Sub-50 mV NEM Relay Operation Enabled by Self-Assembled Molecular Coating

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Abstract

Sub-50 mV operation of nano-electro-mechanical relays is demonstrated for the first time, enabled by an anti-stiction molecular coating. Specifically, a self-assembled monolayer of perfluorodecyltriethoxysilane (PFDTES) is shown to be effective for reducing the switching hysteresis voltage, without dramatically increasing its ON-state resistance, enabling stable device operation at very low voltages.

Introduction

Nanometer-scale electro-mechanical (NEM) switches (relays) are of keen interest for ultra-low-power digital logic integrated circuit (IC) applications because they can achieve the ideal property of zero OFF-state leakage current, which provides for a zero static power consumption [1][2]. To minimize active power consumption, the operating voltage (V_{DD}) of a digital IC should be minimized. V_{DD} scaling for a NEM relay is limited by the switching hysteresis voltage that is caused by contact stiction [3]. In this work, reduction in the contact adhesive forces is demonstrated by the application of an anti-stiction molecular coating which proves effective in reducing V_H without dramatically increasing contact resistance, enabling stable relay operation at lower voltages.

Relay Structure and Operation

Fig. 1(a) shows a plan-view scanning electron microscope (SEM) image of a 6-terminal (6-T) relay developed for digital logic IC applications. This device comprises a movable body electrode suspended by four folded-flexure beams (length L = 12 μm) over a fixed gate electrode. Details of the device fabrication process flow are provided in [4]. For the relays used in this work, the structural (body and suspension beams) material is 1.75 μm-thick *in-situ* boron doped polycrystalline silicon-germanium (poly-$Si_{0.4}Ge_{0.6}$) deposited by low-pressure chemical vapor deposition (LPCVD). The two sets of conducting source and drain (S/D) electrodes are coplanar with the gate electrode, formed from the same layer of 50 nm-thick tungsten (W) deposited by sputter deposition over the insulating substrate. LPCVD SiO_2 was used as the sacrificial material so that the relays could be released using vapor-phase hydrofluoric acid (HF). Al_2O_3 deposited by atomic layer deposition (ALD) is used as the body and substrate insulator material because of its resistance to vapor-HF treatment. As shown in the schematic cross-section of the relay in Fig. 1(b) with an actuation air gap (g_0) of 160 nm and a contact air gap (g_d) of 60 nm in the OFF state, narrow strips of W (50 nm thick) are attached to the underside of the body insulating layer (50 nm thick). These serve to bridge their respective S/D electrodes when the relay is in the ON state, allowing current (I_{DS}) to flow in response to a source-drain voltage difference, as illustrated in **Fig. 1(c)**.

To switch ON the relay, a voltage is applied between the gate and the body, inducing electrostatic force (F_{elec}), to actuate the body downward. When the magnitude of the gate-to-body voltage (V_{GB}) is increased to be equal to or greater than that of the pull-in voltage (V_{PI}), the vertical displacement is sufficient to cause the channels to come into physical contact with their respective S/D electrodes, allowing an abrupt increase in current conduction. When $|V_{GB}|$ is reduced below the magnitude of the release voltage (V_{RL}), the spring restoring force (F_{spring}) of the suspension beams is sufficient to overcome F_{elec} and the contact adhesive forces ($F_{adhesive}$). This enables the structure to return to the off-state position wherein the channels are separated from their respective S/D electrodes.

The relays in this work were tested at room temperature using a vacuum probe station (1.5 μTorr) to avoid oxidation of W which can dramatically increase the contact resistance [5]. Measured current-voltage characteristics for forward and reverse sweeps of the gate voltage (V_G) are shown in **Fig. 2(a)**. By applying a negative body voltage (V_B), the positive value of V_G that is required to turn ON the relay (V_{DD}) can be decreased to $V_{PI} - |V_B|$. The maximum value of $|V_B|$ that can be applied (while ensuring that the relay is OFF at $V_G = 0$ V) is V_{RL}, so that the minimum V_{DD} is the hysteresis voltage $V_H \equiv V_{PI} - V_{RL}$. Sub-200 mV operation with negative body biasing is demonstrated in **Fig. 2(b)**. In a digital logic circuit, the switching devices are used not only to pass low voltage (0 V) as in a "pull-down" device but also to pass high voltage (V_{DD}) as in a "pull-up" device. For a relay to operate as a pull-up device, it must switch ON with *decreasing* V_G. In this case, to achieve ultra-low-voltage operation, a positive body bias should be used as demonstrated in **Fig. 2(c)**.

Fig. 3(a) shows the circuit diagram for an inverter in which the body-biased relay is used as a pull-down device, and **Fig. 3(b)** shows measured input and output voltage waveforms for this circuit.

Molecular Coating

Hydrophobic 1H,1H,2H,2H-Perfluorodecyltriethoxysilane (PFDTES, **Fig. 4(a)**) was selected as the relay coating

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material. The silane functional group of this molecule allows its assembly onto the device surface (Fig. 4(b)) while the fluorinated backbone lowers the surface energy and reduces the surface adhesive forces as shown in Fig. 4(c). After initial testing, relays were coated with PFDTES using a vapor-phase growth process. A few drops of the molecules were placed in close proximity to the relay test chip inside a vacuum desiccator and the pressure was reduced to vaporize the molecules. The chip was left in this environment for ~ 24 hours to ensure full molecular coverage of the device. Upon completion of the growth process, the chip was immediately transferred to the vacuum probe station to minimize exposure to atmosphere.

Results and Discussion

For 6 relays of identical design, I_{DS}-V_G characteristics were tested multiple times (*i.e.* with multiple forward and reverse V_G sweeps) to obtain the average value of V_H. The results shown in **Fig. 5(a)** indicate that the PFDTES coating significantly reduces V_H, by 41% on average both for zero body bias and non-zero body bias. It also reduces V_H variation from one device to another, from 8.3 mV to 7.4 mV (standard deviation) for body-biased relays. From **Fig. 5(b)** it is evident that relays operated with body biasing generally have lower V_H and variability due to lower contact velocity; molecular coating is as effective for reducing V_H in this case.

Fig. 6 shows that the PFDTES does not substantially change the relay ON-state resistance (R_{ON}). This is because despite the insulating nature of the PFDTES, it only forms a very thin monolayer (< 2 nm thick) on the device hence still allowing significant tunneling current between the respective electrodes. Furthermore, the molecular layer may also increase the effective contact area.

Fig. 7(a) shows measured I_{DS}-V_G characteristics for a coated relay with body biasing. Note that although V_H (measured at a current level of 10 nA) is reduced by the PFDTES coating, the transitions between OFF and ON states are less abrupt, *i.e.* the subthreshold swing is increased to ~15 mV/dec. Therefore, a larger gate voltage swing is needed to fully switch the relay ON. However, if a smaller ON/OFF current ratio (*e.g.* 10^4) is sufficient, then the coated relay can be operated with a smaller gate voltage swing. This is in contrast to an abruptly switching relay, which cannot be operated with a gate voltage swing that is smaller than V_H. By applying a body bias to bring the molecular coatings on the S/D and channel electrodes into contact, a metal-molecule-metal "squitch" [7] is effectively achieved. The molecular layer can be engineered for more abrupt switching behavior, through use of synthetic techniques to modify components of the molecular structure including the functional end groups and the spacer backbone. For example, a lower Young's modulus molecular layer can be achieved by changing the spacer group. **Fig. 8** shows an example of shorter alkane molecule with Young's modulus in the GPa regime compared to longer chain poly(ethylene glycol) which exhibits a Young's modulus as low as a few MPa [7-9]. **Fig. 7(b)** shows voltage waveforms for an inverter in which the body-biased coated relay is used as a pull-down device (cf. Fig. 3(b)). As the input voltage amplitude (V_{IN}) decreases, the relay ON-state current is reduced so that it cannot fully discharge the output node and hence the minimum output voltage ($V_{OUT,MIN}$) rises. **Fig. 9** shows voltage waveforms for relay-based inverter circuits, demonstrating sub-50 mV operation ($V_{IN} = V_{DD}$).

Conclusion

Reduction of the hysteresis voltage V_H is key to minimizing the operating voltage of a relay and thereby the active power consumption of relay-based ICs. A self-assembled monolayer PFDTES coating is found to be effective for reducing V_H (by more than 41%) without significantly affecting ON-state resistance, enabling lower voltage operation. Further work is needed to optimize the molecular coating material to achieve a more abrupt switching behavior, to fully realize the benefit of lower V_H for improving NEM relay energy efficiency.

Acknowledgments

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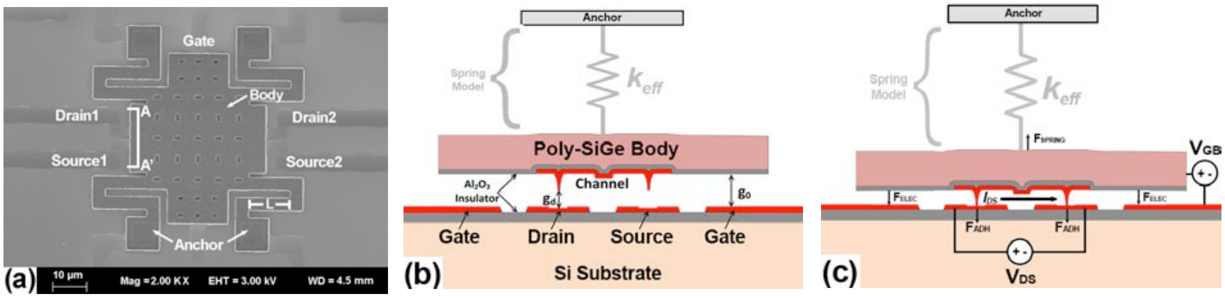

Fig. 1. (a) SEM image of 6-T NEM relay, (b) A-A' cross section in the OFF-state and (c) A-A' cross-section in the ON-state

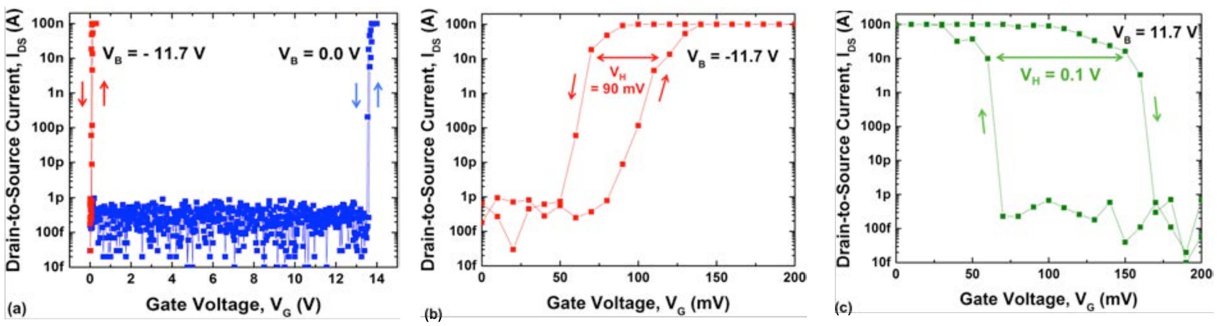

Fig. 2. (a) Measured relay I-V characteristics showing the effect of body-biasing, which is utilized to achieve low-voltage operation for (b) pull-down (N-relay) operation and (c) pull-up (P-relay) operation. I_{DS} is artificially limited to 100 nA in order to prevent Joule heating and subsequent welding at the relay contacts.

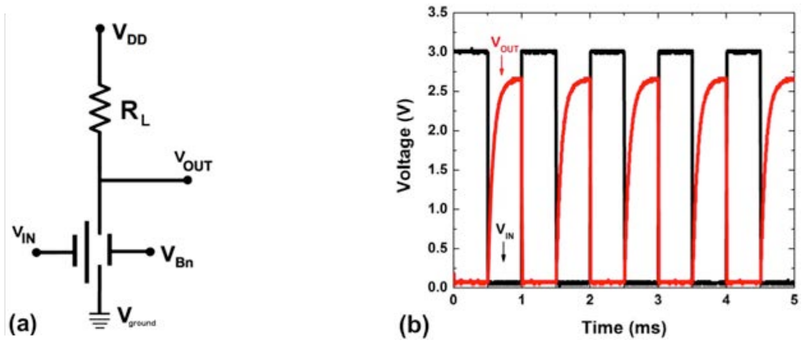

Fig. 3. (a) Relay inverter circuit and (b) measured voltage waveforms for inverter circuit in which a non-coated relay is configured as a pull-down device. R_L = 123 kΩ, $V_{DD} = V_{IN}$ = 3 V, V_{Bn} = -11.75 V, and f = 1 kHz. (v_{OUT} does not reach V_{DD} due to oscilloscope internal resistance $R_{oscilloscope}$ = 1 MΩ.)

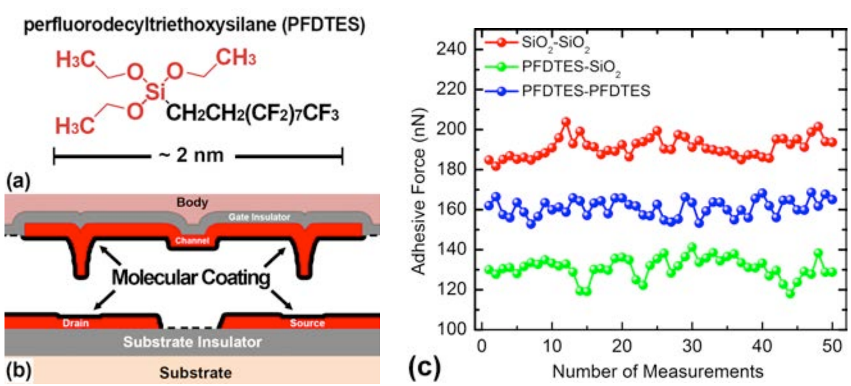

Fig. 4. (a) Molecular structure of PFDTES. (b) Illustration of PFDTES coating, which adheres well to W surfaces due to its silane end-group. (c) Adhesive force measurements characterized via Atomic Force Microscopy. Surface adhesion is decreased with PFDTES coating.

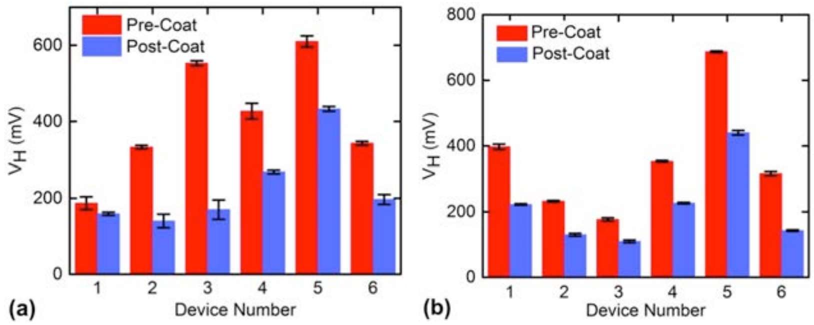

Fig. 5. Summary of measured data, pre- and post-PFDTES coating, showing decrease in switching hysteresis voltage V_H for (a) zero body bias, (b) V_B = - 9 V.

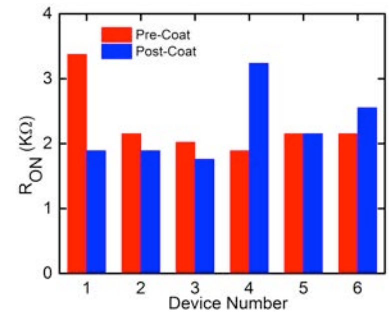

Fig. 6. Measured R_{ON} data showing no significant increase in relay ON-state resistance with PFDTES coating.

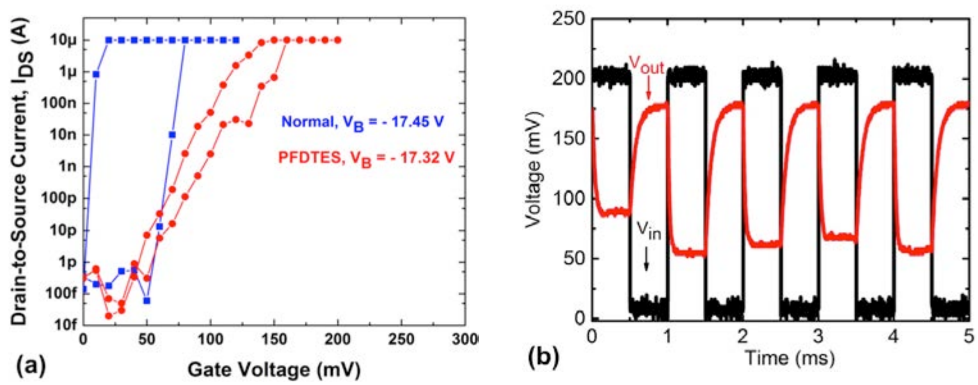

Fig. 7. (a) Measured L = 8 μm relay I-V curves showing that PFDTES coating can provide for ultra-low V_H. (b) Measured voltage waveforms for inverter circuit in which a relay coated with PFDTES is configured as a pull-down device. R_L = 123 kΩ, $R_{oscilloscope}$ = 1 MΩ, $V_{DD} = V_{IN}$ = 200 mV, V_{Bn} = -12.34 V, and f = 1 kHz.

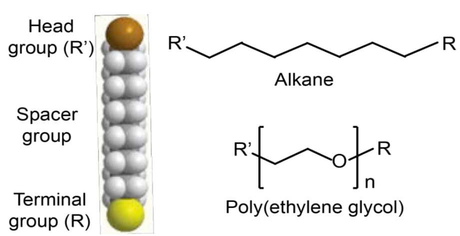

Fig. 8. Through chemical synthesis, molecules can be designed with particular head, terminal and spacer groups to exhibit desired surface selectivity for device functionalization, surface adhesive properties, and electromechanical performance. Here, an alkane molecule with Young's modulus in the GPa regime and poly(ethylene glycol) with Young's modulus in the MPa regime are shown as examples.

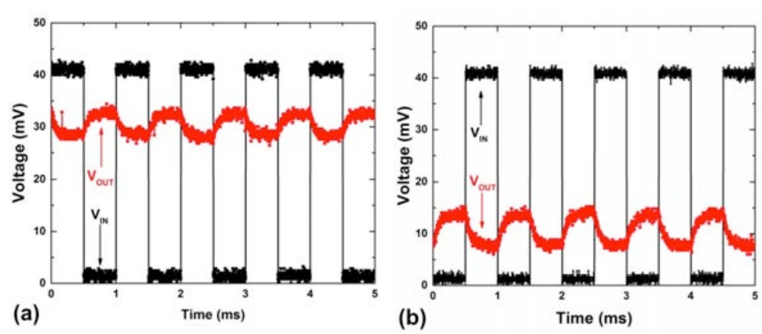

Fig. 9. Measured voltage waveforms demonstrating sub-50 mV relay-based inverter circuit operation: (a) N-relay configuration with V_{Bn} = -14.96 V, and (b) P-relay configuration with V_{Bp} = 14.1 V.
R_L = 123 kΩ, $R_{oscilloscope}$ = 1 MΩ, $V_{DD} = V_{IN}$ = 40 mV, and f = 1 kHz.