

LOW VOLTAGE AND ADHESION LIMITED METAL-MEMS FOR VOLATILE/NONVOLATILE RELAYS

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LOW VOLTAGE AND ADHESION LIMITED METAL-MEMS FOR VOLATILE/NONVOLATILE RELAYS

by

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Submitted

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Dedicated To

MY FATHER

. FOR INFUSING EDUCATION IN MY LIFE !

MY BHAIYA-BHABHI

. FOR NURTURING EDUCATION IN MY LIFE !

MY ALL THE TEACHER(S)

. FOR TRANSFORMING EDUCATION IN MY LIFE !

MY (LATE) MOTHER SUSHILA DEVI

. FOR MY LIFE !

It Shall Be the Duty of Every Citizen of India to Develop the Scientific Temper, Humanism and The Spirit of Inquiry and Reform.

– **FUNDAMENTAL DUTIES [ARTICLE 51A (H)]**

THE CONSTITUTION OF INDIA

CERTIFICATE

This is to certify that the thesis entitled, “**LOW VOLTAGE AND ADHESION LIMITED METAL-MEMS FOR VOLATILE / NONVOLATILE RELAYS**” being submitted by **Mr. SUSHIL KUMAR** to the Indian Institute of Technology Delhi for the award of the degree of “**DOCTOR OF PHILOSOPHY**”, is a record of bonafide research work carried out by him under my guidance and supervision.

In my opinion, the thesis has reached the standard of fulfilling the requirement of all the regulations regarding the degree. The results contained in this thesis have not been submitted, in part or in full, to any other university or institute for the award of any degree or diploma.



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Abstract

Micro/nano-electromechanical (M/NEM) contact relays are widely investigated as volatile/non-volatile switching solutions to computing technologies (memory and logic) because they offer— abrupt on/off switching qualities, no off-state leakage currents and relatively insensitive to external conditions (temperature/radiations). However, despite these benefits, actuation voltages of such electrostatic actuated relays are typically high (~few tens of Volt) for electronics applications and question in contacts re-opening against contacting adhesion. In practice, pull-in is minimum actuating voltage required for the relay to be in contact position (ON-state), whereas adhesion signifies the voltage swing required for the contacts re-opening (OFF-state). But, in the extreme limit, adhesion determines whether the contacts re-opened or remain in contact once the actuating voltage is turned-off (0-Volt), which defines a complete hysteresis loop (HL). This effect sets the ultimate limit on switching threshold and is greatly influenced by the device hysteretic behavior (small/large HL). Therefore, low voltage is always a contradictory requirement in adhesion assisted volatile/non-volatile contact relays. In concert with this aim of finding solutions on low actuation voltage, this thesis presents research on such two essential but dissimilar properties of electro-mechanical system.

This thesis is organized into three major themes proposed as follows. The thesis first discussed the practical issues of sacrificial-oxide (SOX) etching related implications: residual stress and SOX-cut. Such fabrication dependent imperfections in released MEMS are leading concerns for low pull-in relays. We present experiments on refractory transition metal (RTM) integration and demonstrate a verified solution using ns-laser based SOX-releasing method. A detailed experimental exercise is performed which confirms >80% stress-recovery (residual bending reduces from 12.9 μm to 3.2 μm) and controlled molybdenum releasing properties. Another significant advantage is found in refining surface properties for example, reduce surface roughness (7.5 nm to 3.8 nm) and improved electrical conductivity of the Mo metal. The efficacy of using RTM, here, relaxed the restrictions on the application and could be translated into high temperature ($T > 150^\circ\text{C}$) M/NEMS devices.

Next, as a second half to the thesis, a controlled SOX-sidewall thickness filling (STF) assisted 2 Volt contact relay performance is presented which encountered much large

beyond pull-in adhesion ($F_{spring}/F_{adh} \gg 1$). This profound intrinsic geometry effect is uniquely determined by STF of the deposited SOX layer and is experimentally verified. We used commercially adopted Si-SiO₂ process rules and demonstrate a doubly clamped relay design featuring stable actuation (~230% driving efficiency) implies high F_{spring} generation ability without increasing voltage and low pull-in ($V_{PI} = 2$ Volt) which aid sharp ON/OFF hysteretic property ($V_H = 0.9$ Volt). We fabricate devices on tens of μm -scale below sub-micron gap (~90-110 nm) and the entire experiment is performed at room temperature of 25 °C using single structural material (molybdenum) therefore, it offers a robust fabrication against thermal mismatch. One more benefit of using all metal relay is that the same material can be used for active devices and electrical interconnection, such that the integration efforts are significantly reduced.

Then, ON/OFF hysteretic characteristics is harnessed, and a unified *voltage–adhesion* framework is implemented to assess the switching property in high temperatures. We collected a large amount of measurement data and verified our results. The established framework outcomes improve the understanding of how contacting adhesion (dominated by *van-der-Waals* force) beyond pull-in influences contacts' re-opening. A systematic experimental and theoretical evaluation of limiting adhesion between refractory molybdenum metal is presented for a range of temperatures (RT to 300 °C). The results confirm that the decreasing nature of pull-out voltage (13.9 V to 10.8 V) with increasing temperature ensures a large hysteresis window (4.7 V at 300 °C). The fabricated dielectric less metal relay design suppresses the nonidealities (no work function difference and no dielectric-charging) in analysing temperature dependent switching, which is a major improvement over the past approach.

The three-fold M/NEM system's solutions obtained from the research shown here could be translated into high-temperature, low-voltage adhesion limiting relay performance and greatly impact their advanced electronics applications.

सार

माइक्रो/नैनो-इलेक्ट्रोमैकेनिकल (एम/एनईएम) संपर्क रिले की व्यापक रूप से जांच की जाती है कंप्यूटिंग प्रौद्योगिकियों (मेमोरी और लॉजिक) के लिए अस्थिर/गैर-वाष्पशील स्विचिंग समाधान क्योंकि वे प्रदान करते हैं— अचानक चालू/बंद स्विचिंग गुण, कोई ऑफ-स्टेट रिसाव धारा नहीं और बाहरी स्थितियों (तापमान/विकिरण) के प्रति अपेक्षाकृत असंवेदनशील। हालाँकि, इनके बावजूद लाभ, ऐसे इलेक्ट्रोस्टैटिक सक्रिय रिले के सक्रियण वोल्टेज आम तौर पर उच्च ($\sim$ कुछ दसियों) होते हैं वोल्ट का) इलेक्ट्रॉनिक्स अनुप्रयोगों और संपर्कों में प्रश्नों के लिए संपर्क के खिलाफ फिर से खोलना आसंजन. व्यवहार में, पुल-इन रिले के लिए आवश्यक न्यूनतम एक्चुएटिंग वोल्टेज है संपर्क स्थिति (ऑन-स्टेट), जबकि आसंजन इसके लिए आवश्यक वोल्टेज स्विंग को दर्शाता है संपर्क पुनः खुलना (ऑफ-स्टेट)। लेकिन, चरम सीमा में, आसंजन यह निर्धारित करता है कि क्या एक्चुएटिंग वोल्टेज बंद होने (0 वोल्ट) के बाद संपर्क फिर से खुल जाते हैं या संपर्क में बने रहते हैं। जो पूर्ण हिस्टैरिसिस लूप (एचएल) को परिभाषित करता है। यह प्रभाव अंतिम सीमा निर्धारित करता है स्विचिंग थ्रेशोल्ड और डिवाइस हिस्टैरेटिक व्यवहार (छोटा/बड़ा) से काफी प्रभावित होता है एचएल)। इसलिए, आसंजन सहायता में कम वोल्टेज हमेशा एक विरोधाभासी आवश्यकता होती है अस्थिर/गैर वाष्पशील संपर्क रिले। निम्न स्तर पर समाधान खोजने के इस उद्देश्य के अनुरूप एक्चुएशन वोल्टेज, यह थीसिस ऐसे दो आवश्यक लेकिन असमान गुणों पर शोध प्रस्तुत करती है इलेक्ट्रो-मैकेनिकल प्रणाली का।

यह थीसिस निम्नानुसार प्रस्तावित तीन प्रमुख विषयों में व्यवस्थित है। थीसिस में सबसे पहले बलि-ऑक्साइड (एसओएक्स) नक्काशी से संबंधित निहितार्थ: अवशिष्ट तनाव और एसओएक्स-कट के व्यावहारिक मुद्दों पर चर्चा की गई। रिलीज़ किए गए एमईएमएस में ऐसी निर्माण-निर्भर खामियां कम पुल-इन रिले के लिए प्रमुख चिंताएं हैं। हम दुर्दम्य संक्रमण धातु (आरटीएम) एकीकरण पर प्रयोग प्रस्तुत करते हैं और एनएस-लेजर आधारित एसओएक्स-रिलीज़िंग विधि का उपयोग करके एक सत्यापित समाधान प्रदर्शित करते हैं। एक विस्तृत प्रायोगिक अभ्यास किया जाता है जो 80 % तनाव-वसूली (अवशिष्ट झुकने को 12.9 माइक्रोन से 3.2 माइक्रोन तक कम करता है) और नियंत्रित मोलिब्डेनम रिलीज़िंग गुणों की पुष्टि करता है। एक अन्य महत्वपूर्ण लाभ सतह के गुणों को परिष्कृत करने में पाया जाता है, उदाहरण के लिए, सतह की खुरदरापन (7.5 एनएम से 3.8 एनएम) को कम करना और मो धातु की विद्युत चालकता में सुधार करना। आरटीएम के उपयोग की प्रभावकारिता ने, यहां एप्लिकेशन पर प्रतिबंधों में ढील दी और इसे उच्च तापमान ($T > 150$ डिग्री सेल्सियस) एम/एनईएमएस उपकरणों में अनुवादित किया जा सकता है।

इसके बाद, थीसिस के दूसरे भाग के रूप में, एक एसओएक्स-एसटीएफ सहायता प्राप्त 2 वोल्ट संपर्क रिले प्रदर्शन प्रस्तुत किया गया है। गहरा आंतरिक ज्यामिति प्रभाव जो विशिष्ट रूप से जमा एसओएक्स परत के साइडवॉल मोटाई भरने (एसटीएफ) द्वारा निर्धारित किया जाता है, प्रयोगात्मक रूप से सत्यापित किया जाता है जैसे कम वोल्टेज डिजाइन, सीमित आसंजन के खिलाफ समान पुनर्स्थापना बल की आपूर्ति करने के लिए पारंपरिक रिले की तुलना में मजबूत संपर्कों को बंद करना/फिर से खोलना (एफस्विंग/एफएडीएच >> 1). हमने व्यावसायिक रूप से अपनाए गए सी-सी₂ प्रक्रिया नियमों का उपयोग किया और स्थिर सक्रियण (~ 230 % ड्राइविंग दक्षता), कम पुल-इन (वी_{पीआइ} = 2 वोल्ट) की विशेषता वाले एक डबल क्लैम्प रिले डिजाइन का प्रदर्शन किया, जो हिस्टेरिटिक प्रॉपर्टी (वी_{एच} = 0.9 वोल्ट) को तेज चालू/बंद करने में सहायता करता है।). हम सब-माइक्रोन गैप (~90-110 एनएम) के नीचे दसियों माइक्रोन-स्केल पर उपकरणों का निर्माण करते हैं और पूरा प्रयोग एकल संरचनात्मक सामग्री (मोलिब्डेनम) का उपयोग करके 25 डिग्री सेल्सियस के कमरे के तापमान पर किया जाता है, इसलिए यह थर्मल के खिलाफ एक मजबूत निर्माण प्रदान करता है। बेमेल. सभी धातु रिले का उपयोग करने का एक और लाभ यह है कि एक ही सामग्री का उपयोग सक्रिय उपकरणों और विद्युत इंटरकनेक्शन के लिए किया जा सकता है, जिससे एकीकरण प्रयास काफी कम हो जाते हैं।

फिर, चालू/बंद हिस्टेरिटिक विशेषताओं का उपयोग किया जाता है, और उच्च तापमान में स्विचिंग संपत्ति का आकलन करने के लिए एक एकीकृत वोल्टेज-आसंजन ढांचा लागू किया जाता है। हमने बड़ी मात्रा में माप डेटा एकत्र किया और अपने परिणामों को सत्यापित किया। स्थापित रूपरेखा के परिणाम इस समझ में सुधार करते हैं कि पुल-इन से परे संपर्क आसंजन (वैन-डेर-वाल्स बल द्वारा हावी) संपर्कों को फिर से खोलने को कैसे प्रभावित करता है। तापमान की एक सीमा (आरटी से 300 डिग्री सेल्सियस) के लिए दुर्दम्य मोलिब्डेनम धातु के बीच सीमित आसंजन का एक व्यवस्थित प्रयोगात्मक और सैद्धांतिक मूल्यांकन प्रस्तुत किया गया है। परिणाम पुष्टि करते हैं कि बढ़ते तापमान के साथ पुल-आउट वोल्टेज (13.9 वी से 10.8 वी) की घटती प्रकृति एक बड़ी हिस्टैरिसिस विंडो (300 डिग्री सेल्सियस पर 4.7 वी) सुनिश्चित करती है। निर्मित ढांकता हुआ कम धातु रिले डिजाइन तापमान पर निर्भर स्विचिंग का विश्लेषण करने में गैर-आदर्शताओं (कोई कार्य फंक्शन अंतर और कोई ढांकता हुआ-चार्जिंग नहीं) को दबा देता है, जो पिछले दृष्टिकोण पर एक बड़ा सुधार है।

यहां दिखाए गए शोध से प्राप्त तीन गुना एम/एनईएम प्रणाली के समाधानों को रिले प्रदर्शन को सीमित करने वाले उच्च तापमान, कम वोल्टेज आसंजन में अनुवादित किया जा सकता है और उनके उन्नत इलेक्ट्रॉनिक्स अनुप्रयोगों पर काफी प्रभाव पड़ सकता है।

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whereas adhesion ($\propto F_{\text{spring}} \leftrightarrow F_{\text{Adh}}$) signify voltage-swing required for the contacts re-opening. Thus, adhesive force $F_{\text{Adh}} \rightarrow F_{\text{vdW}}$ is the upper limit. (b) But, lowering of V_{PI} is always overlooked by this contacting adhesion limit and it is necessary to correlate electrical ($V_{\text{PI}}/V_{\text{PO}}$) and structural (F_{vdW}) specifications simultaneously. Low pull-in has been reached using body-bias, but it troubles adhesion limit (i.e. moving pull-out curve in current-voltage to the left). (c) It causes the V_{PO} to shift past $V = 0$ axis, in fact a well defined V_{PO} point implies finite V_{H} . (Equation 1.3). Thereby, low pull-in relay implementation is always challenged by the effect of adhesion beyond pull-in. To address this ON/OFF implications, in this thesis in **Chapter 3**, a new relay concept which, due to its design, addresses and offers solutions in many critical aspects such as low voltage design, a rugged contacts closing/re-opening against limiting adhesion ($F_{\text{spring}}/F_{\text{Adh}} \gg 1$) 18

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List of Abbreviations

AFM	Atomic Force Microscopy
BOX	Buried-Oxide
CMOS	Complementary Metal–Oxide–Semiconductor
CB	Cantilever Beam
CPD	Critical Point Drying
CVD	Chemical Vapor Deposition
EM	Electromechanical
EDS/EDX	Energy Dispersive X-Ray Spectroscopy
HL	Hysteresis Loop
IC	Integrated Circuit
M/NEMS	Micro/Nano-Electro-Mechanical Systems
MPW	Multi-Project Wafer
PI/O	Pull In/Out
PVD	Physical Vapor Deposition
RTM	Refractory Transition Metal
RT	Room Temperature
RMS	Root Mean Square
SOI	Silicon-On-Insulator
SOX	Sacrificial Oxide
STF	Sidewall Thickness Filling
SEM	Scanning Electron Microscope
TEM	Transmission Electron Microscopy
vHF	Vapor Hydrogen Fluoride
XRD	X-Ray Diffraction