

Durability of materials for nanoelectromechanical switches studied by scanning probe microscopy

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ABSTRACT

As the size of modern transistors scales down, the problem of energy inefficiency becomes a critical challenge. Nanoelectromechanical (NEM) switches are a candidate approach to replace solid-state transistors in next-generation electronics. Their negligible current leakage and low operation voltage lead to significant reduction in both standby and computing power. However, their biggest drawback is the limited lifetime. Upon cyclic opening and closing, the electrical contacts in NEM switches can undergo various modes of failure including adhesion (sticking shut) and contamination (conductivity loss). In this work, the durability of nanoscale electrical contact materials is studied by scanning probe microscopy (SPM) under NEM switch-like conditions with the goal of understanding the tribo-electro-mechanical mechanisms leading to failure. To do this, we use custom-design SPM-based methodology for high-throughput assessment of candidates for contact materials in durable NEM switches. The evolution of interfacial properties is measured for millions to billions of contact cycles in laboratory timeframes. The accumulation of insulating tribopolymers resulting from airborne carbon contaminants is investigated, and its relationship to adhesion and conductivity changes explored.

Keywords: electrical contact, NEM switch, lifetime, tribopolymer

INTRODUCTION

The scaling of modern transistors has been a driving force for the advances of information technology. However, as the size of transistors scales down, the electronic devices are increasingly energy inefficient. Nanoelectromechanical (NEM) switches are a possible candidate for “beyond CMOS technologies” (1). Compared to solid-state transistors, the different working principle, which involves the physical opening and closing of a gap, leads to nearly zero off-state leakage current and low operating voltage, making NEM switches energy efficient. However, the durability of the electrical contacts, which can fail in various modes including adhesion (sticking shut) and contamination (conductivity loss), severely limits the lifetime of NEM switches. For example, it has been shown on macro- and microscales that cyclic contact between metals can produce an accumulation of insulating tribopolymers which are products of tribochemical reactions from airborne carbon contaminants (2–4). The mechanisms leading to failure are closely related to the properties of the contact material such as its hardness, adhesion, conductivity and catalytic reactivity.

Scanning probe microscope (SPM) provides a powerful tool for the assessment of contact materials under NEM switch-like conditions (5). In such a test, the nano-contact between a probe and a sample, both coated with the candidate contact material, is opened and closed cyclically. When working in the conductive atomic force microscope (c-AFM) mode, the mechanical and electrical properties of the contact, including adhesion and contact conductivity, can be measured, and their degradation are monitored throughout the entire experiments.

RESULTS

Experimental setup

Platinum was coated on Si wafers as well as Si AFM probes using sputter deposition. The typical thickness of the deposited film is around 70-160 nm. The sample and the probe were then mounted into an AFM where a bias voltage can be applied across the tip-sample contact, and the current was measured, as illustrated in Fig. 1(a). A serial resistor of $R_s \approx 62.5$ k Ω was placed to limit the range of the current. Figure 2(b) shows a typical transmission electron microscope (TEM) image of the Pt-coated tip. The radius of the tip apex is around 34 nm.

To simulate the on/off cycling of NEM switches, the tip was vibrated vertically at a typical frequency of 70 kHz, using the tapping mode of AFM. While the tip taps and scans over a small area on the Pt surface (red dashed box in Fig. 1(a)), a Pt-Pt contact was made and broken cyclically between the tip apex and the surface. After every certain number of tapping scans, an image of the surface covering the tapped area was taken, either in tapping mode or in contact mode. The topography and/or

conductivity of the tapped area was compared with the non-tapped area outside. In this way, the change of the mechanical and electrical properties of the surface as a function of cycle number can be monitored. The non-tapped area act as a reference is to correct for the impact of any change on the tip side (e.g. wear of the tip, tribopolymer formation on the tip surface, etc.) or possible systematic drifting of AFM.

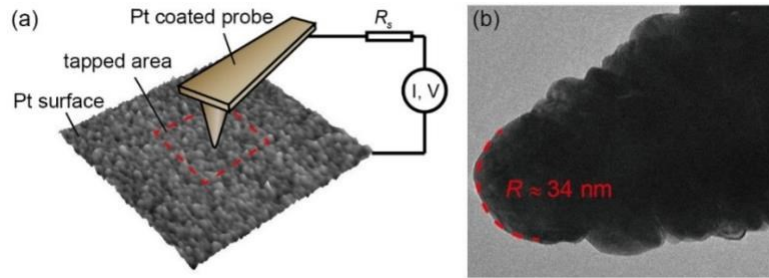


Fig. 1. (a) Experimental setup. A Pt-coated conductive probe was used to tap and scan a small area on the Pt surface, simulating the on/off cycling of a NEM switch. A bias voltage can be applied and the current was measured. (b) TEM image of a Pt-coated probe.

Observation of tribopolymers

The results from a cyclic tapping test as described above is shown in Fig. 2. It is evident from the topography images (Fig. 2(a) to 2(f)) that tribopolymers were formed in the tapped area at the center of the images, and they grew larger in size as cycle number increases. Here one cycle corresponds to one tapping scan, which has 6.8×10^5 times of contact making and breaking. And it can be seen in Fig. 2(b) that after 50 cycles, corresponding to 3.4×10^7 contact cycles, a considerable accumulation of tribopolymers around the contact area is already found.

Volume of tribopolymers is measured on the topography images. The volume change with respect to the very first image is plotted in Fig. 2(g). A linear fitting was performed on the datapoints from cycle 0 to cycle 650. This fitting gives a tribopolymer growth rate of $5.4 \times 10^3 \text{ nm}^3/\text{cycle}$, or equivalently $635 \text{ nm}^3/\text{s}$. The reason to exclude datapoints after cycle 650 is due to the observation of a tip drag event at cycle 650. This is shown in Fig. 2(f), where the white arrow indicates an image artifact caused by the tribopolymers being dragged by the tip during imaging. Such kind of drag events often happens accidentally when imaging the tribopolymers, suggesting that these tribopolymers are very loosely attached on the surface.

The high resonance frequency of AFM probes makes large cycle number tests possible. For a laboratory runtime of 7 hr, a cycle number of 3500 can be achieved, corresponding to 1.6×10^9 times of contact making and breaking. This is comparable to the minimum target lifetime cycle number for a NEM switch device (I). The high cycle number achieved here clearly demonstrate that the SPM-based methodology is suitable for high-throughput assessment for candidates of contact materials.

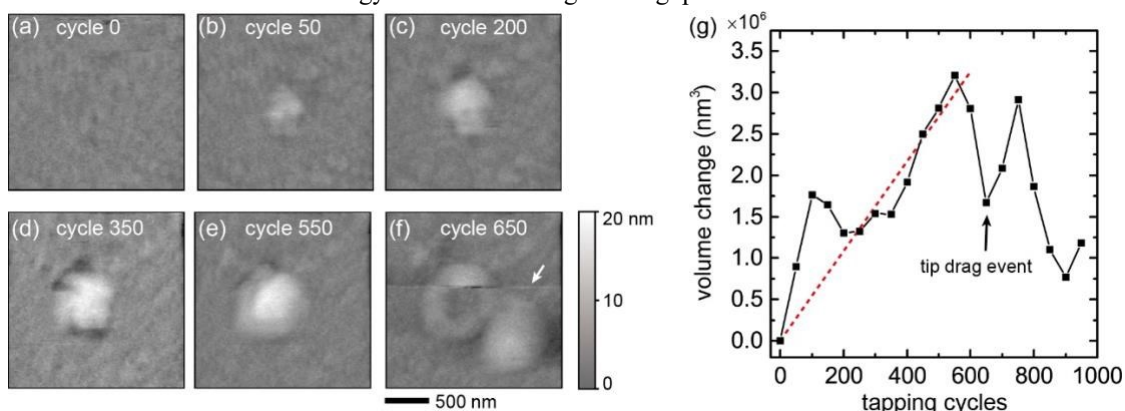


Fig. 2. (a)-(f) AFM topography images. Tribopolymer accumulation forms and grows in size as the cycle number increases. The white arrow in (f) shows an image artifact caused by a tip drag event. All the images share the same scale and color bars. (g) Volume change as a function of cycle number. The arrow marks the tip drag event happened on cycle 650. The datapoints prior to this event is fitted linearly (dashed line), to give a tribopolymer growth rate of $5.4 \times 10^3 \text{ nm}^3/\text{cycle}$.

Electrical contact resistance

The imaging presented in Fig. 2(a)-(f) was conducted with tapping mode, which minimizes the tip-sample interaction but was unable to measure the electrical contact resistance directly. To do so, the similar cyclic tapping tests were repeated, but with imaging in contact mode. The topography images in Fig. 3(a)-(c) show no significant change. However, this does not mean that no tribopolymers were formed. In fact, although the contact force was kept to be as low as possible during

imaging, the contact mode imaging process constantly sweeps the existing and newly formed tribopolymers away, and spread them over the entire imaged area. Therefore, the produced tribopolymers do not pile up within the tapped area as they do in Fig. 2(a)-(f). This interpretation is further supported by the current images in Fig. 3(d)-(f). The surface was initially uniformly conductive on microscale. After 600 tapping cycles, the tapped area becomes less conductive, as indicated by the low current region at the center of Fig. 3(e). After 3400 cycles, due to the sweeping and spreading of tribopolymers, the surface becomes uniformly conductive again, however, with a smaller overall conductivity compared to the initial state. Consistent with this understanding, there is a general trend of increasing contact resistance for both the tapped area and the reference area, as shown in Fig. 3(g). For the tapped area, there is also a rapid initial increase of resistance followed by a decrease superposed on that general trend.

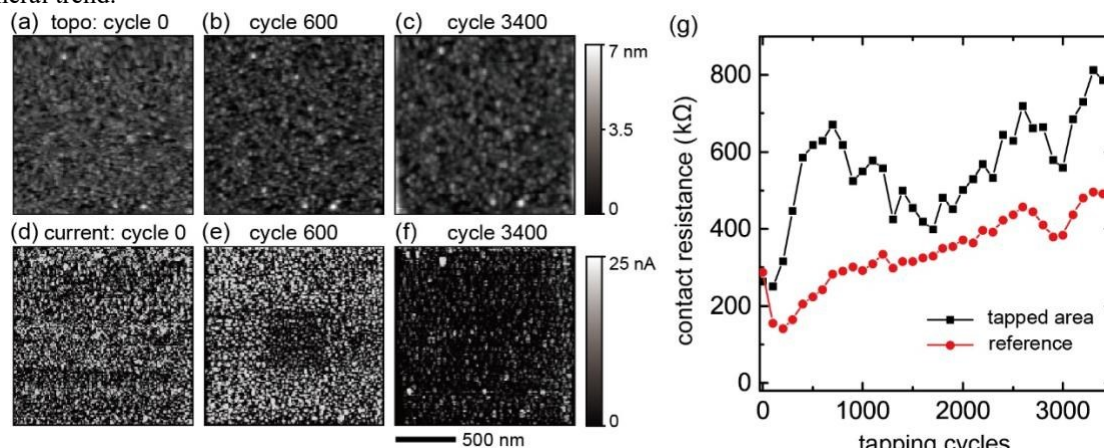


Fig. 3. (a)-(c) AFM topography images. No significant change was observed. (d)-(f) Current images at 1 mV bias. (d) At cycle 0, a generally uniform conductivity is found. (e) At cycle 600, a smaller conductivity is found for the tapped area, indicated by the low current area at the center. (f) At cycle 3400, the surface becomes uniformly conductive again, however, less conductive than cycle 0. All the images share the same scale and color bars. (g) Electrical contact resistance as a function of tapping cycle number, for both tapped area and reference area. A trend of increasing resistance is found for the reference area. Meanwhile for the tapped area, an initial rapid increase of resistance followed by a decrease is superposed on the general increasing trend.

CONCLUSION

In conclusion, we developed a methodology to investigate the durability of nanoscale electrical contact materials with AFM under NEM switch-like conditions. For a Pt-Pt contact, the evolution of interfacial mechanical and electrical properties was measured for up to billions of contact cycles in laboratory timeframes. The accumulation of insulating tribopolymers resulting from airborne carbon contaminants was observed. This accumulation leads to an increase of contact resistance after millions of contact cycles. By measuring tribopolymer volume as a function of cycle number, we are able to estimate its growth rate. This SPM-based high-throughput methodology is effective on screening other candidate materials for nanoscale electrical contacts, and also for the fundamental understanding of failure mechanisms of electrical contacts. These goals, which will be pursued in future researches, can ultimately lead the way to the development of durable and efficient NEM switches.

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