Technische Universität Dresden

DRESDEN concept

Bioelectronics and Neuromorphic Computing with Organic Electrochemical Transistors

Lecture Summer Term 2026

Hans Kleemann, Peiyun Li
(Dresden Integrated Center for Applied Physics and Photonic Materials)

Organizational

- 14 Lectures
- Every Tuesday 16:40-18:10 in ~~SE2/102/U~~ **Kro.2.18**

Date	Lecturer
14.4	Peiyun
21.4	Peiyun
28.4	Hans
5.5	Hans
12.5	Hans
19.5	Peiyun
26.5	No Lecture
2.6	Peiyun
9.6	Peiyun
16.6	Hans
23.6	Hans
30.6	Hans
7.7	Hans
14.7	Hans
21.7	Hans

Outline

(1) OECT introduction (1st Lecture)

- Device structure
- Key curves and parameters
- OECT vs OFET

(2) Basics of Electrochemistry (1st & 2nd Lecture)

- Ion transport mechanisms
- Nernst equation
- Electrochemical double layer
- Cyclic Voltammetry

(3) Doping (2nd Lecture)

- Doping in inorganic semiconductors
- Orbital and Band structure of OSC
- Molecular doping
- Electrochemical doping

(4) Processing methods (3rd Lecture)

- Photolithography
- Printing, peel-off, vacuum
- Fabrication of vertical structures
- Scaling of volumetric devices

Outline

(5) Device Properties and mechanism (4th & 5th Lecture)

- MOSFET
- Bernards model
- Time-constant
- Specific interactions

(6) Materials (6th Lecture)

- Channel
- Electrolyte & electrode
- Hydrogel

(7) Bioelectronic application (7th & 8th Lecture)

- Ionic/biochemical sensing
- Electrophysiology signal detection

(8) Principles of Neuromorphic Computing (9th ~ 14th Lecture)

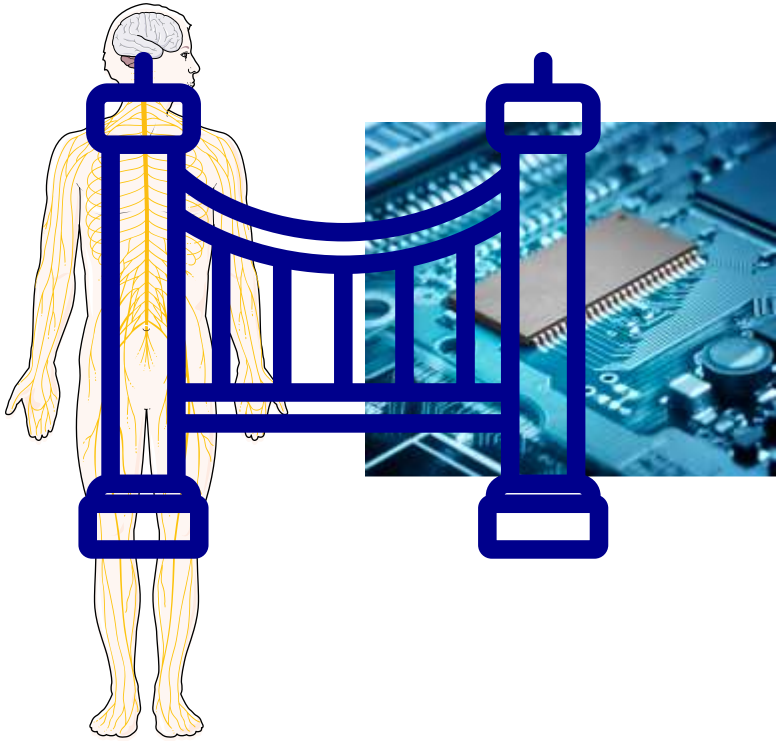
- Synapse
- Neuron
- Neuronal network

1. OECT Introduction

1.1 Motivation

Biology

- Signal transmitted through **ions/chemicals** by neuron system
- Energy provided by efficient **biochemical reactions**
- Sense, transmit, process, memory, act…
- Growing and learning
- Soft tissue, hard bones, wet



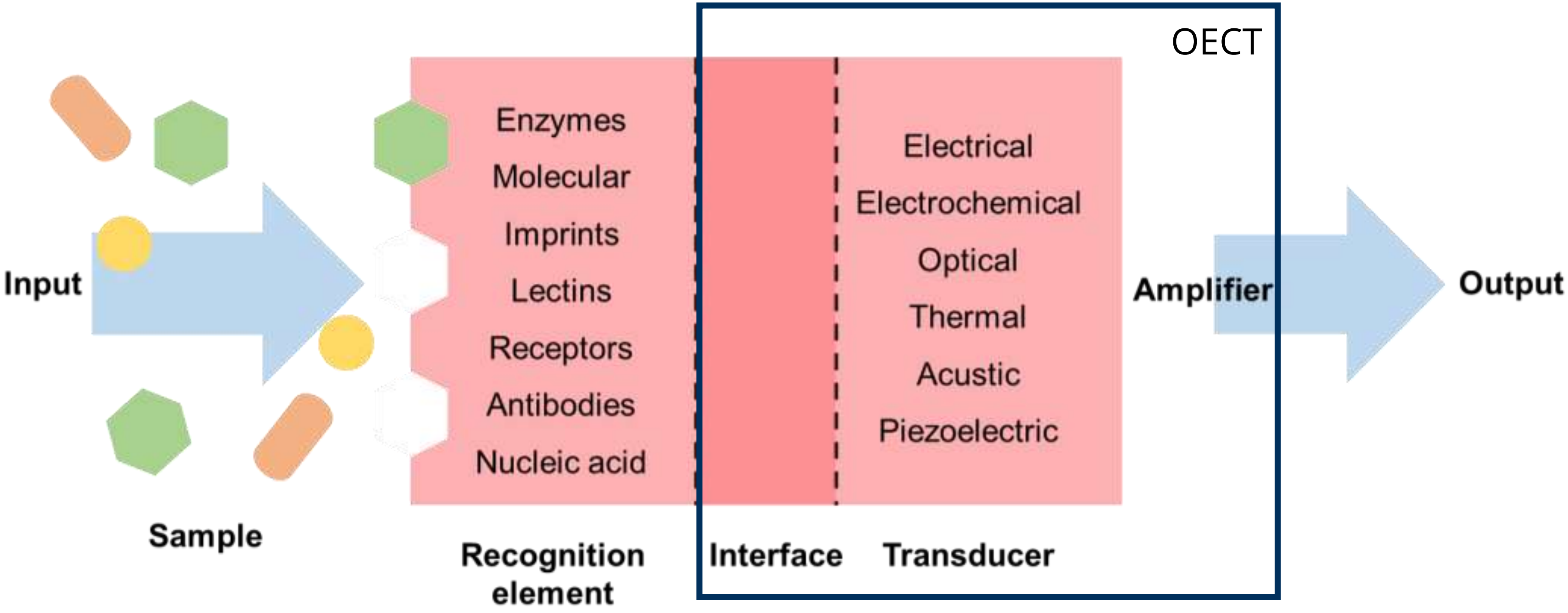
Electronics

- Signal transmit through **electromagnetic wave**
- Energy provided by **electricity**
- Data procession, transmission, storage
- Non-reconfigurable, limited learning
- Hard, dry

An interface bridging biology and electronics is missing

1. OECT Introduction

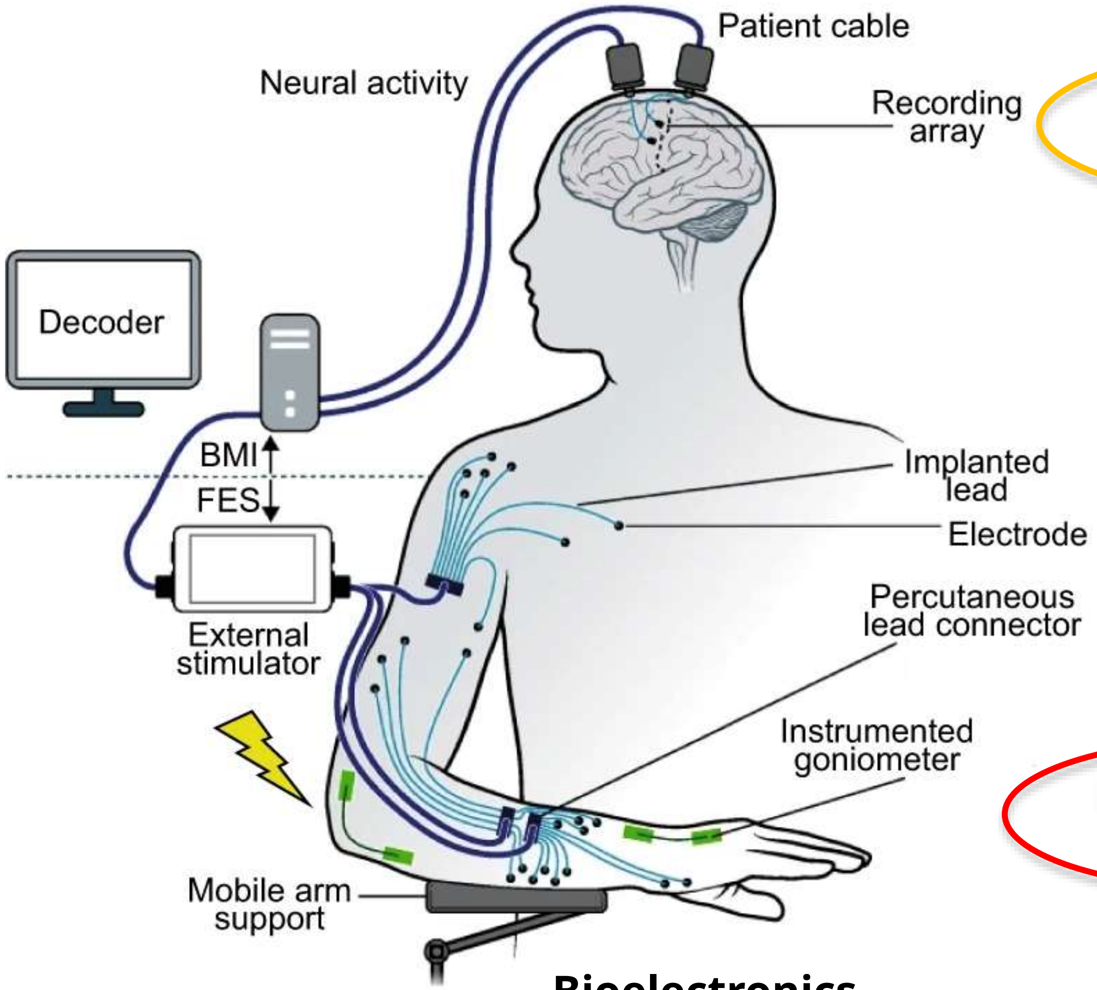
1.1 Motivation



Transducer can transform information from one to another, connecting different system

1. OECT Introduction

1.1 Motivation



ionic/chemicals signal

electronic signal

ionic/chemicals signal

Bioelectronics

1. OECT Introduction

1.1 Motivation

Why neuromorphic computing?

- Emulates the computation schemes and hardware components of biological intelligence.
- Targets more power-efficient, versatile, and fault-tolerant artificial intelligence.
- Current AI already borrows biological concepts, for example spiking neural networks and stochasticity.
- However, most implementations still run on von Neumann architectures, creating a bottleneck between memory and computation.
- This motivates neuromorphic processors built from artificial neurons and synapses.

From cloud AI to edge intelligence

Cloud AI today
Large centralized processing of enormous amounts of mostly unfiltered data.

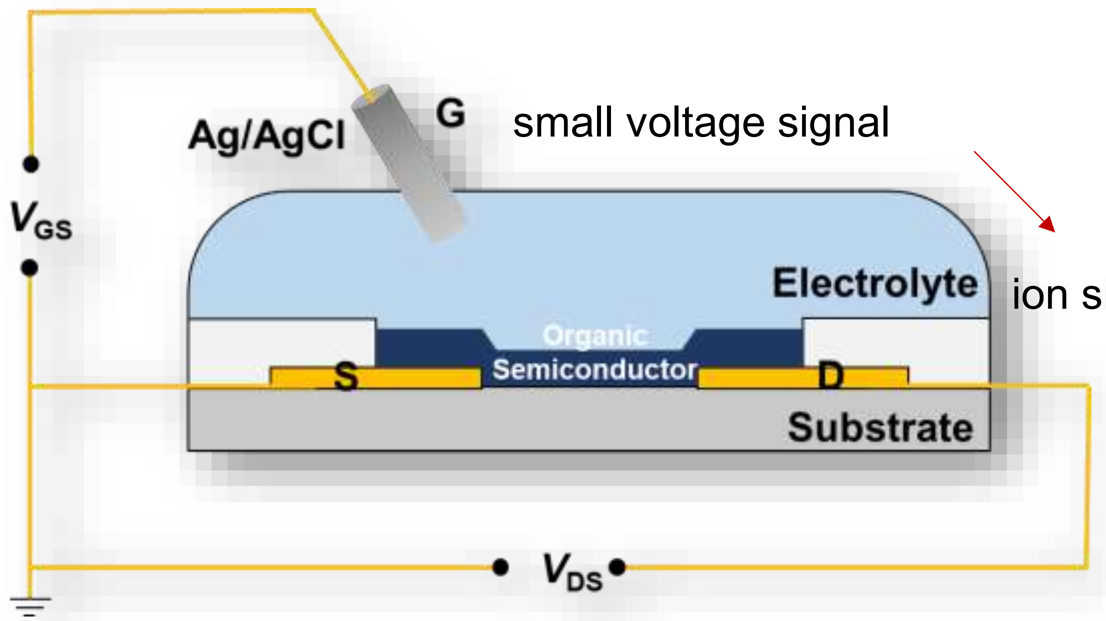
Edge computing
Pre-classification and filtering close to the sensor can greatly reduce power consumption.

Key challenge
Specialized chips are needed, often costly in silicon, and they must interface efficiently with sensors.

1. OECT Introduction

1.2 OECT

Organic Electrochemical Transistor



small voltage signal

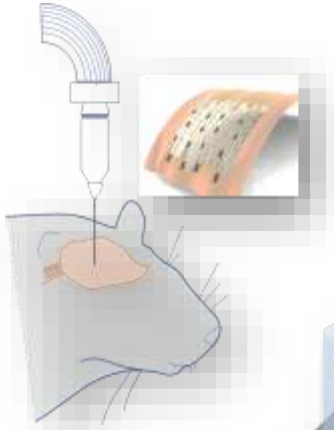
ion signal

huge current signal

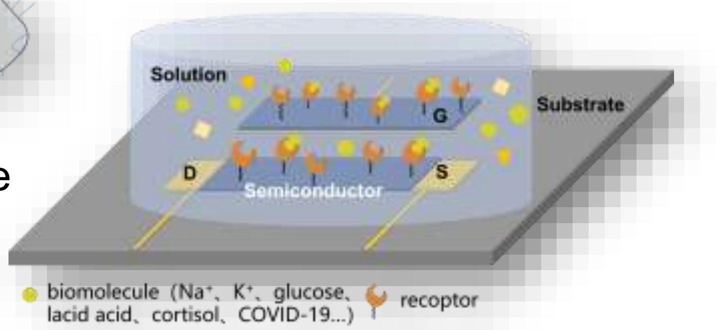
Transducer and Amplifier

- Enable flexibility and biointerface
- Enable working in aqueous/wet environment
- High dielectric capacitance, enable low operation voltage (< 1 V), large sensibility
- Chemical sensing by gate/channel modification
- Possible biocompatibility

neuromorphic computing



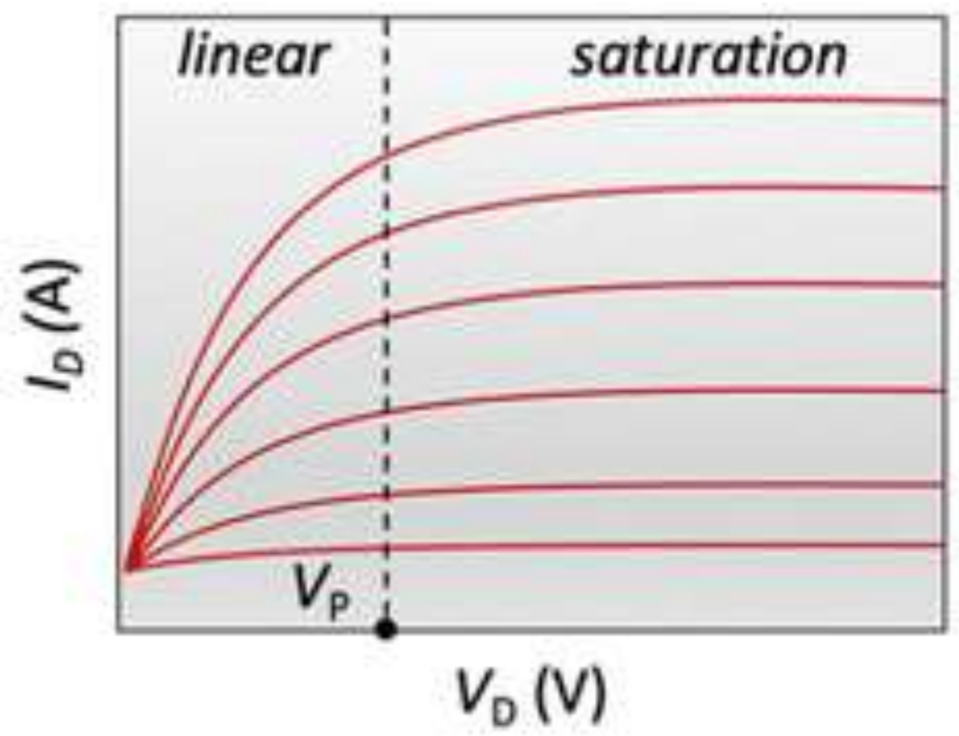
neural interface



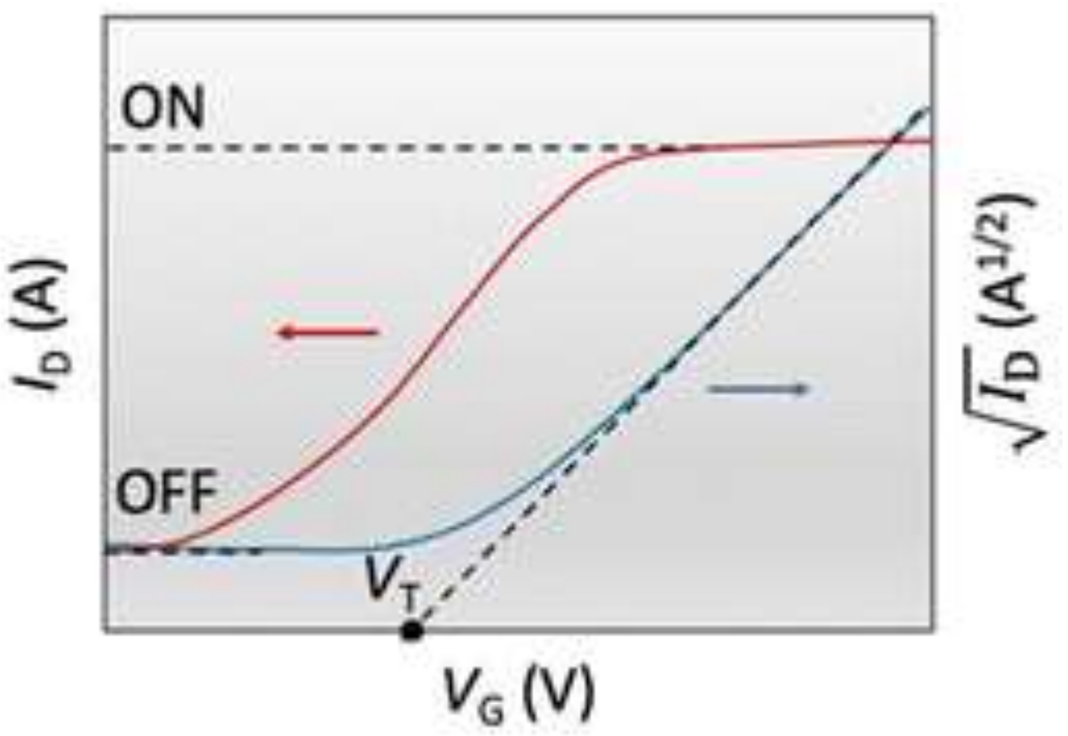
biochemical sensors

1. OECT Introduction

1.2 Key curves and parameters



Output Curve

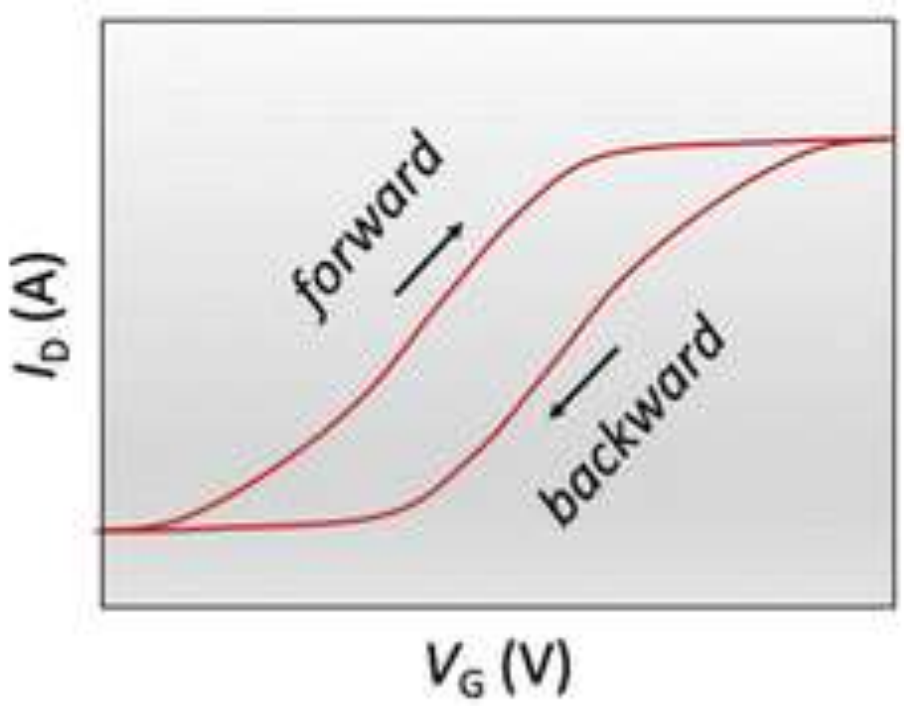


Transfer Curve

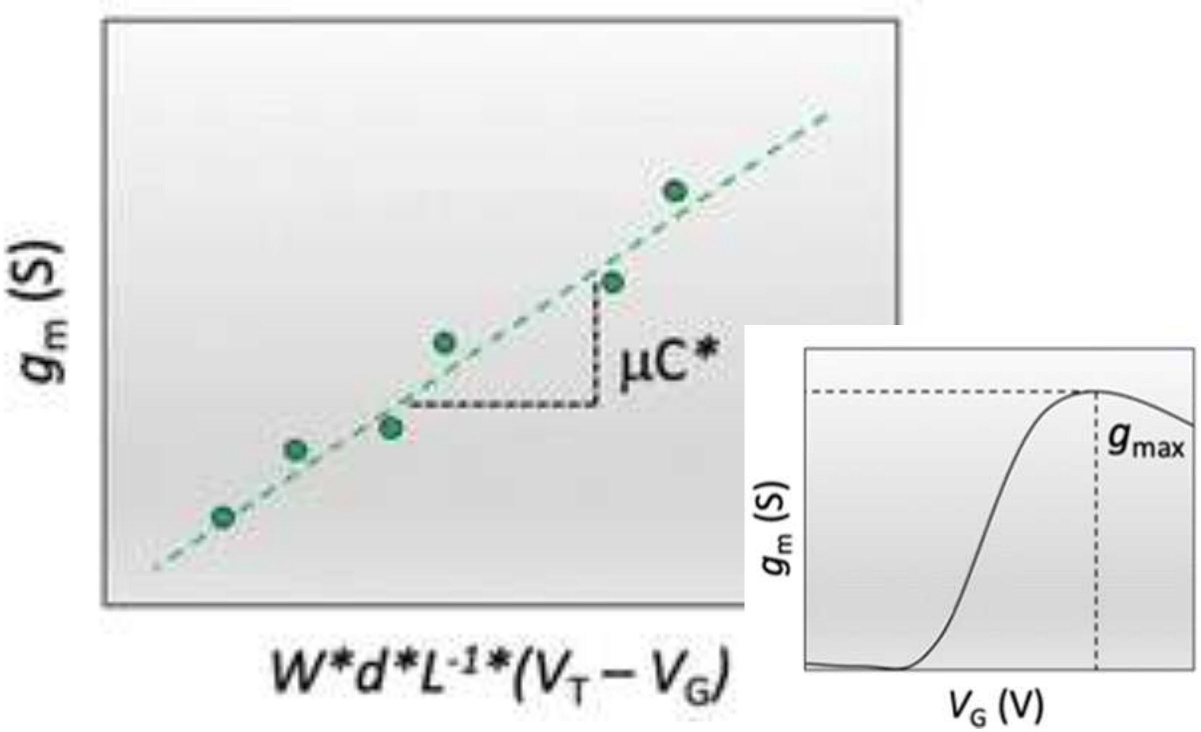
Chem. Soc. Rev., 2023, 52, 1001-1023

1. OECT Introduction

1.2 Key curves and parameters



Hysteresis



$$g_\mathrm{m} = \frac{\partial I_\mathrm{DS}}{\partial V_\mathrm{GS}} = \frac{Wd}{L}\mu C^{*}\,|(V_\mathrm{GS} - V_\mathrm{TH})|$$

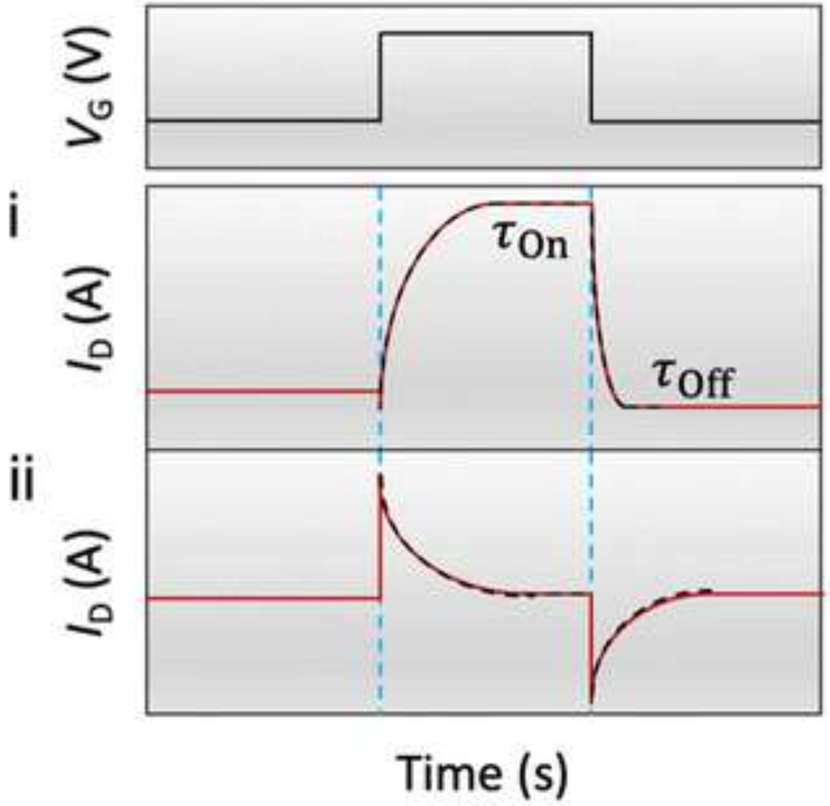
Transconductance

g: conductance, m: mutual

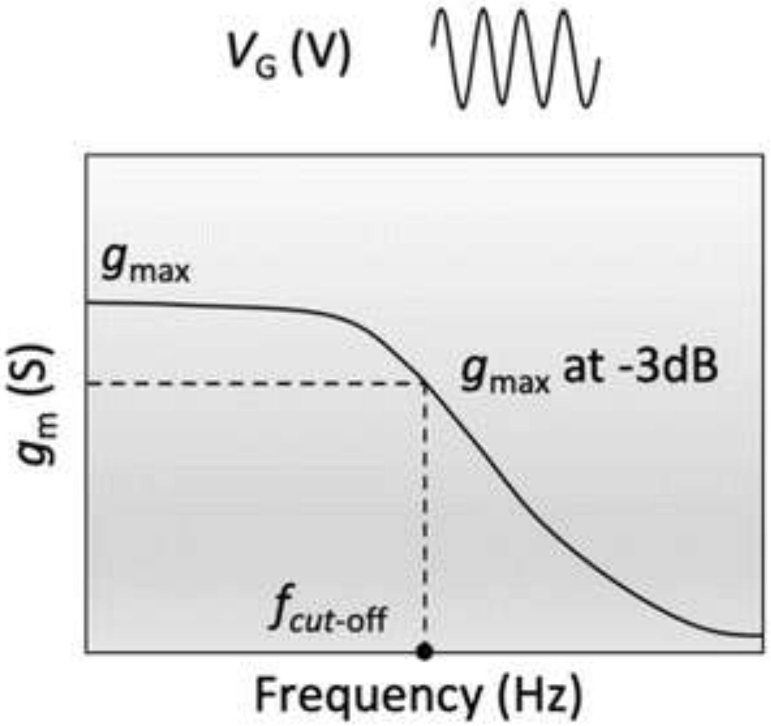
Chem. Soc. Rev., 2023, 52, 1001-1023

1. OECT Introduction

1.2 Key curves and parameters



Transient Curve

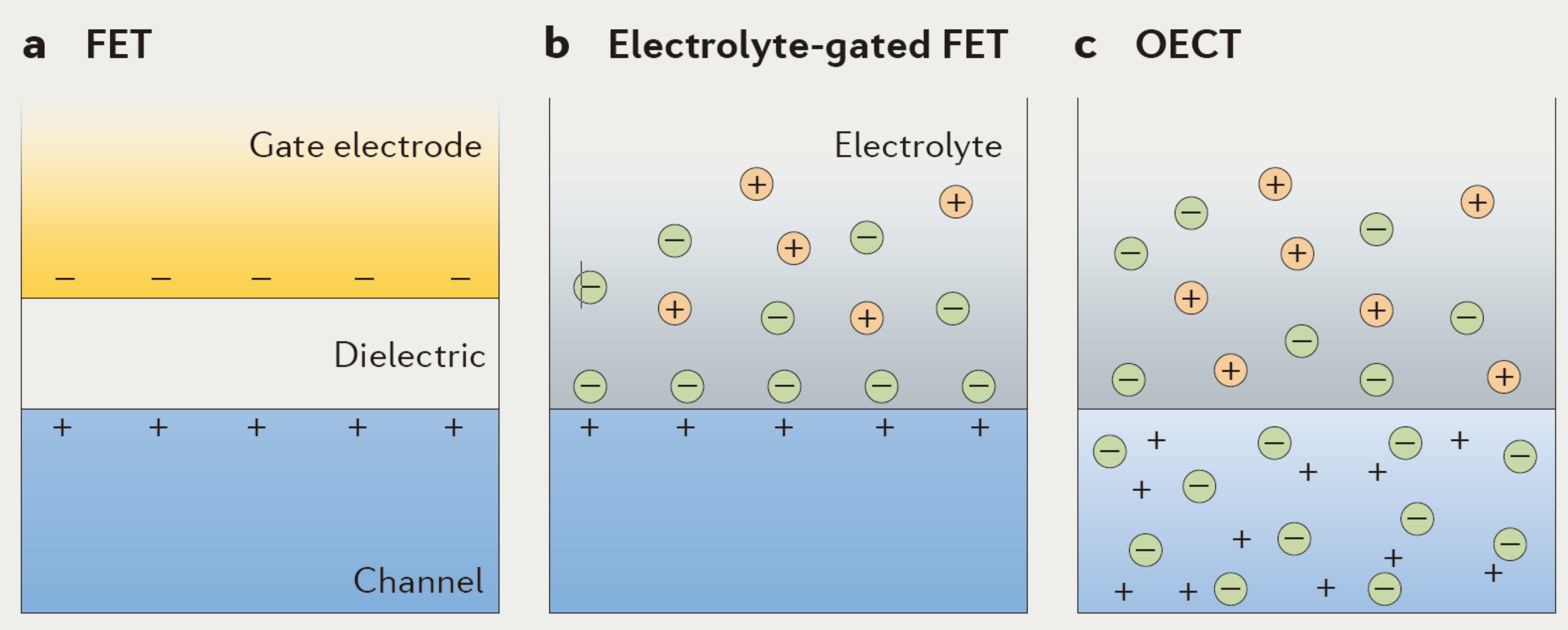


Frequency-depend Curve

Chem. Soc. Rev., 2023, 52, 1001-1023

1. OECT Introduction

1.3 OECT vs OFET

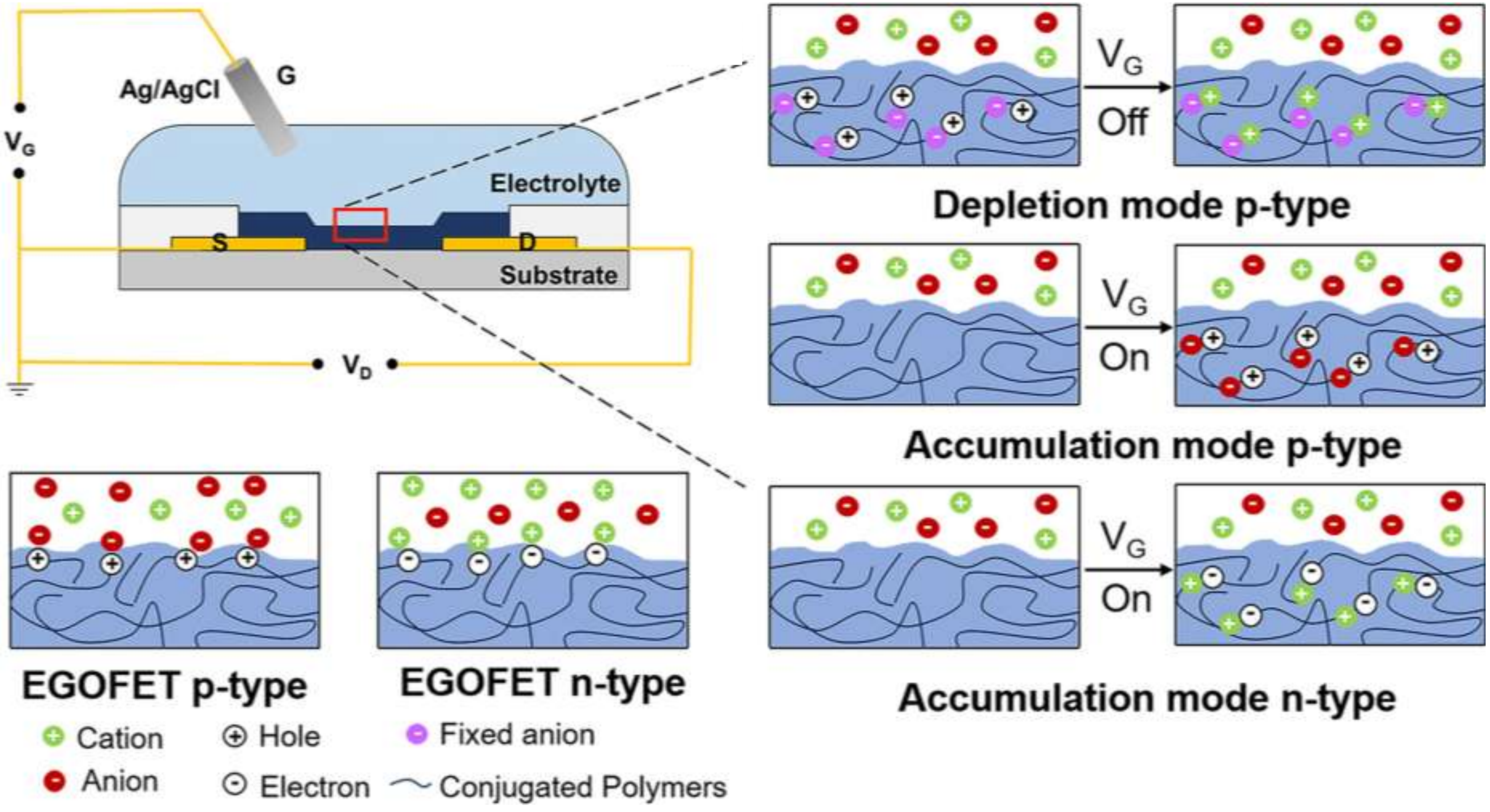


Field effect transistor

Nat. Rev. Mater. 3, 17086 (2018).

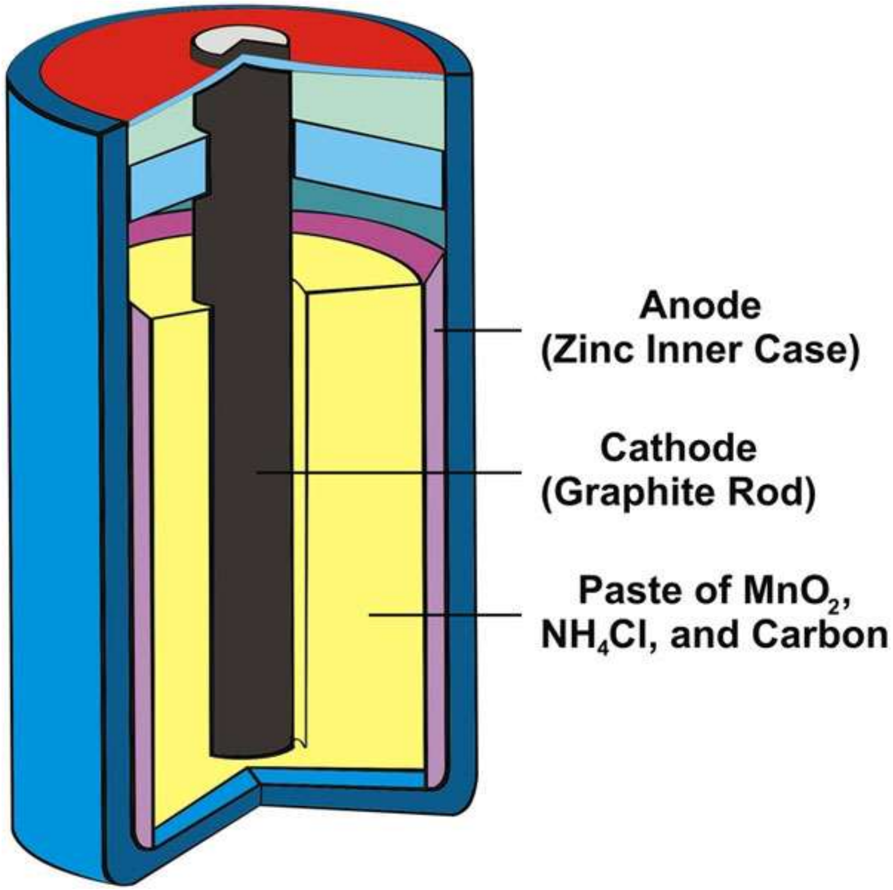
1. OECT Introduction

1.3 OECT vs OFET

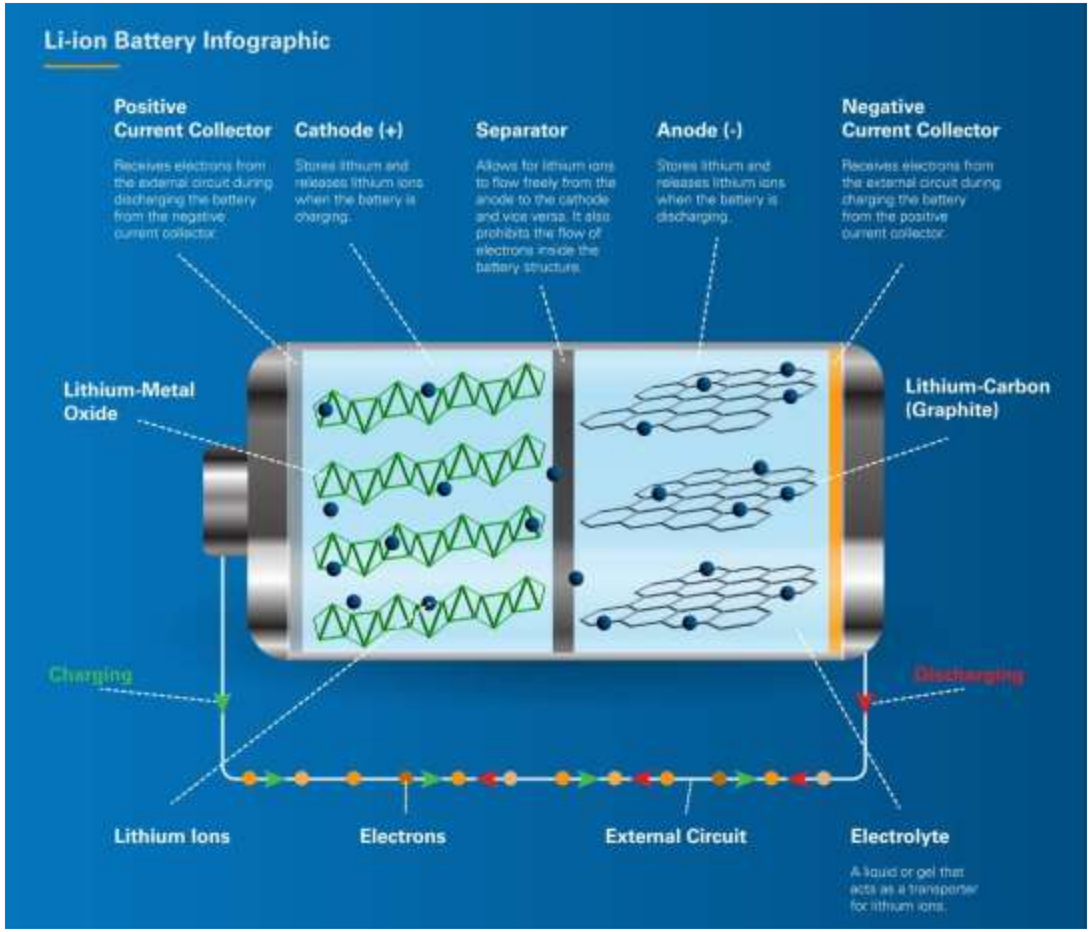


J. Polym. Sci. 2022, 60(3), 377

2. Basics of Electrochemistry



Dry Cell



Lithium-ion Battery

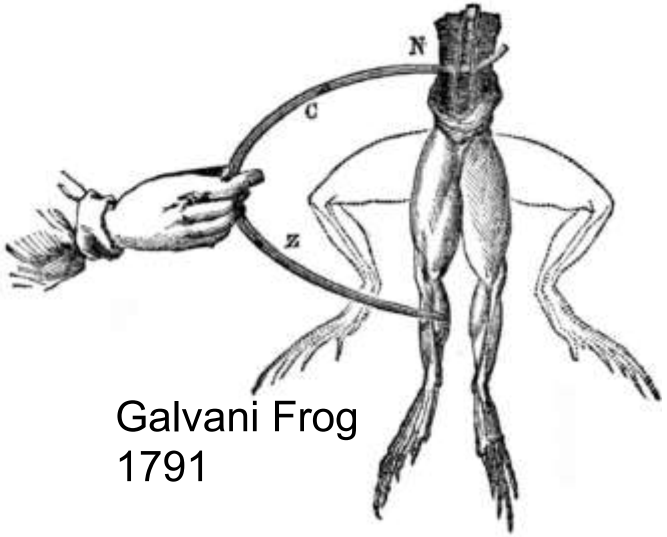
2. Basics of Electrochemistry

Electrochemical Cell/Battery

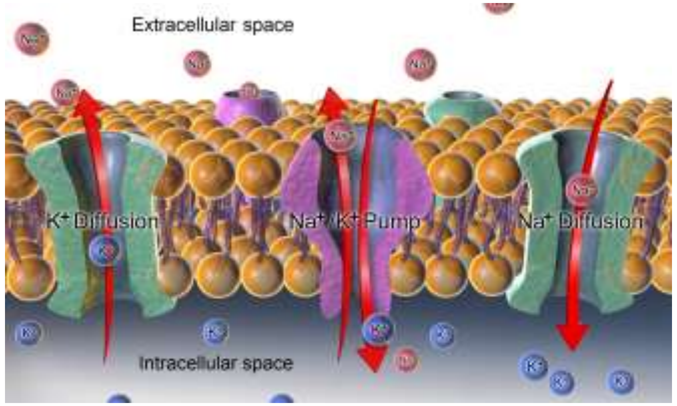
Electrolysis

Metal Corrosion

Electroplate



Galvani Frog
1791



Membrane potential

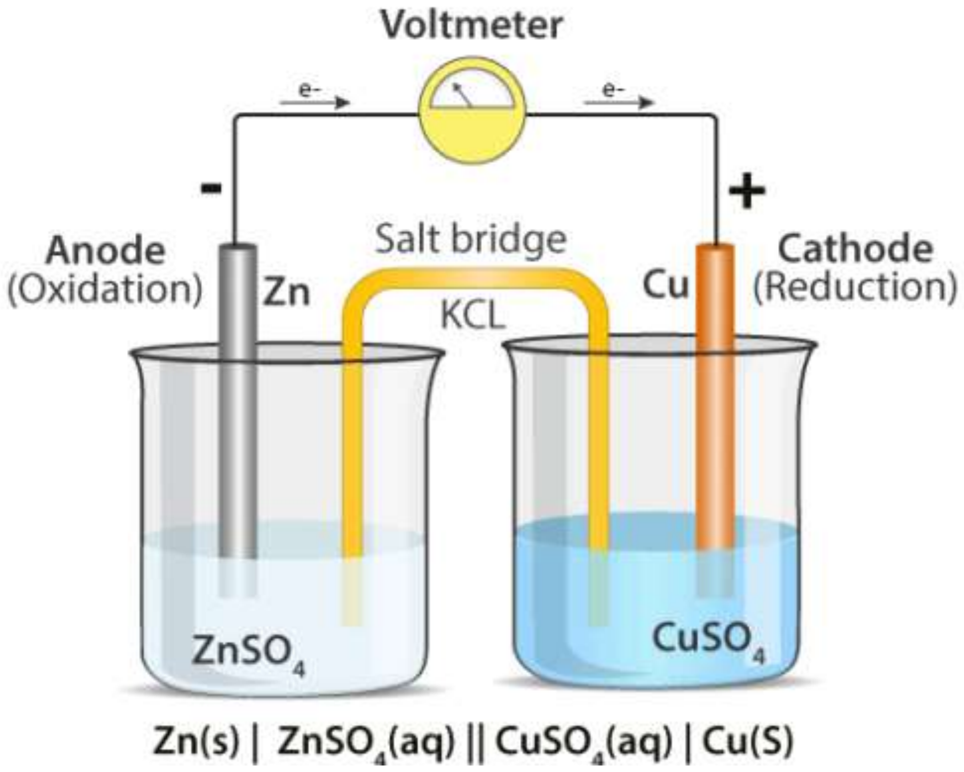
Electrocardiogram (ECG)

Electrophysiology

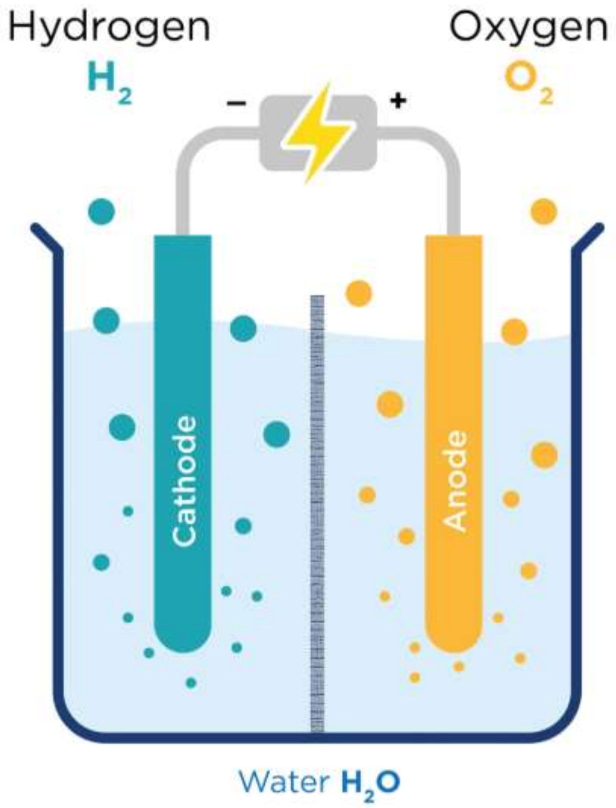
2. Basics of Electrochemistry

Electrochemistry is the branch of physical chemistry concerned with the relationship between electrical potential difference and identifiable chemical change

Electrochemistry is the study of electron movement in an **oxidation or reduction reaction** at a polarized **electrode surface**



Electrochemical Cell

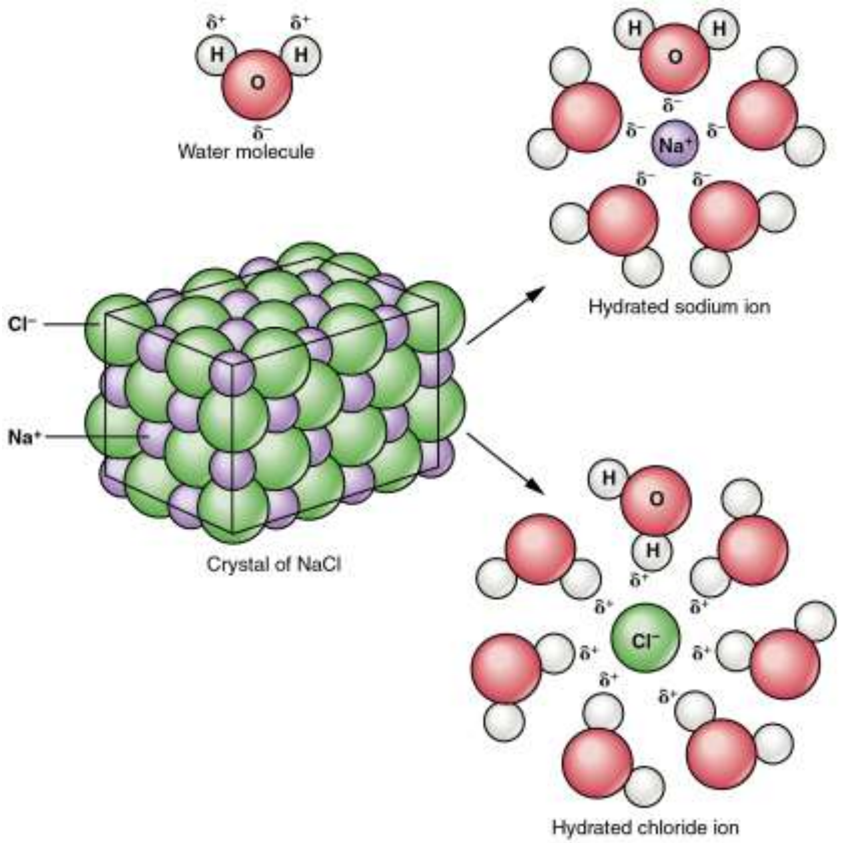


Electrolysis

Anode
Cathode
Electrolyte
Potential

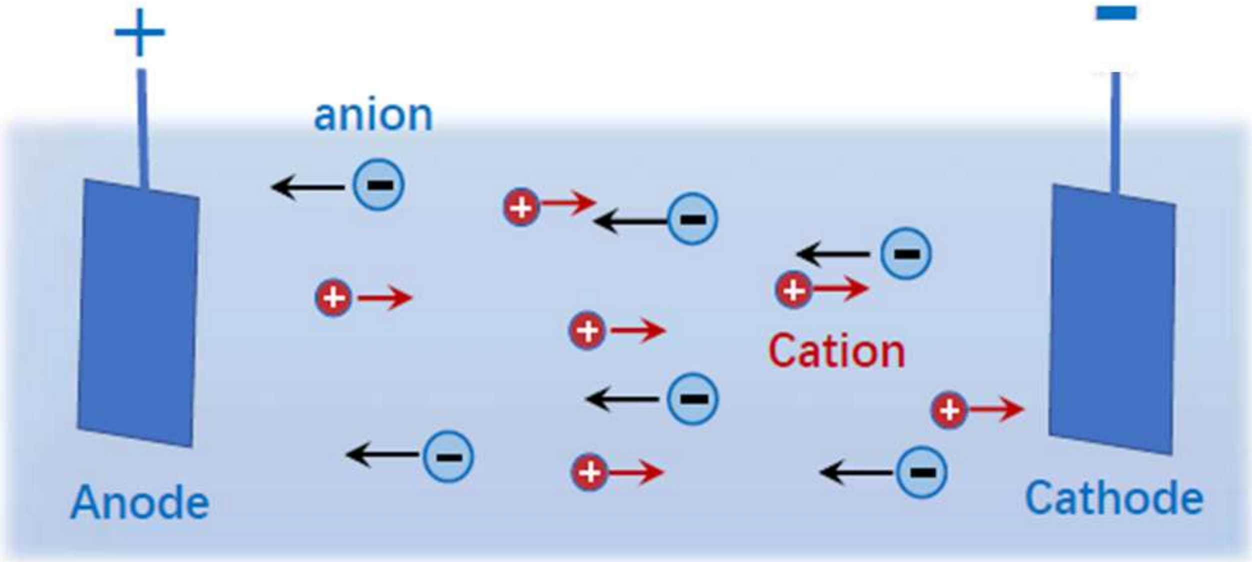
2. Basics of Electrochemistry

2.1 Ion transport mechanisms



$$NaCl\,(s) + H_2O\,(l) \rightarrow Na^{+} + Cl^{-}\,(aq)$$

Dissociation



Ions motion driven by electrical field

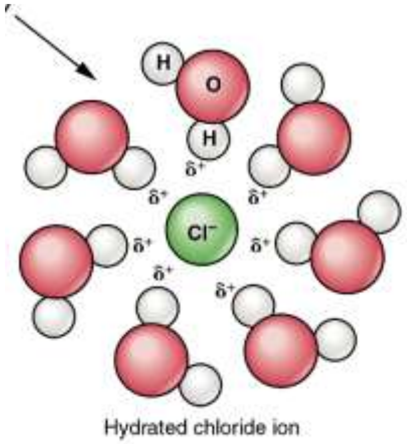
2. Basics of Electrochemistry

2.1 Ion transport mechanisms

Electrostatic (coulombic) forces

$$F(r) = \frac{|q_1 q_2|}{4\pi\varepsilon_r\varepsilon_o r^2}$$

relative permittivity ε_r electric constant ε_o



Solvation shells

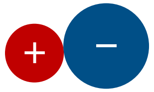
r↑ F↓

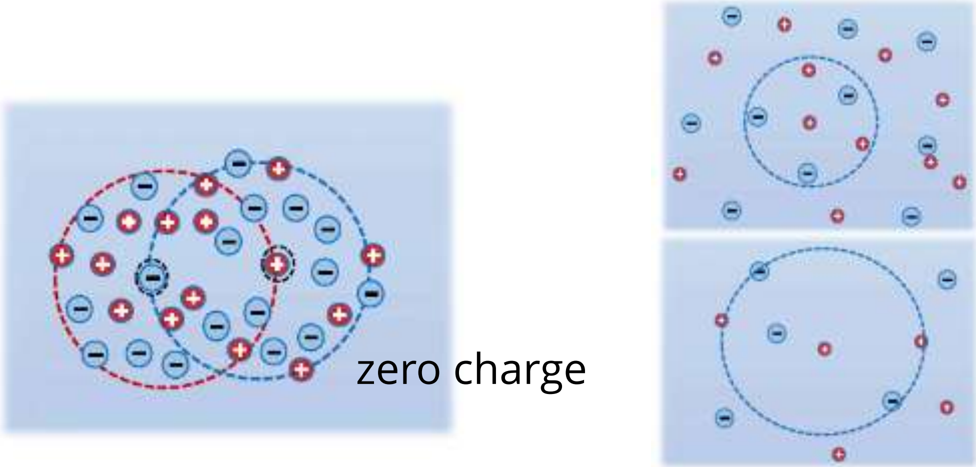
Ion solvations

ion-ion interactions

long-range ion interactions   short-range ion interactions

coulombic interactions > thermal motion ➡ Ion pair formation





zero charge

high concentration

low concentration

Ionic atmosphere

2. Basics of Electrochemistry

2.1 Ion transport mechanisms

activity coefficient

effective concentration

Activity

$$a_i = \gamma_i \frac{c_i}{c^{\ominus}}$$

ion concentration

standard concentration (1 mol/L)

dimensionless

mean ionic activity

$$a_\pm = \left(a_+^{v_+} a_-^{V_-}\right)^{1/(V_+ + V_-)}$$

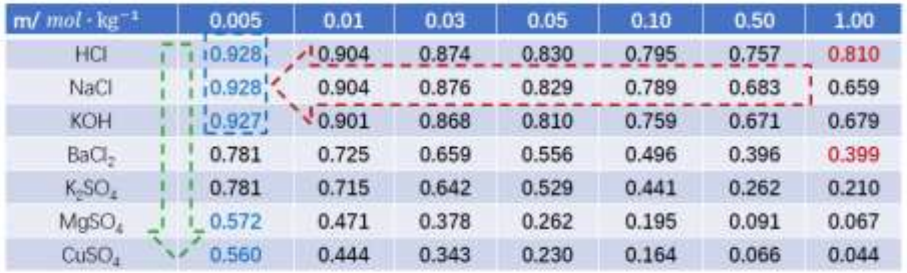
$$\gamma_\pm = \left(\gamma_+^{v_+} \gamma_-^{V_-}\right)^{1/(V_+ + V_-)}$$

$$M_{V_+} A_{V_-}$$

Ideal solution: infinite dilute $\gamma = 1$

Real solution $\gamma < 1$

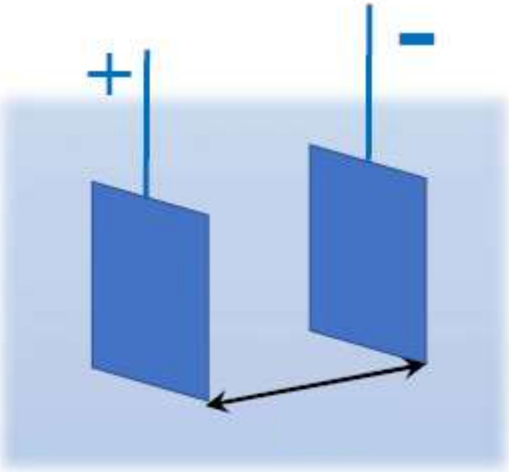
c↑ γ↓ **V_+V_-↑ γ↓**



m/ $mol \cdot kg^{-1}$	0.005	0.01	0.03	0.05	0.10	0.50	1.00
HCl	0.928	0.904	0.874	0.830	0.795	0.757	0.810
NaCl	0.928	0.904	0.876	0.829	0.789	0.683	0.659
KOH	0.927	0.901	0.868	0.810	0.759	0.671	0.679
$BaCl_2$	0.781	0.725	0.659	0.556	0.496	0.396	0.399
K_2SO_4	0.781	0.715	0.642	0.529	0.441	0.262	0.210
$MgSO_4$	0.572	0.471	0.378	0.262	0.195	0.091	0.067
$CuSO_4$	0.560	0.444	0.343	0.230	0.164	0.066	0.044

2. Basics of Electrochemistry

2.1 Ion transport mechanisms



$$u_+ = \frac{E}{v_+}$$

$$u_- = \frac{E}{v_-}$$

Ion Mobility
$cm^2V^{-1}s^{-1}$

E: electric field
v: velocity

$$\sigma = \frac{l}{RA}$$

Ion Conductivity
S/cm

$$\sigma = \frac{j}{E} = e(u_+Z_+n_+ + u_-Z_-n_-)$$

Z: valency
n: amount of substance

2. Basics of Electrochemistry

2.2 Nernst equation

Walther Hermann Nernst

Electrical potential $\phi_r = \frac{-W}{q}$

Work required to move a unit positive charge from infinity to point of interest.

Chemical potential $\mu_i = \mu_i^{\ominus} + RTlna_i$

Chemical potential is defined as the partial molar Gibbs free energy.

$$\mu_i = \left(\frac{\partial G}{\partial n_i}\right)_{T,P,n_j}$$

R: gas constant
T: temperature

Electrochemical potential $\tilde{u}_i = \mu_i + Z_iF\phi$

$$F = eN_A = 96485\ C/mol$$

Faraday constent

$$\Delta G = -nFE = \Delta G^{\ominus} + RTlnQ$$

$$Q = \prod a_i^{v_i}$$

Reaction quotient

Electrode/Cell potential $E = E^{\ominus} - \frac{RT}{nF}lnQ$ full-cell

Nernst Equation $E = E^{\ominus} + \frac{RT}{nF}ln\frac{a_{\mathrm{Ox}}}{a_{\mathrm{Red}}}$ Half-cell

$$OX + ne^- \rightleftharpoons Red$$

Reference

1. Chem. Soc. Rev., 2023, 52, 1001-1023
2. Nat. Rev. Mater. 3, 17086 (2018)

Next class

1. *Chem. Rev*. 2022 , 122 , 12 , 10821–10859
2. *Chem. Rev*. 2022 , 122 , 4 , 4420–4492
3. *Acc. Chem. Res*. 2016 , 49 , 3 , 370–378
4. *Nat. Mater*. 19, 13–26 (2020)

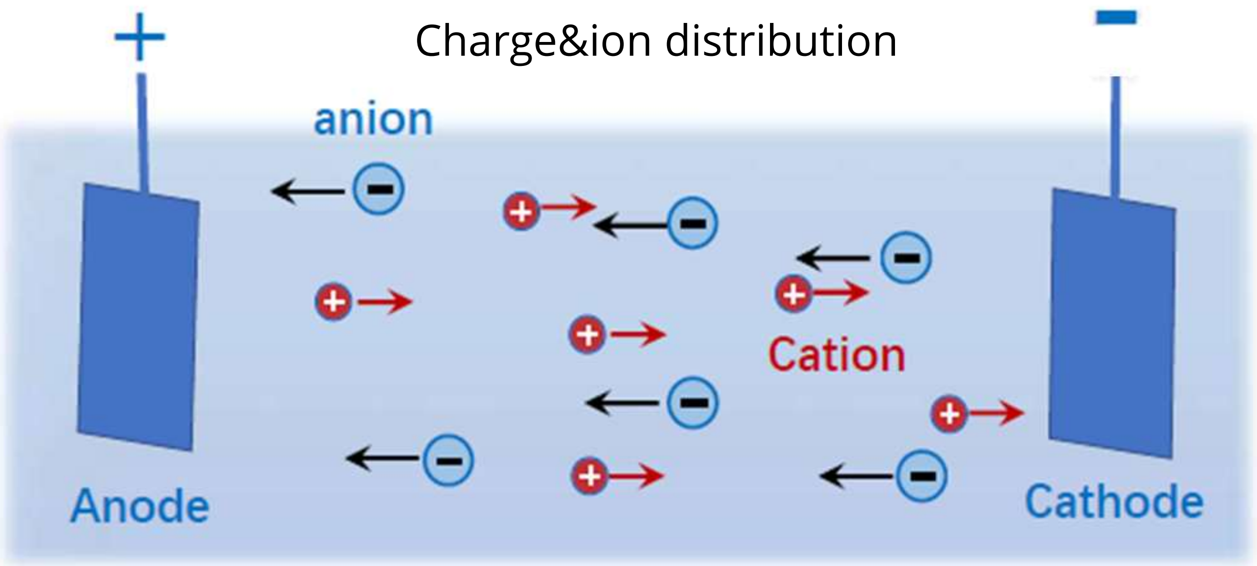
Bioelectronics and Neuromorphic Computing with Organic Electrochemical Transistors

Lecture Summer Term 2026

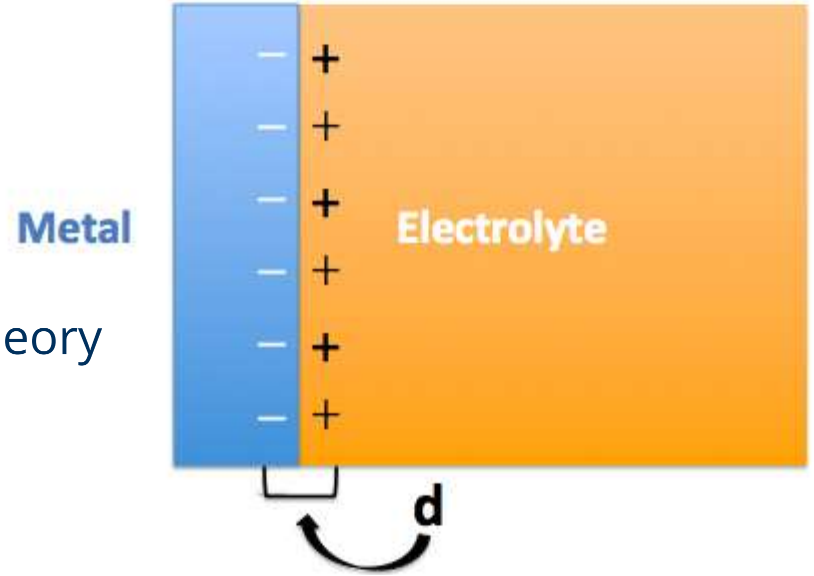
Hans Kleemann, Peiyun Li
(Dresden Integrated Center for Applied Physics and Photonic Materials)

2. Basics of Electrochemistry

2.3 Electrochemical double layer

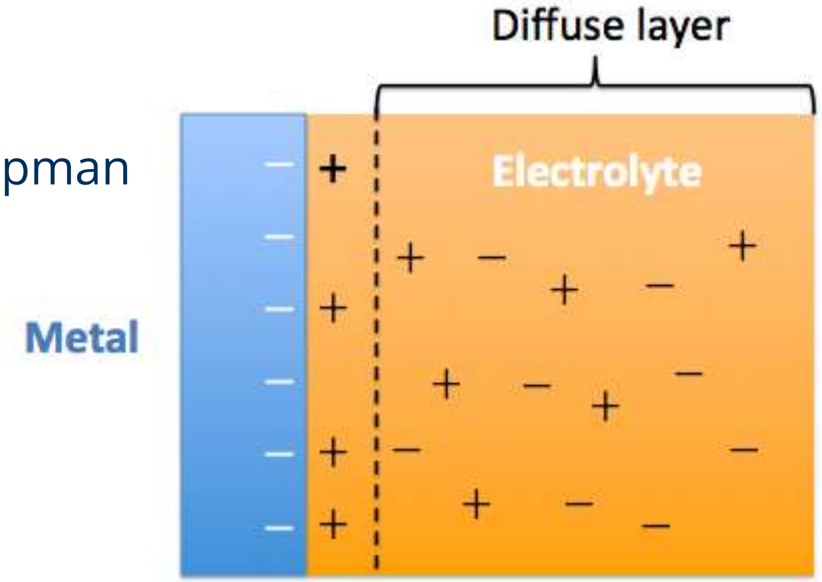

Charge&ion distribution

Helmholtz Theory



$$C = \frac{\varepsilon A}{d}$$

Gouy-Chapman Theory



Poisson-Boltzmann equation

$$\frac{d^2\phi}{dx^2} = \frac{2z^2e^2n_0}{\varepsilon k_B T}\phi$$

$$\phi(x) = \phi_0 e^{-\frac{x}{\lambda_D}}$$

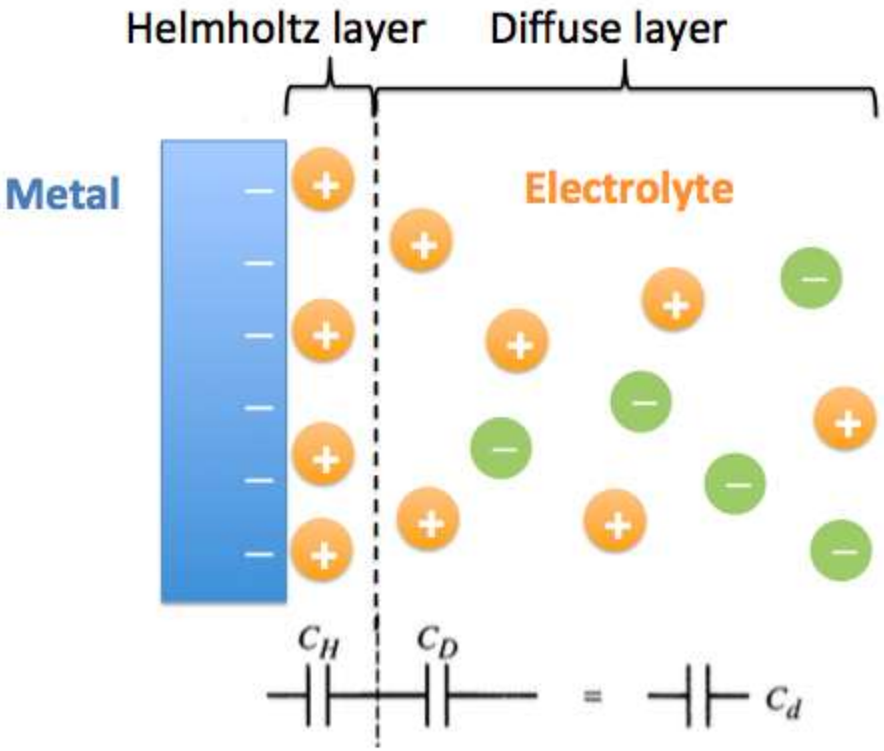
Debye length

$$\lambda_D = \sqrt{\frac{\varepsilon k_B T}{2z^2e^2n_0}}$$

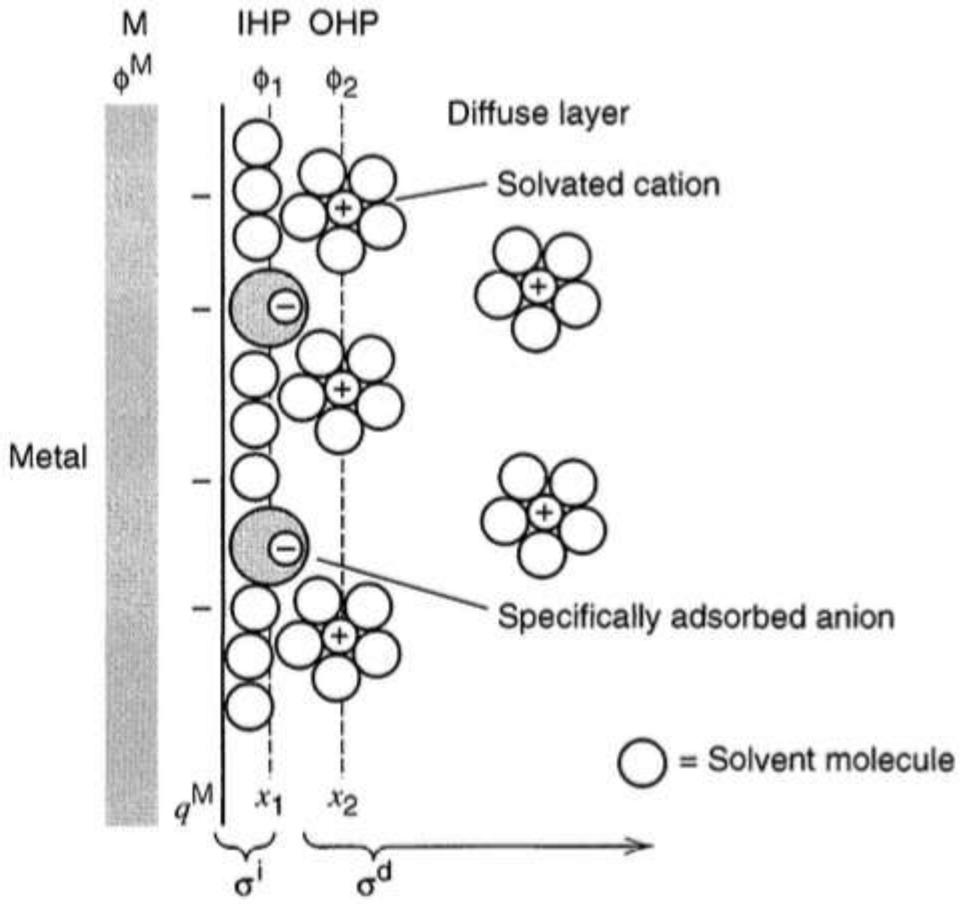
symmetric $z{:}z$ electrolyte

2. Basics of Electrochemistry

2.3 Electrochemical double layer



$$\frac{1}{C_d} = \frac{1}{C_H} + \frac{1}{C_D}$$

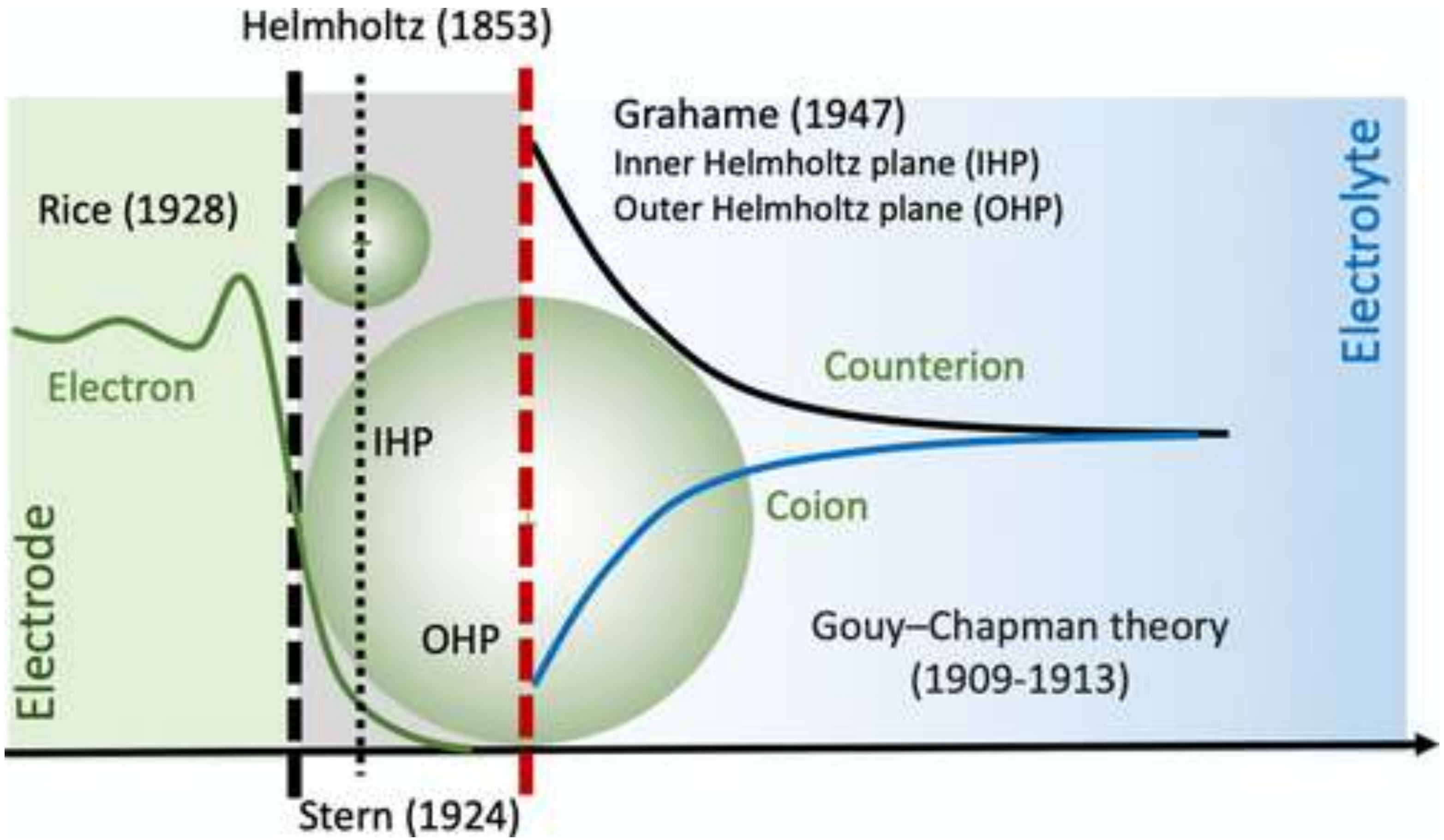


Gouy-Chapman-Stern Theory

Solvation, Adsorption

2. Basics of Electrochemistry

2.3 Electrochemical double layer



Chem. Rev. 2022 , 122 , 12 , 10821–10859

2. Basics of Electrochemistry

2.4 Cyclic Voltammetry

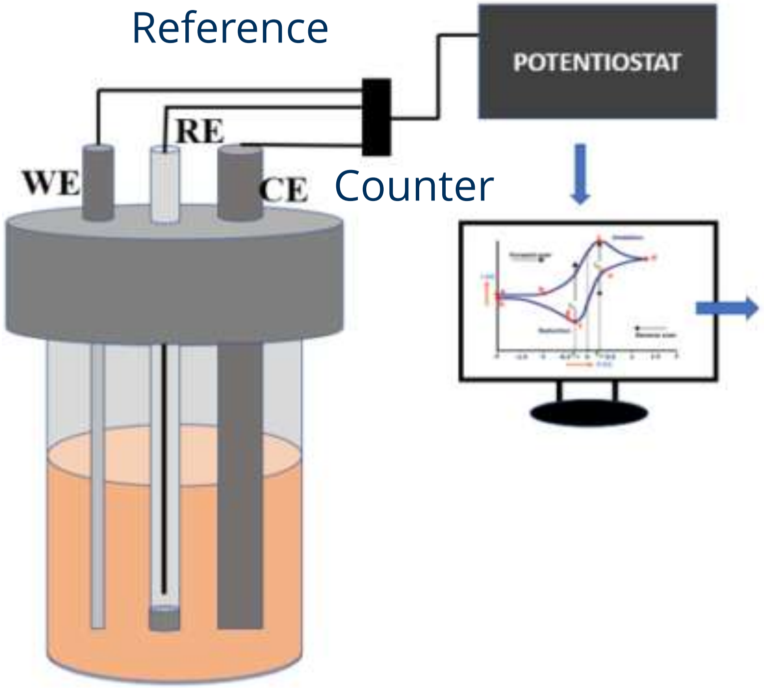
Faradaic current $Ox + ne^- \rightleftharpoons Red$ $i \propto v^{0.5}$

Non-faradaic current $i = C_{dl} v$

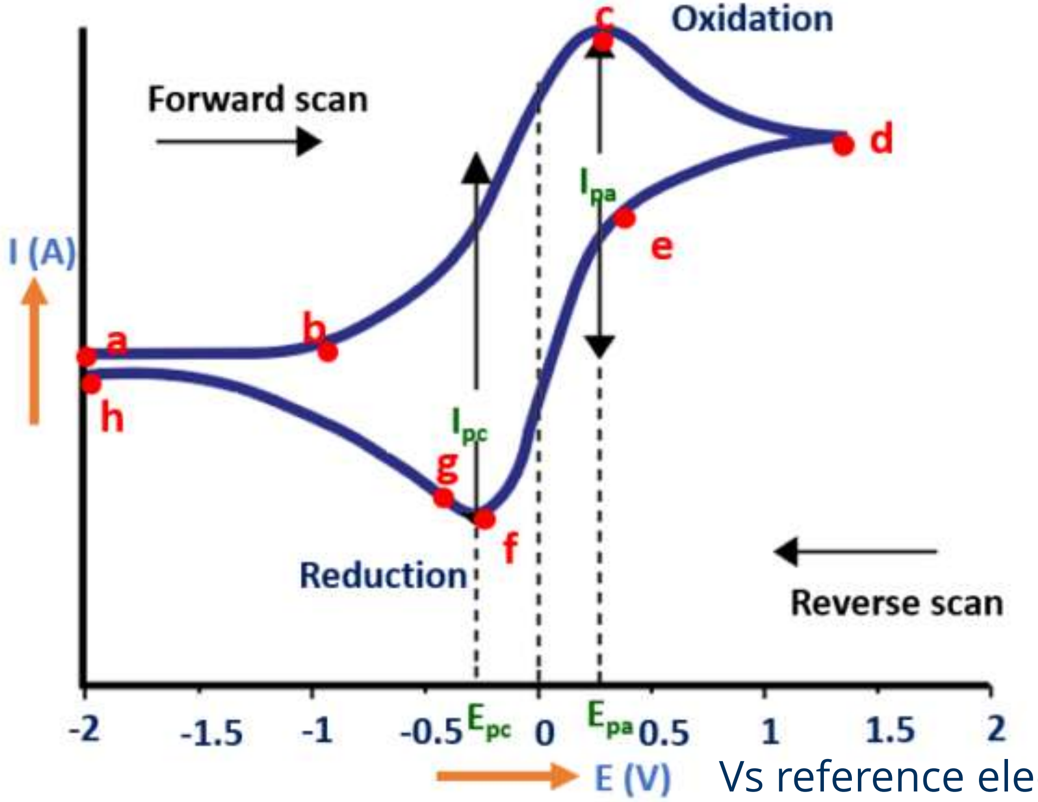
Reference

Working electrode

Counter



three electrode system



Vs reference electrode

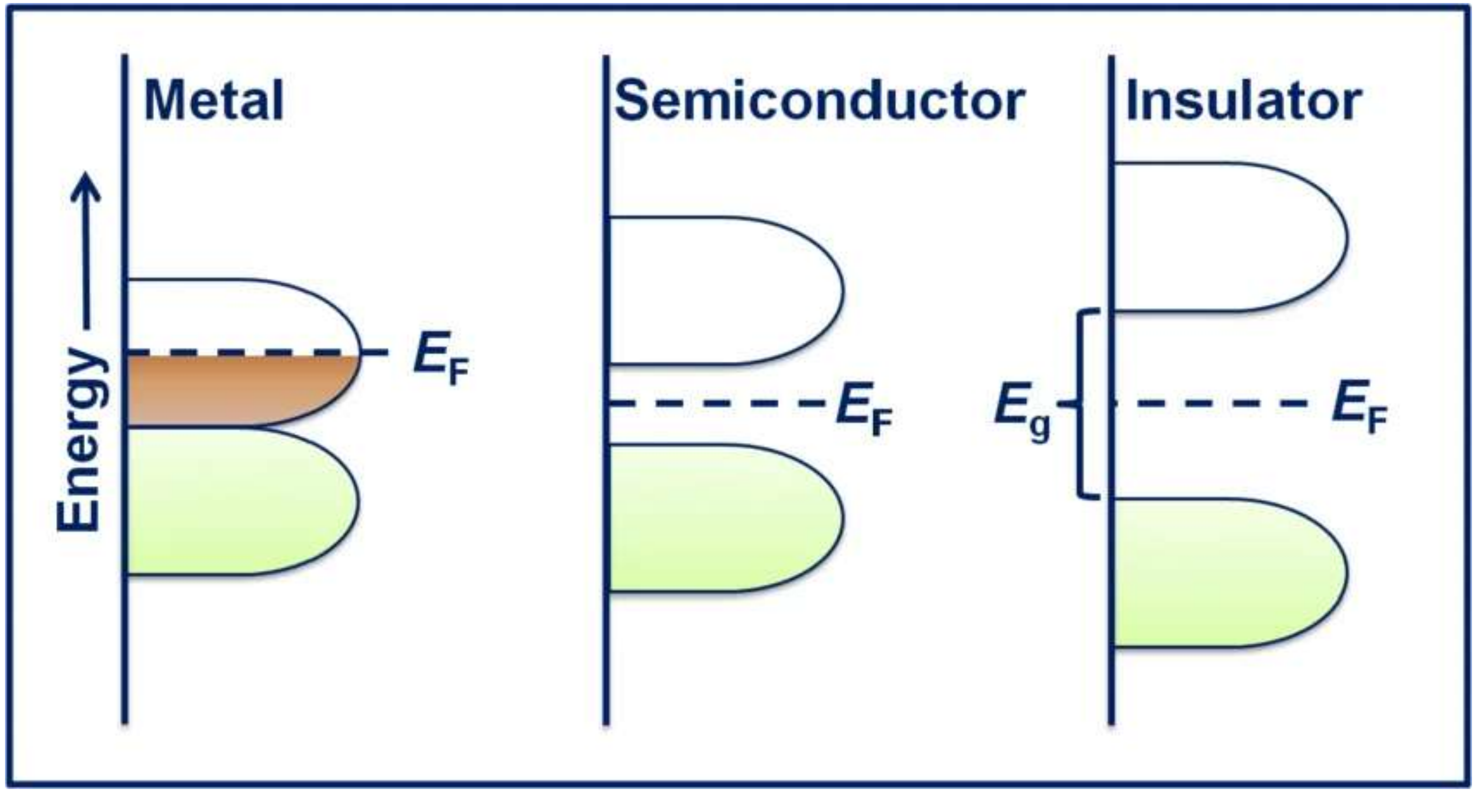
SHE (Standard hydrogen electrode)

Ag/AgCl, +0.197 vs SHE

$Hg_2Cl_2 + 2e^- \rightleftharpoons 2Hg + 2Cl^-$ SCE (Saturated calomel electrode), +0.241 vs SHE

3. Doping

What is doping? Why doping matters?

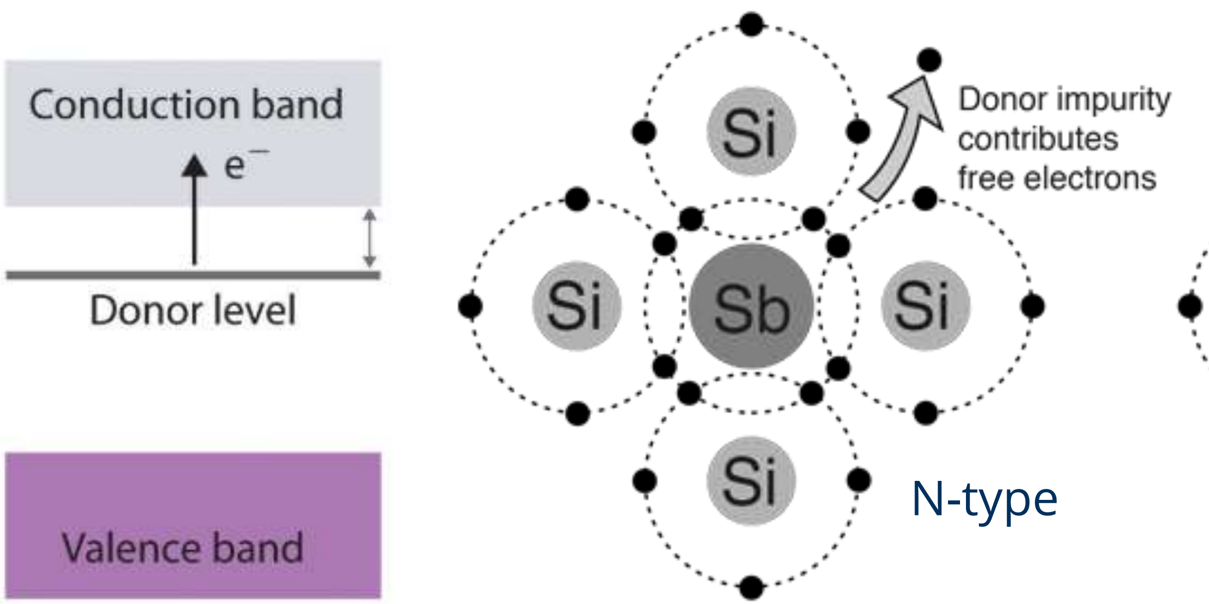


Intrinsic carrier concentration of Si at 300 K: n_i~ 10^{10} cm^{-3}, σ~3*10^{-6} S/cm

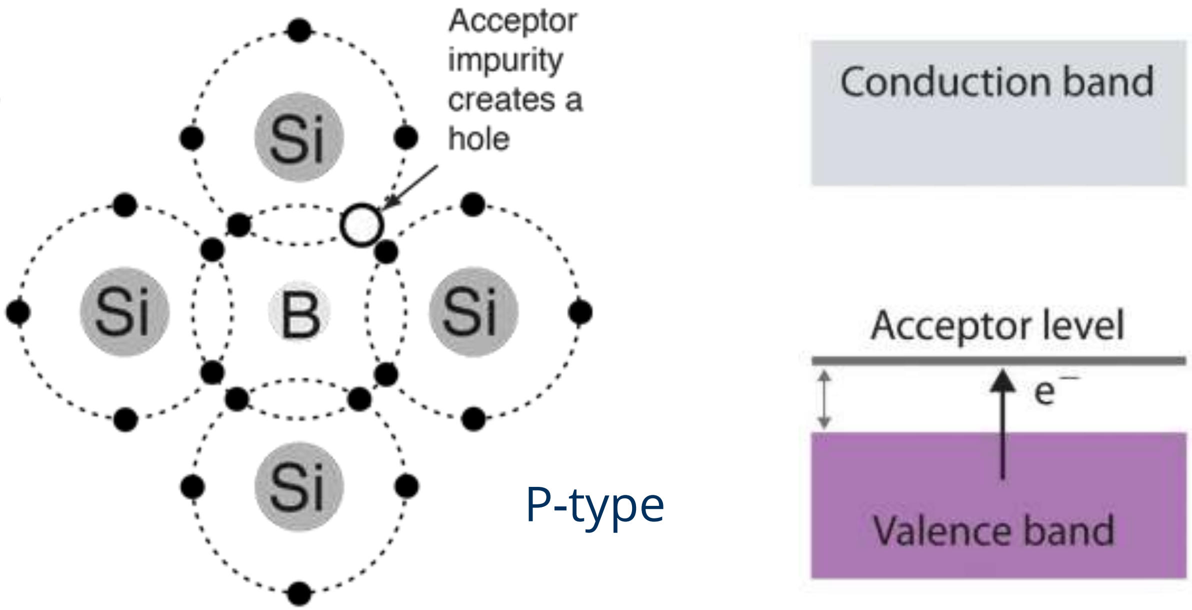
3. Doping

3.1 Doping in inorganic semiconductors

Substitutional (Atomic) doping



N-type



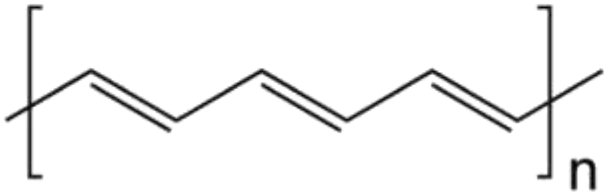
P-type

carrier concentration of doped Si at 300 K

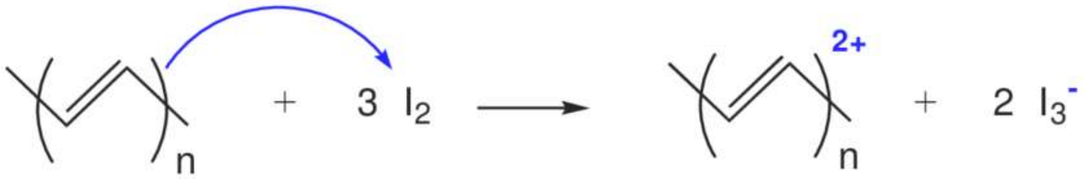
N-doping: N 10^{15} ~ 10^{17} cm^{-3}, σ 0.22~22 S/cm
P-doping: N 10^{15} ~ 10^{17} cm^{-3}, σ 0.077~7.7 S/cm

3. Doping

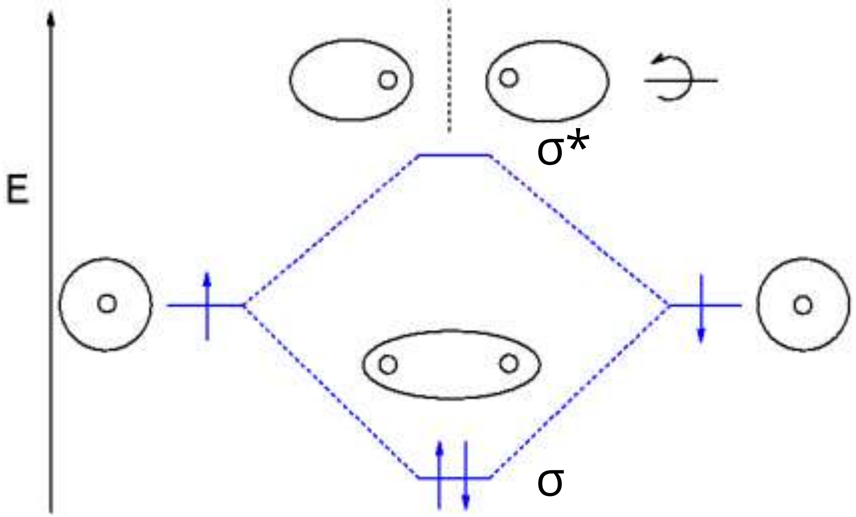
3.2 Orbital and Band structure of OSC



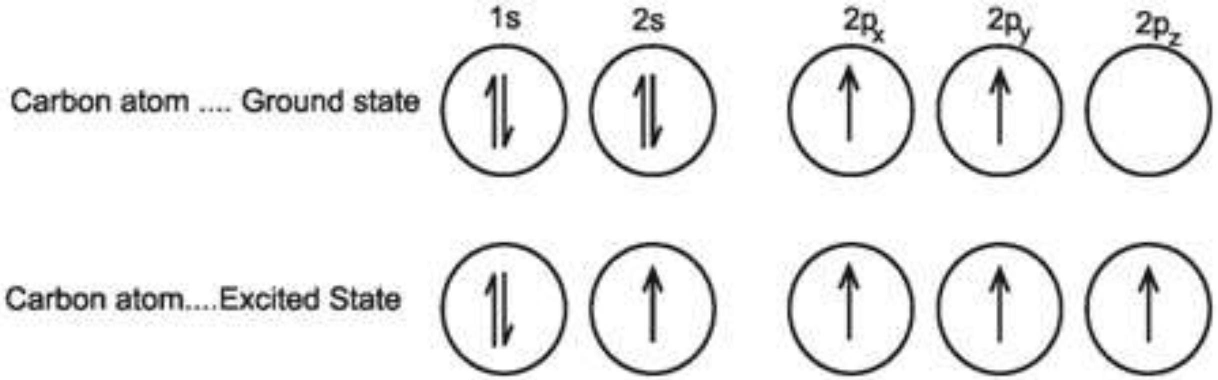
polyacetylene



Conducting polymer
2000 Nobel Prize in Chemistry
Hideki Shirakawa, Alan MacDiarmid and Alan Heeger



H molecular orbital



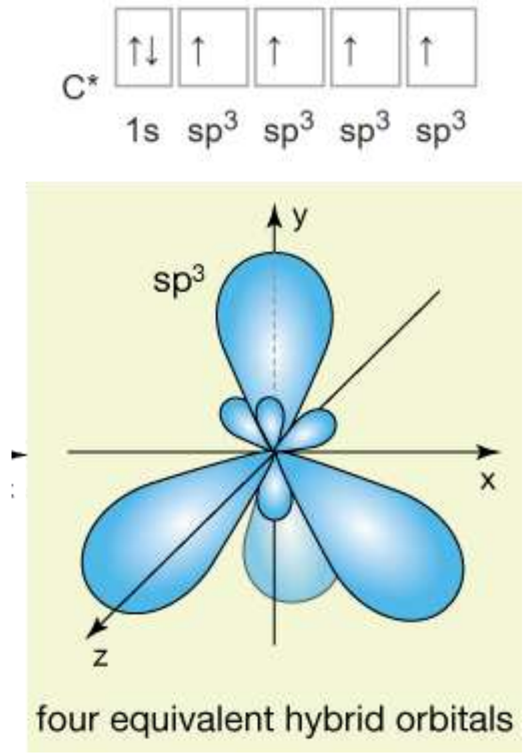
C atomic orbital

Linear combination of atomic orbitals into molecular orbital

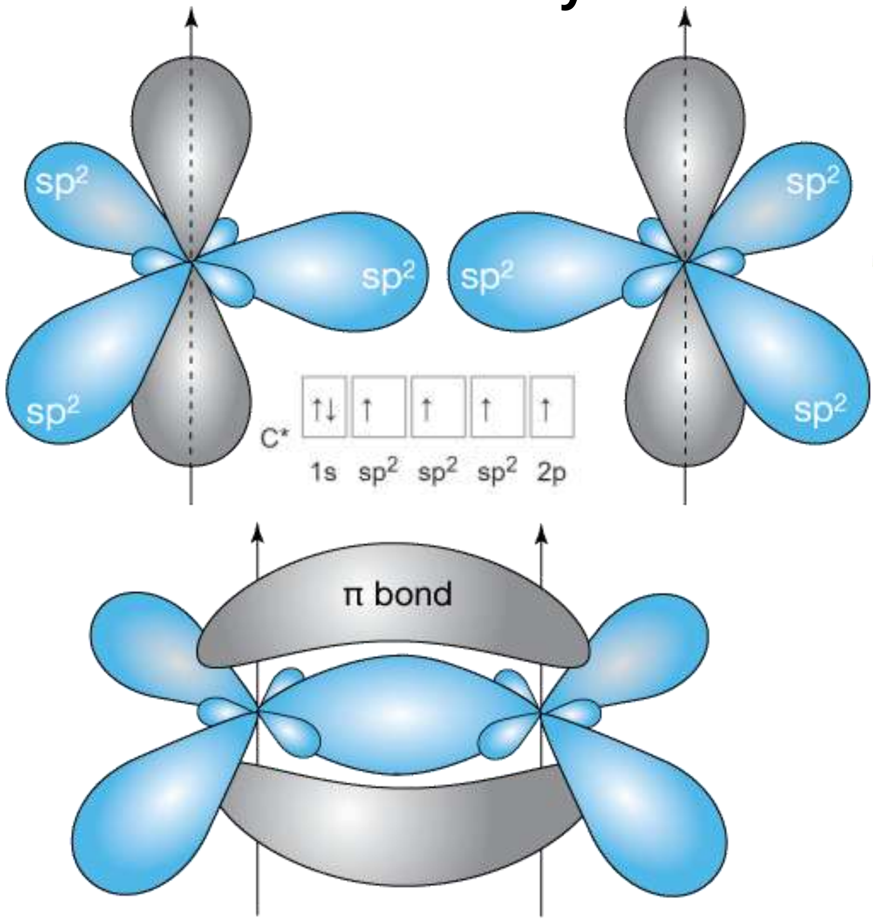
3. Doping

3.2 Orbital and Band structure of OSC

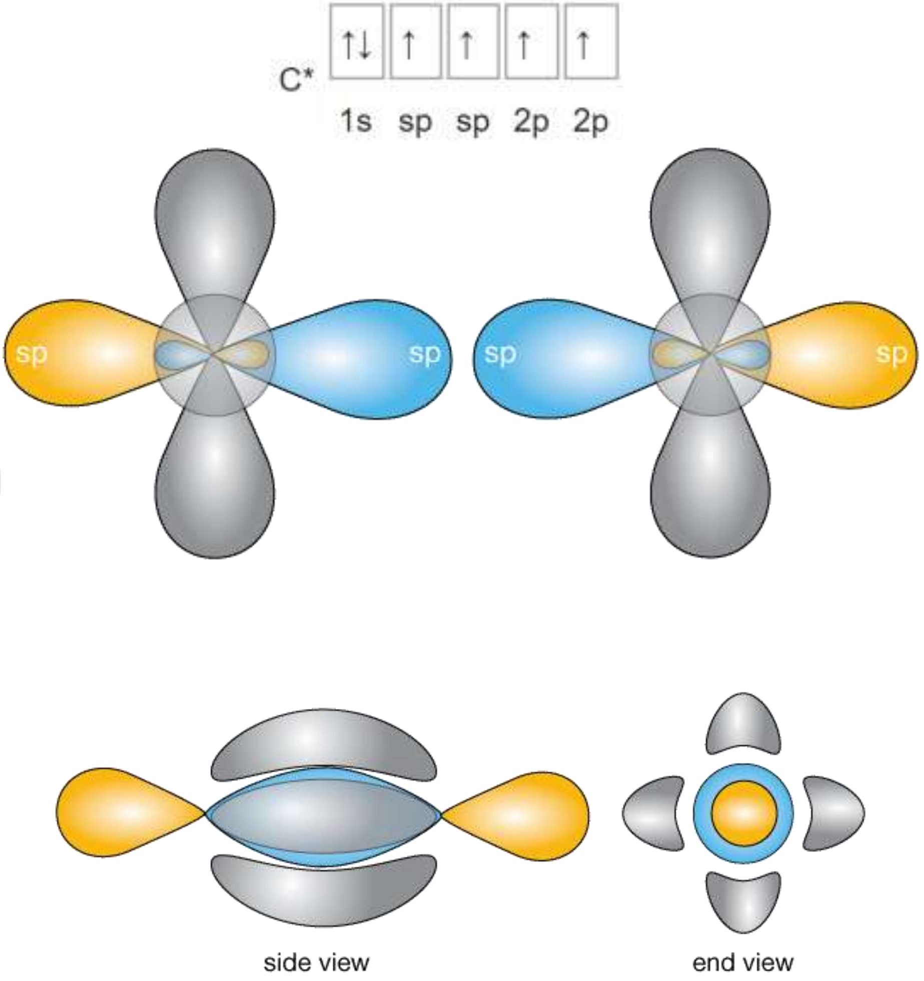
Orbital Hybridization



CH4



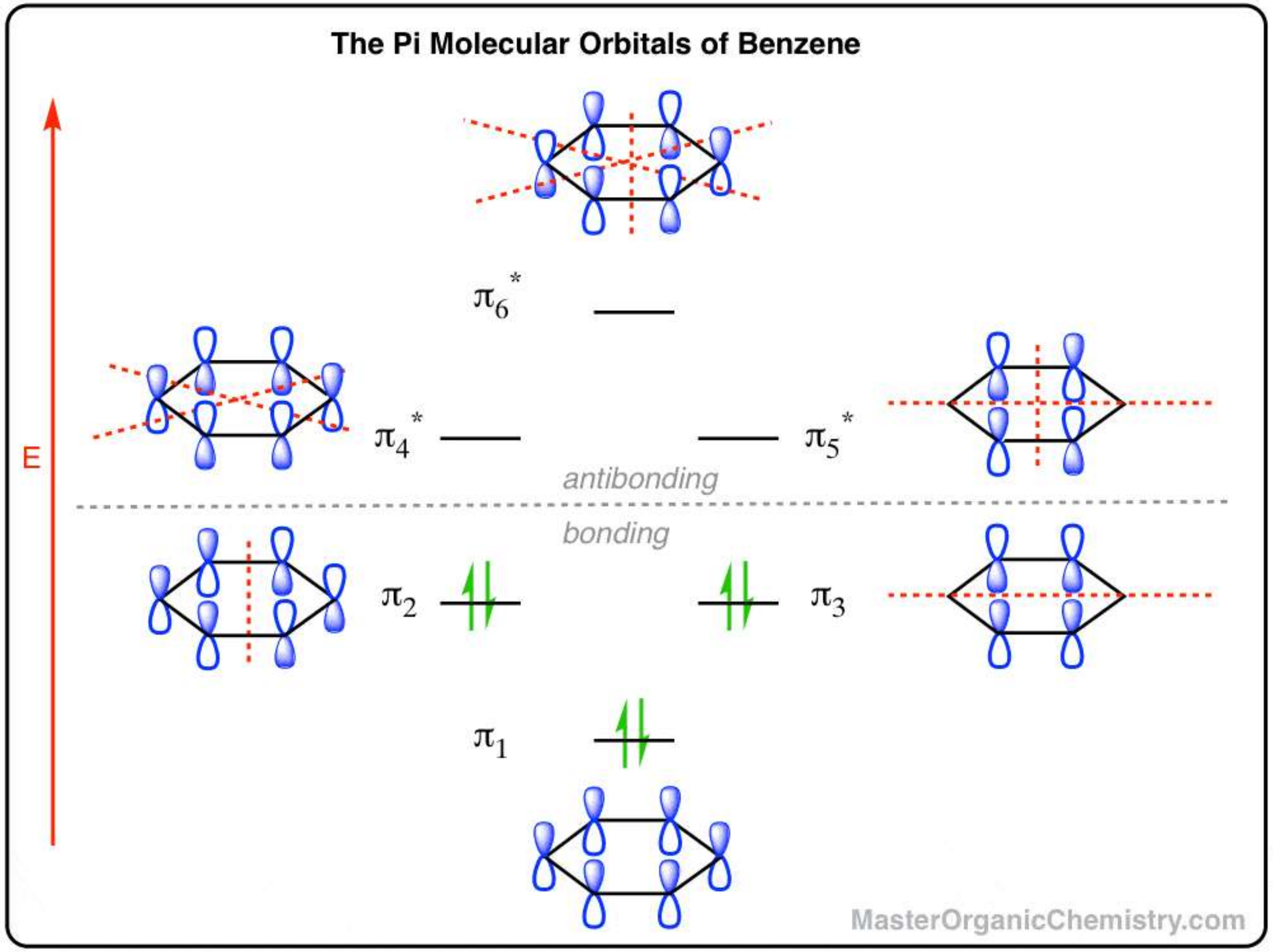
CH2=CH2

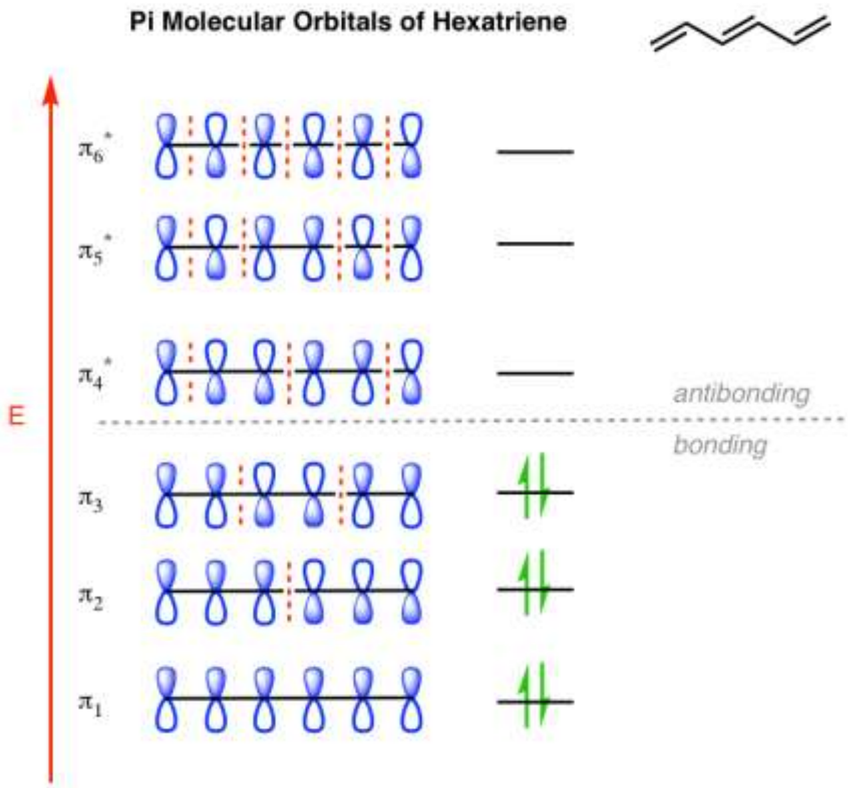


CH≡CH

3. Doping

3.2 Orbital and Band structure of OSC



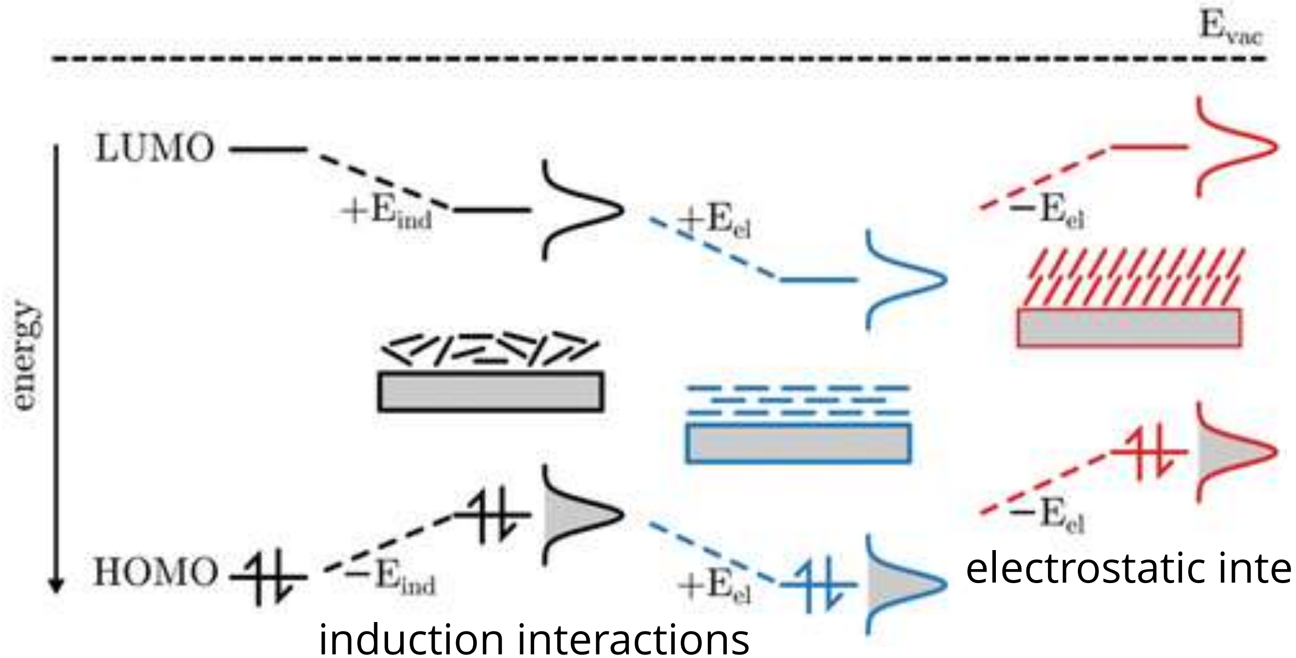


https://www.masterorganicchemistry.com/2017/05/05/the-pi-molecular-orbitals-of-benzene/

3. Doping

3.2 Orbital and Band structure of OSC

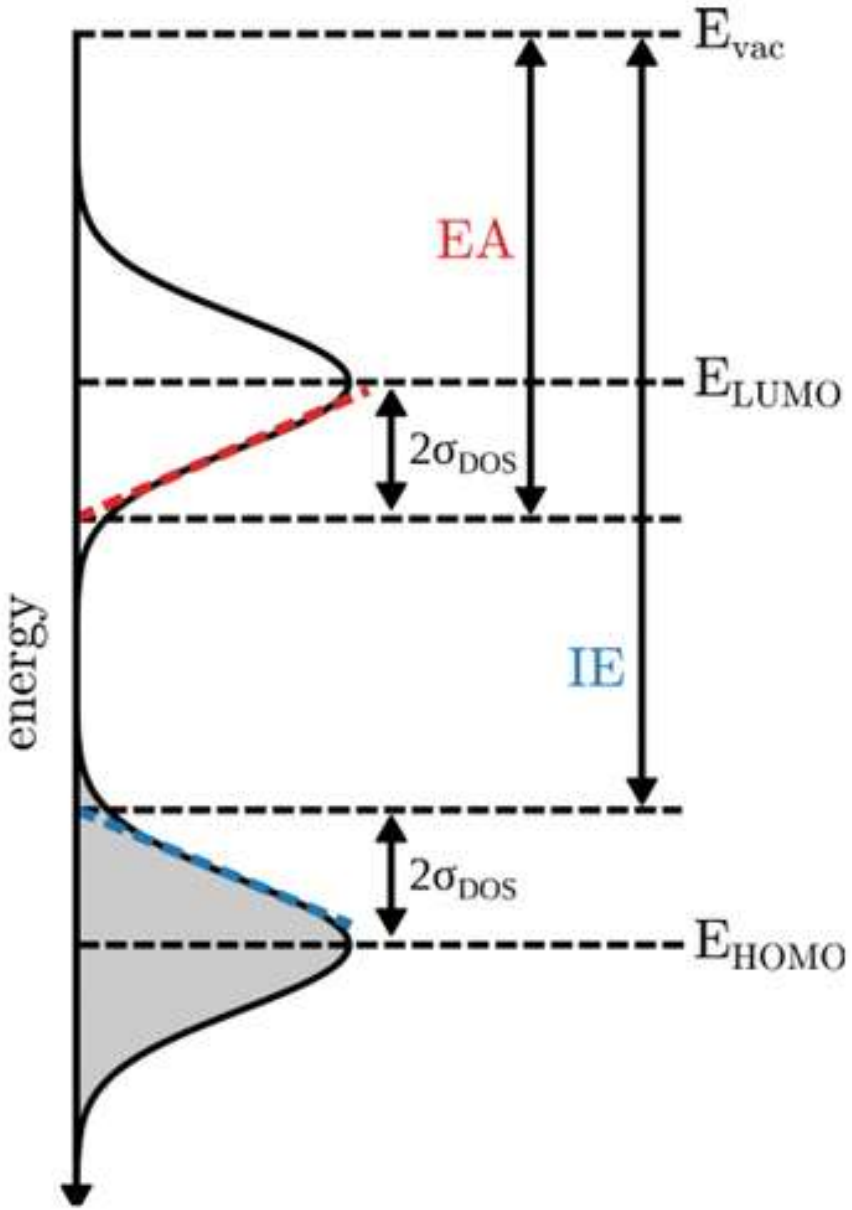
Molecular Orbital and Band structure for OSC



induction interactions

electrostatic interactions

LUMO: lowest unoccupied molecular orbital
HOMO: highest occupied molecular orbital
EA: electron affinity
IE: ionization energy



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3. Doping

3.3 Molecular doping

What are the differences between organic and inorganic semiconductors?

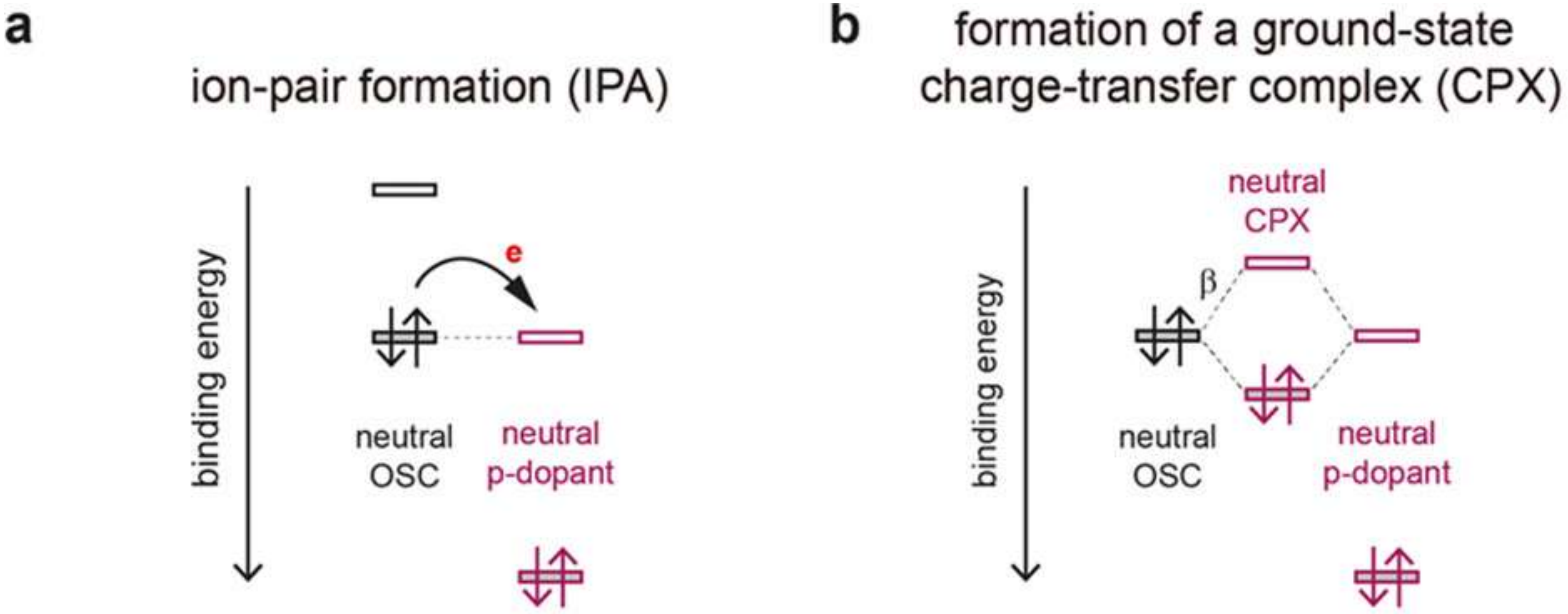
Inorganic	Organic
Strong covalent/ionic bonding	Intramolecular: strong covalent bonding Intermolecular: weak interactions
Typically crystalline	Often polycrystalline or amorphous
Rigid and brittle	Flexible
High carrier mobility	Lower carrier mobility
Band transport dominates	Hopping or mixed transport
High temperature/vacuum processing	Solution processable, low temperature fabrication possibility
…	…

Atomic doping

Molecular/Chemical doping

3. Doping

3.3 Molecular doping



Draw n-doping

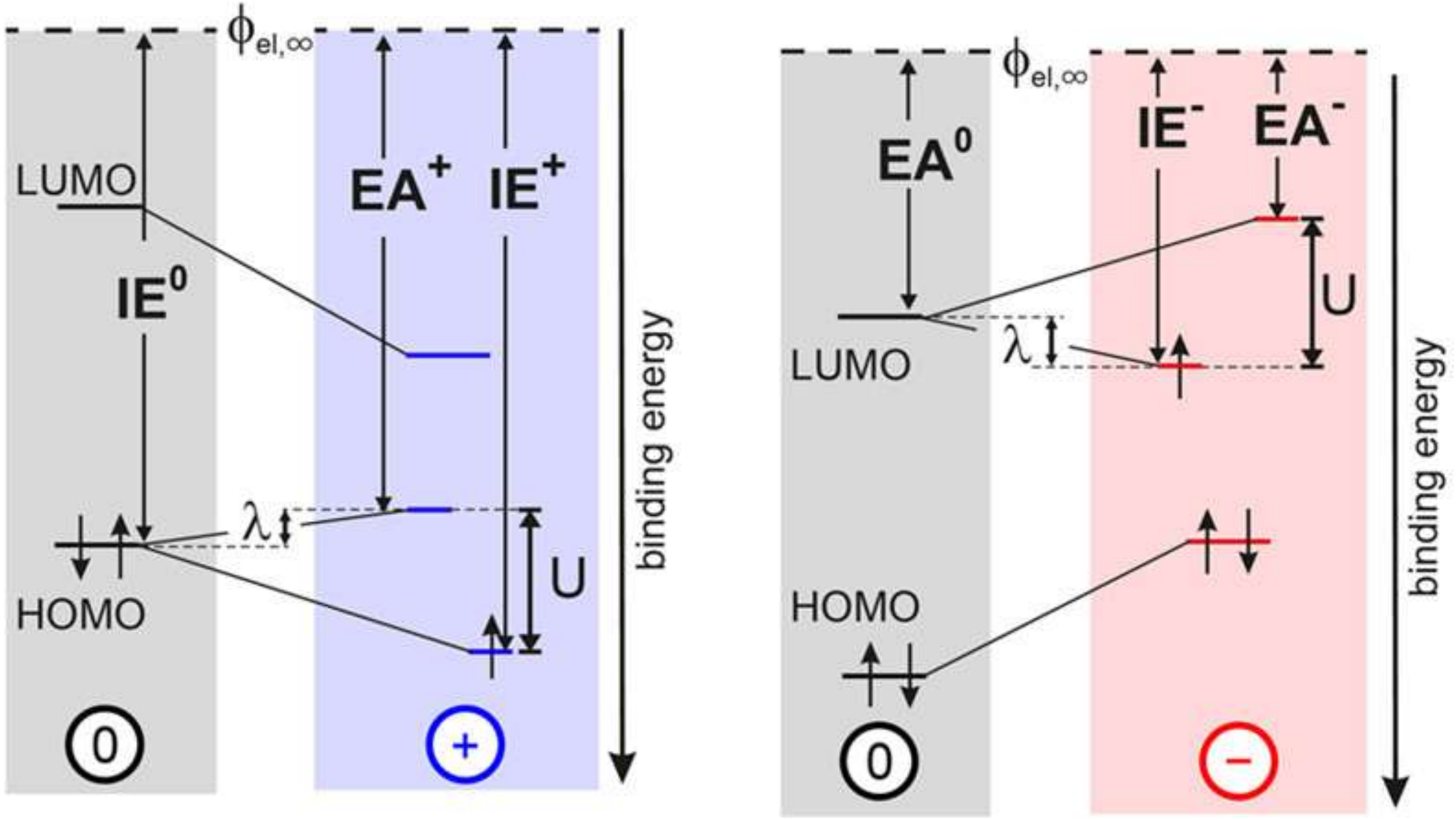
Acc. Chem. Res. 2016 , 49 , 3 , 370–378

3. Doping

3.3 Molecular doping

IPA Integer charge transfer **ICT**

Isolated molecule



λ: reorganization energy
U: Hubbard (Coulomb interaction)

occupied and unoccupied HOMO/LUMO-derived sublevels split

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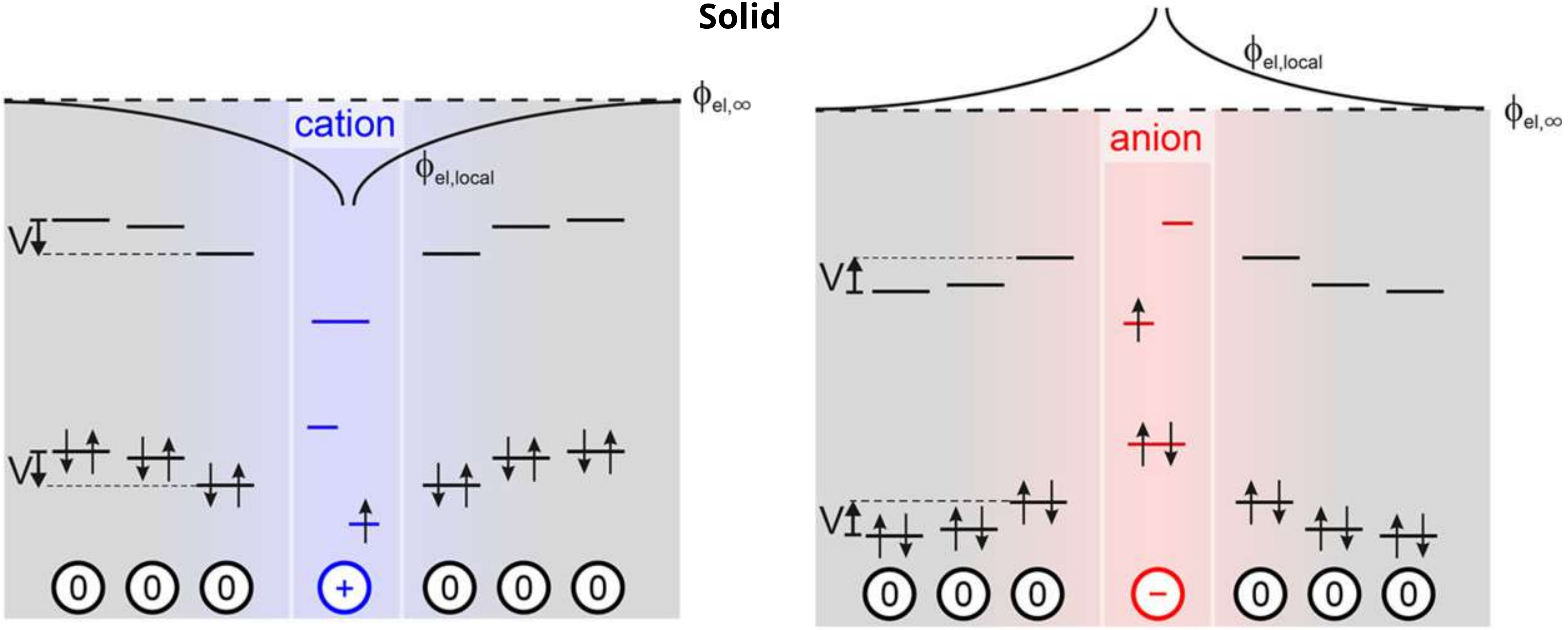
3. Doping

3.3 Molecular doping

IPA Integer charge transfer

Solid



Polaron: quasiparticles formed by the correlation between electron and lattice distortion

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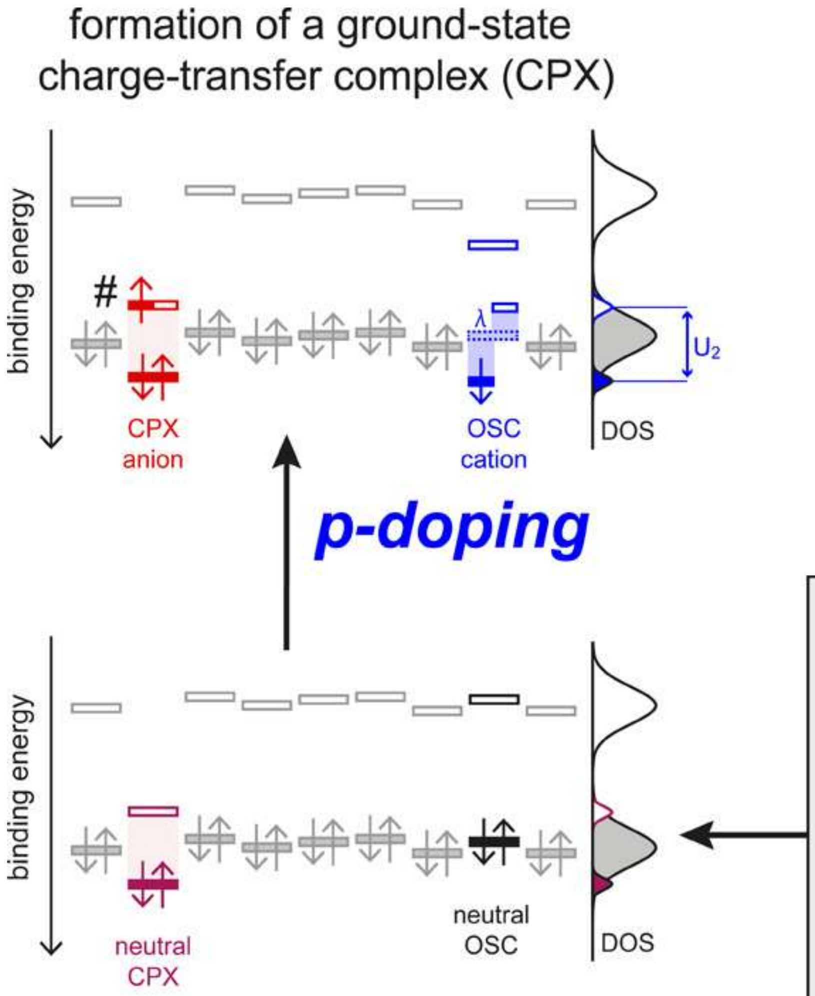
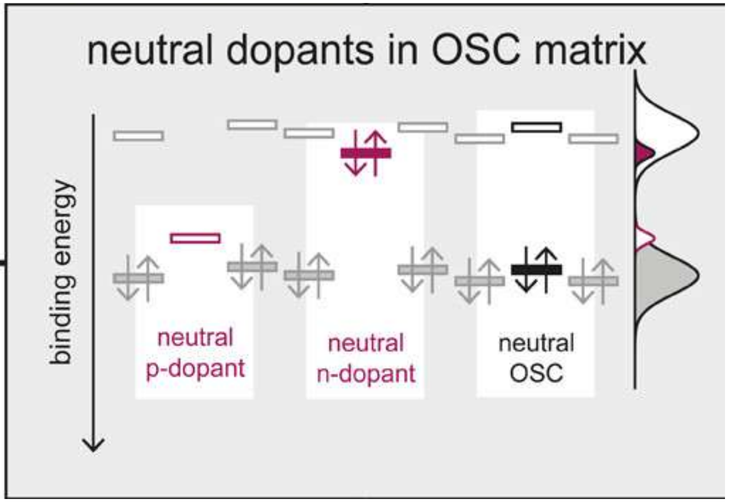
3. Doping

3.3 Molecular doping





CTC

CPX Fractional/partial charge transfer

$$E_{CPX,H/L} = \frac{H_{OSC} + L_{dop}}{2} \pm \sqrt{(H_{OSC} - L_{dop})^2 + 4\beta^2}$$

β: resonance integral

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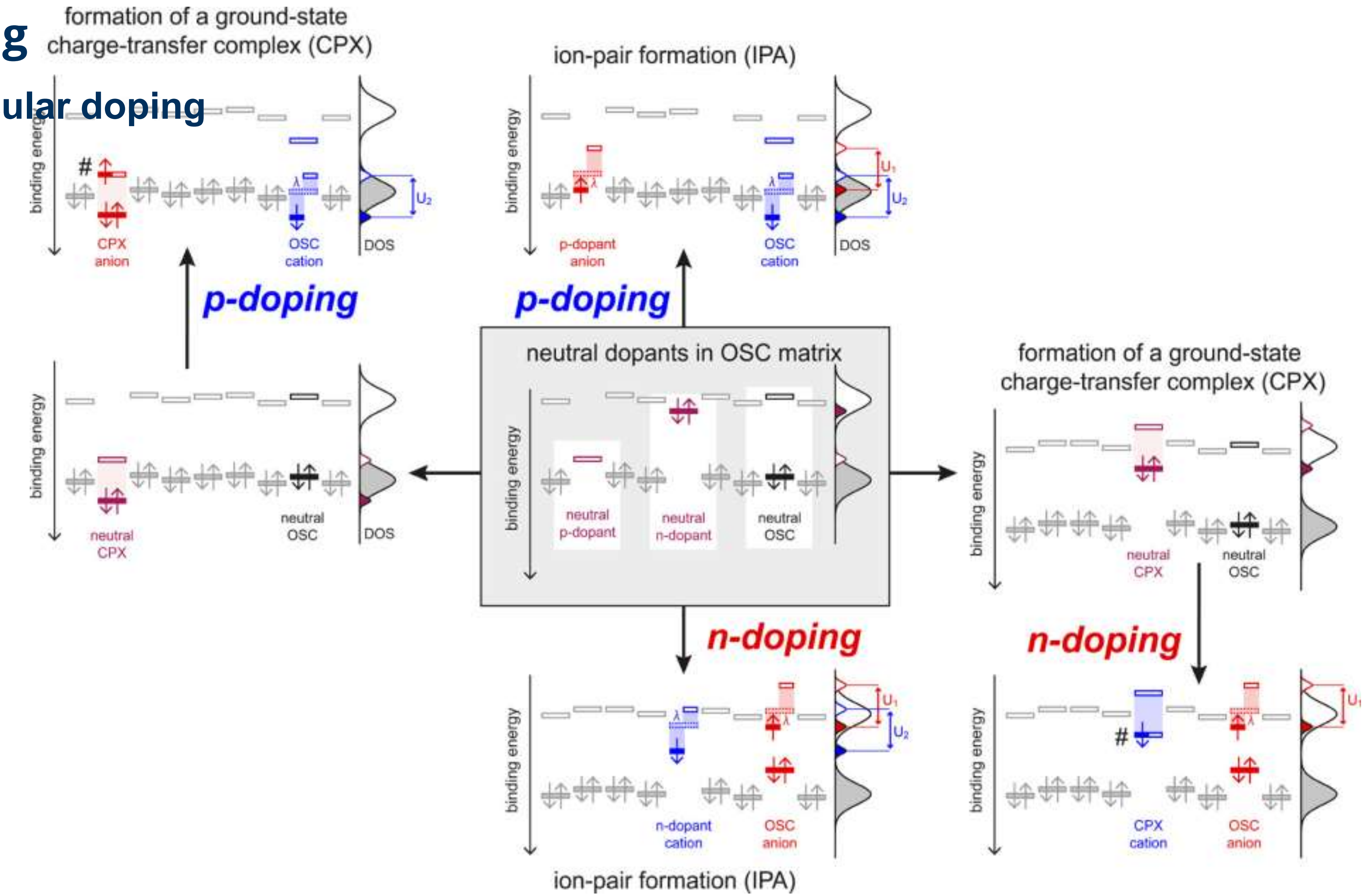
3. Doping

3.3 Molecular doping



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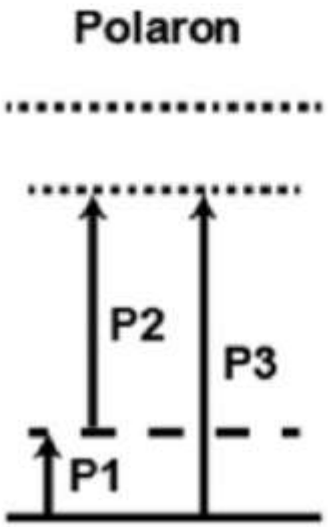
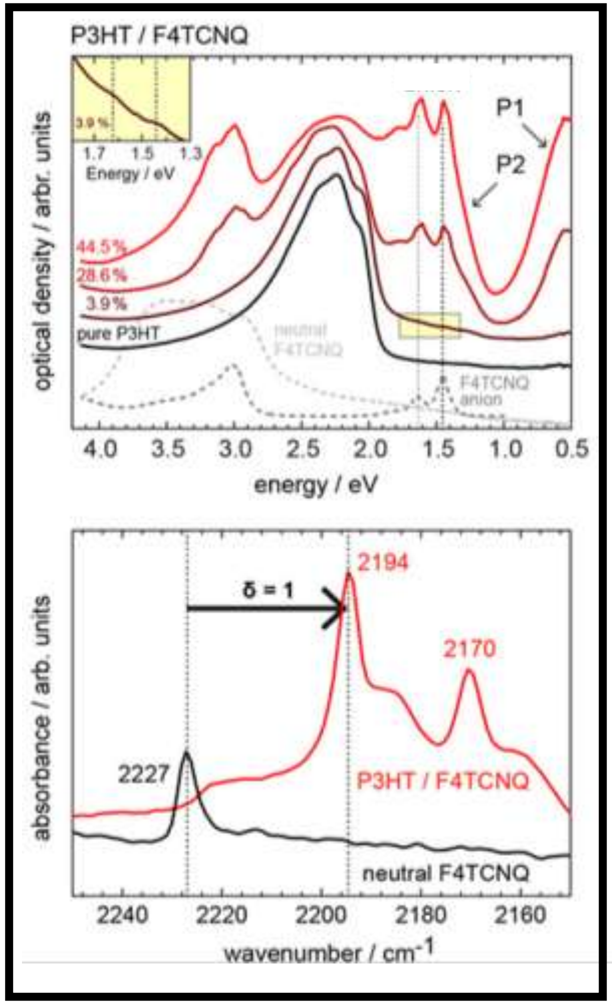
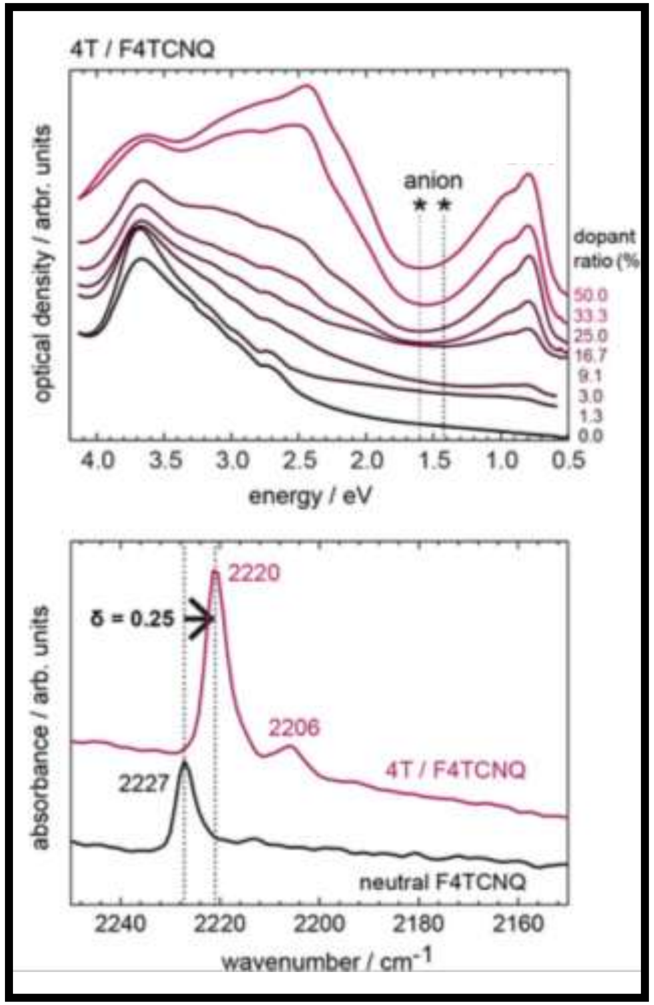
3. Doping

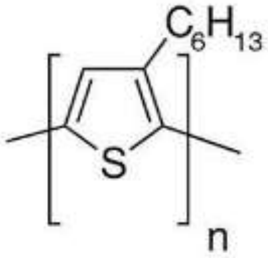
3.3 Molecular doping

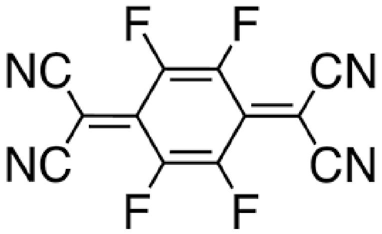
IPA or CPX?

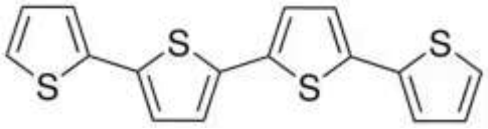












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3. Doping

3.3 Molecular doping

Doping efficiency

$$\eta_{doping} = \eta_{ionization} \times \eta_{dissociation} = \frac{N_{free}}{N_{dopant}}$$

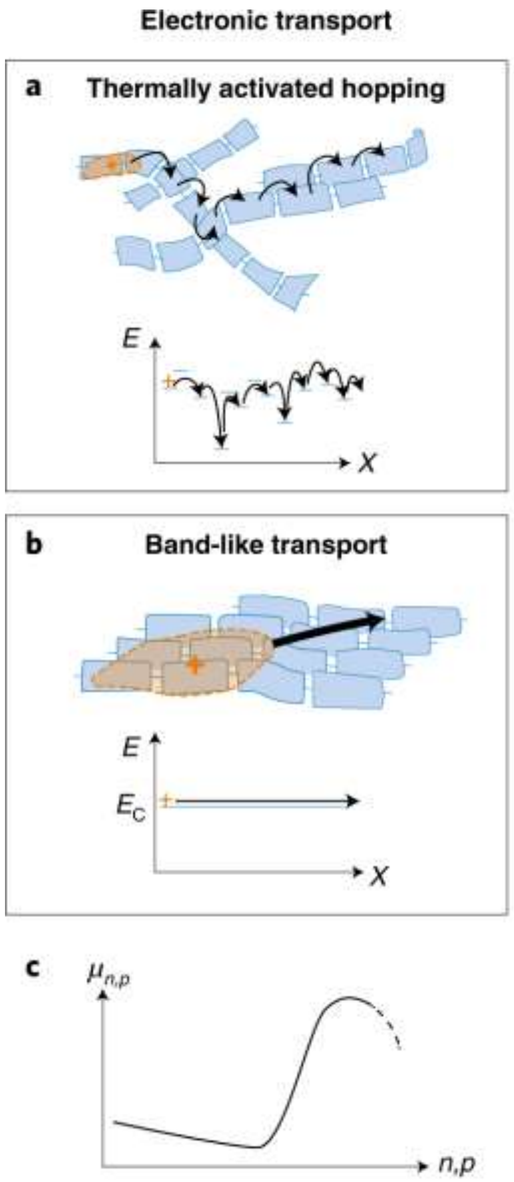
Dopant: energy level, size, ratio
Method: film morphology
…

Carrier transport

$$\mu = \frac{|J_{if}|}{\hbar}\sqrt{\frac{\pi}{\lambda kT}}\exp(\frac{-\lambda}{4kT})\frac{ea^2}{kT}$$

Marcus theory

J: intermolecular transfer integral (electronic coupling)
λ: reorganization energy



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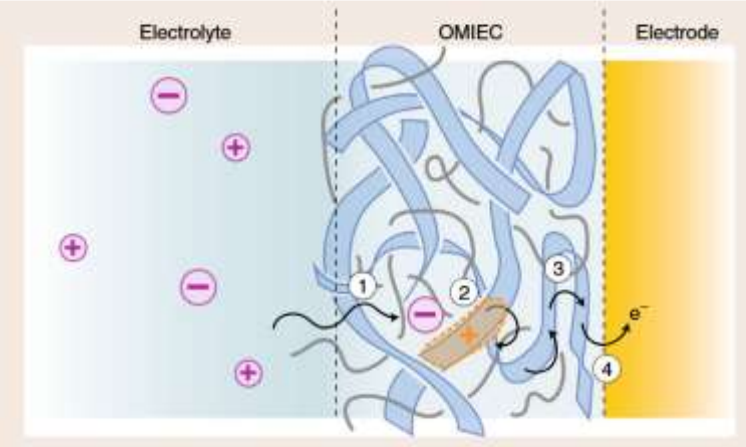
3. Doping

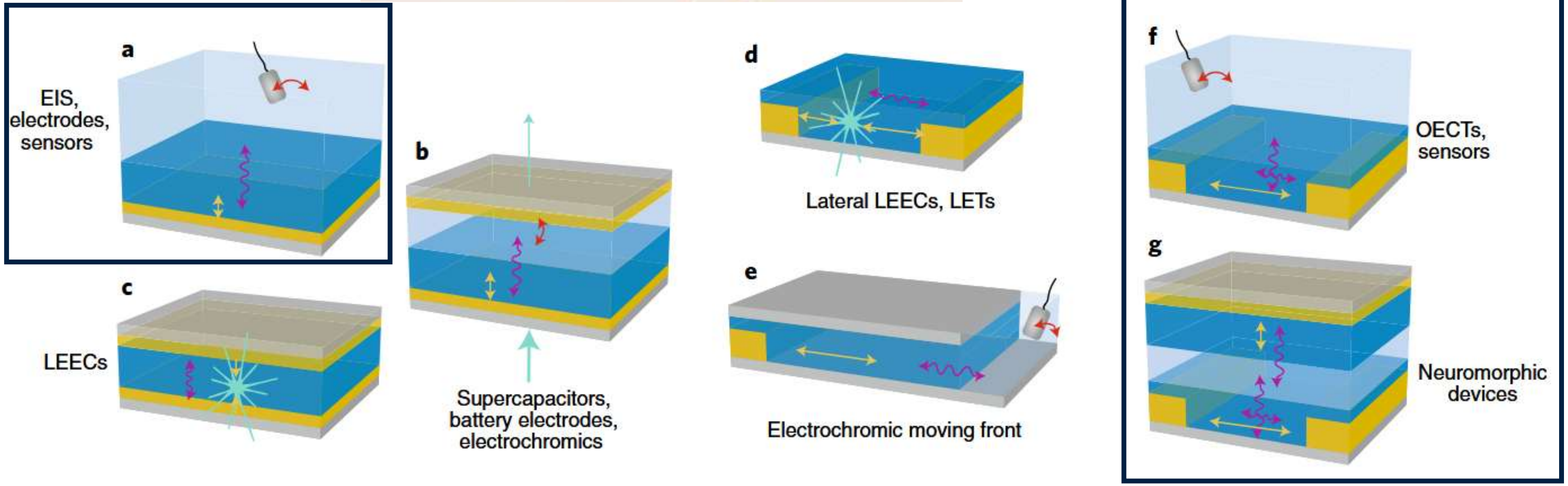
3.4 Electrochemical doping

Electrochromic
Boeing 787



OMIEC
organic mixed ionic–electronic conductors

$$P^0 + C^+ + e^- \leftrightarrow P^- \left(C^+\right) \quad \text{or} \quad P^0 + A^- + h^+ \leftrightarrow P^+ \left(A^-\right)$$



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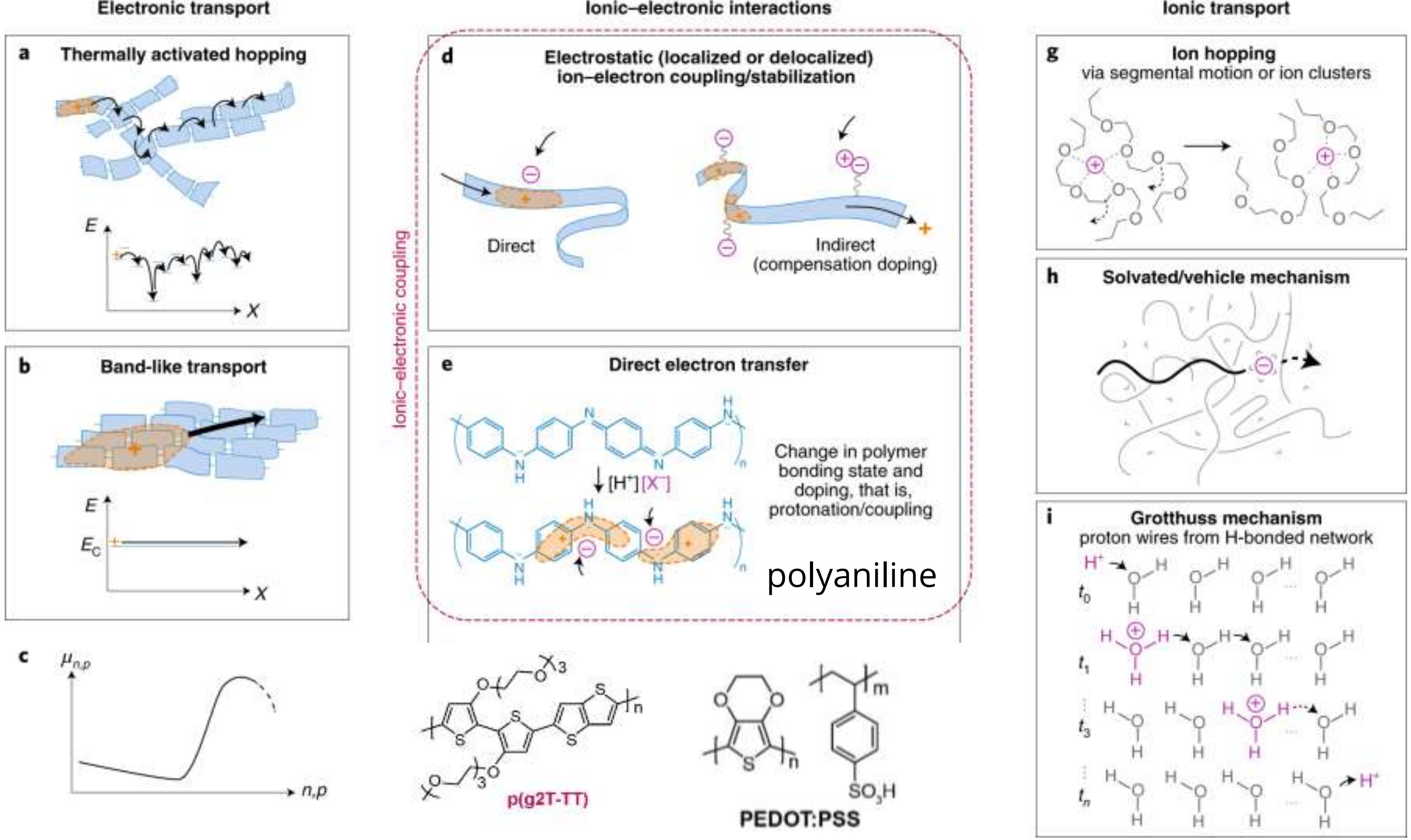
3. Doping

3.4 Electrochemical doping

Ionic-electronic coupling



polyaniline

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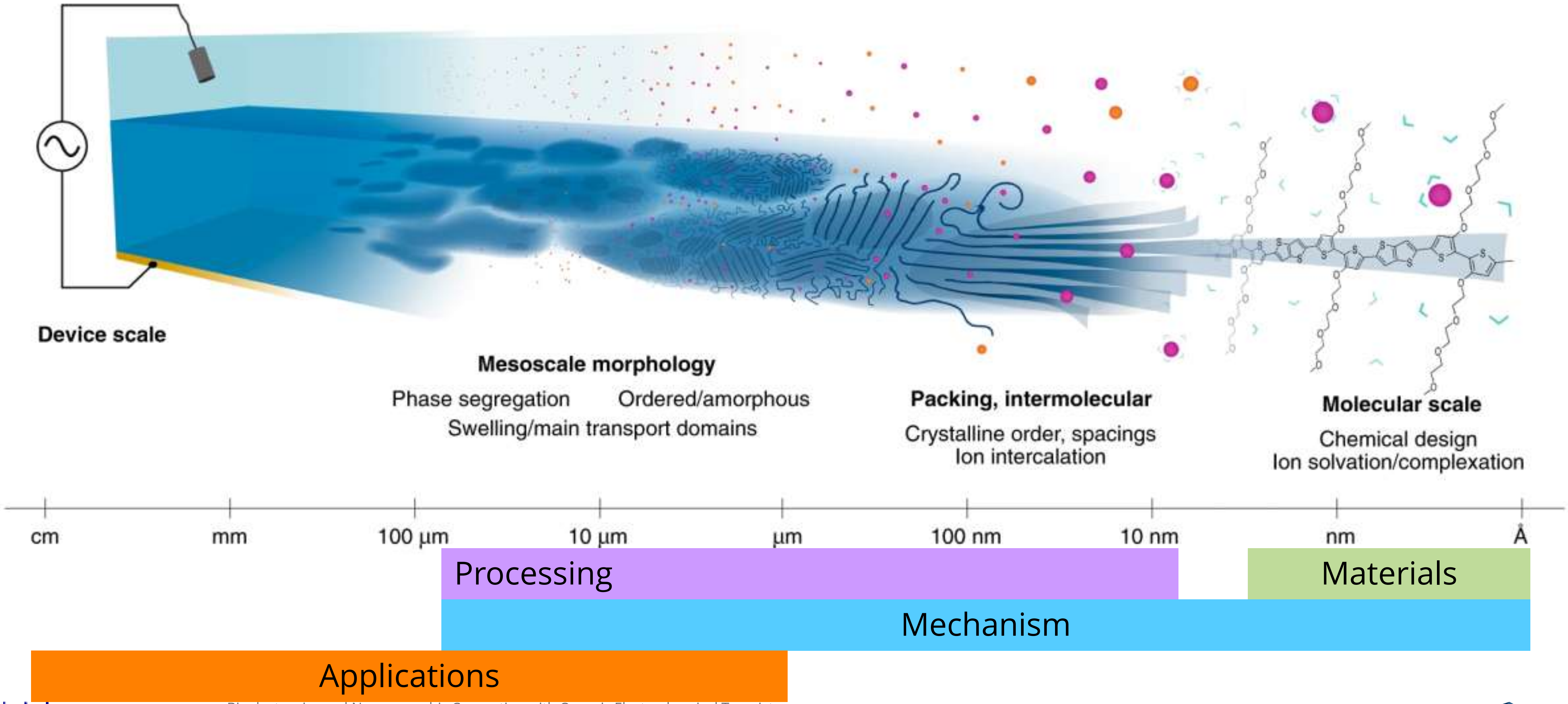
3. Doping

3.4 Electrochemical doping



Processing

Materials

Mechanism

Applications

Nat. Mater. 19, 13–26 (2020)