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RF MEMS electrical contact resistance calculation using mechanical contact simulations and analytical models

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Abstract

The testing and development of contact material or topology can be addressed with a dedicated experimental set up for monitoring test structures. However, it is difficult to perform the tests under realistic conditions. Moreover several works have already been published about the different theories describing rough mechanical contact. But they often ignore interaction between asperities, bulk deformation or elastoplastic deformations. In order to tackle these issues advanced simulation tools are needed. These tools for finite element analysis allow us to model assembly structures quickly and accurately with a minimal amount of effort. We have developed an original reverse engineering method for generating rough surfaces on ANSYS platform, by using the actual shape of the contact surface. We used this method to predict the real contact area between rough surfaces as a function of the applied force using the augmented Lagrangian method. The number of asperities in contact, their sizes and their distribution allow us to discriminate the more appropriate electric contact model in diffusive or ballistic electron transport.

MEM test structures with gold-to-gold electric contacts are fabricated and tested with an experimental set up in NovaMEMS/CNES lab and will allow to validate the new methodology. The contact resistance is monitored during all experiments, to correlate the mechanical and electrical behavior of the structure. The measurements are in progress. We can already expect to some discrepancies due to the difficulty to measure accurately contact material properties and to the potential contamination around the metal contact area. Yet this application is a major concern in RF MEMS ohmic switches and shows an original approach to extract a guideline in choosing a design, materials and process flow to minimize the contact resistance.

I. Introduction

With their extremely low mass and volume, low power consumption and easy integration with electronics, RF MEMS switches have a strong potential to reduce the size and mass of satellite systems and spacecraft with significant cost reduction. Nevertheless, those devices with moveable structures still have some issues to be successfully integrated in industrial products. The first issue deals with the actuation medium and the corresponding reliability. For the DC contact RF MEMS, it has been identified that most of the limitations are related to the quality and the repeatability of the contact that drive the RF performance (insertion losses, isolation, power handling) and the reliability. Metal contacts are source of dominant failure mechanism such as damage, pitting, hardening of the metal contact area, stiction due to microwelding and material transfer, organic deposits and contamination around the contact area. All these failure mechanism are of major concern for long term applications and have to be the subject of an intense research effort. In order to propose new generation of RF MEMS devices, it is important to get a deeper insight on the physic of contact in order to choose appropriate materials, topology and architecture. It has to be furthermore outlined that the insertion of RF MEMS into real architecture will necessitate reduced actuation voltage, dimensions and a better control of the electrical and electromechanical behavior that will give more importance to surface effects and their understanding and modeling.

The aim of this paper is to present a new methodology that will allow the simulation of the DC contact of RF MEMS devices through finite element multi-physic simulation and surface characterization. The innovative tool can thus allow to the designer better understanding the physical phenomena at the contact interface of the studied micro-devices and give some precious guidelines in the choice of contact materials, deposition processes, contact topologies and architectures.

II. Investigation of current methods

The figure 1 sums up the different ways allowing calculation of the electrical contact resistance. Our objective is to develop an accurate method in order to optimize and reduce the electrical contact resistance and in order to decrease the adhesion forces at the contact opening. The implemented tool will allow analyzing the impact of materials, roughness, contact topologies and switch architectures on the contact performances expressed in the contact resistance and the contact reliability.

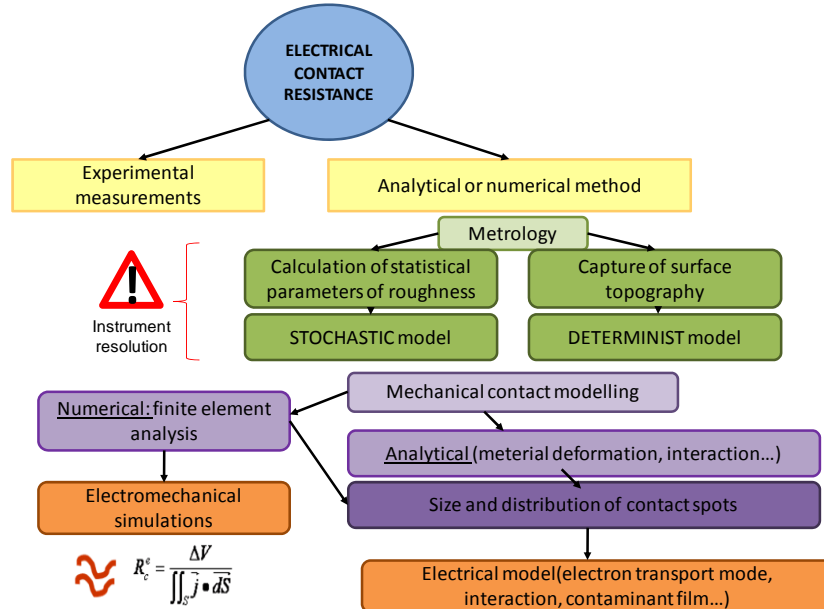


Figure 1: current methods for calculation of electrical contact resistance

1. Interest of a numerical/analytical method compared with an experimental method

To determine the contact resistance, we have choice between an experimental method and a numerical or analytical method. However the experimental method is exposed to many barriers, concerning the fabrication technology or the experimental measurements. The testing and development of contact material or contact topology can be addressed with a dedicated experimental set up for monitoring test structures. Nevertheless, it is difficult to perform the tests under realistic conditions and in particular to duplicate the switch geometry, the contact geometry and the contact force. Moreover, the fabrication process must be optimized and it may take many months to fabricate a set of switches to test a single candidate contact material or contact bump shape. Finally, this method is costly whereas the results interpretation can prove to be difficult when many physical phenomena appear together (heating, creep, surface contamination...).

To the contrary, a numerical or analytical method doesn't constrained us in the choice of one material, one topology, one deposition process or one architecture. Moreover it is possible to investigate each parameter independently.

2. Statistical and determinist approaches to describe the surface roughness

The selection of a numerical or analytical method requires firstly the implementation of a mechanical contact analysis and the first step of this analysis is the surface description. The presence of roughness on solid surfaces results in an imperfect contact that leads to the real area of contact being a fraction of the apparent or nominal area of contact [1]. Therefore, in problems involving actual surfaces it is not possible to neglect the surface roughness because this could lead to evaluate values of contact pressure much smaller than the effective ones and to underestimate the risk of surface failures.

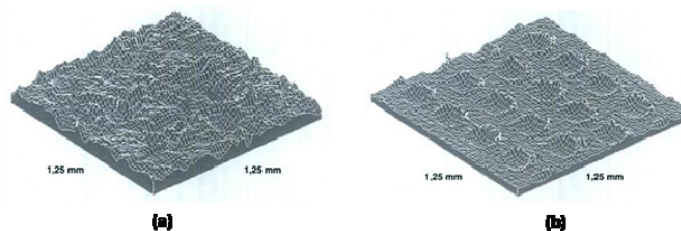


Figure 2: Example of a random topography or stochastic surface (a) and determinist surface (b)

The model of contact mechanics will depend on the manner by which the surfaces roughness will be mathematically described. Two different approaches have been developed to describe the surface: a statistical approach, based on a stochastic analysis, and a deterministic one involving the actual surfaces topography [2].

The fundament of the statistical approach derives from the observation that common engineering surfaces produced by standard machining process are characterized by a random topography. The random topography of surfaces can be described choosing appropriate asperity distribution functions. Referring to a few parameters, the statistical approach is able to provide faster contact problem solutions [3]. However these parameters can be difficult to choose. The necessary input data, that is summit asperity height deviation, mean radius and asperity density cannot indeed be easily calculated through the commercial roughness measuring equipment and depend from the instrument resolution. The use of a deterministic approach can better describe the surfaces.

The contact surfaces of RF MEMS switches are produced by standard technological process (sputtering, evaporating, electroplating) and can thus be described by a stochastic approach. However, electrical contact of such devices are generally very localized due to the patterning of contact bump under the suspended membrane or directly on the coplanar line. With the typically contact force generated by the device ($\sim 100\mu\text{N}$), the apparent contact radius is not larger than 250 nm. Figure 3 shows the topographies, captured by AFM, of the membrane surface and of the signal line. Whereas the contact surface of the membrane seems to be random, the contact surface of the line appears to be disturbed by asperities higher than the neighborhood. It is obvious that the contact between both surfaces will occur through those asperities. And thus a determinist description of the lower contact surface is required to get accurate results.

Moreover, the surface roughness of contact materials will depend of the historical switching of the device. A surface that appears initially stochastic will have to be treated with a determinist approach from a few switching. In order to investigate the degradation mechanism, the use of a determinist approach can better describe the surfaces.

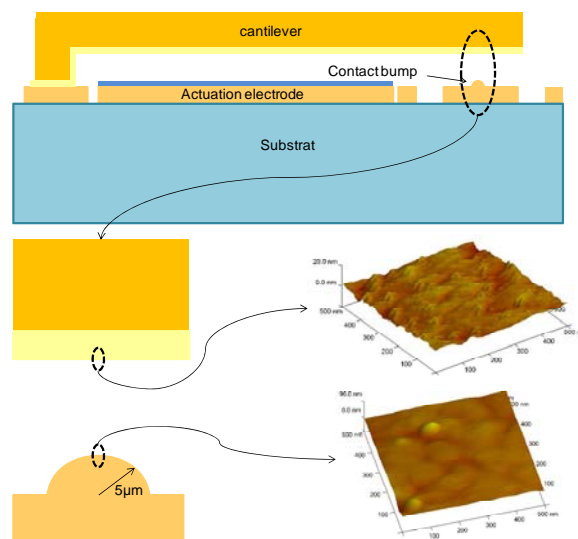


Figure 3: contact surface topographies of the micro-switches captured by AFM

3. Interest of a numerical method compared with an analytical method

The theoretical models imply many assumptions and simplifications. They ignore some or all of the correlation between asperities, implying that asperities are far apart. Moreover, bulk deformation is neglected and plasticity models at the asperities do not consider large deformation theory [3-7]. With the increase of computation capabilities, the numerical methods are of great interest. For an elastoplastic material, finite element analysis is well-adapted and is robust enough to consider interaction between asperities as well as bulk deformation [8-10].

Nevertheless, the representation of micro-geometry demands a high volume of elements, which implies long times of calculation and memory limitations.

Finite element method seems to be very interesting to better understand the physical mechanism at contact interface, but the results accuracy will have to be confirmed by experimentation.

4. Calculation of the electrical contact resistance (ECR)

Two ways can be considered to calculate ECR: the first one is a finite element coupled-field analysis and the second one uses analytical formulations.

The use of a multiphysical finite element software, able to offering a well developed solver to simulate many mechanical contact problems coupled with other physics, is advantageous to directly extract the electric contact resistance between two conductive bodies that come into contact. In particular in Ansys [11], surface-to-surface elements in combination with thermal-electric elements and solid coupled field elements allow modeling of electric current conduction. The method consists in a sequential and coupled-field analysis. The drawback of this method is that it neglects ballistic electron transport and contaminant film resistance, although the low contact forces produced by microswitches results in small contact spots on higher asperity peaks. Thus the method risks underestimating contact resistance for low contact force applications.

In order to evaluate the electrical contact resistance, the use of analytical formulae can better account for the constriction of the electrical current through the separate contact spots. Several works have already been published about the different theories describing the electrical contact [12-18]. The way the electrons are transported through electrical connections (ballistic, quasi-ballistic or ohmic transport between two contact parts of a MEMS switch needs to be determined in order to evaluate the resistance of contact (figure 4).



Figure 4: Schematic illustration of (a) diffusive and (b) ballistic electron transport in a conductor [19]

In general, multiple asperities come into contact resulting in multiple contact spots of varying sizes. The effective contact resistance arising from the contact spots depends on the radii of the spots and the distribution of the spots on the contact surface. The ballistic contact model can be correctly used if the radius of the apparent contact area (that contains all the contact spots) is smaller than the electron mean free path l_e . In this case, the formula of Sharvin's resistance [13] is applied:

$$R_s = \frac{4\rho K}{3\pi a_{eff}}$$

where $K = \frac{l_e}{a_{eff}}$ and where a_{eff} is the effective radius of contact

Considering the case of n elementary spots of radius a regularly spread in a disc of radius \mathcal{R} representing the interface of contact of two metals of equal resistance ρ , an expression of the resistance is proposed by Holm [12] for an ohmic contact model,

$$R_{Holm} = \frac{\rho}{2na} + \frac{\rho}{2R}$$

where the first term represents the resistance of all the spots in parallel, and the second term, the resistance due to the interaction between all the spots.

Greenwood [15] proposed an improved formula for the constriction resistance of a set of circular spots, taking into account the size of different contact spots and their dispersion on the apparent contact area. The electrodes communicate via the spots with no interface film between them.

$$R_{G1} = \frac{\rho}{2\sum a_i} + \frac{\rho}{\pi} \cdot \frac{\sum_{i \neq j} \frac{a_i a_j}{d_{ij}}}{(\sum a_i)^2}$$

with a_i the radius of the spot i , d_{ij} the distance between the centers of the spots i and j .

When a conductive film of surface resistance λ (Ωm^2) is present between two electrodes communicating through a circular spot of radius a , a resistance due to the presence of this film R_{film} has to be added to the constriction resistance:

$$R_{film} = \frac{\lambda}{\pi a^2}$$

For n circular contact spots of radius a_{eff} , the resistance R_{film} of the interface film is:

$$R_{film} = \frac{\lambda}{n\pi a_{eff}^2}$$

5. conclusion

A numerical modeling is thus implemented in order to study in depth the mechanical micro-contact. With the increase of computation capabilities and numerical methods, the topography of the surface can be included in finite element simulations. The electrical contact resistance is then deduced from output mechanical data, such as radii of contact spots or their distribution. The principle of our approach is sum up on the figure 5.

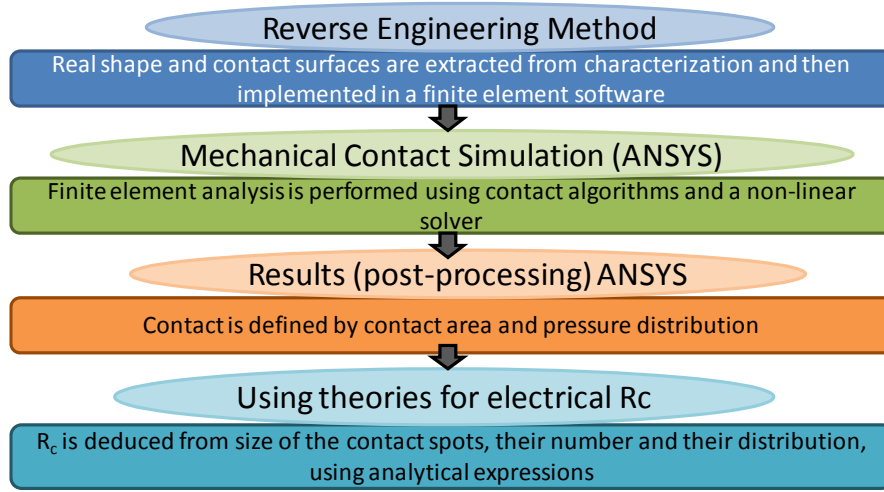


Figure 5: reverse engineering method description to calculate the contact electrical resistance of a micro-switch

III. Selection of the simulation tool

To perform numerical contact simulations, the numerical platform available in LAAS laboratory is under investigation. The commercial software ANSYS [11] is notably tested. It is an industry standard tool for finite element analysis, historically well-known in mechanical and thermal domains. ANSYS manifested a good accuracy on the results with a reduced time of calculation and is able to solve many contact problems (3D, geometrical, status, material nonlinearities...), with a minimum effort from the user. Ansys is an excellent candidate to be used in our project.

IV. Reverse engineering methodology

So far, surface effects were ignored in the analysis, because of the difficulty to generate a rough surface model and also to simplify the model in order to reduce computation times. With the increase of computation capabilities, the topography of the surface can be included in finite element simulations. Thus we describe the new methodology that allows the simulation of the DC contact of RF MEMS devices through finite element multi-physic simulation and surface characterization.

This numerical method is used to predict the real contact area as a function of the contact force between rough surfaces starting from real shape of the surfaces that come in contact. Then using analytical expressions it is possible to extract the electrical contact resistance. The novel approach relies on a reverse engineering method to generate the real shape of the surface. Figure 6 describes the full method developed on ANSYS platform. We used an optical profilometer (VEECO) or an atomic force microscope to capture three-dimensional data points of

contact surfaces. Then, using Matlab functions we convert the closed surface from a stereo-lithographic format to an ASCII file compatible with ANSYS Parametric Design Language (APDL). In the final step, the rough surface was obtained by creating key points from the imported file. Since the key points are not co-planar, ANSYS uses Coons patches to generate the surface, and then we used a bottom up solid modeling to create the block volume with the rough surface on the top. To perform the finite element contact analysis, we choose the combined method based on penalty and lagrangian methods called the augmented Lagrangian method. The post-processing generates the distribution of the contact pressure on the contact surface. The last version of ANSYS (version 11) presents a new option allowing knowing directly the contact area on each element and has simplified us the work of extraction of spots contact area. Thus a program Matlab has next been written by using the latest functions of ANSYS to determine the area of each contact spot and their location on the contact surface. Then we applied Greenwood's analytical formulations to deduce the contact resistance.

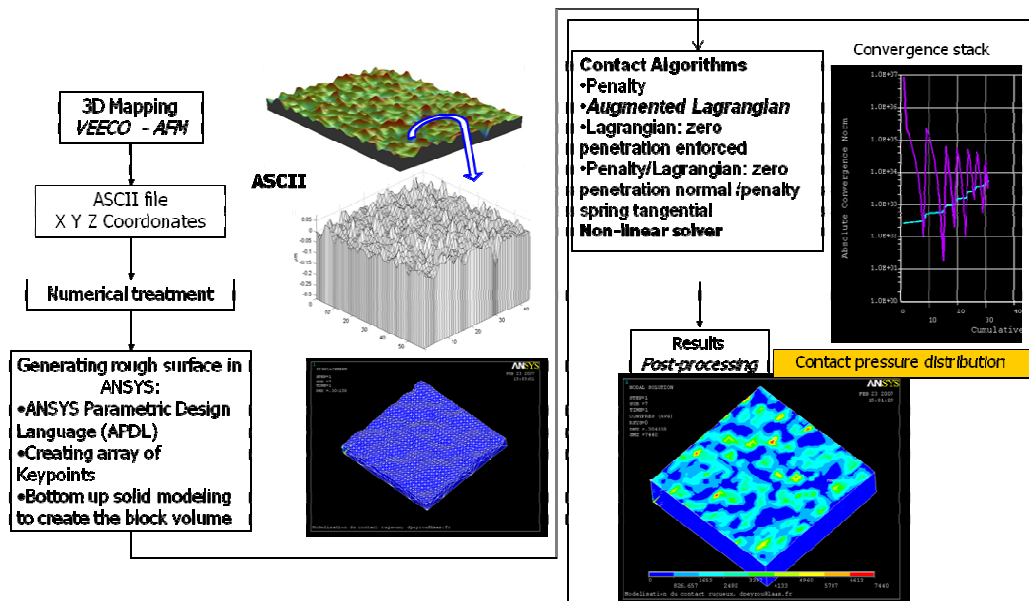


Figure 6: Reverse engineering methodology

V. Limitations of simulations

Some examples were treated from a contact surface captured with the optical profilometer VEECO (figure 7). The obtained resolution step is thus close to $0.9\mu\text{m}$, which allows us to simulate contact problems for large contact surfaces ($25 \times 25 \mu\text{m}^2$). However, this roughness analysis step makes lose a lot of information on the surface characteristics of the contact material. The obtained contact area is thus overestimated and the contact resistance is under-evaluated (figure 8).

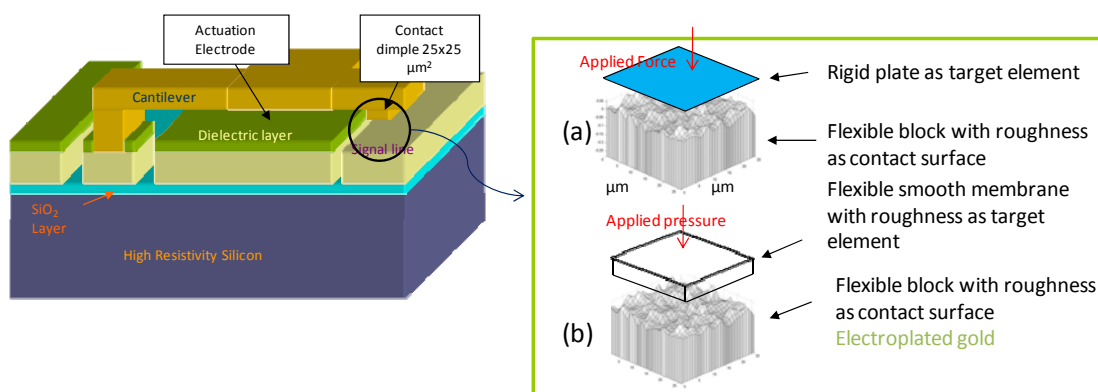


Figure 7: contact model definition

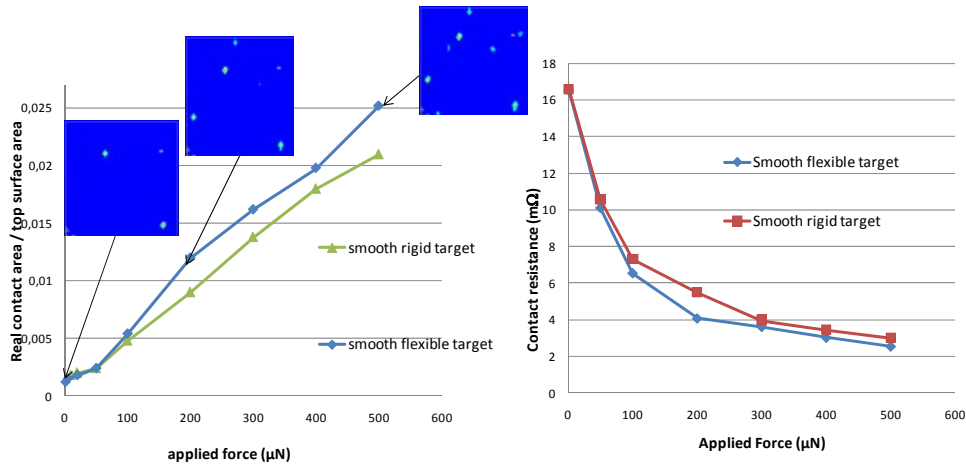


Figure 8: Ratio between real contact area and apparent contact area and contact resistance versus applied force (μN)

The resolution of captured surfaces has thus to be refined and requires the use of atomic force microscopy (AFM). For given sample dimensions, the number of point data is likely to increase and to imply a larger number of elements in the contact model, this demands more resources for the computer to run the simulation.

Our studies show that the implementation of finer details of roughness in the contact model has a great impact on the mechanical contact areas. It seems necessary to take into account a resolution step of at least 10nm of the surface roughness. With this cut off length, the time of calculation can become very significant, and rapidly the available machines in the laboratory fail out off memory. Moreover to obtain reliable results the meshing has to sufficiently refined.

To address this challenge, we propose to reduce the contact model. Two simplification models are proposed on figure 9. The microswitch consists indeed of a suspended membrane that comes into contact on a contact bump patterned on a coplanar line (the bump can also be patterned under the beam) as illustrated on figure 3. The contact bump has a round shape to optimize the contact performance. And thus the contact will occur through the higher asperities. The contact is very localized and thus we can leave aside the roughness in the neighborhood of these higher peaks, limiting thus the number of elements in our contact model.

Moreover the contact surface of the membrane can initially be assumed as smooth due to the fabrication process. Therefore for the first actuations only the roughness on a localized zone of the bump will be depicted and we perform in ANSYS a flexible-to-flexible contact simulation. The contact materials are assumed to be elastoplastic and a bilinear stress-strain curve is implemented.

When the number of actuation cycles is high enough, the surface roughness of the membrane changes and the topography need to be taken into account. Micro-geometries of membrane surface and contact bump surface have to be captured. Now the materials can be considered against elastic, and thus we can perform in ANSYS a rigid-to-flexible contact simulation. The flexible bump will consists of an equivalent elastic material and its roughness will be the sum of both roughness profiles.

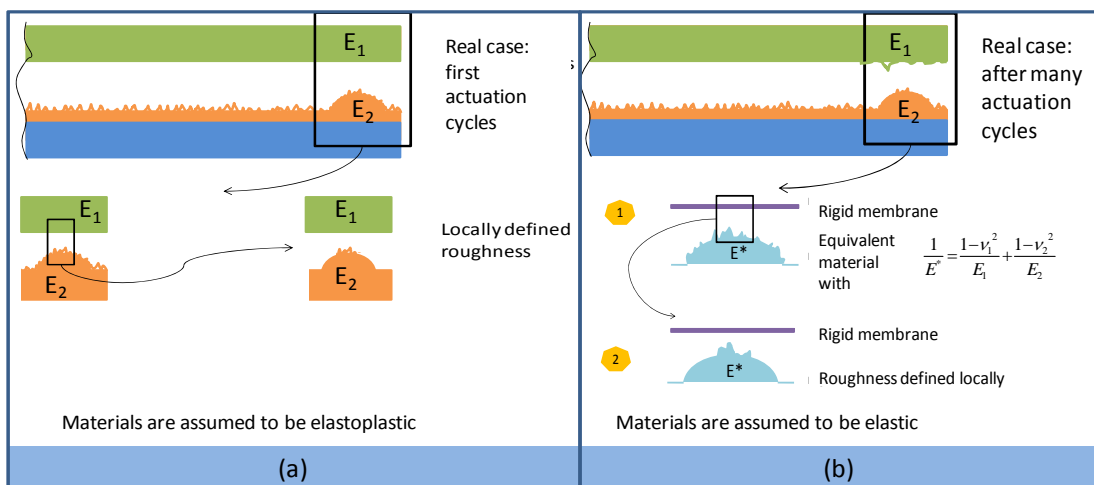


Figure 9: Reduction of the contact model: first case (a): first actuations and elastoplastic materials; second case (b): many actuations and assumed elastic materials

VI. Experimental

MEM test structures with gold-to-gold electric contacts are fabricated in LAAS laboratory and tested with an experimental set up in NovaMEMS/CNES lab to validate the new methodology. The cross section of a schematic structure is illustrated on figure 10 a. Three lengths of suspended beams are considered (240, 300 and 360 μm) with a width of 40 μm . the contact bumps are 10 μm diameter.

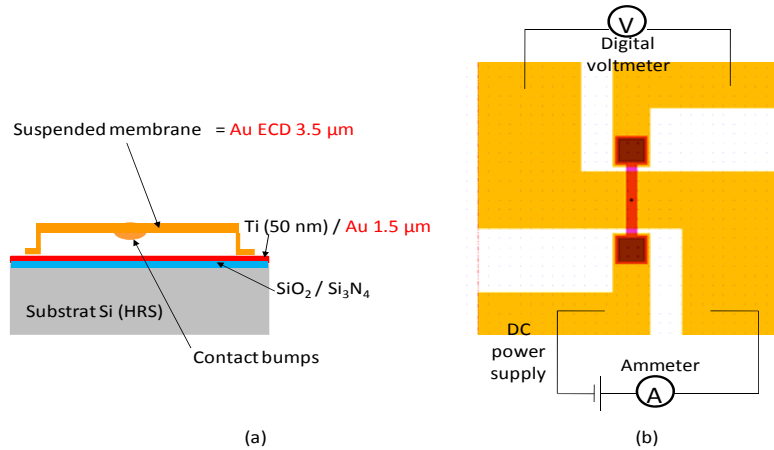


Figure 10: (a) cross section of the fabricated structure; (b) four wires measurement set-up

The set up consists in a MTS nanoindenter with a nanopositioning table used to precisely actuate the microstructure in a mechanical way, controlling the load applied on the free standing part and its resulting displacement. A resistance measurement system has been interfaced with the nanoindenter, and consequently the voltage induced by the current flow is monitored in the control software in the same manner than the load or displacement of the tip. A schematic of the accomplished four point probe is shown in the figure 10 b. In a four probe setup, a current source is used to drive the current in the switch and a Digital voltmeter measures the potential drop through the switch. This set-up filters out the access wire resistances and the contact resistance variation is studied accurately. The contact resistance is thus monitored during all experiments, to correlate the mechanical and electrical behavior of the structure. The measurements are still in progress.

VII. Conclusion

The mainstream toward a more and more propelled miniaturization requires from the RF MEMS switches increased RF performances and reliability. In order to develop an innovative architecture of micro-switches using the ohmic contact in MEMS technology, recognition of surface effects is crucial in order to evaluate accurately the electrical contact resistance and study the degradation mechanisms. An overview of different current methods used to calculate the mechanical contact area between two rough surfaces that come into contact on one hand, and to calculate the electrical contact resistance on other hand is introduced.

Finally, the increase of computation capabilities and numerical methods is to the advantage of use of a multiphysical finite element software. The topography of the surface can be included in numerical simulations and allows providing precious guidelines in the choice of contact materials, deposition processes or contact topologies. The novel approach relies on a reverse engineering method to generate the real shape of the surface. Then a mechanical contact simulation is performed to deduce the size of real contact spot and their distribution. The electrical contact resistance is then calculated by using some analytical formulae.

To describe accurately the microgeometry, it is however required to capture the surface topography with a very small cut off length. Typically, the resolution step of measurements instruments (AFM) doesn't have to overcome 10 nm in the case of low range of contact forces developed by MEMS switches. Reduction of contact models will be implemented by defining only locally the surface roughness on the contact bump and by meshing finely only the higher asperities. These methods will be implemented for MEM test structures with gold-to-gold electric contacts. The contact resistance values obtained by the reverse engineering method will be compared with the experimental measurements performed with a dedicated set up and allow validating the efficiency of our numerical tool.

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