

**INTERNAL DIELECTRIC TRANSDUCED  
MICROELECTROMECHANICAL ACTUATORS  
AND RESONATORS**

**SATISH KUMAR VERMA**



**DEPARTMENT OF ELECTRICAL ENGINEERING  
INDIAN INSTITUTE OF TECHNOLOGY DELHI**

**JULY 2024**

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AND RESONATORS**

**by**

**SATISH KUMAR VERMA**

**DEPARTMENT OF ELECTRICAL ENGINEERING**

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**In fulfilment of the requirements of the degree of doctor of philosophy**

**to the**



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मातापितृभ्यः समर्पितं...

# THESIS CERTIFICATE

This is to certify that the thesis titled **Internal Dielectric Transduced Micro-electromechanical Actuators and Resonators**, submitted by **Satish Kumar Verma (2018EEZ8151)**, to the Indian Institute of Technology, Delhi, for the award of the degree of **Doctor of Philosophy**, is a bona fide record of the research work done by him under my supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

**Prof. Bhaskar Mitra**

Assistant Professor

Dept. of Electrical Engineering

IIT-Delhi, Hauz Khas

New Delhi, India

110 016

Date:

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# ABSTRACT

KEYWORDS: MEMS ; Actuators; Resonators; Electrostatic; Internal Dielectric Transducer.

MEMS actuators and resonators have many promising applications, from RF switches, micro-mirrors, nano-positioners, and ultrasonic transducers to integrated timing references, sensors, and RF filtering. Typically, these devices utilize piezoelectric or electrostatic transduction. The piezoelectric actuators have a full range of motion and bidirectional deflection, whereas resonators have high electromechanical coupling and low motional impedance but have a lower quality factor. The drift of thin-film properties and piezo thickness-dependent resonant frequency makes it difficult to tune. Electrostatic resonators have high-Q, but motional impedance is very high, and electromechanical coupling is low. The external electrostatic transducers are also highly nonlinear.

The heart of almost all microelectromechanical devices are actuators and/or resonators working in symbiosis to implement the desired outcome. In modern MEMS applications, the most desired characteristics for actuators include accurate directional control, analog deflection adjustment, and efficient low-voltage digital switching. Because of their uncomplicated functionality and rapid switching, MEMS actuators are frequently preferred for applications such as RF switches, relays, micro-mirrors, nano-positioners, ultrasonic transducers, and closed-loop sensor systems. These actuators are known for their low power consumption and straightforward manufacturing processes.

This thesis work provides an alternative to piezoelectric transduction for large deflection pull-in free actuators or flexural mode resonators by employing an ultrathin ( $\approx 10$ -nm) dielectric-filled (UDL) structure as an ultrathin internal dielectric for transduction (UDT). UDT has been used for bulk mode resonators with a few nm amplitudes but has not been considered for large deflection actuators. Conventional airgap devices have low coupling coefficients, while alternative piezoelectric devices require complex fabrication. UDL using atomic layer deposition (ALD), on the other hand, is a standard process in all foundries and shows good uniformity over large wafers. The proposed device achieves a coupling coefficient comparable to piezoelectric devices with a more straightforward, CMOS-compatible process.

The study extends to designing and fabricating a hybrid actuation system that combines UDT and airgap actuation in the same device. The hybrid actuation utilized in two ways, the air gap and UDT, can be used synergistically to reduce the pull-in voltage (“hybrid

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downward actuator”). This is especially useful in RF switches where a large gap is desirable to increase the figure of merit. In the upward actuation version of the device, the direction of actuation of the UDT is opposite to that of the airgap transducer, so the two can be utilized to provide bidirectional actuation. This can be useful in deactuation of MEMS switches or in the closed-loop operation of actuators. The air gap combined with an upward actuator is called as “hybrid upward actuator”.

In addition to that, UDL used in these devices can undergo breakdown (BD) primarily due to Poole-Frenkel conduction similar to MOSFET’s and RF switches. Understanding the causes and progression of BD events is essential for improving device performance and reliability. Therefore, the characterization of devices focuses on investigating the BD and reliability characteristics of a UDL ring resonator, previously reported as a pull-in free actuator, thereby serving as a benchmark for evaluating the device’s performance. It also introduces a spiral resonator with internal electrostatic transduction, specifically designed to achieve signal amplification at a higher mode resonance frequency for an asymmetrical area drive and sense electrode configuration.

Furthermore, it explores the design, fabrication, and characterization of depletion layer transducers, which capitalize on internal forces affecting the stationary charges within the space-charge region and combine the advantages of solid dielectric and airgap actuators for transduction. This study also employs the parametric effect for signal amplification by stiffness modulation of a micromechanical resonator with a depletion layer transducer manufactured using a process compatible with CMOS technology.

## सार

**कीवर्ड:** एमईएमएस; एक्ट्यूएटर; गुंजयमान; इलेक्ट्रोस्टैटिक; आंतरिक ढांकता हुआ ट्रांसड्यूसर।

एमईएमएस एक्ट्यूएटर और रेज़ोनेटर में आरएफ स्विच, माइक्रो-मिरर, नैनो-पोजिशनर और अल्ट्रासोनिक ट्रांसड्यूसर से लेकर एकीकृत समय संदर्भ, सेंसर और आरएफ फ़िल्टरिंग तक कई आशाजनक अनुप्रयोग हैं। आमतौर पर, ये उपकरण पीजोइलेक्ट्रिक या इलेक्ट्रोस्टैटिक ट्रांस-डक्टियन का उपयोग करते हैं। पीजोइलेक्ट्रिक एक्ट्यूएटर में गति और द्विदिश विक्षेपण की एक पूरी श्रृंखला होती है, जबकि रेज़ोनेटर में उच्च इलेक्ट्रोमैकेनिकल युग्मन और कम गतित्मक प्रतिबाधा होती है लेकिन इसमें कम गुणवत्ता कारक होता है। पतली-फिल्म गुणों और पीजो मोटाई-निर्भर अनुनाद आवृत्ति के बहाव से ट्यून करना मुश्किल हो जाता है। इलेक्ट्रोस्टैटिक रेज़ोनेटर में उच्च-क्यू होता है, लेकिन गतित्मक प्रतिबाधा बहुत अधिक होती है, और इलेक्ट्रोमैकेनिकल युग्मन कम होता है। बाहरी इलेक्ट्रो-ट्रोस्टैटिक ट्रांसड्यूसर भी अत्यधिक नॉनलाइनर हैं।

लगभग सभी माइक्रोइलेक्ट्रोमैकेनिकल उपकरणों का दिल वांछित परिणाम को लागू करने के लिए सहजीवन में काम करने वाले एक्ट्यूएटर और / या रेज़ोनेटर हैं। आधुनिक एमईएमएस अनुप्रयोगों में, एक्ट्यूएटर के लिए सबसे वांछित विशेषताओं में सटीक दिशात्मक नियंत्रण, एनालॉग विक्षेपण समायोजन और कुशल कम वोल्टेज डिजिटल स्विचिंग शामिल हैं। उनकी सरल कार्यक्षमता और तेजी से स्विचिंग के कारण, एमईएमएस एक्ट्यूएटर को अक्सर आरएफ स्विच, रिले, माइक्रो-मिरर, नैनो-पोजिशनर, अल्ट्रासोनिक ट्रांसड्यूसर और क्लोज्ड-लूप सेंसर सिस्टम जैसे अनुप्रयोगों के लिए पसंद किया जाता है। ये एक्ट्यूएटर अपनी कम बिजली की खपत और सीधी विनिर्माण प्रक्रियाओं के लिए जाने जाते हैं।

यह थीसिस कार्य अल्ट्राथिन ( $\approx 10$ -एनएम) ढांकता हुआ (यूडीएल) संरचना को पारगमन (यूडीटी) के लिए अल्ट्राथिन आंतरिक ढांकता हुआ के रूप में नियोजित करके बड़े विक्षेपण पुल-इन मुक्त एक्ट्यूएटर या फ्लेक्सुरल मोड रेज़ोनेटर के लिए पीजोइलेक्ट्रिक ट्रांसडक्शन का विकल्प प्रदान करता है। यूडीटी का उपयोग कुछ एनएम आयामों के साथ बल्क मोड रेज़ोनेटर के लिए किया गया है, लेकिन बड़े विक्षेपण एक्ट्यूएटर के लिए नहीं माना गया है। पारंपरिक एयरगैप उपकरणों में कम युग्मन गुणांक होते हैं, जबकि वैकल्पिक पीजोइलेक्ट्रिक उपकरणों को जटिल निर्माण की आवश्यकता होती है। दूसरी ओर, परमाणु परत जमाव (एएलडी) का उपयोग करने वाला यूडीएल, सभी फाउंड्री में एक मानक प्रक्रिया है और बड़े वेफर्स पर अच्छी एकरूपता दिखाता है। प्रस्तावित डिवाइस एक अधिक सरल, सीएमओएस-संगत प्रक्रिया के साथ पीजोइलेक्ट्रिक उपकरणों की तुलना में एक युग्मन गुणांक प्राप्त करता है।

अध्ययन एक हाइब्रिड एक्ट्यूएशन सिस्टम को डिजाइन और बनाने तक फैला हुआ है जो एक ही डिवाइस में यूडीटी और एयरगैप एक्ट्यूएशन को जोड़ता है। दो तरीकों से उपयोग किए जाने वाले हाइब्रिड एक्ट्यूएशन, एयर गैप और यूडीटी, का उपयोग पुल-इन वोल्टेज ("हाइब्रिड डाउनवर्ड एक्ट्यूएटर") को कम करने के लिए सहक्रियात्मक रूप से किया जा सकता है। यह आरएफ स्विच में विशेष रूप से उपयोगी है जहां योग्यता के आंकड़े को बढ़ाने के लिए एक बड़ा अंतर वांछनीय है। डिवाइस के ऊपर की ओर सक्रियण संस्करण में, यूडीटी के सक्रियण की दिशा एयरगैप ट्रांसड्यूसर के विपरीत है, इसलिए दोनों का उपयोग द्विदिश सक्रियता प्रदान करने के लिए किया जा सकता है। यह एमईएमएस स्विच के विघटन या एक्ट्यूएटर के बंद-लूप ऑपरेशन में उपयोगी हो सकता है। ऊपर की ओर एक्ट्यूएटर के साथ संयुक्त वायु अंतर को "हाइब्रिड अपवर्ड एक्ट्यूएटर" कहा जाता है।

इसके अलावा, इन उपकरणों में उपयोग किए जाने वाले यूडीएल मुख्य रूप से एमओएसएफईटी और आरएफ स्विच के समान पुल-फ्रेंकेल चालन के कारण टूटने (बीडी) से गुजर सकते हैं। डिवाइस के प्रदर्शन और विश्वसनीयता में सुधार के लिए बीडी घटनाओं के कारणों और प्रगति को समझना आवश्यक है। इसलिए, उपकरणों का लक्षण वर्णन एक यूडीएल रिंग रेज़ोनेटर की बीडी और विश्वसनीयता विशेषताओं की जांच पर केंद्रित है, जिसे पहले पुल-इन फ्री एक्ट्यूएटर के रूप में रिपोर्ट किया गया था, जिससे डिवाइस के प्रदर्शन का मूल्यांकन करने के लिए एक बेंचमार्क के रूप में कार्य किया जाता है। यह आंतरिक इलेक्ट्रोस्टैटिक ट्रांसडक्शन के साथ एक सर्पिल रेज़ोनेटर भी पेश करता है, जिसे विशेष रूप से एक विषम क्षेत्र ड्राइव और सेंस इलेक्ट्रोड कॉन्फ़िगरेशन के लिए उच्च मोड अनुनाद आवृत्ति पर सिग्नल प्रवर्धन प्राप्त करने के लिए डिज़ाइन किया गया है।

इसके अलावा, यह अवक्षय परत ट्रांसड्यूसर के डिजाइन, निर्माण और लक्षण वर्णन की पड़ताल करता है, जो अंतरिक्ष-चार्ज क्षेत्र के भीतर स्थिर चार्ज को प्रभावित करने वाले आंतरिक बलों को भुनाता है और पारगमन के लिए ठोस ढांकता हुआ और एयरगैप एक्ट्यूएटर के फायदों को जोड़ता है। यह अध्ययन सीएमओएस प्रौद्योगिकी के साथ संगत प्रक्रिया का उपयोग करके निर्मित कमी परत ट्रांसड्यूसर के साथ एक माइक्रोमैकेनिकल रेज़ोनेटर के कठोरता मॉड्यूलेशन द्वारा सिग्नल प्रवर्धन के लिए पैरामीट्रिक प्रभाव को भी नियोजित करता है।

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## ABBREVIATIONS

<b>MIM</b>	Metal-Insulator-Metal
<b>UDL</b>	Ultrathin Dielectric Layer
<b>UDT</b>	Ultrathin Internal Dielectric Transduction
<b>MEMS</b>	Micro Electro Mechanical Systems
<b>NEMS</b>	Nano Electro Mechanical Systems
<b>CMOS</b>	Complementary Metal-Oxide Semiconductor
<b>MOSFET</b>	Metal-Oxide Semiconductor Field-Effect Transistor
<b>RF</b>	Radio Frequency
<b>IC</b>	Integrated Circuit
<b>IDT</b>	Internal Dielectric Transduction
<b>IET</b>	Internal Electrostatic Transduction
<b>ALD</b>	Atomic Layer Deposition
<b>vHF</b>	Vapor Hydrofluoric Acid
<b>RIE</b>	Reactive Ion Etching
<b>SEM</b>	Scanning Electron Microscopy
<b>FESEM</b>	Field Emission Scanning Electron Microscopy
<b>FEM</b>	Finite Element Method
<b>SMU</b>	Source Measure Unit
<b>PNA</b>	Parameter Network Analyzer
<b>VNA</b>	Vector Network Analyzer
<b>MS</b>	Metal-Semiconductor
<b>MSM</b>	Metal-Semiconductor-Metal

## NOTATION

$\nu$	Poisson's ratio
$\rho$	Density
$\mu$	Micro
$E$	Young's modulus
$\sigma$	Stress
$k$	Spring constant
$\epsilon$	Permittivity