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ACOUSTIC WAVE SENSORS

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Acoustic waves excited in a piezoelectric medium provide an attractive technology for realizing a variety of sensor that exhibit high sensitivity, small size and portability, fast responses, ruggedness and robustness, high accuracy, compatibility with integrated circuit (IC) technology, excellent aging characteristics and the capability to measure multiple quantities in one sensor package. Sensors based on this technology can be produced using standard photolithography and hence are inexpensive. In this paper acoustic sensing mechanisms and a wide range of bulk and surface acoustic waves used in the sensor development are described. Applications of acoustic sensors in the chemical, environmental, medical, automotive and aeronautic industries are also given.

1. Introduction

There is a need for small, reliable, and inexpensive sensors in a variety of industrial and consumer applications. In the last decade the world sensor market has been growing very fast at an annual rate of about 10%. In 1994 alone sensor sales totaled about 10.5 billion dollars worldwide. The demand for sensor will continue in the foreseeable future due to the fact that further progress in automation and computerization of industrial and consumer products will depend strongly on sensors. As an example one may consider an automobile in which the use of sensor has grown from a few sensors in the twenties to more than 20 in the seventies, and to more than 100 in the nineties. Today's automobile sensor perform such tasks as monitoring engine performance, fuel efficiency, powertrain systems and road conditions which result in improved car performance; driving safety and comfort. Currently, sensor technologies such as silicon, fiber optic, thin and thick film and acoustic are competing for the global sensor market. Acoustic wave technology is emerging as one of the most promising sensor technologies offering several advantages over their competitros.

In the last several years acoustic wave technology has been explored extensively for the development of sensors. Many novel acoustic sensors have been proposed, and extensive research efforts, both theoretical and experimental, have been undertaken in many academic, government and industrial research centers. As a result, critical fundamental knowledge on acoustic sensors has been accumulated and the market opportunities for acoustics sensors are being explored. In this paper acoustics sensing mechanisms and a wide range of bulk and surface acoustic waves used in the sensor development are described. Applications of acoustic sensors in the chemical, environmental, medical, automotive and aeronautic industries are also given.

2. General features of acoustic sensors

In general, acoustic sensors utilize different types of acoustic waves to obtain information about the entity being measured or what is commonly called a measurand. The range of measurands is wide and include a spectrum of chemical, physical and biochemical phenomena. The acoustic waves can be generated and received by a variety of means including piezoelectric, magnetostrictive, electrostatic, electromagnetic, optical, thermal and other [1, 2]. In this paper a class of acoustic sensors which utilize the piezoelectric effect to generate and receive acoustic waves is discussed.

Acoustic sensors are fabricated with piezoelectric materials in which the electro-mechanical transduction takes place within the material. Therefore, piezoelectric materials are often called smart materials due to the internal material transduction process. This material based transduction process does influence very positively the performance of acoustic sensors in terms of their reliability, size and cost. The piezoelectric materials are also very durable, chemically inert and have excellent mechanical properties and very good aging characteristics. Acoustic sensors made with piezoelectric materials such as quartz or lithium niobiate are robust, and environmentally stable.

Acoustic sensors are versatile and can measure, in principle, any type of measurand. Usually, the sensing acoustic wave is accompanying by both mechanical displacements and electric fields. Thus, both the electrical and mechanical properties of the environment can be sensed directly by piezoelectric sensors. One may increase the number of measurands detected by the acoustic sensor by attaching or connecting a specific sensing element to a piezoelectric transducer/substrate. The measurand causes electrical and mechanial changes in a sensing film. Using such a hybrid configuration, theoretically any measurand can be measured by the acoustic sensors. For example, a thin biofilm placed over a bulk resonator can be used to measure the presence of biospecies, or a magnetic field sensitive nickel film placed over the SAW device can be used for sensing magnetic fields.

Usually, acoustic sensors are designed to operate in resonant type sensors configuration as an oscillator. The output sensor signal is a frequency which is a function of the magnitude of the meaurand. This is important feature, since one can measure frequency easily, and the frequency is quasi-digital signal, which makes simple signal processing operations in acoustic sensors. Therefore, acoustic sensors are relatively sensitive, with good resolution and excellent signal-to-noise ratio.

Acoustic sensors configured in an oscillator configuration can be equipped in an antenna and both remote sensing and control can be achieved.

Finally, another important feature of piezoelectric sensor materials is that the same electro-mechanical transduction mechanism can be used not only for a sensing but also for an actuation as well. Since the ultimate purpose of sensing is to supply an information to an observer or a system in order to perform an action, the same piezoelectric technology platform can perform both the sensing and actuating operations. In the recent years several smart structures using piezoelectric elements for both sensing and actuating have been developed. In summary, the piezoelectric sensing platform offers a very versatile technology base for the development of sensors, actuators and smart structures.

3. Acoustic waves, piezoelectric transducers and sensing mechanisms

There are numerous types of acoustic waves which can be used for sensing. The knowledge of their properties is important for the selection of the optimal acoustic wave for a given measurand. The acoustic waves can be classified in a variety of ways. One way to classify the acoustic waves is by mean of their generation, i.e. into the bulk and surface generated acoustic waves. The bulk generated acoustic waves are usually excited by metalized bulk piezoelectric elements such as plates or rods, whereas the surface generated acoustic waves are excited by the interdigital system of metallic electrodes (IDT) placed on the surface of piezoelectric materials. The electrodes are used to connect the transducer with electronic circuitry for the excitation or reception of acoustic waves. Examples of the two most common configurations of piezoelectric transducers, namely a thin metalized disk used for the excitation of bulk waves, and an interdigital transducer (IDT) for the excitation of surface acoustic waves (SAW) are shown in Figure 1.

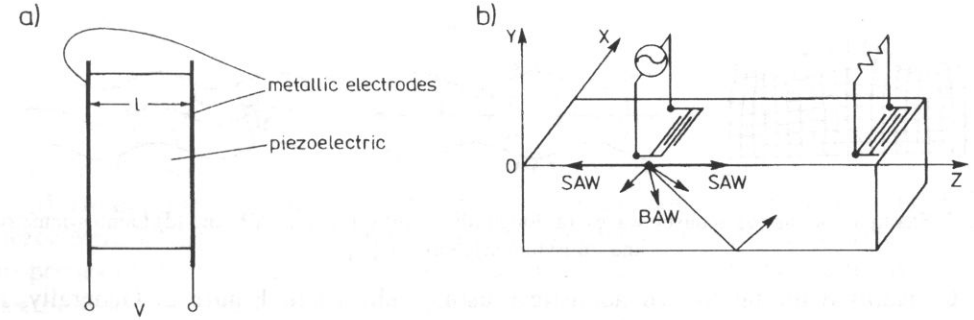

Fig. 1. Typical geometry of piezoelectric transducers used for excitation of the bulk and surface generated acoustic waves.

The different types of acoustic waves which can be excited by a transducer are shown in Figure 2. Some of these waves are schematically illustrated in Figure 3. The acoustic wavs in piezoelectric materials have both the mechanical displacements and electric fields. These electroacoustic field quantities perform the actual "sensing" in acoustic sensors. Acoustic sensors probe the environment with both displacements and electric fields, hence can detect a wider range of measurands than other sensor technologies.

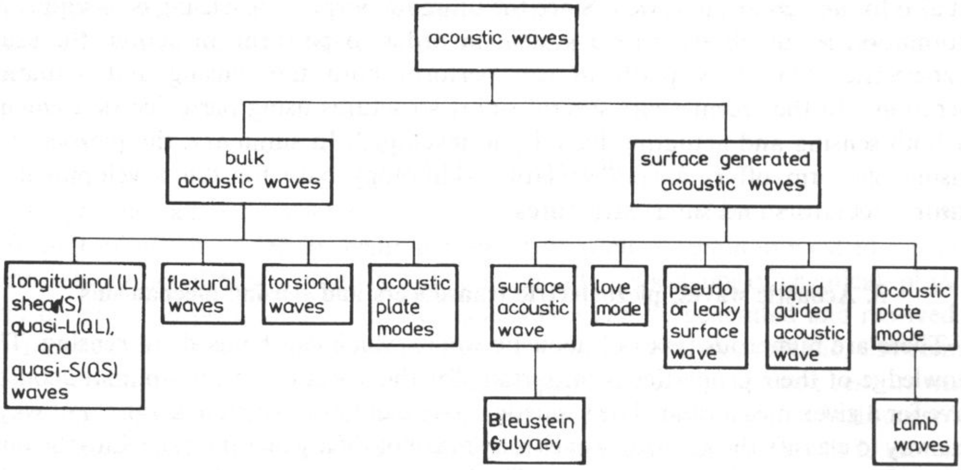

Fig. 2. Classification of acoustic waves

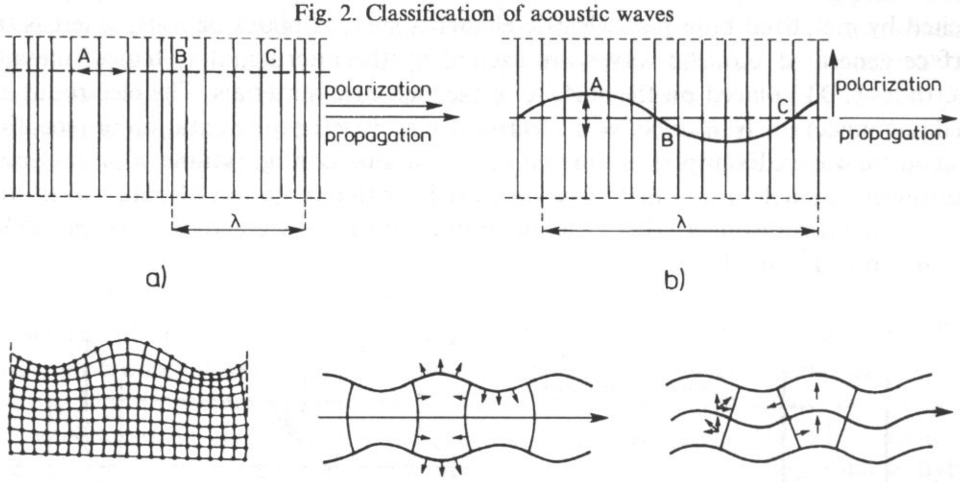

Fig. 3. Examples of various acoustic waves, (a) longitudinal, (b) shear, (c) SAW and (d) Lamb symmetric and antisymmetric mode [1, 2].

Conceptual model for an acoustic sensor is shown in Figure 3. Generally, it consists of a sensing element and an acoustic wave transducer, but also, in some cases, it may consist only of an acoustic wave transducer itself. The **sensing element** is an active substance (for example, a thin biofilm used in an acoustic biosensor) which is selective to the measurand of interest. The **acoustic wave transducers**, which consists of a piezoelectric element with an array of metal electrodes supplies a mean for conversion of usually non-electrical measurands into an output electrical signal.

When a measurand interacts with the sensing element a microscopic physical, chemical and/or biochemical changes are produced. Next, these microscopic changes cause the macroscopic acoustical/mechanical or electrical changes in the sensing element, which in turn modify the acoustic field quantities of the acoustic wave transducer. Subsequently, these acoustic changes are converted/transducted into an output sensor electrical signal by the acoustic wave transducer. For example, in the acoustic immunosensors the antibodies are immobilized in the form of a thin film at the surface of the acoustic wave transducer. When the target antigen is introduced into the sensor environment, the elasticity, density and the viscosity of the film undergoes changes, and these changes modify the acoustic field quantities of the acoustic wave sensor which result in the changes of the output sensor signal. From a sensing point of view, the environment loads the surface, and the surface views the environment as an impedance, either mechanical and electrical, or the both. For most applications, these types of acoustic sensors can be modeled as miniature solid state AC electrical and mechanical impedance meters.

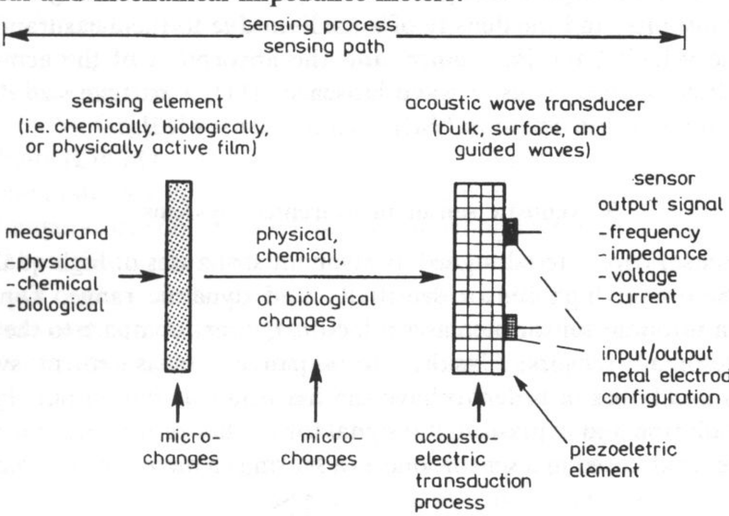

Fig. 4. A conceptual model for an acoustic sensor.

Generally, acoustic sensors can be divided into three groups:

(i) **Homogeneous Acoustic Sensor:** In this case an acoustic sensor consists of the piezoelectric element itself. The measurand does influence directly the electroacoustic properties of the piezoelectric element. The examples are piezoelectric temperature, electric field or viscosity sensors. In principle, any type of a bulk, surface or guided wave acoustic device can be used for this type of sensing. For example, an LST cut quartz bulk resonator has been used as a very sensitive and accurate temperature sensor [3], an ST SAW quart for the determination of acceleration and pressure [4], and a YZ SAW $LiNbO_3$ for the measurement of an electric field [5]. The AT cut quartz is used widely for the measurement of mechanical and electrical properties in liquids [6] and also as a thickness film monitor [7].

(ii) **Hybrid Acoustic Sensor**: In this case a sensor consists of the piezoelectric transducer and a sensing element selective to the measured of interest. The use of sensing element which is usually in form of a thin film allows, in principle, one to detect a wide variety of measurands. The measurand causes changes in the film, which in turn are detected by piezoelectric transducer. The film can be biological, metal, metal oxide and polymer and can be used to probe both gaseous and/or liquid media. For example, a thin tungsten trioxide film is used to detect hydrogen sulfide gas [8], a gold film to detect mercury in water or a polyimide film can detect water vapor [9]. In some application the sensing element could have other form such as a heater structure for flow detection [10]. The probing acoustic wave can be either a bulk wave (S, L, QL, QS), a surface acoustic wave (SAW) or guided bulk acoustic waves (APM, waves on cylinders, rods, etc.).

(iii) **Passive Acoustic Sensor**: The piezoelectric element is not involved in sensing, and is used for transmission and/or reception of acoustic waves into/from the environment. Generally, an acoustic wave is transmitted into a gaseous, liquid or solid medium which undergoes changes due to measurands. The changes in the elastic and viscous constants, and the density of a medium due to the measurand cause the changes in the velocity, the impedance, and the absorption of the acoustic wave. Examples include a bulk acoustic wave biosensor [11], a particle size distribution sensor [12] or an acoustic emission (AE) chemical sensor [13].

5. Acoustic sensor measurement systems

Acoustic sensors are often designed as resonant structures of high quality factor, Q in order to obtain high sensor sensitivity and dynamic range. Typically, the sensitivity of a resonant sensor increases a factor, Q-times compare to the sensitivity of the non-resonant sensors. Usually, accompanying measurement systems are configured as oscillators in order to have the frequency as the output signal which offers high resolution and a quasi-digital signal for further processing. Normally, two acoustic elements are used in a sensor, one as a sensing element, and the second as the

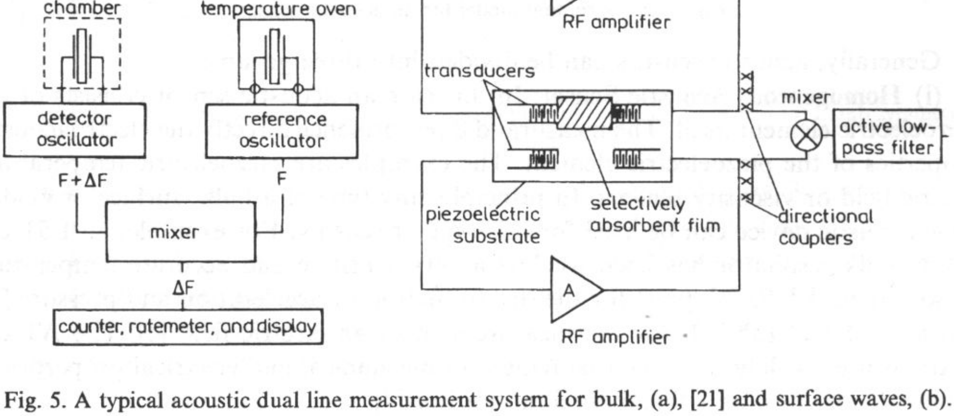

Fig. 5. A typical acoustic dual line measurement system for bulk, (a), [21] and surface waves, (b).

reference in order to eliminate environmental factors such as temperature, mechanical stress or other factors. A typical acoustic measurement system shown is given in Figure 5. The theoretical sensitivity of acoustic sensors can be very high, however, the practical one is much lower due to the loading effect of the measurand causing decrease in the quality factor, Q.

6. Materials and technology

An ideal material for an acoustic sensor is a strong piezoelectric material with good semiconducting, mechanical and temperature properties. Strong piezoelectric properties, good mechanical and thermal properties are necessary for designing wide band, low loss and temperature stable acoustic devices. Such a material will allow the combination of piezoelectric technology with well developed integrated circuit (IC) technology which would result in mass production of inexpensive intelligent acoustic sensors with the signal processing capabilities on a chip. Unfortunately, such a material does not exist at this moment. Currently, some of these desired features are achieved using the hybrid type approach combining zinc oxide (ZnO) and silicon technologies [14, 15]. Gallium arsenide offers a possible single material alternative, however it has a very weak piezoelectric properties [16]. So far, the well known piezoelectric materials such as quartz (SiO_2), lithium niobiate ($LiNbO_3$), and lithium tantalate ($LiTaO_3$) are used to make acoustic sensors. These materials show quite large spectrum of the electro-acoustic properties from being temperature compensated (SiO_2) to haviong a strong piezoelectric properties ($LiNbO_3$). These materials have outstanding mechanical properties, are chemically stable, and can operate at the elevated temperatures . There is a lot research activity towards identifying new cut being temperature or stress compensated cuts in order to have sensors environmentally stable, or just having high value of the temperature or stress coefficients for thermal or mechanical sensors. Recently, the 27°Y-rotated SiO_2 cut was found to be temperature compensated at elevated temperature 200°C which is important in SAW gas sensors applications [17]. Also polymer piezoelectrics are being extensively used for some sensor applications, mostly in the medical area.

Typical acoustic sensors are fabricated with standard photolithography. This technology allows one to fabricate complex sensor electrode patterns and to produce multiple sensor from a single substrate. Recently, micromachining technology has been very popular for the manufacturing of piezoelectric sensors. Micromachining technology, which combines the photolitographic process and either plasma or chemical etching techniques, allows one to create complicated mechanical and electrical sensor structures from a single substrate. An example includes the AT fork resonator technology for watch applications [19] or acoustic force sensor [20].

7. Examples of acoustic sensors

Some recent examples of new acoustic sensor, new sensing mechanisms, new trends in acoustic sensor technology and novel applications are presented below.

A. Acoustic Emission Chemical (AEC) Sensors — a new sensing mechanism

A high frequency piezoelectric microphone can "listen" to the chemical reactions, and identify these reactions. Recently, it was found that many chemical dynamic

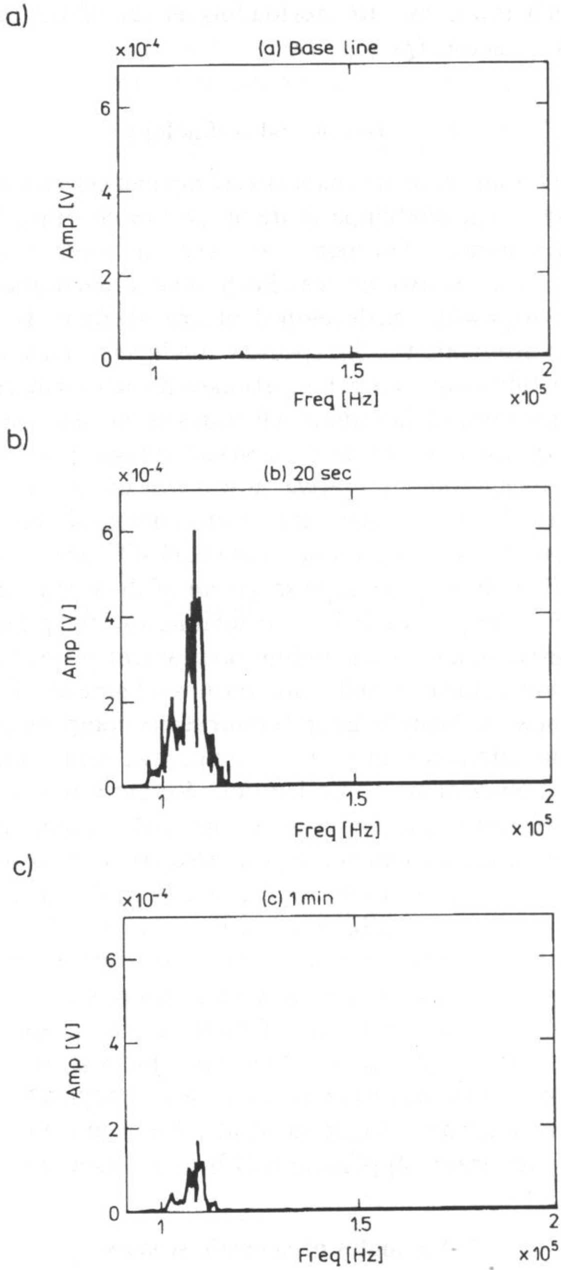

Fig. 6. The AE spectra of dissolution of sodium carbonate taken at different time intervals t = 0, 20 second, 2 and 10 minutes [13].

systems are acoustically active, and during the chemical processes acoustic emission (AE) signals are generated. Based on this phenomena, an AEC sensor was proposed to monitor the caustization process, an important process in paper manufacturing [13]. The caustization process consists of three different reactions. Interestingly, the AE frequency spectra and their time evolution were distinct for these three different reactions. These features of the AE spectra are being used for the identification of chemical reactions and monitoring their kinetics. An example of the time evolution of the AE spectra in the case of the reaction between calcium oxide and sodium carbonate is shown in Figure 6. Potential application of the AEC sensor include process control in the chemical, food and pharmaceutical industries.

B. SAW Gas Sensors — electric impedance change as a sensing mechanism

A change in the electric impedance of thin film due to absorption of hydrogen sulfide (H_2S) gas has been used for the development of a highly sensitive SAW gas sensors. A typical dual oscillator sensor configuration shown in Figure 5 is used. The response to H_2S gas is shown in Figure 7. Here, the changes in the electric conductivity of the thin WO_3 film cause changes in the frequency and the attenuation of the SAW oscillator. Sensitivities of the order parts per billion have been reported

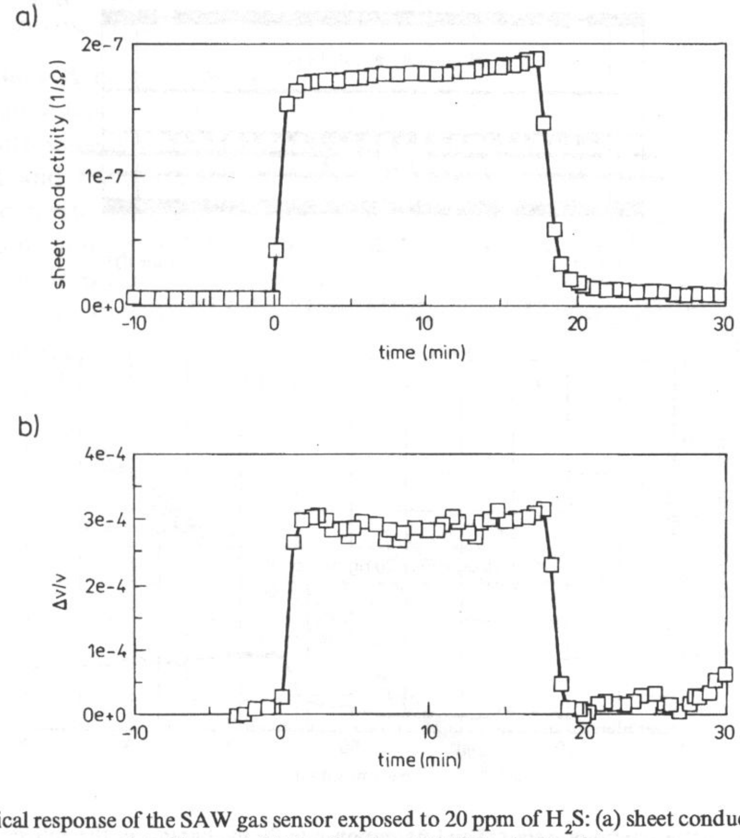

Fig. 7. A typical response of the SAW gas sensor exposed to 20 ppm of H_2S: (a) sheet conductivity of a WO_3 thin film and (b) the fractional SAW velocity change.

for H_2S gas on ST-quartz substrate with 400 A thick WO_3 film [8]. SAW sensors with other metal, metal oxide, polymer and organic films for detection of a variety of gases such as H_2, NO_x, CO have also been reported [21]. In films which do not change their electrical properties when interacting with the measurand, the mechanical impedance of thin film can change. In particular, the changes in the film density (so called mass loading effect) or in the elasticity of the film are responsible for the sensor response. However, the SAW sensor with metal oxide films have shown much better performances in terms of sensitivity, durability, aging and reproducibility.

C. Acoustic Plate Mode (APM) Immunosensor — mechanical impedance as a sensing mechanism

A change in the mass loading and the effective elasticity in the thin immobilized antibody film on a YZ $LiNbO_3$ APM device due to the presence on an antigen has been used for the development of highly sensitive acoustic immunosensors. Here, the transverse guided acoustic wave is utilized for sensing. This wave only penetrates a liquid medium to the depth of an acoustic wavelength which is about a few tens of

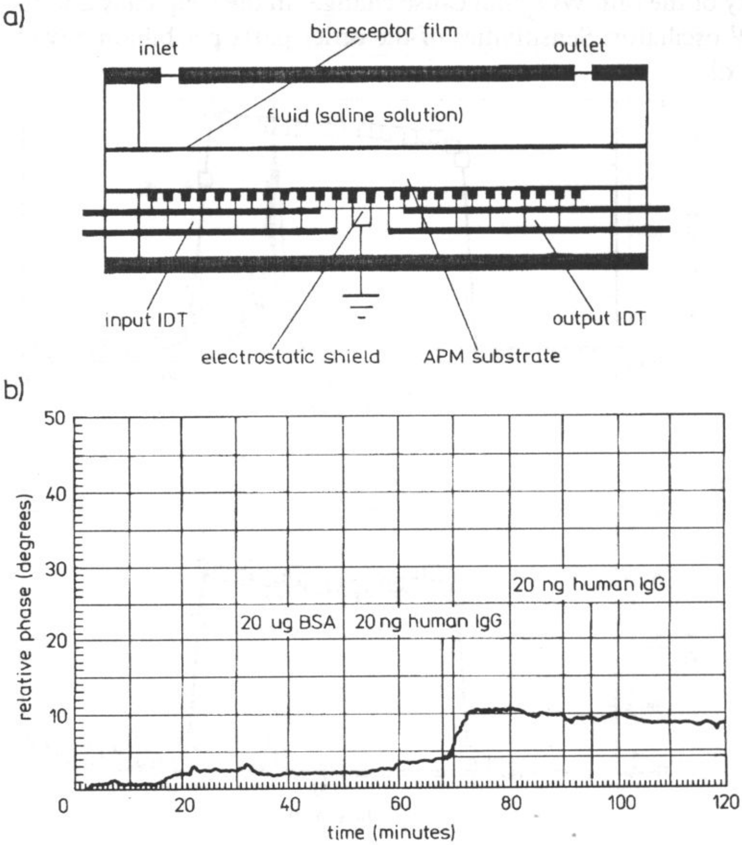

Fig. 8. The APM immunosensor (a) and its response to 20 nanograms of the antigen (b) [23].

microns at the frequency 50 Mhz. Antigen concentrations of the order of nanograms per millimeter were detected [22]. The APM configuration shown in Figure 10 offers a very convenient way to separate the electronics and the biochemical liquid medium. Recently, this configuration has been used to detect the DNA hybridization and to monitor mercury in water with a gold thin film as a sensing medium [23]. Another sensor configuration which is extensively used for monitoring the properties of liquid media a bulk AT cut quartz resonator [6, 18].

D. SAW Adhesion Sensor — monitoring interfacial phenomena

Adhesion strength can be monitored nondestructively with the SAW. In particular, the adhesion of thin polyimide films on ST-cut SAW substrates has been measured. The SAW technique was able to identify the adhesion strength with different adhesion promoters. It can also measure the influence of different environmental conditions such as the level of humidity of the adhesion strength [9].

E. Acoustic Sensors for Other Measurands

Many other chemical, physical and biological quantities or phenomena can be detected with acoustic sensors. Examples include electric and magnetic fields, temperature, gas flow, mechanical quantities as strain, stress and acceleration, viscosity, corrosion etc.

F. Remote Acoustic Sensing

Once an antenna is connected into either a bulk or SAW device it forms a sensor with remote sensing/control capabilities. An antenna supplies a means for remote excitation and reception of the signal from a sensor. Several configurations are possible to create a transmitting and/or receiving antenna. In Figure 9 an example of an configuration is a SAW device with an antenna and a single wide-band input/output transducer with several reflective structures placed on the SAW path is shown. In this case, the SAW is excited by an interrogating RF pulse, and travels along the surface until is reflected from the sequence of reflective structures. Next, the reflected signal is received by the same transducer, and retransmitted as an RF pulse

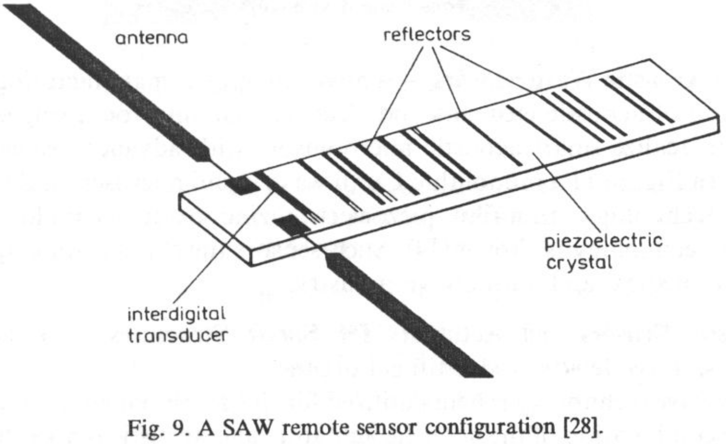

Fig. 9. A SAW remote sensor configuration [28].

into the sender of the interrogating signal. If the measurand is present, than it will change the parameters of the received acoustic wave in the time and frequency domains, and hence the RF pulse parameters. Generally, this type of configurations can be used for the development of remote sensors for a variety of measurands. Recently, this configuration was proposed for the development of a mechanical sensor for the detection of the deformation and stress [24] and a temperature sensor [28].

G. Micromachined Acoustic Sensors — a new manufacturing technology

Inexpensive and high performance acoustic sensors can be manufactured with micromachining technology. This technology uses photolitographic and wet and plasma etching techniques to produce multiple acoustic sensing elements from a single substrate. Examples inlcude a tuning fork quartz resonator used for watch application [19] or a double-ended flexural mode 'string-tension' type resonator force sensor shown in Figure 10 [20].

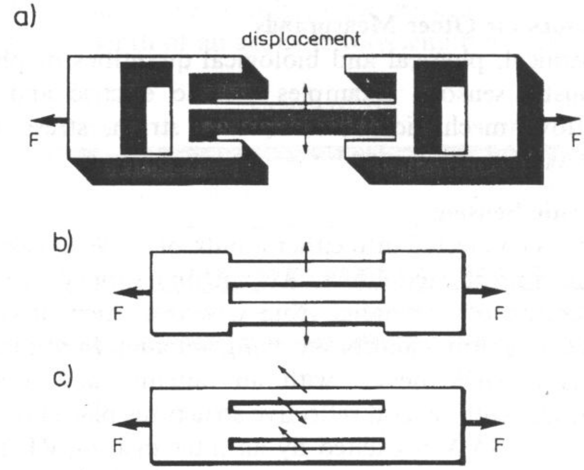

Fig. 10. Micromachined acoustic force sensor: (a) single-beam device, (b) double beam-beam device and (c) triple beam device [20].

H. Smart Acoustic Wave Sensors — a novel integrated manufacturing technology

Integration of acoustic elements and electronic circuitry on a single silicon chip allows one to realize smart acoustic microsensors with advanced signal processing capabilities. In Figure 11 a monolithic Lamb wave liquid microsensor developed with bipolar IC technology, thin-film piezoelectric zinc oxide technology, and micromachining technology is shown [14]. Such sensors may find a wide application in the chemical, medical and automotive industry.

I. Acoustic Sensors and Actuators for Smart Structures — a new class of microsystems, microdevices and artificial organs

Acoustis wave technology is being utilized for the development of smart structures in which the combination of the acoustic actuators and acoustic sensors allows one to

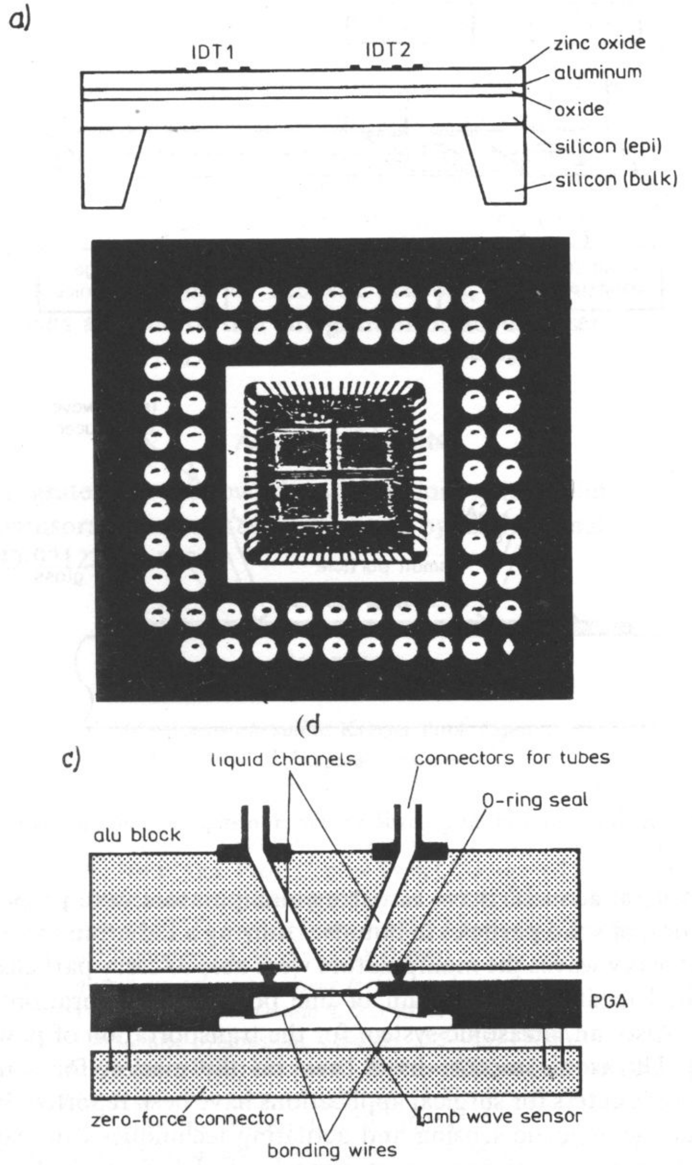

Fig. 11. The monolithic Lamb wave liquid sensor: (a) cross section of a Lamb device, (b) a photograph of a Lamb sensor in a ceramic grid array (PGA) package, chip dimension 10 mm × 10 mm, and (c) PGA-packaged sensor the flow cell [14].

achieve very unique self-control and/or self-adaptive features. An example shown in Figure 12 depicts an active damping system used in the aeronautic industry for controlling the vibration in space vehicle's [25]. Here, the piezoelectric element senses the vibrations, and the other generates the out of the phase acoustic vibrations to cancel the initials vibrations.

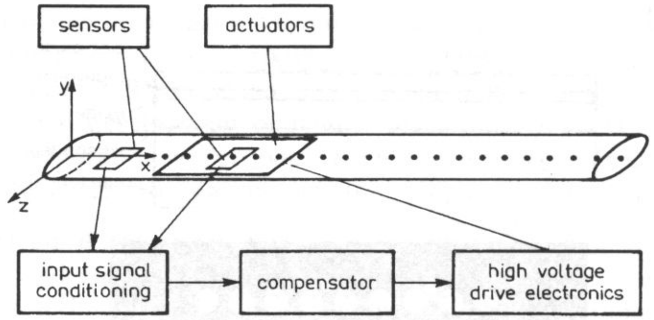

Fig. 12. An active damping system [25]

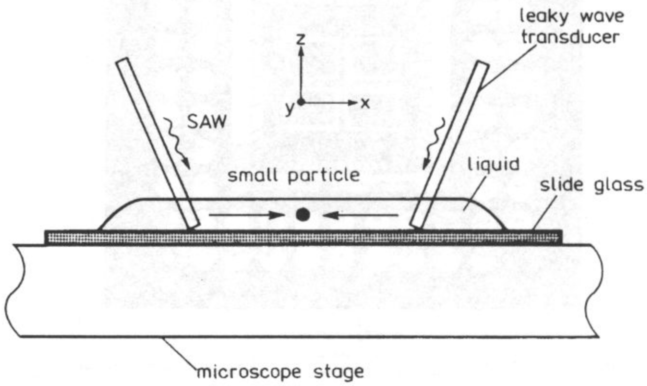

Fig. 13. A schematic representation of the acoustic wave micromanipulator of small particles in liquid [26].

Recently, several acoustic wave actuators/manipulators were proposed for controlling the motion of solid particles in liquids. Utilizing a radiation force generated by either Lamb or leaky waves the manipulators were able to carry particles in the liquid into the required location. A diagram of one possible configurations is shown in Figure 13 [26]. Also, an ultrasonic system for the transportation of powder has been proposed [27]. Ultrasonic motors have been on the market for some time, and recently, ultrasonic cuters for surgical applications have been reported. In general, the combination of the acoustic sensing and actuating techniques can lead toward the development of a new class of micro-electro-mechanical devices which can be used for the development of artificial organs, remote surgery or microrobots.

8. Conclusions

Acoustic waves excited in a piezoelectric medium provide an attractive technology for realizing a variety of sensors that exhibit high sensitivity, small size and portability, fast responses, ruggedness and robustness, high accuracy, compatibility with integrated circuit (IC) technology, and excellent aging characteristics. Sensors bassed on this technology can be produced using standard photolitography and hence are inexpensive. Integration of acoustic elements and electronic circuitry on a single silicon chip allows one to realize smart acoustic microsensors with advanced signal processing capabilities. Acoustic wave technology is also utilized for the development of smart structures in which the combination of the acoustic actuators and acoustic sensors allows one to achieve very unique self-control and/or self-adaptive features. Acoustic sensors have found wide applications in the chemical, environmental, medical, automotive and aeronautic industries. Future work should focus on the miniaturization and packaging of acoustic sensors, the development of acoustic multisensor systems and the further integration of acoustic sensor technology with silicon technology.

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