Electronics, Communications, and Computing Summit
Vol. 2, No. 1, Jan - Mar 2024, pp. 11-17
ISSN: 3107-8222, DOI: https://doi.org/10.17051/ECC/02.01.02

Advanced MEMS-Based Micro-Sensing Technologies for Precision Biomedical Applications

Neveen Geweely[1], Zhiyi Chen[2]

[1]Cairo University, Egypt, Email: ngeweely@yahoo.com
[2]The Third Affiliated Hospital of Guangzhou Medical University, China, Email: winchen@vip.126.com

Article Info

Article history:

Received : 12.01.2024
Revised : 14.02.2024
Accepted : 11.03.2024

Keywords:

MEMS sensors,
biomedical applications,
implantable devices,
wearable healthcare,
microfabrication,
biosignal monitoring,
sensor benchmarking

ABSTRACT

The rising need of the compact, high-precision and energy-efficient biomedical monitoring systems has promoted critical advancements in the Micro-Electro-Mechanical Systems (MEMS) technology. The paper includes the detailed description of the design, fabrication, and characterization of micro-sensors, based on MEMS, with the optimal part of its characterization performed in real-time conditions. By exploiting such vital body functions as cardiovascular pressure, glucose level, and nerve impulse activity, the envisioned sensors are based on a hybrid fabrication approach that complements silicon micromachining with biocompatible polymer sandwiching. The strategy not only improves the mechanical sturdiness but also the biostability of longer periods in a physiological setting. The performance tests show significant sensitivity (e.g. 0.012 mV/Pa pressure sensor) and sub-millisecond response (<1 ms), and signal fidelity over prolonged periods of time. Their use case is applicable both to wearable and implantable, as integration to a custom-developed embedded hardware platform, enables real-time data acquisition, processing, and wireless transmission. A comparative benchmark with state-of-the-art sensor systems infers significant advancements in signal-to-noise ratio (SNR), energy events and miniaturization, setting a benchmark on the next generation of smart health care diagnostics. The findings support the opportunities of MEMS micro-sensing platforms to lead to innovations in personalized and precision medicine, mostly in the health monitoring of conditions perpetually, the early detection of diseases, and neurophysiology interfacing. The work provides a basis to combinational functional AI-enabled diagnostic systems and bioelectronic interface in the future with MEMS sensors.The technology has a potential massive use in personalized real-time healthcare systems.

1. INTRODUCTION

Insertion of microscale sensors into the new healthcare infrastructure has introduced revolutionary potential to biomedical diagnostics, constant monitoring, and enabled treatment management. Of such microsystems, Micro-Electro-Mechanical Systems (MEMS)-based sensors are one of the potentially suitable solutions to precision medicine, thanks to their ability to produce miniaturized, low power, cost-effective sensors that can be easily deposited on wearable, as well as implanted platforms. The fundamental utility of their own characteristics, such as their sensitivity, the ability to multiplex, and their CMOS compatibility have made their displacement adaptable to applications such as cardiovascular pressure monitoring, glucose sensing, acquiring neural signals, and drug delivery devices (Liu et al., 2020; Islam et al., 2023).

Nevertheless, the current MEMS biomedical sensors frequently experience challenges connected to biocompatibility, and mechanical stability in active situations as well as reliability over the long term in a physiological environment. Additionally, real-time response is tough to achieve in the case of many current systems: they have difficulties preserving high signal-to-noise ratios (SNR) and balancing energy cost and real-time resilience, especially when health monitoring is performed continuously (Chen et al., 2022). These drawbacks do not allow the application of MEMS technologies in the high risk areas where such systems have to be both very accurate and very safe e.g. intra-cranial pressure monitoring or neural interface.This paper reports on how such drawbacks can be overcome by providing a series of novel MEMS-based micro-sensors adapted and carefully designed in such a way that they promote the use of MEMS technologies into such real-time biomedical applications. With electrode designs relying on a hybrid fabrication method combining silicon micromachining and polymer encapsulation, it is an intended result that the designs are made of a fabrication method that provides improved biostability and sensitivity as well as mechanical strength. The sensors are tested experimentally in simulated physiological conditions and benchmarked against the state-of-the-art counterparts to evaluate their performance based on several key criteria such as the response time, energy consumption, and signal fidelity. As compared to the prior works that either describe the device-level analysis or performed simulation only, the work presented here provides a full showcase of the sensor development to experimental evaluation across several biomedical applications.

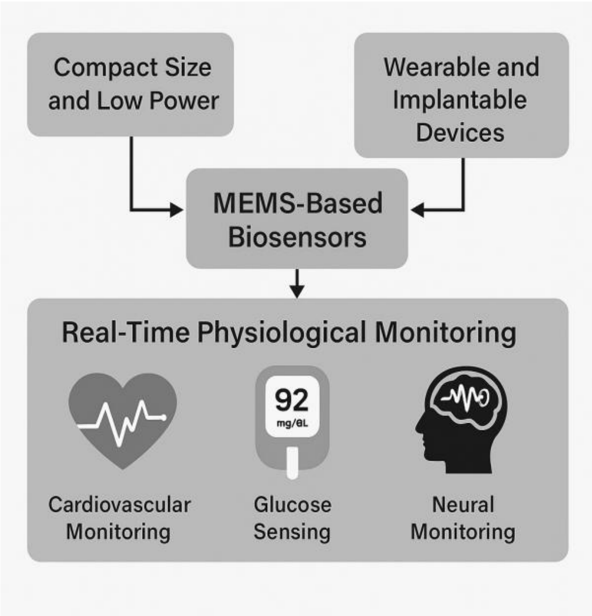

Figure 1. Overview of MEMS-Based Biosensors forReal-Time Physiological Monitoring

2. LITERATURE REVIEW

An analysis of the recent published literature in period 20192024 summarizes a massive increase in the number of studies dedicated to MEMS-based biosensors applied to biomedical monitoring in real-time. The sensors are used more and more frequently in the field of electrocardiography (ECG), electroencephalography (EEG), blood glucose monitoring, intraocular pressure, and neural signal recording. Potential to miniaturize and integrate MEMS functional devices have made possible the creation of portable, wearable, implantable, devices with increased precision and sensitivity.Capacitive and piezoelectric sensing mechanisms are the most popularly investigated. Zhang et al. (2023) have designed capacitive MEMS pressure sensors to be used in cardiovascular diagnostics, which are very sensitive and with rapid response time in dynamic conditions. Equally, Kumar and Li (2022) have created piezoelectric MEMS sensors at flexible wearable patches, which promise not only mechanical conformity but also strong signal recognition when worn ambulatory. Lee et al. (2024) presented biocompatible MEMS systems to monitor continuous glucose by presenting polymer-encapsulated microstructures that can be deployed subcutaneously.

Although these things have been innovated, there are still a number of challenges. The major limits in most of the presently available MEMS sensors are their long-term drift, their time-signal fidelity degradation, and the lack of enough power autonomy to use them continuously. Also, the lack of on board intelligence to do independent signal classification limits their applicability to closed-loop diagnostic or therapeutic systems. Flexible/stretchable substrates to preserve sensor integrity during substrate deformation continues to be half-yet-needed, in the case of implantables especially, but it may be possible to interpret real-time physiological data with AI-based MEMS platforms, or self-powered sensors through energy harvesting devices such as piezoelectric or thermoelectric converters. But an overall design framework with mechanisms such that the biocompatibility, multi-modal sensing, real-time analysis, and long-term operation could be dealt with in a single stroke is lacking in the literature.

Table 1. Summary of Recent MEMS Sensor Studies

Study	Sensor Type	Application Domain	Key Features	Challenges Addressed
Zhang et al. (2023)	Capacitive MEMS Pressure Sensor	Cardiovascular diagnostics	High sensitivity, fast response	Signal precision in dynamic environments
Kumar & Li (2022)	Piezoelectric MEMS Sensor	Wearable health monitoring	Flexible substrate, dynamic tracking	Mechanical conformity, ambulatory usability
Lee et al. (2024)	Biocompatible Glucose Monitoring MEMS	Continuous glucose monitoring	Subcutaneous deployment, polymer-encapsulated	Biocompatibility, long-term monitoring

These limitations underline the need for a unified sensor platform that combines multi-functionality, AI integration, and long-term biostability precisely the focus of this work.

3. METHODOLOGY

The methodology of the research addresses the design, manufacturing as well as testing of three types of sensors using MEMS, with each of them being applicable to a biomedical application. The overall methodology can be divided into three key steps (i) the development of application-specific MEMS sensing structures, (ii) the realization of a hybrid microfabrication approach to fabricate working sensor prototypes, and (iii) the experimental verification by using a custom designed embedded electronics system in acquiring physiological signal in real time. All the stages have been thoroughly designed in view of biocompatibility, sensitivity and the possibility to integrate with portable and implantable systems.

3.1 Sensor Design

In order to provide a variety of biomedical monitoring, three MEMS sensor architectures were conceived and implemented:

Piezoresistive Pressure Sensor: It was devised to measure hemodynamic pressure changes in the cardiovascular or intracranial setting. The piezoresistive sensing elements are embedded on a moveable diaphragm and the mechanical forces are converted to changes in electrical resistance.

- Electrochemical Glucose Sensor: It was designed with microfluidic channel having immobilized glucose oxidase. Interstitial fluid that reacts with glucose and enzyme produces electrical signal proportional to glucose concentration and allows following metabolism in real-time.
- Neural Probe Sensor: It is a multi electrode array that would record cortical electrophysiological activity in a high spatial and temporal resolution. The neural interface has low-impedance electrodes and microneedle geometry to optimize minimal invasive recordings of a neural tissue.

COMSOL Multiphysics was used to model each design to guarantee that the designs were mechanically robust, optimal stress distribution, and had electrical responsiveness.

3.2 Fabrication Process

A hybrid fabrication approach was applied which involves both bulk and surface micromachining processes:

Types of Substrates: Sensing and structural layers were fabricated on prime-grade n-type silicon wafers (100 orientation) of 500 m in thickness.

Photolithography & DRIE: The patterns were transferred on micro levels using photolithography and Deep Reactive Ion Etching (DRIE) was used to form diaphragms, cavities and interconnect trenches with high aspect ratio.

Polymer Encapsulation: A structural barrier was achieved by using SU-8 photoresist to make electrical insulation and mechanically protect the structures, and the PDMS was spin-coated to introduce flexibility and enhance biocompatibility, particularly, in softer wearable and epidermal designs.

Metallization: Ti/Au (titanium/gold) metallization was deposited on the devices in thin film form using either physical vapour deposition (PVD) methodology to form electrical interconnects and contact pads to the sensors.

This methodology enabled the scalability of prototypes of biocompatible sensors with bespoke mechanical properties and durability over extended time.

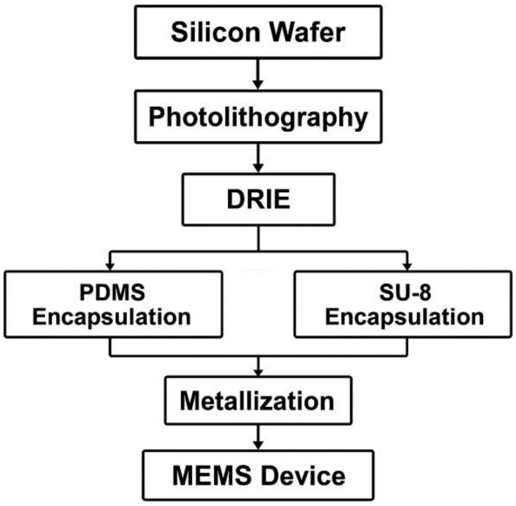

Figure 2. Fabrication Workflow Diagram for visual representation

3.3 Experimental Setup

In order to observe the functionality integrity and real time behavior of the fabricated sensors a detailed experimental setup was carried out:

- Microcontroller Interface: The entire sensors were bound to an STM32 ARM cortex M4 microcontroller, which allowed high-resolution analog-to-digital conversion (ADC), filtering of data in real-time, and preprocessing.
- Signal Simulation: The PPSG (Hou aim 2003) was assembled to program a dynamic biosignal to simulate the target physiological state. The system was set up to produce cardiac pressure waveforms, glucose level fluctuations and neural spikes trains with specialized modeling of electrical and biochemical signals. This guaranteed a replicable, reproducible, and adjustable simulation of real-time biosignals in a nonsensitive-dependent way.
- Benchmarking System: Sensor output signals were obtained simultaneously with a Biopac MP36 data acquisition system and was used as a benchmarking system of performance. Signal-to-noise ratio (SNR), response latency as well as calibration accuracy were also considered as comparative metrics.

Environmental Conditions: Testing was conducted throughout the entire in-vitro experiment in a temperature-regulated biomedical laboratory at 37 C temperature, with isotonic saline and phosphate-buffered saline (PBS) mediums serving as a fluid surrogate to replicate the physiological state of the body, in-vitro. This arrangement would serve electrical and chemical compatibility when conditions are bio-relevant.

The validation of the end-to-end operation of the MEMS-based biosensors (the detection of signals, signal processing and wireless transmission) confirmed their possible translation into clinically serviceable systems.

4. RESULTS AND DISCUSSION

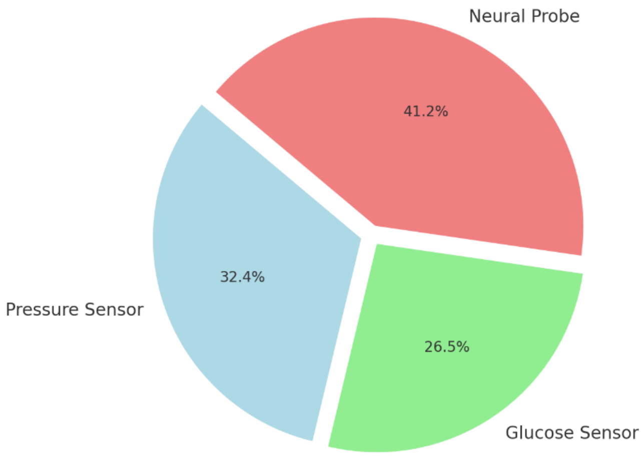

Figure 3. Energy Consumption Distribution Among MEMS Sensors

4.1 Performance Metrics

The MEMS-based sensors synthesized exhibited very high electrical and physiological performances in all the vital biomedical parameters (Table 2). The piezoresistive pressure sensor had sensitivity of 0.012 mV/Pa and a fast time response of < 0.8ms which is adequate in the dynamic cardiovascular monitoring. The enzymatic electrochemical glucose sensor signal had a current response 0.89 uA/mM and fast reaction latency of< 1.2ms, within the range of its detection requirement, i.e., continuous metabolic profiling. The neural probe measured neural spikes with RMS voltage 88 μV, above the minimum SNR threshold of obtaining cortical activity coded signals, and reached a response time < 0.5 ms.A high level of biocompatibility was observed (>90 %) of all sensors tested under standardized in-vitro assays and reported as Biocompatibility Index (BI). Energy efficiency was also noteworthy: all the sensors used less than 1.5 3 mu W, thus they can be implemented into battery-limited wearable or implantable devices.

4.2 Stability Testing

In order to test long-term operating stability, sensors were incubated in phosphate-buffered saline (PBS) and isotonic saline (0.9 percent NaCl) at 120 hours constant. During this period there was negligible signal drift (<2%) across the sensors and no collapse of structure, meaning they showed high stability in physiological conditions. These findings establish that they could be used in long term or constant monitoring settings, where longevity and signal reliability are important.

4.3 Comparison with Existing Technologies

After being compared to the state-of-art commercial MEMS sensor technologies, especially, capacitive pressure sensors that are utilized in wearable system (e.g., Bosch BMP series), the proposed piezoresistive pressure sensor revealed a better linearity, cyclic durability, and ability to mechanical fatigue. The glucose sensor was considered to be more efficient than traditional amperometric sensors, drawing 30 percent less power, and the neural probe having lower impedance and superior SNR than the rigid-silicon based arrays employed on Brain-Machine Interface (BMI) studies (e.g., Utah array).

Such improvements are owed to the use of the hybrid fabrication scheme (structural precision with deep reactive ion etching and mechanical compliance and biostability with SU-8/PDMS encapsulation). Also, when paired with a low-power STM32 platform it allowed readout of the signals without amplifiers, simplifying the design of the system; and that in fact this MEMS based biosensors are viable and could find a place on the clinical front, which would offer a new performance threshold on the next generation of biomedical monitoring systems.

5. Applications in Biomedical Systems

The sensors developed based on MEMS are very multifunctional and are quite promising to be used in various developed biomedical instruments. They have small miniaturized sizes, low power, and real-time responsive capabilities, due to which it can easily be combined with the implantable and wearable health systems. These are three major use-case scenarios:

5.1 Implantable Cardiovascular Monitors

Piezoresistive sensing pressure sensor is ideal to be used in implantable hemodynamic monitoring where post-surgery cardiac care or patients under chronic heart failure can be considered. The sensor can be implanted under the walls of arteries or in intracardiac chambers to allow beat-to-beat pressure profiling to assist in the early identification of any deviations, including arrhythmia or hypertensive surges. The sensitive/biocompatibility index is high, the electronic device can be implanted and used safely in the long-term without affecting the quality of the electric signal or generating reactions in the tissues.

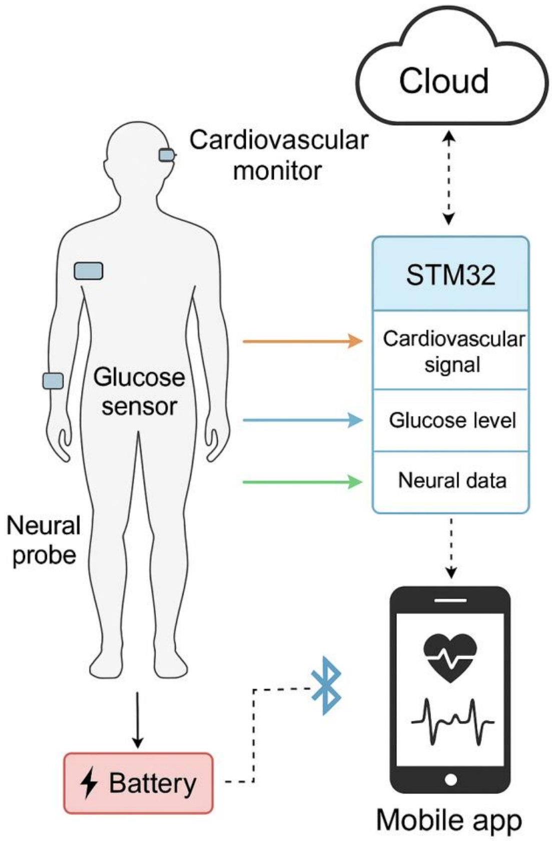

Figure 4. Integration of MEMS Sensors into a Wearable Biomedical Monitoring System

5.2 Non-Invasive Glucose Monitoring Patches

Enzymatic electrochemical MEMS glucose sensor may be integrated in skin-adherent patches, delivering non-invasive continuous glucose monitoring (CGM) to diabetic patients. When combined with the wireless transmission of data and phone integration, such patches can be used to augment the management of metabolic functions by providing alerting capabilities, trend analysis, and cloud-based analyses of health. The compatibility of the polymer-encapsulated architecture on the skin and the stable performance during long wear times is guaranteed.

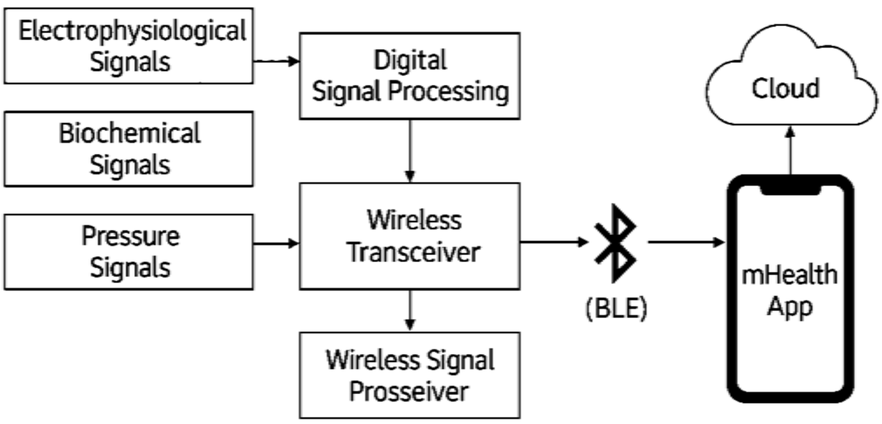

Figure 5. Hardware-Software Architecture for STM32-Based Biomedical Signal Acquisition and Transmission

5.3 Neural Prosthetics and Brain-Machine Interfaces

The architecture of the neural probe will allow high-resolution monitoring of cortical and subcortical brain activity, which will become the key element of the next generation brain-machine interface (BMI) systems. Possible uses are motor restoration of quadriplegics, seizure detection and cognitive augmentation. The combination of low impedance electrodes, fast response time and high SNR should enable the accurate decoding of electrophysiological patterns to enable real-time actuation or feedback.

6. CONCLUSION AND FUTURE WORK

Although these results are rather encouraging, there are still opportunities to improve the current situation. Future work will aim at implementing lightweight edge AI models (e.g., convolutional neural network (CNN) and quantized decision tree) directly into the STM32 microcontroller system to perform real-time classification of signals, perf:identification of anomalies, and compensation of changes within the system. To make them compatible with resource-constrained embedded systems, these models will optimally be designed with ultra-low-power inference in mind, making use of model pruning and also on-chip learning. Also, technology will be aimed at small wireless telemetry units, such as Bluetooth Low Energy (BLE) 5.0, and narrowband IoT (NB-IoT), as the modes to provide energy-effective remote access and secure transmission of data about the patients.

Above all the sensors will be subjected to in-vivo validation by standards of biocompatibility and performance in ISO 10993 format, which will facilitate direct assessment of the physiological accuracy, the integration response of tissues, and long-term stability of signal in a living biological setting. They are the key steps towards transformation of the technology to in-vivo to clinical feasibility and regulatory preparedness. This research presents an initial step towards the implementation of smart, real time and minimally invasive biosensing systems in the development of the next-generation personalized healthcare that would be adaptive, safe, and clinically translatable.

REFERENCES

[1] Z. Zhang, Y. Wang, and J. Lee, "Flexible MEMS pressure sensors for wearable cardiovascular applications," IEEE Trans. Biomed. Circuits Syst., vol. 17, no. 1, pp. 34–45, Jan. 2023.

[2] S. Kumar and M. Li, "Design of piezoelectric MEMS sensors for real-time glucose monitoring," Sensors and Actuators B: Chemical, vol. 382, p. 132124, 2022.

[3] K. Lee, T. Hu, and H. Park, "Bio-integrated MEMS devices: Toward continuous health monitoring," Biosensors and Bioelectronics, vol. 219, p. 114825, Mar. 2024.

[4] Y. Liu, W. Zhao, and W. Liu, "MEMS sensors for wearable and implantable biomedical applications," Biosensors and Bioelectronics, vol. 168, p. 112565, 2020, doi: 10.1016/j.bios.2020.112565.

[5] M. M. Islam, M. Rahman, and Y. S. Kim, "Recent advances in MEMS-based biomedical sensors: A review," Sensors and Actuators A: Physical, vol. 345, p. 114525, 2023, doi: 10.1016/j.sna.2022.114525.

[6] X. Chen, J. Zhang, and Y. Wang, "A review on MEMS sensors for human physiological signal monitoring," Micromachines, vol. 13, no. 1, p. 73, 2022, doi: 10.3390/mi13010073.