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Abstract
This paper demonstrates the validity of a new methodology using a commercial nanoindenter coupled with electrical measurements on test vehicles specially designed to investigate the micro-scale contact physics. Dedicated validation tests and modeling are performed to assess the introduced methodology by analysing the response of gold contact with 5 µm² square bumps under various levels of current flowing through contact asperities. Contact temperature rise is measured leading to shifts of the mechanical properties of contact material and modifications of the contact topology. In addition, the data provide a better understanding of micro-contact behaviour related to the impact of current at low- to medium-power levels.
Keywords: RF-MEMS, gold, micro-contact, contact temperature, nanoindenter, micro-scale contact physics

I- Introduction

From DC up to tens of giga hertz, the bandwidth of RF MEMS switch specifications is spreading more and more. But is the challenge reachable for ohmic contact switches? Even if some successful company now propose some of these breakthrough-told technologies, the gap is still large between the low TRL (Technology Readiness Level) academic demonstrations and the commercially available switches. Several reasons can be exposed to account for this, and one of them is probably the lack of adapted tools to investigate the physics occurring at such a tiny scale. In addition, design of MEMS switches is widely diversified and few comprehensive investigations of micro-contact physics have been reported on a single type of contact. For ohmic contact switches, the main issue is to control precisely the contact pressure and the corresponding temperature. These two parameters are interdependent as soon as some DC or RF signal is flowing through the contact.

As a consequence, new characterization techniques have been recently developed in order to measure the contact resistance functions of the load applied and the contact deformation. Moreover, a precise monitoring of the current intensity and of the associated potential drop is useful to get rid of any parasitic resistance using cross rod methodology configuration. Nevertheless, as these characterization tools are still under development, it is mandatory to assess the results obtained through dedicated validation tests and modeling. The objective of this paper is then to present a so-called validation process of micro bending tests by nanoindentation. This will allow one to rely on the analyses and results presented elsewhere and provided with this methodology.

II- Micro-Contact Theory

First, the micro-contact physically differs from the macro-contact due to the roughness of the contact surface. Only high points on each surface come in contact. Thereby the effective contact area, named asperities or a-spots, is largely smaller than the apparent one (cf. Figure 1)

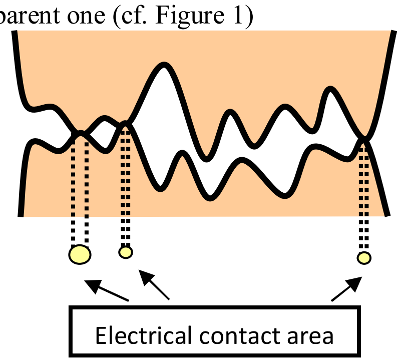


Figure 1 : Scheme of the contact interface pointing out the real electrical contact area

To simplify the model, the contact resistance is assumed to be mainly governed by the constriction resistance as the current flow is constricted through the small asperities leading to the electrical contact ie. the electrical contact is considered strictly ohmic. This electrical resistance is directly linked to the constriction of current lines between both contacts. This constriction of current causes a local increase of the current density and tends to increase the electrical potential between the two sides of the asperity. Thus the expression of this constriction resistance, so called Maxwell resistance $R_{Maxwell}$, can be written for a single circular contact spot of radius *a* as [1]:

$$R_{Maxwell} = \frac{\rho}{2a} \qquad \textbf{(1)}$$

Where ρ is the resistivity of the contact material. During the first contact establishment between the two surfaces, the load applied is generally higher than the yield stress of the contact material. Thus the deformation of the contact asperities is considered to be predominantly plastic. The contact area and the contact load can be linked to the radius of the contact spot a using Abbott and Firestone's plastic contact model [1].

$$a = \sqrt{\frac{A_C}{\pi}} = \sqrt{\frac{F_C}{H\pi}} \qquad \textbf{(2)}$$

Where Ac is the contact area, F_C the contact force and H the Meyer hardness of the softer material

Because of tiny contact spot size due to small contact force available in micro-switches, mechanical, electrical and thermal properties shift from bulk to a specific physics of thin films lead by the geometry of the asperities. For example, heating of the contact spots is extremely localized when the current flows through the contact, whereas the device level remains at room temperature [2]. The highest contact spot temperature T_c called supertemperature T_Θ has already been expressed by Holm as a function of the contact voltage V_c [1]. By considering that electrical contact is strictly ohmic, this equation becomes:

$$T_\Theta = \sqrt{\frac{V_c^{\,2}}{4L} + T_0} \qquad \textbf{(3)}$$

Where L=2.45 x 10^{-8} W.Ω/K² is the Lorentz constant and T_0 the ambient temperature.

III- Experimental Methods

Nanoindentation is firstly designed for material characterization, and is based on the "displacement vs. load" curve obtained by driving a tip into the test material and by monitoring the applied load and the resulting displacement. In our test bench, the nanoindenter's spherical tip is used as a mechanical actuator. The actuation load is thus reproducible and known with a good accuracy, two points which remain hard to achieve with the actual actuations (for example, electrostatic actuation forces often drift due to dielectric charging). Once the bridge is correctly located under the column of nanoindentation, the tip is brought in contact with the surface of the mobile electrode, and then lowered until mechanical and electrical contact between the bridge and the line. From this moment on, the applied load corresponds to the actuation load of the contact. The main difficulty for applying a load on test vehicles remains the accurate location of the tip above the contact. This issue has been here overcome by the use of a nanopositionning table achieving a 20nm X-Y resolution in a defined 100µm-side square. Thus, a pseudo-AFM scan is performed by probing the surface with a fixed stiffness of contact between the tip and the surface. An accurate location can then be reached on the scan.

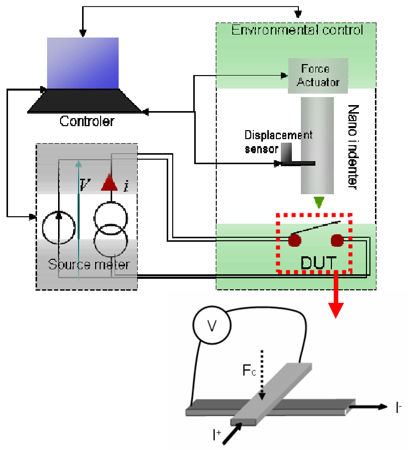


Figure 2 : Principle of the electrical test performed with a nanoindentation tip

The electrical measurements are performed by the use of a four-wires probe: a current flow I_C is applied and the potential drop V_C is independently measured. A schematic view of the set-up can be seen on Figure 2. This method for measuring contact resistance is the same method used in crossed rod contact resistance measurements of Holm [1]: only the contact resistance is measured independently of the voltage drop in the supply wires and access paths. Moreover the environmental chamber allows the control of the temperature of the DUT and of the relative humidity *Rh*.

Specific test vehicles have been designed for contact analysis, enhancing the extraction of characteristic curves. The testing device is composed of a bridge suspended over the contact line. A 5µmx5µm square bump is processed underneath. The stiffness of the bridge is about 480 N/m. The contact material is Au-to-Au because gold is the most popular material for electrical contact due to its high conductivity, its high resistance to oxidation and its low propensity to form alien surface films [3].

IV- FEM modeling of the mechanical actuation

- Punctual loading versus distributed pressure

During the experiments, the actual actuation principle that acts as a distributed pressure is replaced with a punctual load applied with the nanoindenter's tip.

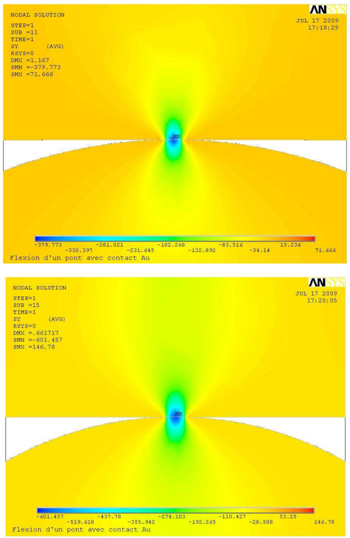
a)
b)


Figure 3 : Stress induced in the bridge and the bump with a) a local load actuation, b) a distributed pressure actuation.

2D FEM simulations were performed using ANSYS® in order to validate this substitution. It can be seen on the figure 3 that the repartition is barely similar between the both but the level of stress is higher with the punctual one. The contact force between the bump and the bridge has been calculated in both cases and is 60 % higher using the punctual force for a same applied load. It can be assumed that the force dissipated in the anchor is lowered using the punctual actuation principle.

- Requirements concerning the tip used

This part will be focused on the comparison between two types of tip: the Berkovitch one (0.320 µm of radius of curvature) and the spherical one (5.9 µm of radius of curvature). It can be seen on figure 4.a that the strain of the bridge close to the contact with the Berkovitch tip is higher than the bridge strain at the bump interface. The stress induced by the Berkovitch tip is 74 % higher and is more localized under the tip than the stress induced by the spherical one. For a same tip displacement, the contact area between the bump and the bridge is 11 % higher using the spherical tip than with the Berkovitch one. The use of a spherical tip allows a better repartition of strain and decreases the stress concentration and plastic deformations under the tip. However the figure 4.b shows that the deformation of the bridge under the spherical tip cannot be neglected.

V- Validation Tests

Metal contacting switches have a large and complex set of failure mechanisms driven by the current level. And current is also known to have a primary influence on contact lifetime in macroswitches, with lifetime decreasing at higher current [3].

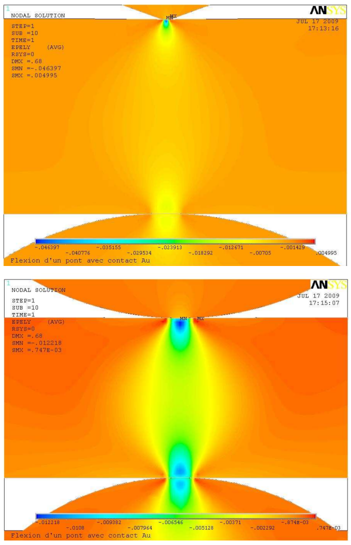
a)
b)


Figure 4: Strain induced by a) a Berkovitch tip actuation; b) a spherical tip actuation in the bridge and the bump.

A campaign of tests has been performed on the test vehicles described in the previous part and the obtained results give us the opportunity to regain the behaviour predicted by the previous models. These studies are focus on the self-heating of the contact with increasing level of current flowing through the contact which is a key issue of contact reliability. The measurements are performed by sweeping the contact current from 1 mA to 100 mA and measuring the contact voltage in a cold-switching way. The impact of current at low- to medium-power levels was investigated to improve understanding of power dissipation at the contact site and more precisely the topological modifications induced. The following results are based on the same 11 successive tests.

- Impact of current at low to medium- levels

Figure 5 shows typical "contact force vs contact resistance" curves for a test structure with a 5µm² square dimple at 11 different levels of contact current for Au/Au contact. This curves point out the relationship between the contact resistance and the force applied on the contact. The contact resistances decrease with the increasing contact force as a function of the contact current and are described by the equation $R_C = AF_C^{-x}$ where A and x are constant parameters for each current level. The deformations of the contact asperities at the contact closure produce a certain degree of strain hardening of the a-spots.

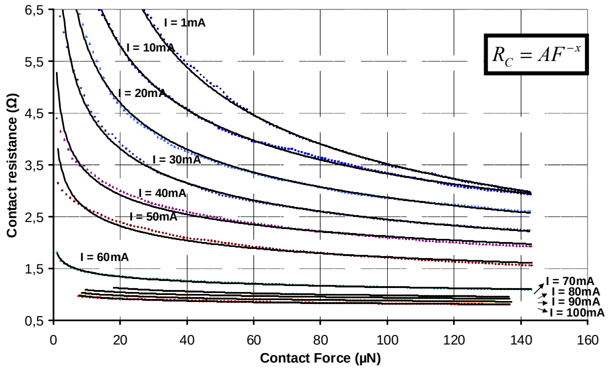


Figure 5 : Contact resistance versus contact force as a function of the contact current

When the softening temperature of the contact material is reached by increasing the level of current, strain hardening disappears in and around the contact interface and the contact area increases. To further examine the heating effect on contact resistance, we focus our study on the contact temperature when the maximum contact load is reached (figure 6).

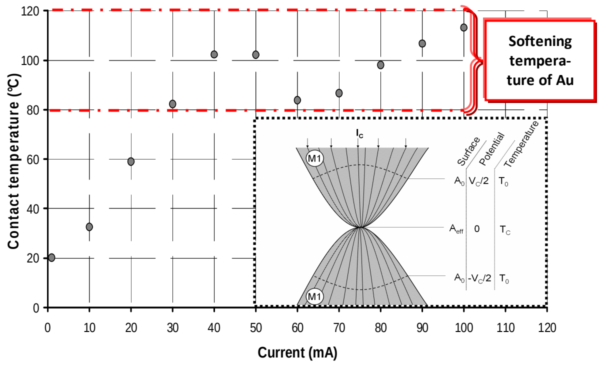


Figure 6 : Contact temperature versus the contact current

The methodology consists in measuring the contact voltage to deduce the contact temperature using equation 3. Figure 6 shows the contact temperature as a function of the contact current for Au/Au contact. The contact resistance continues to decrease keeping the contact temperature roughly constant after reaching the softening temperature ~100°C [2] (ie. the contact softening) from 40 mA.

- Topological modification of the contact surface

As for the number of asperities, *n*, a specific method has been developed based on the mechanical measurements provided by the micro-bending test. When the force is high enough, new asperities come into contact, involving a slight sudden modification of the loading configuration, that is to say a discontinuity in the recording of the stiffness *K*. *n* is then evaluated by counting the number of steps in the "*K* vs. F_C" curve. We observe that the number of asperities in contact increases with the contact current (Figure 7).

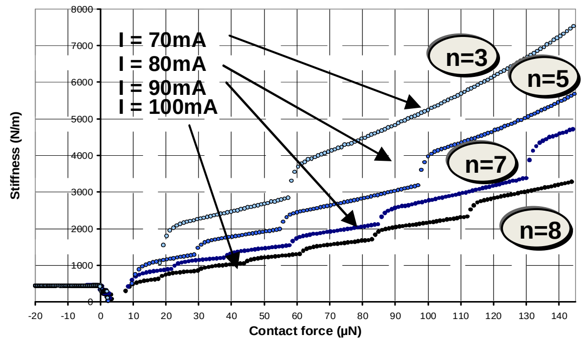


Figure 7 : Evaluation of the number of asperities

The contact temperature (Tc) of contact a-spots could be linked with the contact force depending on the contact voltage [4]. Indeed the plastic deformation of the asperities during the contact formation proceeds more rapidly when the softening temperature is reached [5]. Thus the effective contact area increases inducing a drop of the contact resistance. However the softening of the metal at the asperities of contact reduces the strain hardening of the a-spots and could accelerate the aging of the contact by the activation of thermal failure mechanisms. Therefore the contact temperature of contact metals is probably one of the most important critical parameter for a stable and low contact resistance.

VI- Conclusions and future work

The presented tests and models bring to light the relevance and the validity of this methodology to investigate the micro-contact physics. The presented test vehicles could be manufactured for future work with several contact materials, which mainly govern the robustness of the contact. The knowledge gained will be the identification of the specific failure mechanisms for each contact design in order to bring recommendations for further improvements of the contact reliability.

VII- References

[1] R. Holm, "Electrical Contacts-Theory and Applications," 4th ed. Berlin Germany: Springer-Verlag, 1967.
[2] B. D. Jensen et al., "Effect of nanoscale heating on electrical transport in RF MEMS switch contacts," in Journal of microelectromechanical systems, VOL. 14, NO. 5, pp. 935-946, 2005.
[3] S. T. Patton, "Fundamental studies of Au contacts in MEMS RF switches," in Tribology Letters, VOL. 18, pp 215-230, 2005.
[4] Hyouk Kwon and al., "Investigation of the electrical contact behaviors in Au-to-Au thin-film contacts for RF MEMS switches," *in J. Micromech. Microeng.* VOL., pp. 9, 2008.
[5] A. Fortini et al., "Asperity contacts at the nanoscale: comparaison of Ru and Au," in arXiv:0807., New York, 2008.