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A SHORT REVIEW OF SAW SENSORS

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Abstract

Surface Acoustic Waves (SAWs) are elastic waves travelling along the surface of solid piezoelectric materials with amplitude that decays exponentially with depth. Using an Interdigital Transducer (IDT), these waves can be demonstrated and reproduced in the laboratory in devices called SAW devices. Such devices find many applications as delay lines, filters, resonators and sensors. The present paper provides a snapshot review and a description of the function, operation and latest technical advancements seen in SAW sensors over the period from1997-2015. SAW Sensors using different design and operating principles have been reported in this paper. Compared with other currently available types of sensors, the SAW – based sensors have many advantages like: high sensitivity, quick response time, easy predictability and good stability.

Keywords: *Interdigital Transducer; Surface Acoustic wave.*

1. INTRODUCTION

The existence of surface acoustic wave (SAW) was highlighted by (Rayleigh, 1885). Invention of the Interdigital Transducer (IDT) by (White and Voltmer, 1965) revolutionalised the usage of SAW devices. An Interdigital Transducer (IDT), is a device which consists of two interlocking comb-shaped metallic coatings which are applied to a piezoelectric substrate such as Quartz or Lithium Niobate to essentially convert electrical energy to mechanical energy and vice versa. Such a transducer forms the basis for the design of a wide variety of SAW devices like delay lines, band pass filters, resonators and sensors (Venkatesan *et al.* 2013). An important property of SAW is their extremely low velocity, about 10^5 times less than that of EM waves.

SAW devices respond to the mass and elastic mechanical properties of materials with the device surface. Therefore, they are used as sensors, which sense the physical and chemical properties in gases and liquids. Due to the sensitivity of the surface acoustic wave to even the slightest perturbations, small effects caused by different phenomena can be detected. Almost all physical quantities like surface mass, stress, strain, torque, temperature, pressure etc., can be measured by SAW sensors (Fig. 1) (Scherr *et al.* 1996; Varadan *et al.* 1997). In addition, SAW sensors are miniaturized, rugged, highly sensitive, reliable, cost-effective and show fast real time response (Banu priya *et al.* 2014; Shen *et al.* 2002).

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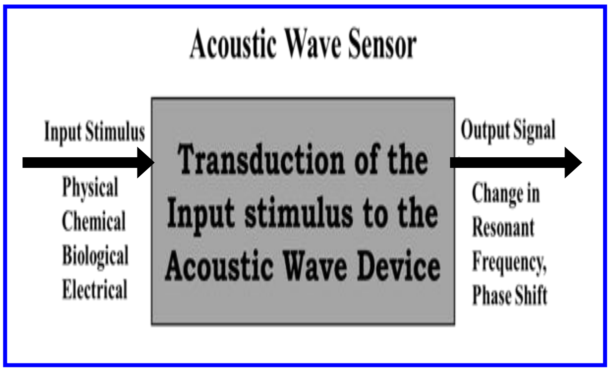

Fig. 1: SAW sensors

The basic principle in a SAW sensor is the change in the propagation velocity of the surface wave as a function of change in the center frequency of the device or insertion loss (Powell *et al.* 2006).

$$\frac{\Delta v}{v_0} = \frac{\Delta f}{f_0} \tag{1}$$

The sensing range of phenomena can be greatly amplified by coating the sensitive area with thin polymer films (Fig. 2) that are sensitive to the physical quantity being measured. The SAW delay line sensor has been placed in a feedback loop of an amplifier to form an oscillator. SAW devices coated with thin polymeric material are most utilized as sensors for the detection and monitoring of vapors and gases (Grate, 2000; Sadek *et al.*

2006; Penza *et al.* 2007; Du *et al.* 2008). In this review paper, we shall explore the considerations for the design of a surface acoustic wave sensor and the possibilities that are available with this particular technology.

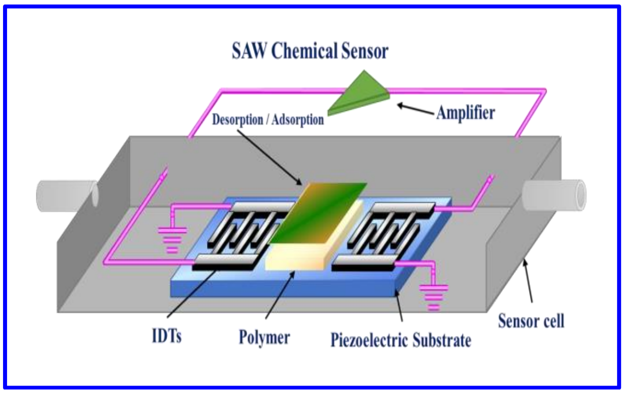

Fig. 2: Structure of a SAW Sensor

2. CHEMICAL SENSORS

Surface Acoustic Wave (SAW) sensors demonstrate superior sensitivity in the detection of chemical agents. Due to their solid state design and fabrication compatible with modern technologies, SAW chemical sensors are extremely reliable (Haresh M. Pandya *et al.* 2013).

In the last two decades surface acoustic wave (SAW) chemical vapor sensors have found numerous applications due to their compact structure, high sensitivity, small size, outstanding stability, low cost, fast real-time response, passivity and above all their ability to be incorporated in complex data processing systems. The SAW sensors have been able to distinguish a wide range of chemical vapors (Wohltjen and Dessy, 1979; Wohltjen, 1984; Ho *et al.* 2003). The basic principle of the SAW sensors is the reversible absorption of chemical vapors by a solvent coating which is sensitive to the vapor to be detected While designing a sensor, choice of polymer type and wave propagation direction are the important parameters.

Moriizumi *et al.* (1994) developed a compact casting system called "Droplet – surface casting method" for deposition of molecular films on a small area of a device surface. A 4 channel odor sensing system was constructed with three sensing channels and one reference channel. The device was ST Quartz 90 MHz SAW Resonator chips, which has 2 resonators on the substrate. Sensor gave different output patterns for different odors. The comparison of Quartz crystal Microbalance (QCM) and SAW sensors showed that, SAW Sensors can have a higher sensitivity than QCM.

Yang *et al.* (1997) studied cyclodextrinsiloxane coatings on SAW devices as sensors for volatile organic compounds (VOCs). The in-situ formation of cyclodextrin and siloxane multilayer thin film efficiently yielded uniform coatings and are sensitive and selective at the gas- solid interface. Nomura *et al.* (1998) have reported investigations on one-port surface acoustic wave (SAW) resonators incorporating Langmuir-Blodgett (LB) films. LB method is suitable to produce a uniform and thin coating film, which is important for the stability and reproducibility of SAW sensors. LB films have the advantage that they can be deposited accurately down to monomolecular thickness. A 90 MHz SAW and a one-port resonator configuration was used as the sensing element. Ultra-thin monolayers of arachidic acid and arachidic acid ethyl ester were deposited. Experimental results showed that the Q values and the resonant frequencies of the resonator device varied with film mass loading on the SAW device surface.

McGill *et al.* (1998) utilized Matrix Assisted Pulsed Laser Evaporation (MAPLE), a thin film deposition technique, to coat high quality polymer films on SAW devices. Pulsed laser deposition is used to deposit a passivation layer of diamond –like-carbon on a SAW device surface to prevent water adsorption. Electrical characteristics like loaded quality factor Q, forward transmission ratio and residual phase noise of polymer coated SAW devices was examined. The polymer coatings deposited with MAPLE technique have less impact on electrical property when compared with devices coated with aerosol coating. A large variation on loaded Q and residual phase noise performance were observed for polymer spray coated SAW devices.

Korsah *et al.* (1998) investigated the fundamental and third harmonic frequency changes to CO_2 and water vapor of bare and coated SAW's operating at 250 MHz. The results showed that sensitivity increased by a factor of three and the detection limit is improved by a factor of two. Three polymers were used in their investigations: BMBT (N,N-bis-(P-methoxybenzylidene)- α, α'- bi-p-toluidine), PEI (Polyethyleneimine) and Versamid 900. PEI was found to be the greatest frequency change in humidity about 5.7 KHz followed by Versamid 900 (1 KHz) and BMBT (700 Hz). Thus PEI was found to be more sensitive to CO_2 compared with the other polymers.

Fang *et al.* (1999) developed a portable SAW sensor array instrument with integrated chemometric software to identify a variety of chemical classes like paraffinics, aroatics, ketones and alcohols. This instrument was an accurate, reliable method of identification and qualification of volatile organic compounds (VOCs) over a dynamic range from low ppm trace levels to high concentrations. The SAW sensor array instrument can be applied to both chemical identification applications and environmental monitoring of trace levels VOCs.

Andrew *et al.* (2000) synthesized, characterized and evaluated a series of hexaflouroisoproponal (HFIP) functionalized aromatic siloxane polymers as vapor sorptive coatings for use with chemical sensors. These strong hydrogen bond acidic polymers readily and reversibly sorb hydrogen bond basic vapors such as nitroaromatic compounds. The most sensitive of the new polymers exhibit SAW sensor detection limits for nitrobenzene (NB) and 2, 4-dinitrotoluene in the low parts per billion (ppb) and low parts per trillion (ppt) concentration range. The paper shows that polymers with favorable physicochemical properties exhibit low water vapor sorption and rapid signal kinetics for nitrobenzene (NB), reaching 90% of signal response in 4 seconds.

Shen *et al.* (2002) investigated and examined the design of ST-cut quartz SAW organophosphorous compound sensors. A complex shear modulus is used to represent different types of polymer (glassy, glassy-rubbery and rubbery). Different propagation directions lead to different wave propagation properties in SAW devices, such as attenuation and velocity. Reports indicate from this study that the glassy-rubbery and rubbery film coated on SAW sensors very sensitively detect organophosphorous vapor. Out of the three types of polymers, glassy-rubbery film is suitable in sensor applications, because it makes signal attenuation significantly. It was suggested that for consideration of sensitivity, acoustic wave dissipation and temperature stability, the optimum suggestion of SAW sensor design should include glassy-rubbery polymer as the chemical interface and ST- X quartz as the substrate.

Levit *et al.* (2002) deposited high surface-to-volume ratio coatings using a spray technique known as Rapid Expansion of Supercritical Solutions (RESS) for chemical sensing applications. The RESS technique is applied to many polymers to make uniform and sensitive sensor surfaces. RESS technique provides a unique way to develop sensors based on glassy and viscoelastic polymers.

Chevallier *et al.* (2009) reported the sensitive coating of diamond nanoparticles [DNP] with SAW transducers. DNP was deposited on SAW sensors by a layer- by- layer deposition method, for chemical vapor sensing. Diamond nanoparticle coated sensors were tested towards dinitro toluene (DNT), dimethylmethyl phosphate (DMMP), ammonia (NH_3) and relative humidity (RH). The sensitivity of sensors with hydrogenated diamond layers was found to be 80 HZ/ppbv for DNT, 4 HZ/ppbv for DMMP and 70 HZ/ppbv for NH_3. NH_3 gas shows high sensitivity, good repeatability and low detection limit at sub-ppm levels when compares to all other target gases.

Haresh *et al.* (2010) focused on the functioning of a Surface Acoustic Wave delay line device with interdigital electrodes. Employing MATLAB algorithm based on the crossed field equivalent circuit model, the approach adopted in this paper allows for accurate SAW device modelling and simulation, wherein the design parameters are varied. The results are then analyzed which ultimately helps in the effective design, development and modelling of such devices for specific applications like sensors. Comparison of simulated results with experimental results were presented for a 300 MHz SAW delay line with uniform IDTs possessing 43.5 finger pairs per IDT and the results showed good agreement between model and experiment. All important parameters like observed frequency shift, time delay, insertion loss and 3dB bandwidth are accurately modelled and predicted. A difference of around 0.4139 dB is observed between the modelled value of insertion loss -28.789 dB and its measured value-29.2029.

Raj *et al.* (2013) utilized a SAW based Electronic-nose (E-nose) coated with different oxides (ZnO, TeO_2, SnO_2 and TiO_2) for the detection of various simulants of chemical warfare agents. ZnO and SnO_2 thin films deposited by RF sputtering are polycrystalline whereas TeO_2 and TiO_2 thin films are amorphous. The E-nose showed good sensitivity toward the four simulants (dimethyl methyl phosphonate (DMMP), dibutyl sulfide (DBS), chloroethyl phenyl sulfide (CEPS) and diethyl chlorophosphate (DECP)) of CWA allowing sub ppm level detection possible. The obtained results showed the capability of E-Nose coated with a different oxide layer to detect stimulant vapors of chemical warfare agents and to discriminate between them even in the presence of interferants vapors.

Raj *et al.* (2015) fabricated ZnO/Quartz based surface acoustic wave (SAW) sensor for the detection of DMMP (dimethyl methyl phosphonate) at room temperature. The sensitivity of the sensor toward DMMP vapors increases with an increase in the thickness of ZnO thin films. A change in elasticity of ZnO films with exposure to DMMP vapors is the dominant sensing mechanism. Various properties of ZnO thin films (roughness, porosity, crystallite size, bond strength etc.) responsible for elastic changes are analyzed by depositing the films under different processing conditions. The ZnO/SAW sensor is also highly selective toward DMMP vapors as compared to other interferants. The results throw light into the elasticity mechanism for SAW sensing along with the possibility of utilizing ZnO/SAW sensor for DMMP detection. The ZnO/SAW sensor having an optimized ZnO thin film is able to detect very low levels of DMMP vapors with good selectivity and fast response time (18 s).

3. GAS SENSORS

Gas sensor is a subclass of chemical sensors. Gas sensor measures the concentration of gas in its vicinity. Gas sensor interacts with a gas to measure its concentration. Each gas has a unique breakdown voltage i.e. the electric field at which it is ionized. Sensor identifies gases by measuring these voltages. The concentration of the gas can be determined by measuring the current discharge in the device. Gas sensors are applied in process control industries, environmental monitoring, boiler control, fire detection, alcohol breath tests and detection of harmful gases in mines, Home safety, grading of agro-products like coffee and spices.

We have focused the work done on gas sensors in a detailed review.

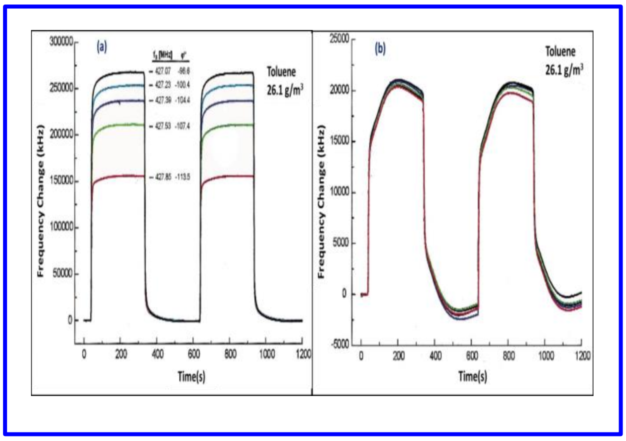

Fig. 3(a&b): Frequency shifts of a thick and thin PECH-coated sensor (Reibel *et al.* 1998)

Reibel *et al.* (1998) used SAW resonators (or) Quartz Bulk Resonator (QMB) within an oscillator circuit as a frequency determining element. Phase position set within a SAW oscillator can cause a dramatic influence towards the chemical sensitivity of polymer coated acoustic resonators. This is shown in Fig. 3(a&b) responses of two sensors with a thick and a thin coating of polyepichlorohydrine (PECH) on sampling with toluene at different set phase positions. For a thick coated PECH sensor, toluene concentration is 26.1 g/m^{3}and for thin coated PECH sensor, it is 44.1g/m^3. In the case of other thin coated polyisobutylene (PIB) sensor, they got negative responses with same phase range with toluene concentration of 36 g/m^3. Finally, they found that each single sensor separately has its own sensitivity characteristics with respect to phase position set of an oscillator.

Beck *et al.* (1999) presented a contactless surface Acoustic (SAW) wave device and its applications as gas sensor. For detection of organic solvents at room temperature, the device was coated with polyepichlorohydrine (PECH), for detection of NO_2 it was coated with copper phthalocyanine (CuPc), and for the detection of the methane in the temperature region from 300 ˚C to 450 ˚C it was coated with SnO_2. The measurements showed that inductively coupled SAW devices are suitable for sensor applications.

Roh *et al.* (2000) developed a new type of SO_2 gas sensor by applying a particular inorganic thin film on SAW devices. The sensors have twin SAW oscillators with a center frequency of 54 MHZ fabricated on $LiTaO_3$ Piezoelectric single crystals. One delay line of the sensor is coated with CdS thin film that selectively absorbs and desorbs SO_2, while the other is uncoated for the use as a reference part. Deposition of CdS thin film is done by spray pyrolysis using an ultrasonic nozzle. The relative change in the frequency of the two oscillators was monitored with a digital signal processing circuit to measure the concentration of the gas. The sensor shows promising performance as a microsensing tool and is capable of measuring concentrations in the air less than 200 parts per billion of SO_2.

Rapp *et al.* (2000) developed a new sensor array to overcome the phase position problems. It has eight multiplexed SAW sensor oscillators with capacity diodes for an automatic phase adjustment and switch for single oscillators within a saw sensor array ie., to manage a multiplexing mode. Two examples of difference curves obtained from a sensor coated with PIB and poly-dimethylsiloxane (PDMS) sampled with xylene at a high concentration (about 1000 ppm) are shown in Fig. 4. Consequently the difference of both curves reflects the pure chemical sensitivity in respect to the changing phase positions. This enables an easy optimization of the signal to noise ratio, expands the choice of coatings for the SAW sensors and improves the sensor to sense reproducibility for a certain coating material.

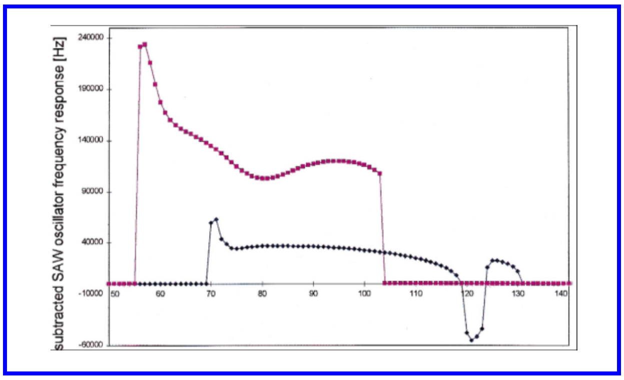

Fig. 4: A plot of the frequency response vs the applied voltage of the capacity diode which correlates with the set phase position within an oscillator of the new sensor array. The large variation of each curve during a run represents the dramatic influence of the set phase position to the sensitivity and thus the potential of optimization of oscillator phase position (Rapp *et al.* 2000).

Plotner *et al.* (2001) integrated two sensors with differently deposited Copper phthalocyanine (CuPc) films detecting NO_2 and O_3 and with a hyperbranched polyester film which responds to NH_3 on self-designed 80 MHZ SAW filters. The sensors proved to be capable to detect gases down to the ppb concentration range.

Yasin *et al.* (2005) have designed and developed the interface circuitries for CMOS based gas sensor. The SAW sensor devices typically run at RF operating frequencies requires most designs to use complex signal conditioning circuitry. Table1 shows a comparison of the signal processing circuitry designed by (Hagleitner *et al.* 2002; Yasin *et al.* 2005). Simulation data showed that the interface circuitries are ten times smaller with lower power supply, compare to (Hagleitner *et al.* 2002).

Atashbar *et al.* (2005) developed and simulated a three dimensional finite element (3D FE) model of a two-port SAW delay line based hydrogen sensor with a palladium thin film between the input and output transducers. ANSYS version 6.1 platform was used for this simulation. The time delay in the particle displacement and the output voltage was found to be 1.4 ηs when the sensor was exposed to less than 3% hydrogen. The Impulse response of the device was simulated, from which frequency response of the system was obtained. Insertion loss of the sensor in the absence of hydrogen was 30.5 dB and when exposed to hydrogen, the insertion loss is 31.5 dB. The 3D representation of the surface acoustic wave propagation on the substrate was demonstrated.

Table 1. Comparison

	Circuitry by (Hagleitner *et al.* 2002)	Circuitry Designed by (Yasin *et al.* 2005)
Technology	0.5μm	0.35μm
Supply Voltage	5V	3.3V
Die Area	8.48mm^2	0.85mm^2
Power Dissipation	NA	38.35mW

Penza *et al.* (2008) designed and fabricated a SAW two port resonator sensors on a ST- cut Quartz substrate operating at a frequency of 433.92 MHz and 915 MHz. Nanocomposite layers based on the filter of Carbon Nanotubes (CNT's), grown by RF plasma enhanced chemical vapor deposition, had been prepared by the Langmuir Blodgett(LB) technique to coat the SAW microdevices for organic vapor sensing, at room temperature. SAW sensing performance towards ethanol, methanol, acetone, m-xylene and toluene were described. The SAW sensor system shows higher sensitivity to ethanol, so ethanol is selected and its sensitivity is measured. Fig. 5 shows a comparison of the chemical patterns in terms of mass sensitivity of the dual SAW device using LB nanocomposite film based on a 10 wt% CNT's cadmium Arachidate coating at 433.92 MHz and 915 MHz. SAW sensitivity increases with higher frequency as theoretically shown in the equation for the gas response of the mass sensitive sensor,

$$\Delta f = C_m f_0^2 (\Delta m / A) \qquad (2)$$

Δf - Frequency shift ; C_m- Mass sensitivity co-efficient; f_0- Fundamental SAW frequency; Δm - Mass change; A - Area of SAW sensing membrane.

Cenni *et al.* (2010) designed a microelectronics interface for a SAW chemical sensor aimed at gas detection. Such a sensor interacts with a gas, identifies its unique breakdown voltage and thereby detects the concentration of the gas. Even minute concentrations of trace gases can be identified. The microelectronics front end architecture was designed at the transistor level with 0.35 μm CMOS technology and the device was embedded in a phase locked loop (PLL) that converted the change of concentration of gaseous mercury into a frequency shift of the loop frequency.

Bostan *et al.* (2010) presented a finite element model for SAW sensors with polymer layers, taking into account mass loading, viscoelastic properties of polymer layers including loss. Simulation of FE model was developed by COMSOL Multiphysics software. Polyisobutylene (PIB) was used as a sensing material. By solving the damped Eigen value problem, center from 150.38 MHz to 150.29 MHz was downshifted, because of the application of PIB coating. At the same time, attenuation of SAW increases with increase in thickness. Fig. 6 explains the frequency shift and attenuation shift Vs toluene (TOL) concentration for SAW sensor (PIB thickness h_0 = 100 ηm). These parameters can be co-related with the experimental results.

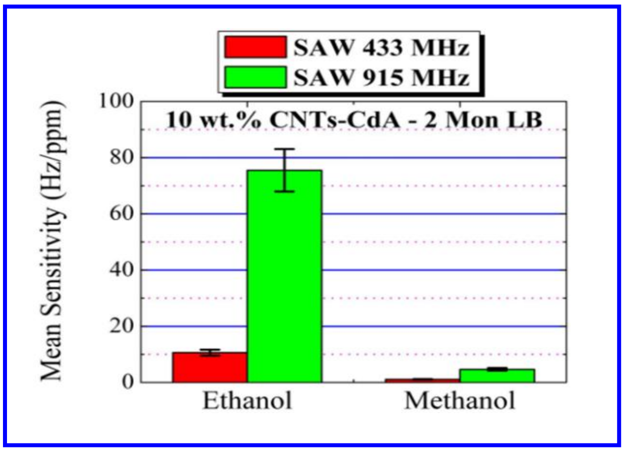

Fig. 5: Comparison of the room-temperature chemical patterns in terms of mean sensitivity towards ethanol and methanol for the dual SAW 433.92 and 915 MHz sensor with the Sensor element coated by a 2-monolayer thick 10 wt. % CNTs-CdA LB nanocomposite film. Hence, thin sensing LB layers are useful to improve the gas sensitivity of the SAW devices with higher resonant frequency (Penza *et al.* 2008).

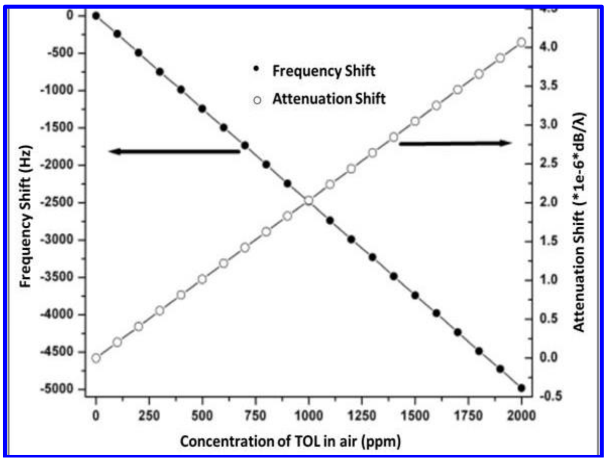

Fig. 6: Frequency shift and attenuation shift vs. TOL concentration for the SAW sensor (Initial PIB Thickness h_0=100 nm) (Bostan *et al.* 2010).

Hsu-Chao Hao *et al.* (2010) developed a SAW sensing array consisting of four two port SAW resonator sensors. Four different polymers were coated on the surface of sensing regions and their frequency responses were investigated. They had suggested that the frequency shift of the designed gas sensor array changes with different concentration of the target gas (NH_3).

Meulendyk *et al.* (2011) detected Hydrogen Flouride gas on quartz substrate using SAW sensors. The effects of 1 to 18 ppm HF exposure on both generalized SAW and shear horizontal SAW quartz sensors was examined. For HF concentration, the frequency response of the pure SH-SAW resonator was 4.6 times greater than GSAW resonator. Pure SH-SAW also had the capability of measuring HF concentrations below 1 ppm. (Fan *et al.* 2012) fabricated acoustic transmissions in SAW gas sensors by multilayered structures consisting of sensitive layer/piezoelectric film/non piezoelectric substrate and simulated theoretically by transfer matrix method. This method was used to evaluate and optimize both surface conductivities (S_c) and sorbed mass (S_m) of the SAW gas sensors. The results showed that frequency shift induced by the variation of surface conductivity is closely related to the initial conductivity and relative dielectric constant of the sensitive layer, while the frequency shift induced by the sorbed mass is almost independent on them.

Rossignol *et al.* (2013) developed a microwave gas sensor with Cobalt Phthalocyanine film (CoPc) at room temperature. The Gas sensing material is a thin layer of (CoPc), sensitive to pollutants, ammonia and toluene in argon flux. The sensor response is a reflected wave when an electric field is propagated in the microwaverange.The results was interpreted the variation of the amplitude of reflected coefficient in decibel as a function of frequency and is shown in Fig. 7.

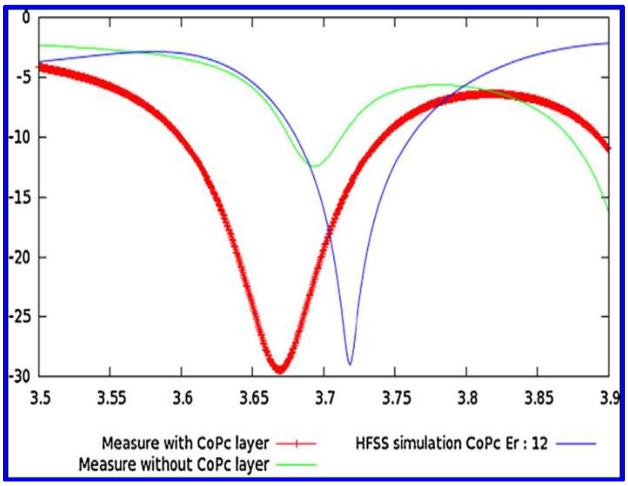

Fig. 7: Variation of the amplitude of reflected coefficient in dB as a function of frequency for the experimental sensor (with and without sensitive layer) and the modeled sensor with HFSS (relative permittivity estimated to 12) (Rossignol *et al.* 2013).

4. CONCLUSION

An attempt has been made in this paper to highlight and describe the physics of SAW gas and chemical sensors with their corresponding principles and mode of operation. Recent research work done in these areas from 1997-2015 has been comprehensively reviewed, discussed, listed and presented. These sensors offer excellent, precise and customized advantages paving the way for an entire new generation of "Smart Sensors".

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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