Comparison of Au and Au–Ni Alloys as Contact Materials for MEMS Switches

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Abstract—This paper reports on a comparison of gold and gold–nickel alloys as contact materials for microelectromechanical systems (MEMS) switches. Pure gold is commonly used as the contact material in low-force metal-contact MEMS switches. The top two failure mechanisms of these switches are wear and stiction, which may be related to the material softness and the relatively high surface adhesion, respectively. Alloying gold with another metal introduces new processing options to strengthen the material against wear and reduce surface adhesion. In this paper, the properties of Au–Ni alloys were investigated as the lower contact electrode was controlled by adjusting the nickel content and thermal processing conditions. A unique and efficient switching degradation test was conducted on the alloy samples, using pure gold upper microcontacts. Solid-solution Au–Ni samples showed reduced wear rate but increased contact resistance, while two-phase Au–Ni (20 at.% Ni) showed a substantial improvement of switching reliability with only a small increase of contact resistance. Discussion of the effects of phase separation, surface topography, hardness, and electrical resistivity on contact resistance and switch degradation is also included. [2008-0049]

Index Terms—Alloys, Au–Ni alloys, electrical contacts, microelectromechanical systems (MEMS), microswitch, radio-frequency (RF) MEMS.

I. INTRODUCTION

Radio-frequency (RF) microelectromechanical systems (MEMS) switches demonstrate great potential for a spectrum of microwave applications. Compared with conventional field-effect transistors and p-i-n diodes, RF MEMS switches offer much lower power consumption, much better isolation, and lower insertion loss. One major obstacle for conventional field-effect transistors and p-i-n diodes, RF MEMS switches. Pure gold is commonly used as a contact material to achieve low contact resistance. Stiction and wear are prone to occur between two soft adhesive contact surfaces while switching. Wear may be described as contact deformation and/or material redistribution, ultimately causing contact surface roughening and affecting local contact force and contact resistance. Contact contamination has also been discussed as a degradation and failure mechanism [2], [3].

There have been some efforts in the device-design field to address this problem of Au-to-Au contact reliability [4], [5]. Notably, Oberhammer and Stemme [6] introduced a mechanically bistable electrostatic switching mechanism to achieve a small passive closing force and a large active opening force for soft metal contacts. On the materials’ side, a few alternative metals and alloys have also been investigated as contact materials for metal-contact MEMS switches. McGruer et al. [7] showed that ruthenium (Ru), platinum (Pt), and rhodium (Rh) were susceptible to contamination and the contact resistance increased after a characteristic number of cycles, while gold alloys with a high gold percentage showed no contact resistance degradation under the same test conditions. Coutu et al. [8], [9] showed that alloying gold with a small amount of palladium (Pd) or Pt extended the microswitch lifetimes, with a small increase in contact resistance. However, at present, comprehensive investigations of the effects of surface topography, alloy composition, and material microstructure on contact resistance and lifetime performance are lacking. In order to build a solid material knowledge base for microswitch designers, correlations among material properties, contacting performance (such as contact resistance and lifetime), and failure modes (such as stiction and wear/material transfer) need to be built based on systematic experimental data for different materials.

The research in this area has been slowed by the long time requirement for fabricating a microswitch with a particular new contact material. Typically, these microswitches are fabricated in Si foundries, and only a limited range of materials may enter the fabrication facility. Second, the fabrication process must be optimized for each material, and it may take many months to fabricate a set of switches to test a candidate contact material. Materials’ compatibility and process integration issues must be addressed in advance for every material to be tested.

Some convenient contact wear test facilities have been used to research the characteristics of microswitches. Notably, Hyman and Mehregany [10] used a modified $X-Y-Z$ micrometer station to investigate the contact physics and test the current-carrying capability of MEMS switches. Schimkat [11] used an accurate loading system to survey materials for...
microrelay actuators. A modified nanoindentor was also used to study the hot-switching degradation of MEMS contacts [12]. One concern about these tests is that they do not closely mimic real microswitches. In particular, the tests have difficulty duplicating the switch geometry (mechanical moving parts are typically microscale cantilever structures with metal films being patterned on the surfaces) and the contact geometry (microcontacts); these are important issues because the contact geometry has a strong influence on the stress and heat distribution across the contacts and, thus, on the switch performance and failure mechanism [13], [14].

In this paper, these issues were addressed by comprehensively testing an alloy series of Au–Ni (with varied nickel compositions) and by utilizing a newly developed switching degradation test facility closely mimicking an actual MEMS switch operation [15].

Aside from the alloys mentioned in the earlier paragraphs, Au–Ni has materials’ characteristics showing it to be a potentially promising alternative to gold. It has been reported that Au–Ni alloy contacts yield much lower adhesion than pure gold contacts [9]. Low-force (as low as 0.6 mN) stable contact and reliable reopening were also achieved in the previous research report. However, in the previous study, only samples with one composition (5% Ni) were investigated, using bulky samples (rivets) as test components instead of a MEMS test structure. Therefore, we have undertaken a study of a wider range of alloy compositions, tested under a configuration typical of MEMS switches. The Au–Ni phase diagram is shown in Fig. 1 [16]. Note that both metals are Face Centered Cubic (FCC) structures and exist as a two-phase mixture at a relatively low temperature under equilibrium conditions. However, a metastable single-phase alloy may also be produced under the low processing temperatures utilized for the film deposition. Thus, a comparison of the metastable solid solutions and the two-phase mixtures of the same overall composition can be undertaken so that both microstructure and composition effects can be examined.

The switching degradation test facility used for this paper utilizes the upper cantilevers from commercial RF MEMS switches and tests these against alternative bottom contact materials, using a modified atomic force microscope (AFM) as described in the following. The emphasis is placed on a comparison of the alloys and correlations between material properties, contact resistance, and contact degradation.

Fig. 1. Au–Ni phase diagram, after Okamoto and Massalski [16].

II. EXPERIMENT

We have designed a unique setup for monitoring MEMS switching behavior by integrating a real MEMS cantilever (from commercial wiSpry switches [17]) and separate thin-film bottom contact materials under test into an AFM [15]. The test configuration is shown schematically in Fig. 2. The contact is made between the upper pure gold microcontacts and bottom candidate contact materials. The contact resistance evolution and the switching motion are both monitored in situ. The test switch is cycled on/off using a piezoelectric actuator. The switching mechanics is designed in such a way that contact resistance failure is highly sensitive to the contact surface degradation. During test, the MEMS cantilever is intentionally flexed in both “on” and “off” states to ensure a calibrated contact force. This present geometry also ensures a nearly vertical contact motion (less than 2.5° tilting) for the upper microcontacts with respect to the bottom contact pads. The contact area then is always located near the front edge of the microcontacts due to this slight tilting. Vertical oscillation of the bottom contact pads alternates the contact points between the cantilever edge (insulating) and the microcontacts, with these two states corresponding to the electrical “open” and “closed” states. We are aware that, in the commercial wiSpry switches with which we are making comparison, the ultimate rise in resistance appears to correlate with substantial deformation of the switch contacts, consistent also with other reports [7], [13]. We have therefore made this test more sensitive to contact deformation by limiting the vertical travel of the piezoelectric actuator. As deformation occurs, the ON-state contact is affected, and resistance rises markedly. As shown later in Section III, this will occur after dramatically fewer cycles than in service, primarily because the limited travel will result in an “out-of-contact” condition after substantially less contact deformation than in the case of the commercial switch. Thus, we can accelerate our investigation of contact degradation as a function of contact material while using the commercial cantilever in a test that is strongly representative of the actual operation.

Further conditions are briefly summarized in the following.

1) The test is typically undertaken under “hot-switching” conditions. This term is used by the electrical switch community for the condition where a field is present
when switch opening and closing takes place. The open circuit voltage ($V_{oc}$) is set at 1 V. The measurement current is 1 mA, a value reached after a current transient. Transient current was limited by adding a parallel and a serial resistor to the noninductive switch circuit. The parallel resistor controls the open circuit voltage; the serial resistor limits the transient current. Our results suggest that the transient accelerates switch degradation, and the transient was therefore limited and kept constant for all the comparative tests.

2) The contact force is calibrated as $\sim 150 \mu N/contact$, which is up to twice the contact force of the wiSpy’s microswitches under service conditions. This increased contact force was adopted to increase the deformation and wear rates but was also carefully controlled for the comparative evaluations of the contact materials. Since the tests were conducted in ambient air, a relatively large contact force also helps to penetrate any surface contamination film that may be present and ensures a metal–metal contact.

Therefore, under the test conditions utilized in this investigation, the effective lifetimes are substantially shortened [15], which enables differences between contact materials to be more readily distinguished.

Pure Au and Au–Ni alloy (with up to 20 at.% Ni) bottom contact samples were prepared using ion-beam sputter deposition. Xenon gas was used in the ion source due to its relatively large mass, reducing energetic bombardment of the growing film. The base pressure was $< 3 \times 10^{-7}$ torr, and the deposition pressure was $2 \times 10^{-4}$ torr. The accelerating voltage for the beam is 600 V and for the beam current is 20 mA. The substrate is a silicon wafer coated with a 1000-Å-thick thermal oxide. A 5-nm chromium (Cr) layer and a 10-nm molybdenum (Mo) layer were deposited as an adhesion layer and a diffusion barrier layer, respectively. A 250-nm film of pure Au or Au–Ni (with various nickel compositions) was then deposited.

The Au–Ni alloy was prepared by cosputtering from a rotatable target partially covered with a piece of the alloying layer, respectively. A 250-nm film of pure Au or Au–Ni (with up to 20 at.% Ni) was then deposited. X-ray photoelectron spectroscopy (XPS) was used to detect the surface chemical composition (X-ray beam is 600 V and for the beam current is 20 mA. The substrate is a silicon wafer coated with a 1000-Å-thick thermal oxide. A 5-nm chromium (Cr) layer and a 10-nm molybdenum (Mo) layer were deposited as an adhesion layer and a diffusion barrier layer, respectively. A 250-nm film of pure Au or Au–Ni (with various nickel compositions) was then deposited.

The Au–Ni alloy was prepared by cosputtering from a rotating gold target partially covered with a piece of the alloying metal (Ni). The atomic percentage was then determined by the fractional target area the nickel occupies (in percent area or, equivalently, the angle $\theta$ in comparison to $360^\circ$) and its sputtering yield ($Y$) compared with that of gold. The required angle $\theta$ was calculated, as follows:

\[
\text{at.} \% \ A = \frac{Y_A \cdot \theta_A}{Y_A \cdot \theta_A + Y_B \cdot \theta_B} \tag{1}
\]

\[
\Rightarrow \theta = \frac{360^\circ}{1 + \frac{1 - \text{at.} \% \ A}{\text{at.} \% \ A} \cdot \frac{Y_A}{Y_B}} \tag{2}
\]

where $A$ and $B$ are the different materials. The sputtering yields of Au and Ni under Xe ion bombardment were taken from Ohring [18]. The in situ rotation of the target ensures the uniformity of the film composition. The films were patterned using standard photolithography to facilitate the four-point probe measurement of the contact resistance during the switching lifetime tests. Ion-beam etching thereafter was used to remove metal films from the uncovered area. N-methyl pyrrolidinone solution and deionized water were used, in sequence, to dissolve the photoresist layer and clean the sample, respectively.

Electrical resistivity data were obtained on as-deposited thin films (before patterning) using the four-point probe technique (MAGNE-TRON Model-700). A four-point sheet resistance correction [19] was applied. Microhardness data were obtained using a Hysitron Triboscope nanoindenter ( Berkovich indenter tip-142.5\° included angle). Surface topographic images were taken on the as-deposited thin films using a CPR AFM. Related software was used to obtain roughness statistics and height-profile analysis. A BRUKER AXS X-ray diffractometer was used to identify the sample structure. RIBER LAS-3000 X-ray photoelectron spectroscopy (XPS) was used to detect the surface chemical composition ($< 10$ nm). The takeoff angle was $\sim 75^\circ$ from the sample surface. A MAC-2 analyzer and Mg K\α (1253.6 eV) source were used in the experiment.

### III. Results and Discussion

Gold alloy lattice parameters obtained by X-ray diffraction (XRD) are shown in Fig. 3 for films of various Ni contents. As shown in Fig. 3, the lattice parameter (measured in the direction normal to the wafer surface) is plotted versus the expected Ni at.%, compared with values for bulk solid-solution alloys (represented by diamonds along the trend line) [20]. The room-temperature-deposited thin films (Fig. 3, triangles) show a larger than expected lattice parameter, consistent with the effects of compressive stress. A series of Au–Ni samples was deposited with 200 °C in situ heating. For these heated samples (Fig. 3, squares), the lattice parameter fits the bulk literature data quite well, indicating that the compressive stress can be minimized by moderate in situ heating. More importantly, we can conclude from the XRD data that all as-deposited samples yield the metastable solid-solution phase (no nickel peaks are observed) and that our Ni content calculation is correct as well.

In order to obtain the stable two-phase mixture, rapid thermal annealing (RTA) was conducted on some samples. Samples were heated at 600°C for 30 s in flowing N\_2 gas. XRD spectra, before and after RTA, are shown in Figs. 4 and 5, respectively. In the spectrum of the RTA sample, Au (111), Au (200),
The properties of the Au and Au–Ni alloys are summarized in Table I. It can be seen that the measured electrical resistivity and microhardness increase with increasing Ni content in the single-phase metastable alloys. Annealing the Au–Ni alloy (20 at.% Ni) to form the two-phase mixture significantly lowers the resistivity and hardness compared with the preannealed values.

The bulk resistivity is not the key parameter for the MEMS switches; rather, it is the contact resistance. We would like to gain some insight into the factors controlling this contact resistance. The relationship between force and contact resistance for gold-contact MEMS switches has been investigated by previous researchers [10], [21], [22]. For a contact radius greater than the electron mean free path, the Maxwell spreading resistance model can be used to calculate the contact resistance. In our test, the nominal contact radius is much larger than the mean free path in gold (≈36 nm); hence, the model should be valid. The contact resistance $R_c$ is described by

$$R_c = \frac{\rho}{2r_c}$$

where $\rho$ is the resistivity and $r_c$ is the contact radius [23]. While two different materials are in contact, the resistivity is estimated as the average of the two. The contact radius can be obtained using an asperity deformation model [22]

$$r_c = \sqrt{\frac{F}{\xi \pi H}}$$

where $F$ is the applied force, $H$ is the hardness of the material, and $\xi$ is the coefficient of the material deformation mode. Different modes are given as $\xi < 0.3$, elastic deformation; $0.3 < \xi < 0.75$, elastoplastic deformation; and $0.75 < \xi < 1$, plastic deformation.

As described elsewhere, the contact force in our test is about 150 $\mu N$/microcontact [15]. Plastic deformation is assumed based on this force over the hundred-nanometer-scale contact area. For the contact between different materials, which is the case in our experiments, the averaged hardness is used for the calculation. The electrical resistivity, microhardness, and the measured and calculated contact resistance data (against upper pure Au microcontacts) for the pure Au and Au–Ni samples are shown in Table I. The calculated and measured contact resistances are also shown in Fig. 6. As the electrical resistivity and microhardness increase with the Ni percentage, the model (calculated values) shows an increase of contact resistance.
resistance. The experimental contact resistance data roughly follow this trend. For pure Au samples, the experimental data fit the calculated contact resistance data quite well. However, for the Au–Ni metastable solid-solution series, the measured contact resistance is much higher than the calculated value. Two-phase Au–Ni samples (20 at.% Ni) showed a much lower contact resistance compared with the solid-solution alloy at the same composition. Furthermore, the model, in this case, again correctly predicted the measured contact resistance based on the physical properties of the films and the contact force.

Based on the analysis made earlier, it might be reasonable to suggest that, for the Au–Ni solid-solution series, the mismatch between the calculated and measured contact resistances is due to the fact that the roughness effect is not included in the model. To gain insight into this issue, a detailed topographic analysis was performed using AFM.

A series of AFM Au–Ni topographic images with grain height analysis and rms surface roughness data is shown in Figs. 7–11. Topographic and error images of a pure gold sample, a solid-solution Au–Ni (20 at.% Ni) sample, and a two-phase Au–Ni (20 at.% Ni) sample are shown, respectively, in Figs. 7–9, where height-profile line scans across the sample...
Fig. 12. Microcontacting tests on pure gold and Au–Ni alloys. Surfaces are also shown (note that the height scale bar in Fig. 6 is different from that in Figs. 7 and 8). The maximum height difference in the line scans and rms surface roughness data are shown in Figs. 10 and 11. The topographic analysis can be summarized as follows.

1) The metastable single-phase Au–Ni alloys show a marked trend of increasing roughness with increasing Ni content.

2) The rapid thermally annealed two-phase Au–Ni alloy (20 at.% Ni) shows an entirely different microstructure with a surprisingly reduced roughness compared with the preannealed state. The mechanism for the surface smoothing is not yet determined.

3) The Au and the two-phase Au–Ni alloy (20 at.% Ni) samples show comparable values of roughness despite very different microstructures and grain sizes. The similar values of contact resistance should also be noted.

Generally, it is assumed that rough surfaces yield lower contact areas than smooth surfaces. As a result, measured contact resistances for Au and two-phase Au–Ni samples fit quite well with calculated values, while solid-solution Au–Ni samples show a higher contact resistance than expected. This paper calls for a more advanced contact resistance modeling, in which the topology effect of the contact surfaces needs to be addressed. Recently, some progress has been made in this area [24].

It is an initially surprising result that the rapid annealing of a metastable solid-solution Au–Ni (20 at.%) sample resulted in a much smoother surface for the two-phase structure. Nevertheless, in the application of metal contacts for MEMS switches, this material processing method enables us to achieve a good combination of low surface roughness, low contact resistance, and increased material hardness.

Pure Au and Au–Ni thin-film test structures were subjected to the switching degradation tests. Hot-switching conditions were selected for the comparisons. The test conditions and unique electrical failure detection mechanism are as described in Section II. The test results are shown in Fig. 12, showing the closed-state resistance as a function of switching cycle (note that a test cantilever has two microcontacts; thus, the resistance in Fig. 12 is roughly twice the contact resistance values in Fig. 6). Failure is indicated by the contact resistance increasing toward the open circuit value. It is clear that the number of cycles before failure increases as the percentage of Ni in the alloy increases.

Typical worn microcontacts on the Au cantilever, as well as the corresponding bottom electrodes in the degradation tests of Au against Au and of Au against solid-solution Au–Ni (20 at.% Ni), are shown in Fig. 13. As indicated by the AFM pictures, the top electrode wear occurs predominantly on one edge, due to a small angle between the top and the bottom contacts. The bottom contacts show material that has been transferred from the upper dimple onto the lower contact. In the case of the Au–Ni alloy (which has seen more than twice as many cycles), this material is distributed over a slightly larger area than the case of pure gold. However, Fig. 13 also shows (and more convincingly confirmed in AFM analysis, not included) that the depression in the center of the contact area, presumably due to plastic deformation, is substantially less in the case of the Au–Ni alloy.

Information revealed by the test can be summarized as follows.

1) Low initial contact resistance was achieved for all the tests. A slight decrease of the initial contact resistance can be observed after a number of cycles. Notably, the contact resistance of solid-solution Au–Ni (20 at.% Ni) drops from the initial value of ∼3.5 Ω to the stable value of ∼1.8 Ω after a couple hundred switching cycles.
“burn-in” period is less obvious for all the other samples. The low initial contact resistance suggests that any surface contamination film is insignificant. The relatively large contact force (150 μN/microcontact) utilized in the tests, as well as the possible arc energy dissipation and transient current heating, may remove surface contamination. In the case of low-force cold switching of RF MEMS switches in ambient air, typically a higher initial contact resistance is observed [2], [25]. Contamination accumulated on the contact surface during cold switching might easily degrade the contact resistance by orders of magnitude.

2) Pure gold yields the lowest cycle number before electrical failure. Solid-solution strengthened Au–Ni alloys showed an increased cycle number with an increased nickel composition. The tradeoff for the extended lifetimes is a relatively higher contact resistance (~1.8 Ω). In the MEMS community, hot-switching failure is thought to be primarily caused by arc-induced material transfer or transient current heating. Mechanical wear is therefore thought to be a minor factor in the hot-switching failure process. However, our data indicate that strengthening the gold alloy substantially retards the contact failure process under hot-switch conditions. This might be an indicator that the arc/current-heating-induced material transfer could be affected by the mechanical properties of the contact materials. A more detailed investigation of the field-induced material transfer mechanisms is being reported elsewhere.

3) Two-phase Au–Ni yields the largest cycle number while providing a stable and acceptable contact resistance (~1 Ω). Compared with the solid-solution Au–Ni alloys, two-phase Au–Ni (20 at.% Ni) films have an intermediate hardness (4.1 GPa) while yielding a much larger contact area due to the film smoothness. However, the intermediate hardness of this material does not fit our original expectation that the switching reliability should increase with the hardness. Furthermore, the large contact area is expected to enhance the material adhesion on the contact surfaces, thus impacting the reliability. The excellent performance of the two-phase alloy, as well as the contrast to the trends displayed by the single-phase alloys, caused us to suspect surface-related effects. In order to investigate the chemical differences between solid-solution and two-phase sample surfaces, the chemical composition of the sample surfaces was examined using XPS, comparing the Au–Ni (20 at.% Ni) solid-solution and the Au–Ni (20 at.% Ni) second-phase precipitation samples.

Fig. 14(a) shows the XPS spectrum of the solid-solution Au–Ni (20 at.% Ni) alloy. The nickel composition is calibrated based on the Ni 2p peak. The nickel atomic percentage is ~11.7% (this value is only representative of the surface composition). Fig. 14(b) shows the XPS spectrum for two-phase Au–Ni (20 at.% Ni). The calibrated nickel composition on the surface is ~30.8 at.% in this case. The high-resolution XPS spectrum on two-phase Au–Ni (20 at.% Ni) is shown in Fig. 14(c). The dominant nickel species on the surface is identified as Ni$_2$O$_3$ from the Ni 2p 3/2 position [28], [29]. Therefore, the precipitation of nickel from solid-solution Au–Ni (20 at.% Ni) alloys might be described as follows. Upon RTA, nickel starts to precipitate from the gold-rich matrix. Moreover, nickel near the surface precipitates preferentially at the surface (as well as at grain boundaries) and is oxidized upon air exposure. The results of the XRD and XPS analyses, taken together with the Au–Ni phase diagram, indicate that, after the RTA processing, some nickel atoms should remain as solid-solution hardening additions to the Au, some Ni exists as Ni-rich precipitates at the nanoscale, and some Ni migrates and forms nanoscale oxidized Ni$_2$O$_3$ islands on the surface. This engineered microstructure, having unique surface and volume compositions and properties, showed the best contacting performance among all the Au–Ni samples. These results point toward the need to understand and control both the following when selecting materials for MEMS contact switch applications: 1) material composition and microstructure and 2) surface structure and properties.
IV. CONCLUSION

In this paper, a newly developed switching degradation test facility was used to evaluate Au–Ni alloys as contact materials for MEMS switches under hot-switching conditions. The experimental data shown in this paper provide a correlation between material properties (such as microhardness, electrical resistivity, surface topology, and surface microstructure) and microcontacting performance. In general, increasing the material hardness increases the switching reliability, compared with pure Au. However, surface roughness needs to be maintained below a certain level in order to avoid detrimental effects on contact resistance. It also has been shown that postdeposition RTA treatment results in a two-phase Au–Ni alloy, which significantly improves the microcontact performance based on its unique material properties. The presence of some Ni$_2$O$_3$ oxide at the surface appears to correlate with a longer switching lifetime. These results suggest that both material volume and material surface properties must be considered for optimizing the properties of alloy thin films for MEMS switching applications.

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REFERENCES


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