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Effects of electrical current and temperature on contamination-induced degradation in ohmic switch contacts

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ABSTRACT

As scaling of silicon-based metal oxide semiconductor field effect transistor approaches its limits, the ohmic switch has recently been regarded as a viable alternative or complementary technology. However, the electrical contacts in these devices are prone to contamination from ambient hydrocarbons that reduces signal transmission through the switch. In this work we report how two key parameters, electrical current and temperature, affect contaminant-induced degradation mechanisms. It is shown that passing electrical current through the contacts significantly increases contamination growth but also increases its conductivity. We also demonstrate that increasing the ambient temperature delays and reduces the rate of contamination growth.

1. Introduction

The rapid scaling of the metal oxide semiconductor field effect transistor (MOSFET) followed Moore's law for the past several decades [1], enabling ubiquitous technology revolutions. However, to continue this trend, an alternative to silicon MOSFETs must be found because as gate length shrinks below 100 nm, electrical leakage constrains further miniaturization [2,3]. As the MOSFET threshold voltage V_T is reduced, leakage increases due to a nonzero subthreshold voltage swing of 70 mV/decade [4,5]. A significant constraint on V_T is imposed by static power dissipation, which in turn prevents the supply voltage, V_{DD}, from decreasing much below 1 V. This then limits the reduction of dynamic power consumption (proportional to V_{DD}^2).

An approach that recently has received widespread attention for solving the leakage problem is to complement or replace the MOSFET with an ohmic nanoswitch [4,6–9]. When such a switch is in the open state, the electrical contacts are separated by an electrically insulating air gap. A piezolectric nanoswitch can be closed with only 10^{-3} V [10–12], requiring 10^6 times less energy than that needed to actuate a MOSFET. This characteristic also renders it attractive for battery-powered portable applications. Micro- and nanoswitches are also of interest for use in harsh environments including high temperature and high radiation doses [13].

The electrical contact reliability in ohmic switches must be improved to enable their implementation. Contact contamination, which increases with actuation cycle count, is a critical challenge because it causes high electrical contact resistance that either impedes or prohibits signal transmission through the switch [14–17]. The contaminant sources include ambient hydrocarbons and other organic compounds which adsorb on the contact surface. In particular, compounds such as acetylene, benzene, benzaldehyde, cyclohexane, and styrene produce the most contamination [20], while simple alkanes including methane and ethane and simple alcohols including methanol and ethanol produce less contamination [20]. Very low quantities of hydrocarbons are sufficient to initiate degradation. A contaminant layer will form in air [15] or even under ultra-high vacuum conditions [18,19].

It is known that the adsorbed layer is transformed into a high molecular weight carbonaceous deposit in sliding contacts [20,21]. Our observations indicated that this transformation only occurs at locations on the contact surface that experience mechanical loading during switch closure and that normal loading is sufficient for it to happen (i.e., no sliding action is required) [22]. Detailed understanding of the mechanisms of deposit formation is lacking [20,21]. It has been suggested that the catalytic properties of the contact surface [20,21] and/or mechanical stress [22] may promote the transformation. Experiments that test dependence on parameters such as temperature and current will provide insight into mechanisms controlling the deposit formation. This in turn may lead to operational guidelines that minimize the deposit.

In this work, we explore the effects of electrical current and temperature on deposit growth and its electrical conductivity. It was previously found that deposit forms on the contacting asperities in the absence of electrical current being passed through the contacts [22]. However, when current was passed, the amount

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of deposit formed was greatly augmented, and the deposit was much more electrically conductive [22]. Here, we demonstrate that increasing the contact temperature delays electrical degradation and inhibits deposit formation. Therefore, the temperature rise induced by the current is not responsible for increased deposit formation. Furthermore, the increase in the deposit's conductivity correlates with a change in the Raman spectrum, which we interpret to be a structural change from sp^3-rich to sp^2-rich carbon with some graphitic structure.

2. Methods

The experiments were performed on thermally actuated microswitches as shown in Fig. 1. These devices were manufactured at Sandia National Laboratories in Albuquerque, NM, USA. Although the contact loads are higher than in nanoswitches, the resulting contact pressures and current densities are approximately the same (see supplemental info in Ref. [23]). The switch can be closed by applying 8 V across the chevron-shaped polycrystalline silicon (polysilicon) thermal actuator. This in turn causes an electric current to pass through the V-shaped legs, resulting in thermal expansion and causing switch closure (as shown in Fig. 1a). A silicon–nitride insulator in the shuttle prevents electrical cross-talk between the contacts and thermal actuator. The resulting load applied at each contact is $\sim 200\ \mu\text{N}$. The apparent contact area over which this load is distributed is $25\ \mu\text{m} \times 2\ \mu\text{m}$. The real contact area is much smaller, being roughly $0.025\ \mu\text{m}^2$, equivalent to a circle with radius $0.09\ \mu\text{m}$ [23]. The contacts are coated with Pt, a commonly used contact material due to its resistance to wear [23]. The contact region examined in the forthcoming images is circled in Fig. 1b.

All switches were cycled 16×10^6 times at a frequency of 250 Hz. Two switching modes were used: mechanical cycling and cold switching.

In mechanical cycling no voltage is applied across the contacts during cycling. However, the electrical contact resistance (R) is measured once per decade by applying 5 V across the contacts and an in-series 500 Ω current-limiting resistor (a total of 8 such measurements are made during the entire experiment). This mode is used here to isolate the mechanical influence of contaminant-induced degradation of the contacts.

In cold switching, 5 V is applied across the contacts and the in-series 500 Ω resistor 0.7 ms after switch closure and removed 0.7 ms before the switch is opened. The R measurements occur during each of the first 100 cycles and 100 times per decade thereafter. Cold switching is used to study how the presence of electrical current contributes to degradation. This switching mode resembles signal transmission in a variety of switching applications.

The measured R values reported here include the $\sim 10\ \Omega$ contribution from outside the contact region due to the traces, wirebonds, and ribbon cable wiring [24].

Prior to each experiment, the switches were placed in an ultra-high vacuum test chamber (for details, see [22]). The system was baked at 200 °C for 24 h in high vacuum to desorb contaminants from the switch contacts as well as the chamber walls. After the chamber cooled down to room temperature at 24 °C, a pressure of $< 10^{-8}$ Torr was established. The system was then filled with N_2 containing 2500 ppm (PPM) benzene (C_6H_6) to a pressure of 0.5 bar. This high concentration ensures that deposit formation is favored over phenomena such as wear [25] or adhesion [26]. The mixture is henceforth referred to as N_2–C_6H_6. We have chosen to work with benzene because it is known to promote deposit buildup [20]. For experiments that were performed at 100 °C or 200 °C, the chamber was heated to the desired temperature and N_2–C_6H_6 gas was controllably released through a valve until the chamber pressure dropped back to 0.5 bar. With this procedure we controlled the contaminant and its concentration, thereby isolating the experiment to the effect of temperature.

After each experiment, the switches were examined optically and with a scanning electron microscope (SEM, FEI Model Quanta 600 FEG) using a 10 kV acceleration voltage. Raman spectroscopy (Horiba Scientific Model LabRAM HR Evolution) was used to compare the structure of the deposits produced in different experiments. A 473 nm (blue) laser with a 0.5 μm spot size was used. The laser power settings used were low to minimize the possibility of burning the specimens. Initial measurements were carried out at 700 μW, however subsequent measurements were made at 38 μW after establishing that the signal quality was acceptable. There was no apparent damage to the specimens at either the 700 or the 38 μW settings.

3. Results

After baking the samples and introducing the N_2–C_6H_6 mixture, $R \approx 20\ \Omega$ in the first cycle. Switches that were *mechanically-cycled* for 16×10^6 times in N_2–C_6H_6 always grew an electrically insulating deposit that created an open circuit. This deposit is barely visible by optical microscopy (top view, Fig. 2b), but it can be clearly seen with an SEM (45° tilt view of the contact sidewall, Fig. 2c). When switches were *cold switched* for 16×10^6 times in N_2–C_6H_6, the amount of deposit produced was always greatly

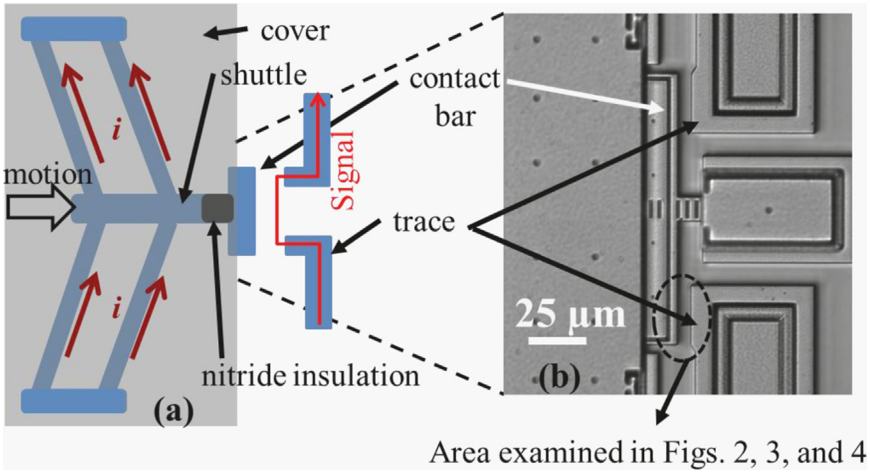

Fig. 1. (a) A top view (that is, plane of sight) schematic of a thermally actuated microswitch with (b) an optical image showing the top view of the electrical contacts. Upon actuation, the contact bar moves towards the contacts. The contacting surfaces cannot be seen here because they are perpendicular to the plane of site.