

## Comparison of layered based SAW sensors<sup>☆</sup>

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### Abstract

A comprehensive investigation of layered surface acoustic wave (SAW) devices is presented. These types of SAW devices have a remarkable performance for gas and liquid sensing applications as confinement of energy in the layers generally increases their sensitivity. Different modes of wave propagations and the effect of the guiding layer thickness and material on the layered devices are discussed in this paper.

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### 1. Introduction

Surface acoustic wave (SAW) devices were first introduced by White and Voltmer [1] at the University of California, Berkeley. They showed that, by patterning interdigital transducers on piezoelectric substrates, mechanical waves could be generated and received. The electronics industry quickly appreciated such an idea and applied such devices for the design and fabrication of analogue devices operating at selected frequencies [2]. By 1985, only 20 years after the introduction of Rayleigh SAW devices, Hartmann [3] listed nine major consumer applications, nine major commercial applications and 18 major military applications of the technology. In recent years, with the discovery of other types of SAWs, fabrication of SAW devices paced up. These include leaky SAWs, surface skimming bulk waves (SSBW) and surface transverse wave (STW).

Recently, there has been a growing attention toward developing SAW devices for sensing various physical and chemical quantities [4]. The interactions between the propagating SAWs and properties of the contact liquid or gas perturb the acousto-electric field. By measuring the magnitude of these perturbations, it is possible to measure the strength of the interactions. SAW devices fabricated on different crystal cuts allow propagation of various SAW waves such as Rayleigh waves (or so-called “true” SAWs [2])

and pseudo-SAWs (i.e. leaky SAW, SSBW and Surface Transverse Wave [2]). The crystal orientation axis is used to designate the piezoelectric crystal cut selected for SAW or pseudo-SAW propagation. By depositing layers onto the substrates, these waves can be transformed. If the propagation velocity of the waves in the deposited layer or the crystal structure of the layer is different from that of the substrate, the waves in the substrates transform and generally become near surface-confined waves.

Attractive features can be obtained by the deposition of thin films onto substrate crystals. Deposition of thin layers onto piezoelectric substrates changes the parameters of the acoustic wave propagation. Furthermore, deposition of piezoelectric films onto non-piezoelectric substrates allows generation of acoustic waves by an electrical signal. It is notable that the first commercial SAW filter was fabricated by the deposition of a ZnO layer onto a SiO<sub>2</sub>/Si substrate in the early 1980s. Some common thin film piezoelectric materials are: ZnO, AlN, PZT and PLZT [5].

In this paper, a brief description of different SAWs and their transformation to confined waves in layers will be presented. Layered SAW sensors will be introduced and their frequency stability will be discussed. Finally, the measurement with different layered SAW devices will be presented.

### 2. Rayleigh wave

The first SAWs were introduced by Lord Rayleigh in 1885, to describe the motion of seismic waves within the

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Table 1  
SAW crystal cuts that allow propagation of Rayleigh waves

Crystal	Velocity (m/s)	Coupling coefficient (%)	Temperature TCF (ppm/°C)	Capacitance per unit length of finger pairs (pF/cm)
ST-cut quartz	3158	0.11	0	0.5
YZ LiNbO <sub>3</sub>	3488	4.5	94	4.5
128° YX LiTaO <sub>3</sub>	3992	5.3	75	5.0
77° YZ LiTaO <sub>3</sub>	3254	0.72	35	4.5

Earth's crust. A Rayleigh SAW has two mechanical displacement components in the sagittal plane. (The plane containing the direction of propagation and the surface normal.) Stress free boundary condition is a necessary but not sufficient condition for the surface character of the wave. The existence of Rayleigh wave can be proven by Lothe–Barnett [6] theory but only for a non-piezoelectric material. The most common piezoelectric substrates that allow that propagation of Rayleigh waves are listed in Table 1 [2]. The highest value of electromechanical coupling coefficient ( $K^2$ ) belongs to LiNbO<sub>3</sub> which generally finds application in wideband SAW filters. 128° YX LiTaO<sub>3</sub> is a cut with reduced bulk wave generation. The coupling coefficient of ST-cut quartz is small, but it is an ideal crystal for the fabrication of stable oscillators and sensors, due to its low temperature coefficient of frequency (TCF) and its narrow band nature. The stability of SAW oscillators using ST-cut quartz is often sufficient for use without external temperature compensation. LiTaO<sub>3</sub> has also found some applications in oscillator and sensor design. The relative newcomer to the SAW piezoelectric field is langasite (La<sub>3</sub>Ga<sub>5</sub>SiO<sub>14</sub>). It has a remarkably small TCF and a higher coupling coefficient than ST-cut quartz. Once it becomes commercially available, langasite may be an excellent choice for SAW sensor fabrication.

### 3. Pseudo-SAWs

In anisotropic crystals there are possible waves having bulk characters, satisfying stress free boundary conditions on the free surface and having both longitudinal and transverse components of mechanical displacements. In certain cases, these waves propagate near the surface, including skimming waves and various types of leaky waves. Sometimes these bulk waves are also called pseudo-SAW as they satisfy boundary stress free condition on the surface even though they are not true surface waves.

If a perturbation on the surface slows down the propagating bulk waves, then the wavefront will be distorted and will be attracted towards the surface. If, on the other hand, a perturbation on the surface has a higher wave velocity, then the wavefront will be distorted in such a way that it turns away from the surface and is said to become rejected [7].

A classical example of an attracting or rejecting surface is a deposited thin layer. In such a case, there are some difficulties determining whether the waves have mostly shear horizontal (SH) components or longitudinal components on the surface. In the presence of a thin film layer, the boundary conditions differ from the free surface case, which is normally assumed in the derivation of wave propagation modes. Such an effect increases the need for a longitudinal displacement component. A result is the availability of three different waves in some crystal cuts with thin deposited thin film layers.

Other type of pseudo-SAWs are generated due to the internal properties of a piezoelectric crystal, when the material near the surface is not so stiffened by the piezoelectricity [7]. The wavefront turns toward the surface and acquire a different surface character. These waves are generally called Bleustein–Galyev (BG) waves. A class of other pseudo-SAWs that propagates along the surfaces of the piezoelectric have a similar specification to BG waves. In 36° LiTaO<sub>3</sub> and 41° LiNbO<sub>3</sub> the leaky waves have predominantly shear displacement and their velocity is slightly lower than fast bulk waves.

### 4. Leaky SAW

There are two possible modes of leaky SAW propagation which can be obtained in certain crystal cuts [2]. The first leaky wave has phase velocity between those of the slow and fast bulk waves. Depending on the choice of piezoelectric crystal and cut, the velocity is greater than that of its Rayleigh wave counterpart is by a factor of 1.3–1.4. The crystal cuts that allow the propagation of leaky waves are shown in Table 2 [2].

Leaky SAW posses a number of attractive features for SAW sensor fabrications:

1. The leaky SAW crystals can have much higher electromechanical coupling coefficient.
2. The leaky SAW crystals have a better temperature stability.
3. Higher power can be applied before the onset of piezoelectric non-linearities.

The main disadvantage is that the propagation is beneath the piezoelectric surface. As a result, they are less sensitive

Table 2  
SAW crystal cuts that allow propagation of leaky SAWs

Crystal	Velocity (m/s)	Coupling coefficient (%)	Temperature TCF (ppm/°C)	Capacitance per unit length of finger pairs (pF/cm)
LST quartz	3948	0.11	0	0.5
64° YX LiNbO <sub>3</sub>	4478	11.3	−81	4.5
41° YX LiNbO <sub>3</sub>	4379	17.2	−80	5.0
36° YX LiTaO <sub>3</sub>	4112	4.7	−32	4.5

to surface perturbations. Depending on the choice of crystal cuts the other wave propagation involves the so-called second leaky wave with phase velocity approximately two times larger than that of the Rayleigh modes [2]. The greatest difficulty in using such modes is the simultaneous presence of other propagation modes.

## 5. Shallow bulk acoustic waves (SBAW)

SBAW propagation involves longitudinal bulk waves with SH polarization [2]. These waves are mostly generated by the parallel electric field whereas Rayleigh waves are generated by the electric field component normal and parallel to the excited fingers.

As the propagation velocity of SBAWs and leaky SAWs are generally very close, most of time they are indistinguishable. The advantages of such modes are generally similar to those of the leaky SAWs with two major differences:

1. SBAW devices can yield good suppression of spurious modes.
2. They are more sensitive to surface perturbations than that of leaky SAWs.

The SBAWs are categorized into two groups. Where there is no energy trapping the SH bulk waves are usually referred to as SSBWs. When energy trapping grating structure is located between input and output IDTs the term surface transverse wave (STW) is used. The most common SAW crystals are shown in Table 3.

The temperature TCF and capacitance per unit length of finger pairs for such devices must be investigated. Although these two parameters are generally an order of magnitude smaller for 90° rotated ST-cut quartz crystals than those of 36° YX LiTaO<sub>3</sub> and 36° YX LiNbO<sub>3</sub>.

## 6. Layered sensors

As mentioned in Section 1, by depositing a thin film onto the active area of the SAW device, a more surface-confined acoustic wave can be obtained. Such a phenomenon normally increases the sensitivity of the device. As with other SAW devices, it is possible to categorize the layered SAW sensors into two types: Rayleigh SAWs and pseudo-SAWs. Due to the surface normal particle displacement in Rayleigh

SAW propagation, such sensors can only be used for gas sensing application. For liquid sensing applications, pseudo-SAWs devices are generally employed, as these modes suffer less damping in contact with liquid.

Investigation of pseudo-SAW devices for sensing applications intensified in the early 1990s as a result of the work undertaken by Gizeli et al. at Cambridge University [7,8]. The work demonstrated the feasibility of using polymer/90° rotated ST-cut quartz love-wave devices as liquid phase biosensors. Unfortunately, the acoustic propagation loss increases quickly with increasing layer thickness of the polymer layer [8,9]. Kovacs et al. [10,11] introduced the SiO<sub>2</sub>/90° rotated ST-cut quartz structure. Acoustic loss in SiO<sub>2</sub> is smaller compared with that of polymers. Later, Ogilvy [12] and Du et al. [13,14] carried out comprehensive studies on the SiO<sub>2</sub>/90° rotated ST-cut quartz structure. More recently, Kalantar-Zadeh et al. [15] introduced piezoelectric layer pseudo-SAWs devices with much higher sensitivities. Layered SAW devices on 90° rotated ST-cut quartz substrate, which is a cut supporting SSBW, normally show higher sensitivities than that of layered leaky SAW devices. Herrmann et al. [16] investigated and compared an SiO<sub>2</sub>/90° rotated ST-cut quartz structure with SiO<sub>2</sub>/36° YX LiTaO<sub>3</sub> structures. The mass sensitivity of a SiO<sub>2</sub>/36° YX LiTaO<sub>3</sub> device is significantly less than that of the device with an ST-cut quartz substrate. Maximum mass sensitivity is obtained when the layer thickness reaches 0.18 of the wavelength. A mass detection limit of 750 pg/cm<sup>2</sup> is obtained for layered sensors based on SiO<sub>2</sub>/90° rotated ST-cut quartz crystal structures operating at approximately 100 MHz [13,14]. For a similar structure with a ZnO guiding layer a 200 pg/cm<sup>2</sup> mass detection limit is obtained [15]. These figures are over 100 times larger than the typical mass sensitivity of a quartz crystal microbalance operating at 10 MHz. The leaky wave of 36° YX LiTaO<sub>3</sub> shows an almost linear temperature dependence: TCF = -45 ppm/°C for a free surface. However, the layered media devices show different TCF from similar devices without layers. At a film thickness of 0.225 wavelengths, the devices provide temperature compensation.

## 7. Frequency stability

The frequency stability of a SAW sensor is one of its most important performance parameters. After the initial frequency of an oscillator is set, it must remain within the allotted frequency range and exhibit specified spectral characteristics. The frequency changes are either systematic or random effects [2]. Predictable sets of effects on the oscillation frequency are considered as systematic effect, they are effects such as frequency versus temperature change. The random effects are not predictable and only statistical parameters can be used to characterize them.

The temperature characteristics are largely determined by the crystal cut. However, other parameters can also

Table 3  
SAW crystal cuts that allow propagation of SSBWs

Crystal	Velocity (m/s)	Coupling coefficient (%)
90° rotated ST-cut quartz	5050	1.9
35° rotated y cut quartz	5100	1.4
36° YX LiNbO <sub>3</sub>	4800	16
36° YX LiTaO <sub>3</sub>	4200	5

influence the temperature effect. The next most important factor is long-term stability or ageing. A high temperature bake prior to the packaging of the SAW device is very important for long-term stability. Another systematic effect is acceleration or vibration effect. It is strongly dependant on how the SAW device is mounted and packaged [17].

Random-frequency fluctuations, which are more difficult to quantify are generally caused by external mechanical or electrical fields.

Quality factor ( $Q$ ) is an important parameter which governs the frequency stability of a SAW device. Increasing device  $Q$  yields higher stability, although improvements may be achieved by other methods, such as a dual delay line structure [13]. Adding reflectors to turn the delay line into a resonator also increases the  $Q$  of the device [18,19]. Some research has already been undertaken regarding SAW reflecting structures for sensing applications [20,21]. Further work must be carried out to obtain reflection coefficients in layered media.

## 8. Measurements

In order to observe the performance of layered SAW devices a variety of guiding layer and crystal substrate combinations were fabricated and their frequency responses were measured. To make a comparison, the SAW transducer patterns were similar for all measurements. They consisted of 64 finger pairs in the input and output IDTs with the periodicity of 48  $\mu\text{m}$  and 150 reflectors on each side. IDT separation was 10 wavelengths and the aperture width is 2.5 mm. A 2  $\mu\text{m}$  thick  $\text{SiO}_2$  or ZnO film is used as the wave guiding layer.

Fig. 1 shows the frequency response of a device with YX  $\text{LiNbO}_3$  substrate before and after deposition of the  $\text{SiO}_2$

guiding layer and after contact with DI-water. Without any guiding layer, YX  $\text{LiNbO}_3$  substrate allows the propagation of Rayleigh mode, SSBWs and leaky SAWs. The leaky SAW and SSBW propagation velocities are very close. As a result, the frequency response from 80 to 100 MHz is a confused combination of these two modes. Deposition of  $\text{SiO}_2$  causes a shift of 450 kHz in the operational frequency of the device. Contact with DI-water completely damps the Rayleigh wave, as the normal particle displacements radiate energy into the liquid. Liquid contact has a significant effect upon shear waves as well.

Fig. 2 shows the response of a device with a  $90^\circ$  rotated ST-cut quartz crystal substrate with a ZnO guiding layer before and after with DI-water contact. By depositing a ZnO layer the operational frequency decreased 21 MHz from the original value 105 MHz. Contact with DI-water caused a 1.6 MHz frequency shift.

Fig. 3 shows the frequency responses of a  $36^\circ$  YX  $\text{LiTaO}_3$  before and after depositing ZnO layer and a thin Au/Cr layer (20/10 nm). As can be seen, there is a 500 kHz frequency shift and 3.5 MHz frequency shift after the deposition of the ZnO layer and the metal layer, respectively.

For devices with  $90^\circ$  rotated ST-cut quartz and  $36^\circ$  rotated YX  $\text{LiTaO}_3$  the DI-water contact increased the 3 dB bandwidth, which means the  $Q$  has decreased. The  $Q$  value is reduced by a factor of 2–3 relative to its value in air. This results in the device having reduced frequency stability in contact with DI-water, although the reduction in the detection limit is not excessive.

Such structures can conveniently used as liquid phase sensors. Liquid can cover the whole surface and sealing can be placed around the pattern. This increases the frequency stability, as there is no need to place sealing gaskets upon the active area of the device. Furthermore, no significant increase in insertion loss was observed after contact with water.

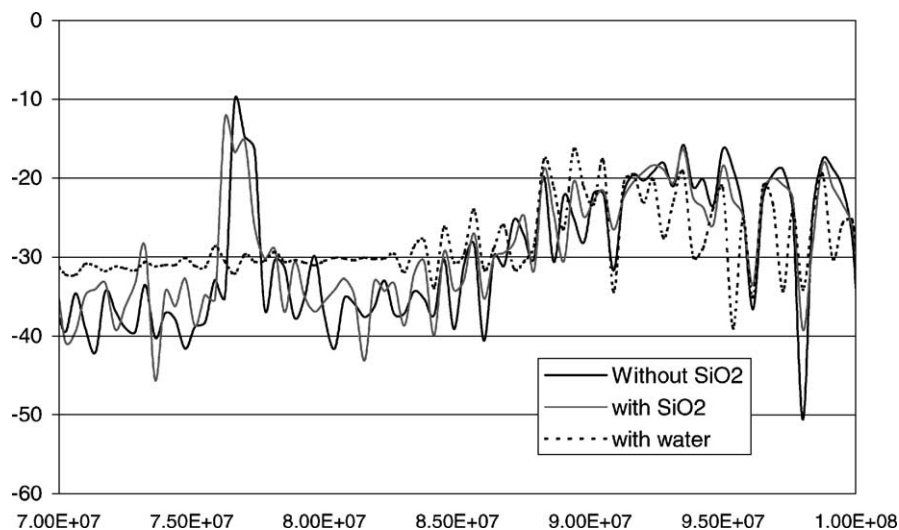


Fig. 1. Frequency response of a YX  $\text{LiNbO}_3$  SAW: the blank SAW, with a  $\text{SiO}_2$  guiding layer and in contact with DI-water.

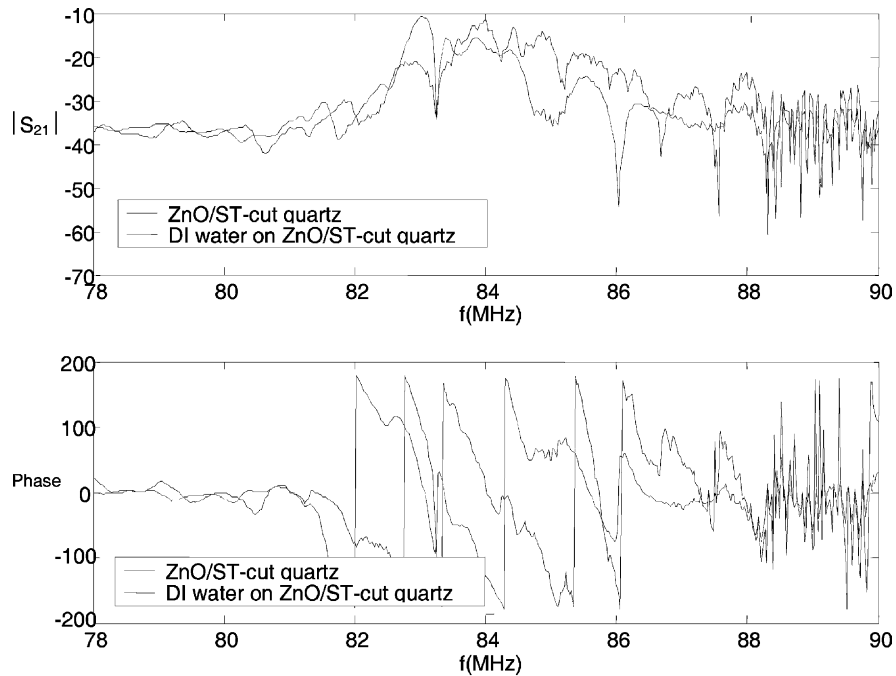


Fig. 2. Frequency response of a ZnO/90° rotated ST-cut quartz crystal in air and in contact with DI-water (magnitude and phase).

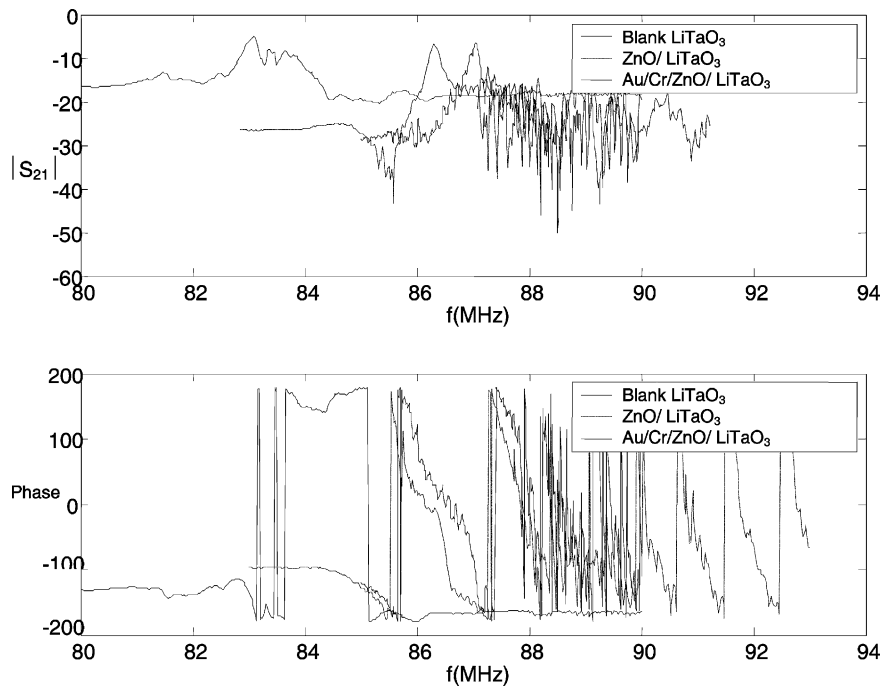


Fig. 3. Frequency response of a ZnO/36° YX LiTaO<sub>3</sub>: blank substrate, with ZnO layer and with a thin film metal layer (magnitude and phase).

## 9. Conclusions

A comprehensive overview regarding the performance of layered SAW devices was presented. Different modes of wave propagation and their layer-confined counterparts were introduced. Frequency stability and noise in such

layered devices were briefly discussed. Finally, frequency measurements for devices based on SiO<sub>2</sub>/YX LiNbO<sub>3</sub>, ZnO/36° rotated YX LiTaO<sub>3</sub> and ZnO/90° rotated ST-cut quartz were presented. It was shown that the insertion loss of these devices does not change significantly in contact with DI-water. The mass sensitivities of such devices are high and

they can operate in liquid media without a significant decrease in their  $Q$  factor.

The authors are currently working to analyse the performance of reflectors in contact with liquid.

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