Investigation of Highly Sensitive and Linearly Responsive SAW Based Gas Sensor for Better N_2 Detection

Nimmala Harathi[1], Binduswetha Pasuluri[2], Argha Sarkar[3](✉), and Naveen Kumar Maurya[4]

[1] Department of Electronics and Instrumentation Engineering, Sree Vidyanikethan Engineering College, Tirupati 517102, Andhra Pradesh, India
[2] Department of Electronics and Communication Engineering, Vardhaman College of Engineering, Shamshabad 501218, Telengana, India
[3] School of Computer Science and Engineering, REVA University, Bangalore 560064, Karnataka, India
argha15@gmail.com
[4] Department of Electronics and Communication Engineering, Vishnu Institute of Technology, Bhimavaram 534202, Andhra Pradesh, India

Abstract. Surface acoustic wave sensors are becoming more and more essential in research. The research has advanced in such a way that SAW sensors are now used in many different fields. The application areas of SAW sensor include gas sensing, biosensor, measurement of many physical parameters like humidity, pressure, temperature and torque. In this study, the SAW sensor is presented as a nitrogen gas sensor. Nanomaterials are introduced to a conventional SAW sensor to strengthen the sensor's performance. The most frequently used nano - materials for applications in gas detection is ZnO. Comsol Multiphysics is used to design a 2D SAW-based gas sensor using ZnO as the sensing material. Finite element analysis (FEA) is used in sensor characterization. Testing is done to determine whether nitrogen gas is present or not in the sensor. The sensor's sensitivity varies depending on whether there is gas present or not while operating at the same frequency. The sensor's frequency range is 3 MHz. Nitrogen gas is present in concentrations varying from 10 ppm to hundreds of ppm. With a rise in concentration, the sensor showed excellent linearity.

Keywords: Surface Acoustic Wave Sensor · Gas Detection · Zinc Oxide · Safety levels

1 Introduction

Lord Rayleigh initially announced the existence of surface acoustic waves during the year 1885. [1]. The surface acoustic waves are therefore referred to as Rayleigh waves. The first surface acoustic wave device was developed in 1965. The SAW sensors are high frequency devices that operate at frequencies between 1 MHz and 300 GHz. Since 1885

P. Pareek et al. (Eds.): IC4S 2023, LNICST 537, pp. 205–215, 2024.
https://doi.org/10.1007/978-3-031-48891-7_17

there is wide variety of improvement s in the surface acoustic wave sensor which made them to use in all application areas like mining applications in the form of gas sensor [2], biomedical area as sensor which can detect HIV and antigens, [3] as chemical sensor, as pressure sensor etc. Harathi. N et al. [2, 4] built a SAW-based gas sensor for hydrogen gas detection, and tested it with gas concentrations varying from 0.1 ppm to 100 ppm. The sensor's response showed proportionality among hydrogen gas concentration as well as displacement. Argha Sarkar et. al. [5] used ZnO as the sensing layer in the implementation of a highly sensitive SAW-based ethylene gas sensor with various electrode orientations. Hasan M et al. [6] developed and simulated SAW-based hydrogen gas sensor with two different active layers and compared the simulation and fabrication results. Neeruganti Vikram et al. [7] constructed a high sensitive 2D model of SAW sensor with two IDT (Inter Digitated Electrodes) and tested different chemical solutions concentration ranging from 1 ppm to 100 ppm. Sarkar A et al. [8] created a nanorod-based SAW methane gas sensor to get rid of crystal intrinsic defects. Beyond this SAW sensors can be used as biosensor, chemical sensor, toque sensor and humidity sensor. The SAW sensors are used for frequency range of megahertz to giga hertz. Above all, the author employed COMSOL for simulation, and finite element modelling was used for analysis.

2 Functionality of SAW Sensor

The three classes of acoustic wave devices are as follows: i) BAW (Bulk Acoustic Wave devices) ii) APM (Acoustic Plate mode devices) iii) SAW (Surface Acoustic Wave devices). These devices can also be further segregated, as indicated in the Fig. 1 and abbreviations are provided in Table 1. Acoustic devices can be used for both liquid and gaseous environments [8, 9].

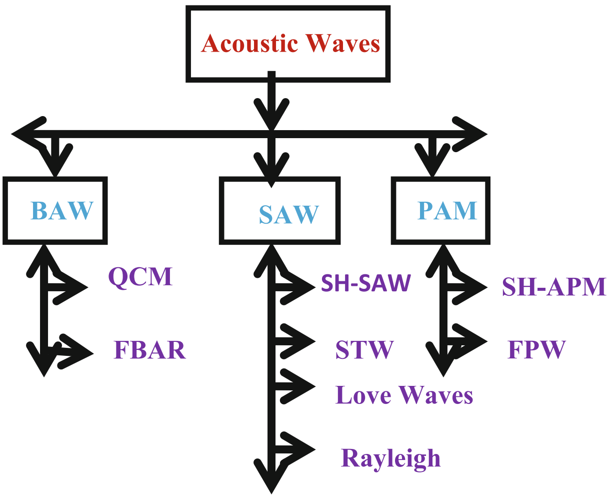

Fig. 1. Classification of Acoustic Devices.

Among all these acoustic devices the surface acoustic wave sensors are mostly preferred because of their operational flexibility, ease of usage and high sensitivity.

Table 1. Abbreviations of SAW Devices

S.No	Abbreviation
1	Quartz Crystal Microbalance (QCM)
2	Shear Horizontal Surface Acoustic Wave (SH-SAW)
3	Surface Transverse Wave (STW)
4	Shear Horizontal-Acoustic Plate Modulator (SH-APM)
5	Flexural Plate Wave (FPW)
6	Film Bulk Acoustic Resonators (FBAR)

The basic construction of SAW sensor is in Fig. 2. A piezoelectric substrate, which serves as the structure's foundation, two interdigitated electrodes the input IDT and output IDT—as well as a sensing layer are required for the development of SAW sensor.

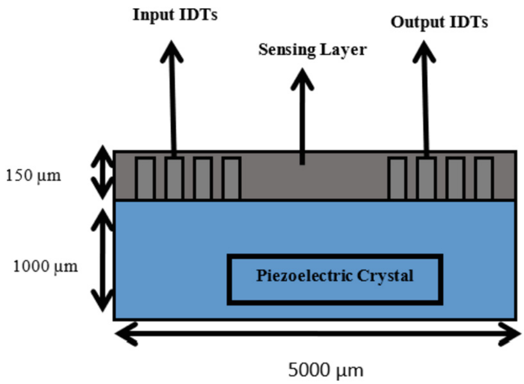

Fig. 2. Construction of SAW sensor

The input and output IDTs are enveloped inside the sensor layer, which is positioned slightly just above piezoelectric substrate. Opposing potentials are given to the IDTs. Because to the switching potentials at the input IDT, whenever an electrical signal is applied, stress forms over the piezoelectric substrate. By their very nature, piezoelectric materials have reversing piezoelectric properties. These crystals modify the physical dimensions of the crystal [10], converting input pressure into an electric signal, and converting input electric signal into input pressure. The IDTs converts electrical signals into acoustic signals at the input and acoustic signals into electrical signals at the output. On the surface of the sensor layer, an area known as the port length is where the generated acoustic signal travels. The three characteristics of the acoustic signal are frequency, phase and amplitude. Because of the unique properties of the sensing layer and piezoelectric substrate, any of the acoustic wave's characteristics can change as it travels through the sensing layer. The acoustic waves alter because of the physical characteristics that are spread across the sensor layer. The acoustic wave's changes have a significant effect on the measure and (physical parameter).

3 Analytical Design of Proposed SAW Sensor

3.1 Piezoelectric Substrate

The piezoelectric substrate serves as the SAW sensor's base. Various piezoelectric materials, such as lithium niobate, quartz, and lithium titanate, are easily accessible in the material catalogue. The SAW sensor's output displacement is greatly influenced by the piezoelectric substrate. To accomplish this, the material must have a high coupling coefficient. The Displacement of the SAW sensor is given in Eq. 1. Where "e" denotes the material's coupling matrix, "S" denotes its strain matrix, "E" is the electric potential somewhere at IDTs, and "ε" denotes the permittivity matrix.

$$d = eS + \varepsilon E \tag{1}$$

Lithium niobate is the piezoelectric material with the highest coupling coefficient and the least crystallographic effects. [11]. Equation 2 gives the piezoelectric material's coupling coefficient V_f is indeed the free surface phase velocity, while V_m would be the metal surface phase velocity. K is the coupling coefficient.

$$K^2 = 2(V_f - V_m)/V_f \tag{2}$$

The coupling matrix of lithium niobate is given in Eq. 3.

$$\mathrm{C} = \begin{pmatrix} c_{11} & c_{12} & c_{13} & c_{14} & 0 & 0 \\ c_{12} & c_{11} & 13 & -c_{14} & 0 & 0 \\ c_{13} & c_{13} & c_{33} & 0 & 0 & 0 \\ c_{14} & -c_{14} & 0 & c_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & c_{44} & c_{14} \\ 0 & 0 & 0 & 0 & c_{14} & (c_{11} - c_{12})/2 \end{pmatrix} \tag{3}$$

The piezoelectric constants are given in Eq. 4.

$$e = \begin{pmatrix} 0 & 0 & 0 & 0 & e_{15} & -e_{22} \\ -e_{22} & e_{22} & 0 & e_{15} & 0 & 0 \\ e_{31} & e_{31} & e_{33} & 0 & 0 & 0 \end{pmatrix} \tag{4}$$

The permittivity matrix is given in Eq. 5

$$\varepsilon = \begin{pmatrix} \varepsilon_{11} & 0 & 0 \\ 0 & \varepsilon_{11} & 0 \\ 0 & 0 & \varepsilon_{33} \end{pmatrix} \tag{5}$$

Lithium niobate's chemical and physical properties such as elastic constants, piezoelectric constants, permeability constants, density are considered. The acoustic wave's velocity (V_o) and wavelength (λ) determine the SAW sensor's operating frequency. The operating frequency is given in Eq. 6. Equation 7 states that the wavelength is a function of the IDT dimensions, where W_e denotes the electrode width and w_{sp} denotes the electrode spacing.

$$f_0 = \frac{V_o}{\lambda} \tag{6}$$

$$\lambda = 2(W_e + W_{sp}) \tag{7}$$

3.2 Sensing Layer

The sensing layer is the heart of SAW sensor. For SAW sensors, there are a vast array of sensing layers available, including metal oxides like zinc oxide, indium oxide, tungsten trioxide, and tin oxide [12]. The sensor layer may be made of N- or P-type semiconductors. Depending on the type of semiconductor material used, an oxidation or reduction reaction occurs when the acoustic wave passes over the sensor layer, changing the conductivity of the layer. Zinc oxide, or ZnO, is the most utilised sensing layer due to its characteristics. ZnO is a semiconductor material of the N-type that can withstand high temperatures ZnO has a strong thermal properties and electron affinity. Inert gases have no effect on ZnO despite these benefits. ZnO is chosen for the sensing layer due to these benefits. ZnO is highly sensitive compared to other sensing layers like GaO, WO_3, InO_3 because of its high conductivity nature and its conductivity varies with the doping levels.

4 Design and Simulation of Proposed Sensor

With the aid of a lithium niobate piezoelectric substrate, a ZnO sensing layer, and aluminium IDTs, a two-dimensional SAW-based gas sensor is constructed in COMSOL Multiphysiscs software. Table 2 includes information on the constructional details. In Fig. 3, the suggested SAW sensor is presented.

Table 2. Geometrical details of Proposed sensor

S.No	Component's identification	Dimensions
1.	Piezoelectric Base	5000 μm × 1000 μm
2.	Interdigitated Transducers	5 μm × 140 nm
3.	Sensing layer	5000 μm × 150 μm
4.	Spacing of electrodes	5 μm
5.	Spacing between IDTs	4000 μm

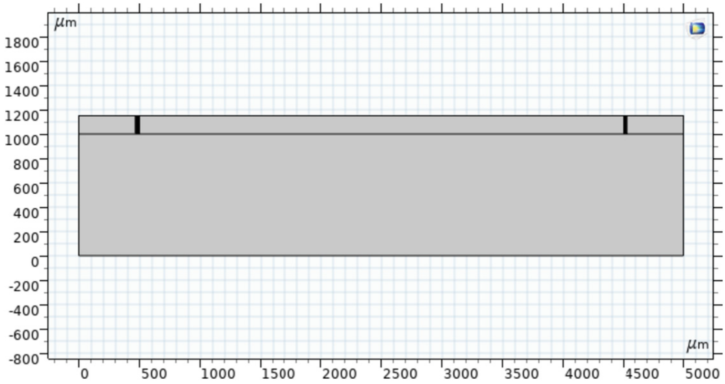

Fig. 3. Front View of developed Sensor

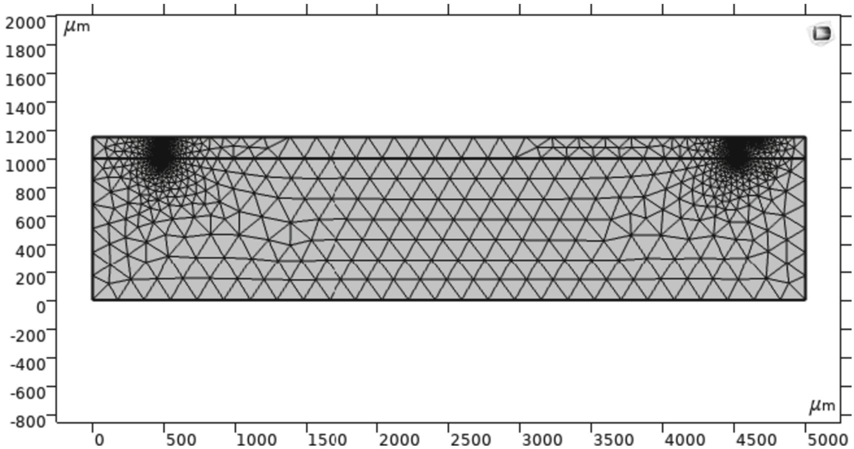

Fig. 4. Mesh analysis of Proposed SAW sensor

The fine meshing is completed in the shortest amount of time, 8 s. The Mesh analysis of the suggested sensor is shown in Fig. 4.

The proposed sensor has been modelled with and without gas applied across the sensing layer. With fluctuations in the displacement, the sensor obtained its maximum displacement at 3 MHz for both with and without gas. The Fig. 5 shows the maximum displacement of SAW sensor without gas. The response of the sensor with and without nitrogen gas is shown in Fig. 6. Gases with less of an odour and colour are nitrogen-based. The combustion process results in the emission of nitrogen into the environment. Nitrogen has a lower than 10 ppm safety limit. The mass density of the sensing layer changes as a result of nitrogen being deposited over it. The reactions of nitrogen gas with organic semiconductors alter the conductivity of the sensor layer, which reduces displacement when nitrogen gas is present. The reduction in the displacement is due to redox reaction between gas and sensing layer.

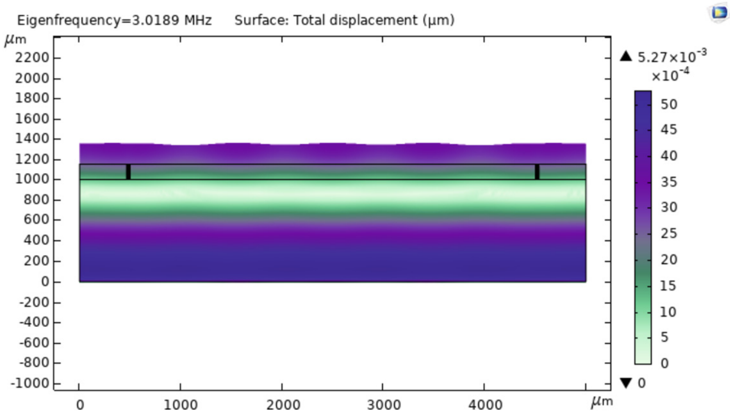

Fig. 5. Sensor displacement in the absence of nitrogen gas

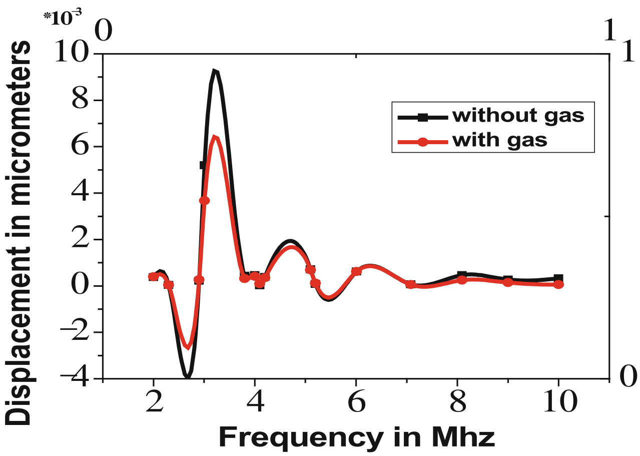

Fig. 6. Displacement of gas sensor

The density on the sensing layer rises as the nitrogen gas concentration rises from 10 parts per million to 100 parts per million, boosting displacement as the gas concentration rises. The sensor exhibited the linear. Figure 7 depicts the gas sensor's surface displacement at a nitrogen gas concentration of 10 ppm. Figure 8 shows the features of the surface displacement of the gas sensor at the maximum nitrogen gas concentration of 100 ppm. The sensor response for changing nitrogen gas concentration is shown in Fig. 9.

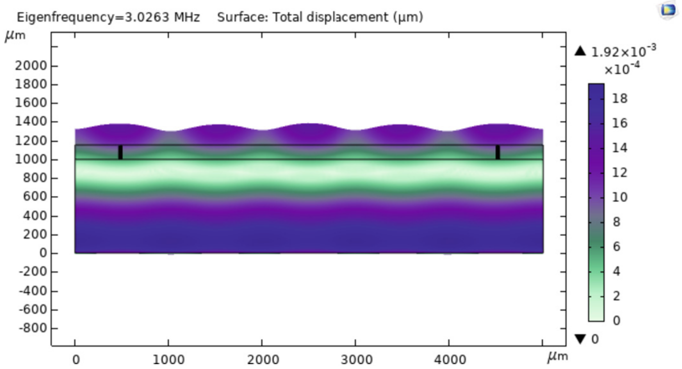

Fig. 7. Gas sensor response at 10 ppm of nitrogen gas

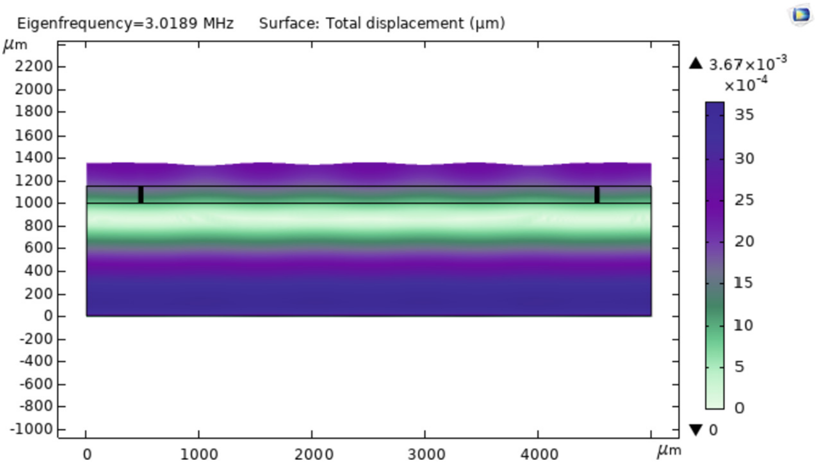

Fig. 8. Response of gas sensor at 100 ppm of nitrogen gas

The gas sensor's linear response to an increase in concentration from 10 ppm to 100 ppm is shown in Fig. 10.

Figure 11 shows the step wise linear characteristics of SAW based nitrogen gas sensor. Due to the low mass density on the sensor layer, the step change in displacement is modest at low concentrations. The stepwise linearity rises with mass density as concentration increases. The mass density of the sensing layer increases with the concentration of gas.

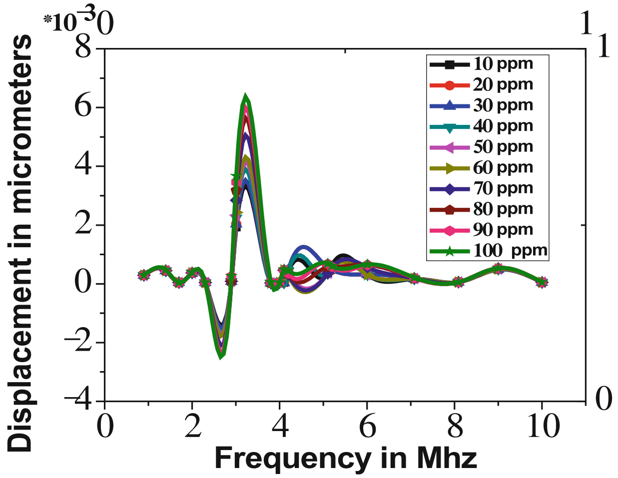

Fig. 9. Response of gas sensor with varying concentration

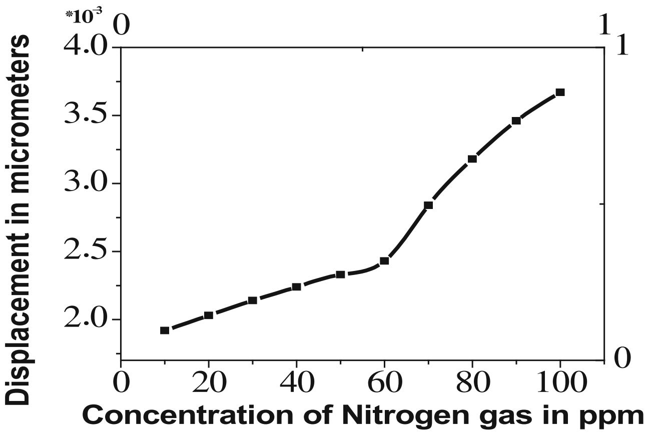

Fig. 10. Linear characteristics of the sensor

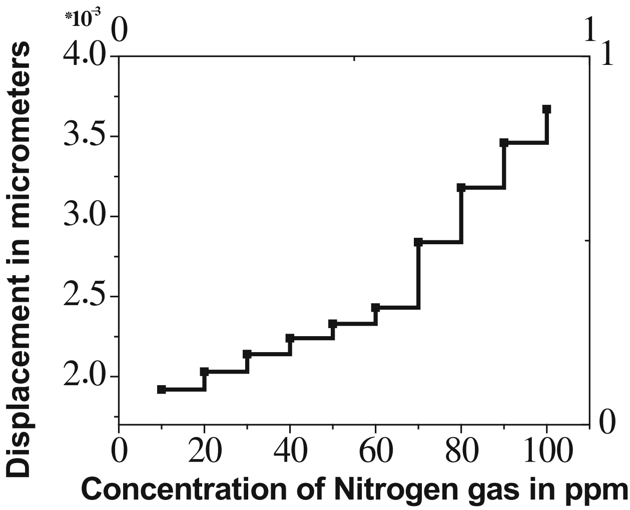

Fig. 11. Step wise Linear characteristics of the sensor

5 Conclusion

Solid mechanics and electrostatics are used to design a two-dimensional gas sensor in COMSOL Multiphysiscs software Multi Physics for the detection of nitrogen gas. The working frequency of the sensor is 3 MHz. The sensor performance is studied for deflection with and without ammonia gas. The deflection without ammonia gas is 5.27 $\times 10^{-3}$ μm and dropped to 3.67 $\times 10^{-3}$ μm in presence of 100 ppm of ammonia gas. The sensor is both sensitive and linearly responsive for ammonia gas.

References

1. Anand, M.: Study of tin oxide for hydrogen gas sensor applications. Thesis, University of South Florida, Graduate School, pp. 1–98 (2005)
2. Awang, Z.: Gas sensors: a review. Sens. Transducers **168**(4), 61–75 (2014)
3. Arabshahi, S., et al.: Simulation of surface acoustic wave NO2 gas sensor based on Zno/XY Linbo3 structure. IJERA **2**, 2120–2123 (2012)
4. Valluru, S.P.R.: Design of FIDT for 3D analysis of MEMS based gas sensor using SAW technology. In: Proceedings of the Comsol Conference, pp1–4. COMSOL, Pune (2015)
5. Sarkar, A., et al.: Design and optimization of ZnO nanostructured SAW-based ethylene gas sensor with modified electrode orientation. Adv. Sci. Technol. Eng. Syst **5**, 263–266 (2020)
6. Du, P., et al.: Simulation of ZnO enhanced SAW gas sensor. In: Proceedings of the Comsol Conference, pp 1–4. COMSOL, Rotterdam (2013)
7. Sarkar, A., et al.: Responsivity optimization of methane gas sensor through the modification of hexagonal nanorod and reduction of defect states. Superlattices Microstruct. **102**, 459–469 (2017)
8. Vellekoop, M. J.: Acoustic Wave Sensors. Theory, Design and Physico-Chemical Applications, by DS Ballantine, RM White, SJ Martin, AJ Ricco, ET Zellers, GC Frye and H. Wohltjen, published by Academic Press, San Diego, ISBN 0-12-077460-7, 436 p. Sens. Actuat. A Phys. **63**(1), 79–79 (1997)

9. Harathi, N., Kavitha, S., Sarkar, A.: ZnO nanostructured 2D layered SAW based hydrogen gas sensor with enhanced sensitivity. Mater. Today Proc. **33**, 2621–2625 (2020)
10. Sarkar, A., et al.: Methane-sensing performance enhancement in graphene oxide/Mg: ZnO heterostructure devices. J. Electron. Mater. **46**, 5485–5491 (2017)
11. Hasan, M.N., et al.: Simulation and fabrication of SAW-based gas sensor with modified surface state of active layer and electrode orientation for enhanced H2 gas sensing. J. of Electron. Mater. **46**, 679–686 (2017)
12. Harathi, N., et al.: PrGO decorated TiO2 nanoplates hybrid nanocomposite for augmented NO2 gas detection with faster gas kinetics under UV light irradiation. Sens. Actuat. B Chem. **358**, 131503 (2022)