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Sensitivity Analysis of ZnO NWs Based Soft Capacitive Pressure Sensors using Finite Element Modeling

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Abstract— **Pressure sensors make an important component of electronic skin and its application in robotics, human-machine interfaces, and health monitoring. In this regard, soft capacitive sensors based on elastomeric dielectric materials and piezoelectric nanowires (NWs) have been shown to have good sensitivity, particularly in the low-pressure range of 0-10 kPa. In this work, we have simulated the capacitive sensors using finite element methods (FEM) to investigate the effect of piezoelectric properties of ZnO NWs incorporated into a polydimethylsiloxane (PDMS) dielectric material. Effect of NWs orientation and their dimensions on the sensitivity of the sensor have been studied. Simulations shows that with ZnO NWs in the PDMS matrix the sensors show higher sensitivity in low pressure range (0-10 kPa) than the bare PDMS based sensors. The estimated values and trends observed in this study were found to have good match with experimental results. Further, the simulation results show that the NWs aspect ratio could also influence the sensitivity of capacitive pressure sensors. The presented study shows the potential for using FEM for optimization of sensor design.**

Keywords—capacitive pressure sensor, FEM simulation, piezoelectric effect, electronic skin

I. INTRODUCTION

A variety of receptors are present at different depths in the human skin to sense external stimuli such as pressure, strain, temperature, shear force etc [1-4]. For the development of electronic skin (e-skin), with similar functionalities, a variety of physical, chemical, and biological sensors have been explored to convert external stimuli into electrical signals [5-13]. It is also desirable to have sensors with good stretchability, large area coverage and flexibility. In order to achieve good sensitivity over an area, the arrays of these sensors are generally placed as an interconnected network within the e-skin [14, 15]. Recently, there has been focus on the development of soft and flexible pressure sensors due to their requirements in applications in areas such as wearable systems, robotics, human-machine interfaces, prosthetics, and other healthcare applications etc [16-23]. Depending on the working mechanism, pressure sensors could be classified as piezoelectric, piezoresistive, capacitive and triboelectric, among which capacitive pressure sensors are widely used because of their low cost and simple fabrication methodology with good sensitivity and stability [9, 23-26].

Typical structure of a soft capacitive pressure sensor includes an elastomeric dielectric material such as polydimethylsiloxane (PDMS), ecoflex etc. sandwiched between two metallic conducting electrodes. To enhance the performance of these sensors, the elastomeric dielectric material with pyramids, air voids or pillars-based microstructures have been explored and sometimes they are also filled with carbon nanotubes, silver nanowires (NWs) etc [27, 28]. In some cases, ZnO nanostructures were embedded in the dielectric material to improve their sensitivity [29]. ZnO is one of the preferred filler materials because of its outstanding functional properties; piezoelectric nature, and biocompatibility. Further, it can be conveniently grown on various substrates using hydrothermal synthesis process [25]. In a recent work, we fabricated the capacitive sensor with ZnO NWs acting as interlayers between each PDMS-electrode interface to effectively use the piezoelectric effect of ZnO NWs [30]. Because of the addition of the ZnO NW at the interface, an increase in sensitivity (around 2-7 times) was observed in the pressure range of 0-10 kPa when compared with sensors based on PDMS dielectric alone. The increase in the sensitivity of the device with ZnO NW was attributed to the anisotropic piezoelectric properties of the ZnO NW. However, the effect of orientation and dimension of ZnO NWs on the sensitivity of the sensor was not elaborately studied. In this study we demonstrate the effect of ZnO NWs, and the influence of their dimension and the orientation on the sensitivity of pressure sensors using Finite element method (FEM) simulations. The simulation results are validated against the previous experimental results. The presented simulation study will aid in designing the capacitive pressure sensors with better sensitivity and performance.

This paper is organised as follows: The methodology for simulation is explained in Section II. The simulation results and comparison with experimental outcome are discussed in Section III. The summary of key outcomes is presented in Section IV.

II. SIMULATION METHODOLOGY

In this study, three configurations for the sensors were considered, as shown in Fig. 1. In the first configuration, a block of PDMS was taken with dimensions 10 µm x 10 µm x 50 µm. The second configuration consists of 144 cylindrical lateral ZnO NWs (forming 9 stacked horizontal layers of ZnO NWs with 16 NWs in each layer) as shown in Fig. 1(b). These lateral ZnO NWs were added uniformly in a block of PDMS having same dimensions as first configuration and were placed near both the top and bottom surfaces along z-axis. In the third configuration (i.e., Configuration 3) 16 x 16 vertical ZnO NWs (having their axis along z-direction) were placed uniformly in x- and y- direction near both the surfaces of PDMS. Table 1 shows the different sensors simulated with

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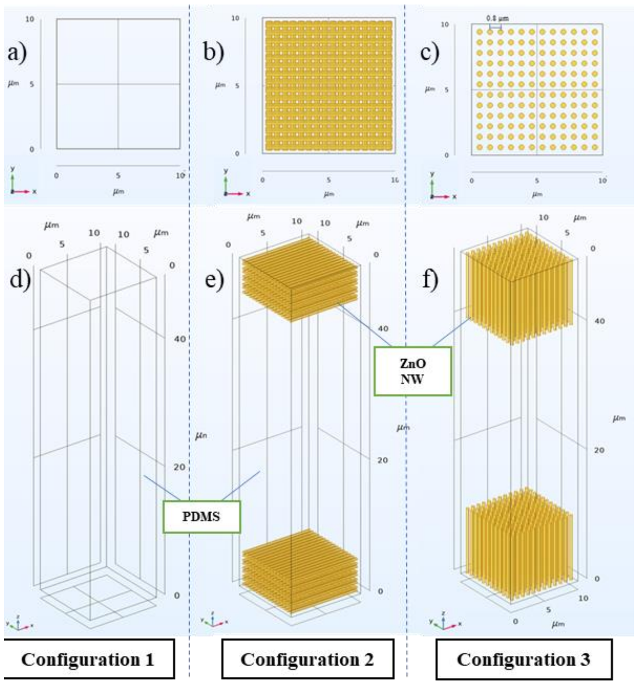

Fig. 1: Geometry for three configurations (1, 2 and 3) used in the simulations. (a-c) are top view and (d-f) are their perspective views.

Table 1: Configuration and dimensions of different sensors simulated (here P, H1 and V(1-5) stands for PDMS, horizontal and vertical respectively)

Sensor/ Properties	**P**	**H1**	**V1**	**V2**	**V3**	**V4**	**V5**
Configuration	1	2	3	3	3	3	3
Radius of ZnO NW (in µm)	-	0.2	0.2	0.2	0.2	0.15	0.25
Length of ZnO NW (in µm)	-	9.5	10	5	1	10	10
Aspect Ratio (L:R)	-	47	50	25	5	66	40

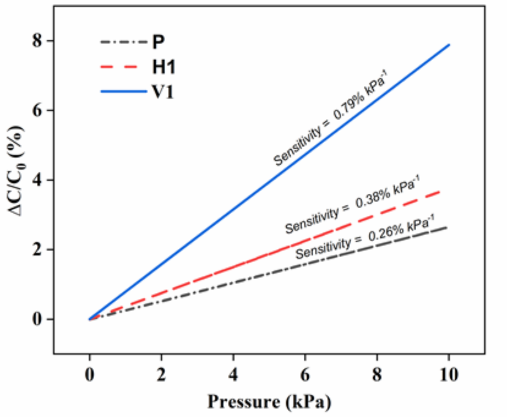

Fig. 2: Variation in relative change in capacitance for sensors P, H1 and V1.

their corresponding configurations, along with details of radius (R), length (L) and aspect ratio of ZnO NWs used. In all the cases, the bottom surface was constrained and grounded while pressure was applied and varied from 0-10 kPa on the top surface in negative z-direction. A terminal voltage of 1V was applied on the same top surface. In all the ZnO NW based sensors, the same number (288) of NWs were used. All the simulations were carried out in COMSOL 6.0 and both *Solid Mechanics* and *Electrostatics* modules of COMSOL were coupled together via the *Piezoelectric Effect* Multiphysics. The material properties for PDMS and ZnO NW were taken from the library of COMSOL Multiphysics as these values have been used previously in modelling the same materials [31]. Air was taken as dielectric material outside the sensors and moving mesh method was used to model the interaction between air and the sensors.

The variation in relative change in capacitance in each of the sensor with applied pressure was calculated as $\%\Delta C/C_0 = (C-C_0)x100/C_0$ where C and C_0 are Maxwell's capacitance of the system at any pressure and zero pressure respectively while the sensitivity $(S) = \Delta(\%\Delta C/C_0)/\Delta P$, where ΔP is the change in pressure or it can be calculated as slope of the $\%\Delta C/C_0$ vs pressure curve.

III. RESULTS AND DISCUSSION

A. *Effect of addition of ZnO NWs and their orientation*

Fig. 2 shows the relative change in capacitance of the sensors and the sensitivity for sensors labelled as P, H1 and V1. The calculated sensitivity for sensor with PDMS only (i.e. P) as dielectric is $0.26\%kPa^{-1}$. This value lies within the range of experimentally measured sensitivity (0.125-$0.8\%kPa^{-1}$) for capacitive sensors with similar design [30, 32]. When the ZnO NWs were placed within the PDMS near the electrodes, the sensitivity for sensors H1 (i.e., sample with NWs parallel to the PDMS surface) and V1 (i.e., sample with NWs perpendicular to the PDMS surface) increased in comparison to sensitivity of sensor P. This shows that addition of ZnO NWs near the electrodes enhances the sensitivity. Similar observations were found during previous experiments carried out in [30]. Also, the level of increase in sensitivity (around 1~3 times) with respect to sensors with PDMS only as dielectric is comparable to the experimentally observed increase (i.e. around 1.3~7 times).

The reason behind increase in sensitivity of the sensors after addition of ZnO NWs can be understood in following way. In sensor P, i.e., PDMS only based pressure sensor, the variation in capacitance is due to only the physical deformation of the elastomeric dielectric layer. The distance between the electrode plates changes which leads to change in capacitance [30]. However, in sensors H1 and V1, when the pressure is applied, ZnO NWs experience stress along their length as shown by von Mises stress distribution plots in Fig. 3 (a) and (c). Being a piezolelectric material, when stress is imposed on the ZnO wurtzite crystal, the polarization of inner ions takes place and thus produces a piezoelectric potential in the material. The potential is created due to the relative displacement of the Zn^{2+} cations with respect to the O^{2-} anions in the ZnO crystal, and these polar charges do not recombine unless the applied stress is removed [25]. The magnitude of piezoelectric polarisation in sensors H1 and V1 has been shown in Fig. 3b and 3d respectively. The induced polarised charge carriers generated along the ZnO NWs interact with PDMS and strengthen the dielectric property of PDMS due to the Maxwell-Wagner-Sillars interfacial polarisation [26]. As a result, charge separation and electric dipole generation takes place and thus the relative change in capacitance and sensitivity for sensors H1 and V1 are higher.

Further, from Fig. 2, it was also observed that sensitivity for sensor V1 is more than that of sensor H1. Under the condition that the length, radius, number density and volume fraction of ZnO NWs remain constant, it shows that sensor with vertical ZnO NWs or perpendicular to the electrode surface show higher sensitivity than sensors having NWs in

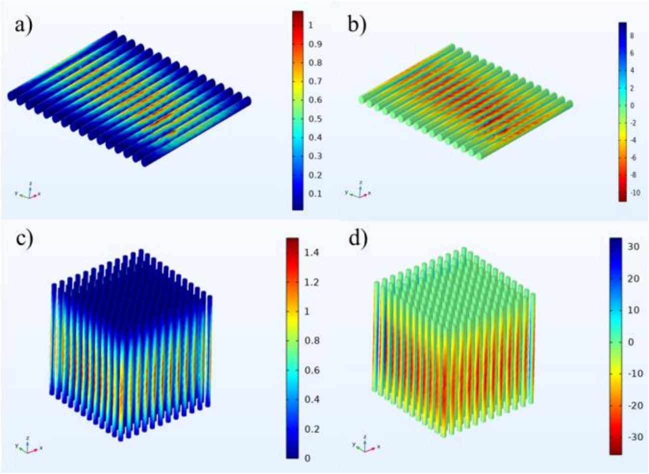

Fig. 3: (a) Von Mises stress (in MPa) and (b) piezoelectric polarization (in mC/m^2) for ZnO NWs closest to the top surface in Sensor H1, (c) von Mises stress (in MPa) and (d) piezoelectric polarization (in mC/m^2) for ZnO NWs closest to top surface in Sensor V1. All the graphs were plotted at the pressure of 10 kPa.

parallel to the electrode surface. This can be understood from the fact that the magnitude of piezoelectric polarisation in sensor V1 is higher than that of sensor H1 as seen from Fig. 3(c) and Fig. 3(d).

B. *Effect of dimensions and aspect ratio of ZnO NWs*

The extracted sensitivity through the change in capacitance with respect to ZnO NWs dimensions is presented in Fig. 4(a-c). The reduction of the NWs diameter leads to increment of surface to volume ratio which has a notable effect in the sensitivity. The highest sensitivity (0.9% kPa^{-1}) is displayed by the NWs with the lowest diameter in the set (150 nm). The length of the NWs have an effect in the tested range of 1-10 µm. However, interplay between length and diameter is helping to design a better sensor as shown in the analysis here. The ability to withstand load varies with the increment of aspect ratio in the sub-200 nm diameter range. As shown in Fig. 4(c), the sensitivity increases proportionally in this range and attained maximum (0.9%) with aspect ratio of 66. The bendability of the ZnO NWs embedded in PDMS matrix enhances the Zn^{2+} and O^{2-} charge separation which leads to the increases change in capacitance reflected in the observed sensitivity.

Interestingly, when comparing the sensitivity of sensors H1 and V3 from Fig. 2 and Fig. 4(b), we observe that sensors with lateral ZnO NWs can have better sensitivity compared to sensors with vertical ZnO NWs under certain conditions, one of them being having larger ZnO NWs in lateral NW based sensors than their vertical NWs based counterparts. Similar trend was observed during experiments in [30] where lateral NWs based sensors had higher sensitivity than vertical ZnO NWs based sensors because of the differences in NW dimensions and density.

IV. CONCLUSION

In this work, FEM simulations were carried out to study the effect of the presence of piezoelectric ZnO NWs, their orientation and dimensions on the relative change in capacitance and sensitivity of soft capacitive sensors using PDMS as dielectric material. The addition of ZnO NWs, increase the relative capacitance and sensitivity when compared with sensors using PDMS alone. Also, it was shown

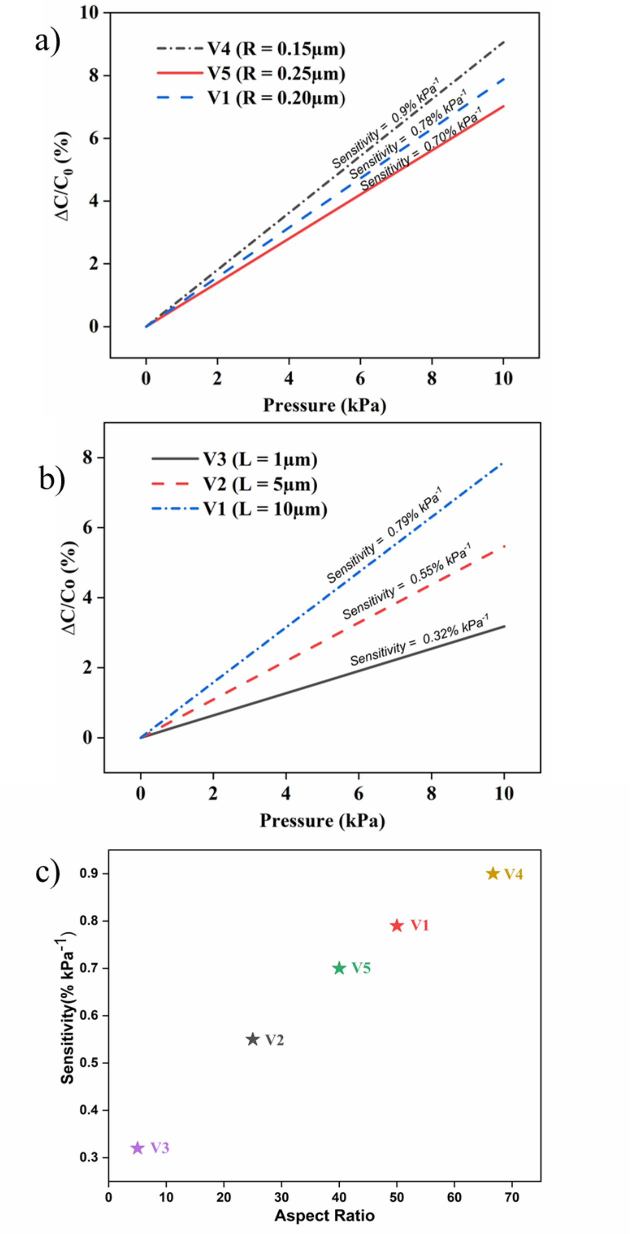

Fig. 4: Effect of (a) radius, (b) length and (c) aspect ratio of ZnO NWs on the sensitivity of sensors.

that on application of pressure, the vertical ZnO NWs based sensors have higher relative change in capacitance than its lateral ZnO NWs based sensors. These observations were validated with previous experimental results which showed similar enhancement trends and sensitivity values. The variation in sensitivity of flexible capacitive pressure sensor with the change in dimensions of ZnO NWs was also explored. The effect of other parameters like dimension of PDMS layer, NW density, etc. as well sensors with mixed orientation of NWs will be further explored in future studies. This simulation framework can be further employed to observe the change in sensitivity of similar piezoelectric NWs based flexible capacitive sensors with different piezoelectric (like PZT, $BaTiO_3$ etc.) and elastomeric dielectric materials. Overall, FEM studies will help in designing and optimising performance of capacitive pressure and other sensors that can be employed in the field of flexible and reliable tactile skins for robotics application.

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