MECHANICAL CHARACTERIZATION OF GOLD THIN FILMS FOR RF-MEMS

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Abstract

Evaporated and electroplated freestanding gold films have been tested to determine their mechanical properties, specifically yield strength, ultimate strength, and ductility. The evaporated specimens were fabricated at two thicknesses, 0.5 and 0.65 microns, on a silicon substrate, and the electroplated specimens were deposited 2.5 microns thick on a quartz substrate. The films were loaded in a uniaxial microtensile tester at varying strain rates (10^{-2} - 10^{-6} s^{-1}) until failure. A finite element model of the specimen was used in conjunction with the displacement data to determine the strain imposed on the film, and these values were used to derive stress-strain curves. The electroplated specimens demonstrated a much higher ductility for the same strain rate than the evaporated specimens, with the ductility for the evaporated films varying from 2.0-4.7% for strain rates from 10^{-3}-10^{-6} s^{-1} and the electroplated from 5.6-10.6% ductility for similar strain rates. Yield and ultimate strength values were similar for the two fabrication techniques, and ultimate strength increased substantially with thickness for evaporated specimens. These films have applications in radio-frequency MEMS devices for use in space systems.

Introduction

The recent missions to Mars launched by both the United States and Europe signified the beginning of an exciting new period of space exploration. The new requirements associated with this endeavor make Microelectromechanical Systems (MEMS) a highly attractive and important technology for the aerospace industry. These micromachines have incredible advantages because they are small, lightweight, cost-effective, and operate on extremely low power. Their micron scale - smaller than the width of a human hair - makes them optimal candidates for applications in aerospace communication, navigation, and electronics. Numerous MEMS devices have been demonstrated to date, such as microsensors and actuators, microengines, high-frequency switches and filters for satellite and spacecraft communications, microgyroscopes and microaccelerometers for spacecraft navigation, optical switches for ultra-fast data transfer, microcantilever arrays for ultra high-density data storage, and even tiny satellites, no bigger than a tennis ball.[1]

Particularly of interest are thin metal films used in many MEMS devices and specifically in high-frequency radio transmission. Because of their small size and unique architecture, these microdevices, called radio-frequency (or RF) MEMS can operate at gigahertz frequencies allowing for incredible bandwidth and extremely high signal-to-noise ratios. Due to their high electrical conductivity, metals are ideal materials for such applications. Gold is particularly attractive for its chemical inertness, resisting both oxidation and corrosion. In MEMS devices, gold would be used in such small amounts that the material's high cost would no longer be a limiting factor, allowing designers to take advantage of its excellent properties.

Little research has been conducted on microscale gold, however, because it is not commonly considered an engineering material. In order for engineers to use gold in their MEMS designs, systematic tests of microscale gold components must be conducted to characterize the material mechanically. This research conducted such a test on microscopic gold specimens using a technique developed by Dr. Ioannis Chasiotis of the Mechanical and Aerospace Engineering Department at the University of Virginia. The goal was to determine elastic modulus, yield strength, ultimate strength, and ductility for gold thin film specimens fabricated through electroplating and electron-beam evaporation.

Current Research

Engineers have been testing MEMS materials for several years, and there is already a body of knowledge on the performance of metals in microtensile tests. Weihs *et al.* conducted some of the earliest tests on gold in 1988, using beam-deflection.[2] In 2000, Huang and Spaepen[3] found the moduli of copper, aluminum, and silver specimens, and Haque and Saif[4] studied yield strength in aluminum in a 2002 study. Only recently, however, has any significant research on gold been conducted. In 2002, Gudlavetti *et al.* performed microtensile tests on gold specimens to find an elastic modulus for the material.[5] Espinosa and Prorok used membrane deflection to test their gold specimens in 2003, obtaining modulus values much lower than those presented by Gudlavetti's group.[6] Even more recently, in 2004, Li and Cima used a different tensile technique called bulge testing to determine elastic modulus and yield strength for gold. They found a very high value for yield strength and modulus values higher than both of the former studies.[7]

For this research, uniaxial tensile tests were conducted via a custom-built microtensile tester. Uniaxial testing has a number of advantages over other testing techniques, such as membrane deflection or bulge-testing. First, the technique allows for direct and highly accurate determination of stress and strain. It also most accurately reproduces the stress environment the material will experience in applications. Most importantly, a uniaxial tensile test allows for the determination of a full stress-strain curve for the material, enabling the determination of additional properties, such as ductility. This paper, therefore, presents a more accurate testing technique than those previously used and consequently, more accurate results.

Gold Specimens

Specimens of two fabrication types were tested. Graduate students Jim Stanec and Charlie Smith in Dr. Scott Barker's Microfabrication Lab at the University of Virginia manufactured evaporated specimens specifically for this project. An evaporated specimen is shown in Figure 1. These specimens were manufactured at two thicknesses (0.5 and 0.65 microns) with a gauge section[1] width of 200 microns and a length of 1000 microns. Etch holes on the long, wide section (called the "paddle") were designed to ensure an even removal of the sacrificial layer beneath the specimen to prevent residual stressing of the film. The specimens are freestanding beams held down by five small tethers. These tethers prevent damage to the specimen prior to testing. The specimen is fully released from the substrate in a process called "probing," where a small tungsten wire is used to break the tethers, completely freeing the paddle and gauge section of the specimen from the substrate. The anchor portion (opposite end from the paddle) remains attached.

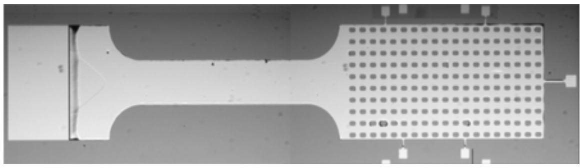

Figure 1: Evaporated thin film specimen, gauge truncated [taken by author]

The electroplated specimens, shown in Figure 2, were fabricated previously for another undergraduate, Daniel Koenigkann[8]; they were also fabricated in the Microfabrication Lab. These specimens were 2.5 microns thick with a gauge width of 50 microns and a length of 300 microns. The same five-tether design was used for the electroplated specimens. Both fabrication types were scanned with an atomic force microscope (AFM) to determine surface roughness. The electroplated specimens were very rough, with an RMS roughness of 350 nm. The evaporated specimens were much smoother, with an RMS roughness of only 5-6nm. Despite this difference in roughness, the grain size for both fabrication types was nearly the same. The evaporated grain size was found by AFM scanning to be 100nm, and the electroplated grain size was found with a scanning electron microscope (SEM) to be 150nm.

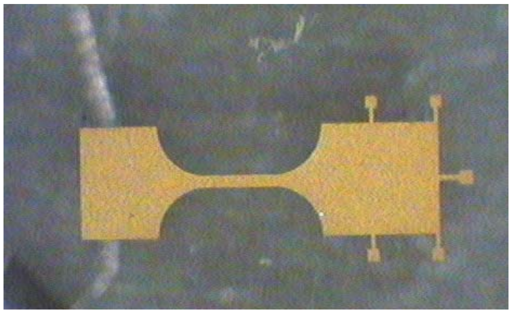

Figure 2: Electroplated thin film specimen[8]

Testing Techniques

The testing technique used in this research was developed by Dr. Ioannis Chasiotis and Dr. Wolfgang Knauss.[9] The specimen to be tested was first mounted onto a load cell. A small glass grip was glued to the paddle of the specimen using UV adhesive glue. The grip was attached to a piezoelectric actuator, which imposes displacement on the specimen while the load cell records the load. Tests were run at varying strain rates, from 10^{-2}-10^{-5} s^{-1} for the electroplated specimens and from 10^{-3}-10^{-6} s^{-1} for the evaporated. The displacement of the actuator was used to determine the overall displacement of the specimen, and this was used to derive strain values. Calibration tests were performed to factor out any displacement in the glue or other components of the apparatus, and this additional displacement was found to be negligible.

Discussion of Results

The experimental results are summarized in Figures 3-5. The charts show stress-strain curves for each specimen tested, with a separate chart for each thickness. Each curve color designates a different strain rate at which the test was run. Table 1 summarizes the numerical values from the plots.

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[1] The gauge section is the long, thin section of the test specimen. It is here that the specimen fails, and so this width is used for stress calculations.

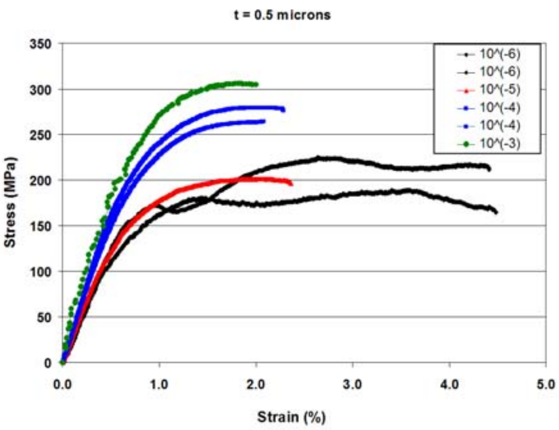

Figure 3: Stress-strain summary plot for evaporated specimens at 0.5 micron thickness.

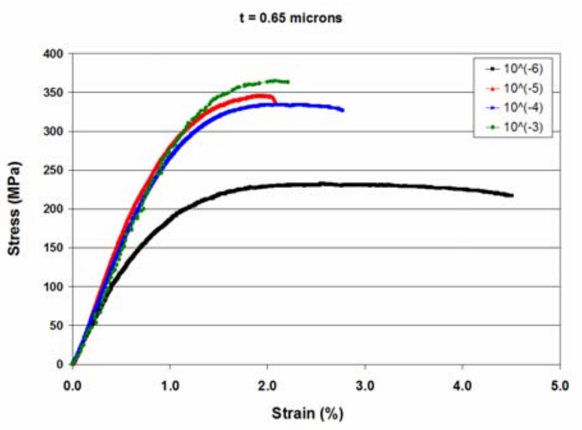

Figure 4: Stress-strain summary plot for evaporated specimens at 0.65 micron thickness.

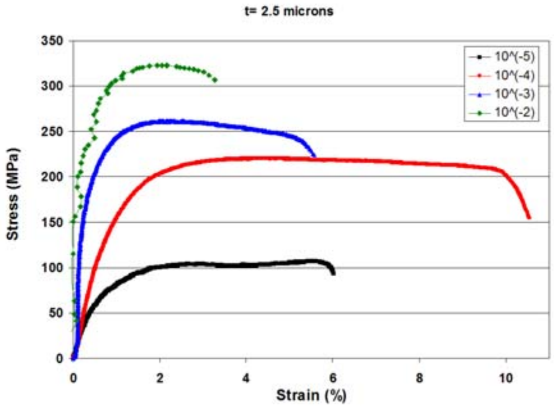

Figure 5: Stress-stain summary plot for electroplated specimens at 2.5 micron thickness

Specimen thickness (μm)/ Strain rate (s^{-1})	Yield Strength (MPa)	Ultimate Strength (MPa)	Ductility (%)
0.5/ 10^{-3}	240	302	2
0.5/ 10^{-4}	198	276	2.4
0.5/ 10^{-5}	210	200	2.4
0.5/ 10^{-6}	155	178	4.5
0.65/ 10^{-3}	300	365	2.2
0.65/ 10^{-4}	280	335	2.8
0.65/ 10^{-5}	233	288	2.3
0.65/ 10^{-6}	180	230	4.7
2.5/ 10^{-2}	270	320	3.4
2.5/ 10^{-3}	220	260	5.6
2.5/ 10^{-4}	155	220	10.6
2.5/ 10^{-5}	70	105	6

Table 1: Summary of stress-strain data

For the evaporated specimens, the ultimate strength clearly increased with thickness. For the films 0.5 microns thick, the strength varied from 178-302 MPa, and for the 0.65 micron thick films, from 230-365 MPa. This is a large jump in strength for such a small change in thickness, and it is consistent for each strain rate. The thicker, electroplated specimens, showed a much lower ultimate strength than would be expected based on the evaporated film results. In fact, the ultimate strength values for the electroplated specimens were as low or lower than the strengths for the thinner of the evaporated specimens, ranging from 105-320 MPa. The implication is that the ultimate strength of the film may be significantly affected by the fabrication technique. These results indicate that evaporated gold films are much stronger in terms of maximum allowable load than electroplated films.

Ductility values for the evaporated specimens were very similar over both thicknesses. Ductility is expressed as percent elongation at failure, or the amount of plastic deformation the specimen underwent as a percentage of the original specimen length. The 0.5 micron thick specimens had ductility values from 2.0-4.5%, and the 0.65 micron thick specimens ranged from 2.2-4.7%. Based upon these data, it would seem that thickness had little if any effect on the ductility of the material. The electroplated specimens, however, demonstrated considerably higher ductility, more than a factor of 2 higher than the evaporated values at 10^{-3} and $10^{-5}s^{-1}$ strain rates. The ductility more than tripled at the 10^{-4} s^{-1} strain rate. This increase in ductility can most likely be attributed to the fabrication technique, as the evaporated specimens indicated little thickness effect on ductility. The electroplating technique appears to produce the more ductile gold films.

Yield strengths for the 0.5 micron thick evaporated specimens varied from 155-240 MPa, and the 0.65 thickness had a range of 180-300 MPa; the 0.65 micron thick specimens had slightly higher yield strengths for the same strain rates (10^{-6} - 10^{-3} s^{-1}). The electroplated specimen values had a much larger spread, varying from 220 MPa down to a low of 70 MPa for strain rates 10^{-3} - 10^{-5} s^{-1}, but the values were mostly similar to the evaporated data. These values for yield strength agree well with literature values, most closely matching those obtained by Weihs[2] and Koenigkann.[8]

Conclusions

In this study, electroplated and evaporated gold films were mechanically characterized using a uniaxial microtensile tester. Yield strength values for both fabrication types were comparable in magnitude, but with the electroplated specimens having a much larger range of values. The electroplated specimens were found to be much more ductile than the evaporated specimens, and they had an ultimate strength comparable to the ultimate strength values for the thinnest of the evaporated specimens. It is clear from the evaporated specimen results that there is a significant thickness effect on ultimate strength, as the strength increased 20-40% for an increase in thickness of 0.15 microns.

The intention of this research was to provide engineers and designers with the mechanical data needed to use gold thin films in RF-MEMS designs. Based on these results, it is clear that the fabrication technique does have an effect on the film's mechanical behavior. Engineers should take this into account when designing device components. If an application requires high strength and low ductility, evaporated films would be best; if the application requires the opposite, lower strength but higher ductility, then electroplated films would be a better choice. If yield strength were an important parameter in the design (and it often is), it would be wise to use evaporated films, as they were proven to be more consistent in their yield strength.

Engineers also need to consider film thickness in their MEMS designs. Thicker films of the same fabrication type were shown to have a much higher ultimate strength than thinner films. If an RF-switch is designed to undergo high loading, a thick film should be used. Based on the results of this study, a small increase in thickness gives a large increase in maximum load. This is a desirable property, because thinner specimens are cheaper (they require less material) and lower mass, which allows them to vibrate faster than thicker films. Hopefully, these data will prove useful to MEMS designers, allowing them to create exciting new technologies for the next generation of space exploration.

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