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SHORT COMMUNICATION

Two-dimensional delay line SAW based Hydrogen gas sensor for leakage detection in pipelines using Palladium nano particles

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Abstract
The world is witnessing a transformative shift towards sustainable energy solutions, and hydrogen gas has emerged as a promising clean energy carrier with the potential to revolutionize our energy landscape. As hydrogen pipelines become an integral part of the infrastructure supporting this green energy transition, ensuring their safety and reliability becomes paramount. Among the critical challenges faced by hydrogen pipeline operators, one of the most pressing is the detection of gas leakage. Detecting hydrogen gas leaks in pipelines is not only essential for maintaining the integrity of the infrastructure but also for preventing potential safety hazards and minimizing environmental impacts. This paper presents a design to detect such leakages using two-dimensional delay line SAW based hydrogen gas sensor using COMSOL Multiphysics. The sensor is constructed with langasite piezoelectric substrate, IDT is built with aluminium and ZnO is used for sensing layer. To enhance the sensitivity of the device palladium nano particles are added to the sensor with extra conductive layer placed in the sensing layer. The proposed sensor is analysed for surface deflection, electric potential with as well as without hydrogen gas by varying the width of conductive layer from 1000µm to 3000µm.In addition to this, sensor is also tested for hydrogen environment with the concentration of gas ranging from 10ppm to 100ppm and sensitivity of the sensor is analysed. The simulated results relieved that the deflection of the sensor decreases with hydrogen gas and surface electric potential increases at all the widths of conductive layer. The conductive layer with width of 3000 µm achieved maximum deflection, electric potential and high sensitivity due to amplification provided by the conductive layer and nano particles. With hydrogen gas the sensor experiences a positive frequency shift due to change in electro acoustic effect on the sensing layer. But the sensor exhibits linearity with deflection and frequency with rise in the concentration of hydrogen gas. Further an electric equivalent model of the SAW sensor is designed using Colpitts oscillator to generate the operating frequency of SAW sensor. Electronic equivalent model is simulated using NI Multisim. The device has shown close approximation of theoretical frequency, simulated frequencies.

Keywords: *COMOSL Multiphysics; Equivalent Model; Gas Leakage Detection; NI Multisim; Palladium Nanoparticles; SAW Sensors.*

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INTRODUCTION

The industrial landscape is progressively embracing hydrogen gas as a versatile and eco-friendly energy source, offering a promising solution to address the challenges of sustainability and carbon emissions reduction. As hydrogen adoption grows in industrial processes, it's safe transportation and distribution through pipelines have become vital components of this evolving energy paradigm. However, with the benefits of hydrogen also come significant responsibilities, particularly in ensuring the integrity and security

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of these pipelines. Among the foremost concerns in the industrial sector is the detection of hydrogen gas leakage in pipelines, a critical aspect in safeguarding personnel, infrastructure, and the environment. Hydrogen, renowned for its clean combustion properties, presents unique characteristics that necessitate specialized detection methodologies.

Being colorless, odorless, and highly flammable, hydrogen leaks can go unnoticed without the right monitoring systems in place, posing severe safety risks to industrial workers and nearby communities. Moreover, leakages, even in minute quantities, can escalate into hazardous situations if left undetected or unmitigated. To address these challenges, cutting-edge technologies and innovative approaches to hydrogen gas leakage detection in industrial pipelines have emerged. These advancements leverage the power of sensor technologies, data analytics, and automation, promising to revolutionize the efficiency and reliability of leak detection systems [1]. Therefore, the development of effective hydrogen gas leakage detection systems is crucial to ensure the safety of personnel and equipment. One promising technology for hydrogen gas leakage detection is the use of MEMS (Micro-Electro-Mechanical Systems)-based surface acoustic wave (SAW) sensors. These sensors are compact, sensitive, and can be integrated into a system for real-time monitoring and early detection of hydrogen gas leaks.

The SAW sensor are microelectromechanical devices with high operating frequency ranging from 30MHz to 3GHz.The SAW devices are highly accurate, with fast response, consumes low power and can be used in wireless applications. The SAW devices find its applications has biosensor, chemical sensor and environmental pollution detection device. The operation of SAW sensor relies on generation and propagation of surface acoustic wave.

Advances in Science, Technology and Engineering Systems journal, 5, 263-266 (2020) explained the development of SAW-based hydrogen gas sensor that uses a lithium tantalate as sensing layer and lithium niobate as the piezoelectric basement. The sensor's functionality was put to the test under different hydrogen concentrations and interdigitated transducer (IDT) sizes. Lower IDT heights resulted in improved performance from the sensor [2]. International journal of engineering researchs and applications 2, 2120-2123 (2012) have explained a novel SAW gas sensor that can detect 100 ppm of NO_2 gas at room temperature and employed ZnO (Zinc Oxide) sensing layer [3]. Sensors and Actuators: B chemical, 117, 442- 450 (2009) elaborated a multilayered SAW sensor that responds to ethylene gas vapours and humidity [4]. Sensors and Transducers,168, 61-75 (2014) have reviewed the pros and cons of gas sensors with polymers in the sensing layer [5]. International conference of Electronics, Communication and Aerospace Technology [IEEE], 2020, have explained LPG gas leakage detection system linked with Internet of Things (IOT) to alert people with SMS when LPG leakages at home [6]. It has been found from the literature that numerous sensors are made with different sensing layers and piezoelectric substrates.

There hasn't yet been a simulation of sensors with variable conductive layer width on the sensing layer and nano particle in sensing layer. So, this paper aims at bridging the gap between these designs. The work continues with a description of the layout in section 2. The design principles for sensors are covered in Section 3. Results are discussed in the concluding section of the paper.

PROPOSED LAYOUT OF THE SENSOR

The basic functionality of SAW gas sensor is shown in Fig. 1. The SAW sensor is formed with piezoelectric substrate as the base and sensing layer over it covering input IDT and output IDT separated with pitch between them. The Pitch is covered with palladium nano particles to enhance the sensitivity of the device. The device is constructed with Langasite piezoelectric substrate due to its high coupling coefficient. The IDTs are constructed with aluminium because of its conductivity and sensing layer is built with ZnO nanomaterial because of its high sensitivity [7]. The geometrical details of proposed design are given in Table 1. The IDTs width is considered to be 5μm and spacing of the IDTS is 5μm making the acoustic wavelength to be 20μm.

The acoustic wavelength is considered to be twice the summation of electrode width and spacing between electrodes. The operating frequency of SAW device is ratio of acoustic velocity of the surface acoustic wave (2732 m/s) to the acoustic wavelength. The so generated acoustic signal undergoes delay in the velocity due to deposition of hydrogen gas on the sensing layer. The delay in the acoustic velocity is in line with the change in mass of sensing layer and frequency shift of acoustic wave. The behaviour of sensing layers various with the doping concentration of ZnO causing a change in conductivity of the sensing layer [8-10].

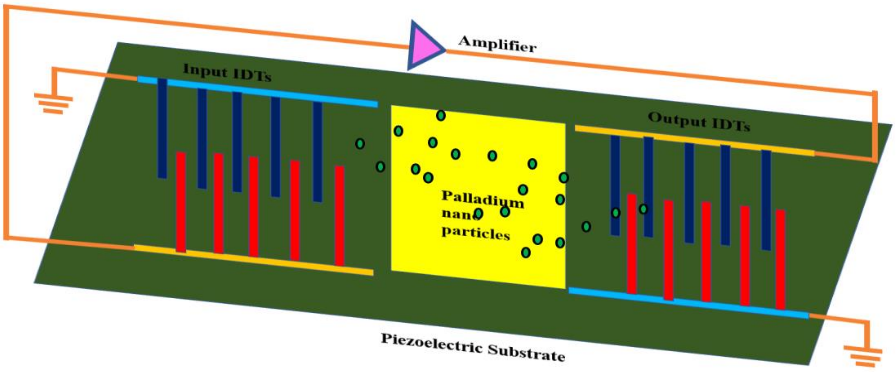

Fig. 1. Front view of SAW gas sensor.

Table 1. Dimensions of Proposed sensor.

S.No	Name of the component	Dimensions
1.	Piezoelectric substrate	5000µm×1000 µm
2.	InterDigitated Transducers	5µm×140µm
3.	Sensing layer	5000µm×150µm
4.	Spacing between electrodes	5µm
5.	Pitch	4000µm
6.	Conductive layer height	130 µm

Table 2. Design Coefficients utilised in sensor.

S.No	constant	onstant otation	Langasite
1.	Elastic constants [Pascal]	c11	94.65
		c12	52.5
		c13	47.64
		c14	7.215
		c33	132.5
		c44	26.92
2.	Piezoelectric constants [C/m3]	e11	0.01935
		e14	0.00915
3.	Permeability constants	ε11	1.904
		ε13	5.051
4.	Density[kg/m3]	ρ	5748
5.	Acoustic Velocity	v	2723

DESIGN CONCEPTS OF THE SENSOR

The two-dimensional SAW device is designed in COMSOL Multiphysics with solid mechanics and piezoelectric studies. The constructional constants of design are given in Table 2 [11]. The boundaries of the sensor are defined with periodic conditions. The electric parameters of the sensing layer are defined with electrostatic studies. The deigned SAW based sensor is shown in Fig. 2. The meshing of sensor is given in Fig. 3 [12-15].

In terms of the electric equivalent circuit, the SAW sensor may be viewed as a two-port network with the input IDT as one port and the output IDT as the second port.

The oscillator, which resides in the interconnectivity of two ports, is the heart of the two-port network. The oscillator is a modified Colpitts oscillator, and the output comes from the emitter instead of the collector. The tank circuit produces the SAW sensor's working frequency. The tank circuit consist of input resistance of SAW sensor and its equivalent capacitor. The simulated electric equivalent model is given in Fig. 4.

The resonant circuit at the top represent the generation of acoustic signal [16, 17]. The electronic model is simulated in NI Multisim and produced maximum voltage of 35V at a frequency of 105MHz.The generated electric signal is given in Fig. 5.

RESULTS AND DISCUSSIONS

The proposed design is studied for hydrogen gas leakages in terms of deflection analysis, electric potential analysis with respect to varying width of conductive layer from 1000µm to 3000µm. Verma and Maheshwari designed a gas sensor with palladium nano particles deposited over the sensing layer to increases the sensitivity of the sensor [18]. The conductive layer is deposited with palladium nano particles to enhance the sensitivity of the sensor. The device has its height deflection at 133.01MHz without gas at 3000 µm of conductive layer width. The propagation of SAW wave on the surface of the sensor is shown in Fig. 6. The deflection plot of the sensor in presence and absence of hydrogen gas with varying conductive layer width is given in Fig. 7 and Fig. 8. With the

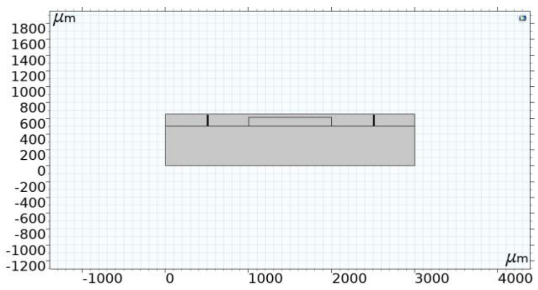

Fig. 2. Construction View of proposed sensor.

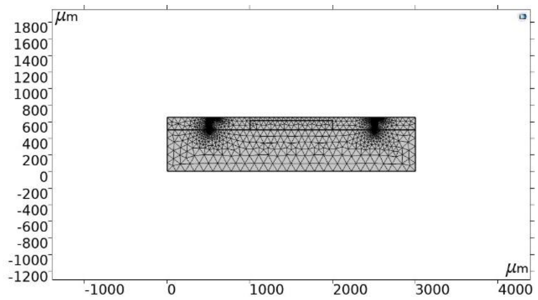

Fig. 3. Meshing View of proposed sensor.

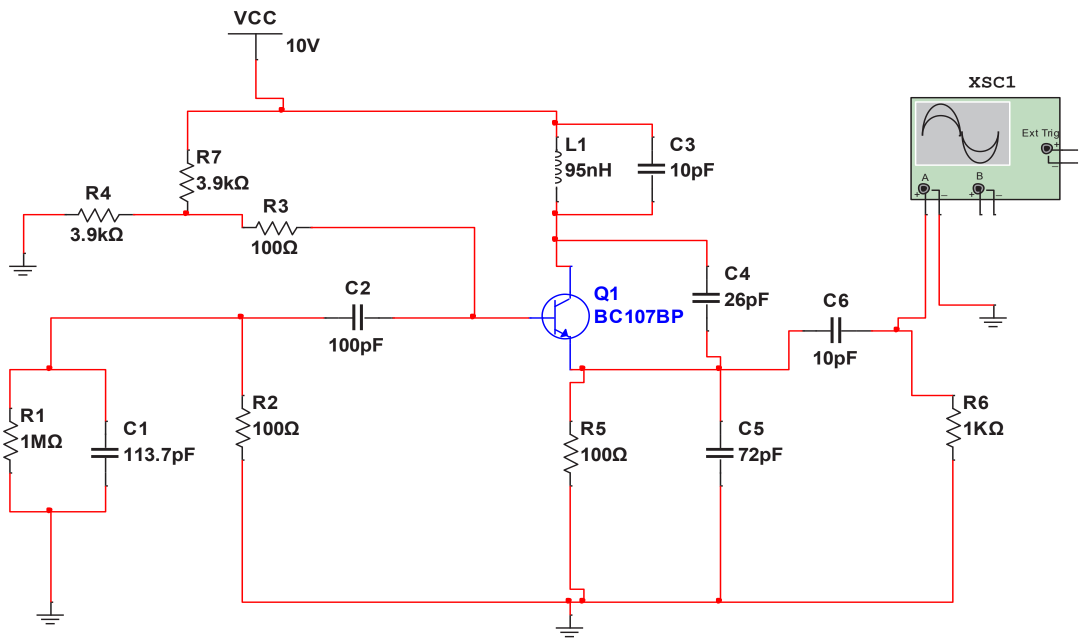

Fig. 4. Electronic equivalent Model of SAW sensor.

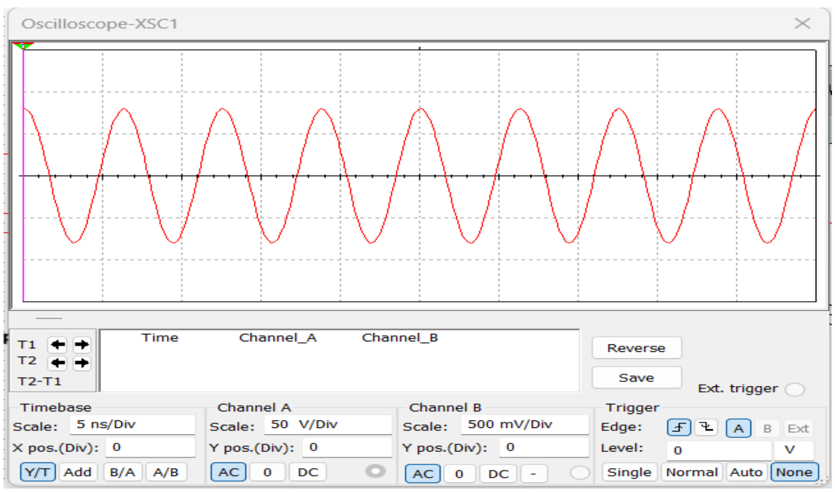

Fig. 5. Response of electronic equivalent model.

increase in conductive layer width the deflection of the sensor increases enhancing the sensitivity of the sensor. Deposition of hydrogen gas increases the mass density of the sensing layer and alters the electro acoustic effect of sensing layer. The deposition hydrogen gas causes a positive shift from the operating frequency. With the increase in the in conductive layer width the electroacoustic width reduces causing a positive shift in the operating frequency.

Fig. 9 shows the electric field at the pitch of the sensor. The electric potential is more concentric at the centre indicating in bright red colour with positive potential. The potential decreases from the away from the centre indicating in pale yellow colour followed by blue colour indicating negative potential. The electric potential distribution on the surface of the sensor with varying conductive layer width is given in Fig. 10 and Fig. 11. In absence of gas the conductivity is maximum at 3000 µm due to presence of conductive layer with maximum width. Verma P. and Maheshwari S. K., designed a hydrogen gas sensor with palladium nanoparticles to enhance the sensitivity of the sensor [19]. With presence of palladium nano particles, the sensor performance can be improved. In presence of hydrogen gas conductivity is decreases with increase in electric potential with increment in conductive layer width. In presence of hydrogen gas, the sensing layer behaves as n-type of semiconductor causing change in conductivity of the surface [20, 21].

SAW sensor as hydrogen gas sensor

SAW based gas sensors are based on adsorbent effect on the surface of the sensor. The perturbation of SAW wave is disturbed with the presence of hydrogen gas over the sensing layer. Deposition of hydrogen gas cause the deviation of mass on the sensing layer leading to change in acoustic velocities change which in turn causes shift in operating frequency. Fig. 12 Shows the deflection and frequency shift plot with hydrogen gas. The deflection and frequency shift are in line with the concentration of the gas making the sensor much more linear.

With respect to the width of conductive layer the performance of the device is effective at 3000µm with high sensitivity. Fig. 13 shows the variation of frequency shift with reference to operating frequency for hydrogen gas concentration with varying conductive layer width. At conductive layer

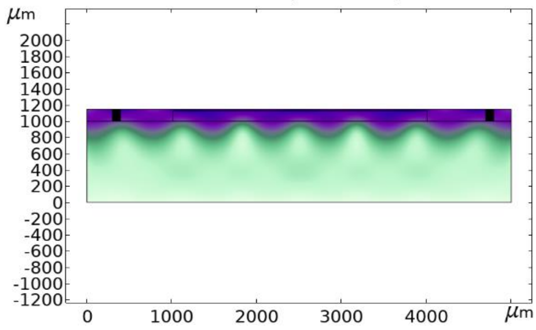

Fig. 6. Transmission of SAW wave from input IDT to output IDT.

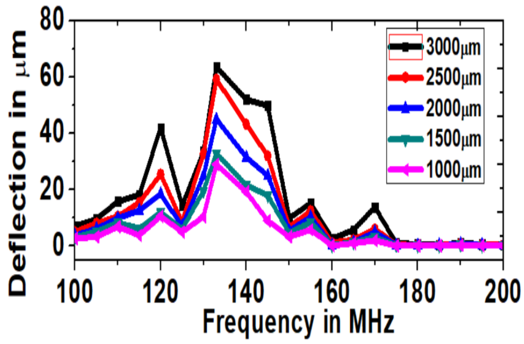

Fig. 7. Deflection Analysis of the sensor without gas.

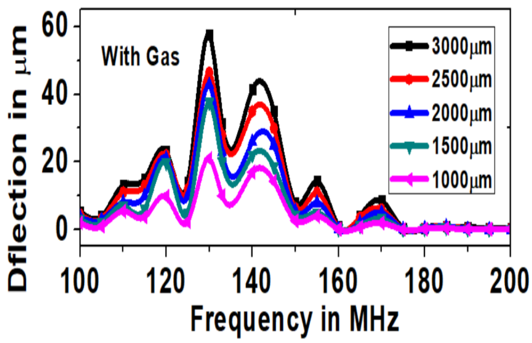

Fig. 8. Deflection Analysis of the sensor with gas.

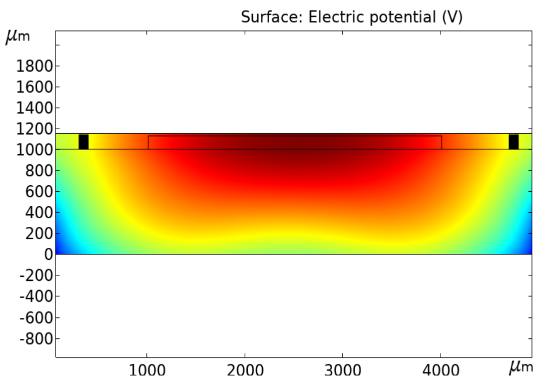

Fig. 9. Field distribution on the surface of the sensor without gas.

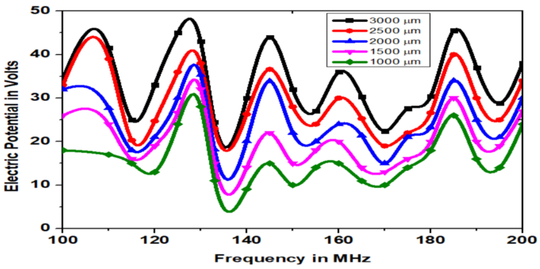

Fig. 10. Distribution of electric potential of sensor without gas.

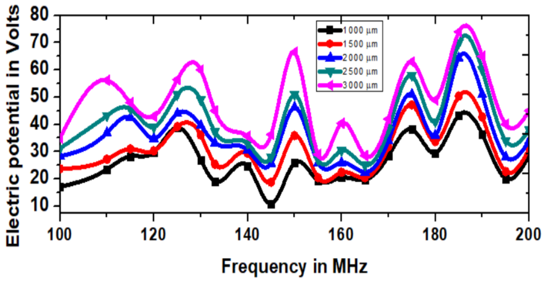

Fig. 11. Distribution of electric potential of sensor with gas.

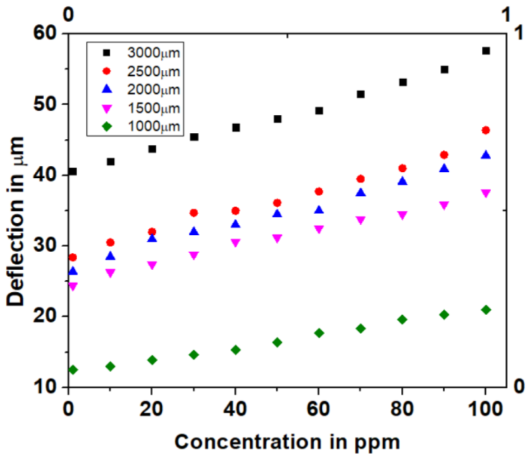

Fig. 12. Reaction of proposed gas sensor for hydrogen gas.

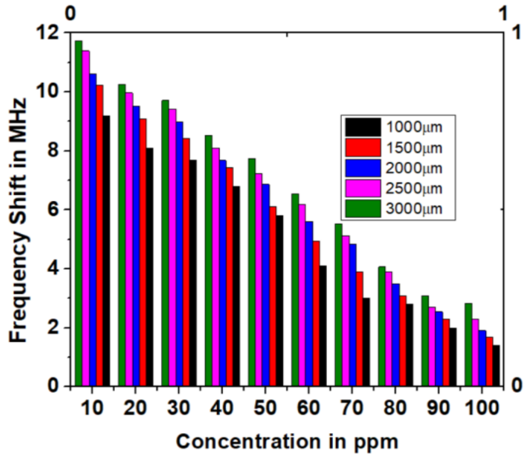

Fig.13. Frequency shift analysis for hydrogen gas as a function of conductive layer width.

Table 3. Overall Performance of the device.

Reported work	Displacement	Operating frequency	Concentration of gas
[22]	2.8 nm		Ethylene gas detection
[23]	2.4 nm	1.31GHz	1 to 1000 ppm of dichloromethane gas
[24]	0.4755nm	44 MHz	
[25]	2.3nm	100 MHz	1 to 130 ppm of hydrogen gas
[26]	6.54 nm	1.31GHz	100 ppm of dichloromethane gas
[27]	0.5nm	30MHz	100 ppm of hydrogen gas
Present work	63.6 µm	133 MHz	1 to 100 ppm of hydrogen gas

width of 3000µm the frequency shift is maximum with maximum electroacoustic velocities (Table 3).

Fig. 14 shows the sensitivity plot of the sensor. The sensitivity of the sensor is expressed with variation of hydrogen gas concentration with frequency shift. The sensor has linear response with hydrogen gas and it is evident from the sensitivity plot.

Surface current Density of Sensor

The surface current density of the sensor is electric current existing per unit area on the surface of the sensor. The surface current density of the sensor is shown in Fig. 15. For defined conductive layer width the charge on the surface is definite making the current density independent of other sensor parameters.

The performance of the sensor simulated in COMSOL Multiphysics software is compared with its electronic equivalent model in terms of electric potential. The comparison response is shown in Fig. 16. The maximum potential of the equivalent model is in terms of 35 V which is half of the 2D model potential [28-30]. The difference in the potential is because of the RC networks and biasing networks available in the equivalent circuit. To operate the transistor in the active region the biasing resistors and the RC networks designed.

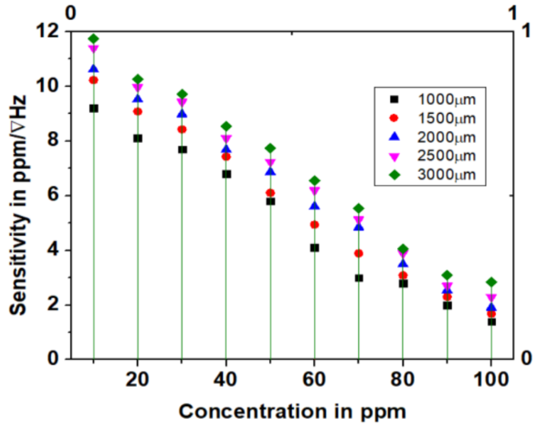

Fig. 14. Sensitivity of proposed sensor.

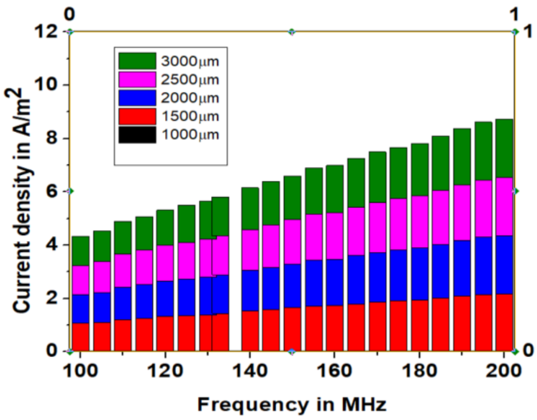

Fig. 15. Surface current density of sensor.

Table 4. Comparison of the performance of the Proposed.

S.No	Width of conductive layer	Theoretical Frequency (MHz)	Simulated Frequency (MHz)	Deflection without gas [μm]	Electric potential without gas [V]	Deflection with gas [μm]	Electric potential with gas [V]	Simulated Frequency with gas at 100ppm [MHz]	Simulated Frequency with gas at 1ppm [MHz]
1.	3000μm			63.6	74	34.1	26	131.2	121.1
2.	2500μm			59.2	70	28	30	131.1	119.9
3.	2000μm	136.15	133.01	45	64.4	23	34	130.5	119.3
4.	1500μm			32.9	50.4	20	40	130.01	118.5
5.	1000μm			29	43.4	10	45.5	129.7	118

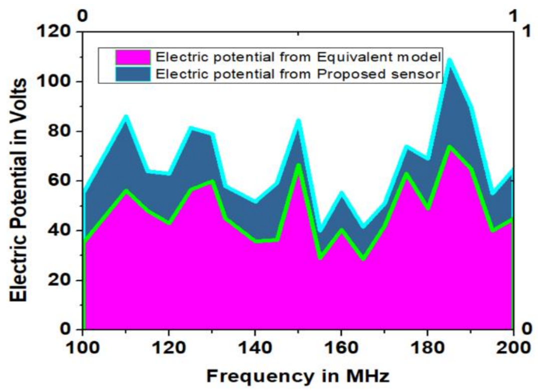

Fig. 16. Comparison of potentials of electronic equivalent model of sensor and its 2-D model.

Table 4 show the performance of the sensor with the previous work. The proposed sensor has better deflection and frequency because of the langasite piezoelectric substrate.

CONCLUSION

A two -dimensional surface acoustic wave sensor for detection of hydrogen gas leakage is designed and simulated in COMSOL Multiphysics and compared the results with its electronic equivalent model being simulated in NI Multisim. From theoretical analysis the operating frequency of the is found to be 136.5MHz. The study from COMSOL Multiphysics indicated operating frequency as 133.01MHz. When the pipeline does not possess gas leakage the sensor with holds the centre frequency. With the leakage in the pipe line the sensor deviates from its centre frequency indicating the leakage of gas. The electronic SAW equivalent model responded at 150 MHz. The difference in the operating frequencies is due to varying operating environments. In COMSOL Multiphysics the sensor is designed materials with its definite material constants. But in the electronic equivalent model design is approximated with its equivalent electronic circuitry which leads to many biasing circuits resulting in change in operating frequency. The sensor is also examined for hydrogen gas with varying conductive layer width on the sensing layer. The presence of palladium nano particle conductive layer enhances the sensitivity of the sensor. With the increase in the width of the conductive layer the conductivity of the sensor increases causing proportional decrement in the electric potential on the surface of the sensor. The sensor response for deflection, frequency analysis and surface current density is studied as a function of hydrogen gas with varying conductive layer width. The sensor has shown linear response for deflection, frequency shift and surface current density for hydrogen gas. The sensor has better performance at conductive layer width of 3000 µm with high deflection, frequency shift and surface current density.

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CONFLICT OF INTEREST

The authors declare that they have no known contest for financial interests or personal engagements that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY

No data is used for the research.

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