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VOLATILE AND NON-VOLATILE NANOELECTROMECHANCIAL SWITCHES WITH RUTHENIUM-ENHANCED NANO CONTACTS

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ABSTRACT

Nanoelectromechanical (NEM) switches have promising applications as volatile or non-volatile electronic switching elements in areas such as low-power logic, memory, and reconfigurable circuits. However, the reliability of nano-scale contacts in NEM switches remains a major challenge. While ruthenium (Ru) has been successfully used for micro-scale contacts in radio frequency (RF) MEMS switches with relatively large dimensions, Ru has not been explored as contact coating in NEM switches. Here, we investigate and demonstrate the effectiveness of Ru-coated nano-contacts in silicon NEM switches, enabling both volatile and non-volatile switching of NEM switches fabricated within the same NEM device layer. These findings have the potential to advance NEM switch technology for low-power and reconfigurable computing applications.

KEYWORDS

Volatile and non-volatile NEM switches, ruthenium (Ru) nano-contact, contact reliability

INTRODUCTION

As the limitations of conventional CMOS scaling become increasingly evident, nanoelectromechanical (NEM) switches have emerged as a promising candidate for beyond CMOS applications due to their sharp ON/OFF transitions, ultra-low OFF-state leakage and reprogrammable switching capability [1-2]. Unlike traditional transistors, NEM switches can operate in either volatile or non-volatile modes, thus offering unique advantages for low-power logic, memory, and reconfigurable circuits [3-4]. Volatile NEM switches return to their original state after removing the actuation voltage, making them suitable for low energy logic applications. In contrast, non-volatile NEM switches retain their state after actuation, enabling zero static power dissipation, which is beneficial for non-volatile memory and ultra-low-power computing [5-7].

Despite the advantages of NEM switches, realizing both volatile and non-volatile functionalities within the same NEM switch platform remains a significant challenge. At the same time, achieving reliable operation of nano-contacts in NEM switches requires maintaining an optimal contact adhesion force while minimizing wear-induced degradation over repeated switching cycles. Previous efforts (Table 1) have explored NEM switches that were fabricated using back-end-of-line (BEOL) metals [8-11], resulting in NEM switches made of metal as the structural material and featuring nano-contacts with relatively low contact resistances. However, these approaches suffer from low switching cycle endurance and reliability issues, limiting their feasibility in practical applications. An all-ruthenium (all-Ru) NEM switch has been demonstrated, sustaining 10^6 switching cycles [12], however fabrication challenges, particularly beam buckling from compressive stress, significantly limited the yield of these all-Ru NEM switches. We have recently demonstrated volatile and non-volatile silicon (Si) NEM switches with Au-coated nano-contacts [13-15], where the Si switches exhibited improved mechanical stability compared to all-metal switches, while the soft nature of the Au contacts resulted in fast contact degradation and wear over time. In contrast, Ru is a promising contact material due to its high hardness (5 GPa), superior wear resistance, and the conductivity of its oxide form (RuO_2), which are properties that can improve contact reliability in miniaturized NEM switches [12,16]. While Ru has been widely explored for micro-scale contacts in larger RF MEMS switches [17-18], to date, no prior work has investigated or demonstrated Ru coatings as nano-contacts in NEM switches.

In this work, we demonstrate Si NEM switches with Ru-coated nano-scale contacts. Remarkably, we realized both volatile and non-volatile NEM switches with Ru-coated contacts in the same NEM switch device layer. We have systematically analysed the effect of different Ru coating thicknesses on the resulting switch performance. Our volatile and non-volatile NEM switches feature a sub-100 nm contact gap, with a dedicated Ru coating design to improve electrical conductance and contact reliability. The volatile Ru-coated NEM switches successfully operated for up-to 500 consecutive hot-switching cycles before encountering stiction failure, while the non-volatile switches operated for up-to 72 cycles before failing due to gate overdrive.

Table 1: NEM switches with metallic nano-contacts.

Ref.	Function	Structure (no. of electrodes)	Structural material (contact material)	Cycles	Pull-in (V)	Year
[8]	Volatile	Out-of-plane (3)	TiN	50 (oil)	8 (oil)	2009
[12]	Volatile	In-plane (7)	Ru	10^6	13	2009
[10,11]	Non-volatile	In-plane (5)	TiN (Cu)	2	10	2020
[15]	Volatile	In-plane (4)	Mono-Si (Au)	20	16	2023
[9]	Non-volatile	In-plane (5)	TiN (Al)	/	3.4	2023
This work	***Volatile***	***In-plane (3)***	***Mono-Si (Ru)***	***500***	***15***	***2025***
	Non-volatile	***In-plane (7)***	***Mono-Si (Ru)***	***72***	***3.6***	

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DEVICE CONCEPT AND FABRICATION

The volatile and non-volatile Si NEM switches used in this work have been designed and optimized in previous works [19-20]. Figure 1(a) and (b) show microscope images of the fully released volatile and non-volatile NEM switches, respectively, with their structural dimensions listed in Table 2.

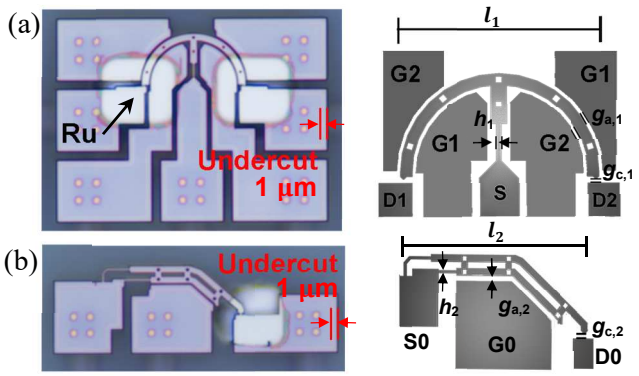

Figure 1: Microscope images (left) and schematics (right) of the fully released in-plane volatile and non-volatile NEM switches.

Table 2: Dimensions of the fabricated NEM switches.

Parameters	Size
Length of the circular beam l_1	11 µm
Length of the angular beam l_2	17 µm
Hinge width h_1/h_2	160 / 220 nm
Original actuation gap $g_{a,1}/g_{a,2}$	225 / 220 nm
Original contact gap $g_{c,1}/g_{c,2}$	120 / 130 nm

The fabrication process of the NEM switches is illustrated in Fig.2. Step i presents the NEM substrate featuring a 250 nm Si device layer. In step ii, the NEM switches are patterned using electron beam lithography (EBL) and reactive ion etching (RIE). Next, we used a lift-off process to deposit a thin Ru coating on the switch contacts. This process starts with spin-coating a double-layer resist mask (top layer photoresist: SPR700, bottom layer lift-off resist: LOR5A), followed by defining a window opening covering both the probe pads and the switch contacts using direct laser lithography (step iii). It should be noted that, before resist coating, a partial release step of the NEM switches is conducted using buffered hydrofluoric acid (BHF) etching for 2 min, creating a 200 nm-deep undercut in the underlying SiO_2 layer, to prevent undesired short-circuits between different switch terminals during Ru metal coating (step iii). A thin Ru coating is then deposited onto the switch contacts and the probe pads by DC sputtering (step iv). After the metal lift-off step, the fabricated NEM switch structure is examined using scanning electron microscopy (SEM) (Fig.3 (a)-(c)). Finally, the movable beams of the NEM switches are fully suspended using a vapor hydrofluoric acid (vHF) release etch (18 Torr, 2 min, 40 sccm HF, Orbis Alpha MEMSSTAR) (step v).

RESULTS AND DISCUSSION

Characterization of Non-volatile NEM Switches

The non-volatile NEM switches consist of seven terminals (Fig.1(a)), including a circular beam connected to the source (S) terminal, which can rotate either clockwise or counterclockwise under an electrostatic force generated by applying a voltage to the corresponding gate terminals. When a sufficiently high gate voltage is applied to gate-pair G1, the switch beam rotates counterclockwise, establishing contact between source (S) and drain1 (D1). Conversely, applying a voltage to gate-pair G2 causes the switch to rotate clockwise, connecting the source (S) to drian2 (D2). Electrical signals can be accessed directly through probing on the metallized probe pads.

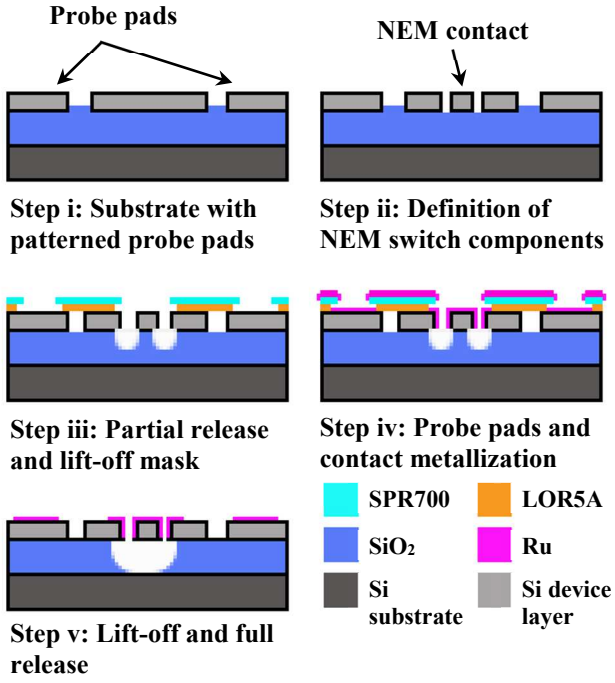

Figure 2: Schematic of Si NEM switch fabrication process: (i) NEM substrate featuring a 250 nm Si device layer, with pre-patterned probe pads. (ii) Definition of NEM switch outline using EBL and RIE. (iii) Partial release of NEM switches and definition of contact areas and probe pads using a double-layer resist mask. (iv) Metallization of probe pads and switch contacts by Ru sputtering. (v) Lift-off to define the Ru contacts and full release of the NEM switches.

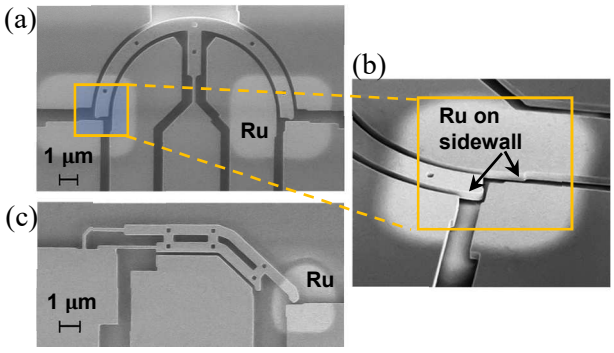

Figure 3: SEM images of (a) a fabricated non-volatile NEM switch, (b) tilted SEM image confirming side-wall coverage with Ru coating on the NEM switches, and, (c) a fabricated volatile NEM switch.

To characterize the electrical properties of the Ru-

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coated non-volatile NEM switches, we conducted measurements of devices with Si contacts (no Ru coating) as reference, and devices with three different Ru contact thicknesses: 35 nm, 45 nm, and 52 nm thick coated Ru contacts. The cycling process involved repeatedly rotating the switch beam counterclockwise and clockwise until failure. The first switching cycle started from the neutral position, where a gate voltage (V_{gate}) was applied to gate-pair G1, swept from 0 V to 10 V and then back to 0 V. This moved the beam counterclockwise until it touched D1. For all further programming cycles, a higher gate voltage sweep (0 V to 38 V) was applied. During these measurements, the drain terminals (D1 and D2) were kept at 10 V with a 1 nA current compliance, while the source terminal (S) remained grounded.

Among the 24 NEM switches we measured with only Si contacts (i.e., no Ru coating), 18 of them showed a first cycle pull-in at around 9 V, however they permanently stuck to the drain after the initial switching due to the high adhesion force between the two Si contact surfaces with the presence of a native SiO_2 layer. The remaining 6 devices either failed to exhibit a pull-in event or suffered from gate leakage, likely due to fabrication inconsistencies. In contrast, devices with 35 nm, 45 nm, and 52 nm thick Ru coatings showed significantly improved performance, with first-cycle pull-in voltages as low as 6 V, 5 V, and 3.6 V, respectively. The reduced pull-in voltages of the Ru-coated switches can be attributed to the partial coverage of the actuation gap by the Ru coating (Fig.3(a)-(b)), which effectively reduces the equivalent actuation gap size. Since the electrostatic force is inversely proportional to the square of the actuation gap, this reduction leads to substantial decrease in the pull-in voltage.

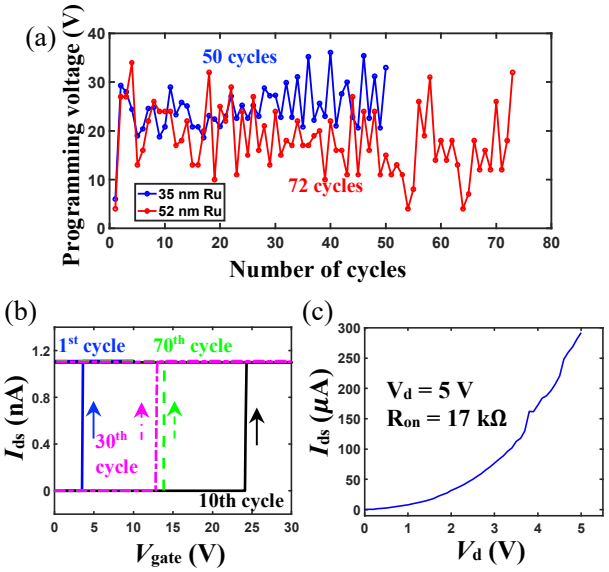

Figure 4: (a) Cycling experiments of switches with 35 nm and 52 nm thick Ru coatings. (b) Example of the counterclockwise cycles of the switch with 52 nm thick Ru. (c) Measured I_{ds}-V_d characteristics of the switch with 45 nm thick Ru.

Additionally, both 35 nm and 52 nm thick coated Ru on the switch contacts resulted in enhanced contact reliability, successfully operating for 50 and 72 reprogrammable cycles, respectively (Fig.4(a)). The selected 1st, 10th, 30th, 70th switching cycles for the 52 nm thick Ru coating are shown in Fig.4(b), without observable signal degradation. Furthermore, we actuated the switch with the 45 nm thick Ru coating using a gate voltage of 38 V, and applied a drain voltage sweep (V_d) from 0 V to 5 V in steps of 0.1 V. The measured I_{ds}-V_d characteristics are plotted in Fig.4(c). The switch on-resistance (R_{on}) is measured to be approximately 17 kΩ at a drain voltage of 5 V.

Characterization of Volatile NEM Switches

The volatile NEM switches consist of three terminals, including an angular beam connected to the source (S0) terminal, along with fixed drain (D0) and gate (G0) terminals (Fig.1(b)). To characterize the pull-in and pull-out performances of the Ru-coated volatile NEM switches, we applied a gate voltage sweep to G0, increasing from 0 to 20 V and then sweeping back down, while biasing the drain at a constant 10 V with a 1 nA compliance and grounding the source.

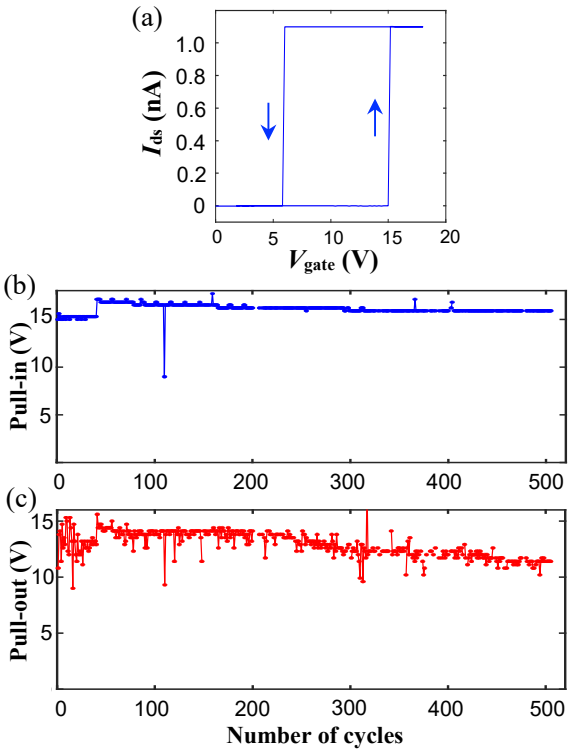

Figure 5: (a) First actuation cycle of a volatile NEM switch. (b) Pull-in voltage evolution, and (c) pull-out voltage evolution of the volatile NEM switch.

Figure 5(a) shows a first-cycle pull-in and pull-out measurements of the volatile NEM switch. The switch shows an initial pull-in voltage at 15 V, and pull-out voltage at 6 V, then survived 500 hot switching cycles before a stiction failure occurred (Fig.5). Throughout the cycling, the pull-in and pull-out voltages remained stable, demonstrating consistent switching behaviour.

CONCLUSION

This work demonstrates Si NEM switches with Ru-coated contacts, suitable for both volatile and non-volatile switch operations. The successful realization of Ru nano-

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contacts in NEM switches enables reliability improvements and is an important step towards the realization of energy-efficient NEM-based computing technologies.

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