Surface Acoustic Wave Sensors (SAWS):

Design for Application

Jared Kirschner

***Abstract*—In the modern world, almost all electromechanical systems use sensors to acquire pertinent information from the environment during operation or to operate more effectively. In many of these applications, there is demand for increased performance along with decreased size and cost of sensor technology. Microelectromechanical systems (MEMS) are an attractive option to fill this demand due to the small resolution of feature sizes ($\approx 1\mu$m) and the ease of mass-production due to compliance with standard microfabrication processes. Within MEMS, surface acoustic wave sensors (SAWS) offer a particularly interesting sensor option due to the wide variety of measurable phenomena—from temperature to biological agents to magnetic field strength—and potential applications—ranging from individual sensors with additional packaging to large-scale, distributed sensor networks. In this paper, we shall explore the design process of a surface acoustic wave sensor both to gain understanding of the range of the design space of surface acoustic wave devices and how to design a SAWS with selected properties for use in a chosen application.**

I. Introduction

SENSORS have become an integral part of our lives. The modern person relies heavily on technology to satisfy his or her wants and needs, and many of these technologies rely heavily on sensors to gather relevant information about the environment. Mobile devices now incorporate ambient light sensors to optimize display and acceleration sensors to allow great levels of interactivity [1]; automobiles now incorporate proximity sensors to avoid accidents and an array of angular rate and acceleration sensors to maintain stability [2], [3]; even our sinks and soap dispensers contain sensors which allow use without contact, increasing public hygiene. Market demand for sensor technology continues to drive the production of smaller, cheaper, and more sensitive sensors at a higher volume. Microelectromechanical systems (MEMS)—micro-scale devices amenable to mass-production due to compatibility with standard microfabrication processes—are particularly well-suited to fit this demand. One class of MEMS sensors, the surface acoustic wave sensor, is of particular interest due to its adaptability to many different applications.

The class of surface acoustic wave technology covers an extremely wide range of applications including filters, oscillators, transformers, and sensors. All of these applications are made possible by the unifying principle of this class of devices—the piezoelectric effect. Surface acoustic wave technology utilizes an interdigitated transducer (IDT) to convert electrical energy into an acoustic wave. The acoustic wave then travels across the surface of the device substrate to another interdigitated transducer, converting the wave back into an electrical signal. As the characteristics of the surface acoustic wave can be modified by the changes in the surface properties as a result of various physical phenomena, sensors can be designed to quantify many different phenomena. In this paper we shall explore the considerations for the design of a surface acoustic wave sensor, and the possibilities that are available with this particular technology.

J. Kirschner is an undergraduate student at Franklin W. Olin College of Engineering, 1000 Olin Way, Needham, MA 02492. E-mail: Jared.Kirschner@Students.olin.edu

II. Theory of Operation

All acoustic wave devices utilize the piezoelectric effect to transduce an electric signal into a mechanical wave. The mechanical wave propagates through the material to another transducer which converts the wave back to an electrical signal. Surface acoustic wave devices specifically use the Rayleigh wave—a transverse, surface wave—in operation. To understand how a surface acoustic wave device can be designed to perform one of its many uses, we must first understand the piezoelectric effect and the behavior of Rayleigh waves.

A. The Piezoelectric Effect

In 1880-81, Pierre and Paul-Jacques Curie discovered that the application of an external force to single crystals of certain materials, including quartz, generated a surface charge on the crystals. The resulting charge is proportional to the mechanical stress applied to the material. As such, crystals which exhibit the piezoelectric effect (piezoelectric crystals) can behave as sensors. Conversely, the Curie brothers discovered one year later that an applied voltage will result in the mechanical deformation of the crystal lattice. In this manner, piezoelectric crystals can behave as actuators as well. [4]

The piezoelectric effect occurs only in anisotropic crystalline materials. If the unit cell of a crystal is isotropic (symmetrical), the net spontaneous charge distribution (polarization) of the unit cell will be zero. However, anisotropic unit cells exhibit a net polarity. [4] In a polycrystalline material, the random orientation of individual grains will tend to cancel the polarization vectors contributed by each grain. However, a polycrystal can be induced to exhibit the piezoelectric effect by heating the material while exposed to a strong electric field. At increased temperatures, diffusion within the material will occur quickly and allow the molecules to re-orient according to the applied electric field. The result is a material in which the individual grains all have net polarization vectors in roughly the same direction, producing an overall polarization in the material as seen in Figure 1 (*left*). [5]

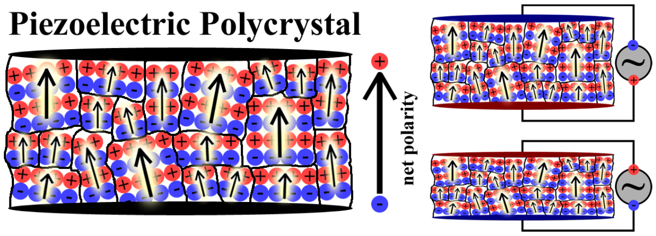

Fig. 1: (*left*) Demonstration of the net polarity of a piezoelectric polycrystal as the sum of the polarity of its individual grains. This polarity would be maximized in a single crystal substrate. (*right*) Demonstration of the response of a piezoelectric material to the application of a potential difference across surfaces in the direction of its net polarity. A voltage of the same polarity will cause the material to contract, while a voltage of opposite polarity will cause the material to expand.

The application of an external force (electrical or mechanical) results in the movement of centers of net positive and negative charge (dipoles) within the unit cell. As the charge distribution within the material is uniform prior to the application of an external force, this movement of dipoles within the material results in a separation of charge in the material. A separation of charge results in an electric field within the piezoelectric material, from which voltage can be measured as the line integral of the electric field along the path between probes. The internal electric field acts to move the charges back towards a state of uniform charge distribution—the equilibrium state. As such, piezoelectric materials are only useful as sensors of dynamic strains, often of oscillatory nature. [4]

The application of a voltage across the material will result in charges within the material moving such that an equilibrium state is obtained with zero internal electric field and all charge concentrate on the surface. The charges on the surface serve to terminate the electric field lines entering normal to the surface of the material due to the applied voltage. In a piezoelectric material, the dipoles within the lattice will either expand or contract to produce the necessary charge distribution, creating a tensile or compressive strain (respectively) within the lattice as seen in Figure 1 (*right*).

As the piezoelectric effect occurs only in anisotropic crystal lattices, it follows that the piezoelectric properties of a piezoelectric material are also anisotropic. Because of this, it is important to consider the cut and orientation of a piezoelectric material during the design and manufacture of a device. We shall also explore other important characteristics of a piezoelectric material for use in a surface acoustic wave sensor.

1) Mechanical Strain ϵ: The mechanical strain ϵ which results from the application of a stress σ is linearly proportional to the compliance S ($S^{-1} = E_y =$ Young's modulus) within the elastic deformation region of the stress-strain curve of the material (below the yield strength σ_s):

$$\epsilon = S\sigma \tag{1}$$

Strain is a dimensionless property which describes the changes in length of a material, defined as the length under stress divided by the equilibrium length (no stress) of the material. With knowledge of the yield strength of a material, we can determine the maximum strain a material can experience without permanent (plastic) deformation.

2) Electromechanical Coupling Factor k: The electromechanical coupling factor k describes the efficiency of the transduction of the piezoelectric material between mechanical and electrical energy and vice-versa:

$$\begin{aligned} k &= \sqrt{\frac{\text{mechanical energy stored}}{\text{electric energy applied}}} \\ &= \sqrt{\frac{\text{electrical energy stored}}{\text{mechanical energy applied}}} \end{aligned} \tag{2}$$

The electromechanical coupling factor is often expressed in terms of k^2, which is the percentage of energy retained after transduction. To maximize device efficiency, a material with a high electromechanical coupling factor should be chosen.

3) Piezoelectric Charge Constant: Due to the anisotropic nature of piezoelectric materials, tensor notation must be used to describe the behavior of the material to stress and strain. For the sake of simplicity, we shall use scalars to describe the behavior of a one-dimensional piezoelectric material.

The following equations describe the behavior of a piezoelectric material [4]:

$$P = d\sigma + \epsilon_\sigma E \tag{3}$$

$$\epsilon = dE + S^E\sigma \tag{4}$$

...where P is the polarization (electric dipole moment per unit volume of material), d is the piezoelectric charge constant, ϵ_σ is the permittivity at constant stress, E is the electric field, and S^E is the compliance at constant electric field.

From Equation 3, we can see that when the external electric field is zero, the polarization is proportional to the piezoelectric charge constant and the stress:

$$P = d\sigma \tag{5}$$

From Equation 4, we can see that when the external stress applied is zero, the strain is proportional to the piezoelectric charge constant and the stress:

$$\epsilon = dE \tag{6}$$

Thus, it can be seen that the piezoelectric charge constant, d, is used for both the direct and the reverse piezoelectric effect. [4] The piezoelectric charge constant is related to the electromechanical coupling factor k by the following relationship [6]:

$$k = d^2\sqrt{S^E\epsilon_\sigma} \tag{7}$$

For maximum efficiency, we wish to select a piezoelectric material with a high piezoelectric charge constant. For a given piezoelectric charge constant, a large compliance (ratio between strain and stress) and large permittivity (ratio between

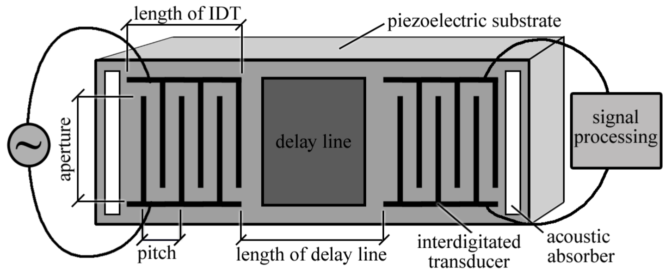

Fig. 2: General structure of a surface acoustic wave sensor with connections to an AC voltage source and a signal processing unit. In some sensors, the acoustic absorbers are replaced with reflectors to decrease insertion loss. A wireless surface acoustic wave sensor can be made by replacing the output IDT and by coupling the input IDT to an RF antenna rather than a voltage source.

electric energy stored and applied voltage) will increase the electromechanical coupling factor—as would be expected.

B. Rayleigh Waves

In 1885, Lord Rayleigh mathematically predicted the existence of the Rayleigh wave—a transverse wave which propagates along the surface of a medium—while analyzing surface wave propagation in solids, particularly as relates to seismic activity. [8] The Rayleigh wave is the mode of transmission for the most damaging waves in an earthquake and for waves on the surface of the open ocean. [9] This is the same mode of propagation as the mechanical waves used in a surface acoustic wave device.

The characteristics of the medium of propagation will determine the angle of oscillation with respect to the surface. The component of the wave perpendicular to the surface is known as a surface acoustic wave (SAW) while the component of the wave parallel to the surface is known as the shear-horizontal surface acoustic wave (SH-SAW) or surface transversal wave (STW). The SAW is a form of Rayleigh wave while the STW is a form of Love wave. In an acoustic wave device, the piezoelectric crystal cut and orientation must be selected such that the generated wave is polarized into a Rayleigh or a Love wave.

Because a Rayleigh wave propagates along the surface of a material rather than through the bulk of the material, the energy of the wave is maximized at the surface. [7] In fact, the energy profile varies by depth approximately proportionally to $e^{-2\pi\frac{y}{\lambda}}$ where y is the depth from the surface and λ is the wavelength. [8] From this relationship, it can be seen that the majority of the energy of the Rayleigh wave is contained within one wavelength from the surface of the material. Because of this, the properties of the surface of the device will influence the characteristics of the wave. Lastly, because Rayleigh waves propagate along the surface of a medium, they can travel much farther than other waveforms without significant attenuation (energy decreases as $\frac{1}{\sqrt{r}}$).

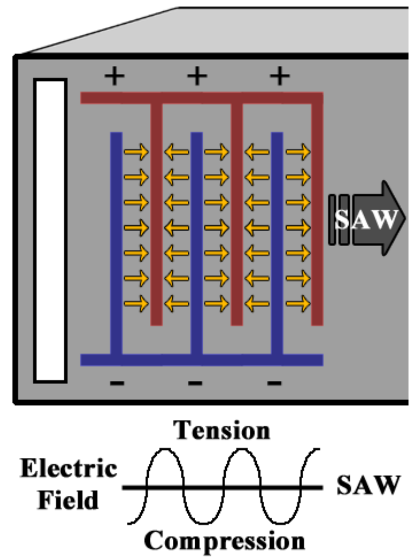

Fig. 3: Demonstrating the electric field (yellow arrows) resulting from the opposing polarity of the electrodes of the IDT (seen in red and blue). The alternating direction of the electric field between fingers creates regions of tension and compression alternating between fingers. This results in the generation of a mechanical wave—the surface acoustic wave (SAW).

C. Device Operation

The basic surface acoustic wave device, as shown in Figure 2, consists of a piezoelectric substrate, an input interdigitated transducer on one side of the surface of the substrate, and a second, output interdigitated transducer on the other side of the substrate. The space between the IDTs, across which the surface acoustic wave will propagate, is known as the delay-line. As the velocity of a mechanical wave is much slower than that of an electromagnetic wave, there is an appreciable delay between the transmitted signal and the received signal between the IDTs.

To operate the surface acoustic wave device, a sinusoidal electric signal (AC) is sent through the first interdigitated transducer. This array of interdigitated electrodes will alternate polarity according to the electrical signal, creating alternating regions of electric fields between fingers as seen in Figure 3. [15] Due to the piezoelectric effect, these electric fields will cause alternating regions of tensile and compressive strain between fingers of the electrodes, producing a mechanical wave at the surface. As the mechanical wave will propagate in both directions from the input IDT, half of the energy of the waveform will propagate across the delay line in the direction of the output IDT. In some devices, a mechanical absorber or reflector is added between the IDTs and the edges of the substrate to prevent interference patterns or reduce insertion losses respectively. [8]

Surface acoustic wave sensors take advantage of the fact that the surface acoustic wave is sensitive to changes in the surface properties of the medium in the delay-line. Often a layer of material with properties sensitive to the measurand (the phenomena of interest) is applied to the surface of the piezoelectric substrate across the delay line. As the surface acoustic wave is coupled with the medium in contact with the surface of the substrate, changes in the added layer of material will modulate the velocity and amplitude of the wave. The coupling of a Rayleigh wave (which has vertical displacement) with a material deposited on the surface of a substrate will be greater than that of a Love wave (which has no vertical displacement). For this reason, the Rayleigh wave (SAW) is used in most acoustic wave sensors. There are, however, cases in which other wave forms are advantageous. For example, when the sensor is operated in an aqueous environment, a surface acoustic wave will be heavily damped from contact with the liquid. To avoid damping, a wave which propagates transversally without a vertical displacement is preferred, such as a Love wave. Though a bulk acoustic wave (which propagates through the bulk of the material) could be used as well, the Love wave is preferred because of its concentration of energy at the surface of the device (similar to a Rayleigh wave).

After passing through the delay line, the acoustic wave reaches the output IDT. By the piezoelectric effect, the acoustic wave will generate an electric field that varies along the length of the substrate. This results in an alternating electrical signal as the output IDT. By comparing the input and output signals, we can quantify the measurand which modulated the acoustic wave. Changes in velocity and amplitude of the acoustic wave will result in changes in amplitude, frequency, phase-shift, and time-delay in the output electrical signal from the original signal. Additional signal processing circuitry or software is necessary to measure these changes.

In some surface acoustic wave sensors, the output IDT is replaced by a reflector. The wave passes through the delay line twice before arriving back at the input IDT. If an antenna is coupled to the input IDT, such a sensor can be wirelessly interrogated by a radio frequency (RF) signal. The same antenna can be used as a transmitter when the signal returns after being reflected. [10] This allows for a centralized wireless data collection system connected to a distributed network of wireless sensors. In this system, each sensor is passive and will operate when powered by an RF signal from the interrogation antenna.

III. Design

Many factors are taken into consideration in the design of a surface acoustic wave sensor. The intended application will determine the relative importance of various factors, such as size, efficiency, and sensitivity. The intended mode of operation (wired or wireless), among other factors, will determine the structure of the sensor. Lastly, the intended market will determine the cost with which all of these considerations must be reconciled. These considerations will guide the determination of system parameters and the choice of materials.

A. Parametric Determinations

Before determining the parameters for a specific surface acoustic wave sensor design, several important device characteristics must be specified. Among these characteristics are the physical size, bandwidth, operating frequency, impulse response, and frequency response of the device. In this paper, we will examine how to achieve a desired physical size, bandwidth, and operating frequency through the selection of various system parameters. The relationship between system parameters and device characteristics such as impulse and frequency response is much more complicated. Analytical and numerical modeling techniques, though helpful, are not yet sufficient to design a sensor with specific, rigidly-defined characteristics. Instead, SAW manufacturers generally produce an array of prototype wafers adapted from existing designs. These prototype wafers are then tested to determine the best design for production. [14]

1) Synchronous Frequency f_o: The synchronous frequency f_o of the device is the frequency f of the generated surface acoustic wave in a neutral environment. Here, a neutral environment is the default environment for a given measurand. In most cases, this is the absence of the measurand. However, in other cases, a non-zero set point may be more appropriate; for example, in temperature-sensing, a reasonable neutral environment might by $0°$ Celsius or room temperature. As the sensitivity of the system will be greatest at the synchronous frequency, the synchronous frequency accordingly for the range of the measurand. It should be noted that the electrical input signal should have a frequency equal to the synchronous frequency of the device to maximize efficiency. If the measurand causes the synchronous frequency to shift, a system without feedback control on the input frequency will experience a slight signal attenuation.

The important parameters in determining the synchronous frequency of the device is the pitch p of fingers of the IDTs (refer to Figure 2). For simplicity, we shall examine the most common IDT design which utilizes 1:1 interdigitation and equal spacing between all fingers on both sides. The pitch of the fingers is then the spacing between two fingers on the same side of the electrode (or twice the distance between the centers of fingers on opposite sides of the IDT). As consecutive fingers (alternating sides of the IDT) are always at equal but opposite voltage assuming a sinusoidal (AC) signal, consecutive fingers mark the location of maximal strain alternating between tension and compression. As such, the wavelength of the wave transduced by the piezoelectric substrate will be equal to p. The following relationship then describes the synchronous frequency of the device:

$$f_o = \frac{v_p}{p} \tag{8}$$

…where v_p is the propagation velocity of a wave in the substrate. It is important to note that v_p is a material property, and that, as a result, the synchronous frequency is both determined by material selection and a design parameter. Though the output IDT need not have the same pitch as the input IDT, the resulting signal attenuation at the output IDT is unlikely to be desirable for a sensor. Such a design decision may, however, be considered in the design of a surface acoustic device filter.

To achieve the intended synchronous frequency, the accuracy and precision of the mask and of the photolithography mask must be high. Though this may not be important in all systems, it may be important for a wireless sensor operating in parallel with many other sensors in the same frequency band. In such systems, the bandwidth must be made as small as possible to prevent sensors from interfering with the response of other sensors. [14]

2) Bandwidth BW: The bandwidth describes the range of the frequency distribution of the acoustic wave generated by the input IDT. The bandwidth of a signal is defined as the lower and upper frequency level at which an attenuation of 3dB (approximately 50%) from the maximal amplitude (at the operating frequency). [11] To increase the bandwidth for a given operating frequency, we can increase the number of pairs of fingers N in the IDT. According to Hirst et al., the bandwidth of the device can be described as follows:

$$BW = \frac{2f_o}{N} \qquad N \in \mathbb{Z} \tag{9}$$

By substituting Equation 8 into Equation 9, we gain new insight into the expression for BW:

$$BW = \frac{2}{Np}v_p = 2\frac{v_p}{l_{IDT}} \tag{10}$$

…where l_{IDT} is the total length of the IDT (in the primary direction of wave propagation), which is equal to the number of pairs of fingers N in the IDT multiplied by the pitch p of the IDT.

By minimizing the bandwidth, we increase the amplitude of the synchronous frequency relative to nearby frequencies, creating a more distinct signal. As such, a smaller bandwidth allows for a sensor with a higher resolution. However, because the bandwidth is dependent on the length of the IDT, the decrease in bandwidth is limited by limitations on the physical size of the sensor.

3) Physical Size: The physical size of the device is parameter for which application and material availability must be considered. The minimum dimensions of the device are determined by the dimensions of the two sets of IDTs (or one IDT and a reflector), the delay line, and any absorbers or reflectors between the IDTs and the edge of the substrate. We have already given an expression for the length of an IDT (refer to Equation 10). To parameterize the length in terms of the pitch and fundamental frequency, we obtain the following:

$$l_{IDT} = PN = \frac{N}{f_o}v_p \tag{11}$$

From Equations 8, 9, and 11, we can infer some limitations on the operating frequency of a SAW sensor. At the lower end of the frequency range, the necessary pitch of the IDT would be quite large. To maintain a sufficiently low bandwidth (resulting in a more precise sensor), a very large sensor would be required. At the higher end of the frequency range, the necessary pitch of the IDT would be quite small, limited by the minimum feature size resolvable by current photolithography techniques. The typical frequency range of a SAW device is 10MHz to 3GHz, corresponding to pitches of approximately 1 μm to 300 μm.

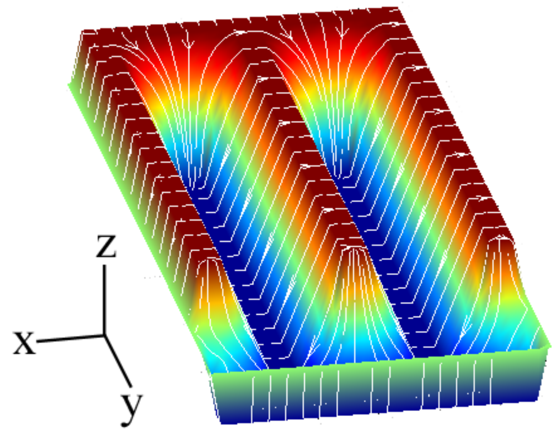

Fig. 4: Demonstrating the voltage and electric field characteristics of a set of interdigitated fingers (y-oriented). The color indicates voltage, ranging from maximal positive (red) to maximal negative (blue). The electric field lines (white) follow the negative gradient of the voltage field. It is clear that at the fringes of the fingers, the electric field moves in the x-direction rather than the desired y-direction. This will result in a stray SAW.

The size considerations of the delay line are dependent upon the nature of the measurand and its interaction with the surface acoustic wave. In applications where time-delay or phase-shift is measured, the length of the delay line proportional to the observable change (as the distance the wave travels between IDTs changes proportionally). In applications where signal attenuation is measured, the magnitude of the change is proportional to the length of the delay line. [12] In both cases, a longer delay line creates a greater change in signal in response to the measurand. The minimum length of the delay line should be determined by the required sensitivity of the device and the limitations of available signal processing.

The width of the piezoelectric substrate is important as it determines the maximum width of the IDTs. The width of the IDTs should be much greater than the pitch of the device, and the horizontal distance between sides of the IDT should be minimized (without risking a short of the IDT due to limitations of and imperfections in the manufacturing process). Doing so will reduce the acoustic waves which propagate at an angle away from the path between the IDTs. This is because the electric field lines between two conductors at different voltages will be normal to both surfaces. As such, the electric field lines at the end of the interdigitated fingers will curve towards the surface of the other electrode, rather than travel in a straight line between fingers as on the remainder of the finger. This behavior can be observed in Figure 4, which shows an interdigitated electrode aligned in the y-direction. The fringing electric field lines at the ends of the fingers will cause wave energy to propagate with a component in the x-direction, which may interfere with the signal directly and after reflection from the edge of the substrate. Though this effect

Material	*Orientation*	*Velocity*	*Temperature Coefficient*	*Coupling Coefficient*	*Cost*
(Name)	(Axis)	(m/s)	(ppm/°C)	(%)	(Qualitative)
Quartz	Y, X	3159	-24	0	Low
Quartz	Y ST, X	3159	0	0.16	Low
Lithium Tantalate	Y, Z	3230	35	0.74	Medium
Lithium Tantalate	167° Y, X	3394	64	N/A	Medium
Lithium Niobate	Y, Z	3488	94	4.6	High
Lithium Niobate	128° Y, X	3992	75	5.6	High
Langasite	Y, X	2330	38	0.37	High

Fig. 5: Common piezoelectric substrate properties. [8]

Metal	*Substrate Adherence*	*Electrical Resistivity*	*Boiling Point*	*Cost*
(Name)	(Qualitative)	(μΩ-cm)	(K)	(Qualitative)
Copper	Good	1.7	3200	Low
Aluminum	Good	2.65	2792	Low
Gold	Poor	2.2	3129	High
Tungsten	Average	5.0	5828	Mid
Titanium	Good	50	3560	Mid

Fig. 6: Relevant properties for common interdigitated transducer metals. [8]

will always be present, it can be minimized by maximizing the ratio between the length of fingers and the spacing between a finger and the other side of the IDT.

The thickness of the material is a balance between the desire for ever-shrinking feature sizes in electronic devices and limitations on the structural integrity of the device. As all piezoelectric materials are crystalline, the substrate is often strong but brittle. The substrate will be able to handle fairly high static loads, but may fail easily in impact. To avoid premature failure of a sensor, there is a limitation on how thin a surface acoustic device can be made.

B. Material Selection

In the design of a surface acoustic wave devices, one must consider a choice of materials for both the piezoelectric substrate and the interdigitated electrodes. If acoustic absorbers are desired, a material selection must be made for them as well.

1) Piezoelectric Substrate: Selecting a piezoelectric substrate involves choosing both a material and a crystal orientation which yields the desired set of properties. Properties to consider are the coefficient of thermal expansion, electromechanical coupling factor, wave propagation velocity, compatibility with standard microelectronic fabrication techniques, and cost. [8] As the coefficient of thermal expansion determined the change in length of a material for a given temperature change, it will also determine how quickly the pitch of an IDT changes as a function of temperature. For a SAW temperature sensor, the thermal dependence of the piezoelectric material should be maximized, but should be minimized for all other applications. The electromechanical coupling factor determines the efficiency with which energy is transduced in the system, and should be maximized. Wave propagation velocity is important in the determination of design parameters (such as the synchronous frequency), but its value in itself is not critical. The only instance in which wave propagation velocity may have a greater importance is at the fringes of the possible frequency range of SAW devices, where an appropriately chosen material may extend the frequency range.

Figure 5 shows the relevant material properties of common piezoelectric materials for SAW sensor design. As stated above, a low coefficient of thermal expansion is desired for most SAW sensor applications (all except temperature sensing). One particular cut of quartz exhibits almost no thermal expansion; unfortunately, it has a low electromechanical coupling factor. For a given amount of power, this would result in a much lower sensitivity. This material selection would eliminate the need for additional sensors to compensate for the temperate drift, but would require higher power to compete with other material choices in terms of sensitivity. The materials in Figure 5 with higher electromechanical coupling factors generally exhibit a higher coefficient of thermal expansion and higher cost than other options. In addition, the availability and lead time of different materials and cuts must be considered. For example, while 128° Y-X cut lithium niobate has the highest electromechanical coupling factor, its availability is much lower than the Y-Z cut lithium niobate. [8] In the context of a high-precision industrial application, the 128° Y-X cut would be more appropriate, whereas in a research setting (or another setting with low production volume), a Y-Z cut would be a better choice.

2) Interdigitated Transducers: Properties to consider in the choice of a material for the interdigitated transducers are substrate adhesion, boiling point, resistivity, and cost. [8] To achieve effective coupling between the IDT and the piezoelectric substrate, good surface adhesion is critical. The boiling point of the material determines which processes can be used for depositing a layer of material onto the substrate. A lower boiling point allows for cheaper, simpler, and faster processes (such as thermal evaporation) to be used. For a given voltage, the electric field generated and transduced into an acoustic wave will be greater for a lower resistivity.

Figure 6 shows the relevant material properties of common choices for interdigitated transducer metals. Though copper appears to be the best overall choice, it has a tendency to diffuse into substrates common to microfabrication, including those mentioned in Section III-B1. The low resistivity of gold makes it an attractive choice for high-sensitivity applications. However, the extremely high cost of gold relative to other materials as well as its poor substrate adhesion (requiring an adhesive layer of titanium or chromium) restricting its application to high-end sensors. [8] For less sensitive sensors or lower volume productions, aluminum is a good choice—with a nice balance of relatively low resistivity, low cost, and good surface adhesion. The low boiling point of aluminum also makes it ideal for fast, cheap deposition processes, such as thermal evaporation. Gold, copper, and titanium can also use the thermal evaporation process, while tungsten requires sputtering of chemical vapor deposition. [8]

3) Acoustic Absorbers: To reduce signal interference caused by mechanical waves moving in the direction opposite the output IDT and other reflected waves, acoustic absorbers can be applied to the surface of the piezoelectric substrate. Some acoustic absorbers are applied manually after the fabrication process. Two examples are waxes and epoxies, which are commonly used as absorbers at higher frequencies. However, other absorbers that are consistent with standard microelectronic fabrication processes are being researched, such as silicon and polyimide. [8]

IV. Manufacturing

After the design for production is selected, we begin the manufacturing process (as outlined in Figure 7). Surface acoustic wave sensors can be made entirely using standard microfabrication techniques. All surface acoustic wave sensors share a similar manufacturing process for the production of the interdigitated electrodes. Some sensors require additional processing, usually in the form of the deposition of a layer of material in the delay line. For the scope of this paper, we shall only discuss the manufacturing process up to the completion of the interdigitated electrodes.

In one version of the process, the wafer is first cleaned before a layer of the interdigitated electrode material is deposited. The type of deposition (sputtering, thermal evaporation, or chemical vapor deposition) used is dependent heavily on the melting temperature of the chosen IDT material. Photoresist is then spun on top of the IDT layer. The photoresist is then patterned by exposure to ultraviolet light through a mask in such a way as to create a positive image of the IDTs after developing. The IDT material is then etched using dry or wet etching. As the most common wet etchants will be isotropic with the piezoelectric substrate, it is greatly preferable to use an anisotropic, dry etch, such as reactive ion etching (RIE). The layer of photoresist can then by removed, completing the process. [8]

A lift-off process can be used instead of the previously described process. In this process, the layer of photoresist will first be spun onto the substrate and patterned in such a way as to create a negative image of the IDTs after being developed. The photoresist will be removed by the developer in such as a way that its features are undercut. When the IDT material is deposited on top of the patterned photoresist, the material for the IDT will be separated from the excess material due to the nature of the undercut of the photoresist. When the photoresist is removed in the lift-off process, the excess IDT material will go with it, completing the process. [17]

V. Applications

The surface acoustic wave sensor is an extremely versatile sensor that can quantify nearly any measurand. Due to the sensitivity of the surface acoustic wave to even the slightest perturbations, small effects caused by many different phenomena can be detected. The basic surface acoustic wave device, for which the manufacturing process is described above, can inherently measure temperature, pressure, strain, torque, and mass-loading. If a material exists which undergoes a change in the presence of a physical phenomena, this material can be deposited across the delay line. In this manner, the range of potential applications of surface acoustic wave sensors can be greatly expanded to include sensing of chemical vapors, biological agents, humidity, light (ultraviolet), and electric and magnetic fields, among other phenomena. In all cases, the measurand is quantified by a change in frequency, a time delay, a phase-shift, or an attenuation between the input and output signals. The variations in the output signal are always fundamentally caused by a change in length of the piezoelectric substrate or an increase in mass in the delay line.

A. Inherent Functionality

Before looking at the extended functionality of surface acoustic wave sensors as allowed by the deposition of thin films across the delay line, we will explore the intrinsic mechanisms with which these sensors quantify a measurand. In doing so, we will understand how to exploit these mechanisms for the design of additional sensors.

1) Pressure, Strain, Torque, Temperature: Pressure, strain, torque, and temperature can all be sensed via the same principle—a change in length along the surface of the piezoelectric substrate. The change in length will affect the spacing between the interdigitated electrodes, altering the pitch. As the pitch determines the synchronous frequency according to Equation 8, the output signal will show a frequency-shift. The change in length will also change the length of the delay line, increasing the time delay between input and output. This can be measured as either a time-delay or a phase-shift, depending on the mode of operation. Since the input signal frequency will not change, but the synchronous frequency of the device will change, the amplitude of the output wave will decrease. As such, signal attenuation could be measured as well. However, this would not provide information as to the direction of the change.

When pressure acts on a diaphragm between a reference cavity and the environment, the diaphragm will bend. As the diaphragm bends, the distance along the surface in tension will increase while the distance along the surface in compression will increase. A surface acoustic wave pressure sensor simply replaces the diaphragm with a piezoelectric substrate patterned with interdigitated electrodes. Strain and torque work in a similar manner, as application to the sensor will cause a deformation of the piezoelectric substrate. [15] A surface acoustic wave temperature sensor can be fashioned from a piezoelectric substrate with a relatively high coefficient of thermal expansion in the direction of the length of the device.

2) Mass: The accumulation of mass on the surface of an acoustic wave sensor will affect the surface acoustic wave as it travels across the delay line. As the velocity of a wave traveling through a solid is proportional to $\sqrt{\frac{E}{\rho}}$ where E is Young's modulus and ρ is the density of the material, the wave velocity will decrease with added mass. [13] This change can be measured by a change in time-delay or phase-shift between input and output signals. Signal attenuation could be measured as well, as the coupling with the additional surface mass will reduce the wave energy. In the case of mass-sensing, as the change in the signal will always be due to an increase in mass from a reference signal of zero additional mass, signal attenuation can be effectively used.

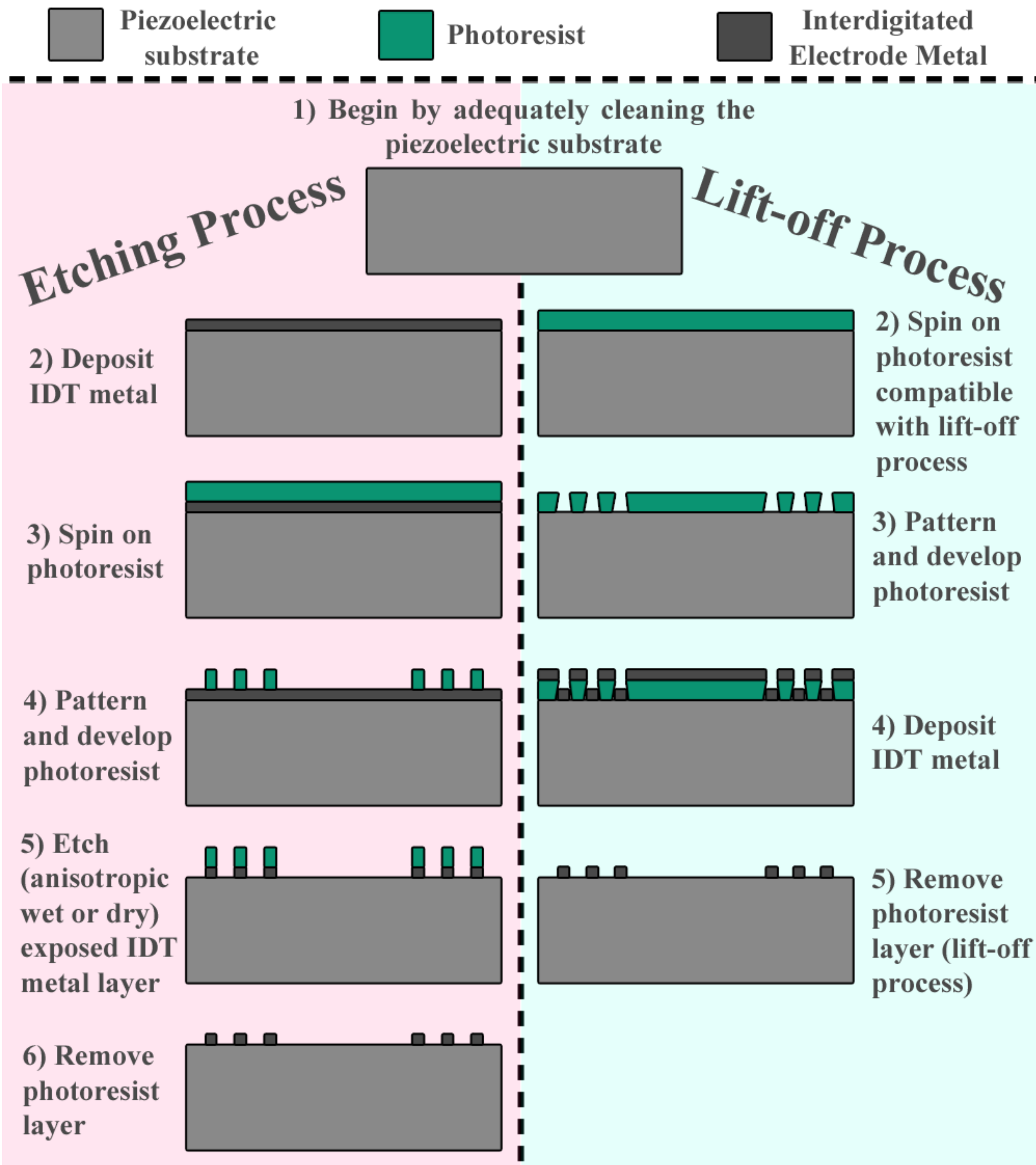

Fig. 7: Process diagram for the production of a surface acoustic wave sensor: (*left*) etching process, (*right*) lift-off process.

B. *Additional Functionality*

Before looking at the extended functionality of surface acoustic wave sensors due to the deposition of thin films across the delay line, we must explore the intrinsic mechanisms with which these sensors quantify a measurand. In doing so, we will understand how to exploit these mechanisms for the production of additional sensors.

From the mechanisms discussed in Section V-A, we can see that a measurand which induces a change in dimension or mass in a surface acoustic wave device can be measured. Though the basic SAW device, which contains a piezoelectric substrate and two IDTs, can sense several phenomena, we are not limited by the change in properties of the piezoelectric substrate in the types of phenomena which can be quantified. By applying a thin film across the delay line which experiences a change in dimension or mass in response to a measurand, we can quantify said measurand using a surface acoustic wave device. This possibility for additional functionality increases the possible design space for surface acoustic wave sensors. Here we shall discuss additional measurands which can be quantified, and the mechanisms through which this is achieved.

1) Chemical Vapors: Chemical vapor sensors use the application of a thin film polymer across the delay line which selectively absorbs the gas(es) of interest. An array of such sensors with different polymeric coatings can be used to sense a large range of gases on a single sensor with a resolution down to parts per trillion, allowing for the creation of a sensitive "lab on a chip." [16]

2) Biological Matter: A biologically-active layer can be placed between the interdigitated electrodes which contains immobilized antibodies. If the corresponding antigen is present in a sample, the antigen will bind to the antibodies, causing a mass-loading on the device. [17] These sensors can be used to detect bacteria and viruses in samples, as well as to quantify the presence of certain mRNA and proteins. (For more information, refer to section V-D1.)

3) Humidity: Surface acoustic wave humidity sensors require a thermoelectric cooler in addition to a surface acoustic wave device. The thermoelectric cooler is placed below the surface acoustic wave device. Both are housed in a cavity with an inlet and outlet for gases. By cooling the device, water vapor will tend to condense on the surface of the device, causing a mass-loading. [18]

4) Ultraviolet Radiation: Surface acoustic wave devices can be made sensitive to optical wavelengths through the phenomena known as acoustic charge transport (ACT), which involves the interaction between a surface acoustic wave and photogenerated charge carriers from a photoconducting layer. Ultraviolet radiation sensors employ the use of a thin film layer of zinc oxide across the delay line. When exposed to ultraviolet radiation, zinc oxide generates charge carriers which interact with the electric fields produced in the piezoelectric substrate by the traveling surface acoustic wave. This interaction decreases the velocity and the amplitude of the signal. [19]

5) Magnetic Fields: Ferromagnetic materials, such as iron, nickel, and cobalt, exhibit a characteristic called magnetostriction, where the Young's modulus of the material is dependent on magnetic field strength. If a constant stress is maintained on such a material, the strain will change with a changing Young's modulus. If such a material is deposited in the delay line of a surface acoustic wave sensor, a change in length of the deposited film will stress the underlying substrate. This stress will result in a strain on the surface of the substrate, affecting the phase velocity, phase-shift, and time-delay of the signal. [8]

C. Comparing SAWS to Other Sensors

Though surface acoustic wave sensors can detect a wide variety of phenomena, there are other, specific sensor options available for each of these phenomena. Here, we shall discuss the relative advantages and disadvantages of surface acoustic wave sensors in comparison to other sensor options.

Surface acoustic wave devices are, in most cases, small, rugged, cost-effective sensors. Though the options for piezoelectric substrate with higher electromechanical coupling factors are generally higher in cost, the incredible sensitivity they offer is very attractive. Due to the fact that a SAW sensor utilizes a mechanical wave to sense the measurand, it is uniquely insensitive to electrical interference by magnetic fields. SAW sensors are also able to operate in a very wide temperature range, though problems with temperature drift depending on substrate choice may require additional sensors and/or circuitry for temperature correction. All SAW sensors can be operated wirelessly by coupling the input IDT to an RF antenna and replacing the output IDT with a reflector. For systems which require no other components than the SAW sensor, the measurements can be taken completely passively. Unfortunately, SAW sensors generally require more signal processing than most devices. Waveforms must be compared for either frequency shifts, phase-shifts, time-delays, or attenuation. However, because of the possibility of wireless sensing, a distributed network of sensors can be measured and analyzed by one centralized data acquisition and processing system.

D. Novel Applications

All scientific and engineering endeavors should exist within a societal context. Though the capabilities of the surface acoustic wave sensor to detect a wide range of phenomena are exciting, such capabilities are worthless if there is no practical use of the sensor. Fortunately, the characteristics of the surface acoustic wave device and its adaptability to many different sensing environments make it an ideal candidate for many novel applications. Here we shall discuss two such applications: the advancement of personalized health care technology and the integration into an intelligent transportation system.

1) Personalized Health Care: Until very recently, the health care industry treated all patients as though they were the same. For a given condition, it was assumed that there existed one ideal treatment for all individuals. Unfortunately, since the genetic and proteomic profile of an individual determines the effectiveness of a specific treatment, this assumption left many patients without proper treatment. However, there has been a recent push for a more personalized health care system which considers genetic and proteomic information in the selection of a treatment. Biological sensors are paramount in gathering the genetic and proteomic information necessary for personalized health care. Surface acoustic wave sensors offer a highly sensitive, cost-effective, and portable solution to this need.

One of the most fundamental ideas of molecular biology is the conversion of genetic code (DNA) to mRNA to proteins. While DNA defines the possible phenotypical states of an organism, it is the products of gene expression—mRNA and proteins—which define the current state of an organism. By studying the DNA of an individual, we can determine the effectiveness of a treatment or risk factors for various conditions. By studying the mRNA and protein expression profiles of an individual, we compare the expression levels of biomarkers—indicators of a disease condition—to the expression level of a neutral case. These same biomarkers can also often be targeted to treat a condition. [20] Here we shall discuss the possibility of the usage of surface acoustic wave sensors in gene expression measurements—the quantification of mRNA and proteins.

Traditionally, mRNA and proteins are quantified through a process known as Western blotting. In Western blotting, a complex protein mixture is first separated by molecular weight through a process known as gel electrophoresis. These separated samples are then transferred to a membrane (usually Nylon). The membrane is then exposed to a primary antibody which will interact with the target analyte. After washing away unbonded primary antibody, the membrane is exposed to a secondary antibody with a linked fluorescent protein which bonds to the primary antibody. The fluorescence of the sample can then be measured (when exposed to the correct light wavelength) and used to quantify the target analyte. This process is relatively time-consuming, low-throughput, and expensive, and relies heavily on the specificity of the antibody. [21]

A surface acoustic wave sensor can be designed to quantify mRNA and proteins of interest by depositing a system of protein cross-linkers and antibodies on the delay-line of a device. If the delay line is exposed to a sample containing non-specific targets and specific targets (antigens of interest corresponding the antibodies on the device), the specific targets will bind to the biologically active layer on the surface of the device, causing a mass-loading. [17] Unfortunately, if the specificity of the antibody is not high enough, some non-specific targets will bind to the biologically active layer as well, causing a measurement error. There is, however, a way to remove this error. The bond energy of specific targets to the substrate will be greater than the bond energy of non-specific targets. In a so-called bond-rupture system, the substrate is shaken at a low frequency at an amplitude such that the non-specific bonds will break, while the specific bonds will not. This bond-rupture system also allows the specific bonds to be removed at higher amplitudes, allowing the sensor to be re-used. [22]

Surface acoustic wave sensors designed to detect biomarkers could be deployed in the hands of health care practitioners, moving this analytical capability from the lab for the first time. These sensors would perform the same analysis as traditional Western blotting faster, with higher precision, and for less cost. The sensors can also be re-used, eliminating the need for new, expensive antibodies after each test.

2) Intelligent Transportation Systems: In the technological era, information is king. Information is used in many different contexts to optimize systems. Advertisers want to know the search and behavioral patterns of customers; sellers dynamically track inventory to prevent product shortages and determine local market trends; machine-learning algorithms are designed to adapt behavior for continuous improvement based on feedback. These "intelligent" systems use information to determine behavior, rather than operating based on predetermined behaviors. Many systems rely on information from sensors of physical phenomena to optimize system behavior. However, the effectiveness of these systems often relies on the existence of a large number of sensor nodes. The nature of a given sensor determines its scalability. For almost any system, wireless sensing must be used, as physical connections across nontrivial distances are not appropriate. On a large-scale, requirements for maintenance must be almost nonexistent. In most systems, a dependence on batteries makes deployment in a large-scale sensor network impossible. Passive wireless surface acoustic wave sensors are particularly well-suited for this type of application.

One such system, the proposed future Intelligent Transportation System (ITS), requires a large-scale distributed sensor network. The aim of ITS is to "best utilise existing infrastructure and provide sustainable transport solutions." [14] One implementation of ITS is the Weigh-in-Motion (WIM) system, which calculates the gross vehicle weight of transportation vehicles. This information can be used to inform vehicle taxation based on gross vehicle weight, enforcement of maximum vehicle weight for the improvement of public safety, point of delivery weighing of bulk loads, and fleet management for hauliers. However, existing systems are either road-based—providing extremely discretized point data—or vehicle based—requiring expensive sensor systems with long installation times. [14] A surface acoustic wave strain sensor could be attached to the axle of a vehicle, providing a passive, wireless sensor which is easily integrated into large-scale, distributed system. This sensor can also be linked with a GPS and mobile communications unit to transmit data back to the haulier control center. Additional surface acoustic wave sensors could be added to monitor relevant vehicle conditions, such as cargo temperature, which are necessary for quality control or vehicle maintenance. This information can then be used by the haulier to direct future system behavior, and by the government to levy taxes based information specific to individual vehicles.

VI. Conclusion

Surface acoustic wave devices offer a wide range of possible functions in a small, durable package. These sensors can function effectively in environments which many other sensors are incompatible with, such as extreme temperatures and magnetic fields. In cases where additional circuitry is not necessary to operate the SAW sensor, these sensors can even be made to operate completely wirelessly without the need for an internal power source. The only limitation on the applications of a surface acoustic wave device is in the range of materials which experience a change in dimension or mass in the presence of a phenomena. Though these devices do require more signal processing than most sensors, it is not difficult to integrate a SAW sensor with additional circuitry and packaging for a specific product, such as a biomarker detector for personalized health care. In addition, the possibility of wireless operation of many of these sensors simultaneously by a central data processing and acquisition system, such as in an ITS, makes this point much less of a concern in light of the advantages of SAW sensors over other sensor technologies. With the proper knowledge of the relevant design parameters and material selection options and how they impact the manufacturing and operation of the sensor, a surface acoustic wave sensor can be designed to fulfill the sensing needs of many applications. As demand for sensing technologies (and, in particular, distributed, wireless sensing networks) increases, expect to see the usage and range of applications of surface acoustic wave sensors to increase as well.

REFERENCES

[1] "2010 Trend: Sensors & Mobile Phones." *ReadWriteWeb*. Web. 06 Dec. 2010. <http://www.readwriteweb.com/archives/2010_trend_sensors_mobile_phones.php>.

[2] Long, Dale J. "Sensors, An Integral Part of Todays Automobile." *Technology Interface Journal*. New Mexico State University, 1999. Web. 06 Dec. 2010. <http://technologyinterface.nmsu.edu/winter99/manufacturing/long/long.html>.

[3] "Collision Avoidance Sensors Information." *GlobalSpec*. Web. 06 Dec. 2010. <http://www.globalspec.com/learnmore/sensors_transducers_detectors/proximity_presence_sensing/collision_avoidance_sensors>.

[4] Madou, Marc J. "Scaling, Actuators, and Power in Miniaturized Systems." *Fundamentals of Microfabrication: the Science of Miniaturization*. Boca Raton: CRC, 2002. 552-59.

[5] "The Piezoelectric Effect." Web. 5 Dec. 2010. <http://www.aurelienr.com/electronique/piezo/piezo.pdf>.

[6] "Piezoelectric Constants, Piezoelectric Charge, Piezoelectric Voltage, Dielectric Constant and Electromechanical Coupling" *APC International, Ltd. Piezo Ceramic Product Manufacturer and Supplier.* Web. 05 Dec. 2010. <http://www.americanpiezo.com/piezo_theory/piezoelectric_constants.html>.

[7] "Acoustic Wave Technology Sensors" *Sensors Magazine*. Web. 05 Dec. 2010. <http://www.sensorsmag.com/sensors/acoustic-ultrasound/acoustic-wave-technology-sensors-936>.

[8] Chin, Matthew L. "A Fabrication Study of a Surface Acoustic Wave Device for Magnetic Field Detection." Thesis. Oregon State University, 2006. *Scholars Archive at OSU*. Oregon State University, 5 June 2006. Web. 5 Dec. 2010. <http://ir.library.oregonstate.edu/xmlui/bitstream/handle/1957/2336/Matt%20Chin%20Thesis%20Final%20Draft.pdf?sequence=1>.

[9] "What Is Seismology and What Are Seismic Waves?" *Geological Engineering and Sciences*. Michigan Tech. Web. 05 Dec. 2010. <http://www.geo.mtu.edu/UPSeis/waves.html>.

[10] Durdag, Kerem. "Wireless Surface Acoustic Wave Sensors." *Sensors and Transducers* 106.7 (2009). Web. 11 Nov. 2010. <http://www.sensorsportal.com/HTML/DIGEST/july_09/P_454.pdf>.

[11] "Bandwidth (Signal Processing)." Wikipedia, the Free Encyclopedia. Web. 05 Dec. 2010. <http://en.wikipedia.org/wiki/Bandwidth_(signal_processing)>.

[12] Yoshida, H., H. Fujimori, T. Kaneko, S. Abe, and H. Morita. "Attenuation of Surface Acoustic Wave Through Sputtered Multi-Layered Nickel Films." *Journal De Physique* 49 (1988). *HAL*. Centre Pour La Communication Scientifique Directe. Web. 6 Dec. 2010. <http://hal.archives-ouvertes.fr/docs/00/22/90/75/PDF/ajp-jphyscol198849C8819.pdf>.

[13] "Wave Speed in a Solid." *PicoScope PC Oscilloscope and Data Acquisition Products*. Pico Technology. Web. 05 Dec. 2010. <http://www.picotech.com/experiments/speed_in_solid/speed_in_solid.html>.

[14] McCormack, Brian, Dermot Geraght, and Margaret O'Mahony. "Design and Manufacture of Surface Acoustic Wave Sensors for Real-Time Weigh-in-Motion." *Instrumentation and Measurement Technology Conference* (2005). *IEEEXplore*. IEEE. Web. 6 Dec. 2010. <http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1604370&userType=inst>.

[15] "TorqSense Technology." *Sensor Technology*. 2010. Web. 11 Nov. 2010. <http://www.sensors.co.uk/technology/pages/torqsense.html>.

[16] "Surface Acoustic Wave Chemical Vapor Sensor." *United States Naval Research Laboratory*. U.S. Navy. Web. 11 Nov. 2010. <http://www.nrl.navy.mil/accomplishments/materials/vapor-sensor/>.

[17] Wu, Claude. "Fabrication of Surface Acoustic Wave Sensors for Early Cancer Detection." *National Nanotechnology Infrastructure Network*. 2006. Web. 11 Nov. 2010. <http://www.nnin.org/doc/NNINreu06Wu.pdf>.

[18] Tennerman, James. "Surface Acoustic Waves to the Mission Control." *InTech*. ISA, Oct. 2001. Web. 06 Dec. 2010. <http://www.isa.org/InTechTemplate.cfm?Section=article_index1&template=/ContentManagement/ContentDisplay.cfm&ContentID=9466>.

[19] Kumar, Sanjeev, Gil-Ho Kim, K. Sreenivas, and R. P. Tandon. "ZnO Based Surface Acoustic Wave Ultraviolet Photo Sensor." *Journal of Electroceramics* 22.1-3 (2009): 198-202.

[20] Kirschner, Jared. "Improving Inferno Data Analysis Software for Proteomics" *Translational Genomics Research Institute*. 31 July 2010.

[21] "Western Blot." *Molecular Biology Protocols*. Web. 05 Dec. 2010. <http://www.molecularstation.com/protein/western-blot/>.

[22] Hirst, Evan R., Yong J. Yuan, W. L. Xu, and J. E. Bronlund. "Bond-Rupture Immunosensors—A Review." *Biosensors and Bioelectronics* 23 (2008): 1759-768.