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Microelectromechanical Systems (MEMS)

Innovation, Manufacturing Techniques
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*Edited by Zdravko Stanimirović
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Microelectromechanical Systems (MEMS) - Innovation, Manufacturing Techniques and Applications

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Meet the editors



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Preface

Microelectromechanical systems (MEMS) are a key area of modern technological development, enabling the design and production of microscale devices with high precision and reliability. These systems play a significant role across various industries, facilitating efficiency and innovation through their ability to integrate diverse materials and advanced manufacturing techniques. MEMS continues to serve as a foundational element in the progression of numerous technological applications.

In addition to their technological contributions, MEMS align with sustainable practices by promoting energy efficiency and reducing material waste. As the demand for smaller and more efficient systems grows, MEMS is expected to evolve further, meeting emerging challenges while offering new opportunities in various domains.

This book compiles contributions from researchers worldwide, offering insights into advanced materials, techniques, and applications in MEMS. Topics include flexible MEMS techniques for multi-physical sensors, highlighting the adaptability of these systems to complex sensing environments, and the use of MEMS in optical and photonic devices, demonstrating their impact on advanced imaging and communication technologies. The book also explores biomedical MEMS, which are advancing healthcare through improved diagnostics and therapeutic tools.

The editors extend their appreciation to the contributors for presenting their work in a clear and accessible manner, making this book valuable for both professionals and those new to the field. We also want to express our sincere appreciation to the IntechOpen team for their exceptional support and dedication in completing this publication.

Dr. Zdravko Stanimirović and Dr. Ivanka Stanimirović

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Section 1

MEMS Trends and Applications

Introductory Chapter: MEMS and Emerging Technologies – Converging Innovations Shaping the Future

Ivanka Stanimirović and Zdravko Stanimirović

1. Introduction

Technological advancements over the past few decades have dramatically transformed industries and the way we interact with the world. Among the most significant innovations are microelectromechanical systems (MEMS) and the array of emerging technologies that are reshaping industries, economies, and societies. MEMS, which integrate tiny mechanical components with electronics, serve as the foundation for advancements in sectors such as health care, automotive, environmental monitoring, consumer electronics, and robotics. Their ability to sense, actuate, and communicate within compact, power-efficient devices has made them indispensable. However, the true potential of MEMS lies not just in their individual applications but in their convergence with emerging technologies like artificial intelligence (AI), quantum computing, biotechnology, neurotechnology, and the metaverse, creating new possibilities and unlocking unprecedented potential.

2. The evolution of MEMS: Miniaturization and integration

MEMS are miniaturized devices that combine mechanical elements, sensors, actuators, and electronics into a single system. Initially developed for aerospace applications, MEMS technology has expanded to many industries, including consumer electronics and medical devices. One key trend is the miniaturization of MEMS, enabling integration into even smaller, more complex systems. Similarly, MEMS technology has revolutionized health care with wearables and diagnostic tools that monitor vital signs, detect diseases, and deliver treatments. As MEMS shrink in size, their applications become more widespread, embedded in everyday objects and enhancing everyday life.

The evolution of MEMS is also marked by increasingly sophisticated sensors and actuators. MEMS sensors now provide highly accurate measurements of parameters like temperature, pressure, and motion, offering real-time data for applications in fields such as environmental monitoring and health care. MEMS actuators, which convert electrical energy into mechanical motion, enable the development of

micro-robots capable of precise tasks in fields like surgery and manufacturing. These advancements are leading to significant breakthroughs in robotics, where precision and energy efficiency are crucial.

3. Power efficiency: The key to advancing MEMS applications

Power efficiency is a key factor in the design of modern electronic systems, and MEMS technology excels in this area. MEMS devices are inherently low power, making them ideal for portable, battery-powered applications. For example, in consumer electronics like smartphones and smartwatches, MEMS sensors and actuators provide enhanced functionality while minimizing energy consumption.

A particularly innovative area in MEMS technology is energy harvesting. MEMS-based energy harvesters [1], such as piezoelectric sensors, capture small amounts of energy from mechanical vibrations, heat, or light and convert it into electrical power. This ability to harvest energy enables MEMS devices to operate autonomously in applications like remote monitoring, wearables, and autonomous vehicles. By integrating energy-harvesting capabilities, MEMS devices can function for extended periods without the need for frequent recharging or battery replacement.

MEMS technology is also pivotal in the Internet of Things (IoT), where power-efficient devices are essential for maintaining real-time data collection and communication between devices [2]. As IoT applications expand, MEMS will continue to play a crucial role in enabling sustainable, autonomous systems.

4. The convergence of MEMS with emerging technologies

The true power of MEMS technology lies in its convergence with other emerging technologies. One exciting development is the integration of MEMS with artificial intelligence (AI) [3]. AI systems, which can learn from data and make autonomous decisions, can be paired with MEMS sensors and actuators to create intelligent systems that adapt to real-time conditions. For example, in autonomous vehicles, MEMS sensors such as accelerometers and cameras can collect environmental data, while AI algorithms process this data to optimize navigation and obstacle avoidance. This synergy between MEMS and AI is also revolutionizing industrial automation, where MEMS systems can monitor and optimize production processes with greater efficiency.

Quantum computing represents another promising frontier in the convergence with MEMS technology [4]. Quantum computing's ability to solve complex problems could lead to breakthroughs in MEMS design, improving device performance and enabling new capabilities. For instance, quantum computing could be used to design advanced materials for MEMS devices or enhance their sensing and actuation functions.

Emerging fields such as neurotechnology and biotechnology are also closely intertwined with MEMS. Brain-computer interfaces (BCIs), which allow individuals to control devices through their thoughts, rely on MEMS technology to create small, power-efficient sensors that interface with the brain [5]. MEMS devices are also integral to biosensors used for early disease detection, personalized medicine, and real-time patient monitoring [6]. As neurotechnology and biotechnology advance, MEMS will continue to play a pivotal role in enabling more effective and accessible healthcare solutions.

5. The future of MEMS and emerging technologies

As MEMS technology continues to evolve, its integration with other emerging fields will drive further innovation. MEMS devices are becoming smarter, more energy-efficient, and more integrated into the digital ecosystem. Their ability to collect, process, and act on data in real time is transforming industries from health care to autonomous vehicles, manufacturing, and beyond.

One particularly promising area for MEMS and emerging technologies is the metaverse, an interconnected virtual world that relies on virtual reality (VR) and augmented reality (AR) technologies [7]. MEMS devices, such as motion sensors and accelerometers, are central to creating immersive VR and AR experiences. As the metaverse grows, MEMS will play a key role in bridging the physical and digital worlds, enabling new opportunities for work, entertainment, and social interaction.

Additionally, as quantum computing, AI, biotechnology, and neurotechnology continue to advance, their integration with MEMS will enable breakthroughs that are currently beyond imagination. For example, MEMS combined with quantum sensors could lead to highly sensitive detection systems for applications in health care, environmental monitoring, and security. The fusion of MEMS, AI, and neurotechnology could produce devices capable of understanding and responding to human behavior, revolutionizing sectors such as health care, consumer electronics, and robotics.

6. Conclusion

MEMS and emerging technologies are poised to transform industries and improve lives in profound ways. The miniaturization, power efficiency, and integration of MEMS systems are driving innovation across diverse fields. Their convergence with cutting-edge technologies like AI, quantum computing, and biotechnology is unlocking new possibilities that will redefine the future of technology. As these fields continue to evolve and converge, they will create solutions to some of the world's most pressing challenges, opening new avenues for progress and discovery. The future of MEMS and emerging technologies is bright, and the next few decades will undoubtedly bring ground-breaking innovations that will change the way we live, work, and interact with the world around us.

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Advanced MEMS Technologies

Zdravko Stanimirović and Ivanka Stanimirović

Abstract

Advanced MEMS (Micro-Electro-Mechanical Systems) represent a critical enabler of modern technology, offering miniaturized, high-performance solutions for industries such as consumer electronics, automotive, healthcare, telecommunications, and industrial automation. Innovations in fabrication techniques, such as advanced lithography, additive manufacturing, and wafer-level packaging, combined with the integration of MEMS with CMOS and AI, have driven rapid advancements in functionality, efficiency, and scalability. The global MEMS market is poised for robust growth, driven by applications in 5G, IoT, wearables, and biomedical technologies. Despite challenges such as high production costs and scaling complexities, increasing demand from emerging markets and advancements in microfabrication position MEMS as a foundational technology for next-generation systems. This chapter explores the state of advanced MEMS technologies, their applications, mathematical modeling methods, market trends, and future prospects.

Keywords: advanced MEMS, fabrication techniques, materials, manufacturing tolerances, mathematical modeling, MEMS market

1. Introduction

Micro-Electro-Mechanical Systems (MEMS) are highly miniaturized devices that integrate mechanical components, sensors, actuators, and electronic circuits on a single silicon or other material-based substrate. These systems operate on the micrometer scale, enabling precise sensing, actuation, and control in various applications. MEMS are foundational in industries such as consumer electronics, automotive, healthcare, and telecommunications, where compact, energy-efficient, and reliable systems are crucial.

Recent advancements in MEMS technologies have transformed their design, manufacturing, and functionality. Innovations in lithography, additive manufacturing, and deposition techniques have enabled the production of smaller, more efficient devices with enhanced performance. Integration with CMOS (Complementary Metal-Oxide-Semiconductor) technology has facilitated the development of MEMS with complex functionalities, while the use of advanced materials like silicon carbide and graphene has expanded their operational limits in harsh environments. Additionally, the fusion of MEMS with artificial intelligence (AI) and the Internet of Things (IoT) is revolutionizing their applications in smart devices, 5G networks, and personalized healthcare.

These advancements are fueling rapid market growth, with MEMS now being integral to autonomous vehicles, wearable medical devices, industrial automation, and smart infrastructure. Despite challenges such as high manufacturing costs and the complexities of scaling production, MEMS continue to evolve, driven by increasing demand for compact, high-performance technologies in both established and emerging markets. This chapter explores the advancements in MEMS fabrication techniques, materials, mathematical modeling methods and their implications for the global MEMS market.

2. MEMS fabrication techniques and materials

Micro-Electro-Mechanical Systems (MEMS) are integral to modern technology, enabling devices ranging from automotive sensors to medical implants, consumer electronics, and environmental monitoring. As demand for smaller, faster, and more integrated MEMS devices increases, fabrication techniques and materials are evolving to meet these challenges (**Table 1**).

The materials used in MEMS fabrication have expanded beyond traditional silicon, opening new possibilities for functionality, performance, and application diversity. New materials allow for better sensor sensitivity, mechanical flexibility, and integration with other technologies.

Silicon remains the primary material in MEMS due to its well-understood properties, compatibility with microelectronics, and mature fabrication processes. Silicon-based MEMS, especially silicon-on-insulator (SOI) wafers, are used in a wide array of applications such as accelerometers, gyroscopes, and pressure sensors [1–6]. Advances in silicon processing have improved the functionality and performance of MEMS devices, making them smaller, more reliable, and more power-efficient.

Two-dimensional (2D) materials like graphene and transition metal dichalcogenides (TMDs) are gaining attention for their unique mechanical, electrical, and thermal properties [7–9]. These materials offer high flexibility, high surface area, and exceptional strength, which make them suitable for flexible MEMS devices, such as wearable electronics and stretchable sensors.

Nanomaterials, including carbon nanotubes (CNTs) and nanowires, are also being integrated into MEMS to improve their mechanical properties and sensor sensitivity [8, 10]. These materials provide ultra-high surface area and exceptional mechanical properties at the nanoscale, which enable the development of MEMS devices with superior performance characteristics, such as higher precision and sensitivity.

Piezoelectric materials generate electrical charge in response to mechanical stress, making them ideal for MEMS actuators, sensors, and energy harvesting devices [11, 12]. Newer materials like zinc oxide (ZnO) and lead-free piezoelectric ceramics are being explored for their better performance and environmental sustainability compared to traditional lead-based materials like PZT (Lead Zirconate Titanate) [13].

As MEMS devices move toward medical and wearable applications, there is a growing interest in soft, bio-compatible materials. These materials, such as hydrogels, elastomers, and biodegradable polymers, are used in devices that must interface directly with biological systems [14, 15]. For instance, soft MEMS devices are increasingly used in flexible and stretchable sensors that can be embedded in medical implants or worn on the skin [16, 17].

As MEMS devices become more complex, the fabrication techniques used to produce them must also evolve to enable higher precision, integration, and flexibility. Several advanced methods are being adopted to meet these demands.

Advanced materials	Applications	Advantages	Challenges
Silicon and Silicon-Based Materials	Vibration sensors, energy harvesters, actuators	Compatibility with CMOS electronics, mechanical and thermal properties, miniaturization and integration, well-developed fabrication techniques, cost-effectiveness	Mechanical limitations, limited material variety, surface roughness and reliability issues, scaling issues, environmental sensitivity
2D Materials and Nanomaterials	Flexible sensors, energy harvesters, photonic devices	High flexibility, enhanced performance, high sensitivity	Large-scale manufacturing and material stability
Piezoelectric and Ferroelectric Materials	Vibration sensors, energy harvesters, actuators	High sensitivity, ability to harvest energy	Cost and material processing
Soft and Bio-compatible Materials	Biomedical devices, wearable sensors, soft robotics	Biocompatibility, flexibility, low weight	Mechanical strength and durability
Advanced fabrication techniques	Applications	Advantages	Challenges
Additive Manufacturing (3D Printing)	Microfluidic devices, lab-on-a-chip systems, custom sensors, actuators	Flexibility in design, reduced material waste, ability to print complex structures	Limited resolution, materials compatibility, scalability
Micro-Stereolithography	Microfluidics, micro-optics, prototyping	High Precision, complex geometries, material versatility	Material limitations, scaling, post-processing
Nano-Printing	Nanoscale patterning: High-density data storage, quantum computing components	High resolution, cost-effective for high-volume production, versatility in material use	Material constraints, complexity of pattern transfer, device alignment
Integration of MEMS with CMOS and Photonics	Smart sensors, MEMS-based communication systems, integrated circuit MEMS devices	Lower cost, reduced power consumption, better performance	Integration of heterogeneous materials and devices, fabrication complexity
Deep Reactive Ion Etching (DRIE)	Microchannels, high-aspect-ratio MEMS devices, micro-fluidics	High precision, deep etching capabilities, improved aspect ratio control	High cost and complexity
Wafer Bonding and Packaging	Packaging, microfluidic systems, multi-layer MEMS devices	High integration, high yield	Precision alignment, yield loss during bonding processes

Table 1.
Advanced MEMS materials and techniques.

Additive manufacturing (AM), or 3D printing, is one of the most transformative trends in MEMS fabrication [18, 19]. Unlike traditional subtractive manufacturing methods, AM builds objects layer by layer, which allows for the production of highly complex geometries with precision. This capability is particularly important for MEMS devices that require intricate structures or multi-material components.

One notable advancement in AM for MEMS is two-photon polymerization (TPP), a form of 3D printing that uses laser light to polymerize resin at very fine resolutions (down to the nanoscale), making it ideal for fabricating intricate microstructures and sensors [20, 21].

Micro-stereolithography, a type of 3D printing using light to cure photopolymer resins, is enabling more precise MEMS fabrication, especially for small-scale and high-precision applications [22, 23]. This technology is particularly useful in applications such as micro-optics and microfluidics, where intricate, high-precision features are required.

Another emerging technique is nano-imprint lithography, which involves applying a mold with nanoscale patterns to the surface of a substrate [24]. This process is capable of producing high-density micro-structures at a low cost, making it an attractive option for mass production of MEMS devices.

The integration of MEMS with Complementary Metal-Oxide-Semiconductor (CMOS) technology has been a long-standing trend in the MEMS industry [25, 26]. CMOS provides low-power, high-performance digital circuitry that is essential for processing the data collected by MEMS sensors. The integration of MEMS with CMOS results in smaller, more energy-efficient, and cost-effective systems that are easier to scale for mass production.

In addition to CMOS, photonics integration with MEMS is becoming increasingly important [27]. MEMS-based photonic devices, such as micro mirrors and optical switches, are crucial for applications in optical communications, LiDAR systems, and sensor networks. The ability to fabricate MEMS structures with photonics opens new opportunities in high-speed data transfer, imaging, and sensing.

Deep Reactive-Ion Etching (DRIE) is a critical etching technique for MEMS fabrication [28], particularly for producing high-aspect-ratio structures such as micro-channels and deep trenches. DRIE allows for precise etching of deep features with vertical sidewalls, which are often required for complex MEMS devices like sensors, actuators, and microfluidic components.

MEMS devices often require wafer bonding techniques to integrate various components into a single structure [29]. Wafer bonding involves joining two or more substrates to create a multi-layer MEMS device, which is essential for creating functional MEMS with integrated electrical, mechanical, and fluidic systems.

In terms of packaging, hermetic sealing is crucial for protecting MEMS devices from environmental factors such as moisture and dust. Advances in packaging materials and techniques are enabling better protection and performance of MEMS devices, particularly in harsh environments such as aerospace and automotive systems.

The MEMS industry is undergoing rapid changes, driven by the increasing demand for smaller, more versatile devices that can serve a wide array of applications. The integration of MEMS with other emerging technologies such as artificial intelligence (AI), Internet of Things (IoT), and wearable technology is creating new opportunities for innovation [30, 31]. Furthermore, the push toward sustainability is prompting the development of MEMS devices that require less power, use eco-friendly materials, and can harvest ambient energy for self-powered systems.

However, challenges remain in the form of cost reduction, manufacturing scalability, and ensuring long-term reliability, particularly for new materials and complex multi-material systems.

3. Tolerances in advanced MEMS manufacturing

In advanced MEMS (Micro-Electro-Mechanical Systems) fabrication, maintaining tight tolerances is crucial to ensure that the devices perform reliably and meet

the specific needs of high-precision applications. Tolerances refer to the permissible variation in the dimensions, geometry, and material properties of microstructures, and they are generally quantified in terms of micrometers (μm) or nanometers (nm). The values of these tolerances are determined by the design requirements of the MEMS devices, the fabrication methods employed, and the application in which the device will be used [32–34].

Dimensional tolerances are typically measured in terms of how much a microstructure's size or feature deviates from the ideal design specification. In advanced MEMS, the dimensional tolerance can range from tens of nanometers to a few micrometers, depending on the specific fabrication process and the required precision. In photolithography, the lateral feature sizes are typically constrained to tolerances of 100–500 nm. However, with the use of advanced techniques like Extreme Ultraviolet (EUV) Lithography, these tolerances can be reduced to approximately 10 nm for cutting-edge applications like ultra-small RF MEMS or nanoscale optical devices. For processes like Deep Reactive Ion Etching (DRIE), the tolerance on the vertical etching of silicon can range from 1 to 2 μm , though advanced etching techniques can achieve tolerances as fine as 50 nm in critical applications like microchannels for fluidic systems. For thin film deposition techniques like Chemical Vapor Deposition (CVD) and Atomic Layer Deposition (ALD), the tolerance on film thickness can typically be controlled to $\pm 5\%$ of the target thickness, with ALD being capable of achieving thickness tolerances of < 1 nm for high-precision coatings.

Geometric tolerances concern the shape, alignment, and orientation of features in MEMS devices. For example, in MEMS sensors where motion or deflection is essential, geometric precision is critical to ensure accurate operation. The alignment tolerance for wafer bonding (used to bond multiple MEMS layers) is typically 1–2 μm , with more advanced wafer bonding techniques achieving < 1 μm in critical applications like microfluidics or 3D MEMS devices. Surface Roughness is often specified for microstructures that affect mechanical or optical properties. For MEMS devices requiring smooth surfaces (such as micro mirrors), surface roughness is typically < 10 nm. This is critical in optical MEMS to minimize light scattering and maintain performance. Material variability can also introduce variations that affect the final tolerances of MEMS devices. The uniformity of the materials used (such as silicon, metals, or polymers) during deposition or etching processes plays a key role. In silicon-based MEMS, material uniformity is typically controlled to $\pm 2\%$ for thickness or doping concentration during processes like epitaxial growth or ion implantation. However, some high-precision applications (like RF MEMS resonators) require much tighter tolerances on doping profiles, often within $\pm 1\%$. For MEMS applications of polymers or metal films (e.g., for micro actuators or interconnects), the thickness and uniformity tolerance is usually $\pm 5\%$ for films, with more stringent requirements (e.g., ± 1 – 2%) for applications that require precise electrical or mechanical properties.

Surface roughness influences the friction, adhesion, and wear properties of MEMS devices, especially in moving parts like actuators or gears. Typical roughness for silicon or silicon nitride surfaces in MEMS applications is typically < 5 nm for high-precision applications. For optical MEMS, roughness may need to be reduced to < 1 nm to prevent degradation of performance, such as in micro mirrors or optical switches.

Achieving these tight tolerances in advanced MEMS fabrication comes with significant challenges. Variations in raw materials (such as wafer defects, doping inconsistencies, or deposition inhomogeneities) can introduce deviations in the final MEMS structure, making it challenging to meet stringent tolerance requirements.

As MEMS devices continue to shrink in size, the difficulty of achieving tight tolerances increases, particularly as classical fabrication techniques may become less effective at the nanoscale. For example, at sub-micron scales, surface effects such as stiction and surface energy become more pronounced, which can complicate the fabrication process and affect dimensional control. Even small variations in processing parameters such as temperature, pressure, or chemical concentration, can significantly impact the final tolerances of MEMS components. Advanced process control methods, such as in-situ monitoring or real-time feedback systems, are increasingly used to improve yield and tolerance accuracy.

4. Mathematical modeling of MEMS devices

Mathematical modeling of Micro-Electro-Mechanical Systems (MEMS) is a comprehensive process that involves creating theoretical frameworks and equations to accurately predict the behavior of MEMS devices, which operate across multiple physical domains. In the mechanical domain, models like Euler-Bernoulli and Timoshenko beam theories describe the bending, deformation, and vibration of microstructures such as beams, cantilevers, and diaphragms [35–37]. These are complemented by plate theories like Kirchhoff-Love for analyzing the mechanical behavior of thin plates under loads [38, 39]. Stress-strain relationships, governed by Hooke's law, provide insights into material elasticity and structural stability [40, 41], while vibration models help assess dynamic responses such as resonant frequencies and mode shapes critical in sensors and actuators [42, 43].

In the electrical domain, mathematical models address electrostatic effects, which are fundamental to capacitive sensors and actuators [44]. These effects are governed by Laplace's or Poisson's equations, with additional formulations to calculate forces resulting from changes in capacitance. Electrical models also incorporate circuit equations, such as those derived from Kirchhoff's laws, to describe the dynamics of resistance, capacitance, and inductance in MEMS applications. These models enable the integration of MEMS devices with external electronic systems for sensing and actuation [45].

Thermal models are critical for analyzing temperature-related phenomena, such as heat transfer, thermal expansion, and thermo-mechanical coupling [46]. Using the heat conduction equation these models help predict temperature distributions and their impact on mechanical stresses and displacements, which is essential for thermal actuators and temperature sensors. Fluidic models focus on the behavior of fluids in confined spaces, governed by the Navier-Stokes equations [47]. Simplifications, such as assuming low Reynolds numbers [48], allow for accurate descriptions of fluid flow in microchannels, which are central to microfluidic devices like micropumps, mixers, and biochips.

Coupled domain models are essential in MEMS, where interactions between multiple physical domains occur [49–51]. For instance, electro-mechanical coupling models capture the influence of electrostatic forces on mechanical deformation, which is vital in capacitive sensors, RF switches, and comb-drive actuators. Thermo-mechanical coupling is another critical area, where heat-induced stresses and expansions are modeled to predict device behavior under varying thermal conditions. Dynamic models describe the time-dependent behavior of MEMS using equations of motion which incorporate mass, damping, and stiffness effects [52]. These models are crucial for analyzing transient responses and stability in accelerometers, gyroscopes,

and other MEMS devices. Frequency domain analyses further characterize resonant and harmonic behaviors, providing insights into the operational limits and sensitivities of MEMS resonators and oscillators.

Simplified lumped-parameter models [53] are often employed to represent MEMS devices as equivalent electrical or mechanical systems, such as spring-mass-damper systems or RC circuits, enabling efficient system-level simulations. These models are particularly useful for integrating MEMS components into broader electronic or control systems. Advanced modeling approaches, such as data-driven methods using machine learning [54], are emerging as powerful tools to predict MEMS behavior by analyzing patterns from simulation or experimental data. These methods reduce reliance on resource-intensive simulations and enable rapid iteration in the design process.

Mathematical modeling serves as the foundation for computational methods like finite element analysis (FEA), finite volume methods (FVM), and boundary element methods (BEM), which provide detailed insights into the physical behavior of MEMS devices under realistic conditions [55, 56]. It also informs experimental validation, where theoretical predictions are compared against empirical data to refine models and enhance reliability. This iterative process ensures that MEMS devices are optimized for performance, durability, and manufacturability, bridging the gap between theoretical design and practical application. Through this multifaceted approach, mathematical modeling enables the design and analysis of increasingly complex MEMS technologies, paving the way for innovation in areas such as sensors, actuators, and microfluidic systems.

5. Advanced MEMS applications

Micro-Electro-Mechanical Systems (MEMS) are critical for a wide range of advanced applications (**Figure 1**) that require miniature, high-performance sensors, actuators, and integrated systems. The combination of mechanical, electrical, and even optical functionality in MEMS devices allows them to serve in diverse fields such as medical devices, automotive, telecommunications, aerospace, and consumer electronics.

When medical and healthcare applications are in question, MEMS have revolutionized the medical field by enabling the development of small, precise, and low-cost devices for diagnostics, therapeutic delivery, and monitoring. MEMS-based sensors are widely used for monitoring physiological parameters such as pressure, temperature, and oxygen levels. MEMS pressure sensors, for example, are used in blood pressure monitors, intracranial pressure monitors, and implantable devices for continuous monitoring. MEMS can enable controlled drug release in response to changing physiological conditions. MEMS actuators are used in devices like micro-pumps that can inject small amounts of medication into the bloodstream, offering targeted and precise drug delivery. MEMS technology also enables miniaturized lab systems that can perform complex biochemical tests on a single chip. Lab-on-a-Chip (LOC) systems have significant potential in diagnostics, such as blood analysis, genetic testing, and point-of-care testing. These devices reduce the time and cost of testing, especially in remote or low-resource environments. MEMS devices are increasingly integrated into neuroprosthetics and biomechanics. For example, MEMS sensors are used in smart orthopedic implants that provide real-time data about the health and function of joints, and brain-machine interfaces (BMIs) are advancing with MEMS-based electrodes that can interface with neural tissue to restore lost functions.



Figure 1.
Advanced MEMS applications.

MEMS technology plays an important role in modern automotive systems, where small size, reliability, and low power consumption are essential. MEMS accelerometers are integral to airbag systems in vehicles. These sensors detect sudden deceleration during a collision and trigger the deployment of airbags to protect passengers. MEMS accelerometers have replaced traditional mechanical sensors due to their small size and faster response times. MEMS-based sensors are used to monitor the pressure in a vehicle's tires. By providing accurate, real-time data on tire pressure, MEMS sensors help improve fuel efficiency and prevent tire-related accidents. MEMS gyroscopes are used in stability control systems, providing accurate information about the orientation of the vehicle. MEMS sensors help improve GPS navigation, road safety, and autonomous vehicle technology. MEMS sensors also enable in-vehicle monitoring systems that track the health and performance of the vehicle's critical components, such as engines, exhaust systems, and fuel efficiency.

MEMS are also central to innovations in telecommunications, particularly in high-performance smartphones, wearable devices, and other personal electronics. MEMS microphones are used in smartphones, hearing aids, and voice-activated devices. These microphones are tiny, durable, and capable of capturing high-quality audio. They offer advantages such as low power consumption, high signal-to-noise ratios, and resistance to environmental factors such as humidity and vibration. MEMS oscillators are replacing traditional quartz-based oscillators in communication systems and consumer electronics. They offer smaller sizes, improved accuracy, and better frequency stability, making them ideal for mobile communication devices, GPS systems, and wireless networks. MEMS actuators are used in haptic feedback systems, such as vibration motors in smartphones or wearables, providing tactile responses to touch interactions. This is especially useful in providing users with sensory feedback in gaming controllers, navigation systems, or mobile devices. MEMS technology is used in digital light processing (DLP) systems for micro mirrors, enabling high-definition displays in projectors and micro-displays in consumer electronics like head-mounted displays (HMDs) and virtual reality (VR) systems.

The aerospace and defense industries leverage MEMS technology for applications that require high precision, durability, and reliability under extreme conditions. MEMS gyroscopes and accelerometers are critical components in Inertial Measurement Units (IMUs), used for navigation in spacecraft, satellites, and drones. These devices are essential for precise guidance and control in flight and missile systems. MEMS-based IMUs are smaller, lighter, and more power-efficient than traditional systems, which is important for miniaturizing defense technologies. MEMS sensors are used to monitor the pressure, temperature, and other environmental factors in satellites, aircraft, and unmanned aerial vehicles (UAVs). These sensors help with real-time monitoring of the aircraft's performance and atmospheric conditions. MEMS-based microthrusters are being developed for the next generation of small-scale satellites and space exploration missions. These micropropulsion systems enable precise movement control for small satellites and space vehicles, allowing for more affordable and efficient missions.

MEMS technology has extended its reach into various industrial applications, including process monitoring, robotics, and automation. MEMS sensors such as accelerometers, gyroscopes, and pressure sensors are used to provide feedback in industrial robotics. These sensors enable precise control of robotic arms, position tracking, and motion detection, facilitating automation in manufacturing processes. MEMS sensors are deployed in infrastructure systems such as bridges, dams, and buildings to monitor their structural integrity. MEMS-based accelerometers and strain gauges are used to detect vibrations, shifts, and stresses in these structures, helping to predict maintenance needs and prevent catastrophic failures. MEMS sensors are integrated into monitoring systems for manufacturing processes such as pressure, flow, and temperature control in reactors, pipelines, and chemical plants. MEMS-based sensors offer precise, real-time measurements that ensure safety, efficiency, and optimization in industrial settings.

MEMS technology is increasingly being used for environmental monitoring and sustainable agriculture practices. MEMS-based gas sensors, such as those for detecting carbon dioxide (CO₂), carbon monoxide (CO), and other pollutants, are used for real-time environmental monitoring. These sensors are valuable for tracking air quality in urban environments and monitoring water quality in rivers, lakes, and oceans. MEMS sensors are used in agricultural applications to monitor soil conditions, moisture levels, and weather patterns. These sensors allow farmers to optimize irrigation systems, improve crop yields, and manage resources more efficiently.

As MEMS technology continues to evolve, several emerging trends are shaping the future of MEMS applications. MEMS devices are increasingly being integrated with Complementary Metal-Oxide-Semiconductor (CMOS) circuits. This integration allows for the creation of highly functional systems-on-chip (SoCs) that combine MEMS sensors and actuators with the processing power of CMOS circuits. This trend is especially prominent in the development of MEMS sensors for the Internet of Things (IoT), where small, energy-efficient, and low-cost devices are essential. MEMS devices are also being designed for energy harvesting, which involves converting ambient mechanical energy into electrical energy. MEMS-based piezoelectric or triboelectric generators are being explored for powering wireless sensor networks, autonomous devices, and remote systems. As the demand for smaller, more efficient devices grows, MEMS technologies are being scaled down to the nanoscale. Nanoscale MEMS are expected to have significant implications for applications in nanorobotics, bioengineering, and nanoelectronics.

6. MEMS market

The MEMS market [57–61] has experienced rapid growth over the last few decades due to increasing demand across various industries. MEMS technology enables the miniaturization and integration of mechanical and electronic components, driving advancements in consumer electronics, automotive, healthcare, aerospace, and industrial automation. The global MEMS market is projected grow at a compound annual growth rate (CAGR) of around 7–10% from 2023 to 2030. This growth is fuelled by emerging technologies like IoT, 5G, and autonomous vehicles.

When regional insights are in question, Asia-Pacific is the largest market, driven by robust electronics manufacturing hubs (China, Japan, South Korea) and rising adoption of MEMS in consumer gadgets. North America is characterized by a strong growth due to advancements in automotive and healthcare applications. Europe is focused on industrial and automotive sectors, particularly in Germany and France. The rapid expansion of the MEMS market is propelled by a growing demand for compact and energy-efficient devices, the widespread integration of MEMS into wearables, AR/VR platforms, and IoT applications, along with breakthroughs in medical technologies like lab-on-a-chip systems and biosensors. Nevertheless, the market contends with key challenges, such as substantial initial manufacturing costs, complexities in scaling and standardizing production methods, and intense competition from emerging nanotechnology-driven solutions.

Major MEMS Application Areas are Consumer Electronics, Automotive, healthcare, industrial, IoT, aerospace and defense (**Figure 2**). When consumer electronics is in question, MEMS are used in accelerometers, gyroscopes, microphones, and pressure sensors found in smartphones, tablets, smartwatches, and AR/VR devices. The consumer electronics sector continues to dominate MEMS demand. In automotive industry MEMS sensors are critical for safety systems (airbags, ABS, tire pressure monitoring), advanced driver assistance systems (ADAS), and autonomous vehicles. MEMS enable precise control, boosting vehicle safety and efficiency. MEMS technologies also drive innovations in medical devices, including drug delivery systems, wearable health monitors, and diagnostic tools (e.g., lab-on-a-chip). The aging

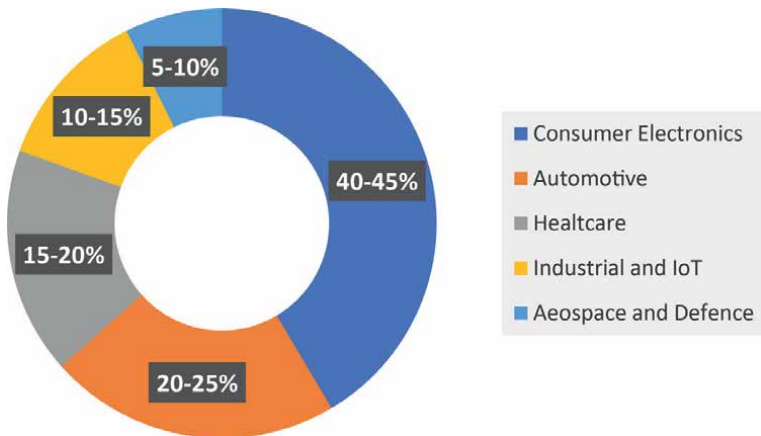


Figure 2.
MEMS market share [57–61].

population and demand for remote healthcare solutions are boosting this sector. MEMS enable predictive maintenance, environmental monitoring, and automation in industries. IoT integration is expanding the use of MEMS in smart homes, factories, and cities. In aerospace and defense MEMS gyroscopes, accelerometers, and pressure sensors are essential in navigation systems, drones, and military equipment, ensuring high performance and reliability.

Key emerging trends in MEMS include their growing applications in IoT, 5G, wearables, miniaturization, integration, and biomedical technologies. MEMS sensors, such as accelerometers, pressure sensors, and humidity sensors, are integral to IoT systems, supporting applications like smart homes, precision agriculture, and healthcare monitoring. In 5G networks, MEMS technology plays a critical role in enabling high-frequency RF switches and filters essential for seamless communication. Wearable devices, including fitness trackers and smartwatches, leverage MEMS for real-time health tracking and motion sensing. Advances in microfabrication are pushing the boundaries of miniaturization, leading to more efficient, high-performance, and low-power MEMS devices. Additionally, biomedical MEMS, such as lab-on-a-chip systems and biosensors, are transforming diagnostics and advancing personalized medicine.

Future prospects for MEMS include increased adoption in emerging markets driven by growing industrialization and rising healthcare needs in regions like India, Southeast Asia, and Africa. Advanced packaging technologies, such as wafer-level packaging and integration with CMOS, are set to enhance device performance while lowering production costs. Furthermore, the integration of MEMS with AI is expected to revolutionize sensing and actuation, enabling predictive analytics and smarter decision-making in various applications.

The MEMS market is poised for significant growth, driven by technological advancements, increased adoption across diverse industries, and rising demand for compact, efficient, and multifunctional devices. Despite challenges, innovations in materials, fabrication processes, and application-specific designs will continue to shape the future of MEMS technology.

7. Conclusion

Advanced MEMS technologies represent a transformative force across multiple sectors, leveraging innovations in fabrication, materials, and design to address evolving demands in precision, efficiency, and miniaturization. These systems are critical in applications ranging from consumer electronics to healthcare, automotive, and telecommunications. MEMS advancements, including integration with artificial intelligence (AI), Internet of Things (IoT), and 5G technologies, are driving their adoption in both traditional and emerging markets.

The MEMS market is experiencing robust growth due to its ability to meet the demands of next-generation technologies. In consumer electronics, MEMS sensors enable functionalities like motion tracking, environmental sensing, and health monitoring in wearables and smart devices. The automotive sector relies heavily on MEMS for Advanced Driver Assistance Systems (ADAS), safety systems, and electric vehicle technologies, while in healthcare, MEMS-based lab-on-a-chip devices and biosensors are revolutionizing diagnostics and personalized medicine. Additionally, MEMS technology supports high-frequency RF components essential for 5G communication networks.

The market's growth trajectory is underpinned by significant trends, including the miniaturization of devices, wafer-level packaging, and advancements in microfabrication techniques, which improve performance and reduce costs. Integration with CMOS technology further enhances MEMS scalability and functionality, making it possible to combine complex electronic systems with precise mechanical components. Emerging regions are expected to contribute significantly to the MEMS market due to increasing industrialization and healthcare demands.

However, challenges remain. High initial manufacturing costs, complexities in scaling production, and competition from nanotechnology alternatives pose obstacles to widespread adoption. These challenges necessitate continued investment in R&D and the development of standardized production processes to drive economies of scale and ensure market competitiveness.

Looking ahead, the fusion of MEMS with AI is expected to elevate their capabilities, enabling advanced sensing, predictive analytics, and smarter decision-making in autonomous systems, industrial automation, and connected devices. The MEMS market is poised to grow steadily as demand for high-performance, energy-efficient devices accelerates globally. This growth positions MEMS as a cornerstone technology in the evolution of smart, interconnected systems, with vast potential to shape the future of multiple industries.

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Conflict of interest

The authors declare no conflict of interest.

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Section 2

MEMS Principles and Devices

Micro-Electro-Mechanical Systems Applications in Optical Devices

Hao Zhai, Selina X. Yao and Zhuang Liu

Abstract

This chapter delves into the revolutionary impact of Micro-Electro-Mechanical Systems (MEMS) on optical devices, driven by advancements in materials science and micro/nano manufacturing techniques. MEMS devices offer unparalleled precision, miniaturization, and low power consumption. Their applications in both traditional and atomic optics will be explored. The incorporation of MEMS into the design of optical elements, including metasurfaces, microslits, and atomic vapor cells, has the potential to significantly enhance optical performance, device robustness, and miniaturization. This chapter presents a comprehensive investigation into the fabrication, characterization, and optimization of MEMS slits and atomic vapor cells, demonstrating their superior performance compared to traditional approaches. These examples demonstrate how MEMS technology is revolutionizing optical device engineering and expanding the possibilities in this field.

Keywords: MEMS, air slit, atomic vapor cell, spectrometer, magnetometer

1. Introduction

Traditional optical components, such as lenses, gratings, slits, etc., have played a pivotal role in the fields of imaging, optical communications, and detection. However, as technology advances and the demand for higher performance grows, the limitations of conventional optical elements have become increasingly apparent. For example, issues such as large size, heavy weight, and bottlenecks in processing accuracy restrict their application in the next generation of miniaturized and highly integrated optical systems. In order to overcome these limitations, micro-electro-mechanical system (MEMS) fabrication technology has been introduced into the design and fabrication of optical devices due to its unparalleled precision and ease of mass production. It has also provided new solutions for the miniaturization and performance optimization of optical components. The capacity of MEMS technology to produce intricate structures at the micro- and nanoscale levels offers significant potential for its utilization in the field of optics. For instance, metasurfaces based on MEMS technology employ sub-wavelength scale nanopillar structures, which can emulate the optical functions of traditional lenses at smaller sizes and even exhibit enhanced optical performance in certain respects. Furthermore, MEMS slits can be utilized in high-resolution imaging spectrometers to achieve notable enhancements in spectral resolution and spectral sensitivity. Another significant application is that

of MEMS atomic vapor cells, which are used to regulate and detect atomic vapors encapsulated in miniaturized MEMS optical cavities through lasers. This application enables the generation of high-precision time-frequency signals and magnetic field measurements and plays an instrumental role in the miniaturization of quantum sensors, including chip-based atomic clocks and atomic magnetometers. Given the extensive range of optical devices and their diverse functionalities, this chapter will not provide an extensive introduction to each individual processing technique. Instead, it will use MEMS slits as a key example to highlight the difference in performance between micro-nano fabrication technology and conventional processing techniques. Additionally, it will examine MEMS atomic gas chambers as a case study to elucidate the design principles, miniaturized fabrication processes, and applications of emerging atomic optical devices. This chapter will demonstrate how micro- and nanofabrication technology enables the overcoming of the limitations of traditional optical design, thereby providing more efficient solutions for new generation optical devices.

1.1 MEMS fabrication of lenses

Imaging is the oldest research direction in the field of optical technology. Conventional refractive lens elements, founded upon geometrical optics, depend on the alteration of their intrinsic optical thickness in a direction perpendicular to the optical axis. This is achieved by regulating the transmission distance of light within the optical material, thereby modifying the optical range and consequently attaining the modulation capacity of the transmitted phase [1]. The performance of the optical element is contingent upon the extinction coefficient of the material employed in the working band, the characteristics of dispersion, and the machining precision of the curved surface. As a nascent planar lightweight imaging element, the metalens, which benefits from the capacity of its constituent units to freely modulate the electromagnetic wave response, which is suitable for fabrication by MEMS methods, has yielded numerous noteworthy research outcomes since its inception [2]. A metalens is a transmissive optical focusing element composed of discrete hypersurface units. The typical structure of a metalens is illustrated in **Figure 1(a)**, where each hypersurface

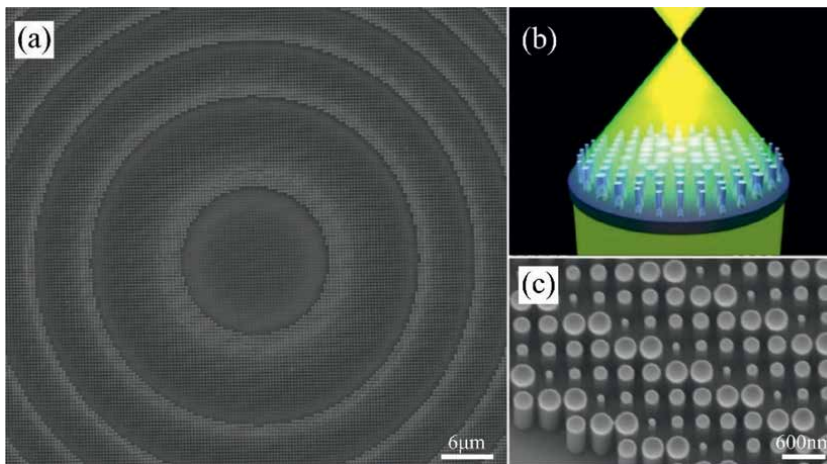


Figure 1.
(a) Top-view SEM image of the center portion of a fabricated metalens. (b) Focusing schematic of metalens.
(c) Side-view SEM image of the edge of the metalens, showing the vertical profile of the nanopillars [3].

unit modulates the transmission phase of the incident light through electromagnetic resonance, among other mechanisms. The optimal configuration entails the conversion of the incident light from a plane wave to a converging spherical wave subsequent to wavefront modulation by the metalens, which then forms a convergence at the designated focal point, as illustrated in **Figure 1(b)**.

Typically, the subunits in a metalens exhibit a consistent height, with variations occurring solely in the structural form or geometrical parameters within the cross-section. This characteristic makes the metalens particularly well-suited for micro-nano processing applications [4], simplifying the production process and making it easy to scale up for mass manufacturing [5]. Furthermore, this technology enables the production of lenses with a planar quality comparable to that of integrated circuits, thereby significantly reducing the volume and weight of the resulting optical devices and systems. This technology has the potential to accelerate the development of lightweight, miniaturized, and integrated optical solutions. The electromagnetic resonance mechanism of the metalens can be incorporated into the design of optical components, facilitating the realization of optical components such as beam splitters [6] and polarization converters [7]. While metalenses offer distinctive advantages in lightweight and integrated optical systems, they also present certain limitations compared to conventional geometrical optical lenses, including optical efficiency, dispersion control, manufacturing cost, operating angle, and polarization dependence. These factors must be taken into account when selecting the most appropriate lens for a given application.

1.2 MEMS fabrication of air slits

An imaging spectrometer is typically composed of several fundamental elements, including an entrance slit, collimation optics, a beam splitting module, and a detector array. The entrance slit, situated at the focal plane of the front objective lens, delineates the field of view (FOV) for the spectrometer. The light emitted from the target is collected by the front objective and directed through the slit, thereby forming a spatially resolved image of the scene. As the dispersed light traverses the spectrometer's optical path, each wavelength component generates a corresponding slit image on the detector, which is subsequently captured and processed. The slit plays a pivotal role in determining the optical performance of the spectrometer. The length of the slit affects the FOV of the spectrometer, while the width influences various parameters, including spectral resolution, scanning strategy, and light throughput. Furthermore, maintaining a uniform slit width is crucial for ensuring a consistent spectral response across the entire FOV.

Currently, common methods of slit processing in imaging spectrometers are mainly laser processing and traditional mechanical processing. Laser processing employs a focused laser beam to achieve precise cutting through the localized high-temperature ablation. However, this method has the tendency to induce defects along the edge of the slit as a result of the excessive thermal effect, which has a detrimental impact on the overall quality of the fabricated slit. Conversely, the fabrication of machined slits typically involves a series of steps. After the slit sidewalls are defined and cut, the slit edge thickness is reduced to approximately 30 μm through the utilization of specialized grinding wheels. Subsequently, the two halves of the slit are joined together. The cutting and grinding processes inevitably result in damage and defects, while the splicing process can potentially introduce coplanarity errors. Therefore, it is unlikely that the required micron-level precision in slit processing can be achieved.

Moreover, the slit made from sheet metal must be assembled with a fixture jig; the increase in volume and weight makes it challenging to apply mechanical processing techniques to the miniaturized star-bearing spectrometer [8].

In contrast to the conventional methods, monocrystalline silicon slits are fabricated using MEMS technology through deep reactive ion etching (DRIE), which ensures simultaneous patterning without introducing mechanical damage or internal stress. The dimensional accuracy of the slit is primarily determined by the resolution of the photolithography process, which is typically below one hundred nanometers. As illustrated in **Figure 2(a)** and **(c)**, a comparative analysis between MEMS slits and mechanically machined slits was conducted under an optical microscope. The MEMS slit exhibited sharper edges, whereas the machined slit displayed visible curvature along the edge. As illustrated in **Figure 2(b)** and **(d)** by the profilometer measurements, the surface roughness within around 100 μm from the MEMS slit edge was markedly lower than that of the machined slit.

Moreover, MEMS technology is therefore advantageous for the manufacture of silicon-based high-aspect-ratio slits, providing superior precision, uniformity, and defect control. This approach markedly enhances reproducibility and renders the mass production of such slits feasible. However, due to the relatively low thickness (on the scale of tens of micrometers) of single-crystal silicon employed in MEMS slits, some degree of light transmission may occur at visible wavelengths. Consequently, high-quality coatings are essential to minimize stray light interference, which is vital for ensuring the fidelity of spectral imaging systems.

1.3 MEMS fabrication of optical vapor cell

The atomic optical vapor cell represents a pivotal element in the regulation and observation of quantum states. The apparatus encapsulates alkali metal vapors, such as rubidium and cesium, within a transparent container, thereby forming a closed atomic ensemble system. By modulating the light signal of a laser and interacting

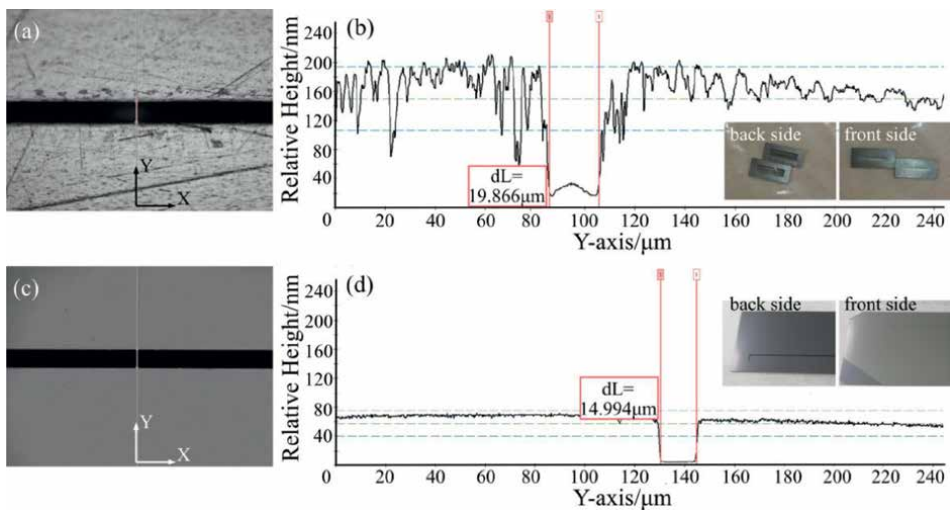


Figure 2. (a) 10 $\times$ optical micrograph of machined air slit. (b) Profiler test curves of the machined slit. (c) 10 $\times$ optical micrograph of MEMS air slit. (d) Profiler test curves of the MEMS slit [9].

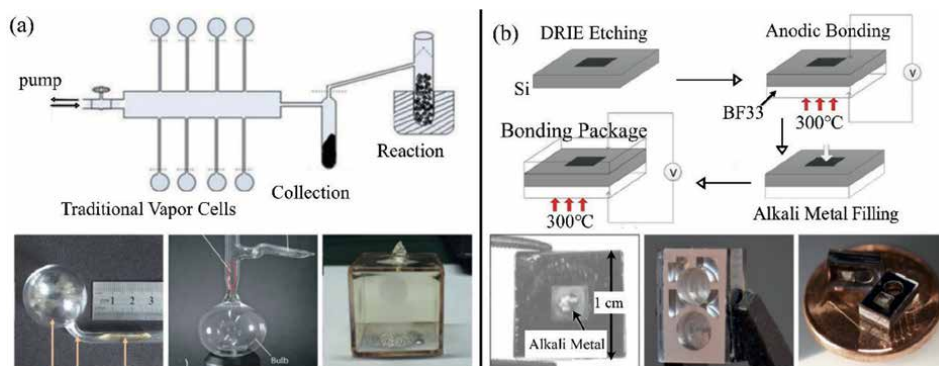


Figure 3.
 Common atomic vapor cells and their fabrication techniques [12–15] (a) Traditional glass-blowing and firing atomic vapor cells. (b) MEMS atomic vapor cells.

with the atomic ensemble in a specific field, high-precision control and detection are achieved, with phase-locked feedback loops formed through circuits, as shown in **Figure 4**. The performance of the atomic vapor cell is the determining factor in the ultimate limits of accuracy and stability in atomic frequency standards. As a fundamental component, atomic vapor cells are employed in a range of applications, including atomic magnetometers, atomic clocks [10], and atomic gyroscopes [11].

There are two main methods for fabricating atomic vapor cells: the traditional glass-blowing and firing technique [12] and the MEMS technology based on semiconductor microfabrication [13]. These two fabrication techniques and the resulting atomic vapor cells are shown in **Figure 3(a)** and **(b)**, respectively. The traditional glass-blowing and firing technique takes advantage of the high saturated vapor pressure and low melting point of alkali metals, allowing them to condense in a low-temperature region. The fabrication is completed by firing the tail tube of the vapor cell using an oxyhydrogen flame, resulting in a “small tail” with a sharp protrusion at the back end of each traditional atomic vapor cell, as shown in **Figure 3(a)** [14, 15]. The traditional glass-blowing method suffers from poor consistency in the fabrication process and is challenging for producing miniature atomic vapor cells with volumes as small as a few cubic millimeters. Additionally, the optical windows of small glass-blown vapor cells are not flat, which adversely affects laser pumping and detection to some extent.

L. A. Liew et al. at NIST first utilized MEMS technology in 2004. They employed micro-nanofabrication techniques such as ultraviolet photolithography and DRIE to pattern and etch silicon wafers, as shown in **Figure 3(b)** [13]. The bonding of silicon wafers with glass wafers was completed using anodic bonding to form a pre-bonded structure. Subsequently, alkali metal elements were filled into the cavity of the

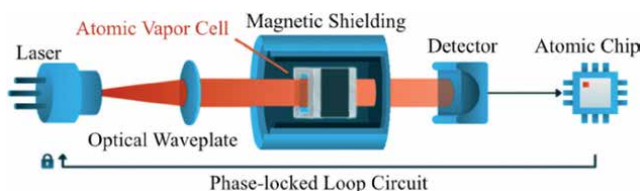


Figure 4.
 A brief overview of the operational principles of an atomic vapor cell.

pre-bonded structure using a micro-liter pipette in a glovebox. Finally, a second-side anodic bonding process was employed to complete the hermetic sealing of the alkali metal vapor cell. The fabricated atomic vapor cell samples are shown in the lower left of **Figure 3(b)**. Compared to traditional glass-blowing and sealing techniques, the MEMS-based fabrication technology for atomic vapor cells offers several advantages, including ease of miniaturization, high robustness, and low cost. It is considered the optimal method for producing miniature atomic vapor cells [14–17].

2. Application of MEMS slits in imaging spectrometers

As spectrometers evolve toward wider coverage and higher resolution, the length of the slit increases while the width decreases. In the case of the geostationary orbit imaging spectrometer, which remains stationary relative to the Earth's rotation, the absence of satellite movement allows for prolonged exposure times. This capability ensures adequate luminous flux, thereby making it feasible to reduce the slit width to achieve high sensitivity. Consequently, the slit width can be finely adjusted to match the pixel size of the detector at the focal plane, potentially reducing the width to dozens of micrometers, which poses a great challenge to the accuracy of slit manufacturing.

2.1 MEMS slits microfabrication

The MEMS air slits were fabricated on a 4-inch SOI wafer, which comprised a metal layer, a device silicon layer, a silicon dioxide buried layer, and a handle silicon layer [18]. The SOI wafer has a $\langle 100 \rangle$ orientation and a diameter of 4 inches, as illustrated in **Figure 5** [9]. Based on MEMS fabrication technology, the theoretically designed length of an air slit can be extended even beyond 100 mm by simply expanding the layout to an 8-inch or 12-inch wafer. However, considering the inherent

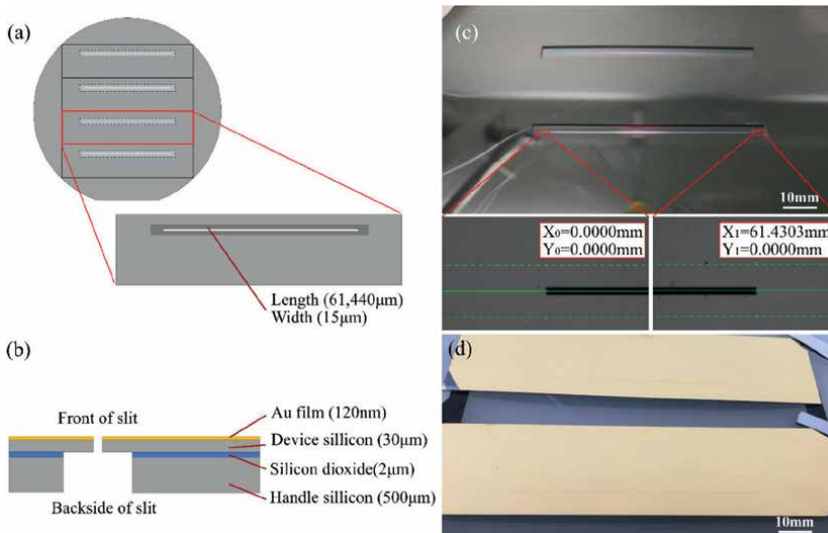


Figure 5. (a) Layout design of MEMS slits [9]. (b) Cross-section of the slit. (c) Backside of MEMS air slit wafer. (d) Front side of fabricated MEMS air slit after dicing.

strength of silicon material, such ultra-long and ultra-thin silicon membranes may struggle to withstand impacts and low-frequency vibrations during transportation. Therefore, designing mechanical supporting structures on the silicon membrane, combined with simulation and reliability testing, presents a potential technical approach to enhance the strength of the slit design.

As the optical signal passes through the slit, each spectral line generated by the dispersive spectroscopy of the spectrometer serves as an image of the slit. The UV photolithography process can transfer the slit layout to the photoresist layer with high fidelity and high precision; ensuring uniformity in spectral line resolution across the FOV is crucial. **Figure 6(a)** displays that the top side underwent exposure using the Photomask-A with the slit pattern. Subsequently, the top surface was subjected to a deep reactive ion etching (DRIE) process called the “BOSCH process” to ensure the perpendicularity and straightness of the slit sidewalls, as demonstrated in **Figure 6(b)**. However, during the BOSCH process [19], the bottom becomes irregular [20], resulting in a non-uniform slit edge after etching through. As DRIE is ineffective in etching SiO_2 , a buried oxide layer in the SOI wafer was employed as an etch-stop layer for DRIE [21], and the width of the bottom of the slit was precisely controlled by adjusting the etching rate, time, and over-etching bottom silicon on the silicon oxide layer. The subsequent stage of the procedure involves repeating the photolithography and etching process on the bottom side, in accordance with **Figure 6(c)** and **(d)**. Subsequently, the SiO_2 at the base of the slit was removed through the process of wet etching, as shown in **Figure 6(e)** [9]. A metal layer was uniformly evaporated onto the surface of the slit structure using an electron beam evaporation system, which successfully suppressed light transmission through regions other than the designated slit area, as illustrated in **Figure 6(f)**.

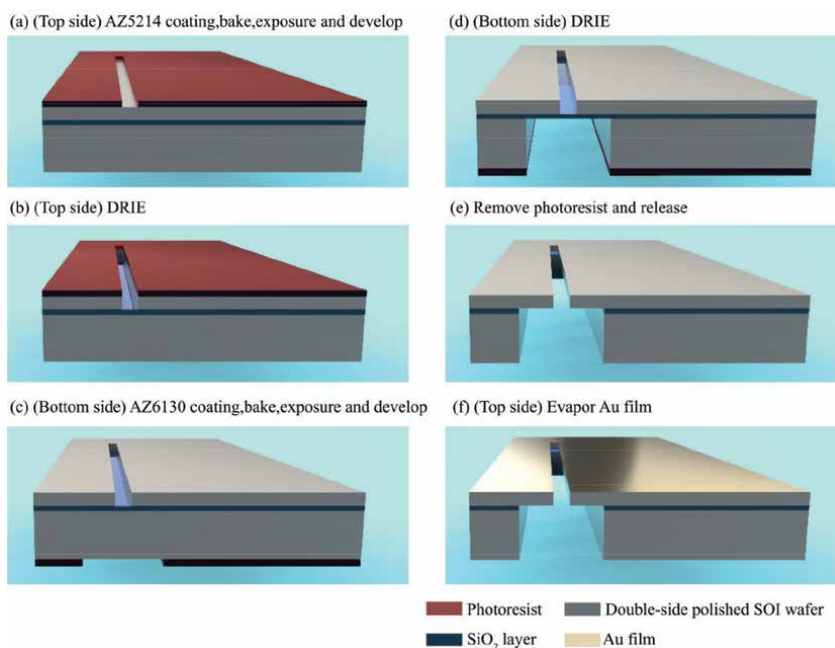


Figure 6.
 The overall fabrication process of the proposed MEMS air slit [9].

As the BOSCH process alternated between flowing passivation gas and etching gas in the reaction chamber [22], a transitional process occurred between the deposition and etching in each repeated cycle, leading to the periodic scallop structures on the slit sidewalls [23]. Given the fact that the presence of periodic scallop structures with a period analogous to the operational wavelength band of the spectrometer may result in interference from stray light signals, in order to reduce the undulation height of the sidewall and modify the periodic scallop structure, the proportion of etching to passivation time in the etching cycle was adjusted, along with the platen HF flow rate during the etching stage, as demonstrated in **Table 1**. The resulting scanning electron microscopy images of the etched cross-sections for each recipe are presented in **Figure 7**. Notwithstanding the enhancement in surface roughness observed in *Recipe 2*, the scallop structure exhibited discernible angular bulges. *Recipe 3* exhibited the lowest surface roughness and produced a more uniform and smoother profile, indicating superior control over sidewall morphology.

By modifying the parameters of the BOSCH process, it is possible to enhance the sidewall morphology to a certain extent. Additionally, this can be accomplished through a combination of LPCVD thermal oxidation and BOE wet etching processes following the DRIE process. The elevated regions of the scallop structures exhibited a slightly elevated chemical potential in comparison to the depressed regions, rendering them more susceptible to the formation of SiO₂ during the thermal oxidation process. Subsequently, a wet etching process utilizing a BOE solution was employed to remove the thin oxide layer that has formed on the surface. This process resulted in a reduction in the amplitude of the scallop structure. The repetition of the thermal oxidation and wet etching steps on multiple occasions has been shown to greatly improve the sidewall morphology. As shown in **Figure 7(d)**, the amplitude of the scallop structure was diminished to 47.4 nm.

2.2 MEMS slit spectrometer performance

The performance test setup for the slit is illustrated in **Figure 8**. The spectrometer is configured in a Wynne-Offner design, incorporating a blazed grating to enhance imaging performance [24]. This configuration not only provides excellent

Heading	Cycle	Time (s)	Platen HF	C ₄ F ₈ (sccm)	SF ₆ (sccm)	O ₂ (sccm)	ETCH H (nm)	ETCH W (nm)
Recipe1 (base)	Depo	1.1	0	370	0	0	1297	332.6
	Etch1	1.0	145	0	200	100		
	Etch2	1.2	36	0	450	0		
Recipe2	Depo	1.1	0	370	0	0	331.2	93.0
	Etch1	1.0	100	0	200	100		
	Etch2	1.2	36	0	450	0		
Recipe3	Depo	0.8	0	370	0	0	506.2	61.87
	Etch1	1.0	145	0	200	100		
	Etch2	0.8	36	0	450	0		

Table 1.
Morphological data statistics for different etching parameters [9].

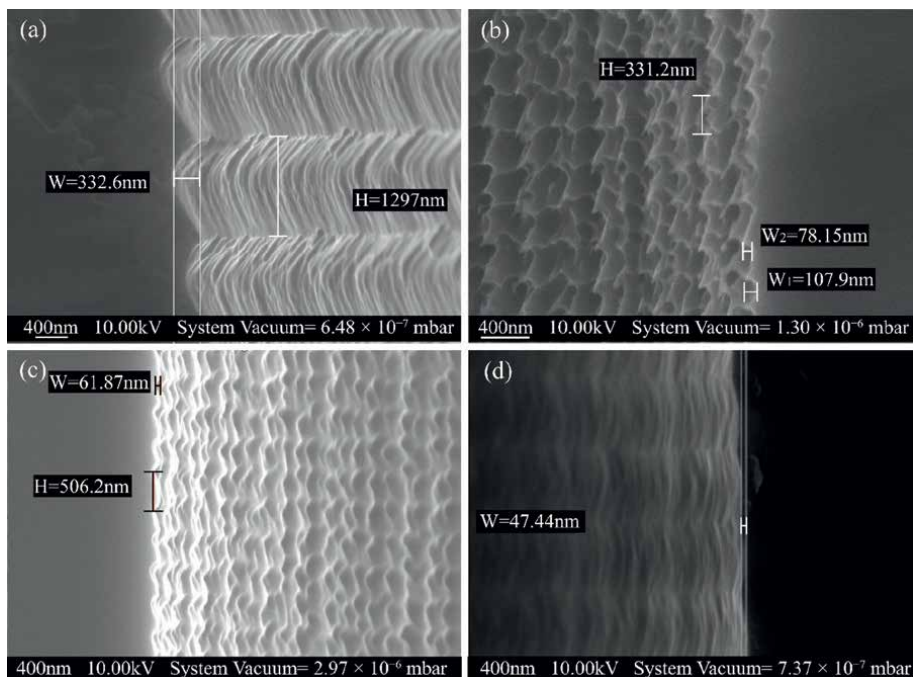


Figure 7.
 Cross-sectional SEM image of the fabricated DRIE scallop [9]. (a) Recipe 1. (b) Recipe 2. (c) Recipe 3.
 (d) LPCVD thermal oxidation + BOE wet etching cyclical process.

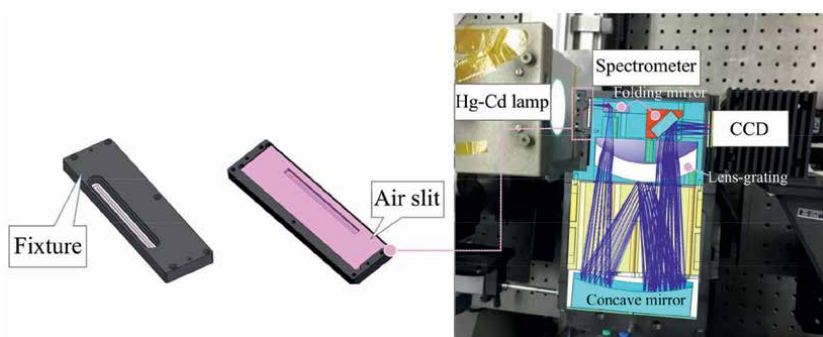


Figure 8.
 Test devices for characterizing the slit properties [9].

astigmatism correction but also permits the use of a longer slit length without compromising the overall compactness of the apparatus. Furthermore, it maintains concentricity and preserves the distortion-free attributes that are characteristic of the classical Offner configuration. The spectrometer setup comprises a lens grating, folding mirrors, and a concave mirror. The slit was positioned at the focal plane of the front objective and the object plane of the spectrometer. The apparatus was uniformly illuminated using a Hg-Cd light source, and a CCD detector with a pixel size of $5.5 \times 5.5 \mu\text{m}$ was employed to capture the characteristic spectral lines. The spectral data were employed for the assessment of the visible-band imaging quality of the slit.

The spectral data at varying positions along the normalized field of view (NFOV), distributed uniformly across the slit length, are illustrated in **Figure 9** [9]. As illustrated in **Figure 9(b)**, the spectral lines displayed high sharpness and low noise levels for different view fields and wavelengths for the MEMS slit. In contrast, the machined slit, as illustrated in **Figure 9(a)**, demonstrated a spectral noise intensity that averaged approximately 1% relative to the spectral signal. The elevated noise levels can be attributed to the mechanically scribed surfaces of the machined slit sidewalls, which act to scatter stray light and consequently elevate the levels of spectral noise. In contrast, the MEMS slit's sidewalls were defined by DRIE-etched scallop-like microstructures, which underwent subsequent optimization to reduce diffuse reflection and minimize spectral noise. Moreover, the MEMS slit exhibited a clear and unobstructed spectrum devoid of discernible stray light noise across the NFOV wavelength plane, which indicates effective design and process control during electron beam coating,

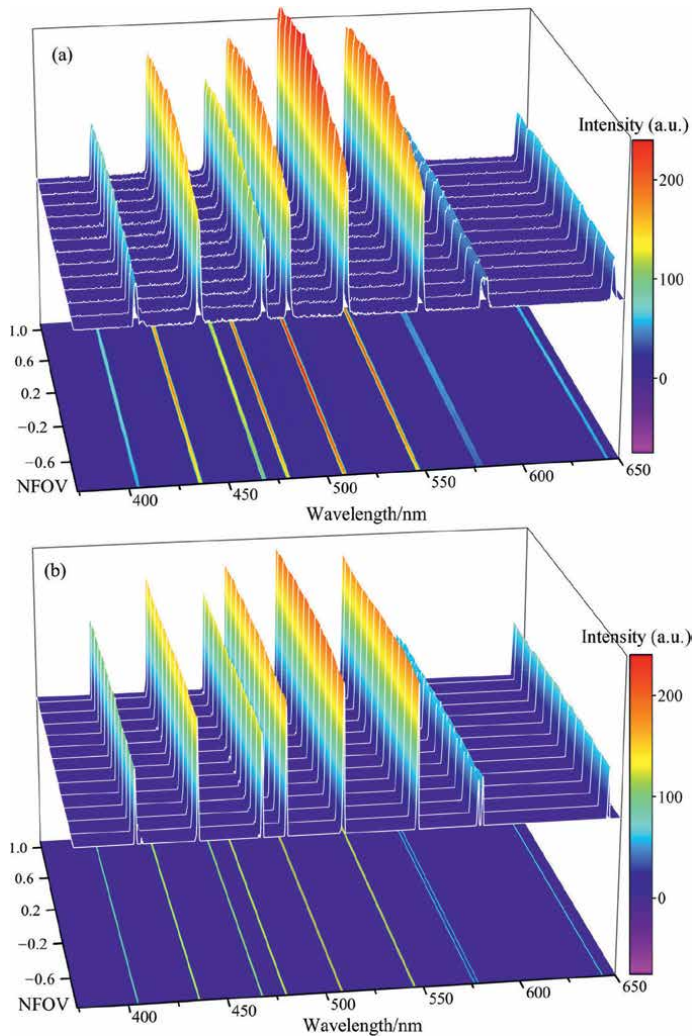


Figure 9.
(a) Spectral lines intensity distribution of machined slit. (b) Spectral lines intensity distribution of MEMS slit [9].

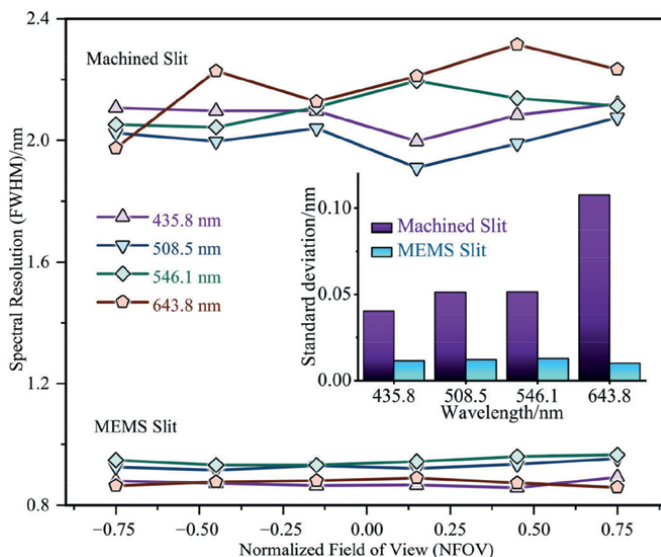


Figure 10.
 Distribution of spectral resolution through NFOV in 435.8, 508.5, 546.1 and 643.8 nm [9].

which successfully minimized light transmission through the slit edges while preventing unwanted metal deposition on the sidewalls.

To quantitatively characterize the imaging performance of the slit, the energy distribution perpendicular to the direction of the spectral lines was fitted with a Gaussian line, the full width at half maximum (FWHM) of the spectral response function (SRF), which is frequently referred to as the spectral resolution. In order to ensure a more uniform distribution across the visible range and to facilitate comparison, four spectral lines were selected with the light intensity values normalized between 0.3 and 0.8. **Figure 10** illustrates the spectral resolution measurements for both machined and MEMS slits across a range of wavelengths and view fields. The MEMS slit exhibited a consistently high spectral resolution of less than 1 nm across the wavelength-NFOV plane, demonstrating stable performance. The statistical analysis demonstrates that the MEMS slit exhibited greater consistency in spectral resolution values across different NFOV, with a standard deviation of less than 0.013. It provides a reliable new fabrication method for high-precision ultra-long air slits, which supports the development of a wide-coverage and high-resolution imaging spectrometer.

3. Application of MEMS vapor cells in magnetometers

An atomic magnetometer is a highly sensitive magnetic field measurement device based on the principles of atomic physics, which is commonly used to measure very weak magnetic fields. These devices are utilized in a variety of applications, such as geophysical exploration, biomedical imaging, and fundamental physics research [22, 23, 25]. The operational principle relies on the interaction between the electronic or nuclear spins of atoms and an external magnetic field. Typically, alkali metal atoms, such as rubidium or cesium, are employed in this process. The process begins by polarizing the atomic spins by optical pumping. When an external

magnetic field is applied to these polarized atoms, their spin directions begin to precess, and the precession frequency is directly proportional to the strength of the magnetic field. By detecting the precession frequency through a probing light beam, the strength of the external magnetic field can be measured with exceptional sensitivity and precision. Magnetometers based on MEMS atomic vapor cells provide several benefits, such as being compact in size and having low power consumption [26].

3.1 MEMS vapor cells microfabrication

The fabrication of the atomic vapor cell represents a critical component of the atomic magnetometer. In comparison to conventional glass-blowing and sealing techniques, MEMS technology offers numerous benefits, including high reliability and low cost. It allows for the wafer-level mass production of atomic vapor cells with dimensions as small as a few millimeters, in line with the ongoing trend toward miniaturization in atomic magnetometers. However, due to the highly reactive chemical nature of alkali metal elements, the filling of these elements into MEMS atomic vapor cells remains one of the primary technical challenges in their fabrication.

The fabrication of an atomic vapor cell required a series of pivotal stages, including the conceptualization of the atomic vapor cell, the patterning of the MEMS substrate material, the preparation and filling of alkali metal elements, and the bonding and cutting of the atomic vapor cell wafer. The initial step involved the transfer of the atomic vapor cell pattern onto an optical mask. Ultraviolet photolithography and microfabrication techniques were employed to transfer the design pattern from the optical mask onto the surface of the substrate material, with photoresist serving as the mask and silicon as the supporting material for the atomic vapor cell. Subsequently, the thick silicon wafer was etched to create the through-holes for the atomic vapor cell cavity, using the DRIE “BOSCH” process. This process ensured high verticality and a high aspect ratio in the etching of the silicon wafer, thus meeting the design requirements for optimal light transmission in the atomic vapor cell for atomic magnetometers. The etching process using the “BOSCH” method is illustrated in steps I through IV of **Figure 11**. During this process, the photoresist pattern was transferred into the bulk material, resulting in a silicon wafer with a hollowed-out structure.

Afterward, anodic bonding was employed to affix the substrate material to the first optical transparent window material. The filling of the ^{87}Rb element and the injection of an inert buffer gas were completed within the pre-bonded structure. The pre-bonded structure was then bonded with the second optical transparent window material, forming a hermetically sealed sandwich-structured atomic vapor cell wafer. Finally, the entire wafer was diced to obtain discrete, individual atomic vapor cells (**Figure 12**).

To mitigate the mismatch between the silicon wafer and the glass wafer due to thermal expansion during the anodic bonding process, it was necessary to align the thermal expansion coefficient of the glass wafer with that of silicon ($\alpha_{\text{Si}} = 4.1 \times 10^{-6} \text{ K}^{-1}$). In most cases, sodium-containing borosilicate glass wafers (Schott Borofloat® 33, BF33) with a thermal expansion coefficient of $3.25 \times 10^{-6} \text{ K}^{-1}$ were utilized as the optical window material. The application of an electric field within a temperature range of 250–300°C resulted in the migration of Na^+ ions within the glass material toward the cathode, while O^{2-} ions accumulated in proximity to the surface on the silicon wafer side. This process resulted in the formation of robust Si-O bonds between the glass and silicon wafers, with a bond strength surpassing that of the bulk materials, leading to excellent hermetic sealing.

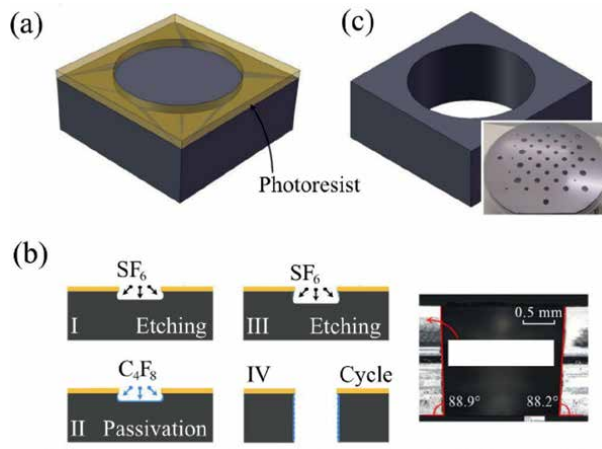


Figure 11.
 Fabrication of the cavity of the MEMS atomic vapor cell [27] (a) Photoresist pattern of atomic vapor cell through hole. (b) The “BOSCH” etching process. (c) Graphic transfer of atomic vapor cell through hole.

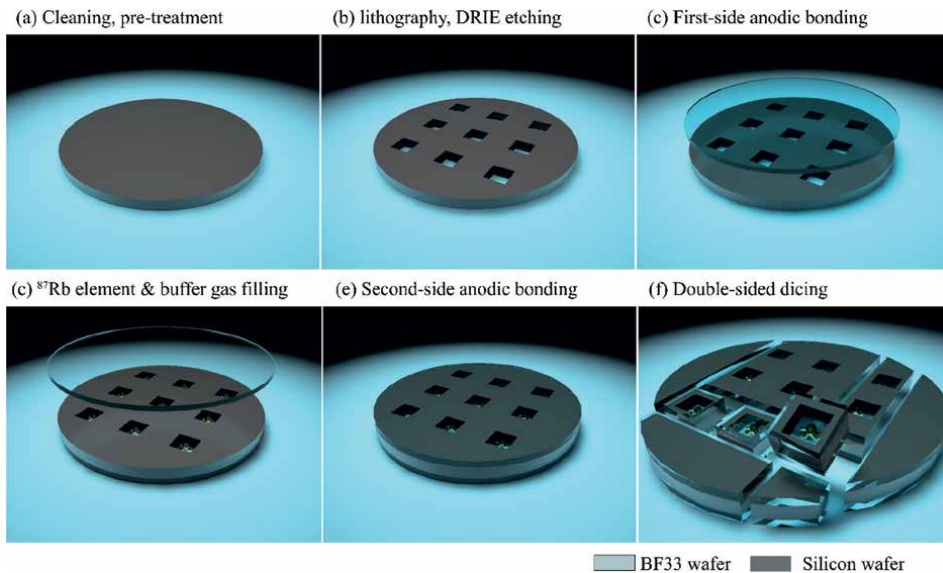


Figure 12.
 The overall fabrication process of the proposed MEMS vapor cells.

3.2 Functional development of alkali metal atom-filled bonding devices

Due to their highly reactive chemical nature in their elemental form, alkali metals can vigorously react with water, oxygen, and carbon dioxide in the atmosphere at room temperature, forming complex products. The filling of alkali metals into atomic vapor cells and the achievement of hermetic bonding pose major technical challenges in the fabrication of miniaturized MEMS atomic vapor cells. The current techniques for filling alkali metals include the micro-liter pipette injection method proposed by L. A. Liew et al. [13], the alkali metal slow-release heating decomposition technique introduced by A. Douahi et al. from the University of Franche-Comté in 2007 [28],

and the UV photolysis of alkali metal azides optimized by S. Woetzel et al. from the Leibniz Institute of Photonic Technology in 2011 [29]. These alkali metal filling techniques come with several challenges, including low volumetric utilization, the introduction of impurities, high cost, and potential contamination of the bonding surfaces. Therefore, it is essential to investigate alkali metal direct evaporation techniques that are compatible with MEMS processes and to develop pollution-free, single-chamber micro-atomic vapor cells (**Table 2**).

By modifying the equipment, it was possible to establish a connection between the alkali metal evaporation apparatus and the wafer bonding apparatus, thus integrating the evaporation and bonding functions into a unified system. This enabled the transfer of pre-bonded structures in a high-purity, low-oxygen environment, thus preventing contamination and oxidation of the alkali metal elements and enhancing the quality and yield of MEMS vapor cells, as illustrated in **Figure 13**. Evaporation coating technology requires the heating of the material to be evaporated to an atomic or molecular state within a vacuum environment. This is achieved through the utilization of techniques such as electric current heating, electron beam bombardment heating, and laser heating. The evaporated atoms or molecules travel in straight lines with relatively long mean-free paths and condense on the substrate surface to form a thin film. Given the low melting point and high saturation vapor pressure of alkali metals (with a saturation vapor pressure around 10^{-2} Torr below 200°C), this method is theoretically more suitable for the preparation of alkali metal vapor cells using vacuum evaporation coating. As illustrated in **Figure 13**, the pre-bonded structure was positioned face down directly above the evaporation crucible, which contains the pre-reacted alkali metal in its elemental form. A shadow mask was employed for patterned deposition, with an in-situ thickness monitor utilized to measure the evaporation thickness and calculate the evaporation rate, thereby achieving quantitative filling of alkali metal within the vapor cell [30].

Element filling method	Features	Disadvantages
Alkali Metal Displacement Reaction Filling Technology: $\text{BaN}_6 + \text{CsCl} \rightarrow \text{BaCl}_2 + 3 \text{N}_2 + \text{Cs}$	Regulating the reaction by temperature.	Impurity residue in products; unable to manufacture small single-chamber vapor cells; not suitable for mass production.
Alkali Metal Azide Decomposition Filling Technology: $2\text{CsN}_3 \rightarrow 2\text{Cs} + 3 \text{N}_2$	UV decomposition	Impurity residue in products; limitations on buffer gas type and pressure.
Alkali Metal Releasing Agent Filling Technology: $2\text{Cs}_2\text{CrO}_4 + \text{ZrAl}_2 \rightarrow 4\text{Cs} + \text{Cr}_2\text{O}_3 + 3\text{ZrO}_2$	Pyrolysis	Impurity residue in products; unable to manufacture small single-chamber vapor cells; uncontrollable amount of element filling.
Direct Alkali Metal Element Filling Technology	No impurity introduction; capable of manufacturing small single-chamber vapor cells; easy for mass production.	Requires specialized equipment; requires design of elemental recycling units.

Table 2.
Alkali dispensing techniques [13, 27–29].

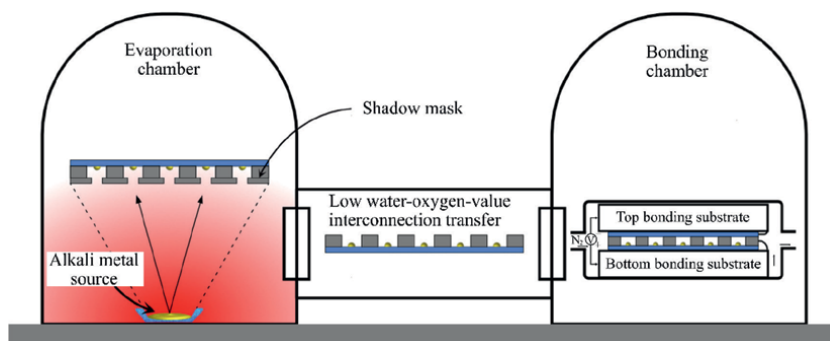


Figure 13.
 Wafer-level alkali evaporation filling and hermetic bonding device [30].

Once the wafer-level evaporation filling of alkali metals was complete, the wafer was transferred from the evaporation chamber to the bonding chamber via a low-water and oxygen transmission channel (water and oxygen content <0.1 ppm), as illustrated in **Figure 13**. As the buffer gas must be sealed within the atomic vapor cell, the magnetometer vapor cell typically requires a nitrogen buffer gas atmosphere with a pressure of 200 Torr [31]. In order to prevent the breakdown of the buffer gas under the aforementioned pressure during the anodic bonding discharge process, it is necessary to bond the silicon side of the pre-bonded structure with the second borosilicate glass at a voltage below 200 V in accordance with Paschen's law. Subsequently, the bonding chamber pressure was reduced to 1×10^{-4} mbar, and a 1000 V voltage was applied to enhance the bonding strength.

Once the hermetic sealing of the atomic vapor cell wafer was completed, its structure was observed and documented (**Figure 14(a)**). The alkali metal elements were clearly visible within the sealed structure. All sample areas of the atomic vapor cell exhibited a high degree of bonding integrity. Finally, the individual atomic vapor cells were separated from one another using mechanical dicing equipment with a diamond wheel (**Figure 14(b)**). Refer to the DEPARTMENT OF DEFENSE TEST METHOD STANDARD ENVIRONMENTAL TEST METHODS FOR MICROCIRCUITS, MIL-STD-883-1, the leak rate of the atomic vapor cell is superior to 1×10^{-9} mbar-L/s.

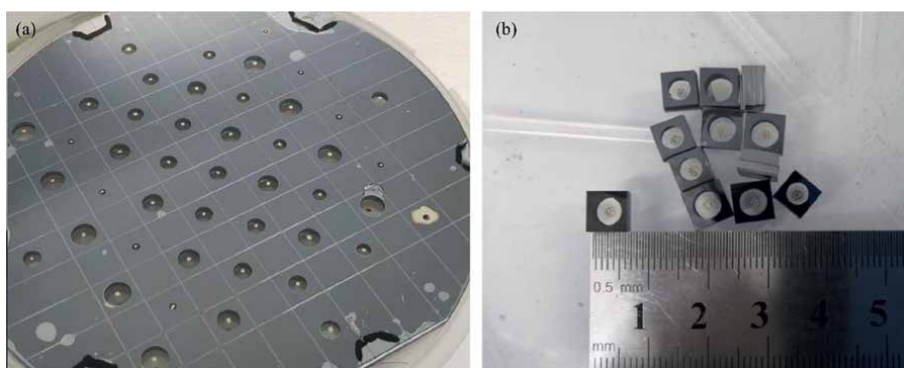


Figure 14.
 (a) 6-inch MEMS vapor cells wafer. (b) sliced MEMS vapor cells.

3.3 Application of MEMS vapor cell magnetic resonance magnetometers

A magnetic resonance magnetometer is employed to ascertain the value of the static magnetic field, designated as B_0 , through the measurement of the Larmor frequency associated with the coherent precession of atomic magnetic moments. In the presence of a magnetic field, circularly polarized laser light transmitted along the z-axis is employed for the optical pumping of alkali metal atoms, thereby polarizing the atomic ensemble between Zeeman sublevels. In the external magnetic field, the macroscopic magnetic moment μ generated by optical pumping interacts with the magnetic field B_0 to produce a torque $\tau = \mu \times B_0$, perpendicular to both μ and B_0 . Under the influence of this torque τ , the magnetic moment undergoes precession around the magnetic field, known as Larmor precession [32]. The precession frequency of the atomic magnetic moment around the magnetic field is the Larmor frequency, denoted as ω_L , which is given by the following equation:

$$\omega_L = \gamma B_0 \quad (1)$$

where γ is the gyromagnetic ratio of the alkali metal (Hz/nT) (**Figure 15**).

If a rotating magnetic field B_1 with a frequency ω is introduced into the system and if the angular frequency ω of B_1 equals the Larmor frequency ω_L , which corresponds to the transition frequency between adjacent Zeeman sublevels, magnetic resonance occurs. Macroscopically, this phenomenon manifests as changes in the intensity of the transmitted light signal. The rotating magnetic field B_1 can be equivalently replaced by a radio-frequency field B_{RF} . By modulating the frequency ω of B_{RF} and monitoring the changes in the intensity of the pump light, the magnitude of the magnetic field B_0 can be determined.

The test system consisted of a heating module, an optical module, a magnetic field module, and a signal acquisition and processing module. The MEMS atomic vapor cell was positioned at the center of the atomic magnetometer sensing system, and the connections between the core component (the atomic vapor cell) and the various modules were illustrated in **Figure 16** [27]. The magnetic field $B_0 = 30 \mu\text{T}$ was applied

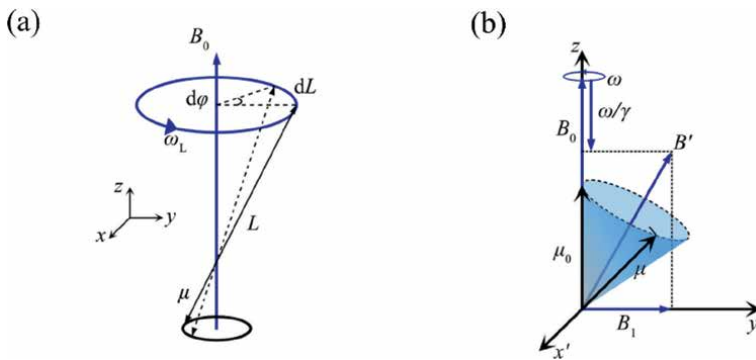


Figure 15. Evolution of alkali magnetic moments in magnetic field (a) Larmor precession of the magnetic moment in the magnetic field B_0 (in the laboratory coordinates system). (b) Evolution of a magnetic moment in the presence of B_0 and rotating magnetic field B_1 (in the rotating coordinate system).

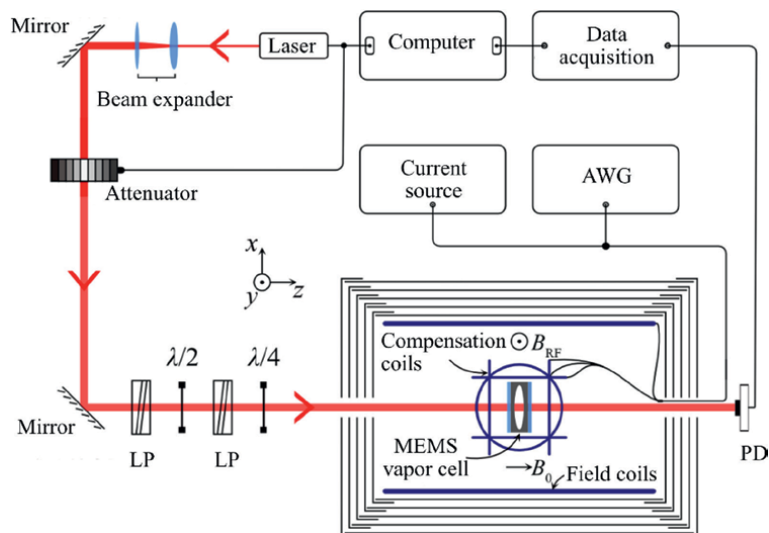


Figure 16.
 Experimental setup for magnetic resonance atomic magnetometer [27].

by a field coil in the magnetic field module, with the current generating the magnetic field driven by a highly stable DC power supply (Keithley 2400SMU). A radio-frequency magnetic field B_{RF} was applied along the y-axis through the field coil of the magnetic field module, and the current generating the radio-frequency magnetic field was driven by an arbitrary waveform generator (AWG, Keysight 33512B). By scanning the frequency B_{RF} of the radio-frequency field B_{RF} within the range of 160 kHz to 260 kHz, the magnetic resonance signal and differential resonance signal of the ^{87}Rb atomic ensemble in the MEMS atomic vapor cell were obtained, as shown in **Figure 17**. The linewidth of the magnetic resonance signal is 1.9 kHz, with a resonance frequency of 209.52 kHz. Using Eq. 1 and the gyromagnetic ratio of ^{87}Rb (6.996 Hz/nT), the calculated B_0 is 29.949 μT , with an error of less than 0.2%, indicating that the developed atomic magnetometer sensing system was capable of performing the basic magnetic field detection functions of an ^{87}Rb atomic magnetometer.

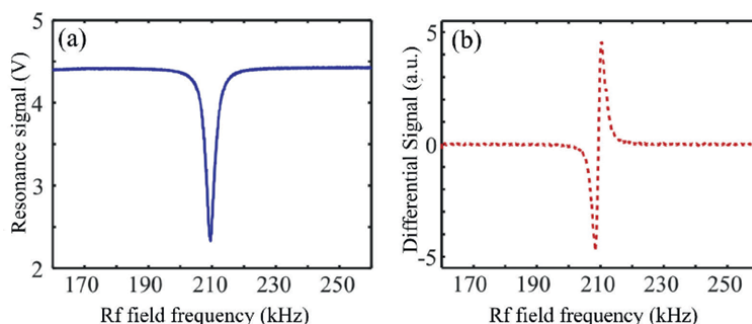


Figure 17.
 Magnetic resonance signal of ^{87}Rb atoms [27]. (a) Magnetic resonance signal (b) Magnetic resonance differential signal.

4. Conclusion

The conclusions drawn from this chapter demonstrate the considerable advances made possible by the utilization of MEMS technology in the fabrication of high-precision optical components. The successful implementation of MEMS techniques, such as DRIE and high-resolution photolithography, has enabled the development of optical devices with enhanced performance, superior miniaturization, and enhanced robustness. This has been demonstrated through the fabrication of high-aspect-ratio MEMS slits, metasurfaces, and atomic vapor cells, all of which have exhibited enhanced accuracy and repeatability. To illustrate, MEMS slits have been demonstrated to achieve a spectral resolution of less than 1 nm, thereby exhibiting exceptional stability across different wavelengths and NFOV. This is a significant improvement over traditional mechanical processing techniques, which often introduce defects and inconsistencies. Moreover, MEMS-based vapor cells have facilitated the advent of novel avenues in quantum sensing applications, offering heightened sensitivity and stability as a consequence of sophisticated bonding techniques and optimized gas sealing. These developments demonstrate the potential of MEMS technology to deliver scalable, mass-producible, and high-precision optical elements for cutting-edge applications in integrated photonics, quantum sensing, and compact spectroscopic systems. It is recommended that future research concentrate on the further refinement of MEMS processes with a view to achieving greater precision and the investigation of novel applications in emerging optical and photonic fields. This would serve to establish MEMS technology as a fundamental element in the development of modern optical devices.

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Flexible MEMS Techniques for Multi-Physical Sensors

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and Junze Li*

Abstract

Flexible microelectromechanical systems (MEMS) represent a promising frontier in advanced micromachining technologies, imparting mechanical flexibility to a wide range of electronic devices. This adaptability positions flexible MEMS at the forefront of innovation in smart wearables, soft robotics, and human-machine interaction. In this chapter, we provide a comprehensive review of flexible MEMS techniques and their applications, with a focus on flexible sensors. Section 1 outlines the research motivations and highlights the key advantages of flexible MEMS. In Section 2, we discuss common flexible materials and detail two principal MEMS fabrication approaches: direct process on flexible substrate (i.e. conventional MEMS process aided by rigid carrier, inkjet printing, laser processing), and transfer printing techniques (i.e. soft lithography, screen printing, transfer processed components from donor carrier to receiver substrate). Section 3 reviews the applications of flexible MEMS in various multi-physical sensors, including those for pressure, strain, temperature, and humidity, as well as integrated multifunctional sensing systems. Lastly, we address the critical challenges facing flexible MEMS sensors and offer perspectives on their future development.

Keywords: flexible MEMS, flexible pressure sensor, flexible strain sensor, flexible temperature sensor, flexible humidity sensor, transfer printing, carrier wafer, inkjet printing, screen printing, soft lithography, laser processing

1. Introduction

Microelectromechanical systems (MEMS) sensors, which convert physical stimuli into measurable electrical signals, have become increasingly vital components in the advancement of wearable electronics, the Internet of Things (IoT), and artificial intelligence [1–3]. Among the various MEMS sensors, such as pressure sensors, strain gauges, and temperature sensors, their role in everyday life continues to grow in importance [4–7]. However, most MEMS sensors are fabricated from silicon or other inorganic semiconductor materials, resulting in mechanically rigid and brittle structures that are unsuitable for flexible applications and smart wearables. The

critical challenge in extending MEMS sensors to flexible scenarios lies in achieving the necessary flexibility and seamless integration into fully flexible systems.

Flexible electronics, which allow circuits and electronic components to maintain functionality during bending or stretching, are poised to revolutionize the electronics industry [8–13]. The rapid development of flexible electronics in recent years has catalyzed the emergence of flexible MEMS technologies, marking a transformative period in sensor technology and enabling novel applications across diverse fields, including healthcare, environmental monitoring, robotics, and wearable electronics [14–18]. These flexible MEMS devices, which integrate miniaturized mechanical and electronic components onto bendable and stretchable substrates, offer unparalleled advantages in versatility, conformability, and functionality. Unlike traditional rigid sensors, flexible MEMS sensors can conform to complex surfaces and endure dynamic mechanical deformations, making them particularly suited for applications requiring intimate contact with irregular or moving surfaces, such as human skin or robotic end-effectors. The ability to maintain performance under bending, stretching, and twisting makes flexible MEMS an ideal candidate for next-generation sensing systems.

This chapter delves into the techniques underlying flexible MEMS, covering the materials, manufacturing methods, and applications in flexible sensors. Initially, we introduce common flexible materials that meet the manufacturing demands of flexible MEMS devices. We then discuss two primary types of flexible MEMS fabrication techniques including direct processing on flexible substrates and transfer printing. Following this, we review exemplary MEMS-based flexible electronics capable of sensing various physical stimuli, including pressure, strain, temperature, and humidity. Finally, we address the critical challenges and provide perspectives on the future development of flexible MEMS sensors.

2. Flexible MEMS techniques

2.1 Flexible materials

The development of high-performance flexible MEMS devices necessitates the use of soft and flexible materials that exhibit high mechanical compliance and favorable electrical properties, while also being amenable to large-area processing. The selection of materials with both high mechanical flexibility and specific adhesion properties is crucial for the successful fabrication of flexible MEMS electronics. In this context, we introduce several common flexible materials utilized in MEMS processing, focusing on both substrates and active layers.

Polyimide (PI) is widely regarded as one of the most promising candidates for flexible MEMS substrates due to its exceptional thermal stability, minimal creep, high mechanical strength, and excellent insulating properties [19]. Additionally, PI demonstrates resistance to weak acids and bases, as well as to commonly used organic solvents such as ethanol and acetone [16]. PI can be categorized into non-photosensitive and photosensitive types, with the latter capable of being micropatterned via lithography. Typically, uncured PI exists as a gel-like liquid, which can be spin-coated onto a carrier wafer and then cured at high temperatures to form a uniform film. However, it is important to note that PI lacks the ability to recover under large strains, which limits its application as a highly stretchable substrate.

Polydimethylsiloxane (PDMS), a type of silicone, is another prominent substrate material for flexible electronics due to its ease of processing, mechanical robustness, high transparency, chemical inertness, biological compatibility, and satisfactory thermal stability [20]. PDMS films exhibit over 95% transmittance in optical bands, stretchability exceeding 100%, and the ability to recover after tension, torsion, or compression, making them a promising candidate for flexible optoelectronics. Surface modifications, such as charge physical adsorption or plasma irradiation, can be employed to create patterns with adhesive or non-adhesive regions on the PDMS surface, enabling the selective bonding of active layer materials. Other materials, including hydrogels, fibers, and commercial synthetic polymers such as polyethylene terephthalate (PET), polyethylene naphthalate (PEN), and polyurethane (PU), are also suitable candidates for flexible MEMS manufacturing [21].

Active layer materials, which are capable of maintaining device functionality during bending or stretching, represent another critical component in flexible electronics. While conventional MEMS processing typically employs metal and semiconductor films, these rigid materials are prone to cracking under large tensile loads, ultimately leading to device failure and limiting their applicability in hyper-stretchable electronics [10]. To address this limitation, nanowires have emerged as a promising building block for active layers in flexible electronics, owing to their excellent mechanical flexibility and electrical properties [22, 23]. Carbon materials such as graphene [24] and carbon nanotube (CNT) [25] have also garnered significant interest for use in flexible electronics due to their intrinsic flexibility, good electrical conductivity, high chemical and thermal stability, and scalability for mass production. Additionally, conductive polymers, including PEDOT:PSS, polypyrrole, and polyaniline, are recognized as outstanding active materials for flexible electronics, thanks to their exceptional mechanical flexibility, lightweight nature, and compatibility with flexible substrates [26]. Notably, conductive polymer composites, formed by mixing an insulating polymer matrix with conductive fillers such as CNTs, graphene, carbon black, metal nanowires, or conductive particles, offer another viable option for flexible MEMS processing [27].

2.2 Direct process on flexible substrate

2.2.1 Conventional MEMS process aided by rigid carrier

Conventional MEMS manufacturing process based on silicon or other semiconductor wafers encompass a suite of techniques such as photolithography [28], etching techniques like wet etching [29] and dry etching (i.e., reactive ion etching (RIE) [30], inductively coupled plasma (ICP) etching [31]), as well as film deposition techniques such as physical vapor deposition (PVD) [32], chemical vapor deposition (CVD) [33], atomic layer deposition (ALD) [34], and electroplating [35]. These methods are complemented by various packaging techniques that ensure the structural integrity and functionality of MEMS devices [36]. A prominent approach in flexible MEMS fabrication involves direct processing on flexible substrates, drawing parallels with traditional MEMS processes. However, the inherent softness and susceptibility to deformation of flexible substrates pose significant challenges for micromachining. To address these issues, rigid carrier wafers, such as those made from silicon or glass, are typically employed to support the flexible substrate during processing. The rigid carrier must adhere robustly to the flexible substrate throughout the fabrication

process, ensuring stability and preventing delamination. The bonded layer between the rigid carrier and the flexible substrate functions as an interlayer or sacrificial layer, facilitating the selective detachment of the flexible MEMS device from the carrier post-fabrication. This interlayer must also exhibit resistance to the corrosive effects of organic solvents, acids, and bases encountered during processing. Here, we detail some typical flexible MEMS techniques, with PI and PDMS substrates serving as exemplars.

In flexible PI MEMS manufacturing, the initial and critical step involves wafer preparation, aided by a rigid carrier. One viable approach is to directly affix a commercial PI film onto a rigid carrier using a bonding layer, thereby mitigating uneven warping of the PI film, as illustrated in **Figure 1a**. For example, Taptimthong et al. employed a silicone adhesive layer resistant to acetone and isopropyl alcohol to bond a PI film to a silicon wafer. Following MEMS processing, the bonding layer was chemically etched or softened using a xylene-based solvent such as Roticlear®, enabling the fabricated flexible PI device to be peeled off from the carrier wafer [37]. Another method involves spin-coating uncured PI liquid onto a rigid carrier and curing it into a film. To facilitate the detachment of the final PI-based device from the supporting carrier, a sacrificial layer such as SiO₂, nickel, or aluminum, must be deposited on the carrier wafer before spin-coating with PI liquid. This sacrificial layer can be selectively removed through wet etching using an appropriate chemical reagent after MEMS processing, as depicted in **Figure 1b**. It is crucial to apply a photoresist layer to the device's front side during the wet etching of the sacrificial layer to protect the circuit from corrosion. Building on this approach, Lim et al. utilized a SiO₂ sacrificial layer and wet etching with buffered oxide etch solution to develop a flexible PI-based microchannel electrode array device for selective subdiaphragmatic vagus nerve recording [38].

The lift-off process is a key approach in surface micromachine for MEMS manufacturing [39]. However, the application of this process to PDMS substrates is challenging, as PDMS tends to swell when immersed in acetone, a solvent commonly used in traditional lift-off processes to etch photoresist [40]. This swelling behavior limits the compatibility of PDMS with conventional lift-off methods. To address this limitation, water-soluble sacrificial layers, such as poly(acrylic acid) (PAA) and Dextran, have been successfully employed in the PDMS-based lift-off process [41].

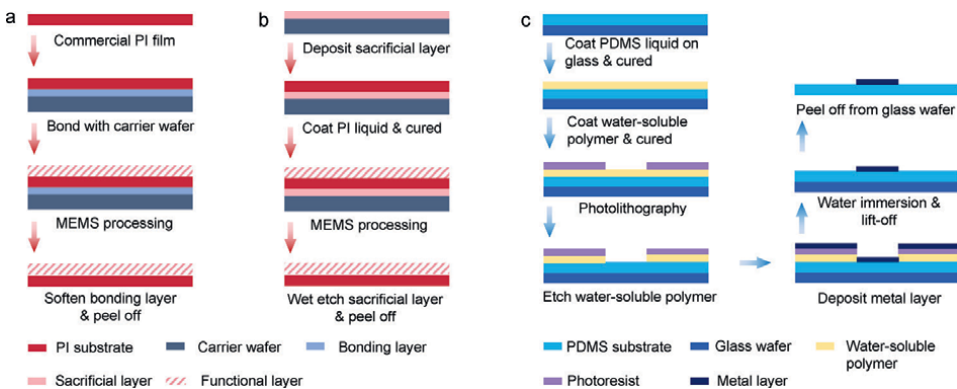


Figure 1. (a) Direct process based on commercial PI film bonded on carrier wafer. (b) Process based on cured PI and wet etch sacrificial layer. (c) Water-soluble lift-off process on PDMS substrate.

Figure 1c shows this process flow diagram. Initially, liquid PDMS is spin-coated onto a glass carrier wafer and cured to form a uniform film. Subsequently, a water-soluble polymer is spin-coated and cured on top of the PDMS film. After the photolithography step, the exposed areas of the water-soluble polymer are dry-etched to create the desired pattern. A metal layer is then deposited onto the wafer surface. Immersion in water dissolves the sacrificial layer, leaving behind the patterned metal layer. Finally, the PDMS-based device is carefully peeled off from the glass wafer using tweezers. For instance, Guo and DeWeerth developed an effective lift-off method using PAA as a sacrificial layer to pattern high-density gold interconnects on a PDMS substrate [42]. The resulting parallel traces, 10 μm wide with a 20 μm pitch, exhibited excellent electrical properties and could withstand longitudinal tensile strains ranging from 1–2%. It is important to note that silicon wafers are not recommended as carrier substrates in this context, as cured PDMS adheres strongly to silicon, making it difficult to peel off without the use of additional sacrificial interlayers and chemical etching methods.

2.2.2 Inkjet printing

Inkjet printing is a material-efficient deposition technique that utilizes liquid-phase materials, or inks, composed of solutes dissolved or dispersed in a solvent. Inkjet printing techniques can be divided into thermal inkjet printing [43], piezoelectric inkjet printing [44], aerosol jet printing [45], and electrohydrodynamic jet printing [46]. Fundamentally, the ink is propelled through a nozzle by the action of heat or piezoelectric forces, generating droplets of uniform size and velocity. These droplets are then directed toward the substrate surface at a specific initial speed, influenced by gravity and air resistance. Upon contact with the substrate, the droplets spread under the influence of kinetic energy and surface tension, forming defined shapes on the substrate surface. As the solvent evaporates, the droplets solidify, leaving behind the desired pattern. As an emerging fully digital MEMS fabrication process, inkjet printing enables the direct, precise, and repeatable deposition of functional materials onto various flexible substrates, allowing for the formation of specific shapes and structures without the need for photomasks, stencils, or other auxiliary equipment. This approach offers significant advantages in flexibility and material conservation, making it a promising technique for advanced MEMS manufacturing.

Inkjet printing, while advantageous in certain respects, does not achieve the same level of dimensional precision as traditional MEMS fabrication techniques based on lithography and silicon micromachining. The horizontal resolution of patterns produced by inkjet printing is inherently lower than that achievable through photolithography, and the control over layer thickness is less precise than that afforded by physical or chemical vapor deposition methods. Despite these limitations, inkjet printing offers significant benefits over conventional micromachining, including higher time efficiency, reduced costs, and superior compatibility with soft substrates. These attributes position inkjet printing as a leading method for the fabrication of flexible printed electronics. Through inkjet printing technology, a diverse range of inks such as conductive, insulating, sacrificial, piezoelectric, and two-dimensional materials, can be deposited to manufacture flexible MEMS devices [47]. **Figure 2a** shows the process flow of the inkjet printing for micropatterns. Initially, the flexible substrate, supported by a rigid carrier wafer, undergoes pre-treatment steps such as dust cleaning, preheating, drying, and plasma treatment. Next, inkjet printing is employed to deposit the functional layer with the desired pattern onto the flexible

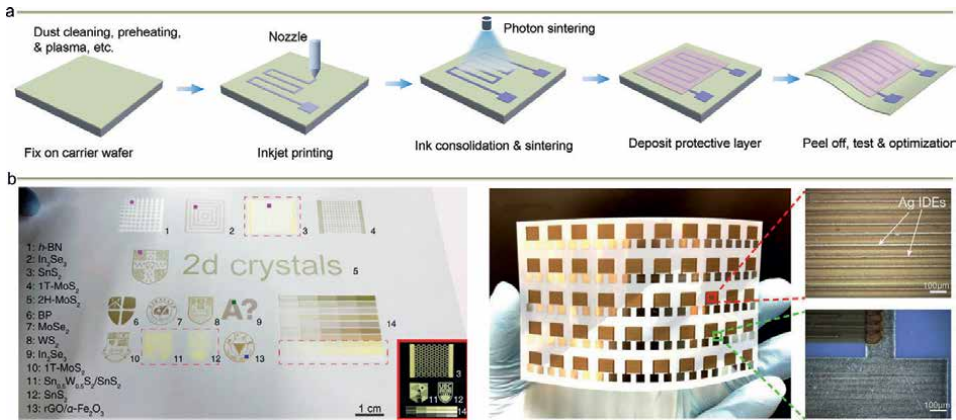


Figure 2. Inkjet printing. (a) A typical process flow of inkjet printing to produce micropatterns. (b) A general ink formulation of different 2D crystals on PET substrate. Reproduced from [48] under the terms of CC BY 4.0.

substrate. Following deposition, ink consolidation is achieved by evaporating the organic solvent from the droplets. After the curing step, while some inks can be used after drying at room temperature, most require additional sintering processes such as thermal, photonic, electrical, plasma, or chemical sintering, to achieve the final conductive structures or functional properties. Once a protective layer is applied to the printed patterns, the flexible device is carefully peeled off from the carrier wafer for subsequent performance testing and optimization. Recently, Hasan and co-workers introduced a binary solvent ink formulation that leverages a novel drying mechanism based on Marangoni-enhanced spreading [48]. This innovative formulation facilitates uniform deposition of various 2D crystals and their derivatives on flexible substrates, as shown in **Figure 2b**, thereby enabling scalable and even wafer-scale flexible MEMS manufacturing processes.

2.2.3 Laser processing

Laser processing utilizes the interaction between laser beams and material surfaces to achieve micromachined manufacturing. Depending on the mode of operation, laser sources can be categorized into continuous wave and pulsed modes. Continuous wave lasers are known for their effective coherence and stable beam profiles, although their energy output tends to be relatively low [49]. In contrast, pulsed lasers deliver bursts of energy with durations ranging from microseconds to femtoseconds, resulting in high instantaneous power that induces localized superheating followed by rapid self-quenching [50]. The adaptability of computer-controlled laser processing allows for quick turnaround times, enhanced accuracy, and cost-effectiveness. This non-contact and clean processing method provides precise control over shape, size, and print registration, making it increasingly favored in the production of flexible electronics.

To date, many laser processing techniques such as laser cutting, laser drilling, laser pyrolysis, laser oxidation, laser sintering, and laser ablation, etc., have been employed for micromachining directly on flexible materials to manufacture MEMS devices via maskless and digitally programmable routes. For instance, Bai et al. fabricated flexible strain sensors of copper electrodes by using laser direct writing method for

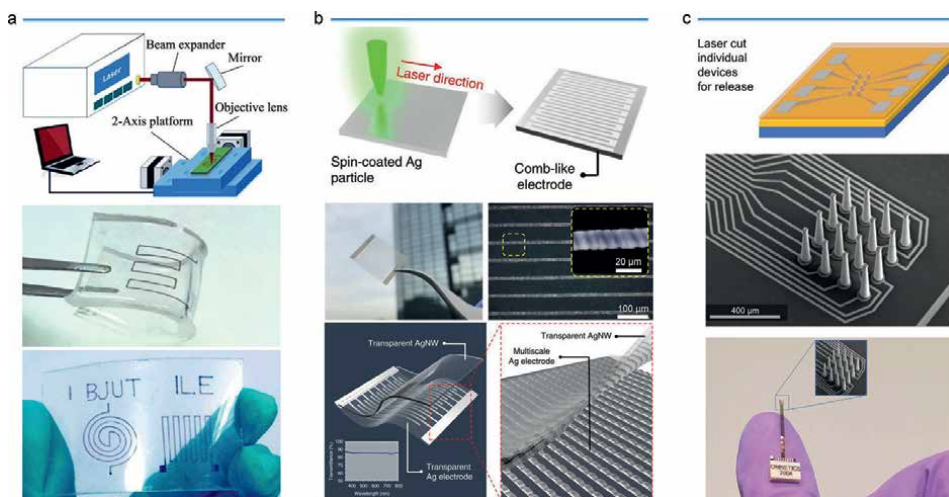


Figure 3.
 Laser processing. (a) Schematic diagram of the laser processing setup, and different processed patterns on flexible substrate. Reproduced from [51] under the terms of CC BY 4.0. (b) Laser induced transparent Ag interdigital electrode for 3D touch. Reproduced from [52] under the terms of CC BY 4.0. (c) Direct laser writing of 3D electrodes on flexible substrates. Reproduced from [53] under the terms of CC BY 4.0.

health monitoring [51]. By programmatically controlling the movement of the platform, various patterns were created using laser writing, as illustrated in **Figure 3a**. Similarly, Kim et al. developed a transparent interdigital silver electrode by selectively converting silver particles into continuous micro-comb-shaped metal patterns with a 100 μm interval and 20 μm width using laser processing (**Figure 3b**). By integrating transparent silver nanowire films, they created a transparent and flexible touch system capable of sensing 3D information within a single device, facilitated by functionally designed self-generated multiscale structures [52]. More recently, Gardner et al. introduced a rapid direct laser writing technique for fabricating 3D electrodes on flexible wafer-scale substrates (**Figure 3c**) [53]. The resulting 3D structures exhibit a high aspect ratio, with electrodes reaching 350 μm in height and 20 μm in diameter at the recording tip. These electrodes successfully captured electrophysiological signals from both birds and mice, demonstrating the potential of laser processing in advanced flexible MEMS applications.

2.3 Transfer printing

2.3.1 Soft lithography

Soft lithography, a term originally defined by Xia and Whitesides [54], encompasses a suite of rapid microfabrication techniques that utilize elastomeric materials to form patterns through the molding of a master template. This approach facilitates the creation of three-dimensional structures on flexible substrates and enables the generation of well-defined and controllable surface chemistries. Notably, soft lithography is cost-effective, experimentally straightforward, and has become a valuable tool in the fabrication of flexible MEMS devices. The process of soft lithography can be broadly divided into two stages: the fabrication of the template and its subsequent use in molding patterned structures onto a flexible elastomer. Templates are typically

produced through conventional photolithography and etching methods, although natural materials with unique microstructures, such as flowers and leaves, have also been explored as potential templates. Here, we focus on two of the commonly used soft lithographic techniques: replica molding and microcontact printing.

In replica molding, an uncured liquid polymer is poured into a microstructured template, and after curing, the polymer is peeled off, resulting in a structure that mirrors the template (**Figure 4a**). To facilitate the removal of the polymer from the template, a release agent or plasma treatment is often applied to the template's surface. In cases where a structure similar to the original template is desired, a second molding process is employed using the complementary structure obtained from the first molding. For example, our group has previously reported the fabrication of a micro-cone ionic gel using double replica molding from the leaf of *Calathea zebrina* as a biological template. This gel serves as the dielectric layer in a highly sensitive flexible iontronic sensor (**Figure 4b**) [55]. Similarly, Chen et al. utilized conventional photolithography and etching to create a silicon mold with micropyramid-shaped grooves. By coating the mold with a CNT/PDMS ink, curing it, and then peeling off the cured material, they produced a CNT/PDMS composite film with two-stage micropyramid arrays (**Figure 4c**), which was subsequently employed in pressure sensor applications [56].

Microcontact printing is an exceptionally appealing and robust transfer technique that leverages the inherent advantages of soft lithography, including its ease of process and the use of inexpensive equipment, to create precise patterns over large surface areas. This method ensures high fidelity in pattern transfer, owing to the conformal contact between the substrate and the raised features of the stamp. The process flow for microcontact printing is illustrated in **Figure 4d**. Initially, a PDMS stamp is fabricated by molding it against a silicon template, following the principles of replica molding. The stamp is then coated with a functional ink before being pressed onto the flexible target substrate, thereby transferring the ink in a micropatterned form onto the substrate. An illustrative example of this technique is provided

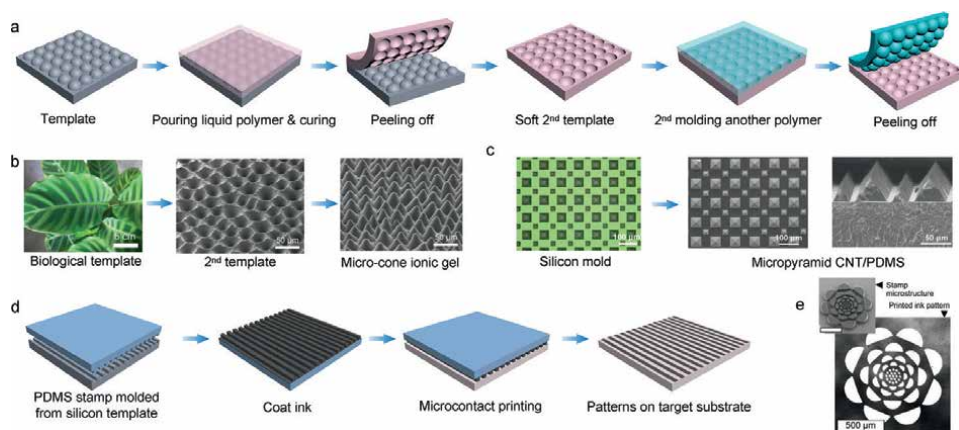


Figure 4. Soft lithography. (a) Process flow of first replica molding for inverse structure, and second replica molding for positive structure as original template. (b) Images of molding the micro-cone ionic gel from *Calathea Zebrine* leaf. Reprinted with permission from [55]. Copyright (2018) WILEY-VCH. (c) CNT/PDMS film with micropyramid arrays molded from a silicon template. Reproduced with permission from [56]. Copyright (2024) ACS Publications. (e) Process flow of microcontact printing technique. (f) SEM images of a stamp microstructure and printed ink pattern. Reproduced from [57] under the terms of CC BY 4.0.

by Kim et al., who developed an ultrathin, high-resolution flexographic microcontact printing process using nanoporous stamps (**Figure 4e**) [57]. The resulting printed patterns exhibit remarkably uniform nanoscale thicknesses, ranging from 5 to 50 nm, and display high-fidelity replication of the stamp features, with an edge roughness of approximately 0.2 nm. This technique achieves continuous printing at a speed of 0.2 m/s, offering a combination of resolution and throughput that significantly exceeds the capabilities of conventional industrial printing technologies.

2.3.2 Screen printing

The origins of screen printing can be traced back to China in 960 CE, when it was used to apply intricate patterns to textiles using colored inks [58]. This historical technique has since inspired the development of functional inks, including conductive inks and sensing layers, for various applications. The fundamental principle of screen printing involves transferring ink from a patterned mesh on a screen onto a target substrate. As illustrated in **Figure 5a**, the process begins with the alignment of the flexible substrate on a carrier wafer, ensuring precise registration with the screen. Ink is then pushed through the mesh using a squeegee, which applies pressure to deposit the ink in the desired pattern onto the substrate. After printing, the substrate undergoes curing and additional processing to solidify the patterned ink layer. Several factors influence the quality of the final print, including the properties of the ink (such as viscosity, thixotropy, and conductivity), the characteristics of the screen (including mesh count, line diameter, and material), the squeegee parameters (speed, angle, and type), and the pre-treatment of the substrate. These variables collectively determine the accuracy and effectiveness of the screen-printing process.

Screen printing has emerged as a pivotal transfer printing technique for the fabrication of flexible electronics, significantly reducing production costs and enhancing manufacturing efficiency. For instance, Fukuda et al. demonstrated fully screen-printed organic thin-film transistor devices and circuits on 1-mm-thick

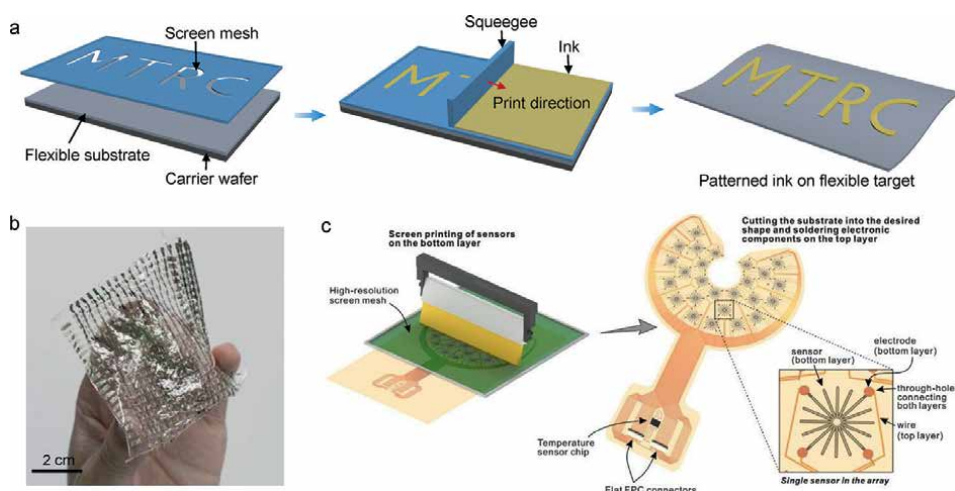


Figure 5. Screen printing. (a) Schematic process flow of screen printing. (b) Photographs of screen-printed organic thin-film transistors. Reproduced from [59] under the terms of CC BY 4.0. (c) Schematic of screen-printed flexible sensor array on flexible circuit board. Reproduced from [60] under the terms of CC BY 4.0.

polyethylene-C films over large areas, as depicted in **Figure 5b**. Remarkably, these devices maintained stable performance even under 50% compression strain [59]. Similarly, Chang et al. developed a large-area flexible sensor array on a PI substrate, measuring $150 \times 150 \text{ mm}^2$, utilizing screen printing. This approach underscores the method's cost-effectiveness and potential for high-throughput production in flexible electronics applications [61]. In a further advancement, Zymelka et al. introduced a novel concept by arranging thin-film strain sensors in a concentric layout on a flexible polyethylene naphthalate (PEN) substrate via screen printing [60]. All the sensors in the array are integrated onto a flexible circuit board with a specially designed shape, which makes the developed devices inexpensive and easy to install quickly.

2.3.3 Transfer processed components from donor carrier to receiver substrate

The most common form of transfer printing employs a soft, elastomeric stamp to mediate the physical transfer of processed components from a donor carrier wafer to a secondary receiver substrate [62–64]. **Figure 6a** illustrates the schematic flow of this transfer printing technique. In preparation for transfer printing, MEMS components are first fabricated on a donor carrier wafer, typically made of silicon or glass, using conventional MEMS processes. The stamp is then brought into contact with the donor substrate, where it picks up the processed components. Subsequently, the stamp, now bearing the MEMS devices, is aligned with the receiver substrate to print the components onto the new surface. It is worth noting that some components require only a single transfer printing step, in which the flexible stamp itself serves as the final receiver substrate [67, 68].

In order to effortlessly pick up the processed components from the donor carrier, sacrificial layer such as metal film [65, 67], PAA [69], and silk fibroin [64], is needed to be introduced between the substrate and MEMS devices. This method, which involves etching the sacrificial layer to achieve delamination, is commonly referred to as wet transfer printing. For example, Liu et al. developed a

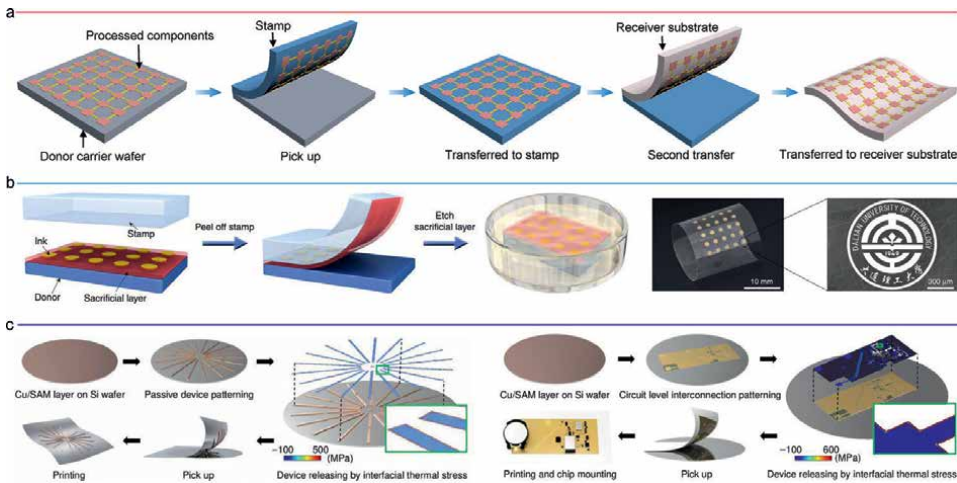


Figure 6. Flexible transfer of the processed MEMS devices. (a) Schematic process flow of transfer printed components from donor carrier to receiver substrate. (b) Wet transfer release by etching sacrificial layer, and the transferred logo patterns. Reproduced from [65] under the terms of CC BY 4.0. (c) Dry transfer release by interfacial thermal stress. Reproduced from [66] under the terms of CC BY 4.0.

straightforward transfer printing method by dissolving the PAA sacrificial layer, enabling the transfer of gold patterns from a silicon wafer to a PDMS substrate [69]. They further advanced the technique by introducing nanoscale ink transfer printing [65]. In this method, patterned ink is processed on a copper sacrificial layer deposited on a PMMA donor carrier. A 3 M Scotch tape, used as the stamp, picks up the patterned ink along with the sacrificial layer from the donor substrate. The stamp with the transferred ink is then obtained by wet etching the copper sacrificial layer, as depicted in **Figure 6b**.

However, wet transfer printing is not without its limitations, particularly in terms of product quality, as issues such as displacement and shape distortion can arise due to uncontrollable fluid movement and slow chemical diffusion. To address these challenges, dry transfer printing techniques have been developed, offering reliable and instantaneous release of devices from the donor substrate. For instance, Heo et al. reported an efficient dry transfer printing method that utilizes atomic diffusion control at heterogeneous interfaces [66]. By exploiting the differences in the coefficients of thermal expansion between dissimilar adjacent materials, processed patterns and microdevices can be easily picked up under the influence of interfacial thermal stress (**Figure 6c**). More recently, Shin et al. proposed a non-destructive dry transfer printing strategy based on stress-controlled metal bilayer films during magnetron sputtering [70]. This method successfully transferred metal films and high-temperature treated compound films onto flexible or stretchable substrates, enabling the fabrication of two-dimensional flexible electronic devices and three-dimensional multifunctional devices.

3. Applications in flexible multi-physical sensors

3.1 Flexible pressure sensor

Pressure, defined as the ratio of force to the area over which it is applied, is a fundamental parameter in both natural phenomena and human societal functions. Flexible pressure sensors, which transduce mechanical pressure into measurable electrical signals, are instrumental in various applications due to their ability to operate across a wide range of pressure regimes, including ultra-low (<1 Pa), low (1–10 kPa), medium (10–100 kPa), and high pressures (>100 kPa). These sensors have found widespread use in fields such as wearable technology, soft robotics, clinical diagnostics, and human-computer interaction, owing to their unique ability to detect and respond to pressure changes across these ranges [71–73]. For practical applications, an ideal flexible pressure sensor must satisfy key performance criteria, including high sensitivity, broad detection range, linearity, rapid response time, and durable stability. To meet these demands, extensive research efforts in flexible MEMS technologies have focused on the development of novel materials, innovative sensing mechanisms, and advanced fabrication techniques.

One widely adopted approach to enhancing sensor sensitivity involves the engineering of microstructures within the functional materials. Microstructures such as micropylamids [74, 75], biomimetic microstructures [55, 76], porous structures [77], interlocked microstructures [78], and sandpaper microstructures [79, 80] in functional materials have demonstrated significant potential in amplifying electrical responses to subtle external pressures. For example, the Bao group pioneered the use of micropylamid arrays as a microstructured rubber dielectric layer in the

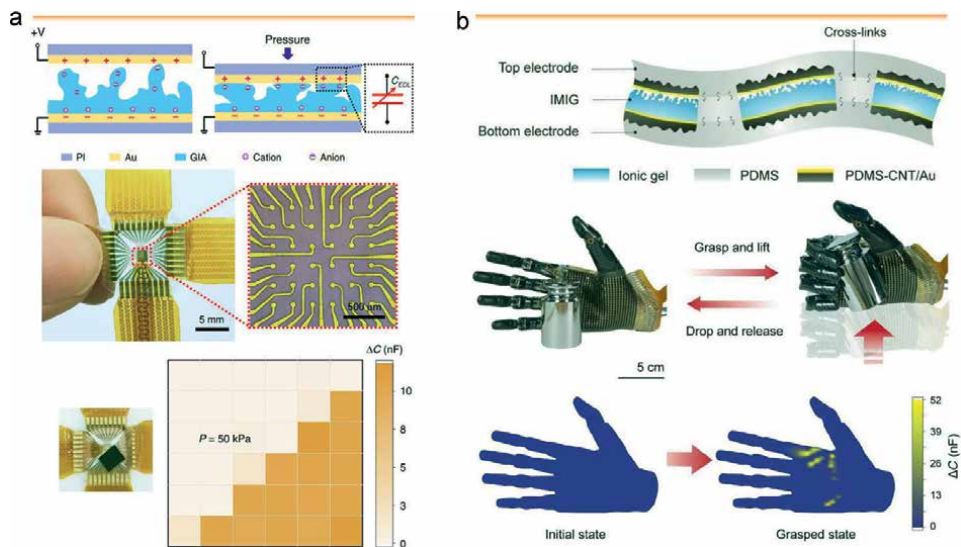


Figure 7. Applications in flexible pressure sensors. (a) Structure of the iontronic pressure sensor, micro sensor array and its demonstration in pressure distribution mapping. Reproduced from [79] under the terms of CC BY 4.0. (b) Embedment of sensing elements for robotics applications. Reproduced from [80] under the terms of CC BY 4.0.

development of a highly sensitive flexible capacitive pressure sensor [75]. This sensor, fabricated using a silicon mold processed through photolithography and wet etching, was capable of detecting the minute pressure exerted by a fly landing on its surface. In another advancement, Guo et al. designed a highly sensitive iontronic pressure sensor with a graded intrafillable architecture, achieving a sensitivity of over 220 kPa^{-1} across a 360 kPa range [79]. This sensor, manufactured using soft photolithography and lift-off techniques, features a 6×6 micro sensor array composed of microelectrodes and a microstructured ionic gel film, making it suitable for pressure distribution mapping (**Figure 7a**). To address the issue of array crosstalk, the group later introduced a highly stable iontronic sensor array, enhanced through laser processing and chemical bonding techniques [80]. By employing laser drilling to create numerous holes in a PDMS interlayer for embedding an ionic gel layer, and using laser-cut CNT-PDMS/Au film to form the circular electrode array, they achieved a robust, highly sensitive, and crosstalk-free sensing system (**Figure 7b**). The chemical bonding process ensured the secure integration of the independent ion gel units with the PDMS spacer and encapsulation layers, resulting in a 28×28 sensor array with potential applications in robotic manipulation and object recognition, boasting a recognition accuracy of 99.5%.

3.2 Flexible strain sensor

Strain, a fundamental physical quantity in mechanics, represents the relative displacement between particles in a material under external force, typically denoted as ϵ , that is, $\epsilon = \Delta L/L_0$. This dimensionless measure, often expressed as a percentage or in microstrain ($\mu\epsilon$), is crucial for understanding material deformation. Flexible strain sensors, which convert mechanical deformations into electrical signals, have garnered significant attention due to their wide-ranging applications

in structural health monitoring, motion detection, and human healthcare. Recently, these sensors have also shown promise as artificial sensory skin for soft robotics, enabling robots to interact dynamically with their environment, including humans.

Flexible strain sensors generally consist of active sensing elements affixed to a soft, elastic substrate. Advances in novel materials and MEMS manufacturing techniques have revolutionized the design and functionality of these sensors, making them adaptable to various applications. For example, Li et al. developed a flexible constant strain sensor using a lift-off process and laser cutting, featuring a serpentine sensing pattern and a sandwich packaging structure [81]. The resulting device exhibited large sensing ranges, high gauge factors, and excellent repeatability and linearity in electrical responses, making it suitable for ground tests during Tianwen-1, China's inaugural Mars exploration mission (**Figure 8a**). Similarly, Zymelka et al. created a low-cost Wheatstone-bridge strain sensor array via screen printing, which was successfully deployed in structural health monitoring of a highway bridge in one of Japan's largest cities. This system accurately detected and localized cracks in the bridge structure (**Figure 8b**) [60]. Beyond engineering applications, flexible strain sensors are also poised to make significant contributions to biomedical and wearable electronics. Rogers's group, for instance, reported a tissue-on-chip system integrated with compliant 3D frameworks and strain sensors [82]. This system not only measured motion but also accurately gauged contractile forces with high temporal resolution, enabling detailed characterization of millimeter-scale engineered muscle tissues (**Figure 8c**). In another innovative example, Tao et al. developed a flexible strain sensor based on laser-induced graphene, offering advantages such as one-step fabrication and high efficiency [83]. This sensor, capable of both generating and detecting sound, holds potential as an intelligent artificial throat (**Figure 8d**), a breakthrough that could profoundly assist individuals with speech disabilities.

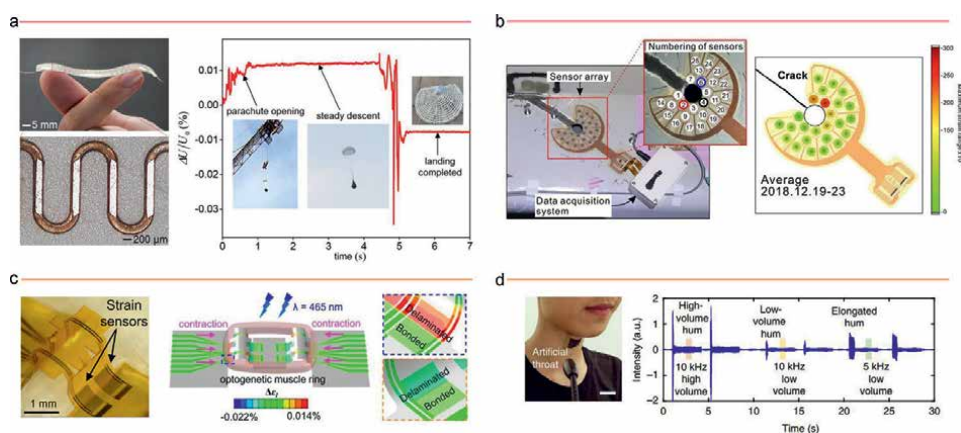


Figure 8. Applications in flexible strain sensors. (a) A flexible constant strain sensor, and its application in parachute monitoring. Reprinted with permission from [81]. Copyright (2022) ACS Publications. (b) Screen-printed sensors array for structural health monitoring of a bridge. Reproduced from [60] under the terms of CC BY 4.0. (c) Flexible strain sensor for characterization of millimeter-scale engineered muscle tissues. Reproduced from [82] under the terms of CC BY 4.0. (d) Strain sensor-based artificial throat with sound-sensing ability. Reproduced from [83] under the terms of CC BY 4.0.

3.3 Flexible temperature sensor

Temperature, a fundamental and widely measured physical quantity, exhibits temporal and spatial variations that are critical for monitoring environmental conditions and physiological activities. Temperature sensors, which transduce these variations into electrical signals, represent the largest segment of the sensor market by volume. Notably, many other sensors, such as those measuring humidity, pressure, flow, strain, and gas concentration, are temperature-dependent, necessitating the integration of temperature sensors to compensate for thermal fluctuations [84]. Recent advancements in flexible temperature sensors, driven by innovations in flexible MEMS techniques, have enabled large-area fabrication, marking a significant trend in the field. For instance, Xiao et al. introduced a novel wafer-scale PI MEMS process to develop highly sensitive flexible temperature sensors [85]. Unlike traditional methods that rely on wet etching sacrificial layers between the carrier wafer and flexible electronics, their approach employs PDMS as an interlayer, allowing for direct peeling of the flexible PI-based temperature sensor after micromachining the Pt/TiW sensing layer and passivation layer. The resulting device exhibits a high-temperature coefficient of resistance (TCR) of 2800 ppm/°C.

Temperature sensing provides critical information about external environments. For example, highly accurate flexible multifunctional sensor sheets with a TCR of $0.97 \pm 0.62\%/^{\circ}\text{C}$ have been developed for efficient thermal management systems [86]. These sensors can dynamically monitor air flow and visualize large-scale airflow distribution on curved surfaces (Figure 9a). In the realm of health monitoring, precise body temperature measurements can aid in disease diagnosis, accident prevention,

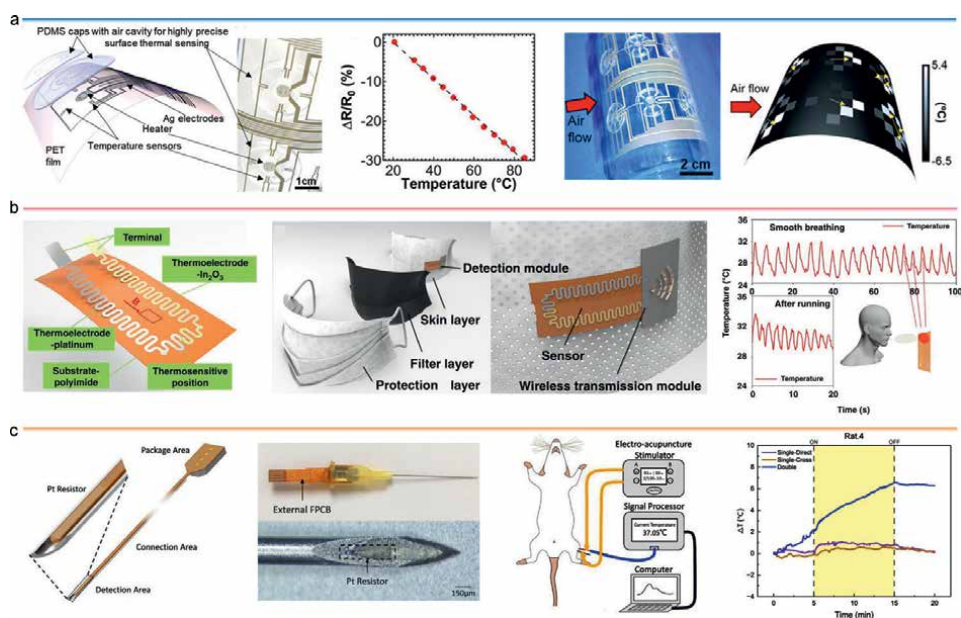


Figure 9.

Applications in flexible temperature sensors. (a) Highly precise temperature sensor array for thermal management. Reprinted with permission from [86]. Copyright (2019) ACS Publications. (b) A thin-film temperature sensor that can be integrated with mask for respiratory monitoring. Reproduced from [87] under the terms of CC BY 4.0. (c) A Pt microsensor integrated at the needle tip for in situ acupoint temperature monitoring. Reproduced from [88] under the terms of CC BY 4.0.

and environmental assessments. Ren et al. developed a flexible three-dimensional microsensor combining platinum and indium oxide to form a thermocouple using flexible MEMS processes [87]. Such a flexible sensor can be integrated into a mask to monitor human respiratory patterns during physical activity (**Figure 9b**). Recently, Li et al. proposed a flexible Pt thermistor temperature sensor that can be integrated at the needle tip and mass-produced on silicon wafers via flexible MEMS technique [88]. Operating within 30–50°C range, the sensor demonstrates a sensitivity of 5.00 $\Omega/^{\circ}\text{C}$, a nonlinearity of $\pm 0.39\%$ FS, and a repeatability error of $\pm 2.62\%$ FS. Significantly, this sensor has been applied to in vivo acupoint temperature monitoring in rats (**Figure 9c**), highlighting its potential for future research in acupoint temperature analysis.

3.4 Flexible humidity sensor

Humidity, a critical physical parameter that quantifies the concentration of water vapor in a gas, plays a vital role across diverse domains, including industrial manufacturing, agriculture, meteorology, national defense, and healthcare. Humidity is commonly measured in two ways: absolute humidity, which quantifies the water vapor content within a specific volume, and relative humidity (RH), defined as the ratio of the current water vapor pressure to the pressure required for saturation at a given temperature, typically expressed within a range of 0–100% RH. An ideal humidity sensor should possess attributes such as ease of fabrication, high sensitivity, rapid response time, linearity, minimal hysteresis, high reproducibility, low cost, scalability for mass production, long-term stability, and minimal temperature drift.

The diverse environmental demands for humidity measurement have spurred significant advancements in device architecture, material innovation, and flexible MEMS manufacturing techniques [89]. For instance, Alonso et al. achieved wafer-scale integration of all-graphene humidity sensors through water-based solution processing [90]. These sensors, manufactured on 4-inch silicon and PET wafers, are flexible, transparent, and compatible with contemporary complementary metal-oxide-semiconductor (CMOS) and roll-to-roll processes (**Figure 10a**). In another development, Xuan et al. proposed a high-performance flexible Lamb wave humidity sensor, employing graphene oxide as the sensing layer on a piezoelectric ZnO film deposited on flexible polyimide substrates (**Figure 10b**) [91]. Remarkably, the sensor maintained its performance even under severe bending conditions of up to 1500 μe . In practical applications, flexible humidity sensors have demonstrated utility in non-contact physiological monitoring. For example, a sensor based on a bio-inspired, atomically precise tunable graphene-polymer heterojunction exhibited high sensitivity across a wide RH range (0–97%), enabling real-time recording of humidity fluctuations during speech and respiration [92]. This capability allows for detailed speech feature analysis and accurate monitoring of respiration rates (**Figure 10c**). Recently, a thin-film GaN-based humidity sensor was fabricated via magnetron sputtering, with inkjet-printed interdigitated electrodes atop the GaN sensing layer [93]. This design achieved an enhanced sensitivity of 8.53 nF/% RH across a 0–100% RH range. The sensor demonstrated its potential as a low-cost platform for real-time monitoring applications by effectively assessing the transpiration cycle of plants through water level monitoring directly attached to leaves, without damaging meat strip freshness, underscoring its future potential in flexible electronics.

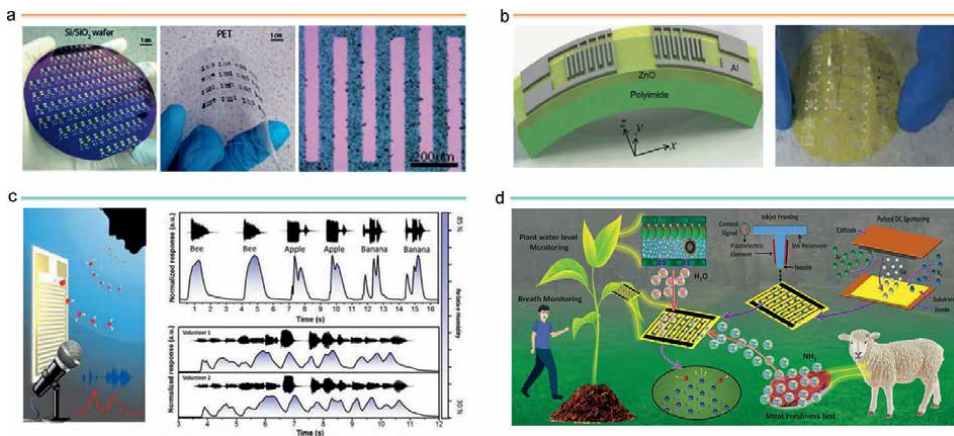


Figure 10.

Applications in flexible humidity sensors. (a) Wafer-scale integration of all-graphene humidity sensors, and being transferred onto flexible PET substrate. Reproduced from [90] under the terms of CC BY 4.0. (b) A flexible humidity sensor based on Al electrodes and piezoelectric ZnO thin films. Reproduced from [91] under the terms of CC BY 4.0. (c) Application demonstration of humidity fluctuation information for voiceprint recognition anticounterfeiting. Reprinted with permission from [92]. Copyright (2018) ACS Publications. (d) A flexible GaN humidity sensor processed via magnetron sputtering and inkjet printing, and its application concept diagram. Reproduced from [93] under the terms of CC BY 4.0.

3.5 Integrated multifunctional sensing system

The advent of IoT technologies has revolutionized modern society by seamlessly integrating billions of objects equipped with sensors, processors, and actuators, enabling these systems to interact and adapt to stimuli in a dynamic manner [94]. Despite these advancements, traditional flexible sensor platforms remain limited, typically comprising only one or two sensing modules, along with data processing units and power supplies. This limitation renders them insufficient to meet the increasingly complex demands of IoT applications. Consequently, there is growing interest in the development of flexible and wearable multifunctional sensing systems capable of simultaneously distinguishing and responding to a variety of stimuli from the environment, including pressure, strain, temperature, and humidity. These systems are particularly appealing due to their high stretchability, low cost, lightweight nature, and exceptional biocompatibility.

The rapid progress in novel sensing materials, flexible MEMS fabrication techniques, and innovative electronic configurations have greatly advanced the integration of multifunctional sensor systems. These integrated systems can conform to irregular surfaces, converting surface deformations into electrical signals, thus demonstrating significant potential in applications such as electronic skins, health monitoring, human-machine interaction, and intelligent prosthetics. For example, For instance, Wang et al. developed a multifunctional sensing system featuring skin-inspired, highly stretchable, and conformable matrix networks, as illustrated in **Figure 11a**. This system extends the capabilities of electronic skin to include, but not be limited to, sensing pressure, plane strain, temperature, humidity, light, magnetic fields, and proximity. It also enables simultaneous multi-stimulus detection, adjustable sensing ranges, and large-area expandability [95]. Similarly, Kim and collaborators created a stretchable silicon nanoribbon-based multifunctional electronic system, equipped with ultrathin, single-crystalline silicon nanoribbon

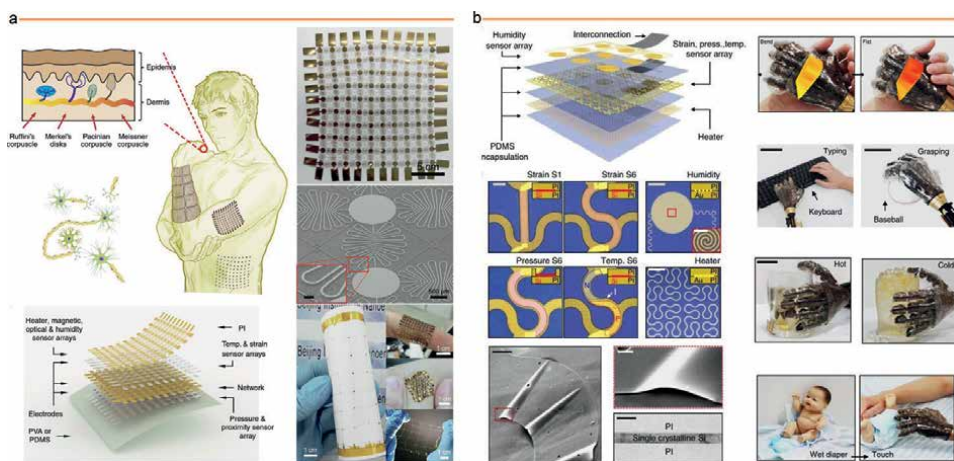


Figure 11. Applications in flexible multifunctional sensing system. (a) Skin-inspired highly stretchable and conformable matrix networks for multifunctional sensing. Reproduced from [95] under the terms of CC BY 4.0. (b) Flexible integrated sensing electronics for skin prosthesis. Reproduced from [96] under the terms of CC BY 4.0.

sensors for strain, pressure, and temperature, along with humidity sensors, electro-resistive heaters, and stretchable multi-electrode arrays for nerve stimulation [96]. This integrated system functions as a smart prosthesis, endowing artificial skin with sensory capabilities to respond to diverse external environments, such as hand-shakes, typing, grasping, and baby care, as depicted in **Figure 11b**. Recently, Gao's team employed a scalable inkjet-printing approach to develop a physicochemical-sensing electronic skin system with robust, long-term sensing capabilities for stress response monitoring [97]. Enhanced by a machine learning pipeline, this system enables multiplexed, non-invasive monitoring of critical stress-related physiological signals such as pulse waveform, galvanic skin response, and skin temperature, as well as electrolytes (Na^+ , K^+ , and NH_4^+) and sweat metabolites (glucose, lactate, and uric acid) during daily activities.

4. Conclusion and perspective

So far, we have provided an overview of the principal flexible MEMS techniques, including direct processing on flexible substrates and transfer printing, along with their associated applications in flexible multi-physical sensors, highlighting a promising trajectory for next-generation wearable electronics. Despite these remarkable advancements, several critical challenges persist:

1. Engineering reliability remains a continuous challenge, particularly in ensuring the long-term operation of flexible MEMS devices. The reliable packaging of these devices while maintaining their mechanical flexibility is particularly daunting. Additionally, establishing connections that minimize electrical loss while maximizing mechanical robustness presents significant difficulties. Flexible sensors hold immense promise across various industries, including aerospace, chemical processing, deep-sea, and polar exploration, where they must endure complex conditions such as extreme temperatures, high humidity, heavy

salinity, and multi-coupling mechanical force loading. To realize the practical applications of these flexible MEMS electronics, it is crucial to intensify research on engineering reliability and failure analysis.

2. Technological breakthroughs in scalable manufacturing are essential for transitioning flexible MEMS electronics from the laboratory to the market. Currently, most flexible MEMS devices remain in the conceptual or experimental stages, hindered by high production costs, low manufacturing output, and inconsistent batch reliability. There is an urgent need to develop more efficient, dependable, and large-scale flexible MEMS fabrication processes, encompassing operators, manufacturing machinery, materials, methods, and environments. Moreover, enhancing the quality management of flexible MEMS products is of paramount importance.
3. Integrated flexible microsystems that incorporate a greater variety of multi-functional MEMS sensors and actuators are increasingly in demand to meet the requirements of complex and diverse applications. For instance, a multifunctional integrated flexible system should be capable of simultaneously collecting, processing, communicating, and actuating data related to force, heat, humidity, sound, light, magnetic fields, and chemical information from a specific target. More importantly, intelligent signal processing modules would empower flexible MEMS sensors with higher efficiency, and potential for artificial intelligence. Big data collected by sensors together with training model of machine learning can provide strong support for decision-making and execution of human or robotics.

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Conflict of interest

The authors declare no conflict of interest.

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Novel MEMS Auditory Capacitive Structure with Octagonal Diaphragm

Sina Taherian

Abstract

BioMEMS devices, or biomedical microelectromechanical systems, represent a transformative integration of microscale engineering and life sciences. By operating at scales comparable to biological structures, these devices enable precise and localized interactions with cells, tissues, and organs. Miniaturization enhances sensitivity, speed, and accuracy while reducing power consumption, sample volumes, and invasiveness, making these devices highly effective for applications in diagnostics, monitoring, and therapy. Smaller BioMEMS devices offer numerous advantages, including faster response times, improved integration with biological systems, and extended battery-powered functionality, especially for implantable applications. Advances in material science and design techniques have further improved their performance, enabling higher sensitivity for detecting physiological changes and more efficient therapeutic solutions. This chapter introduces a miniature auditory capacitive structure designed with a focus on enhancing performance through advanced geometric optimization and effective size reduction. The device incorporates an octagonal diaphragm into tilted serpentine meanders to achieve superior flexibility and responsiveness while maintaining structural integrity. By applying innovative geometrical modifications and electrostatic principles, the design demonstrates significant advancements in functionality. Key aspects of the study include electrostatic equations, pressure-displacement relationships, and the alignment of simulation results with theoretical predictions. Through this work, we demonstrate how the miniaturization of BioMEMS not only reduces device dimensions but also optimizes their performance in complex environments, paving the way for more efficient and innovative biomedical applications.

Keywords: MEMS, auditory capacitive device, tilted serpentine meanders, miniature device design, octagonal diaphragm

1. Introduction

Auditory capacitive devices are used to transform sound waves into electrical current. These days, it is hard to imagine a computer, tablet, or smartphone without an auditory device. The many uses of MEMS (microelectromechanical systems) technologies have contributed to the widespread use of mobile devices like tablets,

smartphones, and so forth. Mobile devices frequently employ MEMS components including resonators [1–3], medical pressure devices [4], and microphones [5].

MEMS devices are gradually replacing conventional components in mobile devices due to their smaller size and greater sensitivity. There are three main categories of MEMS auditory devices: capacitive [6], piezoelectric [7], and piezoresistive [8]. Lower power consumption [9], improved sensitivity [10], and a less temperature effect have contributed to the widespread adoption and study of MEMS auditory devices [11]. Sound pressure is measured by the capacitance difference between the movable plate and the lower plate. The auditory devices that use piezoelectricity are called piezoelectric auditory devices [12].

MEMS are a rapidly developing industry where compactness, efficiency, and enhanced performance are always in demand. These efforts resulted in the development of a unique MEMS auditory capacitive device design, which is described in this chapter. Most people will be familiar with the electret auditory device (ECM) or the MEMS auditory device (MCM). The capacitive auditory device outperforms other types of auditory devices in terms of sensitivity while simultaneously producing minimal noise. Using a perforated aluminum diaphragm, a monocrystalline silicon wafer as a back plate, and silicon oxide as a sacrificial and isolating layer between the back plate and diaphragm, reference [13] presented a new MEMS auditory device that is small in size, inexpensive, and simple to fabricate.

Previous studies [14–17] have investigated several types of edge-clamped diaphragms in order to reduce diaphragm stress and stiffness of the structure, resulting in enhancing their mechanical sensitivity. Earlier research [18–21] have demonstrated that as the stress on the diaphragm decreases, the mechanical sensitivity of MEMS auditory devices increases. Conventional auditory devices utilize diaphragms and other known designs in order to detect sound. Despite implementing all of the mentioned methods, the auditory device showed low sensitivity and a significant pull-in voltage.

The purpose of this research is to develop a new MEMS capacitive auditory device with an octagonal diaphragm supported by tilted serpentine meanders in order to minimize the auditory device size. This diaphragm is remarkably flexible and performs better than others despite its small size ($0.15\text{ mm} \times 0.15\text{ mm}$) and air gap ($1.5\text{ }\mu\text{m}$). The resonant frequency of this unique auditory capacitive device design lowers considerably to 26 kHz when subjected to pressures of up to 150 Pa. Therefore, this auditory capacitive device design has been developed to withstand a minimum pressure of 150 Pa, resulting in an extraordinary sound level capability of 137 dB, above the limits of human sound production capability. The mechanical sensitivity of the device is 9 nm/Pa, while the capacitive sensitivity of the device is 15.4 fF/Pa. Thorough research and simulations using IntelliSuite software have been conducted to confirm the analysis. The study also compares this type of auditory capacitive device to previous research, emphasizing its smaller size and higher efficiency. This chapter is organized as follows: the first section provides a context for the work. The MEMS capacitive auditory device's design and operating principle are outlined in Section 2. The MEMS capacitive auditory device simulation results are discussed in Section 3, and the study concludes in Section 4.

2. Proposed structure concept

2.1 Structural design and configuration

The MEMS auditory device design, as depicted in **Figure 1**, incorporates a number of structural enhancements that distinguish it from prior designs. The structure has

been completely designed using Solidworks software, and it is important to emphasize some significant improvements. The auditory capacitive device has been designed with a unique diaphragm shape in the form of an octagon, which is connected to four sets of tilted serpentine meanders. The configuration is symmetrical, with beams carefully positioned in each of the diaphragm's four corners. In contrast to earlier designs that used square or circular diaphragms, this configuration not only minimizes the auditory capacitive device's overall size but also significantly enhances its performance. **Figure 1a** depicts the basic structure of the proposed microelectromechanical systems (MEMS) auditory device. The octagonal diaphragm used in our auditory capacitive device has a thickness of just 2 μm .

The size of the moveable component is 150 μm^2 , and there is a gap of 1.5 μm between the diaphragm and the fixed plate. Moreover, instead of using holes to reduce damping effects, we decided to use tilted serpentine meanders (with nine beams in series on each side, with lengths that increase as they approach the diaphragm), which ensure enough spacing between each beam. The beams have been strategically connected, with one end fixed to the octagonal diaphragm, while the other end is attached to the substrate. **Figure 1b** presents a cross-sectional view of the auditory capacitive device's structure.

The structure is composed of a polysilicon octagonal membrane connected to the tilted serpentine meanders and a fixed membrane separated by an air gap. **Table 1** contains more information about the diaphragm's physical properties. The auditory capacitive device discussed in this article exhibits an incredible ability to endure pressures of up to 150 Pa.

Using Eq. (1), this pressure tolerance corresponds to 137 dB, which is exactly in line with the criteria of a high-performance MEMS auditory device.

$$\text{SPL} = 20\text{Log}_{10}(P/P_0) \quad (1)$$

The symbol SPL is used to express the sound pressure level, measured in decibels (dB). P_0 represents the reference sound pressure, which is equal to 20 μPa , while P represents the actual pressure. Following extensive investigation and analysis, we

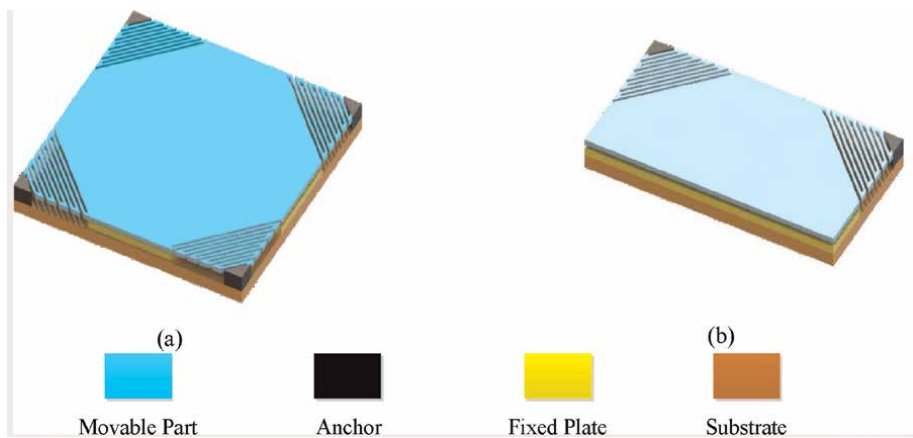


Figure 1.
Schematic structure of the MEMS capacitive auditory device. (a) Octagonal diaphragm connected to the four tilted serpentine meanders. (b) Cross-section view of auditory device structure.

Symbol	Description	Dimension
L	Length of the beams from small to large	12, 18, 24, 30,36, 44, 50, 56, 62 μm
—	Movable part thickness	2 μm
—	Device material	Polysilicon (E = 169 Gpa)
g	Air gap	1.5 μm
b	Beam width	2 μm
—	Number of beams	9
—	Air gap between every beams	2 μm
$A = 2\alpha \times 2\beta$	Movable area: Tilted serpentine meanders + Octagonal diaphragm	150 $\mu\text{m} \times 150 \mu\text{m} \times 2 \mu\text{m}$
K_m	Mechanical Stiffness	15/52 N/m
M	Movable Part Mass	0.234 ng
f_r	Primary Resonant Frequency	41 kHz

Table 1.
Physical parameters of the MEMS auditory device.

concluded that an auditory capacitive device capable of withstanding pressures of up to 137 dB would be optimal in this field.

We successfully achieved our objective by changing the shape of the diaphragm from a traditional square or circular design to an octagonal diaphragm, integrating tilted beams in each corner. In comparison with earlier works, we not only significantly improved the auditory capacitive device's performance but also reduced its dimensions.

2.2 Mechanical analysis of the proposed structure

The mechanical analysis of the structure described in this article is completely covered in this section. As seen in **Figure 1**, the diaphragm is carefully connected to four sets of identical tilted serpentine meanders, resulting in an auditory capacitive device design that is completely symmetric. The diaphragm's movement is strongly restricted to the vertical z-axis due to the symmetrical structure, as depicted in **Figure 2**. Therefore, it can be concluded that these four sets of tilted beams are parallel to each other.

In order to determine the maximum displacement of the diaphragm that is supported by tilted serpentine meanders, it is necessary to calculate the spring constant of each beam located on both sides of the diaphragm. For this purpose, we have described how to calculate the tilted serpentine meanders' maximum displacement. Following this, we employed the governing equation of motion, combined with the essential boundary conditions for the proof mass, in order to determine the maximum deflection of the diaphragm that occurs at its origin.

Each guided-end beam's equation of motion at a constant pressure P is [22]:

$$\frac{d^4 \delta_b(z)}{dz^4} = \frac{P}{EI} \quad (2)$$

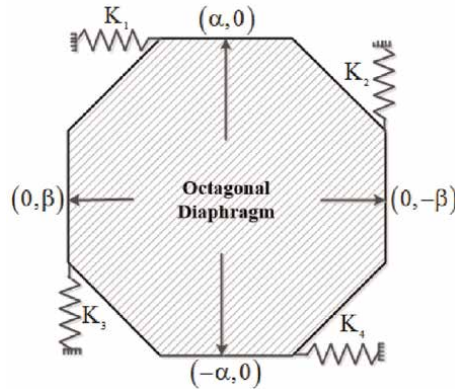


Figure 2.
 A simplified schematic springs modeling of the diaphragm.

The symbol $\delta_b(z)$ represents the displacement of the beam along the z -direction. E denotes the Young's modulus of the polysilicon material, while I represents the moment of inertia. The equation shown above can be interpreted as a fourth-order ordinary differential equation with respect to the variable " z ". As a result, the deflection of the beam can be determined by conducting four subsequent integral with respect to the variable " z ":

$$\delta_b(z) = \frac{P}{24EI} z^4 + \frac{\alpha_1}{6} z^3 + \frac{\alpha_2}{2} z^2 + \alpha_3 z + \alpha_4 \quad (3)$$

Where α_1 – α_4 are the constants of integrations. To solve Eq. (3), we determine the constants of integration from the boundary conditions:

$$\delta_{b1}(L) = \delta_p(\alpha), \quad \delta'_{b1}(L) = 0 \quad (4)$$

$$\delta_{b2}(0) = 0, \quad \delta'_{b2}(0) = 0 \quad (5)$$

$$\delta_{b2}(L) = \delta_p(\beta), \quad \delta'_{b2}(L) = 0 \quad (6)$$

$$\delta_{b3}(0) = 0, \quad \delta'_{b3}(0) = 0 \quad (7)$$

$$\delta_{b3}(L) = \delta_p(-\beta), \quad \delta'_{b3}(L) = 0 \quad (8)$$

$$\delta_{b4}(0) = 0, \quad \delta'_{b4}(0) = 0 \quad (9)$$

$$\delta_{b4}(L) = \delta_p(-\alpha), \quad \delta'_{b4}(L) = 0 \quad (10)$$

Furthermore, we considered the following boundary condition at the end of each beam:

$$EI \frac{d^3 \delta_b(z)}{dz^3} \Big|_{z=L} = 0 \quad (11)$$

Now we must determine α_1 – α_4 from Eq. (3), to satisfy the boundary conditions. Using Eqs. (4) and (11) in Eq. (3) gives:

$$c_1 = \frac{-PL}{EI}; c_2 = \frac{PL^2}{3EI}; c_3 = 0; c_4 = 0 \quad (12)$$

By substituting Eq. (12) into Eq. (3), we get the following results of the beam profile:

$$\delta_b(z) = \frac{P}{24EI} z^4 - \frac{PL}{6EI} z^3 + \frac{PL^2}{6EI} z^2 \quad (13)$$

The maximum deflection of the beam occurring at $Z = L$, is calculated from Eq. (13) as [23]:

$$\delta_b(\max) = \frac{PL^4}{24EI} \quad (14)$$

The effective stiffness of the each guided-end beam under uniform pressure $\mathbf{P}$ is defined as follows:

$$K_b = \frac{PL}{\delta_b(\max)} = \frac{24EI}{L^3} \quad (15)$$

The maximum displacement of parallel beams b_1, b_2, b_3 , and b_4 to the applied pressure $\mathbf{P}$ that occurs at the endpoint $Z = L$ is then computed by:

$$\delta_b(L) = \frac{PL}{4K_b} \quad (16)$$

However, based on Kirchhoff's assumptions, the governing differential equation for the thin plate under a uniform pressure $\mathbf{P}$ is as follows:

$$\frac{\partial^4 \delta_p(x, y)}{\partial x^4} + 2 \frac{\partial^2 \delta_p(x, y)}{\partial x^2} \frac{\partial^2 \delta_p(x, y)}{\partial y^2} + \frac{\partial^4 \delta_p(x, y)}{\partial y^4} = \frac{P}{D} \quad (17)$$

Where D , called the bending rigidity of the plate, is a constant given as:

$$D = \frac{Eh^3}{12(1 - \nu^2)} \quad (18)$$

We assume the movable part of the pressure device is subjected to an external uniform pressure coefficient $\mathbf{P}$. As can be seen from **Figure 2**, the maximum displacement occurs at the center of the diaphragm, we find the following expressions for maximum plate deflections [4]:

$$\delta_p(\max) = \delta_b(L) + \frac{16P}{\pi^6 D} \sum_{m=1,3,5,\dots}^{\infty} \sum_{n=1,3,5,\dots}^{\infty} \left[\frac{1}{mn \left[\left(\frac{m}{\alpha} \right)^2 + \left(\frac{n}{\beta} \right)^2 \right]^2} \right] \quad (19)$$

Besides, the resonance frequency of the structure depends on geometry and material properties. The resonance frequency of the auditory capacitive device diaphragm can be defined as follows:

$$f_{r0} = \frac{1}{2\pi} \sqrt{\frac{K_m}{M}} \quad (20)$$

2.3 Electrostatic analysis of the proposed device

In a MEMS capacitive structure, pull-in voltage determination is crucial. The suggested device in this study has been examined electrostatically in order to determine pull-in voltage.

The purpose of this section is to conduct an electrostatic analysis of the capacitive structure illustrated in **Figure 1**. The fixed plate is situated at a distance of g from the diaphragm, and the moveable section can only move toward the fixed plate. When no pressure is applied to the moveable part, the diaphragm moves by biasing the DC-loaded microstructure. The change in capacitance value, resulting from the deflection of the diaphragm, can be detected by the utilization of a connecting electronic circuit. By applying a certain value of DC voltage between two plates, an electrostatic force is generated that pulls the movable part downward a distance Z . The capacitance value between two parallel plates (neglecting the fringing effect) for an octagonal diaphragm capacitive structure is given by:

$$C = \frac{\epsilon_0 \epsilon_r A}{g - z} \quad (21)$$

where ϵ_0 , ϵ_r , A , g , and Z are the dielectric constant in free space, the relative permittivity of the gap space medium concerning the free space, the overlap area between the two plates, the initial air gap between two plates, and the displacement in the Z direction, respectively. The electrostatic attraction force (F_e) can be calculated by dividing the capacitor's stored energy by the position of the moving plate. The electrostatic force acting on the moving plate is stated as follows:

$$F_e = \frac{1}{2} \left(\frac{\partial C}{\partial z} \right) V^2 = \frac{\epsilon_0 \epsilon_r A V^2}{(g - z)^2} \quad (22)$$

Through the derivation of the electrostatic force from the displacement, we can determine the electrostatic spring constant (K_e) as follows:

$$K_e = \left(\frac{\partial F_e}{\partial z} \right) = \frac{\epsilon A}{(g - z)^3} V^2 \quad (23)$$

The resonance frequency of the auditory capacitive device structure changes from Eq. (20) to Eq. (24) with the application of voltage between the plates.

$$f_r = \frac{1}{2\pi} \sqrt{\frac{K_m - K_e}{M}} \quad (24)$$

Therefore, from Eq. (22), it can be seen that increasing the voltage increases the electrostatic force, which in turn increases the electrostatic spring constant according to Eq. (23). As shown in Eq. (24), when the electrostatic spring constant increases, the resonance frequency of the structure decreases.

The electrostatic spring constant (K_e) caused by the voltage applied to both the fixed and moveable plates equals the mechanical stiffness (K_m) arising from the

beams at equilibrium. Pull-in instability occurs when the electrostatic stiffness exceeds the mechanical stiffness, causing the diaphragm to contact the bottom plate. The following equation is obtained as a result of setting the electrostatic stiffness equal to the mechanical stiffness:

$$V = (g - x) \sqrt{\frac{K_m(g - z)}{\epsilon A}} \quad (25)$$

As previously mentioned, the octagonal diaphragm is linked to four identical sets of tilted serpentine meanders, which can be regarded as being parallel to each other. Consequently, we can determine the mechanical stiffness (K_m) of the auditory capacitive device presented in this article using the following formula:

$$K_m = 4K_b \quad (26)$$

In the formula above, K_b represents the mechanical stiffness of each set of tilted serpentine meanders. As depicted in **Figure 1**, each of the four sets of tilted serpentine meanders comprises nine beams, all sharing the same width and thickness but varying in length. To compute the mechanical stiffness of each beam set, we can employ the following formula:

$$\frac{1}{K_b} = \frac{1}{K_1} + \frac{1}{K_2} + \frac{1}{K_3} + \dots + \frac{1}{K_9} \quad (27)$$

Furthermore, we can calculate the mechanical stiffness of each of the nine beams located at every corner of the diaphragm using the following equation:

$$K = \frac{Ehb^3}{L^3} \quad (28)$$

Normally, the mechanical restoring force and electrostatic force are balanced. However, if the voltage load is greater than a specific threshold, the electrostatic force will dominate, which will ultimately result in the collapse of the structure. The phenomenon mentioned is commonly known as “pull-in instability”. When the gap thickness is three times the plate deflection, an unusual equilibrium condition occurs.

To accurately estimate the position of the pull-in phenomenon, it is necessary to find the maximum voltage at which the derivative of voltage with respect to displacement (dV/dz) equals zero. As a result, the distance that the pull-in happens can be obtained as follows:

$$z = \frac{g}{3} \quad (29)$$

Upon substituting the Eq. (29) into Eq. (25), the pull-in voltage for auditory capacitive device presented in this article can be written as follow:

$$V_{Pull-In} = \sqrt{\frac{8K_m g^3}{27\epsilon A}} \quad (30)$$

The capacitive sensitivity of the capacitive pressure sensor under uniform pressure P is defined as:

$$S_c = \frac{\Delta C}{C_0 P} \quad (31)$$

Where ΔC is the capacitance value changes of the diaphragm, C_0 is the initial capacitance, and P is the applied pressure. From Eq. (31), we can conclude that the sensitivity increases with increasing capacitor changes and decreases with increasing pressure and beginning capacitance value. In addition, mechanical sensitivity is also another important parameter that should be determined for capacitive pressure devices. This sensitivity can be calculated from the derivative of the displacement with respect to the applied pressure:

$$S_m = \frac{d\delta_p}{dp} \quad (32)$$

3. Result and discussion

This section examines the findings of the auditory capacitive device shown in **Figure 1** in terms of the movable part's maximum displacement, resonance frequency, capacitance value, and stress distribution using IntelliSuite software. The characteristics and parameters of the auditory capacitive device presented in this chapter are listed in **Table 1**. This structure was designed and modeled using SolidWorks and IntelliSuite software. The movable component of the auditory capacitive device is attached to the anchor, and the bottom plate is fixed to the substrate. There is also a $1.5 \mu\text{m}$ gap between the octagonal diaphragm and the fixed bottom plate, which allows the movable plate to be lowered toward the fixed plate under uniform pressure up to 150 Pa and very low voltage between the two plates, causing a measurable change in capacitance. Polysilicon with Young's modulus of 169 GPa is the material used in both fixed and moveable plates. To ensure accurate simulation results that closely align with theoretical analysis, we employed a mesh size of $3 \mu\text{m}$ squares in IntelliSuite software modeling. The findings of the evaluation of the auditory capacitive device in terms of frequency and static are shown in the graphs below.

Figure 3 shows that when the auditory capacitive device diaphragm is subjected to a pressure of 150 Pa , it moves around $1.2 \mu\text{m}$ in the z -direction. As the distance between the upper and lower plates is approximately $1.5 \mu\text{m}$, plate collisions are impossible. In **Figure 4**, we use the Finite Element Method (FEM) to investigate the stress distribution across the octagonal diaphragm connected to the tilted serpentine meanders. At the borders of the beams and the diaphragm, there is a significant concentration of stress.

Figure 5 provides an in-depth analysis of the graph illustrating the relationship between pressure and displacement. Upon applying pressure up to 150 Pa , or 137 dB , the movable part of the structure moves by around $1.2 \mu\text{m}$. This figure shows that the theoretical result, obtained using the formulas presented in the chapter, is in good agreement with the simulation result. Next, we examine the pressure versus resonance frequency plot shown in **Figure 6**. When the pressure on the movable part increases, the movable and fixed plates get closer together. This reduces the gap between them and increases the capacitance. Because there is an inverse relationship between resonance frequency and capacitance, the resonance frequency of the structure increases. The auditory capacitive device's resonance frequency drops dramatically from 41.757 kHz to 26.434 kHz when pressure increases gradually up to 150 Pa .

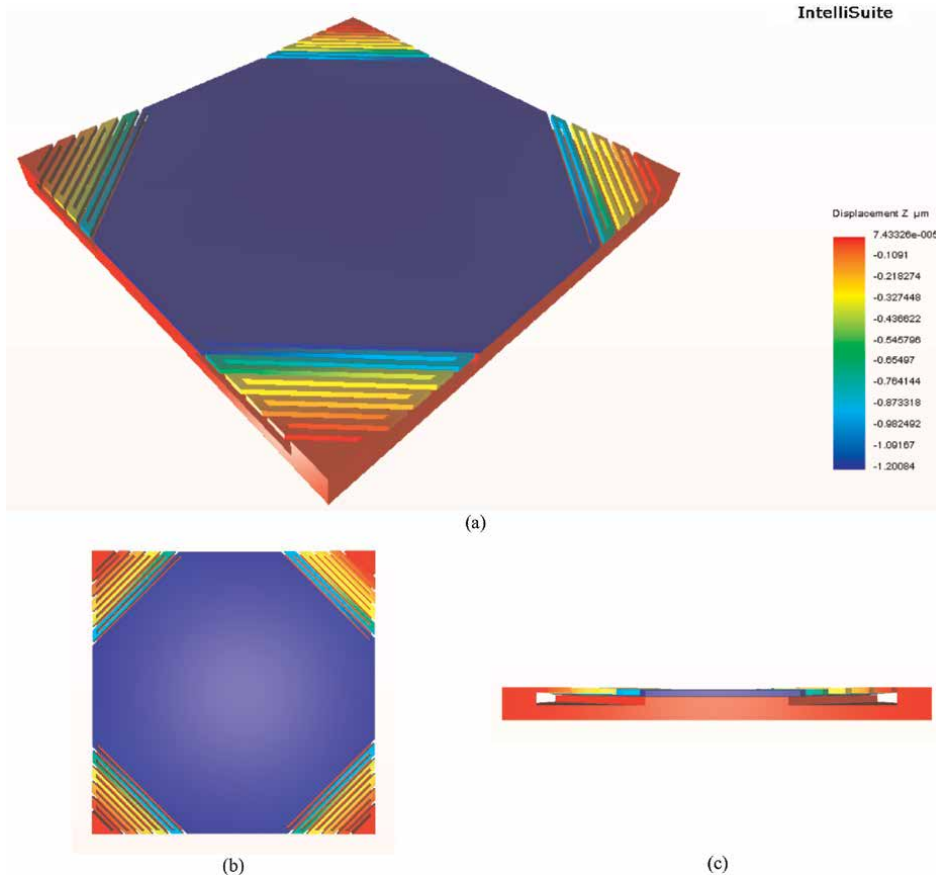


Figure 3. The maximum deflection of the octagonal diaphragm under an applied pressure of 150 Pa. (a) Isometric view, (b) Top view, (c) Front view.

The relationship between capacitance and pressure is illustrated in **Figure 7**. A careful investigation indicates that when pressure increases, the space between the diaphragm and the fixed plate narrows, which increases the capacitance value. This figure shows that the theoretical result, obtained using the formulas presented in the chapter, is in good agreement with the simulation result.

The resonance frequency response diagram of the auditory capacitive device is shown in **Figure 8**. According to this figure, the structure's primary resonance frequency is exactly 41.757 kHz. This means that at this frequency, the auditory capacitive device's diaphragm experiences the maximum displacement, indicating the point at which the auditory capacitive device is most sensitive to sound vibrations. **Figure 9** depicts the relationship between resonance frequency and voltage. As the voltage gradually increases to its maximum value of 7 V, a significant decrease in the resonance frequency is seen. Specifically, the resonance frequency decreases from its initial value of 41.757 kHz to 27.538 kHz. Consequently, this phenomenon results in an upward trend in capacitance. The auditory capacitive device's capacitance formally increases from 0.1214 pF to 0.2321 pF when the pressure increases up to 150 Pa.

Figure 10 shows the maximum displacement of the flexible part in relation to changes

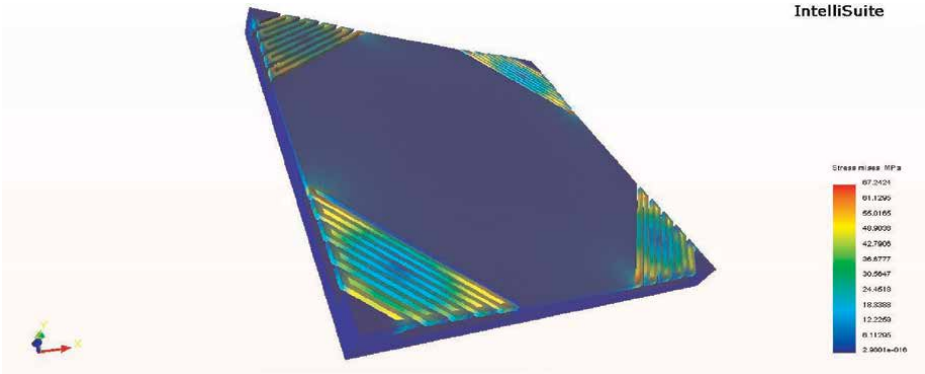


Figure 4.
Stress distributions on the octagonal diaphragm.

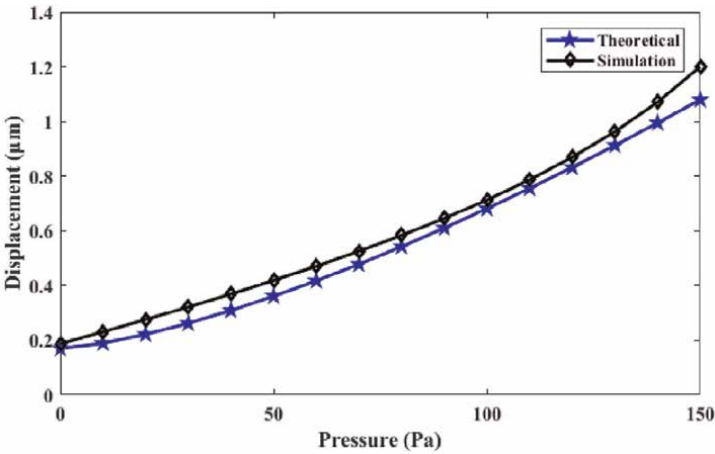


Figure 5.
The maximum displacement of the diaphragm connected to the tilted serpentine meanders against external uniform pressure.

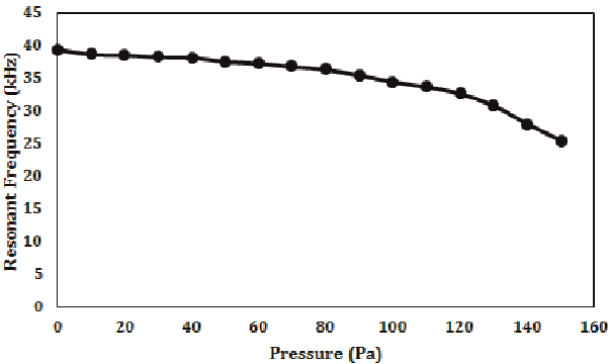


Figure 6.
Resonant frequency versus increasing applied pressure for the proposed device.

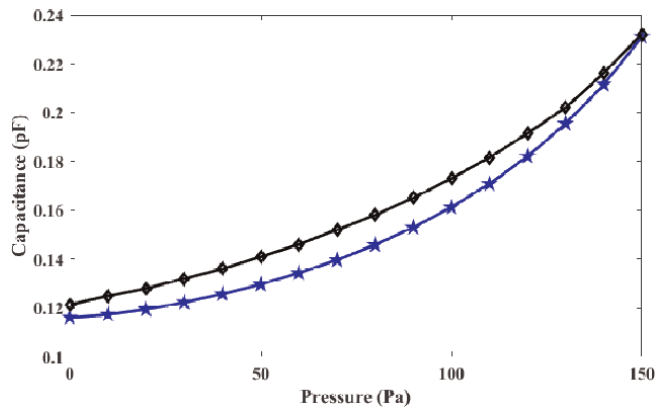


Figure 7.
Capacitance values versus applied pressure for the octagonal diaphragm supported by tilted serpentine meanders.

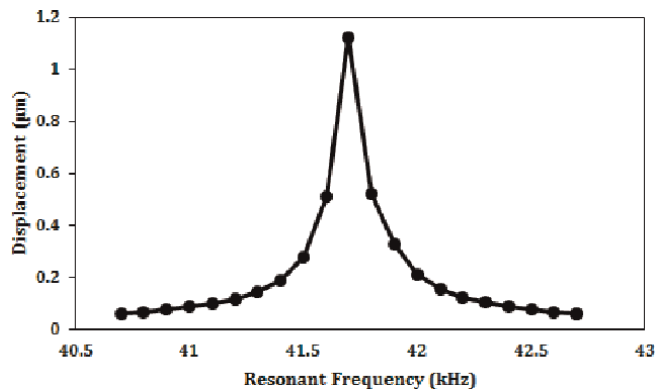


Figure 8.
Plot for the deflection of proposed device, which is supported by tilted serpentine meanders, versus its primary resonant frequency.

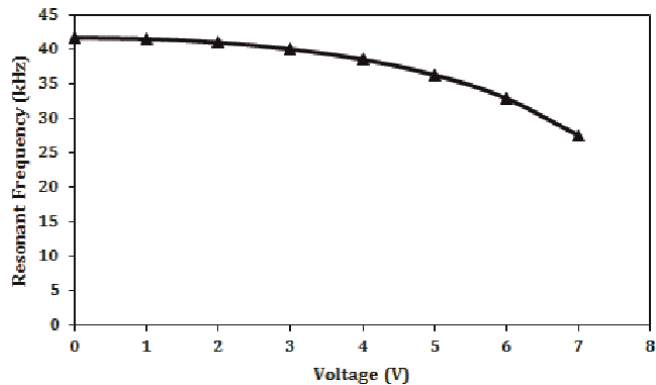


Figure 9.
Resonant frequency versus biasing DC voltage.

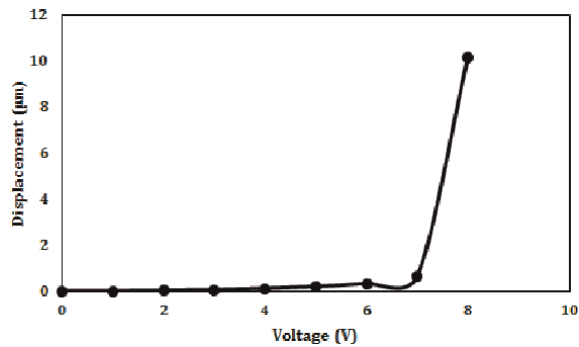


Figure 10.
A vertical displacement (Z direction) of the diaphragm versus voltage (V).

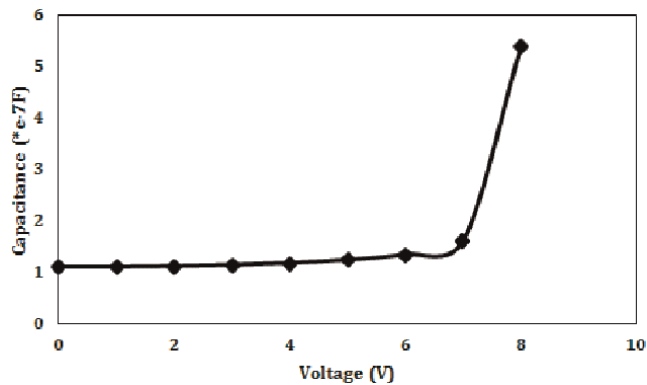


Figure 11.
A Capacitance values versus voltage (V) for the diaphragm connected to the tilted serpentine meanders.

Reference	Structure of diaphragm	Size (mm ²)	Pressure tolerance threshold (Pa)	Resonance frequency (kHz)	Capacitive Sensitivity (fF/Pa)	Mechanical sensitivity (nm/Pa)
[13]	Traditional Square Diaphragm	0.5	150	166.794	0.15	0.309
[6]	Square Diaphragm Supported by Frog Arms	0.5	30	21.504	27.45	9.893
This Research	Octagonal Diaphragm Supported by Tilted Serpentine Meanders	0.15	150	41	15.4	9

Table 2.
Comparison of mems auditory capacitive devices.

in voltage. The diaphragm connected to the beams can move up to one-third of the distance between itself and the bottom plate when the voltage is increased to 7 V. Additionally, the pull-in voltage of the auditory capacitive device in this study is 7 V. The IntelliSuite simulation shows a displacement of up to 0.6538 μm with an air gap of 1.5 μm. **Figure 11** depicts the relationship between capacitance and voltage.

As the voltage increases from 0 V to 7 V, the capacitance value increases from 1.095 pF to 1.601 pF.

The comparison between an auditory capacitive device with a simple diaphragm, an auditory capacitive device with an octagonal diaphragm supported by tilted serpentine meanders, and a diaphragm connected with frog arms is presented in **Table 2**. It can be observed that the auditory capacitive device provided in this article, although being smaller in size than the previous studies, can withstand higher pressure. As a result, the best MEMS auditory capacitive device is the octagonal diaphragm attached to the tilted serpentine meanders.

4. Conclusion

In this study, we first provided a concise introduction to the applications and operational principles of MEMS capacitive pressure sensors. Subsequently, we focused on the analysis and simulation of an auditory capacitive device, which comprises an octagonal diaphragm and tilted serpentine meanders. The purpose of incorporating tilted serpentine meanders is to decrease the stiffness of the diaphragm. To conduct the analysis and simulation, we employed the Finite Element Method (FEM) tool, specifically the IntelliSuite software. An enhancement in sensitivity has been attained by modifying the diaphragm geometries and including tilted serpentine meanders into the auditory capacitive device, as opposed to the conventional MEMS auditory capacitive device. The capacitive sensitivity within the specified pressure range is measured to be 15.4 (fF/Pa). Hence, a comparative analysis between the auditory capacitive device depicted in this study and prior research reveals that the implementation of a capacitive pressure sensor featuring an octagonal diaphragm, with dimensions smaller than those employed in previous endeavors ($150\text{ }\mu\text{m} \times 150\text{ }\mu\text{m}$), makes it more suitable for the measurement of sound pressure within the 0–150 Pa range (up to 137 dB).

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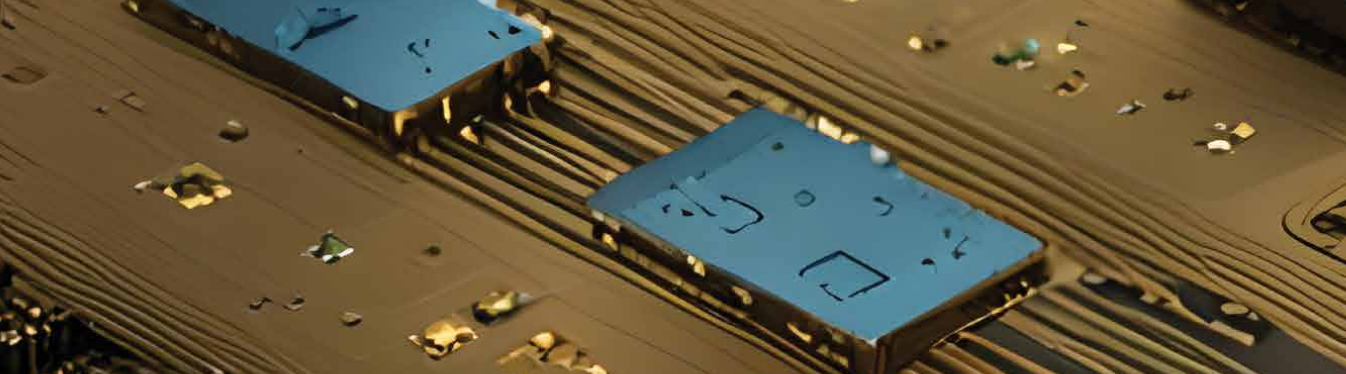
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*Edited by Zdravko Stanimirović
and Ivanka Stanimirović*

To present their latest work in the field of Microelectromechanical systems (MEMS), researchers from distant parts of the world have joined their efforts and contributed their ideas according to their interest and engagement. Their chapters will give you the opportunity to learn about advanced materials, techniques, and applications in MEMS.

The topics presented included flexible MEMS techniques for multi-physical sensors, highlighting the adaptability of these systems to complex sensing environments and the use of MEMS in optical and photonic devices, demonstrating their impact on advanced imaging and communication technologies. The book also explores biomedical MEMS, which are advancing healthcare through improved diagnostics and therapeutic tools.

The editors hope the book will allow professionals and readers not involved in the immediate field to understand and enjoy the topic.

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