A Review of Surface Acoustic Wave Sensors: Mechanisms, Stability, and Future Prospects

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Abstract

Purpose

Surface acoustic wave (SAW) sensors have attracted great attention worldwide for a variety of applications in measuring physical, chemical and biological parameters. However, stability has been one of the key issues which have limited their effective commercial applications. To fully understand this challenge of operation stability, this paper systematically reviewed mechanisms, stability issues and future challenges of SAW sensors for various applications.

Design/methodology/approach

This review paper starts from different types of SAWs, advantages and disadvantages of different types of SAW sensors, and then stability issues of SAW sensors. Then recent efforts made by researchers for improving working stability of SAW sensors are reviewed. Finally, it discusses the existing challenges and future prospects of SAW sensors in the rapidly growing Internet of Things (IoT) enabled application market.

Findings

A large number of scientific articles related to SAW technologies was found, and a number of opportunities for future researchers was identified. Over the past 20 years, SAW related research has gained a growing interest of researchers. SAW sensor has attracted more and more researchers worldwide over the years, but the research topics of SAW sensor stability only own an extremely poor percentage in the total research topics of SAWs or SAW sensors.

Originality/value

Though SAW sensors have been attracting researchers worldwide for decades, researchers mainly focused on the new materials and design strategies on SAW sensors to achieve good sensitivity and selectivity, and little work can be found on stability issues of SAW sensors, which are so important for SAW sensor industries and one of the key factors to be mature products. Therefore, this paper systematically reviewed the SAW sensors from their fundamental mechanisms, to stability issues, and indicated their future challenges for various applications.

Key words

Surface acoustic wave (SAW), sensors, stability, Internet of Things (IoT), review

1. INTRODUCTION

SURFACE acoustic wave (SAW) sensors have been attracting researchers worldwide for decades. They have numerous advantages over conventional sensors, e.g., low cost (Stoukatch et al., 2021; Morales-Rodríguez, 2018), high sensitivity (Zhou et al., 2022), fast response (Wang et al., 2022a; Wang et al., 2019; Wang et al., 2022b), low power consumption (Chu and Zhang, 2022), small size (Malocha et al., 2013), etc. Also, they are compatible with microelectromechanical systems (MEMS) technologies (Ali and Prasad, 2020). To date, a large number of studies on SAW sensors have been carried out to achieve a wide variety of functions to measure physical/mechanical (Hribšek et al., 2010; Tang et al., 2022; Wang et al., 2020; Yu, 2018; Tang et al., 2015; Kim et al., 2019; Tang et al., 2020; Gamba et al., 2014, Zhao et al., 2022; Tang et al., 2021; Li et al., 2020; Lü et al., 2014; Tang et al., 2018a; Feng et al., 2019; Fan et al., 2022; Tang et al., 2018b; Pan et al., 2021; Memon et al., 2021; Müller et al., 2015; Tang et al., 2017; Li et al., 2019; Yang et al., 2023), chemical (Zhang et al., 2020; Kumar and Prajesh, 2022; Abraham et al., 2019; Afzal et al., 2013; Gao et al., 2018; Pasupuleti et al., 2022a; Kus et al., 2021; Vanotti et al., 2021; Pasupuleti et al., 2021; Pasupuleti et al., 2022b; Zhu et al., 2021; Wang et al., 2022; Devkota et al., 2022; Grabka et al. 2021; Gakhar et al., 2022; Kabir et al., 2015; Harathi et al., 2020; Yang et al., 2017; Lim et al., 2011; Ghosh et al., 2019; Kuznetsova et al., 2018; Mainuddin et al., 2011; Wang et al., 2015; Wang et al., 2022; Xiong et al., 2021; Luo et al., 2021; Li et al., 2020; Devkota et al., 2020; Nikolaou et al., 2016; Tian et al., 2023) and biological (Rana et al., 2028; Zhang et al., 2017; Prabakaran et al., 2022; Yao et al., 2019; Ji et al., 2019; Huang et al., 2021; Zhang et al., 2021; Agostini et al., 2018; Yue et al., 2022; Agostini et al., 2019; Kogai et al., 2017; Lo et al., 2021; Tigli et al., 2010; Hirst et al., 2011; Gao et al., 2021; Greco et al., 2020; Li et al., 2022; Bröker et al., 2012; Rauf et al., 2023; Sisman et al., 2017; Chen et al., 2014; Gagliardi et al., 2023) parameters, which are usually named SAW physical/mechanical sensors (temperature, pressure, torque, strain, tension, etc.), SAW chemical/chemo-sensors (pH, CO, CO_2, H_2, NO_2, ClO_2, etc.), and SAW biosensors (DNA, alpha-fetoprotein, carcinoma embryonic antigen, etc.). They are summarized in Table I, II and III. Through reviewing large quantities of literatures, researchers mainly focused on the new materials and design strategies on SAW sensors to achieve good sensitivity and selectivity. However, little work can be found on stability issues of SAW sensors, which are so important for SAW sensor industries and one of the key factors to be mature products.

During the life span of a mature commercial sensor, repeatable and stable sensing signals must be maintained (Chai et al., 2022). Apart from the above reason, recent emergence of the Internet of Things (IoT) enabling technology boosts the commercial sensor market and requires stable mature sensors for long-term monitoring tasks (Qi et al., 2020; Qi et al., 2018). Sensors for IoT usage should be stable and reliable to achieve cost- effective purpose (Qi et al., 2017). This trend even poses more challenges in improving stability and reliability of sensors. Researchers have made some efforts on the stability of sensors. For instance, Chai et al. (2022) reviewed the stability of metal oxide semiconductor gas sensors, identified five key factors which influence the stability and raised six improvement methods. Zhang et al. (2022) presented low contents cellulose nanocrystals composites for the achievement of excellent thermal stability for preparing flexible resistance strain sensors. Zhu et al. (2022) utilized piezo-phototropic effect to achieve long-term stability of a Flexible self-powered $CsPbI_3$/rGO/P(VDF-TrFE) pressure sensor and photodetector. Zhao et al. (2022) prepared a sensitive MoS_2 photodetector cell with high air-stability for multifunctional in-sensor computing. Wang et al. (2022) prepared a MXene-composited gelatin organohydrogel to achieve environmental stability and self-adhesiveness for multifunctional sensors. Khabisi et al. (2022) analysed the thermal stability of piezomagnetic nano-sensors and nano-actuators considering the flexomagnetic effect. However, the aforementioned work did not have a systematic review on the stability of SAW sensors and cannot make a comprehensive instruction on the improvement of SAW sensor stability.

To our knowledge, SAW sensors are constructed by substrate materials, interdigital transducers (IDTs), reflectors, packages, and possible sensitive films (for chemical and bio- sensors). The enhancement of the stability and reliability of the above components and the sensing effects or reactions is an effective approach to reduce uncertainties during the operations of SAW sensors. Furthermore, it can also improve the accuracy and precision of SAW sensors. Though the providers of commercial SAW sensors do have long-term tests on the stability before the products are put into market, the data of stability tests are usually confidential to the public, which limits the research work of stability. Moreover, there is no specific international standard on sensor stability at the moment (Chai et al., 2022; Fadel et al., 2016). In an effort to be aware of the critical factors which influences the stability performance of SAW sensors, this paper conducts a systematic review on the-state-of-the-art in SAW sensors, some critical factors influencing stability, methods for improving stability, and finally discusses the challenges and future trends of SAW sensor technologies.

As shown in Figure 1, an extensive literature review by examining relevant articles from major academic databases was undertaken (Elsevier (Science-Direct), Springer, Wiley, IEEE (Institute of Electrical and Electronic Engineers), RSC (Royal Society of Chemistry), ACS (American Chemical Society), and MDPI (Multidisciplinary Digital Publishing Institute)). Search terms include the key words ‘Surface Acoustic Wave’, ‘Surface Acoustic Wave Sensor’, and ‘Surface Acoustic Wave Sensor Stability’. As a result, we found a large number of scientific articles related to SAW technologies and identified a number of opportunities for future researchers. Over the past 20 years, SAW related research has gained a growing interest of researchers. About half of articles were published in Elsevier journals. SAW sensor has attracted more and more researchers worldwide over the years, but the research topics of SAW sensor stability only own an extremely poor percentage in the total research topics of SAWs or SAW sensors.

The rest of the paper is organized as follows. Section II gives a review of the mechanisms and the state of the art in SAW sensor technologies. Section III presents the stability issues and improvements of SAW sensors. Section IV discusses the challenges and future research trends of SAW sensors.

TABLE I

STUDIES OF SAW PHYSICAL/MECHANICAL SENSORS IN RECENT YEARS (SOURCE: TABLE BY AUTHORS)

References	SAW modes	Sensing objects	Delay line / resonator	Active / passive
Hribšek et al., 2010	-	Review of SAW sensors in mechanical engineering	-	-
Tang et al., 2022; Tang et al., 2015; Tang et al., 2020; Tang et al., 2021; Tang et al., 2018a; Tang et al., 2018b; Tang et al., 2017	Rayleigh	Pressure	Delay line	Passive
Wang et al., 2020	Rayleigh	Strain	Delay line	Passive
Yu, 2018; Li et al., 2020	Rayleigh	Pressure	Resonator	Passive
Kim et al., 2019; Zhao et al., 2022	Rayleigh	Temperature	Resonator	Passive
Gamba et al., 2014	Rayleigh	Temperature	Delay line	Passive
Lü et al., 2014; Feng et al., 2019	Rayleigh	Yarn tension	Delay line	Active
Fan et al., 2022	Rayleigh	Strain	Resonator	Passive
Pan et al., 2021; Memon et al., 2021	Rayleigh	Pressure	Resonator	Active
Müller et al., 2015	Sezawa	Temperature	Resonator	Active
Li et al., 2019	Rayleigh	Strain	Resonator	Active

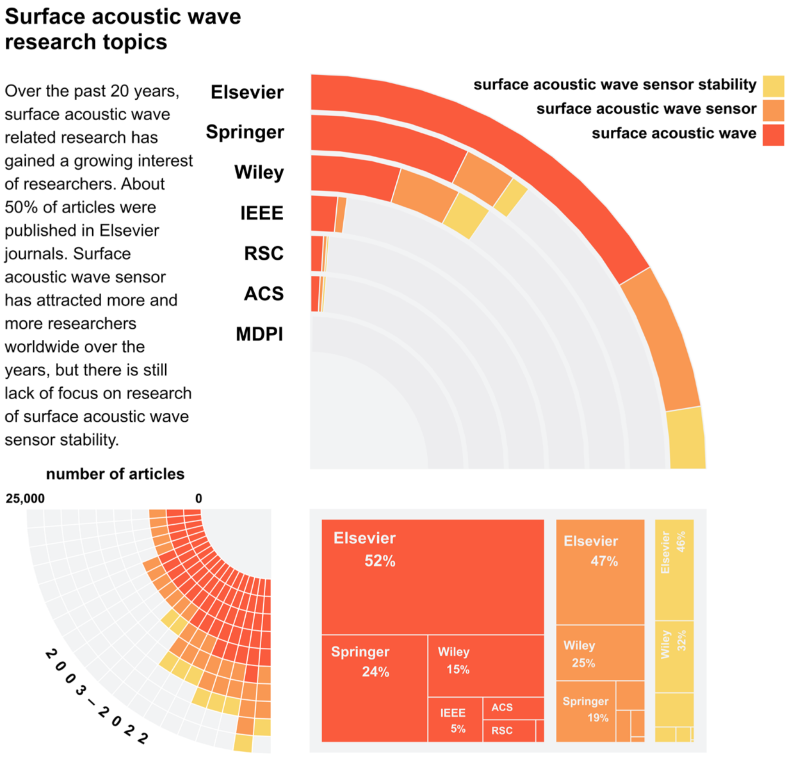
TABLE II

STUDIES OF SAW CHEMICAL SENSORS IN RECENT YEARS (SOURCE: TABLE BY AUTHORS)

References	SAW modes	Sensing objects	Delay line / resonator	Active / passive
Zhang et al., 2020	-	Review of SAW ultraviolet photodetectors	-	-
Kumar and Prajesh, 2022	-	Review of SAW gas sensors	-	-
Abraham et al., 2019; Gao et al., 2018; Kus et al., 2021	Rayleigh	VOCs	Resonator	Active
Afzal et al., 2013; Gakhar et al., 2022	-	Review of SAW VOCs sensors	-	-
Pasupuleti et al., 2022a; Pasupuleti et al., 2021	Rayleigh	NO_2	Resonator	Active
Poisson et al., 2021	Rayleigh	CO	Delay line	Active
Pasupuleti et al., 2022b	Rayleigh	CO	Resonator	Active
Zhu et al., 2021	Rayleigh	NH_3	Resonator	Active
Wang et al., 2022a	Rayleigh	CO_2 and humid	Delay line	Active
Devkota et al., 2022; Yang et al., 2017; Wang et al., 2022b	Rayleigh	H_2	Delay line	Active
Grabka et al., 2021	Rayleigh	Dimethyl methylphosphonate	Resonator	Active
Kabir et al., 2015	Rayleigh	Elemental mercury vapor	Delay line	Active
Harathi et al., 2020	Rayleigh	H_2	Resonator	Active
Lim et al., 2011	Rayleigh	CO_2, NO_2 and temperature	Delay line	Passive
Ghosh et al., 2019	Rayleigh	CO_2	Resonator	Active
Kuznetsova et al., 2018	Sezawa	Humid	Delay line	Active
Mainuddin et al., 2021	Rayleigh	Chemical warfare agents	Resonator	Active
Wang et al., 2015	Rayleigh	Organophosphorous Compounds	Resonator	Active
Xiong et al., 2021; Luo et al., 2021	Rayleigh	NO_2	Delay line	Active
Li et al., 2020	Rayleigh	Ethanol	Resonator	Active
Devkota et al., 2020	Rayleigh	CO_2 and CH_4	Delay line	Passive
Nikolaou et al., 2016	Love	VOCs	Delay line	Active

TABLE III
STUDIES OF SAW BIOSENSORS IN RECENT YEARS (SOURCE: TABLE BY AUTHORS)

References	SAW modes	Sensing objects	Delay line / resonator	Active / passive
Rana et al., 2018	Love	Uric acid	Delay line	Active
Zhang et al., 2017	Love	Nucleic acid	Delay line	Active
Prabakaran et al., 2017	Love	Amino acid	Delay line	Active
Yao et al., 2019	Love	E. coli l-asparaginase	Delay line	Active
Ji et al., 2019	SH-SAW	Pseudomonas Aeruginosa	Delay line	Active
Huang et al. 2021; Zhang et al., 2021	-	Review of SAW biosensors	-	-
Agostini et al., 2018	Rayleigh	Sub-nanomolar biosensor	Resonator	Active
Yue et al., 2022	Rayleigh	Wearable SAW indirect biosensor	Resonator	Passive
Agostini et al., 2019	Rayleigh	SAW microfluidics-based lab-on-a-chip biosensor	Resonator	Active
Kogai et al., 2017	Rayleigh and SH-SAW	Immunosensor	Delay line	Active
Lo et al., 2021	SH-SAW	Antigen transferrin receptor	Delay line	Active
Tigli et al., 2010	Rayleigh	Mammoglobin	Delay line	Active
Hirst et al., 2011	Rayleigh	Bond rupture	Delay line	Active
Gao et al., 2021	SH-SAW	SAW phononic metasurface based gravimetric biosensor	Resonator	Active
Greco et al., 2020	Love	Ultra-high-frequency SAW real-time biosensor	Delay line	Active
Li et al., 2022	Love	Carcinoembryonic antigens	Delay line	Active
Bröker et al., 2012	Love	Cancer cells	Delay line	Active
Rauf et al., 2023	Leaky SAW	Protein kinase A activity in cell lysates	Delay line	Active
Sisman et al., 2017	SH-SAW	Biomarkers of prostate cancer	Delay line	Active
Chen et al., 2014	Sezawa	Human IgE	Delay line	Active



Over the past 20 years, surface acoustic wave related research has gained a growing interest of researchers. About 50% of articles were published in Elsevier journals. Surface acoustic wave sensor has attracted more and more researchers worldwide over the years, but there is still lack of focus on research of surface acoustic wave sensor stability.

Figure 1 Statistics of scientific articles related to Surface Acoustic Wave, Surface Acoustic Wave Sensor and Surface Acoustic Wave Sensor Stability (Source: Figure by authors)

2. STATE OF THE ART IN SAW SENSOR TECHNOLOGIES

2.1. SAWs

Lord Rayleigh (1885) found SAW propagating in semi-infinite isotropous materials. Then White and Voltmer (1965) successfully used inter-digital transducer (IDT) deposited on piezo-crystals to excite and detect SAW. Since SAW devices were invented, they had been applied to a variety of signal processing techniques including filtering, retardation, pulse compression, correlation, convolution etc. and in fields of radar, aerospace, radio and television, communication etc. With the development of radio frequency identification (RFID) technologies, the demand of RFID-tags keeps increasing (Yang and Wu, 2014; Yang, 2013; Yang et al., 2013). Moreover, SAW RFID-tags plays an important role in RFID industries. Then based on different types of SAW devices, SAW sensors have been developed and investigated in the recent years (Pohl, 2000; Bulst et al., 2001; Drafts, 2001; He et al., 2015). It can be seen that SAW technologies show great potentials in a wide range of applications, which attract researchers worldwide.

The propagations of SAWs are considered as the fundamentals of SAW sensors, which enable a wide range of sensing functions. SAWs are elastic waves propagating along the surface or interface of an elastic solid (Wu, 1983; Wu et al., 1983), which have different modes, including Rayleigh wave, Lamb wave, Bleustein-Gulyaev-Shimizu (BGS) wave, Leaky SAW, Shear Horizontal (SH)-SAW, Love wave, Stoneley wave, Sezawa wave, etc. (Akedo, 2010; Lu et al., 2021; Kiełczyński, 2022; Kadota et al., 1996; Plessky and Thorvaldsson, 1995; Chen et al., 2022; Darinskii and Shuvalov, 2021; Hadj-Larbi and Serhane, 2019; Fu et al., 2022). The most common SAW mode utilized in physical SAW sensors is Rayleigh wave, which is the first discovered SAW and one of the classic SAW modes. It has longitudinal and shear components and is coupled to the medium to propagate on the surface of the substrate (usually the acoustic energy is concentrated in the range of one wavelength below the surface of the substrate), and the acoustic wave velocity is about 5 orders of magnitude lower than the electromagnetic wave velocity (Rayleigh, 1885; Wu, 1983). However, Rayleigh-SAW sensors are not appropriate for sensing tasks in liquid environment, as Rayleigh-SAWs release energies into ambient liquid environment, which leads to attenuations of SAW energies. In order to resolve this problem, Love-SAW sensors are designed for sensing in ambient liquid environment. Love-SAW is a surface acoustic wave that only moves horizontally perpendicular to the propagation direction of SAW, and its particle vibration has no vertical component. It can be imagined as a kind of in-seam wave. The substrate is taken as the upper boundary of the groove, and total reflection occurs on both sides of the boundary of the groove (Wu, 1983). Figure 2 shows the comparisons of Rayleigh and Love SAWs.

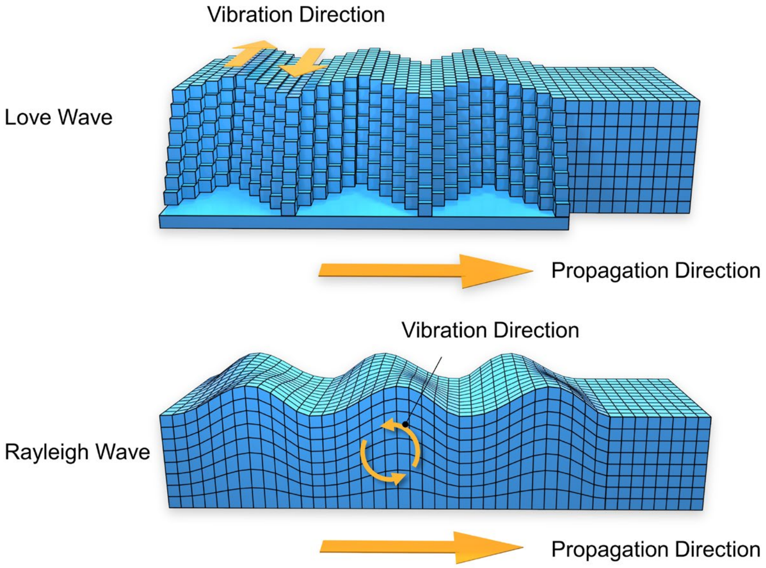


Figure 2 Comparisons of Rayleigh and Love SAWs (Source: Figure by authors)

2.2. SAW sensors

The fundamental structure of SAW sensor is mainly composed of one or more than one IDT, reflection gates (reflectors) and a substrate (usually a substrate is made of piezoelectric material) as the propagation medium of SAWs. Figure 3 is an example of SAW sensor node. The fundamental work principles of a SAW sensor consist of two main parts. The first part is the radio frequency (RF) signal interrogation and response. When the IDT fabricated on the piezoelectric substrate receives RF signal, it converts the RF signal to the SAW. The reflectors also fabricated on the substrate reflect the propagating SAW back to the IDT which can convert SAW back to RF signal. The second part is the sensing principles. SAW is sensitive to the changed physical, chemical or biological parameters because of its propagation properties, based on which high sensitivity sensor can be produced. When changed physical, chemical or biological parameters acting on the surface of SAW device in different mechanisms, the disturbances can change the SAW propagation velocity and amplitude. Measurement can be achieved by measuring the corresponding changes in output RF signal (phase, frequency or amplitude) (Tang et al., 2022).

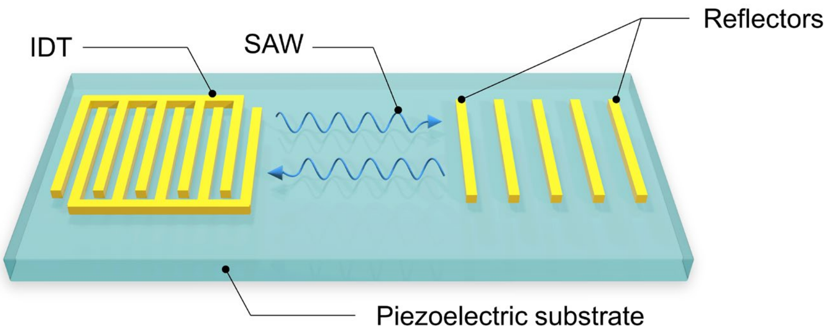


Figure 3 An example of SAW sensor node (Reflective delay line type) (Source: Figure by authors)

Actually, the structures of SAW sensors are various, but they all have two fundamental components, i.e., IDT and piezoelectric substrate. Based on different operation principles, SAW sensors can be designed into two types, i.e., SAW delay line sensors and SAW resonator sensors, and a mix of the two types (Tang et al., 2015; He et al., 2015). Based on whether the sensor nodes need direct power supply, SAW sensors can be divided into two types, i.e., active and wireless passive SAW sensors. Active SAW sensors need direct power supply (Marcu et al., 2016). They usually utilize delay line or active resonator oscillator (both delay line and active resonator oscillator are different forms of reflectors on piezoelectric substrate) structures. The frequency of output signal is easy to interface with the adaptive timely processing system. At present, SAW chemical/gas sensors and SAW biosensors mostly utilize active design. On the other hand, wireless passive SAW sensors do not need direct power supply (Tang et al., 2022). They combine wireless reading system and wireless passive SAW sensor node. Antenna is connected to the IDT for RF signal receiving and emitting back. They generally utilize passive device structures such as single-end pair resonator or reflective delay line to achieve wireless measurement of various parameters. At present, SAW physical sensors such as temperature, humidity, pressure and torque have utilized wireless passive design, which can be applied to harsh environments (Tang et al., 2022; Liu and Zeng, 2016). Based on the functions of SAW sensors are proposed to achieve, they are designed into physical/mechanical, chemical and biological sensors.

2.3. Components of SAW sensors

1) IDT

The IDT is utilized to excite, receive and detect SAWs on the surface of piezoelectric substrate to achieve the conversion from radio frequency (RF) signals to SAWs and the reconversion from SAWs to RF signals (Tang et al., 2022). As the most important component of SAW devices, the characteristics of IDT is the key to determine the performance of SAW devices (Yu, 2018). IDT is configured by conductive thin-film electrodes. It is usually formed by deposition of metal on the surface of piezoelectric substrate using semiconductor manufacturing process. It is formed by two groups of alternating periodic comb bands which are called cross-finger electrodes. Each set of cross-finger electrodes is connected to a bus bar. A typical IDT structure is shown in Figure 4 (Yu, 2018). *L* is the length of periodic cross-finger electrodes, *W* is the acoustic aperture, *a* and *b* are the width and interval of cross-finger electrodes respectively. When *a* and *b* are equal and to a quarter of *L*, it is called uniformed IDT which is the simplest and most widely used IDT. Otherwise, it is called ununiformed IDT (Yu, 2018). Through literature review, most research articles focused on uniformed IDT SAW sensors.

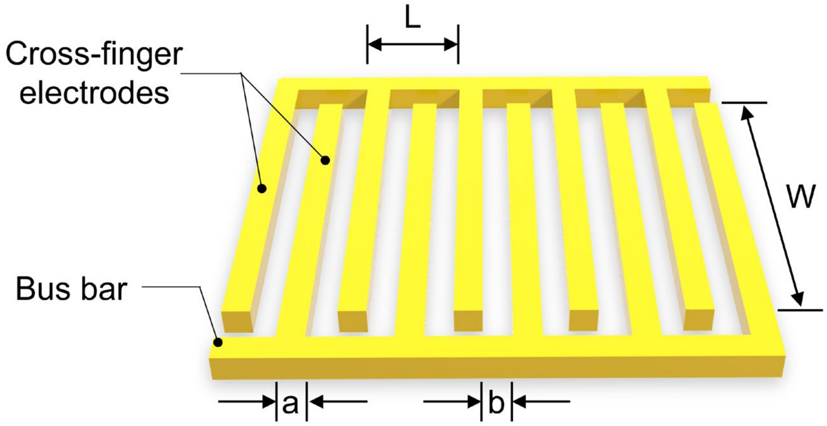
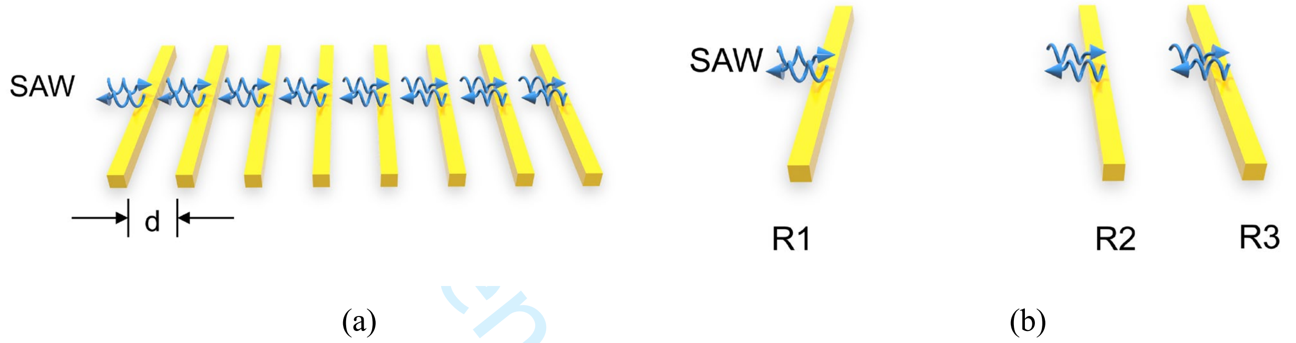


Figure 4 A typical IDT (Source: Figure by Yu, 2018)

2) Reflector

Figure 5 (a) shows the reflection gates of SAW resonators. Symbol *d* is the periodic interval length of Bragg reflectors (Tang et al., 2015). Bragg reflectors are the key for a SAW resonator to form acoustic cavity on the surface of piezoelectric substrate. By setting $d=0.25\lambda_{SAW}$, the SAW reflected by each gate reaches the same phase, and therefore by this setting the reflection effect is strongest and thus the acoustic resonator is formed. The quality factor *Q* of a SAW resonator is the most concerned index in its design. The high *Q* can be achieved by increasing the reflection coefficient of Bragg reflectors and the number of their periods (Yu, 2018; Soluch, 1999).

Figure 5 (b) shows the reflection gates of SAW delay lines. The SAW delay lines usually have several separate metal straps (delay lines) etched on a piezoelectric substrate for SAW reflections to produce different time delays on response RF signals. The parameters to be measured influence these time delays resulting in the phase shifts of response RF signals. Therefore, usually, the parameters to be measured are functions of phase shifts by utilizing SAW delay line sensors (Tang et al., 2022).



(a) (b)

Figure 5 Reflection gates of SAW sensors: (a) resonator (Bragg reflectors); (b) delay line (Source: Figure by Yu, 2018)

3) Substrate materials

As the carrier of SAW generation, propagation and conversion, piezoelectric substrate is a key component that affects the performance of SAW sensor. SAW sensors consist of optically polished piezoelectric substrates or piezoelectric thin films applied to different types of substrates, upon which thin film conductive electrodes are patterned using photolithographic processes common to the semiconductor industry. Therefore, the selection of appropriate piezoelectric material and the material manufacturing plays important roles in the eventual performance of SAW sensors. Piezoelectric single crystals (PSCs), piezoelectric ceramics and piezoelectric films (PFs) are the three most common substrates used in SAW devices (Fukuda et al., 1998; Chen et al., 1997).

PSCs are generally anisotropic materials, and the same material with different cutting directions has significant differences in its properties. Notable features of PSCs are low insertion losses, good temperature characteristics, high repeatability and reliability indicators, but its cost is high. Therefore, special attention should be paid to different cutting directions when making SAW devices utilizing PSCs (Jang et al., 2022).

Piezoelectric ceramics are piezoelectric materials with the highest electromechanical coupling coefficient, which are easy to process and can be made into almost any desired shape. They have wide applications and their cost is low. They can change their temperature coefficients, dielectric constants and other parameters by the selection of their elements, the change of the additives and sintering conditions. The disadvantage of piezoelectric ceramics is that they have pores inside, so the surface uniformity is not ideal after surface grinding, and their consistencies cannot be guaranteed. Moreover, their frequency loss is high and repeatability is poor (Zhao et al., 2019).

In a SAW device, the energy of SAW is concentrated in the surface layer of the piezoelectric substrate, the thickness of which is about one SAW wavelength. Therefore, the SAW device can be fabricated by utilizing PF with a thickness of about one wavelength on a non-piezoelectric substrate such as glass instead of PSC or piezoelectric ceramic as substrate. The PFs utilized for this purpose are required to have the same excellent characteristics as the PSCs or piezoelectric ceramic. The material type, thickness, non-piezoelectric substrate material and other parameters of PF determine the sound speed, centre frequency and delay time of SAW propagating in it. The main advantage of PF materials is that they can be easily integrated with semiconductor electronic devices as monolithic devices, enabling the integration of SAW devices and peripheral circuits. SAW devices using PF materials have wide application frequency range, high energy conversion efficiency, and easy to integrate with semiconductor process, but it is not easy to obtain PF with good repeatability and excellent piezoelectric properties (Pinto et al., 2022).

2.4. Types of SAW sensors

Figure 6 shows different types of SAW sensors with different IDT and reflector structures. According to different working principles, SAW sensors can be classified into delay line type, resonator type or a mixture of the two types (Tang et al., 2015; He et al., 2015). The parameters to be measured influence on time delays and phase shifts of response signals of SAW delay line sensors, while the parameters to be measured influence on the resonant frequency of response signals of SAW resonator sensors.

1) SAW delay line sensors

Based on different structures (with or without reflecting gate), SAW delay line sensors are classified into non-reflective type and reflective type. The former is usually utilized in design of active SAW sensors, while the latter is mostly utilized in design of wireless passive SAW sensors (He et al., 2015).

(a) SAW non-reflective delay line sensor

SAW non-reflective delay line sensor usually contains two IDTs, but no reflection gates. One IDT acts as the input unit which completes the electromagnetic wave to SAW conversion, while the other IDT acts as the output unit which completes the SAW to electromagnetic wave reverse conversion. Once the external parameters to be measured are changed, the SAW velocity and the distance between two IDTs subsequently change, leading to the change of time delays and phase shifts of response signals. Therefore, the change of parameters to be measured can be calculated by the change of time delays or phase shifts.

(b) SAW reflective delay line sensor

The main difference between reflective delay line and non-reflective delay line structures is whether the sensor structure owns reflection gates. The reflection gates are utilized for reflections of SAW propagations. Similarly, the changes of SAW velocity and the distances between the IDT and reflection gates caused by the changes of parameters to be measured lead to the changes of time delays and phase shifts of response signals. Not like a single way propagation of SAW in non-reflective design, SAW propagations in reflective delay line design have a round trip. The IDT of a SAW reflective delay line sensor not only converts RF signals to SAWs but also reconverts reflected SAWs back to RF signals.

2) SAW resonator sensors

SAW resonator sensors are classified into two types based on their structures: dual-port and single-port. The former is mainly designed for active SAW resonator sensors, while the latter is usually designed for wireless passive SAW resonator sensors.

(a) Dual-port SAW resonator sensor

Dual-port SAW resonator sensor has two identical IDTs paralleled in the centre, and two groups of Bragg reflectors are fabricated symmetrically on both sides of the two IDTs. One IDT acts as the input unit to convert RF signals to SAWs, and the other IDT acts as the output unit to convert SAWs back to RF signals. Once the external parameters to be measured are changed, the SAW resonant frequency subsequently changes. Therefore, the change of parameters to be measured can be calculated by the change of the resonant frequency shifts.

(b) Single-port SAW resonator sensor

Single-port SAW resonator sensor has only one IDT which is bidirectional. The IDT acts as both input and output of RF signals. It receives RF signals and converts them to SAWs, and also reconverts SAWs back to RF signals. The changes of parameters to be measured lead to the changes of SAW resonant frequency. The single-port structure is convenient for wireless passive design.

3) Comparisons on SAW delay line and resonator sensors

Figure 6 shows different types of SAW sensors: a) SAW non-reflective delay line; b) SAW reflective delay line; c) Dual-port SAW resonator; d) Single-port SAW resonator sensor. Table IV summarized the comparisons on SAW delay line and resonator sensors.

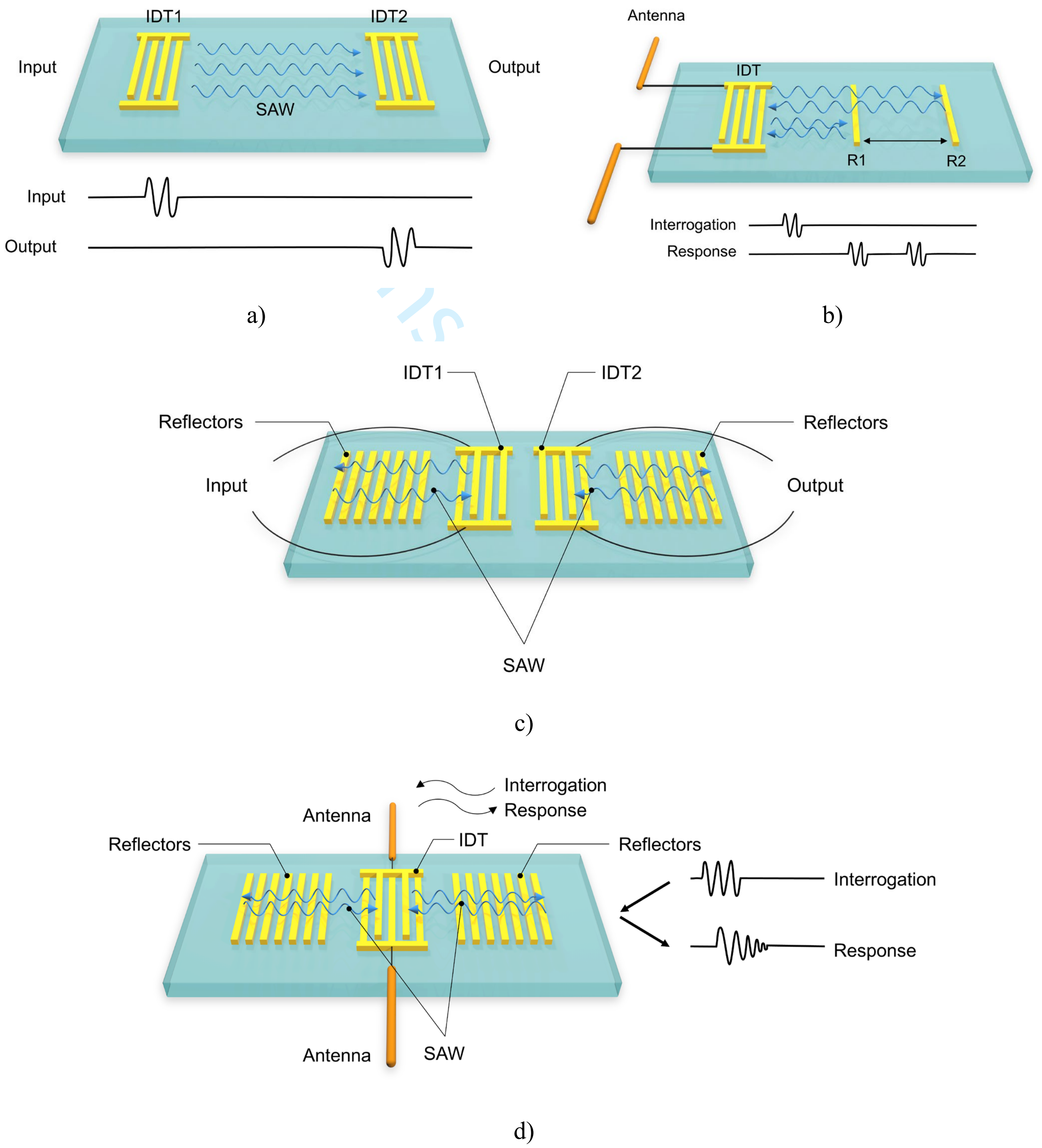


Figure 6 Different types of SAW sensors: a) SAW non-reflective delay line; b) SAW reflective delay line; c) Dual-port SAW resonator; d) Single-port SAW resonator sensor (Source: Figure by Yu, 2018)

TABLE IV
COMPARISONS ON SAW DELAY LINE AND RESONATOR SENSORS (SOURCE: TABLE BY TANG, 2019)

	SAW delay line	SAW resonator
Embedded ID	Yes	
Resolution	Lower than resonator due to its characteristics (obtain sensing information in time domain)	Higher than delay line due to its characteristics (obtain sensing information in frequency domain)
Interrogation period	Several tens ms	Below 1 ms
Signal processing	Decipher sensing information by time delays or phase changes compared with original interrogation signals	Decipher sensing information by obtaining resonant frequency changes from the response signals
Application range	Wide	Narrower than delay line
Multi-sensor integration	Yes	Not as easy as delay line
Structure	Brief	Not as brief as delay line

2.5. Sensing objects

Figure 7 summarized the research status of SAW sensors through examining relevant articles from Web of Science database, while Figure 8 summarized the recent 20 years' research status. Figure 7 shows that approximately 44% research topics on SAW sensors are related to SAW chemical sensors, then 37% to SAW physical/mechanical sensors and 19% to SAW biosensors. Furthermore, the researches of SAW sensors have been increasing rapidly in recent 20 years, especially in recent 10 years. Figure 8 shows that in recent 20 years, research topics on SAW physical, chemical and bio- sensors own similar percentages as the entire historical statistics in Figure 7. The total number of articles related to SAW sensors is gradually increasing year by year, while SAW chemical and bio- sensors owns more and more percentages in the total statistics. The aforementioned statistics on SAW sensors gives a guide and identified a number of opportunities for future researchers on SAW sensor developments.

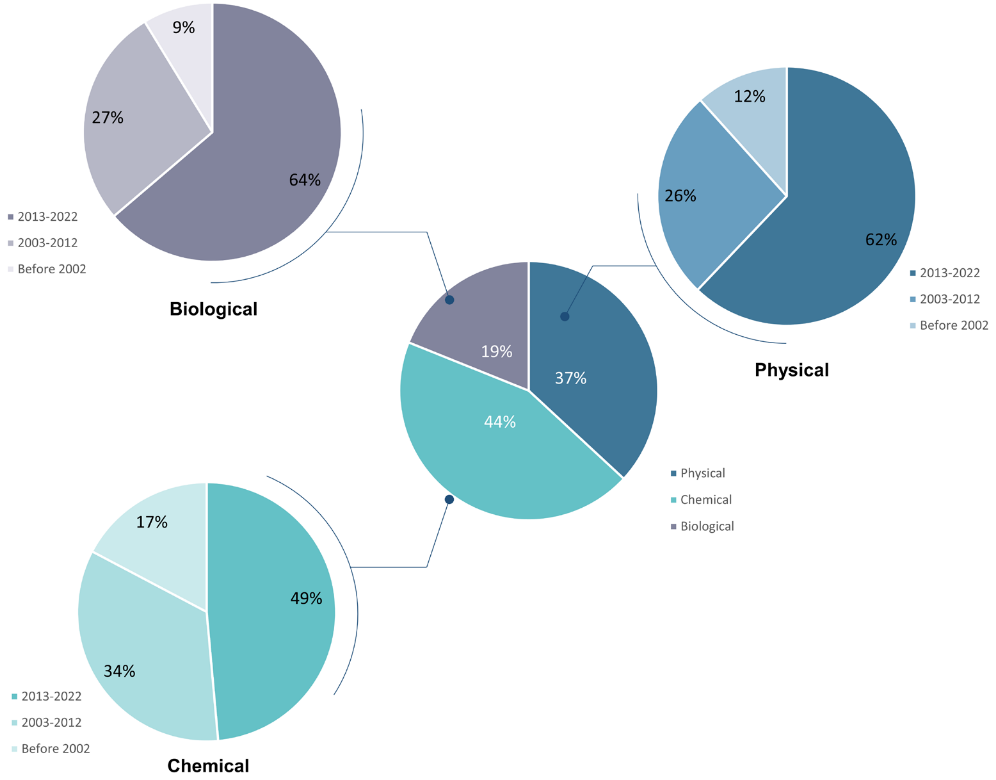


Figure 7 Research status of SAW sensors (Web of Science) (Source: Figure by authors)

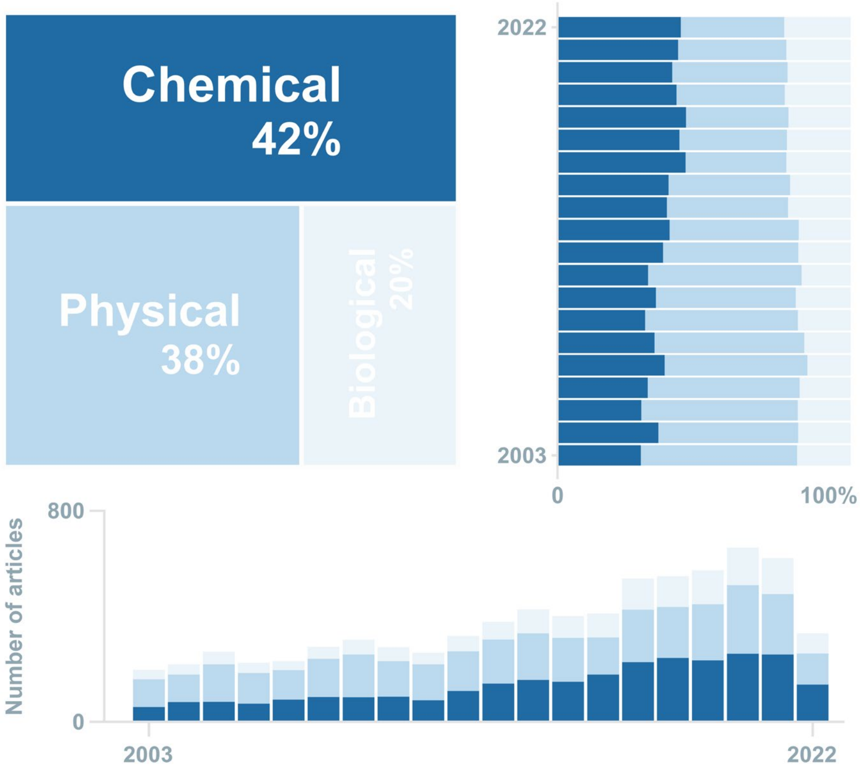


Figure 8 Recent 20 years' research status of SAW sensors (Web of Science) (Source: Figure by authors)

3. STABILITY ISSUES AND IMPROVEMENTS

The stability issues of SAW sensors are summarized in Table V. For SAW sensors, the disruptions on SAW propagations cause the change of response RF signals. The reasons of disruptions could be various, e.g., the deformation of sensor substrates, the changes of mass loads on sensing areas, etc. A variety of ambient environmental parameter changes could lead to the disruptions on SAW propagations. Subsequently, the response RF signals reconverted by IDTs are changed with the changes of SAWs. Compared to other research topics of SAW sensors, the efforts made by researchers to improve the stability of SAW sensors are much fewer. In order to keep a constant sensing performance and to reduce non-to-be-measured influences, stability issues of SAW sensors should be paid more attentions by researchers.

3.1. Temperature stability

Among all stability issues of SAW sensors, temperature stability is the most common one and investigated by researchers. Temperature change has a significant influence on the deformation of the substrate, which causes the change on SAW propagation, and this eventually leads to the interference on response RF signals. The temperature instability of a SAW sensor chip can cause it difficult to calibrate. Pan et al. (2021) analysed the influence of temperature on the pressure sensitivity of SAW pressure sensor. Dual-channel temperature compensation design is usually utilized to eliminate the influence of temperature in SAW sensors. Kalinin et al. (2016; 2011) utilized non-paralleled dual-channel design for temperature stability of SAW resonator strain and torque sensors. Our previous investigations on wireless passive SAW reflective delay line pressure sensor [11] utilized a one-IDT and opposite directional dual-channel design for temperature compensated of SAW pressure sensor. Wang et al. (2007) investigated a molecularly imprinted polymer coated SAW gas sensor with enhanced sensitivity utilizing a high frequency stability oscillator. Fu et al. (2014) also utilized a SAW stable oscillator design to design a highly sensitive strain sensor. Temperature-stable substrate materials are also the key to fabricate SAW sensors with high temperature stability. Caron et al. (1996) identified a sequence of crystallographic orientations along the rotated Y-cut in quartz as appropriate temperature stable piezoelectric substrates for SAW gas sensors. Xue et al. (2022) developed a SAW pressure sensor based on Langasite, which can measure pressure up to 1000 °C. Wang et al. (2020) developed a temperature-compensated wireless passive SAW strain sensor utilizing a Y-cut 35° X quartz substrate patterned by one-port resonator with perfect temperature stability. In summary, recent studies by researchers worldwide tried to compensate the temperature impacts on SAW sensors by dual-channel design or utilizing temperature-stable substrate materials. Actually, the temperature-stable packaging strategies of SAW sensor nodes could be another approach to improve the temperature stability, but it was rarely investigated by researchers.

3.2. Stability of sensitive materials of SAW chemical/bio- sensors

For SAW chemical and bio- sensors, stability of sensitive materials is another key factor impacting the entire sensor stability and durability performance. The ambient environment may cause the alterations of the chemical or bio- characteristics of the sensitive materials, which further leads to the instability of the SAW chemical/bio- sensors. Lupan et al. (2021) indicated that in order to obtain moisture-resistant sensors, it is essential to minimize the effects of -OH on sensitive films. In terms of sensing materials of SAW gas sensors, Suematsu et al. (2016) indicated that the interferences caused by -OH can be reduced by −OH poisoning, and Chai et al. (2022) summarized that the stability of sensitive materials could be enhanced by improving the synthesis/deposition method. The micro- and nano-structures of sensitive materials can improve stability performance of SAW chemical and bio- sensors. For instance, Tang et al. (2020) reported cellulose nano-crystals as a sensitive and selective layer for high stability SAW hydrogen chloride gas sensors. Pasupuleti et al. (2022) reported a highly stable langasite based SAW NO_2 gas sensor using 2D g-C_3N_4 at TiO_2 hybrid nanocomposite. Jandas et al. (2020) investigated a highly stable, love-mode SAW biosensor using Au nanoparticle-MoS_2-rGO nano-cluster doped polyimide nanocomposite for the selective detection of carcinoembryonic antigen. It can be obtained from Chai et al.'s (2022) work that we could improve SAW sensor stability by improving the synthesis/deposition methods of sensitive materials on the sensing areas of

SAW sensors. In summary, recent studies tried to improve stability of sensitive materials of SAW chemical/bio- sensors by improving fabrication methods to immobilize the sensitive layers or utilizing materials which are stable or stable in chemical/bio- reactions.

3.3. Internal stresses influencing on stability of SAW physical/mechanical sensors

For some SAW physical/mechanical sensors (especially pressure-related SAW sensors), internal stresses during manufacturing/packaging processes can also cause instability of the sensor performance. They are not easy to avoid during manufacturing processes. In order to solve the internal stress problem, optimal manufacturing and packaging technologies should be addressed. For instance, Chen (2010) had a case study on pressure sensors for the packaging effect investigation of wafer-level chip scale packaging with a central opening. François et al. (2015) presented a high temperature packaging method for SAW transducers acting as wireless passive sensors. Borzì et al. (2022) conducted a high-resolution X-ray diffraction and micro-computerized tomography multiscale investigation of stress and defects induced by a novel packaging design for MEMS sensors. Chen et al. (2009) developed a novel plastic package for pressure sensors fabricated using the lithographic dam-ring approach to enhance the internal stress influences. In summary, researchers tried to improve packaging technologies to reduce internal stresses influencing on stability of SAW physical/mechanical sensors.

TABLE V
STABILITY ISSUES ON SAW SENSORS (SOURCE: TABLE BY AUTHORS)

	Temperature stability	Stability of sensitive materials	Internal stresses
SAW physical/mechanical sensors	Yes	N/A	Yes
SAW chemical/bio-sensors	Yes	Yes	N/A

4. PROSPECTS

SAW sensors have been developed for more than 30 years. They show great potential and commercial value in a wide range of applications. A variety of novel, superior and low-cost SAW sensors will influence every aspect of our daily life (He et al., 2015; Javaid et al., 2021; Mohankumar et al., 2019). The research of SAW technology tends from signal processing and communication market to another larger emerging sensor market (Javaid et al., 2021; Chen et al., 2022; Chen et al., 2017). In order to meet this market demand, SAW sensors need further improvements on their performances in the following aspects.

4.1. High accuracy and sensitivity

Accuracy and sensitivity are basic indexes for sensors (Javaid et al., 2021). For instance, the accuracy of a wireless passive SAW pressure sensor can reach 7.22 kPa (Tang et al. 2022). A SAW biosensor can reach low detection limit of 5.5 and 25.0 pg/mL with and without gold staining for the real-time detection of Alpha-Fetoprotein in biological fluids (Rauf et al. 2021). The sensitivity of a SAW relative humidity sensor based on flake-like nanodiamond-chitosan composite film can reach −4.93 kHz/% for the adsorption process and −4.83 kHz/% for the desorption process (Tian et al. 2023). In some fields, such as angular rate, temperature, humidity, and some gas sensors, the detection accuracy and sensitivity of SAW sensors cannot be as good as traditional sensors (He et al., 2015). Therefore, some new methods and technologies are required for the improvement of sensing performance and system stability. For example, SAW gas sensor needs to improve the frequency stability of oscillator from its physical structure, device design, and circuit system planning (Zhou et al., 2022). The detection accuracy, sensitivity and stability of SAW sensors can be improved by selecting and synthesizing sensitive materials with excellent performance, and preparing sensitive thin films (Prabakaran et al. 2022). Sensor array (Verma and Yadava, 2015; Sunil et al., 2015) and pattern recognition technologies (Qi et al., 2017; Zhu et al., 2021; Zhu et al., 2022) can also be utilised for improving performance.

Even though researchers have made great efforts to improve accuracy and sensitivity of SAW sensors, but the basic stability issues which greatly influence the accuracy and sensitivity of SAW sensors lack of attentions. They should be paid more attentions in the future by researchers.

4.2. Small size, portable and wireless passive sensors

Sensors are usually utilized and integrated in mechanical and/or electronic systems. Therefore, in order to meet the requirements of various application eras, SAW sensors must be small-sized, portable and with low power consumption (Malocha et al., 2013). Thanks to the state-of-the-art microelectronic/micromechanical fabrication technologies, SAW sensor nodes can be fabricated to as small as 1.5mm × 1.5 mm by utilizing CMOS fabrication processes (Tigli et al., 2010), which can be further improved in the future with the development of microelectronic/micromechanical fabrication technologies. Taking advantages of the wireless passive characteristics of SAW sensors, Kalinin et al. (2016; 2011) from Transense UK have developed various wireless passive SAW sensors for different industrial applications, and Yue et al. (2022) developed wearable wireless passive SAW sensors for biomedical applications. Wireless passive sensors are so important in portable, large-area-deployment, and harsh environment sensing scenarios. The investigations on wireless passive sensors based on SAW devices are future trend and will be more and more popular.

4.3. Multifunctional integration/low cost

The single-functional sensor is gradually out of date, which is mainly because of the high cost of utilizing single-functional sensors, the difficulty of system integration and the low stability. Consequently, the multi-functional integrated SAW sensors have become hot spots of interest (He et al., 2015). Even multi-functions are integrated in a single small sensor chip, they still own uncomplex structures and small size. They can greatly reduce the cost of SAW sensor systems. For example, a wireless passive SAW sensor integrating temperature, pressure and electronic tag has a simple structure and almost the same size as a single-functional sensor, which effectively reduces the cost (Tang et al., 2022). Malocha et al. (2013) have investigated the multi-functional integrations of SAW sensors for years and have achieved remarkable progresses. The integration of sensing functions with similar detection principles is the trend to develop SAW sensors in the future.

TABLE VI
COMPARISONS ON MULTIFUNCTIONAL AND SINGLE-FUNCTIONAL SAW SENSORS (SOURCE: TABLE BY AUTHORS)

	Cost	Size	Design difficulty
Multifunctional SAW sensors	Saving cost	Can be as small as a single-functional sensor	Do not increase much design difficulty compared to single-functional sensor
Single-functional SAW sensors	High to use more sensor nodes	Do not have advantage on size compared to multifunctional sensor	Similar design difficulty compared to multifunctional sensor

4.4. Smart WSN/IoT

Sensors are the tongs for obtaining information in intelligent applications. They have become the teleneuron of robots. Smart wireless sensor networks (WSNs) are the whole neural networks of intelligent applications (Zhang et al., 2022; Zhang et al., 2021; Wu et al., 2020; Wu et al., 2022). IoT connect all systems for communications and intelligent controls (Suresh et al., 2022; Chen et al., 2018). For example, a remote raw water monitoring and control system was developed as internet of water things (IoWT) by researchers (Júnior et al. 2021). A two-layer energy efficient framework utilizing wireless SAW sensor network for leakage detection in monitoring water distribution system was proposed (Tang and Wu, 2014). Radio-frequency identification (RFID) or SAW sensors were utilized for smart-monitoring applications in sewer systems was developed (Tatiparthi et al. 2021). Therefore, the development of SAW sensors to realize the intelligence of SAW sensor systems combined with smart WSNs and IoT is the future research trend.

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