Characterisation of thin polymer films by QCM-D

Sofia Svedhem, Assist. Prof.

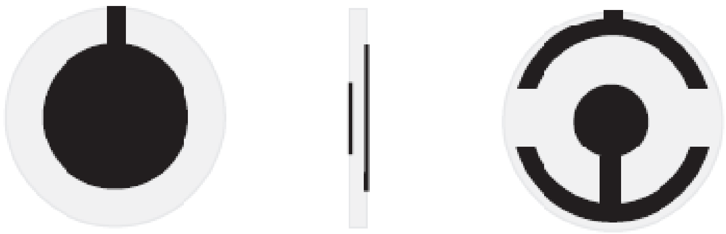
Biological Physics group
Dept. of Applied Physics, Chalmers University of Technology

Outline

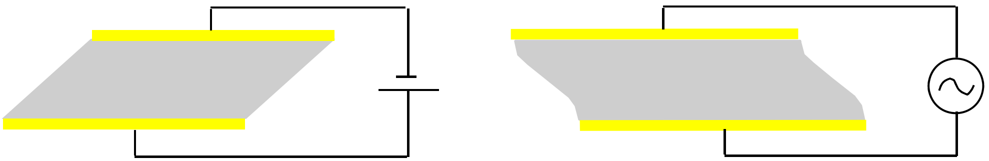
- The principle of QCM-D
- Polysaccharide multilayers
- Polymeric drug carriers

Quartz is a piezoelectric material

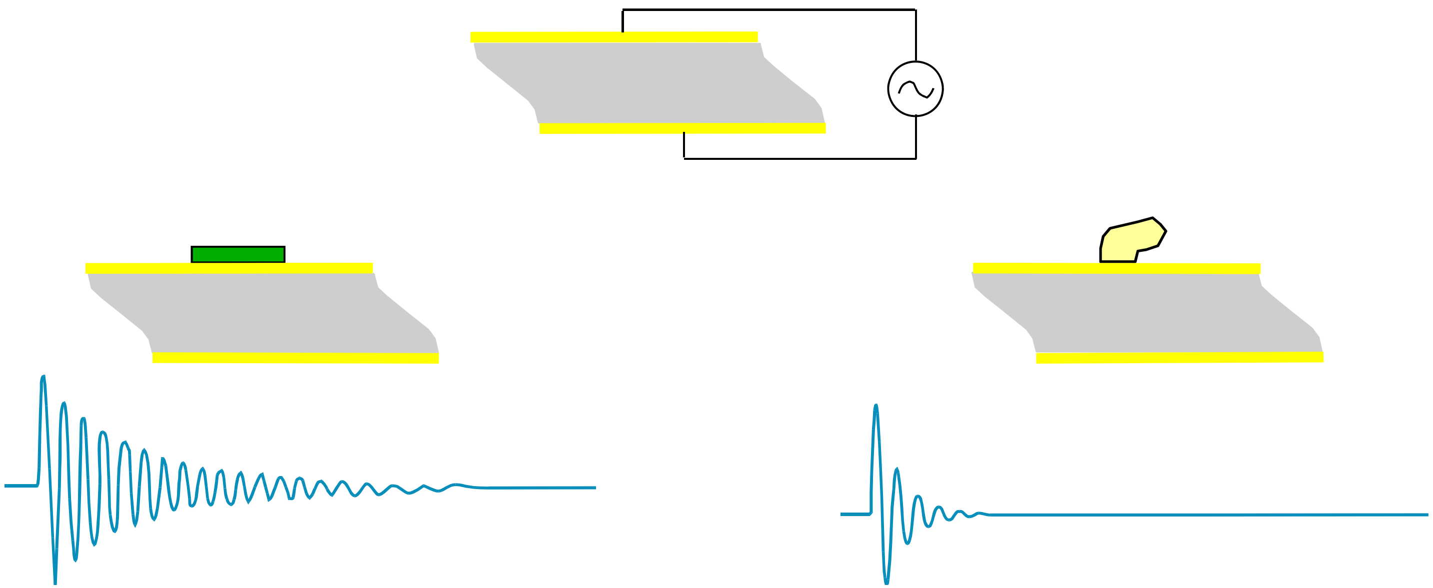
AT-cut quartz with gold electrodes



top view side view bottom view



QCM-D



Δf is proportional to the mass of the attached film (ng/cm^2 sensitivity)

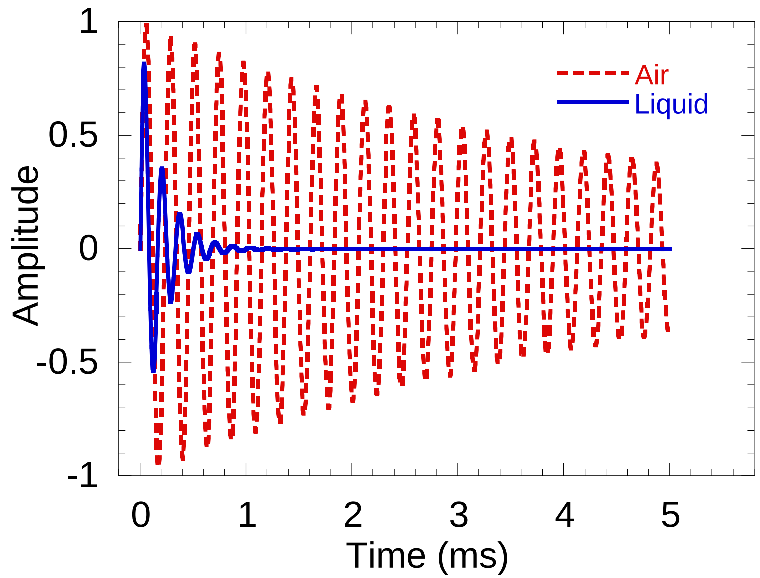
ΔD is related to the viscoelasticity

1) Rodahl, M., Höök, F., Krozer, A., Kasemo, B. and Breszinsky, P., *Quartz crystal microbalance setup for frequency and Q factor measurements in gaseous and liquid environments*, Review of Scientific Instruments 66 (1995) 3924-3930

2) Rodahl, M. and Kasemo, B., *Frequency and dissipation-factor response to localized liquid deposits on a QCM electrode*, Sensors and Actuators B (1996) 111-116

3) Rodahl, M., Höök, F., Fredriksson, C., Keller, C., Krozer, A., Brzezinski, P., Voinova, M. and Kasemo, B., *Simultaneous frequency and dissipation factor QCM measurements of biomolecular adsorption and cell adhesion*, Faraday Discussions 107: Acoustic waves and Interfaces, Lester UK 107 (1998) 229

The Dissipation factor



Mathematical representation

$$A(t)=A_0\cdot\exp(-t/\tau)\cdot\sin(2\pi f t+\phi)$$

$$D=1/\pi f\tau$$

Rodahl, M., Höök, F., Brzezinski, P and Kasemo, B. (1995) *Rev Sci Instr*, 66, 3924-3930.

Overtones

- The fundamental frequency of the crystal depends on its thickness
- Overtones can be excited for odd multiples of the fundamental mode (n = 1, 3, 5, 7, ...)

Fig. 2.6: A schematic illustration of thickness-shear mode displacements. In A) the fundamental mode: the thickness of the crystal, t_q, equals half an acoustic wavelength. In B) the third overtone: the thickness of the crystal equals 3/2 acoustic wavelengths.

Figure taken from Malin Edvardsson, PhD thesis 2007

Radial sensitivity

the mass uptake *sensitivity function* is associated with the oscillation amplitude distribution

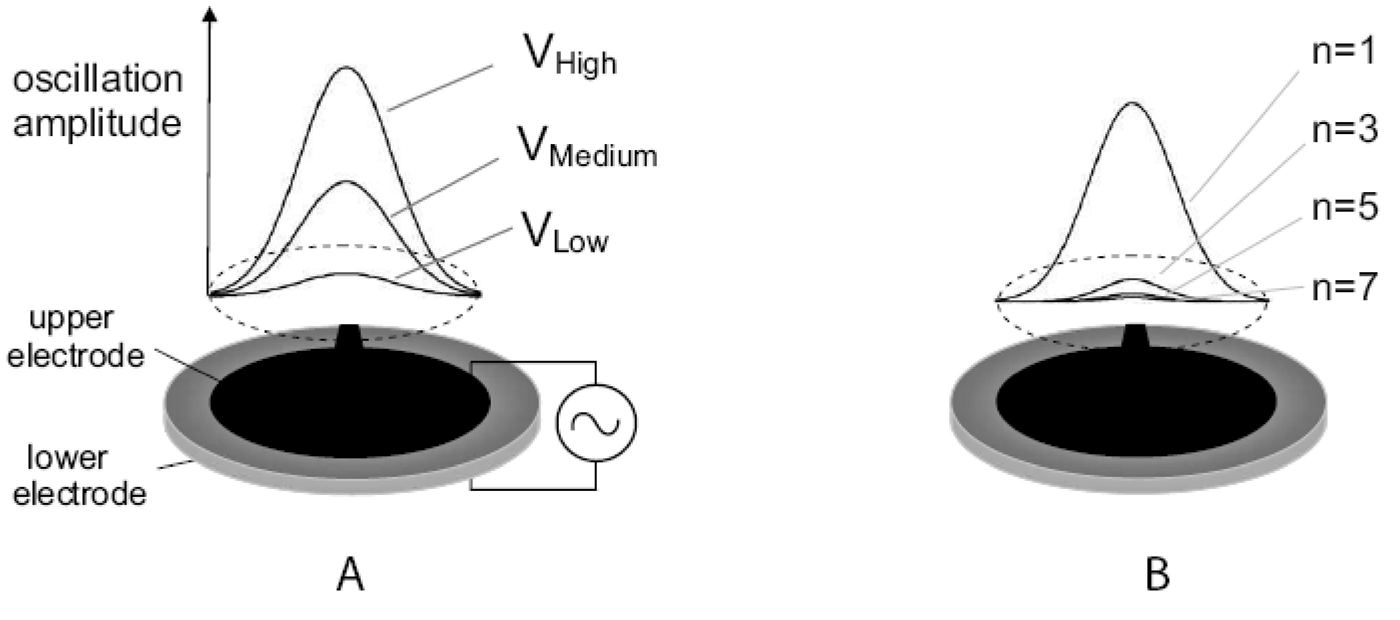


Fig. 2.8: Schematic illustration of how the Gaussian surface displacement distribution varies with A) the applied voltage, and B) the harmonic.

Penetration depth

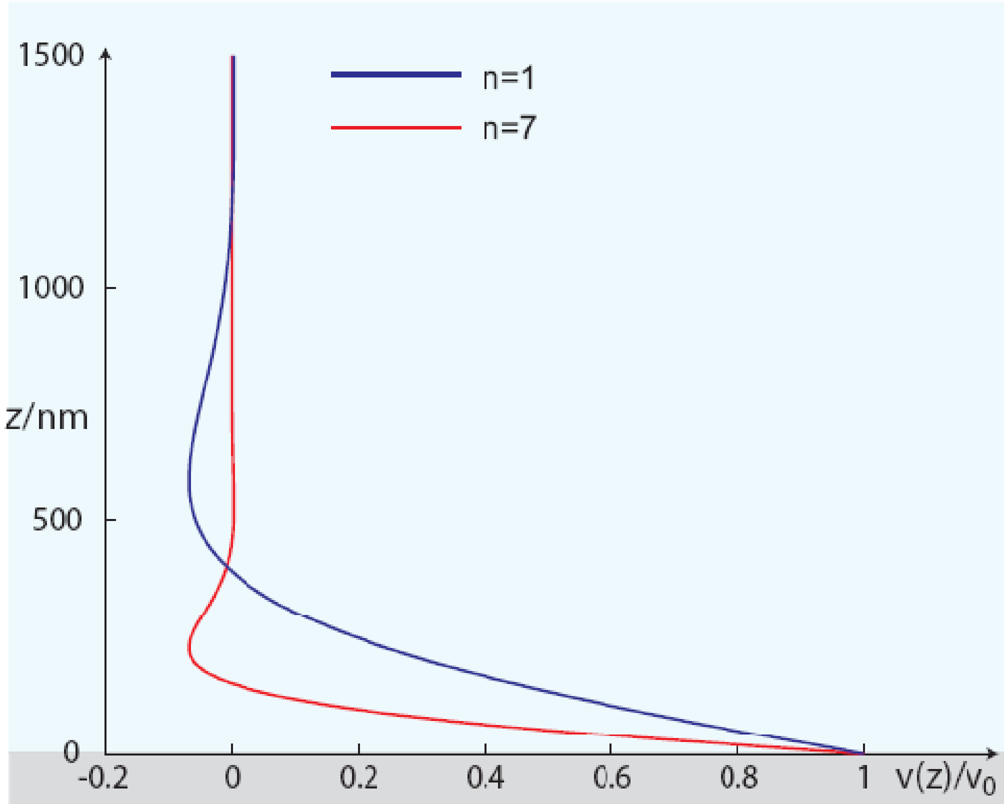


Fig. 2.13: Normalized shear wave velocity as a function of the distance from the oscillating surface according to eq. 2.26. Shown are the velocity distributions for $n = 1$ and $n = 7$ at surface peak velocity.

Modelling of rigid films

Sauerbrey equation:

$$\Delta m = -C \cdot \Delta f$$

where *C* is the mass sensitivity

for a 5 MHz crystal $C = 17.7$ *ng*/(cm^2 Hz)
for a 10 MHz crystal $C = 4.4$ *ng*/(cm^2 Hz)

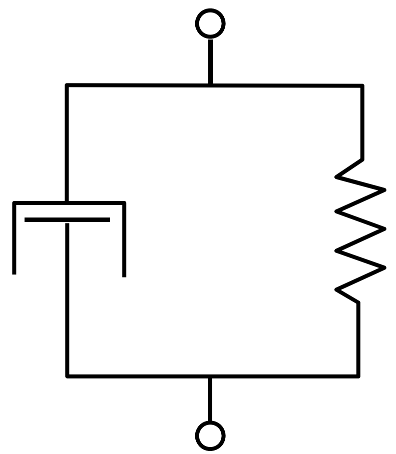
NB. For non-rigid films (ΔD high compared to Δf),
the Sauerbrey equation will underestimate the adsorbed mass.

Modelling of non-rigid films

For dissipative films (ΔD high compared to Δf):

$$\Delta m = f(\Delta f, \Delta D)$$

Using a Voigt-element to represent the adsorbed film, information on mass, viscosity and thickness can be obtained.



QCM versus QCM-D

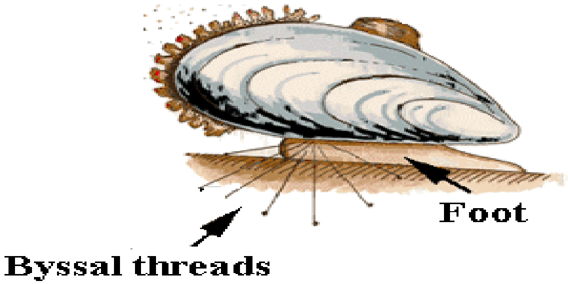
The old film thickness monitor on a new arena - biosensing in the liquid phase, and simultaneous and f and D measurements

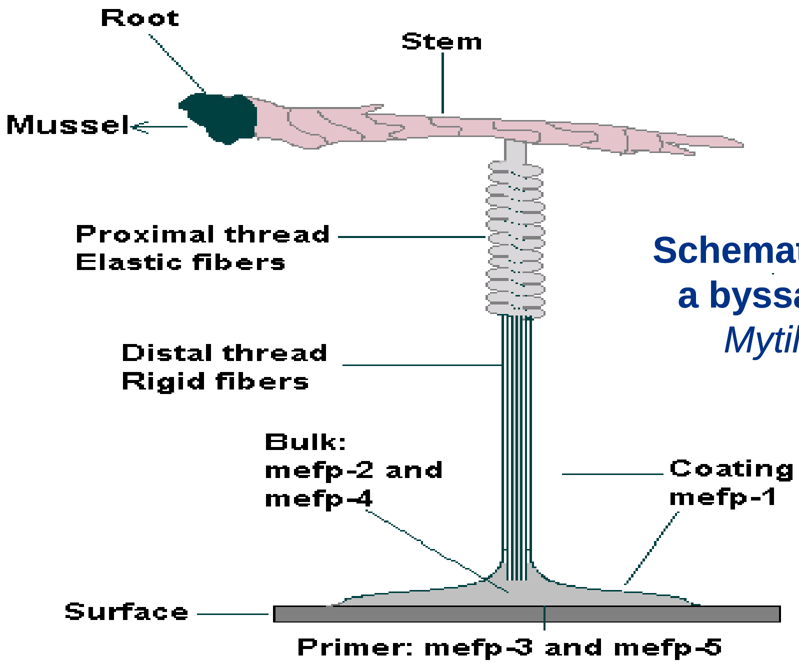
QCM-D measures hydration and trapped water

Example 1: Cross linking of mussel adhesive protein, MEFP. (The glue used by blue mussels to attch to stones in the sea).

Example 2: The lipid vesicle – surface interactions

Cross linking of mussel adhesive protein, MEFP.

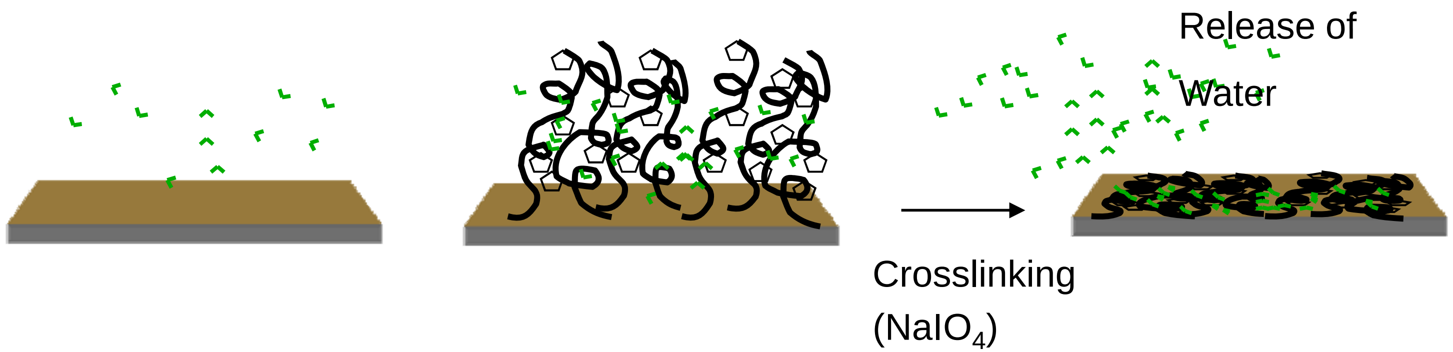


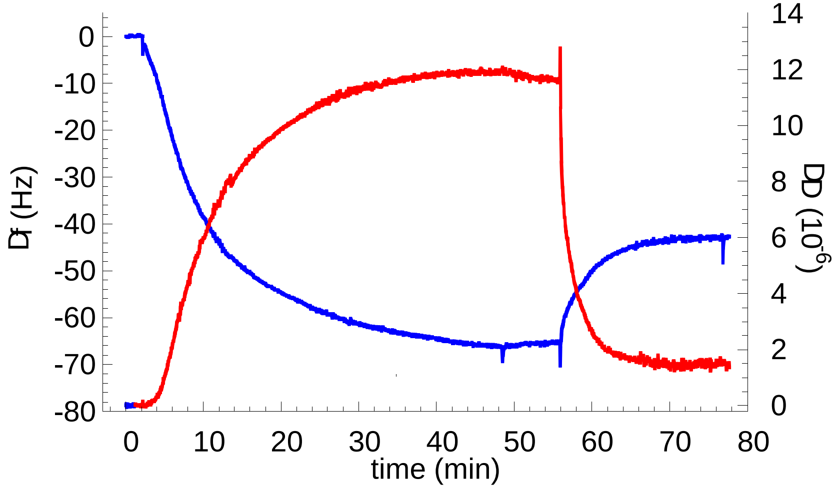


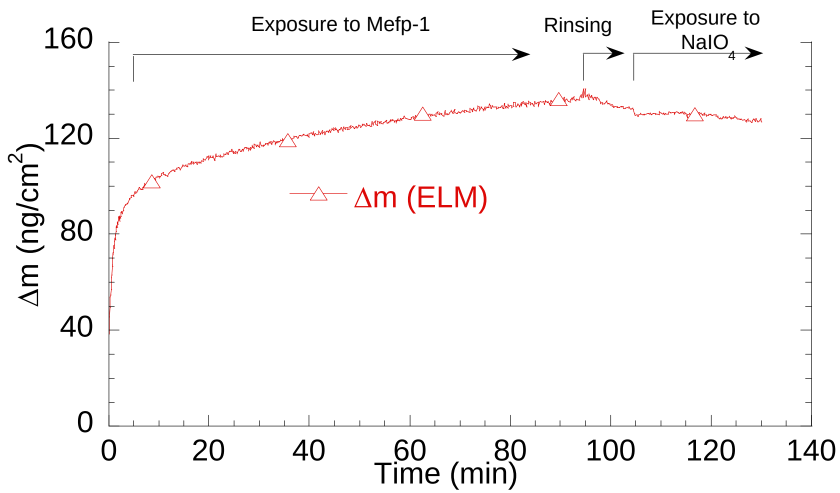
Schematic picture of a byssal thread of *Mytilus edulis*

Höök, F., *et al*., Analytical Chemistry, 2001. **73**(24): p. 5796-5804.

Cross linking of mussel adhesive protein, MEFP.

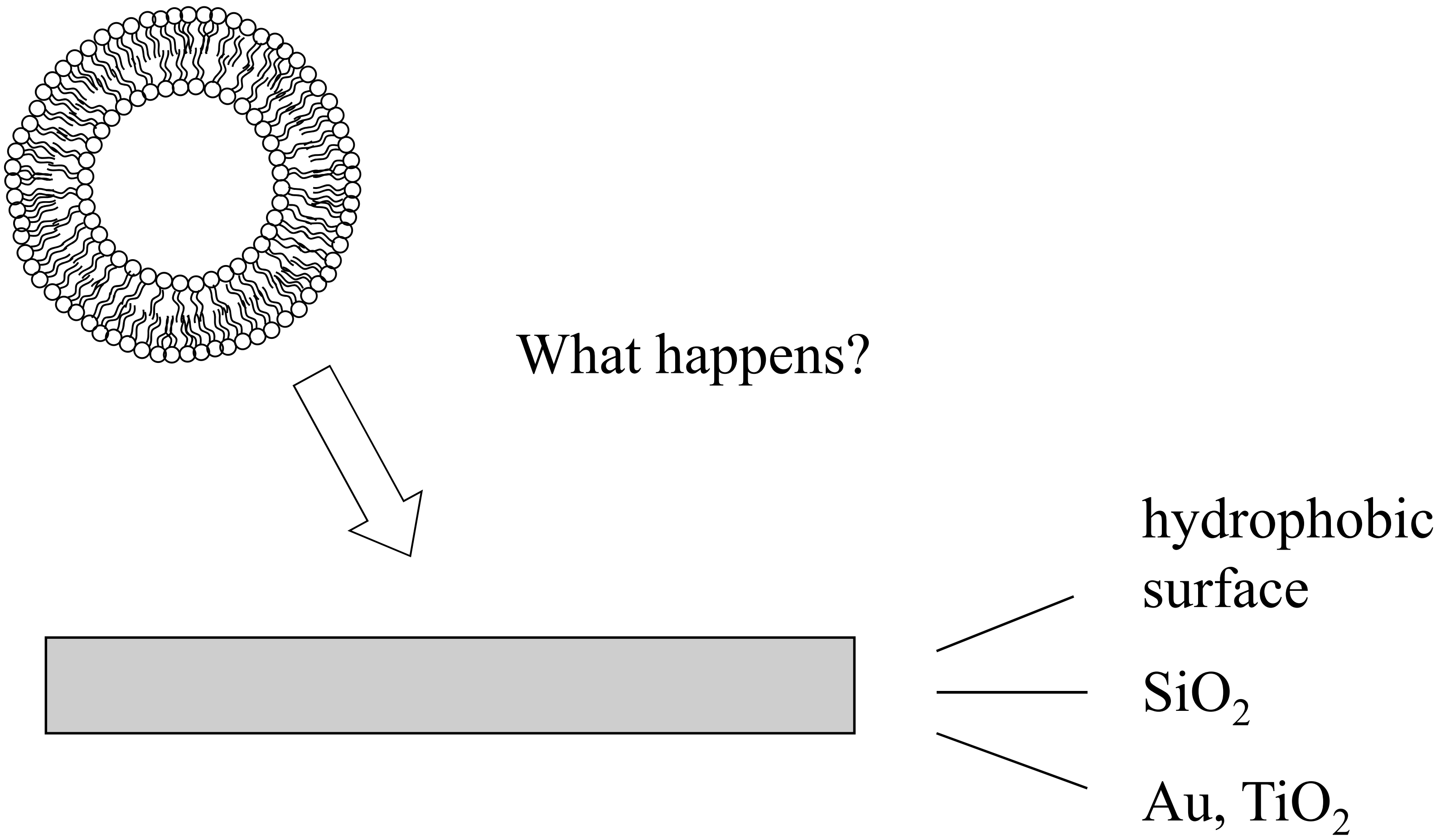




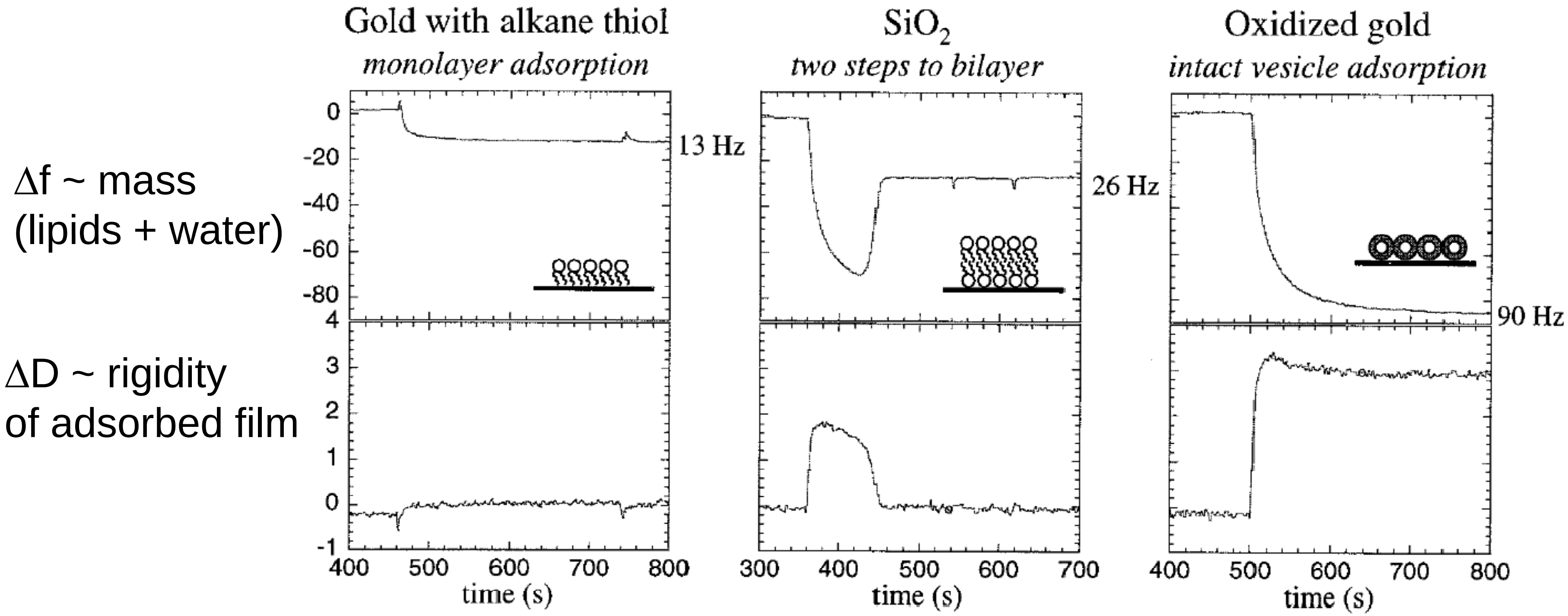


Höök, F., et al Analytical Chemistry, 2001. **73**(24): p. 5796-5804.

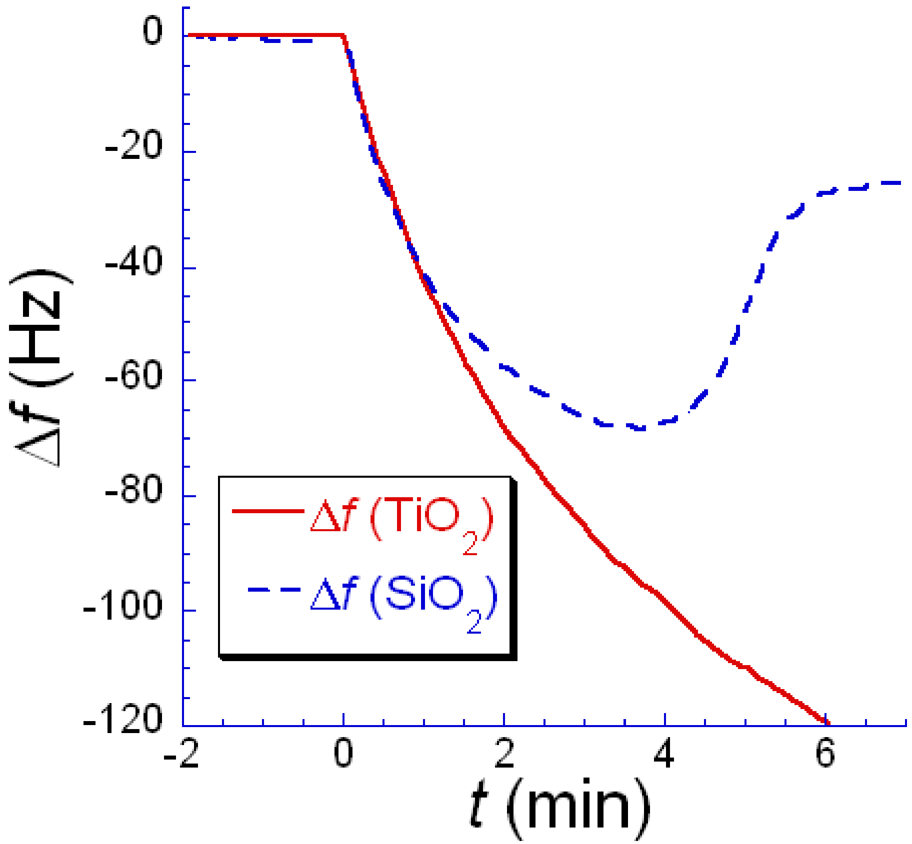
A vesicle approaching a surface …

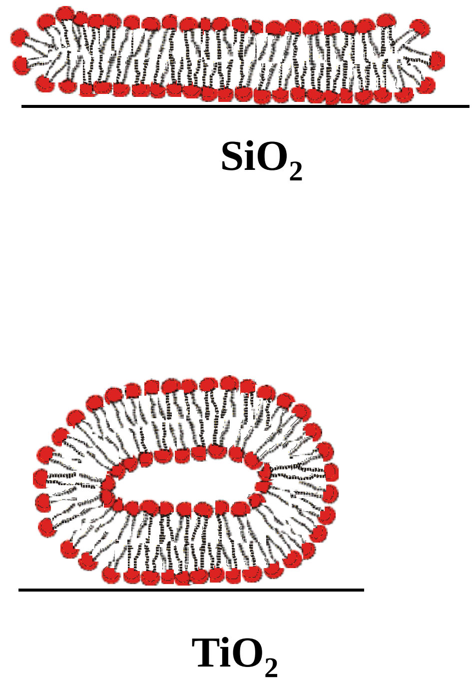


Vesicle-Surface Interactions by QCM-D

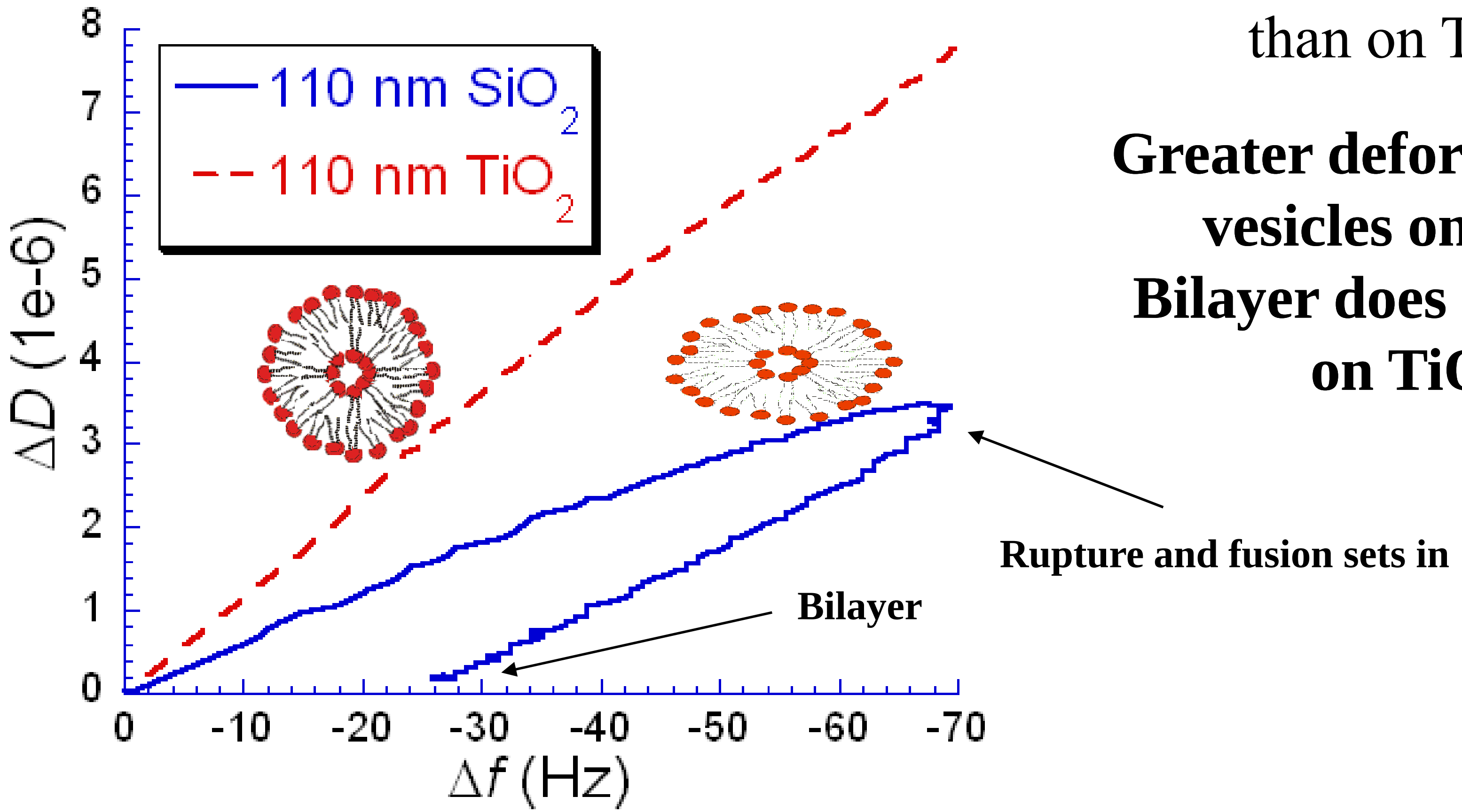


Vesicle adsorption onto SiO_2 and TiO_2





ΔD vs. Δf plots

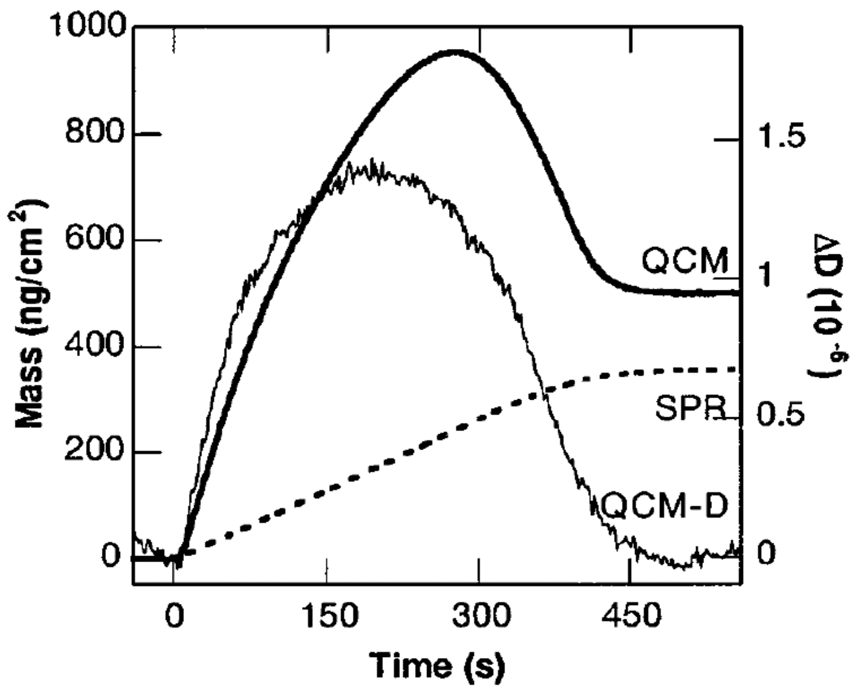


Lower $\Delta D/\Delta f$ on SiO_2 than on TiO_2

Greater deformation of vesicles on SiO_2. Bilayer does not form on TiO_2

QCM-D needs to be combined with an optical technique to separate the contributions from biomolecular mass and solvent mass

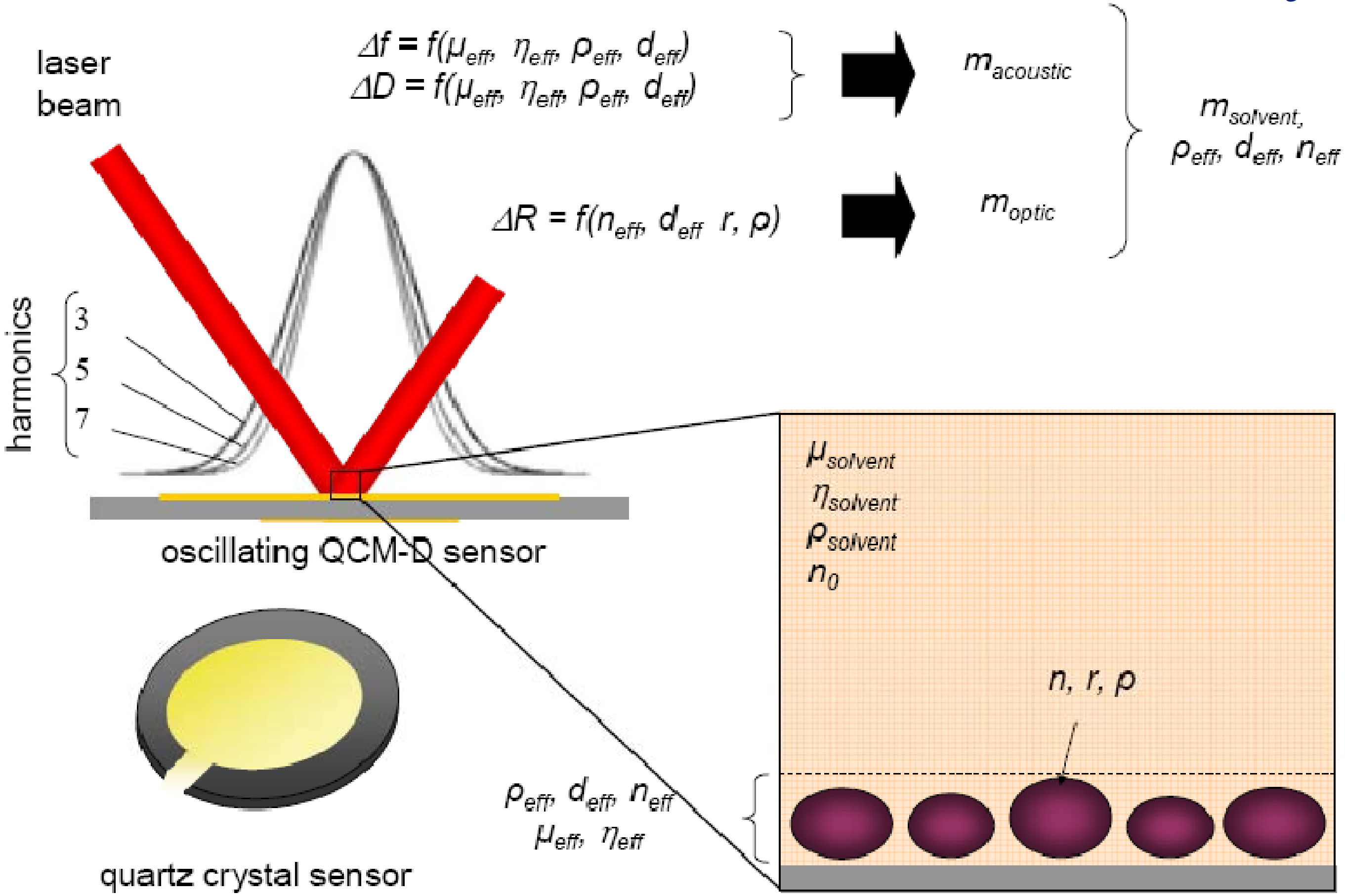
QCM-D versus SPR



Keller C.A. *et al.*, Phys Rev Lett 84:5443-5446 (2000)
NB. these experiments are separate experiments; in an extension simultaneous measurements were performed in a combined SPR/QCM-D flow cell as described in Reimhult E. *et al.*, Anal Chem 76:7211-7220 (2004)

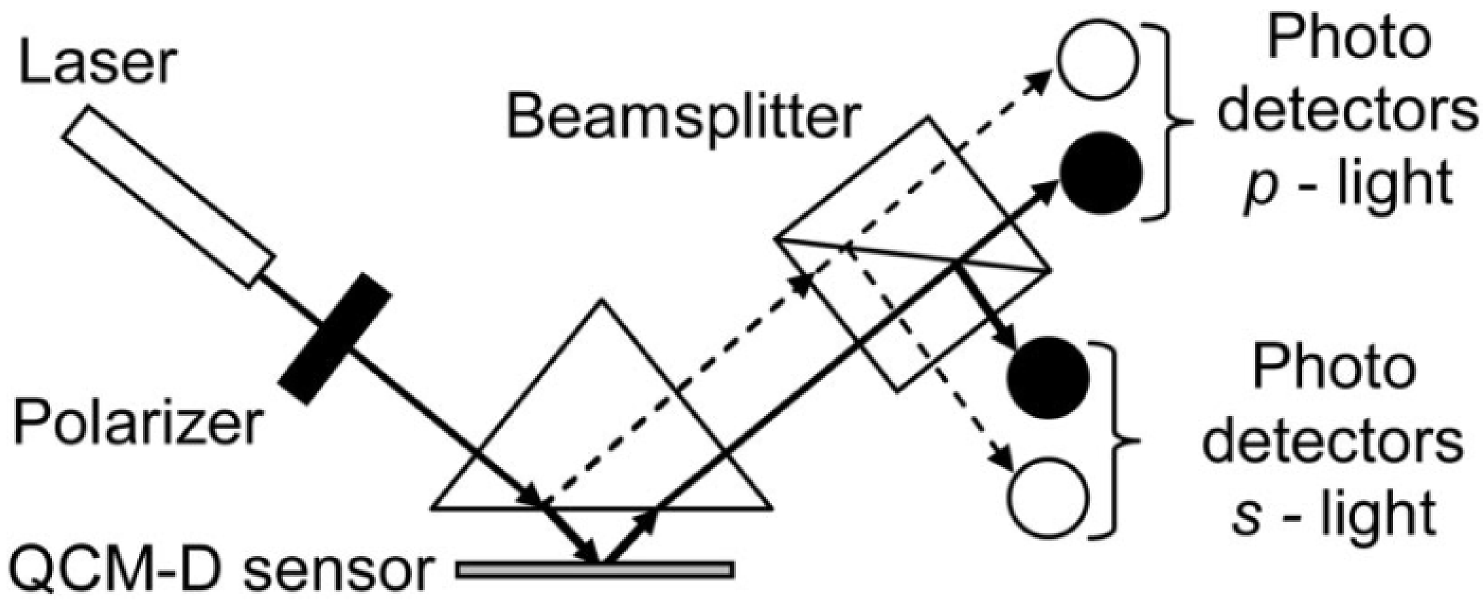
QCM-D and reflectometry on the same sensor surface

Combined QCM-D/Reflectometry



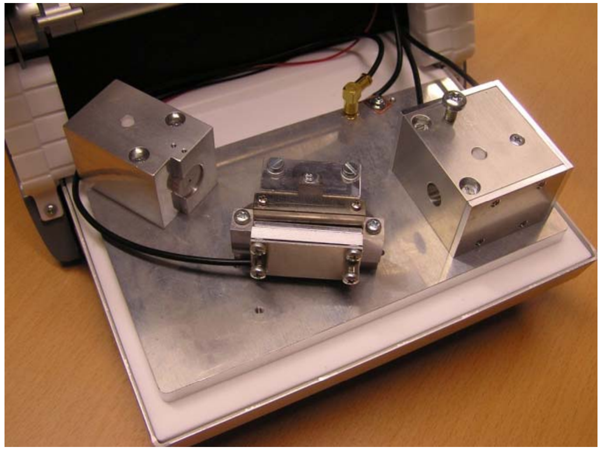
G.Wang, M.Rodahl, M.Edvardsson, S.Svedhem, G.Ohlsson, F.Höök, and B.Kasemo, Rev Sci Instr, 2008;
M.Edvardsson, S.Svedhem, G.Wang, R.Richter, M.Rodahl, and B.Kasemo, Anal. Chem., 81:349-361, 2009

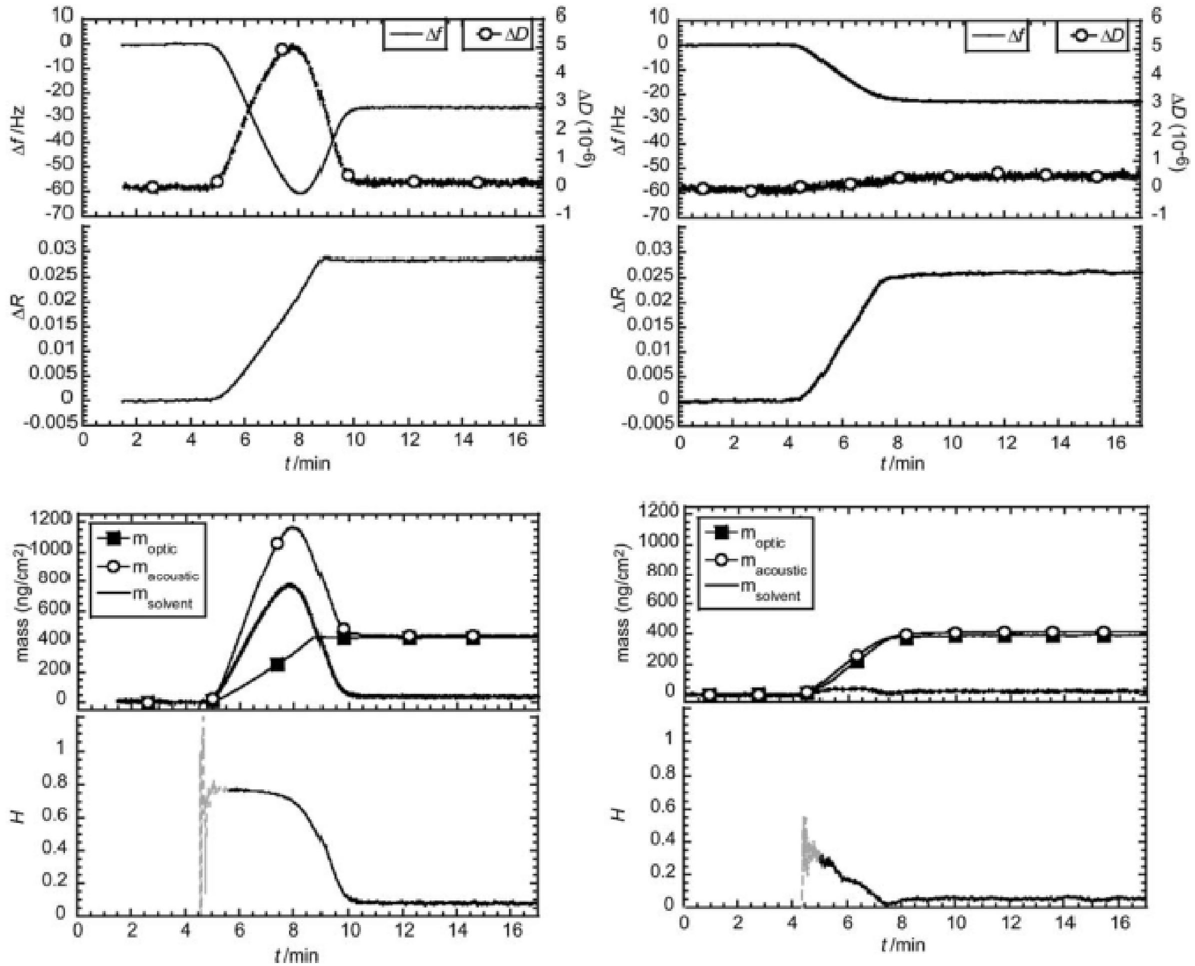
Combined QCM-D/Reflectometry



G.Wang, M.Rodahl, M.Edvardsson, S.Svedhem, G.Ohlsson, F.Höök, and B.Kasemo, Rev Sci Instr, 2008;
M.Edvardsson, S.Svedhem, G.Wang, R.Richter, M.Rodahl, and B.Kasemo, Anal. Chem., 81:349-361, 2009

QCM-D – reflectometry (simultaneous detection)





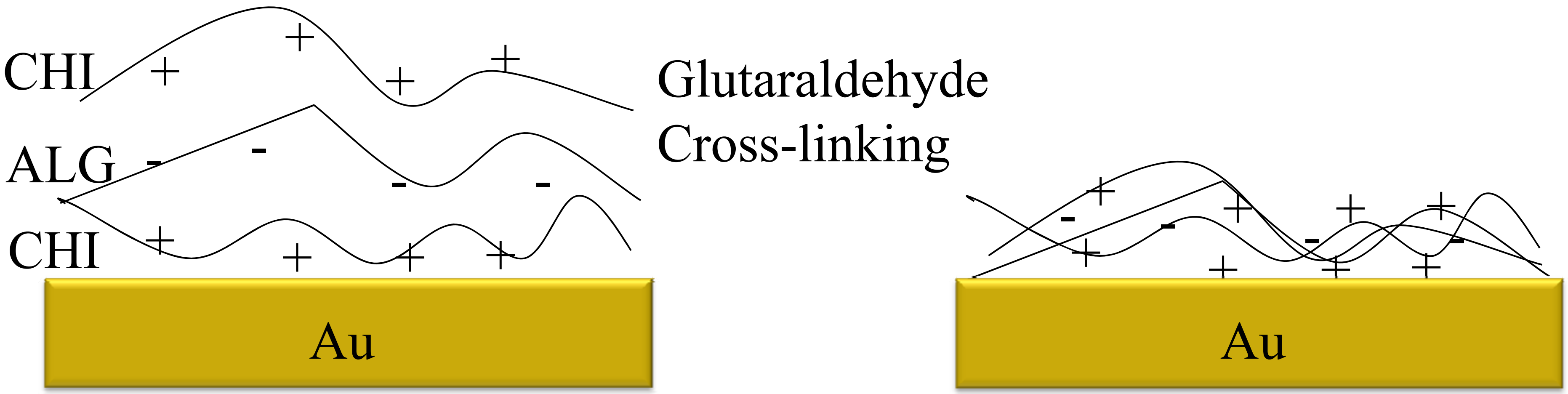
a joint Chalmers-Q-sense project

M. Edvardsson, S. Svedhem, G. Wang, R. Richter, M. Rodahl, and B. Kasemo, Anal. Chem., 81:349-361, 2009
G. Wang, M. Rodahl, M. Edvardsson, S. Svedhem, G. Ohlsson, F. Höök and B. Kasemo, Rev Sci Instr 79:075107, 2008

QCM-D for monitoring of polyelectrolyte multilayer build-up

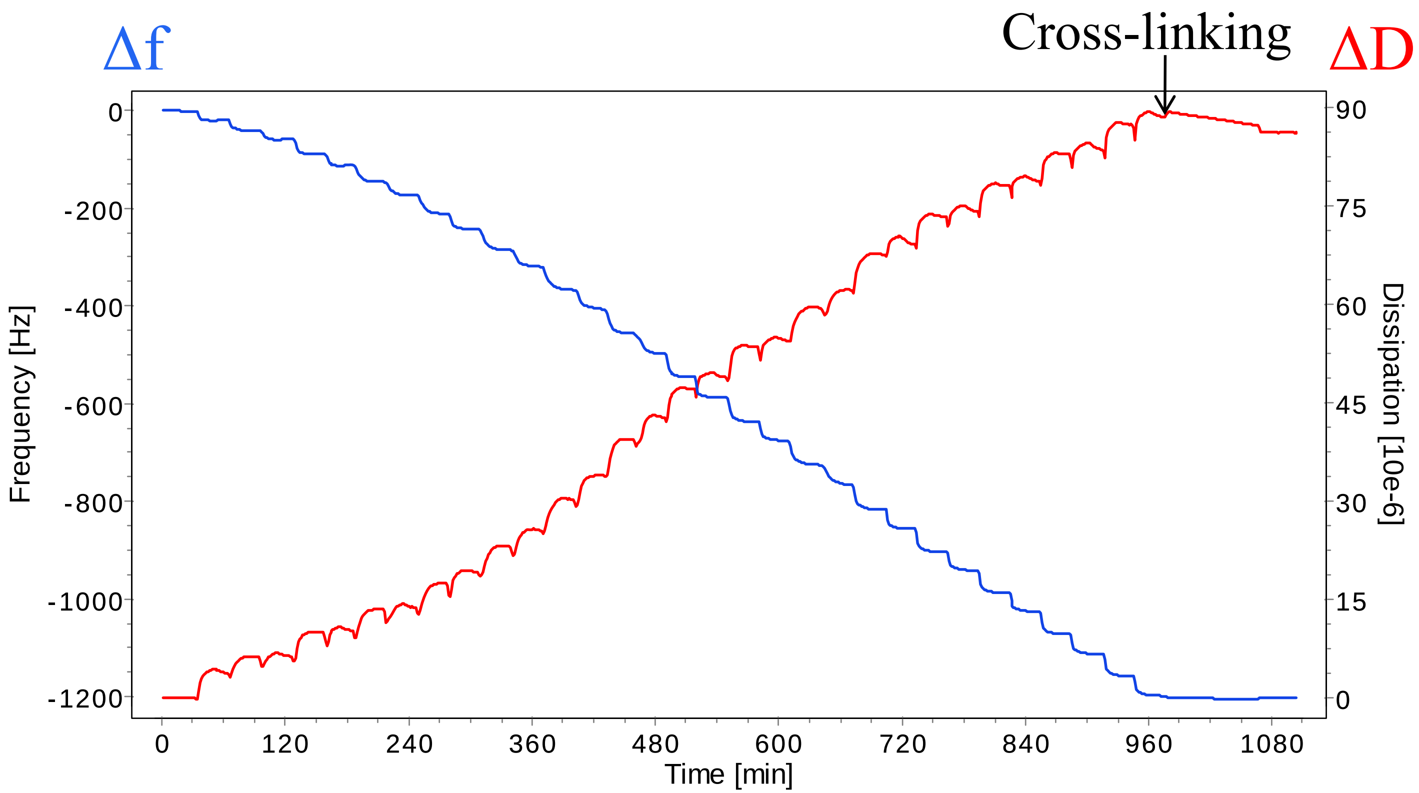
Chitosan/alginate multilayers

Application example from Q-Sense demonstrating multilayer build-up based on work by Alves et al.



Alves N. M., Picart C., Mano J. F., *Self Assembling and Crosslinking of Polyelectrolyte Multilayer Films of Chitosan and Alginate Studied by QCM and IR, Spectroscopy* Macromol. Biosci. **2009**, 9, pp: 776–785

Chitosan/alginate multilayers

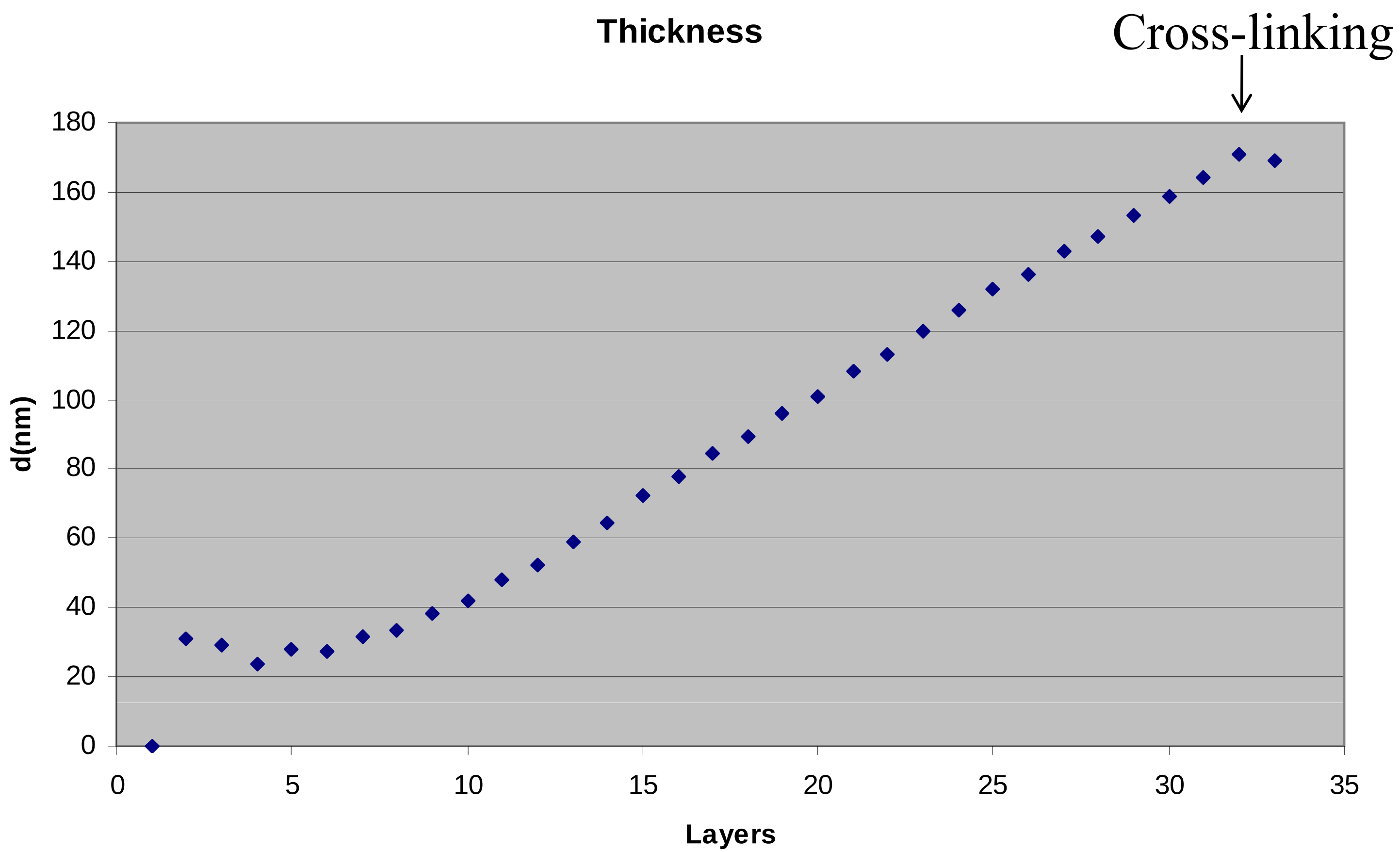


In good agreement with Alves et al, showing almost linear layer build-up and only partial cross-linking.

Erik Nilebäck, Q-Sense

Chitosan/alginate multilayers

Results modeled in Qtools using the Voigt model, parameters from Alves et al.



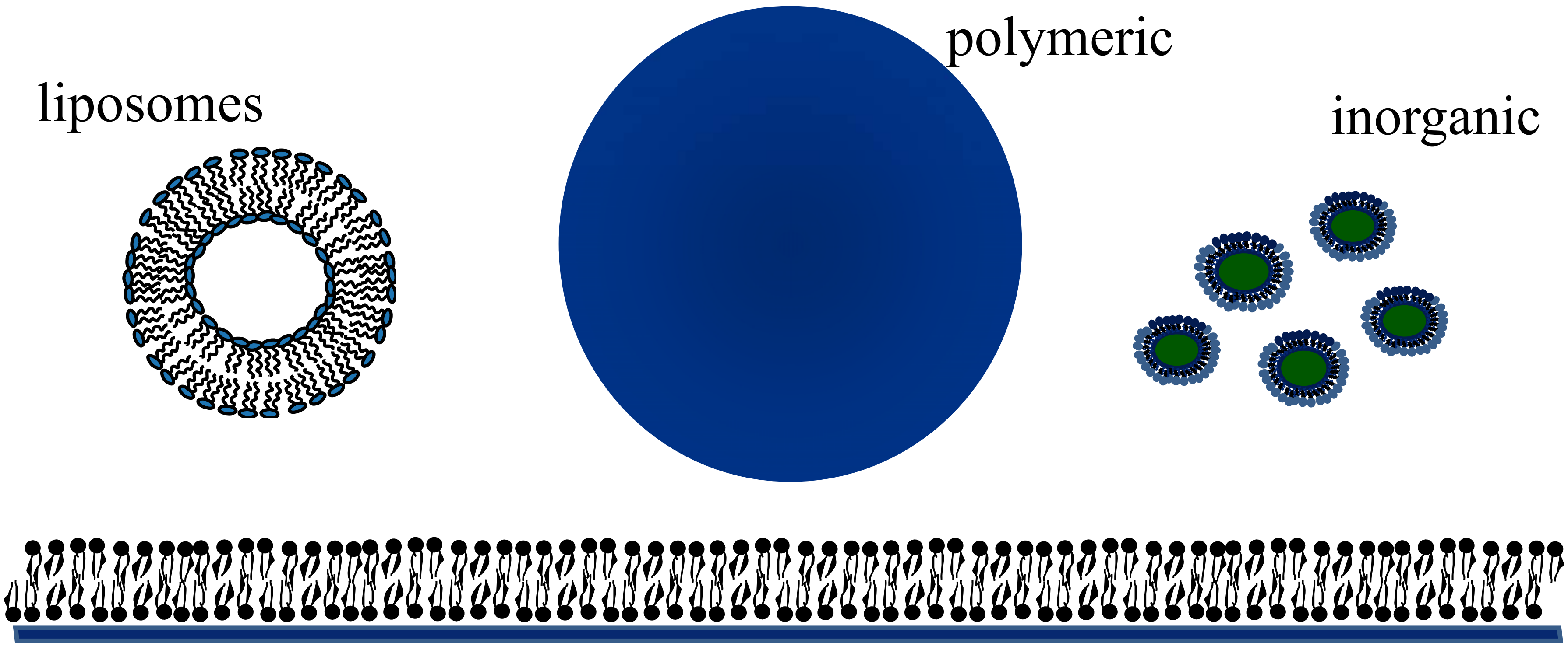
Erik Nilebäck, Q-Sense

[animation showing multilayer build-up]

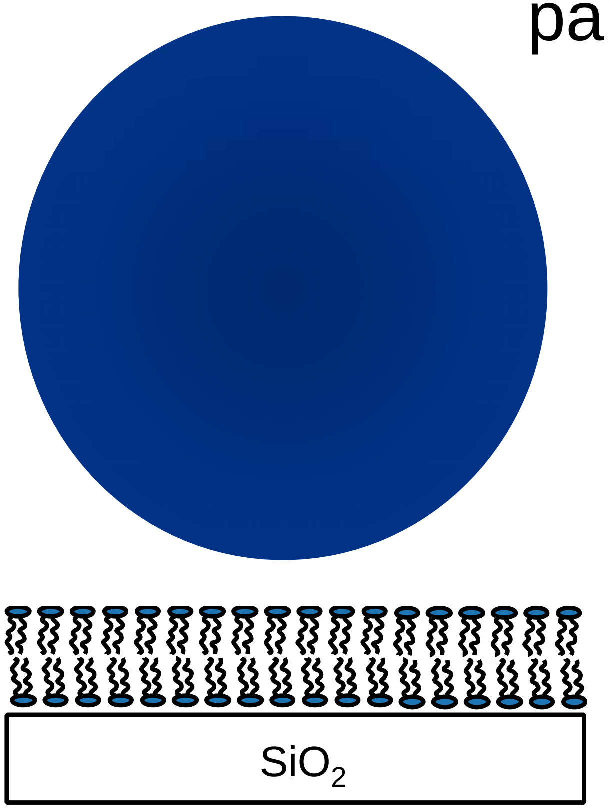
[animation showing swelling of a polymer layer]

QCM-D for monitoring of nanomaterial – lipid membrane interactions

Nanomaterial – membrane interactions



nano-
particle

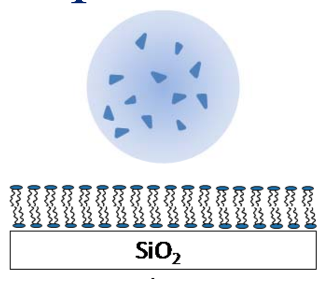


How much?
How fast?
Viscoelastic properties?
Water content?
Membrane integrity?

model lipid membrane;
variation of charge

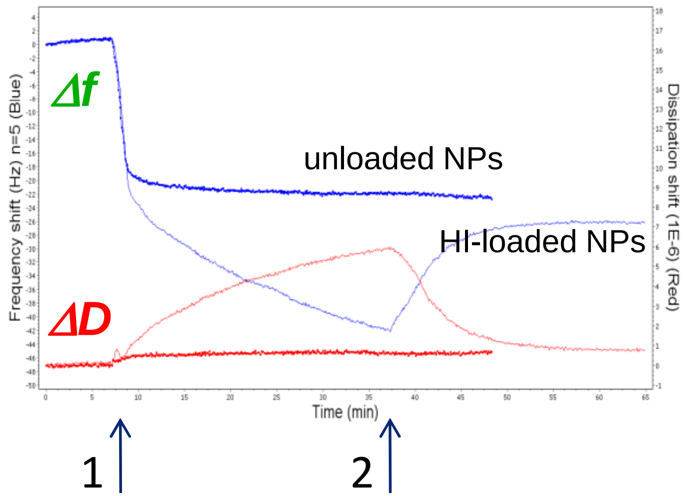
Interaction of cationic NPs with charged lipid membranes.

NPs: Unloaded cationic polymeric NPs
Dito loaded with human insuline (NP-HI),
(Zeta pot. = +26 mV, Size ≈ 200 nm)

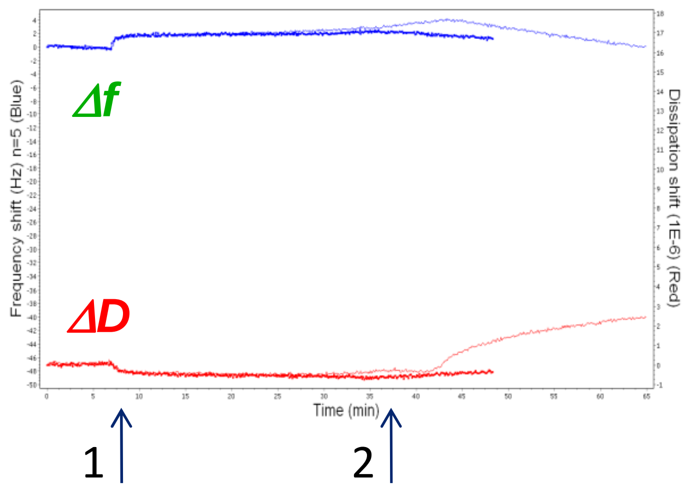


QCM-D responses

POPS:POPC (1:3)
(negatively charged membrane)



POEPC:POPC (1:3)
(positively charged membrane)



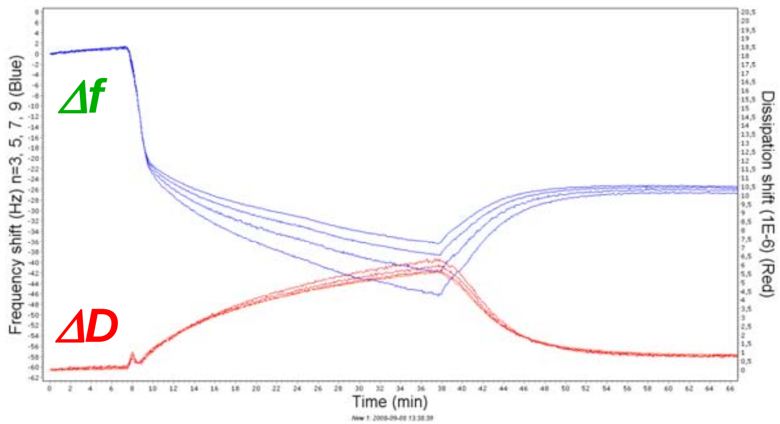
1. Injection of polymer-insuline complex (——)/polymer (▬▬)
2. Rinse with phosphate buffer

Nanoparticles provided by Ch. GRANDFILS, Univ. de Liège

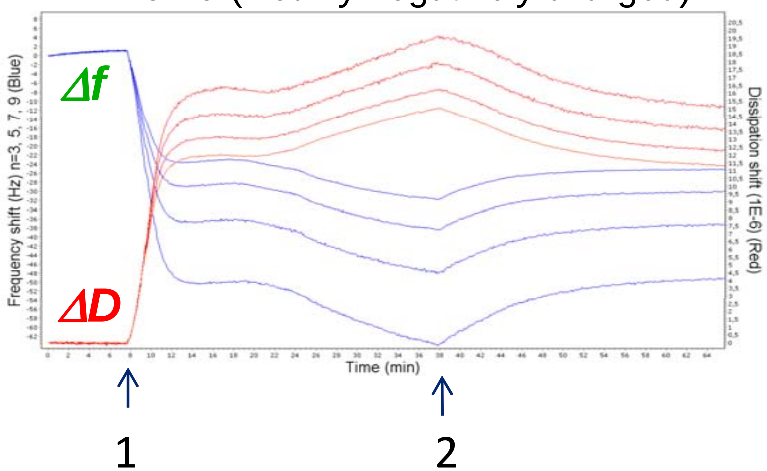
Frost R. *et al.*, in manuscript

Interaction of cationic NPs with charged lipid membranes.

POPS:POPC 1:3 (negatively charged)



POPC (weakly negatively charged)



Positively charged particles bind more strongly (low dissipation) to a more negatively charged lipid membrane (POPS:POPC 1:3).

Differences in response between overtones (n= 3, 5, 7, 9) indicate a viscous structure on the surface.

1. Injection of polymer-insuline complex (NP-HI)
2. Rinse with phosphate buffer

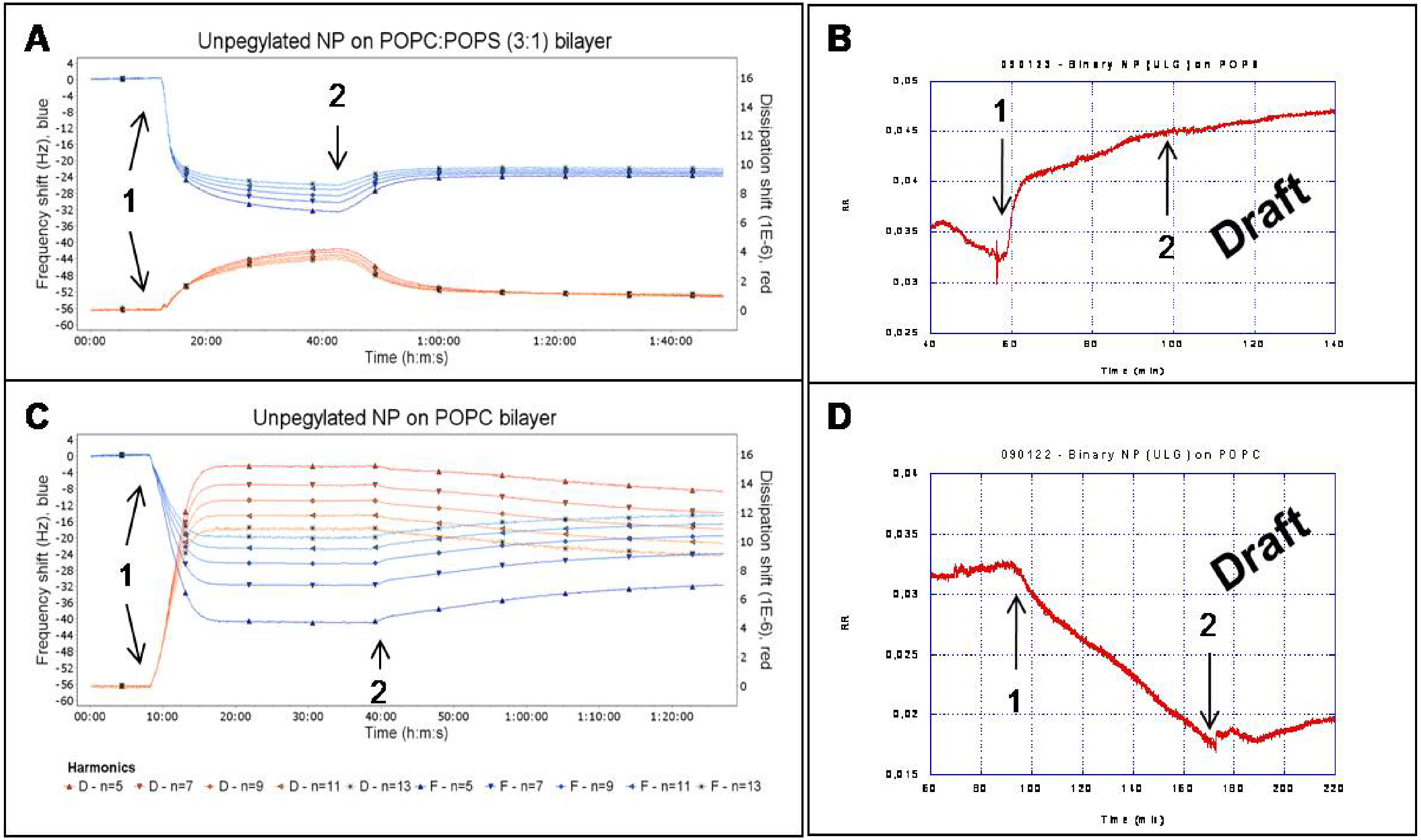
Nanoparticles provided by Ch. GRANDFILS, Univ. de Liège

Frost R. *et al.*, in manuscript

QCM-D | **Reflectometry**

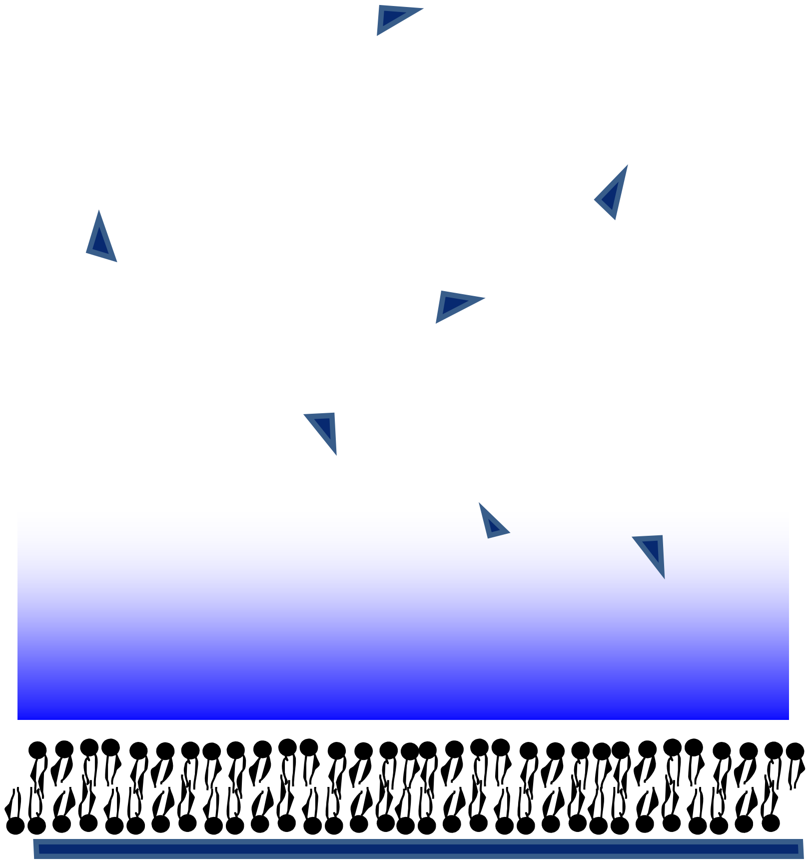
NPs on POPC/ POPS (3:1)

NPs on POPC

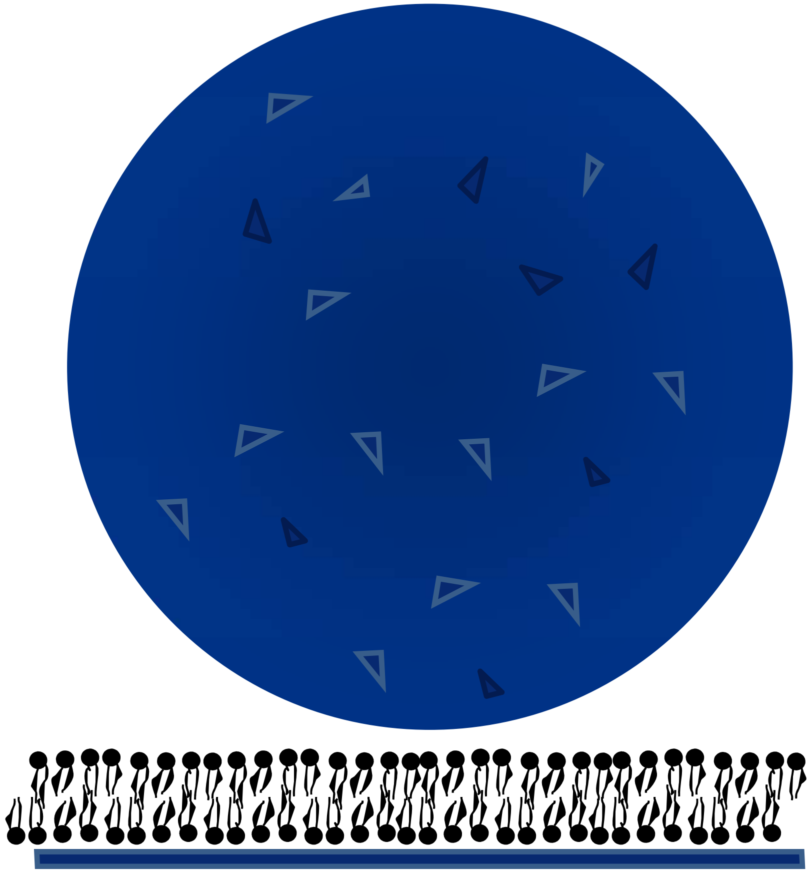


Frost R. *et al*., in manuscript

Proposed model



POPS:POPC 1:3 (negatively charged)



POPC (weakly negatively charged)

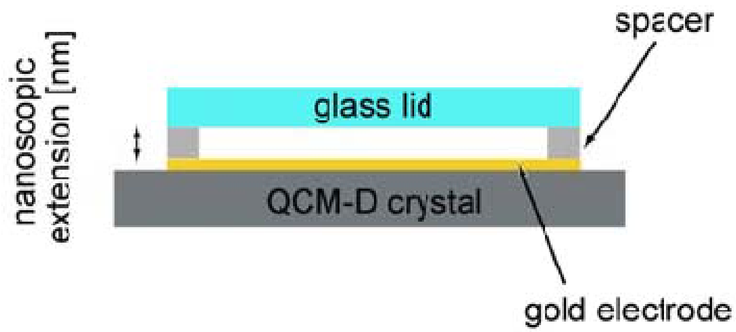
Frost R. *et al*., in manuscript

QCM-D for monitoring of phase transitions

A nanocell for QCM and QCM-D sensing

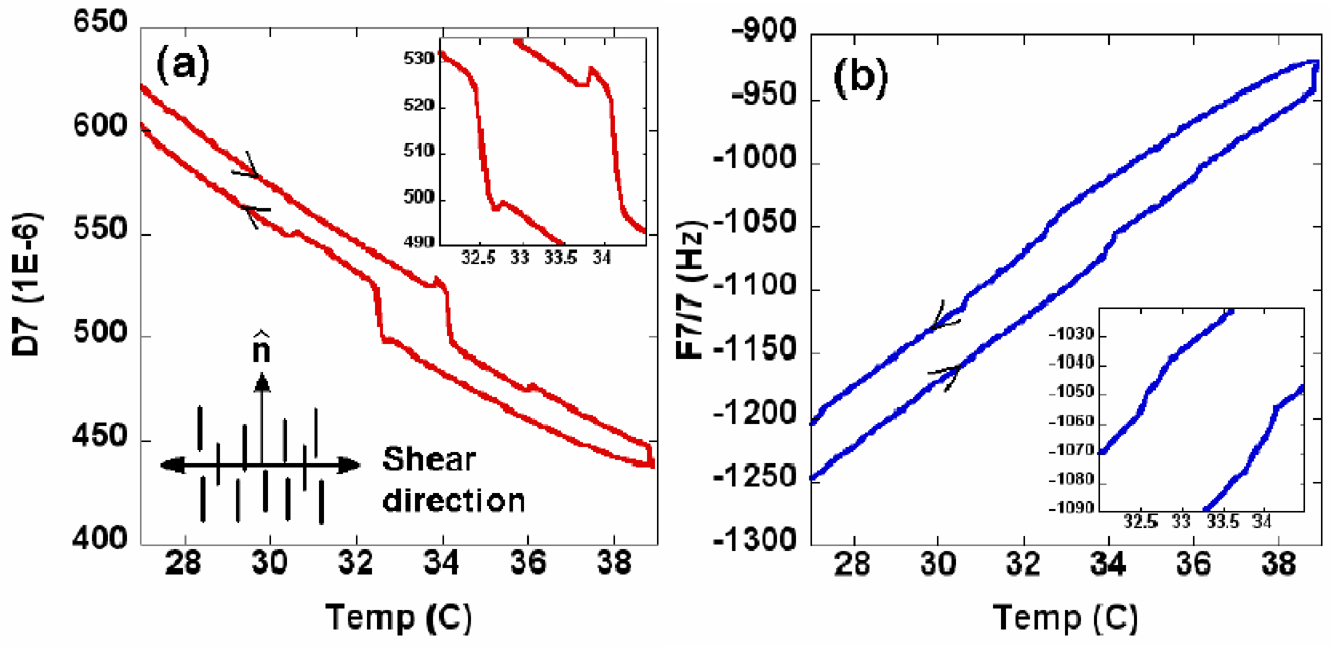
G. Ohlsson, C. Langhammer, I. Zorić and B. Kasemo

Rev. Sci. Instr., 2009



Application example:

Phase transition of liquid crystals



Conclusion

- QCM-D is very useful for the nano-scale characterisation of thin polymer films at surfaces.
- Complementary techniques are needed for a full picture.

Acknowledgement

- Chemical Physics and Biological Physics groups at Chalmers
- The EU FP6 IP NanoBioPharmaceutics, the FP7 project Find&Bind
- Swedish Research Council,Vinnova
- Q-Sense