Surface acoustic wave devices for sensor applications*

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Abstract: Surface acoustic wave (SAW) devices have been widely used in different fields and will continue to be of great importance in the foreseeable future. These devices are compact, cost efficient, easy to fabricate, and have a high performance, among other advantages. SAW devices can work as filters, signal processing units, sensors and actuators. They can even work without batteries and operate under harsh environments. In this review, the operating principles of SAW sensors, including temperature sensors, pressure sensors, humidity sensors and biosensors, will be discussed. Several examples and related issues will be presented. Technological trends and future developments will also be discussed.

Key words: surface acoustic wave; sensor; sensor application
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1. Introduction

The surface acoustic wave (SAW) was first explained by Lord Rayleigh, who described the surface mode of the propagation of an acoustic wave in a piezoelectric material[1]. Later, an easy way to generate a surface acoustic wave was found by White and Voltmer by using interdigital transducers (IDT)[2]. Since then, SAW devices have played an important role in many fields because of their various advantages.

A surface acoustic wave is a kind of acoustic wave that propagates along the surface of a material. It is generated by IDT electrodes, which are periodic metallic bars, deposited on a piezoelectric material. When a sinusoidal wave with a period identical to the IDT period is applied, vibration occurs beneath the IDTs generating an acoustic wave perpendicular to the direction of the IDTs. This wave propagates on the surface of the piezoelectric material away from the IDTs in both directions. With regards to the depth of the wave, it is localized in the surface region, penetrating only a wavelength deep into the bulk region. This means that it has a very high energy density at the surface, hence the name *surface* acoustic wave. The wave velocity in the piezoelectric material is 10^{-5} smaller than the electromagnetic wave, therefore the SAW wavelength transmitted in the piezoelectric material is a factor of 10^{-5} times smaller than the electromagnetic wave, making it a compact device.

Fabrication of SAW devices mainly requires either the deposition or etching of IDTs on a piezoelectric material. The fabrication of IDTs benefits from CMOS process technology, so it is capable of large scale production. However, most piezoelectric materials used for SAW devices cannot be grown by CMOS technology. Therefore, the integration of SAW devices and silicon IC processes are not compatible. A MEMS-CMOS technology facilitates the integration of SAW devices and its data processing circuit.

SAW devices mainly have two kinds of structures. The first is a two port device, also called a delay line, shown in Figure 1(a) where there are two sets of IDTs. The signal is applied on the first set of IDTs, or the input IDT, which generates the surface wave. This wave is then transmitted to the other set of IDTs, or the output IDT, where the received signal can be collected and analyzed. The transmission function is directly determined by the shape of the IDT, therefore the design and easy fabrication of IDTs makes SAW devices widely used as filters in transceivers and other signal processing modules in TV sets and mobile phones etc[3−6]. Besides, as the SAW energy is mainly confined in the surface region, a slight change in the surface condition makes the signal received from the output IDT different, and that lays the foundation of SAW devices working as high sensitivity sensors. The second kind of SAW structure is a one port device, also called a resonator shown in Figure 1(b). It has only one IDT set. Besides the IDT, there are also grating reflectors that can trap the surface wave, forming a resonating cavity where the SAW effect is enhanced. Similarly, the change at the surface of the SAW resonator can change the property of SAW, making the SAW resonator a sensitive detector. Moreover, if the signal from the output IDT is amplified by an amplifier and then fed back to the input IDT of the delay line structure, then this will be another type of SAW resonator that

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(a) Schematic of a two-port device (b) Schematic of a one-port device

Figure 1. Two kinds of SAW devices.

Table 1. TCF and sound velocity of traditional surface acoustic wave materials.

Material	$LiNbO_3$ Y–Z	$LiNbO_3$ 128°Y–X	$LiNbO_3$ 64°Y–X	$LiTaO_3$ X–112°Y	Quartz ST–X
TCF (ppm/℃)	94	75	80	18	0
Sound velocity (m/s)	3488	3979	4742	3300	3159

has been widely used for sensors application.

The factors that can affect the surface condition include temperature, pressure, humidity, mass loading and alike. Accordingly, SAW devices can work as a temperature sensor[7–11], pressure sensor[12–17], humidity sensor[18–21], and a sensor that can detect any mass change or electric field variation at the surface. Mostly, a layer sensitive to a certain chemical is deposited at the delay line area of the SAW device, allowing the analyte to be attached on to the area, or react with the sensitive layer, making a mass change so that the density of the analyte can be detected. Furthermore, specially designed IDTs enable SAW based accelerometers and gyroscopes[22–28].

SAW devices can also be used in passive mode without the need for batteries[29, 30]. An antenna can be added to the input IDT and the signal received by the antenna can then stimulate the SAW, which can be used for sensing as mentioned before.

The sensing principle, together with the compact nature, ease of fabrication, wireless operation, and various other benefits make SAW devices very attractive for sensors and devices in different fields. In this review, we will first talk about the principle for sensing in detail including the temperature dependent characteristics. Afterwards, various kinds of sensors will be discussed. Applications of SAW based sensors such as SAW based inner body measurement will be shown. New materials used in SAW based humidity sensors will be briefly mentioned. As the interest in bio-sensing is increasing, SAW based biosensors will also be discussed to show its advantages in bio-sensing. Finally, trends and future development of SAW devices will be discussed.

2. Principles for sensing applications

Surface acoustic waves are stimulated by applying a sinusoidal wave on the IDTs that are deposited on a piezoelectric material. The wave properties strongly depend on the substrate material, the shape of the IDTs, and the material deposited on the piezoelectric substrate.

A main parameter utilized in the sensing application of SAW is the wave speed. Different piezoelectric materials have different wave speeds. A large wave speed enables the SAW to take less time to transmit from one IDT to another. A SAW delay line structure mainly uses this property for sensing different concentrations of analytes.

The wavelength of the SAW is another parameter that is frequently mentioned. Only when the applied signal wavelength is equal to the intrinsic wavelength of the SAW, which is the period of the IDT, can the SAW be stimulated.

According to the relationship between wave speed, wavelength, and frequency

$$f_0 = \frac{v}{\lambda}, \tag{1}$$

where v is the wave speed of the SAW in a piezoelectric material, λ is the SAW wavelength, and f_0 is the SAW resonance frequency. A larger wave speed and a smaller wavelength enable a higher resonance frequency, which can increase the sensitivity of the sensor[31].

IDTs are fabricated as periodic bars with uniform lengths, widths, and gaps when used for sensing applications. A smaller IDT width, and thus smaller wavelength often results in a higher frequency. While in some applications, different IDT width/gap ratios can generate higher harmonic waves[32].

The wave speed can be determined by a large number of factors. It can be changed at any time as the temperature and analytes concentration change. Therefore, it is the most important in sensing applications.

The temperature has a tremendous effect on the wave speed. This effect can usually be described as the temperature coefficient of frequency (TCF). TCF is defined as the relative change in frequency with temperature.

$$\mathrm{TCF} = \frac{1}{f_0}\frac{\mathrm{d}f_0}{\mathrm{d}T} = \frac{1}{v}\frac{\mathrm{d}v}{\mathrm{d}T} - \frac{1}{\lambda}\frac{\mathrm{d}\lambda}{\mathrm{d}T}, \tag{2}$$

where T is the temperature of the SAW device and λ is constant. This effect is both used for a SAW delay line sensor and a SAW resonator sensor. However, this temperature effect has a reverse impact on other types of sensing. Table 1 lists the sound velocity and TCF of traditionally used materials for SAW devices[6].

Other factors that characterize the atmosphere surrounding the waveguide, along which the surface wave propagates, are pressure and humidity. With a slight fluctuation of pressure, mass loading of the acoustic wave guide can be influenced. With a change of humidity, the wave propagation is disturbed both due to its interaction with the electric field and also due to its direct condensation on the waveguide. The electric field is associated with the surface wave of water particles with a comparatively high dipole moment. Water condensing can be easily avoided by means of a sufficiently high working temperature[33].

Table 2. TCF of different materials and different structures.

Material	$LiNbO_3$	Quartz	$LiTaO_3$	ZnO/ Glass*	ZnO/ diamond/Si*	SiO_2/ZnO/ diamond/Si*	AlN/ diamond	AlN/ Al_2O_3	ZnO/ Al_2O_3
TCF (ppm/℃)	70–95	0	18–32	25	22–30	0	12–24	71	35–48

Items marked with an * are theoretically calculated values by Hideaki Nakahata[41].

External factors that can change the wave speed of the SAW is usually the formation of a thin layer deposited on the piezoelectric substrate on which the SAW is propagated. When analytes interact with this thin layer, either the electric field has a small difference or a mass loading effect is introduced. In this way, the sensing of gases, chemicals, bio-molecules etc., are completed by sensing changes in conductivity of the sensing layer or by observing mass changes when specific molecules are absorbed[34].

Mass changes, together with most factors that can affect wave speed, are not macroscopic to measure. This kind of change is mostly measured by fabricating a kind of resonator and then measuring the change in the resonance frequency. According to the Sauerbrey equation, the resonance frequency has a linear relationship with mass loading, which makes it a very promising mass sensor,

$$\frac{\Delta f}{f_0} \approx -\frac{\rho_m t_m}{\rho_0 t_0} = -\frac{\Delta m}{m_0}, \tag{3}$$

where m_0 is the equivalent mass of the resonant part of the device, ρ_m and t_m are the density and the thickness of the mass on the SAW propagating path, and ρ_0 and t_0 are the density and the thickness of the unloaded resonator respectively[35–37].

A second kind of SAW measurement is done by measuring the time the SAW travels from one IDT to another, such as the SAW delay line depicted before. Yet another way of measurement is done by a round trip time such as in a wireless measurement.

3. SAW devices for sensor applications

3.1. Temperature sensor and temperature compensation

The temperature dependence property can be used to fabricate a temperature sensor. A typical SAW resonator based temperature sensor is reported in the literature by Borrero *et al*. They fabricated a SAW temperature sensor using 128° Y–X $LiNbO_3$ and also tested the pressure and impedance property of this kind of device[8]. The sensor was based on the one-port SAW resonator model where the number and width of the IDTs were determined with the assistance of the COMSOL simulation software. The resonator had an IDT width of 15 μm, 20 IDT finger pairs, an acoustic aperture of 15λ and 100 electrodes on each side of the IDT pairs. The results showed that in a range between 50 and 200 ℃, the frequency had a linear relationship with temperature, which laid a good foundation for temperature measurement. Detailed data showed that the sensitivity is 87.81 ppm/℃, which was very close to the theoretical value shown in Table 1, and the accuracy was $\pm$0.61%. In this article, pressure characteristics and impedance characteristics were also studied. The sensitivity of the SAW device working as a pressure sensor and impedance sensor was 0.9 ppm/kPa and 0.0023 dB/Ω, respectively.

The TCF of traditional piezoelectric materials like $LiNbO_3$, $LiTaO_3$ and quartz have already been listed in Table 1. In recent years the resonant frequency dependency on temperature of new materials and new structures has been widely studied. Emanetoglu *et al.* studied the TCF of ZnO film on sapphire[38]. For the thickness of ZnO $h_{\rm Zno}/\lambda$ from 0.03 to 0.15, the TCF changed from –59 to –42 ppm/℃, for temperature changes between 20 to 120 ℃, showing a nearly constant TCF of ZnO film on a sapphire substrate. Bu *et al.* studied the temperature characteristics of single crystal bulk AlN on the (0001) direction and found a very small TCF as low as −19 ppm/℃, which was smaller compared to many materials used for SAW devices like those listed above[39]. Li *et al.* fabricated a temperature sensor based on the AlN/Si SAW device[7]. As this was not a bulk AlN SAW device, the measured TCF was not –19 ppm/℃, rather, it was –69.9 ppm/℃. This kind of SAW temperature sensor can work at high temperatures up to 500 ℃ due to AlN's superb thermal properties. Table 2 lists the TCF of some commonly studied SAW materials and structures[6, 40–44].

SAW for wireless temperature sensing takes advantage of the round time that SAW travels. The most intriguing property is that it is battery free while doing measurement. This kind of sensor is mainly fabricated in the formation of a delay line in which a pulse signal is applied and a series of pulses are received. Reindl *et al.* designed a wireless SAW based temperature sensor[45]. The schematic picture is shown in Figure 2. The antenna of the SAW transponder receives an RF burst in the VHF/UHF band transmitted by the radar transceiver. Next, the reader unit performs a radar measurement of the impulse response of the SAW transponder via a high frequency electromagnetic radio link. Temperature changes also affect the SAW velocity and thereby, by measuring the response pattern, temperature changes can be obtained. The resolution of this system is $\pm$0.2 ℃. This kind of wireless sensor benefits a remote sensing system while obtaining a good enough resolution, especially for high temperature sensing.

SAW temperature sensors can be fabricated in a capsule and be planted into the inner body to monitor real time temperature. Inner body temperature measurement was tried by Martin and his colleagues[46]. They packaged a $4 \times 1.6 \times 0.5$ mm^3 SAW single port resonator in a ceramic package and connected it to a small pigtail-like antenna. In vivo test in a dog demonstrated the capability of the setup to wirelessly interrogate the SAW resonator, however, the response deformed due to attenuation.

Frequency response varies with materials and structures. Those having a large TCF are apparently suitable for fabricating temperature sensors, however, this in turn causes deterioration in accuracy in other types of sensors. Therefore, the sensor may not be accurate without adding a temperature compensation part. Quartz can have a TCF of zero; however, the coupling

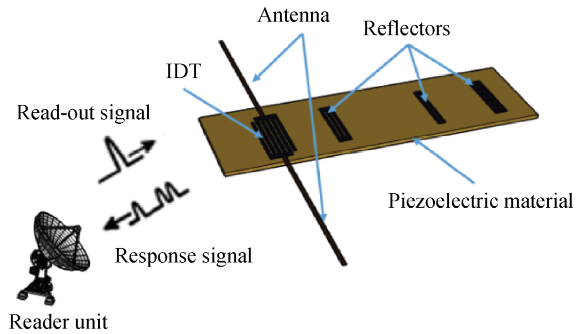


Figure 2. (Color online) Schematic of the operating principle of a SAW-based radio-link temperature measurement system. (Redrawn from Reference [45]).

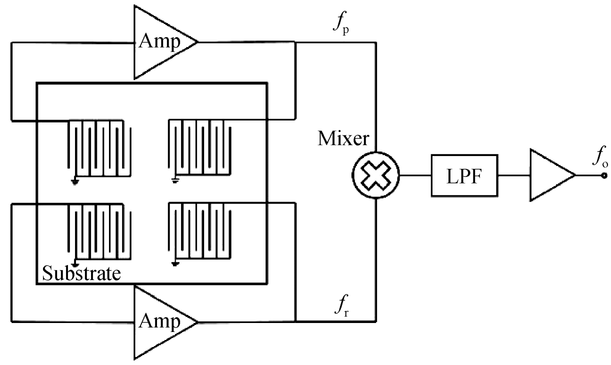


Figure 3. Temperature compensation using an additional SAW and mixer.

coefficient is not high[47]. Therefore, other methods should be used for temperature compensation.

SiO_2 is commonly used to compensate the negative TCF of most piezoelectric materials used to fabricate SAW devices[47]. Calculations have been done on the thickness versus TCF for the layered SAW device $AlN/SiO_2/Si$[48]. Results showed that a temperature compensated structure can be obtained with AlN(1 μm)/SiO_2(1.3 μm)/Si(4 μm) in which TCF $= -0.8$ ppm/℃. This is quite a small TCF and in this case the temperature effect can be eliminated. A $LiNbO_3$(film)/SiO_2/$LiNbO_3$ (substrate) structure SAW device was also found to have a very small TCF for GHz SAW devices[47]. Besides inner-layered SiO_2, depositing SiO_2 as a cover layer can also have the same effect. Zhang *et al.* simulated and verified their simulation result by testing[49]. A $LiNbO_3$ SAW device covered with a layer of SiO_2 was simulated to get the SiO_2 layer thickness so that the TCF of the device was zero. Later experiments verified that the TCF equaled to zero at a thickness of 0.3λ. A large electro-mechanical coupling coefficient of 7.92% was also obtained at such a SiO_2 thickness.

For a general method for temperature compensation, an additional SAW device and a mixer can be used[50]. Shown in Figure 3, one SAW acts as a reference sensor and the other as a sensing unit. As the two SAW sensors can be placed to experience the same temperature but only one sensor can sense the pressure change, any interference that can affect frequency change can be cancelled out after the mixer. This way of temperature compensation is more accurate and is widely used in the sensing field[51–54].

3.2. Pressure sensor

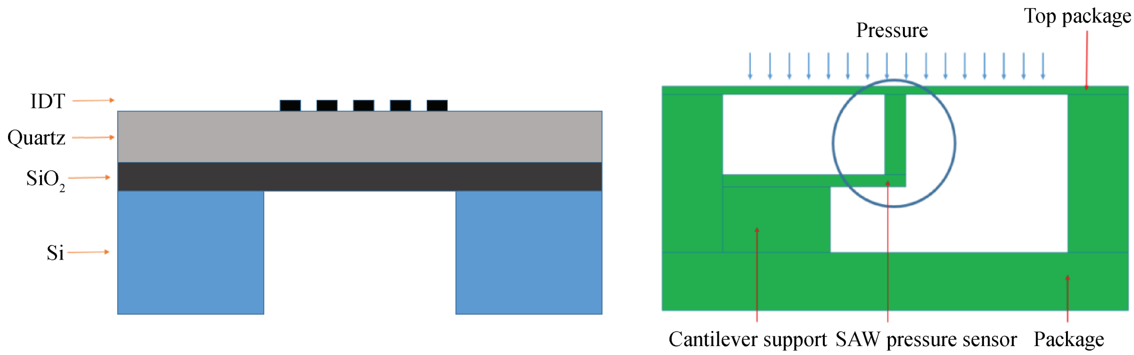
The SAW velocity is strongly affected by the pressure applied onto the surface of piezoelectric material. Therefore, a SAW pressure sensor can be designed according to the pressure-frequency relationship. The substrate is often etched beneath the sensing part of the sensor to enhance the pressure sensitivity such as the pressure sensor that Grousset *et al.* have designed[55]. The SAW pressure sensor was fabricated on a single crystal AT-cut quartz film transferred onto a bulk silicon substrate. The Si substrate was etched using deep RIE to expose the sensing area. The schematic structure is shown in Figure 4(a). The quality factor of this device was 12500 at a resonance frequency of 430 MHz. The resonance frequency showed a linear relationship with pressure applied onto the quartz membrane and a pressure sensitivity of 25.8 kHz/bar from 0 to 4.8 bar was measured. Another way for pressure sensing requires the fabrication of a cantilever (Figure 4(b)) to suspend the device in air as developed by Borrero *et al.*[8]. They simulated the pressure distribution of the device, especially in the circle in Figure 4(b) and the cantilever was placed where a high linear response can be obtained. They measured a 0.9 ppm/kPa sensitivity of their pressure sensor.

SAW pressure sensors can be used in a car tire pressure monitoring system (TPMS)[56–59]. This kind of sensor takes advantage of the fact that a SAW can be used wirelessly and without a battery. With a one-port SAW resonator and antenna, the TPMS can be stimulated by signals of different frequencies and then received back from the SAW. The sensitivity of such a pressure sensor can be approx. 8.19 kHz/bar[58].

SAW pressure sensors can also be used for inner-body testing. In a trial for a blood pressure sensor, Liang *et al.* amplified the signal of a SAW device by a Colpitts oscillator which was powered by coil coupling[60]. A static test showed a 1.75 kHz/mmHg sensitivity and the standard deviation was less than 1 mmHg. The following in vivo test in a lab rat measured a 95 mmHg mean pressure and got the heart rate which modulated the blood pressure rate. Another in vivo SAW based blood pressure sensor was fabricated to be the first known wireless pressure data from the left ventricle of the heart of a living swine[61]. A prototype of the SAW blood pressure sensor was able to monitor changes in blood pressure around the clock and this was consistent with a commercialized catheter-tip transducer, because it benefited from a well-designed antenna[62].

3.3. Humidity sensor

If the SAW sensor is exposed to a humid atmosphere, the sound velocity will change due to the water having condensed on the sensor. In response to humidity, various changes in the sensor can be exploited for the sensing of humidity. These include (i) mass loading effect, (ii) film conductivity changes and then the electric field associated with SAW changes, and (iii) elasticity changes. Nomura *et al.* fabricated their SAW humidity sensor based on conductivity changes[53]. A 128° YX $LiNbO_3$ SAW device was coated with a kind of hygroscopic polymer called polystyrene sulfonic acid. In the range of 40%



(a) One kind of pressure sensor structure. (Redrawn from Reference [55])

(b) Another kind of pressure sensor structure. (Redrawn from Reference [8])

Figure 4. (Color online) Two kinds of SAW pressure sensor structures.

to 80 R.H. the sensor response varied linearly with R.H., with a velocity change of approximately 20 m/s for a 10% change in R.H., Tashtoush *et al.* reported a thin polyXIO film coated 50 MHz YZ-cut $LiNbO_3$ SAW device, with a range of R.H. of 0 to 100% and a hysteresis effect of the order of 5%, based on the mass loading and viscosity effect[63].

New materials were found to be able to contribute to humidity sensing. The properties of graphene oxide (GO) are found to be influenced by humidity[64]. A SAW humidity sensor using a graphene oxide sensing layer was studied[65]. SAW devices based on ZnO/glass substrate were coated by GO and the sensitivity and response time was measured. Ultra-fast and sensitive results were found. The frequency shift was exponentially correlated to the humidity change. The humidity sensor showed high sensitivity at a broad humidity range from 0.5%RH to 85%RH with < 1 s rise time. For a 225 MHz SAW with a 9.16×10^{-6} m^2 area 200–300 nm GO coating, the sensitivity can be as high as 265.18 kHz/5%RH.

Graphene is shown to be a material suitable for a SAW humidity sensor. Rimeika *et al.* demonstrated and investigated the response to air humidity of 200nm thick graphene layers on a YZ $LiNbO_3$ SAW sensing layer[66]. Under low RH, frequency was linearly dependent on humidity while under high RH, frequency shows a super-linear dependence on humidity, which can be explained by different principles for different RH. Guo *et al.* obtained similar conclusions[67].

In another study, MWCNT/Nafion performed as a sensing layer[68]. An excellent sensitivity of about 400 kHz/%RH in the range from 10% to 80%, a good linearity, and a short response time were measured.

3.4. Gas sensor and E-nose application

SAW devices can also be used for various kinds of electronic-nose (e-nose) sensors. This usually requires the absorption of certain kinds of gases on a thin sensing layer usually made of polymers or metal oxides.

Penza *et al.* fabricated a sensor that shows a high sensitivity response towards NH_3 gas and excellent selectivity with respect to the main interfering gases such as CO, CH_4, H_2, and O_2 at room temperature by depositing polypyrrole films on the SAW surface as gas absorbent layers[69]. Lee *et al.* made a SO_2 sensor using twin SAW oscillators with one coated with a CdS film[54]. SO_2 can be absorbed by the CdS film and the induced mass loading and electric field change can shift the frequency proportional to the SO_2 concentration. The sensor was capable of measuring concentrations in air less than 200 ppb SO_2. Qin *et al.* also fabricated a SO_2 sensor coated with triethanolamine (TEA) modified with boric acid (H_3BO_3) and showed a linear frequency change with SO_2 in the range of 0.5–8.0 ppm[70].

Lim *et al.* fabricated a reflective delay line SAW sensor that can measure CO_2, NO_2 and temperature simultaneously[71]. By taking advantage of a passive SAW, sensing can be done without a battery, and the measurement of NO_2, CO_2 and temperature can be done simultaneously. The structure of this device is shown in Figure 5. By depositing Teflon AF 2400 for CO_2 sensing and ITO for NO_2 sensing, this device can reach a sensitivity of 2.12 /ppm for CO_2 and 51.5/ppm for NO_2, respectively.

Raja and his group did research on sensing of chemical warfare agents (CWA) using SAW devices[72]. ZnO, TeO_2, SnO_2 and TiO_2 were deposited for the detection of dimethyl methylphosphonate (DMMP), dibutyl sulfide (DBS), chloroethyl phenyl sulfide (CEPS) and diethyl chlorophosphate (DECP), respectively. Four simulants of CWA can be well separated and sub ppm level detection can be reached. Diesel, benzene and methanol sensing has also been investigated[73].

Sehra *et al.* did research on the concept of an electronic tongue[74]. The electronic tongue classified correctly the four basic tastes of sweet, sour, salt, and bitter without a selective biological or chemical coating.

3.5. Biosensor

Due to its small size and wireless control, together with its multifunctional capabilities, label free and high accuracy make SAW devices a very promising component of biosensors. On one hand, SAW can be fabricated in a capsule and be planted into the inner body to access the body information we need wirelessly, such as inner body temperature mentioned before. On the other hand, the high accuracy makes it a perfect device for protein molecules, ultra-small cells or DNA detection.

The high accuracy of the SAW sensor significantly benefits the detection of small cells and DNA molecules. A third order harmonic mode surface acoustic wave that had a frequency

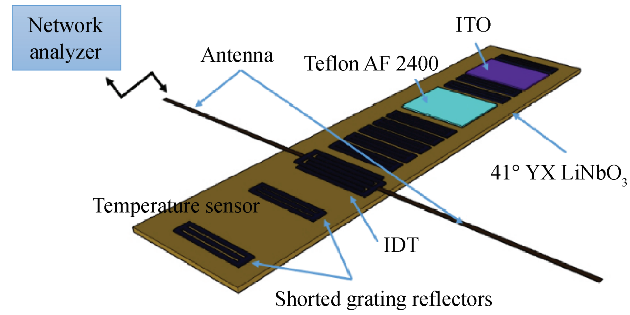


Figure 5. (Color online) Schematic view of a wireless chemical sensor system (Redrawn from Reference [71]).

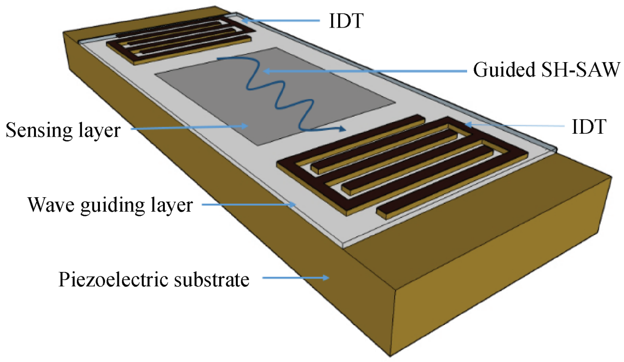


Figure 6. (Color online) Structure of Love mode SAW device.

of 6.4 GHz has been achieved using $LiNbO_3$, and the device has been used to detect DNA sequences and cells[37]. Gold was used as the sensing layer for DNA detection in this work, and gold is also frequently used for SAW bio-sensing. The probe DNA and target DNA were successively attached to the surface and the resulting frequency change of the SAW resonator was measured. For the DNA detection, a sensitivity of 6.7×10^{-16} g/cm^2/Hz was achieved, and this sensitivity was high enough to distinguish a single hybridized DNA. EMT6 and 3T3 cancer cells were used to further study the sensitivity of the sensor and it was found that a single cell was able to be detected, which laid the foundation of accurate diagnosis of cellular mutation that can cause cancer. Moreover, the authors have performed repeated experiments on DNA and cancer cells and their results show a steady sensing ability.

Bio-chemicals often need to be detected in solutions to know their concentration. However, when immersed in aqueous liquids, the traditional Rayleigh SAW tends to radiate into the liquid because the displacement component is perpendicular to the surface. Another kind of SAW named the Love mode SAW is capable of conquering this difficulty. Love waves are guided acoustic modes which propagate in a thin layer deposited on a substrate. The acoustic energy is concentrated in this guiding layer where the displacement component is parallel to the surface. Figure 6 shows the structure. Quite a lot of work has been done on Love mode SAW biosensors[52, 75–79]. Some research work has been conducted on Love mode liquid sensors as well[80–86], however, in this review we mainly focus on Love mode biosensors. For traditional piezoelectric materials, SiO_2 and PMMA are frequently used as the wave guiding layer. PDMS is frequently used to fabricate channels due to its various advantages[87], and PMMA is also used.

Zhang *et al.* have reported a prostate specific antigen(PSA) sensor based on the Love Wave biosensor[52]. In this sensor, $LiTaO_3$ with Al IDTs were coated with a wave guiding layer of SiO_2, and then an Au sensing layer was deposited for PSA attachment. Subsequently a microfluidic channel was fabricated using PDMS to ensure that liquid can flow between the IDTs. Two SAW resonators were fabricated with one acting as a reference, and a detection limit of 10 mg/mL was obtained.

A Love mode SAW for microorganism detection has also been studied such as by Hao *et al.*[79]. In their study, SiO_2 was used as the wave guiding layer, APTES as the functional layer, and PMMA as the channel material. The sensitivity of this sensor can be 3 μg/mL for anti-IpaB antibody. A biological warfare agents (BWA) sensor was studied as well, obtaining a sensitive and fast response to the target antigen[78].

4. Trends and future development

High sensitivity makes SAW devices very suitable for sensor applications. The sensing principle is mainly based on the velocity change of acoustic wave transmitted in the piezoelectric material, and then measured by frequency change or time delay. Various kinds of sensors have been investigated among which several kinds have been briefly introduced in this review.

Since SAWs were found to be easily stimulated by IDT, sensors like temperature sensors, pressure sensors etc. were widely investigated using traditional piezoelectric materials like $LiNbO_3$. With their development, SAW sensors have been investigated in a broad range. Nowadays, with the development of bioengineering, as well as precision medicine, more and more researchers have been doing experiments on the SAW biosensor, as shown in the biosensor part of this review. Protein, DNA, bacteria, and cancer cells detection have drawn a lot of attention. Lab-on-a-chip has gained popularity in recent years, and SAW has seen itself become useful in manipulation of liquids and separation of cells. Measurement can also be done using SAW as a lab-on-a-chip device as mentioned in Section 3.5. Nevertheless, more work needs to be done to fabricate portable biosensors. Due to its portability, high sensitivity, cost efficiency, and simple structure, together with a signal processing unit, make SAW sensors very attractive in future daily life.

As shown in Section 2, a higher operating frequency leads to a high sensitivity. Therefore, high frequency and super high frequency (SHF) SAWs have been investigated. SAW sensors up to GHz have been developed[88–92]. For high frequency devices, both materials and structure as well as fabrication processes need to be studied. Several ways to fabricate high frequency devices are shown below.

First, using materials that have a high sound velocity, high frequency piezoelectric materials including ZnO and AlN have been studied. ZnO has a sound velocity of more than 4000 m/s and AlN has a sound velocity of around 5600 m/s, which is almost twice that of $LiNbO_3$.

Second, using a layered structure. Sapphire has a sound velocity of around 6000 m/s and diamond has the highest sound velocity up to now more than 10000 m/s. Optimized thickness of AlN has been deposited onto diamond to acquire a velocity of more than 8000 m/s[93], and ZnO on diamond has a velocity of 5100 m/s[94].

Third, using electron-beam lithography (EBL). As optical lithography can hardly fabricate line below 1 μm, for EBL it is easy to fabricate lines on the order of nanometers[37, 95, 96].

Though quite a lot of advantages have been shown for SAW sensors, various challenges still exist. The biggest one is the peripheral circuit. Frequency response and time delay is measured using a network analyzer, which is large and expensive. However, for portable and cheap use of SAW, a better signal processing circuit is needed. Especially for SHF SAW, a circuit made using discrete devices is not possible due to the high speed. Another problem is CMOS compatibility. SAW is fabricated using piezoelectric materials, and the growth of these materials is not compatible with CMOS technology. This further constrains the integration of a signal processing circuit with SAW sensors. Therefore, either fabricating traditional piezoelectric materials using CMOS technology is required or finding new CMOS compatible piezoelectric materials is needed as a crucial issue in the further development and mass production of SAW sensors.

5. Conclusion

SAW devices are small, sensitive, inexpensive and easy to fabricate, and can work without a local power source. They can be used in various fields such as signal processing, sensing and so on. In this review, the SAW device operating principle is explained and the working mechanisms as temperature sensor, pressure sensor, humidity sensor, E-nose and biosensor, are explained. Large TCF benefits temperature sensing while it interferes with other sensing, therefore reference channels are often fabricated for more accurate pressure sensing, biosensing and so on. Low TCF material or SiO_2 coated SAW can be directly used as sensors because of its low influence by temperature. SAWs can also be stimulated wirelessly. By taking advantage of this property, a temperature sensor can be fabricated for inner body temperature measurement, for high temperature sensing and so on. Also, TPMS and blood pressure sensor can be fabricated using SAW because it can sense pressure and it can work wirelessly. SAW has shown its wide usage especially in gas sensing, liquid sensing, bio-sensing, toxic gas sensing and CWA detection. DNA, cancer cells and antigens can be detected using SAW sensors with extremely high sensitivity, which benefits medical treatment.

Though SAW is a very attractive device for sensors applications, more investigations are required, especially towards the high frequency operation. A wider set of applications need to be tested. The compatibility with CMOS technology and signal processing circuit is a big issue which needs to be solved. Despite these difficulties, SAW devices continue to be widely studied and used for sensors applications.

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