Rayleigh Surface Acoustic Wave (SAW) devices

SAW mode of propagation

Lord Rayleigh, 1881: “On waves propagating along the plane of an elastic solid”

- A Rayleigh wave is composed of a longitudinal and a vertical shear component

- Wave bound to the surface → effectively is an evanescent wave

- The amplitude of the surface wave (~ 10Å) is small compared with the wavelength and falls off exponentially with the distance from the surface.

- Penetration depth of the wave into the substrate varies inversely proportional with the frequency.

- see animations in:
  http://www.kettering.edu/~drussell/Demos/waves/wavemotion.html
Surface Acoustic Wave (SAW) device

White, Voltmer 1965: “Direct piezoelectric coupling to surface acoustic waves”

- Interdigitated (IDT) thin-film metal electrodes deposited on top of a piezoelectric substrate

- When a potential is applied to an IDT, it causes a periodic displacement of the surface (and also a surface potential wave).

\[
V_R \equiv \text{velocity of the Rayleigh wave} \quad (3158 \text{ m/s for ST-cut quartz})
\]

\[
f_0 = \frac{V_R}{\lambda} = \frac{V_R}{4d} \quad \equiv \text{resonance frequency}
\]
Surface Acoustic Wave (SAW) device

Oscillator circuit

- **Delay**: a) delay between applied electric field and displacement
  b) Delay due to propagation time
  c) Delay in the amplifier

- **Attenuation**

\[ \omega = \frac{(2n\pi - \varphi_e) V_R}{L} \]

**Mass sensitivity**

- Any factor affecting \( V_R \) will change the resonance frequency \( f_0 \)

\[
\frac{\Delta \nu}{\nu_0} = \frac{1}{\nu_0} \left[ \frac{\partial \nu}{\partial m} \Delta m + \frac{\partial \nu}{\partial c} \Delta c + \frac{\partial \nu}{\partial T} \Delta T + \frac{\partial \nu}{\partial \sigma} \Delta \sigma + \frac{\partial \nu}{\partial p} \Delta p \right]
\]

\( m \equiv \text{surface mass} \quad T \equiv \text{temperature} \quad p \equiv \text{pressure} \\
(\sigma \equiv \text{surface conductivity})

Biochemical Sensors

José Antonio Garrido, Tel. 089/ 289 12766, garrido@wsi.tum.de
Mass sensitivity

Wohltjen (Sens. Actuat. 1984, Vol5, pg 307) → assuming the presence of a thin (h<<λ), lossless, isotropic, insulating film:

\[ \Delta f = C_S f_0^2 \frac{\Delta m}{A} - k f_0^2 \xi(\mu, \eta) \]

\( C_S \equiv \) mass sensitivity (\( \sim 1.35 \times 10^{-6} \text{ cm}^2 \text{ s g}^{-1} \)) of the substrate for quartz

\( \Delta f \propto f_0^2 \) \( \Rightarrow \) higher frequency of operation by reducing the finger and gap width of the interdigitated transducers.

in principle SAW could be operated to give mass sensitivities down to the fg (10^{-15} g) level!

\( \Rightarrow \) main disadvantage: Rayleigh SAW devices cannot be operated in liquids

- the out-of-plane component (shear vertical) couples into the liquid and generates a compressional wave. \( \leftrightarrow \) very efficient process
Surface Acoustic Wave (SAW) device

Signal measurements
- Attenuation (two port IDT)
- Delay or Phase shift (two port IDT)
- Resonance frequency (one port IDT)

Sensor Principles 1 -
Influence of Physical Effects on SAW Properties

<table>
<thead>
<tr>
<th>SAW property</th>
<th>Change in bulk elastic constants</th>
<th>Stress loading / Stiffening</th>
<th>Mass loading</th>
<th>Viscous loading</th>
<th>Electrical loading</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Attenuation</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Reflection factor</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Time delay</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Sensor Principles 2 -
Origin of Physical Effects

<table>
<thead>
<tr>
<th>Effect</th>
<th>Possible origin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change in bulk elastic constants</td>
<td>Mechanical forces (static stretching, compressing, twisting, bending, acceleration etc.)</td>
</tr>
<tr>
<td></td>
<td>Temperature</td>
</tr>
<tr>
<td></td>
<td>Electric field</td>
</tr>
<tr>
<td></td>
<td>Radiation (light, corpuscular radiation, etc.)</td>
</tr>
<tr>
<td>Stress loading / Stiffening</td>
<td>Gas adsorption by a coating (change of elastic constants in layer)</td>
</tr>
<tr>
<td></td>
<td>Effect of electromagnetic field on electrostrictive or magnetostrictive coating</td>
</tr>
<tr>
<td>Mass loading</td>
<td>Gas adsorption by a coating (mass effect)</td>
</tr>
<tr>
<td>Viscous loading</td>
<td>Friction caused by interaction with loading liquid or viscoelastic polymer</td>
</tr>
<tr>
<td>Electrical loading</td>
<td>Change of conductivity or permittivity in a coating or in a loading liquid</td>
</tr>
</tbody>
</table>
Surface Acoustic Wave (SAW) device

Signal measurements

- Attenuation (two port IDT)
- Delay or Phase shift (two port IDT)
- Resonance frequency (one port IDT)

Examples -
Selected SAW Chemosensors from the Literature

<table>
<thead>
<tr>
<th>Analyte</th>
<th>Sensitive coating</th>
<th>Sensitivity [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂O</td>
<td>Polystyrene sulfonic acid sodium</td>
<td>507.6</td>
</tr>
<tr>
<td>CO₂</td>
<td>Polyethyleneimine</td>
<td></td>
</tr>
<tr>
<td>H₂S</td>
<td>WO₃</td>
<td>5</td>
</tr>
<tr>
<td>NO₂</td>
<td>Copper-Pthalocyanine</td>
<td>13.1</td>
</tr>
<tr>
<td>Octane (alkane)</td>
<td>Polydimethylsiloxane</td>
<td>0.1</td>
</tr>
<tr>
<td>Ethanol (alcohol)</td>
<td>Hydroxybutylmethylcellulose</td>
<td>0.9</td>
</tr>
<tr>
<td>Acetone (ketone)</td>
<td></td>
<td>0.6</td>
</tr>
<tr>
<td>Acetic acid (carboxylic acid)</td>
<td>α-tricosenoic acid</td>
<td>0.007</td>
</tr>
<tr>
<td>Dimethylphosphonate (organophosphorous compound)</td>
<td>Mercaptopoundecanoic acid with Cu²⁺</td>
<td>0.15</td>
</tr>
<tr>
<td>Toluene (aromatic compound)</td>
<td>Ethylene/vinylacetate copolymer</td>
<td>7.2</td>
</tr>
<tr>
<td>Dichloromethane (chlorin. hydrocarb.)</td>
<td>Polycarbonate resin</td>
<td>1</td>
</tr>
<tr>
<td>Citral (terpene)</td>
<td>Phosphatidyethanolamine</td>
<td>45.2</td>
</tr>
<tr>
<td>Tetrahydrofuran (heterocyclic comp.)</td>
<td>Triphenylmethyl</td>
<td>0.002</td>
</tr>
</tbody>
</table>

Examples -
Selected SAW Physical Sensors from the Literature

<table>
<thead>
<tr>
<th>Measurand</th>
<th>Device</th>
<th>Freq. [MHz]</th>
<th>Substrate</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>DL</td>
<td>90</td>
<td>AlN/Si</td>
<td>27 ppm/kPa</td>
</tr>
<tr>
<td>Force</td>
<td>DL</td>
<td>8.3</td>
<td>LiNbO₃</td>
<td>10.8 ppm/kN</td>
</tr>
<tr>
<td>Strain</td>
<td>DL</td>
<td>10.9</td>
<td>PZT</td>
<td>21 ppm/10⁻⁶</td>
</tr>
<tr>
<td>Position (linear)</td>
<td>DL</td>
<td>8.3</td>
<td>LiNbO₃</td>
<td>120 ppm/µm</td>
</tr>
<tr>
<td>Acceleration</td>
<td>DL</td>
<td>251</td>
<td>Quartz</td>
<td>45 ppm/(m/s²)</td>
</tr>
<tr>
<td>Flow rate</td>
<td>DL</td>
<td>73</td>
<td>LiNbO₃</td>
<td>204 ppm/(cm²/s)</td>
</tr>
<tr>
<td>Liquid viscosity</td>
<td>DL</td>
<td>30</td>
<td>LiNbO₃</td>
<td>2.7 ppm/cP</td>
</tr>
<tr>
<td>Liquid density</td>
<td>DL</td>
<td>6</td>
<td>ZnO/Si₃N₃</td>
<td>30 000 ppm/(g/cm³)</td>
</tr>
<tr>
<td>Electric field</td>
<td>R</td>
<td>85</td>
<td>Li₂B₄O₇</td>
<td>300 ppm/(V/µm)</td>
</tr>
<tr>
<td>Voltage</td>
<td>DL</td>
<td>900</td>
<td>LiNbO₃</td>
<td>0.93 ppm/V</td>
</tr>
<tr>
<td>Liquid conductivity</td>
<td>DL</td>
<td>51</td>
<td>LiTaO₃</td>
<td>13 400 ppm/(S/m)</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>DL</td>
<td>140</td>
<td>Fe-B/Quartz</td>
<td>0.38 ppm/(A/m)</td>
</tr>
<tr>
<td>Temperature</td>
<td>DL</td>
<td>43</td>
<td>LiNbO₃</td>
<td>92.13 ppm/°C</td>
</tr>
<tr>
<td>Radiation dose</td>
<td>R</td>
<td>199</td>
<td>Quartz</td>
<td>0.48 ppm/(J/kg)⁰.⁵</td>
</tr>
<tr>
<td>Thin film thickness</td>
<td>DL</td>
<td>75</td>
<td>LiNbO₃</td>
<td>9.25 ppm/µm</td>
</tr>
</tbody>
</table>
Acustoelectric response

- The evanescent electric field associated with the acoustic wave is coupled to the surroundings’ charge carriers.

- Acustoelectric coupling results in:
  i) Wave velocity decrease
  ii) Attenuation

In contrast, mass loading produces a linear decrease of velocity.
Incoming sound energy, transmitted as pressure variations of the cochlear fluid, is sensed and amplified by the three rows of OHCs, which can sense deflection of their stereocilia or of pressure. The cell body of OHC can change length almost instantaneously.

The three rows of OHC has the same function that the IDT of a SAW device. By reacting to the sound energy, a standing wave, ripples at the surface of the tectorial membrane, is generated.

Hensen’s stripe is ideally placed to absorb acoustic energy from the resonant cavity and deliver it to the stereocilia of the Inner Hair Cells (IHC) underneath.
Shear Horizontal Acoustic Plate Mode (SH-APM)

- Pseudo surface waves, horizontally polarized bulk shear waves in a thin piezoelectric plate
- The surface displacement of the SH wave is in the plane of the substrate surface → no out-of-plane displacement
  - Wave motion not damped by contact with a liquid

### Mass sensitivity

\[
\Delta f = C f_0 \rho \quad \text{at high frequency}
\]
\[
C \propto \frac{1}{b}
\]
\[
\Delta f \propto f_0^2 \quad 13-50 \text{ MHz}
\]

- Sensitivity weakly frequency dependent when compared to QCM or Rayleigh SAW

SH can operate with the sensing liquid and the IDTs on opposite sides of the plate avoiding the problem of electrical coupling between the electrodes.

- In liquid operation at 345 MHz
- Immunoglobulin (IgG) antibodies immobilized on the sensitive path
- Antigen detection:
  - detection limit of about 33 pg
  - sensitivity of 110 kHz/ (ng/mm²)

![Image of a Surface Acoustic Wave Immunosensor](image)

- 20 µL injections (2.1 µg/µL)

![Graphs showing phase shift and frequency change](graphs)

a) saturation of sensitive layer

b) frequency dependence → viscosity effect?
Lamb wave – Flexural Plate Mode (FPM) devices

- Special case of the Rayleigh wave, in which the thickness of the medium in which it propagates is of the order of the wavelength
- The finger spacing (and thus the frequency) are chosen to fulfill that the thickness of the FPM is thin compared to the wavelength
- Particle displacements for Lamb waves are elliptical as with Rayleigh wave
  - longitudinal and shear-vertical components

The FPW is arranged with respect to electrical IDT excitation so that only antisymmetric or flexural waves are propagated in the device
Lamb wave – Flexural Plate Mode (FPM) devices

- The propagation velocity is quite different from that of Rayleigh waves, allowing lower frequency of operation (5MHz)
- Velocity of flexural wave is significantly slower than the compressional velocity of sound in liquids
- The compressional (or evanescent) wave induced into a fluid in contact with the device does not excessively attenuate the wave motion

\[ \nu = k \left[ \frac{B}{M + (\rho_f K / k)} \right]^{1/2} \]

\[ k = \frac{2\pi}{\lambda} \]

\[ K = \sqrt{1 - \left(\frac{\nu}{\nu_f}\right)^2} \]

\[ K / k = \delta \]

increases in both mass loading of the membrane (adsorption) and fluid density (gel formation, melting/freezing of the fluid) will modify the acoustic wave velocity and will produce a frequency shift

\[ \Delta f = S_m.f\Delta m \]

\[ \Delta m = \rho\delta \]

typically \( S_m \equiv 950 \text{ cm}^2 \text{ g}^{-1} \) at 2.6MHz

\[ \delta \equiv \text{evanescent wave penetration distance} = \frac{\lambda}{2\pi} \left[ 1 - \left(\frac{\nu}{\nu_f}\right)^2 \right]^{1/2} \]

\[ B \equiv \text{effective plate stiffness} \]

\[ \rho_f \equiv \text{density of the loaded fluid} \]

\[ M \equiv \text{unloaded mass} \]

Advantages of FPM:
- High sensitivity
- Flexibility of detection at either surface

Disadvantages of FPM:
- Fabrication cost (membrane fabrication)
- Device fragility
Love wave devices

also known as surface-skimming bulk wave

Conventional SH device with a guiding layer deposited on it

- The energy of the bulk wave is concentrated in the guiding layer due to its lower shear acoustic velocity.
- The amount of energy transferred into the layer depends on the thickness and the acoustic properties of the layer.

\[ \Delta f = C(l, h)f\rho \]

\[ C(l, h) \equiv \text{The sensitivity is a function of guiding layer material (l) and thickness (h)} \]

- Love wave sensors have the advantage of SH devices (no losses in liquids) and a better sensitivity to mass loading (due to the concentration of the wave near the surface).

QCM (10MHz) → 0.23 Hz µg^{-1}
SH-SAW (158MHz) → 1.2 Hz µg^{-1}
Love (110MHz) → 26.4 Hz µg^{-1}
Love wave devices

Influence of guiding layer thickness

- As the thickness of the layer increases more of the bulk wave is concentrated in that layer, and therefore the sensitivity increases.

- At a certain thickness the layer does no longer behaves as a thin layer but as a plate, and the wave energy decreases along with the sensitivity.

**Important**: the acoustic attenuation of the layer determines the propagated energy to a receiving IDT.
Lord Rayleigh (1929) predicted that shear waves propagating at a solid-liquid interface would be attenuated by the viscous loading of the fluid.

\[ \Delta f \propto \left( \frac{\pi f_0 \eta \rho}{\eta} \right)^{1/2} \quad \eta \equiv \text{liquid viscosity} \quad \rho \equiv \text{liquid density} \]

- The viscous wave generated at the interface decays within the liquid.

\[ e^{-\frac{z}{\xi}}, \quad \xi = \left( \frac{\eta}{\pi f_0 \rho} \right)^{1/2} \quad \Rightarrow \text{if} \quad \eta \uparrow, \text{the shear wave penetrates further into the liquid} \]