet	Dry	Dry
Isotropic/ Anisotropic	Anisotropic	Anisotropic	Anisotropic	Isotropic	Anisotropic or Isotropic
Etch rate on Si <100> ($\mu\text{m}/\text{min}$)	0.3-1.25	0.5-1	0.3-1	1-10 per pulses/cycle	0.5-2.5
Etch rate on silicon nitride (nm/min)	Very low	Very low	1-10	Low	100-400
Etch rate on doped silicon	Low on highly doped Si	Low on highly doped Si	Low on highly doped Si	Not sensitive to doping	Not sensitive to doping
Etch rate on silicon oxide	Low	Low	Low	Very low	Low
Cost	Moderate	Low	Low to medium	Moderate to high	Moderate to high

Table 2.1: Properties of common bulk etching solution and methods [14]

2.2.2 Surface Micromachining

As the name suggests, surface micromachining process creates microstructures that reside near the surfaces of the substrate. Different from the bulk micromachining process, it doesn't involve removal or etching of bulky substrate materials. Moveable and functional microstructures are created layer by layer, using the substrate wafer as the mechanical support.

The key portion in surface micromachining is the deposition, patterning and etching of thin sacrificial layers. In ideal cases, the sacrificial material should provide a mechanically rigid and chemically reliable support for the structural layer. The etchants must have good selectivity and be able to etch off the sacrificial materials without affecting the structural layer. In addition, the etchants should have proper viscosity and surface tension characteristics, to facilitate the releasing process. A common set of compatible materials used in surface micromachining are poly-Si structural layers and silicon dioxide (SiO_2) sacrificial layers. All these layers are deposited by low pressure chemical vapour deposition (LPCVD). Hydrofluoric acid solution is used to dissolve SiO_2 with minimal effect on the poly-Si layer [16].

One prime advantage of the surface micromachining processes is the compatibility with integrated circuit (IC) fabrication. An increasing number of MEMS components and devices are made by surface micromachining processes in recent years, including various types of MEMS switches [17]. The process flow to fabricate a typical ohmic-contact type MEMS switch will be given in section 2.4.1.

2.2.3 Micromolding

In some applications, more complex and thick three-dimensional microstructures are required. Micromolding technologies have been developed to achieve high aspect ratio in 3D devices. LIGA, a German acronym for *Lithographie* (Lithography), *Galvanoformung* (Electroplating), *Abformung* (Moulding), is an example of such micromolding processes [16].

LIGA was developed in the 1980s, using X-ray lithography and electroplating to form micro-sized metallic parts or precision molds. A typical process flow is shown in Fig. 2.4 [18]. The major advantages of X-ray lithography are high intensity and excellent parallelism, and the disadvantages include high cost and difficulties in making X-ray mask. Poly-methyl methacrylate (PMMA) is the most common photoresist. It is coated on the substrate by casting or gluing, and the thickness can reach several hundred μm . To make the metal structures, both metal and alloy can be deposited by electroplating. The important issues include adhesion, residual stress and hydrogen bubble [16].

2.3 MEMS switches

A simple and common MEMS device is a MEMS switch. Since the demonstration of the first MEMS switch specially designed for microwave applications under the support of DARPA (Defense Advanced Research Projects Agency) in 1991 [19], MEMS switches have been drawing immense research interests and efforts in a broad range of applications. There have been successful examples of transition from prototypes to commercialized products, and the market is still

expanding as shown in Fig. 2.2. The MEMS switches provide attractive alternatives in military radars (e.g. electronically scanned array, circulator in TR modules), communication systems (e.g. adaptive filters, steering antennas), space applications (e.g. redundancy matrix, reflect array antennas) and so on [14, 20, 21].

Figure 2.4: A typical LIGA process in 3 steps, lithography, electroplating and molding [18].

2.3.1 Configurations of MEMS Switches

In a MEMS switch, there are basically two distinct parts: the mechanical section and the electrical section. The former is related to device actuation. There are several actuation mechanisms, including thermal, piezoelectric, electromagnetic, as well as electrostatic. The concerned issues on the actuation part are the attainable force, power consumption, reliability and ease of fabrication.

Thermal actuation relies upon the stress generated by thermal mismatch. It utilizes the property of thermal expansion to produce motion, which is caused by the current flow (joule heating) across the actuator. The strain ε developed from low temperature (T_0) to elevated temperature (T_1) due to the thermal mismatch is expressed by

$$\varepsilon = (\alpha_A - \alpha_B)\Delta T = (\alpha_A - \alpha_B)(T_0 - T_1), \quad (2.1)$$

where α_A and α_B are coefficients of thermal expansion of materials A and B respectively. Typically there is no deflection in the actuator at T_0 . However the thermal strain deforms or deflects the actuator at an elevated temperature of T_1 , if the heated actuator is not constrained and has certain degrees of freedom to expand. Thermal actuation scheme is able to provide sufficient force and displacement with appropriate designs. It has advantages of cheap implementation, VLSI compatibility and well established technology. On the other hand, the main drawback is the relatively low working frequency, which is determined by the rate of heat up and heat dissipation [22].

Piezoelectric actuation depends on piezoelectric crystals, which generate deformation of crystal in response to an applied voltage, and vice versa, produce electrical charge separation in response to an applied mechanical stress. The advantages are sufficient mechanical force and low power consumption. However, the piezoelectric actuation scheme needs correct microstructure, composition, crystallographic texture, and polarization or poling for optimum material performance and response. The actuation must work under Curie temperature (T_c), to avoid the minimal piezoelectric effect. The displacement is generally small, unless the actuator is in large size or stacked. Therefore, piezoelectric actuation scheme is not a popular choice in MEMS [22].

Electromagnetic actuation is a common actuation scheme used for macroscopic devices. The conventional magnetic actuator utilizes current-carrying coils to generate magnetic flux which is captured and guided to a movable plate, inducing the magnetic force in a magnetic material to actuate the movable plate, as shown in Fig. 2.5 [23]. In the design of actuator, materials with high magnetic permeability are required, to minimize the magnetic reluctance. Electromagnetic scheme has the advantages of low actuation voltage and large actuation force available. The problem with magnetic actuator is that the coils are typically two-dimensional and limited in three-dimensional due to the difficulty of fabrication. The choice of magnetic materials is also limited, as the electromagnetic actuation is prone to high power consumption and heat dissipation [14, 22].

Electrostatic actuation is the most prevalent scheme for MEMS devices. The electrodes of typical MEMS switches can be seen as a parallel plate capacitor. When an actuation voltage is applied across the electrodes, an electrostatic force is induced

on the movable structure. The advantages of electrostatic actuation scheme are virtually zero power consumption, small electrode size, general simplicity, and relatively low cost. However, in most cases, it requires an actuation voltage of 30-80 V, and the use of CMOS upconverters becomes necessary [17]. To date, only electrostatic actuated MEMS switches have demonstrated operations for a frequency band of DC-100 GHz with a lifetime of more than 100 million cycles. A typical MEMS switch with electrostatic actuation scheme is reviewed in section 2.4.

Figure 2.5: Illustration of a magnetic actuator [23].

For the electrical section, a MEMS switch can be either in series or shunt configurations. In the series configuration, the switch is placed between the signal line and ground, and in the shunt configuration, it is placed between two transmission lines to switch the signal path. In terms of contact type, there are two kinds of MEMS switches: the metal-to-metal (DC) contact switch and the capacitive switch. DC

contact switches are often used as series switches, while capacitive switches are used as shunt switches in most cases. The signal is conducted through the metal contacts in DC contact switch, and the applicable signal frequency ranges from DC to 60 GHz [20]. For capacitive switches, the contact is made between metal and dielectric material. The capacitance modulation during operation leads to the variation of signal impedance. Switching between “on” and “off” state is thus realized. In “on” state, the signal is transmitted, and it is shorted to ground in “off” state. The applicable frequency ranges from 10 to 120 GHz [20]. In our work, we focus on the contact behavior of DC contact MEMS switches.

2.3.2 Comparison of PIN, FET and MEMS switches

Performance comparison among PIN, FET and MEMS switches is shown in Table 2.2 [20]. MEMS switches outperform semiconductor switches in several areas, such as power consumption, on-state resistance (insertion loss), cutoff frequency and isolation. The actuation voltage, switching time and power handling capabilities are the limitations of MEMS switches.

Parameter	PIN	FET	MEMS
Voltage (V)	± 3 -5	3-5	30-80
Current (mA)	3-20	0	0
Switching time	1-100 ns	1-100 ns	1-300 μ s
Power Consumption (mW)	5-100	0.05-0.1	0
On-state series resistance (Ω)	2-4	4-6	0.5-2
Insertion loss (dB)	0.7-2	>2	0.1-0.2
Cut-off frequency (THz)	1-4	0.5-2	20-80
Isolation	Medium	Low	High
Power handling (W)	<10	<10	<1

Table 2.2: Performance comparison of PIN diode, FETs and RF MEMS switches [20].

2.4 A typical DC Contact MEMS Switch

In this section, we use a classical MEMS switch with cantilever beam structure as an example, to review the fabrication process of typical DC contact MEMS switches, and the key concepts in mechanical modelling of MEMS devices. The inline switch was developed by McGruer and Zavracky at Northeastern University in 1999 [24]. It demonstrated superior RF performance, with an actuation voltage between 60 and 80 V. The isolation is -40 dB at 4 GHz and -27 dB at 20 GHz. The insertion loss is -0.15 dB from 0.1 to 20 GHz.

2.4.1 Fabrication Procedure

The fabrication procedure of the abovementioned MEMS switch is shown in Fig. 2.6 [24]. A gold layer is deposited on the adhesion layer, to define the transmission line and the bottom actuation electrode. A sacrificial layer (Cu) of 1 μm is then deposited. The tip region is defined by a partial etch for electrical contact, followed by performing a complete etch to define the anchor region. The contact dimple made of a refractory material is then deposited on the partial etched region. The suspended cantilever beam and transmission lines are electroplated, with a thickness of 7 to 9 μm . It is released by using wet etching techniques to remove the copper sacrificial layer. In this design, the mechanical structure is very rigid, resulting in a high actuation voltage (60 – 80 V).

Figure 2.6: The fabrication procedure of the Northeastern University inline DC contact MEMS switch [24].

2.4.2 Mechanical Modeling

2.4.2.1 Actuation Voltage

As mentioned in section 2.3.1, for MEMS switches using electrostatic actuation scheme, the electrodes can be treated as two parallel plates (Fig. 2.7). The bottom electrode is fixed in this case, and the upper electrode is the cantilever beam. Given the area of the bottom electrode is A , the capacitance of the parallel plates is

$$C = \frac{\varepsilon_0 A}{g}, \quad (2.2)$$

where ε_0 is the permittivity, and g is height of the beam above the bottom electrode. The initial gap between the up and bottom electrode is g_0 . When an actuation voltage is applied, there will be an induced attractive force between the parallel plates, and the cantilever beam (upper electrode) will be pulled down towards the bottom electrode. Meanwhile, the stored energy of the capacitor increases due to an increase in the capacitance. Therefore, we have

$$\frac{V^2}{2} dC = F_e dg, \quad (2.3)$$

where dC and dg are the changes in capacitance and beam height, respectively, F_e is the electrostatic force and V is the actuation voltage applied. F_e can be expressed as

$$F_e = \frac{1}{2} V^2 \frac{dC}{dg} = -\frac{1}{2} \frac{\varepsilon_0 A V^2}{g^2}. \quad (2.4)$$

Figure 2.7: Illustration of the parallel plates (electrodes) for a typical MEMS switch using electrostatic actuation scheme.

On the other hand, there is a mechanical force F_m acting on the cantilever in the opposite direction of the electrostatic force F_e , which is known as mechanical restoring force. It is caused by the structure stiffness, and can be written as

$$F_m = k\Delta g = k(g_0 - g), \quad (2.5)$$

where k is the spring constant of the beam structure. When the cantilever is in equilibrium state, i.e., $F_e + F_m = 0$, the voltage is found to be

$$V = \sqrt{\frac{2k}{\epsilon_0 A} g^2 (g_0 - g)}, \quad (2.6)$$

The “pull-in” distance d_{pi} can be defined as the deflection of the upper plate when the electrostatic force overcomes the mechanical restoring force, and then contact dimple on the beam is brought into contact with the bottom contact [20]. By taking the derivative with respect to g of Equation (2.6) and setting it to zero, the pull-in distance is found to be $\frac{g_0}{3}$. Substituting this value back into Equation (2.6), the “pull-in” voltage can be expressed as

$$V_{pi} = \sqrt{\frac{8k}{27\epsilon_0 A} g_0^3}, \quad (2.7)$$

which is the minimum voltage required to actuate the switch.

2.4.2.2 Spring Constant

To obtain the spring constant k , the cantilever beam model was developed by Euler – Bernoulli beam bending theory and the principle of superposition [25]. In

addition, it was assumed that the beam is flat and not curled due to residual stresses during fabrication. Before “pull-in”, the cantilever is illustrated in Fig. 2.8(a), with a fixed end at $x = 0$, a free end at $x = l$, and an intermediately placed load F_a . F_a is modelled as point source located above the centre of the actuation electrode. The spring constant is estimated to be

$$k = \frac{Ewt^3}{2a^2(3l-a)}, \quad (2.8)$$

where E is the elastic modulus, w , t and l are the width, thickness and length of the beam, respectively, and a is the load position.

Figure 2.8: (a) Cantilever model with a fixed end at $x = 0$, a free end at $x = l$, and an intermediately placed load F_a ; (b) Improved beam model taking the anchor part into consideration [26].

Coutu *et al.* came out with an improved beam model as a follow-up on the modeling work of Meng *et al.* [27], as shown in Fig. 2.8(b) [26]. It takes the anchor into consideration, which is fixed to the substrate and has a straight edge. The modified spring constant is

$$k_m = \frac{Ewt^3}{2(1-\nu^2)a^2[-L^3 + 3aL^2 + (L-a)^3 + 6aLl]}, \quad (2.9)$$

where E is the elastic modulus, w , t and L are the width, thickness and length of the beam, respectively, a is the load position, ν is Poisson's ratio, and l is the height of the anchor.

2.4.2.3 Contact Force

In DC contact MEMS switches, the contact force F_c is the compressive force that deforms the contact material to form electrical contact at “on” state. In general, F_c is quite small for switches using electrostatic actuation scheme, and a voltage higher than V_{pi} is always applied to increase F_c and therefore reduce the contact resistance. When the actuation voltage is increased, there is an extra bending on the cantilever. Figure 2.9 shows the beam condition after “pull-in”, with a fixed end at $x = 0$, an intermediately placed load F_a at $x = a$, and a supported end at $x = l$. The reaction force at the supported end is the contact force F_c and the load F_a (at $x = a$) is the electrostatic force. Derivation of the contact force can be realized by using the static equilibrium equations ($\sum F_x = 0$, $\sum F_y = 0$, $\sum M = 0$) [28] and the superposition

principle. Calculation of the analytical form can be more complicated when the beam deflection, deformation of contact material and the anchor part are taken into account.

Figure 2.9: Cantilever model with a fixed end at $x = 0$, an intermediately placed load F_a at $x = a$, and a supported end at $x = l$ [29].

To better solve the contact force, commercial software with integrated mechanical or electromechanical packages such as ConventorWare [30], Corning Intellisense [31] and MEMSCAP [32] have been applied. The flow of numerical computation is shown in Fig. 2.10. The accuracy is dependent on the knowledge of residual stress on the beam due to fabrication processes. In general, the contact force is about 30 to 60 percent of the electrostatic force. The remaining part of F_a contribute to the beam flexure and the reaction force at the beam anchor [20].

Downscaling of MEMS switches benefit in multiple ways, including increased frequency, reduced power consumption, increased integration density & functionality and reduced batch fabrication cost. On the other hand, reduced contact force could become a bottleneck. A factor of α decrease in linear dimension will decrease the electrostatic force by a factor of α^2 [2]. The electrical contact performance can be comprised due to the drastically reduced contact force upon scaling.

Figure 2.10: Flow chart of the numerical computation for mechanical modeling of MEMS devices.

2.5 Electrical Contact Modeling

The electrical contact is the most important part in a DC contact MEMS switch. It determines the switch performance and is closely related to the reliability issues. In this section, the deformation models, electron transport modes and electrical contact resistance models are reviewed.

2.5.1 Material Deformation Models

Despite the improving microfabrication techniques, the surface of contact materials is never really flat and smooth. The real (actual) contact area is always much smaller than the apparent contact area in micro-devices. In the early studies, Hertzian theory was implemented to simulate the contact area between two interacting bodies, based on an assumption of pure elastic deformation [33]. In a follow-up work of Holm, a completely plastic deformation model was employed, as the stress at certain local contact sites could be much higher than the overall stress [34]. The contact resistance was resolved by using normal contact force and material hardness. Holm's model has been widely accepted by the researchers in the field of electrical contact. For cases where plastically deformed contact parts are encapsulated in elastically deformed material, the Chang, Etison and Bogy (CEB) elastic-plastic model was introduced in 1987 [35]. These models provide the fundamental models for the contact study, and they can still be referred to in the electrical contact modeling of MEMS switches. Details of elastic, plastic and elastic-plastic models are given as below.

For elastic deformation of a single surface asperity, the contact area A and normal contact force F_{cE} are defined as functions of vertical asperity deformation in Equations (2.10) and (2.11) accordingly [33],

$$A = \pi R \alpha \quad (2.10)$$

$$F_{\text{cE}} = \frac{4}{3} E' \alpha \sqrt{R \alpha} \quad (2.11)$$

where R is the curvature peak radius, α is the vertical deformation of asperity, and E' is the Hertzian modulus. To derive the Hertzian modulus, Equation (2.12) can be used:

$$\frac{1}{E'} = \frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}, \quad (2.12)$$

where E_1 and E_2 are the elastic modulus for contact one and two, ν_1 and ν_2 are the Poisson's ratio for contact one and two. For a circular contact area, the radius of the contact area can be obtained through Equations (2.10) and (2.11), with

$$r = \sqrt[3]{\frac{3F_{cE}R}{4E'}}. \quad (2.13)$$

For plastic deformation, Abbott and Firestone's model is used, assuming sufficiently large contact load and no material creep [36]. The contact area A and normal contact force F_{cp} are defined in Equations (2.14) and (2.15):

$$A = 2\pi R\alpha \quad (2.14)$$

$$F_{cp} = HA \quad (2.15)$$

where H is the hardness of the softer material. And the contact radius r can be expressed as

$$r = \sqrt{\frac{F_{cp}}{\pi H}}. \quad (2.16)$$

For the transition stage between elastic and plastic deformations, the asperity contact area A and normal contact force F_{cEP} are defined in the CEB model by

$$A = \pi R \alpha \left(2 - \frac{\alpha_c}{\alpha}\right) \quad (2.17)$$

$$F_{\text{cEP}} = K_H A \quad (2.18)$$

where α_c is the critical vertical deformation when the elastic-plastic behavior starts and K_H is the hardness coefficient [35]. α_c and K_H are given as

$$\alpha_c = R \left(\frac{K_H H \pi}{2E'} \right)^2 \quad (2.19)$$

$$K_H = 0.454 + 0.41\nu \quad (2.20)$$

This CEB model was further improved by Chang, with a new force equation based on the observation that the ideal plastic deformation normally begins at $3Y$ [37]:

$$F_{\text{cEP}} = \left[3 + \left(\frac{2}{3} K_Y - 3 \right) \frac{\alpha_c}{\alpha} \right] YA \quad (2.21)$$

$$K_Y = 1.1282 + 1.158\nu \quad (2.22)$$

$$Y = 0.354H. \quad (2.23)$$

where K_Y is the yield coefficient and Y is the yield strength. The radius of the circular contact area in the updated CEB model is therefore

$$r = \sqrt{\frac{F_{\text{cEP}}}{\pi H \left[1.062 + 0.354 \left(\frac{2}{3} K_Y - 3 \right) \left(\frac{\alpha_c}{\alpha} \right) \right]}} \quad (2.24)$$

In MEMS switches, the contact force is determined by the switch design and the applied voltage, while the contact area is determined by surface topography, material hardness, as well as the elastic modulus [38]. There have been two types of contact area models developed: (I) the single asperity model and (II) the multi-asperities model [36, 39]. The individual local electrical contact spots are assumed to be close to each other in the single asperity model, and the effective contact area is thus defined as the sum of each local contact spot (instead of the parallel combination). The multi-asperities model is based on the following assumptions: (a) no interaction between the surface asperities; (b) randomly distributed asperity height; (c) the same radius of curvature for the asperity peaks; and (d) isotropic contact surface [39]. Normally the single asperity model is used to predict the upper bound of contact resistance, and the lower bound is predicted by the multi-asperities model [40]. For a conventional MEMS switch, the contact resistance is usually measured when certain surface asperities are plastically deformed to form stable electrical contact.

2.5.2 Electron Transport Modes and Contact Resistance Model

Electrical transport in a conductor can be described as ballistic, quasi-ballistic and diffusive, depending on the radius of effective contact area (r) and the electron mean free path (λ) [41]. For most metals, λ is around 50 nm. Ballistic transport takes place when $r \ll \lambda$, diffusive transport takes place when $r \gg \lambda$, and quasi-ballistic transport takes place when r is comparable to λ . The constriction resistance at the contact asperity is described as [42]

$$R_c = f\left(\frac{\lambda}{r}\right)R_M + R_s = \frac{1+0.83\left(\frac{\lambda}{r}\right)}{1+1.33\left(\frac{\lambda}{r}\right)} \frac{\rho}{2r} + \frac{4\rho\lambda}{3\pi a^2}, \quad (2.25)$$

where ρ is the electrical resistivity of the contact material. R_M is the Maxwell resistance due to lattice scattering and R_s is the Sharvin resistance due to boundary scattering. The Maxwell term dominates the overall contact resistance in the diffusive electron transport region, and the Sharvin term dominates in the ballistic transport region as the electrons are projected through the conductor without lattice scattering. The term $\frac{\lambda}{r}$ is known as the Knudsen number (K) in Wexler's Gamma function, which is shown in Fig. 2.11 [43]. The maximum value of $f(K)$ is 1 in the diffusive transport region, and the minimum value is 0.624 in the ballistic transport region.

In the contact modeling work of MEMS contact, surface microscopy techniques such as optical profilometry, stylus profilometry and atomic force microscopy (AFM) have been applied by several research groups to obtain the topographical data. Dickrell *et al.* proposed a voxel surface model with the measured device surface topography, to further predict the shape of the contact area [44]. Rezvanian *et al.* used the roughness data (acquired from AFM) to construct an accurate surface representation by fractal geometry, and the asperity deformation process was analysed as a function time [45]. Kogut *et al.* derived a contact model based on fractal geometry surface topography description, elastic-plastic deformation of surface asperities and size-dependent electron transport mode [46]. In general, those modeling work showed reasonable agreement with the experimental measurement data, for a contact force in the region of hundreds micronewtons or

higher. However, when the contact force is scaled down in miniature MEMS or NEMS components, the validity of those contact models is comprised.

Figure 2.11: A plot of Wexler’s Gamma function with respect to the Knudsen number [43].

2.6 Electrical Contact Issues

2.6.1 Contact Materials

Silver and silver alloys have been the most widely used contact materials in macroscopic relays and switches, due to its highest electrical conductivity among all metals, as well superior mechanical properties. On the other hand, silver and its alloys tarnish when exposed to water or air. There is usually a sulfide layer on the surface which is nonconductive [34]. It is not really a problem in macro-relays or switches, as the applied contact force (N range) is sufficient to penetrate or break the

nonconductive sulfide layer in most cases. However, it can be real obstacle in micro-switches. The contact forces of MEMS switches (μN range or even lower in NEMS) are usually well short of penetrating or breaking the surface layer of silver and its alloys to form good electrical contact. Therefore, they are no longer acceptable as contact materials for micro-switches.

On the other hand, gold to gold electric contact has been typically used in MEMS switches due to its low electric resistivity, and resistance to surface oxide [20, 47-49]. The low hardness of gold, however, leads to adhesion problems in MEMS switches. Adhesion of contacts during repetitive cycling could eventually lead to device failure such that the switch is stuck closed at “on” state [50]. Nevertheless, the knowledge gained from macro-switches can be transferred to micro-switches, for example, gold alloys with nickel, palladium or platinum elements are able to increase the material hardness effectively, while the trade-off is higher resistance [51]. Schimkat studied Au-Ni alloy (Au-(5%)Ni) contacts, and suggested that Au-Ni alloys could be useful in micro-switches [52]. Coutu *et al.* presented a guideline for selection of metal alloys by utilizing the equilibrium binary alloy phase diagrams [51]. The phase diagram for Au-Ni alloys is shown in Fig. 2.12 [53]. Single-phase alloys are preferred as the crystal structures of the metal alloys do not change physically with increased temperature; while miscibility gaps should be avoided to ensure reliable deposition of contact alloys during fabrication, and removal of the intermetallic compounds (brittle and highly resistive), which may be formed inadvertently. Binary alloys Au-(6.3%)Pt and Au-(3.7%)Pd displayed enhanced cycling lifetime with small increase in the electrical contact resistance [51]. Yang *et al.* carried out an in-depth

study of Au-Ni alloys, and found that a two phase Au-(20%Ni) could improve the contact performance significantly [54].

Figure 2.12: Equilibrium binary alloy phase diagram for gold-nickel alloys [53].

Besides gold alloys, platinum group metals have also been widely studied due to their increased hardness (compared to gold) and stable electrical properties [21, 55]. To keep the contact resistance at an acceptable level, Majumder *et al.* employed a contact scheme with multiple parallel contacts [56], and Duffy *et al.* applied an actuation voltage higher than 80 V [55].

2.6.2 Arcing and Field Evaporation

The metal phase arc has been considered as a possible cause of the drastic fluctuations of contact resistance in several reports [57, 58]. Studies of arcing can be traced back to the early 20th century, when the electrical relays and switches were

developed [34]. For the electrical contacts in medium or high power circuits, vaporization of contact material takes place due to arcing at a high current level, and then the violently produced vapor ‘blows’ out drops of liquid metal from the contact. Consequently, there is directionless material transfer between the electrodes, which is dominated by field induced current heating. Directional material transfer can be observed at lower power level, due to different material transfer mechanisms. MEMS switches are generally used for low power applications, and metal phase arc is made possible by the small device dimensions and surface roughness, even below the transient voltage level defined by Paschen’s law [59]. Localized joule heating could melt or even evaporate the contact material in the constricted contact area. Strong electric field due to the narrow separation between electrodes may cause emission of electrons (from the cathode), which excite and ionize the metal atoms stepwise. The ionized metal atoms are then transferred towards the cathode following the direction of the electric field. This arcing process is sustained by cathodic electron emission [60]. To date, the minimum reported arc current and voltage for gold contacts are 0.35 A and 12.42 V respectively [61].

Yang *et al.* revealed that field evaporation could be another mechanism for the contact resistance fluctuation and degradation under “non-arc” test conditions [61, 62]. The gold contacts were characterized by an atomic force microscope (AFM). Experimental results showed that transfer of gold contact material occurred under a minimum voltage of 3 V and current of 1 mA, which is far below the voltage and current required for metal phase arcing. The directionality of material transfer further supported field evaporation as the mechanism behind the contact instability.

2.6.3 Surface Contamination

Contamination layer on the surface of metal contact material has been frequently mentioned in the contact studies of micro-switches, as a plausible cause of the discrepancies between proposed contact models and experimental measurement results under low contact load [40, 63, 64]. However, its role in formation of stable electrical contact is not well understood, nor has been studied in depth. The composition of the contamination layer is dependent on the contact material, fabrication process as well as the ambient conditions. For DC contact MEMS switches, gold has been a popular choice. Although it is resistant to oxidation, an insulating film of a few angstroms to a few tens angstroms has been constantly identified on the gold surface. Patton and Zabinski used Auger electron spectroscopy (AES) to analyse the surface of freshly cleaned gold samples, and the spectrum is shown in Fig. 2.13 [47]. Besides gold peaks, carbon and oxygen peaks were observed due to surface contamination.

Tringe *et al.* used time-of-flight secondary ion mass spectroscopy (TOF-SIMS) and X-ray photoelectron spectroscopy (XPS) to compare surface conditions of gold contact before and after ozone treatment [65]. The same contaminant species (carbon and oxygen) were found on the fresh samples. The alien contamination layer could be due to absorption of air-borne species such as carbon dioxide, or the fabrication processes during sample preparation. Surface contamination of platinum group contact materials (platinum, rhodium and ruthenium) was also studied, and a notable work was presented by Chen *et al* [66, 67]. It was found that platinum group materials have higher surface contamination rates than gold, which could be due to their partially

filled *d*-band electron structures and greater surface reactivity associated with their catalytic nature [68, 69]. Therefore, they suggested that MEMS switches with platinum group contact materials were prone to contamination failure compared to those with gold contacts.

Figure 2.13: Auger electron spectrum of a freshly cleaned Au sample. Carbon and oxygen contaminant species are identified [47].

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Chapter 3

Quasi Contact Behaviors of Au-to-Au Micro-contact under Low Contact Force

3.1 Introduction

Radio Frequency Microelectromechanical (RF MEMS) switches have been drawing a lot of research interest in the past two decades, due to their several advantages such as high isolation, low insertion loss, zero power consumption and high linearity [1]. RF MEMS devices can offer attractive alternatives in switching networks, portable wireless systems, phased arrays and so on [2]. On the other hand, the reliability of RF MEMS switches is a major concern for long term applications. There have been a number of reports in this area, including both experimental measurements [3–6] and computational simulations [7,8]. Generally, for capacitive switches, the lifetime is affected by the charging effects in the dielectric layer, and for DC contact type of MEMS switches, the reliability is limited by the metal contacts.

Compared to bulk metals, the microscopic contact behavior remains an important yet not fully understood topic. In micro-contacts, surface morphology has to be taken into consideration. The reliability and RF performance are closely related to the physical contact made between the prominent asperities at the contact surfaces. Load cycling tests have been performed for RF MEMS switches [3, 9–12], to investigate the degradation mechanism of the metal contacts under different testing conditions. Meanwhile, the behavior of microscopic contacts during a single load test

has been intensively studied, with the electrical contact resistance R_c as an important parameter to understand the contact behavior [13–16]. It was found that the relation between R_c and contact force can be divided into three regions, as shown in Fig. 3.1.

Figure 3.1: Schematic plot of contact resistance R_c versus contact force during contact making. Region I: unstable region; Region II: gradual reduction of R_c ; Region III: negligible reduction of R_c .

A typical contact cycle starts from an unstable contact region (Region I) with a drastic fluctuation of the electrical contact resistance R_c , followed by a stable but gradual reduction of R_c in Region II. Finally, it reaches a steady state with small R_c in Region III. A minimum contact force F_{min} is required to establish the stable electrical contact. F_{min} of 10 to 50 μN were reported in the literature for soft Au-to-Au contacts [13–15]. When the contact force exceeds F_{min} (Region II), the gradual reduction of R_c could be attributed to plastic deformation of surface asperities until the high force region (Region III), in which R_c is determined by film thickness effects on a

macroscopic scale [14]. However, to the best of our knowledge, the quasi electrical contact behavior under low contact force (Region I) remains unexamined.

In conventional RF MEMS switches, the contact force during operation ranges from tens to hundreds μN for Au-to-Au contacts [13, 17], which is larger than $F_{\min}$ in most cases. For MEMS switches not using Au-to-Au contacts, the contact force is significantly higher (e.g., OMRON's switch with 5 mN per contact [18]). For RF applications, it is important to have a stable and low contact resistance. Therefore, past studies of contact behavior mainly focused on the stable region, including the load cycling tests. There is an increasing demand to scale down the MEMS components towards sub-micrometer dimensions for various applications such as NEMS logic gates and memories [19, 20]. As a result, the contact force is drastically reduced to a value even smaller than 1 μN [2, 19], which is far below the $F_{\min}$ reported in references [13] and [14] for Au-to-Au contacts. As a result, it is necessary to look into the unstable electrical contact behavior in the low contact force region.

On the other hand, for a stable metal-to-metal contact, it has been reported that the contact behavior is affected by the existence of an insulating alien film on the surface [9, 11, 12]. However, its role during the early stage of contact making has not been investigated due to the absence of characterization work [15]. Hermetic packaging is widely used to minimize the influence of the environment and improve reliability. The purpose of this work is to examine the unstable contact behavior of Au-to-Au micro/nano-contacts under low contact force, since Au has been considered as an important candidate for contact material in MEMS DC switches due to its low electric resistivity and resistance to surface oxidization. X-ray photoelectron spectroscopy (XPS) techniques are used for the analysis of the sample surfaces. The

mechanism behind the instability of electrical contact resistance is discussed under a framework of trap-assisted tunneling. It should be pointed out that the main objective of this work is to identify the critical role of the alien film on the contact surface in determining the contact behavior under low contact force. The Au-to-Au contact is used as a test vehicle for the study.

3.2 Experiments

A devised nanoindentation platform was applied to perform the experiments in this work (see Fig. 3.2). The setup is built on an active optical table (T48W, Nexus, Newton, NJ, United States), to isolate the testing system from vertical and horizontal vibrations. The piezo-actuator is the key part in this configuration, which converts an electrical signal into a precisely controlled physical displacement. It is connected with a PC workstation, and used to produce smooth and continuous vertical motion within a range of a few nanometers repeatedly. The contact part uses a “ball-on-flat” configuration. The tip of the piezo-actuator is brought into contact with the sample placed on the X-Y stage during contact making; meanwhile, the changes in contact voltage *versus* loading time are captured by a digital storage oscilloscope (PicoScope 2204, Pico Technology, Cambridgeshire, United Kingdom), with a maximum sampling frequency of 100 MHz. Coaxial cables with Bayonet Neill–Concelman (BNC) connectors are used for the connections, to minimize the delay time and avoid any possible electrical interference. Similar systems could be found in the literature for contact tests [14, 15, 21]. Fine control of the ball position with the piezo-actuator allows the tests to be performed under low contact force with high accuracy and repeatability.

environment for one complete lithography cycle using AZ photoresist (AZ 1518) before the contact tests, to mimic the surface condition of gold contact after microfabrication. AZ 1518 of 1.5 μm thickness was spun on the sample followed by prebake at 100 °C for 60 s on a hotplate. After that, the samples underwent standard ultraviolet (UV) exposure and hotplate postbake (115 °C for 60 s). The photoresist was finally removed by acetone before the samples were loaded into the system for contact testing.

A large number of contact tests were performed under precisely controlled operational conditions. The tip displacement velocity of the piezo-actuator was fixed at (10 ± 0.9) nm/s, and the applied contact voltage varied from 80 to 300 mV. On the other hand, we took one sample from each group right before the contact tests, to study the contact surfaces by X-ray photoelectron spectroscopy (Quantera SXM system, ULVAC-PHI, Chigasaki, Japan). The chemical composition of the sample surface was revealed in the wide scan spectra. The variation of the atomic composition with film depth was obtained by XPS depth profiling techniques. The film surface was bombarded with Argon ions at controlled power, and the composition was analyzed after every 6 s of the bombarded erosion.

3.3 Results and Discussion

3.3.1 Quasi Contact Behavior during Contact Making

In general, the test results show similar behavior as reported in references [14, 15]. A typical curve of contact voltage *versus* loading time for samples in Group B is shown in Fig. 3.3(a).

Figure 3.3: (a) Contact voltage and contact force as functions of time for a typical Au-to-Au contact in Group B; (b) Zoom-in from 4.88 to 4.92 s, shows a typical two level random telegraph signal (RTS).

The contact voltage V_c was measured between the gold coated ball tip of the piezo-actuator and the sample surface. In this case, the applied voltage was 95 mV. Fast fluctuations of V_c were captured by the oscilloscope from 1.06 to 6.94 s, before

formation of stable electrical contact with V_c less than 5 mV. Figure 3.3(b) zooms in on the time-axis from 4.88 to 4.92 s during the transition period. The switching behavior is similar to a two level random telegraph signal (RTS), which fluctuates between “on” and “off” states. At “on” state, there is current flow between the ball tip and sample surface, and the electrical contact is open at “off” state.

Meanwhile, it is interesting to note that, during the fast voltage fluctuations in the unstable region, a decrease in “on” state contact voltage can be observed. It indicates a reduction of electrical contact resistance R_c . The calculated “on” state R_c in the unstable region is shown in Fig. 3.4, and it drops from around 30 to 1 Ω . In addition, we found that the electrical contact resistance at the “on” state could be well fitted using a relation $R_c \sim t^{-n}$ with $n \approx 0.5$. Since the relation between the contact force and tip displacement is almost linear after initial contact and the tip displacement velocity is fixed, therefore, $R_c \sim F_c^{-0.5}$ is expected. This strongly suggests that the plastic deformation of the asperities, which was observed in the beginning of the stable contact (Region II) by Kwon *et al.* [14], could start from the very early stage of the contact process even in the unstable region. In this case, the contact force at the beginning of unstable region is ~ 250 nN, and the minimum contact force required to reach the stable region is ~ 18 μ N. The contact force at the transition point from elastic to plastic deformation for a single asperity was calculated to be around 100 nN by Majumder *et al.* [3], and our result is in good agreement with this value.

Figure 3.4: Contact resistance *versus* loading time. A relation of $R_c \propto t^{-0.5}$ is illustrated by the solid line for reference.

For the “fresh” samples in Group A, a typical curve of contact voltage *versus* loading time is shown in Fig. 3.5. Similar to Group B, instability of electrical contact was observed in the low contact force region. In this case, the switching behavior lasts for about 0.8 s, which is remarkably shorter, compared to those samples underwent lithography process. The contact forces at the starting and ending points of the transition region are ~ 500 nN and ~ 4 μ N respectively.

Figure 3.5: Contact voltage and contact force as functions of time for a typical Au-to-Au contact in Group A.

The distributions of the durations of the unstable region for both groups A and B under two applied voltage levels are shown in Fig. 3.6. Experimental data of 20 independent loading tests are used for each probability plot. It can be seen that samples exposed for one lithography cycle (Group B) have much longer transition periods than those “fresh” samples (Group A). This clearly indicates that the contact behavior at the initial contact stage could be strongly related to the surface contamination during the fabrication process. Moreover, the duration of unstable region is largely affected by the applied contact voltage. A higher V_c results in a much shorter unstable region. Total annihilation of the fluctuations was observed for V_c beyond 250 mV during the contact tests. This suggests that fast switching behavior in the unstable region should be associated with the mechanisms related to electrical conduction. The possibility of pure mechanical deformation such as contact bouncing

or other external vibrations, which are irrelevant to electrical bias, can be ruled out. In the past, sudden and stochastic changes in the contact resistance profile are often attributed to arcing or field evaporation in switch applications [21]. However, a minimum current of 350 mA and a minimum voltage of 12.5 V are required for arcing to happen, and for field evaporation the reported minimum current and voltage are 1 mA and 3-4 V respectively [10, 21], which are far beyond the currents (< 0.5 mA) and contact voltages (< 300 mV) in our experiments.

Figure 3.6: Probability plot of the duration of the unstable region based on 20 independent tests for four combinations of testing conditions (Group A, $V_c = 95$ and 150 mV; Group B, $V_c = 95$ and 150 mV).

3.3.2 XPS Analysis of Contact Surfaces

To validate the presence of the alien contamination layer at contact surfaces, selected samples from each group were characterized by XPS techniques, which measure the elemental composition at the parts per thousand range, empirical formula, chemical state and electronic state of the elements that exist within a material. XPS spectra are obtained by irradiating a material with a beam of X-rays while simultaneously measuring the kinetic energy and number of electrons that escape from the top 0 to 10 nm of the material being analyzed in high vacuum or ultra-high vacuum conditions. It is found that the sample, which underwent one cycle of lithography process, shows a much thicker alien layer with stronger signal intensities for O, N and C. As shown Fig. 3.7, there are three peaks centered at 543.1, 410 and 284.2 eV for the samples, which could be assigned to O 1s, N 1s and C 1s, respectively. This layer could be due to the polymer residues induced by the fabrication process or absorption of air-born species [17, 21, 22]. For the sample from Group B with photoresist residues, stronger O 1s, N 1s and C 1s signals are identified than the case of Group A. The spectrum of the sample after plasma cleaning is also shown in the figure as a reference.

Figure 3.7: XPS spectra of the samples taken from Group A, Group B and after surface plasma treatment. Alien films containing O, N and C are identified for both samples.

The results of depth profiling using XPS are shown in Fig. 3.8. The percentages of atomic concentrations of C and Au are plotted *versus* sputtering time. The etch rate of polymer (photoresist) is estimated to be 2 nm/min. Using Au percentage of 80% as a reference, the thickness of the alien film is around 0.4 and 2 nm for the sample from Group A and Group B, respectively. The sample exposed after a complete lithography cycle has a thicker alien layer, which is consistent with the stronger O 1s, N 1s and C 1s signals of the XPS spectra in Fig. 3.7.

Figure 3.8: XPS depth profiling (a) sample from Group A; (b) sample from Group B.

3.3.3 Mechanism of Contact Resistance Fluctuation

Due to the existence of an alien film on the contact surface, the electrical contact may remain non-metallic at the initial contact stage at low contact force. Stable electrical contact only forms when the insulating contamination layer is eventually penetrated mechanically or broken down under current or heat. In the

unstable region, electrical conduction can be attributed to tunneling process through the alien films, and traps located at the contact interface may play a very important role in determining the charge transport. The on-off behavior can be explained by the charge trapping and detrapping processes as illustrated in the inset of Fig. 3.9. The “on” state occurs when there are conduction between the Au electrodes due to the electrons tunneling through the insulating layer via the electron traps at the contact interface. Once the traps are occupied, the electrical conductance switches to the “off” state.

To further investigate the fast switching behavior in the unstable region, time intervals of each “off” state were statistically analyzed for Group B. Fig. 3.9 shows a typical histogram of the time intervals extracted from a contact voltage *versus* loading time curve. It can be seen that there is a distinct peak with time constant of approximately 1.1 ms, which could be associated with the trapping and detrapping processes of electrons from the traps located at the contact interface. Considering electron capturing and releasing at these interface traps, the time constant (τ) under a small electric field can be estimated by [23]:

$$\tau(x) = \tau_0 \exp\left(\frac{4\pi\sqrt{2m_t^*E_t}}{\hbar} x\right) \quad (3.1)$$

where τ_0 is the charge transferring characteristic time, m_t^* is the electron tunneling effective mass, E_t is the trap energy with respect to the conduction band edge, $\hbar$ is Planck’s constant, and x is the trapped charge position. Using $\tau_0 = 10^{-13}$ s [24–26], $m_t^* = 0.4m_0$, $\hbar = 6.625 \times 10^{-34}$ J·s, $x = 2$ nm, the corresponding trap energy level at the contact interface is 3.16 eV. If the traps are the mid-band traps located at the center of

bandgap, a bandgap of around 6.3 eV for the alien layer will be expected. This is in good agreement with the typical bandgap of the polymers used for microfabrication process such as photoresist and polyimide. [27, 28]

Figure 3.9: A typical histogram of the time intervals for “off” state for a sample measured at 95 mV. Inset shows the energy band diagram of the Au/Insulator/Au structure. Electrons tunnel through the traps located at the contact interface between the alien films.

3.4 Summary

The instability of electrical contact behavior in low contact force region has been investigated and analyzed experimentally for Au-to-Au micro/nano-contacts. XPS techniques were applied to characterize the contact surface. The results reveal that the alien film plays an important role in determining the unstable behavior at

initial contact stage. This is clearly evidenced by the presence of a remarkable transition region on the samples exposed to photoresist, which leads to a much thicker alien contamination layer. The RTS observed in the unstable region can be explained under a framework of trap-assisted electron tunneling through the alien film.

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Chapter 4

Low Frequency Noise in the Unstable Contact Region of Au-to-Au Micro-contact

4.1 Noise in MEMS

Rapid development of microfabrication technology opens up the possibilities for MEMS devices to be utilized in a wide range of application areas, including optical MEMS, Bio-MEMS, RF MEMS, microfluidics system, and so on [1]. On the other hand, noise is well known to be the performance limiting factor in engineering systems. Before the down-scaling trend swept the electrical and electronic industry, the influence of intrinsic device noise was trivial, as the unwanted disturbances were generally dominated by extrinsic sources [2]. However, when it comes to the era of micro-system, the balance between intrinsic and extrinsic noises has been modified. The discrete and statistical nature of the energies and motions are no longer negligible due to the miniaturization [3, 4]. The intrinsic noise is of equal or even more importance in determining the device performance. For instance, the limit of detection (LOD) and minimum required input signals are set by intrinsic noise levels for sensors and actuators nowadays [3].

The major extrinsic noise sources of MEMS include the electromagnetic waves and mechanical motions, which could be affected by device packaging [5]. Meanwhile, the intrinsic noise of various MEMS devices has been drawing a lot of research attention. Coupling of electrical, mechanical, optical and other mechanisms

raises a primary challenge in the design, modeling and optimization of MEMS. The interaction of noise energy with an extremely small mass in miniaturized MEMS or NEMS could cause distortions that comprise the system performance. Gabrielson studied the mechanical-thermal noise in MEMS sensors, and used Nyquist's relation to model the spectral density of the fluctuating force related to the mechanical resistance [6]. Mechanical-thermal noise was characterized together with electrical sources such as shot noise and flicker noise in a follow-up study by Djuric, to calculate the performance limitation of accelerometers, sensing probe cantilevers and thermal infrared detectors [7]. Vig and Kim suggested that at submicron dimensions, the applications of ultra-small resonators were likely to be limited by the thermal noise, the frequency noise due to temperature fluctuations and adsorption/desorption [8]. In RF MEMS devices such as switch-based phase shifter, resonator and voltage-controlled oscillator (VCO), the effects of Brownian, electrical-thermal, and mechanical-thermal noise were investigated, which resulted in both amplitude and phase noises [9-11].

However, the electrical contact noise of DC contact MEMS/NEMS components has not received much attention so far, which could be another important noise source contributing to degradation of device performance in several applications including switches and logical gates. In chapter 3, we have studied the quasi contact behavior of Au-to-Au micro-contact in the unstable region under a framework of trap-assisted tunneling, and such contact instability could result in low frequency noise (LFN) in MEMS devices. Scaling down of MEMS components to sub-micrometer and nanometer region makes them more susceptible to unstable contact behaviors, due to the drastically reduced contact force [12-14]. In this chapter, Fourier transform is used

to convert the time domain measurement results under low contact load to the frequency domain. The low frequency noise (LFN) of the Au-to-Au micro-contact of MEMS switches is investigated. Lorentzian and $1/f^2$ components are identified in the power spectral density (PSD) of the electrical conduction noise. The mechanisms of the noise components are further analyzed. The results show that the trapping-detrapping process of electrons at the contact interface could be an intrinsic noise source in DC contact MEMS/NEMS components.

4.2 Fourier Transform and Spectral Analysis

The Fourier transform has long been used systematically in the fields of computational sciences, physical sciences and engineering. For a signal $x(t)$, which is not required to be periodic or time-limited either, the frequency domain contents of $x(t)$ can be defined by its Fourier transform [15]

$$X(f) = \int_{-\infty}^{\infty} x(t)e^{-j2\pi ft} dt, \quad (4.1)$$

where the independent variable f represents the continuously varying frequency, and the frequency domain is the entire real axis. In the real world, the signals are only available as a sequence of samples collected at equally spaced intervals. In other words, the input function in the time domain is finite and discrete. Therefore, the discrete Fourier transform (DFT) is used to perform Fourier analysis in many practical applications [16]. In DFT, a sequence of N real or complex numbers $x[0], x[1], \dots, x[N-1]$ is transformed into an N -periodic sequence of complex numbers:

$$X[k] = \sum_{n=0}^{N-1} e^{-i\frac{2\pi}{N}nk} x[n], \quad (4.2)$$

where $k = 0, 1, \dots, N-1$. Each $X[k]$ encodes the phase and amplitude of a sinusoidal component of $x[n]$. The sinusoid's frequency is k/N cycles per sample.

When the DFT is used for spectral analysis, the $x[n]$ sequence usually represents a finite set of evenly spaced samples of some signal $x(t)$ in the time domain. Converting the continuous time signal to discrete time samples could cause a type of distortion called aliasing, when the sampling rate is lower than the Nyquist rate determined by the signal bandwidth [16]. In addition, the conversion of signal from an infinite (or extremely long) sequence to a practicable size could entail leakage distortion that reduces the resolution of DFT [15]. Therefore, choosing an appropriate sampling rate as well as a reasonable sequence length is important in suppressing distortions for DFT.

The DFT can be implemented by numerical algorithms using computational software. To evaluate the standard DFT defined in Equation (4.2), $O(N^2)$ operations are required, as there are N $X[k]$ in the output, and each output requires a summation of N terms. In the last century, mathematicians have exploited symmetries and redundancies in the DFT to decrease the number of computations needed [17, 18]. Such algorithms are collectively known as fast Fourier transforms (FFT). The well-known radix-2 Cooley–Tukey algorithm reduces the complexity to $O(N \log_2 N)$, if N is an integral power of 2. In some computer programs, zero padding strategy is applied to input exactly 2^n samples (by appending zeros to the input data so that the data length is extended to the next power of 2).

In this work, we use computational software for conversion of the measurement results in the unstable region from time domain to frequency domain. Sample groups A and B were prepared in the same way as described in Chapter 3. Group B was tested after one complete lithography cycle, and Group A was treated as the “fresh” reference group. The computation of discrete Fourier transformation (DFT) is performed by an executor that includes multiple C code blocks from the software library FFTW. Cooley-Turkey FFT algorithm is implemented in these blocks to reduce the process time. The power spectral density is computed using the auto-correlation function of the input signal. A sampling period of 2×10^{-5} s is determined by the digital storage oscilloscope in the experimental setup, and a rectangular window is chosen to suppress the distortion.

4.3 Physical Origin of the Low Frequency Noise under Low Contact Load

Figure 4.1(a) shows a typical power spectral density (PSD) of the contact voltage (V_c) fluctuations as a function of frequency from a sample in Group B. The corresponding time domain signal is shown in Fig. 4.1(b) for reference. If the contact noise is due to the current tunneling and carrier trapping and detrapping in the insulating alien layer, the spectral noise density should be in the form of Lorentzian type [19]. The Lorentzian type spectrum associated with trapping and detrapping in dielectrics can be expressed as

$$\frac{S_N}{N^2} = \frac{S_I}{I^2} = \frac{S_V}{V^2} = K \frac{4\tau_p}{1 + (2\pi f \tau_p)^2} \quad (4.3)$$

Figure 4.1: (a) Power spectral density (PSD) of the conduction noise in the unstable region for Au-to-Au contacts measured from a typical sample of Group B. The experimental data is fitted by superimposing $1/f^2$ and Lorentzian components (dashed lines); (b) The corresponding measurement result in time domain.

where τ_p is the relaxation time in the correlation function, with $1/\tau_p = 1/\tau_t + 1/\tau_d$. τ_t and τ_d are average trapping and detrapping times, respectively. N is the total number of free charge carriers. For the electron trapping-detrapping process at a single active trap energy which is evidenced by the two-level RTS behavior shown in Fig. 3.3(b), K can be expressed as

$$K = \frac{1}{N^2} \frac{\tau_p}{\tau_t + \tau_d}. \quad (4.4)$$

As to the carrier trapping and detrapping process, the ratio between τ_t and τ_d can be written as [20]

$$\frac{\tau_t}{\tau_d} = g \exp\left(\frac{E_T - E_F}{kT}\right), \quad (4.5)$$

where g is the degeneracy factor and usually considered as unity for electrons, E_T is the trap energy, E_F is the Fermi level, T is the absolute temperature and k is the Boltzmann constant.

For the electron tunneling through the alien layer via the mid-gap traps, we would expect a small discrepancy between E_T and E_F , and thus similar values of the average trapping and detrapping time from Equation (4.5). Therefore, substituting $\tau_t = \tau_d = 2\tau_p$ into Equations (4.3) and (4.4), we have

$$\frac{S_V}{V^2} = \frac{1}{N^2} \frac{1}{1 + (2\pi f \tau_p)^2}. \quad (4.6)$$

Indeed, the PSD of the contact voltage noise in Fig. 4.1(a) for Group B samples can be well fitted by superimposing a Lorentzian noise component in conjunction with a $\frac{1}{f^2}$ noise. The $\frac{1}{f^2}$ noise can be attributed to the resistance fluctuation of the contact metal, as a result of inhomogeneous local conductivity [19].

A typical PSD of the reference group (Group A) is shown in Fig. 4.2(a), and the corresponding signal in time domain is shown in Fig. 4.2(b). Despite the remarkable difference in the duration of unstable region in time domain, which is due to the variance in thickness of the alien film, the contact noise in the frequency domain can still be seen as the superposition of Lorentzian and $\frac{1}{f^2}$ noise components.

For the samples of Group A and Group B in Figs. 4.1 and 4.2, the number of carriers (N) and the relaxation time (τ_p) can be extracted based on the experimental data with the aforementioned two noise components. This allows us to estimate trap density (n_t) at the contact interface with the radius of effective contact area a , which can be determined from the electrical contact resistance R_c at the ending point of the unstable region as a first order approximation [21, 22]. Using electron mean free path of 38 nm in Au and electrical contact resistivity of $3.6 \times 10^{-8} \Omega \cdot \text{m}$ [23], the relaxation time (τ_p) and the trap density (n_t) at the contact interface are obtained to be 0.2 ms, $2.9 \times 10^{19}/\text{cm}^3$ and 0.5 ms, $3.6 \times 10^{19}/\text{cm}^3$ for Group A and Group B, respectively. These extracted parameters are tabulated in Table 4.1 for easy reference.

Figure 4.2: (a) Power spectral density (PSD) of the conduction noise in the unstable region for Au-to-Au contacts measured from a typical sample of Group A (reference group). The experimental data is fitted by superimposing $1/f^2$ and Lorentzian components (dashed lines); (b) The corresponding measurement result in time domain.

	thickness of contamination layer (nm)	relaxation time (τ_p) (ms)	trap density (n_t) (/cm ³)
Group A (Reference group)	0.4	0.2	2.9×10^{19}
Group B (After one lithography cycle)	2	0.5	3.6×10^{19}

Table 4.1: Extracted parameters (relaxation time and trap density) of Group A and Group B based on fitting of noise components.

The reduced relaxation time for the sample from Group A (reference group) implies a faster trapping-detrapping process, which could be due to the thinner alien film on the contact surface. The trap density values agree well with the previous experimental measurements of the trap density in polymers used for microfabrication process, which ranges from 2×10^{19} to $7 \times 10^{19}/\text{cm}^3$ [6, 24, 25].

4.4 Summary

In summary, the Fourier transformation has been applied in order to characterize and analyze the electrical conduction noise of Au-to-Au micro-contact in the unstable contact region. Fundamental knowledge is gained on the quasi contact stage under low contact load. A Lorentzian type low frequency noise component, which could be associated with the electron trapping and detrapping in the alien layer located at the contact interface, is identified and investigated. The results provide further insights to properties of the alien contamination layers that are widely presented at metal contact surfaces in MEMS devices.

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Chapter 5

Analysis of the Electrical Contact Formation Process with Statistical Means

5.1 Modeling of Electrical Contact Resistance

The contact resistance is the most important and universal characteristic of all electrical contacts. The classical bulk contact resistance was demonstrated by two cylinders in contact at their bases, with the base used as the contact area [1]. It is clearly not valid for micro-contacts, as no matter how the contact surfaces appear to be identical, they are completely different from a microscopic point of view. No surface is perfectly smooth, and when two rough surfaces are brought close to each other, the outermost asperities (known as "a-spots") meet and form the real contact area.

Substantial work has been done on the theory and modeling of micro-contact resistance [1-3]. In general, the constriction resistance of two conductive rough surfaces at the "a-spots" could be modeled in two steps by assuming negligible contamination on the electrical contact's surface. The first step was to determine the effective contact area as a function of contact force under elastic, elastic-plastic and plastic deformation models [3-5], followed by determining the contact resistance based on the sizes of the effective contact areas in ballistic, quasi-ballistic or diffusive electron transport regions [6-8]. Those modeling work showed reasonable agreement with the experimental measurements over the interested force range (100-200 μN) for

conventional MEMS switches. However, the contamination on the contact surface could be one source of the anomalies [2, 3].

5.2 A Knowledge Gap in Understanding the Electrical Contact Formation

The downscaling trend of MEMS components towards the dimensions of sub-micrometers and nanometers could drastically reduce the contact force to the range from less than 1 μN to around 50 μN [9, 10]. In such a low force region, electrical contact instability has been constantly observed in micro-contact tests [11-13]. In Chapter 3, we have experimentally investigated the quasi contact behavior, and found that the surface contamination plays an important role in determining the contact behavior for DC MEMS switches [14]. “Burn-in” process under a contact voltage of 2-3 V or the “Schaltreinigung” procedure (pre-switching with 50 V dc, 50 mA in nitrogen) was often applied to mitigate the effects of the surface contamination film and obtain appropriate resistance values [15, 16]; however, those methods can be destructive to miniature MEMS switches due to the high voltage and current level. Therefore, it becomes necessary to take the surface contamination into consideration when looking into the micro-contact resistance. Tunneling effect between the metal electrodes separated by the thin insulating film was discussed in Chapter 3 and 4, as a plausible origin of resistance instability at the initial contact stage under low contact force. However, there is still a knowledge gap in understanding the overall electrical contact formation process from the initial unstable contact behavior to the establishment of stable contact in one contact cycle. This is due to the

nondeterministic nature of the unstable contact behavior, as well as the difficulties in quantifying the properties of the contamination film.

In this chapter, the evolution of the electrical contact behavior is investigated in detail with statistical means. Au-to-Au contact is used as a test vehicle and two groups of samples are prepared. Same as the previous chapters, Group A is the reference group while samples Group B are exposed in the MEMS fabrication environment for one complete lithography cycle to mimic the surface condition of Au after microfabrication. The results reveal the overall picture of electrical contact formation process between two conductive surfaces separated by an insulating contamination film, and provide valuable insights into the unstable behavior of micro-contacts for DC switches in low force region.

5.3 Poisson Analysis in the Unstable Region

Similar to the quasi contact tests described in Chapter 3, the experiment is performed under precisely controlled operational conditions, with tip displacement velocity of 10 ± 0.9 nm/s and applied voltage between 80 and 300 mV. A typical curve of contact voltage *versus* loading time for samples in Group B is shown in Fig. 5.1(a). The contact voltage V_c was measured between the gold coated ball tip of the piezo-actuator and the sample surface. The applied voltage was 95 mV. An unstable contact region with fast fluctuations of V_c can be clearly observed, before formation of stable electrical contact. The duration of the unstable region (t_{unstable}) is about 6.84 s. Details of the voltage fluctuation during the transition are shown in Fig. 5.1(b) for easy reference. The two-level random telegraph signal (RTS) fluctuating between “on” and “off”

states has been discussed under the framework of trap-assisted tunneling process in the contamination film in the previous chapters.

Figure 5.1: (a) Contact voltage *versus* loading time for a typical Au-to-Au contact formation process in Group B; (b) A close-up from 4.62 to 4.64 s, showing a two-level fluctuating signal between “on” and “off” states.

With the presence of the alien hydrocarbon at the metal surface, it is generally believed that the insulating alien layer needs to be broken before the stable electrical contact can be formed. Although it has been found that the contact behavior in the unstable region is dominated by the electric related mechanism [14], a microscopic picture for the contact formation in this region remains unclear. In order to better elucidate the evolution of the electrical contact and understand the process of contact formation in the initial unstable region, the transition region was re-examined under four continuous and overlapping time periods (Frames I, II, III, and IV), as shown in Fig. 5.1(a). Each time frame lasted for 2 s. The number of voltage fluctuations (N_f) from “off” state to “on” state was extracted from the experimental data of Fig. 5.1(a). By performing hypothesis tests using MATLAB, we found that N_f follows a Poisson distribution in the first three time frames at a confidence level of 95%; while in the last time frame, the distribution of N_f becomes non-Poisson. A Poisson distribution can be represented by

$$P_k = \exp(-\lambda) \frac{\lambda^k}{k!}, \quad (5.1)$$

where P_k is the probability that k events take place during a time interval t , λ is the mean number of events per interval. Multiplying $k!$ and taking the logarithm at both sides of Eq. (1) gives

$$\ln(P_k \times k!) = k \times \ln \lambda - \lambda. \quad (5.2)$$

In Fig. 5.2, $\ln(P_k \times k!)$ is plotted as a function of k . It is shown that the experimental data can be well fitted by a straight line for the first three time frames in Figs. 5.2(a),

5.2(b), and 5.2(c), respectively. Furthermore, the slope and the y-intercept of the fitted line are logarithmically correlated. On the other hand, the relation between $\ln(P_k \times k!)$ and k is no longer linear for the last time frame, as shown in Fig. 5.2(d). These fitting results fully corroborate the outcome of the hypothesis tests. The distribution of the switching events from “off” state to “on” state evolves from Poisson to non-Poisson during the transition region.

(Figure continued on the next page)

Figure 5.2: Statistical distribution of voltage fluctuations (“off” state to “on” state) with a time interval $t = 40$ ms for 4 continuous and overlapping time periods in the transition region, (a) Time Frame I; (b) Time Frame II; (c) Time Frame III; (d) Time Frame IV.

The Poisson distribution is widely applicable in diverse experimental situations, to describe the occurrences of a random event. Therefore, the switching events from “off” to “on” state in the first three time frames are statistically independent, implying that electrical conduction does not keep memory of the switching history [17]. In other words, the conductive spot in a switching event N_1 exerts no influence on the consecutive switching event N_2 , which could occur at any other possible spot as shown in Fig. 5.3(a). This agrees with the trap-assisted tunneling model, assuming that those traps are distributed randomly in the contamination film between the metal electrodes [14]. However, the switching events start to become dependent in the late stage (Frame IV), suggesting that electrical conduction tends to take place at certain “weak” spots, which degrade faster than the others, as shown in Fig. 5.3(b). The electrical breakdown of the contamination film at the end of unstable region could be caused by accumulation of the conductive “weak” spots that eventually lead to the formation of defect-assisted path. This entire process is consistent with the generally accepted weakest-link scenario of dielectric breakdown [18], in which a number of independent and potentially conductive spots compete to develop a conduction path under stress.

Figure 5.3: Schematic plot of the switching events (a) in the first three time frames, switching event N_1 and the consecutive event N_2 are independent; (b) in the last time frame, successive switching events (N_1, N_2, N_3, N_4 and N_5) tend to occur at the degraded “weak” spot.

5.4 Weibull Analysis

The Weibull analysis was performed to further understand the contact formation process, which has been a useful tool to describe the statistics of typical weakest-link behaviors in various research areas, such as the reliability study of the gate oxide in field-effect transistors (FETs) [19, 20]. In this case, we use time-to-stable contact formation t_{SCF} to represent the electrical stress time before stable electrical contact in one contact cycle, and its cumulative distribution function (CDF) can be described by the following equation:

$$F(t_{\text{SCF}}) = 1 - \exp\left[-\left(\frac{t_{\text{SCF}}}{\tau}\right)^\beta\right], \quad (5.3)$$

where τ is the characteristic time constant, denoting the time-to-stable contact formation at approximately the 63rd percentile, and β is the Weibull shape factor. For the benefit of visually assessing the fit of data, Equation (5.3) may be rewritten as

$$\ln\{-\ln[1 - F(t_{\text{SCF}})]\} = \beta \ln(t_{\text{SCF}}) - \beta \ln(\tau). \quad (5.4)$$

The term on the left side has been defined as a Weibit W in the literature [20], where $W = \ln\{-\ln[1 - F(t_{\text{SCF}})]\}$. Plotting W versus $\ln(t_{\text{SCF}})$ yields a straight line in the Weibull model, which is also known as Weibull plot. Figure 5.4(a) shows the Weibull plot of the typical experimental results for Group B. Four sets of data were extracted from 20 independent loading tests under different applied voltage levels (90, 120, 150, and 180 mV). The reference lines are the least-square fit of each data set.

Figure 5.4: (a) The Weibull distributions of stress time before stable contact formation for 20 independent loading tests under different applied voltage levels in Group B. The electric fields in this case are simply taken to be applied voltage divided by the thickness of the insulating film. (b) Exponential fit of the characteristic time constant *versus* electric field.

It is interesting to note that the values of the Weibull shape factor β are very close to each other. Meanwhile, the characteristic time constant τ to form a firm contact is 11.40, 7.13, 4.29, and 2.56 s, respectively. It clearly suggests that the τ is related to the electric field E in the alien hydrocarbon layer, and the time required to achieve stable electrical contact (t_{SCF}) reduces with increasing electric field. Figure 5.4(b) shows the characteristic time constant τ *versus* the electric field E . The exponential dependence of τ on E is in good agreement with the $1/E$ model, which was first proposed by McPherson and Baglee to analyze the acceleration factors for the electrical stress of thin silicon oxide based on the generalized Eyring equation [21]. Despite that the physics behind the dielectric breakdown phenomena could differ due to the disparate insulating material properties and molecular nature of the "weak" spots, the role of the electric field may still be described quantitatively under the framework of $1/E$ model in this case. We can at least conclude that the contact formation process is significantly field enhanced.

The Weibull plot of the typical experimental results for Group A is shown in Fig. 5.5. The data were extracted from 20 independent loading tests under three different applied voltage levels (90, 120, and 150 mV). Similar to Group B, the Weibull shape factor β is insensitive to the applied voltage; instead, it appears to be closely related to the thickness of the contamination film (T). In the analytical models of dielectric breakdown statistics, the conductive "weak" spots are represented by defective cubic structures with a lattice constant (a_i) as shown in Fig. 5.6.

Figure 5.5: The Weibull distributions of stress time before stable contact formation for 20 independent loading tests under different applied voltage levels in Group A.

Figure 5.6: Schematic plot of the defects and breakdown triggering condition (formation of a percolation path by defective cells).

Following the weakest-link principle, dielectric breakdown can be assumed to take place when a percolation path is formed by n defective cubic cells aligning in one column, with $T = n \times a_i$ [18]. To better describe the relation between the thickness of the contamination film and the Weibull model, it is necessary to introduce an interface equivalent thickness T_{int} as an adhoc concept, and a shape parameter α for the “weak” spot [22, 23]. As a result, the Weibull shape factor is

$$\beta = \alpha \frac{T_{\text{int}} + T}{a_i} \quad (5.5)$$

Here, we use a sphere based cell model as a first order approximation, with α of 0.56 [22]. β and T obtained from the testing results for Group B and Group A are $\sim 2, 4$ nm and $\sim 0.9, 0.8$ nm, respectively. Note that the β is larger than 1 for Group B, but slightly smaller than 1 for Group A. The values of a_i and T_{int} can then be estimated by solving Equation (5.5), which are 1.6 nm and 1.8 nm, respectively. In this simplified geometrical model, the formation of an electrical conduction path through the contamination film is inherent to the electrical breakdown process in a dielectric, which is triggered by overlapping spherical defective cells with a radius of 1.6 nm between the Au contacts. The reduction of β with decreasing T could be due to the decrease of the critical number of defective cells required to establish a percolation path [23]. In addition, the Weibull shape factor is an important indicator of the types of failures in the studies of dielectric breakdown [18]. A β smaller than 1 for the Weibull plot of Group A suggests intrinsic breakdown caused by the native defects, which often occurs for ultra-thin insulating film [20]; while $\beta > 1$ for Group B suggests extrinsic breakdown, which could be attributed to the defects generation

under high electric field stress, leads to the formation of percolation path in the alien hydrocarbon layer and thus low contact resistance metal-to-metal contact.

5.5 Summary

In summary, the evolution of the electrical contact behavior during contact formation has been investigated with statistical means. The results reveal that the electrical conduction in the contamination film follows the weakest-link principle. The occurrence of the switching behavior (fluctuation between “on” and “off” states) has a statistically independent nature, till the generation of certain “weak” spots at the end of the unstable region. The electrical contact formation process is found to be electrical field enhanced and sensitive to the thickness of the contamination film based on Weibull analysis. A geometrical picture could be established to interpret the breakdown of the alien contamination film at the metal surface, in which the stable electrical contact is eventually established by overlapping “weak” spots that form a percolation path between the gold micro-contacts.

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Chapter 6

Effect of Mechanical and Hot Switching Stresses on Quasi Contact Behaviors of Au-to-Au and Ru-to-Ru Contacts

6.1 Introduction

As mentioned in the previous chapters, micro-contact is the key part of DC MEMS switches, and understanding of the contact behavior is crucial in the design and optimization of reliable MEMS devices. Load contact cycling tests have been performed extensively to evaluate the lifetime of MEMS switches under various testing conditions, such as pure mechanical cycling and hot switching [1-6]. For hot switching, the contacts are opened and closed with a bias voltage applied, so that there is an additional current effect during cycling. In general, two types of contact failures, the mechanical failure and the resistive failure are defined. The mechanical failure is typically related to the stiction of micro-contacts, when the restoring force is not enough to break the electrical contact at the “off” state, rather than the fatigue or fracture of the micromachined structure. For the resistive failure, even though there is no specific definition, Rebeiz described it as an electrical contact resistance R_c greater than $5\ \Omega$ for radio frequency (RF) applications, which leads to an insertion loss of -0.5 dB [1]. Nevertheless, both mechanical and resistive failures were discussed in the stable contact region, and it will be interesting to see how the contact cycling affects the contact behavior in the transition region.

For cycling studies in the literatures, electrical contact resistance R_c has been used as the primary indicator of the cycling effects [1-6]. Despite the valuable observations and comparisons that focus on evaluating appropriate contact materials for MEMS switches, the contact degradation has been noted rather than studied in depth. This is due to the challenges in characterizing the micro-contact surfaces [7]. Traditional microscopy techniques are incapable of *in situ* micro-contact characterization of MEMS switches, and inspection of the micro-contact surfaces can only be accomplished by destructive means. In addition, the contact forces in typical MEMS switches are approximately three orders of magnitude smaller than the classical definition of micro-contact force, which is on the order of a hundred mN. Therefore, the real contact only takes place at the prominent asperities, and the contact spot size is estimated to be comparable to the electron mean free path [8, 9]. The extremely localized contact area could substantially comprise the validity of the characterization work.

Based on the statistical means and the percolation model discussed in Chapter 5, here we explore the feasibility of quasi-static tests as an alternative means to study the changes of micro-contact surface conditions under cycling in this chapter. Besides R_c , time-to-stable contact formation t_{SCF} is introduced as another parameter to investigate the effects of pure mechanical switching and hot switching in the framework of Weibull analysis. In addition to Au-to-Au contact scheme, Ru-to-Ru contact scheme is also evaluated. Ru has been considered as a promising alternative material for micro/nano switches due to its higher hardness and melting point than Au, which could mitigate the stiction problem (mechanical failure) in Au micro-contacts. However, Ru-to-Ru contact is more prone to resistive problems. Aside from its

relatively higher resistivity than Au, the surface reactivity of Pt-group materials is another major concern [1, 10-12]. So far, it is unclear how the surface contamination of Ru affects the contact behavior at the initial stage of contact formation. In this chapter, a comparative study on the effects of mechanical and hot switching stresses on quasi contact behaviors of Au-to-Au and Ru-to-Ru contacts is performed.

6.2 Experimental

6.2.1 Sample Preparation and Characterization

Both Au and Ru samples used for this testing were deposited by sputtering. For the Ru/Ti stack on the ball tip of the piezo-actuator and polished Si sample, 0.1 μm Ti was deposited as an adhesive layer, followed by 1 μm Ru film under DC power of 200 W, chamber pressure of 2.5 mTorr and Ar gas flow rate of 30 sccm. Preparation of the Au samples using similar processes was described in Chapter 3.

X-ray photoelectron spectroscopy (XPS) was used to analyze the surface condition of the fresh Ru samples. C 1s, O 1s and N 1s species were identified in the spectrum, suggesting the existence of an alien film which is similar to the Au samples mentioned in the earlier chapters. The thickness of the alien film was determined by XPS depth profiling. Figure 6.1 shows the percentages of atomic concentration of Ru with respect to the sputtering depth. Using Ru percentage of 80% as a reference, the thickness of the absorbed contamination layer on Ru surface is found to be close to the case of fresh Au sample, which is ~ 0.4 nm.

Figure 6.1: XPS depth profiling results of Ru.

6.2.2 Mechanical Switching, Hot Switching and Quasi-static Tests

For pure mechanical switching, there is no voltage applied across the contacts during cycling. The contact force was calibrated to be approximately 100 μN , to imitate the force level in actual MEMS operations. The switching signal was generated by the controller module of the piezo-actuator, and the cycling frequency was 10 Hz.

For hot switching, a voltage is applied across the contacts, and there is a current flow in every cycle when the electrical contact is made. Two voltage levels

(100 and 200 mV) were applied. Settings of the contact force and the cycling frequency were identical to pure mechanical cycling.

20 quasi-static tests were carried out before cycling, immediately after 2000 cycles, 10000 cycles and 50000 cycles, respectively, for both pure mechanical and hot switching conditions. The tip displacement velocity was kept at (10 ± 0.9) nm/s, and the applied voltage was 90 mV.

6.3 Results and Discussion

6.3.1 Effect of Pure Mechanical Cycling on Quasi Contact Behavior

For Au-to-Au contacts, the effect of pure mechanical cycling on the duration of instable contact t_{SCF} is shown in Fig. 6.2. The Weibull plot of t_{SCF} in Fig. 6.2(a) is based on 20 quasi-static tests after different cycling times (0, 2000, 10000, and 50000 cycles), and the reference lines are the least-squares fit for each data set. The Weibull shape factor β versus the cycling numbers is plotted in Fig. 6.2(b). It can be seen that, in general, pure mechanical cycling has no significant impact on the value of Weibull shape factor for Au-to-Au contact. Referring to the sphere based cell model discussed in Chapter 5, the relation between the Weibull shape factor β and the thickness of the contamination film T is given by

$$\beta = \alpha \frac{T_{int} + T}{a_i}, \quad (5.5)$$

Figure 6.2: (a) The Weibull distributions of t_{SCF} for Au-to-Au contact under pure mechanical switching condition, with their least-squares fitting results as the reference lines. (b) The Weibull shape factor *versus* cycling numbers.

where a , a_i and T_{int} are constants in this case. Therefore, β can be directly correlated to T . A slight drop in the value of β after the first 2000 cycles implies a thinner alien film,

which could be due to partial removal of the physical absorbed layer at the surface of contact asperities under mechanical load. However, it appears that this layer readily recovers its coverage on the contact surface in the laboratory environment, regardless of the ongoing cycling process. After 50000 cycles, the value of β is close to the initial level before cycling tests. It is believed that such an alien hydrocarbon film is very persistent on the micro-contact surface of Au contacts [1-5], and as we have highlighted in the previous chapters, it needs to be taken into consideration for micro-contact studies of Au.

The results of Ru-to-Ru contact under pure mechanical cycling are shown in Fig. 6.3. Unlike the Au-to-Au contact, the Weibull shaper factor is clearly affected by the cycling numbers. An increase in the cycling number leads to a larger β , thus thicker surface contamination layer. From the Weibull plot of 20 quasi-static contact tests before cycling, β is estimated to be 1.2 by the least-squares fitting method. Assuming an identical interface equivalent thickness T_{int} , the radius of the spherical defective cell a_i is 1.2 nm then. The thickness of the alien film after 2000, 10000 and 50000 cycles can be determined by substituting the values of a_i and β into Equation (5.5), which are ~1.2, 2.4, and 4 nm, respectively, as shown in Fig. 6.3(b).

It is known that Pt-group materials, such as Ru, Pt and Rh, have greater surface reactivity compared to Au, which is associated with their catalytic nature [13-15]. Meanwhile, their partially filled d -band electron structures make them prone to chemical reactions with air-borne molecules such as carbon dioxide, while Au is more chemically inert due to its filled d -band structure [16]. Therefore, the adsorbent on the surface of Pt-group materials can further undergo a polymerization process, and transform into a compound of cross-linked polymers with high molecular weight [17].

Figure 6.3: (a) The Weibull distributions of t_{SCF} for Ru-to-Ru contact under pure mechanical cycling condition, with their least-squares fitting results as the reference lines. (b) The Weibull shape factor and alien film thickness *versus* cycling numbers.

Although the thickness of the alien film on the surfaces of fresh Ru and Au are similar, the distinction between the film properties formed during the cycling tests is clearly evidenced by different a_i (Au-to-Au, 1.6 nm; Ru-to-Ru, 1.2 nm), which implies

the difference of alien films at the Au and Ru contact surfaces. The experimental results suggest that subsequent mechanical loading plays an important role in promoting the buildup of surface contamination on Ru contact. During cycling, sliding and rubbing are inevitable among the prominent asperities that form physical contact. These actions can relocate the polymer to a different site, thus enabling formation of new polymer at the original spot. A large number of repetitive cycles lead to accumulation of polymer on the contact surface. This is consistent with the study on the development of “friction polymer” on the noble metal contacts by Hermance and Egan [14].

6.3.2 Effect of Hot Switching on Quasi Contact Behavior

Hot switching is an important switching mode for several applications, such as the MEMS/NEMS logic memories, in which the voltage is applied across the contacts during “on” and “off” states. In addition to the mechanical stress, the electrical stress could also contribute to the modification of micro-contact surfaces and thus changes in the quasi contact behavior. In this section, we study the hot switching effect for Au-to-Au and Ru-to-Ru contacts.

6.3.2.1 Au-to-Au Contact

The results of Au-to-Au contact under hot switching conditions with applied voltages of 100 and 200 mV are shown in Figs. 6.4(a) and 6.4(b) respectively. A few outliers are identified in those Weibull plots, which suggest different β values under the same testing condition. This could be due to variations in the thickness of contamination film at the local contact sites (different T), or the types of defects as a

result of inhomogeneous film property (different a_i). Least-squares fitting were performed without considering the outliers, followed by extraction of the values of β .

Figure 6.4: The Weibull distributions of t_{SCF} for Au-to-Au contact under hot switching condition at two applied voltage levels, (a) $V_a = 100$ mV; (b) $V_a = 200$ mV.

Figure 6.5 shows the Weibull shape factors after different numbers of cycling at two applied voltage levels ($V_a = 100$ & 200 mV), together with the referenced pure mechanical switching ($V_a = 0$ mV). It can be seen that β remains relatively stable for Au-to-Au contact in both hot and mechanical switching conditions. There is no obvious correlation between the β and the applied voltage level V_a . On the other hand, a drop in β happens after the 1st 2000 cycles under both applied voltage levels, and continuous cycling brings β close to its initial value, which is identical to the case of pure mechanical cycling.

Figure 6.5: The extracted Weibull shaper factors *versus* cycling numbers under different applied voltage levels (pure mechanical cycling with $V_a = 0$ mV, hot switching with $V_a = 100$ mV and $V_a = 200$ mV) for Au-to-Au contact.

6.3.2.2 Ru-to-Ru Contact

In the mechanical switching tests of Ru-to-Ru contact (section 6.3.1), it has been found that the β increases substantially with the cycling number, which could be attributed to buildup of polymer on the contact surface upon repetitive mechanical loading. Similar behavior is also observed during the hot switching tests, as shown in Fig. 6.6(a). Thickness of the contamination film grows continuously from 0.8 to 4.6 nm and 3.5 nm after 50000 cycles, under an applied voltage of 100 mV and 200 mV respectively. It has been widely reported that DC MEMS switches with Pt-group contacts suffer from resistive failures in the reliability studies, and accumulation of surface contaminants has been hypothesized as the root cause [10, 16-18]. Such hypothesis is well supported by our experimental results, and it is reasonable to believe that the quasi contact test combined with Weibull analysis has certain level of predictive power on the failure modes.

Meanwhile, it should be noted that the applied voltage V_a during hot switching could affect the growth rate of the surface contamination layer. Weibull shaper factor and the film thickness are plotted *versus* V_a in Fig. 6.6(b), including the case of pure mechanical cycling with V_a of 0 mV. It can be seen that hot switching under 100 mV produces the largest β after the same cycling numbers. In other words, buildup of the contamination layer is enhanced by the applied voltage of 100 mV during cycling. However, when the applied voltage is further increased to 200 mV, the growth of insulating film slows down. The growth rate at $V_a = 200$ mV is even lower than the case of pure mechanical switching.

Figure 6.6: (a) The Weibull shape factor and alien film thickness *versus* cycling numbers for Ru-to-Ru contact under hot switching at two applied voltage levels (100 mV and 200 mV); (b) The Weibull shape factor and insulating contamination film thickness *versus* the applied voltage levels after 2000, 10000 and 50000 cycles.

To better understand the dependence of surface condition on the applied voltage during hot switching, the effect of localized joule heating due to current flow at the constricted contact area has to be considered. Following the asperity deformation model, Fig. 6.7 illustrates half of the contact. It is known that the isopotential surfaces in a contact are also isothermals [19], and here we assume a symmetric contact with the far surface at room temperature T_0 . The maximum temperature T_c is at the constricted contact surface. The differential of the isothermal temperature can then be written as [8]

$$dT = -I\phi dR_t \quad (6.1)$$

where dR_t is the differential of thermal resistance, I is the current and ϕ is the electric potential.

Figure 6.7: Illustration of a half contact, with the potential, resistance and temperature labeled at the contact surface, intermediate surface and far surface.

By assuming that the heat transfer is dominated by conduction through the asperities, we have

$$dR_t = \frac{dR_e}{\rho_e k_e} = \frac{d\phi}{I \rho_e k_e} \quad (6.2)$$

at any isothermal-isopotential surface, where R_e is the electrical resistance, ρ_e is the electrical resistivity, and k_e is the thermal conductivity. Substituting Equation (6.2) into Equation (6.1) gives

$$dT = -\frac{\phi}{\rho_e k_e} d\phi. \quad (6.3)$$

By integrating both sides from the contact surface to the far surface, we have

$$\int_{T_0}^{T_c} \rho_e k_e dT = \int_0^{\frac{V_c}{2}} \phi d\phi. \quad (6.4)$$

According to the Wiedemann-Franz law that has been shown to be applicable even in submicron and nanometers region [20, 21], the product of the electrical resistivity ρ_e and thermal conductivity k_e is proportional to the temperature T , with Lorentz number L as the proportionality constant, i.e. $\rho_e k_e = LT$. Equation (6.4) can thus be rewritten as

$$\int_{T_0}^{T_c} LT dT = \int_0^{\frac{V_c}{2}} \phi d\phi. \quad (6.5)$$

By solving Equation (6.5), the relation between the temperature at the contact surface T_c and the contact voltage V_c is obtained:

$$T_c^2 - T_0^2 = \frac{V_c^2}{4L}, \quad (6.6)$$

where T_0 is 300 K , and the Lorentz number L is $2.44 \times 10^{-8} \text{ V}^2 \text{K}^{-2}$ [22, 23]. As a result, the temperature at the contact surface during hot switching under 100 mV and 200 mV can be estimated to be $\sim 438 \text{ K}$ and $\sim 705 \text{ K}$ respectively.

The enhancement of contamination buildup on Ru-to-Ru contact during hot switching under 100 mV could be associated with the rise of local temperature at the contact surface compared to pure mechanical cycling. A higher temperature leads to increased chemical reactivity on the Ru surface, thereby promotes the polymer deposition and accumulation. This phenomenon has been reported in the literature, although the specific mechanism of the catalytic polymerization process remains unclear [13, 14, 24]. On the other hand, when the maximum temperature at the contact surface rises to $\sim 705 \text{ K}$ at a higher contact voltage of 200 mV, the surface oxidation of Ru has to be taken into account. It is known that a minimum temperature, which has been reported to be between 500 K and 600 K [25, 26], is required for Ru to form its stable oxide RuO_2 . Therefore, repetitive hot switching under 200 mV could result in the formation of RuO_2 on the Ru-to-Ru contact surface, and slow down the polymer build-up at the early stage of the cycling tests. Since RuO_2 has a low resistivity comparable to metal materials, it reduces the effective thickness of the insulating contamination film, and thus lowers the Weibull shaper factor, as shown in Fig. 6.6(b). It should be noted that the amount of RuO_2 on the contact surface easily saturates, since the chemisorbed layer hinders further intake of oxygen [27]. This may further explain why the slow growth of the insulating film upon cycling under 200 mV only happens at the beginning of the cycling.

6.4 Summary

In this chapter, quasi-static contact tests and the statistical means introduced in Chapter 5 to study the impacts of cycling on Au-to-Au and Ru-to-Ru micro-contact surfaces have been discussed. Time-to-stable contact formation t_{SCF} is shown to be an effective indicator of the surface conditions under different switching modes. It is found that Au-to-Au contact is relatively stable upon cycling under the force level of conventional MEMS switches, and variation in the applied voltages of 0, 100 and 200 mV during switching does not significantly alter the thin insulating contamination film at the contact surface. The hydrocarbon film is believed to be persistent, as it easily recovers its coverage under all testing conditions. On the contrary, Ru-to-Ru contact is sensitive to the loading cycles, due to the partially filled d -band electron structures of Ru and its catalytic nature. It is found that the thickness of insulating contamination film at the contact surface quickly increases during repetitive switching. Furthermore, the growth of the alien layer at Ru contact surface is related to the applied voltage, as it affects the temperature at the contact spot by localized joule heating, which is a governing parameter in surface chemical reactions. In conclusion, the results shown in this chapter demonstrate a new and effective *in situ* approach to investigate the micro-contact surfaces under various cycling conditions from a microscopic point of view. It provides insight to understand degradation of metal contact surface during cycling, which is of great importance for the reliability of DC MEMS switches.

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Chapter 7

Conclusion and Future Work

7.1 Conclusion

The electrical contact behavior of metal micro-contacts has emerged as an important topic in design, modeling and optimization of DC MEMS/NEMS components and devices. This dissertation has explored various aspects of the micro-contact behavior, including quasi contact behaviors at the initialization stage of contact formation, origin of the electrical contact instability, low frequency noise in the unstable region and the physical mechanisms behind, establishment of electrical contact from unstable region to formation of stable contact, effects of various stress conditions on quasi contact behaviors of Au-to-Au and Ru-to-Ru contacts, etc. To conclude, this chapter briefly summarizes the major contributions presented in this dissertation.

The Au-to-Au micro-contact behavior during the initial stage of electrical contact formation was investigated. A nanoindentation stage was utilized for the contact tests under precisely controlled experiential conditions, and XPS techniques were applied to characterize the contact surface. Contact instability was clearly observed when the contact force is below a threshold value ($F_{\min}$). The experimental results reveal that the asperity deformation process, which is conventionally observed in the stable region, could start from the early stage of contact formation in the unstable region. The alien contamination film on the metal contact surface plays an important role in determining the unstable contact behavior, which is evidenced by the

presence of a remarkable transition region on those samples exposed in microfabrication environment (after one complete lithography cycle). Meanwhile, the duration of the unstable region is found to be largely affected by the applied voltage, implying that the quasi contact behavior should be associated with mechanisms related to electrical conduction, rather than pure mechanical factors that have been frequently reported in the previous contact studies such as contact bouncing. The rapid fluctuation of contact voltage in the unstable region is explained under a framework of electron tunneling through the alien contamination film.

The noise behavior of Au-to-Au micro-contact for DC contact type MEMS/NEMS has been experimentally studied in the unstable contact region. By fitting the power spectral density (PSD) curve, the electrical conduction noise is identified to be the superposition of two noise components, Lorentzian and $\frac{1}{f^2}$. The Lorentzian component can be attributed to the tunneling current and carrier trapping-detrapping process in the dielectric layer, which is in good agreement with the two-level (“on” and “off” states) random telegraph signal observed in the time domain. The $\frac{1}{f^2}$ noise could be due to the inhomogeneous local conductivity of the thin gold film. The number of carriers (N) and the relaxation time (τ_p) were extracted from the Lorentzian spectrum. A trap density in the order of $10^{19}/\text{cm}^3$ at contact interface were further estimated based on N and τ_p , and it is consistent with the previous experimental measurements of the trap density in polymers used for microfabrication process.

The evolution of the electrical contact behavior during contact formation has been investigated in detail with statistical means. It is unveiled that the electrical conduction in the contamination film follows the weakest-link principle. The switching events from “off” to “on” state observed in the random telegraph signal are statistically independent, till the generation of certain “weak” spots close to the end of the unstable region. By performing Weibull analysis, it is found that the process of contact formation is electrical field enhanced and sensitive to the thickness of the alien contamination film on the contact surface. In the proposed geometrical model, the formation of an electrical conduction path through the contamination film is inherent to the electrical breakdown process in a dielectric, which is triggered by overlapping spherical defective cells (“weak” spots) between the Au micro-contacts. The radius of the spherical cell could be estimated from the experimental data. The results provide further insights to the contact formation process in the MEMS/NEMS components and devices, from the unstable contact region to the establishment of stable electrical contact in one contact cycle.

A comparative study has been conducted to investigate the impacts of cycling under various conditions on Au-to-Au and Ru-to-Ru contacts, as both materials are popular candidates for the contact part of micro/nano switches. The experimental results are discussed in the framework of Weibull analysis, and t_{SCF} (time-to-stable contact formation) is shown to be an effective indicator of the surface conditions. It is found that Au-to-Au contact is relatively stable upon cycling, and variation in the applied voltages (0, 100 and 200 mV) does not significantly alter the thin insulating contamination film at the contact surface. On the other hand, the thickness of the alien film increases during repetitive cycling for Ru-to-Ru contact, which could be

attributed to the catalytic nature of Ru and its partially filled *d*-band electron structures. Moreover, the growth of the alien film on Ru is related to the applied voltage, as it affects the temperature at the contact spot by localized joule heating, and the surface chemical reactions of Ru is temperature-sensitive. A new and effective *in situ* approach is demonstrated to study the degradation of metal micro-contact surface during cycling, which is of great importance for the reliability of DC type of MEMS/NEMS devices.

7.2 Recommendations for Future Work

Based on the above research results that have been achieved, there are several challenging issues that await further explorations in future.

With the extracted information of the alien layer and the trap properties, including the band gap, trap energy level, trap density, trapping and detrapping time constants, size of the defect cell and so on, it would be possible to simulate the contact behavior coupled with the weakest-link behavior (percolation model) theoretically. We strongly recommend a follow-up study in this direction, as it will be interesting to find out how the simulation results agree with the experimental data and mechanisms discussed in this work.

The electrical contact behavior of metal micro-contacts has been studied in detail by using a devised nanoindentation platform. The future work can be focused on the contact instability on device level. Driven by the down-scaling trend, the contact force of scaled MEMS or NEMS devices easily falls into the region of sub-micro-newton and nano-newton, resulting in unstable contact behavior during operation. The

dynamic response of the mechanical structure (cantilever beam, etc.) may need to be taken into consideration in the study of quasi contact behavior on actual MEMS/NEMS components and devices.

As discussed in this work, the performance of MEMS/NEMS devices could be comprised due to the contact instability, for example, phase noise in the microwave circuits and reduced minimum detectable limit (MDL) in sensor applications. We have shown that the alien contamination film on the micro-contact surface plays an important role in determining the quasi contact behavior. Therefore, it will be of great importance to look into the impact of microfabrication process of various MEMS structures on the performance of MEMS/NEMS.

The quasi static tests and cycling tests in our work were conducted in clean room environment. It will also be interesting to investigate the micro-contact behaviors in a test chamber with different ambient conditions and temperatures. Such studies will provide better insights into the surface reactions of the micro-contacts. It may potentially advance the packaging technology for MEMS/NEMS components.

Author's Publications

The publications are sorted in chronological order, starting with the latest one.

Journal publications

[1] **Haodong Qiu**, Hong Wang, and Feixiang Ke, “Effect of mechanical and hot switching stresses on quasi contact behaviors of Au-to-Au and Ru-to-Ru contacts – a comparative study,” submitted to *Journal of Applied physics*.

[2] **Haodong Qiu**, Hong Wang, and Feixiang Ke, “Towards a better understanding of the electrical contact formation process of the metal contact for DC MEMS/NEMS switches with statistical means,” *Japanese Journal of Applied physics*, vol. 53, pp. 087201, 2014.

[3] **Haodong Qiu**, Hong Wang, and Feixiang Ke, “Low frequency noise in the unstable contact region of Au-to-Au microcontact for microelectromechanical system switches,” *Applied Physics Letters*, vol. 104, pp. 254102, 2014.

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