CMOS-COMPATIBLE MEMS PIRANI GAUGE FOR BROAD RANGE VACUUM MEASUREMENTS

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by

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Dedicated to my Grandfather

Certificate

This is to certify that the thesis entitled "**CMOS-Compatible MEMS Pirani Gauge for Broad Range Vacuum Measurements**" being submitted by **Manu Garg** to IITD/NYCU Joint Doctoral Degree Program, Indian Institute of Technology Delhi for the award of degree of '**Doctor of Philosophy**' is a record of bonafide work carried out by him. He has worked under our joint supervision and guidance and has fulfilled the requirement for the submission of this thesis, which in our opinion has reached the requisite standard. The results contained in this work has not been submitted, in part or full, to any other University or Institution for the award of any degree or diploma.

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Manu Garg

Thesis Abstract

MEMS-based Pirani gauges are an improvement to conventional techniques namely Q-factor extraction and helium leak test. MEMS-based Pirani gauges offer high precision and cost-effective way of in-situ vacuum monitoring. These are primarily important to check the seal quality of a packaged device and calibrate primary device output over time. In context to the existing implementations, MEMS Pirani gauge either relies on wafer bonding or wire bonding techniques to integrate with CMOS circuitry. These approaches are prone to additional noise and parasitic effects thereby limiting the system performance. Also, the higher solid heat conduction losses limit the lower detection capability of the gauge and narrow the full-scale dynamic range. Further, the fabrication constraints associated with minimum suspension gaps and mechanically reliable structures are of critical concern. To address these issues in emerging MEMS Pirani gauges, the thesis focuses on the development of a monolithically integrable, CMOS-MEMS Pirani gauge with a wider dynamic range and lower power consumption for vacuum detection in packaged microsensors.

Firstly, a polymer MEMS-based Pirani gauge is presented. In this work, an SU-8-based dielectric membrane is integrated with the heating element to reduce the solid heat conduction through anchors. The structure is optimized for stress-free release and a quantitative comparison of the proposed gauge is established by comparing the gauge performance with conventional dielectric materials like silicon dioxide (SiO_2), silicon nitride (Si_3N_4), and aluminum oxide (Al_2O_3). Afterward, a metal oxide (V_2O_5) based miniaturized heating element is explored to further reduce the solid conduction and improve the lower detection capability. Although these works investigate dimensional and structural optimizations and explore key parameters affecting device performance, the full-scale dynamic range still needs improvement. Thereafter, a tunable electrode is introduced to electrostatically tune the heat conduction gap between the heating element and heat sink/substrate. Hence, a much lower gap can be achieved to further improve the sensitivity at higher pressure and extend the dynamic range. These optimizations build a fundamental base to develop a post-CMOS compatible microfabrication approach enabling monolithic integration with the standard CMOS process. Lastly, two post-CMOS MEMS platforms based on a nanogap TiN heating element and a metal-based heating element are presented to realize a monolithically integrable device.

Keywords: CMOS-MEMS, Joule Heating, MEMS, Monolithic Integration, Pirani Gauge, Vacuum Detection.

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थीसिस सार

माइक्रो विद्युत यांत्रिक प्रणाली (एमईएमएस)-आधारित पिरानी गेज पारंपरिक तकनीकों अर्थात् गुणवत्ता कारक निष्कर्षण और हीलियम रिसाव परीक्षण में सुधार है। एमईएमएस-आधारित पिरानी गेज वास्तविक काल शून्यक जांच का उच्च परिशुद्धता और लागत प्रभावी तरीका प्रदान करते हैं। ये मुख्य रूप से पैक किए गए यंत्र की सील गुणवत्ता की जांच करने और समय के साथ प्राथमिक यंत्र पैदावन को अंश-शोधन करने के लिए महत्वपूर्ण हैं। मौजूदा कार्यान्वयन के संदर्भ में, एमईएमएस पिरानी गेज या तो कॉम्प्लीमेंटरी मेटल ऑक्साइड सेमीकंडक्टर (सीएमओएस) सर्किटरी के साथ एकीकृत करने के लिए वेफर बॉन्डिंग या वायर बॉन्डिंग तकनीकों पर निर्भर करता है। ये दृष्टिकोण अतिरिक्त शोर और परजीवी प्रभावों से ग्रस्त हैं जिससे सिस्टम प्रदर्शन सीमित हो जाता है। इसके अलावा, उच्च ठोस ताप चालन हानि गेज की कम पता लगाने की क्षमता को सीमित करती है और पूर्ण पैमाने पर गतिशील रेंज को सीमित करती है। इसके अलावा, न्यूनतम निलंबन अंतराल और यांत्रिक रूप से विश्वसनीय संरचनाओं से जुड़ी निर्माण बाधाएं गंभीर चिंता का विषय हैं। उभरते एमईएमएस पिरानी गेज में इन मुद्दों को संबोधित करने के लिए, थीसिस पैकेज्ड माइक्रोसेंसर में शून्यक जांच के लिए व्यापक गतिशील रेंज और कम बिजली की खपत के साथ एक अखंड रूप से एकीकृत, सीएमओएस-एमईएमएस पिरानी गेज के विकास पर केंद्रित है।

सबसे पहले, एक बहुलक एमईएमएस-आधारित पिरानी गेज प्रस्तुत किया गया है। इस कार्य में, लंगर के माध्यम से ठोस ताप संचालन को कम करने के लिए एक SU-8-आधारित ढांकता हुआ झिल्ली को हीटिंग तत्व के साथ एकीकृत किया जाता है। संरचना को तनाव-मुक्त रिलीज के लिए अनुकूलित किया गया है और प्रस्तावित गेज की मात्रात्मक तुलना सिलिकॉन डाइऑक्साइड (SiO_2), सिलिकॉन नाइट्राइड (Si_3N_4), और एल्यूमीनियम ऑक्साइड (Al_2O_3) जैसी पारंपरिक ढांकता हुआ सामग्री के साथ गेज प्रदर्शन की तुलना करके स्थापित की गई है। इसके बाद, ठोस चालन को और कम करने और कम पहचान क्षमता में सुधार करने के लिए एक धातु ऑक्साइड (V_2O_5) आधारित लघु ताप तत्व का पता लगाया जाता है। हालाँकि ये कार्य आयामी और संरचनात्मक अनुकूलन की जांच करते हैं और डिवाइस के प्रदर्शन को प्रभावित करने वाले प्रमुख मापदंडों का पता लगाते हैं, पूर्ण पैमाने पर गतिशील रेंज में अभी भी सुधार की आवश्यकता है। इसके बाद, हीटिंग तत्व और हीट सिंक/सब्सट्रेट के बीच ताप संचालन अंतर को इलेक्ट्रोस्टैटिक रूप से ट्यून करने के लिए एक ट्यून करने योग्य इलेक्ट्रोड पेश किया जाता है। इसलिए, उच्च दबाव पर संवेदनशीलता को और बेहतर बनाने और गतिशील सीमा का विस्तार करने के लिए बहुत कम अंतर प्राप्त किया जा सकता है। ये अनुकूलन मानक सीएमओएस प्रक्रिया के साथ अखंड एकीकरण को सक्षम करने के लिए पोस्ट-सीएमओएस संगत माइक्रोफैब्रिकेशन दृष्टिकोण विकसित करने के लिए एक मौलिक आधार बनाते हैं। अंत में, एक मोनोलिथिक रूप से एकीकृत डिवाइस का एहसास करने के लिए नैनोगैप टाइटेनियम नाइट्राइड (टीआईएन) हीटिंग तत्व और धातु-आधारित हीटिंग तत्व पर आधारित दो पोस्ट-सीएमओएस एमईएमएस प्लेटफॉर्म प्रस्तुत किए गए हैं।

संकेत शब्द: CMOS-MEMS, जूल तापन, एमईएमएस, अखंड एकीकरण, पिरानी गेज, शून्यक जांच.

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List of Abbreviations

BEOL	Back End of Line
BHF	Buffer Hydrofluoric Acid
CMOS	Complementary Metal Oxide Semiconductor
DRIE	Deep Reactive Ion Etching
DUT	Device Under Test
FEM	Finite Element Modeling
FIB	Focused Ion Beam
FFT	Fast Fourier Transform
HAR	High Aspect ratio
IMD	Inter Metal Dielectric
KrF	Krypton Fluoride
MCP	Monolithically Compatible Process
MEMS	Micro Electromechanical Systems
MFC	Mass Flow Control
PDMS	Fourier Transform Infrared Range
PEB	Post Exposure Bake
PMMA	Field Effect Transistor
RIE	Reactive Ion Etching
SB	Soft Bake
SEM	Scanning Electron Microscope
SPM	Scanning Probe Microscopy
SSP	Single Side Polished
TCR	Temperature Coefficient of Resistance

TSMC	Taiwan Semiconductor Manufacturing Company
TSV	Through Silicon Via
UV	Ultraviolet
VHF	Vapor Hydrofluoric Acid