

ENHANCING BLOOD PRESSURE SENSITIVITY: INNOVATIVE C-SHAPED SLOT DESIGN IN MICROSENSOR SYSTEMS

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Abstract. *In this article, we successfully developed and simulated a wearable pressure sensor for monitoring blood pressure. This sensor utilizes MEMS technology and is based on LC wireless, eliminating the need for a battery system. The sensor is constructed with a metal-insulator-metal capacitive design, featuring a diaphragm measuring $1.1\text{ mm} \times 1.1\text{ mm}$ and with a thickness of $22\text{ }\mu\text{m}$. Furthermore, we devised a unique C-shaped circular slot diaphragm to enhance sensitivity by reducing the mechanical rigidity of the membrane. Our design and simulation were conducted using COMSOL Multiphysics. From our findings, we observed that the frequency response to varying pressure ranged from 285 to 445 MHz. Additionally, our results yielded a mechanical sensitivity of 125.7 nm/mmHg , along with a sensor sensitivity of 1.49 fF/mmHg . Notably, the sensor with the novel C-shaped circular slot diaphragm exhibited high-pressure sensitivity, surpassing that of a clamped diaphragm by 15.5%.*

Keywords: Biomedical monitoring, blood pressure, microsensors, pressure measurement, capacitive sensors, polyimides, sensitivity.

1. INTRODUCTION

Monitoring blood pressure is a crucial aspect of healthcare. The assessment and management of hypertension are not only costly but also carry grave implications for the individuals concerned [1]. High or low blood pressure can be indicative of hypertension, stroke, heart failure, and other ailments or circumstances [2]. Consequently, it is imperative to consistently and accurately observe blood pressure.

The current methodologies for measuring blood pressure encompass the utilization of non-occlusive monitoring through the implementation of PWP technologies [3] as well as the utilization of IoMT-based wearables [4], [5]. Nevertheless, these apparatuses have constraints in terms of their sensitivity. The advancement of non-invasive, wearable blood pressure measuring technology presents an exceptional prospect to transform this field by furnishing precise and frequent sensing capabilities beyond the confines of medical facilities [6]. A review examines the challenges and advances of non-invasive blood pressure

measurement techniques, highlighting the importance of accurate and frequent monitoring in realistic scenarios [6]. A viable method for blood pressure measurement involves employing a MEMS sensor, which converts blood pressure into an electrical signal [7]. The study of materials and their manufacturing processes, materials used in wearable MEMS devices, underlines the need for meticulous technical evaluation to optimize their performance [8], [9]. These collective findings underscore the importance of sensitivity in blood pressure measurement technology and the imperative for further advancements in this domain. Numerous studies have explored the complexities associated with developing highly sensitive MEMS sensors. Ambiguity, however, suggests that improving the resonant frequency of chemical sensors can improve sensitivity, although this is limited by difficulties associated with deflection detection and the application of coatings [10]. An implanted wireless blood pressure sensor with a polyimide membrane in the form of a circular clamped capacitor is presented [11]. Conversely, traditional wireless microsystems possess certain drawbacks, including high power consumption, large size, and limited sensitivity.

In this paper, we present a groundbreaking approach to address these constraints by introducing an innovative configuration of a circular MEMS sensor with a C-shaped slot. This innovative design will improve blood pressure sensitivity, decrease power consumption, and minimize size. We discuss the design and simulation of the suggested MEMS sensor in this way and compare its performance to that of a conventional MEMS sensor.

2. DESIGN AND SIMULATION

The suggested design intends to improve blood pressure sensor sensitivity by using a unique C-shaped slot circular structure inside the MEMS capacitive sensor. The MEMS capacitive sensor is composed of a diaphragm that deforms owing to external pressure with a coil that creates an inductance variation as a result of membrane deformation.

An external circuit detects the variation in inductance and converts it to a voltage output.

The proposed microsensor system is made up of a metal-insulator-metal (MIM) capacitive setup with a 600 μm radius and 22 μm thickness circular diaphragm with a C-shaped slot. Figure 1 depicts the schematic design of the proposed MEMS capacitive pressure sensor.

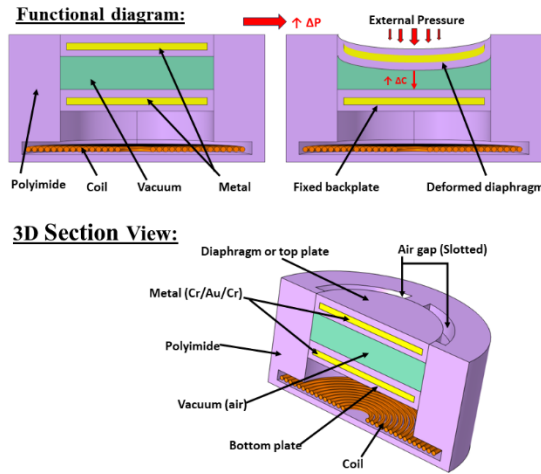


Figure 1. Schematic diagram of the proposed microsensor system.

The diaphragm is constructed of polyimide, which is biocompatible and a flexible material. The plate is constructed of metal (Cr/Au/Cr), which has a high melting point and is an excellent conductor. A vacuum gap between the diaphragm from the coil decreased parasitic capacitance and enhanced sensitivity. Table 1 shows the design parameters of the proposed MEMS sensor. Table 2 lists the material properties of the diagram.

Table 1 Design parameters of the proposed microsensor.

Thickness [μm]				Radius [μm]	
diaphragm	vacuum	(Cr/Au/Cr)	polyimide	Sensor	diaphragm
t	h	t_{metal}	t_{poly}	r_s	r
22	32	(0.01/0.1/0.01)	76	1100	600

Table 2 Material properties of the diaphragm.

Materials / Properties	Polyimide	Cr	Au
Young's modulus [Gpa]	2.98	279	70
Density [Kg/m^3]	1300	7150	19300
Poisson ratio	0.34	0.21	0.41
Electric conductivity [S/m]	—	7.9×10^6	4.56×10^7

The slotted diaphragm is intended to improve the diaphragm displacement under external pressure. The unique feature of

this design is the C-shaped slot that is purposefully carved into the circular diaphragm construction. This C-shape slot is similar to a semicircular groove positioned around the circumference of the circle. The cross-section and the top view of the proposed diaphragm are shown in Figure 2 and Figure 3, respectively.

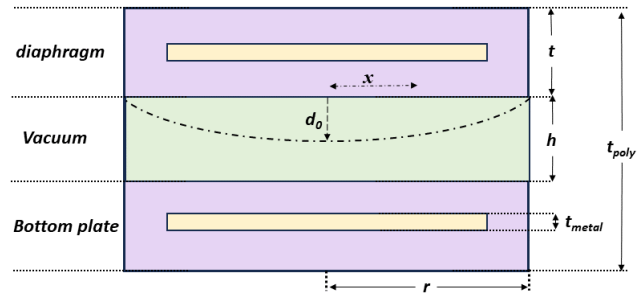


Figure 2. Cross section of the proposed diaphragm.

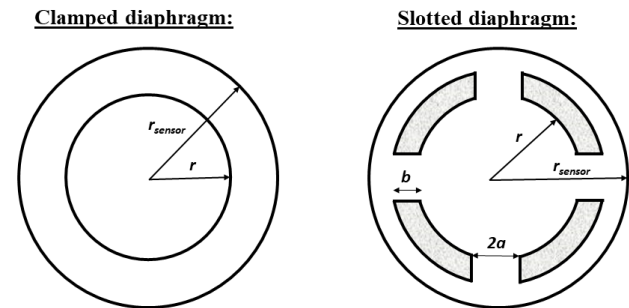


Figure 3. Top view of the diaphragm with the clamped and slotted diaphragm.

The C-shaped slot's purpose is to give the diaphragm large regulated flexibility so that it can respond to changes in applied pressure by more displacement. This novel design focuses on overcoming mechanical rigidity difficulties that are inherent in the clamped diaphragm, which frequently restricts sensitivity. This structural change is thought to improve sensitivity by allowing for larger variations in displacement, capacitance, and resonant frequency, resulting in the more precise transformation of minor pressure variations into observable electric signals.

The displacement equations explaining the pressure-induced deformation of the clamped circular diaphragm are given below, with maximum displacement d_0 at the center of the circular plate [12]:

$$d_0 = \frac{Pr^4}{64D \left[1 + 0.488 \left(\frac{d_0}{t} \right)^2 \right]} \quad (1)$$

$$D = \frac{Et^3}{12(1-\vartheta^2)} \quad (2)$$

Where P , r , D , t , E , and α are respectively applied pressure, diaphragm radius, flexural rigidity, diaphragm thickness, Young's modulus, and Poisson's ratio. The deflection $d(x)$ in the x -axis direction of the plate where x is the axial distance from the center of the diaphragm given by:

$$d(x) = d_0 \left(1 - \frac{x^2}{r^2} \right) \quad (3)$$

When the distance between two plates changes as external pressure is applied to the top plate, the capacitance changes. In actuality, the proposed circuit is made up of two series capacitors: a constant polyimide capacitor, C_{poly} , and a variable capacitor, C_{disp} . The following equations describe the capacitance changes caused by membrane displacement:

$$C_{disp} = \varepsilon_0 \int_0^{2\pi} \int_0^r \frac{x dx d\theta}{h-d(x)} = \frac{C_0}{\sqrt{\alpha}} \tanh^{-1}(\sqrt{\alpha}) \quad (4)$$

$$C_0 = \varepsilon_0 \frac{A}{d} \quad (4)$$

$$\alpha = \frac{d_0}{h} \quad (5)$$

$$C_{poly} = \frac{\varepsilon_0 \varepsilon_{poly} \pi r^2}{d_{poly}} \quad (6)$$

$$C_{total} = \frac{C_{disp} C_{poly}}{C_{disp} + C_{poly}} \quad (7)$$

Where ε_0 , h , C_0 , A , and C_{total} are the permittivity of free space, the thickness of the gap, the capacitance in parallel plate, Area, and the total capacitance, respectively. This microsensor is made up of a variable capacitance (C), and inductor (L). The resonance frequency of an LC microsensor may be defined as a function of both its capacitance and inductance:

$$f_{res} = \frac{1}{2\pi\sqrt{LC}} \quad (8)$$

The sensitivity of the sensor caused by pressure variations given by:

$$S_m = \frac{\Delta d}{\Delta P} = \frac{d_{max} - d_{min}}{P_{max} - P_{min}} \quad (9)$$

$$S_c = \frac{\Delta C}{\Delta P} = \frac{C_{max} - C_{min}}{P_{max} - P_{min}} \quad (10)$$

Where S_m and S_c are the mechanical and capacitance sensitivity.

3. RESULTS AND DISCUSSION

COMSOL Multiphysics software is used to simulate and analyze the proposed design's mechanical behavior, resonance frequency, and sensitivity to the applied pressure range. We applied a pressure range of 0-250 mmHg. To simulate diaphragm deformation, we utilized the Structural Mechanics Module and the AC/DC Module. The design parameters and material characteristics of the suggested MEMS sensor, as presented in Table 1 and Table 2 of the current study were utilized. We used the finite element method (FEM) to simulate the performance of the proposed MEMS sensor. The FEM is capable of resolving complicated geometries while producing reliable and accurate results. The simulation results are expected to provide insights into the electrical and mechanical properties of the unique C-shaped slot design, as well as its ability to improve blood pressure sensitivity when compared to the clamped design of the MEMS sensor.

In this section, we will discuss the effects of slot distance variation on the mechanical deformations of the suggested C-shaped slot diaphragm. As shown in Figure 3, a represents the slot distance, which is the distance between the two sides of the slotted diaphragm. We varied the slot distance between 5 and 200 μm . The simulation results for various slot distance values are shown in Figures 4 and 5. Figure 4 depicts the displacement variations as a function of applied pressure for various slot distance values.

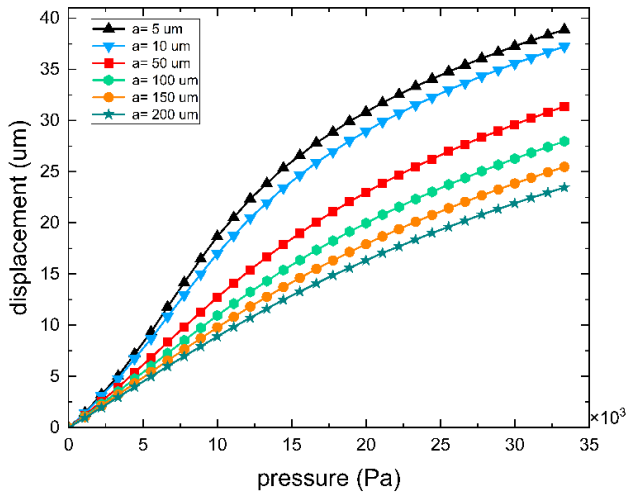


Figure 4. Displacement variations as a function of applied pressure for various slot distance values.

From Figure 4, we notice that when the slot distance “ a ” increases, it also increases the displacement for an applied pressure. This signifies that the larger slot distance diaphragm deforms more than the smaller slot distance diaphragm. This is because an increased slot distance causes a greater amount of stress around the slot, resulting in a higher displacement of the diaphragm.

Figure 5 depicts Von Mises stress variations as a function of applied pressure for various slot distance values. The Von Mises is a measure of similar stress in a material that induces mechanical strain.

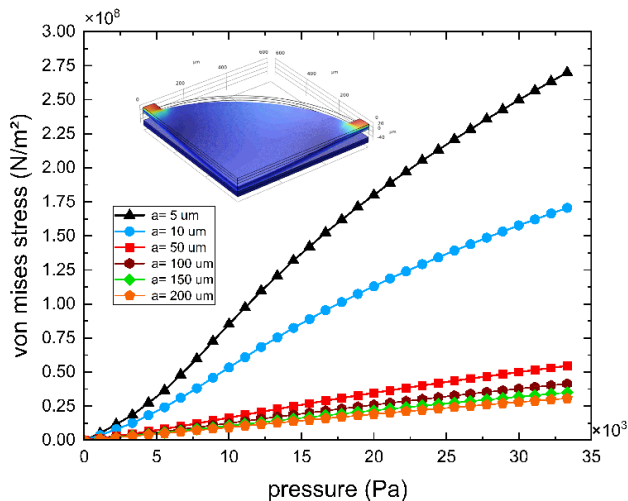


Figure 5. Von Mises stress of the diaphragm under different blood pressures and slot distances.

From Figure 5, we show that when the slot distance “ a ” is smaller than 50 μm , the Von Mises stress increases dramatically as pressure increases. This indicates that the diaphragm with the shortest slot distance is under more

stress than the diaphragm with the longest slot distance. This explains the nonlinearity observed in Figure 4 when the slot distance is around 5 and 10 μm . The nonlinearity suggests that the plate deforms more than the linear elasticity theory expects and may suffer mechanical deformation or damage. Diaphragm damage can have an impact on the MEMS sensor’s performance and reliability. As a result, we conclude that the optimal slot distance value is 50 μm , which has a moderate Von Mises stress and a linear displacement within the applied pressure range.

In this section, we will discuss the effects of slit circle width on the Von Mises stress of the proposed C-shaped slot diaphragm. As shown in Figure 3, b represents the slit circle width, which is the distance between the two circular slits of the slotted diaphragm. We varied the slit circle width between 5 and 100 μm . The simulation result for various slit circle width values is shown in Figure 6.

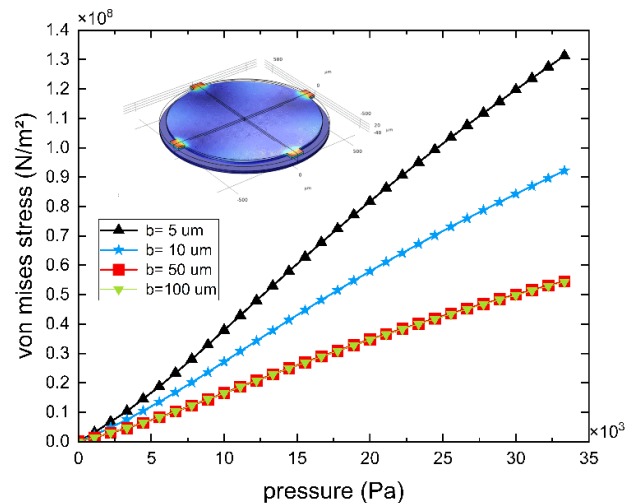


Figure 6. Von Mises stress of the diaphragm under different slit circle widths.

From Figure 6, we show that when the slit circle width “ b ” is smaller than 50 μm , the Von Mises stress increases dramatically as pressure increases. This indicates that the diaphragm with the shortest slit circle width is under more stress than the diaphragm with the longest slit circle width. The maximum stress is 54 MPa at the center and edge of the proposed slotted diaphragm, which is less than the yield point of polyimide. The yield point of polyimide is 80 MPa. As a result, we conclude that the optimal slit circle width value is 50 μm , which has a moderate Von Mises stress and a linear displacement within the applied pressure range.

Therefore, the optimal values for slot distance “ a ” and slit circle width “ b ” in the suggested diaphragm are 50 and 50 μm , respectively. These parameters optimize the design of

the C-shaped slot circular MEMS sensor for improved blood pressure sensitivity.

In this part, we compare and evaluate the outcomes of two different simulations, clamped and C-shaped circular slot diaphragm in MEMS sensors. Figure 7 is a set of 3D graphs that depict the surface displacement of the clamped and slotted diaphragm. The figure compares the surface deflection at a minimum and a maximum pressure of 0 to 33.33 Kpa. The 3D modeling results are obtained from the COMSOL Multiphysics software. We observe that the highest central displacement of a clamped diaphragm is 18.4 μm , while the maximum displacement of a C-shaped slot diaphragm is 31.4 μm .

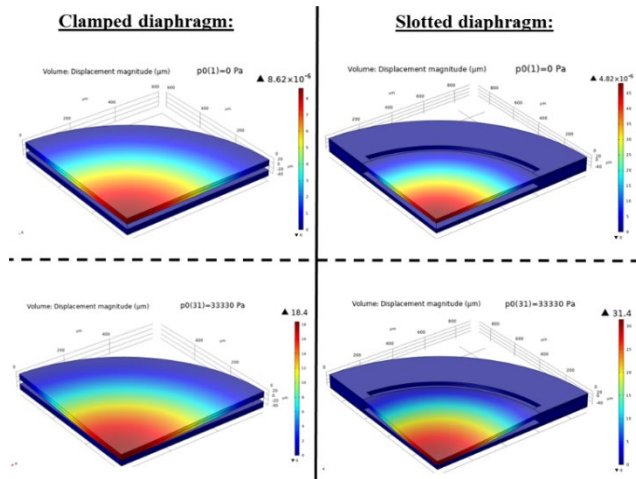


Figure 7. Modeling results of the diaphragm under applied pressure for the clamped and slotted designs.

Figure 8 shows the deflection of the diaphragm under applied pressure for the clamped and the C-shaped slot membrane. The deflection is obtained within the diaphragm center, where the most deformation occurs. To validate the simulation results, we made a theoretical graph for the clamped circular membrane and compared the simulation results with the results of the literature [11], which proves the accuracy of the simulation results we performed. The results show that the slotted plate has a higher displacement than the clamped diaphragm at all pressure ranges.

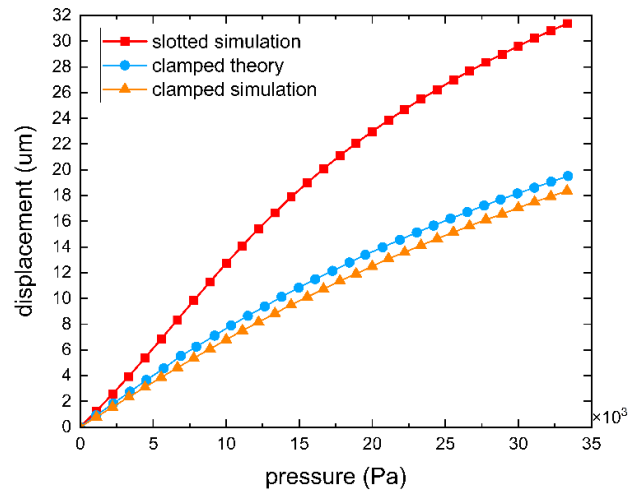


Figure 8. Displacement of the diaphragm under applied pressure for the clamped and slotted designs.

However, the difference between the two deflection increases as the pressure increases. For example, at 5 KPa, the clamped membrane has a displacement of 3.9 μm , while the slotted plate has a deflection of 5.9 μm , resulting in a difference of 2 μm .

At 33.33 Kpa, the clamped membrane has a deflection of 18.4 μm , while the slotted simulation has a deflection of 31.4 μm , resulting in a difference of 13 μm . This suggests that the C-shaped circular slot diaphragm is more effective at higher pressure, but the clamped circular diaphragm has more linearity at lower pressure.

We can conclude from the comparative analysis and outcome evaluations of the clamped and C-shaped slot diaphragm that the slit has a substantial influence on membrane deformation and stress under blood pressure. The slit improves the MEMS sensitivity at higher pressures while decreasing sensitivity at lower pressures. As a result, the ideal design of the MEMS sensor should consider the conflict between slit circle width, slot distance, and pressure range.

Figure 9 shows the capacitance of the proposed C-shaped circular plate under applied pressure. The results show that the capacitance increases linearly with the pressure, which indicates that the proposed MEMS sensor can measure the pressure accurately and effectively.

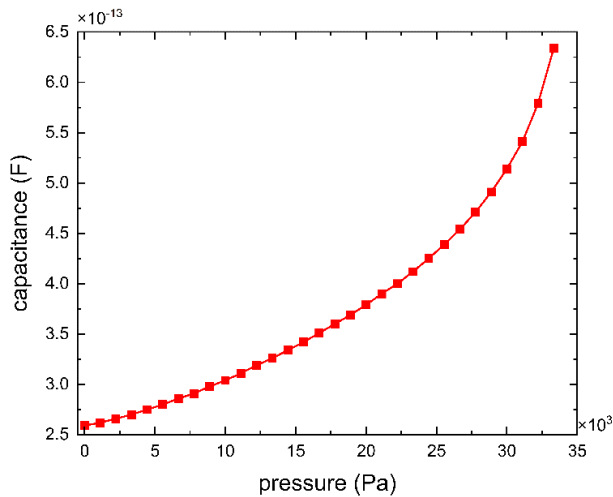


Figure 9. The capacitance of the proposed C-shaped circular plate under applied pressure.

Table 3. Comparison between previous works and new designs.

Ref	Material	Size [mm]	shape	mechanical sensitivity	capacitive sensitivity
[13]	Silicon	2.2×2.2	circular cuff	—	1 fF/mmHg
[14]	Su-8 polymer	3.13×3.16	circular	1.25 pm/mmHg	—
[11]	polyimide	2.2×2.2	circular	73.6 nm/mmHg	1.29 fF/mmHg
This work	polyimide	2.2×2.2	slotted circular	125.7 nm/mmHg	1.49 fF/mmHg

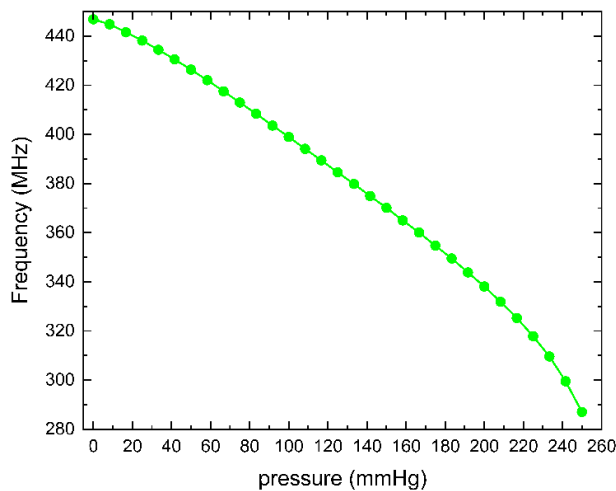


Figure 10. Resonance frequency under applied pressure.

According to the findings of this study, future advancements in capacitive blood pressure sensors may entail more investigation of structures and dielectric material, as well as the creation of novel microsensor designs. Table 3 shows a comparison between this work's results and previous works.

Figure 10 shows the simulation results of the resonance frequency under applied pressure for the MEMS sensor. The results show that the resonance frequency decreases as the pressure increases, which indicates that the wearable MEMS sensor can detect pressure changes by measuring the frequency changes. The maximum frequency is around 445 MHz at a pressure of 0 mmHg, and the minimum frequency is around 285 MHz at a pressure of 250 mmHg. The normal range of blood pressure is between 80 mmHg and 120 mmHg, with the frequency ranging from around 385 MHz to 410 MHz. The simulation results demonstrate the feasibility and reliability of the proposed wearable MEMS sensor for blood pressure measurement.

The sensitivity of the proposed MEMS sensor and the conventional sensor is calculated at 1.49 fF/mmHg and 1.29 fF/mmHg, respectively. Table 3 shows the comparison between previous works and new designs. The proposed wearable MEMS sensor has a sensitivity enhancement of 15.5% compared to the conventional blood microsensor system.

4. CONCLUSION

The purpose of this research is to suggest a unique C-shaped slot circular MEMS sensor that has been designed and simulated to improve blood pressure sensitivity. The design, which consists of a circular diaphragm with an inserted C-shaped slit, allows for more membrane deformation under blood pressure. An analysis of slit circle width and slot distance effects on diaphragm deflection and stress under varied pressure was conducted. The outcomes of the simulations showed that the suggested design outperformed the conventional system by 15.5%, with optimized slit circle width and slot distance of 50 μm each. Notably, capacitive sensitivity was obtained at 1.46 fF/mmHg whereas mechanical sensitivity was at 125.7 nm/mmHg. This study

highlights the design's potential to revolutionize blood pressure measuring technology, providing opportunities for enhanced healthcare. Future advancements in wireless blood pressure sensors may entail more investigation of structures and dielectric material, as well as the creation of novel microsensor designs.

5. Acknowledgments

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6. REFERENCE

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