Influence of The Sticking Effect on The Contact Resistance of a MEMS DC-Contact Switch

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Abstract: An improved model of the contact resistance in a MEMS DC-contact switch is presented and the sticking effect is included. In this model, the JKR theory is used to determine the sizes of contact spots and the electrical contact theory is used to estimate the contact resistance. The relationship between the contact resistance and the applied force has been investigated in different cases for a common Au-Au contact. The results suggest that the contact resistance is related to the applied force, the number of asperities, and the surface energies of contact materials. However, the height distribution of asperities has little influence on the contact resistance. The comparison between the improved model and the measurements that have been reported suggests the sticking contact model is more reasonable than the elastic contact model especially at low applied forces.

1. Introduction

MEMS DC-contact switches have received increasing attention in recent years because of their low power consumption, low insertion loss, high isolation and the ability to be integrated with other electronic devices. The typical structure of the MEMS DC-contact switch consists of an all-metal cantilever and three electrode terminals which are respectively called “source”, “gate” and “drain” (Figure 1). At the free end of the cantilever there is a bump placed on the bottom surface. The cantilever is pulled down when an actuating voltage is applied between the gate and drain terminals, and the electrical contact occurs between the bump and the drain electrode.

**Figure 1.** The schematic of a MEMS DC-contact switch (Top view and lateral view)
Contact resistance is one of the most important parameters used to describe the performances of the MEMS DC-contact switch. Some other parameters such as the scattering parameters, the power handling ability and the reliability are also affected by the contact resistance\textsuperscript{1}. There’re two components that contribute to the contact resistance, namely the constriction resistance and the film resistance. Because of the roughness of contact surfaces, only a few asperities will make the real contact and form some contact spots called “a-spots”. The constriction resistance occurs as current flowlines constrict at the a-spots while the film resistance is created by thin insulation layers on the contact surfaces.

A model of the contact resistance has been reported by Majumder et al.\textsuperscript{2}. The model is based on an elastic-plastic contact of a rough surface with a plat plane and the contact resistance contains only the constriction resistance. The model agrees with the experiment at large applied forces; however, it overestimates the contact resistance at low applied forces. It is well known that the effects of surface forces are significantly important in the MEMS domain\textsuperscript{3}. Therefore the sticking forces should be taken into account. This paper proposes an improved model of the contact resistance which considers the sticking effect to clarify the characteristics of the electrical contact behavior of the MEMS DC-contact switch at low applied forces.

2. Improved model of the contact resistance

The model of the contact resistance is derived with the help of the technique applied by Majumder et al.\textsuperscript{2}. The JKR theory is then used to correct the discrepancy aroused by the sticking effect at low applied forces. The final purpose of this paper is to obtain a relationship between the contact resistance and the applied force. Firstly, the sizes of a-spots are determined by the applied force. Subsequently, the contact resistance is estimated by these sizes.

2.1. Geometric model of the contact surfaces

A closer look at the contact surface reveals that the surface is actually rough and is made up of a lot of asperities. The assumptions of the topographies of two opposite contact surfaces are as follows:

- One of the contact surfaces has some amount of roughness and the other is flat. This is reasonable because in many cases, two opposite contact surfaces have different roughness and one is much more flat than the other.
- The rough surface is idealized as a flat plane with some asperities.
- All asperities have the same tip radius and their heights follow a certain normal distribution.

2.2. Calculations of the contact area

The well known Hertz theory is commonly used to describe the elastic contact in macro devices. However, in the scales of MEMS devices the sticking effect should not be neglected. The sticking effect is a complex phenomenon. It may involve the interatomic bonding forces, the Vander Waals forces, the Casimir effect and so on. The surface energy is the parameter used to characterize the sticking effect.

![Figure 2](image-url)

**Figure 2.** The contact of an asperity with a plat plane: (a) before contact; (b) after contact
Consider a single asperity contact with a plat plane as shown in Figure 2, and assume both contact materials are identical. According to the JKR theory the relationship between the contact radius $a$ and the applied force $F$ is as follows:

$$ F = \frac{4E'a^3}{3R} - 4\left(\pi\gamma a^3\right)^{1/2} $$  \hspace{1cm} (1)

with

$$ E' = \frac{E}{2(1-\nu^2)} $$  \hspace{1cm} (2)

where $R$ is the tip radius of the asperity, $\gamma$ is the surface energy of the contact material, $E$ is the Young’s modulus and $\nu$ is the Poisson coefficient.

Both the sticking contact (JKR model) and the elastic contact (Hertz model) are calculated. The vertical deformation can be expressed as a function of the contact radius:

$$ w = \frac{a^2}{R} - 2\left(\frac{\pi a}{E'}\right)^{1/2} $$  \hspace{1cm} (3)

While $\gamma=0$, all above relationships degenerate to the Hertz theory. Considering an Au-Au contact with $R=100$nm, the differences between the elastic contact and the sticking contact are shown in Figure 3.

2.3. Estimations of the contact resistance

Assume the contact surfaces are clean so that the contact resistance is equivalent to the constriction resistance. For a single a-spot separating two semi-infinite conductors, the Holm theory predicts the contact resistance $R_c$ given by:

$$ R_c = \frac{\rho}{2a} $$  \hspace{1cm} (4)

where $\rho$ is the resistivity.

For a multiple-spot contact, the contact resistance is not only related to the radii of all a-spots but also related to the distribution of these spots on the contact interface. Given the number of the a-spots is $n$ and each a-spot has a radius of $a_i$, the contact resistance reaches the minimum $R_{c,MIN}$ when the radii of these a-spots are small compared to the separations between them:

$$ R_{c,MIN} = \frac{\rho}{2\sum_{i=1}^{n} a_i} $$  \hspace{1cm} (5)
If the radii of the a-spots and the separations are comparable, the current flowlines through different a-spots will impact each other so that the contact resistance increases. While all the a-spots are close enough to converge into a single spot the maximum of the contact resistance $R_{c\text{MAX}}$ is arrived at:

$$R_{c\text{MAX}} = \frac{\rho}{2 \left( \sum_{i=1}^{n} a_i^2 \right)^2}$$  \hfill (6)

In MEMS devices, the sizes of a-spots are much smaller than those in macro devices so that the dimension effect should not be neglected. If the sizes of a-spots are smaller than the mean free length, the resistance increases because of the scattering of electronics. According to the Maxler theory for a single spot contact, the contact resistance should be corrected as:

$$R_e = \frac{\rho}{2a} \Gamma \left( \frac{l_e}{a} \right) + \frac{4\rho l_e}{3\pi a^2}$$  \hfill (7)

where $\Gamma$ is a function of $l_e/a$. While $l_e/a < 1$, $\Gamma \approx 1$; while $l_e/a > 1$, $\Gamma \approx 0.69$.

Equation (6) and Equation (7) are corrected as follows:

$$R_{c\text{MIN}} = \left( \sum_{i=1}^{n} \left( \frac{\rho}{2a_i} \Gamma \left( \frac{l_e}{a_i} \right) + \frac{4\rho l_e}{3\pi a_i^2} \right) \right)^{-1}$$  \hfill (8)

$$R_{c\text{MAX}} = \left( \frac{\rho}{2} \sum_{i=1}^{n} \frac{1}{a_i^2} \right) \Gamma \left( \frac{l_e}{\frac{1}{\sum_{i=1}^{n} \sqrt{a_i^2}}^2} \right) + \frac{4\rho l_e}{3\pi \left( \frac{1}{\sum_{i=1}^{n} \sqrt{a_i^2}} \right)^2}$$  \hfill (9)

2.4. Calculation steps

To find out the relationship between the contact resistance and the applied force, follow the steps below:

- Assume the number of asperities on the rough surface is $n$ and all asperities have the same tip radius $R$.
- Let the heights of asperities follow a certain normal distribution and generate a group of random values of the heights.
- Suppose the vertical deformation at the highest asperity is $w$ and the largest height is $h$ so that the vertical deformation at another asperity with a height of $h_i$ can be expressed as $w_i = \begin{cases} h_i - w & \text{if } h_i > h - w \\ 0 & \text{if } h_i \leq h - w \end{cases}$.
- Treat $w$ as an intermediate variable. The overall applied force is equal to the sum of the force applied on each asperity. The relationship between the sizes of a-spots and the overall applied force can be determined by Equation (1) and Equation (3).
- The contact resistance can be estimated from the sizes of the a-spots by Equation (8) and Equation (9).
- Combine the above two steps so that the relationship between the contact resistance and the applied force can be determined.
- Given the same normal distribution as above, generate a new group of random values and repeat the calculations above again. Average the results after 50 times repetitions.

3. Results and discussions

Since Au is a commonly used contact material in MEMS DC-contact switches, now consider the case of an Au-Au contact. There are three parameters that may affect the contact resistance, i.e. the number of asperities, the distribution of asperity heights, and the surface energies of contact materials.
Figure 4. Relationship of the contact resistance and applied force as the bump has different numbers of asperities. Each asperity has a radius of 100nm and the height distribution of the multi asperities follows \( N(100\text{nm},(50\text{nm})^2) \). The contact material is gold and the contact resistance is estimated by an upper band and a lower band.

Firstly, assuming the tip radius of each asperity \( R=100\text{nm} \), the surface energy \( \gamma=1400\text{J/m}^2 \) (the ideal value of Au), and the height distribution follows \( N(100\text{nm},(50\text{nm})^2) \), the influence of the number of asperities on the contact resistance is investigated. As shown in Figure 4, for a single asperity contact, there is only one curve (from Equation (7)) used to describe the contact resistance while for a multiple-asperity contact, the contact resistance is estimated by a lower band (from Equation (8)) and an upper band (from Equation (9)). The separation between the lower band and the upper band results from the different local distributions of the a-spots. It is apparent that the more the a-spots the larger the separation will be. The contact resistance decreases as the number of asperities increases because the contact surface seems to be more even as the number of asperities is larger so that the sticking effect is more evident.

Secondly, assuming the number of asperities \( n=50 \), the tip radius \( R=100\text{nm} \), the surface energy \( \gamma=1400\text{J/m}^2 \) and the average height of asperities is 100nm, the contact resistance as a function of the applied force in the cases of different standard deviations is calculated. As shown in Figure 5, the height distribution of asperities has little influence on the contact resistance. It can be seen that the

Figure 5. Relationship of the contact resistance and applied force as the height distribution of asperities has different variances. The number of asperities is fifty and each asperity has a radius of 100nm. The contact material is gold and the contact resistance is estimated by an upper band and a lower band.

Figure 6. Relationship of the contact resistance and applied force as the surface energy is different. The number of asperities is fifty. Each asperity has a radius of 100nm and the height distribution follows \( N(100\text{nm},(50\text{nm})^2) \). The contact resistance is estimated by an upper band and a lower band.
variations of each separation between the lower band and the upper band are not notable because most asperities have touched the lower plane and formed the a-spots at the beginning of the contact in the present of the sticking effect.

Lastly, assuming the number of asperities \( n = 50 \), the tip radius \( R = 100\text{nm} \), and the height distribution follows \( N(100\text{nm}, (50\text{nm})^2) \), the effect of the surface energy on the contact resistance is calculated. The results are shown in Figure 6. As the surface energy \( \gamma \neq 0 \), the stiction disappears and it degenerates to the case of an elastic contact. While \( \gamma = 1400\text{J/m}^2 \) which is the ideal value of Au, the contact resistance is two orders smaller than that of an elastic contact at low applied forces. In most cases, the actual value of the surface energy is much smaller than that of an ideal case because of the films or contaminations on the contact surfaces. From Figure 6 it can be seen even if the surface energy decreases to one tenth of the ideal value, the sticking effect is still prominent.

The elastic contact model \((\gamma = 0)\) related above is similar to that proposed by Majumder et al.\textsuperscript{2} at low applied forces. As reported by Majumder et al.\textsuperscript{2}, the contact resistance predicted by their model is significantly larger than the measurements at low applied forces. According to the experiments, the contact resistance is less sensitive to the contact force and its value is in the order of \( 0.1\Omega \) in a larger scope of the applied forces. This is consistent with the results predicted by the sticking contact model.

4. Conclusions
An improved model of the contact resistance which considers the sticking effect is presented. The main conclusions are below:

- The contact resistance is affected by the applied force, the number of asperities, and the surface energies of contact materials.
- The height distribution of asperities has little influence on the contact resistance because most asperities have touched the lower plane at the beginning of the contact due to the sticking effect.
- There are evident differences in the contact resistant between the elastic contact and the sticking contact especially at low applied forces.

The improved model agrees with the experiments taken by Majumder et al.\textsuperscript{2}. The contact resistance significantly decreases at low applied forces because of the sticking effect. This effect benefits the performance of the electrical contact. However, it is not advisable to enhance the sticking effect because it may cause the hysteresis as the contact is opened. Therefore it is a tradeoff between the contact resistance and the hysteresis.

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