Mechanical Nano-characterization of Gold for MEMS Contact Switches

Marwan Al-Haik[1], Shane Trinkle[1], and Hartono Sumali[2]

[1]Department of Mechanical Engineering
University of New Mexico,
Albuquerque, NM 87131

[2]Applied Mechanics Development Department
Sandia National Laboratories
MS 1070, PO Box 5800, Albuquerque, NM 87185, USA

Abstract

Mechanical properties of micro/nanoscale structures are needed to design reliable microelectromechanical systems (MEMS). This study presents a basic step toward the understanding of the reliability and failure of the gold film used for MEMS. The mechanical properties of gold film and surface damage under impact were investigated in the normal-force regime of 1-2 mN. Nanomechanical characterization of the gold films was carried out. Hardness, elastic modulus and resistance against fatigue failure were measured by nanoindentation and nanoimpact using a nanoindenter. The results provide guidelines and assessment of elastic/plastic deformation, and surface impact characteristics of the gold film. The tests used in this study can be used to evaluate the mechanical properties of micro structures for use in MEMS.

Nomenclature

A	Indentation projected are, m^2	n_s	Poisson's ratio
E	Young's Modulus, Pa	P	Indentation load (N).
H	Hardness, Pa		

Introduction

During the past decade, several new fabrication techniques helped popularize microelectromechanical systems (MEMS), and numerous novel devices have been reported in diverse areas of engineering and science. One such area is microwave and millimeter wave systems. The recent and dramatic developments of personal communication devices forced the market to acquire miniaturized efficient devices, which in some cases is possible only by the development of radio frequency (RF) MEMS. RF MEMS are used for actuation or adjustment of a separate RF device or component, such as variable capacitors, switches, and filters [1]. Recently, RF-MEMS switches have been considered among the most promising devices used in wireless applications as they exhibit microsecond time responses in GHz range signals [2], give low insertion losses, and require low power consumption [3].

RF MEMS metal contact switches are ideally suited for many applications, such as phase shifters in phased array radar, reconfigurable antennas in satellite communication systems, RF tags, and personal communication systems [3]. These devices are typically actuated through electrostatic attraction of the armature to the substrate electrodes. Typical device dimensions are on the order 100 μm, fabricated in plates a few μm thick. The forces available to the MEMS designer range from tens to hundreds of nN, with larger-scaled bulk micromachined devices perhaps attaining several μN. With switching speed as a major motivating factor in telecommunications, device sizes and forces are being reduced in order to optimize performance.

Among the most important performance criteria of RF-MEMS switches are low contact resistance and high reliability. Serious reliability issues including contact area damage wear and dielectrics charging remain unanswered for RF-MEMS [4]. A reliability goal of more than 10^8 hot-switched cycles during the RF MEMS switch practical use [2] can be achieved through the selection of the appropriate contact material(s). Low contact resistance of MEMS switches requires contact materials with low resistivity, low hardness and high chemical resistance to corrosion [5]. Numerous materials have been tried for contact materials. Silver and its alloys are among the most widely used contact material in macro switch due to their superior electrical and mechanical properties. However, silver and its alloys tend to form a nonconductive sulfide layer on the surface. This sulfide surface layer is a real obstacle in MEMS switches since the contact forces of MEMS switches (μN range) are usually well short of penetrating the surface layer [5]. Alternatively, gold-on-gold electric contact has been typically used in MEMS switches due to its low electric resistivity, and high resistance to surface oxidation. The low hardness of gold, however, leads to adhesion problems in MEMS switches. The low hardness of gold as well as the adhesive force between gold contacts also causes wear, deformation and adhesion of contacts during cycling, which eventually lead to failure of the MEMS switch, such

that it is stuck closed or its contact resistance increases with increasing switch cycles [6]. Moreover, the buildup of adventitious carbon on gold was noticed to cause failure of the RF switches.

An important challenge in the reliability of this RF- MEMS is to understand contact failure [7]. In many cases, impacts between contacting surfaces increase the contact resistance so much that it is out of specifications after only a few thousand cycles. A major cause of contact failure is surface damage due to mechanical impact, asperity welding and ripping off, and chemical reactions on the contacting surfaces. A nano-scale understanding of how contacting surfaces evolve with repeated impacts is therefore crucial to understanding how electrical resistance in micro contacts changes with time.   Another important challenge in assuring the reliability of MEMS contact switches is to determine relevant mechanical properties of the MEMS component, such as elastic and plastic tensile properties, fatigue properties and so on. In many cases, the sizes of MEMS devices are such that their mechanical properties are not same as those for the bulk materials, as mechanical properties in micro-scale depend on the size and fabrication process. The smallest dimension of the MEMS comprises merely a few grains of the gold. Therefore, evaluation of mechanical properties is a challenging problem for the design of MEMS devices.

Experiment

The test sample discussed in this paper was fabricated from gold as described in reference [8] as part of the development of MEMS switches [9]. Figure1 shows an electron microscope (ESEM) micrograph of the test structure. The device comprises a plank supported by four folded-beam springs. Each of the springs is supported by an anchor, which is in turn fixed to the substrate in a raised position. The springs and the supported plank are from the same fabricated layer about 3.7 µm above the substrate. In its operation, when the device is energized electrostatically the plank moves down toward the substrate. When the device is de-energized, the springs bring the plank back to its raised position. In this paper, the geometry is not as important as the material, since the test was done only on an anchor.
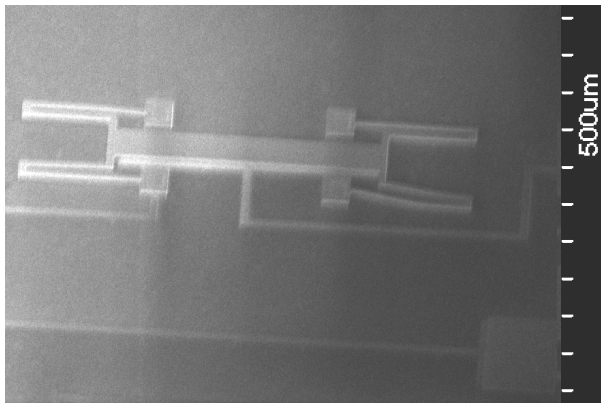

FIGURE 1: ESEM MICROGRAPH OF THE SAMPLE. FILM THICKNESS APPROX 5 µm.

To measure mechanical properties of the test structure material, mechanical nano-characterization tests were carried out using a NanoTest™ system manufactured by Micro Materials. The NanoTest is a pendulum-based depth-sensing system with the sample mounted vertically and the load applied electromagnetically as shown schematically in Figure 2. Current in the coil causes the pendulum to rotate about its frictionless pivot so that the diamond probe penetrates the sample surface. Test probe displacement is measured with a parallel plate capacitor achieving sub nanometer resolution. A Berkovich (three-sided pyramidal) diamond indenter was used for measuring the Hardness and modulus of the gold plates. The area function for diamond (the relationship between projected contact area and contact depth) was calibrated by indentations into fused silica from 10 to 100 mN. A series of 5 indentations (located 3 µm apart as shown in Figure 3-B), were load-controlled to 2 mN maximum load. Other experimental conditions were:

(1) preset initial load: 0.05 mN
(2) loading rate=unloading rate:0.1 mN/s
(3) hold at maximum load top account for creep: 30 s
(4) hold at 80% to determine the thermal drift rate: 30 s.

The optical microscope of the Nano test system was used to accurately locate the region of interests. Indentations were spaced sufficiently far apart so that the indentation behavior was not affected by the presence of adjacent indentations. The instrument's software corrected all data for thermal drift and instrument compliance. The data were subsequently analyzed with the Oliver and Pharr method [10].

To test the surface failure of the gold film it is necessary to produce an alternating contact stress with a relatively high frequency. This is achieved by the pendulum impulse technique. Essentially for each impact the pendulum is pushed away from the specimen by means of a small solenoid and then released to allow the probe to accelerate toward the specimen. Since the accelerating force, the distance moved, the pendulum damping, and the pendulum effective mass are known, the impact energy can be calculated. The gold film remains stationary and the pendulum is moved to create individual quantifiable impacts. The gold film damage under fatigue is shown in Figure 3(C).
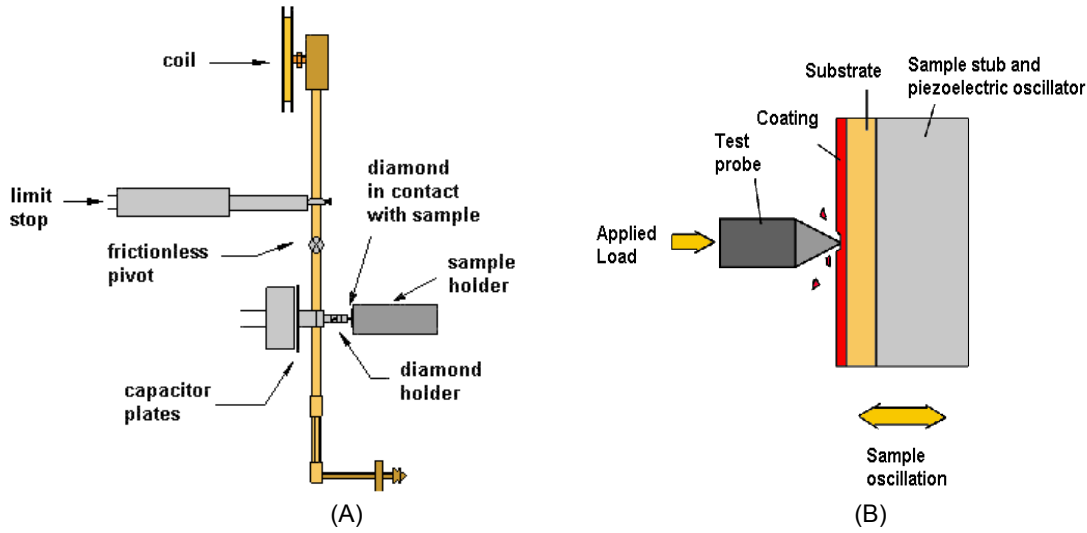
FIGURE 2: (A) SCHEMATIC DIAGRAM OF THE NANOTEST SYSTEM. (B) OPERATING PRINCIPLE OF THE NANOIMPACT TECHNIQUE.
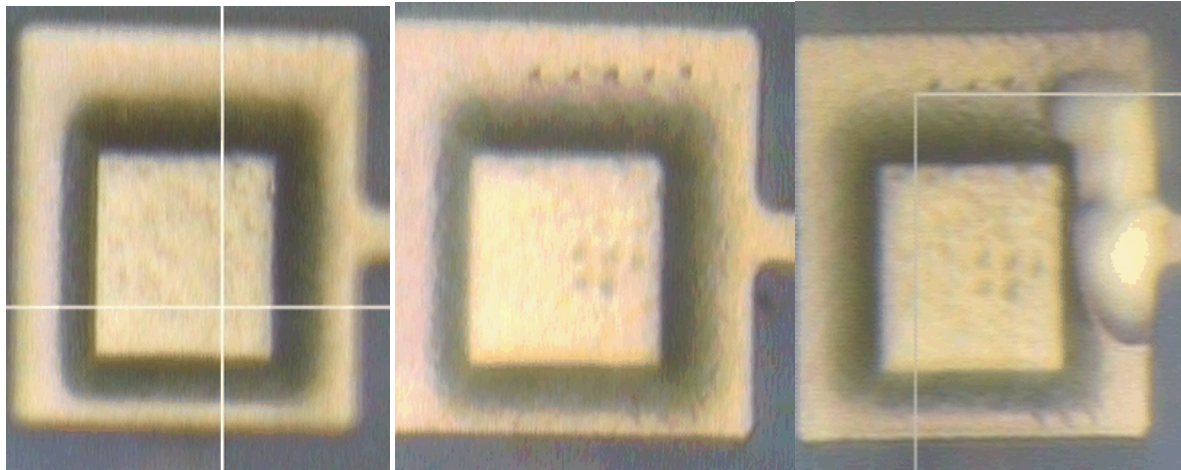

FIGURE 3: OPTICAL MICROSCOPE IMAGE OF THE RAISED POST ANCOR (A) BEFORE NANOINDENTATION (B) AFTER NANOINDENTATION, AND (C) AFTER NANOIMPACT TESTS. ALL IMAGES AT 800 X MAGNIFICATION.

Data Processing

The depth vs. load unloading data for each indentation curve, shown in Figure 4, was fitted to a power law fit to determine the mechanical properties of the test sample. The power law function has the form

$$P = a(h - h_c)^m \tag{1}$$

where a, h_c and m are constants. The plastic depth h_c is determined from the expression

$$h_c = h_{max} - e(CP_{max}) \ , \tag{2}$$

where C is the contact compliance equal to the tangent at maximum load. The value of e depends on the indenter geometry. For a Berkovich indenter, e is 0.75. The diamond area function $A(h_c)$ has been previously determined, according to the

calibration of a fused silica sample. The hardness (H) is determined from the peak load (P_{max}) and the projected area of contact, A:

$$H = \frac{P_{\max}}{A}$$ (3)

To obtain the elastic modulus, the unloading portion of the depth-load curve is analyzed according to a relation which depends on the contact area:

$$C = \frac{\sqrt{p}}{2E_r\sqrt{A}}$$ (4)

where C is the contact compliance and E_r is the reduced modulus defined by

$$\frac{1}{E_r} = \frac{\left(1-n_s^2\right)}{E_s} + \frac{\left(1-n_i^2\right)}{E_i}$$ (5)

where n_s = Poisson's ratio for the sample, n_i = Poisson's ratio for the indenter (0.07), E_s = Young's modulus for the sample and E_i = Young's modulus for the indenter (1141 GPa).
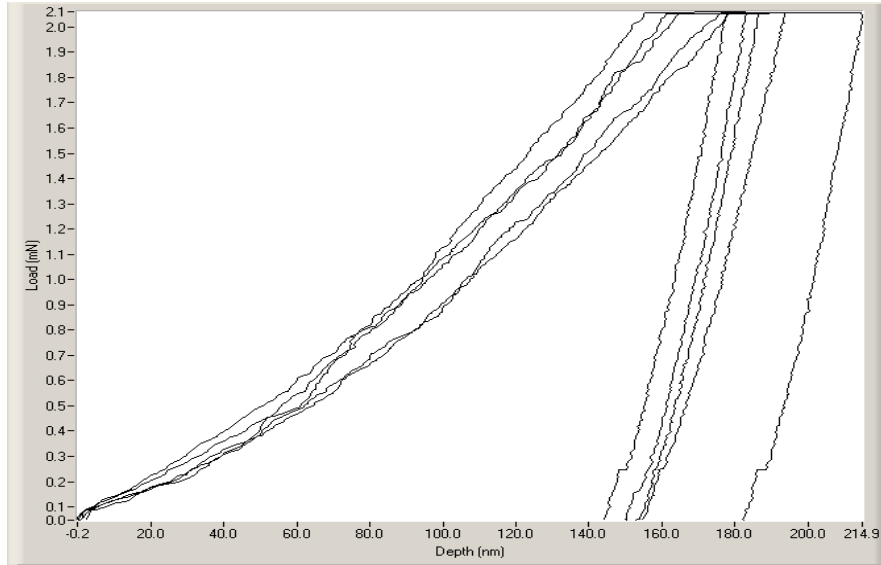

FIGURE 4: NANOINDENTATION CURVES FOR 5 DIFFERENT LOADING-UNLOADING CYCLES AT A MAXIMUM LOAD OF 2mN AND LOADING RATE OF 0.1 mN/S. THE DATA OF THE LOAD-DEPTH CURVESARE USED TO CALCULATE BOTH THE MODULUS AND HARDNESS OF THE GOLD FILM.

Figure 5-(A) shows pendulum impulse test data for the gold films. The curve actually consists of small juxtaposed constant-depth segments obtained during a short surface dwell period following each impact. A static load of 2mN was applied throughout the test. There was no failure at this load during normal indentation testing. The Rockwell spherical diamond indenter (25 μm in diameter) was used for this test. The indenter impacted the gold surface repetitively, leading to a gradual accumulation of surface damage by a fatigue process.

Results and Conclusion

The average values for the reduced modulus and the hardness for the five indentations on the gold film are E_r= 75.95 $\pm$9.159GPa and H= 2.89 $\pm$0.435 GPA, respectively. Reported results on elastic modulus at room temperature for thin films of Au are divergent. Nanoindentation tests give a value of around 100 GPA [11], whereas Membrane Deflection Experiments give lower values of around 55 GPA [12]. However, it is reasonable to expect a higher value for the elastic modulus, as internal stress within the thin film plays a dominant role when the dimensions are shrunk from bulk macroscale to microscale dimensions.
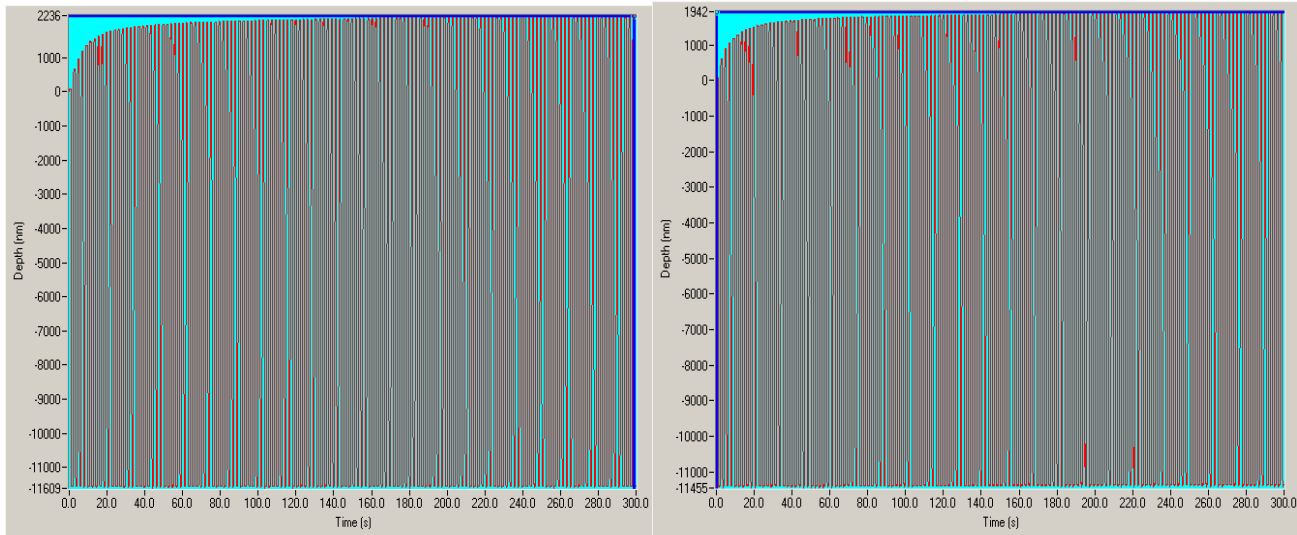
FIGURE5: (A) IMPACT TEST ON THE 5μ GOLD FILM. APPLIED LOAD 2 MN USING 25 μ ROCKWELL DIAMOND PROBE. (B) REPEATING THE IMPACT TEST OVERV THE SAME SPOT REDUCED THE DEPTH INDICATING WORK HARDENUING.

The impact test shows the following qualitative results: plastic deformation was produced by the first few impacts, followed by intervals of relatively slow depth increase. However, unlike the brittle material behavior there was no rapid depth increase. The results indicate ductile behavior without adhesion failure as the probe approaches the gold film. These data can be useful in deriving the work hardening information. Repeating the impact test at 2 mN over the same spot on the gold film, Figure 5 (B), shows a reduced depth; indicating work hardening. Similar results for aluminum thin film on sapphire were observed by other researchers [13].

Acknowledgments

References

[1]   Varadan, V. K., Vinoy K.J., K.A. Jose, 2003, <u>RF MEMS and Their Applications</u>, John Wiley & Sons Ltd, West Sussex, England.
[2]   Yao, J. J., 2000, " RF MEMS from a device perspective," *Journal of Micromechanics and Microengineering*, 10, p R9–
[3]   Rebeiz, G. M., 2003," <u>RF MEMS, Theory, Design and Technology</u>, John Wiley and Sons, New Jersey.
[4]   Hyman, D., and Mehregany, M., 1999, "Contact physics of gold microcontacts for MEMS switches*," IEEE Trans. on Components and Packaging Technologies*, 22, p 357-364.
[5]   Lee, H., Coutu, R.A., Mall, S. land Leedy, K.D., 2006, "Characterization of metal and metal alloy films as contact materials in MEMS switches," *Journal of Micromechanics and Microengineering,* 16, p 557–563.
[6]   Coutu Jr., R.A., Kladitis, P.E., Leedy, K.D and Crane, R. L., 2004," Selecting metal alloy electric contact materials for MEMS switches*," Journal of Micromechanics and Microengineering,* 14, p1157–64.
[7]   Majumder. S., McGruer, N.E., Adams, G.G., Zavracky, P.M., Morrison, R.H., and Krim, J., 2001, "Study of contacts in an electrostatically actuated microswitch," Sensors *and Actuators, a: Physical*, 93, p 19-26.
[8]   Dyck, C.W., Plut, T.A., Nordquist, C.D., Finnegan, P.S., Austin, F., Reines, I., and Goldsmith, C.,2004, "Fabrication and Characterization of Ohmic Contacting RF MEMS Switches", *SPIE Conference on Micromachining and Mic*rofabrication, 5344, p 79-88.
[9]   Sumali, H., Kuppers, J. D., Czaplewski, D.A. Massad J.E. and Dyck, C. W., 2005," Structural dynamics of an RF-MEMS switch," IMECE2005-80956, *Proceedings of 2005 ASME IMECE*, November 5-11, 2005. Orlando, Florida, USA.
[10] Pharr, G.M., Oliver, W.C., and Brotzen, F.R., 1992 "On the generality of the relationship among contact stiffness, contact area, and elastic modulus during indentation", *Journal of Materials Research*, 7, p 613-617.
[11] Moody, N. R., Yang, N., Adams, D. P., Cordill, M. J., and Bahr D. F., 2002, "The effects of copper on the interfacial fracture of Au films," in *Thin Films—Stresses and Mechanical Properties IX*. Pittsburgh, PA: Materials Research Society, vol. 695, p L7.5.1–L7.5.6.
[12] Espinosa, H. D. and Prorok, B.C.,2003, "Size effects on the mechanical behavior of Au thin films," *J. Mater. Sci.*, 38, p 4125–4128.
[13] Beake, B.D., Goodes, S.R., and Smith, J.F., 2001," Microimpact testing: A new technique for investigating thin films toughness, adhesion, erosive wear resistance, and dynamic hardness," *Surface Engineering*, 17, p187-192.