Acoustic Wave Devices

ME2082

Lecture 8-7
Acoustic wave devices

- **Surface acoustic wave sensors**
  - biological and chemical sensor
  - viscosity sensor
  - force sensors
  - stress/strain sensors

- **Bulk Sensors**
  - acoustic pressure sensor
  - pressure sensors
  - accelerometers

- **Plate wave ((lamb wave))**
  - Piezo-motors

- **Monolithic SAW device**
  - SAW on piezoelectric substrate
  - SAW on non-piezoelectric substrate (e.g.)
    - Bi-layer or multi-layer
    - Polycrystalline structure
    - roughness larger
  - Common configuration to excite SAW wave
    - IDT--interdigital transducer
    - frequency determined by the photolithographic process
Acoustic wave devices

- Acoustic waves can be excited by various means such as mechanical impact, pulsed thermal energy, or the inverse piezoelectric effect. The last is by far the most important for acoustic devices.

- There are two groups of acoustic devices which make use of two distinctive transducer types: surface acoustic wave (SAW) and bulk acoustic wave (BAW) devices.
  - The SAW employs interdigital transducers (IDTs), i.e., thin-film metal comb (‘finger’) structures as depicted in the Figure. The principle of IDTs: if an alternating electric field is applied at the comb structure, a time-harmonic periodic deformation is induced in the piezoelectric substrate underneath. Thus, an acoustic wave perpendicular to the finger direction is excited by each finger pair.
  - The BAW is generally excited by means of thin-film transducers covering the excited volume of a piezoelectric material.

Interdigital transducer (IDT) for the excitation of surface acoustic waves (SAW)
Acoustic wave devices

BAW

Top view of a TSM consisting of a quartz disc, metal electrodes and electric contacts. The smaller figure illustrates the wave motion and the direction of particle displacement.

SAW

Top view of a SAW delay line consisting of a quartz plate and interdigital metal transducers. The lower figure indicates the wave motion and direction of surface particle displacement.
Acoustic wave devices

Example: BAW-- Quartz thickness shear mode (TSM) resonators

For the case of thin, rigid and uniform mass layer on the surface of the device, there is a relationship between the mass increase ($\Delta m$) at the quartz surface and the resonant frequency shift ($\Delta f$)

$$\Delta f = -\frac{2 f_0^2}{(\rho_Q \mu_Q)^{1/2}} \times \frac{\Delta m}{A}$$

where $f_0$ is the resonant frequency of the quartz crystal, $A$ is the active area of the coated crystal, $\mu_Q$ is the shear modulus of the quartz crystal and $\rho_Q$ is the density.
Acoustic wave devices

Example: BAW-- Quartz thickness shear mode (TSM) resonators

For the liquid loading, Kanazawa and Gordon found that for the Newtonian liquid contacting with one side of resonator sensor, the resonant frequency shift depends upon the viscosity ($\mu_L$) and density ($\rho_L$) of the liquid

$$\Delta f = -\frac{f_0^{3/2}(\rho_L \eta_L)^{1/2}}{(\pi \rho_Q \mu_Q)^{1/2}}$$

Quartz crystal microbalance.
Acoustic wave devices

Example: BAW-- Quartz thickness shear mode (TSM) resonators

The electrical admittance spectra $Y(\omega)$ generated from BVD model is given by:

$$Y(\omega) = G + jB$$

$$= \frac{1}{R_1 + j\omega L_1 + 1/j\omega C_1} + j\omega C_0$$

For unperturbed TSM resonator, the series resonance frequency $f_s$ at which G is maximum ($G_{\text{max}}$), is given by:

$$f_s = \frac{1}{2\pi} \frac{1}{(L_1 C_1)^{1/2}}$$
Acoustic wave devices
Quartz TSM resonator impedance

Graph showing the magnitude and phase of impedance with reduced frequency $f/f_s$.
Acoustic wave devices

Principle of the coupling of a shear-oscillating surface to a viscous liquid.
Acoustic wave devices

Quartz thickness shear mode BAW

Frequency

Figure 2.1-9. Frequency decrease of different QCM sensors versus the square root of the density-viscosity product \((\rho_L \eta_L)^{1/2}\).

Calculated values of phase versus resonance frequencies in water.
## Acoustic wave devices

**Table 2.1-1. Classification of microacoustic modes suitable for sensor application (acronyms are used where widely introduced into the literature)**

<table>
<thead>
<tr>
<th></th>
<th>Sagittal polarization</th>
<th>Shear-horizontal polarization</th>
<th>Longitudinal polarization</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Half-space</strong></td>
<td>Reflected Rayleigh waves</td>
<td>Leaky waves, SSBW, SH-SAW, Bleustein-Gulyaev waves</td>
<td>QLL-SAW</td>
</tr>
<tr>
<td><strong>Plate</strong></td>
<td>FPW (Lamb waves)</td>
<td>SH-APM</td>
<td>-</td>
</tr>
<tr>
<td><strong>Layered structure</strong></td>
<td>-</td>
<td>Love waves, STW</td>
<td>-</td>
</tr>
<tr>
<td><strong>Bulk</strong></td>
<td>-</td>
<td>QCM</td>
<td>-</td>
</tr>
</tbody>
</table>
Acoustic wave devices

Example: BAW-- Quartz crystal microbalance (QCM) gas sensor

Typical response to 50 ppm of NO₂ of the device coated with NO₂-absorbing polymer
Acoustic wave devices

Example: BAW-- Quartz crystal microbalance (QCM) gas sensor for ammonia detection at ppb level

QCM is coated with fibrous polyacrylic acid (PAA) membrane
For SAW device

- If multiple finger pairs exist, interference occurs yielding to a maximum SAW magnitude if

\[ f_n = \frac{2n+1}{\lambda} \cdot v, \quad n = 0,1,2,3,\ldots \]

with the excitation frequency \( f \), the acoustic wave velocity \( v \) of the particular mode, and the transducer period \( \lambda = 2(a+b) \).

- Hence an IDT is a frequency-selective element. The frequency of the lowest order mode \( f_o \) is called the characteristic frequency.
SAW: Basic Acoustic Structures

- One of the simplest and best known acoustic structures is the delay line shown in Figure. The transducer IDT1 serves as the input for an electric radio-frequency (RF) signal which is transformed by means of the inverse piezoelectric effect into an acoustic wave traveling to the output transducer IDT2. Here, a re-transformation takes place back into the electrical domain. Hence the electrical signal experiences a delay $\tau$ because the acoustic wave is five orders of magnitude slower than the velocity of light:

$$\tau = \frac{CC}{\nu}.$$
Acoustic wave devices

- If no transmission loss occurs, the delay line transfer function $H_{DL}(f)$ can be written as

$$H_{DL}(f) = H_1(f) \cdot H_2(f) \exp(-j2\pi f \cdot \tau).$$

with the transfer functions $H_1(f)$ and $H_2(f)$ of IDT1 and IDT2, respectively.

- The magnitude of the transfer function depends on the IDT characteristics, whereas CC determines the phase $\phi$

$$\phi(f) = -2\pi \cdot \frac{CC}{v} \cdot (f - f_o)$$

- Hence, amplitude and phase characteristics can be chosen independently of each other. Changes of both quantities due to external influences may serve as measuring effects.
Acoustic wave devices

- **By Materials**
  - Bulk wave
  - Surface wave
  - Flexural plate wave
- **By wave forms**
  - Longitudinal wave
  - Transverse wave
  - Raleigh wave (mixed long. and trans. wave)
- **Bulk Materials**
  - Quartz
  - Piezo-ceramic materials
- **Thin films materials**
  - ZnO
  - PZT
  - organic polymer
  - GaAs

**Surface acoustic wave transducers**

Electrical - Mechanical Transducer → Mechanical - Electrical Transducer

Electrical input → Mechanical output

Frequency Amp. Phase → Delay line

Oscillator

(temperature, mass, stress, morphology)
Acoustic wave devices

Important parameters:
Frequency: \( f \)
Pitch
Phase velocity: \( v_p \)
Acoustic wave devices

$\lambda = 4d$

$fo = \frac{\nu_0}{\lambda}$

Figure 3.1. (a) Schematic of a typical IDT, showing the finger width ($d$) and bandwidth ($W$). (b) Launching of a SAW by applying a potential across alternating fingers of an IDT.

Figure 2.13. Flexural plate-wave sensor and cross section showing plate motion. Note deposition of ZnO on a thin silicon membrane.

$$\frac{\Delta \nu}{\nu_0} = \frac{1}{\nu_0} \left[ \frac{\partial \nu}{\partial m} \Delta m + \frac{\partial \nu}{\partial c} \Delta c + \frac{\partial \nu}{\partial \varepsilon} \Delta \varepsilon + \frac{\partial \nu}{\partial \sigma} \Delta \sigma ight]$$

$$+ \frac{\partial \nu}{\partial T} \Delta T + \frac{\partial \nu}{\partial p} \Delta p + \cdots$$
Acoustic wave devices

**SAW chemical sensors**

**TABLE 4** Summary of Various SAW Chemical Sensors

<table>
<thead>
<tr>
<th>Measurand</th>
<th>Chemical Interface</th>
<th>SAW Substrate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Organic vapor</td>
<td>Polymer film</td>
<td>Quartz</td>
</tr>
<tr>
<td>SO₂</td>
<td>TEA&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Lithium niobate</td>
</tr>
<tr>
<td>H₂</td>
<td>Pd</td>
<td>Lithium niobate, silicon</td>
</tr>
<tr>
<td>NH₃</td>
<td>Pt</td>
<td>Quartz</td>
</tr>
<tr>
<td>H₂S</td>
<td>WO₃</td>
<td>Lithium niobate</td>
</tr>
<tr>
<td>Water vapor</td>
<td>Hygroscopic</td>
<td>Lithium niobate</td>
</tr>
<tr>
<td>NO₂</td>
<td>PC&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Lithium niobate, quartz</td>
</tr>
<tr>
<td>NO₂, NH₃, CO, SO₂, CH₄</td>
<td>PC&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Lithium niobate</td>
</tr>
<tr>
<td>Vapors of explosives, drugs</td>
<td>Polymer films</td>
<td>Quartz</td>
</tr>
<tr>
<td>CO₂, Methane</td>
<td>C&lt;sup&gt;c&lt;/sup&gt;</td>
<td>Lithium niobate</td>
</tr>
</tbody>
</table>

<sup>a</sup> TEA = Triethanolamine.  
<sup>b</sup> PC = Phthalocyanine.  
<sup>c</sup> C = No chemical interface used. Detection based on changes in thermal conductivity produced by the gas.
Acoustic wave sensors

Dual delay line configuration.

Device characterization with a network analyzer.
Acoustic wave devices

SAW Devices

- Measurement Methods: Oscillator vs. delay line approach
  - Oscillator: frequency \( \Delta f/f = S_m \Delta m \)
    
    \( S_m: \) mass sensitivity, \( \Delta m: \) mass/unit area

- Delay line: phase shift (time delay)
  - amplitude (dispersion)
  - quality factor (Q)

Love Mode SAW

- High sensitivity

Flexural Wave (Lamb) Plate

- High sensitivity than SAW
- Using a low velocity lamb wave allows the device to operate at low frequency
- The velocity can be made lower than the velocity of compression wave in common liquid, permitting low loss operation
- Heat capacity is low due to the reduced thickness
Acoustic Wave Devices

- Love Mode SAW Devices as gas sensor

![Diagram of Love wave delay line and oscillator setup]

Fig. 1. (a) Cross-section of a Love wave delay line. (b) Oscillator setup.

Table 1

| Sensor/wave type                        | Typical $|S_m|$ in cm²/g |
|-----------------------------------------|------------|
| Quartz crystal microbalance             | 10–20      |
| (bulk wave resonator)                   |            |
| Rayleigh wave                           | 100–200    |
| Acoustic plate mode device              | 10–40      |
| Lamb wave (flexural plate mode)         | 200–1000   |
| Love wave                               | 150–500    |
Acoustic wave devices

SEM of liquid traps at the border between an IDT and the propagation path of a Love mode sensor
**Acoustic Wave Devices**

- Love Mode SAW Devices

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Fig. 2. Transmission function (forward scattering parameter $S_{21}$) of the delay line with and without coating. Electromagnetic cross-talk using a time domain gate.
Love Mode SAW Device as gas sensor

Relative frequency change $\frac{\Delta f}{\Delta f_c}$ due to MMP exposure for imprinted and non-imprinted (control) device.

2-methoxy 3-methyl pyrazine, MMP, is a substance used in perfume industry.
Acoustic Wave Devices

- Love Mode SAW Devices as gas sensor
Acoustic wave devices

Fig. 28 FPW sensor. Insets show cutaway view of membrane, velocities of $A_0$ and $S_0$ modes, and the relatively large decrease of oscillation frequency produced by mass loading.
Acoustic wave devices

Lamb Wave sensor

The phase velocity $v_{ph}$ of a stress-free $A_0$ Lamb wave can be derived as

$$v_{ph} = \frac{2\pi}{\lambda} \cdot \sqrt{\frac{d^3 \cdot E}{M_{eff} \cdot 12 \cdot (1 - \nu^2)}}$$

Effective mass

$$M_{eff} = m_{pl} + m_{ads} + \rho \cdot \delta + \sqrt{\frac{\rho \cdot \eta}{2\omega}}$$
Acoustic wave devices

TABLE 1  Factors that Affect Ultrasonic Wave Velocity

<table>
<thead>
<tr>
<th>Influence</th>
<th>Mode</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change elastic stiffness</td>
<td>B, S, P</td>
<td>Temperature change; sorption</td>
</tr>
<tr>
<td>Change density</td>
<td>B, S, P</td>
<td>Temperature change; polymer curing; sorption</td>
</tr>
<tr>
<td>Change piezoelectric stiffness</td>
<td>B, S, P</td>
<td>Dielectric loading; illumination of semiconductor</td>
</tr>
<tr>
<td>Change thickness</td>
<td>B, P</td>
<td>Etching; deposition; sorption</td>
</tr>
<tr>
<td>Change length</td>
<td>B, S, P</td>
<td>Temperature change; change of transducer position</td>
</tr>
<tr>
<td>Change tension</td>
<td>P</td>
<td>Pressure; acceleration force</td>
</tr>
<tr>
<td>Reactive surface</td>
<td>B, S, P</td>
<td>Sorption</td>
</tr>
<tr>
<td>Dissipative surface loading</td>
<td>B, S, P</td>
<td>Viscous fluid loading</td>
</tr>
</tbody>
</table>

B, S, and P denote bulk, surface, and flexural plate modes respectively.

TABLE 2  Application Summary of Three Major Piezo-Films ZnO, AlN, and PZT

<table>
<thead>
<tr>
<th>Applications</th>
<th>ZnO</th>
<th>AlN</th>
<th>PZT</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure sensors</td>
<td>✓</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Gas sensors</td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Bulk acoustic resonators</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Plate mode sensors</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Accelerometers</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>TV VIF filters</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>SAW devices</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Actuator/translator</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

These key films are considered essential for producing high-performance acoustic sensors. Table 2 shows a summary of possible applications and potential

- **Consideration when designing an acoustic wave devices**

  1. value of electromechanical coupling;
  2. good adhesion to substrate;
  3. resistance to environmental effects (e.g., humidity, temperature);
  4. VLSI process compatible (e.g., deposition methods and etching);
  5. temperature and acceleration sensitivity;
  6. cost effectiveness.
Acoustic wave devices

- **Measurement Methods: Oscillator vs. delay line approach**
  - **Oscillator:** frequency $\Delta f/f = S_m \Delta m$
    
    $S_m$: mass sensitivity, $\Delta m$: mass/unit area

- **Delay line:** phase shift (time delay)
  - amplitude (dispersion)
  - quality factor ($Q$)

### TABLE 2.6. Characteristics of Acoustic Wave Devices

<table>
<thead>
<tr>
<th>Device</th>
<th>Wave Launched</th>
<th>Particle Displacement Components</th>
<th>Transducers</th>
<th>Operating Frequency (MHz)</th>
<th>Analytical Phase</th>
<th>Mass Sensitivity $^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSM</td>
<td>Bulk</td>
<td>Transverse</td>
<td>Planar Electrode</td>
<td>5–15</td>
<td>Gas, liquid</td>
<td>$- \frac{1}{\rho_m d}$</td>
</tr>
<tr>
<td>SAW</td>
<td>Surface</td>
<td>Transverse Parallel</td>
<td>IDT</td>
<td>30–500</td>
<td>Gas</td>
<td>$-f_0 \frac{K_1}{\rho_m V}$</td>
</tr>
<tr>
<td>FPW</td>
<td>Surface</td>
<td>Transverse Parallel</td>
<td>IDT</td>
<td>2–7</td>
<td>Gas, liquid</td>
<td>$- \frac{1}{2 \rho_m d}$</td>
</tr>
<tr>
<td>SH-APM</td>
<td>Surface</td>
<td>Transverse</td>
<td>IDT</td>
<td>25–200</td>
<td>Gas, liquid</td>
<td>$- \frac{J}{\rho_m d}$</td>
</tr>
<tr>
<td>STW</td>
<td>Surface</td>
<td>Transverse</td>
<td>IDT</td>
<td>200–500</td>
<td>Gas, liquid</td>
<td>$-f_0 \frac{K_2}{\rho_m V}$</td>
</tr>
<tr>
<td>TRAW</td>
<td>Bulk</td>
<td>Piezoelectric Horn</td>
<td></td>
<td>0.2–0.5</td>
<td>Gas, liquid</td>
<td>$- \frac{L}{\rho_m a}$</td>
</tr>
</tbody>
</table>

$^a$ Relative to the direction of wave propagation.

$^b$ Key: $\rho_m$: density of sensor material; $d$: plate thickness; $V$: acoustic wave velocity; $f_0$: unperturbed device frequency; $K_1$: constant depending on plate properties; $K_2$: constant depending on plate properties and grating; $a$: radius of cross section of thin rod; $J = 0.5$ for $n = 0$ and $J = 1$ for $n > 0$; $L = 1$ for first extensional mode and $L = 1/2$ for first flexural mode. Both FPW and SH-APM expressions include the free isotropic plate assumption.
**Acoustic Wave Devices**

![Image of acoustic wave devices](image)

**Table 1** Survey of some of the properties of various acoustic wave devices\(^{12,15–18}\)

<table>
<thead>
<tr>
<th>Type of device</th>
<th>Particle displacement (relative to the wave propagation direction)</th>
<th>Typical operation frequency MHz</th>
<th>Mass sensitivity(^a,b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSM</td>
<td>Transverse</td>
<td>5–20</td>
<td>(-1/(\rho t))</td>
</tr>
<tr>
<td>SAW</td>
<td>Transverse and parallel component</td>
<td>30–500</td>
<td>(-f_0K_1/(\rho V))</td>
</tr>
<tr>
<td>FPW</td>
<td>Transverse and parallel component</td>
<td>2–7</td>
<td>(-1/(2\rho t))</td>
</tr>
<tr>
<td>SH-APM</td>
<td>Transverse</td>
<td>25–200</td>
<td>(-J/(\rho t))</td>
</tr>
<tr>
<td>STW</td>
<td>Transverse</td>
<td>200–500</td>
<td>(-f_0K_2/(\rho V))</td>
</tr>
<tr>
<td>TRAW</td>
<td>Transverse (flexural mode) and parallel (extensional mode)</td>
<td>0.2–2</td>
<td>(-1/(\eta \rho a))</td>
</tr>
<tr>
<td>Tube</td>
<td>Parallel (extensional mode)</td>
<td>2</td>
<td>(-1/[\rho(b - a_1)/(1 + a_1/b)])</td>
</tr>
</tbody>
</table>

\(^a\) Mass sensitivity \((S_m)\) is defined as \(S_m = \lim (\Delta \nu)/(v_0 \Delta m) \Delta m \rightarrow 0\), where: \(\Delta m\) is added mass, \(\Delta \nu\) is change in phase velocity and \(v_0\) is unperturbed phase velocity. \(^b\) \(\rho\), Density of the sensor material; \(t\), plate thickness; \(f_0\), fundamental, unperturbed frequency of the device; \(K_1\), constant dependent on the properties of the plate of the SAW device; \(V\), wave velocity; \(J\), \(J = 1/2\) for an isotropic plate mode \((n_1)\) \(n_1 = 0\) and \(J = 1\) for \(n_1 > 0\); \(K_2\), constant dependent on the properties of the STW device; \(n\), \(n = 1\) for the first extension mode and \(n = 2\) for the flexural mode; \(a\), radius of the thin rod; \(b\) and \(a_1\), external and internal diameter of the tube, respectively.
# Acoustic wave devices

<table>
<thead>
<tr>
<th>Property</th>
<th>QCM</th>
<th>HF-QCM</th>
<th>SH-APM</th>
<th>Love</th>
<th>STW</th>
<th>Lamb</th>
<th>Reflected Rayleigh</th>
<th>SSBW, leaky</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode</td>
<td>Bulk</td>
<td>Bulk</td>
<td>Reflected plate</td>
<td>Film waveguide</td>
<td>Grating waveguide</td>
<td>Ao plate</td>
<td>Surface</td>
<td>Surface</td>
</tr>
<tr>
<td>Sensitivity:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>$\eta$</td>
<td>+</td>
<td>++</td>
<td>+</td>
<td>++</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>0</td>
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<td>$\rho$</td>
<td>(+)*</td>
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<td>++</td>
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<td>$c$</td>
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<td>-</td>
<td>-</td>
<td>0</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>$\delta, \varepsilon$</td>
<td>-</td>
<td>-</td>
<td>0 to ++</td>
<td>- to +</td>
<td>0</td>
<td>-</td>
<td>++</td>
<td>0 to ++</td>
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<tr>
<td>Typ frequency (MHz)</td>
<td>2–20</td>
<td>20–100</td>
<td>50–200</td>
<td>50–500</td>
<td>50–500</td>
<td>1–10</td>
<td>50–500</td>
<td>50–500</td>
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<tr>
<td>Sensitivity determined by</td>
<td>Plate thickness</td>
<td>Plate thickness</td>
<td>Plate thickness</td>
<td>Waveguide thickness, frequency</td>
<td>Frequency</td>
<td>Membrane thickness</td>
<td>Frequency</td>
<td>Frequency</td>
</tr>
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<td>Frequency determined by</td>
<td>Plate thickness</td>
<td>Plate thickness</td>
<td>Plate thickness, IDT period</td>
<td>IDT period</td>
<td>Membrane thickness, IDT period</td>
<td>IDT period</td>
<td>IDT period</td>
<td></td>
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<tr>
<td>Cross sensitivities</td>
<td>Pressure (temp.) (electrical liquid properties)</td>
<td>Pressure (temp.) (electrical liquid properties)</td>
<td>Pressure, electrical liquid properties (temp.)</td>
<td>(Electrical liquid properties) (temp.)</td>
<td>Electrical liquid properties (temp.)</td>
<td>Pressure, electrical liquid properties (temp.)</td>
<td>Electrical liquid properties (temp.)</td>
<td>Electrical liquid properties (temp.)</td>
</tr>
</tbody>
</table>
Acoustic wave sensors

High relative humidity range sensor based on polymer-coated STW resonant device

Layout of a polymer-coated STW resonator

Frequency response of uncoated STW device (S12-parameter).

Humidity frequency characteristics (HFC)
Acoustic wave devices

Influence of Newtonian liquid viscosity on Love wave phase velocity
Acoustic wave devices

Liquid sensor probe using reflecting SH-SAW delay line

Schematic view of the SAW sensor probe using edge reflection (six channel reflecting SAW sensor). SH-SAW shows complete reflection at free edge of the substrate.

Reflected pulse trains obtained by the SH-SAW sensor constructed on 36° YX LiNbO3 substrate.
Acoustic wave devices

- Starting materials, silicon (100) with required epi layers
- Wafer is thermally oxidized and the front side is patterned for the cantilever beam
- EDP etching for the opening through the epi layers
- ZnO capacitor fabrication steps
- Back side patterning with gold and thick resist for ECC etching
- End view of beam after ECC etching is complete

Fig. 20 Cross-section of Si cantilever-beam accelerometer designed for two-sided etching. (a) Drawn to scale. (b) Vertical scale increased to show detail of composite structure.

◆ Cantilever beam accelerometer
Acoustic wave devices

Output response of a typical monolithic accelerometer, $g^2$ error term is 50 dB below linear term.

- Accelerometer
Vibration and acceleration sensors

- Force is converted into displacement
- Spring elastic constant:
  \[
  c = \frac{3 \times E \times I}{L^3} \\
  I = \frac{b \times h^3}{12}
  \]
  \[E_{\text{quartz}} \approx 65 \cdot 10^9\]
- Cut of frequency for mechanic vibration of typical SAW substrate \(\sim\) few kHz

Figures from Ref. 3


Vibration and acceleration sensors

- Additional seismic mass and damping can be added to the substrate tip
- Remote readout

Sensor readout vs. acceleration
(membrane of a loudspeaker)

**Torque Sensors**

Rigidly mounted to a flat spot on a shaft
Shaft experiences torque
→ torque will stress the sensor

Two SAW torque sensors at right angles:
→ When one is in compression, the other is in tension
→ temperature drift effects can be minimized

Provides lower cost and higher reliability than competing technologies

A SAW gyro sensor on 128° Y-cut LiNbO₃

Coriolis force generates a secondary SAW in the orthogonal direction (at least in theory)


Humidity Sensors

- Mass loading, acoustoelectric and viscoelastic effects contribute to change in SAW velocity\(^\circ\)
- Example with polymer hygroscopic film @ 50 MHz\(^\circ\)
- Many different hygroscopic films can be used \(^\circ,\circ,\circ,\circ\)

Figures from Ref. \(^\circ\)

Dew point sensor

- Temperature controlled SAW sensor exposed to the ambient atmosphere → water will condense at the dew point temperature

- A 50 MHz YZ-cut LiNbO$_3$ SAW dew point sensor$^\circledast$ with reported resolution of ±0.025°C (vs. ±0.2°C for optical sensor)

$^\circledast$ Vetelino et. Al., “Improved dew point measurements based on a SAW sensor”, Sensors and Actuators, B 35, p. 91, 1996
Voltage sensor

ZnO-SiO₂-Si layered structure

485 MHz double oscillators with metal waveguides on 128° LiNbO₃

Achieved response
(Ref. 1)

Achieved response
(Ref. 2)

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Flow Sensor

- A SAW oscillator is heated above ambient temperature and placed in the path of flowing gas → convective cooling results in a change in the oscillator frequency

A 73 MHz 128° Y-cut LiNbO₃ heated to 55°C shows $\Delta f = 142$ kHz for flow rate variation from 0 to 1000 cm³/min

Others

- **Magnetic field Sensors**
- **Water content Sensors**
- **Vapor chemical Sensors**

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Acoustic Wave Devices

**Advantages:**
- Good sensitivity
- Small size & light weight
- Remote reading (in some cases)
- Cost effective (in some cases)

**Disadvantages:**
- Some sensor types still at laboratory stage
- Only few products are available commercially?
Electrostatic ink jet printer

Pressure plate length $L : 2.853 \text{(mm)}$
Pressure plate width $W : 108 \text{(\mu m)}$
Pressure plate thickness $T : 2.15 +/- 0.35 \text{(\mu m)}$
Air gap length $g : 0.18 +/- 0.018 \text{(\mu m)}$
Nozzle diameter $D_n : \phi 28 +/- 2 \text{(\mu m)}$
Nozzle length $L_n : 25 \text{(\mu m)}$
Electrostatic ink jet printer

Fig.3: The mechanism of ink ejection: (a) initial state, (b) DC voltage is applied between the pressure plate and the electrode, (c) DC voltage is reduced to 0 and an ink drop is ejected

1) High printing quality (such as for bar code)
2) High speed printing (high throughput)
3) Small size
4) Low power consumption
5) Long life and durability under heavy duty usage
6) Low acoustic noise
7) Plain paper printing versatility

Typical driving voltage V: 26.5 (V)
Driving (ejecting) frequency f_d: \( \leq 16 \) (kHz)
Nozzle pitch p: 141.2 (\( \mu \) m)
Ink drop weight w: 22.5 (ng/drop)
Ink drop velocity v: 6.5 (m/sec) +/-20%
Deviation of ejecting direction: \( \leq 1^\circ \)
Electrostatic ink jet printer

Fig. 4: Fabrication process of the nozzle substrate
(a) Multiple step mask patterning
(b) 1st deep-RIE
(c) 2nd deep-RIE
(d) Thermal oxidation and patterning
(e) Wet anisotropic etching
(f) Final thermal oxidation

Fig. 5: Cross-sectional SEM photographs of a nozzle (a) after 1st deep-RIE and (b) after 2nd deep-RIE
Electrostatic ink jet printer

Fig. 10: Fabrication process of the cavity substrate
(a) Boron diffusion and thermal oxidation
(b) Multiple-step mask patterning
(c) 1st KOH wet anisotropic etching
(d) 2nd KOH wet anisotropic etching
(e) Final thermal oxidation and common electrode formation

Fig. 11: Roughness of the etched surface after (a) 1st, 35% KOH etching and (b) 2nd, 2.5% KOH etching