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Review on MEMS based Acoustic Sensors

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Abstract:With the rapid development of cellular network technology of the fifth generation (5 G), future sensors and microelectromechanical systems (MEMS)/Nanoelectromechanical systems (NEMS) are playing an increasingly critical role in the provision of information in our daily lives. This review paper presents the trends and perspectives of future MEMS Acoustic sensors in development. This paper presents a review of MEMS devices based on acoustic wave which provide a promising technology platform for the development of sensitive, portable, real-time sensors. MEMS manufacture of acoustic wave based sensors allows for miniaturization of devices, reduction of power consumption and integration with electronic circuits. Film bulk acoustic wave resonators (FBAR), surface acoustic wave resonators (SAW) and SAW delay lines are the acoustic wave based MEMS devices reported in the literature and presented in this review. Different approaches to realization of FBARs, SAW resonators, and SAW delay lines are presented for different biochemical applications. Methods for integrating the acoustic wave MEMS devices into microfluidic systems and strategies for functionalization will also be discussed.

Keywords:Acoustic wave, Acoustic sensor, Bio-sensors, MEMS, Resonator

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INTRODUCTION

Acoustic waves based MEMS[1] devices offer a promising technology platform for a wide range of applications because of their high sensitivity and wireless capability. These devices use as their sensing mechanism an acoustic wave that propagates through or on the surface of a piezoelectric material. Any variations to the propagation path characteristics affect the wave's velocity or amplitude.

Torque and tire pressure sensors, gas sensors, biosensors for medical applications, and industrial and commercial applications (vapor, humidity, temperature, and mass sensors) are important applications for acoustic wave devices as sensors. This chapter focuses on two key applications of MEMS-based acoustic wave devices; (1) biosensors, and (2) telecommunications. The advancement of the micro-electromechanical systems (MEMS) has facilitated the development of biosensors and various telecommunications devices.

Miniature, portable, and low-cost biosensors manufactured using MEMS technologies have been developed with increasing interest. The acoustic wave device[2] is integrated in a microfluidic system for biological applications, and the sensing area is coated with a bio-specific layer. When a bio-analyte interacts with this sensing layer, there will be physical, chemical, and/or biochemical changes. Typically, changes in mass and viscosity of the bio-specific layer may be detected by analyzing changes in the acoustic wave properties such as sensor velocity, attenuation, and resonant frequency. Simple electronic readout characterizing these sensors is an important advantage of the acoustic wave biosensors. Using conventional electronics, the measurement of the resonant frequency or time delay can be done with high degree of precision.

Currently, a limitation for biological applications of acoustic wave devices is that they require expensive electronic detection systems, such as network analysers. Small, portable and packaged in a highly integrated cost-effective system must be a final product targeting the end-user market. In future, sample pre-treatment, purification and concentration, as well as a good interface between the user and the integrated sensing system, also needs to be developed for acoustic wave biosensors integrated in a lab-on-chip device.

Acoustic wave devices have historically been widely used in the telecommunications industry, primarily in mobile cell phones and base stations. Surface Acoustic Wave

(SAW)[3] devices are capable of powerful signal processing and have functioned successfully as filters; The last 60 years have been the resonators and duplexers. Though SAW devices are technologically mature and have served the telecommunications industry for several decades, they are typically manufactured on piezoelectric substrates and packaged as discrete components. The SAW device's wide flexibility and capacity to form filters, resonators has been the motivation for integrating such devices on silicon substrates. For the manufacture of a CMOS SAW resonator in 0.6 µm AMIs CMOS technology, standard complementary metal oxide semiconductor (CMOS)[4] technology with additional MEMS post-processing was utilized. The advantage of using standard CMOS technology to manufacture a SAW resonator is that active circuitry can be manufactured on the same electronic chip, adjacent to the CMOS resonator.

Acoustic wave-based telecommunications devices have different requirements as compared to biosensors. The biosensors operate at frequencies within the MHz range where high frequency (GHz) operating acoustic wave devices operating as filters or resonators are expected to operate and have high quality factors and low insertion losses. With advances in lithographic techniques, the acoustic wave-based devices have the advantage of meeting the telecommunications industry's stringent requirement to have Qs in the range of 10,000 and compatibility with silicon.

Also critical to marketing the acoustic wave devices is a simple, robust, cheap packaging method. Integrating the MEMS biosensor based on an acoustic wave into the microfluidic[5] system is a complex matter. The integration technique is influenced by the process of manufacturing the sensors and the type of biological applications. The sensor could be embedded in a microfluidic tank in some applications. In the case where the biological application requires the introduction of different biological solutions on the sensor sensitive area, the biosensor could be embedded in a microfluidic channel. The packaging of the telecommunication acoustic wave devices is less complicated as these devices are embedded in the package and need not be in contact with liquid.

1. Acoustic Wave MEMS Devices as Biosensors:

Miniature, portable, and low-cost biosensors manufactured using MEMS technologies have been developed with increasing interest. MEMS technology was adopted in the Integrated Circuit (IC) industry and applied to the miniaturization of a wide range of systems including devices based on acoustic wave. Recent technological advances in MEMS processes make it possible to manufacture thin piezoelectric films and integrate acoustic wave-based devices and electronics on a common silicon substrate. The MEMS biosensors acoustic wave presented in this chapter could be categorized into two main groups; resonators, and delay lines.

The Acoustic Wave Based MEMS devices are integrated into a microfluidic system for biological applications, and the sensing area is coated with a bio-specific layer. When a bio-analyte interacts with this sensing layer, there will be physical, chemical, and/or biochemical changes. Typically, changes in mass and viscosity of the bio-specific layer may be detected by analyzing changes in the acoustic wave properties such as sensor velocity, attenuation, and resonant frequency. Simple electronic readout characterizing these sensors is an important advantage of the acoustic wave biosensors. Using conventional electronics, the measurement of the resonant frequency or time delay can be done with high degree of precision.

The acoustic wave based delay lines reported as MEMS biosensors in the literature are surface acoustic wave (SAW) delay lines consisting of two sets of interdigitated transducers (IDT)[6] made on the same side of a thin layer of piezoelectric material. One set of IDTs generates the acoustic wave, and the second set of IDTs is used to detect the acoustic wave. In the case of a biosensor, as illustrated in Figure 1 the surface between these two sets of IDTs is covered with a biological layer sensitive to the analyte to detect.

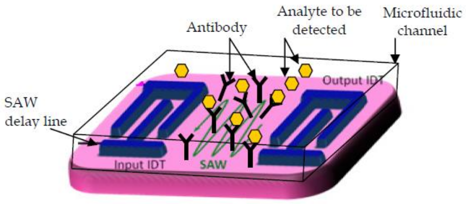

Figure 1: SAW Delay Line Biosensor Integrated in a Microfluidic Channel

The absorption of the analyte on the sensitive layer will result in a time delay in the propagation of the acoustic wave. The main drawback of the acoustic wave-based devices when used as biosensors is the degradation of the performance due to liquid damping. The quality factor Q decreases in liquid (usually more than 90 % decrease) and negatively affects sensitivity of the device. Since most biological applications are performed in liquid, only few types of acoustic wave devices can be integrated into microfluidic channels without significant sensor performance degradation.

1.1 Film Bulk Acoustic Wave Resonators (FBAR):

Due to high frequency resonators, the thin film manufacturing technology has made substantial progress in recent years. The expensive single crystalline substrates used for quartz crystal microbalance (QCM) resonators could be replaced with a wide range of thin piezoelectric films in the case of MEMS-based FBAR resonators. FBAR[7] resonators made of a thin piezoelectric substratum and excitation electrodes are manufactured on both sides of the piezoelectric substrate. Because of the low damping of the acoustic wave in the liquid, the FBAR resonators could be integrated into a microfluidic system and successfully used for bio sensing applications.

Figure 2 illustrates a MEMS FBAR biosensor containing aluminum nitride (AlN) as piezoelectric film. The AlN film is 2µm thick. Al electrodes at the bottom and top were patterned with standard lithography and etching process. The top-and-bottom-electrode overlap defines the active area where the acoustic wave is generated. The AlN thin films were grown with the crystallographic axis inclined at an angle of 30 ° relative to the normal surface, in order to produce a shear acoustic wave FBAR. Due to low loss operation in liquid and small reduction of the quality factor Q, the shear mode is preferred for liquid application instead of longitudinal method. The silicon wafer was etched from the rear side to produce a free standing membrane used to acoustically isolate the resonator from the substratum and define a cavity. This cavity was additionally connected to a microfluidic transport system for the delivery of analytes to the resonator's bottom electrode. The underside electrode is the sensing electrode for this type of FBAR. An Au layer was evaporated thermally onto the Al electrode base to create a biochemically suitable surface for subsequent testing. The sensor was tested in solution with different albumin concentrations, and the detection limit was 0.3 ng/cm^2.

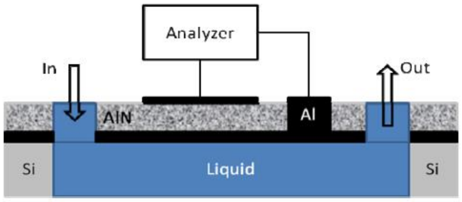

Figure 2: Schematic of a Shear Wave FBAR with a Microfluidic Transport System

1.2 SAW Delay Lines as Biosensors:

Lines of delay of surface acoustic wave (SAW) were also studied for bio-sensing and could be integrated in microfluidic systems.

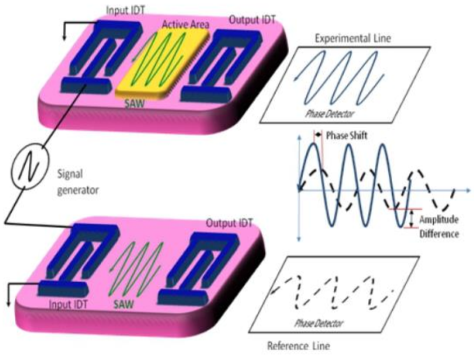

Figure 3: A SAW Delay Line Consists in Input IDT and Output IDT Fabricated on a Piezoelectric Substrate

A SAW delay line consists of two IDTs, which are electrode pairs made by photolithography on the same side of a thin piezoelectric layer. A sinusoidal voltage applied to the input IDTs translates into a mechanical oscillating strain that forms a SAW propagating along the piezoelectric thin film surface.

Two delay lines operate in parallel, with one line acting as a line of reference and the other as an experimental line. A sinusoidal voltage is applied to the IDT input, which develops an alternating electric field which is translated by the piezoelectric effect[8] into a mechanical SAW. The SAW's velocity is affected by the mass charge, the liquid viscosity and the substrate surface temperature. Any velocity difference between the two delay lines will be reflected as a phase shift and a difference in amplitude.

1.3 Guided Surface Acoustic Wave resonators:

One subcategory of SAW, the Love propagation style, is especially promising for chemical and bio-sensing applications due to its high sensitivity to mass loading and the ability to calculate with minimal propagation loss in liquid environments. It is possible to guide the shear horizontal waves by placing a thin guide layer on a SH-SAW sensor.There is a lower sensitivity in the bare SH-

SAW resonator because the acoustic wave[9] goes deeper into the substrate. It is possible to guide the shear horizontal waves by placing a thin guide layer on a SH-SAW sensor. There is a lower sensitivity in the bare SH-SAW resonator because the acoustic wave goes deeper into the substrate. Waves propagating through the guiding layer are called Love waves. As waveguide materials, dielectrics such as silicon dioxide, silicon nitride, and most polymers can be used. Polymers have a lower shear wave speed and are therefore recommended for SAW sensors in Love mode. When the waveguide layer is thin and does not charge or attenuate the traveling acoustic wave, the acoustic efficiency is improved. Figure 4 illustrates a typical SAW Love Mode sensor.

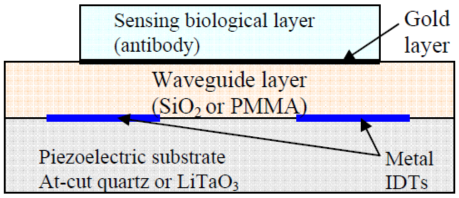

Figure 4: Illustration of a Love mode Surface Acoustic Wave Sensor Formed by a Piezoelectric. Substrate, the Waveguide Layer, IDTs, and the Sensing Layer.

2.Acoustic Wave MEMS Devices used for Telecommunications:

In recent decades, the explosive growth of the telecommunications industry has created a demand for high-quality, compact, and mobile radio frequency (RF) modules. Typically these mobile terminals are composed of RF integrated circuits (RFICs)[10] and a multitude of passive components. Driven by the success of the wireless technology business, and marked progress in manufacturing techniques for submicron semiconductors. In recent years, the acoustic wave technology has advanced to the GHz range. Acoustic wave devices are typically referred to in telecommunications according to their mode of propagation of the acoustic wave; bulk and surface. Bulk acoustic wave devices have propagation of the acoustic waves through the substrate. Surface acoustic wave resonators (SAW) have the acoustic waves propagating along the device's top surface. In this section we will illustrate current activities for both film and surface modes in the acoustic wave resonators.

A typical SAW device (shown in Figure 5) consists of a piezoelectric substratum with metallic thin film structures such as IDTs and reflectors deposited on top of the surface of the substrate. A SAW device's operating principle is based on the piezoelectric effect in which an applied microwave voltage input at the transmitting (input) IDT generates a propagating acoustic wave on the substrate surface. This propagating acoustic wave in turn produces a surface-localized electrical field that can be detected and translated back into an electrical signal at the IDT port output. Unlike SAW delay-lines that operate on the basis of traveling acoustic waves, Using standing waves SAW resonators operate. The presence of reflectors, which contain the acoustic waves within the cavity, creates standing waves, or resonances. The array of metal strips or reflectors minimizes losses by reflecting and containing the acoustic waves inside the cavity, thus reducing the wave losses that propagate outwards.

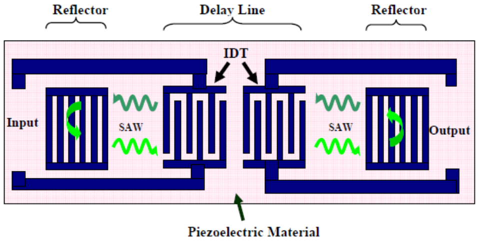

Figure 5: Schematic of a Surface Acoustic Wave Resonator

CONCLUSION

This chapter focuses on two major uses of MEMS devices based on acoustic wave; (1) biosensors and (2) telecommunications. Without significant degradation of the quality factor, only few types of acoustic wave devices could be integrated into microfluidic systems. The MEMS acoustic wave based devices reported as biosensors in the literature are film bulk acoustic wave resonators (FBAR) and SAW resonators and delay lines. SAW devices in the Love mode are often used as biosensors because the acoustic energy is confined to the sensing surface resulting in higher sensitivity to surface disturbance. The experimental results show that biosensors from the Love mode have a high sensitivity to detection.

Acoustic waves provide promising technology platform for the development of biosensors and RF-MEMS filters and resonators of small size and low power. The MEMS acoustic wave biosensors are highly sensitive, small in size and portable, Fast responses, robustness and robustness, high precision, integrated circuit (IC) technology compatibility and excellent aging characteristics. Sensors based on this technology can be produced using standard photolithography, and can therefore be produced as relatively cheap devices. The integration of acoustic elements and electronic circuitry on a single silicone chip enables the realization of smart acoustic micro-sensors with advanced capabilities for signal processing. Biosensors based on acoustic waves offer the possibility to observe binding events of proteins and other important biological molecules in real time at relevant sensitivity levels and at a low cost.

In this chapter they also present acoustic wave MEMS devices used in telecommunications applications. Telecommunications equipment has different requirements over biosensors, Where high frequency (GHz) operating acoustic wave devices are expected to operate as filters or resonators, they have high quality factors and low insertion losses. SAW devices have traditionally been widely used in the telecommunications industry but with advances in lithographic techniques, FBARs are gaining rapid popularity. FBARs have the advantage of meeting the Telecommunications industry's stringent requirement to have Qs in the 10,000 range and compatibility with silicon.

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