Review Papers

Review of Surface Acoustic Wave Sensors for the Detection and Identification of Toxic Environmental Gases/Vapours

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Detection and identification of toxic environmental gases have assumed paramount importance precisely in the defense, industrial and civilian security sector. Numerous methods have been developed for the sensing of toxic gases in the environment ever since surface acoustic wave (SAW) technology came into existence. Such SAW sensors called electronic nose (E-Nose) sensor use the frequency response of a delay line/resonator. SAW device is focused and given importance. The selective coating between input and output interdigital transducers (IDTs) in the SAW device is responsible for corresponding changes in operating frequency of the device for a specific gas/vapour absorbed from the environment. A suitable combination of well-designed SAW delay lines with selective coatings not only help to improve sensor sensitivity and selectivity but also leads to the minimization of false frequency alarms in the E-Nose sensor. This article presents a comprehensive review of design, development, simulation and modelling of a SAW sensor for potential sensing of toxic environmental gases.

Keywords: toxic gases; SAW sensors; E-Nose; gas sensors; selective coating.

1. Introduction

The concentration of chemical pollutants in the environment has increased tremendously due to various factors like rampant industrialization, sudden population growth, and gross mismanagement of natural resources (AFZAL *et al.*, 2013; JAKUBIK *et al.*, 2016; MSEDDI *et al.*, 2016; SINGH *et al.*, 2016; RAJ *et al.*, 2017). These chemical pollutants come in various forms such as toxic industrial chemicals (TICs), volatile organic compounds (VOCs), hazardous gases, chemical warfare agents, explosive vapours, environmental pollutants, etc. As such, there is an urgent need for the development of stable technologies for their timely detection and identification in the environment (MATATAGUI *et al.*, 2011b; RAJ *et al.*, 2013b; LUO *et al.*, 2013). Chemical warfare agents (CWAs) are weapons of mass destruction which can cause instant death or temporary incapacitation or permanent impairment in humans and other living organisms. A good chemical sensor needs to have many desirable traits like better selectivity, sensitivity, lower response time, fewer false alarm rates, low power consumption, reliability over distinct environmental conditions, swift

recovery time, portability and a simple user interface (HARMER, MARQUIS, 2004; HO *et al.*, 2005; RAJ *et al.*, 2010; AFZAL *et al.*, 2012; JAKUBIK *et al.*, 2016).

A lot of effort has been put by researchers around the globe for the development of reliable techniques for detection of such chemicals in the environment. Raman spectroscopy, Ion mobility spectroscopy, Flame photometry, Infra-red spectroscopy, Surface acoustic wave (SAW) technology, Calorimetric, Conductometric, Photo ionization and Flame ionization are some of the existing techniques for this purpose (WOHLTJEN, DESSY, 1979; CHANG, SHIH, 1998; MOORE 2004; SFEROPOULOS, 2009; SINGH *et al.*, 2016). Each method has its own advantage as well as a limitation of their hands-on application as a sensor. Among these techniques, SAW technology is one of the promising and efficient technologies for sensing of chemical agents at lower concentration levels (ppm and ppb). Precise detection of hazardous chemical compounds in gaseous and liquid environments is possible with the help of such SAW sensors. These sensors have the advantage of being compact sized, affordable, highly sensitive and being reliable (WOHLTJEN, DESSY, 1979; CHANG, SHIH, 1998; MOORE, 2004; SFEROPOULOS,

2009; Jakubik, 2011; Raj *et al.*, 2013b; Luo *et al.*, 2013; Singh *et al.*, 2016).

The adsorption and absorption of chemical agents by sensitive layer in a SAW sensor causes change in attenuation and phase velocity of acoustic waves propagating on the surface of the piezoelectric substrate which is then measured in terms of change in frequency (Abraham, 1995; Matatagui *et al.*, 2009; Raj *et al.*, 2010; Raj *et al.*, 2012a). A suitable combination of piezoelectric substrate, interdigital transducers (IDTs), and selective coating is an essential requirement for efficient design and fabrication of SAW sensors (Wilson, Atkinson, 2007a; Khaneja, Mittal, 2008; Tigli, Zaghloul, 2008; Pandya, 2010; Venkatesan, Pandya, 2013; Banupriya *et al.*, 2014; Sharma *et al.*, 2014). The present paper aims to provide a comprehensive review and critical analysis of such SAW sensors.

2. SAW sensor devices

Research studies on SAW sensor devices reveals that the SAW technology has great potential for applications in high frequency electronic devices (from a few MHz to GHz) for data processing, telecommunication etc. (Knauer *et al.*, 1997; Dickert *et al.*, 1998; Morgan, 1998; Kumar *et al.*, 2004; Smith, Hinson-Smith, 2005; Hao *et al.*, 2010). In addition to this, SAW sensors are identified to be a promising candidate for gas sensing applications. A piezoelectric substrate, sensitive region and IDTs are the basic requirements for any SAW sensor (Fig. 1). Piezoelectric single crystal, ST-X Quartz (SiO_2) (Morgan, 1998; Hao *et al.*, 2010), Lithium Tantalate ($LiTaO_3$), Lithium Niobate ($LiNbO_3$), Langasite ($La_3Ga_5SiO_{14}$), GaAs, ZnO films (Tasaltin *et al.*, 2012), and GaN films are some of the efficient substrates of interest due to their peculiar properties in different SAW sen-

sor applications. However, ST-X Quartz and $LiNbO_3$ are the most commonly used piezoelectric substrates preferred for chemical sensing because of their zero temperature coefficient of delay (TCD) and wide bandwidth (Matatagui *et al.*, 2009; 2011b; Hao *et al.*, 2010; Jakubik *et al.*, 2016).

IDTs are metal electrodes usually made up of aluminum (Al), gold (Au) or copper (Cu) placed on a piezoelectric substrate for the generation and detection of surface acoustic waves. Although gold has superior electrical properties, its acoustic losses are very high. Relatively aluminum serves as inert metal as well as good adhesive and it has low attenuation. Therefore, it is predominantly used as an electrode material (Plesski, 2005). Different IDT structures have been studied by many researchers ever since a pair of two combs like metal thin films developed photolithographically by White and Voltmer in 1965 as an IDT has become so popular due to its fascinating properties. The geometry of IDTs might be either single or double or apodized depending upon the specific applications (Pandya, 2010; Banupriya *et al.*, 2014; Sharma *et al.*, 2014). Any SAW sensor device is basically either a SAW delay line or resonator device and it is described below.

2.1. SAW delay line

A SAW delay line is one of the earliest devices consisting of an input IDT and output IDT placed on a piezoelectric substrate as presented in Fig. 1a. At the input IDT, the applied electric field produces mechanical waves (due to the inverse piezoelectric effect) which are transmitted towards the output IDT and converted back to electrical field (due to piezoelectric effect). The delay (τ) produced by the SAW sensor depends on the distance between the centres of input and output IDTs (L) and the SAW velocity for a par-
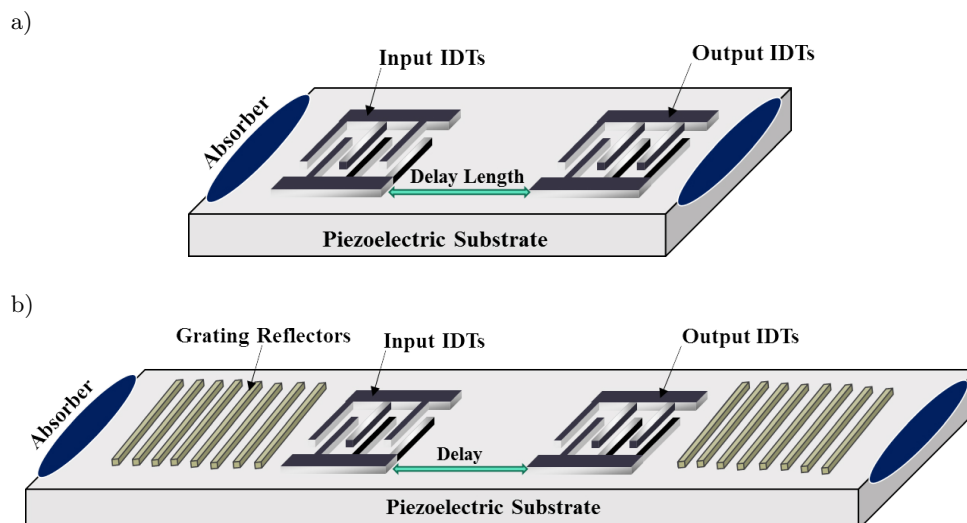

Fig. 1. Schematic design of SAW: a) delay line and b) resonator.

ticular substrate (v_0) which is expressed as $\tau = L/v_0$ (VENKATESAN, PANDYA, 2013; PANDYA *et al.*, 2013; BANUPRIYA *et al.*, 2014; PRIYA *et al.*, 2016).

2.2. SAW resonator

The resonator is a device which oscillates at its resonant frequency with greater amplitude. SAW resonators have found applications in narrow band filters, highly selective band stop or band pass filters, and many other devices. SAW resonators have reflective gratings placed on both sides of IDT in the form of an array with spacing $\lambda/2$. Figure 1b shows the typical design of a two port SAW resonator. The reflected surface acoustic waves from the gratings give rise to a standing wave pattern which forms a resonant cavity around the IDTs. This helps to obtain resonators with moderately high quality factor (KHANEJA, MITTAL, 2008; NIMAL *et al.*, 2009; VENKATESAN, PANDYA, 2013; PANDYA *et al.*, 2013; BANUPRIYA *et al.*, 2014).

The SAW delay line and resonators are promising devices for chemical sensing applications due to the ease of fabrication, relatively large sensitive area and reliability over other devices. The absorbers made of thin silicon film are placed on both the ends of the substrate to ensure the unidirectional flow of acoustic waves which helps to overcome the loss due to interference (PANDYA, 2010; AFZAL *et al.*, 2013; PRIYA *et al.*, 2016).

3. Simulation and modelling of SAW sensors

The performance of a SAW sensor primarily depends on the operating frequency and sensitive layer in the active region of the sensor. Therefore, parameters such as number of IDT finger pairs, finger width, acoustic aperture, transducer periodicity, electromechanical coupling coefficient, substrate velocity, operating frequency, and IDT geometry have to be taken into consideration before the fabrication of a SAW sensor (AFZAL *et al.*, 2013; BANUPRIYA *et al.*, 2014; SHARMA *et al.*, 2014; PRIYA *et al.*, 2016). The prefabrication modelling and simulation of SAW sensors using standard models is helpful to optimize these parameters for real time analysis. Different models have been developed for this purpose. Delta function model, impulse response model (PANDYA *et al.*,

2013; PRIYA *et al.*, 2016), coupling of modes model (KHANEJA, MITTAL, 2008; SHARMA *et al.*, 2014), crossed-field equivalent circuit model and transmission matrix model are some of the models which are analyzed by many researchers (PANDYA 2010; SHARMA *et al.*, 2014; PRIYA *et al.*, 2016). Finite element analysis performed on either COMSOL Multiphysics or ANSYS platform has been found to be a useful method for three dimensional analysis of SAW sensors (EL GOWINI, MOUSSA, 2010).

A complete model which gives combined physical and chemical response of a sensor has yet to be developed, but still significant contributions from modelling helps to improve the performance of SAW sensors.

4. SAW sensor fabrication process

This section briefly describes the fabrication process of SAW sensors reported in various literature and it is similar to that used for integrated chips (Fig. 2). The thermal evaporation technique is commonly employed for metallization of aluminum or copper layer (~ 200 nm) on a specified piezoelectric substrate. The IDT pattern is designed using AutoCAD by the conversion of design data into a standard format for mask pattern generation followed by the photo resistive coating. Figure 3 shows a typical AutoCAD design of
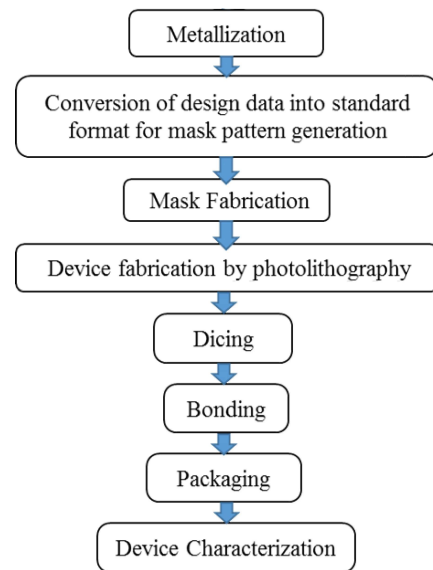
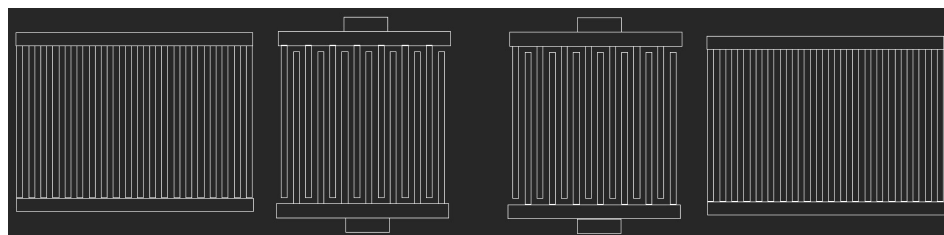Fig. 2. Steps involved in the fabrication of a SAW sensor.

Fig. 3. Typical AutoCAD design of a two port SAW resonator.

SAW sensor. Ultrafine pattern processing of IDT has been performed using the photolithographic technique. These SAW sensors are fabricated in a clean room having less than 100 particles per cubic meter. Subsequent etching, dicing, bonding and packing have to be done before testing of a SAW sensor using a vector network analyser (KNAUER *et al.*, 1997; KHANEJA, MITTAL, 2008; SFEROPOULOS, 2009; PANDYA, 2010).

5. SAW chemical sensing process

A SAW chemical sensor is based on a SAW delay line or resonator device connected in the feedback loop of a high frequency amplifier along with a phase compensation network resulting in a SAW oscillator configuration. Figure 4 and 5 show a typical design of the SAW chemical sensor. The target chemical vapour/gas along with carrier gas passes through the sensitive region between a pair of IDTs. Change in frequency can be observed due to the absorption of analyte by the sensing layer of the SAW sensor. SAW devices having a higher operating frequency will have greater sensitivity to target gas, whereas change in frequency depends on the concentration of analyte to be tested (DICKERT *et al.*, 1998; MORGAN, 1998; KUMAR *et al.*, 2004; WILSON, ATKINSON, 2007b; RODRÍGUEZ-MADRID *et al.*, 2013; MATATAGUI *et al.*, 2015; RAJ *et al.*, 2015a).

The sensing response of the SAW chemical sensor is influenced by various parameters including pressure, temperature, electrical conductivity (HARMER, MARQUIS, 2004; MOORE, 2004; HO *et al.*, 2005; JAKUBIK, 2011), humidity (MITTAL *et al.*, 2015), electric loading, mass loading, elastic loading (RAJ *et al.*, 2012a; JAKUBIK *et al.*, 2016) etc., depending upon the nature of sensing layer. The frequency shift is either positive or negative depending upon the sensing analyte. Initially, target vapour molecules are trapped by pores or grain boundaries of the sensing layer which leads to the negative frequency shift $(-\Delta f)$ due to elastic loading. Subsequently, the vapour molecule gets adsorbed on the sensitive layer and causes a positive frequency shift $(+\Delta f)$ due to the mass loading effect as reported by (RAJ *et al.*, 2012a; 2012b; 2013a; 2017). Frequency shift can be positive or negative due to mass loading and elastic loading, and it depends on the analyte. The mass loading (Δm) can be calculated using a relation comprising of the volume of the sensitive material (V_f), solution concentration of the sensitive material (C_s), partition coefficient $(k = C_s/C_v)$, vapour concentration (C_v) and it is given by (MATATAGUI *et al.*, 2009; 2011b)
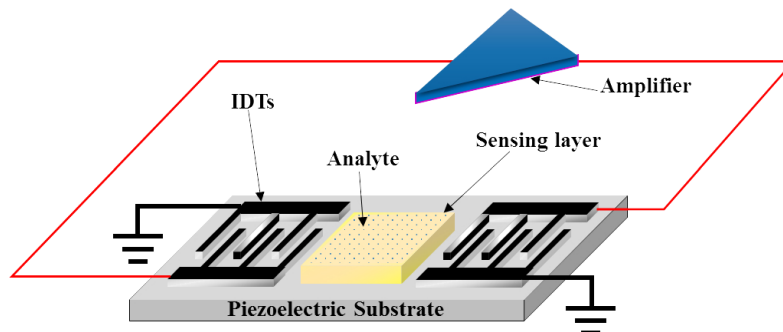
$$\Delta m = C_s V_f = k C_v V_f.$$
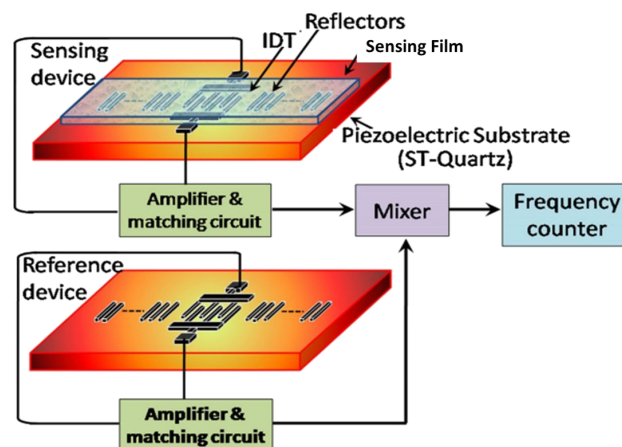

Fig. 4. A typical SAW chemical sensor.

Fig. 5. A schematic of a resonator based SAW sensor in oscillator configuration (RAJ *et al.*, 2015a).

The frequency shift (Δf) of a SAW oscillator due to mass loading can be obtained using the relation (MATATAGUI *et al.*, 2009; 2011b)

$$\Delta f = (k_1 + k_2)f_0^2(\Delta m/A) = (k_1 + k_2)f_0 h k C_v,$$

where, k_1 and k_2 are constants of the piezoelectric substrate, h, f_0 and A are the coated film thickness, unperturbed resonant frequency of the SAW oscillator and the area of the sensing film, respectively. The sensing layer plays a pivotal role in sensing properties of a SAW sensor and therefore, a study of selective coating materials and their properties is of paramount interest for many researchers (MATATAGUI *et al.*, 2011b; RAJ *et al.*, 2013a; 2013b; 2015a; 2017; JAKUBIK *et al.*, 2016).

Table 1. Brief review of polymers used as a selective coating in SAW sensors.

Sensitive coatings	Piezoelectric substrate	Operating frequency [MHz]	Analyte	Analyte concentration	Author (Ref.)
Polymer (SXFA)	ST-X Quartz	433.9	Methanol, benzene, diesel, DMMP	1000–4000 ppm 400–1600 ppm 12–48 ppm 1–0 ppm	SINGH *et al.* (2016)
Polymers (PIB, PECH, PVA, PMA, carbowax etc.)	ST-X Quartz	300	VOCs (ethanol, acetaldehyde, acetone, chloroform etc.)	ppb–ppm	VERMA, YADAVA (2015)
Polymer	ST-X Quartz	–	VOCs, Nerve agent simulant, explosive vapor, etc.	–	JHA *et al.* (2014)
Polymer	ST-X Quartz	163	Nerve agent simulant (DMMP)	0.04–1 ppm 0.25–10 ppm	MATATAGUI *et al.* (2012)
Polymers (PECH, PIB, PEM, carbowax etc.)	ST-X Quartz	157	Nerve agent simulant (DMMP, DCE), VOCs (Toulene)	Sub ppm	MATATAGUI *et al.* (2011a)
Polymers (P4VP, PEG, PS, PSMC etc.)	128° YX LiNbO₃	100	VOCs (methanol, ethanol, acetone, amine and trimethylamine)	–	HAO *et al.* (2010)
Polymers (PIB, PDMS, PECH, SXCN, PEI etc.)	ST-X Quartz	200	VOCs (Toluene), Nerve agent simulant (DMMP), Explosives (DNT, TNT), TICs (Benzene)	–	JHA, YADAVA (2010)
Polymer	LiNbO₃	70.3	VOCs (methanol, ethanol)	300 ppm	BALCERZAK *et al.* (2010)
Polymers (bisphenol, carbowax, polysiloxane, fluoropolyol)	Quartz, LiNbO₃, ZnO/glass	36–434	Nerve agent and its simulant (DMMP, Sarin), Explosives (DNT)	1 ppm, 0.4 ppm, 0.1 ppm	NIMAL *et al.* (2009)
Polymers	ST-X Quartz	–	VOCs (Toulene)	540 ppm	MATATAGUI *et al.* (2009)
Polymers (SXFA, OV₂₅, PECH)	ST-X Quartz	100	Nerve agent simulant	0.05–0.4 ppm 0.1–0.8 ppm	ALIZADEH, ZEYNALI (2008)
Polymer	ST-X Quartz	434	DMMP	5–40 ppm	DU *et al.* (2008)
Polymers (PIB, PECH, PDMS, PBD, PIP etc.)	ST-X Quartz	39.6–264	Nerve agent simulant	5 ppm	JOO *et al.* (2007)
Polymer (Bisphenol)	ST-X Quartz	433.92	DMMP	0.5 ppm, 0.1 ppm	NIMAL *et al.* (2006)

Table 2. Metal oxides as a selective coating in SAW sensors.

Sensitive coatings	Piezoelectric substrate	Operating frequency [MHz]	Analyte	Analyte concentration	Author (Ref.)
Metal oxide (ZnO)	ST-X Quartz	433	Ammonia	25–590 ppm	Raj *et al.* (2017)
Metal oxides (ZnO and TiO$_2$)	ST-X Quartz	175	TICs, VOCs (Toulene, Xylene)	10 ppm, 5 ppm, 10 ppm	Matatagui *et al.* (2015)
Metal oxide (SnO$_2$)	ST-X Quartz	433.9	NO$_2$ gas	20 ppm	Raj *et al.* (2015a)
Metal oxide (ZnO)	ST-X Quartz	433.9	Nerve agent simulant	5–1600 ppm	Raj *et al.* (2015b)
Metal oxides (ZnO, TeO$_2$, SnO$_2$, and TiO$_2$)	ST-X Quartz	433.9	DMMP and methanol	100–500 ppb 0.5–5 ppm	Singh *et al.* (2014)
Metal oxides (ZnO, TeO$_2$, SnO$_2$, and TiO$_2$)	ST-X Quartz	433.9	Chemical Warfare Agents (DMMP, DBS, CEPS, and DECP)	Sub ppm level	Raj *et al.* (2013b)
Metal oxide (ZnO)	ST-X Quartz	433	VOCs (acetone, trichloroethylene, chloroform, ethanol, n-propanol and methanol)	100–5000 ppm	Tasaltin *et al.* (2012)

5.1. Vapour recognition materials

The sensitive layer is an integral part of a SAW chemical sensor. Interaction of target gas molecules on the sensitive layer greatly enhances the sensing property of SAW chemical sensors (Matatagui *et al.*, 2009; Jakubik *et al.*, 2016). Therefore, the sensitive layer should have greater sensitivity, selectivity, short recovery time and long term stability. The surface morphology, structural, electrical and elastic properties strongly influence the sensing properties of the sensitive layer. As a result the physical parameters such as surface roughness, crystallite size, film thickness, resistivity etc., need to be optimized in order to improve the interaction of target gas molecules (Hao *et al.*, 2010; Raj, 2012; Raj *et al.*, 2015a). Afzal *et al.* (2013) has reported that metal oxides, carbon nanotubes, supramolecular structures, molecularly imprinted polymers, self-assembled monolayers and a variety of other polymers have been used as sensitive layer for identification and detection of chemical vapours. Polymers (Hao *et al.*, 2010; Afzal *et al.*, 2013; Singh *et al.*, 2016), metal oxides (Raj, 2012; Raj *et al.*, 2013a; 2015a; Afzal *et al.*, 2013; Singh *et al.*, 2014) and their nanostructures have been widely used for these purposes because of their improved performance over other materials and some of them are depicted in Tables 1 and 2.

5.1.1. Sensitive coating polymers

Polymers have been extensively used as sensitive coatings for SAW chemical sensors over the past few decades due to their short response time, high sensitivity and room temperature operation. For coating polymers as sensitive layers methods like spin coating, solvent casting, dip coating, drop dry method and spray coating method have been used by many researchers (Alizadeh, Zeynali, 2008; Du *et al.*, 2008; Nimal *et al.*, 2009; Singh *et al.*, 2016). In drop dry method, the quantity of polymer loaded on the sensitive region could be known exactly and therefore it is found to be a simpler and efficient method (Nimal *et al.*, 2009; Singh *et al.*, 2016). A different class of polymers has been used depending upon their affinity towards the specific analyte to be detected Table 1). Nimal *et al.* (2009) have developed flouropolyol and polysiloxane polymer coated handheld SAW resonator and dispersive delay line based devices for the detection of CWAs and explosives, respectively. And they have reported that the developed sensor shows reproducible results for more than three years. One of the major drawbacks of using polymer sensitive layer is that their stability and repeatability changes over a long time in different environmental conditions (Nimal *et al.*, 2009). At higher temperatures, the polymer films are more flexible. Consequently the device may misbehave. Therefore metal oxides as sensitive layer are good alternative to overcome these difficulties and for the sustainable development of SAW sensors.

5.1.2. Metal oxide sensitive coatings

Semiconducting metal oxides and their nanostructures have been recently emerging as efficient sensing materials for chemical vapour/gas sensors (Barsan *et al.*, 2007; Wetchakun *et al.*, 2011; Afzal *et al.*, 2012; 2013; Raj *et al.*, 2013b; Islam *et al.*, 2015).

Metal oxides like ZnO, WO$_3$, SnO$_2$, CuO, CeO$_2$ etc., have been widely explored for these purposes (Raj et al., 2013a; 2015a; 2017; Afzal et al., 2013; Singh et al., 2014; Mseddi et al., 2016). The methods such as ion beam assisted reactive deposition, molecular beam epitaxy, pulsed laser deposition, chemical vapour deposition, electron cyclotron resonance, RF or DC magnetron sputtering, sol-gel, atomic layer deposition, electron spray technique etc., were utilized to deposit high quality metal oxide thin films. Over other methods, RF sputtering has been identified to be a promising method for metal oxide coating of SAW sensors (Raj et al., 2013a; 2015a; 2017; Afzal et al., 2013; Mseddi et al., 2016). Among different metal oxide materials, tin oxide (SnO$_2$) and zinc oxide (ZnO) are extensively studied for SAW based gas sensors. Further, ZnO is a well-known piezoelectric material in that it does not degrade the SAW propagation characteristics and hence, it is effectively utilized for the detection of target gas molecules (Raj et al., 2017). Binary mixture of DMMP and methanol have been recognized at ppb and ppm levels, respectively, by using an array of metal oxide sensitive layers (ZnO, TeO$_2$, SnO$_2$ and TiO$_2$) as reported by Singh et al. (2014). Haridas et al. (2010) have developed an array of sensor using SnO$_2$ thin films loaded with nano clusters of different catalysts like platinum, palladium, silver and copper oxide for the detection and identification of LPG, methane, ammonia, and H$_2$S from a mixture of gases.

6. Pattern recognition and SAW E-Nose sensor

The arrangement of selectively tuned hardware (sensor) and software trained to identify gases or odours as a function that can simulate a mammalian nose is called an Electronic Nose or E-Nose. For Sensing of different gases in a mixture, one will need highly selective sensors. Even if this is achieved, the number of sensors will be equal to the number of target gases, which is a difficult task (Haridas et al., 2010; Raj et al., 2015a). A single sensor operating at different temperatures or an array of four or five sensors composed of selectively tuned sensitive layers preferably polymers (Alizadeh, Zeynali, 2008; Singh et al., 2016) or metal oxides (Hao et al., 2010) would be helpful for these purposes. As the number of response signals from the sensor increases, there is a critical need for the development of a software based pattern recognition tool such as principal component analysis (PCA), artificial neural networks (ANN) and partial least square analysis (PLS) to analyze complex data (Singh et al., 2014; 2016). Recently, Harpreet (Singh et al., 2014; 2016) have utilized PCA and ANN for the development of SAW mono polymer and an array of metal oxide based sensors. They have reported that PCA has redundancy over temperatures and sens-

ing layer of sensor. They have successfully implemented ANN pattern recognition for the recognition of DMMP, methanol and some other chemical compounds.

6.1. Chemical vapour generation and delivery system in SAW sensors

SAW E-Nose sensors are needed to be optimized with combination of different chemical vapours/gases for field applications. Therefore, generation and delivery of vapours of different compounds at various temperature are of paramount interest to many researchers (Kannan et al., 2004; Raj et al., 2010; 2013b; Singh et al., 2014; 2016). Figure 6 presents a schematic diagram of vapour generation and delivery system. It consists of flasks (F1 and F2) wounded with heater wire for the generation of vapour from liquids whose concentration can be altered using fine flow controllers (M1–M5) with the help of carrier gas (N$_2$). PID controllers are used for controlling the temperature on the flask. Solenoid valves (S1 and S2) are used for rapid switching between carrier and target gas.
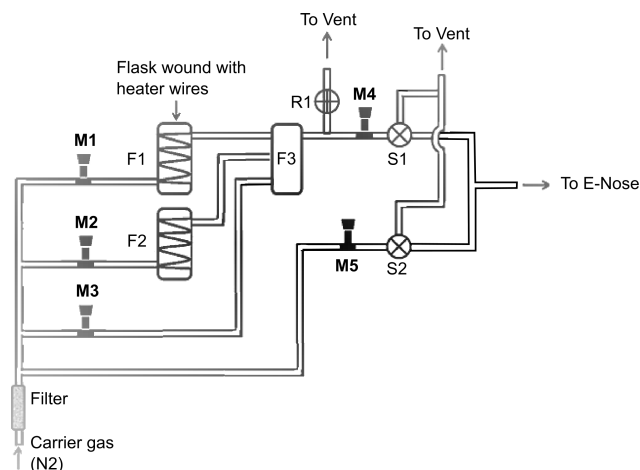

Fig. 6. Schematic diagram of sample vapour generation and delivery system (Singh et al., 2014).

The concentration of a chemical compound could be calculated using weight loss method by evaluating their evaporation rate over different time (Nimal et al., 2006; Raj et al., 2010; 2013a, 2015a; Raj et al., 2013; Singh et al., 2016). Supply of carrier gas (N$_2$) through S2 helps desorption of target gas molecules absorbed/adsorbed on the sensor surface.

7. Current issues and future development of SAW sensors

Environmental monitoring of hazardous air pollutants such as carbon monoxide, sulfur dioxide, nitrogen dioxide, VOCs, and CWAs is very much essential to form a toxin free environment. Thus, there exists an ever increasing demand for the development of smart

sensor technology for the timely detection of these compounds (Harmer, Marquis, 2004; Ho *et al.*, 2005; Joo *et al.*, 2007; Hao *et al.*, 2010; Matatagui *et al.*, 2011b). SAW sensors are aptly suitable for these applications because of their high sensitivity, portability, low cost, quick response, recovery time etc. Globally, SAW delay line and resonator devices are widely exploited as chemical sensors and it has been widely investigated using traditional piezoelectric materials like $LiNbO_3$ and Quartz as piezoelectric substrates (Harmer, Marquis, 2004; Smith, Hinson-Smith, 2005; Nimal *et al.*, 2009; Banupriya *et al.*, 2014).

The working principle of SAW sensor is based on the velocity change measured in terms of frequency and time delay. Hence, the high frequency [MHz] and ultra-high frequency [GHz] SAW devices are mainly of interest. The effective use of piezoelectric materials like ZnO and AIN, helps in the development of ultra-high frequency SAW devices (Knauer *et al.*, 1997; Dickert *et al.*, 1998; Raj *et al.*, 2010). Optimizing the sensing layer is another important aspect for the enhancement of sensing properties. Nanostructured metal oxides have been investigated recently by many researchers for this purpose. The presence of nano pores and discrete energy levels would be helpful to improve the sensitivity by means of mass loading effect in SAW sensors.

Although significant efforts have been made in the development of unique sensing layers, sensing of discrete analyte is still very challenging. Since an array of sensors is used here, pattern recognition tools such as ANN and PCA can be used for recognition but still the presence of unknown compound which is not preloaded into SAW E-nose library cannot be easily recognized. Further, SAW sensors are not compatible with CMOS technology, which constrains their use in the integration of a signal processing circuit (Matatagui *et al.*, 2011b). In addition to this, as the sensitivity gets increased to sub ppm levels, the selectivity and accuracy become complex under various environmental parameters such as humidity (Li *et al.*, 2015; Mittal *et al.*, 2015), temperature (Li *et al.*, 2015), etc. Therefore the possibility of false frequency alarms increases, which eventually decreases sensor performance (Morgan, 1998; McGill *et al.*, 2000; Dewan *et al.*, 2008; Rock *et al.*, 2008; Sferopoulos, 2009; Lim *et al.*, 2011; Matatagui *et al.*, 2011b). Hence, there is always need for the development of compatible handheld SAW sensors for careful monitoring of environmental threats. Intensive research on nanostructured properties of existing sensitive layer materials or the invention of novel materials with better structure, morphological properties and greater stability over time and temperature might be the need of the hour in such cases.

Nowadays, SAW sensors are extensively used as electronic filters in many electronic devices such as mobile phones, television, RFIDs and much more. They are also widely used in industrial and military applications as well. Such SAW sensors can tolerate wide temperature ranges and can perform well under high radiation environments too. Moreover, as these sensors are capable of operating passively without active electronic circuits, they can be employed for wireless detection of threats under harsh environments (Raj *et al.*, 2017; Devkota *et al.*, 2017; Fu *et al.*, 2017).

8. Concluding remarks

SAW chemical sensors are effectively utilized for the detection of chemical threats in the environment. This paper presented an overview of the design, development, simulation and modelling of a SAW device and the modifications required in them for their effective use and understanding.

Polymers, metal oxides and their nanostructures are widely used as sensing layer for enhancement of sensing property up to sub ppm level. An array of sensors and pattern recognition tools (PCA and ANN) is widely useful for enhanced sensitivity and selectivity of SAW E-Nose sensors. Chemical vapour generation and deliver systems find their significance for laboratory testing of SAW chemical sensors. The paper also highlights the various challenges and their possible solutions faced in the design and development of SAW sensor systems. The authors strongly opine that integration of chemical and biological sensors into a single handheld device might be an important step in the future development of SAW sensors in terms of environmental monitoring.

Acknowledgments

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