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Improved Micro-Contact Resistance Model that Considers Material Deformation, Electron Transport and Thin Film Characteristics

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# SECTION I. Introduction

Micro-switches exhibit superior performance and are expected to be direct replacements for field effect transistors (FET) and PIN diode switches for radio frequency (RF) applications. In order to accommodate this expectation, high-performance, high reliability, micro-mechanical devices, capable of billions of switching cycles, are needed for RF micro-electro-mechanical systems (MEMS) applications.1

Predicting micro-switch performance (i.e. contact resistance) is an important design tool routinely used by macro switch engineers. Modeling contact resistance, using Holm's theory, is typically a first step when designing a macro relay.2 For micro-switch engineers, however, the design task is more difficult because Holm's theory cannot be directly applied. This is primarily because the available contact force, when using micro-switches, is very low and cannot guarantee excellent performance when using traditional contact materials. In addition, micro-contact resistance theory is generally not well understood and therefore contact resistance predictions typically do not match measured data exactly.3 This gap between modeled and measured data is often attributed to contaminant films being present on the micro-contact's surface and not inadequacies in the theory.

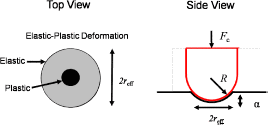
Because of the contact force limitation, micro-switches are often fabricated using thin film gold contacts due to gold's relatively high conductivity and low material hardness. The low hardness value enables reasonable micro-switch performance despite the low contact force. Unfortunately, micro-switches with gold contacts also tend to fail either closed or by developing elevated contact resistance with increased switching cycles. The physics behind these two failure modes is also not well understood, but appears to be related to contact force and how the contact surface evolves. Attempts by designers to increase contact force (and lower contact resistance) by optimizing mechanical switch designs often leads to accelerated degradation and unacceptable device reliability. This is summarized by the observation that while higher contact force results in better performance, when using relatively soft contact materials, it also reduces device reliability due to adhesion or degraded performance.

In an attempt to improve micro-switch reliability, some research groups have investigated using harder contact materials such as platinum, “platinum group”, gold alloys4–5,6 and more compliant contact materials like CNTs.3 Recently, it was reported that RF MEMS switches have been tested to more than 1.4 trillion cold-switched cycles.7 The devices were tested in a packaged, hermetic environment to minimize contaminant films and the specific electric contact material was not discussed. Although, device reliability was excellent, micro-switch contact resistance performance predictions were not published hinting at a heuristic design approach. In other words, the mechanical design, extremely hard contact materials and parallel contacts were all used to “engineer away” the above failure modes and compensate for not fully understanding the micro-contact physics. Although this is a reasonable approach right now, improvements to micro-contact resistance modeling and micro-switch reliability theory will ensure future breakthroughs. Additionally, reliability models, based on accelerated test methods, will be extremely beneficial for predicting micro-switch lifetimes while minimizing valuable test time. The following section develops an improved micro-contact resistance model for better predicting micro-switch performance.

# SECTION II. Improved Micro-Contact Resistance

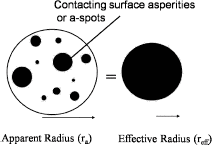
## A. The Baseline Analytic Model

The baseline micro-contact resistance model used here was previously derived by the author and accounts for material deformation and electron transport.6 An elastic-plastic (EP) material deformation model was used to account for the higher contact pressure developing at individual a-spot peaks despite the low contact forces being generated by typical micro-switches (i.e. tens of ). Fig. 1 depicts the hemispherical upper and planar lower contacts and the EP model used in this study.



**Figure 1.**Elastic-plastic material deformation model: hemisphere and plate contact pair.

The baseline model also assumes that the contacting a-spots were sufficiently close together and dependent thereby justifying a single effective a-spot conducting area model shown in Fig. 2.



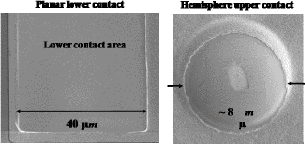
**Figure 2.**Single effective a-spot model.

Equation [1](https://ieeexplore.ieee.org/document/#deqn1) is used to calculate the effective radius of an EP a-spot,6

(1)

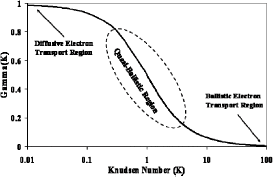
Where,  is a-spot vertical deformation and  is the critical deformation where EP deformation begins.

This single effective a-spot assumption was further justified by using sputtered and co-sputtered thin film contacts with exceptionally low measured surface roughness values 0 ∼ 30–50 Å) and tightly packed material grain structures (∼50 nm in diameter). The low surface roughness was measured using AFM and is qualitatively observed visually in Fig. 3 which shows a fabricated micro-switch contact pair.



**Figure 3.**Hemisphere and planar micro-switch contact pairs with low surface roughness.

Based on the radius of the conducting area, and how it compares with the mean free path of an electron, current flow can be described as ballistic, quasi-ballistic or diffusive. Mikrajuddin, et al. derived a gamma function, shown in Fig. 4, that is ideally suited for micro-contact resistance modeling.8



**Figure 4.**Plot of Mikrajuddin et al.'s derived Gamma function.

Holm's theory, based on diffusive electron flow, accurately predicts macro switch contact resistance but under predicts micro-switch contact resistance. Majumdar et al. addressed this by using Sharvin's equation (2) for resistance based on ballistic electron transport.9,10

(2)

where the Knuden, , is defined by .

The naming convention used in this paper describes the particular electron transport region and how the contact material is deforming. For example, (2) above is a contact resistance equation used to calculate ballistic transport  due to EP deforming contacts .

Wexler connected the diffusive and ballistic electron transport regions using a Gamma function to “toggle” between the two regions.11 This model well represents micro-switch behavior, in that, micro-contacts are generally not large enough to support complete diffusive transport nor are they usually small enough to support only ballistic transport. This is true especially when using the single effective area model because of a-spot dependence. In other words, because the area is summed, the smaller portions of the overall area will support ballistic transport and the larger portions of the overall area will support diffusive transport. Clearly, Wexler's interpolation (3) is appropriate when using the single effective area model. The only question is how to set the Gamma function to accurately represent a real device. This will be estimated by considering measured surface roughness and actual contact area.

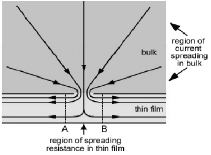
(3)

The baseline EP model, summarized above, neglected the effects of using thin film electric contact materials and attributed differences between modeled and measure data entirely to contaminant films.6 Yunus et al. identified this oversight and theorized that thin film effects were, in part, responsible for the differences.3 Kwon et al., however, concluded that differences between modeled and measured data, when using soft thin film contacts, were due to a relatively hard underlying substrate that limited contact area growth with increased contact force.12 This could be the case when high contact force (i.e. several mN's) is used in conjunction with thin contact films. In a typical MEMS device, however, the available contact force is usually limited to 100–200 *µN*. The difference between measured data and modeled predictions is most likely due to a combination of contaminant film resistance and distorted constrictions, due to thin film spreading resistance, not being considered.2,13

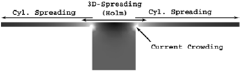
## B. Thin Film Improvements

Often times, in micro-switches, the radius of the effective contact area is dimensionally similar to the actual electric contact film thickness. Fig. 5 depicts typical current flow lines that originate in a bulk region and flow into a thin film region.13

The sharp curving of the current flow lines result in a “thin film” effect that is analogous to the well known “skin” effect observed in high frequency microwave systems.14 In addition to theoretical consideration, increased contact resistance due to thin film spreading resistance has been experimentally verified.3 Based on the discussion above, the baseline analytic model was modified to incorporate the effects of thin films, current crowding and distorted constrictions shown in Fig. 6.14



**Figure 5.**Schematic comparison of the region of spreading resistance in a solid conductor with the corresponding region in a thin film conductor.13



**Figure 6.**Regions of different spreading resistance contributions.14

Norberg et al. analytically modeled Fig. 6 as the algebraic sum of the Maxwell-Rayleigh spreading resistance in a cylinder, corrected for non ideal current flow (4), and the resistance due to a radial current that is spread into a thin film cylinder (5). It was recognized, however, that this approach resulted in a spreading resistance overestimation due to both models making similar contributions.14 To avoid this overestimation, each of the terms in (6) was weighted with a coefficient function that was determined using finite element analysis (FEA). The resulting equation (6) is an approximation for the spreading resistance exhibited by the model shown in Fig. 6 where the weighting coefficients,  and , are functions of both film thickness (d) and effective a-spot radius . Equation (5) does not account for the contact film “thinning”, observed by Kwon, et al., so an additional variable, α (i.e. vertical a-spot deformation), was subtracted from,  (i.e. film thickness) in (5)resulting in (7).

(4)(5)

where  is the outer radius of modeled thin film cylinder shown in Fig. 6 and 7.

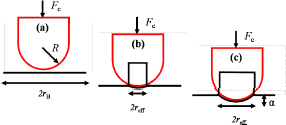
(6)

(7)

Equation (8) is used, in the model presented here, as the basis for the diffusive current flow in micro-contacts because it accounts for previously not considered “thin film” effects.

(8)

In a typical micro-switch contact area pair, the upper contact can be considered a long constriction due to its overall thickness (i.e. 5–7  is typical) because it is physically part of the mechanical structure of the beam.2 The lower contact, however, is best described as a distorted constriction due to its relative thickness (i.e. 500 nm).2 In addition, RF MEMS switch lower contacts are usually deposited on highly resistive substrates to enhance RF performance which exacerbates the “thin film” effects exhibited by the lower contact. Fig. 7 depicts how the single effective area and Norberg's thin film effects models apply to micro-switch electrical contacts.



**Figure 7.**Norberg's thin film spreading resistance model applied to a micro-switch contact pair. (a) prior to making contact (b) Initial contact, upper contact modeled as a cylinder (c) The upper contact cylinder's volume increases with increased contact force.

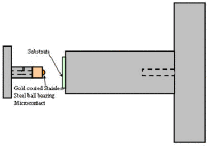
## C. The Improved Analytical Model

The improved micro-contact resistance model is based on (3) that accounts for EP material deformation and for electron transport. The ballistic term is given by (2) and the diffusive term, which accounts for thin film effects, is given by (8) with (7) substituted for  and  (1) substituted for effective radius. The Gamma function is represented by Fig. 4 and the weighting coefficients,  and , are taken from FEA data plots provided in.14 Modeled and measured data will be compared later.

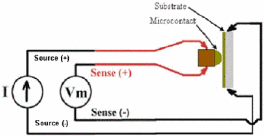
# SECTION III. Test Set-up and Results

A modified nano-indentation apparatus, shown in Fig. 8, was used to test micro-contacts by applying low contact force  while simultaneously measuring contact resistance. A hemisphere-shaped upper and a planar lower contact pair were used during testing.3

A Keithly 580 micro-ohmmeter was used to apply a constant DC current (1 mA) while measuring voltage in the four-wire contact configuration depicted in Fig. 9.3



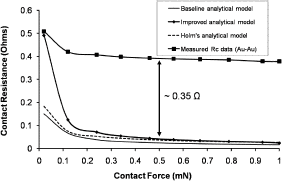
**Figure 8.**Schematic of Modified Nanoindentor.3



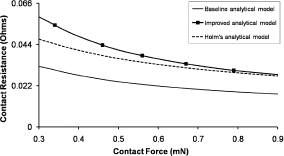
**Figure 9.**Schematic of contact zone with its electrode and CR measurement.3

The micro-contacts were brought into contact at a controlled rate of 0.2 *mN/sec* until the maximum targeted load was achieved. The applied load was then held for 10 sec to ensure that a peak load resistance was measured. The micro-contacts were then unloaded at the same rate until separation was achieved.3 Fig. 10 compares measured contact resistance data to predictions made using Holm's model for plastically deformed a-spots,2 the baseline analytical model6 and the improved analytical models discussed previously. The baseline and improved analytical models were based on EP material deformation and assumed 2% plastic deformation. The baseline model predictions assumed complete diffusive transport  while the improved model used Mikrajuddin, et al.'s Gamma, shown in Fig. 4, to “toggle” between ballistic and diffusive electron transport.8 In addition, the improved model implemented thin film considerations developed by Norberg, et al.14 At 0.5 mN, Fig. 10 shows a consistent  difference between the measured and modeled data. This anomaly was, most likely, due to a measurement bias error and was not attributed to contaminants on the gold electric contact films. This hypothesis is substantiated since all the analytical models converge at elevated contact force values.

Fig. 11 depicts the portion of Fig. 10 between 0.3 mN and 0.9 mN and reveals several key results. First the baseline model predicts contact resistance that is approximately 16  lower than Holm's plastic deformation-based model. This is due to the baseline model's Gamma function being fixed to predict 100% diffusive electron transport.



**Figure 10.**Measured and modeled contact resistance data for Au-Au micro-contacts.

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**Figure 11.**Comparison between the baseline, improved and Holm's contact resistance models.

Normally, the baseline model predicts micro-contact resistance that is “slightly” higher  than Holm's model when ballistic transport is included. Next, at approximately 0.5 mN of applied contact force, the improved model predictions are approximately  higher than Holm and approximately 20  higher than the baseline model (due to the Gamma function choice). Also, when the applied contact force is greater than 0.5 mN the improved and Holm models converge by approximately 0.9 mN while the baseline model converges with Holm at a much slower rate. The convergence of all these models at elevated contact forces is a positive indication that the lower contact force predictions (for which the new models were derived) are useful.

# SECTION IV. Conclusions

The purpose of this work was to improve a previously developed analytic micro-contact resistance model. Previous differences between modeled and measured data were attributed to contaminant films. In the improved model, thin film characteristics are included to improve modeling accuracy. Overall, the improved micro-contact resistance model closely predicts actual micro-switch behavior and the resulting modeled data matches the measured data.

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