Acoustic Wave Technology Sensors

Bill Drafts

***Abstract*—A brief overview of acoustic wave sensor physics, materials, sensor types, and applications is presented in this paper. Emphasis is placed on the different types of acoustic wave sensors, their respective advantages, and their specific applications in industry.**

***Index Terms*—BAW sensors, SAW sensors, sensor applications.**

I. Introduction

ACOUSTIC wave devices have been in commercial use for over 60 years. The telecommunications industry is the largest user of these devices, consuming approximately three billion acoustic wave filters annually, primarily for mobile cell phones and base stations. These devices are typically surface acoustic wave (SAW) devices, and act as bandpass filters in both the RF and IF sections of the transceiver electronics. There are several new emerging applications for acoustic wave devices as sensors that may eventually equal the demand of the telecommunications market. These include automotive applications (torque and tire pressure sensors), medical applications (biosensors), and industrial and commercial applications (vapor, humidity, temperature, and mass sensors). Acoustic wave sensors are competitively priced, inherently rugged, very sensitive, and intrinsically reliable. Some are also capable of being passively and wirelessly interrogated (no sensor power source required).

II. Acoustic Wave Technology Overview

Acoustic wave sensors are so named because they utilize a mechanical, or acoustic, wave as the sensing mechanism. As the acoustic wave propagates through or on the surface of the material, any changes to the characteristics of the propagation path affect the velocity and/or amplitude of the wave. Changes in velocity can be monitored by measuring the frequency or phase characteristics of the sensor and can then be correlated to the corresponding physical quantity that is being measured.

Virtually all acoustic wave devices and sensors use a piezoelectric material to generate the acoustic wave. Piezoelectricity was discovered by the brothers Curie in 1880, received its name in 1881 from Hankel, and remained largely a curiosity until 1921, when Cady discovered the quartz resonator for stabilizing electronic oscillators [1]. Piezoelectricity refers to the production of electrical charges by the imposition of mechanical stress. The phenomenon is reciprocal. Applying an appropriate electrical field to a piezoelectric material creates a mechanical stress. Conversely, by applying an appropriate mechanical stress, an electric field will be created. Piezoelectric acoustic wave sensors apply an oscillating electric field to create a mechanical wave, which propagates through the substrate and is then converted back to an electric field for measurement.

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The author is with Microsensor Systems Inc., Apopka, FL 32703 USA.
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III. Piezoelectric Substrate Materials for Acoustic Wave Sensors

There are several piezoelectic substrate materials that may be used for acoustic wave sensors and devices. The most common are quartz (SiO_2) and lithium tantalate ($LiTaO_3$), and to a lesser degree, lithium niobate ($LiNbO_3$). Each material has specific advantages and disadvantages, which include cost, temperature dependence, attenuation, and propagation velocity. Table I lists some relevant specifications for each material, including the most popular cuts and orientations [2]. An interesting property of quartz is that it is possible to select the temperature dependence of the material by the cut angle and the wave propagation direction. With proper selection, the first-order temperature effect can be minimized. An acoustic wave temperature sensor may be designed by maximizing this effect. This is not true of $LiNbO_3$ or $LiTaO_3$, were a linear temperature dependence always exists for all material cuts and propagation directions.

Other materials that have commercial potential include gallium arsenide (GaAs), silicon carbide (SiC), langasite (LGS), zinc oxide (ZnO), aluminum nitride (AlN), lead zirconium titanate (PZT), and polyvinylidene flouride (PVDF).

IV. Fabrication of Acoustic Wave Devices

The sensors are made by photolithography, using a process as detailed in Fig. 1.

The manufacturing process begins by carefully polishing and cleaning the piezoelectric substrate. As shown in Fig. 1(a), metal, usually aluminum, is then deposited uniformly onto the substrate. The device is then coated with a photo-resist, which is spun on and then baked to harden it. The coated device is then exposed to UV light through a mask [see Fig. 1(b)]. The mask contains opaque areas, which correspond to the areas to be metallized on the final device. The exposed areas undergo a chemical change, allowing them to be removed using a developing solution [see Fig. 1(c)]. This exposes areas of metal, which are chemically etched away. The remaining photo-resist is then removed, leaving the final device, as shown in Fig. 1(d).

The pattern of metal that remains on the device is called an interdigital transducer (IDT). By changing the length, width, position, and thickness of the IDT, the performance of the sensor can be maximized.

TABLE I
PHYSICAL PARAMETERS OF MORE COMMONLY USED PIEZOELECTRIC MATERIALS

Material	Orientation	Velocity (m/s)	Temperature Coefficient (ppm/°C)	Attenuation at 1 GHz (dB/μS)	Cost
Quartz	Y, X	3159	-24	2.6	Lowest
Quartz	ST, X	3158	0	3.1	Lowest
Lithium Tantalate	Y, Z	3230	35	1.14	Medium
Lithium Tantalate	167 rotation	3394	64	-	Medium
Lithium Niobate	Y, Z	3488	94	1.07	High
Lithium Niobate	128 rotation	3992	75	-	High

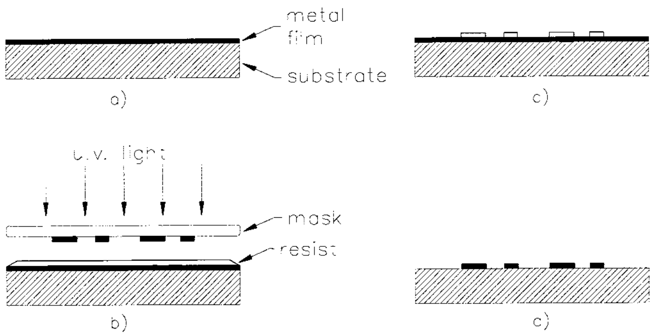

Fig. 1. Acoustic wave devices are manufactured using the same photolithography process that integrated circuits use. The only difference is that no junction exists in acoustic wave devices.

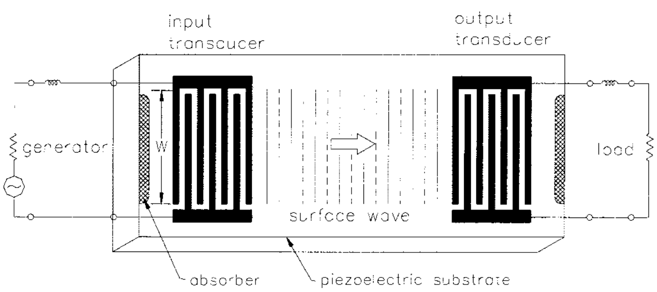

Fig. 2. Typical acoustic wave device consists of two sets of IDTs. One transducer converts electric-field energy into mechanical wave energy, while the other transducer converts the mechanical energy back to an electric field.

V. ACOUSTIC WAVE PROPAGATION MODES

Acoustic wave devices are described by the mode of wave propagation through or on a piezoelectric substrate. Acoustic waves are distinguished primarily by their velocities and displacement directions; many combinations are possible, depending on the material and boundary conditions. The IDT of each sensor provides the electric field necessary to displace the substrate to form an acoustic wave. The wave propagates through the substrate, where it is converted back to an electric field at the other IDT. Fig. 2 shows the configuration of a typical acoustic wave device. Transverse, or shear, waves have particle displacements that are normal to the direction of wave propagation and can be polarized so that the particle displacements are parallel to or normal to the sensing surface. Shear horizontal wave motion indicates transverse displacements polarized parallel to the sensing surface, whereas shear vertical motion indicates transverse displacements normal to the surface.

If the wave propagates through the substrate, the wave is called a bulk wave. The most commonly used bulk acoustic wave (BAW) devices are the thickness shear mode (TSM) resonator and the shear-horizontal acoustic plate mode (SH-APM) sensor. If the wave propagates on the surface of the substrate, it is known as a surface wave. The most commonly used surface wave devices are the SAW sensor and the shear-horizontal surface acoustic wave (SH-SAW) sensor, also know as the surface transverse wave (STW) sensor. The mode of propagation dramatically affects the sensor's performance and how the sensor is manufactured.

All acoustic wave devices are sensors in that they are sensitive to perturbations of many different physical parameters. Any change in the characteristics of the path over which the acoustic wave propagates will result in a change in output. All the sensors will function in gaseous or vacuum environments, but only a subset of them will operate efficiently when they are in contact with liquids. The TSM, SH-APM, and SH-SAW all generate waves that propagate primarily in the shear horizontal motion. The shear horizontal wave does not radiate appreciable energy into liquids, allowing liquid operation without excessive damping. Conversely, the SAW sensor has a substantial surface-normal displacement, which radiates compression waves into the liquid, causing excessive damping. An exception to this rule occurs for devices utilizing waves that propagate at a velocity lower than the sound velocity in the liquid. Regardless of the displacement components, such modes do not radiate coherently and are, thus, relatively undamped by liquids.

Other acoustic waves that are promising for sensors include the flexural plate wave (FPW), Love wave, surface skimming bulk wave (SSBW) and the Lamb wave. Before reviewing application examples, it is helpful to briefly review each sensor type.

VI. BULK WAVE SENSORS—TSM RESONATOR

The TSM, also widely referred to as a quartz crystal microbalance (QCM), is the best-known, oldest, and simplest acoustic wave device. As Fig. 3 depicts, the TSM typically consists of a thin disk of AT-cut quartz with parallel circular electrodes patterned on both sides. The application of a voltage between these electrodes results in a shear deformation of the crystal.

The device is known as a resonator because the crystal resonates as electromechanical standing waves are created. The displacement is maximized at the crystal faces, making the device sensitive to surface interactions. The TSM resonator was originally used as a deposition sensor to measure metal deposition rates in vacuum systems [3, p. 39]. The sensor is typically used in an oscillator circuit, where the oscillation frequency

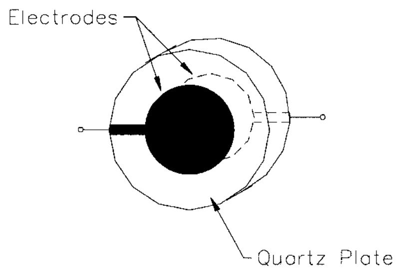

Fig. 3. Although it is the oldest acoustic wave device, the TSM resonator is still used today for measuring metal deposition rates.

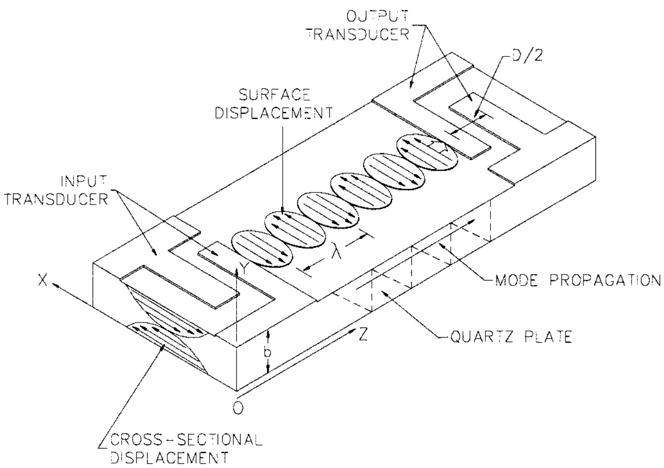

Fig. 4. In the SH-APM sensor, the waves travel between the top and bottom surfaces of the plate, allowing sensing on either side.

tracks the crystal resonance and indicates mass accumulation on the device surface. In the late 1960's, the TSM resonator was shown to operate as a vapor sensor.

The TSM features simplicity of manufacture, ability to withstand harsh environments, temperature stability, and good sensitivity to additional mass deposited on the crystal surface [4]. As a result of its shear wave propagation component, the TSM resonator is also capable of detecting and measuring liquids, making it a good candidate for a biosensor. Unfortunately, these devices have the lowest mass sensitivity of the sensors examined. Typical TSM resonators operate between 5–30 MHz. Making very thin devices that operate at higher frequencies can increase the mass sensitivity, but thinning the sensors beyond the normal range results in fragile devices that are difficult to manufacture and handle. Recent work has been done to form high-frequency TSM resonators utilizing piezoelectric films and bulk silicon micromachining techniques [5].

VII. Bulk Wave Sensors—SH-APM Sensor

SH-APM sensors utilize a thin piezoelectric substrate, or plate, that serves as an acoustic waveguide, confining the energy between the upper and lower surfaces of the plate (see Fig. 4). As a result, both surfaces undergo displacement, thus, detection can occur on either side. This is an important advantage, as one side contains the IDTs that must be isolated from conducting fluids or gases, while the other side can be used as the sensor.

As with the TSM resonator, the relative absence of a surface-normal component of wave displacement allows the sensor to come in contact with liquid for biosensor applications. SH-APM sensors have been successfully used to detect microgram per liter levels of mercury, which is adequate for Safe Drinking Water Act compliance testing [6]. Although more sensitive to mass loading than the TSM resonator, SH-APM sensors are less sensitive than surface wave sensors. There are two reasons. First, sensitivity to mass loading and other perturbations depends on the thickness of the substrate, with sensitivity increasing as the device is thinned. The minimum thickness is constrained by manufacturing processes. Second, the energy of the wave is not maximized at the surface, which reduces sensitivity.

VIII. Surface Wave Sensors—SAW Sensor

In 1887, Lord Rayleigh discovered the SAW mode of propagation [7] and, in his classic paper, predicted the properties of these waves. Named for their discoverer, Rayleigh waves have a longitudinal component and a vertical shear component that can couple with a medium placed in contact with the device's surface (see Fig. 5). Such coupling strongly affects the amplitude and velocity of the wave. This feature enables SAW sensors to directly sense mass and mechanical properties. The surface motion also allows the devices to be used as microactuators. The wave has a velocity that is about five orders of magnitude slower than the corresponding electromagnetic wave, making Rayleigh surface waves among the slowest to propagate in solids. The wave amplitude is typically about 10 Å and the wavelength ranges from 1 to 100 μm [8].

Fig. 6 details the deformation field due to a SAW propagating along the z-axis and the associated distribution of potential energy. As evident, Rayleigh waves have virtually all their acoustic energy confined within one wavelength of the surface. As a result, SAW sensors have the highest sensitivity of the acoustic sensors reviewed.

Typical SAW sensors operate from 25 to 500 MHz. One disadvantage of SAW sensors is that the Rayleigh wave is a surface-normal wave, making the SAW device poorly suited for liquid sensing applications. When the SAW sensor is contacted by a liquid, compressional waves are created, causing an excessive attenuation of the surface wave.

IX. Surface Wave Sensors—SH-SAW Sensor

If the cut of the piezoelectric crystal material is rotated appropriately, the wave propagation mode changes from a vertical shear SAW sensor to a SH-SAW sensor. This dramatically reduces the losses when liquids come in contact with the propagating medium, allowing the SH-SAW sensor to operate as a biosensor. Fig. 7 depicts the SH-SAW device, with the wave propagation mode highlighted.

X. Comparison of Acoustic Wave Sensors

In general, the sensitivity of the sensor is proportional to the amount of energy that is in the propagation path that is being perturbed. BAW sensors typically disperse the energy from the

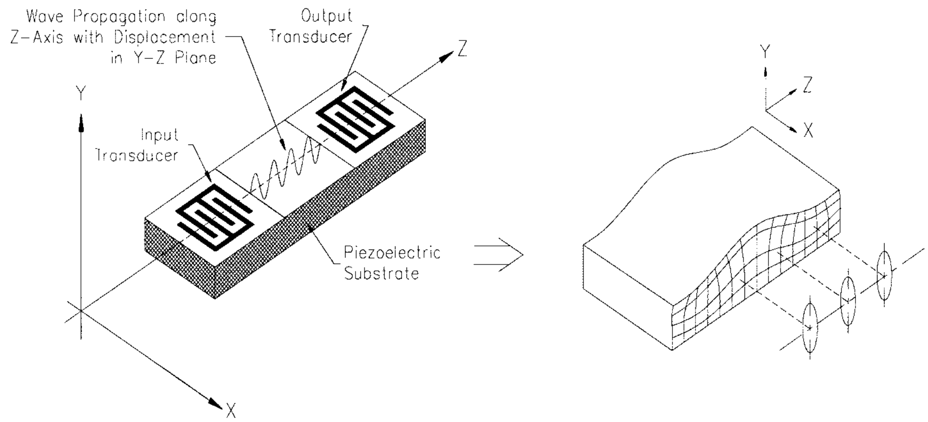

Fig. 5. Rayleigh waves move vertically normal to the surface plane of a SAW sensor. SAW sensors are very sensitive to surface changes, but do not work well for most liquid sensing applications.

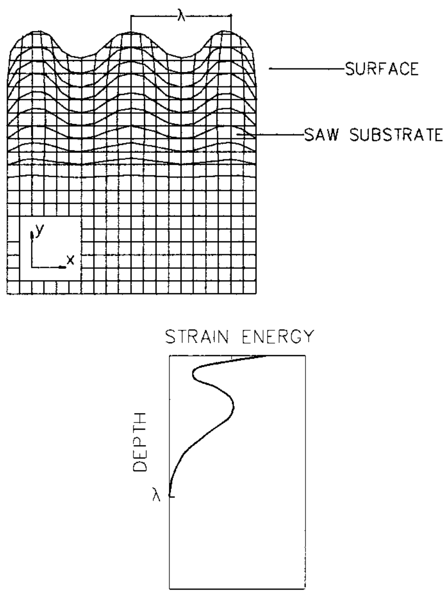

Fig. 6. Wave energy is confined to within one wavelength from the surface of a SAW sensor. This characteristic yields a sensor that is very sensitive to interactions with the surface.

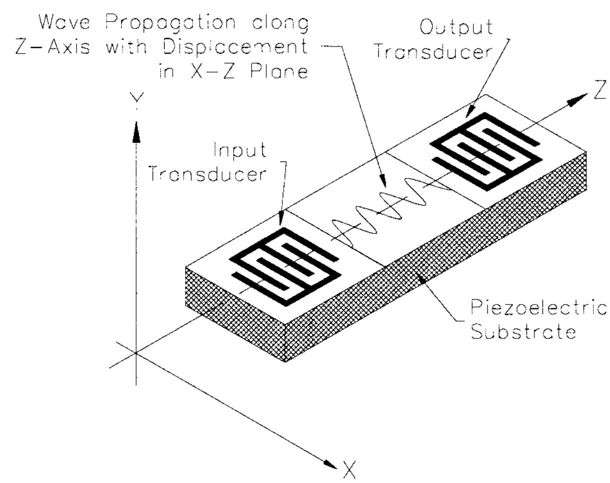

Fig. 7. By correctly selecting the orientation of material cut, the SH-SAW will dominate. These waves have a displacement that is parallel to the device's surface.

surface through the bulk material to the other surface. This distribution of energy minimizes the energy density on the surface, which is where the sensing is done. Surface wave acoustic sensors, conversely, focus their energy on the surface, making them typically more sensitive sensors. Table II compares some important specifications of several sensors [3, p. 144], [9]. Other design considerations when selecting acoustic wave sensors include oscillator stability and noise level.

XI. Sensor Applications

All the acoustic wave sensors are sensitive, to varying degrees, to perturbations to many different physical parameters. Fig. 8 shows some commercially available acoustic wave sensors. As a matter of fact, all acoustic wave devices manufactured for the telecommunications industry have to be hermetically sealed to prevent any disturbances to the device, as this will be sensed by the device, causing an unwanted change in output.

The range of phenomena that can be sensed by acoustic wave devices can be greatly expanded by coating the devices with materials that undergo changes in their mass, elasticity, or conductivity when exposed to some physical or chemical stimulus. The sensors become pressure, torque, shock, and force sensors when a stress is applied to them, changing the dynamics of the propagating medium. They become a mass, or gravimetric, sensors when particles are allowed to contact the propagation medium, changing the stress on it. By selecting a coating that absorbs only specific chemical vapors, a vapor sensor is made. This sensor works by effectively measuring the mass of the absorbed vapor. If a coating is applied that absorbs specific biological chemicals in liquids, the sensor becomes a biosensor. Selecting the correct orientation of propagation can lead to a wireless temperature sensor, as mentioned previously. As the temperature changes, the propagating medium changes, affecting the output. Detailed below are some of the more common applications of acoustic wave sensors.

TABLE II
COMPARISON OF ACOUSTIC SENSORS

Sensor Type	Sensitivity (Example in (Hz/MHz) / (ng/cm^2)	Factors Determining Sensitivity	Motion at Device Surface	Immersible?	Operating Frequency	Mechanical Strength
TSM	Low (0.014)	Plate Thickness	Transverse	Yes	Low (5-20 MHz)	Med
APM	Low-Med (0.019)	Plate Thickness, IDT Finger Spacing	Transverse	Yes	Med-High (25-200 MHz)	Med
SAW	High (0.20)	IDT Finger Spacing	Normal and Transverse	No	High (30-500 MHz)	High
SH-SAW	Med-High (0.18)	IDT Finger Spacing	Transverse	Yes	High (30-500 MHz)	High

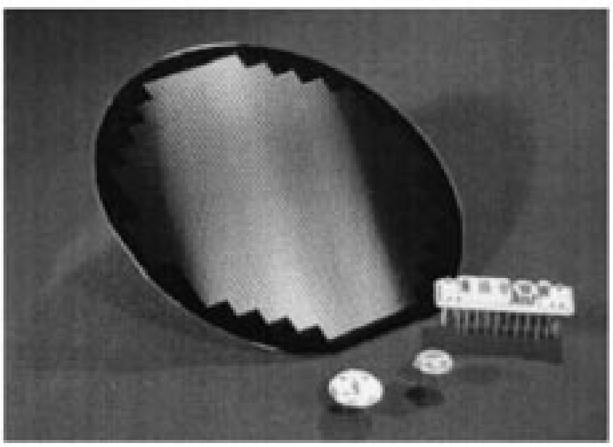

Fig. 8 Acoustic wave sensors are commercially available in several form factors. Most sensors begin as processed wafers, and then are tested, diced, and mounted into packages *(Photo Courtesy Microsensor Systems Inc.).*

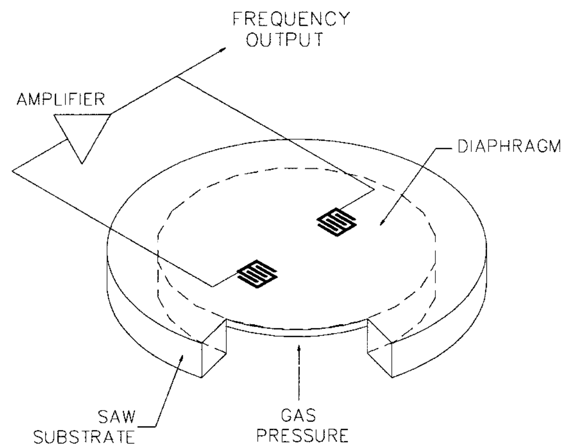

Fig. 9. Frequency of the SAW changes with stress. As the diaphragm flexes due to pressure, the SAW sensor changes its output. Unfortunately, changes in temperature also cause a change in output.

XII. TEMPERATURE SENSOR

Surface wave velocities are temperature dependent and determined by the orientation and type of crystalline material used to fabricate the acoustic wave sensor. Temperature sensors based on SAW delay-line oscillators have millidegree resolution, good linearity, and low hysteresis [10]. However, SAW sensors are very sensitive to mass loading, therefore, the SAW temperature sensor must be sealed in a hermetic package. Recently, a 124-MHz ST-cut quartz SSBW temperature sensor was reported to have a temperature coefficient of 32 ppm/°C and a resolution of 0.22 °C [11]. The sensor also exhibited three orders of magnitude less sensitivity to mass loading than SAW sensors. The response time was found to be 0.3 s, while BAW sensors were ten times slower. The acoustic wave temperature sensors have the additional benefit of requiring no power and being wireless, making them well suited for use in remote locations.

XIII. PRESSURE SENSOR

In 1975, a SAW pressure sensor was the first reported use of SAW technology for a sensor application [12]. SAW wave velocities are strongly affected by stresses applied to the piezoelectric substrate on which the wave is propagating. The SAW pressure sensor is formed by allowing the SAW device to become a diaphragm, as depicted in Fig. 9.

Historically, SAW pressure sensors have been plagued by uncompensated temperature drifts. These drifts can be minimized by adding a reference SAW device close to the measuring SAW on the same substrate and mixing the two signals [13]. One SAW sensor acts as a temperature sensor, whose proximity to the pressure sensor ensures that both are exposed to the same temperature. However, the temperature sensor SAW must be isolated in such a way that it is not exposed to the stresses that the pressure SAW experiences. Fig. 10 shows a temperature-compensated dual-SAW pressure sensor.

SAW pressure sensors are passive (no power required), wireless, low cost, rugged, and extremely small and light weight,

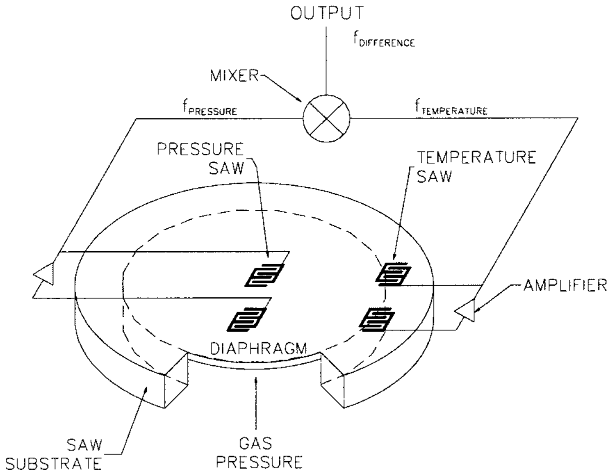

Fig. 10. Adding a second strategically placed SAW effectively minimizes the temperature drift of the SAW pressure sensor.

making them perfect for measuring pressure in moving objects, such as car and truck tires. These characteristics provide advantages over current technologies such as capacitive and piezoresistive sensors, which require operating power and are not wireless. Recently, a SAW pressure sensor weighing less than 1 g with a resolution of 0.73 psi was integrated into a car tire with excellent results [14]. Such a system allows the operator to view the tire pressure in each tire from the comfort of the cabin. Correctly inflated tires lead to improved safety, greater fuel efficiency, and longer tire life. This technology is particularly interesting for the new run flat (also called zero pressure or extended mobility) tire market.

XIV. Torque Sensor

If the SAW device is rigidly mounted to a flat spot on a shaft, and the shaft experiences a torque, this torque will stress the sensor and turn it into a wireless passive lightweight torque sensor. As the shaft is rotated one way, the SAW torque sensor is placed in tension. As the shaft is rotated the other way, it is placed in compression. For practical applications, two SAW torque sensors are utilized such that their center lines are at right angles (see Fig. 11) [15]. With this system, when one sensor is in compression, the other sensor is in tension. Since both sensors are exposed to the same temperature, the difference of the two signals minimizes any temperature drift effects.

When compared to other torque sensors, including resistive strain gauges, optical transducers, and torsion bars, SAW torque sensors offer lower cost, higher reliability, and wireless operation. The monitoring of torque on trucks and cars will significantly improve handling and braking, as torque is a much better measurement of wheel traction than the currently used revolution-per-minute sensors.

XV. Mass Sensor

SAW sensors are excellent mass or gravimetric sensors, and are the most sensitive to mass loads of the sensors evaluated. This opens up several applications, which includes particulate sensors and film-thickness sensors. If the sensor is coated with an adhesive substance, it becomes a particulate sensor. Any particle that lands on the surface will remain, and it will perturb the wave propagation. A mass resolution of 3 pg for a 200-MHz ST-cut quartz SAW has been reported, which was 1000 times more sensitive than the 10-MHz TSM resonator tested [16]. Particulate sensors are used in clean rooms, air quality monitors, and atmospheric monitors.

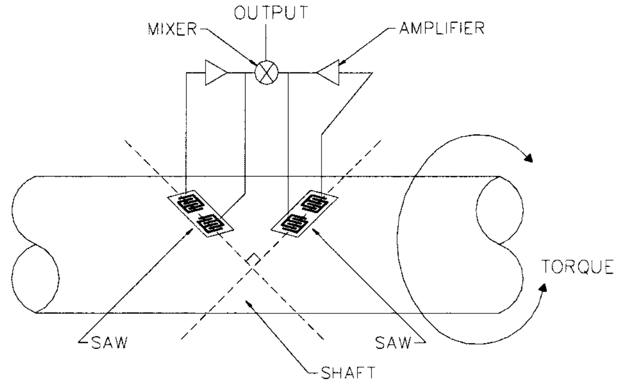

Fig. 11. Stress in the shaft is transferred to the SAW sensor, which changes its output frequency with stress, and, therefore, torque. The addition of another SAW minimizes temperature effects.

Thickness sensors fundamentally work the same as the particulate sensors, except they are not coated. The measured frequency shift is proportional to the mass of the deposited film and, via the film density and acoustic impedance, gives the film thickness. This method is accurate, provided that the film is thin (ideally no more than a few percent of the acoustic wavelength) [17]. Most commercially available thickness sensors are based on TSM resonators.

XVI. Dew-Point/Humidity Sensor

If a SAW sensor is temperature controlled and exposed to the ambient atmosphere, water will condense on it at the dew-point temperature, making it an effective dew-point sensor. Current commercial instruments for high-precision dew-point measurements utilize optical techniques, which have cost, contamination, accuracy, sensitivity, and long-term stability issues. A 50-MHz YZ-cut lithium niobate SAW dew-point sensor has been developed that is immune to common contaminants, has a resolution of ± 0.025 °C (compared to ± 0.2 °C for an optical sensor), is low cost, and significantly more stable [18].

Acoustic wave sensors with an elastic hygroscopic polymer coating make excellent humidity sensors. Three operational mechanisms contribute to the sensors' response: mass loading, acoustoelectric, and viscoelastic effects, each of which can be effectively controlled to yield an accurate low-cost humidity sensor. A 50-MHz YZ-cut lithium niobate SAW coated with polyXIO has been demonstrated as a humidity sensor, with a range of 0% to 100% relative humidity and a hysteresis on the order of 5% [19]. Also, a 767-MHz AT-cut quartz SH-SAW sensor coated with a plasma modified hexamethyldisiloxane (HMDSO) polymer has recently been demonstrated as a humidity sensor, with a sensitivity of 1.4 ppm/% relative humidity and a 5% hysteresis. This was found to be 4–10 times more sensitive than a 14-MHz TSM resonator coated with the same polymer [20].

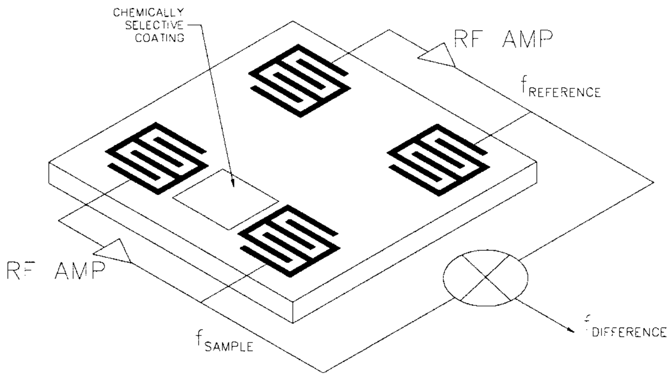

Fig. 12. By coating a SAW device with a chemically sorbtive polymer, a chemical vapor sensor is made. Adding another SAW device minimizes the temperature drift and provides a manageable difference frequency.

In the same category, a 434-MHz YZ-cut lithium niobate SAW sensor has been used as a remote water sensor [21], while an 86-MHz XY-cut quartz Love wave sensor has been demonstrated as an ice sensor [22].

XVII. Vapor Chemical Sensor—Coated and Uncoated

Chemical vapor sensors utilizing SAW sensors were first reported in 1979 [23]. Most SAW chemical sensors rely on the mass sensitivity of the sensor in conjunction with a chemically selective coating that absorbs the vapors of interest, resulting in an increased mass loading of the SAW sensor. Fig. 12 details such a sensor. As with the temperature-compensated pressure sensors, one SAW is used as a reference, minimizing the affects of temperature variations.

There are several design considerations to be made when selecting and applying the chemically sorptive coating. Ideally, the coating is completely reversible, meaning it will absorb the vapor and completely desorb it given a clean air purge. The rate at which the coating absorbs and desorbs should be fairly quick, for instance, less than 1 s. The coating should be robust, such that it will not be damaged by caustic vapors. The coating should be selective, only absorbing very specific vapors while not absorbing others. The coating needs to operate over a usable temperature range. It should be stable, reproducible, and sensitive. And, finally, its thickness and uniformity are very important.

Chemical vapor detection and identification is possible if several SAW sensors, each with a unique chemically specific coating, are placed in an array. Each SAW sensor will have a different output given the same vapor exposure. Utilizing pattern recognition software, a diverse list of volatile organic compounds can be detected and identified, yielding a very powerful chemical analyzer. A commercially available analyzer utilizing an array of four SAW sensors is shown in Fig. 13.

TSM resonators have also been successfully utilized for chemical vapor sensing [24]. In addition, SAW chemical vapor sensors have been made without coatings. This method utilizes a gas chromatograph column to separate the chemical vapor components and a temperature-controlled SAW that condenses the vapor and measures the corresponding mass loading [25].

Fig. 13. Commercially available SAW chemical vapor analyzer. This handheld analyzer utilizes an array of four SAW sensors, each coated with a different polymer *(Photo Courtesy Microsensor Systems Inc.)*.

XVIII. Biosensor

Similar to the chemical vapor sensors, biosensors detect chemicals, but in liquids, not vapors. As mentioned previously, the SAW device is a poor choice for this application, as the vertical component of the propagating wave will be suppressed by the liquid. Biosensors have been fabricated using the TSM resonator, SH-APM, and SH-SAW sensors. Of all the known acoustic sensors for liquid sensing, a special class of the SH-SAW, called a Love wave sensor, has the highest sensitivity [26]. Love wave sensors place a waveguiding coating on top of an SH-SAW, such that the energy of the shear horizontal waves are focused in that coating. A biorecognition coating is then placed on top of the waveguiding coating, forming the complete biosensor. Successful detection of antigoat IgG in the concentration range of 3×10^{-8} to 10^{-6} moles using a 110-MHz YZ-cut SH-SAW with a polymer Love waveguide coating has been achieved [27].

XIX. Conclusion

Acoustic wave sensors are extremely versatile sensors that are just beginning to realize their commercial potential. They are competitively priced, inherently rugged, very sensitive, intrinsically reliable, and offer the additional benefit of being passively wirelessly interrogated. Wireless sensors are beneficial when monitoring parameters on moving objects, such as tire pressure on cars or torque on shafts. Sensors that require no operating power are highly desirable in remote locations, making these sensors ideal for remote chemical vapor, moisture, and temperature sensors. As a result of their mass sensitivity, they can be used in numerous physical, chemical, and biological applications. Other applications include measuring force and acceleration, shock, angular rate, viscosity, displacement, flow, and film characterization. The sensors also have an acoustoelectric sensitivity, allowing the detection of pH levels, ionic contaminants, and electric fields. SAW sensors have proven to be the most sensitive sensors in general, as a result of their larger energy density on the surface. For liquid sensing, a special class of SH-SAW sensors, called Love wave sensors, have proven to be the most sensitive. Much work is continuing in developing these sensors for future applications.

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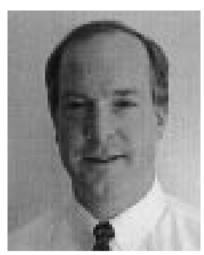

Bill Drafts received the B.S.E.E degree from the University of Arizona, Tucson, in 1987, and the M.S.E.E. and M.B.A. degrees from the University of Central Florida, Orlando, in 1990 and 1995, respectively.

He is currently the Vice President and General Manager of Microsensor Systems Inc. (a Sawtek Company), Apopka, FL, where he is engaged in pioneering acoustic wave technology sensors and instrumentation. Prior to joining Microsensor Systems Inc., he was a Division Manager of F. W. Bell, a world leading magnetic sensor and instrument manufacturer. He possesses over 13 years of sensor and instrument design and management experience, and holds three patents and one pending. He has authored or co-authored several articles on magnetic, electrical current and acoustic wave sensing technologies.

Mr. Drafts is a licensed Professional Engineer in the state of Florida.