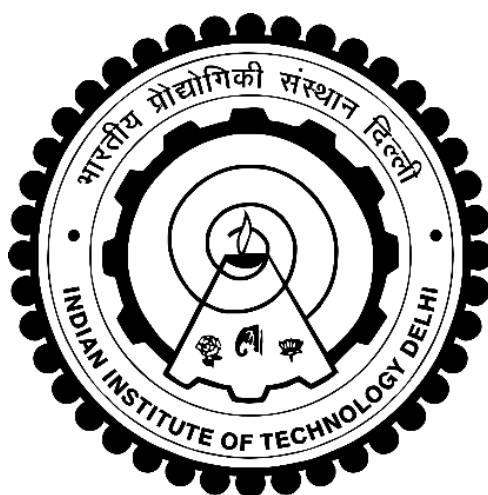


CMOS-COMPATIBLE MEMS PIRANI GAUGE FOR BROAD RANGE VACUUM MEASUREMENTS

MANU GARG



**CENTRE FOR APPLIED RESEARCH IN ELECTRONICS
INDIAN INSTITUTE OF TECHNOLOGY DELHI**

JULY 2024

©Indian Institute of Technology Delhi (IITD), New Delhi 2024

CMOS-COMPATIBLE MEMS PIRANI GAUGE FOR BROAD RANGE VACUUM MEASUREMENTS

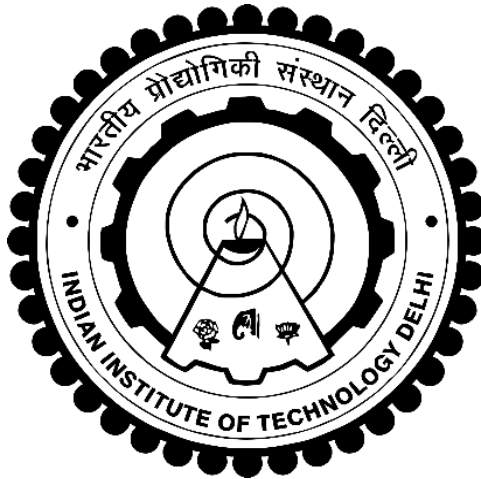
by

**MANU GARG
(2019TIZ8300)**

Centre for Applied Research in Electronics (CARE)

Submitted

*in the fulfillment of the requirements of the degree of Doctor of Philosophy
to the*



INDIAN INSTITUTE OF TECHNOLOGY DELHI, NEW DELHI

JULY 2024

*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.


Dr. Rushparaj Singh
Associate Professor
Centre for Applied Research in Electronics
Indian Institute of Technology Delhi
Hauz Khas, New Delhi-110016

Centre for Applied Research in Electronics (CARE)
Indian Institute of Technology Delhi
Hauz Khas, New Delhi-110016



Dr. Yi Chiu

Professor

Department of Electronics and Electrical Engineering

National Yang Ming Chiao Tung University

Hsinchu, Taiwan (R.O.C.)-30010

Acknowledgments

I want to begin by conveying my heartfelt appreciation to my thesis advisors, *Prof. Yi Chiu*, and *Prof. Pushpapraj Singh*. Their unwavering support, motivation, invaluable guidance, and profound knowledge have been instrumental throughout my journey. Their consistent encouragement, patience, and timely advice have significantly broadened my perspectives and understanding. They generously devoted extensive time to both technical and non-technical discussions, aiding me not only in manuscript preparation for journals but also in crafting my thesis. Their contributions have undeniably been pivotal in shaping my research career.

My gratitude also extends to *Prof. Samaresh Das*, whose constant encouragement and support have been a driving force. I am equally grateful to my doctoral committee members, *Prof. Ananjan Basu*, *Prof. Dhiman Mallick*, from IIT Delhi, and *Prof. Yu-Ting Cheng* from NYCU. Their insightful comments and valuable suggestions during the evolution of this research work have been invaluable.

I would also like to acknowledge *Dr. Ravindra Mukhiya* for his enlightening discussions. Furthermore, I extend my sincere thanks to the entire faculty of the Centre for Applied Research in Electronics (CARE), IIT Delhi, for their contributions. I am particularly thankful to the coordinators of the IITD-NYCU Joint Degree Program, which offered me the opportunity to conduct research in Taiwan, a hub of semiconductor technology.

My appreciation goes to the Nano Facility Centre (NFC) at NYCU Taiwan, the Taiwan Semiconductor Research Institute (TSRI), the Nano Research Facility (NRF), and the Central Research Facility (CRF) at IIT Delhi for their exceptional fabrication and characterization facilities. I extend my gratitude to the Prime Minister's Research Fellowship (PMRF)-India, the Ministry of Human Resource Development (MHRD)-India, the National Science and Technology Council (NSTC)-Taiwan, and the MediaTek Foundation for their financial support.

I am indebted to *Dr. Dhairya S. Arya* and *Mr. Sushil Kumar* for guiding me into the realm of research and illuminating my path with microfabrication and technical writing skills. I am also thankful for the camaraderie of fellow researchers at the Microelectronics Lab, IIT Delhi, especially *Dr. Veerendra Dhyani*, *Dr. Wasi Uddin*, *Dr. Vaibhav Rana*, *Dr. Akshay Moudgil*, *Dr. John Wellington*, *Dr. Prathisha Gangwar*, *Dr. Alka Jakhar*, *Mr. Sumit Sharma*, *Mrs. Harmanpreet Kaur*, *Mr. Mujeeb Yousuf*, *Ms. Richa Mudgal*, *Mr. Khanjan Joshi*, and *Ms. Tamkeen Farooq*.

I would like to express gratitude to my colleagues at the HiMEMS lab at NYCU, particularly *Mr. Fang Wei Tsai*, *Mr. Yu Chi Chuang*, *Mr. Liang-Kai Wang*, and *Mr. Yuan-Chieh Lee*, for their assistance and making my stay in Taiwan memorable. I extend my thanks to my friends at National Tsing Hua University: *Mr. Jimmy Chou*, *Mr. C.Y. Chen*, and *Ms. Jyoti Satija*, without whom my research would not have been possible. I must also mention my amazing friends in particular *Ms. Nidhi*, *Ms. Jyoti*, and *Mr. Rishabh Kamra* for being a significant part of my journey and making life's adventures more beautiful during my time at NYCU, Taiwan.

Lastly, I want to express profound gratitude to my entire family, especially my parents, sister, cousins, and *Ms. Sodabah Liaskhel* for their unconditional love, unwavering support, and constant encouragement. Most importantly, I am deeply thankful to my grandfather, *Mr. Ramesh Kumar*, for his patience and unwavering support throughout my Ph.D. journey; words cannot adequately capture the extent of my appreciation for having you by my side.

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.

This page is intentionally left blank

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/सब्स्ट्रेट 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.

This page is intentionally left blank

Contents

<i>Abstract</i>	i
<i>थीसिस सार</i>	iii
<i>List of Figures</i>	ix
<i>List of Tables</i>	xvii
<i>List of Abbreviations</i>	xix
Chapter 1 Introduction to MEMS Pirani Gauge	1-19
1.1 Overview of MEMS Pirani gauge.....	3
1.2 Operating principle.....	4
1.3 Analytical model.....	6
1.4 Literature review.....	9
1.4.1 CMOS MEMS integration.....	16
1.5 Rationale and objective.....	17
1.6 Organization of the thesis.....	18
 Chapter 2 Dielectric Investigation for Pirani Gauge Applications...	 20-39
2.1 Introduction.....	21
2.2 Structural overview.....	22
2.3 Device fabrication and stress engineering.....	23
2.3.1 Fabrication process flow.....	23
2.3.2 Stress Engineering.....	24
2.4 Measurement setup and preliminary testing.....	28
2.4.1 Measurement Setup.....	28
2.4.2 Critical current and TCR characterization.....	29
2.5 Results and Discussion.....	30
2.5.1 Temperature distribution.....	30
2.5.2 Anchor effect modeling.....	33
2.5.3 Pressure-dependent response.....	34
2.6 Summary.....	38
 Chapter 3 Vanadium Pentoxide (V₂O₅) based MEMS Pirani Gauge	 40-50
3.1 Introduction.....	41

3.2	Material synthesis and characterization.....	42
3.2.1	Raman spectroscopy and X-ray diffraction.....	43
3.2.2	Stress Mapping.....	44
3.3	Structural overview.....	46
3.4	Fabrication process flow.....	47
3.5	Preliminary testing.....	48
3.5.1	TCR characterization.....	48
3.6	Results and discussion.....	49
3.6.1	Temperature distribution.....	49
3.6.2	Pressure-dependent response.....	50
3.7	Summary.....	50
Chapter 4	Tunable MEMS Pirani Gauge.....	52-62
4.1	Introduction.....	53
4.2	Structural overview.....	54
4.3	Design concepts.....	55
4.4	CMOS-compatible fabrication process flow.....	56
4.5	Preliminary testing.....	58
4.5.1	Experimental pull-in analysis.....	58
4.6	Results and discussion.....	59
4.6.1	Temperature distribution and thermal stress.....	59
4.6.2	Deformation and effective gap.....	60
4.6.3	Pressure-dependent tunable gauge response.....	61
4.7	Summary.....	63
Chapter 5	Post CMOS-MEMS Implementation.....	64-82
5.1	Introduction.....	65
5.2	Structural overview.....	66
5.2.1	TiN-based Pirani gauge.....	66
5.2.2	Metal-based Pirani gauge.....	67
5.3	Post CMOS-MEMS implementation.....	68
5.3.1	TiN-based Pirani gauge fabrication process flow.....	68
5.3.2	Metal-based Pirani gauge fabrication process flow	71

5.4	Measurement setup and preliminary testing.....	72
5.4.1	Measurement setup.....	72
5.4.2	Optical profilometry.....	73
5.4.3	Experimental pull-in characteristics for TiN devices.....	74
5.5	Results and discussion.....	75
5.5.1	Temperature distribution	75
5.5.2	Pressure-dependent gauge response.....	77
5.5.3	Noise analysis.....	77
5.6	Summary.....	82
Chapter 6	Conclusion and Future Outlook.....	83-89
6.1	Summary of the research.....	85
6.2	Contribution of the thesis.....	86
6.3	Future outlook.....	88
6.3.1	Optiimized geometry with TiN heating element.....	88
6.3.2	All-around heat sink structure.....	88
6.3.3	Vertically integrated heating elements.....	88
6.3.4	Integrated gauge with on-chip readout.....	89
	<i>Appendix-I</i>	91
	<i>References</i>	93
	<i>List of Publications</i>	105

This page is intentionally left blank

List of Figures

Figure No:	Title of Figure	Page No:
Figure 1.1	The standard architecture of a typical MEMS Pirani gauge.	4
Figure 1.2	(a) Typical S-shaped curve for a standard Pirani gauge, (b) Illustration of different operational regimes corresponding to Knudsen's number [11].	5
Figure 1.3	A typical MEMS Pirani gauge illustrating the dimensional parameters and biasing.	6
Figure 1.4	A one-dimensional model of MEMS Pirani gauge.	7
Figure 1.5	Surface micromachined μ -hotplate structures upheld by flexures (a) A diode-based micro-Pirani gauge supported by two cantilever beams reported by Wei et al. [24], (b) A polysilicon-based μ -hotplate supported by four flexures reported by Robinson et al. [25], (c) Cr/Pt metal heater supported on SiO ₂ /Si ₃ N ₄ membrane reported by Paul et al. [26], (d) Pt heater-based Pirani gauge reported by Shie et al. [27].	10
Figure 1.6	Surface micromachined diaphragm-based structures (a) A nanoporous anodic aluminum oxide-based structure reported by Jeon et al. [29], (b) Pirani gauge reported by Dams and Schreiner et al. [30].	11
Figure 1.7	A polymer polyamide-based structure reported by Fan et al. [23] to achieve superior thermal isolation owing to the lower thermal conductivity of polyamide i.e., 0.167-0.25 W/m.K.	11
Figure 1.8	Surface micromachined μ -bridge type Pirani gauges (a) Wafer-level packaged MEMS Pirani gauge with surrounded heat sinks reported by Kong et al. [12], (b) A polysilicon coil-based micro-Pirani gauge reported by Swart et al. [31], (c) A tube-shaped buried Pirani gauge with small footprint [34], (d) Carbon nanotube Pirani gauge reported by Yu et al. [35].	12

Figure 1.9	A suspended graphene strip-based Pirani gauge demonstrates the role of the suspended gap in shifting the gauge's measurement range towards higher pressures [36].	13
Figure 1.10	Bulk micromachined Pirani gauge with extended length, reduced width, and thickness for enhancing the lower detection limit [5].	13
Figure 1.11	A fusion study by integrating two Pirani gauges with different lengths to increase the overall dynamic range [37].	14
Figure 1.12	A series microbridge-based Pirani gauge consisting of multiple SiO ₂ anchors along the length of the microbridge was reported in [39].	14
Figure 1.13	A microbridge-based Pirani gauge consisting of multiple heat sinks along with a capping wafer was bonded to the device wafer to package the gauge [40].	15
Figure 1.14	A poly-SiC microbridge-based Pirani gauge to achieve pressure monitoring at high temperatures was reported by Mo et al., [41].	15
Figure 2.1	Illustration of a MEMS Pirani gauge based on Polymer (SU-8) material. The device operates in a constant current mode, generating heat that is dissipated through mechanisms including gaseous conduction (Q_{gas}), solid conduction (Q_{solid}), and radiation losses (Q_{rad}) [53].	23
Figure 2.2	Fabrication process flow for fabrication of polymer MEMS Pirani gauge.	24
Figure 2.3	Temperature profile for processing of SU-8 indicating soft bake, UV exposure, post-exposure baking, development, and thermal curing steps (a) Temperature Profile (T1) with 90 °C soft bake, 110 °C post-exposure bake, and ramp and hold thermal cycle with 20 minutes hold time for curing SU-8. (b) Temperature Profile (T2) with 90 °C soft bake, 110 °C post-exposure bake, and ramp & hold thermal cycle with 40 minutes hold time for curing SU-8. (c) Optimized temperature profile (T3) with 90 °C soft bake without quenching, 110 °C post-exposure bake without quenching, and ramp & hold thermal cycle with 30 minutes hold time for curing SU-8.	26

Figure 2.4	(a) The cross-sectional SEM image of the fabricated μ -bridge processed with the temperature profile (T1) consisting of 20-minutes of hold time, demonstrating the device being snapped down onto the substrate, (b) The cross-sectional SEM image of the produced μ -bridge, processed using the temperature profile (T1) and a 15-minute hold time, also displays the device being snapped down onto the substrate, (c) A cross-sectional SEM image of the fabricated μ -bridge, subjected to temperature profile (T2), revealing the device fracturing from one of the anchor points due to elevated tensile stress, (d) cross-sectional SEM image of the polymer MEMS Pirani gauge's fabrication, carried out with the temperature profile (T3), (e) cross-sectional SEM image of the polymer MEMS Pirani gauge's fabrication, carried out with the temperature profile (T3), (f) Top SEM view of the fabricated polymer MEMS Pirani gauge.	27
Figure 2.5	The stress measurement results associated with three different temperature profiles: T1, T2, and T3. (a) The microbridge produced with T1 shows a compressive stress of -41 MPa and undergoes snapping down onto the substrate. (b) The microbridge manufactured with T2 exhibits a tensile stress of approximately 61 MPa and experiences fracture from one of the anchors. (c) In contrast, the microbridge fabricated with T3 reveals a compressive stress of around -24 MPa and achieves successful fabrication with a flat trajectory.	28
Figure 2.6	Experimental setup for characterizing polymer MEMS Pirani gauge. The vacuum probe station is connected to a parameter analyzer for IV measurements and the vent valve is connected to the N2 cylinder via MFC for controlling chamber pressure [59].	29
Figure 2.7	Experimental characterized fusing trend for the fabricated polymer MEMS Pirani gauge.	30
Figure 2.8	Normalized resistance variation with temperature for computing temperature coefficient of resistance (TCR) of Nickel. A TCR value of 0.55 %/K is obtained.	30

Figure 2.9	Simulated temperature distribution of the sensing element along the length at 2 mA. The highest temperature is observed at the microbridge's center, with values of 127.61 °C, 88.83 °C, 40.3 °C, and 33.26 °C recorded for devices employing SU-8, SiO ₂ , Si ₃ N ₄ , and Al ₂ O ₃ respectively.	31
Figure 2.10	The simulated temperature distribution within the composite structure at the anchor region, comprised of nickel/dielectric/silicon. Notably, the device utilizing an SU-8 dielectric exhibits a notable elevation in surface temperature at the anchor point.	32
Figure 2.11	(a) Break down of heat conduction model for G_s . The model includes two heat resistance in series i.e., one for the sensing element and the other for the anchor. (b) Equivalent thermal conduction model of the polymer μ -PG representing various temperature nodes. The k_p consists of two heat resistances fostering parallel heat conduction while k_s consists of Ni/SU-8 stack at the anchor.	33
Figure 2.12	Calibration curve for polymer Pirani gauge with different dielectric μ -bridge materials. The dynamic range of the SU-8-based gauge is 30 Pa to 105 Pa which is wider than the devices with conventional dielectric materials.	36
Figure 2.13	Output voltage change characteristics of the SU-8 dielectric μ -bridge polymer MEMS Pirani gauge. The blue line indicates $V_L(p)$ curve and red line indicate the $V_H(p)$ curve plotted on a double logarithmic scale. With a detection limit of 50 μ V, the computed p_L is 30 Pa.	36
Figure 2.14	Drift analysis over 24 hours, with measurements taken at 2-hour intervals at $p=30$ Pa.	37
Figure 2.15	Output voltage characteristics of the Pirani gauge with and without considering the anchor effect.	37
Figure 2.16	A comparative simulated error percentage incorporated in Q_{solid} without considering the anchor effect for different dielectric materials.	38

Figure 3.1	Three zone annealing furnace setup for the formation of V_2O_5 .	43
Figure 3.2	Raman spectra of the synthesized V_2O_5 film.	43
Figure 3.3	X-ray diffraction analysis of the synthesized V_2O_5 film.	44
Figure 3.4	Stress mapping (a) Si/SiO ₂ substrate exhibiting a compressive stress of -50 MPa, (b) Deposited vanadium film showing a bow height of $\sim -3.73 \times 10^{-4}$ mm in the majority area, (c) V_2O_5 film showing negligible bow height (highlighted in red) in the majority area.	45
Figure 3.5	Conceptual schematic of MEMS Pirani gauge with metal oxide (V_2O_5) as a sensing element.	46
Figure 3.6	Fabrication process flow of the metal oxide (V_2O_5) based Pirani gauge a) Starting substrate consisting of 300 nm of thermally grown SiO ₂ . b) Formation of sensing element V_2O_5 by annealing patterned vanadium (~ 40 nm) at 450 °C in an oxygen environment. c) Formation of Metal (Au) interconnects. d) Vapor Hydrofluoric release of V_2O_5 film.	47
Figure 3.7	SEM image of the fabricated MEMS Pirani gauge (a) Top-view, (b) Cross-sectional view of suspended V_2O_5 film.	47
Figure 3.8	Temperature dependent resistant measurement of the synthesized V_2O_5 film.	48
Figure 3.9	Simulated temperature distribution along the sensing element's length at 4 Pa at an input current of 15 μ A.	49
Figure 3.10	Output voltage characteristics at a current bias of 15 μ A.	50
Figure 4.1	Conceptual schematic of tunable MEMS Pirani gauge showing different states of operation.	54
Figure 4.2	Theoretical calculation of transition pressure with gap variation between the heating element and heat sink.	55
Figure 4.3	CMOS-compatible three-mask fabrication process of electrostatically actuated all metal MEMS Pirani gauge.	57
Figure 4.4	Scanning Electron Microscope (SEM) image of the fabricated device highlighting different electrodes and zoomed-in area of the cross-sectional view at the center of the heating element.	57

Figure 4.5	Experimentally characterized pull-in characteristics of the fabricated device showing different regions of operation corresponding to the driving voltage. The pull-in voltage (V_{pi}) of the device is ~ 15 V. For $V_s \geq 15$ V the device enters the State ‘C’ i.e., Forbidden state.	58
Figure 4.6	Temperature profile of the heating element for different values of I_{bias} at 10 Pa.	59
Figure 4.7	Maximum temperature and maximum stress at 6 mA for a pressure range of 10 Pa to 10^6 Pa.	60
Figure 4.8	Displacement profile of the heating element corresponding to a pressure range of 10 Pa to 10^6 Pa at $V_s = 13.8$ V. The center of the beam displaces maximum at $p=10^6$ Pa i.e., ~ 159 nm.	60
Figure 4.9	Effective gap (g_{eff}) corresponding to different pressures.	61
Figure 4.10	(a) Voltage variations in State ‘A’ ($V_s = 0$ V) and State ‘B’ ($V_s = 13.8$ V) with pressure from 10 Pa to 10^6 Pa at an $I_{bias} = 6$ mA. (b) Error corresponding to each data point in State ‘A’ and State ‘B’ over the entire pressure range.	62
Figure 4.11	Output voltage characteristics of the proposed all-metal tunable MEMS Pirani gauge. The operating range of the gauge is 40 Pa to 5×10^5 Pa in a tuned response with the coupled electrostatic operation.	63
Figure 5.1	Structural schematic of the TiN-based MEMS Pirani gauge.	67
Figure 5.2	Structural schematic of the metal-based MEMS Pirani gauge.	68
Figure 5.3	Post-CMOS fabrication process flow of the proposed TiN-based Pirani gauge integrated into BEOL layers using standard TSMC $0.35 \mu\text{m}$ 2P4M CMOS process.	69
Figure 5.4	(a-d) Optical images of the fabricated TiN devices with different lengths (e) SEM and FIB image showing the cross-sectional view of the $60 \mu\text{m}$ device, (f) SEM image of the test structure to confirm the releasing, (g) Wire bonded chip for electrical characterization.	70

Figure 5.5	Post-CMOS fabrication process flow of the proposed wet meal etching-based Pirani gauge integrated into BEOL layers using standard TSMC 0.35 μm 2P4M CMOS process.	71
Figure 5.6	Optical and SEM images of the fabricated metal-based Pirani gauge highlighting the cross-sectional view at the FIB cut area.	72
Figure 5.7	Test platform for electrical testing of the proposed gauges.	73
Figure 5.8	White light interferometer analysis for computing residual stress and effective gap (a) TiN with $l = 60 \mu\text{m}$, (b) TiN with $l = 70 \mu\text{m}$, (c) TiN with $l = 80 \mu\text{m}$, (d) TiN with $l = 90 \mu\text{m}$, and (e) Metal-based device.	74
Figure 5.9	Experimental pull-in characteristics of the fabricated TiN devices with different lengths.	74
Figure 5.10	Simulated temperature distribution of the sensing element along the length for different devices (a) TiN with $l = 60 \mu\text{m}$, (b) TiN with $l = 70 \mu\text{m}$, (c) TiN with $l = 80 \mu\text{m}$, (d) TiN with $l = 90 \mu\text{m}$, and (e) Metal-based device.	76
Figure 5.11	(a) The pressure-dependent voltage response of different devices over a pressure range of 1 Pa to 10^6 Pa, (b) Error associated with each data point over the entire pressure range.	78
Figure 5.12	Voltage characteristics for computing the (a) lower detection limit p_H and (b) higher detection limit p_L .	78
Figure 5.13	Experimental setup for characterizing the broadband noise level of the fabricated devices.	78
Figure 5.14	Device: TiN $60 \mu\text{m}$ (a) Time domain voltage output signal measured across source and drain (b) Fast Fourier Transform (FFT) of the voltage measured across source and drain.	80
Figure 5.15	Device: TiN $70 \mu\text{m}$ (a) Time domain voltage output signal measured across source and drain (b) Fast Fourier Transform (FFT) of the voltage measured across source and drain.	80
Figure 5.16	Device: TiN $80 \mu\text{m}$ (a) Time domain voltage output signal measured across source and drain (b) Fast Fourier Transform (FFT) of the voltage measured across source and drain.	80

Figure 5.17	Device: TiN 90 μm (a) Time domain voltage output signal measured across source and drain (b) Fast Fourier Transform (FFT) of the voltage measured across source and drain.	81
Figure 5.17	Device: Metal (a) Time domain voltage output signal measured across source and drain (b) Fast Fourier Transform (FFT) of the voltage measured across source and drain.	81
Figure 6.1	Normalized output voltage variations in response to pressure for the designs presented in this thesis.	87

List of Tables

Table No:	Title of Table	Page No:
Table 1.1	A summary of the Pirani gauge implementations and their performance	15
Table 2.1	Dimensional specifications of the polymer MEMS Pirani gauge	23
Table 2.2	Thermal conductivity (k) of SU-8 and conventional dielectric materials	32
Table 3.1	Dimensional specifications of the metal oxide (V_2O_5) based MEMS Pirani gauge	46
Table 4.1	Dimensional specifications of the tunable MEMS Pirani gauge	55
Table 5.1	A summary of maximum deformation and effective gap	73
Table 5.2	Material properties of TiN used in this work	75
Table 5.3	Biasing parameters for characterizing the broadband noise level	79
Table 5.4	Summary of broadband noise level for different devices	81
Table 6.1	A comparison of the state-of-the-art and the different gauges developed in this thesis	87

This page is intentionally left blank

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