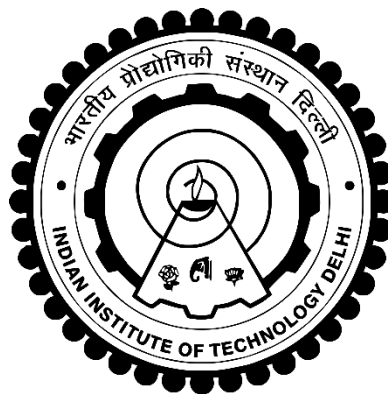


WAFER-LEVEL VACUUM PACKAGING FOR MEMS TECHNOLOGY

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DECEMBER 2023

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WAFER-LEVEL VACUUM PACKAGING FOR MEMS TECHNOLOGY

by

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Department of Electrical Engineering

Submitted

in fulfilment of the requirements of the degree of doctor of philosophy

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

DECEMBER 2023

Dedicated to my
parents and my
family members

CERTIFICATE

This is to certify that the thesis entitled, “**WAFER LEVEL VACUUM PACKAGING FOR MEMS TECHNOLOGY,**” being submitted by **Mr. VIKRAM MAHARSHI** 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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Acknowledgements

I would like to thank my supervisors, Dr. Bhaskar Mitra, and Dr. Ajay Agarwal for their valuable guidance, advice and encouragement throughout this work. Their continuous guidance, generous support and constant encouragement have helped me to broaden my views and knowledge in the subject matter. They have devoted a lot of his time for technical and nontechnical discussions. Also, they have helped me a lot in preparing manuscripts for Journals and in thesis writing. I will always remember their contribution in the future.

Also, I would like to express my sincere gratitude to my research committee members: Prof. Dhiman Mallick, Prof. Vikrant Tiwari and Prof. Madhusudan Singh, for being in my committee and giving me valuable suggestions during the evaluation of my research work.

I am thankful to Mrs. Priya Vinayak and Mr. Sumit Sharma for the collaborative interdisciplinary work to develop sensors for different applications. I appreciate the company of researchers from Bhaskar Mitra research group, especially Mr. Imran Ahmad, and Mr. Aamir Saud Khan who have made useful contributions to this work by way of discussions and suggestions. I also thankful to my friends Saiman Kumawat, Rahul Dhayal and Akshay Moudgil for their constant support during my Ph.D. journey.

I would like to thank Central Research facility (CRF) and Nano Research Facility (NRF), Physical Testing laboratory, CART Lab of IIT Delhi, CSIR CEERI, Pilani, Physics lab, Delhi University for providing the device fabrication and characterization facilities.

I would like to express my deepest feelings of gratitude to all my family members, especially my parents, wife Snehwati, sisters Vinita and Veerta and my son Rudra, for their consistent encouragement and unconditional love. Their support, care, guidance and encouragement have been priceless, especially during the challenging times. At last, I deeply feel debt towards Mother Nature for inspiring and rejuvenating the constructive energy in me.

Vikram Maharshi

Abstract

Ever since the introduction of MEMS devices, constant research has been going on to improve their performance by packaging them with minimum size. There is a need for low-cost and hermetic wafer-level vacuum packaging of microdevices for commercializing MEMS products. This opens the opportunity to study various adhesive materials for wafer-wafer bonding purposes, thin film encapsulated vacuum packages, and getter performance for stable vacuum inside the package for a longer duration. Although many dedicated works are being done all over the world, a large number of questions are still to be answered in this field. Therefore, this research focuses on developing wafer-level vacuum packages for MEMS and IC technology.

This dissertation discusses the development and characterization of a thin film-encapsulated MEMS vacuum package. The formation of the anodized porous alumina membrane was optimized, which is used as a capping layer inside the MEMS package. The getter material was integrated inside the package in a pore-sealing manner, which avoids exposure to atmospheric conditions, resulting in excellent adsorption. The texturing of the getter by depositing over a porous alumina membrane increases the film's surface-to-volume ratio. The pore-sealing getter method is not restricted to APA (Anodized Porous Alumina) membranes but can be applied to other porous membranes with small enough pore sizes. The high aspect ratio nano porous alumina membrane has the advantage that the sealing material is not deposited inside the package and avoids degradation of the device's performance. The silicon pirani was used inside the package to monitor the pressure change. Furthermore, the package was characterized using I-V characterization of pirani over the last 550 days; the initial drop and stabilization of the pressure were observed.

An indigenous way of introducing the getter in thin film encapsulation was demonstrated in order to prevent the high-temperature getter activation and to make an active generation of the vacuum inside the package. The thin film-encapsulated vacuum package was fabricated, integrating a glow discharge getter into the package. The thin-film encapsulated package was fabricated using anodized porous alumina as a capping layer and PECVD silicon dioxide as the sacrificial layer. A silicon pirani gauge was used to monitor the pressure changes inside the sealed cavity. The two titanium-gold film electrodes were separated by $\sim 300\text{ }\mu\text{m}$ and placed above the capping layer. The package was sealed at 50

μ Torr pressure using evaporated aluminium oxide. A glow discharge is formed in the cavity when a voltage $>800\text{V}$ is applied at room temperature. The sputtered titanium from the discharge reacts with available reactive gas molecules and reduces the vacuum of the micro package. After the glow discharge getter activation, a decrease in the pressure of $50\text{ }\mu\text{Torr}$ from $2\text{ }\mu\text{Torr}$ was observed for the volume of $1.65\times 10^{-6}\text{ cm}^3$. The pressure in the micro package might be below the reported one since the limiting sensitivity of the MEMS pirani gauge.

Additionally, this work provides insight into an adhesive-based bond interface that offers a hermetic bond interface. A wafer-capped vacuum package utilizing recrystallized parylene as an adhesive layer was fabricated and characterized. The parylene material was recrystallized by thermal annealing at 250°C for 30 minutes using a hot plate. The XRD, FESEM, and FTIR results confirm the increase in the crystallinity without degradation of the material; the recrystallized parylene was used as a bonding layer between the two wafers. A stable interface for the parylene-parylene bond is ensured by the testing machine (UTM). The FESEM and Infrared imaging was performed to examine the homogeneous and defect-free bonding. The getter material was used inside the package to create the vacuum due to the unavailability of a vacuum bonding tool. The hermeticity of the bond interface was examined by characterizing the pirani, which is placed inside the package.

A low-temperature hybrid bonding integrating copper and parylene material for 3D integration was developed. The parylene was deposited using a chemical vapor deposition process over electroplated copper bumps, which induces a higher topology. The parylene has a higher tolerance for height topology and surface roughness. Parylene and recrystallized parylene were used in separate experiments to create a hybrid bond interface. To obtain the hermetic bond interface, the recrystallized parylene material was used. The recrystallization of the parylene was performed at 250°C for 30 mins. The homogeneous, stable and hermetic bond interface provided by parylene makes it the optimum bonding substance for hybrid bonding. Chemical mechanical polishing (CMP) was performed to planarize copper/parylene topology and flatten the roughness of a copper surface. The copper and parylene material were bonded simultaneously at 300°C . A homogenous bond of copper to copper and parylene to parylene bonding interface without any significant bonding voids was obtained. The bond interface's tensile and shear bond strength was evaluated using a universal testing machine. The contact resistance of the copper-copper

bond interface was achieved at $279.16 \text{ m}\Omega\cdot\text{cm}^{-2}$. The developed hybrid bonding is well suited for 2.5 and 3D heterogeneous integration.

This dissertation study offers a novel perspective on wafer-level packaging, specifically for thin film-encapsulated and adhesive thermocompression-bonded MEMS vacuum packages.

सार

एमईएमएस उपकरणों की शुरुआत के बाद से, उन्हें न्यूनतम आकार में पैकेजिंग करके उनके प्रदर्शन को बेहतर बनाने के लिए निरंतर शोध चल रहा है। एमईएमएस उत्पादों के व्यावसायीकरण के लिए माइक्रोडिवाइसेज की कम लागत वाली और हेमेटिक वेफर-स्तरीय वैक्यूम पैकेजिंग की आवश्यकता है। इससे लंबी अवधि के लिए वेफर-वेफर बॉन्डिंग उद्देश्यों, पतली फिल्म एनकैप्सुलेटेड वैक्यूम पैकेज और पैकेज के अंदर स्थिर वैक्यूम के लिए गेटर प्रदर्शन के लिए विभिन्न चिपकने वाली सामग्रियों का अध्ययन करने का अवसर खुलता है। हालाँकि दुनिया भर में कई समर्पित कार्य किए जा रहे हैं, फिर भी इस क्षेत्र में बड़ी संख्या में सवालों के जवाब दिए जाने बाकी हैं। इसलिए, यह शोध एमईएमएस और आईसी प्रौद्योगिकी के लिए वेफर-स्तरीय वैक्यूम पैकेज विकसित करने पर केंद्रित है।

यह शोध प्रबंध एक पतली फिल्म-एनकैप्सुलेटेड एमईएमएस वैक्यूम पैकेज के विकास और लक्षण वर्णन पर चर्चा करता है। एनोडाइज्ड झरझरा एल्यूमिना झिल्ली के गठन को अनुकूलित किया गया था, जिसका उपयोग एमईएमएस पैकेज के अंदर कैपिंग परत के रूप में किया जाता है। गेटर सामग्री को छिद्र-सील तरीके से पैकेज के अंदर एकीकृत किया गया था, जो वायुमंडलीय स्थितियों के संपर्क से बचाता है, जिसके परिणामस्वरूप उत्कृष्ट सोखना होता है। छिद्रपूर्ण एल्यूमिना झिल्ली पर जमा होने से गेटर की बनावट फिल्म के सतह-से-आयतन अनुपात को बढ़ाती है। छिद्र-सीलिंग गेटर विधि पीएए झिल्लियों तक ही सीमित नहीं है, बल्कि छोटे छिद्र आकार वाले अन्य छिद्रपूर्ण झिल्लियों पर भी लागू की जा सकती है। उच्च पहलू अनुपात नैनोपोरस एल्यूमिना झिल्ली का लाभ यह है कि सीलिंग सामग्री पैकेज के अंदर जमा नहीं होती है और डिवाइस के प्रदर्शन में गिरावट से बचाती है। दबाव परिवर्तन की निगरानी के लिए पैकेज के अंदर सिलिकॉन पिरानी का उपयोग किया गया था। इसके अलावा, पैकेज को पिछले 550 दिनों में पिरानी के I-V लक्षण वर्णन का उपयोग करके चित्रित किया गया था; दबाव की प्रारंभिक गिरावट और स्थिरीकरण देखा गया।

उच्च तापमान गेटर सक्रियण को रोकने और पैकेज के अंदर वैक्यूम की सक्रिय पीढ़ी बनाने के लिए पतली फिल्म एनकैप्सुलेशन में गेटर को पेश करने का एक स्वदेशी तरीका प्रदर्शित किया गया था। पतली फिल्म-एनकैप्सुलेटेड वैक्यूम पैकेज का निर्माण किया गया था, जिसमें पैकेज में एक ग्लो डिस्चार्ज गेटर को एकीकृत किया गया था। कैपिंग परत के रूप में एनोडाइज्ड झरझरा एल्यूमिना और बलिदान परत के रूप में पीईसीवीडी सिलिकॉन डाइऑक्साइड का उपयोग करके पतली-

फिल्म इनकैप्सुलेटेड पैकेज का निर्माण किया गया था। सीलबंद गुहा के अंदर दबाव परिवर्तन की निगरानी के लिए एक सिलिकॉन पिरानी गेज का उपयोग किया गया था। दो टाइटेनियम-गोल्ड फिल्म इलेक्ट्रोड को $\sim 300 \mu\text{m}$ से अलग किया गया और कैपिंग परत के ऊपर रखा गया। वाष्पीकृत एल्यूमीनियम ऑक्साइड का उपयोग करके पैकेज को $50 \mu\text{Torr}$ दबाव पर सील कर दिया गया था। जब कमरे के तापमान पर 800V से अधिक का वोल्टेज लगाया जाता है तो गुहा में एक ग्लो डिस्चार्ज बनता है। डिस्चार्ज से निकला हुआ टाइटेनियम उपलब्ध प्रतिक्रियाशील गैस अणुओं के साथ प्रतिक्रिया करता है और माइक्रो पैकेज के वैक्यूम को कम करता है। ग्लो डिस्चार्ज गेटर सक्रियण के बाद, 1.65×10^{-6} सेमी³ की मात्रा के लिए $2 \mu\text{Torr}$ से $50 \mu\text{Torr}$ के दबाव में कमी देखी गई। एमईएमएस पिरानी गेज की सीमित संवेदनशीलता के कारण माइक्रो पैकेज में दबाव रिपोर्ट किए गए दबाव से कम हो सकता है।

इसके अतिरिक्त, यह कार्य एक चिपकने वाले-आधारित बॉन्ड इंटरफ़ेस में अंतर्दृष्टि प्रदान करता है जो एक हेमेटिक बॉन्ड इंटरफ़ेस प्रदान करता है। चिपकने वाली परत के रूप में पुनर्क्रिस्टलीकृत पैरिलीन का उपयोग करके एक वेफर-कैपड वैक्यूम पैकेज तैयार किया गया और उसे चित्रित किया गया। एक गर्म प्लेट का उपयोग करके 30 मिनट के लिए 250°C पर थर्मल एनीलिंग द्वारा पैरिलीन सामग्री को पुनः क्रिस्टलीकृत किया गया था। एक्सआरडी, एफईएसईएम और एफटीआईआर परिणाम सामग्री के क्षरण के बिना क्रिस्टलीयता में वृद्धि की पुष्टि करते हैं; पुनर्क्रिस्टलीकृत पैरिलीन का उपयोग दो वेफर्स के बीच एक बंधन परत के रूप में किया गया था। परीक्षण मशीन (UTM) द्वारा पैरिलीन-पैरिलीन बंधन के लिए एक स्थिर इंटरफ़ेस सुनिश्चित किया जाता है। सजातीय और दोष-मुक्त बॉन्डिंग की जांच करने के लिए FESEM और इन्फ्रारेड इमेजिंग का प्रदर्शन किया गया। वैक्यूम बॉन्डिंग टूल की अनुपलब्धता के कारण वैक्यूम बनाने के लिए गेटर सामग्री का उपयोग पैकेज के अंदर किया गया था। बॉन्ड इंटरफ़ेस की हेमेटिकिटी की जांच पिरानी की विशेषता के द्वारा की गई, जिसे पैकेज के अंदर रखा गया है।

3डी एकीकरण के लिए तांबे और पैरिलीन सामग्री को एकीकृत करने वाला एक कम तापमान वाला हाइब्रिड बॉन्डिंग विकसित किया गया था। पैरिलीन को इलेक्ट्रोप्लेटेड तांबे के उभारों पर एक रासायनिक वाष्प जमाव प्रक्रिया का उपयोग करके जमा किया गया था, जो एक उच्च टोपोलॉजी को प्रेरित करता है। पैरिलीन में ऊंचाई टोपोलॉजी और सतह खुरदरापन के लिए उच्च सहनशीलता है। हाइब्रिड बॉन्ड इंटरफ़ेस बनाने के लिए पैरिलीन और पुनर्क्रिस्टलीकृत पैरिलीन का उपयोग अलग-अलग प्रयोगों में किया गया था। हेमेटिक बॉन्ड इंटरफ़ेस प्राप्त करने के लिए, पुनर्क्रिस्टलीकृत पैरिलीन

सामग्री का उपयोग किया गया था। पैरिलीन का पुनर्क्रिस्टलीकरण 30 मिनट के लिए 250 °C पर किया गया था। पैरिलीन द्वारा प्रदान किया गया सजातीय, स्थिर और भली भांति बंधन इंटरफ़ेस इसे हाइब्रिड बॉन्डिंग के लिए इष्टतम बॉन्डिंग पदार्थ बनाता है। तांबे/पैरिलीन टोपोलॉजी को समतल करने और तांबे की सतह के खुरदरेपन को समतल करने के लिए रासायनिक यांत्रिक पॉलिशिंग (सीएमपी) की गई थी। तांबे और पैरिलीन सामग्री को 300°C पर एक साथ जोड़ा गया था। बिना किसी महत्वपूर्ण बॉन्डिंग रिक्तियों के तांबे से तांबे और पैरिलीन से पैरिलीन बॉन्डिंग इंटरफ़ेस का एक समरूप बंधन प्राप्त किया गया था। बॉन्ड इंटरफ़ेस की तन्यता और कतरनी बॉन्ड ताकत का मूल्यांकन एक सार्वभौमिक परीक्षण मशीन का उपयोग करके किया गया था। कॉपर-कॉपर बॉन्ड इंटरफ़ेस का संपर्क प्रतिरोध $279.16 \text{ m}\Omega\cdot\text{cm}^{-2}$ पर हासिल किया गया था। विकसित हाइब्रिड बॉन्डिंग 2.5 और 3डी विषम एकीकरण के लिए उपयुक्त है।

यह शोध प्रबंध अध्ययन वेफर-स्तरीय पैकेजिंग पर एक नया परिप्रेक्ष्य प्रदान करता है, विशेष रूप से पतली फिल्म-एनकैप्सुलेटेड और चिपकने वाला थर्मोकम्प्रेशन-बॉन्ड एमईएमएस वैक्यूम पैकेजों के लिए।

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List of Abbreviations and Symbols

Abbreviations

WLP	Wafer-level Packaging
MEMS	Microelectromechanical System
TSV	Through silicon via
CMOS	Complementary Metal Oxide Semiconductor
CVD	Chemical Vapor Deposition
SOI	Silicon on Insulator
EDS/EDX	Energy Dispersive X-ray Spectroscopy
FESEM	Finite-Element Scanning Electron Microscopy
XRD	X-ray Diffraction
RIE	Reactive Ion Etching
SEM	Scanning Electron Microscopy
AFM	Atomic Force Microscopy
FTIR	Fourier Transform Infrared
UV	Ultraviolet
DRIE	Deep Reactive Ion Etching
DBI	Direct Bonding Interface
HI	Heterogeneous Integration
PI	Polyimide
NCP	Non-conductive Paste
TCB	Thermocompression Bonding

TCE	Coefficient of thermal expansion
IR	Infrared
PMMA	Polymethyl methacrylate
APA	Anodized Porous Alumina
CMP	Chemical Mechanical Polishing
UTM	Universal Testing Machine
TGA	Thermogravimetric Analysis
DSC	Differential scanning calorimetry
BTA	Benzotriazole
PR	Photoresist
FWHM	Full Width at Half-Maximum

Symbols

λ	Wavelength
n	Diffraction order
d	Interplanar Distance
θ	Diffraction angle
δ	Size of Crystallite
σ	Conductivity
J	Current Density
W	Watt
V	Voltage
D	Dimensional
$^{\circ}\text{C}$	Degree Celsius
eV	Electron Volt
Hz	Hertz
h	Planck Constant
K_B	Boltzmann Constant