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Ion-sensitive field-effect transistors

Basics and Applications

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Introduction

- Introduction of potentiometric sensors
  - Measuring the electrical potential difference at a solid/liquid interface
  - Nernst Equation
    - $\Delta\varphi = RT/F \ln a_{i1}/a_{i2}$
    - $a_{i1,2} = f_i \, c_i$ = activiy of ions i
  - Constant potential drop at the inner surface of the bulb
  - Contact between inner KCl solution and the outer solution
  - Electrochemical couple

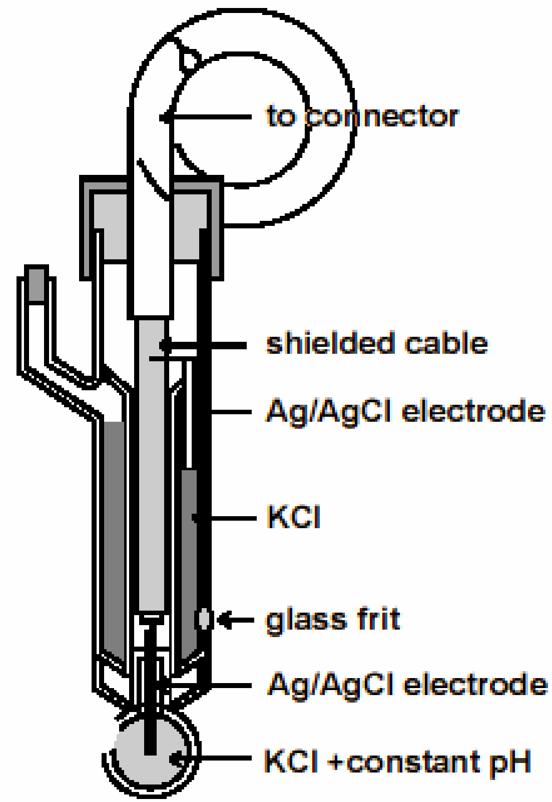
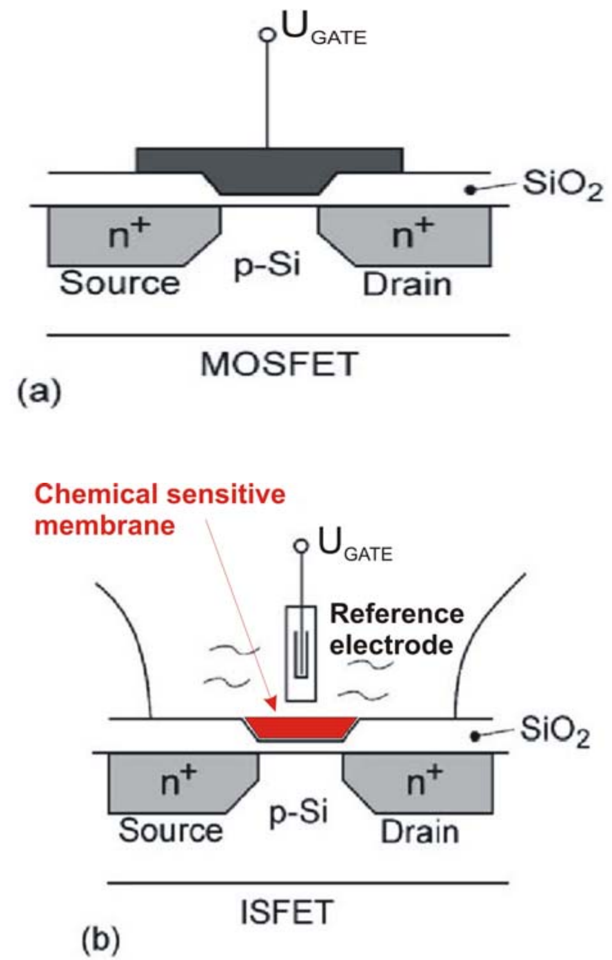


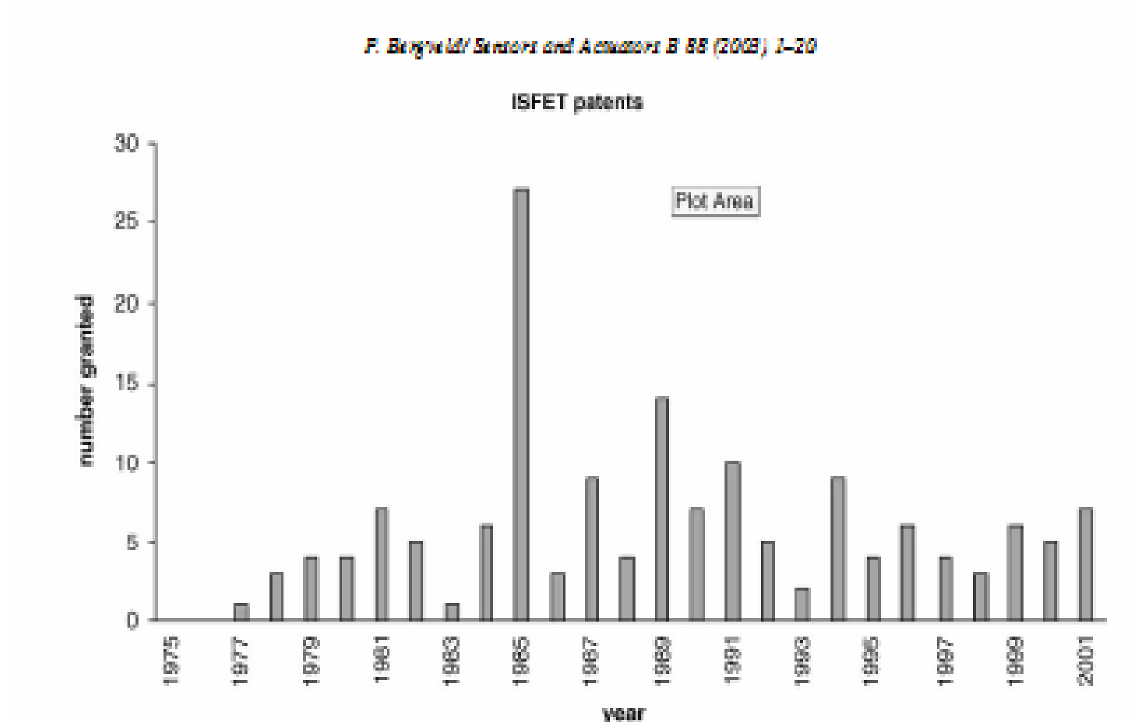
Fig.1
Cross sectional view of combined pH electrode.

Introduction

- Problem of miniaturizing
  - Less stable
    → problematic for in vivo measurments
- Bergveld 1970: „Development af an Ion-Sensitive Solid-State Device for Neurophysiological Measurements"
- Advantage of chip technology
  - cheaper
  - Improved characteristics
  - Reproducability
- Ion-Sensitive Field-Effect Transistor (ISFET)
  - small and rigid
  - fast response



Introduction



- Industry: Development of patents
- Markets:
  - Food industry
  - Biomedical industry
- Biocompatibility is still a big problem for in vivo measurements
- Future: inline-monitoring of industrial processes

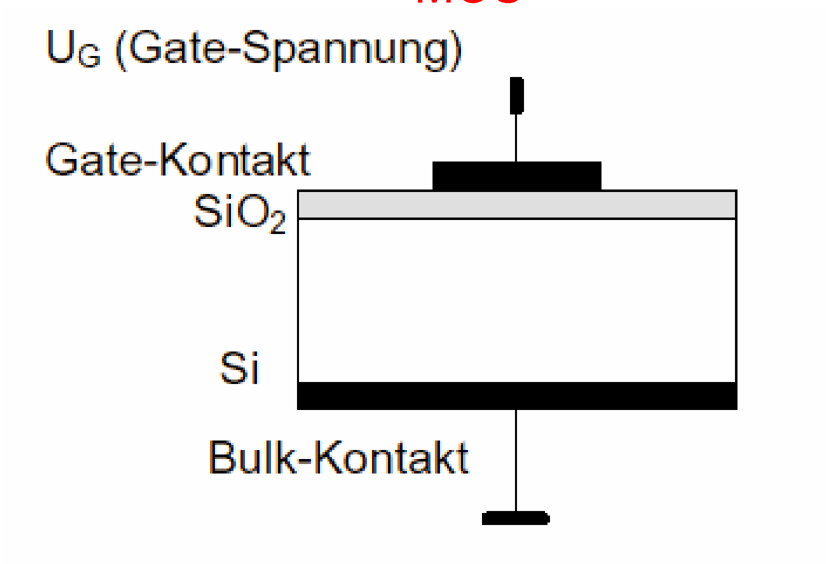
MOSFETs

MOS-system

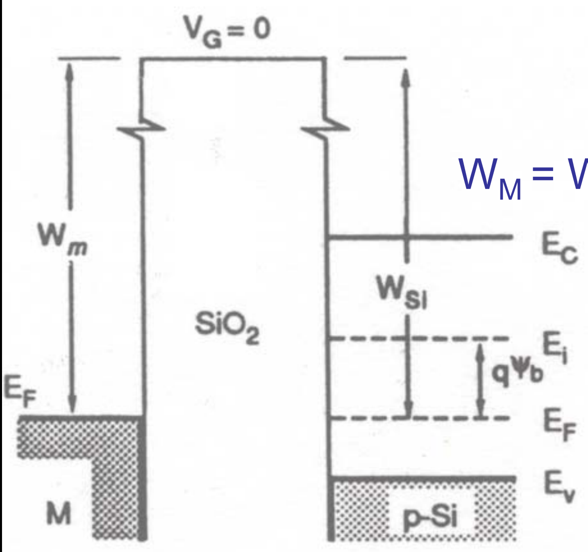
- Metal – Oxide – Semiconductor
  - Field effect: Voltage V_G induces charges at the surfaces → electric field
  - Ideal MOS-structure
    - $W_M = W_{Si}$
    - perfect insulator
    - no charges inside the oxide

ψ_B = difference between intrinsic fermi energie E_i and fermi energie E_F after doping

MOS



Ideal MOS structure

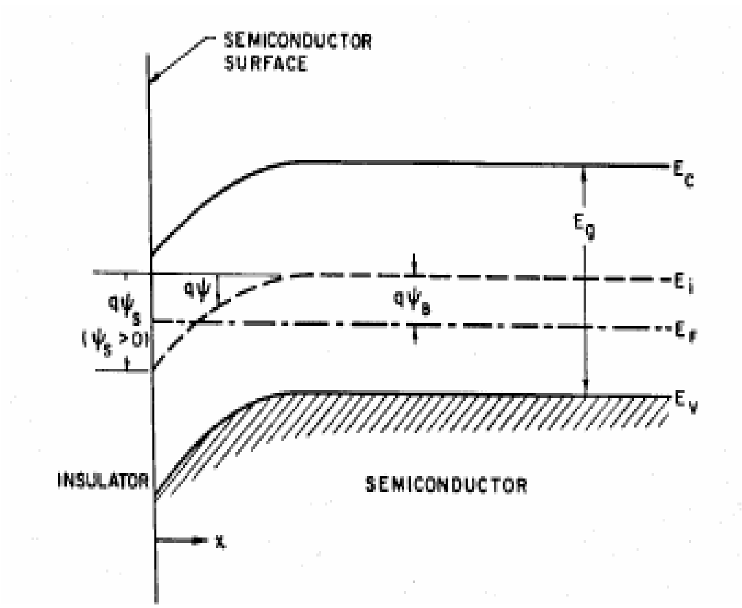


$W_M = W_{Si}$

MOSFETs

MOS-system

- Apply a voltage V_G
  - Inducing surface charges /space charges
  - Bending: due to surface charges/applied potential



Ψ_S = potential at the semiconductor surface, determines the bending

Calculation by solving Poisson Equation

Boundary conditions:

i) electric field E = 0 inside sc

ii) electric field E ~ Q_S

Leads to a relation between surface charges Q_s and the surface Potential

Ψ_s= 0 = Flatband condition (ideal MOS)

MOSFETs

MOS-system

P-type semiconductor

$V_G < 0$

$E_{F,M}$ increasement

→ upward bending

Accumulation fo holes at the sc/ oxide inetrface

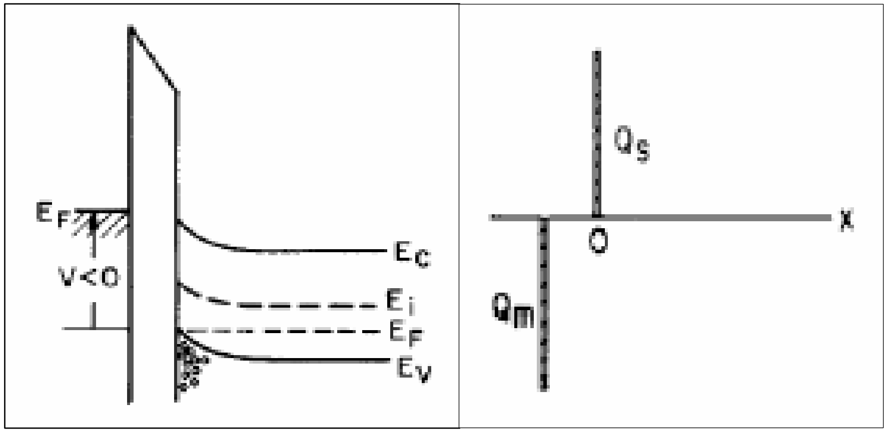
$V_G > 0$

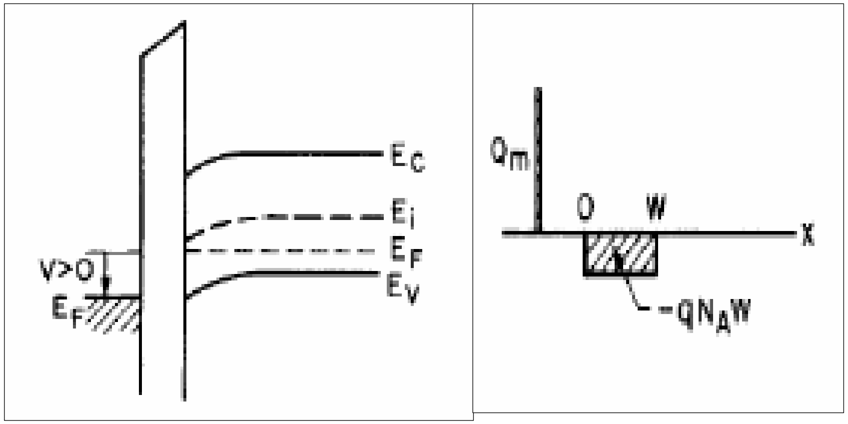
$E_{F,M}$ decreasement

→ downward bending

Depletion of charge carriers (holes) negative space charge

(insulating layer)





MOSFETs

MOS-system

P-type
semiconductor

$V_G >> 0$: Inversion

Strong downward bending →

$E_i < E_F$: E_F closer to E_C than to E_V

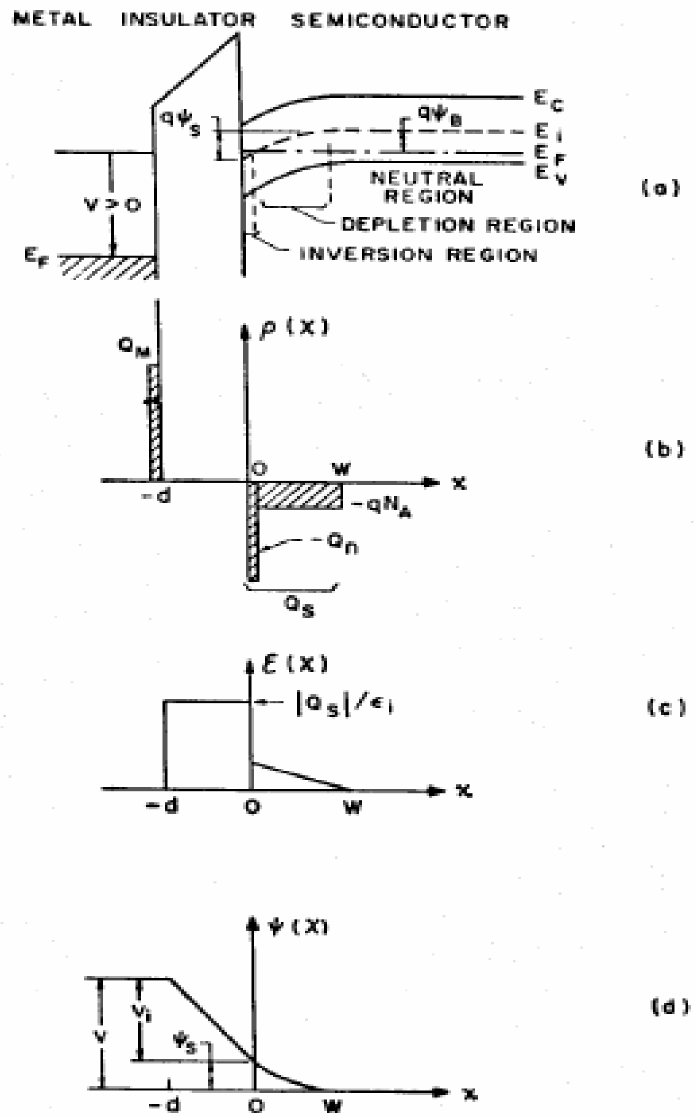
$N_e > N_h$

Strong depletion:

SC far away from Equilibrium $n * p = n_i^2$

→ generation of electron-hole couples

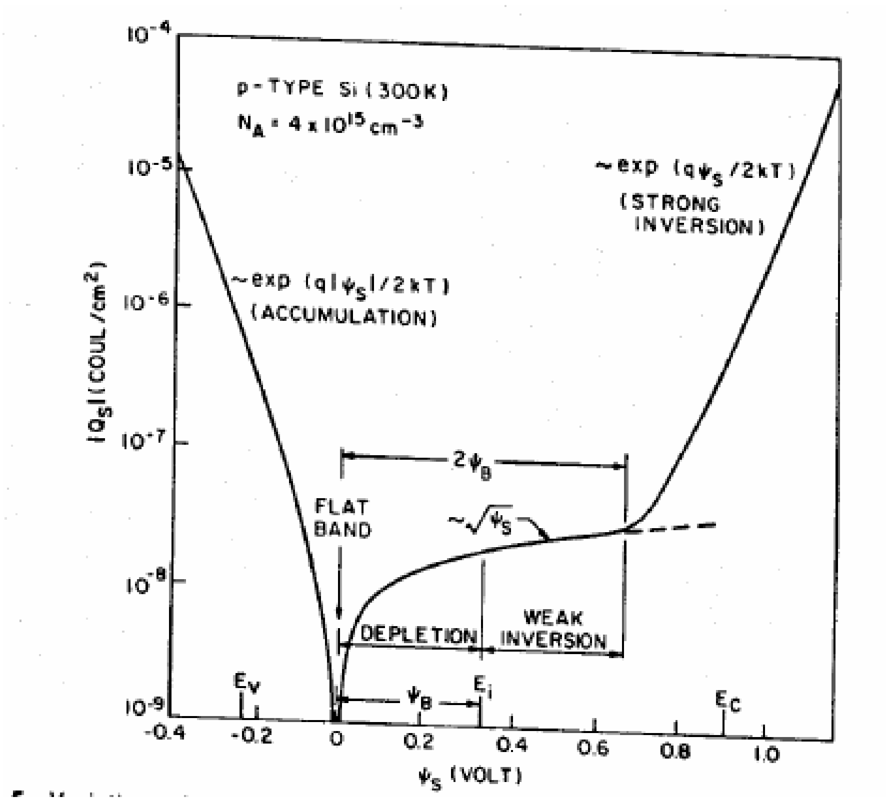
accumulation of electrons at the Si/Ox interface



MOSFETs

MOS-system

Distribution of surface charge Q_s



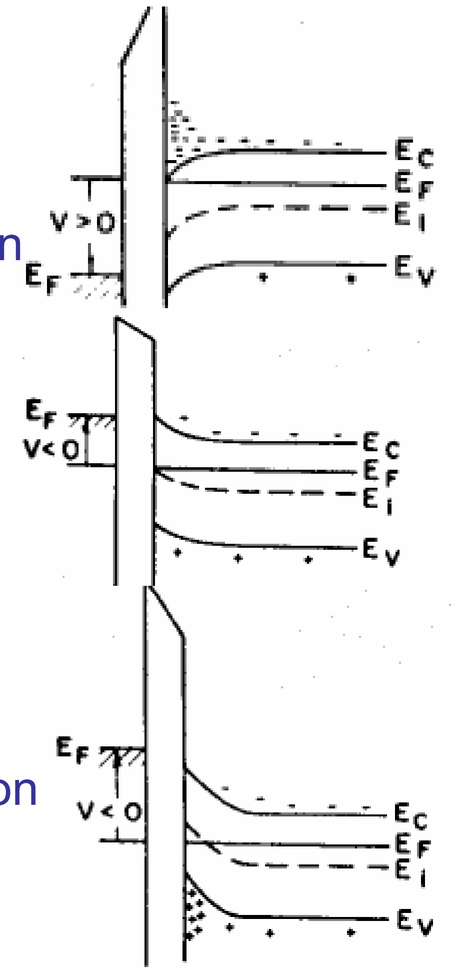
n – type semiconductor

Equivalent situation, with changed polarity

accumulation

depletion

inversion



MOSFETs

MOS-system

Strong inversion definition:

$$\Psi_S(inv) = 2\Psi_b$$

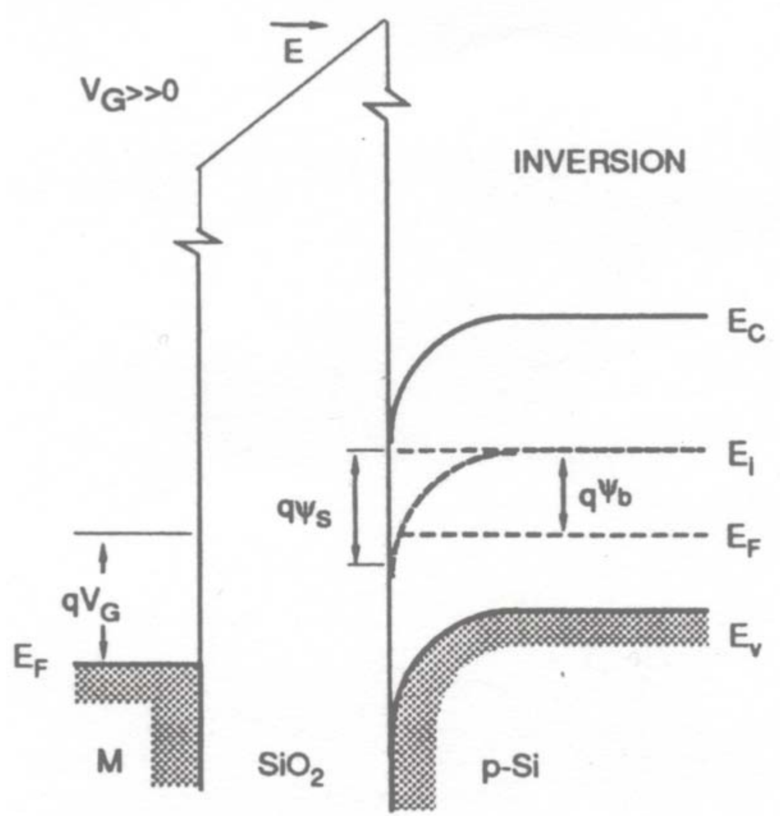
Threshold voltage U_T:

voltage required to induce and inversion layer

$$U_T = U_G(inv) = 2\Psi_b + \Psi_i$$

$$\Psi_i \equiv \frac{-Q_D}{C_i} = \frac{-Q_D}{\varepsilon_i} d_i$$ ≡ potential across the insulator

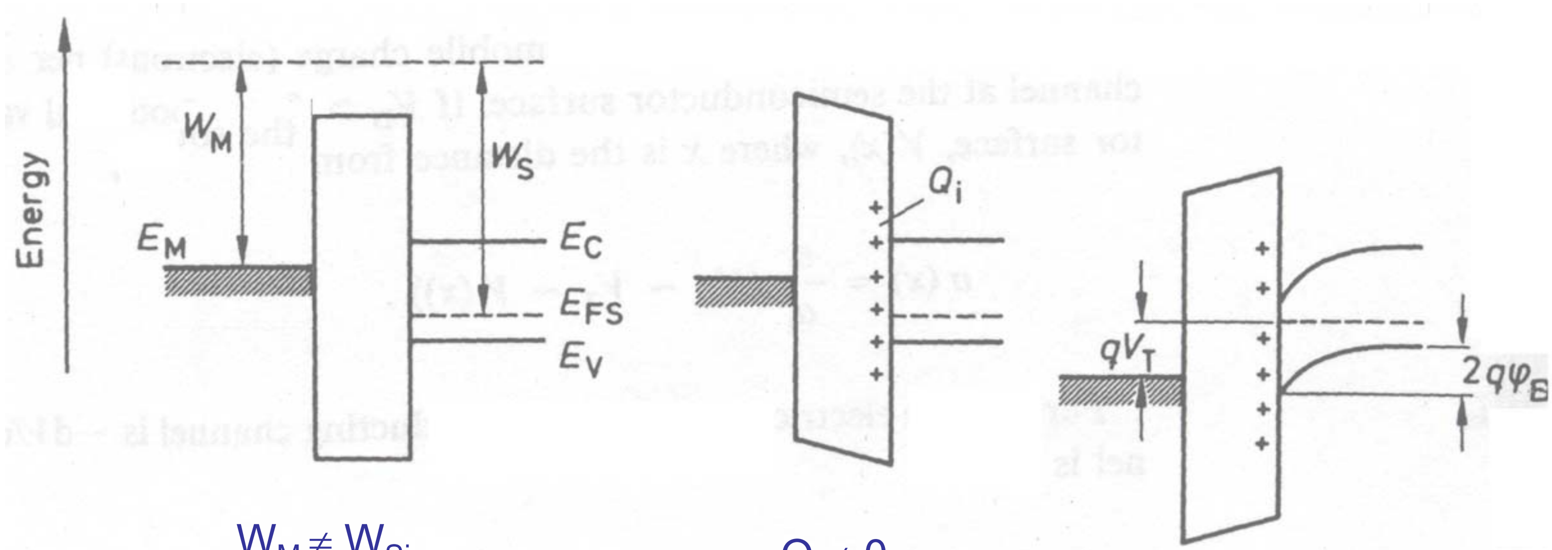
$$-Q_D \equiv -qN_A^- W_d$$ ≡ depletion region charge



MOSFETs

MOS-system

Non-ideal MOS structure



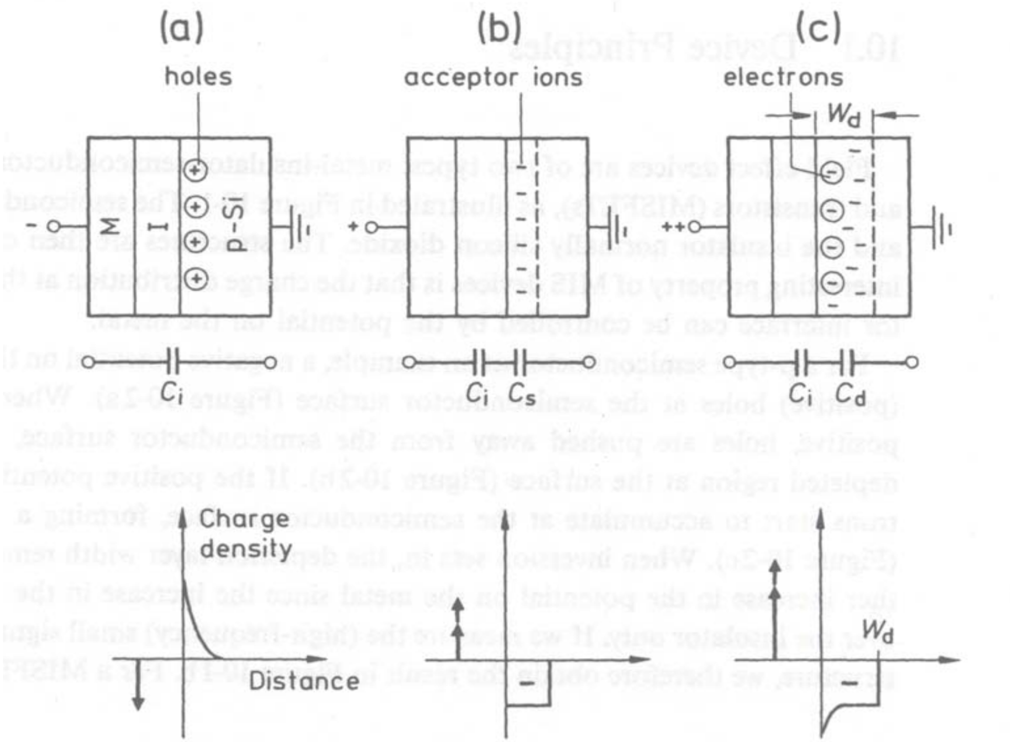
$W_M \neq W_{Si}$ $Q_i \neq 0$

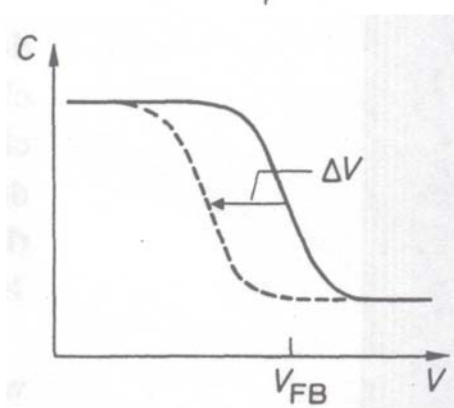
Flat-band voltage: $$U_{FB} = \frac{\Delta W_{m/Si}}{q} - \frac{Q_i}{C_i}$$ ⇨ $$U_T = U_{FB} - \frac{Q_D}{\varepsilon_i} d_i + 2\Psi_b$$

Voltage required to induce and inversion layer: first must achieve flat-band condition, then accommodate the charge in the depletion region and finally induce the inversion region

MOSFETs

MOS-system





a) accumulation:

$C = C_{max} = Ci$

b) depletion:

$1/C = 1/Ci+1/C_s$

$C < C_{max}$

c) inversion:

low frequencies (< 100 Hz)

$C = C_{max}$

high frequencies (> 100 Hz)

recombination/regeneration of electron – hole couples cannot keep up with voltage variation

→ depletion zone acts as a dielectric

$C = C_{min}$

MOSFETs

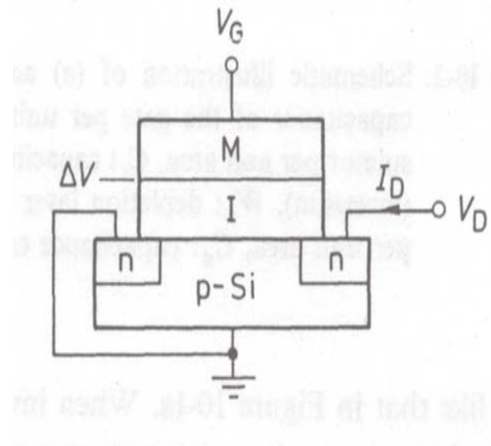
MOSFET operation

V_G = 0: two contra biased p-n junctions

I_D = leakage current

$V_G > V_T$: Inversion channel induced

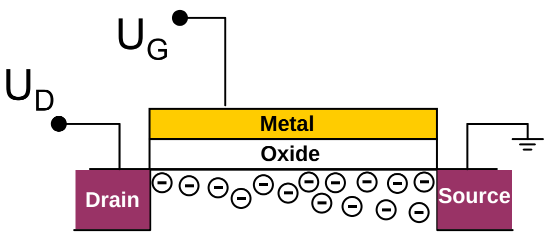
I_D can flow



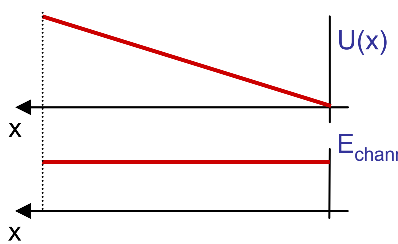
$$C = \frac{dQ}{dU} \Rightarrow \sigma = \frac{\varepsilon_i}{d_i}\left(U_G - U_T\right) \equiv$$

induced mobile charge (C/m[-2]) in the conducting channel

U_{DS}=0V



$$\sigma = \frac{\varepsilon_i}{d_i}\left(U_G - U_T - U(x)\right)$$



$$E_{channel} = -\frac{d\phi}{dx}$$

Linear decrease of U(x) along the n-channel

U(0) = U_D

U(L) = 0

MOSFETs

MOSFET operation

Integration:

$$I_D = K\left((U_G - U_T)U_D - \frac{U_D^2}{2}\right)$$

for $U_D < U_G - U_T$ linear region

$U_D = U_G - U_T$ = pinch off

inversion channel vanishes

→depletion remaining

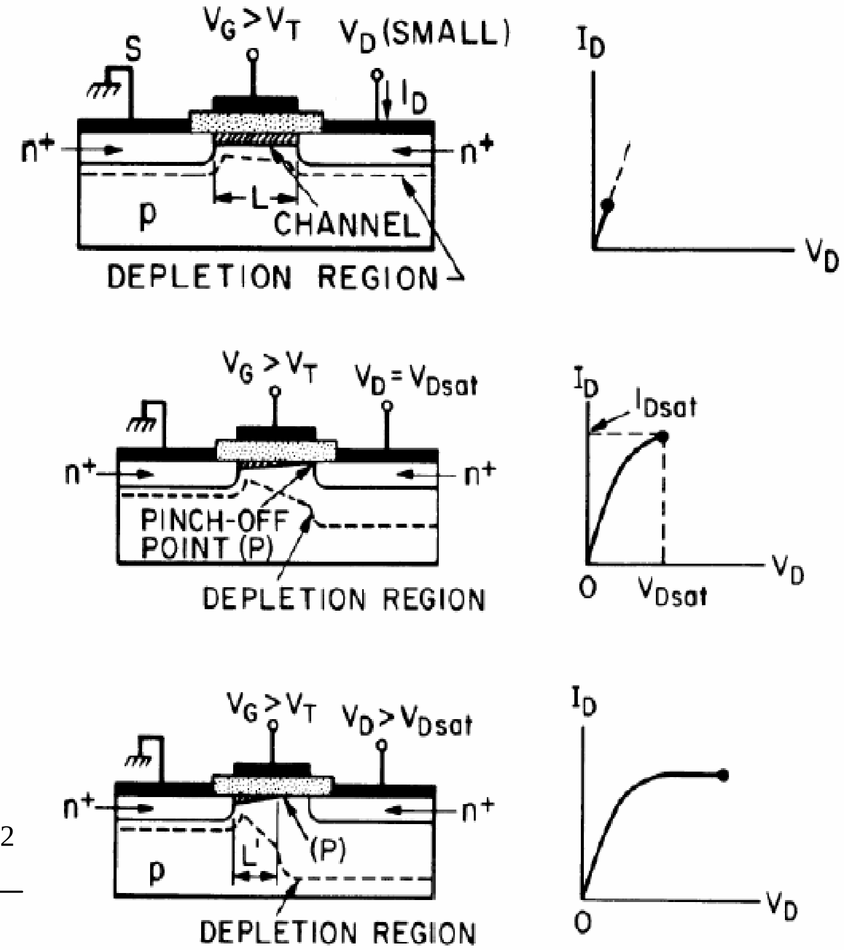
$U_D > U_G - U_T$ = saturation

Lenght of channel reduces

→Resistance increases

→ I_D stays constant

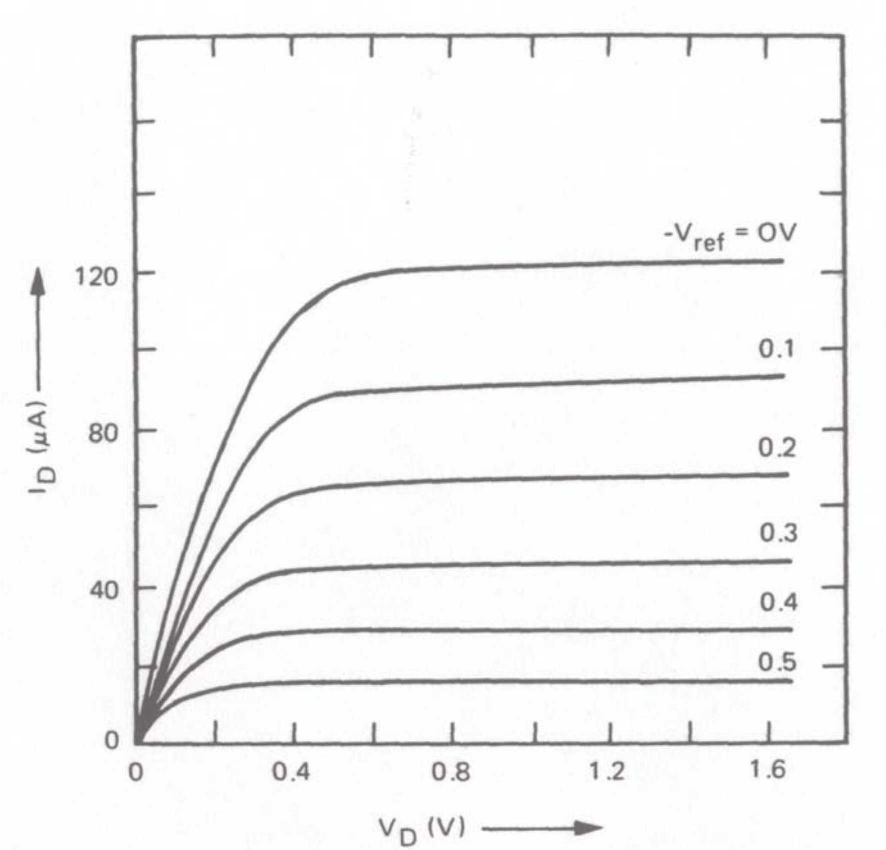
$$I_D = K\frac{(U_G - U_T)^2}{2}$$



MOSFETs

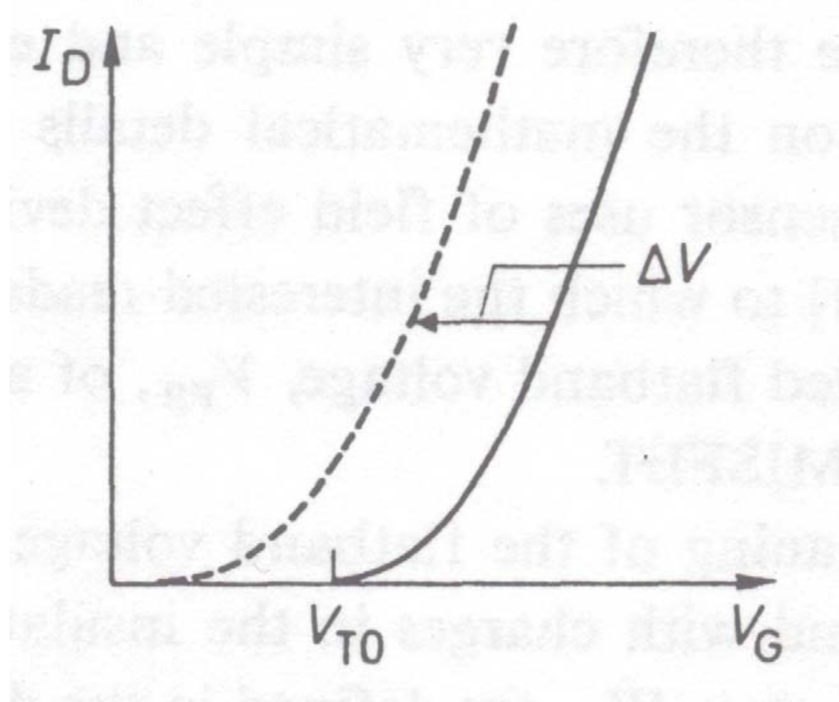
MOSFET operation

I_D vs. V_D at constant V_G



Voltage shifts:

required Flatband Voltage in nonideal MOSFETs

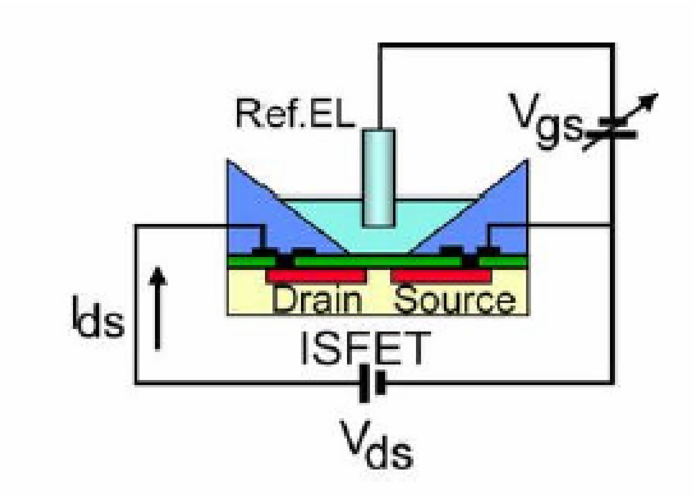


U_T depends of oxide thickness: small d_i → big C_i → small U_T

limit: electric field strength for break through

ISFETs

Basic Idea: removal of the metal plate of an MOSFET and expose the oxide to an electrolyte



Important: encapsulation of the chip

U_G: Potential applied between reference electrode and earth

Possible Respond mechanisms:

1. Interfacial potential at electrolyte-oxide interface (s.MOSFET)
2. Diffusion of species through the oxide

Diffusion: slow process (d_{oxide} ~1000 A, t ~ 10^4 s)

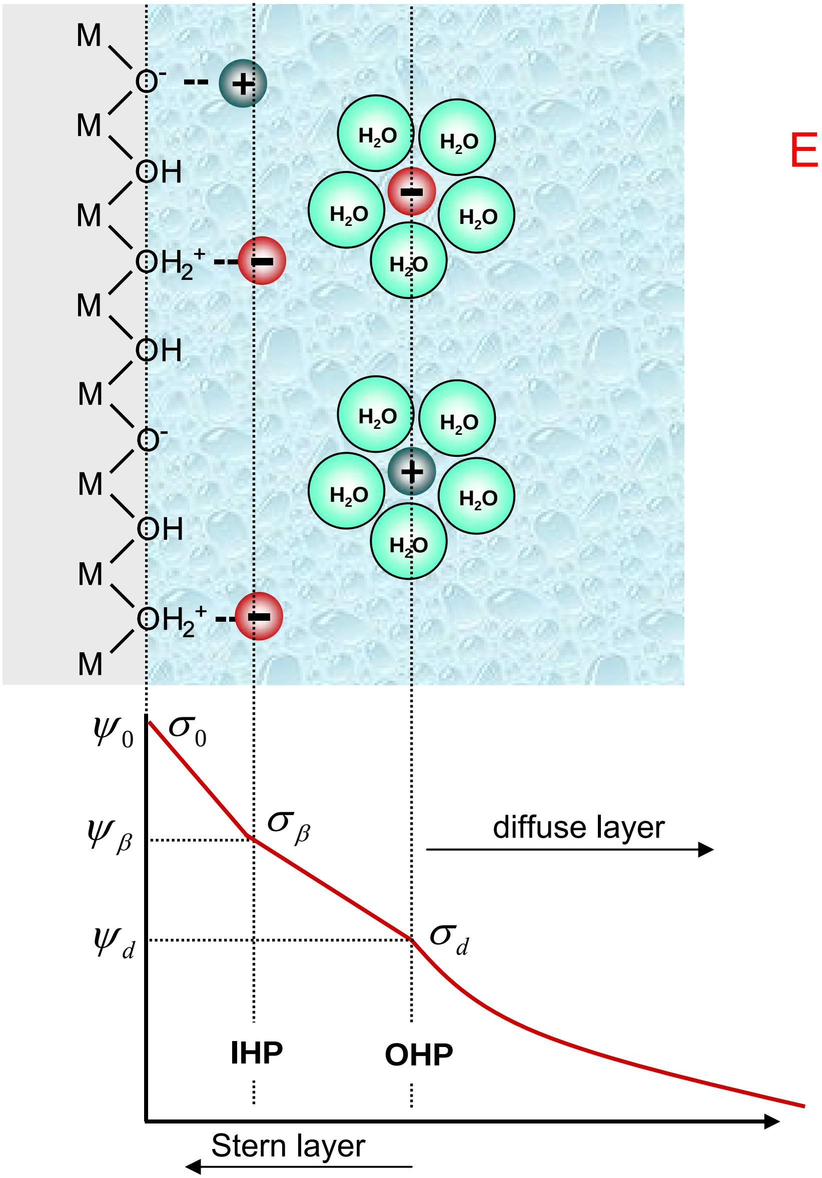
no dependence of oxide thickness has been watched

→ not the major respond mechanism

(current drift)

ISFETS

EOS-system



Electrolyte/Oxide/Semiconductor Interface

Inner Helmholtz Plane (IHP)

- Specifically adsorbed ions
- amphoteric hydroxyl groups

Outer Helmholtz Plane (IHP)

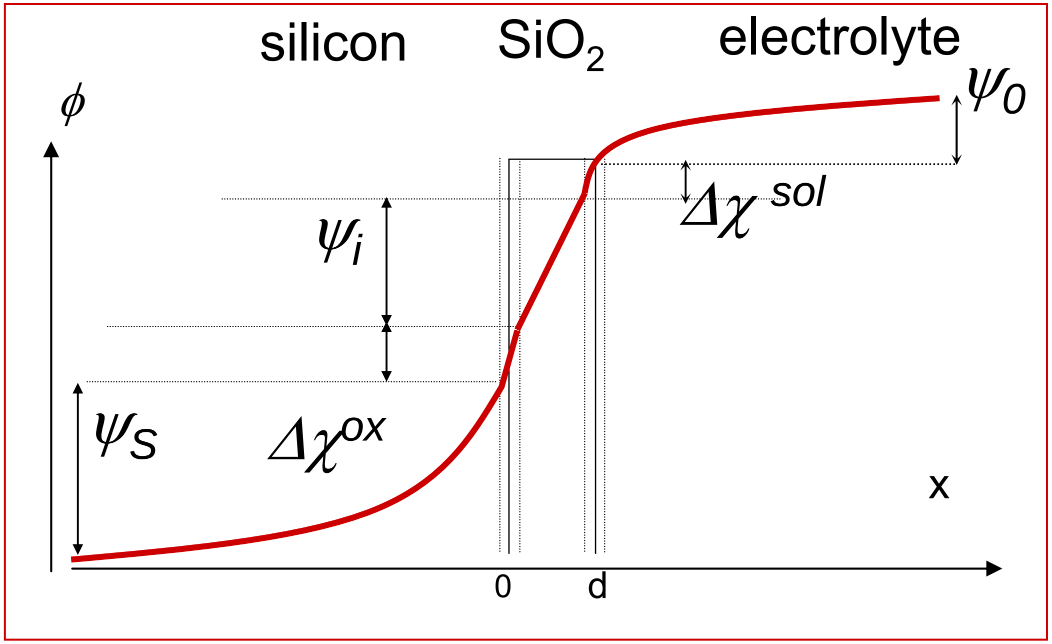
- closest approach of solvated ions

Diffuse (Gouy-Chapman) Layer

- diffuse charge region into the bulk electrolyte

ISFETS

EOS-system



flat band potential (ψ_S=0)

Potential drop across:

- Solution (Bulk → diffuse layer→ OHP → IHP
- Oxide /Electrolyte surface dipoles
- Capacitance of the oxide
- Oxide/Semiconductor interface dipoles
- Semiconductor

$$U_{FB} = U_{\mathrm{Ref}} - \psi_0 + \chi^{sol} - \frac{W_{Si}}{q} - \frac{Q_i}{C_i}$$

$W \equiv$ Si work function

$Q_i / C_i \equiv$ oxide potential drop

$U_{\mathrm{Ref}} \equiv$ reference electrode potential

$\psi_0 \equiv$ potential drop in the electrolyte

$\chi^{sol} \equiv$ electrolyte surface dipole potential

ISFETS

EOS-system

First Approach: Nernst Equation

Interface between solid (oxide) and liquid (electrolyte)

Equilibrium: $\mu_i^{ox} = \mu_i^{sol}$

Electrochemical Potential in one phase

$$\mu_i = \mu_i^0 + RT\ln a_i + z_i F\Phi$$

a_i = activity of component i

a_{ox}= 1

Potentialdifference:Galvani Potential

$$\Delta \Phi = \Phi_{sol} - \Phi_{ox} = \Delta\mu_i^0 + RT/F \ln (a_i^{sol})$$

$$\text{For } i = H^+: U_{interface} = E_0 + RT/F \ln(a_{H+})$$

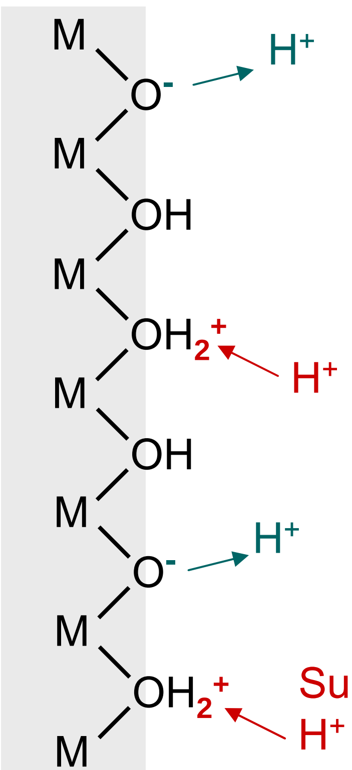
In real measurements: strong derivations from Nernstian behaviour

For good insulators (Si_3N_4, Al_2O_3) thermodynamic equilibrium between electrolyte and oxide cannot be achieved

ISFETS

pH-sensitivity and Site-Binding Model

Amphoteric behaviour of Oxides



proton donor

$M - O^- + H^+ \longrightarrow M - OH$

$$k_a = \frac{[M - O^-][H^+]_S}{[M - OH]}$$ acidity constant

neutral site

proton acceptor

$M - OH + H^+ \longrightarrow M - OH_2^+$

$$k_b = \frac{[M - OH][H^+]_S}{[M - OH_2^+]}$$ basicity constant

$[H^+]_S \equiv$ concentration of protons at the oxide/electrolyte interface ⇨ $pH \equiv -\log_{10} [H^+]_b$

Surface charge: $\sigma_0(pH) = \sum [OH_2^+] - \sum [O^-]$

Surface sites: $N_S = \sum [OH_2^+] + \sum [O^-] + \sum [OH]$

N_S (SiO_2) ≈ 5×10^{14} cm^{-2}

N_S (Al_2O_3) ≈ 8×10^{14} cm^{-2}

ISFETS

pH-sensitivity and Site-Binding Model

Equilibrium of H^+ between the oxide surface and the bulk solution

Ψo = potential difference between surface and bulk solution = ***Ψs - Ψb***

$\left[H^+\right]_S$ related to $\left[H^+\right]_b$ by equating the electrochemical potential

$$\Rightarrow \mu_{H^+}^S + kT\ln\left[H^+\right]_S + q\psi_0 = \mu_{H^+}^b + kT\ln\left[H^+\right]_b$$

constant

$$\left[H^+\right]_S = \left[H^+\right]_b \exp\left(\frac{-q\psi_0}{kT}\right)\exp\left(\frac{\mu_{H^+}^b - \mu_{H^+}^S}{kT}\right)$$

$$\Rightarrow \left[H^+\right]_S = \left[H^+\right]_b \exp\left(\frac{-q\psi_0}{kT}\right)$$

Boltzmann…

ISFETS

pH-sensitivity and Site-Binding Model

Number of Surface sites: $N_S = \sum[OH_2^+] + \sum[O^-] + \sum[OH]$

Results in a surface charge $\sigma_0(pH) = \sum[OH_2^+] - \sum[O^-]$

$\sigma_0 = 0$ → pH_{pzc} = pH, at which the total surface charge is zero

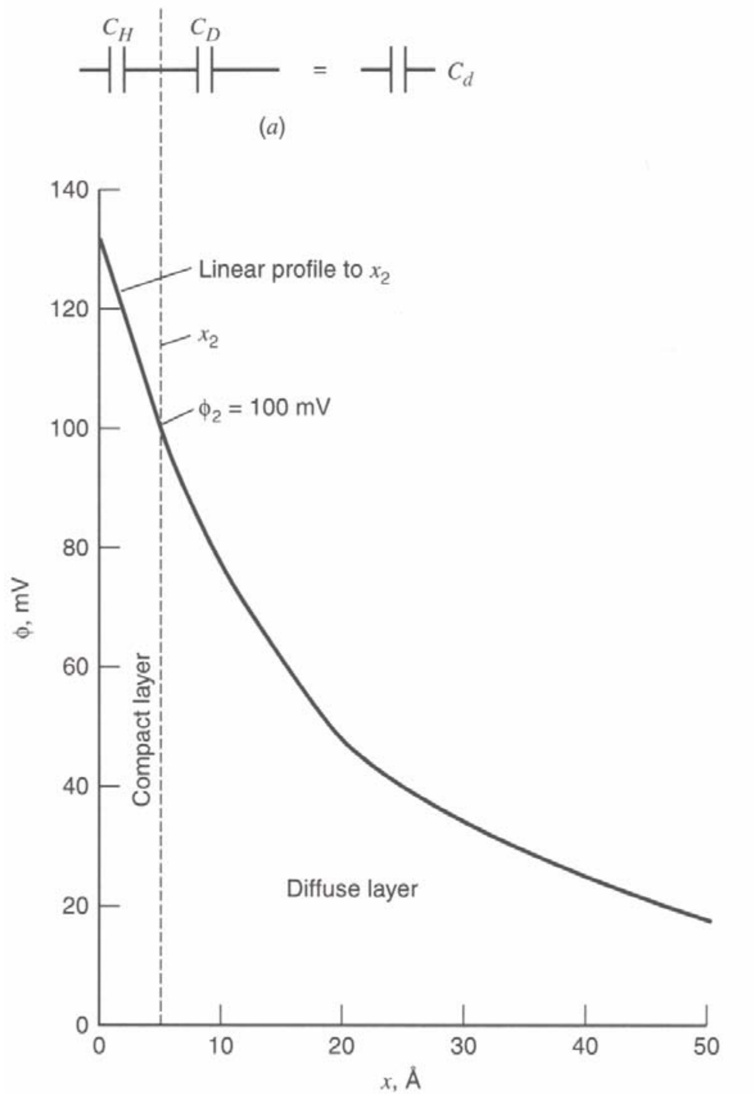
→ **$[M - O^-] = [M - OH_2^+]$**

With previous equations , this is leading to:

$$2.303 \cdot (pH_{pzc} - pH) = \frac{e\psi_0}{kT} + \ln\left(\frac{[M - OH_2^+]}{[M - O^-]}\right)^{\frac{1}{2}}$$

ISFETS

pH-sensitivity and Site-Binding Model



$$-\psi_0 = \frac{\sigma_d}{C_H} + \frac{2kT}{q}\sinh^{-1}\left(\frac{\sigma_d}{\left(8kT\varepsilon\varepsilon_0 n^0\right)^{1/2}}\right)$$

potential drop in the Helmholtz double layer

potential drop in the diffuse layer

when the ion concentration in the solution (n^0) is medium-high

$$\psi_0 = \frac{-\sigma_d}{C_d} = -\sigma_d\left(\frac{1}{C_H} + \frac{2kT}{q}\left(8kT\varepsilon\varepsilon_0 n^0\right)^{1/2}\right)$$

ISFETS

pH-sensitivity and Site-Binding Model

using the *charge neutrality* equation ⟹ $$\sigma_0 + \sigma_d = -(Q_{Si} + Q_i)$$

Q_{Si} ≡ charge in the Si inversion channel

~10^{11} charges/cm^{-2}

→ $Q_{Si} \approx 10^{-8} C/cm^2$

Q_i ≡ charge inside the insulator

Q_i << Q_{Si}

σ_0 ≡ charge on the insulator surface

σ_d ≡ charge on the electrolyte side of the double layer

→ dominated by C_H (~10^{-5} F/cm^{-2})

→ $\sigma_d \approx 10^{-5} C/cm^2$

σ_d >> Q_{Si}

⟹ $\sigma_0 = -\sigma_d$

$$\sigma_0 = \psi_0 C_d$$

linear relation between surface charge and potential

ISFETS

pH-sensitivity and Site-Binding Model

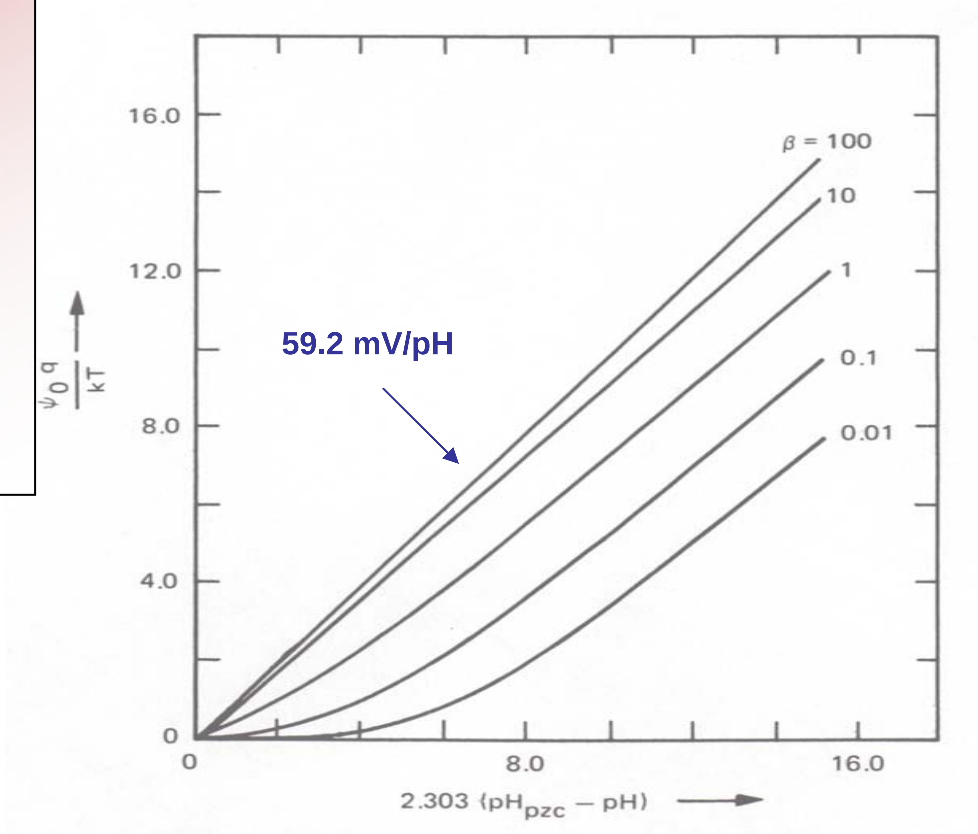
Leading to an expression for the pH sensitivity of an ISFET

$$\psi_0 = 2.303\frac{kT}{q}\left(pH_{pzc} - pH\right)\left(\frac{\beta}{1+\beta}\right)$$

$$\beta = \frac{2q^2 N_S \left(k_a k_b\right)^{1/2}}{kTC_d} \equiv$$

sensitivity factor

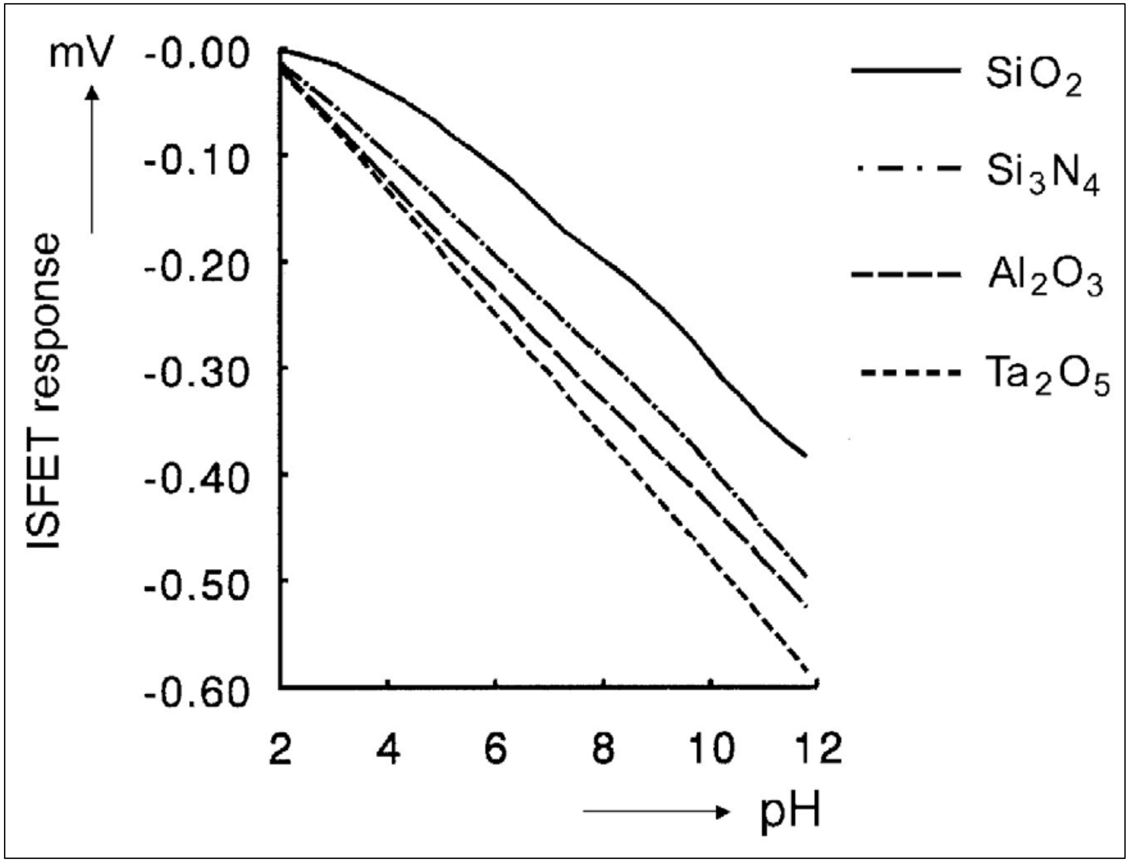
For ***β*** >>1: Nernstian Response



ISFETS

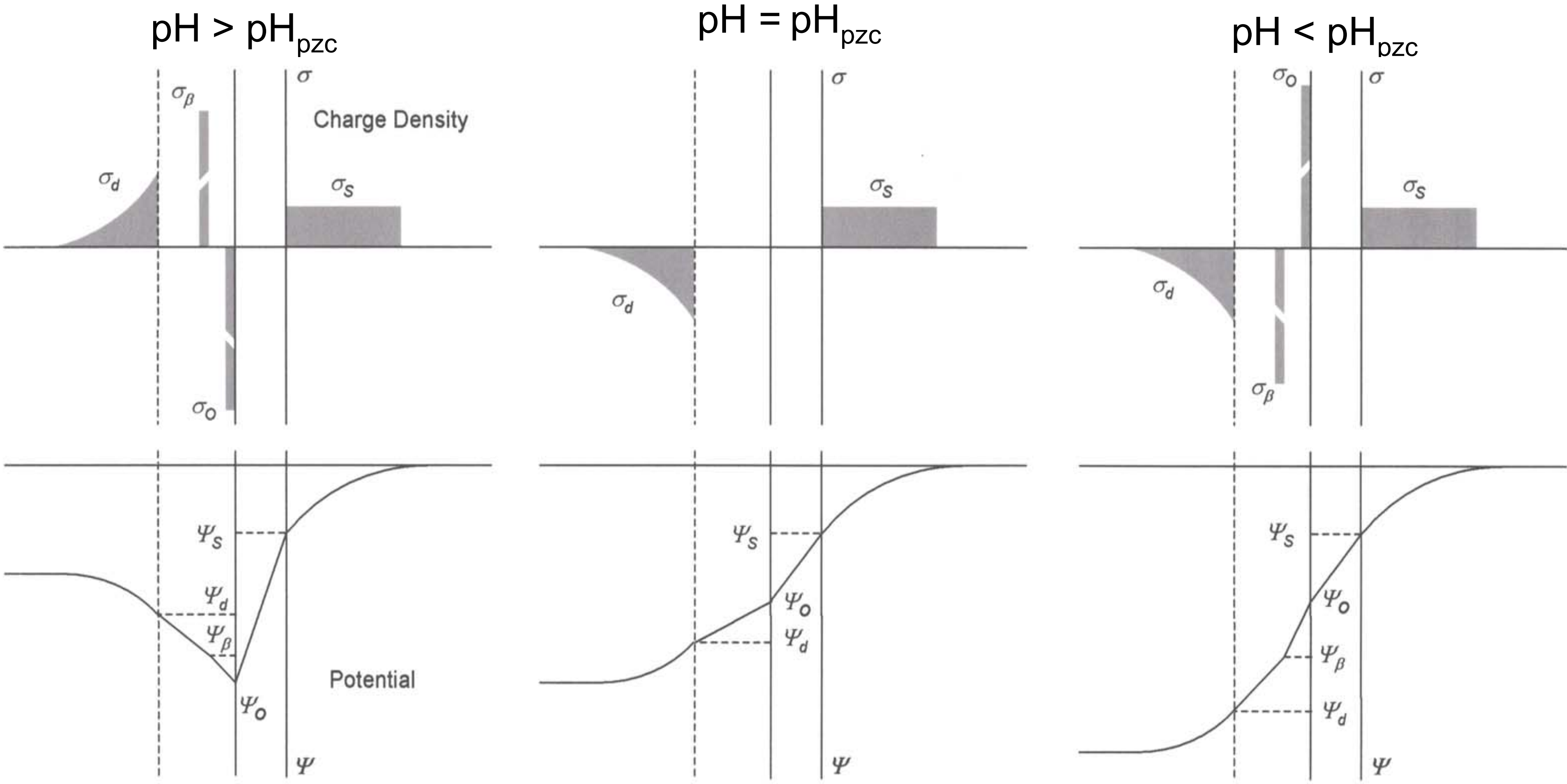
pH-sensitivity and Site-Binding Model

Sensitivity depends on the used oxide material



ISFETS

pH-sensitivity and Site-Binding Model



$$U_G = U_{\text{Ref}} + \frac{1}{q}W^{Si} - \psi_0 - \frac{Q_i}{C_i} + \psi_S + \chi^{sol}$$

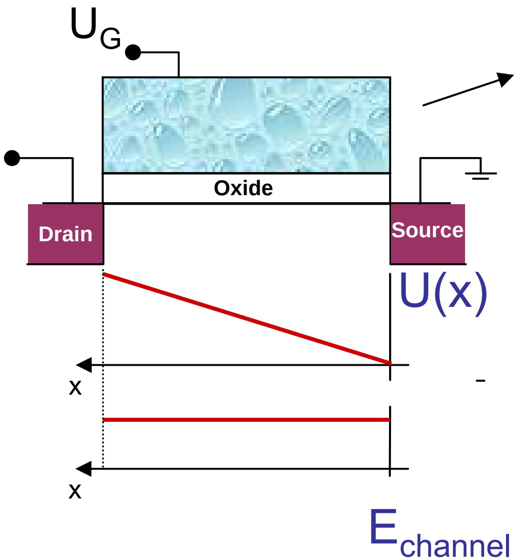
$$\psi_0 = 2.303\frac{kT}{q}\left(pH_{pzc} - pH\right)\left(\frac{\beta}{1+\beta}\right)$$

ISFETS

pH-sensitivity and Site-Binding Model

Reminding the MOSFET/ ISFET concept

$$U_{FB} = U_{\mathrm{Ref}} - \psi_0 + \chi^{sol} - \frac{W_{Si}}{q} - \frac{Q_i}{C_i}$$

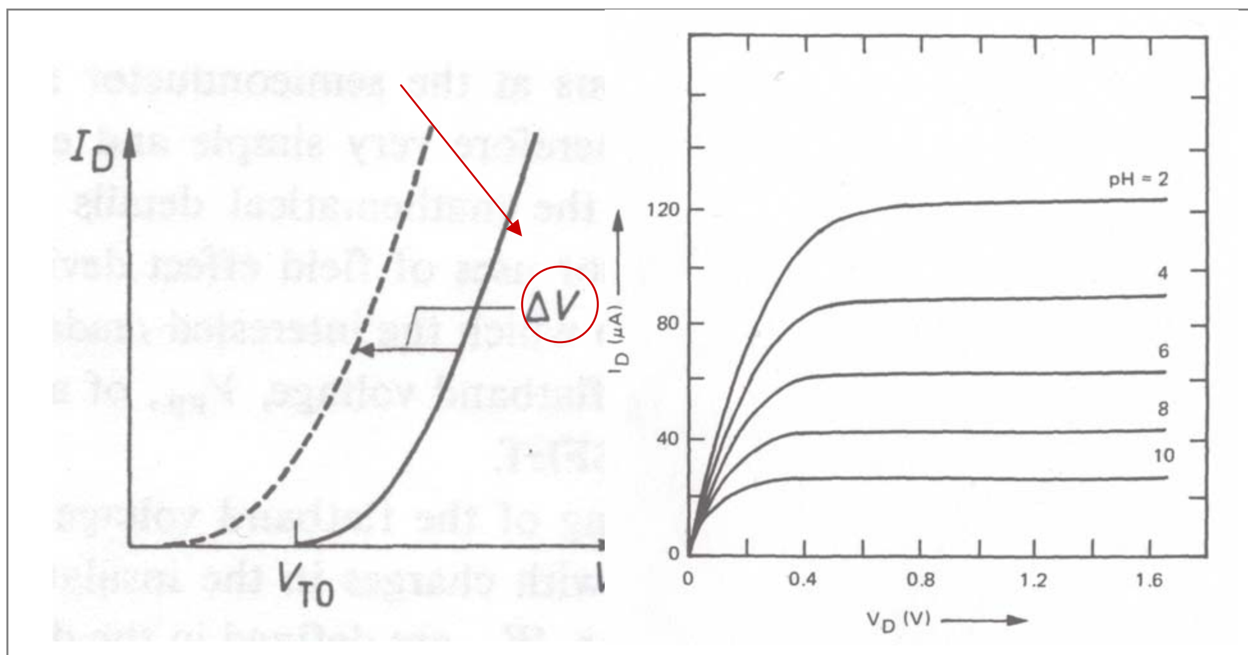


$$U_T = U_{FB} - \frac{Q_D}{\varepsilon_i} d_i + 2\Psi_b$$

$$I_D = K \frac{(U_G - U_T)^2}{2}$$

$$\psi_0 = 2.303 \frac{kT}{q} (pH_{pzc} - pH) \left(\frac{\beta}{1+\beta} \right)$$

$$\psi_0(pH) \Rightarrow U_T(pH)$$



ENFETs

Concept

Functionalisation of oxide surfaces

Deposition of polymeric membranes on the gate insulator

→ Matrices for immobilisation of enzymes

Common material: polyvinylchloride (PVC)

Immobilisation mechanisms

i) entrapment in polymeric network

ii) entrapment in gel matrix

iii) crosslinking with multi-functional agent

iv) covalent bonding to sensor surface

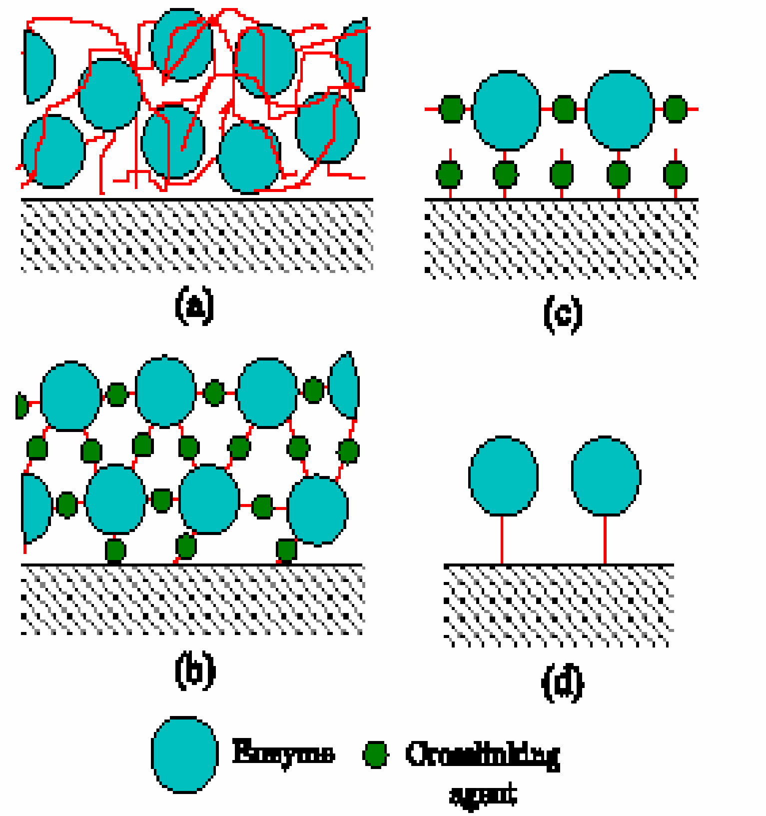
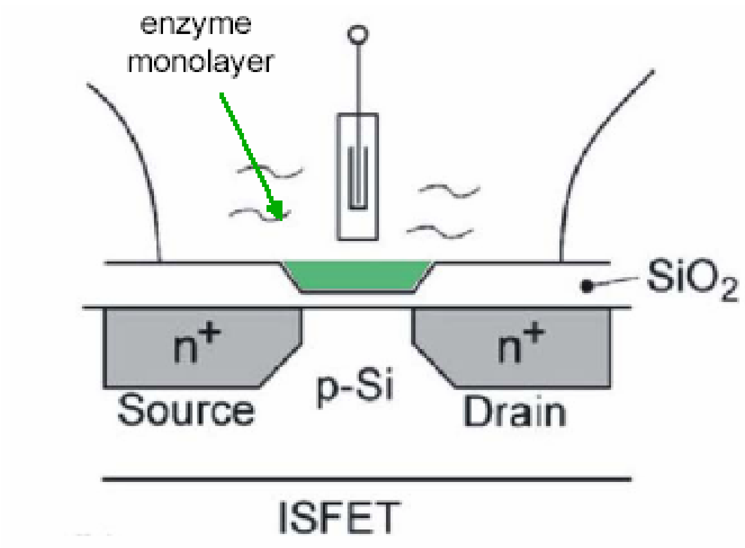


Fig. 4. Methods of enzyme immobilisation: a) entrapment in gel matrix, b) crosslinking with multi-functional agent, c), d) covalent bond with and without bi-functional agent respectively

ENFETs

Example

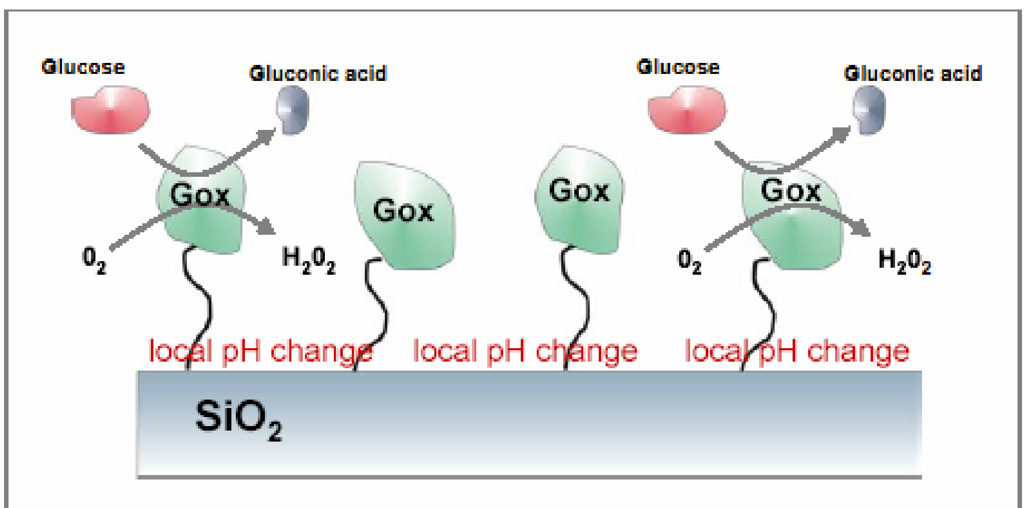
Glucose ENFET



Glucose oxidase immobilised at the insulator surface

Reaction in membran layer

$$\text{Glucose} + O_2 + H_2O \xrightarrow{\text{Glucose oxidase}} \text{Gluconate} + H^+ + H_2O_2$$



local pH change induced by enzyme biocatalyzed transformations

Detection of pH change with ISFET structure

→ Detection of glucose

Sensor/Actuator Systems

Control of the pH of a solution = coulometry

Coulometric generation of H^+ / OH^- by electrochemical reactions at generating electrodes

$2H_20 + 2e^- \rightarrow H_2 + 2\ OH^-$	**Reduction**
$2H_20 \rightarrow 0_2 + 4e^- + 4\ H^+$	**Oxidation**

Coulometry is an absolute method of ion generation

Boundary conditions

i) well known stoichiometry

ii) no side reactions occur

iii) Current efficiency ~ 100%

Sensor signal can be adjusted, to induce a defined change of pH

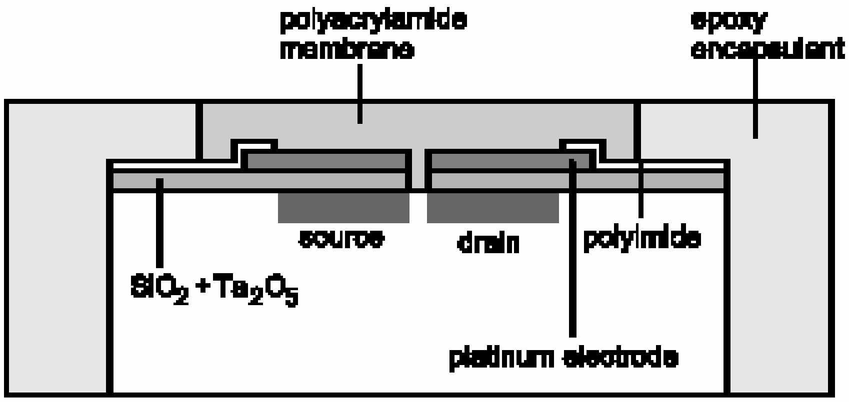
Sensor/Actuator Systems

Modified ENFET

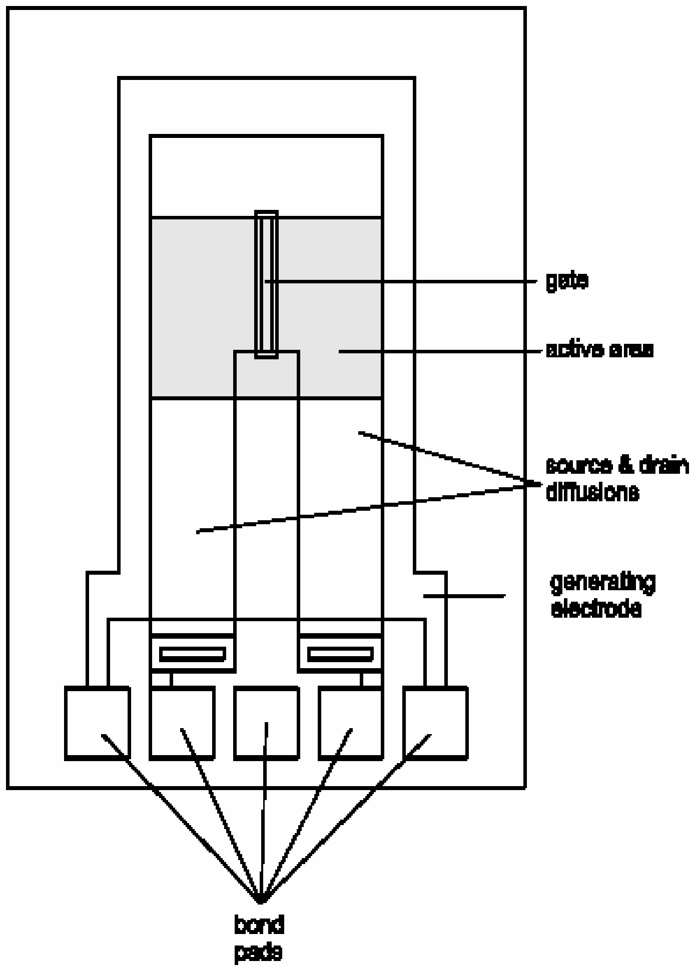
Generating platinum electrodes arround gate

Excellent stability of urease → ideal sensitive enzyme

Immobilised in polyacrylamide membrane



(b)



Sensor/Actuator Systems

Limitation for simple ENFET

C_{buffer} , enzyme kinetics and reaction equilibrium depend on pH

ENFET: Strongly nonlinear response

Dynamic range depends on composition of the sample

Sensor/Actuator System:

ENFET measures pH inside membrane

→ pH control through coulometric generation of H^+/OH^-

Response of ENFET $$\partial V_{out} / \partial [S] = EB / \beta$$

B = sensitivity of ISFET	E = enzymatic sensitivity
β = buffer capacity	[S] = substrate concentration

E > 0 = acidic reaction

E< 0 = alkaline reaction

Sensor/Actuator Systems

Similar: electrochemical actuator

Small changes in pH: $\partial V_{out} / \partial I = AB / \beta$

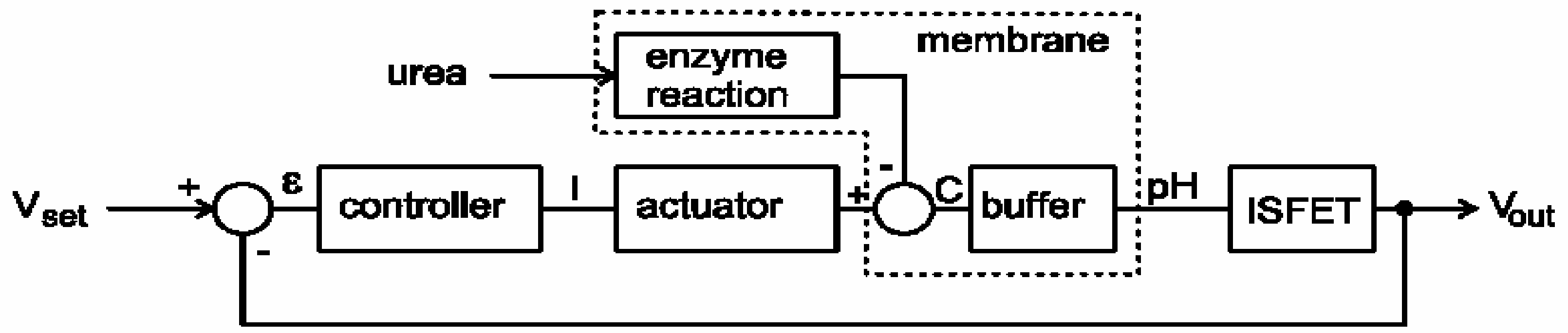
I = current through generating electrode

A = sensitivity of sensor-actuator system

$\partial V_{out,current} = -\partial V_{out,enzyme}$ ⇨ $\partial I / \partial [S] = -E/A$

independent from buffer capacity

⇨ Linear response on [S]



Sensor/Actuator Systems

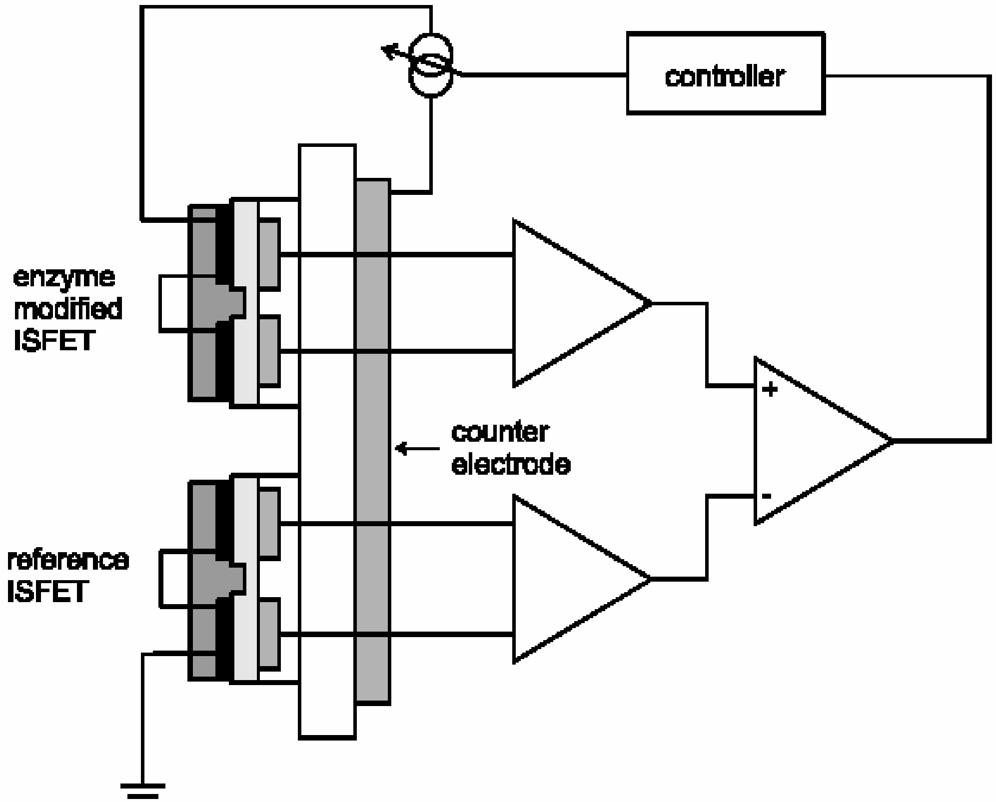


Fig. 12
Measurement set-up for the pH-static enzyme sensor

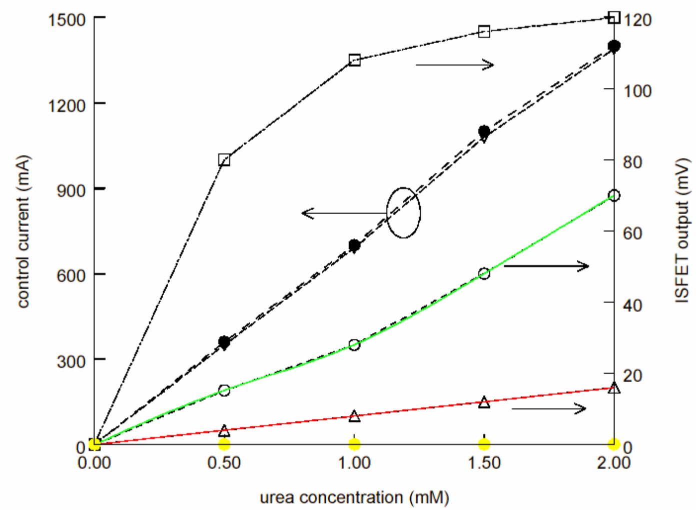
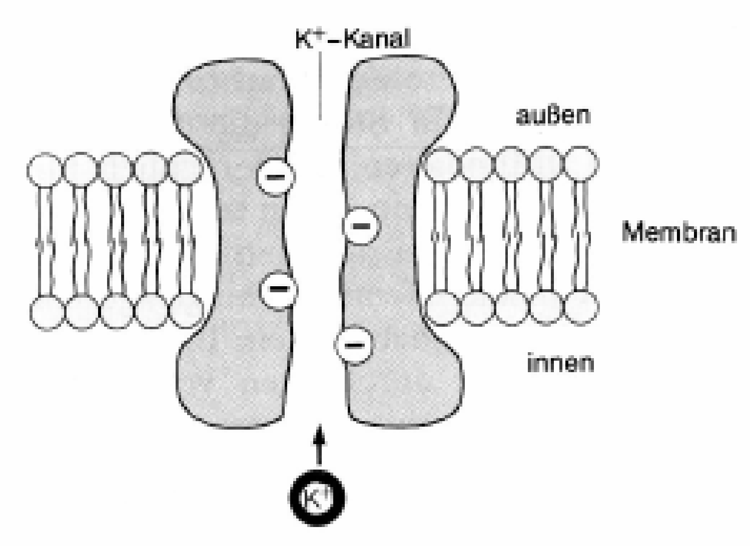


Fig. 13
Response of a classical ISFET-based enzyme sensor (open symbols) compared with that of the pH-static sensor (filled symbols) in sample solutions with different buffer capacity.
▶ : low buffer; ▶ : medium buffer; Δ: high buffer

BIOFET

- Basic Principle
  - Interaction of biological system with a FET structure
  - Electrochemical processes in cells
    - **Cell membrane: embedded ion channels allow ion transfer**
    - **Potential drop:**
    - **action potential: induced change of permeability**



Depolarisation

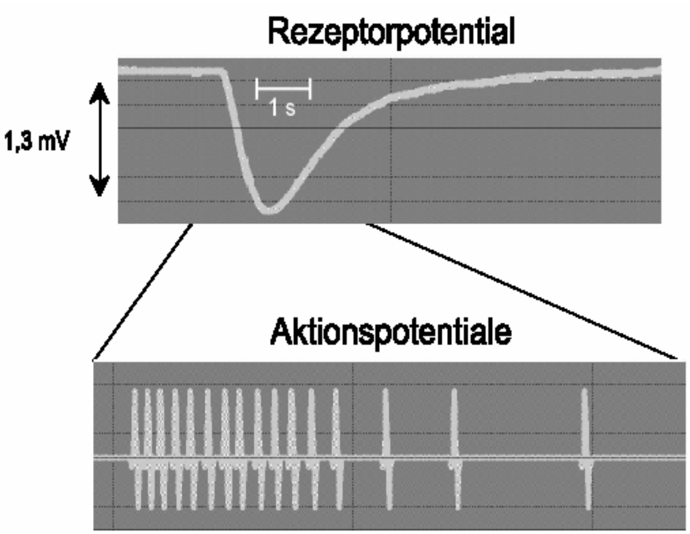
Opening of quick channels → Potentialstep in $U_{Membrane}$

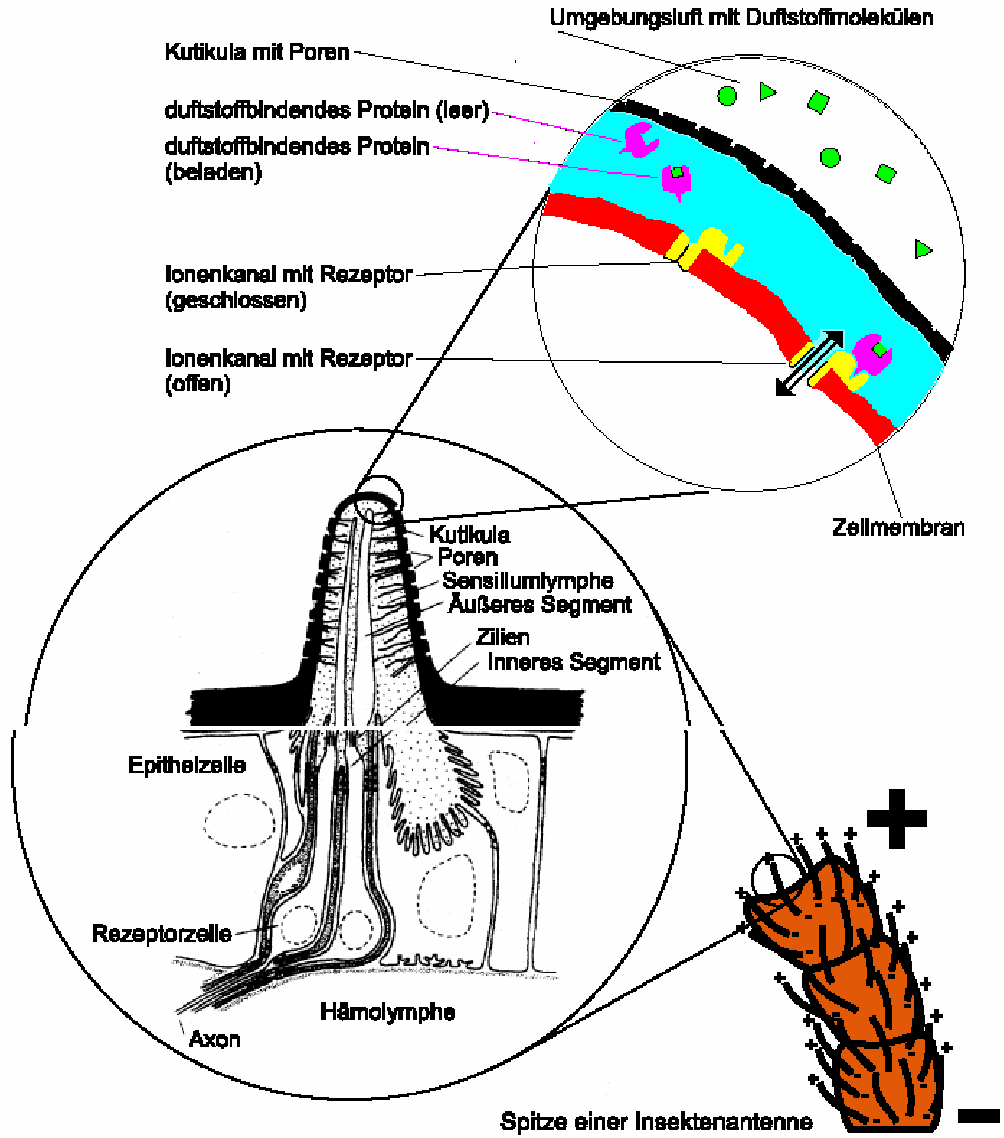
Repolarisation

Opening of slow channels → $U_{Membrane}$ = ignition value

BIOFET

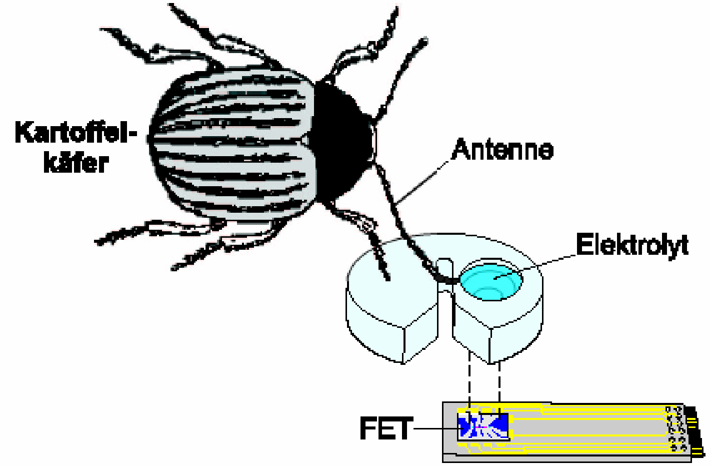
- Insect antenna
  - Information of [S] is transformed in an electrical signal
  - Polarisation in sensing hairs
  - Total dipole along the anten
  - Receptorpotential → action potential



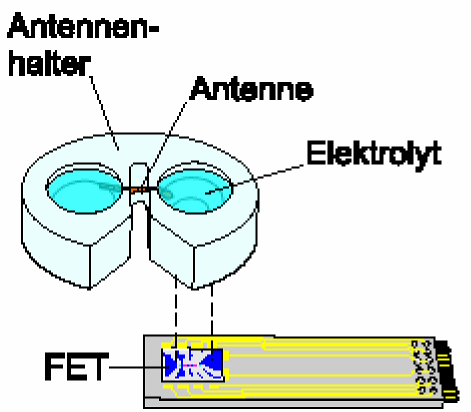


BIOFET

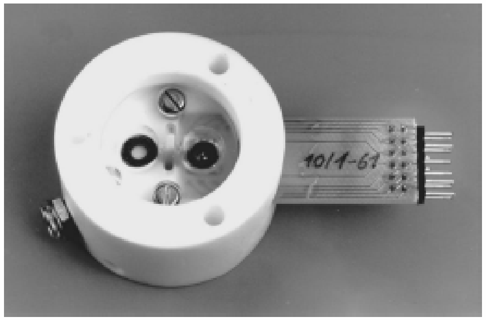
- Coupling of antenna and FET
  - electrolyte
  - constant-Voltage mode: change of antenna potential causes change in FET surface potential
  - local peak in $I_D([S])$



A) Whole-Beetle-Anordnung



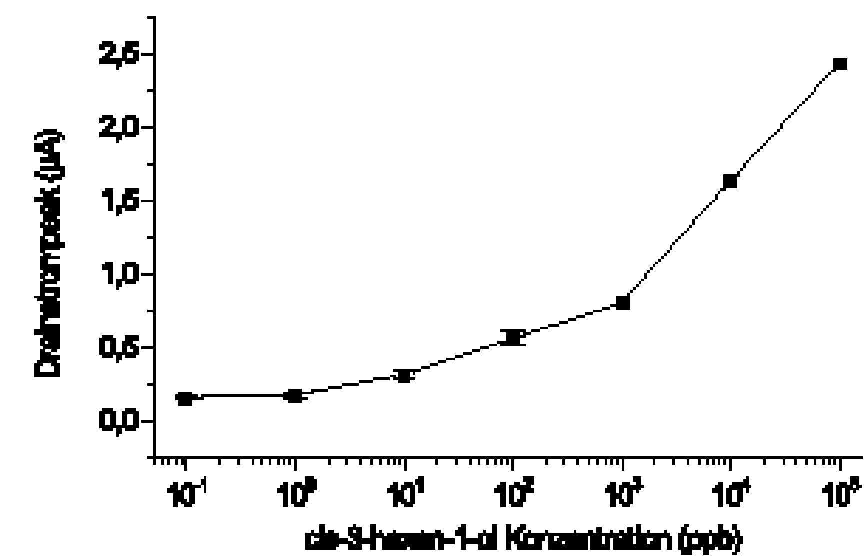
B) Isolated-Antenna-Anordnung

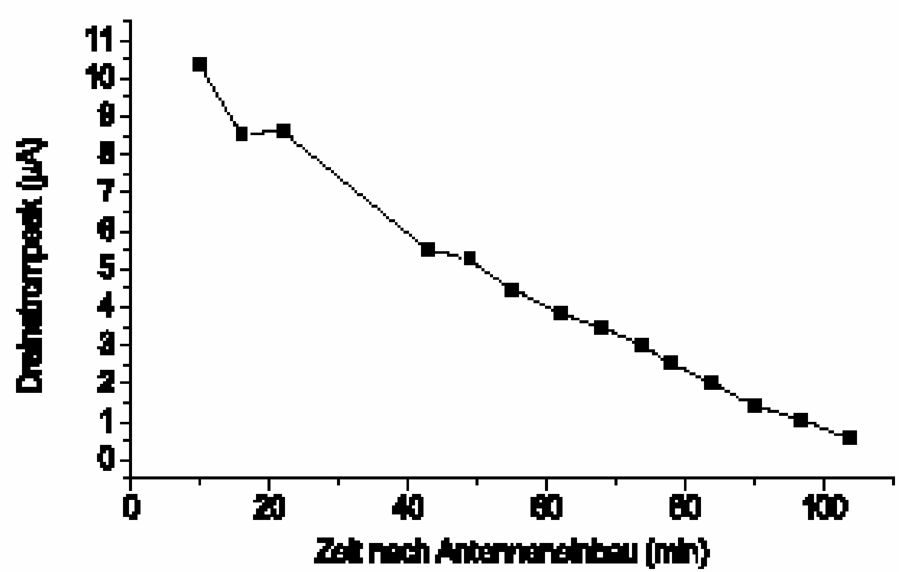

C) Sensorkopf mit Antennenhalter und FET

BIOFET

- Correlation between peak amplitude and [S] → sensing of [S]

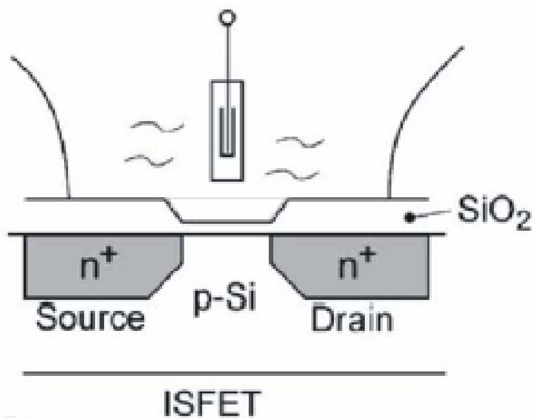
- Possible application
  - Agriculture (Leptinotarsa decemlineata)
  - Fire detection
    (Phaenops cyanea)





Surface Charge sensitivity

DNA sensor



- Gate potential controlled by the electrical charge associated with the gate interface.
- surface charge sensitivity ?

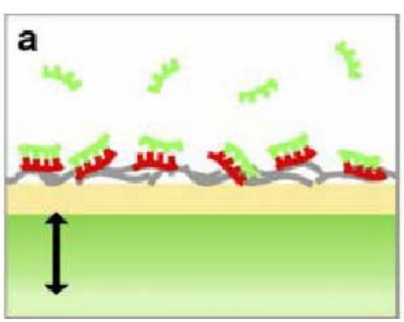
Surface charge density and surface potential

$$\sigma_0 = \sqrt{8kT\varepsilon\varepsilon_0 n^0}\,\sinh\left(\frac{q\psi_0}{2kT}\right)$$

Grahame equation

DNA: intrinsic negative charge at sugarphosohate backbone

Probe DNA: bound to PLL surface



Target DNA: binding to complementary DNA

→surface charge

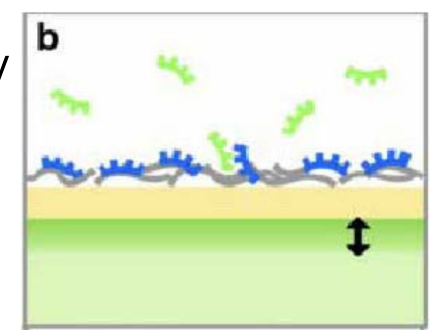
→depletion

→region,potential change

Probe DNA: bound to PLL surface

noncomplementary DNA:

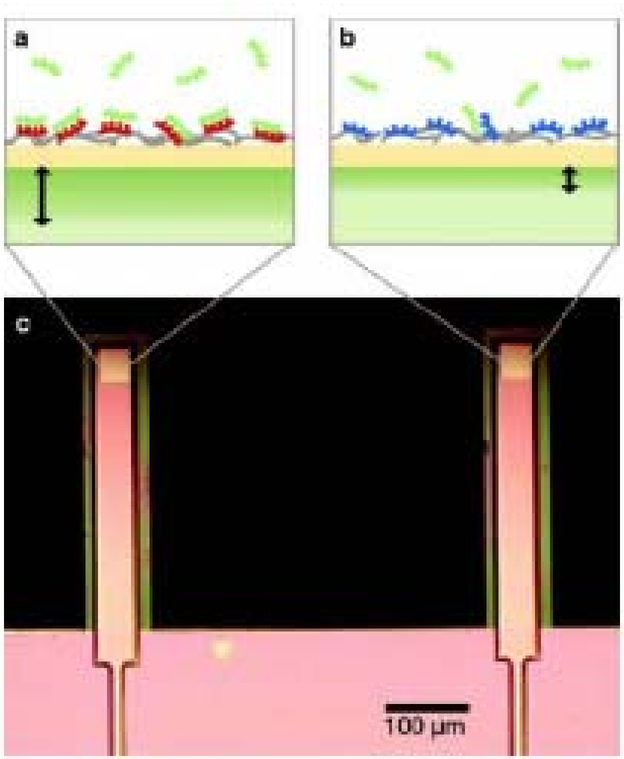
→ No binding

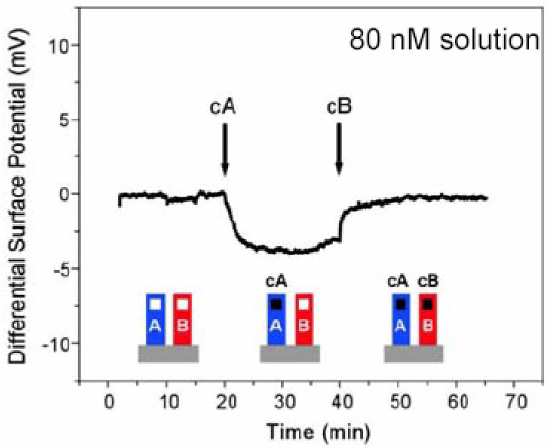


Surface Charge sensitivity

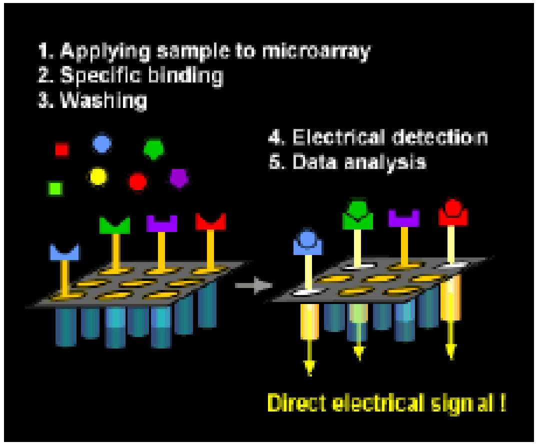
DNA sensor

Measurment of the differential surface potential enables DNA detection





- resolution: 2nM or 8ng/ml DNA
- 3×10^4 hybridized 12-mer oligonucleotides/μm^2 → $\approx$ 3mV



Application of New Materials

GaN

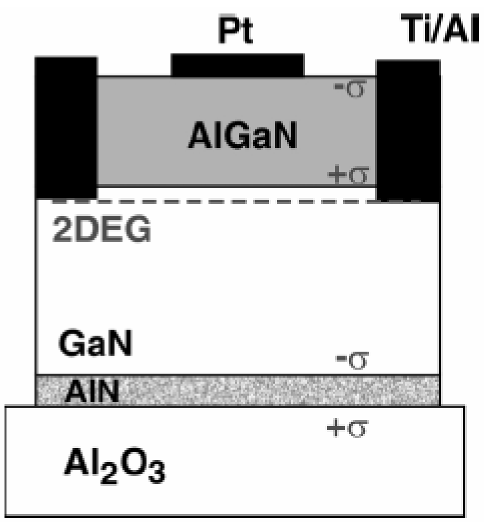
Advantages of wide-bandgap materials:

i) no generation of unwanted charge carriers (optical, thermal)

ii) Strong chemical bondings → mechanical and thermal stability

Sensor concept: modulation of charge carrier density in 2DEG near the AlGaN/GaN interface

AlGaN / GaN heterostructure



Formation of a 2DEG:

Dicontinuity of microscopic dipole density in the wurzite crystal at the AlGaN / GaN interface

Strong electronegativity of N

→ dipolemoments along the bondings between Ga – N / Al - N

Application of New Materials

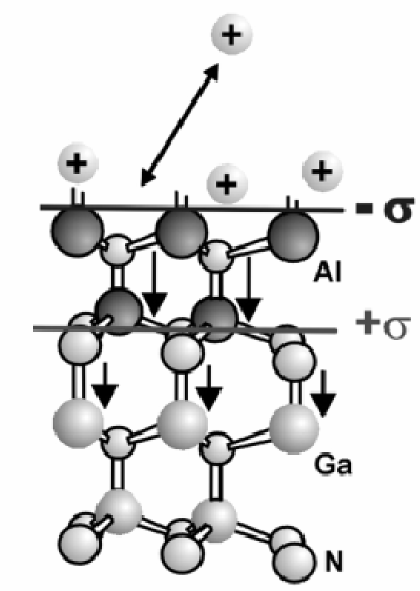
GaN

Different strength of ionic bonds of III-nitrides

⇨ Change of macroscopic polarisation P at the AlGaN / GaN interface

$P_{AlGaN} > P_{GaN}$ ⇨ Electrostatics $\sigma = P$ = Surface charge with opposite sign at the two surfaces perpendicular to P

⇨ $E = \sigma / \varepsilon_0(\varepsilon - 1)$ = Internal electric field permanent polarisation



Internal interface: consider $\Delta P = P_{AlGaN} - P_{GaN}$

⇨ Surface charge $+\sigma$ at AlGaN / GaN

Surface charge $-\sigma$ at terminated at AlGaN surface

Interacts with surrounding compensating ions

Application of New Materials

GaN

Surface charge between GaN / substrate interface can be neglected

Potential landscape:

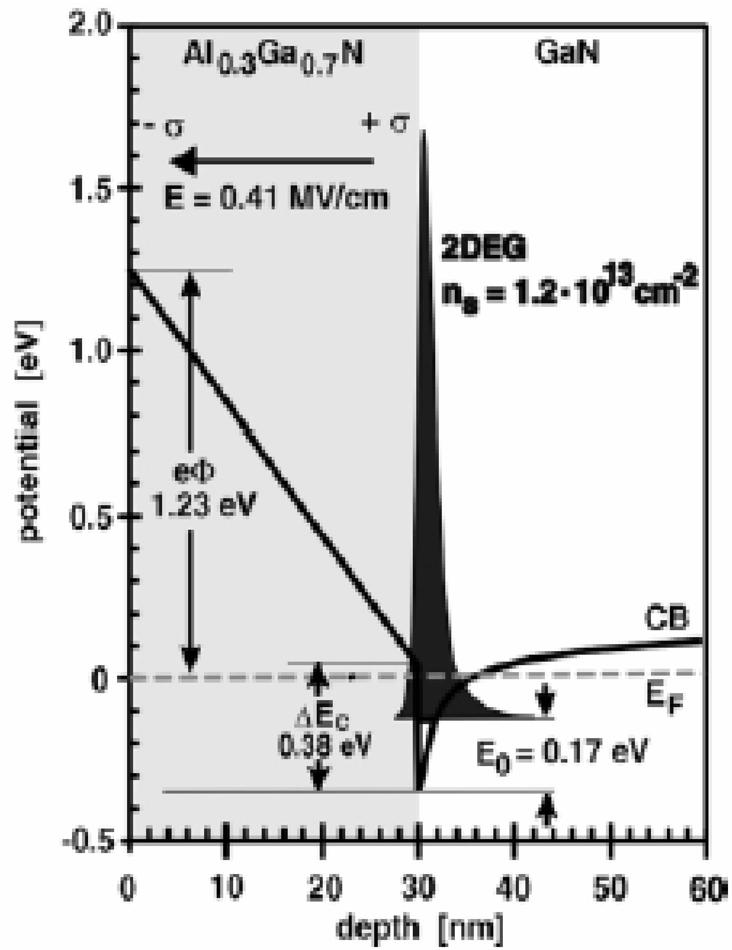
$+\sigma$ ⇨ downward bending

accumulation of electrons

High density $n_e \sim 10^{13}\ \mathrm{cm}^{-2}$

2DEG: seperated from surface through insulating AlGaN layer

→ strong confinement



Ion sensitive:

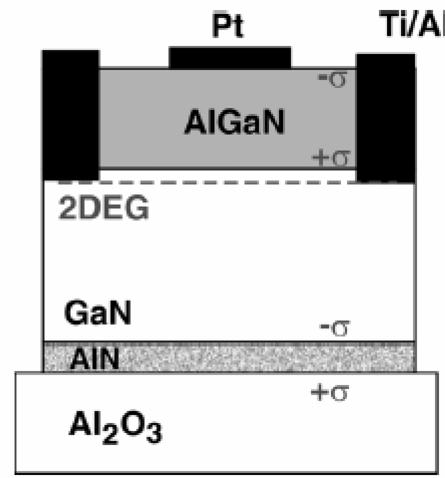
X^+/X^- adsorbed → e^- gained / lost in 2DEG

affects conductivity / current

Application of New Materials

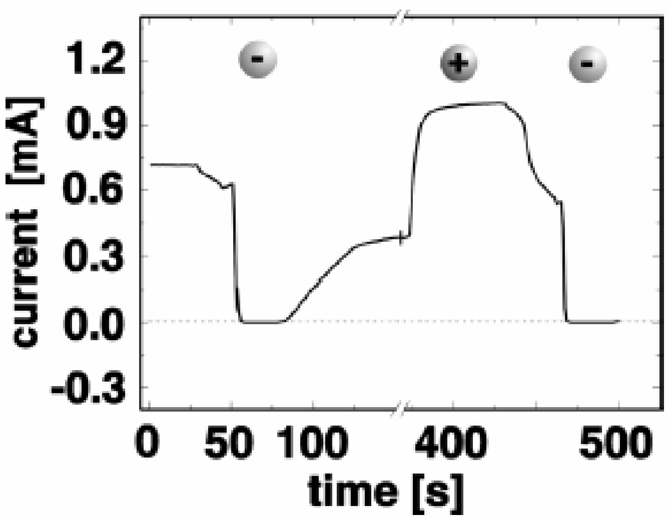
GaN

Removal of Pt-electrode → ISFET



High sensitivity:

negative ions: strong depletion of n-channel → no current



positive ions: strong accumulation along n -channel→ current

Ion	$\Delta\phi_{surface}/dec.$
H^+	$56 - 57$mV
K^+	< 2mV
Na^+	< 5mV
Ca^{2+}	< 2mV
Cl^-	< 2mV

Response: pH sensitivity near to the Nernstian limit

Application of New Materials

GaN

Further advantages:

- high signal to noise ratio
- chemically stable
- no toxic to living cells

⇨

great potential for physiological measurements (e.g. cell potentials)

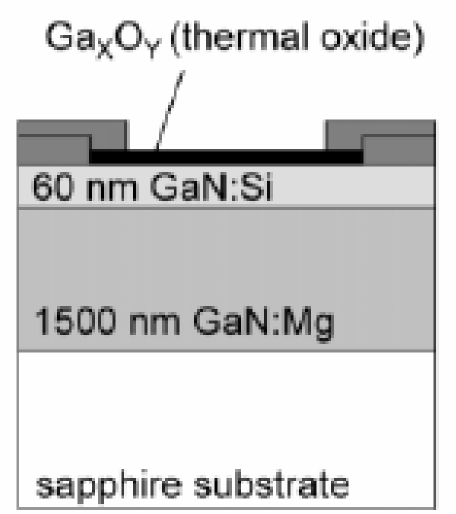
Improved heterostructure

n – doped channel: GaN:Si

p – doped bulk: GaN:Mg

→ Strong confinement of 2DEG

→ Enhanced sensitivity



Application of New Materials

Diamond

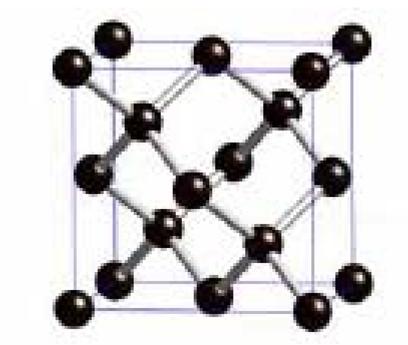
PROPERTIES

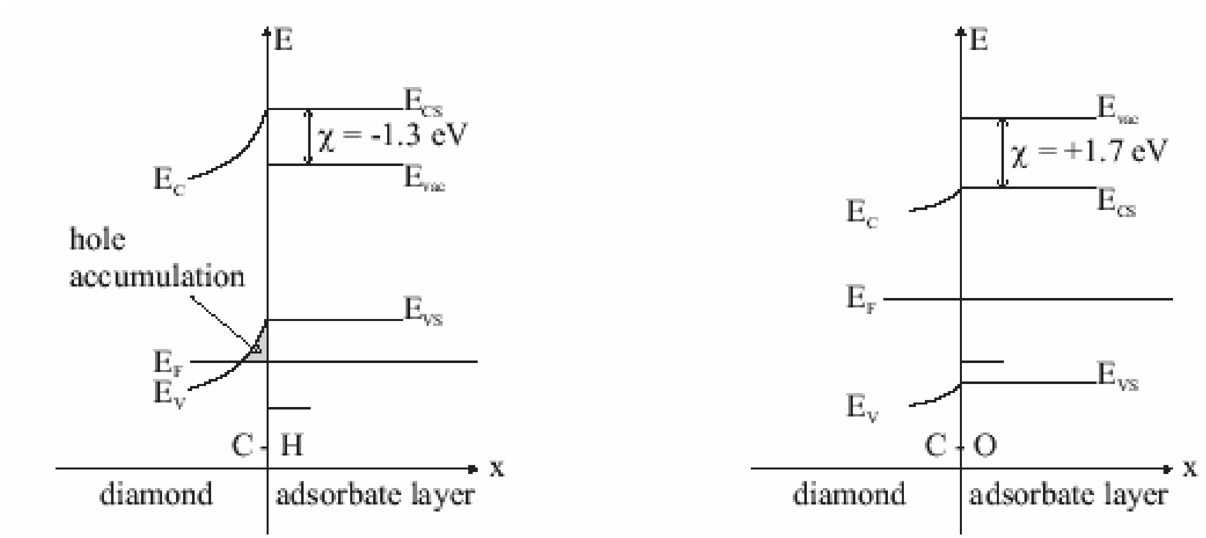
- large bandgap (5.45 eV)
- H-termination
- O-termination
- good biocompatibility

formation of dipoles

Influence on electron affinity

$= \chi = E_{vac} - E_{cs}$

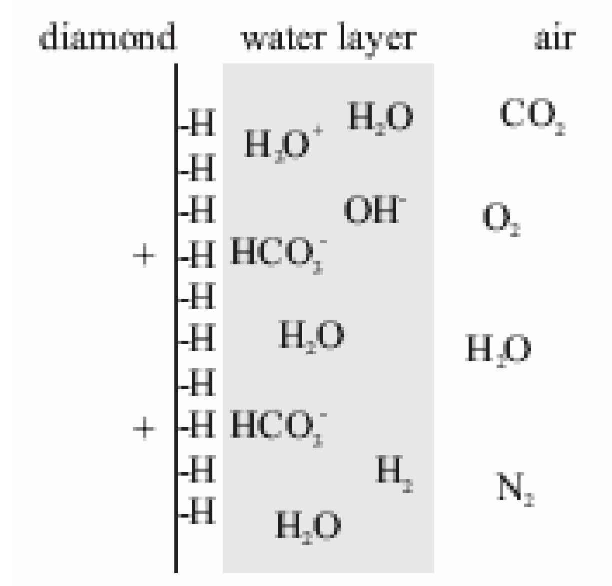




Application of New Materials

Diamond

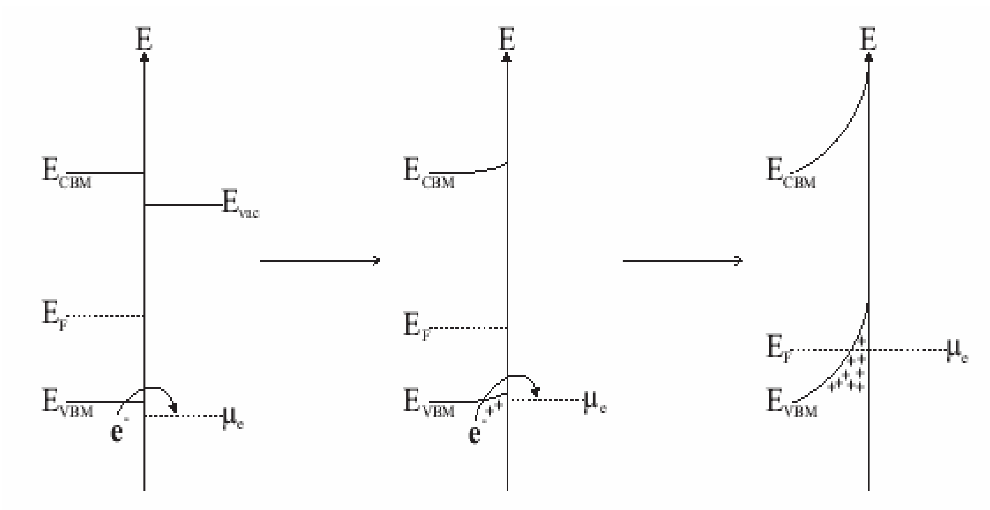
- Surface conductivity of H-terminated diamond (Transfer-Doping-Model)
  - air exposure is essential
  - spontaneously formation of acidic water layer
  - redox reaction



$$2\,H_3O^+ + 2\,e^- \rightleftharpoons H_2 + 2\,H_2O$$

electron transfer into the liquid ($\mu_e < E_F$)

$$\rho_s = 10^{13}\ \text{cm}^{-2}$$



Application of New Materials

Diamond

- pH-sensitivity of O-terminated diamond
  - Ozon treatment of H-terminated surfaces
  - amphoteric behaviour

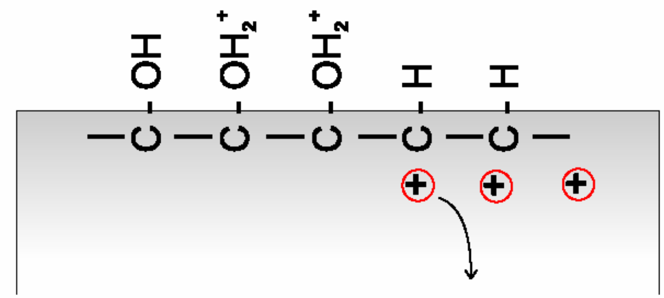
$$C - OH \rightleftharpoons C - O^- + H^+$$

$$C - OH + H^+ \rightleftharpoons C - OH_2^+$$

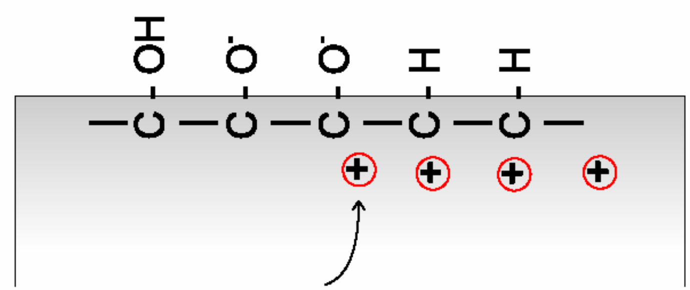
  - pH-sensitivity:

    site binding model

modulation of 2-D hole gas at H-terminated sites



(a) low pH - reducing accumulation of holes in the channel



(b) high pH - enhancement of hole density in the channel

Application of New Materials

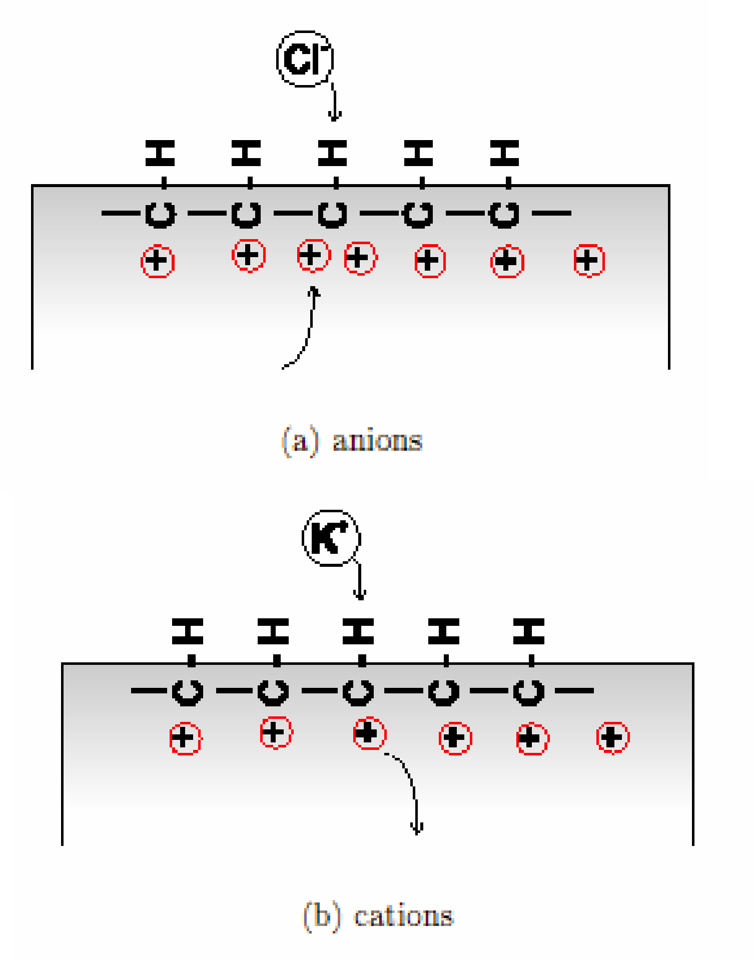
Diamond

- Ion Sensitivity (Kawarada,2002)
  - H – terminated diamond shows sensitivity to anions and cations

    (e.g.Cl^- ,I^- ,Br^-)

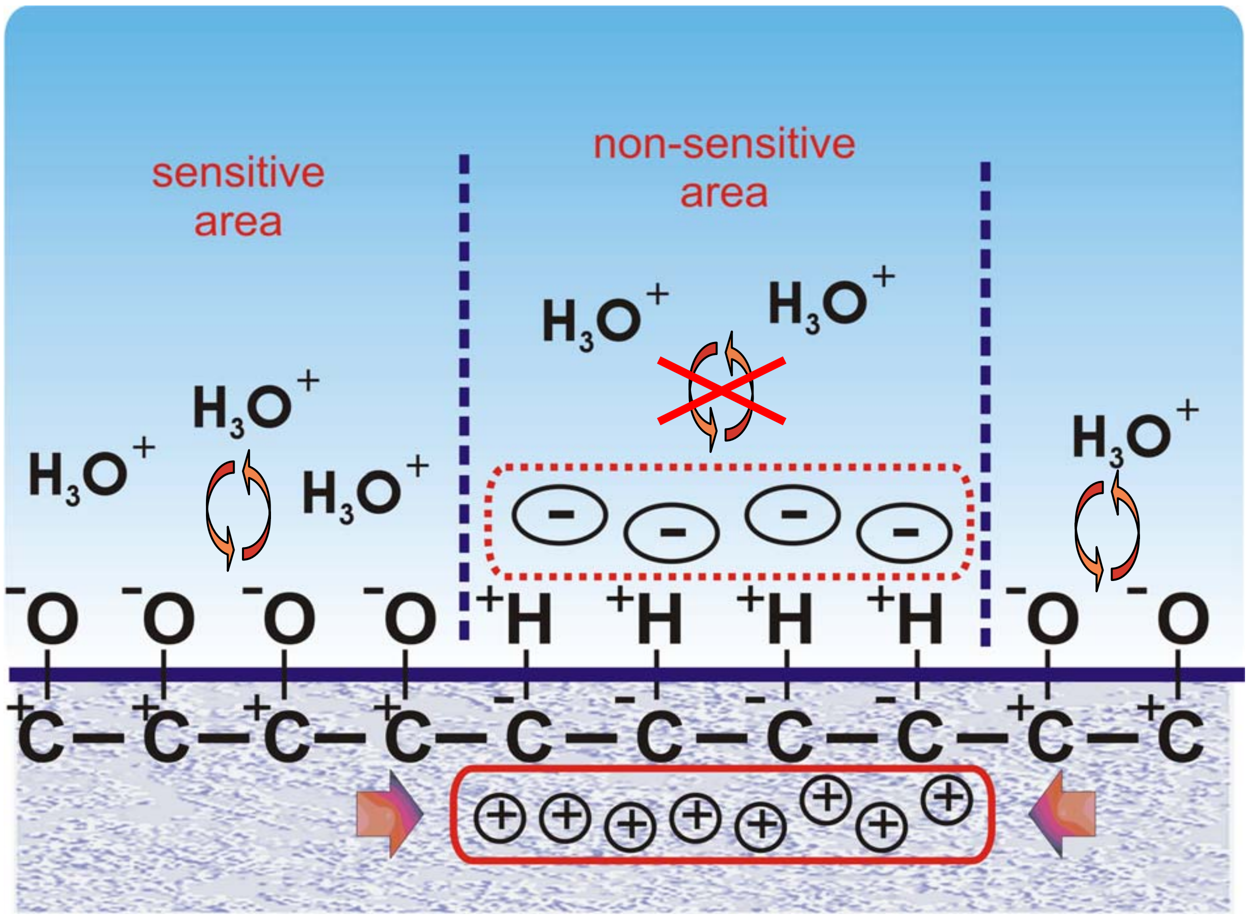
  - No sensitivity at
  - O-terminated surfaces

Not reproducable so far



Application of New Materials

Diamond

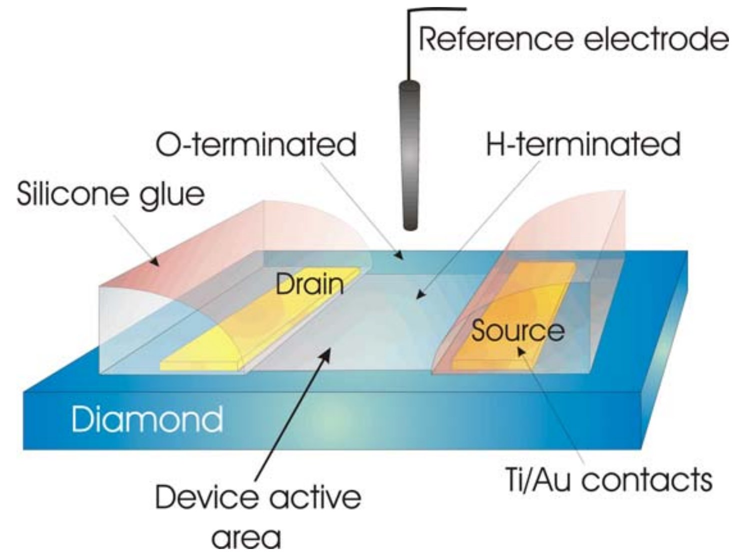


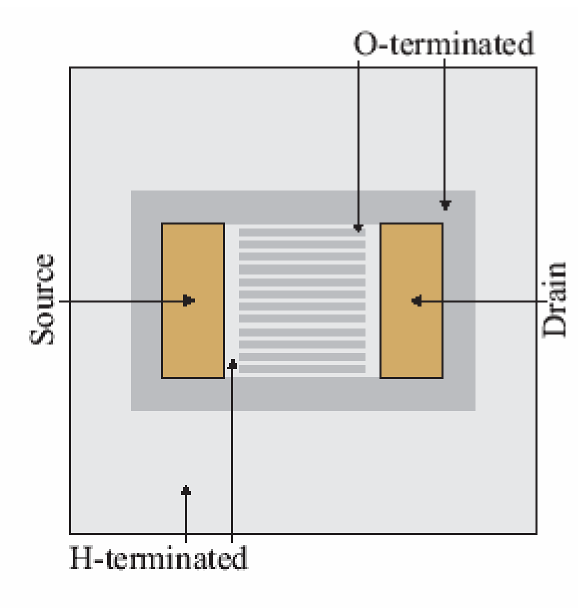
lateral modulation of the conductive channel

Application of New Materials

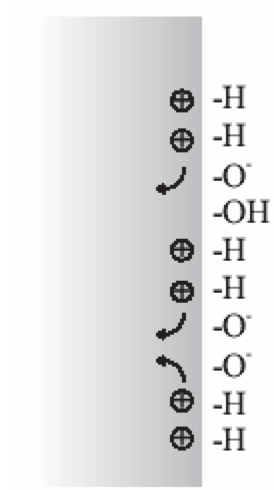
Diamond

- pH-sensitive Device
  - Combination of „conducting“ H -terminated and „pH -sensitive“ O -terminated areas

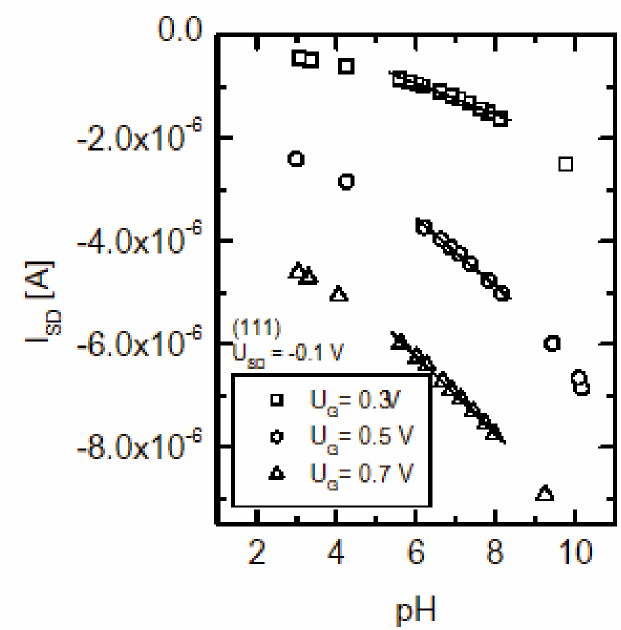




(a) sample top view



(b) crossection



Conclusions

- ISFET: basis for many bio-/chemical sensors
- Miniaturizing and high integration
- No commercial breakthrough, caused by:
  - High drift
  - Miniaturization of reference electrodes (insufficient stability)
  - Exposure to corrosive electrolytes (lifetime): improved passivating necessary

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- **[9]** S. Sze, *Physics of Semiconductor Devices*, second edition, John Wiley & Sons, 362 – 391, 430 – 445 (1985)

THANK YOU FOR YOUR ATTENTION!

Questions?