Surface acoustic wave (SAW) sensors

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Basic operation

An acoustic wave sensor uses mechanical (acoustic) waves to sense multiple phenomena from the device's environment, which are registered as changes in the wave's phase, amplitude, and/or frequency relative to some reference. For surface acoustic wave (SAW) sensors, the device operation itself is fairly simple:

1. An electromagnetic impulse signal is sent to the device via wired connection or wireless antenna
2. The electromagnetic signal is transduced into a surface acoustic wave by an interdigital transducer (IDT)
3. The surface acoustic wave propagates along the surface of the substrate
4. The acoustic impulse response wave is transduced back into an electromagnetic signal
5. The electromagnetic response signal is transmitted for processing
The electromagnetic response is then analyzed to compare its frequency, phase, and amplitude to some reference. Based on this comparison, certain properties of the device's environment may be deduced, such as temperature, strain, pressure, force, and mass.

**Basic device components**

The basic components of a SAW sensor are:

1. A **piezoelectric substrate** which generates electrical charges from mechanical force, and vice versa
2. At least one **interdigital transducer (IDT)** to convert electromagnetic waves to acoustic waves, and vice versa
3. An **area of propagation**, in some cases conceived as a delay line (see below), through which the acoustic wave propagates

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**Figure 1: Overview of surface acoustic wave sensor operation. Graphics edited from source**[^7].

[^7]: Source reference.
SAW sensors may also include an additional filtering or packaging element to sense many types of phenomena indirectly. The sensor in this case is not directly sensing the phenomenon, but instead sensing the response of the filtering or packaging element to its presence.

The piezoelectric effect

The IDTs and propagation area of a SAW sensor is built on a piezoelectric substrate, which uses the piezoelectric effect to respond to mechanical forces by generating a voltage, and vice versa. This voltage is proportional to the amount of force applied to the device as well as the type of force applied (i.e. tension and compression produce opposite polarities). Furthermore, this effect is reciprocal, so the device will also respond to an electric field by generating a mechanical response that is proportional to the field's strength and polarity.

The material of the device's piezoelectric substrate determines the velocity of the acoustic wave, which is in the range of 1500-4800 m/s. This is $10^5$ times slower than the electromagnetic wave velocity, allowing for a long delay along a relatively short area of propagation.

Interdigital transducers (IDTs)

An interdigital transducer consists of a series of comb-like conductive structures with an interleaving pattern that resembles fingers, or "digits" (see Figure 3). Using the piezoelectric effect, the IDTs convert the electromagnetic current of the impulse signal into acoustic waves and vice versa.

Figure 2: Diagram of a surface acoustic wave sensor using a delay line. Source: http://en.wikipedia.org/wiki/File:Surface_Acoustic_Wave_Sensor_Interdigitated_Transducer_Diagram.png
Figure 3: A generic IDT with pitch \( p \) (left); Frequency response of a generic IDT (right). Adapted from source\(^9\).

The acoustic waves propagate in both directions of each "digit," creating constructive and destructive interference among the waves. Where constructive interference (and therefore wave amplitude) is maximized, the wave is said to be at the synchronous frequency, or \( f_S \) (also termed the characteristic frequency). The period length, or pitch, between an IDT’s fingers affects this frequency respective to the velocity of the waves along the propagation area. This relationship is expressed as:

\[
A(f) = \frac{1}{2p} \cos \left( \frac{2\pi f S}{V} \right)
\]

This relationship shows that changes in either an IDT’s pitch or in the velocity of the SAW can be identified by determining the synchronous frequency of the device and comparing it to some reference.

Device configurations

Typically, SAW devices use either a one-port resonator or a two-port delay line configuration. The two-port delay line configuration (pictured above) consists of one input IDT, one output IDT, and an area of propagation in between called the delay line.
The one-port resonator configuration includes only one IDT element for transducing both impulse and response signals. In these devices, the area of propagation leads to a reflector element, which reflects the acoustic wave back into the same IDT that produced it. The slow propagation speed of the mechanical wave (mentioned above) allows sufficient time for the electromagnetic impulse to be completely transduced (or dissipated) before the reflected acoustic response is captured by the single IDT.

**Acoustic wave types**

SAW sensors are only a subset of acoustic wave sensor devices. Acoustic wave sensors are generally classified based on the propagation mode of the acoustic wave employed, firstly ordered as either a surface acoustic wave or a bulk acoustic wave device.

In bulk acoustic wave (BAW) sensors, the acoustic wave travels through the interior, or "bulk", of the piezoelectric substrate. Some sub-classifications are: thickness shear mode (TSM) resonators; shear-horizontal acoustic plate mode (SH-APM) sensors.

In surface acoustic wave (SAW) sensors, the acoustic wave travels on the surface of the substrate. Some sub-classifications are: Rayleigh surface wave sensors (generally known as SAW sensors); shear-horizontal surface acoustic wave (SH-SAW) sensors, also known as surface transverse wave (STW) sensors.

SAW devices are typically more sensitive to velocity and amplitude changes due to the propagation of the wave on the surface of the delay line, where it can be affected more easily by the external environment. This results in higher sensitivity to environmental stimuli such as humidity, radiation, and viscosity.

*Figure 4: Propagation of a Rayleigh SAW with shear vertical component. Source: http://www.tjhsst.edu/~jlafever/wanimate/Wave_Properties2.html*
Rayleigh surface acoustic waves include a vertical shear component which further increases sensitivity to the device’s external environment. However, this vertical shear component also undergoes severe damping when placed in a liquid medium, rendering Rayleigh SAW devices best suited for only gas and vacuum environments.

SH-SAW sensors employing acoustic waves without a shear vertical component (e.g. surface transverse waves) are better suited for operation in liquid environments since their shear horizontal components do not lose much energy into liquids external to the device.

**Sensor characteristics**

**Transfer functions**

Due to the application-specific nature of IDTs, substrate materials, device configurations, and other considerations, transfer functions for SAW sensors are also often application-specific and based on experimental data.

However, transfer functions for the two-port delay line configuration may be generalized. One such transfer function used for rapid simulation tools is as follows

\[
f(f, k, \lambda, CS, NP, X) = \frac{H_1(f)H_2(f)}{1 - H_1(f)H_2(f)}
\]

where \(f\) is the frequency, \(k\) is the piezoelectric coupling coefficient, \(\lambda\) is the delay between IDTs in wavelengths, \(CS\) is the capacitance for an IDT digit pair per unit length, \(NP\) is the number of IDT digit pairs, and \(X\) is defined as:

\[
X = \frac{\lambda}{CSNP}
\]

A more simplified transfer function for a two-port delay line can be written as:

\[
f(f, H_1, H_2, \tau) = \frac{H_1(f)H_2(f)}{1 - H_1(f)H_2(f)}
\]

where \(H_1\) and \(H_2\) are individual IDT transfer functions, and \(\tau\) is the delay of the electric signal due to the delay line.
While the magnitude of the delay line transfer function depends on the characteristics of the individual IDTs, the phase of the response is only dependent on the delay and signal and synchronous frequencies:

Some sample frequency responses of various SAW sensors are given in the figures below:

Figure 6: This SAW Hg sensor responds to Mercury concentrations with varying frequency response slopes. Plotting the initial frequency slopes results in a fairly linear response that can be used to accurately determine Mercury concentration.$^1$
Figure 7: This SAW NO sensor responds to Nitric Oxide concentrations with varying frequency response magnitudes. As with the example above, the sensor's response can be approximated linearly to an extent.

Sensitivity

SAW sensor sensitivities are also dependent on their wavetype, configuration, components, materials, and applications. Some typical sensitivities are listed below:

<table>
<thead>
<tr>
<th>Physical quantity</th>
<th>Linear coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>up to 100 ppm*/K</td>
</tr>
<tr>
<td>Pressure, stress</td>
<td>2 ppm/kPa</td>
</tr>
<tr>
<td>Force</td>
<td>10 ppm/kN</td>
</tr>
<tr>
<td>Mass loading</td>
<td>30 ppm/g-cm²</td>
</tr>
<tr>
<td>Voltage</td>
<td>1 ppm/V</td>
</tr>
<tr>
<td>Electric field</td>
<td>30 ppm/V·m⁻¹</td>
</tr>
</tbody>
</table>
SAW sensors are often valued for their high degree of sensitivity due to the concentration of energy at the device’s surface, where the external environment can have a greater effect. However, this is oftentimes a design challenge. For example, whereas surface acoustic waves with shear vertical components are very sensitive to changes in gaseous environments, they can undergo severe damping in liquid environments. Furthermore, in environments with large temperature fluctuations, a SAW sensor’s piezoelectric substrate can be affected by these fluctuations, often necessitating an additional “reference” configuration to control for such effects.

**Interface electronic circuits**

**Excitation**

SAW sensors are fundamentally passive, in that they need no additional energy other than an excitation impulse to operate. However, the sensor’s response must be processed to evaluate synchronous frequency, amplitude, and/or phase shift before any useful data is recovered from the sensor system.

**Signal conditioning**

Input impedance varies depending on the sensor package, but is typically ~50 ohms for easy impedance matching with test equipment.

As SAW devices often use a low-power signal for excitation input, and response signal power is derived from the input signal, response signals typically require amplification for processing. However, wireless signal transmission from the SAW is possible without amplification up to short distances.

Highly sensitive SAW sensor systems may need to quantitatively determine very small signal changes. High-precision methods for phase detection and frequency response analysis are often needed for such applications, requiring digital signal processing techniques like the fast Fourier transform, zero-crossing, and sine-wave fitting.

**Noise**

Noise can distort SAW outputs due to many unwanted second-order effects, including:

1. Electromagnetic feedthrough between IDTs, causing amplitude and phase ripple
2. “Triple-transit interference” associated with SAW reflections, causing ripple effects
3. Mass-loading by IDT digits, causing SAW velocity changes
4. Unwanted bulk wave emissions accompanying SAW emissions, causing passband distortion
5. Finite source and load impedances, causing frequency-dependent voltages across IDTs
6. IDT diffraction similar to optical systems, causing changes in transition band and shape

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*Figure 8: Linear coefficients for physical effects on SAW sensors*. \(^6\) *ppm = parts per million.*

**For example, when measuring pressure, a change in SAW frequency of \(2 \times 10^{-6}\) corresponds to a change in pressure of 1 kPa.**
7. Harmonic frequencies generated by the input IDT (may be desirable or undesirable, depending on application)

Manufacturing materials and processes

Piezoelectric substrate materials

Piezoelectric substrates are anisotropic (i.e. directionally dependent) crystalline structures, where each individual crystal inside of a substrate has its own polarity. In a polycrystalline material the different polarities of the individual crystallites may cancel each other out, but by applying a ferroelectric polarization process (heating the material while exposing it to a strong electric field), the material's individual polarities can be aligned, and the material as a whole will exhibit the piezoelectric effect just as its individual crystallites do.

While all SAW sensors require a piezoelectric crystalline material, the exact choice of material is dependent on the sensor's application. If the device is meant to measure temperature, a material with a high temperature coefficient is desirable to increase sensitivity to temperature changes. In virtually all other applications, a material with a low temperature coefficient is desirable to minimize unwanted effects due to temperature changes. As Figure 9 below shows, a substrate's temperature coefficient is dependent not only on the material used, but also the material's crystal orientation, or cut. A substrate's coupling factor, which measures efficiency of energy transduction between mechanical and electromagnetic forms, is also dependent both on cut and material.

<table>
<thead>
<tr>
<th>Substrate material</th>
<th>Crystal cut</th>
<th>Linear TK*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lithiumniobate LiNbO₃</td>
<td>rotated 128 Y/X cut Y/Z standard cut</td>
<td>72 ppm**/K 92 ppm/K</td>
</tr>
<tr>
<td>Lithiumtantalate LiTaO₃</td>
<td>X/112Y 36 Y/X rotated cut</td>
<td>18 ppm/K 30 ppm/K</td>
</tr>
<tr>
<td>Quartz (SiO₂)</td>
<td>ST-X cut</td>
<td>0 ppm/K</td>
</tr>
</tbody>
</table>

*Figure 9: Temperature coefficients at room temperature for SAW piezoelectric substrate materials. **TK = temperature coefficient. **See note on figure 8 above for explanation of ppm.

Intedigital transducer materials

The choice of metal used for IDTs also tends to be application-specific, although generally a low resistance is desirable as this typically makes the transduction process more efficient. The strength of the metal's adhesion to its substrate, and the boiling point of the metal (which determines the types of depositing processes available) are also important factors, as is cost. Figure 10 below compares these properties of common IDT materials:
<table>
<thead>
<tr>
<th>Metal</th>
<th>Substrate adherence</th>
<th>Electrical resistivity (-cm)</th>
<th>Boiling point (K)</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>Good</td>
<td>1.7</td>
<td>3200</td>
<td>Low</td>
</tr>
<tr>
<td>Aluminium</td>
<td>Good</td>
<td>2.65</td>
<td>2792</td>
<td>Low</td>
</tr>
<tr>
<td>Gold</td>
<td>Poor</td>
<td>2.2</td>
<td>3129</td>
<td>High</td>
</tr>
<tr>
<td>Tungsten</td>
<td>Average</td>
<td>5.0</td>
<td>5828</td>
<td>Mid</td>
</tr>
<tr>
<td>Titanium</td>
<td>Good</td>
<td>50</td>
<td>3560</td>
<td>Mid</td>
</tr>
</tbody>
</table>

*Figure 10: Properties of common IDT materials*

**Manufacturing process**

Manufacturing a simple SAW sensor with a two-port delay line configuration requires little more than the application of the interdigital transducers onto the piezoelectric substrate. Two alternative processes for this application are shown in Figure 11 below. A photoresist mask is used to aid in both processes. Additional processing may be required, depending on the sensor's application and configuration.
Figure 11: Process diagram for etching and lift-off processes for manufacturing a SAW sensor\textsuperscript{3}
Applications

Acoustic wave sensors are very versatile in that they may be used alone or as part of a filtered sensor to measure many phenomena, including:

- mass
- temperature
- pressure
- stress, strain, and torque
- acceleration
- friction
- humidity and dewpoint
- UV radiation
- magnetic fields
- viscosity

Acoustic wave devices have been in commercial use for over 70 years, and their most common use is in the telecommunications industry as filters for signal processing applications. Recently, however, interest in acoustic wave devices for sensing applications has risen greatly due to their low cost, reliability, sensitivity, flexibility to measure many phenomena, and mature technology.

References and further reading


