CONTACT RELIABILITY IMPROVEMENT OF A POLY-SIGE BASED NANO-RELAY WITH TITANIUM NITRIDE COATING

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ABSTRACT

This work reports a TiN coated contact implemented in a vertically actuated SiGe-based Nano-Electro-Mechanical (NEM) relay. It is shown that covering the bottom of the movable SiGe beam (the armature) with a TiN layer in the contact region will improve the contact performance of the relay with lowering the on-resistance, R_{ON}, by around 4 orders of magnitude and by enhancing the number of switching cycles without degradation. This NEM relay provides an optimal combination of small motional volume (~0.02μm^3) and long mechanical lifetime (>10^{10} in vacuum). Furthermore, with a total contact area of 0.01μm^2 (among the smallest reported so far), an on-resistance of ~1MΩ has been achieved.

KEYWORDS

NEM relay, poly-SiGe, TiN, lifetime, pull-in voltage, contact resistance, AFM spectroscopy.

INTRODUCTION

Nano-Electro-Mechanical (NEM) relays, *e.g.* the one shown in Fig. 1, with zero leakage current and abrupt switching behavior, are emerging as one of the most promising alternatives for ultra-low power switching applications [1]. Several works have reported switches with a small motional volumes but with a limited lifetimes, or, a good lifetime but with a large motional volume (Fig. 2(a)). Moreover as shown in Fig. 2(b), downsizing the contact area in the miniaturized switches leads to dramatic increase in the contact resistance. The time response of relay-based circuits is limited by mechanical pull-in time (typically 1-100nsec) rather than the electrical charging delay, τ_{RC}. Therefore for 0.1-1fF load capacitance the on-resistance R_{ON} can be as high as 100kΩ-100MΩ [8]. It is clear though that the lower R_{ON} the better in particular for achieving a high I_{on}/I_{off} ratio, a better energy efficiency and also less heat generation during the ON-state (and consequently less contact degradation). Here we report on a NEM relay combining a long lifetime with a small motional volume and a reasonably low R_{ON} for a very small contact area.

The choice of the material for the beam and the contacts is playing a critical role in the reliability of NEM relays [11]. When reducing the motional volume down to the nanometer scale, some metal like materials fail in achieving the required mechanical performance [2], [9]. On the other hand, metal-like materials are best suited to achieve low contact resistance for small contact area devices [2]. When two such rough films come into physical contact, the actual area of conduction is much smaller than the total surface area since electrical contacts occur exclusively at asperities or local maxima of the film surfaces [12]. The contact material determines the resistivity at the asperities. The flow of current through each asperity is limited by two mechanisms: (1) when the contact radius (r) is small compared to the electron mean free path (λ), the resistance due to the lattice scattering mechanism, which is called Maxwell resistance, can be calculated as $R_M = \rho/(2r)$ (assuming that the resistivity of the contact material is ρ), and (2) when r is larger than λ, the resistance caused by the boundary scattering of electrons, which is referred to as the Sharvin resistance, can be calculated as $R_S = 4\rho\lambda/(3\pi r^2)$. Note that both Maxwell and Sharvin resistances contribute to the overall contact resistance [13] and both are proportional to the resistivity of the contact material (ρ).

In this paper, we combine the good mechanical performance of a SiGe beam with a metal contact realized with TiN material. Titanium nitride is a good contact material due to its high mechanical wear resistance, high melting point, high thermal and electrical conductivity, and chemical resistance [3]. In MEMS 2014, we presented the fabrication and initial characterization results of a SiGe-based NEMS relay [9]. In order to address high on-resistance and contact degradation issues of SiGe made relay the contact part is covered with a thin film of TiN.

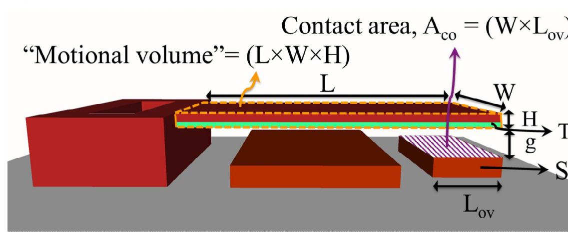


Figure 1: Basic representation of SiGe NEM relay with dissimilar contact SiGe(bottom)/TiN(top). The meaning of 'motional volume' is also explained.

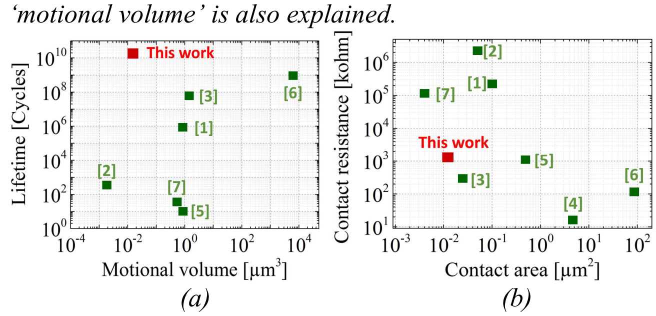


Figure 2: Benchmarking for performance of the key NEM relays (a) lifetime versus motional volume (b) on-resistance versus contact area (R_{ON} is defined as division of V_{DS} to I_{DS}).

MATERIAL PROPERTIES

The adhesion force between a surface and the tip of an atomic force microscope cantilever can be determined by recording force–distance curves with an atomic force microscope (AFM) [14]. A conductive plateau-type highly doped silicon tip with a 1.8μm diameter contact area (Nanosensors, PL2-FMR-2) were used to mimic the adhesion between two parallel surfaces. Force-distance curve measurement was performed in 10^{-5}mbar ambient. The samples were preheated up at 100ºC before running measurement in order to remove the thin water film on top of the surface and exclude the capillary force from the measured adhesion force.

As indicated in Table 1, TiN is a better contacting material than SiGe due to its high mechanical wear resistance (hardness), high melting point, high thermal and electrical conductivity [10]. Covering the contact area with TiN helps lowering the contact resistance and the temperature rise during the current flow and therefore improves contact reliability due to local Joule heating.

Although residual stress of TiN looks rather high (compressive in the range of 300-500MPa), it is helpful to compensate the downward strain gradient of the SiGe beam.

Based on the usual convention, positive strain gradient indicates that the layer is more tensile towards the top resulting in upward bending for cantilever structures after release. Downscaling the layer thickness while keeping low resistivity for ultra-thin poly-SiGe leads to relatively high strain gradient. A nano-size Cantilever Beam Array (CBA) with varying lengths was scanned using AFM to measure the beams' deflection with few nm resolutions. Deflection measurement of cantilever beams as a function of length can be used to determine accurate values for structural layer strain gradient. AFM image of SiGe CBA shows downward bending of cantilevers after release with extracted strain gradient of 0.02 μm^{-1}. As it can be seen in Fig. 4, AFM imaging of CBA with SiGe/TiN stack in structural layer illustrates the upward bending of cantilevers after release and the reduction of beam strain gradient to 0.007μm^{-1}.

Table 1: Material properties of poly-SiGe and TiN.

Material property	Unit	Material	
		$Si_{20}Ge_{80}$	TiN
Electrical resistivity	Ωm	4×10^{-5}	2×10^{-6}
Thermal Conductivity	W/mK	3	28
Residual stress (compressive)	MPa	-50	-300
Melting point	°C	~1000	3000
Young's modulus	GPa	110	390
Hardness	GPa	9	32
Adhesion force of surface to AFM tip	nN	212	121
Strain gradient of SiGe	μm^{-1}	-0.02 (+0.007 for SiGe/TiN stack)	

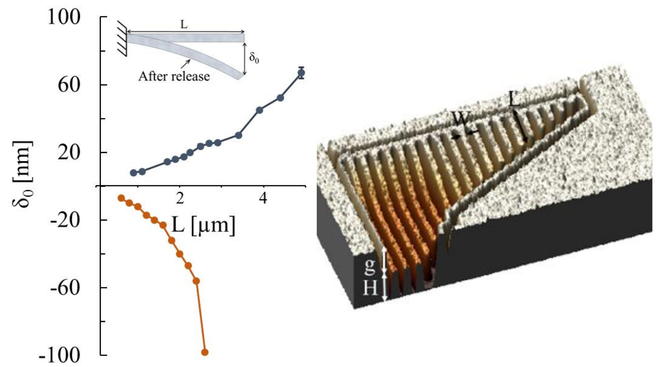


Figure 3: Measured tip deflection of a nano-size CBA with varying lengths using AFM to find the equivalent strain gradient (SG) of 100nm $Si_{13}Ge_{87}$ and 90nm $Si_{13}Ge_{87}$/20nm TiN; inset: Tilted 3D AFM image of SiGe CBA deflected downward due to negative strain gradient within the layer, L = (0.3μm - 7μm) , W = 200nm, g = H = 100nm.

DESCRIPTION OF PROCESS FLOW

The schematic view of the relay cross section, SEM and AFM images of a fabricated three-terminal relay are shown in Fig. 5(a), (b) respectively. The bottom metal lines are processed with tungsten and Si-oxide and SiC are served as the passivation layer on top of the metal lines to protect the CMOS below during the vapor-HF release process. After opening the vias to connect the metal lines, SiGe is used as electrode material, where the contact area and gate of the device are defined. The wafer is next planarized using a SiOx polishing process (CMP), followed by the deposition of the sub-100nm relay sacrificial layer. After patterning the anchors, a 10-20nm thick TiN is conformally deposited using MOCVD followed by growing a thin poly-SiGe at 400ºC using CVD. The structural layer is patterned on the minimum feature size of 200nm. Finally, the devices are released in VHF. The deposition conditions of the ultra-thin SiGe structural layer were optimized to achieve minimum resistivity and low strain gradient.

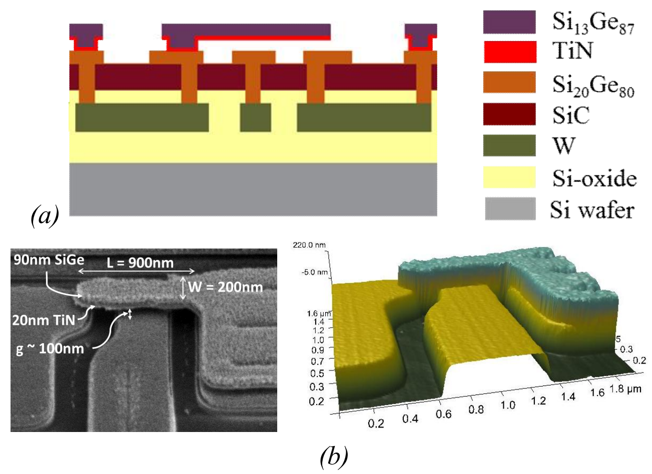
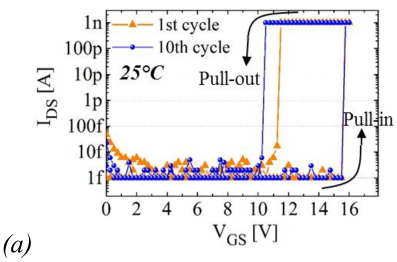


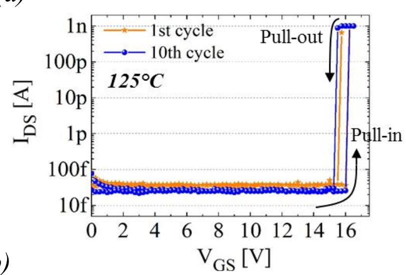
Figure 4: (a) Schematic cross section of the relay (b) SEM photograph and AFM image of a fabricated 3T NEM relay.

EXPERIMENTAL RESULTS & DISCUSSION

The hysteresis I_D-V_G measurement of a NEM relay over 10 operating cycles at room temperature and at 125ºC illustrates stable pull-in and pull-out voltages during cycling, and also the functionality of the relay in high temperature environment (Fig. 6(a) & (b)). The difference in pull-in and pull-out voltages at different temperatures can be attributed to residual stress variations with temperature or to presence of moisture on the contact region at room temperature. Overall, in high temperature environment the hysteresis curve is clearly reduced as compared to room temperature device operation.



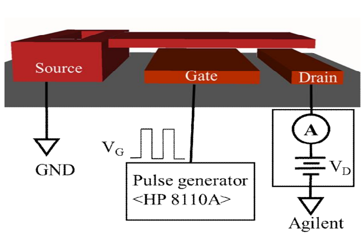
(a)



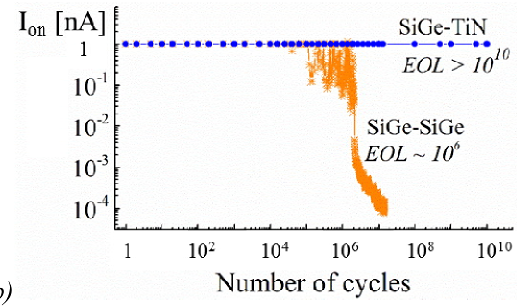
(b)

Figure 5: 1[st] and 10[th] measured hysteresis I_{DS}-V_{GS} of a NEM relay with SiGe-TiN contact (a) at RT (b) at 125°C (V_{DS} = 2V, in vacuum).

In order to estimate the lifetime of the relay, a periodic square-wave-like waveform with a peak voltage of 16V was applied to gate, the drain terminal was connected to a constant voltage of 2V and the source terminal was grounded (Fig. 7(a)). The measurement was performed with a frequency of around 20 kHz in vacuum with a pressure of 10^{-5} mbar and at 100ºC temperature to remove water and other contaminations on the contacting surfaces. As can be seen in Fig. 7(b), the on-current for the relay with SiGe-SiGe contact starts to degrade after around 10^6 cycles, while the one with SiGe-TiN contact is still fully functional after 10^{10} cycles. The measurement for relay with SiGe-TiN was stopped after 4 days while the device was still perfectly functional.



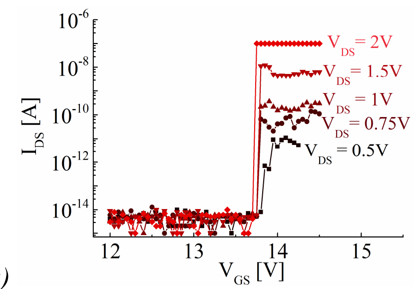
(a)



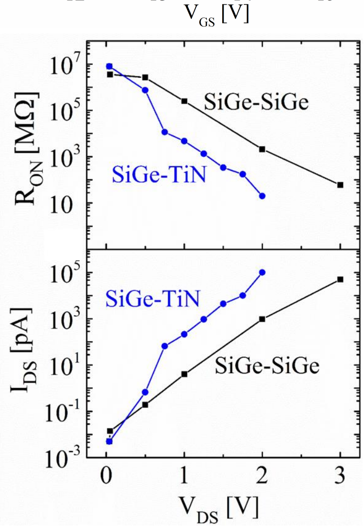
(b)

Figure 6: (a) Schematic representation of the measurement set up (b) Evolution of on-current with number of switching cycles for SiGe-SiGe contact versus SiGe-TiN contact showing End-Of-Life(EOL) of SiGe-SiGe (EOL is defined as more than two orders of magnitude reduction of on-current) occurs at 10^6th cycle while for SiGe-TiN, EOL >> 10^{10}.

The I_{DS}-V_{GS} characteristics of the NEM relay with SiGe-TiN contact for different drain voltages is shown in Fig. 8(a). Since there is no linear relationship between the voltage and the current, it indicates that there is no ohmic resistance at on-state in the contact region. Comparing the I_{DS}-V_{DS} characteristics of relays with SiGe-SiGe and SiGe-TiN contacts illustrates that for similar V_{DS}, the current is always higher for SiGe-TiN contact indicating the lower contact resistance of SiGe-TiN (Fig. 8(b)).



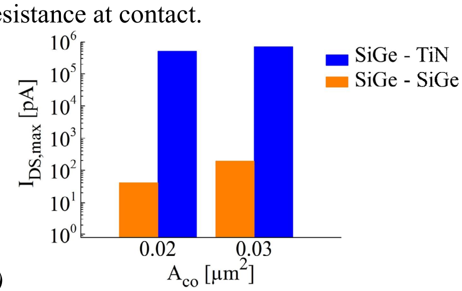
(a)



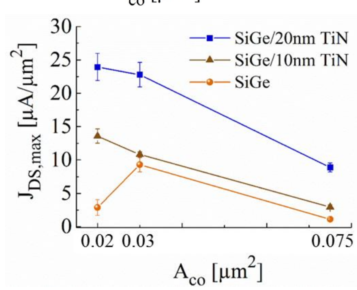
(b)

Figure 8: (a) Measured I_{DS}-V_{GS} curves at different V_{DS} for SiGe-TiN contact (b) measured current passing through SiGe-SiGe and SiGe-TiN contacts as a function of V_{DS} at $V_{GS} = V_{PI} + 0.5 \approx 14V$ indicating the lower on-resistance of SiGe-TiN contact compared to SiGe-SiGe one.

The maximum current flowing through the SiGe-SiGe and SiGe-TiN contacts with the same drain voltage is shown in Fig. 9(a). $I_{DS,max}$ is the maximum current that can flow through the contact without stiction of the beam to the drain. Considering that the resistance is inversely proportional to the on-current, it can be concluded that with SiGe-TiN contact, a reduction of on-resistance by a factor of 10^4 can be achieved. Figure 8(b) presents the maximum current density (defined as $I_{on,max}/A_{co}$) of the relay with different contact materials as a function of the apparent contact area, A_{co}, which is the overlap length of the source with the drain. Since the actual contact area is smaller than A_{co}, the real current density is higher than what Fig. 9(b) shows. The higher current carrying capability of SiGe-TiN contact with thicker TiN is illustrated in this figure. As seen in Fig. 8(b), covering SiGe with 10nm TiN results in improving the maximum current density for small contact area due to mitigating the high current density-induced welding and 20nm TiN improves the maximum achievable current density significantly due to much lower electrical and thermal resistance at contact.



(a)



(b)

Figure 9: (a) Maximum I_{on} for SiGe-SiGe contact versus SiGe-TiN contact for two different contact area (A_{co}) (b) maximum current density with V_{DS} = 2V showing more significant improvement of I_{on} for 20nm TiN compared to 10nm TiN.

CONCLUSION

A robust 3-terminal NEM relay has been successfully designed, fabricated and tested. In this process flow, poly-SiGe was used to provide good mechanical reliability and TiN was used as a better performed contacting material to improve the contact resistance and lifetime of the NEM relay. The thin TiN layer was also used to address the issues related to high and downward strain gradient of poly-SiGe layer.

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