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Acoustic Waves for Liquid Phase Sensing

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Overview

1. Basics of Acoustic Waves

- Sensing Principles
- Acoustic Wave Modes
- Devices

2. Layer Guided Acoustic Waves

- Love Waves & Plate Modes with Layers
- Generalized Sauerbrey and Kanazawa & Gordon

3. Advanced Concepts

- Higher Frequency and Multiple Modes
- Interfacial Slip/Coupling
- Super-hydrophobic Sensor Principles

Basics of Acoustic Waves

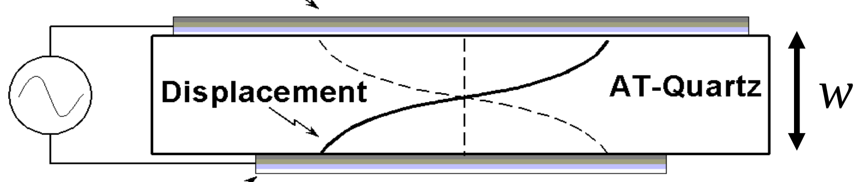
QCM Sensing Principles

Thickness Shear Mode Vibration

Sharp resonance

Frequency given by quartz thickness, w

$$v_s = f\lambda \quad \Rightarrow \quad f = 2v_s/w$$



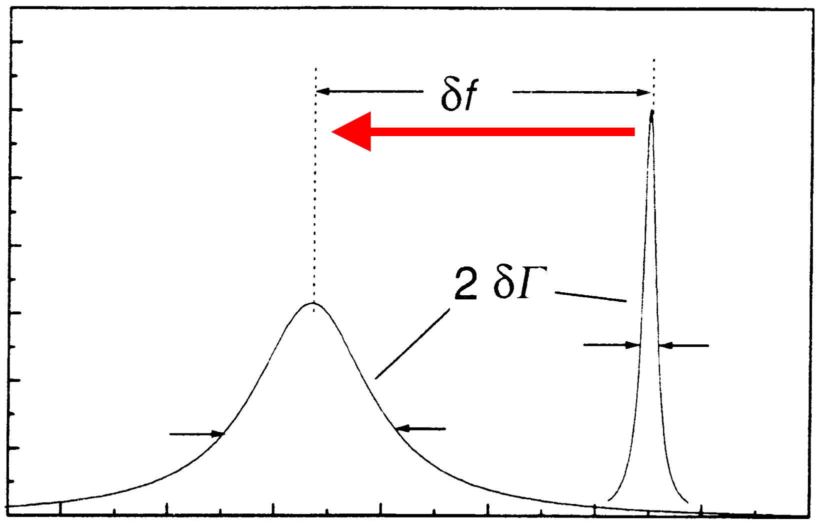
Mass Loading or Immersion

Frequency reduces due to mass

Resonance broadens due to polymer/liquid

Sauerbrey equation $\Rightarrow \Delta f \propto -f^2 \Delta m/A$

Kanazawa & Gordon $\Rightarrow \Delta f \propto -\sqrt{(\eta\rho)}\, f^{3/2}$



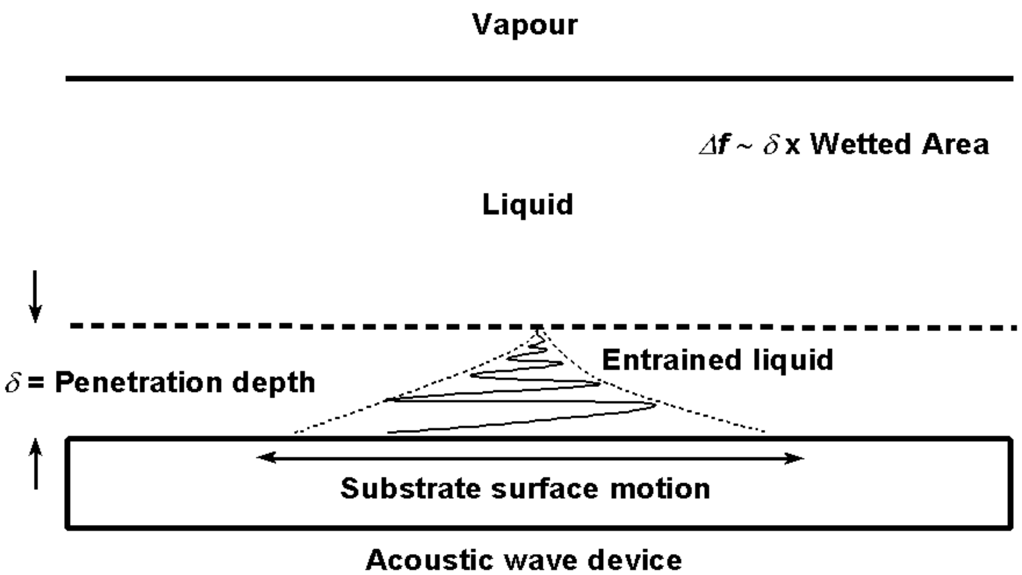
Sensitivity to mass or viscosity-density product increases with frequency

Liquids and Penetration Depth

Shear Mode Vibration

- Entrains liquid
- Liquid oscillation decays
- Penetration depth

$$\delta = (\eta / \pi f \rho)^{1/2}$$



Liquid Sensing

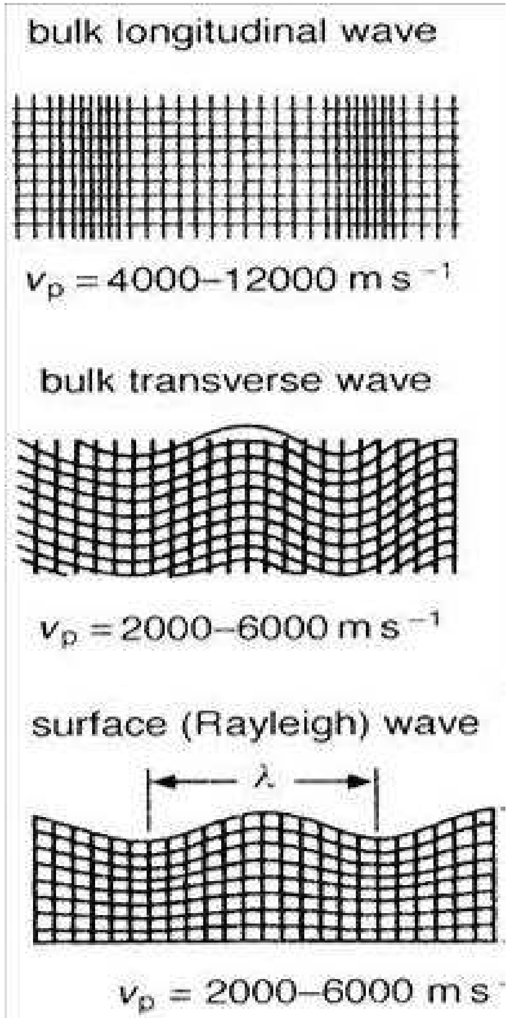
Sense liquid mass (via viscosity-density product) within penetration depth

	QCM	SAW
For water	5 MHz $\delta \sim 250$ nm	500 MHz $\delta \sim 25$ nm

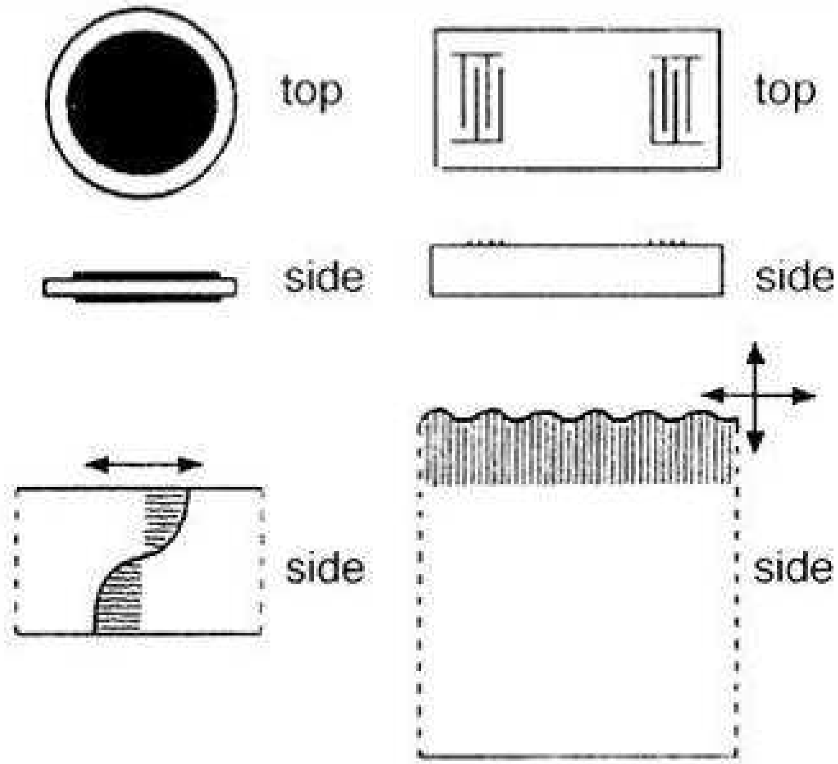
Penetration depth/sensing zone decreases with frequency

Acoustic Waves

Acoustic Waves



QCM versus SAW

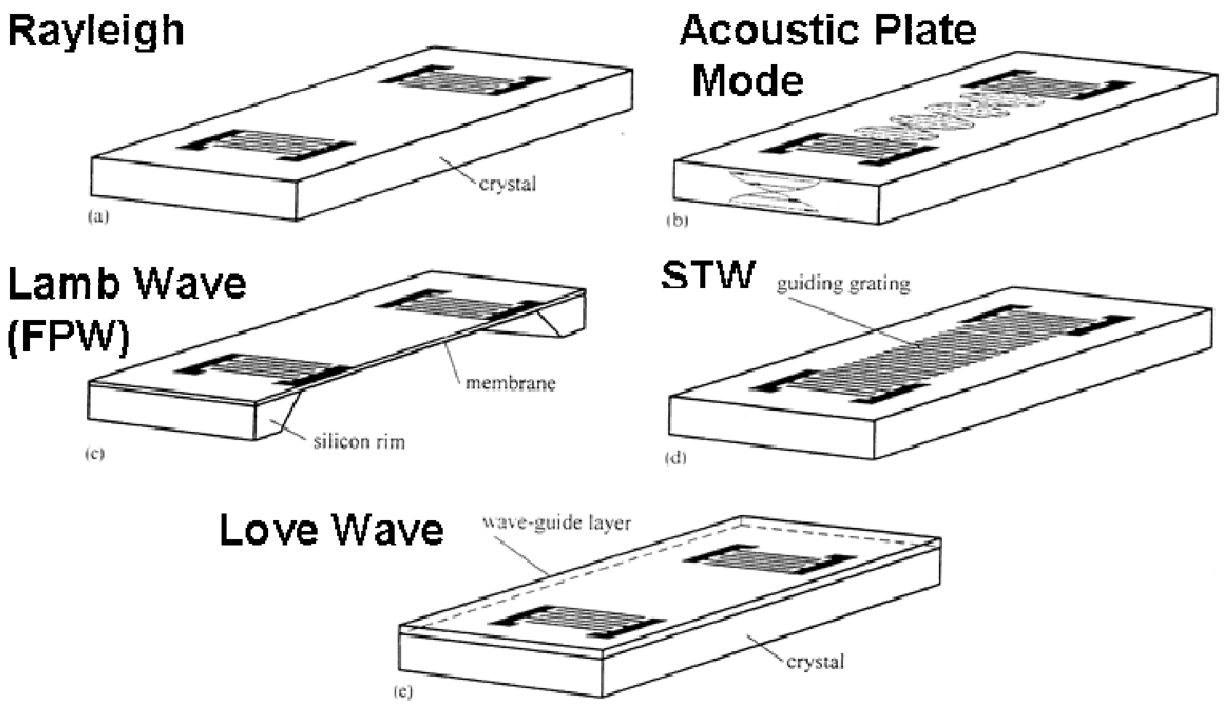


QCM – frequency determined by thickness

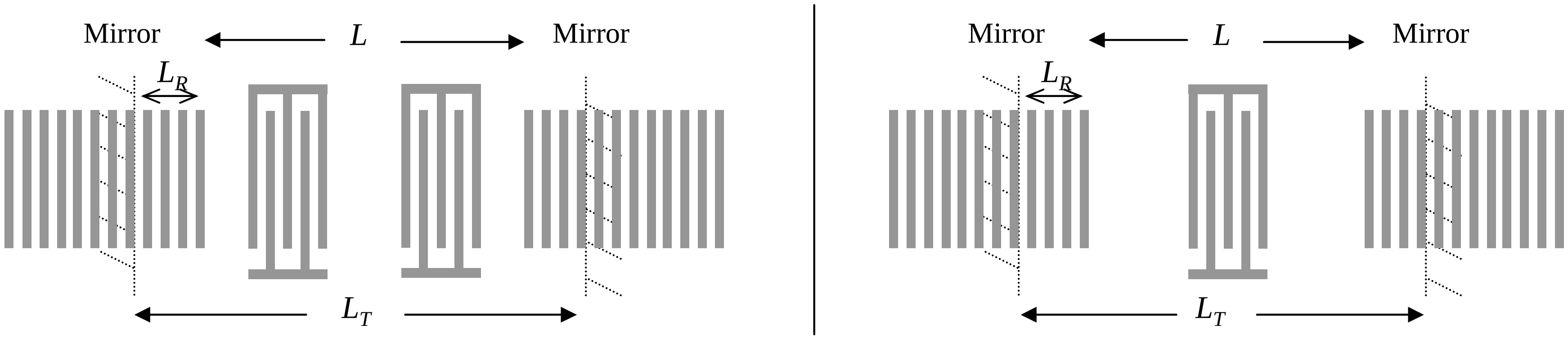
SAW – frequency determined by fingers

Acoustic Wave Modes

Delay Lines



Resonators



Acoustic Waves - Comparisons

Thickness Shear Mode

Quartz crystal microbalance (QCM)

Surface Acoustic Waves (SAWs)

Rayleigh waves, Love waves, Surface transverse waves (STWs),

Lamb waves/Flexural plate waves (FPWs)

Acoustic Plate Modes (APMs)

Shear horizontally polarised SAWs (SH-SAWs)

Surface skimming bulk waves (SSBWs)

Mode	Rel. Sens.	Complexity	Robustness	Gas/Liquid
QCM	Low	Low/Xtal	Med	g+l
SAW	High	Med/metal on Xtal	High	g
Love	High	Med/film+metal+Xtal	High	g+l
STW	High	Med/metal on Xtal	High	g+l
Lamb	High	High/membrane	Low	g+l
APM	Med	Med/metal on Xtal	Med	g+l

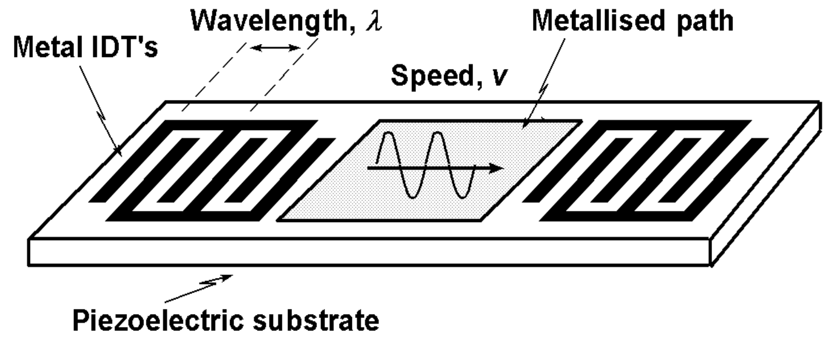
Surface Acoustic Waves

Surface Acoustic Wave

Mechanical wave along a surface

+electric field

Detection of attached mass, density-viscosity product and conductivity

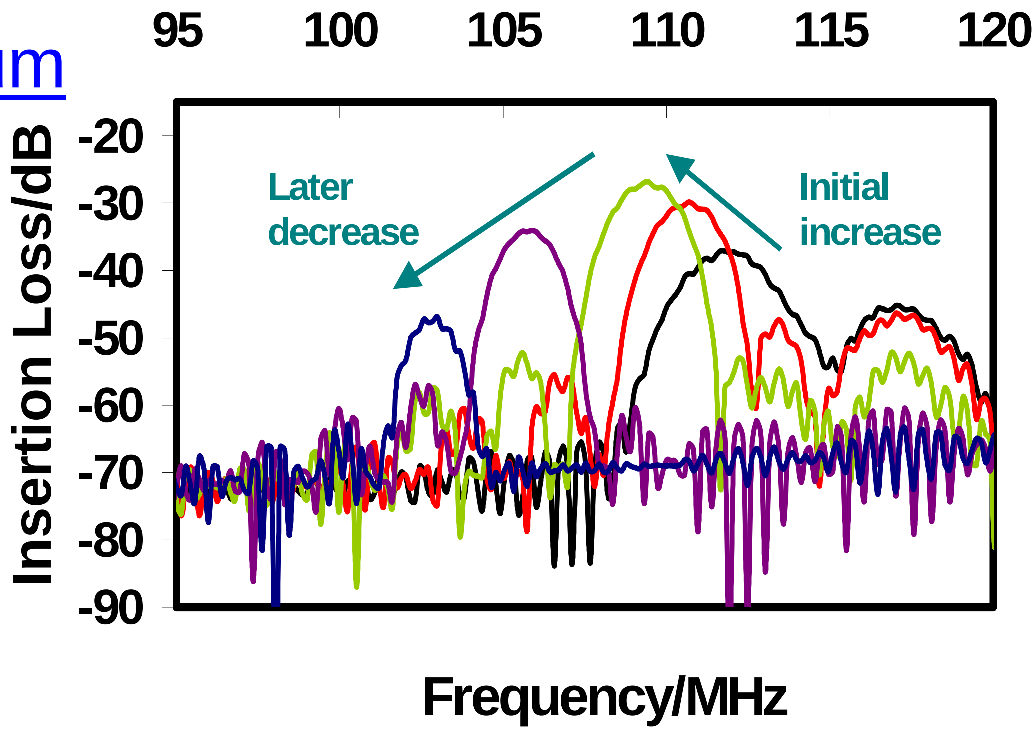


Example Love Wave Spectrum

Delay line and SSBW

110 MHz on Quartz

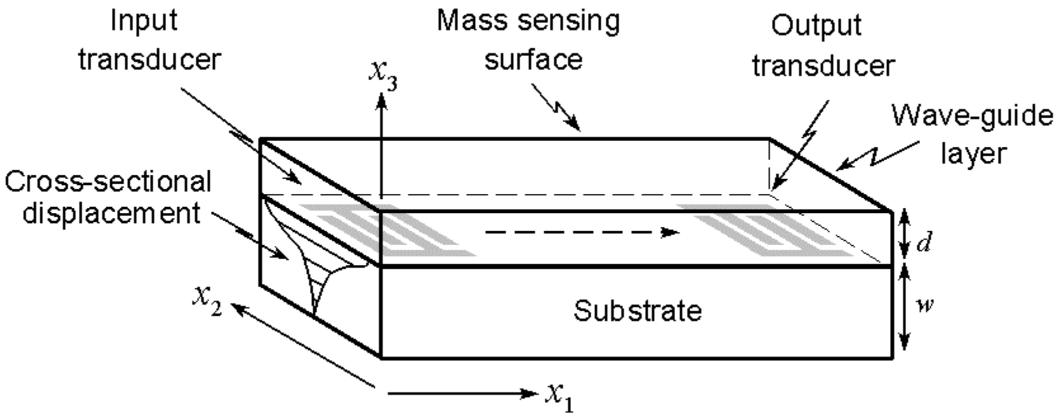
Response to polymer guiding layer thickness



Layer Guided Acoustic Waves

Love Waves versus SH-APMs

Love Wave

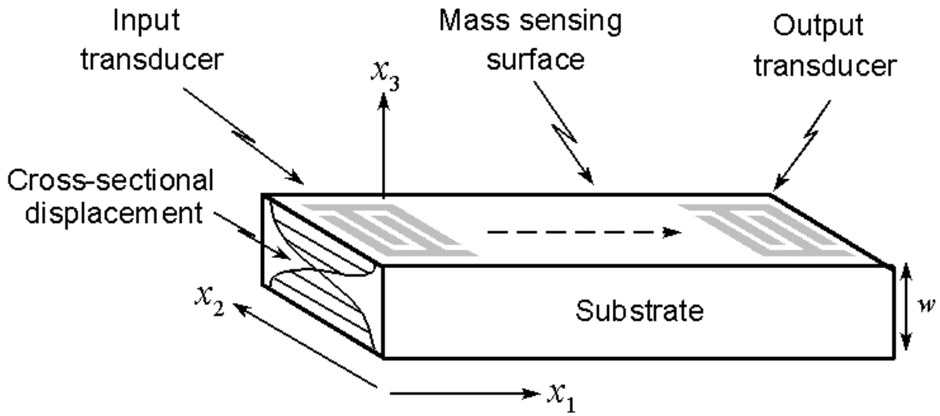


Layer guided SH-SAW with $v_l < v_s$

Surface localised wave

Increased sensitivity

SH-APM



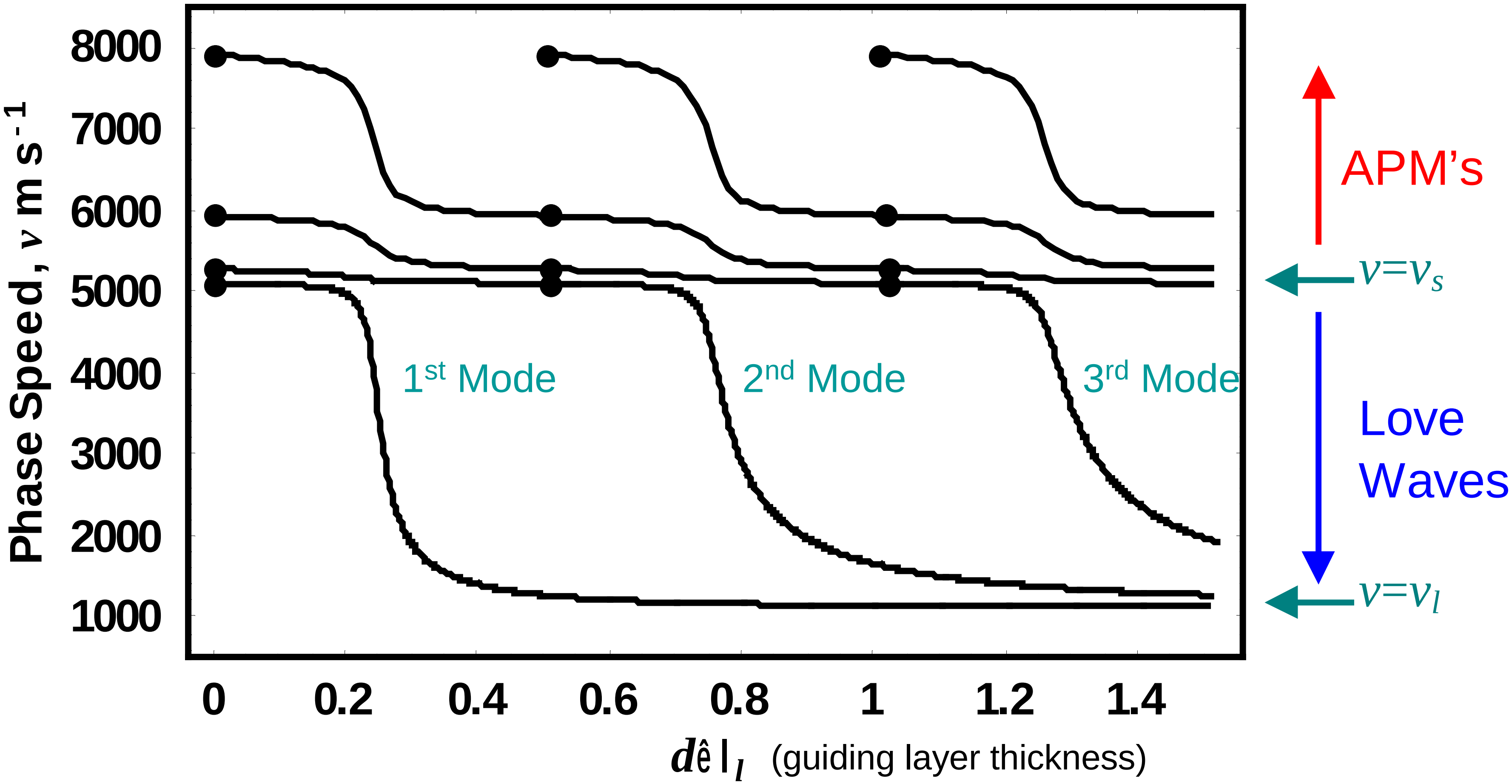
"QCM with propagation"

Substrate resonance

Sensing via both faces

Increased sensitivity versus isolation between sensing face and transduction

Generalized Love Waves - Dispersion Curve



Shear mode in substrate-to-shear mode in layer transition

Increased mass/liquid sensitivity related to slope of dispersion curve

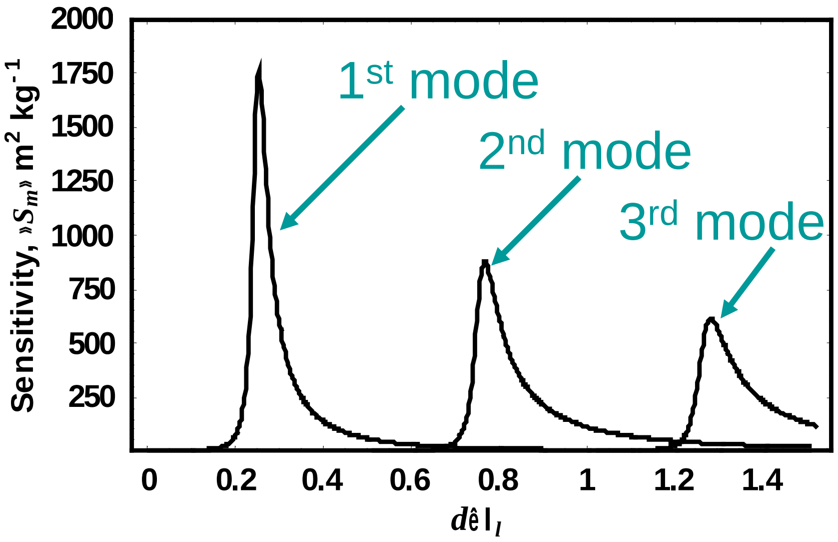
Phase Speed Mass Sensitivity

$$S_m = \lim_{\Delta m \to 0} \frac{1}{\Delta m}\left(\frac{\Delta v}{v_o}\right) \approx \frac{f_o}{\rho_l v_l}\left(\frac{d \log_e v}{dz}\right)_{z_0}$$

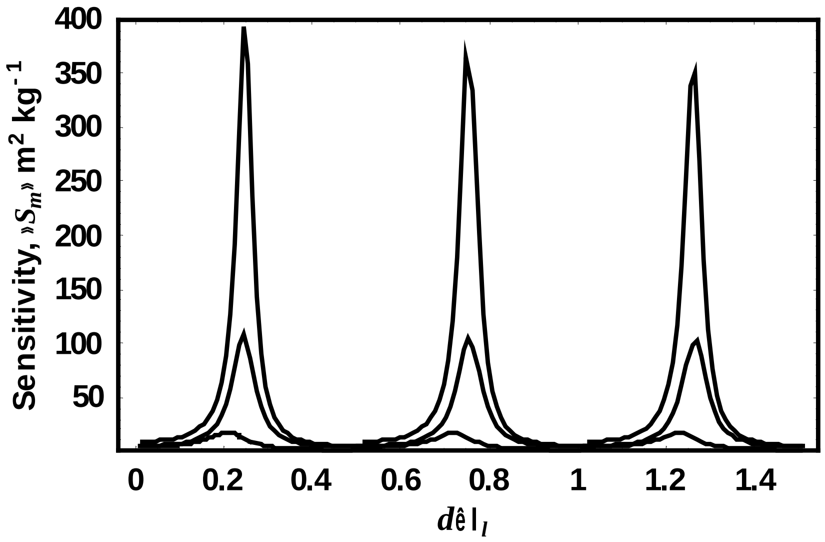
Δm is mass per unit area being sensed, $z = df/v_l$ is the normalized thickness

"Rigid" mass $\Rightarrow$ Mass sensitivity is slope of dispersion curve[1]

Love Waves



Layer-Guided SH-APMs



Generalized Sauerbrey/Kanazawa & Gordon

Polymer Waveguide on Polymer Substrate

Complex velocity shift

$$\frac{\Delta v}{v_o} \approx \left(\frac{1 - v_f^2 / v_o^2}{1 - v_l^2 / v_o^2} \right) \left(\frac{d \log_e v}{dz} \right)_{z=z_o} \left(\frac{\tan\left(T_f^o h\right)}{T_f^o h} \right) \frac{\omega \rho_f h}{2\pi v_l^\infty \rho_l}$$

$\omega \Delta m / A$

$(\rho \eta \omega)^{1/2}$

Complex slope factor
from polymer waveguide

tan*x*/*x* factor gives mass/liquid loading limits

$$\left(\frac{\tan\left(T_f^o h\right)}{T_f^o h} \right) \rightarrow \begin{cases} 1 & h \rightarrow 0 \\ \dfrac{-\sqrt{-2j}}{2h\left(1 - v_f^2 / v_o^2\right)} \sqrt{\dfrac{2\eta_f}{\omega \rho_f}} & h \rightarrow \infty \quad \text{and} \quad \omega\tau \rightarrow 0 \end{cases}$$

Sauerbrey/
solid limit

Kanazawa/
liquid limit

Advanced Concepts

Love Waves and Higher Frequency

Established QCM Sensor Principle

Mass sensitivity $\propto$ Fundamental frequency

Higher frequency $\Rightarrow$ Higher mass sensitivity

Love Waves on a (Semi-) Infinite Substrate

Controlling factor is guiding layer thickness x frequency $z = d/\lambda_l = df/v_l$

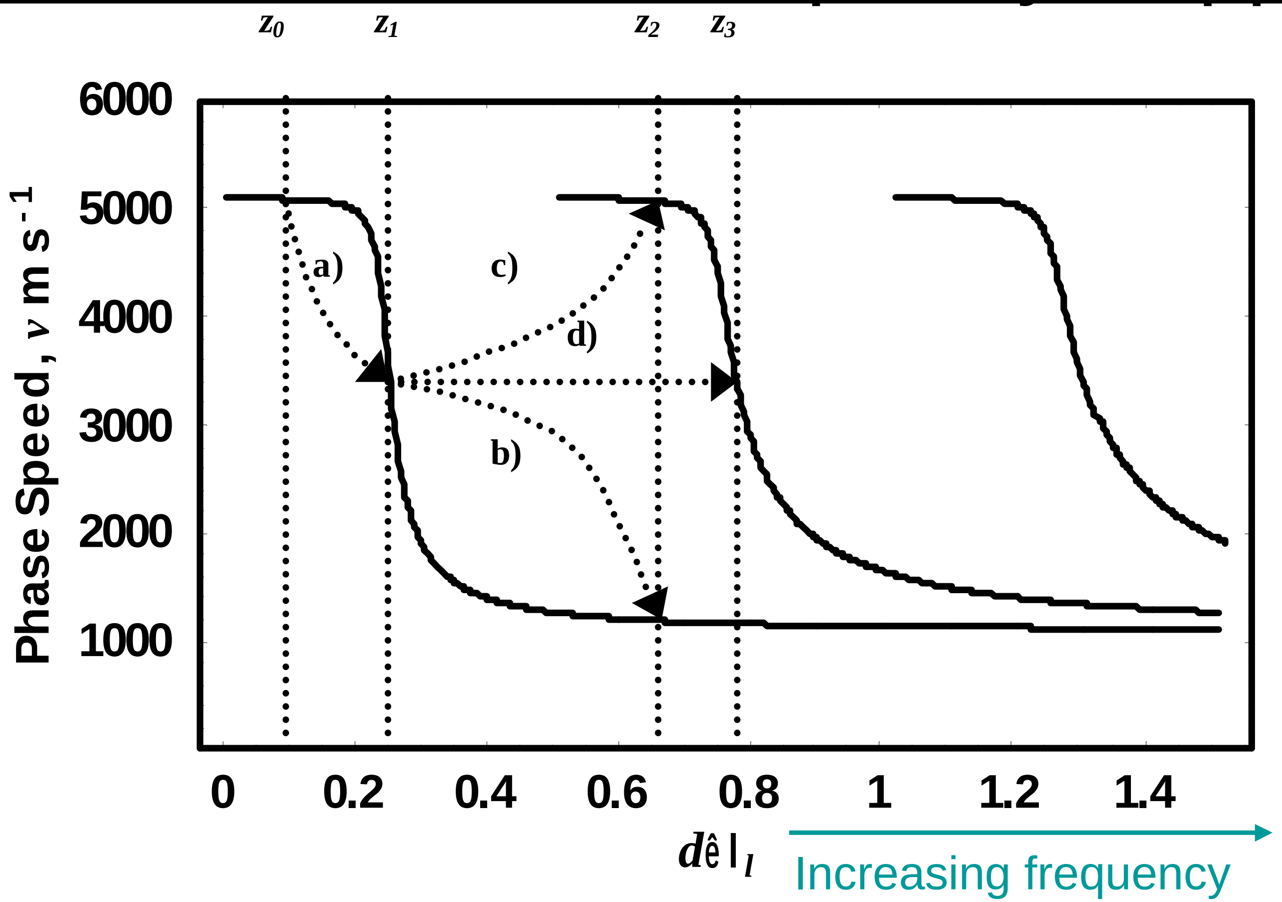
$$S_m = \lim_{\Delta m \to 0} \frac{1}{\Delta m}\left(\frac{\Delta v}{v_o}\right) \approx \frac{f_o}{\rho_l v_l}\left(\frac{d \log_e v}{dz}\right)_{z_0}$$

Mass sensitivity $\propto$ Frequency $\times$ Slope Factor

Slope operating point $z_o \propto d \times f$

Increasing frequency <u>may</u> or <u>may not</u> increase sensitivity

Love Waves and Frequency Hopping



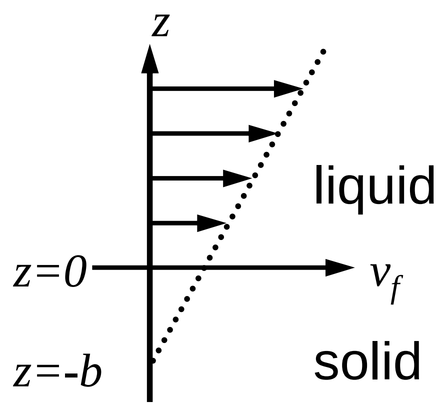
No Mode Change	Mode Change
Transition a) ⇒ Higher mass sensitivity	Transition c) ⇒ Lower mass sensitivity
Transition b) ⇒ Lower mass sensitivity	Transition d) ⇒ Higher mass sensitivity

“Slip” Boundary Condition v Trapped Mass

Average Position of Solid-Liquid Interface

Slip length, b, to model average position of an interface

Negative b $\Rightarrow$ Effective interface moves to liquid side of boundary



Newtonian Liquid

Kanazawa & Gordon result for no-slip modified by “slip” correction using b/δ

$$\left(\frac{\Delta\omega}{\omega}\right)_{slip} \approx \left(\frac{\Delta\omega}{\omega}\right)_{no\,slip}\left(1-\frac{2b}{\delta}\right)$$

Slip length to penetration depth

Negative Slip Length

Define a mass as $\Delta m_f = b\rho_f$

$$\left(\frac{\Delta\omega}{\omega}\right)_{additional} \approx \left(-\frac{2b}{\delta}\right)\left(\frac{\Delta\omega}{\omega}\right)_{no\,slip} = \frac{\omega\Delta m_f}{\pi\sqrt{\mu_s\rho_s}}$$

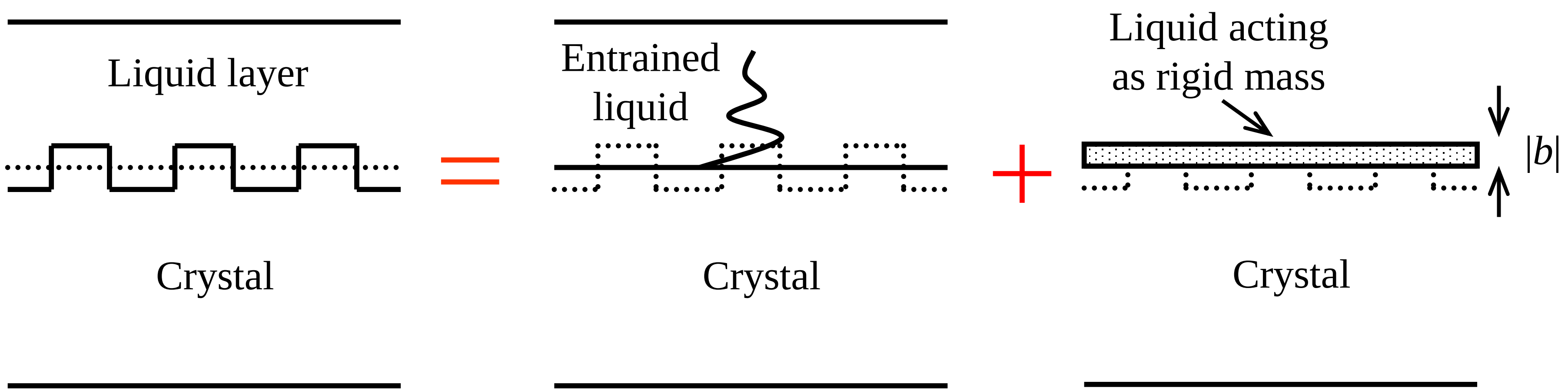
Sauerbrey result for trapped “rigid” liquid mass

Pictorial Interpretation

Negative Slip Length

slip boundary condition = no-slip boundary condition + rigid “water” mass layer

(Kanazawa liquid response) (Sauerbrey “liquid” mass response)



Acoustic Reflection View

Substrate Supports Standing Waves

Cavity length increases ⇒ additional frequency decrease

Limitations on "Slip" B.C./Trapped Mass View

Effectively assuming equal reflectivity at peaks and troughs of topography

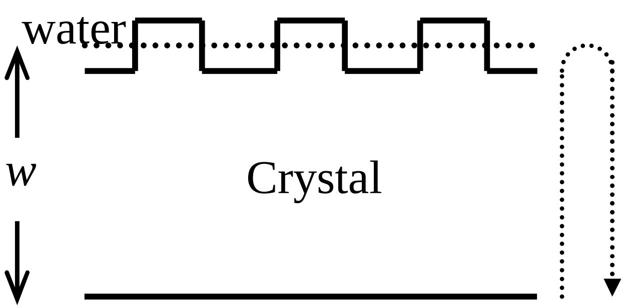
Cannot necessarily use additivity of liquid entrainment + trapped mass when incomplete liquid penetration occurs

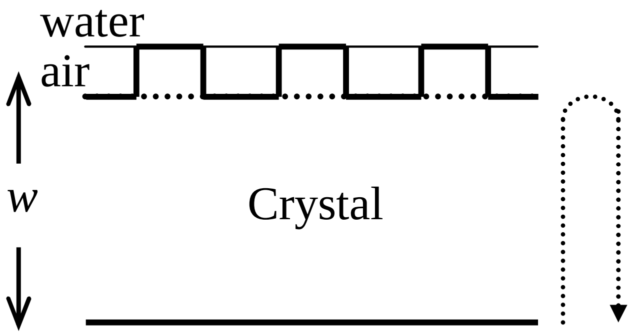
Order of Magnitude Estimates – QCMs

Is Positive Δf Possible?

Possibly, if effective cavity length decreases due to changes in reflectivity

Incomplete liquid penetration versus liquid penetration?





Effective QCM Cavity Lengths, *w*

$$v = f\lambda \quad \Rightarrow \quad \Delta w/w = -\Delta f/f$$

(v approx constant)

f = 5 MHz and w = 330 µm

Δw	$\lvert \Delta f \rvert$
100 Å	150 Hz
100 nm	1.5 kHz
1 µm	15 kHz
10 µm	150 kHz

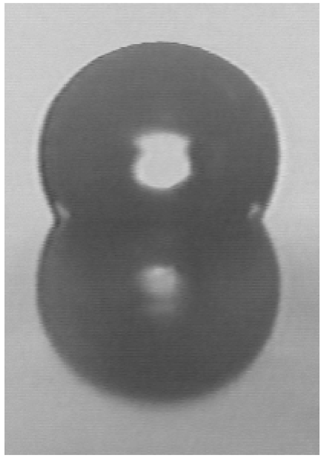
Super-Hydrophobic Surfaces

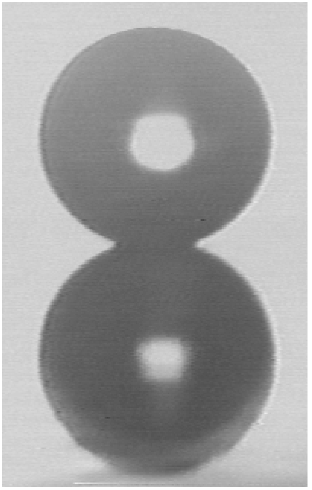
Contact Angle

Side view images of droplet

Identical chemical functionality

Different topography



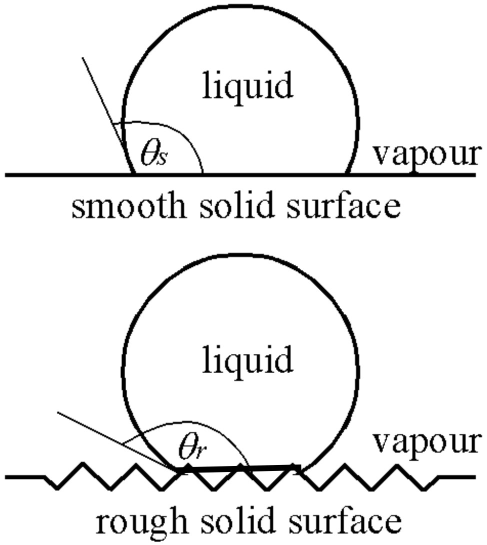


Physical Cause

Surface roughness/ topography

Incomplete liquid penetration (or)

Greater solid-liquid interfacial area



New Sensor Principle

Change hydrophobicity to cause super-hydrophobic transition

Response of QCM/SAW may alter by far more than due to mass change

The End

Acknowledgements

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  Wetting/Super-hydrophobic QCM, slip and diffuse interface concepts

  Matching slip length to slip parameter in boundary condition
- Richard Cernosek and Lisa Thiesen — Air Trapping and Wetting
- Ralf Lücklum

  Slip parameter in boundary condition and wetting concepts

  Air trapping and wetting
- Mike Newton and Neil Shirtcliffe — Superhydrophobicity