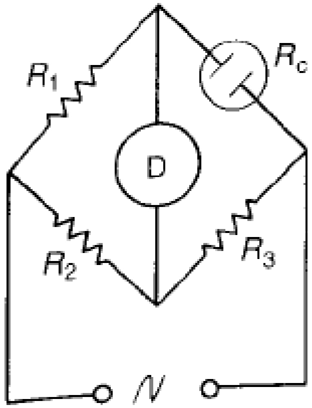
Lecture 4

Conductance sensors. ChemFET. Electrochemical Impedance Spectroscopy. Practical consideration for electrochemical biosensors.

Conductivity

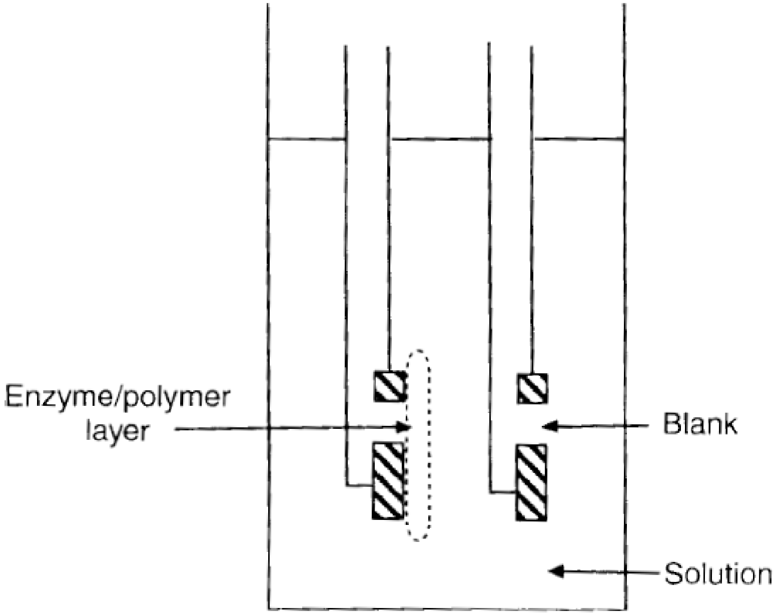
$$V = I \times R = \frac{I}{L},\ \text{L - conductance} \qquad L = \kappa A / l,\ \ \Lambda = \kappa / [C]$$

- Directly proportional to the concentration of ions in the solution
- Depends on charge, mobility and degree of dissocation of ions
- Any reaction that produces change in a number of ions or in the charge of ions can be monitored.
- No selectivity in itself



$$R_c = R_3 \times \frac{R_1}{R_2}$$

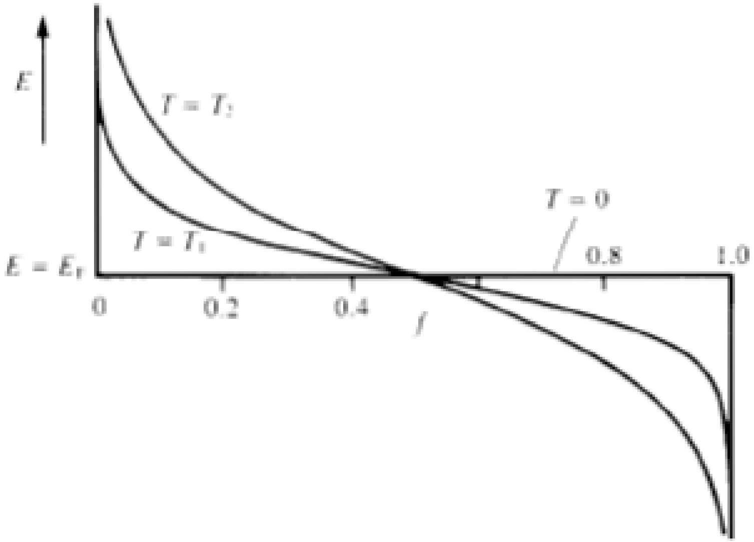
$$L_c = \frac{1}{R_c} = \frac{R_2}{R_1 R_3}$$

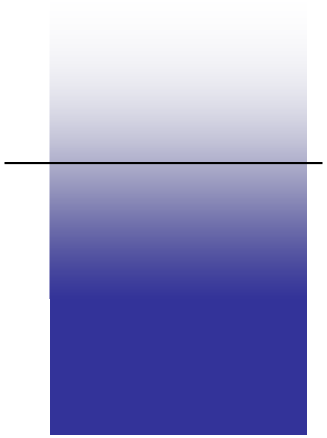


Electrode: solid metal

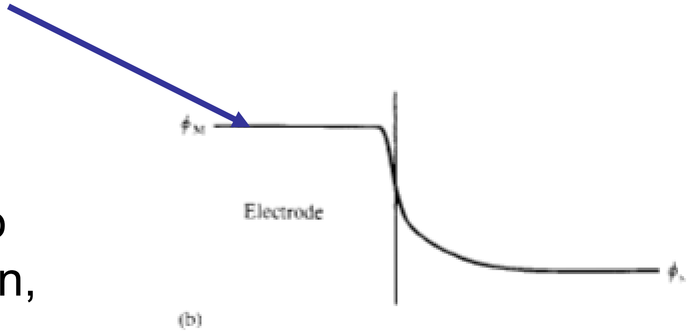
- Fermi distribution
  only electrones within kT of Ef
  can be transferred

$$f = 1/(1+\exp(E-E_F)/kT)$$





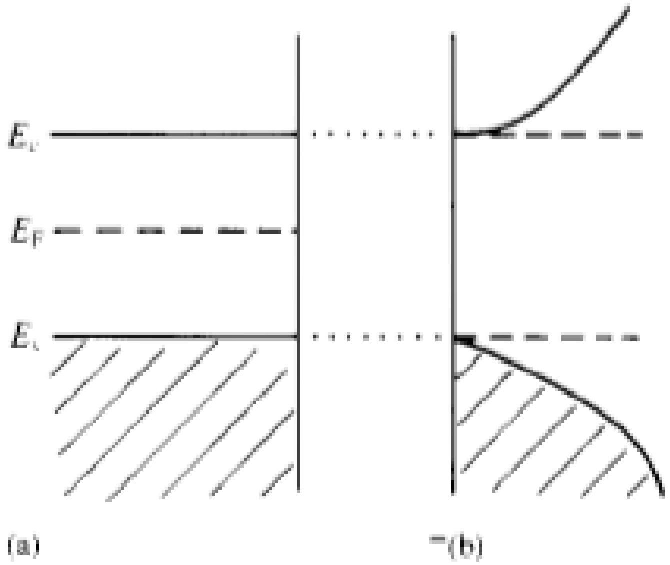
- High electron density



Additional effect related to crystallographic orientation, reorganisation of metal surface during potential cycling etc.

Semiconductor electrode (intrinsic semiconductor)

- Band gap
- E_f in the middle of the gap
- Number of excited electrons¨~exp(-E_g/2kT)
- Lower density of state, space-charge region is large and therefore most of potential variation occurs there (Cd~10-100uF, Csc<1uF)



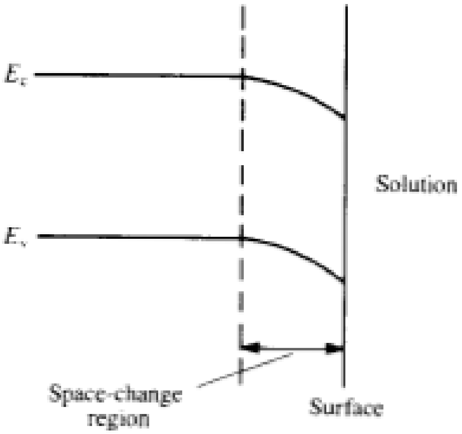
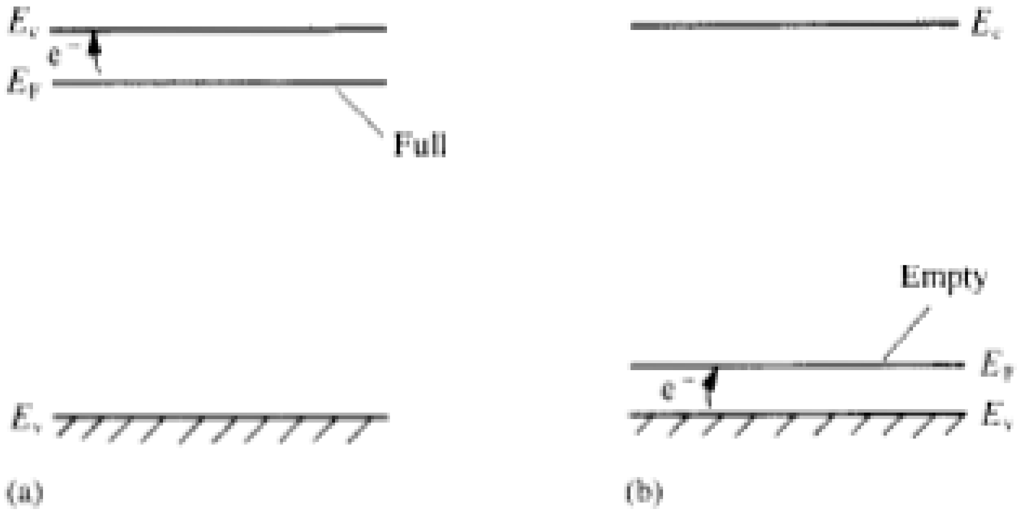


Table 3.1. Bandgap energy, E_g, and corresponding wavelength λ_{bg} (important for photo-excitation) of some semiconductors of electrochemical interest[25]. Zone of visible light (300 → 950 nm)

Semiconductor	E_g/eV	λ_{bg}/nm
SnO_2	3.5	350
ZnO	3.2	390
$SrTiO_3$	3.2	390
TiO_2	3.0	410
CdS	2.4	520
GaP	2.3	540
Fe_2O_3	2.1	590
CdSe	1.7	730
CdTe	1.4	890
GaAs	1.4	890
InP	1.3	950
Si	1.1	1130

Doped semiconductors



N-type

P-type

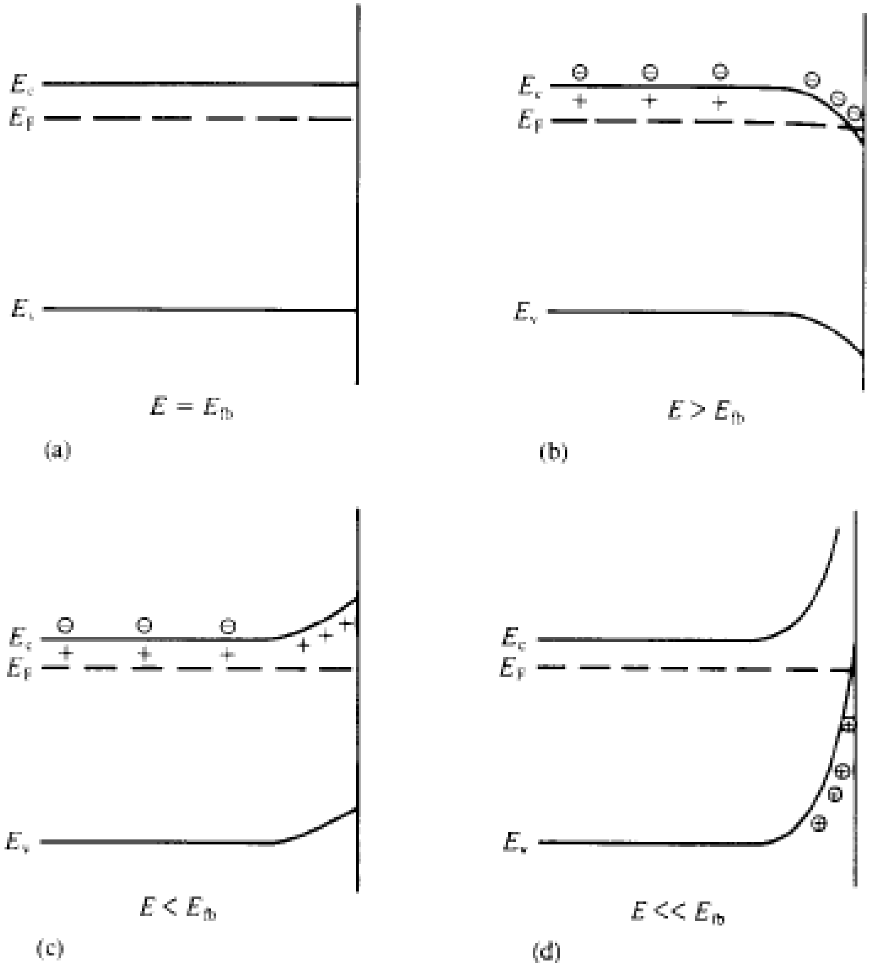
Types of space charge region in n-type semiconductor

Flat-band potential

Accumulation layer

Depletion layer

Inversion



$E = E_{fb}$ (a)

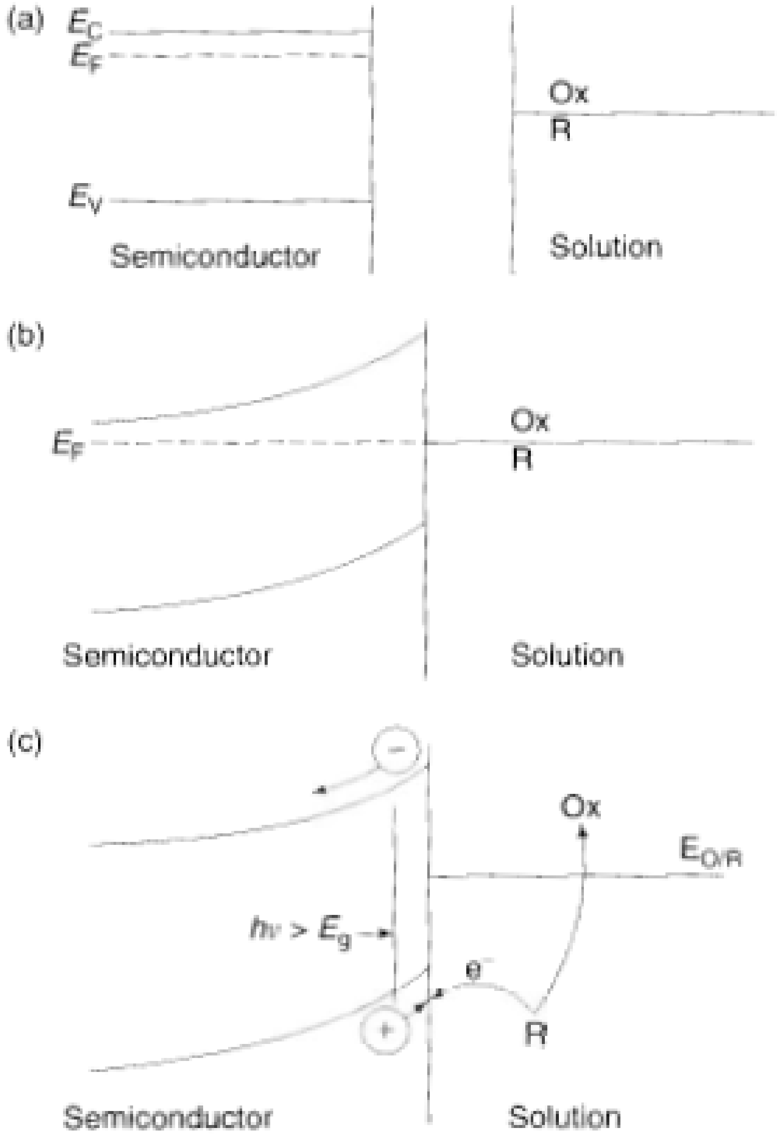
$E > E_{fb}$ (b)

$E < E_{fb}$ (c)

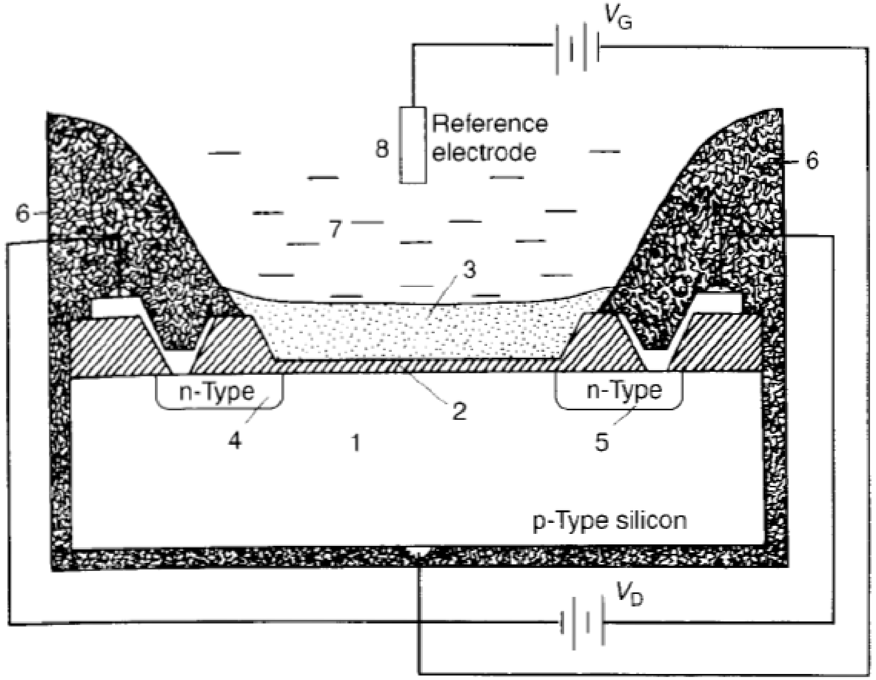
$E << E_{fb}$ (d)

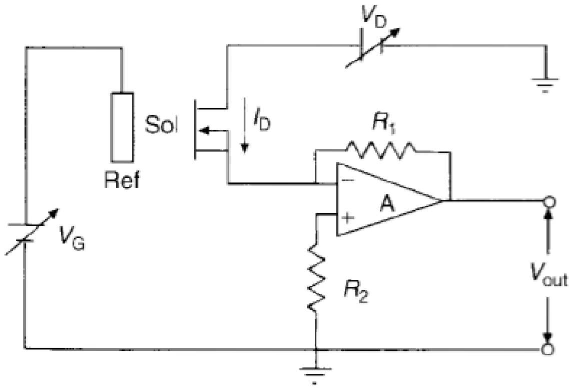
Semiconductor-solution contact

- semiconductor and liquid separated:
- equilibrium in the dark: Fermi level is aligned to E^0.
- photocatalysis

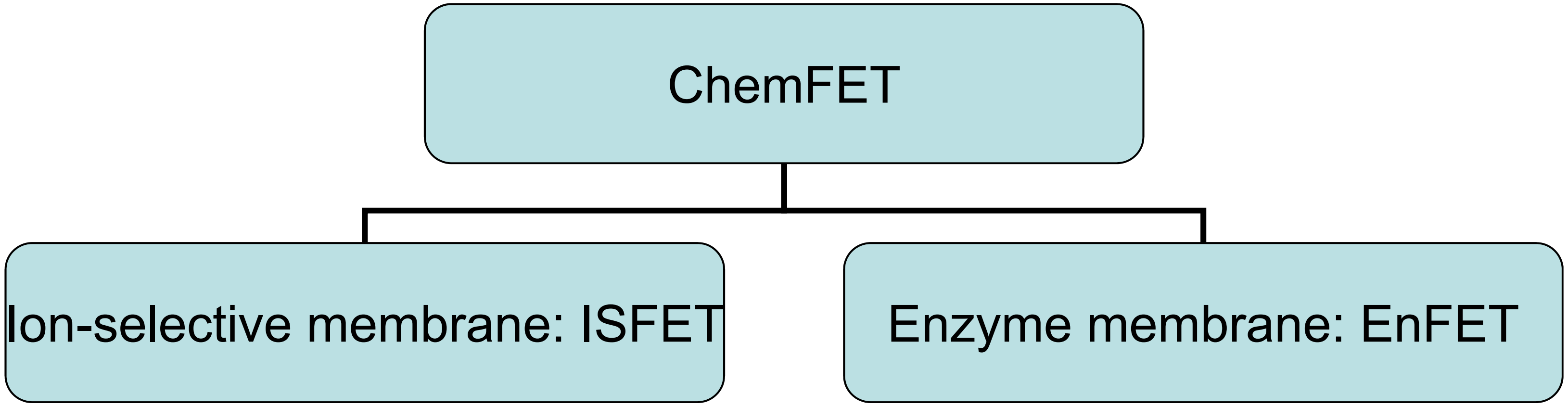


ChemFET: Chemically sensitive FET





ChemFET: Chemically sensitive FET



ChemFET

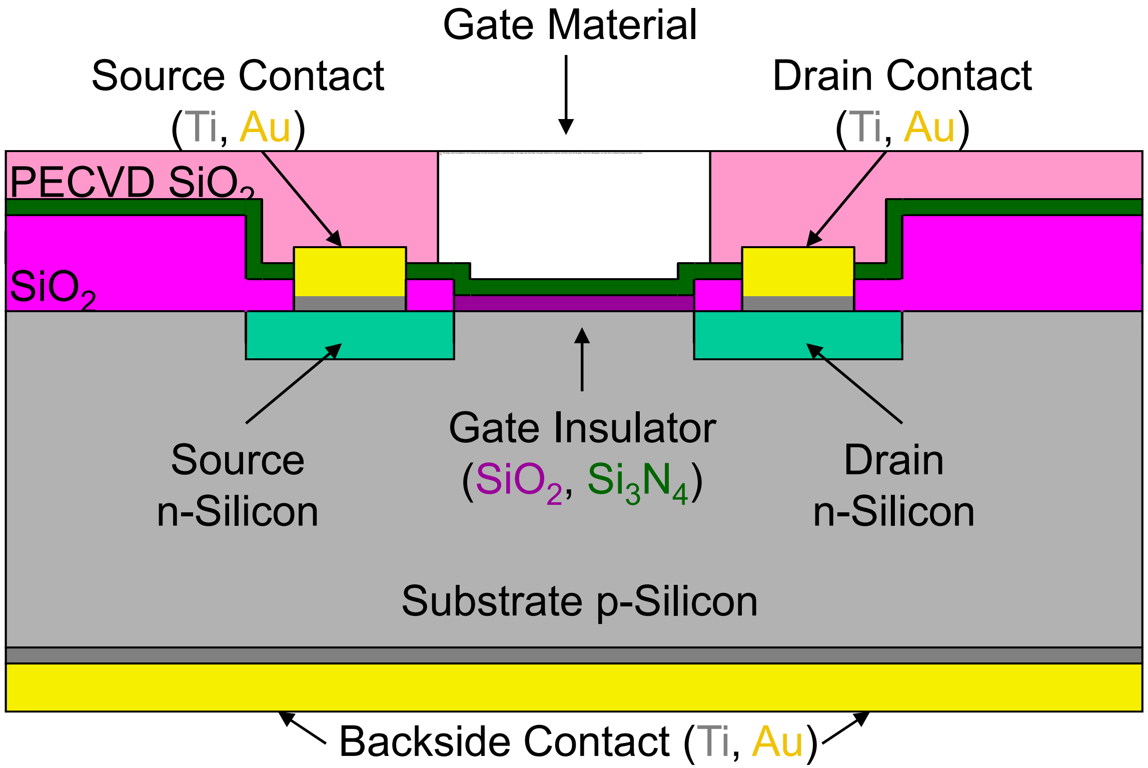
Ion-selective membrane: ISFET

Enzyme membrane: EnFET

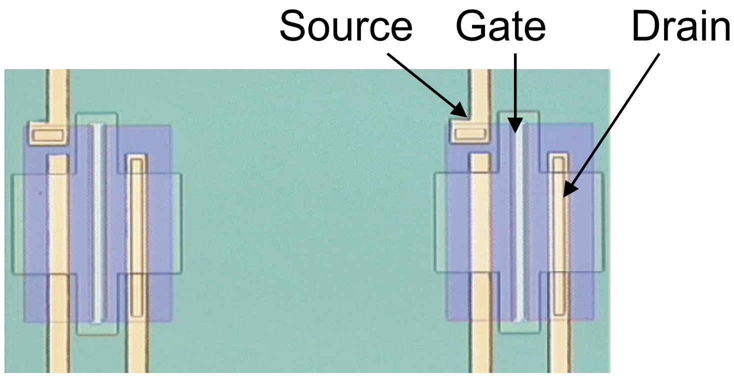
- Membranes with mobile ion-exchanger
- Membranes containing neutral ionophores
- Membranes with fixed ionic sites

- based on interaction of enzyme with analyte, extremely selective

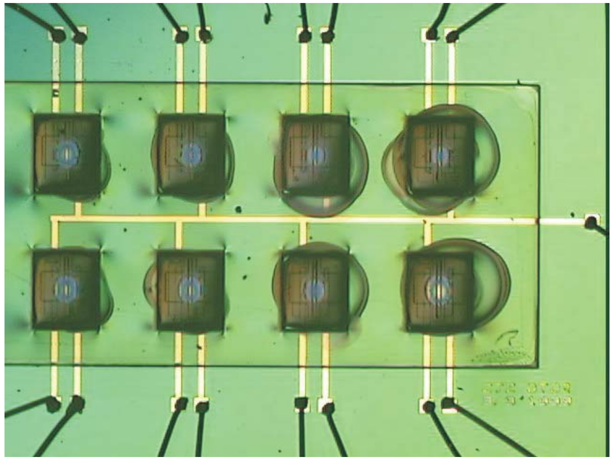
ChemFET fabrication



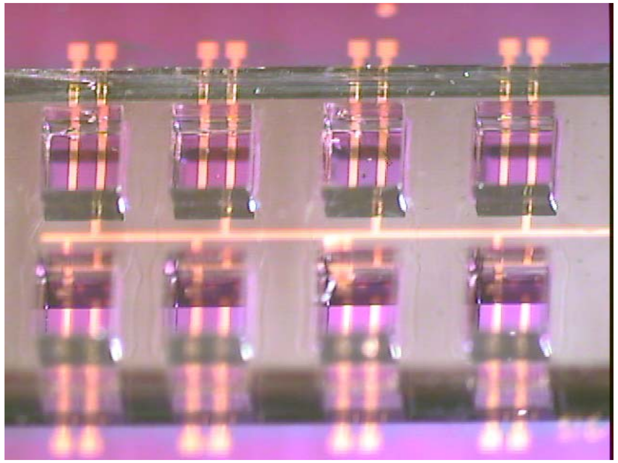
Process Snapshots



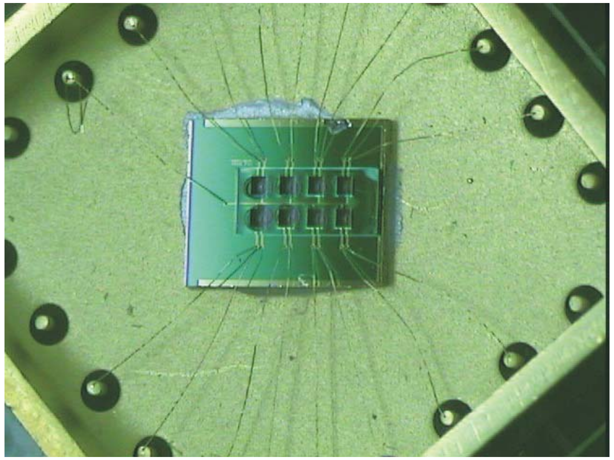
Working Area Lithography



Conducting Polymer Deposition



Epoxy Well Definition



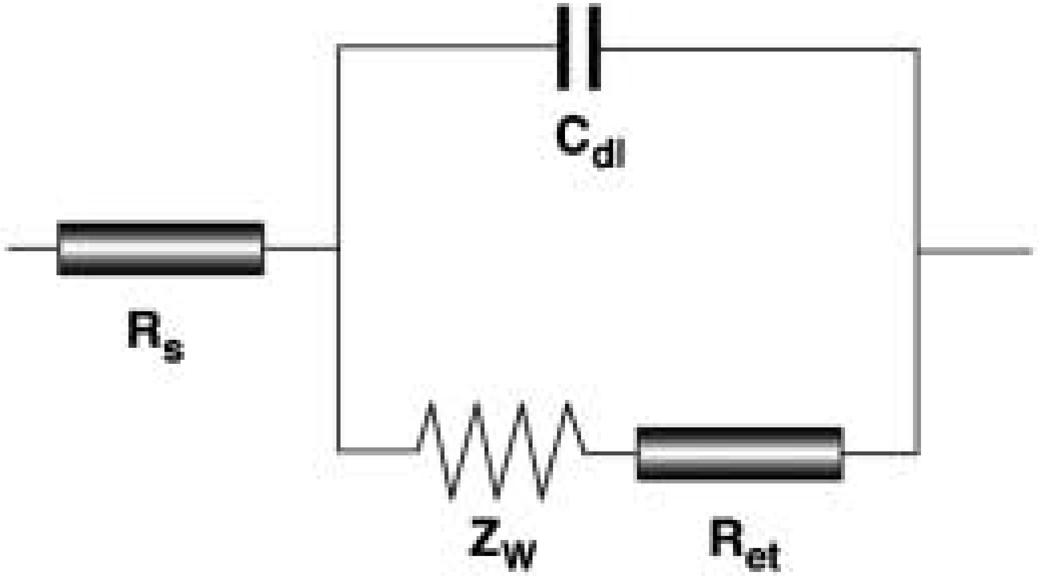
Wire bonded to Header

Impedance spectroscopy

- Reactions on the surface (e.g. formation of a recognition complex) will lead to change of capacitance and resistance of electrode-solution interface
- Impedance is a complex resistance encountered when current flows through a circuit containing resistors, capacitors and inductors

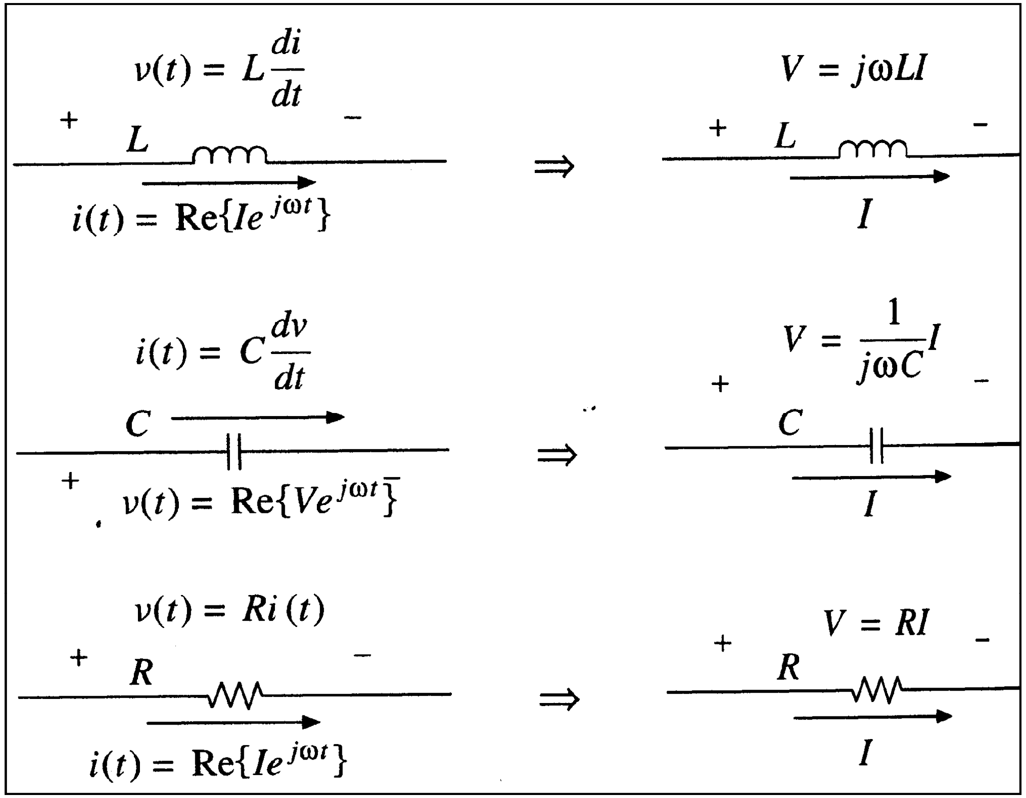
Randles and Ersher equivalent circuit model

- C_{dl} – double layer capacitance
- R_{et} – electron transfer resistance
- R_s – Ohmic resistance of the solution
- Z_w – Warburg impedance due to diffusion of ions from bulk to the surface

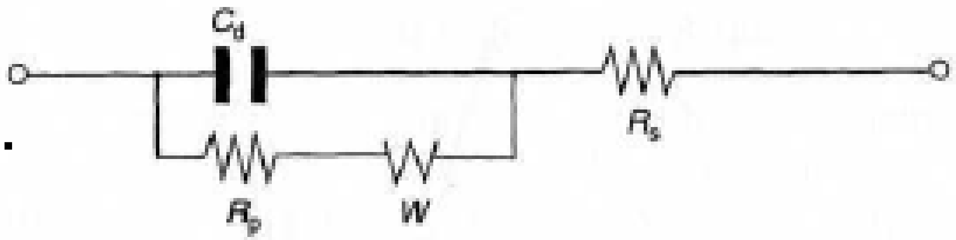


Impedance spectroscopy

- From the circuit theory: impedance of basic electric elements:



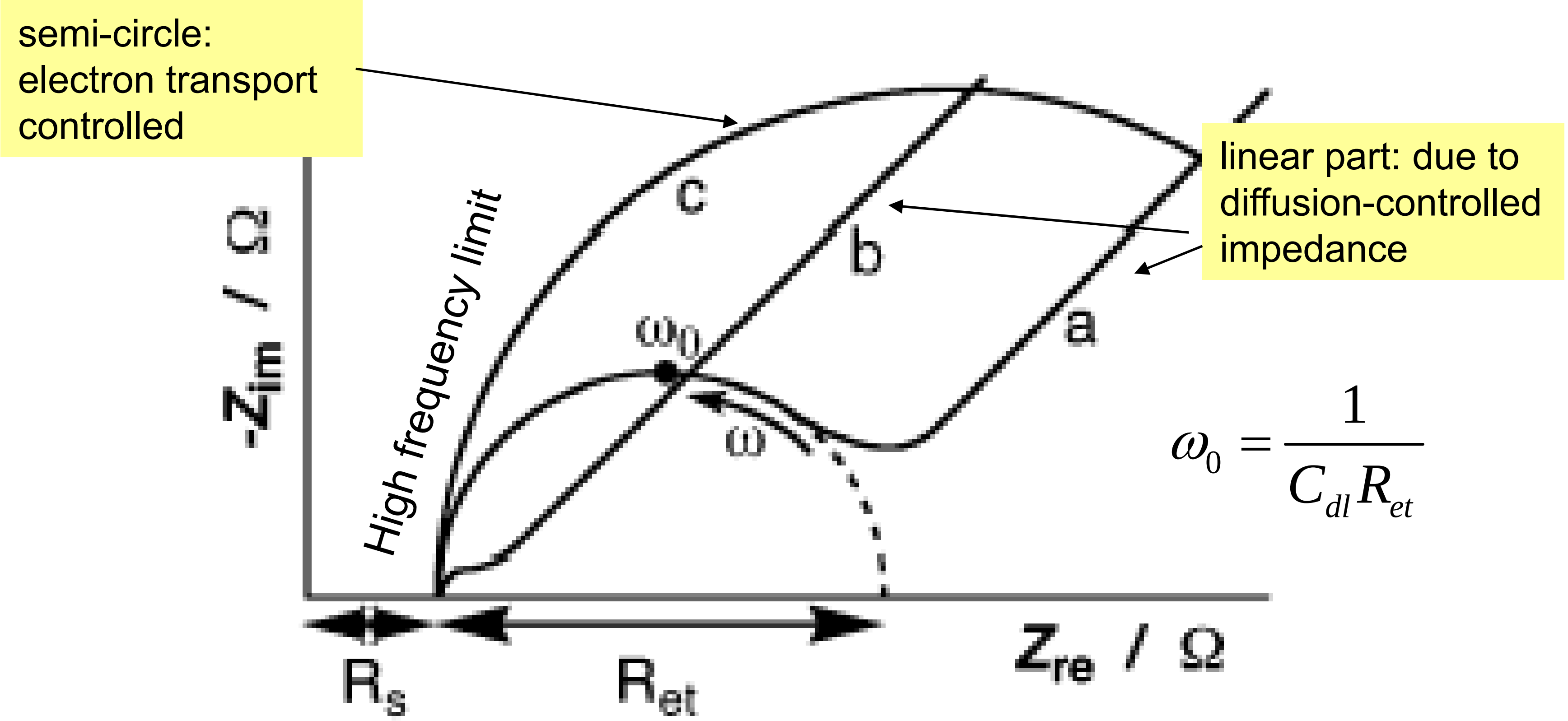
- So, we can calculate the impedance of our circuit…



Impedance spectroscopy

- The impedance can written as:

$$Z(\omega) = R_s + \frac{R_{et}}{1+\omega^2 R_{et}{}^2 C_d{}^2} - j\omega \frac{R_{et}{}^2 C_d}{1+\omega^2 R_{et}{}^2 C_d{}^2} = Z' + jZ''$$



semi-circle: electron transport controlled

linear part: due to diffusion-controlled impedance

$$\omega_0 = \frac{1}{C_{dl} R_{et}}$$

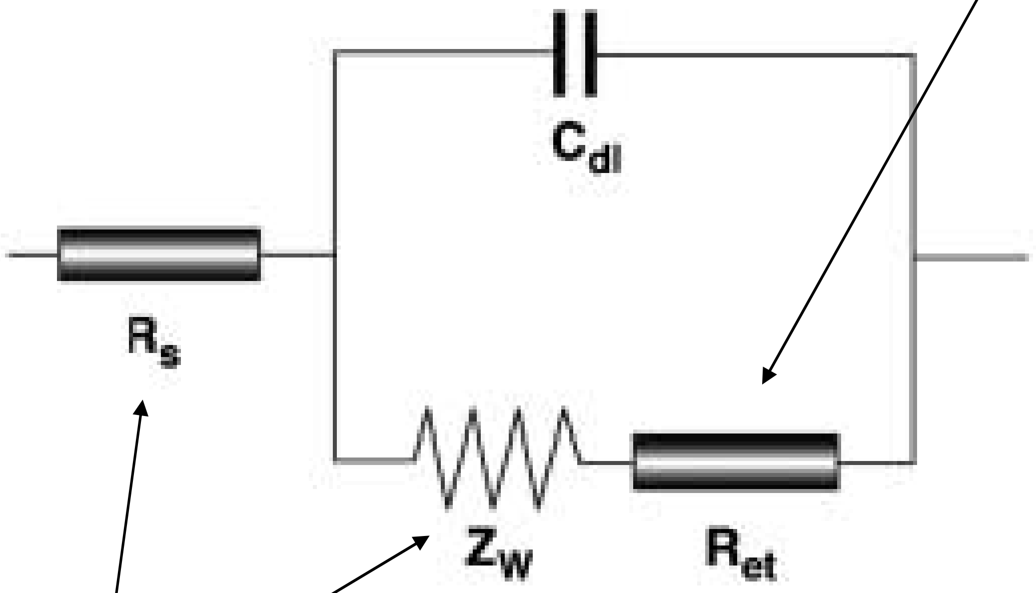
- Typical frequency range: 10mHz – 100 kHz (limited by the wires and e/chem cell)

Impedance spectroscopy

Depend on dielectric and conductive properties of the interface

$$\frac{1}{C_{\mathrm{dl}}} = \frac{1}{C_{\mathrm{bare}}} + \frac{1}{C_{\mathrm{mod}}}$$

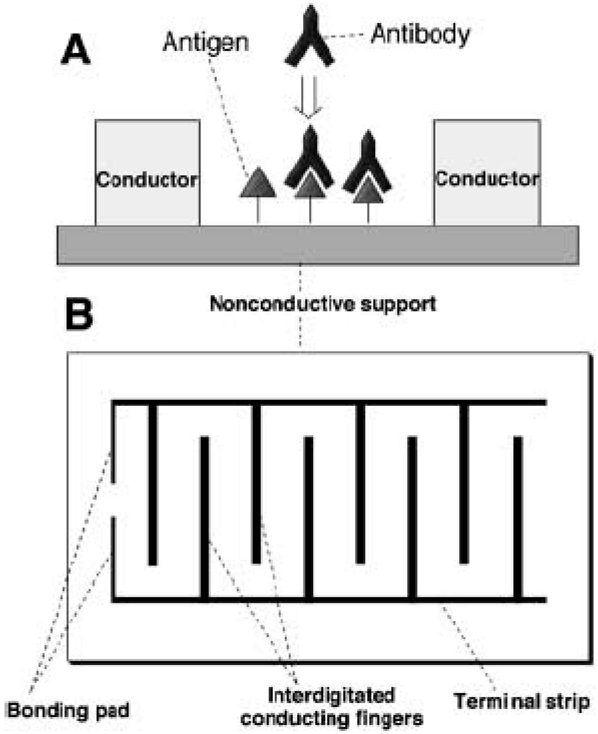
$$R_{et} = R_{\mathrm{bare}} + R_{\mathrm{mod}}$$



Represent bulk properties of the solution, not affected by the reactions at the interface

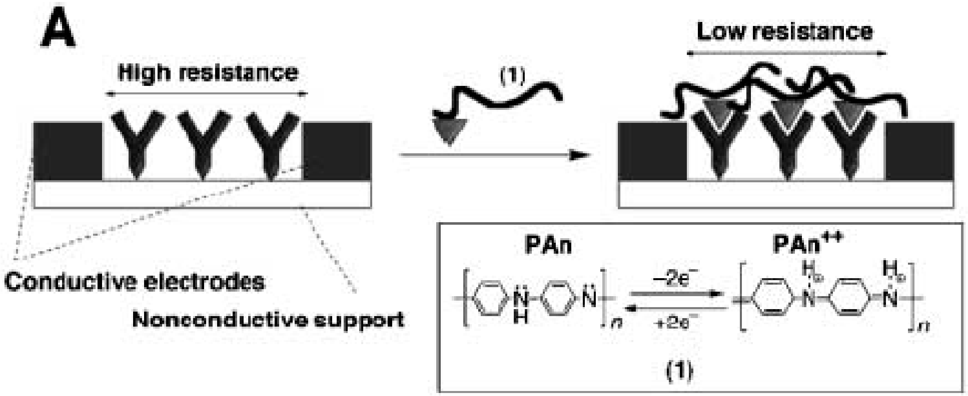
Immunosensors based on impedance spectroscopy

- **In-plane impedance measurements**
- Affinity binding in the gap results in the change of the electrical properties affecting the impedance between the electrodes:
- main contribution: capacitive changes due to change in dielectric constant
- Variations:
  - labelling IgG with bubble generating enzyme (e.g. catalase) to increase the change in dielectric constant
  - labelling IgG with conductive polymer chains
  - discontinuous metallic film in the gap

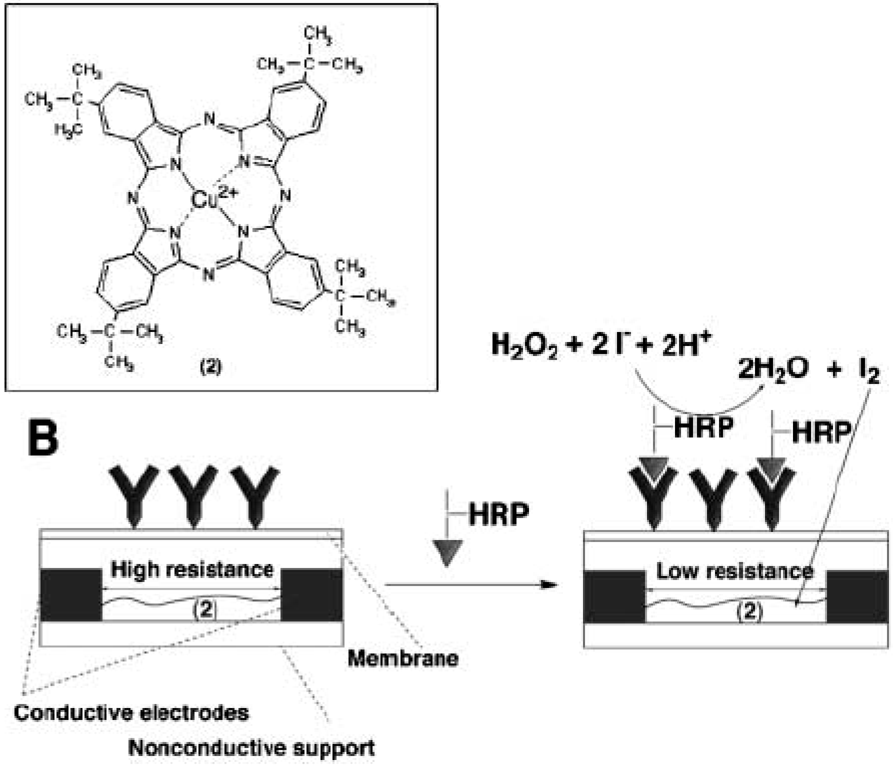


Immunosensors based on impedance spectroscopy

- **Examples**



Increase in conductivity upon binding of polyaniline labelled IgG

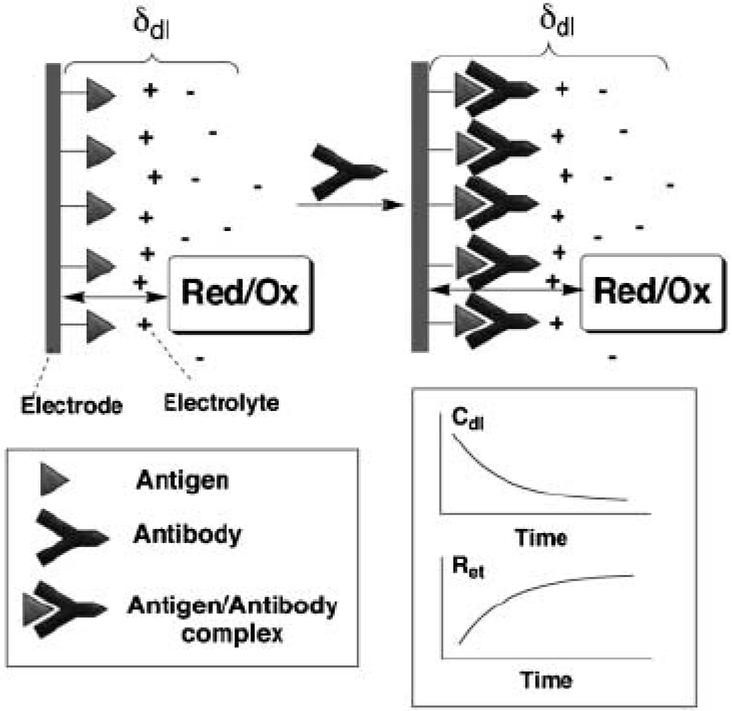


Increase in conductivity of copper phtalocyanine upon I_2 doping

Immunosensors based on impedance spectroscopy

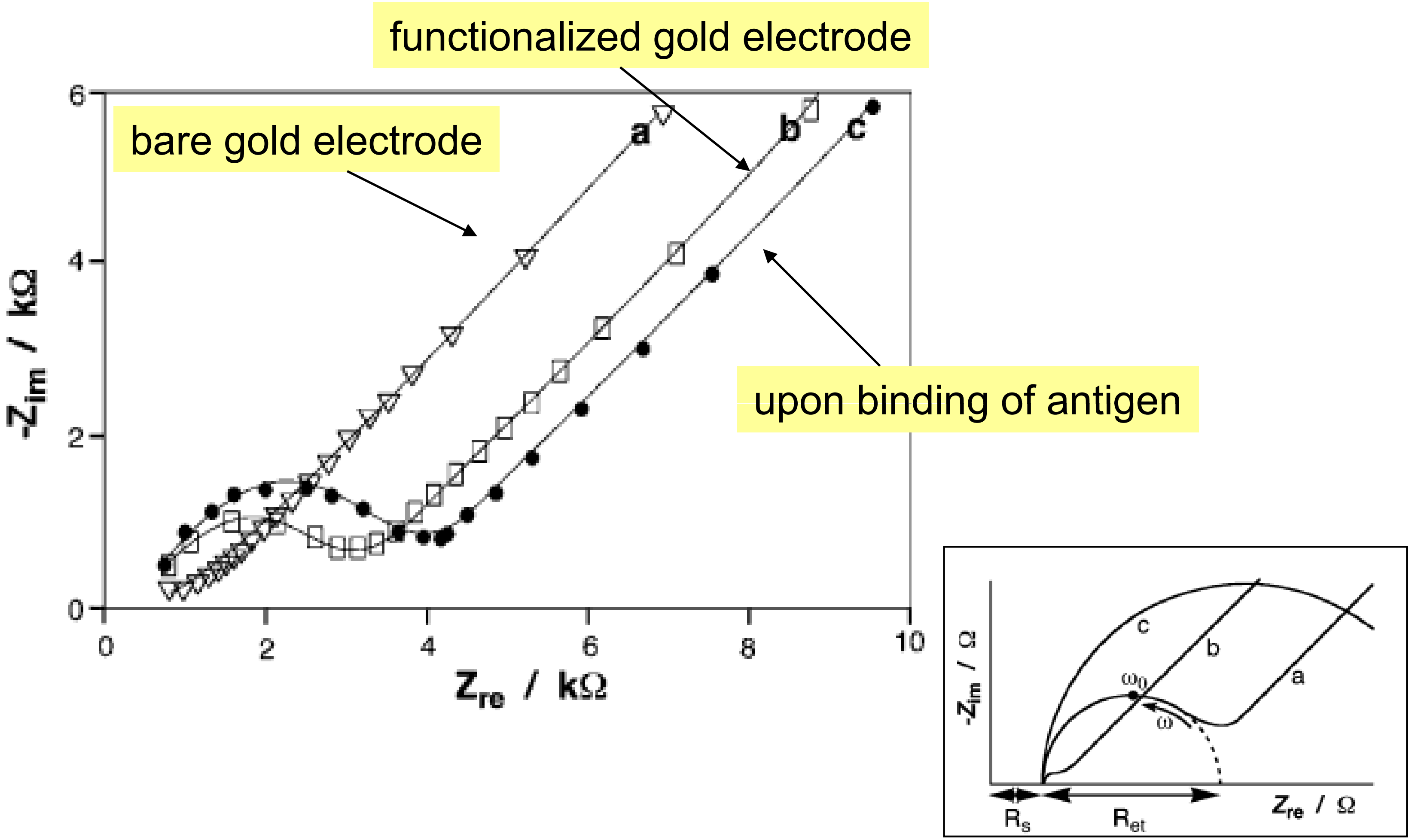
- **Interfacial impedance measurements**

- Formation of antigen-antibody complex results in:
  - increase of the **double-layer thickness**
  - **insulation** of the electrode surface in respect to redox couple added to the solution



Immunosensors based on impedance spectroscopy

- **<u>Example:</u>** sensor for foot-and-mouth disease using faradeic spectroscopy (with 2mM $Fe(CN)_6)^{-3/-4}$)



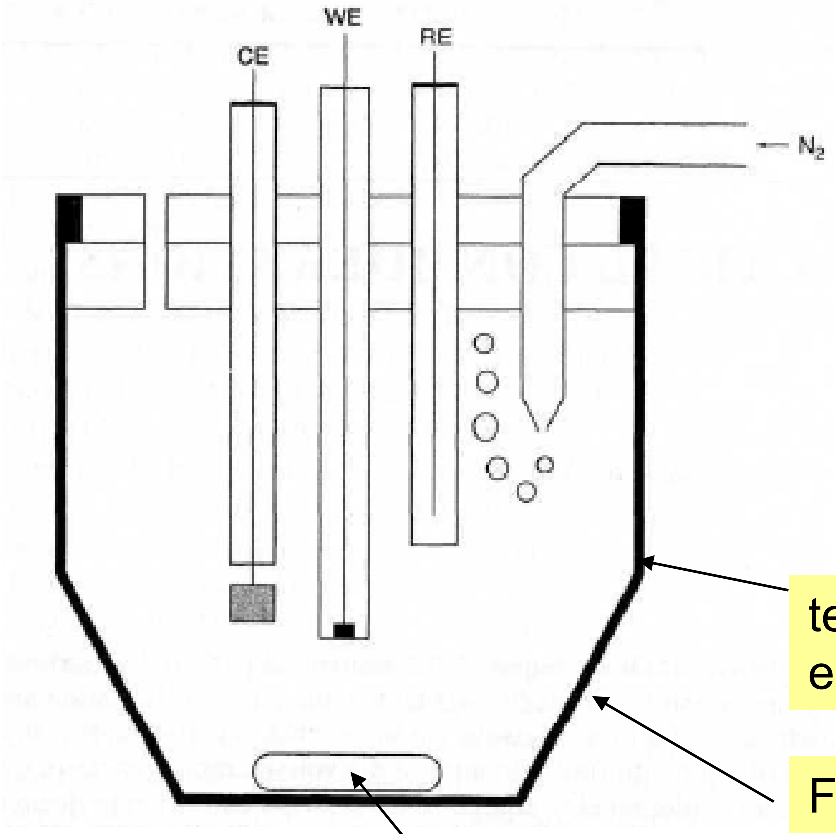
functionalized gold electrode

bare gold electrode

upon binding of antigen

Practical considerations

Electrochemical cell for voltammetry



gas purging: oxygen removal is essential for many experiments as oxygen and its products can affect the process in question

$$O_2 + 2H^+ + 2e \rightarrow H_2O_2 \quad \text{-0.1V vs SCE}$$

$$H_2O_2 + 2H + 2e \rightarrow 2H_2O \quad \text{-0.9V vs SCE}$$

temperature controlled environment

Faraday cage

magnetic stirrer

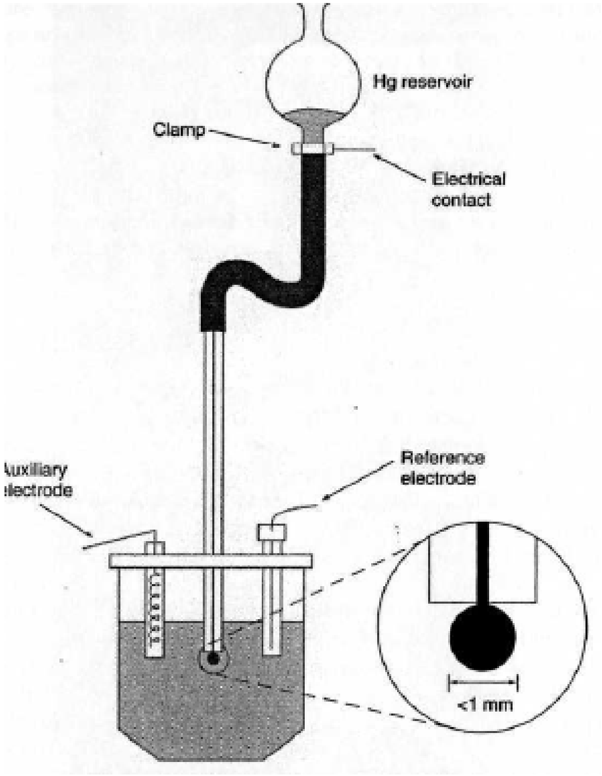
Instrumentation

- Fully automated system for voltammetry measurements

- Research grade system with capability for multiple techniques

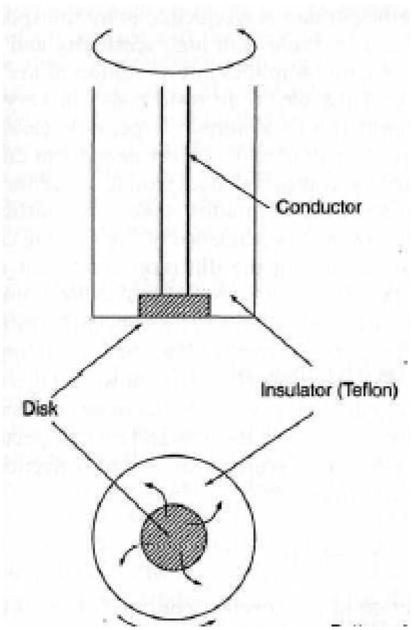
Working electrodes

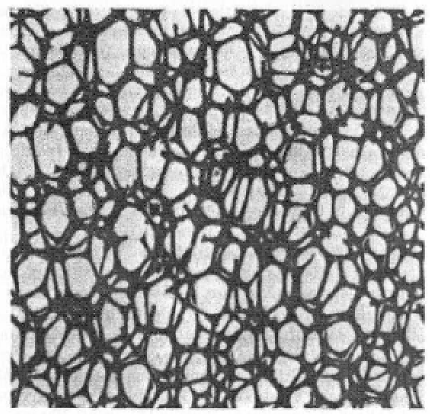
- Dropping mercury electrode (DME)



Working electrodes

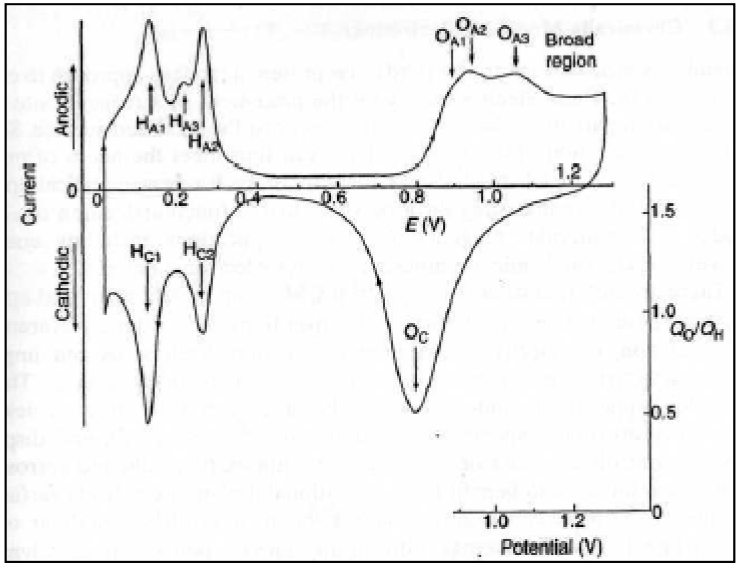
- Solid electrodes:
  - stationary (usually cylindrical rod in an insulating sleeve)
  - rotating
- Material for solid electrodes:
  - carbon
    - glassy carbon: wide potential window, chemically inert, can be made porous
    - carbon paste electrode: graphite powder+ organic binder
    - diamond electrodes (boron-doped): low double layer capacitance (due to absence of C-O bonds), extreme hardness
  - metal electrodes: good electron transfer kinteics





Working electrodes

- Material for solid electrodes:
  - – metal electrodes made of noble metals:
    - good electron transfer kinetics
    - large anodic window
    - small cathodic window due to low hydrogen overvoltage (-0.2 – -0.5V depending on pH)
    - high background currents associate with formation of surface oxide and hydrogen layers
  - – other metals can be used depending on application (Cu, Ni, Ag, Pt-Ru etc.)

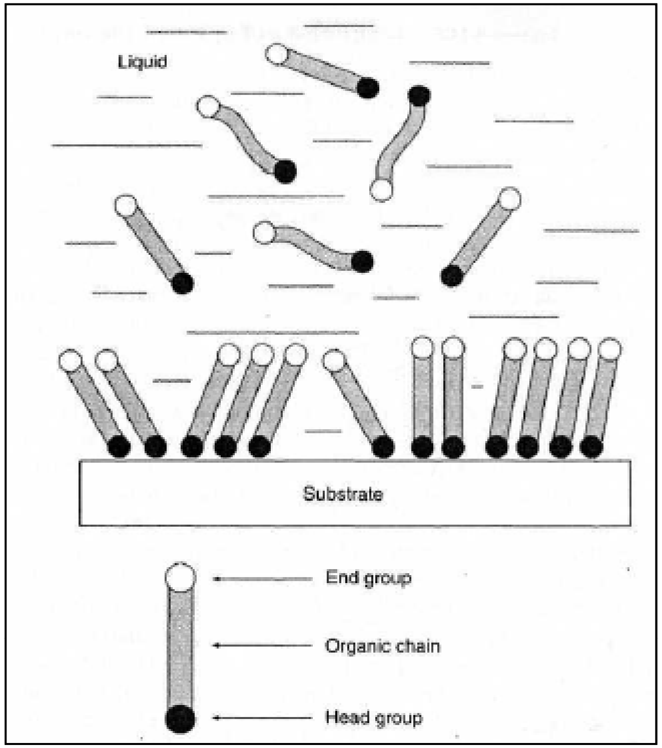


Pt oxide formation and reduction in 0.5M H_2SO_4.

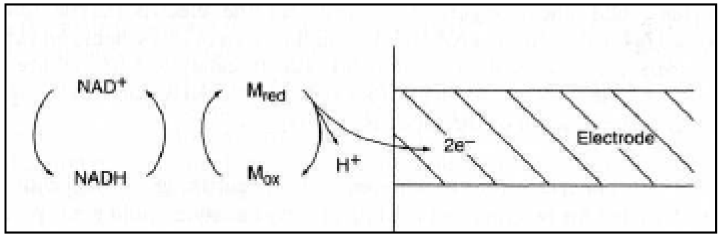
Working electrodes

- Chemically modified electrodes: properties of electrode are deliberately changed by placement of a reagent onto the surface
  - self assembled monolayers

$$RSH + Au \rightleftarrows RS - Au + e^{-} + H^{+}$$

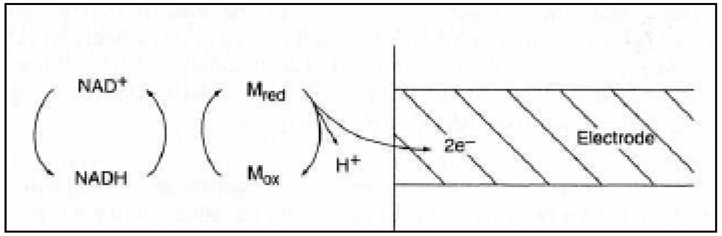


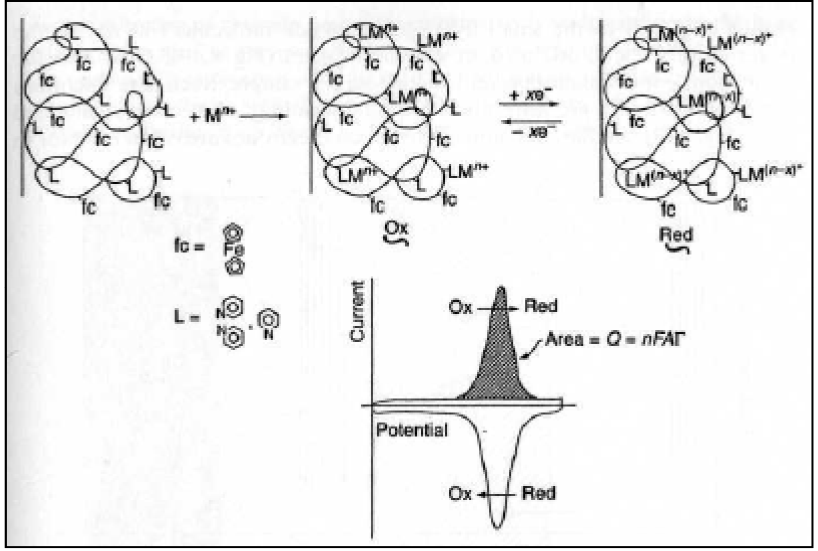
  - CNT modified electrodes
  - Sol-gel encapsulation of reactive species (3D hydroxilated network is formed for entrapment of a modifier)
  - Electrocatalytically modified electrodes (with mediator, e.g. NADH, Co-phtalocyanine etc.)
  - Pre-concentrating electrodes



Working electrodes

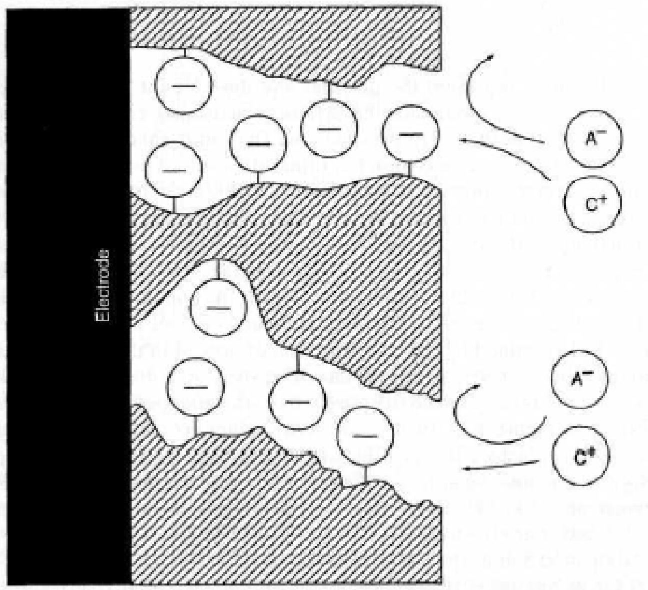
- Chemically modified electrodes:
  - CNT modified electrodes
  - Sol-gel encapsulation of reactive species (3D hydroxilated network is formed for entrapment of a modifier)
  - Electrocatalytically modified electrodes (with mediator, e.g. NADH, Co-phtalocyanine etc.)
  - Pre-concentrating electrodes: collecting analyte via nonelectrolytic step
  - Permselectrive coating: improving selective by allowing transport of analyte while excluding the unwanted species



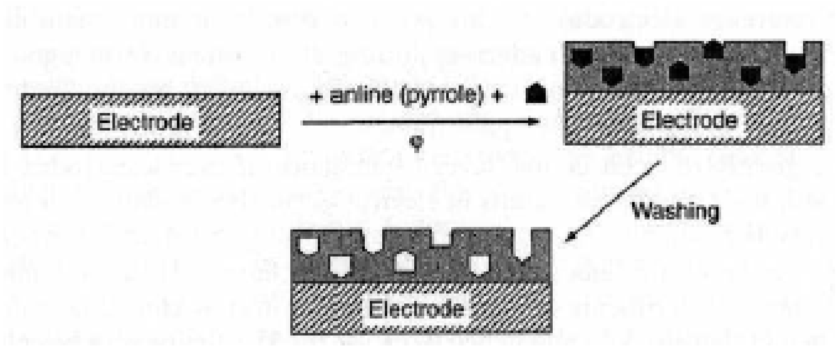


Working electrodes

- Chemically modified electrodes:
  - Permselectrive coating: improving selective by allowing transport of analyte while excluding the unwanted species, e.g.
    - via size exclusion
    - via charge exclusion
  - Conducting polymer
    - possibility to switch between conducting and insulating form
    - polymer nanowires
    - molecular imprinted polymers via electropolymerization



Nafion-coated electrode: excluding anionic interference due to negatively charged sulfonated groups in the pores



Working electrodes

- Microelectrodes
  - measurement of in microflow systems,
  - analysis of small samples
  - in vivo measurements
  - possibility to work in highly resistive solutions
  - reduced double layer capacitance
  - large component of spherical diffusion