Techniques to evaluate the mass sensitivity of Love mode surface acoustic wave biosensors

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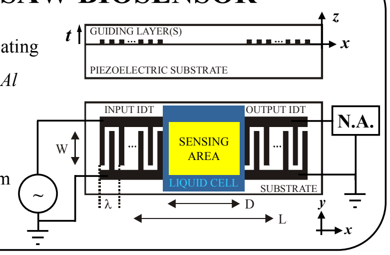
INTRODUCTION

- **Love mode**: shear-horizontal surface acoustic wave guided in single or multiple layer coatings on a piezoelectric substrate
- **Biosensing**: acoustic signal (delay phase angle and insertion loss) shifts caused by the adsorption of biomolecules from a liquid medium (e.g. antibodies in blood sample)
- **Purpose of the research**: experimental and theoretical investigation of the sensing characteristics of the Love mode device for its application as biosensor

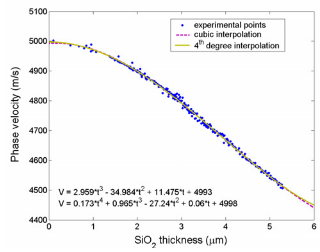
LOVE MODE SAW BIOSENSOR

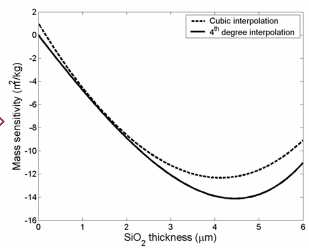
- Structure: ST-cut quartz substrate; t = 1.2 µm PECVD SiO_2 coating
- IDT: 100 split fingers pairs of 200 nm *Al*
- Center frequency f_0 = 123.5 MHz
- Wavelength λ = 40 µm, L = 9 mm
- Sensing area: D = 4.7 mm, W = 3.2 mm covered with 50 nm *Au*
- Static liquid cell above sensing area



EXPERIMENTAL TECHNIQUES

1) Experimental measurement of the dispersion curve

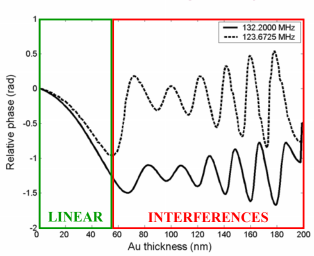


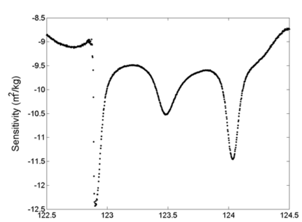


- Thick PECVD SiO_2 (> 5 µm) wet etching in fluorhydric acid
- Continuous monitoring of the transfer function during the etching
- Mass sensitivity obtained by derivation of the dispersion curve

2) Sensitivity evaluated by modifying the surface density Δσ

✓ Gold thin film etching: $\Delta\sigma = \rho\,\Delta h$





- 200 nm **gold etching** ↑ in KI/I_2
- Δh = 50 nm *Au* etching (linear part)
- ρ = 19300 kg/m³ → **Δσ = 96500 ng/cm²**
- Parasitic interferences enhanced by *Au*

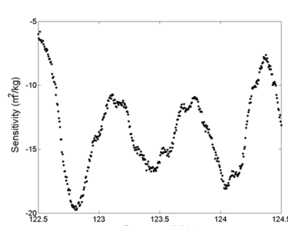
✓ Copper electrodeposition: Δσ ~ current

- Sensing area = working electrode
- Rough surface:
  - hydrodynamic drag effect
  - overestimated mass sensitivity: $S_{\phi,\sigma} = -27.43 \pm 1.74\ \mathrm{m^2/kg}$

Δσ (ng/cm²)	Δφ (mrad)	Δα/Δφ (dB/rad)
1286 ± 75	−255.8 ± 16.6	−2.20 ± 0.47
3534 ± 53	−737.6 ± 5.5	−1.77 ± 0.06
3928 ± 107	−785.8 ± 15.2	−1.79 ± 0.12

✓ CTAB adsorption: Δσ ~ surface coverage

- Small molecule (M_w = 365 g/mol)
- Monolayer formation: **Δσ = 137 ng/cm²**
- Attenuation < noise level (0.05 dB)
- Surface coverage ~ solution concentration



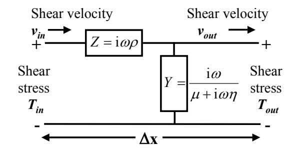
- **Surface density or viscous thin layer ?** →
  - similar phase and attenuation shifts
  - distinction density/viscosity impossible

	Rigid	Viscous h = 1.5nm	Viscous $h > 3\delta$
Δφ (mrad)	−17	−20	−254
Δα (dB)	0.01	0.005	2.35

THEORETICAL TECHNIQUE

✓ Mechanical transmission lines model

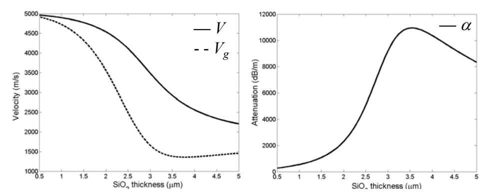
- **Block approach** for each layer of the structure with density ρ, shear stiffness μ, viscosity η
- Parallel/series connection along x/z directions
- Complex coupling angle θ
- **Transverse resonance principle**



$k_x = k\sin\theta \quad Z_{0x} = Z_0 \sin\theta$

$k_z = k\cos\theta \quad Z_{0z} = Z_0\cos\theta$

- **Dispersion curve** →
  - phase velocity $V(t)$
  - group velocity $V_g(t)$
  - attenuation $\alpha(t)$



✓ Sensitivity evaluation

- Mass sensitivity:

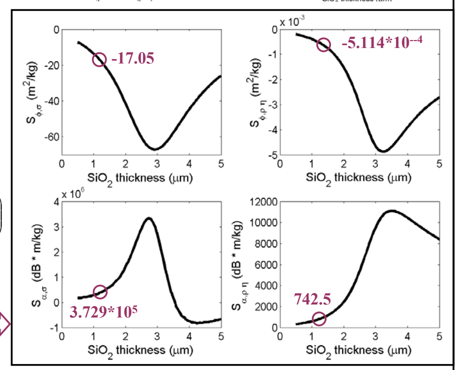
$$S_{\phi,\sigma} = \frac{1}{V}\frac{dV}{d\sigma} \cong \frac{1}{\rho t}\frac{V_g - V}{V}$$

- Sensor response model:

$$\begin{pmatrix} d\phi \\ d\alpha \end{pmatrix} = \begin{pmatrix} kD & 0 \\ 0 & D \end{pmatrix} \begin{pmatrix} S_{\phi,\sigma} & S_{\phi,\rho\eta} \\ S_{\alpha,\sigma} & S_{\alpha,\rho\eta} \end{pmatrix} \begin{pmatrix} d\sigma \\ d\sqrt{\rho\eta} \end{pmatrix}$$

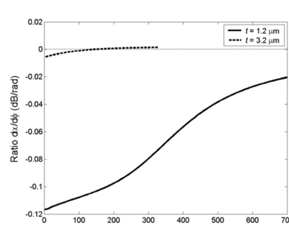
Structure — Intrinsic S

$$\begin{pmatrix} \frac{1}{\rho V}\frac{dV}{dt} & \frac{1}{V}\frac{dV}{d\sqrt{\rho\eta}} \\ \frac{d\alpha}{\rho\, dt} & \frac{d\alpha}{d\sqrt{\rho\eta}} \end{pmatrix}$$



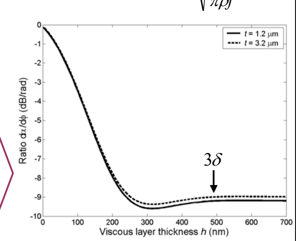
✓ Rigid or viscous sensing ?

- Ratio *attenuation shift* to *phase shift*: $\frac{d\alpha}{d\phi} = \frac{S_\alpha}{kS_\phi}$
- Decay length: $\delta \cong \sqrt{\frac{\eta}{\pi\rho f}}$



RIGID: $d\sqrt{\rho\eta} = 0$, $\frac{\mu}{\eta} > f_0$

VISCOUS: $d\sigma = 0$, $\frac{\mu}{\eta} < f_0$



- Theoretical value for $\lim h \to 0$
- Sensitive to SiO_2 thickness
- Theoretical value for $h > 3\delta$
- Insensitive to SiO_2 thickness

✓ Biosensing = viscous sensing

- μ/η from ~1 to ~ 10 MHz $< f_0$
- h from ~1 to ~20 nm < $3\delta_{water}$ (150 nm)

→ **BIOSENSING = VISCOUS SENSING with unknown parameters: ρ, η and h**

- Calibration by viscous solutions not enough to evaluate $S_{\phi,\rho\eta}(h)$ and $S_{\alpha,\rho\eta}(h)$

CONCLUSION

- Mixed contribution of density and viscosity interactions for biomolecules
- Modeling is needed to extract both contributions to the acoustic signal