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Conducting Probe Atomic Force Microscope as a Relevant Tool for Studying Some Phenomena in MEMS Switches

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Abstract As the reliability of electrical microcontacts has proved to be the main limitation to a fast-growing production of ultraminiaturized switches, a thorough understanding of their failure mechanisms is an all-important purpose. This paper aims at showing that conducting-probe Atomic Force Microscopy (cp-AFM) is an adequate tool to actuate and study electrical contacts. By choosing relevant cantilevers and operating mode of the cp-AFM, dimensions, gap and force level representative of existing microelectromechanical switches (MEMS switches) are obtained. With two examples, the advantages of using a cp-AFM in force mode for studying physical phenomena at very low scale are highlighted. The reported investigations concern material transfer between contact parts and contact bounces. Those two undesirable phenomena induce surface damages and impinge reliability of MEMS switches. In both cases an explanatory scenario of phenomena occurring at nanoscale is proposed and preventive recommendations for improving the lifetime of such devices are suggested.

Keywords Microelectromechanical switches · Electrical micro-contacts · Material transfer · Fowler–Nordheim effect · Bounces

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1 Introduction

As many other fields, electrical commutation has not escaped the general trend to miniaturization and various microelectromechanical switches (MEMS switches) have been developed in the last 20 years drawing on the microelectronics process facilities. However a large spreading of these components still remains delayed by the limited reliability of the so-obtained electrical contacts. This is due to the fact that phenomena involved in microcontacts may notably differ from the classical physics of macroscopic contacts and therefore cannot be addressed by a simple scale reduction [1]. The main difference lies in the very low forces exerted in microswitches, typically tens to hundreds of micronewtons, which lead to extremely small contact areas and thus a high dependence to surface conditions such as roughness, coating nature and thickness or possible contamination [2]. Much effort has been carried out in recent years to clarify the behavior of microcontacts, leading to the development of several setups. Those setups are either "laboratory-made" [3, 4] or based on commercial apparatus, such as nanoindenter [5, 6] or Atomic Force Microscope (AFM) [7–17]. The research works with an AFM-based setup were mainly performed to determine the proper material for micro/nano-contacts or to characterize the degradation mechanisms. Among the main degradation mechanisms in hot switching conditions (i.e. open/close cycles under applied voltage), previous studies have highlighted some material transfer from one contact part to the other, as well as the existence of contact bounces inducing increased wear and closing time [1].

In this paper the relevance of using an AFM for studying contacts and other physical mechanism at the microscale is highlighted. The observation of two unwanted phenomena (material transfer and contact bounces) on RF MEMS switch is first reported in Sect. 2. Then the AFM-based experiment and the advantages of using such a setup to perform well-controlled conditions of actuation and
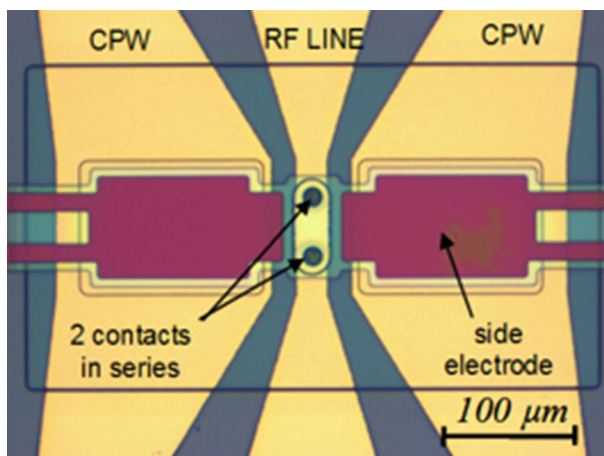
Fig. 1 Schematic view of the RF electrostatic MEMS switch elaborated at the CEA-LETI

measurement are detailed in Sect. 3. Finally results of experiments to characterize the material transfer and the contact bounces are detailed in Sect. 4.

2 Observations on the MEMS Switch

Experiments on a RF electrostatic MEMS switch have been carried out in the CEA-LETI laboratory. The design consists in a clamped–clamped membrane with two side electrodes and Ru/Ru contacts (Fig. 1). Further details of the switch can be found in [12].

A DC bias voltage of ± 50 V has been applied to the electrodes. The voltage applied to the contact and the maximum current are respectively 5 V and 100 µA (resistive load). After millions of cycles in hot switching conditions at 5 V and more, the failure of the switch is caused by the stiction of the contacts, i.e. the switch remains definitively in the closed state [1, 12]. Material transfer between the two contacts can then be observed, always from anode to cathode. A typical observation by Scanning Electron Microscope (SEM) of this material transfer is shown in Fig. 2.

Bounces are also undesirable phenomena that can happen in a MEMS switch. Several authors have proposed to adjust the actuation voltage in order to avoid contact bouncing [18, 19]. Recent papers also noticed the presence of bounces before the switch failure [20]. In that case, bounces could be used as a relevant indicator of the end of life of the switch. A recent paper also showed that bounces can be observed at very low actuation velocity (v = 6 nm/s) during the closing sequence (contact make) [21]. More surprisingly at low velocity a bounce can also be observed during the opening sequence. Such bounces cannot be explained by the classical theory of the impact at high velocity of the mobile electrode on the fixed one.

Those two phenomena (material transfer and bounce at low velocity) remain unexplained by the macroscopic physics. The next two sections will show how the
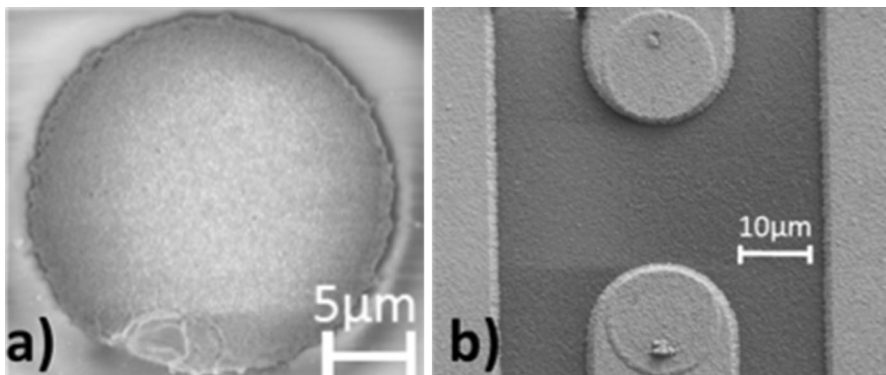
Fig. 2 SEM observation of the material transfer: **a** mobile contact and **b** *fixed line* (depending on the polarity a crater or a mound is obtained)

AFM is a relevant tool to reproduce and study such phenomena at the microscopic scale.

3 Specific Experimental Set-Up for Microcontacts Study

The experimental setup is based on a commercial AFM (Veeco, Dimension 3000). It is used in force mode, i.e. a mode that consists in approaching and retracting a cantilever above the surface at a controlled velocity and height [22]. A tipless silicon cantilever and a Si substrate, respectively covered by a 200 nm and 1 μm gold layer deposited by Physical Vapor Deposition (PVD) mimic a microcontact. The AFM cantilever has a spring constant around 150 N/m, a value that allows reproducing a contact force level commonly found for microswitches (~ 150 μN). Its resonance frequency is around 580 kHz. An external circuit is used to control the applied voltage to the contact and the electrical current (Fig. 3). The contact voltage is measured directly by a digital oscilloscope.

This AFM-based experimental setup offers multiple advantages to study a micro-gap. It provides a direct control of the mechanical motion thanks to the piezo-actuator and the retroaction loop of the AFM. So, the kinetic of approach/retract sequences is perfectly controlled. The photodiode detector provides direct information on the cantilever deflection, that is, on the mechanical behavior of the beam closed to the contact. A cantilever deflection, lower than 1 nm, can be measured thanks to the high sensitivity of the photodiode. The AFM controller is also used to synchronize the electrical data with the cantilever deflection. This allows drawing voltage and current as a function of the gap between the cantilever and the substrate. Experiments can be performed under air or nitrogen (even vacuum), but results presented in this paper have been obtained under ambient air at atmospheric pressure and room temperature.

Note that the geometry of the cantilever plays an important role in the study of the microcontact. Here, a tipless cantilever is used which assumes that either a single or a few asperities are into contact (ideal case of single asperity contact can be performed by using a conductive tip at the end of the cantilever). This is in good agreement with multi-asperities contact in MEM switches where most of the current
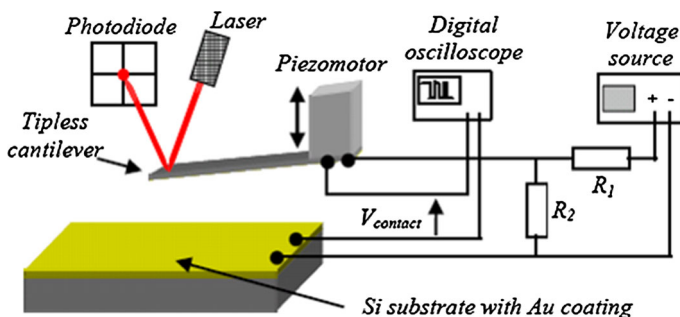
Fig. 3 Schematic view of the AFM-based experimental set-up

is conducted through a few asperities [23]. Different geometries can be tested by using the various commercial tips sold by AFM probes providers. One of the difficulties remains to have a good electrical contact. To better mimic their contact geometry, several authors have also directly used their own MEMS membrane as the cantilever [8, 14]. Then a wide range of materials have been tested thanks to this setup which is also one of the main advantages of using an AFM [13, 14, 17].

4 Typical Results with the AFM

4.1 Material Transfer

With the AFM-based experimental bench described above, 50 cycles have been performed between a golden tipless cantilever and a silicon substrate covered by Au, Ru or Pt. According to the polarity of the mobile cantilever, a mound or a crater of matter is observed after the tests (Fig. 4). The transfer is also always observed from the anode to the cathode, similarly to what occurs in MEMS switches. It is also in good agreement with previous reported works about material transfer [15, 16, 24].

The contact voltage has been varied from 0 V to 15 V during the experiments and it was observed that the material transfer is highly increased above a threshold voltage of about 5 V (Fig. 5). Those two observations are similar to what has been shown by Yang et al. [24] where deposition of material on the substrate is observed when the latter is polarized as a cathode for voltage of 6 V. However, in our experiments, no clear material transfer has been observed or measured for 0 V switching voltage as also stated by [15].

A major advantage of using an AFM in force mode is that the influence of many parameters can be studied separately. The results of these investigations are reported in Table 1.

One of the main results is that the material transfer predominantly occurs during the closing phase. With the same AFM-based experiment, the voltage and the current have been monitored during the contact closure to understand in depth the phenomenon. A typical result is shown in Fig. 6. It reveals that some current peaks
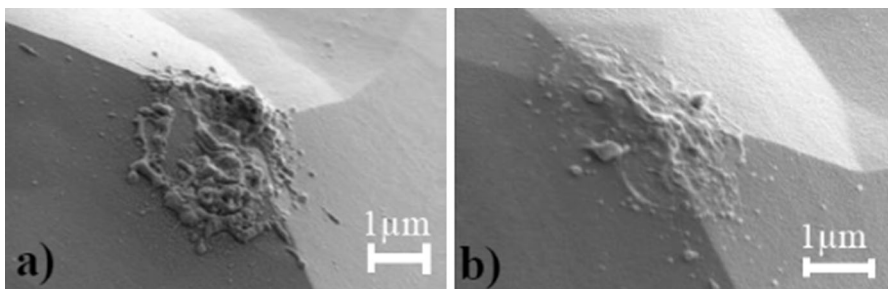

Fig. 4 SEM observation of the cantilever extremity after 50 approach/retract cycles: **a** anode polarity and **b** cathode polarity
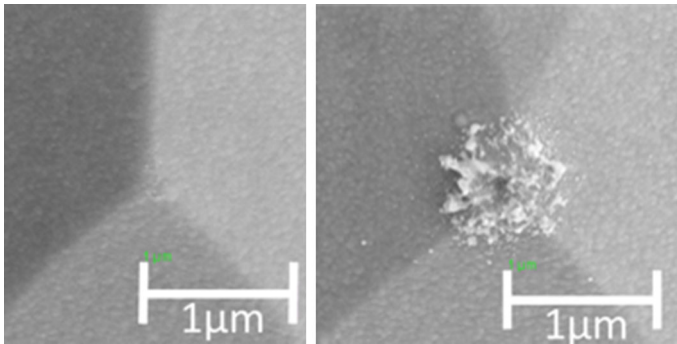
Fig. 5 SEM observation of the AFM cantilever extremity after 50 cycles for switching voltage of 0 V (*left*) and 10 V (*right*)

Table 1 Effects of the different parameters on the material transfer

Parameters	Observations
Closing/opening sequence	More material transfer at the closure of the contact (ratio 10:1)
Voltage	Threshold voltage about 4–6 V at which the material transfer appears
Current	No influence (from 10 µA to 10 mA)
Material	No significant difference between Au, Ru or Pt contacts
Actuation velocity	Higher transfer at low velocity
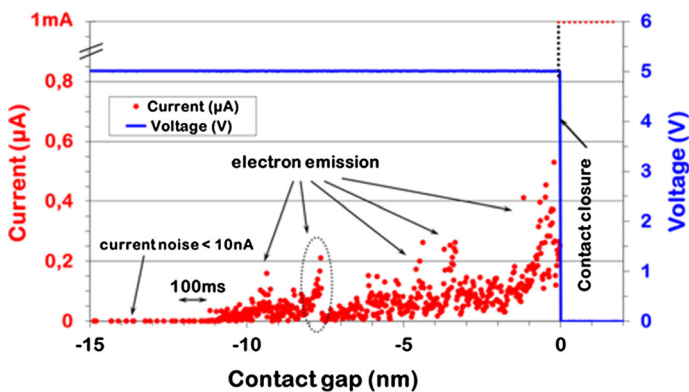
Fig. 6 Typical current measurement during the closing sequence with the AFM-based experiments

can be measured in the last nanometers before the contact closure. Such a phenomenon has also been observed in [11, 16]. This current is attributed to electron emission from the cathode. Indeed the electric field in the last nanometers is high enough ($>10^8$ V/m) to produce emission such as described by Fowler–Nordheim
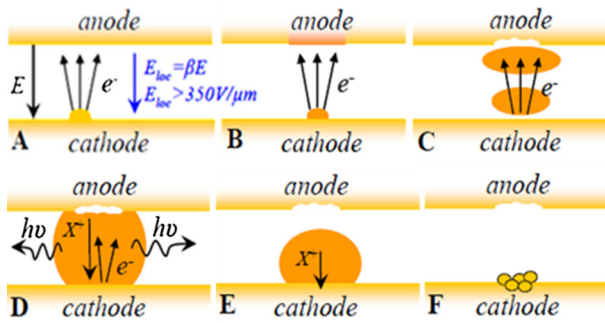
Fig. 7 Suggested scenario to explain material transfer at the micro and nano scales

theory. The emission is enhanced by local asperities that locally increase the electric field by a factor β. It has been proved recently that significant current emission is produced in air, nitrogen and vacuum at nanometric distances for electric field approaching 350 V/µm [25, 26]. It means that at 5 V switching voltage, current emission can be produced in the last 15 nm and repeated at each cycle, finally bringing the material transfer observed on the above figures.

A scenario to explain the transfer is suggested in Fig. 7. It has been built up according to the observation of electron emission and also to the presence of a metal plasma at such distance attested by spectroscopic analyses [27]. Electrons are emitted from the cathode due to the intense local electric field (A). They directly impact the anode as the gap distance is lower than the mean free path of electrons (B). Metallic atoms are ejected from the anode due to electron bombardment as well as the emitter vaporizes due to the current flow (C). A plasma is produced and expands in the gap producing light emission (D). When the plasma goes out because it is not enough sustained with electron emission, metal ions are deposited onto the cathode, producing the observed metal mounds (E,F).
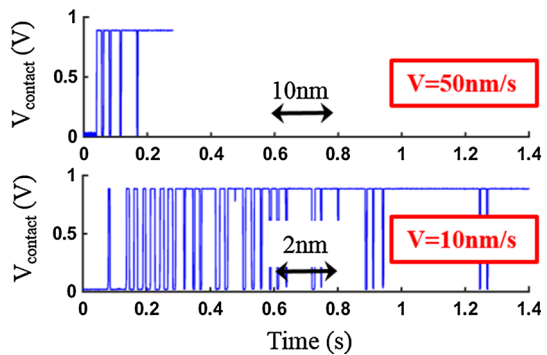
4.2 Bounces

Bounces at low velocity can be easily studied by the AFM-based experiments as the AFM provides a good control of the actuation velocity in the force mode. The complete study of contact bounce can be found in the paper [21]. It has been shown that contact bounces at low velocity can be reproduced similarly to those observed with MEMS switches [21]. To ensure that such a bounce is not due to an electrical phenomena in our measurement circuit, the mechanical signal of the AFM cantilever has been monitored simultaneously with an electric closure or opening of the contact (Fig. 8) according to the setup shown in Fig. 3. The electric bounce is clearly associated to a mechanical motion of the AFM cantilever.

Moreover by modifying the velocity of the AFM cantilever, it is observed that the number of bounces decreases when the velocity increases (Fig. 9). Such a result is contrary to the results commonly observed in macroscopic contact for which bounces are explained by the high kinetic energy of the mobile part. However, by
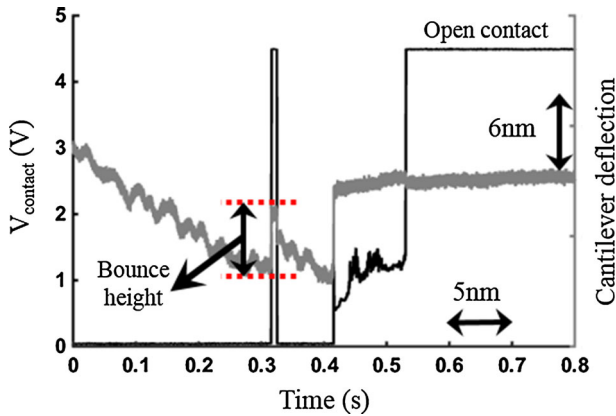
Fig. 8 AFM cantilever information correlated with an electrical bounce

Fig. 9 Number of bounces according to the cantilever velocity, during the opening sequence

translating the time to distance at which this phenomenon occurs (for 0.2 s, d = 10 nm for 50 nm/s and d = 2 nm for 10 nm/s), it can be observed that the bounces appeared in the same order of space interval (around 10–12 nm in the case of Fig. 9).

To explain such results an analysis of the balance of forces in the contact has been considered. It shows that three main forces (cantilever return, electrostatic and adhesion) are involved and compete with each other. For a critical distance of typically several tens of nanometers, the electrostatic force becomes higher than the restoring force of the cantilever. This latter is then attracted towards the fixed electrode until the contact is obtained. At that moment, the voltage contact vanishes, and consequently the electrostatic force, so that the restoring force possibly becomes higher than the adhesion force (it is the case in our experiments), leading to the contact re-opening. It can be noticed that the opening is much slower than the electrostatic charge dissipation and not related to the cantilever frequency (580 kHz). Then some of the mechanisms involved into adhesion force are time

dependent and reduce the speed to open the contact. This scenario can be repeated all the easier since the cantilever velocity is low.

5 Conclusion

This paper investigates the relevance of using an Atomic Force Microscope to study electrical contacts at the microscale in order to understand the behavior of MEMS switches and thus be able to improve their reliability. It has been shown through two examples that the force mode available on any AFM equipment can become a powerful and versatile tool offering characteristics similar to MEMS switches when using a tipless cantilever with an adequate stiffness. Several physical mechanisms can be reproduced and deeply studied as many parameters can be easily and separately modified or observed. It has been proved that both undesirable phenomena investigated in the study (material transfer and bounce) specifically result from the nanometric scale of the gap between contact parts. However they entirely differ regarding their sensitivity to closure/opening conditions. Such results highlight the arduousness of MEMS switches optimization and the crucial importance of AFM-based experiments to carry it through.

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