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Overview of Micro-Machining and Micro-Electromechanical Systems (MEMS)

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ABSTRACT
The quest for technological advancement for parts and systems with lightweight, low energy consumption, greater mobility, as well as higher efficiency and reliability, has birthed an era of miniaturized (micro-size) components and microsystems. These systems have found applications in inkjet printers, computer disk drives, accelerometers, projection display chips, blood pressure sensors, optical switches, micro-valves, and biosensors, among others. Micro-machining is a process that uses specialized tools and techniques to create small parts and components with precise dimensions and tolerances. It is a fabrication technology to produce components that make up micro-electro-mechanical systems (MEMS) with sizes in the range of micrometers to millimeters. The ability to fabricate and manipulate microscale structures and devices has the potential to revolutionize many aspects of technology and industry. In this review paper, an overview of the history of MEMS is provided, including classifications of MEMS, principles, and applications of micro-machining and MEMS. This review paper also provided insights into MEMS fabrication methods, the challenges, and the future prospects of these technologies.

Keywords: Technological advancement, Systems, Micro-machining, Micro-system, Microelectro mechanical System, Reliability, Miniaturized, MEMS fabrication.

I. INTRODUCTION

Micro-electro-mechanical systems (MEMS) are an advanced technology that allows integration of mechanical and electrical components to form a miniaturized devices or systems. These multifunctional devices (or systems) leverages integrated circuit (IC) batch processing techniques to fabricate these sophisticated devices, blending the precision of mechanical engineering with the intricacies of electrical engineering (Wang et al. 2024; Algamili et al. 2024; Geetha 2011). MEMS devices and systems have the ability to sense, control, and actuate on the micro-scale and producing effects that can influence the macro-scale. MEMS fabrication abhor the design, engineering, and manufacturing expertise from various technical fields, including integrated circuit fabrication technology, mechanical engineering, materials science, electrical engineering, chemistry, and chemical engineering. This multidisciplinary approach is essential for the development and advancement of MEMS technology. Other fields like fluid engineering, optics, instrumentation, and packaging also play an important role in the manufacture of MEMS devices and systems. MEMS devices are typically made using semiconductor fabrication processes similar to those used in the production of integrated circuits (ICs) (Torkashvand 2024; Mohd et al. 2020; Dibyendu 2015). The manufacturing of MEMS devices involves several key steps, including design, material selection, wafer processing, and packaging which are subset of microsystem technologies (MST) (Senturia 2002; Maluf and Williams 2004).

According to Madou (2011), MST encompasses a broader field that includes the design, fabrication, and application of microsystems. Fatikow and Kötter (2016), reveals that MST involves the integration of miniaturized mechanical, electrical, and optical components onto a single microchip or substrate, as shown in Fig. 1.

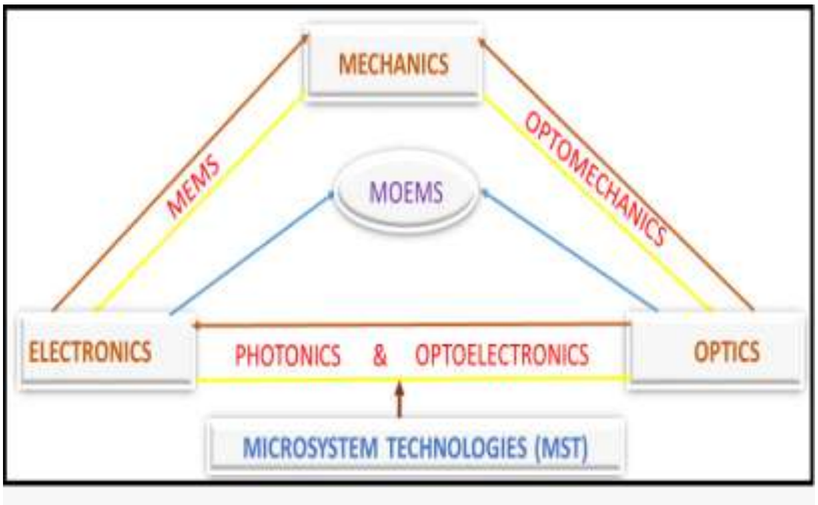


Figure 1: Divisions of Micro-system Technology (MST)

MEMS refer to the devices and systems created using this technology, while MST encompasses the broader field that includes design, fabrication, and application of such devices. MST focuses on the development of complete micro-systems that can perform complex functions by combining various technologies and components (Senturia 2002; Madou 2011; HSU; 2001).

Victor, (2000) in his research findings stated that microelectromechanical systems (MEMS), which range in size from micrometers to millimeters, are integrated micro-devices or systems that combine electrical and mechanical parts. They are made using batch processing methods that are compatible with integrated circuits (IC). These systems can work alone or in groups to have effects on the macro scale, and they can sense, control, and act on the micro-scale (MCNC, 1999). MEMS are new technologies that have changed the field of microelectronics. They also have a new line of miniaturized electromechanical products, such as sensors, actuators, switches, accelerometers, light reflectors, and communication devices that have been used in many different ways (Victor, 2000; Madou 1997; Trimmer 1996; Bryzek 1996). In micromachining, specialized tools and techniques are used to create small parts and components with precise dimensions and tolerances. The process involves the use of a variety of tools, such as lasers, water jets, and electrical discharge machines (EDMs). The tools are used to cut, shape, and finish the parts. The process is highly accurate and can produce parts with very tight tolerances (Varadan and Varadan 2000). Micromachining refers to the fabrication and machining of micro-scale structures and devices with dimensions in the range of tens of micrometers to several millimeters (Hung and Corliss 2019). It involves a variety of techniques and processes used to create these micro-scale structures, including lithography, etching, electroplating, and laser machining.

According to Michael (2013), MEMS are a subset of micromachining, and refer specifically to the integration of mechanical and electrical components on a micro scale. These components can be used to create a wide range of devices and systems, including accelerometers, microfluidic devices, and pressure sensors. One of the key benefits of micromachining and MEMS is the ability to create highly miniaturized devices and systems, which can be used in a variety of applications including healthcare, consumer electronics, and aerospace. For example, micro scale accelerometer are used in smartphones to detect the movement of the device, and microfluidic devices are used in lab-on-a-chip systems for chemical and biological analysis (Torkashvand 2024; Jack 2001 Bulk et al. 1996). One of the major challenges in micromachining and MEMS is the need for precise control over the microscale dimensions of the structures being fabricated (Michael, 2013). This is typically achieved through the use of photolithography, which allows for the creation of very fine features with dimensions in the range of a few micrometers. However, this process can be time-consuming and expensive, and there is ongoing research into developing alternative methods for micromachining and MEMS fabrication (Michael, 2013).

There are several process that can be used in micromachining and MEMS depending on the type of devices needed to be fabricated, some of them are shown in Fig 2. Also, different materials are used in the MEMS fabrication which includes Silicon substrates, Glass, Quartz, Pyrex, Ceramics, Piezoelectric crystals, Packaging materials, and various polymers. Silicon is the most commonly used material due to its mechanical strength, availability of specialized equipment and processes for working with it. However, the usage of these materials depends on the specific application requirements.

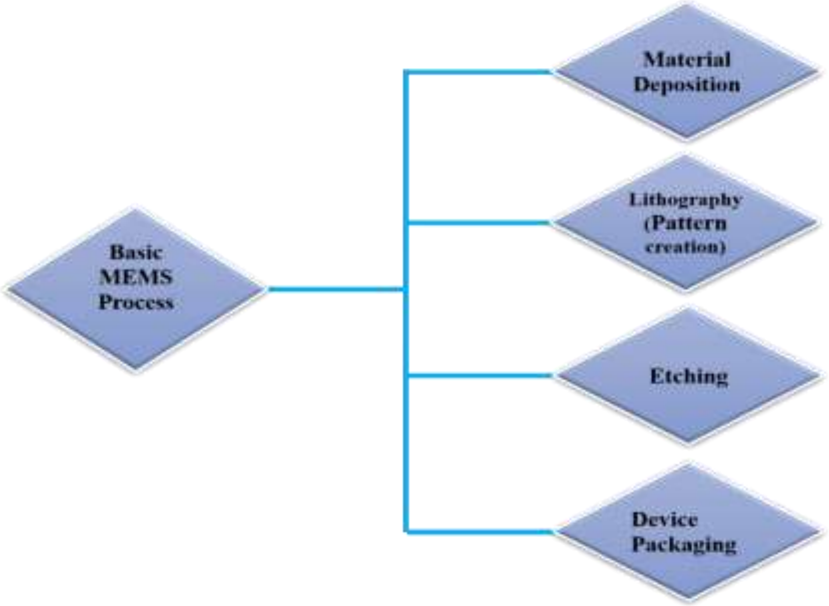


Figure 2: MEMS/Micromachining fabrication process.

The History of MEMS

The history of MEMS is relatively short, but the field has grown rapidly in recent years. The development of MEMS technologies happened as a result of the great efforts of several individuals at different times and places. These efforts lead to the development of many MEMS technologies for various applications. The timeline that encompasses numerous initiatives leading to MEMS development is provided in Table 1. It provides a comprehensive overview of some turning points in the evolution of micro electromechanical systems as we know them today.

Table 1: Periodical advancement in of MEMS:

YEAR	EVENT
1952	The first MEMS device, a surface acoustic wave (SAW) filter, is invented by James E.
1960	The first MEMS accelerometer is invented by William B. Greason at Honeywell.
1970	The first MEMS gyroscope is invented by Richard S. Kalman at MIT.
1980	The first MEMS pressure sensor is invented by James E. Morris at Honeywell
1985	The first MEMS inkjet printer is invented by Mark A. Grinis at Xerox PARC.
1990	The first MEMS optical switch is invented by David A. Thompson at IBM.
1995	The first MEMS microphone is invented by Paul L. McWhorter at Analog Devices.
2000	The first MEMS accelerometer for airbag deployment was introduced by Bosch. The first MEMS gyroscope for automotive navigation was introduced by Infineon.
2005	The first MEMS pressure sensor for medical diagnostics was introduced by STMicroelectronics.
2010	The first MEMS optical switch for data communications was introduced by Infineon.

A primary motivation behind pursuing product miniaturization with utmost precision is the aspiration to manufacture multifunctional products characterized by their lightweight nature, enhanced mobility, reduced energy consumption, and high quality (Lamidi et al. 2024). In addition, the discovery of advanced materials, including superalloys, composites, ceramics, and others, which possess impressive strength-to-weight ratios, coupled with the evolution of advanced machining techniques boasting ultra-high precision, makes the miniaturization of components viable. (Bao et al. 2020). Micro-machining involves the fabricating of micro-scale structures and devices using various techniques, such as photolithography, etching, and deposition. The first micro-machining technology was developed in the 1960s, when researchers at the Xerox Corporation used photolithography and etching to fabricate micro structures on silicon wafers. Since then, micro-machining has been widely used in the production of microelectronic devices, such as microprocessors and memory chips.

Micromachining and MEMS structures are made using various materials, such as silicon, glass, and polymers, and are fabricated using various techniques, such as photolithography, etching, and deposition. (Kciuk et al. 2020) in their research assessed the blast threat to armoured vehicle crew by making use of MEMS accelerometer. MEMS accelerometer was employed to determine the acceleration experienced by the crew in order to estimate the blast pressure and impulse. At the end of their study it was concluded that MEMS accelerometer can be effectively employed to assess the blast threat to armored vehicle crew. According to (Li et al. 2020) patient movement was tracked in a mechanical diagnostics device using a triaxial MEMS accelerometer. High sensitivity and low noise was achieved with the use of piezoresistive sensing element. The accelerometer was designed to be lightweight and tiny and such can be suitable for use in a medical diagnostic device.

Components and Devices for Microsystem Technology (MST) and Microelectromechanical Systems (MEMS)

MEMS (Microelectromechanical Systems) and MST (Microsystems Technology) are closely related fields that involve the integration of miniaturized mechanical, electrical, and optical components onto a single microchip or substrate. Both focus on the design, fabrication, and application of devices and systems at the microscale. These devices typically consist of micro-mechanical structures, such as sensors, actuators, and other components, integrated with electronic circuits on a microchip. MEMS devices are designed to interact with the surrounding environment, sensing various physical phenomena and responding to them through mechanical movements or electrical signals. Examples of such devices include accelerometers, gyroscopes, pressure sensors, microphones, and inkjet print heads while MST, on the other hand, encompasses the broader field that includes the design, fabrication, and application of microsystems with focuses on the development of complete microsystems that can perform complex functions by combining various technologies and components. It involves the integration of multiple components, including MEMS devices, electronics, optics, and fluidics, into a single system according to Fig. 1.

These microsystems can be found in applications such as biomedical devices, optical communications, automotive systems, aerospace technology, and environmental monitoring. The fabrication of MEMS and MST devices typically involves utilizing semiconductor manufacturing techniques, similar to those used in the production of integrated circuits (Jack 2001). MEMS can be classified into various categories based on different criteria. Here are some its common classifications:

❖ Based on Operation Principle:

a. Sensor MEMS: They are devices that are primarily designed to sense and measure physical quantities such as pressure, acceleration, temperature, humidity, etc.

b. Actuator MEMS: They are devices that are designed to convert electrical signals into mechanical motion or physical action, such as microvalves, micro-mirrors, microgrippers, etc.

c. Sensor-Actuator MEMS: These are hybrid devices that integrate both sensing and actuation capabilities into a single device. They can sense a physical quantity and subsequently actuate a response based on the measured data.

❖ Based on Structure and Design:

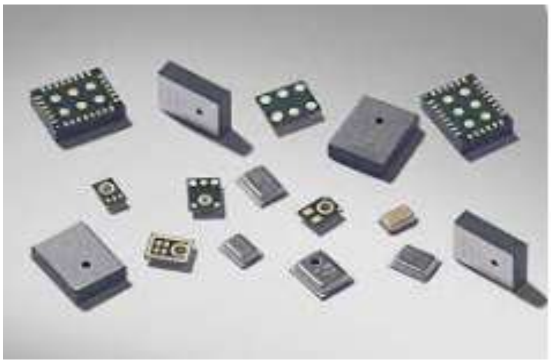
a. Bulk MEMS: These devices are fabricated by bulk micro machining techniques where silicon or other materials are selectively etched to form three-dimensional structures.

b. Surface MEMS: These devices are fabricated using surface micro machining techniques, where thin films of materials are deposited and patterned on a substrate to create the desired structures.

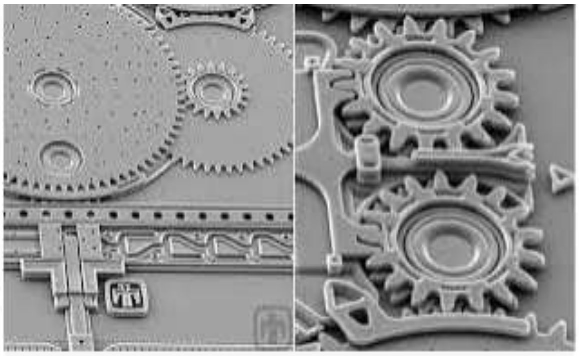
c. Lateral MEMS: These devices are primarily planar structures that move or respond in the plane of the substrate, such as micro cantilevers or micro resonators.
d. Vertical MEMS: These devices have structures that move perpendicular to the substrate, such as micros witches or micro mirrors.

❖ **Based on Application:**
a. **Automotive MEMS**: These MEMS devices are specifically designed for automotive applications, such as airbag deployment sensors, tire pressure sensors, inertial measurement units (IMUs), etc.
b. **Medical MEMS**: These MEMS devices find applications in the medical field, including lab-on-a-chip devices, implantable sensors, drug delivery systems, microfluidic devices, etc.
c. **Consumer Electronics MEMS**: These MEMS devices are used in consumer electronics products, such as smartphones, gaming devices, fitness trackers, microphones, projectors, etc.
d. **Industrial MEMS**: These MEMS devices cater to various industrial applications, including pressure sensors, flow sensors, accelerometers, gyroscopes, etc.
These classifications provide a general overview of the different categories of MEMS devices, but it's important to note that the field of MEMS is vast and continually evolving, leading to the emergence of new classifications as technology advances.

Source: Avem & Mouser (2016)



Source: Jonathan, (2021)



Source: Naghmeh, (2019)

Figure.3: Images showing some MEMS examples

The four phases in the MEMS Industry:

1. **Invention:** New MEMS technologies and devices are developed during this stage. Both tiny, entrepreneurial businesses and university research are frequently the driving forces behind this phase. This phase formed the building block for which other phases in MEMS developed.
2. **Commercialization:** This stage is distinguished by the creation of MEMS devices for industrial uses. Larger, more established businesses that have the financial means to commercialize MEMS technologies frequently drive this phase.
3. **Growth:** The widespread use of MEMS devices in a range of applications defines this stage. The rising demand for MEMS devices from a number of sectors, including the automotive, medical, and consumer electronics industries, frequently propels this phase.
4. **Maturity:** The MEMS industry is still expanding during this phase, but it is doing it more slowly than it did during the boom phase. The creation of novel MEMS technology and applications frequently drives this phase.

The MEMS market is still expanding, and it is anticipated that this growth will continue in the years to come. The development of new MEMS technologies, the rising demand for MEMS devices from a variety of industries, and the decreasing cost of MEMS devices are some of the drivers that are propelling the expansion of the MEMS business (Algamili 2021; Mohd et al. 2020; Mishra et al. 2019).

Here are some of the most important MEMS devices and technologies that have been developed in the past few decades:

- **Micro-accelerometers:** Micro-accelerometers are used to measure acceleration. They are used in a variety of applications, such as airbag deployment, navigation, and gaming.
- **Micro-gyroscopes:** Micro-gyroscopes are used to measure rotation. They are used in a variety of applications, such as navigation, gaming, and stabilization.
- **Micro-pressure sensors:** Micro-pressure sensors are used to measure pressure. They are used in a variety of applications, such as airbag deployment, medical diagnostics, and industrial process control.
- **Micro-flow sensors:** Micro-flow sensors are used to measure fluid flow. They are used in a variety of applications, such as fuel injection, medical diagnostics, and environmental monitoring.
- **Micro-optical devices:** Micro-optical devices are used to manipulate light. They are used in a variety of applications, such as displays, sensors, and optical communications.

Processes Involved in the Manufacturing of MEMS Devices (Microfabrication Techniques)

There are a number of different techniques and processes that are used in micromachining and MEMS fabrication on a micron scale. The field of semiconductors established the usage of some of these techniques while others were particularly developed for the purpose of micro-machining and fabrication of MEMS (Torkashvand et al. 2024; Bentacourt and Brannon 2006; Voldman et al. 1999). Generally, in the micromachining or fabrication of MEMS, the combination of bulk and surface micromachining are employed. The specific manufacturing process used to make a MEMS device depends on the device's design and its intended application. However, all MEMS devices are made using a combination of the processes explained below and as shown in figure 4.

Micro machining: Micro-machining is a process used to create structures with dimensions in the micrometer range. Micromachining is used to create a variety of MEMS devices, including micro-accelerometers, micro-gyroscopes, and micro-pressure sensors (Senturia, 2002). There are two main types of micromachining: bulk micromachining and surface micromachining. Bulk micromachining is a process used to create structures by removing material from a substrate. Surface micromachining is a process used to create structures by adding material to a substrate (Senturia, 2002).

Lithography: Lithography is a process used to create patterns on a substrate. Lithography is used to create the structures that make up MEMS devices, such as the electrodes and the membranes. There are two main types of lithography: photolithography and electron beam lithography. Photolithography is a process used to create patterns on a substrate using light while electrons are used to create patterns on a substrate in electrons beam lithography.

Etching: Etching is a process used to remove material from a substrate. Etching is used to create the features that make up MEMS devices, such as the channels and the cavities. There are two main types of etching: wet etching and dry etching. Wet etching is a process used to remove material from a substrate using a chemical solution while dry etching is a process used to remove material from a substrate using plasma.

Deposition: Deposition is a process used to add material to the surface of a substrate. The deposition is used to create the layers that makeup MEMS devices, such as the electrodes and the membranes (Hamdana et al. 2018; Pershin and Slipko 2019). There are two main types of deposition: physical vapor deposition (PVD) and chemical vapor deposition (CVD). PVD is a technology used for the deposition of thin films on materials to be employed for diverse applications some of which are to improve tribological behaviour, enhance optical properties, improve aesthetic qualities, and several other applications in various fields (Tokashvand et al. 2024; Baptista et al. 2018; Korhonen et al. 2018; Fox-Robinovich et al 2016; Hoche et al. 2014), while CVD involves the addition of a solid on a heated surface through a chemical reaction in the vapor phase (Torkashvand et al. 2024; Pierson 1998; Conti et al. 2020; Won et al. 2022)

Bonding: Bonding is a process used to join two or more substrates together. Bonding is used to create the structures that makeup MEMS devices, such as the micro-accelerometer and the micro-gyroscope. There are two main types of bonding: anodic bonding and solder bonding. Anodic bonding is a process used to join two or more substrates together using an electric field while Solder bonding is a process used to join two or more substrates together using solder.

Microelectromechanical systems (MEMS) devices are typically made using semiconductor fabrication processes, similar to those used in the production of integrated circuits (ICs). The manufacturing of MEMS devices involves several key steps, including design, material selection, wafer processing, and packaging (Senturia, 2001; Maluf and Williams 2004) as shown in Fig. (3).

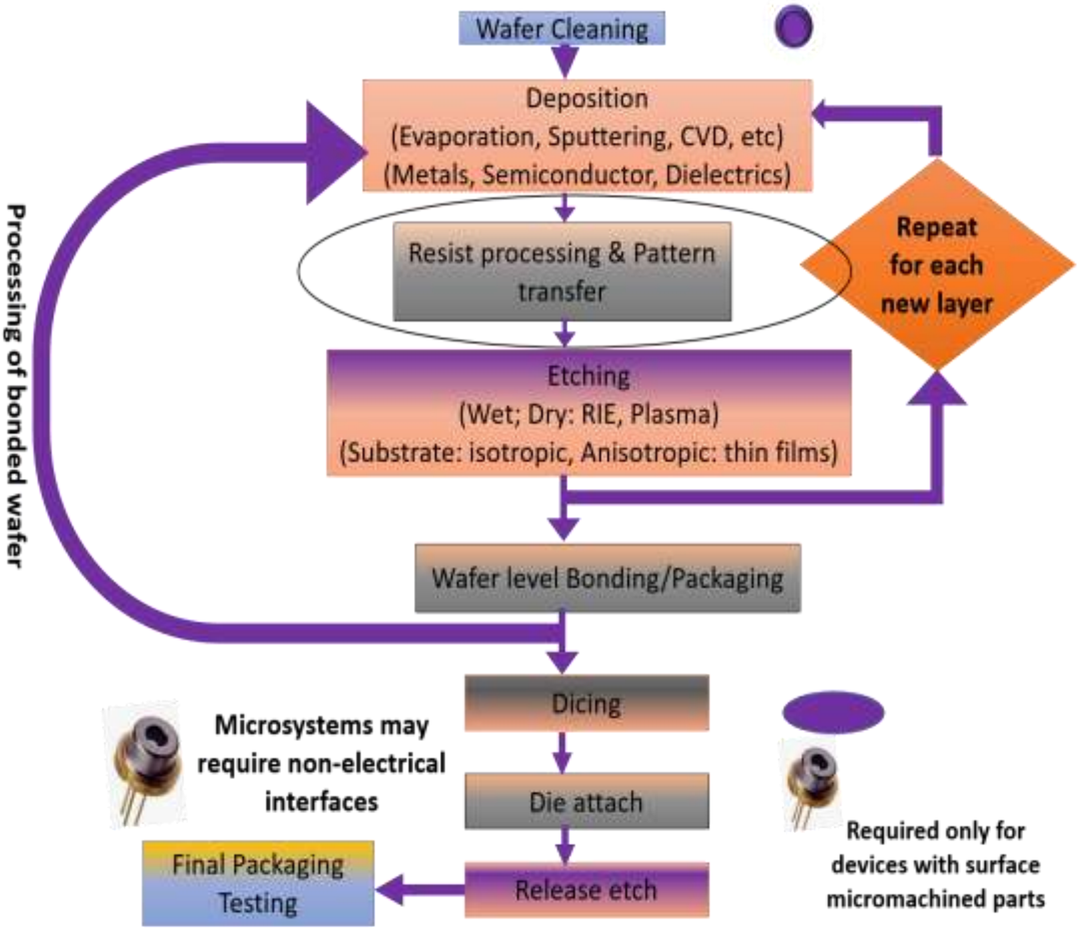


Figure. 3: Steps and Processes involved in MEMS Manufacturing

Key Steps in the Manufacturing of MEMS Devices and Systems:

Design: The first step in creating a MEMS device is the design phase. Engineers use computer-aided design (CAD) software to create the layout and geometry of the device, including the microstructures and electrical components.

Material Selection: Depending on the desired functionality of the MEMS device, suitable materials are chosen. Common materials used in MEMS fabrication include silicon, silicon dioxide, metals (such as gold or aluminum), polymers, targets and various chemicals.

Wafer Processing:

a. Substrate Preparation: Typically, a silicon wafer is used as the base material for MEMS fabrication. The wafer is thoroughly cleaned and prepared to ensure a contamination-free surface.

b. Thin Film Deposition: Films are deposited onto the wafer using techniques like physical vapor deposition (PVD), chemical vapor deposition (CVD), or magnetron sputtering system. These films may serve as structural layers, conductive layers, or insulating layers.

c. Lithography: A layer of photosensitive material, called photoresist, is applied to the wafer surface. A photomask, containing the desired pattern, is then used to expose the photoresist to ultraviolet light. This process defines the areas where subsequent etching or deposition steps will occur.

d. Etching: Etching techniques such as wet etching or dry etching (plasma etching) are used to selectively remove material from the wafer or film. This step creates the desired microstructures and features of the MEMS device.

e. Doping: If necessary, dopants can be introduced into the wafer to modify its electrical properties. This step is typically performed using ion implantation or diffusion processes.

f. Metallization: Metal layers are deposited and patterned to create electrical interconnects and contacts between different components of the MEMS device.

Packaging: Once the MEMS device is fabricated on the wafer, it needs to be packaged to protect it from oxidation or any other environmental factors and provide electrical connections. Packaging involves encapsulating the wafer with a protective material, and connecting the device's electrical terminals to external leads or connectors.

Advantages of Micromachining

One of the main advantages of micromachining is its ability to produce parts with very tight tolerances. This allows for parts to be made with high precision and accuracy. Additionally, the process is relatively fast and cost-effective compared to traditional machining methods. It also allows for complex shapes to be created with ease.

Disadvantages of Micromachining

Despite its advantages, there are some drawbacks to micromachining. One of the main disadvantages is that it can be difficult to achieve high levels of accuracy when working with very small parts. Additionally, the process can be time-consuming and expensive due to the specialized tools and techniques required. Finally, the process can be dangerous due to the use of lasers and other high-powered tools.

Micromachining VS Precision Machining

Micromachining is a manufacturing technique that ensures the manufacture of miniaturized products (devices, complex structures and systems) with ultra-high precision, multifunctional, lightweight, less mobility, less energy consumption, and higher efficiency (Jack 2001). This machining method makes the miniaturization of components and microsystems very feasible (Bao 2020). Taniguchi, (1983) reveals that the trend in machining advancement is determined by the achievement of machining accuracy and speed of achieving the final products. This trend is followed from conventional machining (1 to 100 um) to ultra-precision machining (1 nm) up to micromachining with product dimensions of about (1 to 500 um), the size cannot be achieved by any other machining process (Byrne, 2003).

Mechanical and Industrial Applications of Micromachining and MEMS

Micromachining and MEMS technology have been widely used in many industries for various applications, including sensors, actuators, displays, and communication devices (Mishra et al. 2019; Kageyama et al. 2018; Collet & Liu 2013).

SENSORS:

MEMS sensors are widely used in various applications, such as security alarms, automotive, healthcare, and environmental monitoring. For example, MEMS accelerometers are used in automotive applications to measure acceleration, deceleration, and vibration, while MEMS gyroscopes are used to measure orientation and angular velocity (Algamili 2021; Mohd et al. 2020). In healthcare, MEMS sensors are used to monitor vital signs, such as heart rate, blood pressure, and body temperature, while in environmental monitoring, MEMS sensors are used to measure temperature, humidity, and air quality.

ACTUATORS:

MEMS actuators are used to convert electrical signals into mechanical motion, and are widely used in various applications, such as microfluidics, medical devices, and robotics. For example, MEMS microvalves are used in microfluidic devices to control the flow of fluids, while MEMS motors are used in medical devices, such as drug delivery systems, to deliver precise dosages of medication. In robotics, MEMS actuators are used to provide fine motion control, allowing for the creation of small and highly precise robots (Qu et al. 2017; Sigh & Patrikar 2019).

DISPLAY:

MEMS displays are used to create high-resolution and flexible displays, and are widely used in various applications, such as mobile phones, tablets, and wearable devices. For example, MEMS displays use microscale structures to create pixels, which can be controlled to display different colors and patterns. These displays are highly energy efficient and have a long lifespan, making them ideal for use in portable devices.

COMMUNICATION DEVICES:

MEMS technology is also widely used in the development of communication devices, such as mobile phones, laptops, and wireless routers. For example, MEMS microphones are used to capture sound and convert it into electrical signals, while MEMS oscillators are used to generate precise frequency signals for wireless communication (Mohd et al. 2020; Dennis et al. 2015; Algamili 2021). More of the applications are highlighted below;

Accelerometers and pressure sensors are the MEMS components that are the most developed. Since 1979, the automotive industry has employed MAP (manifold absolute pressure) sensors. Many cars contain one of these sensors in their electronic engine control system, according to (Grace, 1999). Blood pressure sensor applications in medicine frequently involve pressure sensors as well. Since 1990, automobiles have employed accelerometers as airbag crash sensors. The incorporation of diagnostic capabilities into sensors allows for the identification of internal device failures in addition to a large decrease in bulk. Mechanical masses supported by flexures and integrated sensors are components of a micromachined accelerometer. The sensor is put together through integration and then placed in a sealed, rigid package. The sensor has a moving beam structure to detect relative movement in addition to a set of fixed beams. The proximity of the beams might lead to stiction. In 1999, Hartzel and Woodilla created a mechanism for predicting field failures due to stiction. The creation of an IC package for a micromachined accelerometer for automotive applications was discussed by (Spangler 1999). The usage of surface-mountable packages rather than single-in-line-through packages (SIP) was designed in their most recent development activity. The old die product was given new life by the surface-mountable device (SMD) version, which also complied with surface-mount component specifications.

Challenges and Future Prospects of Micromachining and MEMS

Despite the wide range of applications and successes of micromachining and MEMS, there are still several challenges that need to be addressed in order to advance these technologies. Some of the key challenges include:

Temperature drifts: MEMS sensors sometimes have a larger drift over temperature. These defects can only affect material that do not possesses temperature compensation or heating capabilities. MEMS sensor typically have lower precision. Therefore, it is highly required to identify the MEMS that perfectly match your device operation. MEMS sensors are perfect for applications that do not need the highest accuracy such as industrial automation, platform leveling, position control and pitch and roll measurements. This is why MEMS electrolytic sensors are the perfect fit for many different fields and at a low cost.

Cost: The production of micromachined and MEMS devices can be expensive, especially for large-scale production. This can limit the adoption of these technologies in certain applications which will reduce its usage in low income communities.

Reliability: Micromachined and MEMS devices can be prone to failure due to their small size and complexity. Improving the reliability of these devices is crucial in order to ensure their long-term performance.

Materials: The choice of materials for micromachining and MEMS is limited, and there is a need for the development of new materials that are suitable for these technologies. Researchers are urged to intensify their work to discover more abundant and cost-effective materials for the scarce ones.

Regardless of these challenges, the future prospects for micromachining and MEMS are bright. These technologies are expected to continue to advance and find new applications in various fields, including healthcare, energy, and transportation. In particular, the integration of micromachining and MEMS with other emerging technologies, such as artificial intelligence and the Internet of Things, is expected to lead to the development of novel and highly advanced systems (Mohd et al. 2020).

The future of MEMS and sensors; the need for use in Artificial Intelligence

To realize global awareness, we also need artificial intelligence (AI), but first, we have challenges to solve. Activity tracking, for example, requires accurate live classification of AI data. Relegating all AI processing to a main processor, however, would consume significant CPU resources, reducing available processing power. Likewise, storing all AI data on the device would push up storage costs. To marry AI with MEMS, we must do the following:

1. Decouple feature processing from the execution of the classification engine to a more powerful external processor.
2. Reduce storage and processing demands by deploying only the features required for accurate activity recognition.
3. Install low-power MEMS sensors that can incorporate data from multiple sensors (sensor fusion) and enable pre-processing for always-on execution.
4. Retrain the model with system-supported data that can accurately identify the user's activities.

There are two ways to add AI and software in mobile and automotive applications. The first is a centralized approach, where sensor data is processed in the auxiliary power unit (APU) that contains the software. The second is a decentralized approach, where the sensor chip is localized in the same package, close to the software and the AI (in the Digital Signal Processors (DSP) for a Complementary Metal-Oxide Semiconductor (CMOS) image sensor, for example). Whatever the approach, MEMS and sensors manufacturers need to understand AI, although they are unlikely to gain much value at the sensor-chip level.

II. CONCLUSION

In conclusion, micromachining is a process that can be used to create small parts and components with precise dimensions and tolerances. It has many advantages, such as its ability to produce parts with tight tolerances and its cost-effectiveness compared to traditional machining methods. Micromachining and MEMS are emerging technologies that have revolutionized the field of microelectronics and have been widely used in various applications, such as sensors, actuators, displays, and communication devices. However, there are some drawbacks to the process, such as its difficulty in achieving high levels of accuracy and its potential danger due to the use of high-powered tools. Despite these drawbacks faced by this technology in various filed, micromachining and MEMS remain an essential tool for many industries and has many potential applications. Their future prospects are bright, and they are expected to continue to advance and find new applications.

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