

Contact Properties of Titanium Nitride Sidewall Coating for Nanoelectromechanical Electronics

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ABSTRACT

The contact properties of thin film titanium nitride (TiN) used as the conductive coating in laterally actuated nanoelectromechanical relays are studied. The relays are made of polycrystalline silicon and a ~30nm thick ALD deposited TiN covers the sidewalls of the source and drain as the contact material. The on-state resistance and the adhesion force between the source and the drain in NEM relays are measured under different conditions. The measurement results show that while the adhesion force is nearly constant for different drain voltages, the contact resistance highly depends on the drain voltage and also on the contact pressure and notably reduces as these two parameters increase. The endurance tests performed on the NEM relays also show that the cyclic contact under cold and hot switching conditions, notably degrades the contact surfaces and drastically increases the on-state resistance of TiN coated sidewalls.

Keywords: low-power electronics, NEM relay, contact properties, on-state resistance, adhesion force.

1 INTRODUCTION

Scaling in CMOS technology has followed Moore's law [1] in the past fifty years and is considered as one of the major advancements in electronics industry resulting in faster and cheaper computation. Smaller devices are known not only for their better performance but also for their energy efficiency since they require less power to operate. However, excessive scaling to nanometer-range devices reverses the power saving due to off-state current leakage. This causes a major drawback as the CMOS technology attempts to further reduce the device dimensions, because in nanometer-size devices, the static power dissipation is the dominant source of energy consumption [2]. Recently, hybrid NEM-CMOS low power electronics and logic gates have been successfully demonstrated [3-5] as a solution to eliminate the current leakage in some applications. These electromechanical switches use electrostatic actuation to deform the source and make physical contact between the source and the drain.

The relay performance highly depends on the physical properties of source-drain contact such as on-state resistance and adhesion force. The contact resistance

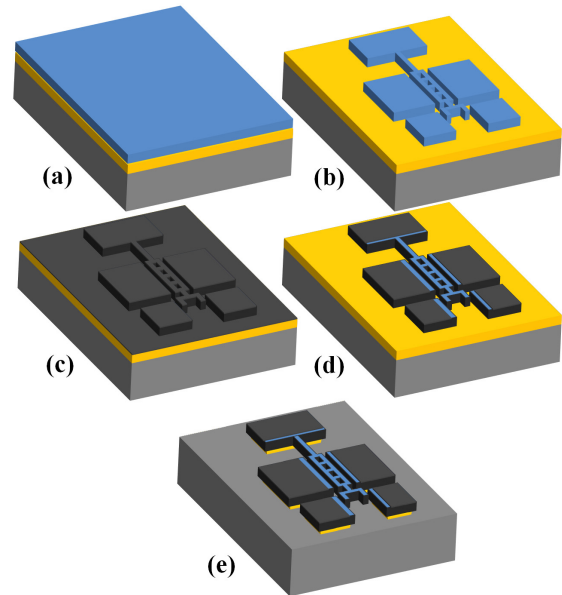


Figure 1: Fabrication process of laterally actuated NEM relays: (a) deposition of 2 μm SiO_2 as insulating layer and 1 μm of polysilicon as structural layer, (b) patterning the relay structure in polysilicon layer using RIE, (c) ALD deposition of ~30nm thick TiN, (d) patterning TiN on contact pads and sidewalls of source, drain and gate, and (e) release in 49% HF followed by critical point drying (CPD).

dictates the operating drain voltage and power consumption, and the adhesion force determines the pull-in/pull-out hysteresis. Any change in the contact resistance or adhesion force over the life of a relay may drastically affects its performance or even result in failure. In the present work, the on-state resistance and adhesion force between source and drain in NEM switches are characterized for polysilicon nanoelectromechanical relays with ~30 nm thick titanium nitride (TiN) coating on the contact area.

2 FABRICATION

Figure 1 displays the fabrication process for NEM relays studied in this work. The structural layer is a 1 μm thick polycrystalline silicon deposited on a 2 μm thick silicon dioxide sacrificial layer which isolates the relay from the substrate. The relay structure is patterned in

polysilicon layer using reactive ion etching (RIE). A ~30 nm thick titanium nitride (TiN) is then deposited on the wafer by atomic layer deposition (ALD) as the conductive, contacting material. A photoresist mask and a chlorine plasma etch is used to remove TiN deposited on the SiO₂ and isolate the source, drain and the gate, leaving TiN only on the contact pads and the sidewalls of relay. The device is finally released using 49% hydrofluoric acid (HF) followed by critical point drying (CPD) to prevent stiction. The fabricated devices are kept in nitrogen glove box with positive pressure all the time after their release.

Figure 2 shows the SEM image of a fabricated relay. The relays used in this study have decoupled electrostatic and structural elements [6] as shown in Figure 2. The electrode part of source is rigid and the deformations occurs in the beam to create the contact between the source and the drain. This allows us to increase the contact force after pull-in by applying overdrive voltage at the gate.

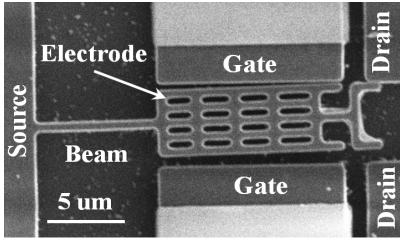


Figure 2: SEM image of a polysilicon NEM relay with ALD TiN sidewall coating and decoupled beam and electrode source.

3 CONTACT PROPERTIES OF TIN COATED NEM RELAYS

The on-state resistance and adhesion force between the source and drain are measured using actual NEM relays and not test structures. This helps us to determine the material properties of ALD TiN coating and also to characterize the device itself under real working conditions. Figure 3 displays the measured I_{DS} - V_{GS} response of a laterally actuated NEM relay used to determine the adhesion force and contact resistance in on-state position. All measurements are done in the over-pressured nitrogen glove box to minimize the oxidation or other surface contaminations during the storage and test.

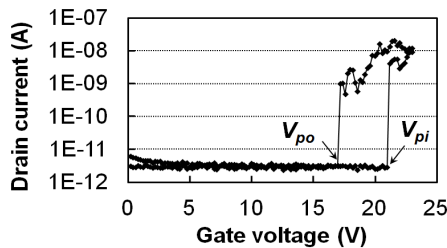


Figure 3: I_{DS} - V_{GS} response of the NEM relay with distinct pull-in and pull-out. V_{pi} and V_{po} respectively represent the pull-in and pull-out voltages.

3.1 Adhesion Force

Finite element simulations [7] and actual I_{DS} - V_{GS} response, shown in Figure 3, are used to accurately measure the adhesion force as small as few nN. When the voltage increases, the electrostatic force between the electrode and gate deforms the beam such that at pull-in it overcomes mechanical force stored in the beam and changes the relay status to on. This point is shown in Figure 3 as V_{pi} . Further increase in actuation voltage increases the contact pressure and, as will be shown later, reduces the on-state resistance. When the gate voltage reduces, due to electrostatic hysteresis and adhesion force, the source stays in contact with drain at voltages below V_{pi} . Further decrease in gate voltage causes pull-out, V_{po} , where structural force stored in the beam overcomes the electrostatic and adhesion forces. Just before separation of the source and the drain, shown in Figure 4a, there is a balance between electrostatic, structural and adhesion forces:

$$F_{Ahd} = F_S - F_E \quad (1)$$

where F_{Ahd} , F_S and F_E represent adhesion, structural and electrostatic forces, respectively. To accurately determine the adhesion force for each voltage sweep, the pull-out voltage is applied to the gate in the finite element simulations to determine the marginal adhesion force needed to keep the source and drain in contact at that gate voltage. Different relays may experience different pull-out, therefore the simulation is repeated for a range of V_{po} to determine the corresponding adhesion forces. Figure 4b displays the simulation results. Negative and positive contact forces shown in Figure 4b correspond to compressive and adhesion force, respectively.

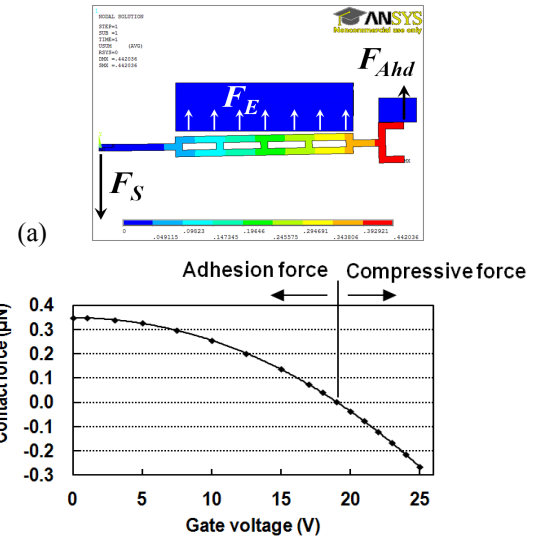


Figure 4: (a) FEM model of a NEM relay simulating the static equilibrium before pull-out. (b) Contact force versus gate voltage for a NEM relays obtained using ANSYS® simulations.

The results of adhesion force measurements for different drain voltage values (V_{DS}) are presented in Figure 5. In Figure 5a and 5b the measured adhesion force for two cases of “no overdrive” and “20% overdrive” gate voltage (V_{GS}), respectively, are compared. Higher overdrive voltage means larger contact pressure between the source and the drain. The drain voltage increases for each relay from 0.1V to 2.0V and the pull-out voltages are recorded to determine the adhesion force. The error bars in Figure 5 indicate the variation of adhesion force for different devices. The average adhesion force for ALD TiN coating in both plots display slight increase, however, for relays with higher contact pressure the error bars at higher drain voltage are much larger, implying that some of the relays under higher contact pressure and higher current exhibit larger adhesion force. The overall large error bars in different test conditions also show the stochastic nature of adhesion force which highly depends on the contacting surfaces and the number of contacting asperities in nanoscale.

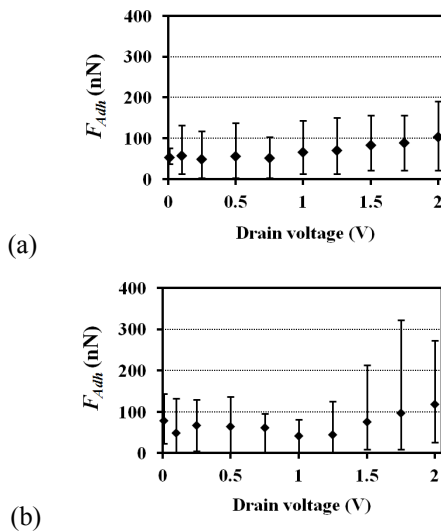


Figure 5: Adhesion force in side walls of ALD TiN coated NEM relays as a function of drain voltage: (a) without overdrive voltage, (b) with 20% overdrive gate voltage.

3.2 Contact Resistance

The on-state resistance of thin TiN coated NEM relays was measured for different drain voltages for two cases of “no overdrive” and “with 20% overdrive voltage” and is presented in Figure 6. The test results show that the on-state resistance, R_{ON} , not only depends on the drain voltage, but also drastically decreases when higher contact pressure is applied. Larger contact force further pushes the asperities and increases the real contact area by increasing the compressive stress at the tip of the asperity. Increase in drain voltage results in higher current passing through the contacting asperities which could generate excessive Joule heating. This modifies the contacting area if the contacting asperities are heated enough to soften and consequently increases the contact area. Applying drain voltages higher

than 2V frequently results in permanent stiction due to nanowelding caused by generated heat at tip of asperities.

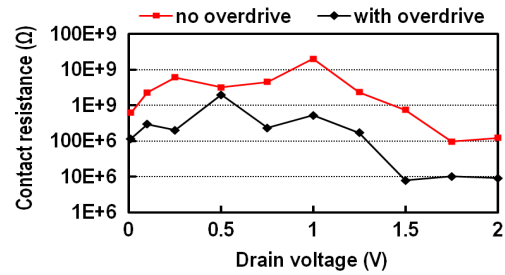


Figure 6: The contact resistance of TiN coated NEM relays subjected to different drain and overdrive voltages.

Figure 7 shows the relationship between adhesion force and on-state resistance for the same tested devices displaying a slight correlation between lower contact resistance and higher adhesion force. This relation is especially important for relay design to ensure the relay is strong enough to provide restoring force that can separate the source and drain and prevent the permanent stiction in low resistance devices.

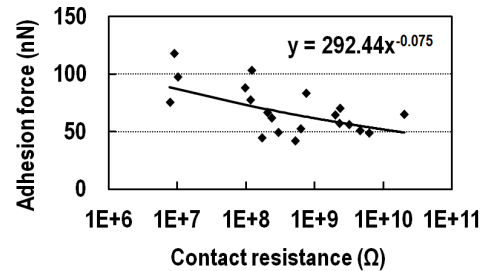


Figure 7: Correlation between adhesion force and contact resistance in TiN coated NEM relays, where lower contact resistance results in larger adhesion force.

3.3 Endurance Test

The endurance of sidewall TiN coating is studied using accelerated life-time tests. Figure 8 shows the contact resistance and adhesion force of a 5-terminal relay tested on two sides with low and high overdrive gate voltages. The relay is subjected to step gate voltage with 2sec ON and OFF time. R_{on} and F_{Adh} are measured after each 100 switching cycles for total of 500 cycles (1000 sec on-state time). The results display drastic increase in on-state resistance indicating a rapid degradation of contact surface. Although higher contact force can decrease the resistance, it cannot prevent the degradation. The adhesion force between source and drain also slightly decreases as the number of switching cycles increases. Excessive heat generated at the limited number of contacting asperities, possible surface contamination and testing environment are believed to contribute to the surface degradation. To further study the effect of the drain current on the surface properties, the relays were also tested for 10,000 cycles with 0.1sec on/off

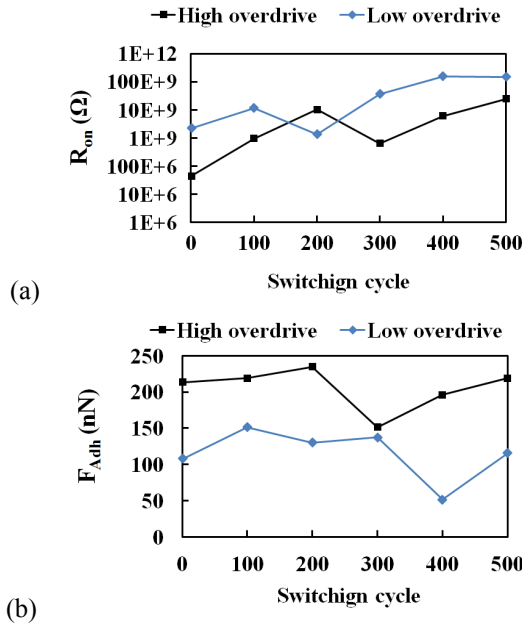


Figure 8: (a) On-state resistance and (b) source-drain adhesion force in accelerated life-time test of TiN coated NEM relays. Each switching cycle includes 2sec of “on” and “off” time. $V_{GS} = 25V$ and $30V$ for low overdrive and high overdrive, respectively, and $V_{DS} = 2V$ for both cases.

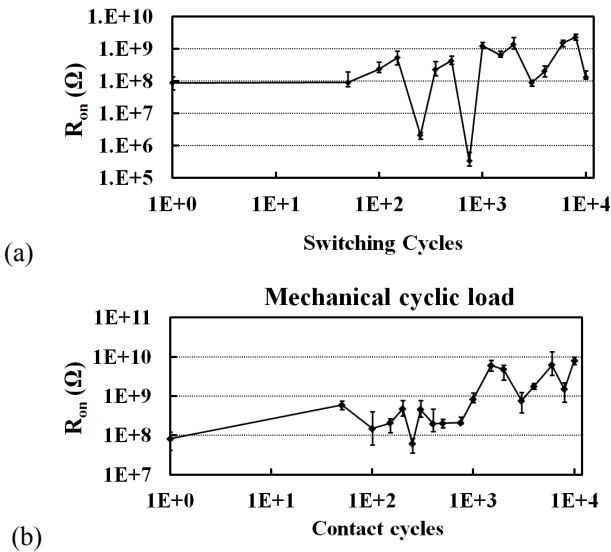


Figure 9: Contact resistance in cyclic switching test for ALD TiN coated NEM relays: (a) hot switching with $V_{DS} = 1V$ and 100ms on/off steps, and (b) cold switching (mechanical contact, $V_{DS} = 0V$). The error bars show the variation of contact resistance in each switching cycle.

with and without drain voltage (hot and cold switching) and R_{on} was measured periodically. The test results presented in Figure 9 compares the cold and hot switching with the same switching time and reveal that even when there is no current, R_{ON} increases (Figure 9b) after ~1000 mechanical

contact. This suggest that the possible contamination due to cyclic contact could affect the surface and degrade it even when there is no excessive temperature rise due to Joule heating.

4 CONCLUDING REMARKS

Contact properties of ALD TiN coated polysilicon NEM relays were investigated. The adhesion force and on-state resistance were measured under different drain voltage and contact pressure and also over life of the relays. The measurements suggest that when higher current passes through source-drain contact or the contact pressure increases the contact resistance decreases. Moreover, the endurance hot and cold switching tests show relatively rapid degradation of contact surfaces, where drastic increase in on-state resistance is observed.

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