2 Overview of Acoustic-Wave Microsensors

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2.1 Introduction

The term acoustic-wave microsensor in its widest meaning can be used to indicate a number of significantly different devices. Their common characteristic is the fact that acoustic waves are involved in the operating principles.

Acoustic-wave microsensors can be grouped into the following three classes.

1. Microfabricated, or miniaturized, sensors where acoustic waves, i.e. matter vibrations propagating in elastic media, are involved in the sense that they define the domain of the measurand quantity. Examples of this type of devices are accelerometers, microphones, and acoustic-emission pick-ups. The piezoelectric effect, though often used, is not necessarily required in this class of sensors.
2. Microfabricated, or miniaturized, sensors that emit and receive acoustic waves in a surrounding medium along a distance which is typically longer than several wavelengths, in order to sense the properties of the medium and/or the presence and nature of internal discontinuities. This class of devices essentially includes ultrasound transducers, both single-element and arrays, for acoustic inspection, monitoring, and imaging in air, solids, and liquids. The majority, though not the totality, of these devices base their functioning on the piezoelectric effect, mostly because of its reversibility and efficiency.
3. Microfabricated, or miniaturized, sensors in which acoustic waves propagate and interact with a surrounding medium, in such a way that the degree of interaction or the properties of the medium can be sensed

and measured from the characteristics of the acoustic or electro-acoustic field in the sensor itself [1].

The sensors of this latter kind essentially behave as acoustic waveguides which, depending on the configurations, can be made responsive to a wide range of physical quantities, like applied stress, force, pressure, temperature, added surface mass, density and viscosity of surrounding fluids. In addition, sensors can be made responsive to chemical and biological quantities by functionalizing their surface with a coating which, depending on its composition, is (bio)chemically active and works as a "receptor" for the analytes to be detected (see Chap. 11). The coating film has the role of a (bio)chemical-to-physical transducer element, as it converts signals from the (bio)chemical domain into variations of physical parameters, typically the equivalent mass, stiffness, or damping, that the acoustic sensor can detect and measure. (see also Chaps. 3, 10, 11, 12, 13, 14)

This class of acoustic-wave sensors makes an extensive use of the piezoelectric effect and comprises a number of device types that differ either in the nature of the acoustic waves involved or in configurations adopted.

In the following, the main characteristics of piezoelectric acoustic-wave microsensors belonging to the class 3 will be illustrated.

2.2 General Concepts

The basic principle of operation for a generic acoustic-wave sensor is a traveling wave combined with a confinement structure to produce a standing wave whose frequency is determined jointly by the velocity of the traveling wave and the dimensions of the confinement structure. Consequently, there are two main effects that a measurand can have on an acoustic-wave microsensor: the wave velocity can be perturbed or the confinement dimensions can be changed. In addition, the measurand can also cause a certain degree of damping of the travelling wave.

An important distinction between sensor types can be made according to the nature of the acoustic waves and vibration modes involved in different devices. The devices usually have the same name as the wave dominant in the device.

In the case of a piezoelectric crystal resonator, the traveling wave is either a bulk acoustic wave (BAW) propagating through the interior of the substrate or a surface acoustic wave (SAW) propagating on the surface of the substrate (see Fig. 2.1).
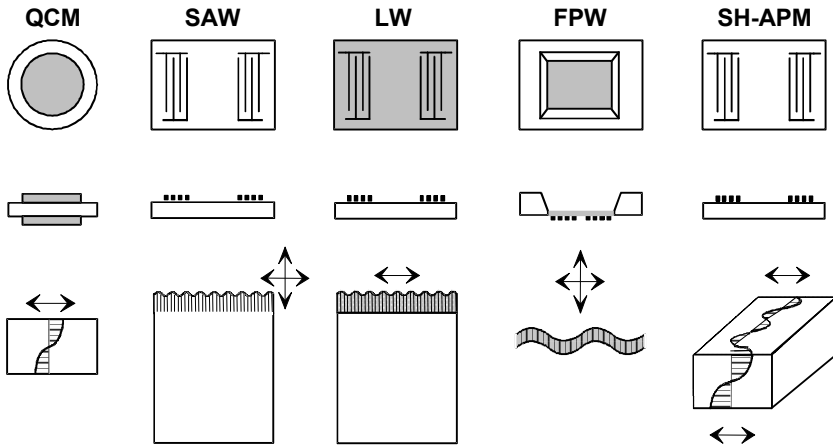
Fig. 2.1. Different types of acoustic-wave sensors

In the bulk of an ideally infinite unbounded solid, two types of bulk acoustic waves (BAW) can propagate. They are the longitudinal waves, also called compressional/extensional waves, and the transverse waves, also called shear waves, which respectively identify vibrations where particle motion is parallel and perpendicular to the direction of wave propagation. Longitudinal waves have higher velocity than shear waves.

When a single plane boundary interface is present forming a semi-infinite solid, surface acoustic waves (SAW) can propagate along the boundary. Probably the most common type of SAWs are the Rayleigh waves, which are actually two-dimensional waves given by the combination of longitudinal and transverse waves and are confined at the surface down to a penetration depth of the order of the wavelength. Rayleigh waves are not suited for liquid applications because of radiation losses.

Shear horizontal (SH) particle displacement has only a very low penetration depth into a liquid (see Chap. 3), hence a device with pure or predominant SH modes can operate in liquids without significant radiation losses in the device. By contrast, waves with particle displacement perpendicular to the device surface can be radiated into a liquid and cause significant propagation losses, as in the case of Rayleigh waves. The only exception are devices with wave velocities in the device smaller than in the liquid.

Other surface waves with important applications in acoustic microsensors are Love waves (LW), where the acoustic wave is guided in a foreign layer and surface transverse waves (STW), where wave guiding is realized with so-called gratings.

Plate waves, also called Lamb waves, require two parallel boundary planes. The lowest anti-symmetric mode is the so-called flexural plate wave (FPW).

Acoustic plate modes (APM), although generated at the device surface, belong to BAWs.

Devices based on acoustic waves shown in Fig. 2.1 are shortly described in the next section. Other types of waves or devices not described here are pseudo-SAW (or leaky SAW) [2] , surface skimming bulk waves [3], Bleustein-Gulyaev-waves [4, 5] as well as magneto-SAWs [6] .

2.3 Sensor Types

2.3.1 Quartz Crystal Thickness Shear Mode Sensors

The oldest application of quartz crystal resonators (QCR) as sensors is the quartz crystal microbalance (QCM or QMB). These sensors typically consist of a thin AT-cut quartz plate with circular electrodes on both parallel main surfaces of the crystal. BAWs are generated by applying an electrical high-frequency (HF) signal to the electrodes. QCMs are operated as resonators in an almost pure thickness-shear mode, hence the sensors are also called TSM sensors.

The sensor resonant frequencies are inversely proportional to the crystal thickness. For the fundamental mode, resonance frequencies of 5 to 30 MHz are typical. For higher frequencies the crystals can be operated at overtones. Nowadays high-frequency QCRs with fundamental frequencies up to 150 MHz are available. The required crystal thickness down to 1 µm is prepared by chemical milling and, for mechanical stability reasons, the etching of the crystal is limited to the region of the electrode area, leading to inverted-mesa structures.

After their first use as frequency-reference elements in time-keeping applications in 1921 by W. Cady and as a microbalance in 1959 by G. Sauerbrey [8], quartz crystals have become probably the most common acoustic-wave sensors, finding application in the measurement of several other quantities and, in turn, opening the way to the development of newer and more specialized sensors. The typical configuration is as single-element sensors, but multisensor arrays on the same crystal have been recently proposed [9, 10].

The basic effect, common to the whole class of acoustic-wave microsensors, is the decrease in the resonant frequency caused by an added surface mass in the form of film. This gravimetric effect motivates the

denomination of quartz-crystal microbalance and is exploited, for instance, in thin-film deposition monitors and in sorption gas and vapor sensors using a well-selected coating material as the chemically-active interface [11, 12].

Within a certain range, the frequency shift Δf is sufficiently linear with the added loading mass Δm regardless of the film material properties, and the sensitivity $\Delta f/\Delta m$ is proportional to f^2 [8]. For higher loading, the sensor departs from the gravimetric regime and the frequency shift becomes a function of the mass as well as of the viscoelastic properties of the film [13] (see Chaps. 3, 14).

TSM quartz sensors can also operate in liquid, due to the predominant thickness-shear mode. In this case, the frequency shift is a function of liquid density and viscosity [14] (see Chap. 3), which makes it possible to use TSM quartz resonators as sensors for fluid properties [15]. In addition, the mass sensitivity and in-liquid operation can be advantageously combined, and TSM sensors coated with (bio)chemically-active films can be used for in-solution (bio)chemical analysis, for instance in the chemical, biomedical and environmental fields [16] (see Chaps. 9, 11, 12, 13, 14).

Mass sensitivity and liquid density-viscosity sensitivity are two special cases of the more general sensitivity of all acoustic-wave microsensors to the so-called surface acoustic load impedance, which is discussed in Chap. 3. Because of its importance and simplicity we further limit the discussion here to mass sensitivity and applicability of the devices in a liquid environment.

2.3.2 Thin-Film Thickness-Mode Sensors

These are BAW sensors based on thickness-mode waves that, as opposed to TSM quartz crystals, are of the longitudinal type, at least in the early implementations of the concept. They are made by electroded piezoelectric thin films and are therefore also termed film bulk acoustic resonator (FBAR) sensors. Films of piezoelectric materials, such as AlN or ZnO, are created in the form of diaphragms photolithographically defined and etched starting from a silicon substrate. In this way, a very low thickness can be obtained that causes a high resonant frequency, up to 1000 MHz [17] and above. This, in turn, determines a high mass sensitivity in gravimetric applications.

As opposed to free-standing, or suspended, homogeneous resonators, composite resonators can also be used where the piezoelectric film is deposed on a nonpiezoelectric substrate, such as silicon, with intermediate

layers with different acoustic impedances. Composite film resonators can display improved thermal stability due to the property matching that can be obtained among different layers. A significant case is when the layers have alternate high and low acoustic impedances, thereby forming a Bragg reflector which acts as an acoustic mirror that isolates the film from the substrate [18]. This configuration is often termed as solidly-mounted resonator (SMR). The structures of suspended and SMR FBARs are shown in Fig. 2.2. The SMR solution has the effect to decrease the effective thickness and is especially interesting for sensing applications, because it avoids the need of etching away the silicon to form the thin suspended diaphragm. This advantageously mitigates the problem of fragility.

Composite resonators can also be made by resonant piezo-layers (RPL) of lead-zirconate-titanate (PZT) films screen printed on alumina substrate [19]. RPL sensors display a mass sensitivity comparable or slightly higher than TSM quartz sensors at the same frequency, though the thermal stability is worse. Most likely due to their porosity, thick-film RPL sensors with chemically functionalized surface apparently offer an improved sensitivity as sorption sensors in air [20].

Thickness-longitudinal-mode sensors have many analogies with TSM quartz sensors. One important difference is that, in the former ones, the vibrations normal to the sensor surface irradiate energy into a surrounding liquid, which makes thin-film thickness longitudinal mode sensors generally unsuitable for (bio)chemical applications in solutions.

For this reason, efforts have been aimed to the development of shear-mode FBAR sensors. Recently reported devices have a configuration similar to thickness-longitudinal-mode sensors with the difference that they exploit the oriented growth of ZnO piezoelectric films to generate thickness-shear-mode vibrations [21]. As an alternative, shear-wave generation using lateral field excitation has also been reported [22]. Shear-mode FBARs are expected to have a high potential especially for highly integrated biochemical sensor arrays, though the very high operating frequencies (in the range 1-10 GHz) can pose significant challenges to the readout electronic circuits and instrumentation.
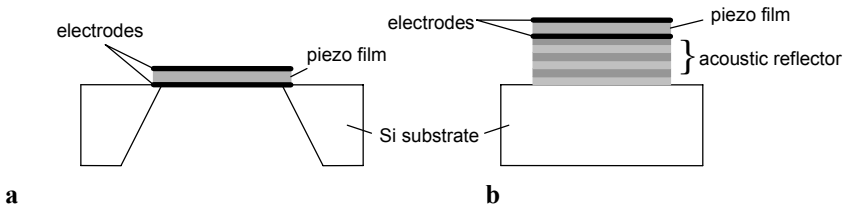

Fig. 2.2. Film bulk acoustic resonator (FBAR) sensors: **a** free-standing structure; **b** solidly-mounted resonator (SMR) structure

2.3.3 Surface Acoustic Wave Sensors

Surface acoustic wave (SAW) sensors are made by a thick plate of piezo-electric material, typically ST-cut quartz, lithium niobate or lithium tantalate, where predominantly Rayleigh waves propagate along the upper surface [23].

Surface wave generation is efficiently accomplished by a particular electrode configuration named interdigital transducer (IDT) (Fig. 2.3a). An IDT, in its simple version, is formed by two identical comb-like structures whose respective fingers are arranged on the surface in an interleaved alternating pattern. The IDT period length d, or pitch, is the spacing between the center of two consecutive fingers of the same comb. When an AC voltage is applied to the IDT, acoustic waves are generated which propagate along the axis perpendicular to the fingers in both directions. The maximum wave amplitude is obtained when constructive interference among the fingers occurs. This happens at the characteristic or synchronous frequency $f_o = v/d$, where v is the SAW velocity in the material. Typical SAW characteristic frequencies are 30-500 MHz. Two basic configurations are possible: one-port SAW resonators with a single IDT, and two-port SAW delay lines with two IDTs separated by a distance L.

Similarly to what happens with BAW devices, SAWs can be used as high-frequency reference elements in filters and oscillators, but they can also be made responsive to a variety of quantities to have them work as sensors [24].

The primary interaction mechanisms are those that affect the frequency by changing the wave velocity, the IDT distance, or both. Temperature, strain, pressure, force, and properties of added surface materials are examples of measurand quantities. In particular, the accumulated surface mass produces a decrease in frequency.

Compared to QCMs, the higher values of the unperturbed frequency and the fact that vibrations are localized near the surface, becoming more affected by surface interactions, determine a higher sensitivity of SAWs in gravimetric applications.

This fact is advantageously exploited in sorption gas and vapor sensors where SAWs coated with chemically-active films (Fig. 2.3b) can achieve significantly low detection limits [25].

Due to the configuration of the IDT electrodes, SAW sensors are also responsive to the electric properties of the coating film or the surrounding medium by means of the acoustoelectric coupling.

The improvement over quartz crystal TSM sensors offered by SAW sensors in air cannot be extended in liquids because of the vibration

component normal to the surface involved in Rayleigh waves, which causes acoustic energy radiation into the liquid with a consequent excess of damping.

In principle, IDTs can generate a spectrum of transversal horizontally and vertically polarized waves as well as longitudinal waves, which propagate on the surface or into the volume of the piezoelectric material [7]. Material properties, crystal cut, and sensor geometry are responsible for which modes appear and in what extent. A whole family of SAW-like devices has been developed. The most important ones are further described.
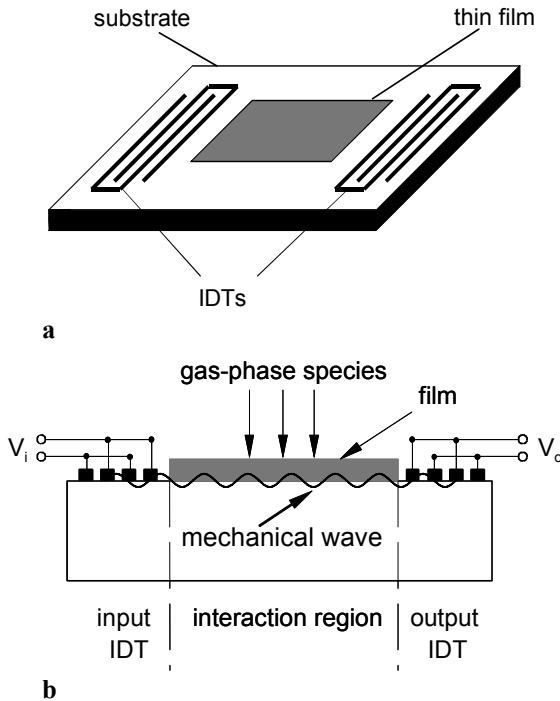

Fig. 2.3. a Interdigital transducer configuration as used in SAW sensors; **b** structure of a SAW sensor

2.3.4 Shear-Horizontal Acoustic Plate Mode Sensors

Shear-horizontal acoustic plate mode (SH-APM) sensors are quartz plates with thickness of a few wavelengths, where shear-horizontal (SH) waves are generated by means of two IDTs positioned on one surface of the plate [26] (Fig. 2.4).

SH waves have particle displacement predominantly parallel to the plate surface and perpendicular to the propagation direction along the separation path between the two IDTs and hence are suited for operation in contact with liquid. Typical operation frequencies of SH-APM sensors are 20-200 MHz. APMs are a series of plate modes with slightly different frequencies. The difference between these frequencies decreases with decreasing plate thickness. To select a dominant SH mode, material and crystal cut, IDT design and oscillator electronics must be optimized. APMs have antinodes on both device surfaces so that each of them can be used as a sensing surface. In particular, the electrode-free face can be made (bio)chemically active and analysis in solution can be performed with a complete separation between the electric side and the liquid side.
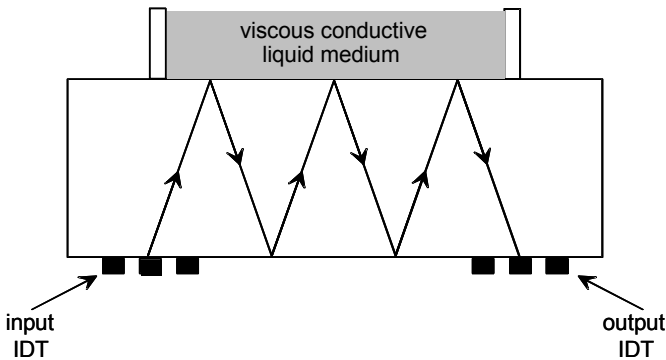

Fig. 2.4. Structure of an APM sensor

2.3.5 Surface Transverse Wave Sensors

Surface transverse wave (STW) sensors are devices in which shear vibrations are confined in a thin surface area on the face where the IDTs are placed. This wave confinement is obtained by inserting a metallic grating between the IDTs that introduces a periodic perturbation in the wave path and lowers the wave velocity at the surface [1, 27].

Since the vibration energy density is concentrated on a thin layer near the surface, the device is very responsive to surface perturbations and, in particular, it provides a high mass sensitivity. As shear vibrations are predominant, STW sensors (also called SH-SAW) are indicated for in-liquid applications and are mainly used with chemically-modified surfaces for analysis in solutions.

2.3.6 Love Wave Sensors

Love wave (LW) sensors are rather similar to STW sensors in that they involve shear vibrations confined in the upper surface.

The wave confinement is in this case obtained by depositing a thin layer of a material with low acoustic-wave velocity over a quartz plate where two IDTs are realized. Such an added overlayer, typically of silicon dioxide or polymethylmethacrylate (PMMA), works as a waveguide and keeps most of the vibration energy localized close to the surface, regardless of the plate thickness. This has the same positive effect on the mass sensitivity as the gratings in STW sensors and, once again, in-liquid operation is permitted by the shear-mode vibrations [28, 29].

Love-mode sensors are mainly used in (bio)chemical analysis in solutions.

A generalized Love-wave theory considers APMs and Love waves as the two solutions of the dispersion equation of a substrate with finite thickness [30].

2.3.7 Flexural Plate Wave Sensors

In thin plates, i.e. diaphragms with thickness smaller than the wavelength, a series of symmetric and antisymmetric plate modes can be generated. These so-called Lamb waves have a particle displacement similar to Rayleigh waves [31, 32], i.e. particle motions describe a retrograde ellipsis with the major and minor axes normal and parallel to the surface, respectively. The wave velocity depends on the plate material and the plate thickness. The advantage of the lowest antisymmetric mode, the so-called flexural plate wave (FPW) mode, is a wave velocity smaller than that of SAW devices. It decreases with decreasing plate thickness and becomes lower than the wave velocity of liquids.

This determines a couple of unique features that makes FPW sensors very attractive. The first is that, for a given wavelength, the corresponding frequency is comparatively low, in the range of 5-20 MHz, which alleviates the requirements on the associated electronics.

The second is that FPW sensors are best suited to the measurement of fluid properties, such as liquid viscosity, and gravimetric (bio)chemical analysis in solutions. In this latter application, the plate being very thin and significantly affected by surface perturbations, the achievable mass sensitivity can be extremely high [33]. Typically, the plate is a few-micron thick rectangular silicon-nitride diaphragm with a piezoelectric overlayer,

such as zinc oxide, in which the waves are generated by means of IDTs (Fig. 2.5). Unfortunately, those FPW sensors are still fragile and the fabrication process must be further optimized. Another version of excitation involves a magnetic field [34].
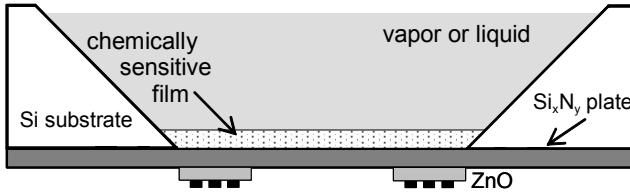

Fig. 2.5. Structure of a FPW sensor

2.3.8 Other Excitation Principles of BAW Sensors

The most known quartz crystal microbalance may reveal some limitations when applied as chemical or biochemical sensor. Sensitivity to the mass of molecular species is a very unique advantage of acoustic sensors. However, acoustic sensors are inherently nonspecific. The core of chemical analysis involving surfaces is therefore a method for immobilization of the target molecule on the surface of the transducer (see Chaps. 11, 12), hence mainly a question of surface chemistry and application to complex (bio)molecular systems. From that point of view, the necessity of metal electrodes at the surface interacting with the medium to be investigated is a limitation of applicable surface chemistry. In addition, a simple replacement method for the sensor element, which does not require a skilled operator, is an issue of practical interest. Electrical connection to electrodes on the sensor element can therefore become a critical design factor.

Two other principles can overcome these limitations, lateral field excitation (LFE) and direct magnetic generation. The classical LFE design is characterized by two electrodes covering completely the left and the right side of a quartz disc just leaving a small straight gap between them. A lateral electrical field is confined in the gap and excites acoustic vibration, thenceforth the name [35]. Magnetic excitation has been utilized for non-destructive material testing, for example in automotive industry. In a static magnetic field acoustic waves are generated and detected in the material by radio frequency (RF) coils placed next to the test sample. The device has therefore been called electromagnetic acoustic transducer (EMAT) [36].

Just recently both principles have been modified for microacoustic resonator sensors. LFE sensors utilize the same piezoelectric crystal that is

used in QCM, namely AT-cut quartz. The electrodes are located only in the bottom surface leaving the top sensing surface blank (Fig. 2.6) [37].

The bare surface gives now access to the large variety of silicon based surface chemistry. On the other hand one loses the shielding effect of the top electrode. The aspect ratio between electrode gap distance and crystal thickness is about 3-6. The electric field is not completely confined between the electrodes. Consequently, the electric field penetrates partly into the medium adjacent to the sensing surface of the crystal. This feature can provide access to additional relevant physical material properties of the material under investigation, namely the electrical parameters permittivity and conductivity. The sensor response to electrical properties can be much larger than that to density-viscosity [38].
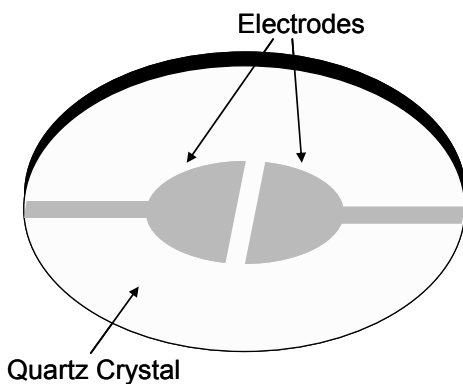

Fig. 2.6. Lateral Field Excited (LFE) sensor

For the understanding of the extraordinary sensor response to electrical properties of a liquid analyte, one must consider the change in the (electrical) boundary conditions at the sensing surface. As a result of liquid application the electrical field distribution changes depending on conductivity and permittivity of the liquid and experimental conditions (grounding). As long as the sensor faces a medium which features a relative permittivity, ε_r, lower than that of quartz the electrical field is distributed mainly in lateral direction. For a medium featuring a dielectric permittivity higher than that of quartz the internal lateral electric field component decreases in strength and components of the traditional thickness field excitation (TFE) will be amplified. As a consequence, the wave propagation properties of the acoustic wave change, hereby modifying the resonance frequency of the sensor. In other words, the sensitivity to electrical properties of the adjacent liquid does not directly appear in the sensor response, they become effective via changes in the acoustic wave generation scheme and acoustic

properties of the crystal [39]. Distinction of the contributions to the sensor response from liquid density and viscosity on the one hand and permittivity and conductivity on the other requires advanced analysis.

By combining magnetic direct generation with an acoustic resonator it is possible to excite a mechanical resonance in the element. The coil is driven with a stationary RF current or around mechanical resonance (Fig. 2.7). When coinciding with the electrical resonance of the coil which can be adjusted by bridging the coil with a parallel capacitance, the result is a detectable signal response that is improved by the quality factors Q of both resonances. This combination of utilizing a single planar spiral coil was termed magnetic acoustic resonator sensor (MARS) [40].

The advantage of such an acoustic sensor is the ability to utilize a large variety of different materials and material combinations which have been exempt before, i.e., there is no need for piezoelectric materials. Furthermore, a variety of different modes of vibration can be excited. The planar coil setup for magnetic direct generation can also be used to remotely excite piezoelectric transducers. A static magnetic field is not necessary here, since the excitation mechanisms are fundamentally different. This magneto-piezoelectric coupling has been successfully employed to bare, electrode-free quartz crystals [41]. Due to the absence of a large parallel capacitance an additional feature of this excitation principle is the possibility to generate evanescent waves over the megahertz to gigahertz frequency range with the unique ability to focus the acoustic wave down onto the chemical recognition layer.
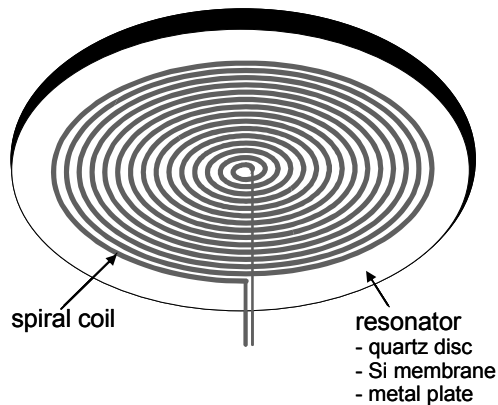

Fig. 2.7. Magnetic direct generation with spiral coil. For non-piezoelectric resonators a permanent magnet below the spiral coil and a conductive lower surface is required

The description of magnetic direct generation of acoustic waves in non-piezoelectric plates requires Maxwell's equations and involves two mechanisms. For the first mechanism, according to Lenz's law, in a conductive layer placed in parallel above the coil eddy currents are generated that will flow in the opposite clockwise direction as the primary current in the coil. The second mechanism involved consists of the interaction between the eddy currents and a magnetic field. Superposing the induced movement of a charge with the magnetic field will result in the Lorentz force that is capable of exciting acoustic waves in the plate.

A first option to provide such a magnetic field is to generate it externally in the form of a static field. The Coulomb force due to the electric component of the electromagnetic field created by the primary current is negligible when using an additional strong static magnetic field. For a spiral coil, and therefore circular flowing eddy currents, the direction of the Lorentz forces will be radial. Due to these forces alternating with the primary current frequency, the crystal lattice of the material will start to vibrate and an acoustic wave is generated in the sensor element. A standing acoustic wave then appears if the frequency corresponds to one of the eigenmodes of the element and if the force distribution is compatible with the mode shape of the resonance. At resonance, the vibration of the crystal lattice achieves significantly increased displacements resulting in a second perpendicular induction current component, which is superposed with the eddy currents. Both induced currents affect the mutual inductance between primary coil and the resonator element, whereas the second part only takes a measurable effect in mechanical resonance, which can thus be detected by an RF analyzer circuit monitoring the coil parameters [42].

A second option to provide the required magnetic field is to exploit the same RF field that is generated by the coil and used to produce the eddy currents. The magnetic field is assumed to be sinusoidal at frequency f. As a consequence, the interaction between the eddy currents and the magnetic field itself causes Lorentz forces at frequency $2f$ that can set the conductive structure into resonance if $2f$ coincides with the frequency of a proper vibration mode. This frequency doubling action is a distinctive consequence of the nonlinearity in the force generation mechanism [43, 44].

As a further alternative to classical solutions with quartz crystal sensors, a configuration and method has been developed for contactless readout of the resonance response of a TSM resonator array [45]. The configuration uses a crystal with a large common electrode on the front face, and a number of small equal electrodes on the back face, as shown in Fig. 2.8. This leads to localized sensing regions via the confined energy trapping under the small back electrodes. Each back electrode is capacitively coupled to a

tip electrode separated by a stand-off distance. The tip consists of a small disc and a guard ring, which confine the electric field to the electrode area and make the measurement unaffected by the stray parallel capacitances. A localized mass load added on the front electrode can be consistently detected and measured by scanning the correspondent back electrode, irrespective of the tip-to crystal stand-off distance.

The proposed method may be attractive for the perspective development of monolithic TSM sensor arrays with contactless scanning, because it avoids the problems of routing connections to multiple electrodes, at the same time minimizing the influence of stray contributions external to the crystal.
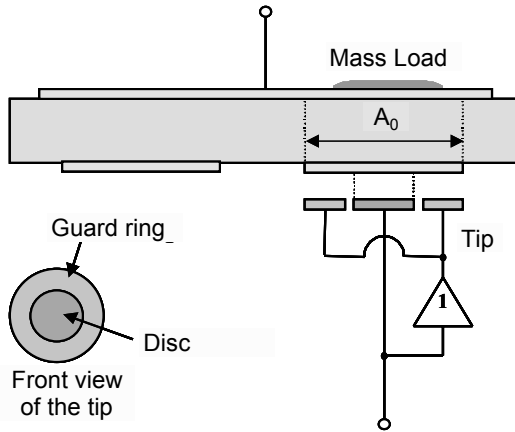

Fig. 2.8. Contactless localized readout of a quartz TSM resonator

2.3.9 Micromachined Resonators

Silicon technology can make a new generation of resonators available with the capability to detect even smaller masses, the capability to fabricate arrays with a much larger number of elements per unit area, the capability of monolithically integrated electronic circuitry and mass production at low costs. Magnetic direct generation applied to Si membranes is a sophisticated example of the new generation. Nowadays the most prominent example are cantilevers which are applied as chemical sensors [46]. Cantilever sensors are typically made of silicon, silicon nitride, or silicon dioxide. A great variety of dimensions and shapes is available [47]. Analog to acoustic sensors, micro electro mechanical systems (MEMS) based sensors are inherently nonspecific, consequently they also need immobilization of chemically sensitive materials on the transducer surface.

As sensors, cantilevers can be used in the resonant mode or in a non-resonant regime. Analog to acoustic sensors, the devices are sensitive to the mass of molecular species when used in the resonant mode. The mass sensitivity depends on the force constant, which is a function of geometry and the effective Young's modulus. One major challenging issue is improvement of the quality factor of the resonator. Values of Q of about 100 in the upper kilohertz frequency range in air enable a mass resolution in the picogram range. Calibration of the sensor is required because beam thickness is usually not precisely enough known.

One example of the nonresonant application is the stress generated bending. Changes in surface stress can be the result of physical interaction, for example electrostatic forces between charged molecules on the surface, or of chemical nature, e.g. analyte absorption induced swelling of a chemically sensitive coating during chemical sensing.

In liquid environment, especially in biosensing applications, the out-of-plane, or flexural, vibration of the cantilever is strongly damped and results in an essentially reduced Q of a few tens only. It can be enhanced by incorporating the cantilever in an amplifying feedback loop. Another approach avoids the out-of-plane vibration. For example, disc-shaped microstructure can operate in a rotational in-plane mode with resonance frequencies in the upper kilohertz range.

The FBAR sensors described in Section 2.3.2 are another example of micromachined resonators that are attracting current interest and will probably go through further development.

Another group of acoustic sensors, usually called ultrasonic sensors, shares some features with acoustic microsensors but there are also some remarkable differences. According to the device classification given in Section 2.1 they belong to the class 2. Similar to acoustic microsensors of the class 3, the acoustic wave is usually generated and detected with a piezoelectric device. By contrast, the acoustic wave in this case travels along several wavelengths through the bulk of material of interest. Level and flow meters are two famous examples of a variety of applications of ultrasonic sensors. Ultrasonic sensors have also proven their capabilities as chemical sensors. Micromachined Ultrasonic Transducers (MUT)s are the MEMS version of ultrasonic sensors [48-50]. They can be driven capacitively or piezoelectrically at radio frequencies. 1D and 2D arrays are available. MUTs are very promising for microfluidic applications.

2.4 Operating Modes

Piezoelectric acoustic-wave sensors invariably have an electrical port where a driving AC signal is applied that generates vibrations via the converse piezoelectric effect (induced strain proportional to applied voltage). Such vibrations propagate through the sensor interacting with the measurand quantity, and are transduced back to the electrical domain via the direct piezoelectric effect (induced charge proportional to applied stress). Depending on the way the electrical output signal is exploited, two categories of sensors can be distinguished.

In one-port sensors the electrical output can be thought as generated across the same port, i.e. the same couple of electrodes, where the input is applied. In two-port sensors the electrical output is physically available at a second port, distinct from the input one, realized by a dedicated pair of electrodes.

For both one-port and two-port sensors, the effect of the measurand quantity produced on the wave propagation can be measured in two different methods.

In the first method, called the open-loop, or passive, or nonresonant method, an excitation signal coming from an external generator is applied to the sensor input and the corresponding response signal at the output is detected.

Usually, the measurement is performed by a network analyzer which provides the excitation signal as a fixed-amplitude sine wave swept over a frequency range, detects the output, and directly visualizes the output/input ratio as a complex function of frequency, i.e., taking both amplitude and phase into account.

The open-loop operation mode has the advantage of providing the maximum of information on the electrical behavior of the sensor and further on, via the acoustic behavior of the sensor, on the measurand/sensor interaction. The limitations are that extracting such information is not always straightforward, since it implies a certain knowledge of sensor operation and modeling. Moreover, network/impedance analyzers are typically costly instruments.

An alternative to swept-frequency analysis is the use of transient analysis, in which a sinusoidal excitation at the resonant frequency is applied at the sensor input and suddenly removed, and the resulting output oscillatory damped response is examined. This method is mostly used with quartz crystal TSM sensors [51] (see Chap. 5).

In the second method, called the closed-loop, or active, or resonant method, the sensor is configured as the feedback element of an electronic amplifier. In practice, the connection schemes are different for one-port and two-port sensors, but the principle in both cases is actually the same.

By a proper choice of the amplifier it is possible to establish positive feedback around the loop and make the sensor/amplifier combination work as an oscillator, which continuously sustains and tracks oscillations in the sensor at one of its resonant frequencies (see Chap. 5). In one-port devices, like quartz crystal TSM sensors, the sensor behaves like a mechanical resonator. Conversely, SAW, FPW and APM and LW configured as two-port devices behave as acoustic delay lines.

The closed-loop configuration has the advantage that it provides a continuous reading of the resonant frequency, allowing to follow the evolution of the experiment in real time without the need for repeated measurements of the sensor open-loop response.

For comparatively low-frequency sensors, oscillator circuits can be relatively simple and inexpensive, while for higher-frequency sensors the design becomes less straightforward.

A fundamental point to keep in mind with oscillators, that can also become their main limitation in high-accuracy applications, is that, in general, the sensor resonant frequency and the output frequency of the oscillator circuit are not exactly equal under every load conditions. This is due to the combination of the sensor and amplifier phase responses that determine an oscillation condition in the loop at a frequency which, in some cases, can be appreciably different from the sensor resonance (see Chap. 5).

In particular, great care must be taken with oscillators when the sensor is heavily loaded either acoustically, due to a thick viscoelastic coating, or dielectrically, due to immersion in liquid, or both. In such cases, the oscillation frequency of the oscillator can become significantly different from the resonant frequency of the sensor, causing errors in the interpretation of the results. As a limiting case, oscillations can even stop in the circuit, though the sensor resonant frequency of course still exists, with the negative consequence of restricting the operating range.

Special oscillator designs developed for heavy-load conditions should be adopted in these cases (see Chap. 5).

A further limitation of oscillators is that they usually provide the measurement of a single parameter of the sensor response, namely its resonant frequency. There are oscillators that incorporate circuitry for the simultaneous measurement of the vibration amplitude in addition to its frequency,

therefore providing information also on the amount of damping undergone by the sensor. Concepts on electronics are further discussed in Chap. 5.

2.5 Sensitivity

The parameter of acoustic-wave sensors that is primarily employed for measurement is the fundamental resonant frequency f. From theory, in the case of quartz crystal TSM sensors, the series resonant frequency f_s where the real part of admittance has a maximum must be measured to be in accordance with the theoretically predicted values. Additional parameters ranging from damping and phase shift, to the complete spectrum provide an increasing degree of further information.

Limiting to the resonant frequency f, it can be generally expressed as:

$$f = \frac{v}{2l} = \frac{1}{2l}\sqrt{\frac{c}{\rho}} = \frac{1}{2\pi}\sqrt{\frac{K}{M}} \tag{2.1}$$

where l is the frequency determining dimension (e.g. the crystal thickness in a QCM), v is the wave velocity, c is the effective elastic stiffness (e.g. the shear stiffness constant in a QCM), ρ is the mass density, K and M are the lumped equivalent spring and mass associated with the particular vibration mode. Note that M is definitely different from the rest mass of the sensor.

The fractional frequency variation can then be derived as a function of the variations of the individual parameters caused by an external quantity as follows:

$$\frac{df}{f} = \frac{dc}{2c} - \frac{d\rho}{2\rho} - \frac{dl}{l} = \frac{dK}{2K} - \frac{dM}{2M} \tag{2.2}$$

The sensitivity towards a measurand x can be defined as the ratio df/dx.

Despite its simplicity, Eq. (2.2) has a certain general validity in indicating the effect of a measurand on the resonant frequency and in finding the associated sensitivity.

In particular, those measurands that increase the effective stiffness c, or equivalently the spring constant K, cause f to rise. Examples are tensile stress or bending.

On the contrary, those measurands that increase either the effective density ρ, or the length l, or equivalently the equivalent mass M, cause f to decrease. A typical example is mass loading. The Sauerbrey equation for the

mass sensitivity of a QCM can be easily derived from Eq. (2.2) by assuming that the load only changes the thickness l and leaves the average density and stiffness unaltered (see Chap. 1).

In general, the higher the sensor unperturbed frequency f, the greater the frequency shift at parity of measurand value. For instance, SAW sensors in the 100 MHz range have a higher mass sensitivity than TSM sensors in the 10 MHz range. However, considering sensitivity as a benchmark to compare different sensors can be misleading. In fact, a higher value of the *nominal* sensitivity as apparently granted by a higher resonant frequency does not necessarily imply a higher value of the *usable* sensitivity in a practical device.

For instance, a QCM can be operated with a sensitive coating much thicker than that on a SAW sensor, which results in a higher amount of gas absorbed in the coating.

Therefore, it is more appropriate to use the reduced, or fractional, sensitivity $S=(df/dx)/f$ to normalize for the unperturbed frequency.

The typical fractional mass sensitivities, where the mass is intended for unit surface area, for different sensor types are compared in Table 2.1 [52-54]. It should be noted that the sensitivity is only one factor to the ultimate goal of achieving a high resolution, i.e., a discrimination capability of small incremental values of the measurand [55]. High resolution implies good frequency stability.

Table 2.1. Comparison of the characteristics of different acoustic-wave sensors

Sensor type	FRO[a]	S_m[b]	Examples (*)			OL[f]
			FO[c]	FN[d]	S/N[e]	
TSM quartz	5-30	12-70	10	0.2	110	Yes
Thin-film BAW	900-1000	400-700				No
SAW	30-500	100-500	160	2	100	No
SH-APM	20-200	20-40	100	4	5	Yes
STW	100-200	100-200				Yes
LW	100-200	150-500	110	2	125	Yes
FPW	5-20	200-1000	5	1	450	Yes

[a] Frequency Range of Operation [MHz]
[b] Surface mass sensitivity ($[Hz\ MHz^{-1}\mu g^{-1}cm^2]$)
[c] Frequency of Operation [MHz]
[d] Frequency Noise [Hz]
[e] Sensitivity-to-Noise ratio ($[MHz^{-1}\mu g^{-1}cm^2]$)
[f] Operation in Liquid
(*) Data taken from: [57-59].

Short-term frequency stability is mostly determined by the sensor, especially by the coating and the measurement environment, in combination with the oscillator electronics. Sensors with higher values of the quality factor Q for the resonance in question provide a better stability at parity of electronics. Therefore, a significant figure of merit for a sensor is actually the sensitivity-quality factor product SQ [56].

Long-term frequency stability is typically dominated by thermal drift and material aging or degradation, however, these effects must be related to the time scale of sensor signal changes.

To counteract drift effects a differential configuration can be helpful, with one sensor exposed to the measurand and a second identical sensor screened from it. Both sensors are subjected to the influencing quantities, such as temperature. By taking the difference of the signals from the sensor/reference pair, the common-mode perturbing factors can be compensated to some extent.

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