## Contact resistance in flat thin films


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Contact Resistance in Flat Thin Films

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Abstract— MEMS-fabricated electrical contacts are commonly used in MEMS relays. These electrical contacts can be as simple as two flat surfaces coming into contact [1]. Modeling their contact force/resistance relationship can be difficult because much of the theory on contact resistance was developed for macro-scale contacts [2], and contact properties for MEMS-scale contacts do not always agree with those predicted by this theory [3]. One contribution to this disagreement is that when the dimensions of the contact thickness are on the order of the a-spot dimensions, the spreading resistance is affected [4]. In order to determine the relationship between contact force and resistance for a wide range of parameters, we have developed a two-coupon test system which allows the properties of these contacts to be empirically determined. The design of the two-coupon system allows for the rapid fabrication of multiple contact materials and geometries. The two-coupon system was used to test the contact resistance properties of sputtered and electroplated Au films in thicknesses of 0.1μm, 0.3μm, and 0.5μm. Contact force was measured using a custom flexural force gauge and the 4-point contact resistance was measured using an integrated Kelvin Structure [5]. The results are compared to traditional Holm theory to determine the effects of film thickness on spreading resistance.

Keywords- thin films; contact resistance

I. INTRODUCTION

Traditional contact theory assumes that when two surfaces meet at a single contact spot, the electrical current flow lines spread in all directions upon exiting the contact spot, as shown in Fig. 1a. Holm theory holds that the spreading resistance between these two surfaces is [2]

\[ R_s = \frac{\rho}{4a} + \frac{\rho}{4a} \]  

where \( \rho \) is electrical resistivity and \( a \) is the contact spot radius. However, in thin films, where the film thickness \( L \) is on the order of the contact spot radius \( a \), the geometry of the contact limits the current lines from spreading in all directions. Instead, the current lines must curve fairly rapidly, as shown in Fig. 1b.

Figure 1. a) The current flow lines between two bulk materials meeting at a contact spot as assumed in traditional contact theory. b) The current flow lines between two thin films meeting at a contact spot.

Several methods have been used to determine the effect of the ratio between contact radius \( a \) and film thickness \( L \), \( a/L \), on contact resistance. One method uses a mathematical model to predict the dependence of normalized contact resistance (as defined as the ratio between actual contact resistance and that predicted by Eq. (1)) on the ratio \( a/L \) [4]. This method theorizes that thin film geometry causes the spreading resistance to be constrained to a much smaller region than the region where the spreading resistance takes place in non-thin films. This method finds that the thin film affected normalized contact resistance is given by [4]

\[ R_N = \frac{4}{\pi} \sum_{n=0}^{\infty} \left( \frac{\coth(\lambda_n L/b) \sin(\lambda_n a/b)}{(J_1(\lambda_n))^{2}} \right) - \frac{2(a/L)}{\pi} \ln(b/a) \]  

where \( R_N \) is the normalized spreading resistance and \( b \) is the outer film radius for a cylindrical contact. These geometries are defined in Fig. 2. In Eq. (2) the argument for the Bessel function of the first kind of order 1, \( \lambda_n \), is
When a force is applied to two thin films in contact, the Holm radius \( a_H \) is given by the classic formula [2]

\[
a_H = \sqrt{\frac{F}{\pi H}}
\]

where \( F \) is force and \( H \) is hardness. Film thickness is not a factor in this equation; therefore, films having identical compositions but different film thicknesses will have identical values of \( a_H \) for a given applied force \( F \). Assuming that as with traditional Holm theory, this value \( a_H \) can be substituted for the constriction radius \( a \) when determining contact resistance, then the \( a/L \) values for any given applied force will decrease as film thickness increases. According to Fig. 3, when \( a/L \) decreases, normalized contact resistance will increase. Therefore, in this model, normalized contact resistance increases as film thickness increases.

Other work suggests that Holm theory actually underestimates contact resistance for thin films. In [6], it is pointed out that in the derivation of Eq. (1), Holm assumes the constriction depth is equal to the constriction radius. However, this is not applicable in films where the Holm radius is on the order of the film thickness. In [6], an FEM model was developed to look at the contact geometry shown in Fig. 4.

The simulations in [6] found that contact resistance decreased as film thickness increased over the range of \( L = 1-50 \). The \( a/L \) values investigated went as high as 30. Additionally, the contact resistance predicted for a film thickness of 1 \( \mu m \) at \( a/L = 5 \) was roughly 12 times that of Holm.

The mathematical model in [4] suggests that contact resistance increases with increasing film thickness, whereas the FEM in [6] suggests that contact resistance decreases as film thickness increases. Additionally, [4] predicts contact resistance below that predicted by Eq. (1), whereas [6] predicts contact resistance above that of Eq. (1). However, these two models looked at very different ranges. The model in [4] was limited to \( a/L < 0.5 \) whereas the model in [6] looked at much higher \( a/L \) values. However, the data shown in [6] only looked at film thicknesses where \( L > 1 \mu m \).

It is not immediately obvious how either of these models would perform outside of the ranges presented in [4] and [6]. Therefore, measurements were performed on film thicknesses of \( L = 0.1 \mu m, 0.3 \mu m, 0.5 \mu m \) and \( a/L = 0-17 \). The results were evaluated on their own as well as compared to those predicted by [4] and [6] in their respective ranges.
II. SAMPLE PREPARATION

A two-coupon system was used to measure the contact resistance between two films of multiple thicknesses of sputtered and electroplated Au. The system consists of a bottom silicon coupon having 1) a metal trace and 2) three spherical contacts as well as a top silicon coupon having 1) a metal trace, 2) a flexible membrane with a stiff center cylinder, and 3) three KOH etched pits. The coupons are assembled by placing the KOH etched pits of the top coupon over the spherical contacts of the bottom coupon. This type of assembly creates a pseudo kinematic coupling, allowing for repeatable positioning [7]. This system is described in detail in [5]. The assembly leaves a gap between the top and bottom metal traces. When a force is applied to the stiff cylinder in the center of the membrane, the membrane strains which brings the two metal traces into contact [5]. The traces are each 1mm wide. The diameter of the stiff cylinder in the center of the membrane is 4 mm making the overall apparent contact area 4mm². The metal traces create a Kelvin structure allowing for the isolation of the contact resistance. This assembly and Kelvin structure are shown in Fig 5.

![Image of assembled coupons and Kelvin structure](image)

The contact area in this case is rectangular, unlike the circular contact discussed in [4] and [6]. However, it is reasonable to believe the individual contact spots are round. A not-to-scale drawing of a few individual contact spots in relation to the rest of the trace is shown in Fig. 6.

For the experimental set up, the contact length \( l = 4 \text{mm} \) and the contact width \( w = 1 \text{mm} \) making the apparent area of contact 4mm². However, the Holm radius corresponding to the actual area of contact is on the order of 1-10 \( \mu \text{m} \). It is hypothesized that even though the macro-geometry is rectangular, the contact spots act locally much like those modeled in [4] and [6]. This is because \( a_H << w \) and \( a_H << l \).

Because of this inequality of scale, it is unlikely that the current flow lines immediately around the contact spots will be affected by the macro-geometry. However, it is acknowledged that this is an assumption and that there might be a small effect to contact resistance caused by the macro geometry which this paper does not account for.

Also considered was the true flatness of the contact. In designing of this fixture, achieving flatness was a top priority. The actual flatness across the contact can vary by as much as 200 nm. This means that there is a possibility of the contact rocking immediately after touchdown. No physical evidence of this rocking was seen under normal conditions; however, when a current greater than one Ampere was put through the contact, the contact did tend to fail along one edge, suggesting that the pressure may have been higher on that edge.

The sputtered coupons were prepared by sputtering a 0.03 \( \mu \text{m} \) Ti adhesion layer followed by 0.1 \( \mu \text{m} \), 0.3 \( \mu \text{m} \), or 0.5 \( \mu \text{m} \) of sputtered Au. An oxide layer insulated the Ti from the silicon substrate. Both the top and bottom coupons had identical films.

The electroplated coupons were prepared by sputtering 0.03 \( \mu \text{m} \) Ti adhesion layer followed by a 0.1 \( \mu \text{m} \) Au seed layer. On top of this seed layer, 0.1 \( \mu \text{m} \), 0.3 \( \mu \text{m} \), or 0.5 \( \mu \text{m} \) of additional Au was plated. Again, an oxide layer isolated the traces from the silicon substrate and both the top and bottom coupons had identical films.

Due to the difficulty in measuring the hardness of films with thicknesses less than 1 \( \mu \text{m} \), the hardness of the sputtered film was approximated as 3.5 GPa and the electroplated films as 1 GPa [8, 9]. The surface roughness of the sputtered films
was found to be about 6 nm while the surface roughness of the electroplated films was found to be about 14 nm.

The resistivity of the sputtered samples was measured as \( \rho = 4.27 \times 10^{-8} \, \Omega \cdot m \). This value was consistent across all three thicknesses of the sputtered film samples. This is significantly higher than the bulk resistivity of Au. Sputtered films are known to have a higher than bulk contact resistivity [10]. Resistivity can be affected by various mechanisms such as temperature, electron surface scattering, impurities, intragranular defects, and scattering at grain boundaries [10]. It has also been shown that in thin sputtered Au films with an adhesion layer of Ti, the Au and Ti can form an alloy of significantly higher resistivity [11]. The resistivity of the electroplated samples was also measured. Taking into account the resistivity of the seed layer as a parallel resistance, the resistivity of the adhesion layer of Ti, the Au and Ti can form an alloy of higher than bulk resistivity of Au. Sputtered films are known to have a higher than bulk contact resistivity [10].

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### III. Testing and Results

#### A. Testing Procedure

During the experiment, a force gauge compressed the top membrane bringing the two metal traces into contact, as shown in Fig. 5. The overall displacement of the membrane, the force, and the contact resistance were recorded throughout the test. When the membrane stopped moving, contact was made. This also corresponded to the first time finite contact resistance was seen since no oxides or films impeded current flow. This is the point where the contact sees zero force. After this point, force was further increased to 10 mN. The current was sourced at 5 mA and 4-wire resistance was measured using a Keithley 2420 source measure unit.

#### B. Sputtered Film Results

The contact resistance as a function of contact force was measured for the three thicknesses of sputtered Au films. The results along with the values calculated by traditional Holm theory using Eq. (1) and Eq. (5) are shown in Fig. 7. The resistivity used to calculate the Holm prediction was the measured resistivity of the sputtered film, \( 4.27 \times 10^{-8} \, \Omega \cdot m \).

The results show contact resistance decreasing as film thickness increases. The 0.1 \( \mu \)m and 0.3 \( \mu \)m films both showed significantly higher contact resistance than that predicted by Eq. (1). The 0.5 \( \mu \)m film showed slightly lower contact resistance than the Holm theory. When contact force was increased significantly, contact resistance did drop below 1 m\( \Omega \), indicating that there is no significant bulk resistance in the test setup. The force gauge is accurate within 10\( \mu \)N and the resistance measurement is accurate to approximately 20\( \mu \Omega \). These results have a similar trend to the FEM presented in [6]. In both cases, the contact resistance decreases with increasing film thickness. However, the results of [6] showed a significantly higher overall contact resistance than seen in these experimental results.

These same results are shown plotted as normalized contact resistance \( R_N \) vs. \( a/L \) are shown in Fig. 7. The normalized contact resistance is the measured resistance divided by the resistance predicted by Holm theory. The \( a \) value is calculated from Eq. (5) using the approximated hardness of 3.5 GPa.

At values of \( a/L > 1 \), there is a clear trend of increased normalized contact resistance as \( a/L \) is increased. This trend appears somewhat linear. However, at values of \( a/L < 1 \), this trend does not exist. In this region, the normalized contact resistance drops below 1. It makes sense that the relationship between normalized contact resistance and \( a/L \) would be different in this range. At values of \( a/L < 1 \), the Holm radius is less than the film thickness. However, at values of \( a/L > 1 \), the Holm radius is greater than the film thickness.

One interesting note is that [4] shows a decreasing normalized contact resistance with increasing \( a/L \) in the region of \( a/L < 0.5 \), just as the experimental data shows a decreasing normalized contact resistance with increasing \( a/L \) in the region.
of $a/L < 1$. Unfortunately, the force gauge used was rather course; so, it is difficult to look at the experimental results where $a/L < 0.5$ and, therefore, difficult to directly compare these results.

C. Electroplated Seed Layer Correction Factor

Determining the contact resistance for the plated Au was slightly more difficult because of the added effects of the seed layer. Traditional contact resistance theory models this added resistance as shown in Fig. 9a. However, this model assumes all of the current lines travel into the seed layer. In this test setup, as shown in Fig. 9b, only a portion of the current flow lines travel into the seed layer. In traditional modeling, the additional resistance $R_a$ of the transition from the electroplated Au into the sputtered seed layer would be [12]

$$R_a = \left(\frac{8}{\pi}\right)\left(\frac{\rho_p}{\rho_s}\right)\frac{L}{a} \quad (8)$$

where $\rho_p$ is the resistivity in the plated region, $\rho_s$ is the resistivity in the sputtered region, $L$ is thickness of the electroplated region, and $a$ is the Holm radius. However, the fraction of current that actually travels in the bulk $R_{s\%}$ is defined as

$$R_{s\%} = \frac{1}{\left(\frac{\rho_p}{L_p}\right) + \left(\frac{\rho_s}{L_s}\right)} = \frac{\rho_p / L_p}{\rho_p / L_p + \rho_s / L_s} \quad (9)$$

where $l$ and $w$ are the length and width of the bulk contact trace. Therefore, an approximation of the additional resistance added by the transition from the plated region to the sputtered region $R_{ac}$ is

$$R_{ac} = R_s/R_a \quad (10)$$

Therefore, the contact resistance for the plated films $R_{cp}$ is

$$R_{cp} = R_m - R_{ac} \quad (11)$$

where $R_m$ is the resistance measured in the Kelvin structure. All of the results for the electroplated films have been corrected to remove the additional resistance added by the transition from from the plated region to the sputtered region.

D. Electroplated Film Results

Three thicknesses of plated Au films were tested. The results along with the values calculated by traditional Holm theory using Eq. (1) and Eq. (5) are shown in Fig. 10. The resistivity used to calculate the Holm predictions was the measured value of 2.18 x 10^{-8} \Omega m. As with the sputtered films, contact resistance increased for thinner electroplated films. All three film thicknesses had contact resistances higher than those predicted by Holm theory. Once again, this increase in contact resistance with decrease in film thickness corresponds to the trend seen in [6]; however, the magnitudes of contact resistance are still lower than those seen in [6].

![Figure 10. Contact resistance of plated thin Au films and the contact resistance predicted by Holm Theory.](image_url)
This plot shows that normalized contact resistance tends to increase with $a/L$ for $a/L > 1$. While the normalized contact resistance does not drop below 1 at low values of $a/L$, as it does in the sputtered films, it does exhibit a downward trend in the region $a/L < 1$ similarly to how normalized contact resistance decreases with $a/L$ in the region $a/L < 0.5$ in [4]. However, there is not enough experimental data in the range of $a/L < 0.5$ to make a direct comparison to the theory presented in [4].

Finally, the relationships between normalized contact resistance and $a/L$ for both the sputtered films and the electroplated films were plotted together, which is shown in Fig. 12. In both cases, the trend in normalized contact resistance shifts around $a/L = 1$. This may be because at this point, there is minimal spreading and constricting of the current flow lines.

IV. SUMMARY

A two coupon system was used to measure the effect of the ratio between contact area and film thickness on contact resistance. The contact resistances between sputtered Au films as well as between electroplated Au films were measured. The resulting contact resistances were higher than those predicted by Holm theory. Their normalized contact resistances were compared to the ratio between the Holm radius and the film thickness, $a/L$. In high ranges of force, contact resistance increased with decreasing film thickness. The normalized contact resistance proved to be dependant on $a/L$. For high values of $a/L$, contact resistance increases with $a/L$, similarly to the trend seen in [6]. For low values of $a/L$, the contact resistance decreased with $a/L$, similar to the trend seen in [4]; however, there is insufficient data to make far reaching conclusions about this portion of the data. It is clear that this relationship has two distinct regions. In the first region where $a/L < 1$, normalized contact resistance decreases with increasing $a/L$. This is where the Holm radius is less than the film thickness. In the second region where $a/L > 1$, normalized contact resistance increases with increasing $a/L$. This is where the Holm radius is greater than the film thickness. The exact mechanism for this transition is not completely understood. Future work will include looking at the region where $a/L < 0.5$ with a finer force gauge to see how closely these results match those seen in [4] as well as looking closely at the region near $a/L = 1$ to investigate the transition from the area where Holm radius is less than film thickness to the area where Holm radius is greater than film thickness.

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