



ORGANIC ELECTRONICS

Principles, devices and applications

Metal Organic interfaces

D. Natali

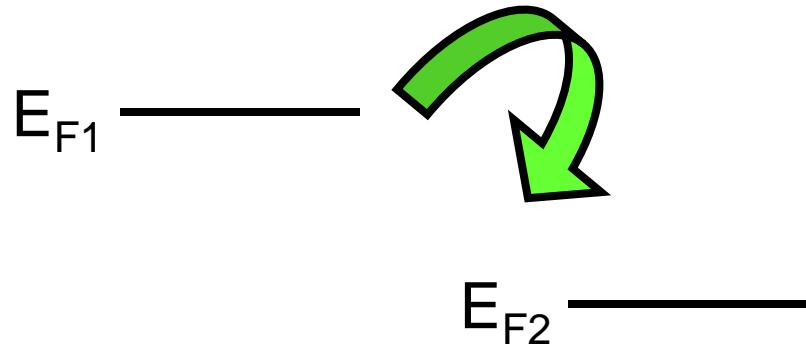
Milano, 23-27 Novembre 2015

Outline

- general concepts
- energetics
- Interfaces: tailoring
- injection mechanisms

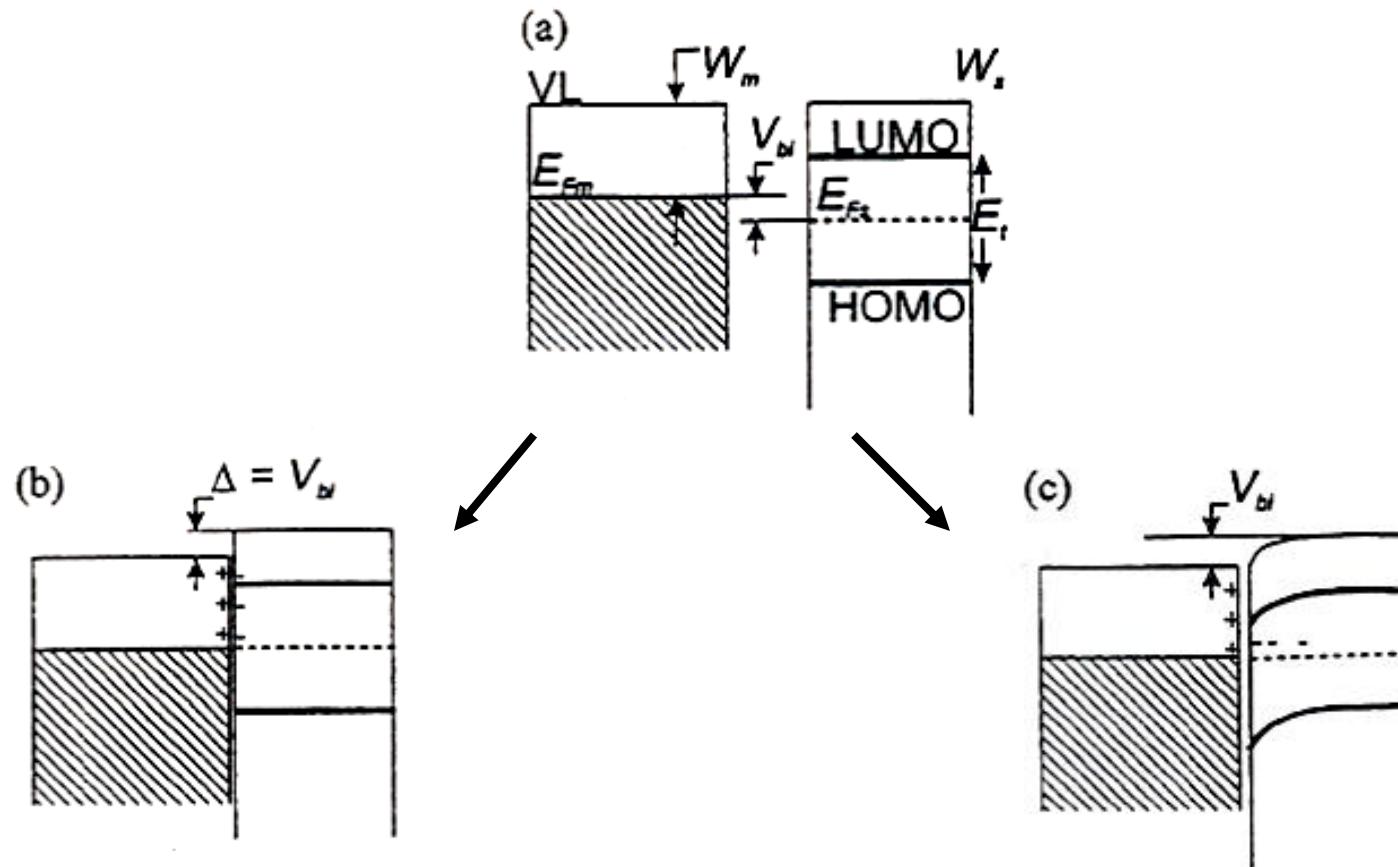
Thermal Equilibrium (1)

@Thermal Equilibrium a common Fermi level is established
by means of *charge transfer*...



..from higher lying to lower lying Fermi level

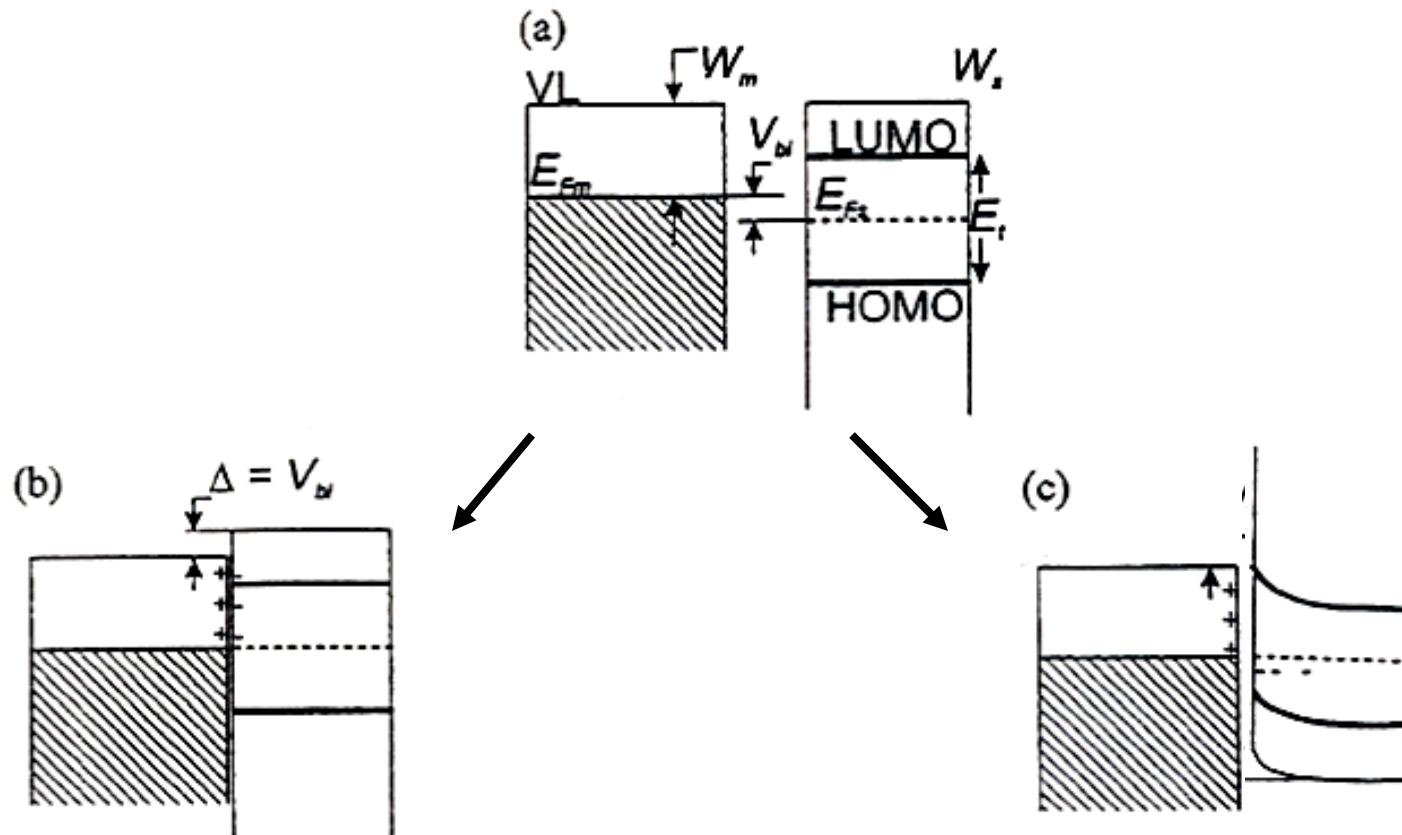
Thermal Equilibrium (2)



Interface dipole layer

Space charge region

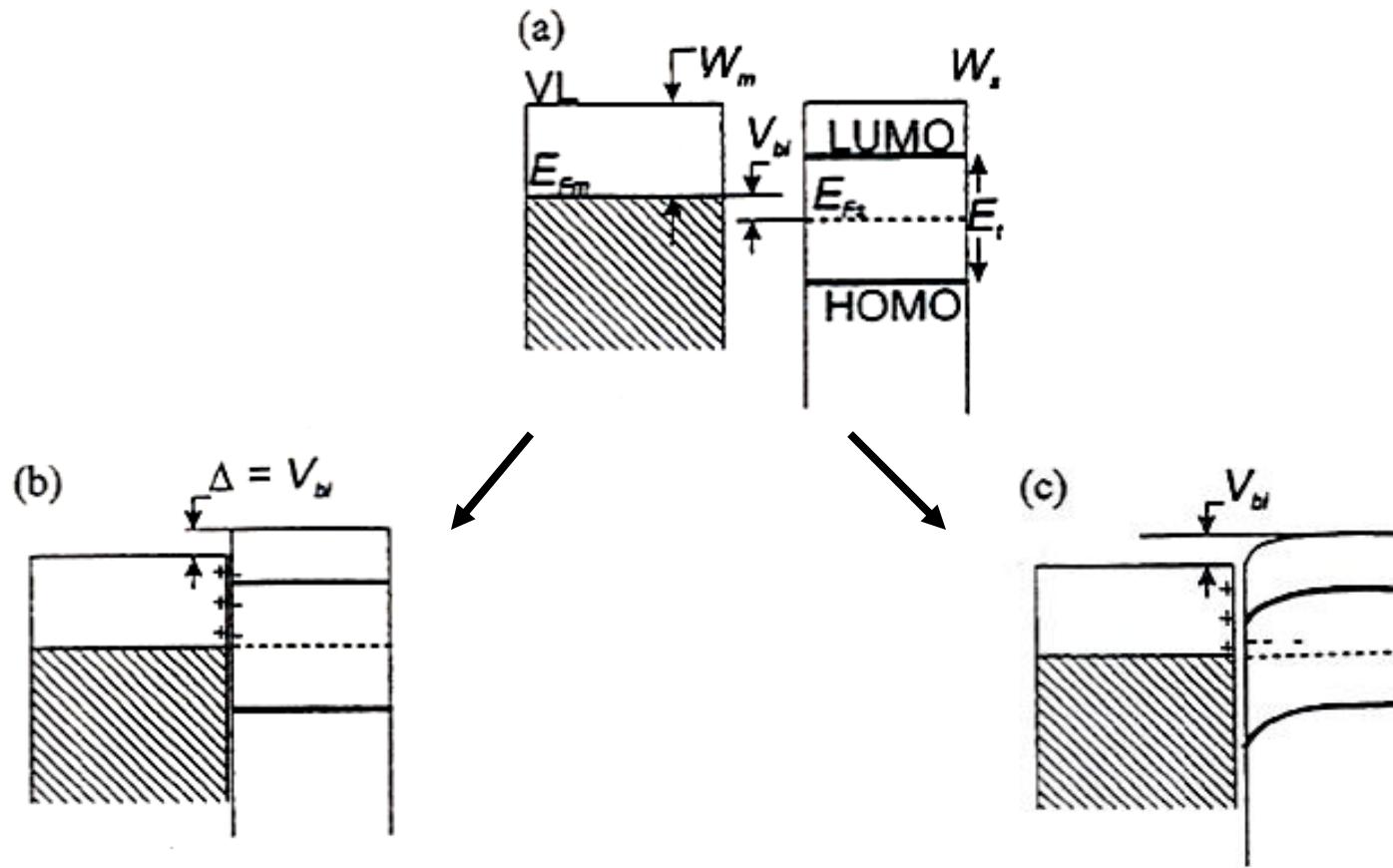
Thermal Equilibrium (2)



Interface dipole layer

*Depleted, poorly conductive
(poorer than bulk)
space charge region*

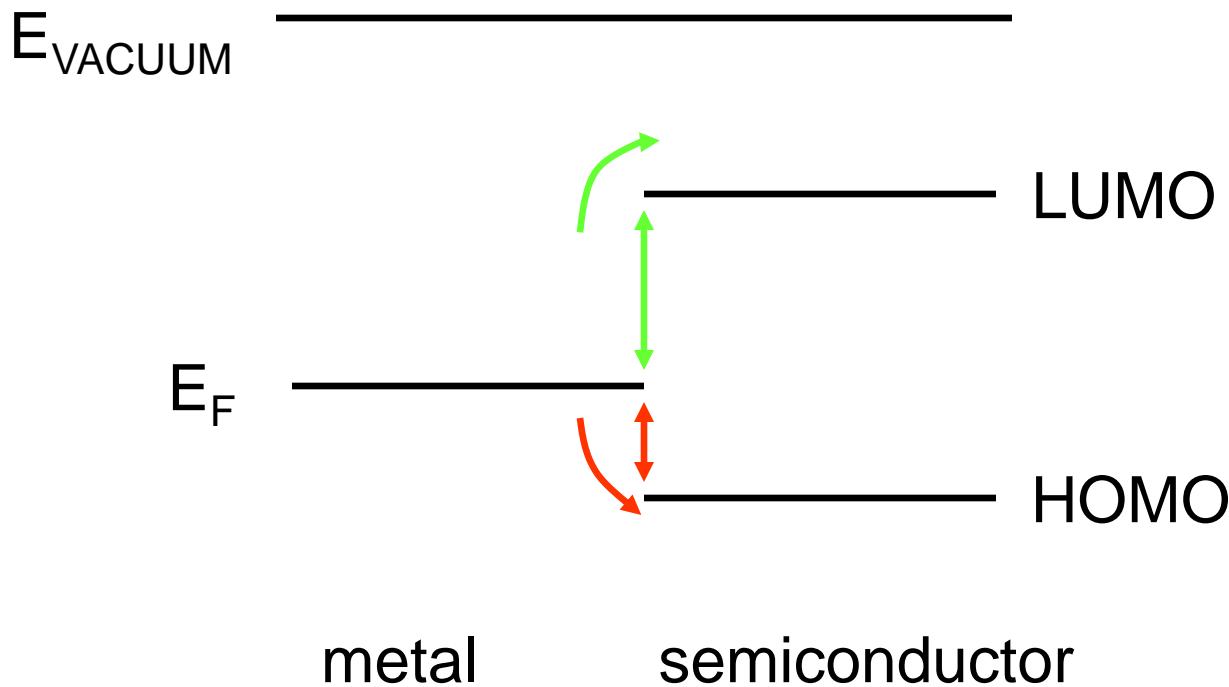
Thermal Equilibrium (2)



Interface dipole layer

Accumulated, *highly conductive*
(higher than bulk)
space charge region

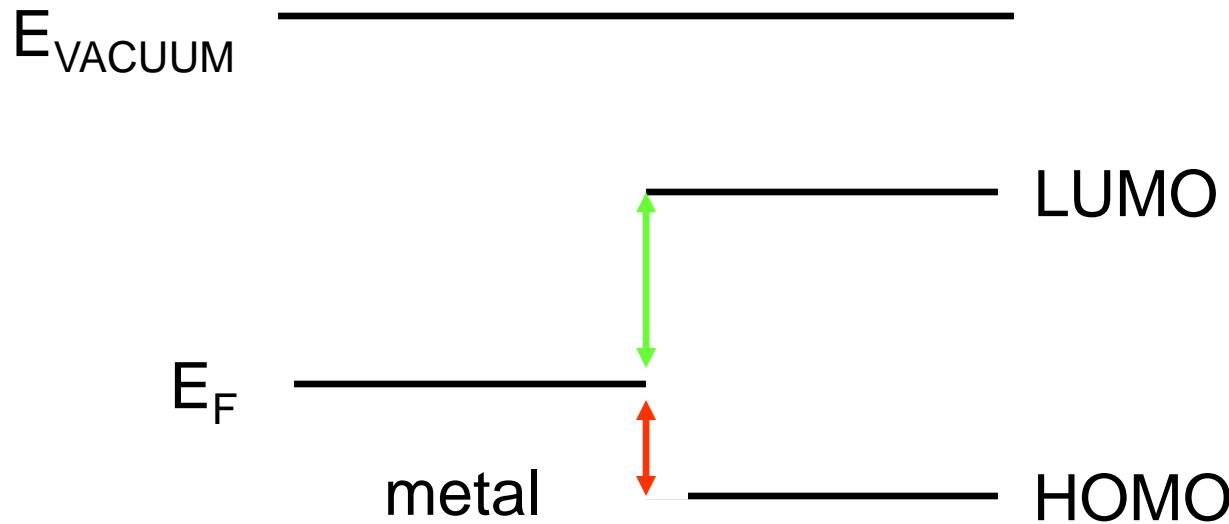
Metal-semiconductor contacts



Φ_{Be} barrier to electron injection

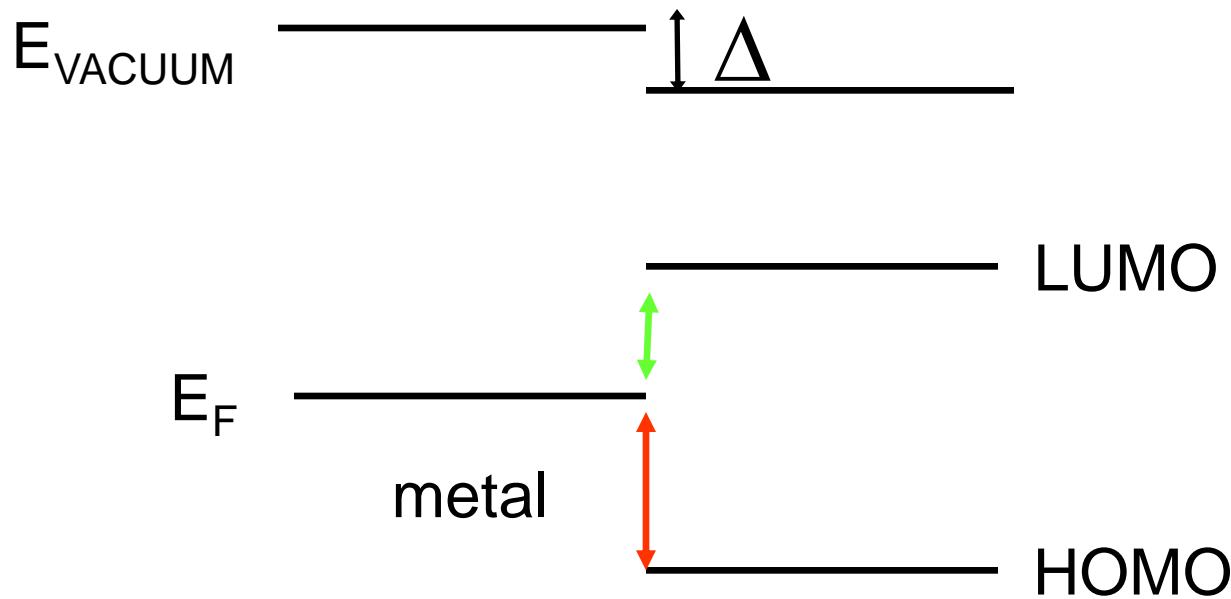
Φ_{Bh} barrier to hole injection

Interface dipoles (1)



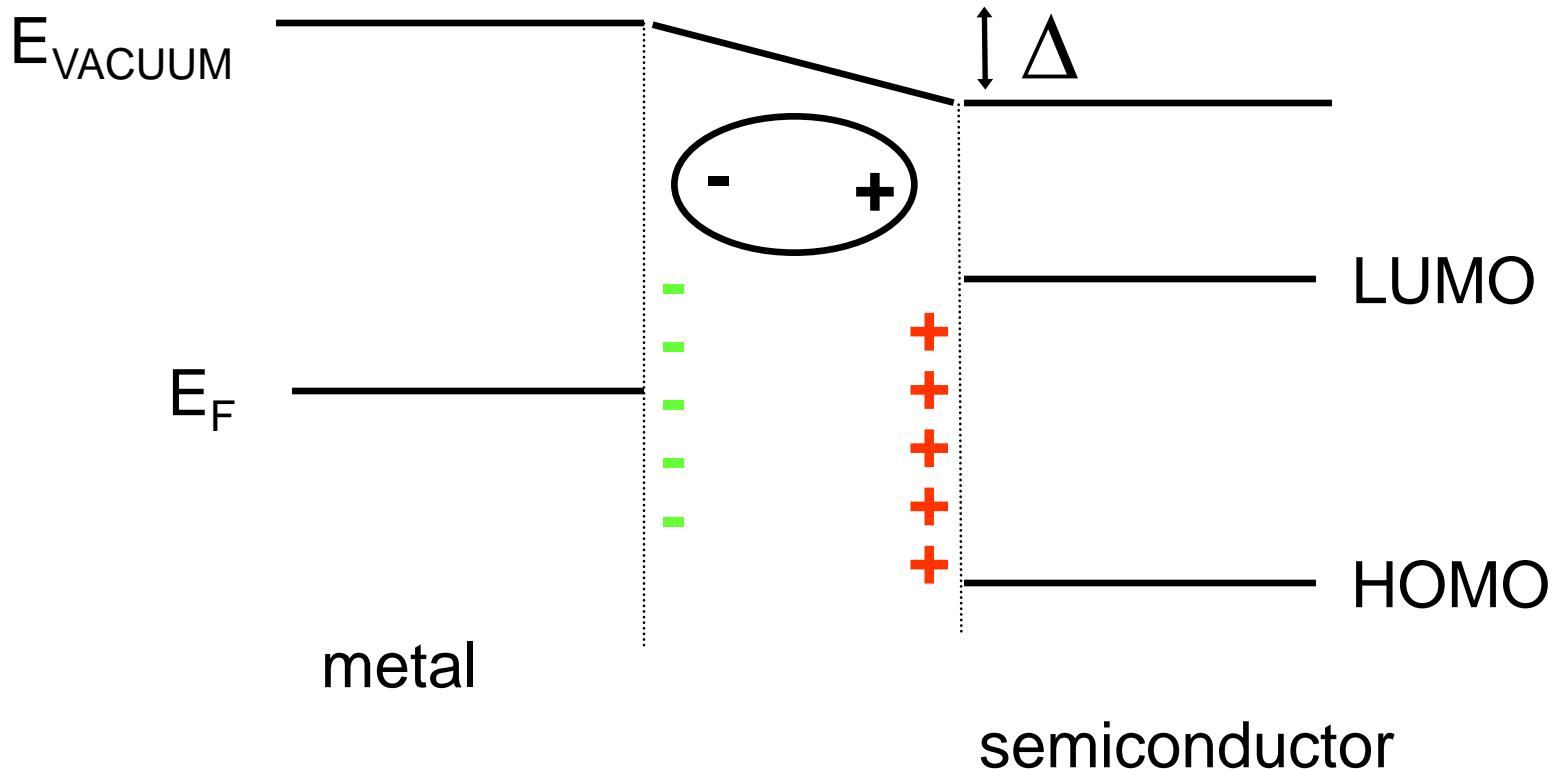
Barriers Φ_{Be} and Φ_{Bh} do change!!

Interface dipoles (1)

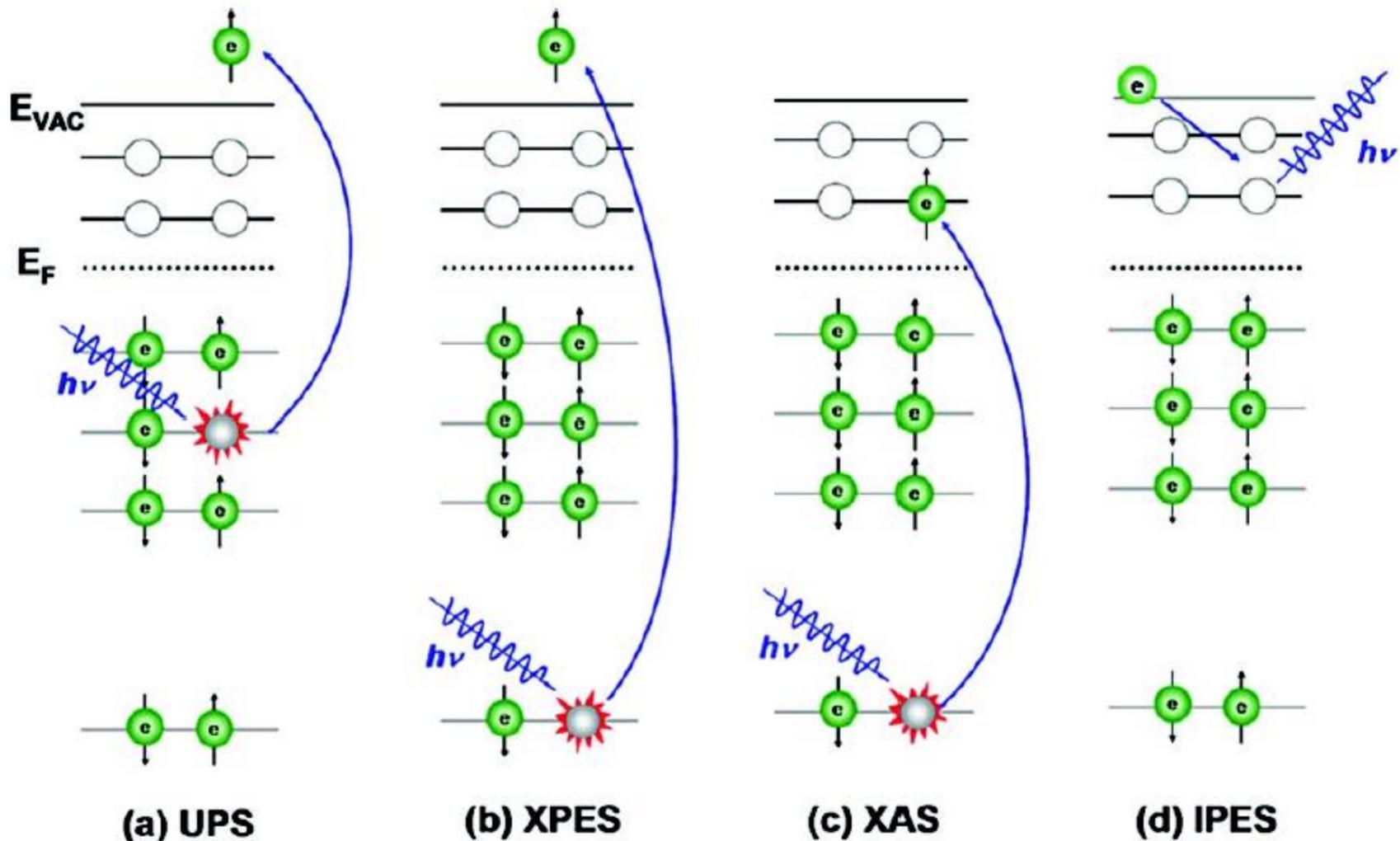


Barriers Φ_{Be} e Φ_{Bh} do change!!

Interface dipoles (2)

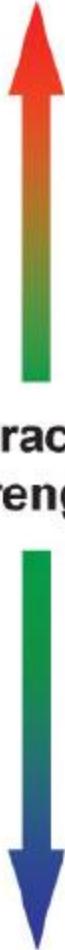


Spectroscopical techniques



Interface interaction strength

Weak



Interaction strength

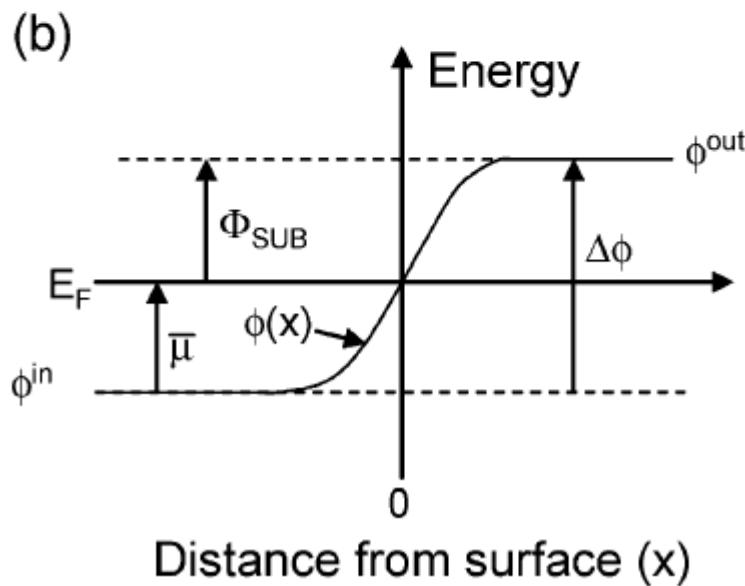
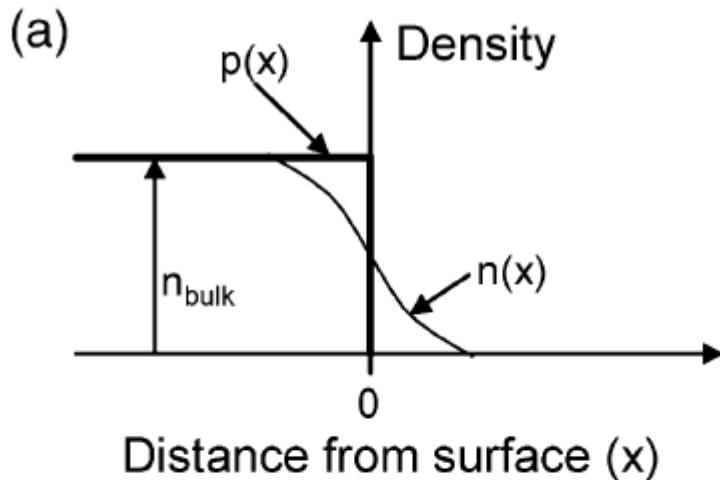
Strong

Example of interface	Interaction type	Refs.
Noble gas atoms or saturated hydrocarbons on clean metal surfaces	Physisorption, absence of charge transfer	59, 61-63
π -conjugated molecules and polymers on organic or passivated metal surfaces	Physisorption, possible integer electron charge transfer through tunneling	22, 68
π -conjugated molecules on non-reactive clean metal surfaces	Weak chemisorption, possible partial charge transfer	21, 80
(π -conjugated) molecules on reactive clean metal surfaces	Strong chemisorption, covalent bonding between molecule and metal, (partial) charge transfer	20
(π -conjugated) molecules with intrinsic dipole and anchoring groups on clean metal surfaces	Strong chemisorption, covalent bond at <i>specific</i> sites of the molecule and metal, (partial) charge transfer, surface dipole	24, 97

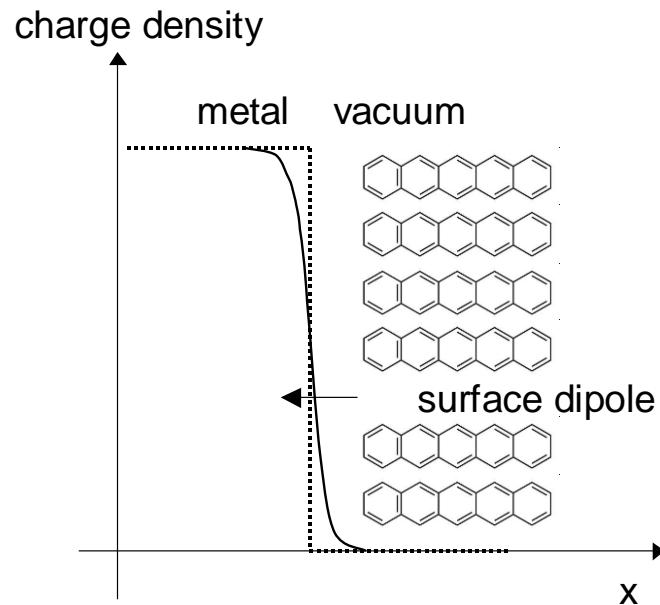
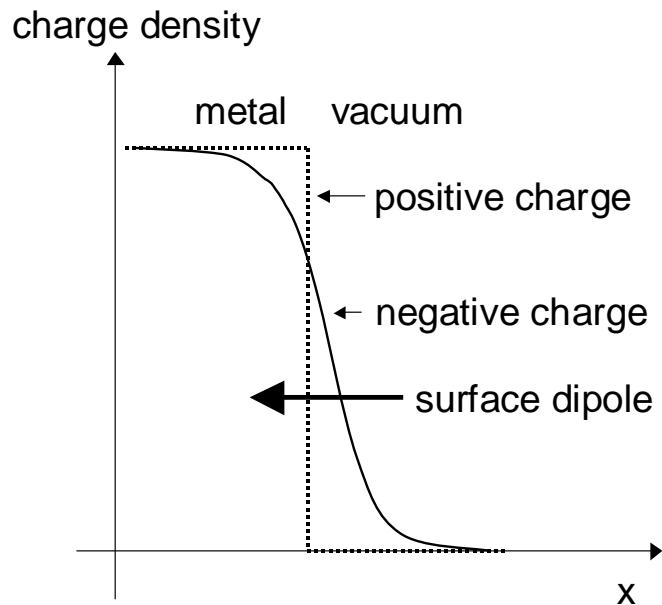
Metal/organic interfaces:

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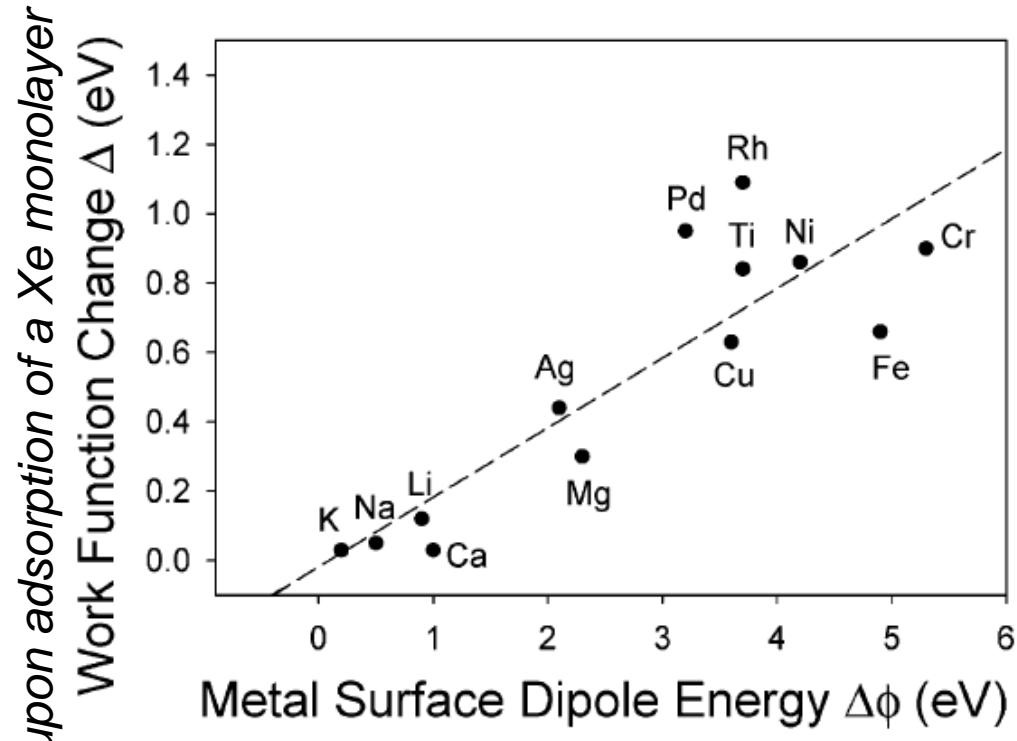
Real Metal surfaces: pushback effect



Real Metal surfaces: pushback effect



Real Metal surfaces: pushback effect



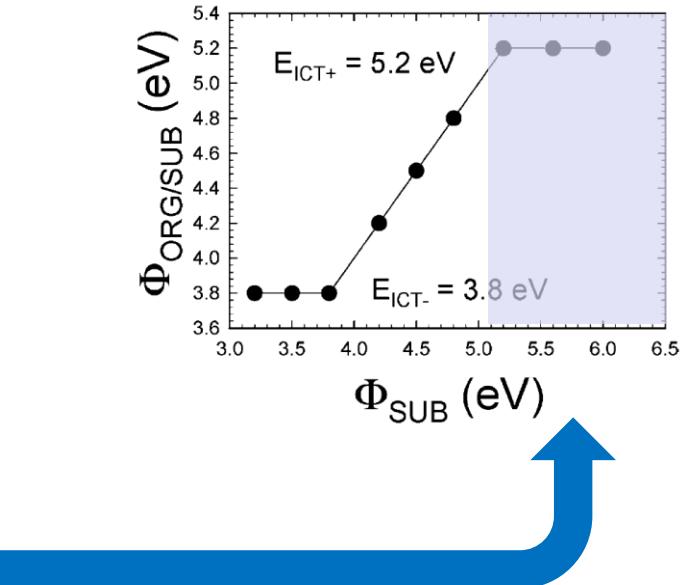
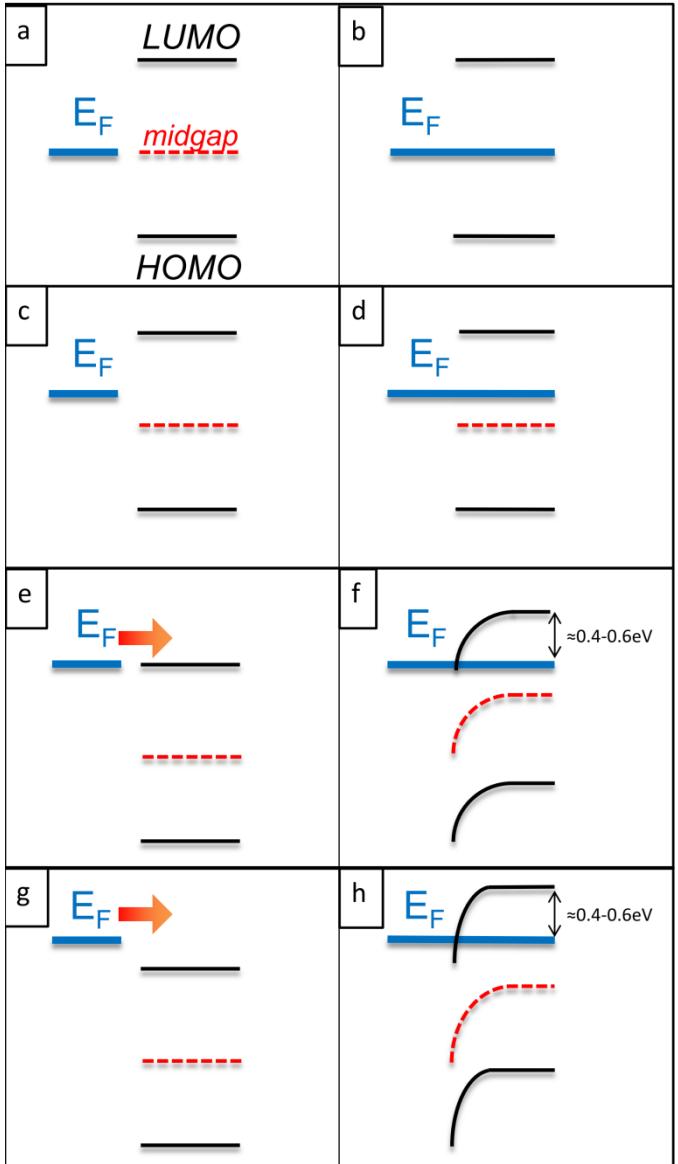
	1	2	3	4	5	6	7
Polymer-on-Au	4.4	4.5	4.6	4.5	4.4	4.4	4.5
Au-on-Polymer	4.4	4.5	4.4	4.5	4.4	4.5	4.4

Metal/organic interfaces:



Interaction strength	Example of interface	Interaction type	Refs.
Weak	Noble gas atoms or saturated hydrocarbons on clean metal surfaces	Physisorption, absence of charge transfer	59, 61-63
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	(π -conjugated) molecules on reactive clean metal surfaces	Strong chemisorption, covalent bonding between molecule and metal, (partial) charge transfer	20
Strong	(π -conjugated) molecules with intrinsic dipole and anchoring groups on clean metal surfaces	Strong chemisorption, covalent bond at <i>specific</i> sites of the molecule and metal, (partial) charge transfer, surface dipole	24, 97

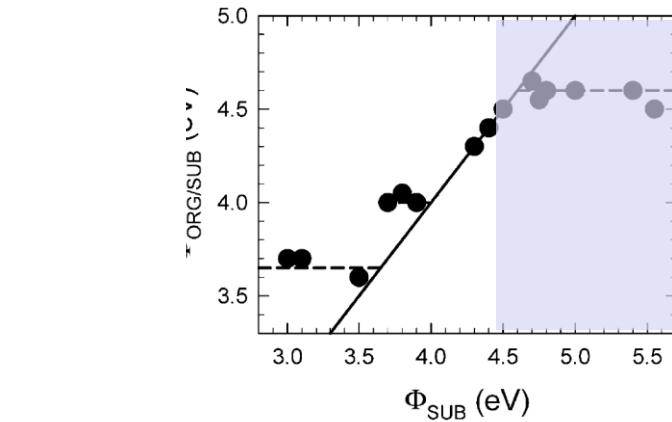
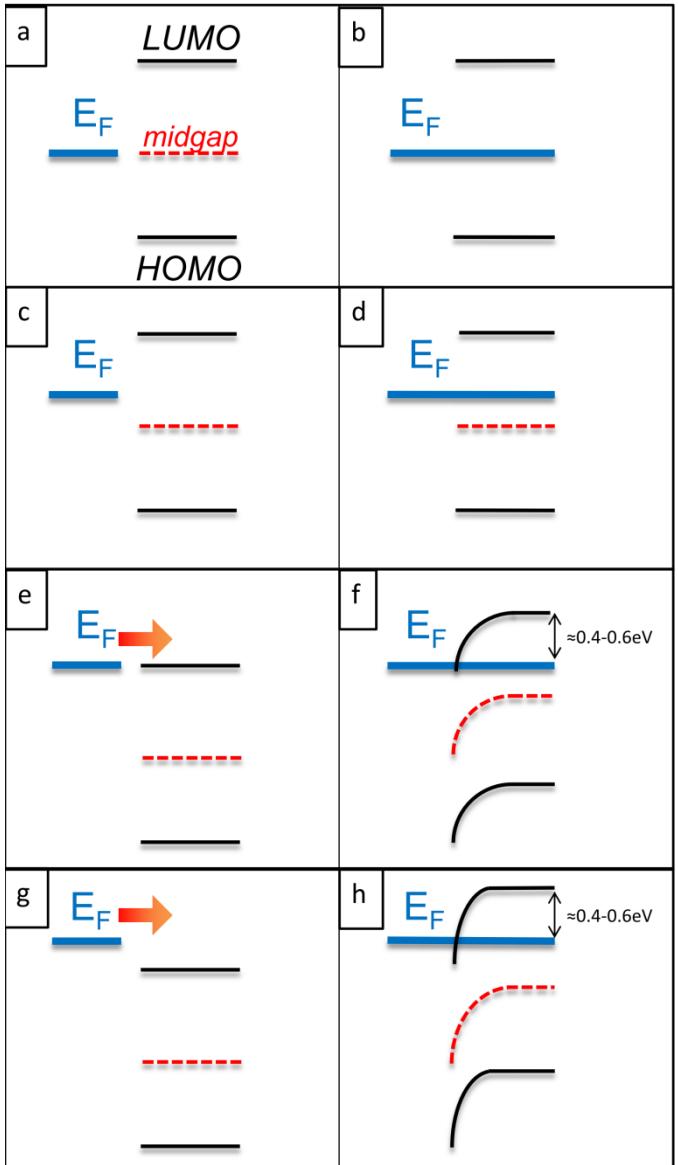
Physisorptive regime



Interaction strength	Example of interface	Interaction type	Refs.
Weak	Surface passivation or adsorption of a dense metal surface	Pseudoelectrostatic or charge transfer	30, 41, 47
Medium	Investigated includes the interaction of organic molecules with solid and liquid surfaces	Pseudoelectrostatic, possible image charge effect, dipole-dipole coupling	22, 28, 31, 32, 33
Strong	Interactions where the non-polar solute does not have a compact molecule or diffuse short-lived surface	Strong, chemisorption, electron transfer, molecular and ionic, space charge	31, 38
Very strong	(a) compact molecule with permanent dipole moment or dense near-surface layer	Strong, chemisorption, electron transfer, ionic bonding, ionic bonding, ionic bonding, surface dipole	34, 37

Physisorptive regime

Interaction strength	Weak	Example of interface	Interaction type	Ref(s)
Weak	Weak	Surface passivation or electron transfer between molecules on the same surface	Passivation, electron or hole transfer	30, 41, 47
Medium	Medium	Investigated includes adsorption of organic molecules on metal and metal surface	Physisorption, possible intermolecular interaction, electron transfer	22, 28, 30, 31, 32, 33, 34, 35
Strong	Strong	Molecules adsorb on metal surface due to strong interaction with metal, possible charge transfer	Strong, chemisorption, electron transfer, electron and hole transfer	31, 36
Very Strong	Very Strong	(Inorganic) molecule or ion adsorb on metal surface due to strong interaction with metal, possible charge transfer	Strong, chemisorption, electron transfer, electron and hole transfer	34, 37



Physisorptive regime: who cares Φ_B ?

$$n_1 \propto N_{\text{eff}} \exp^{-\Phi_B/kT}$$

$$\rho = \frac{e n_1}{\left(\frac{x}{L_1} + 1 \right)^2}$$

$$L_1 \propto \sqrt{\frac{\phi_{th}}{n_1}}$$

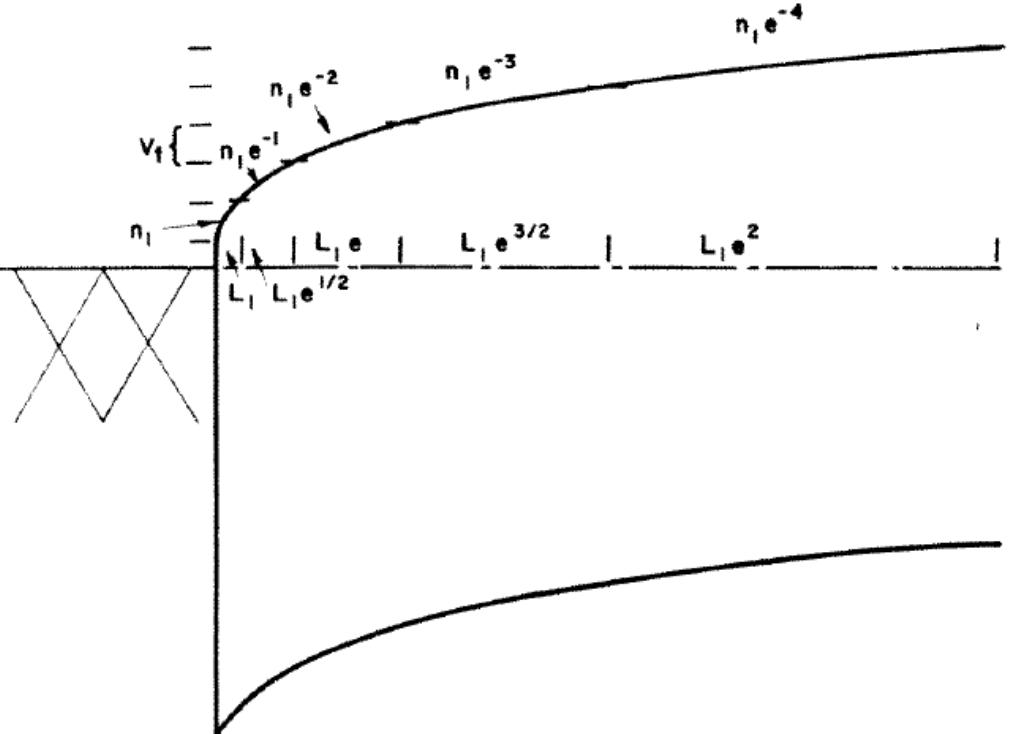
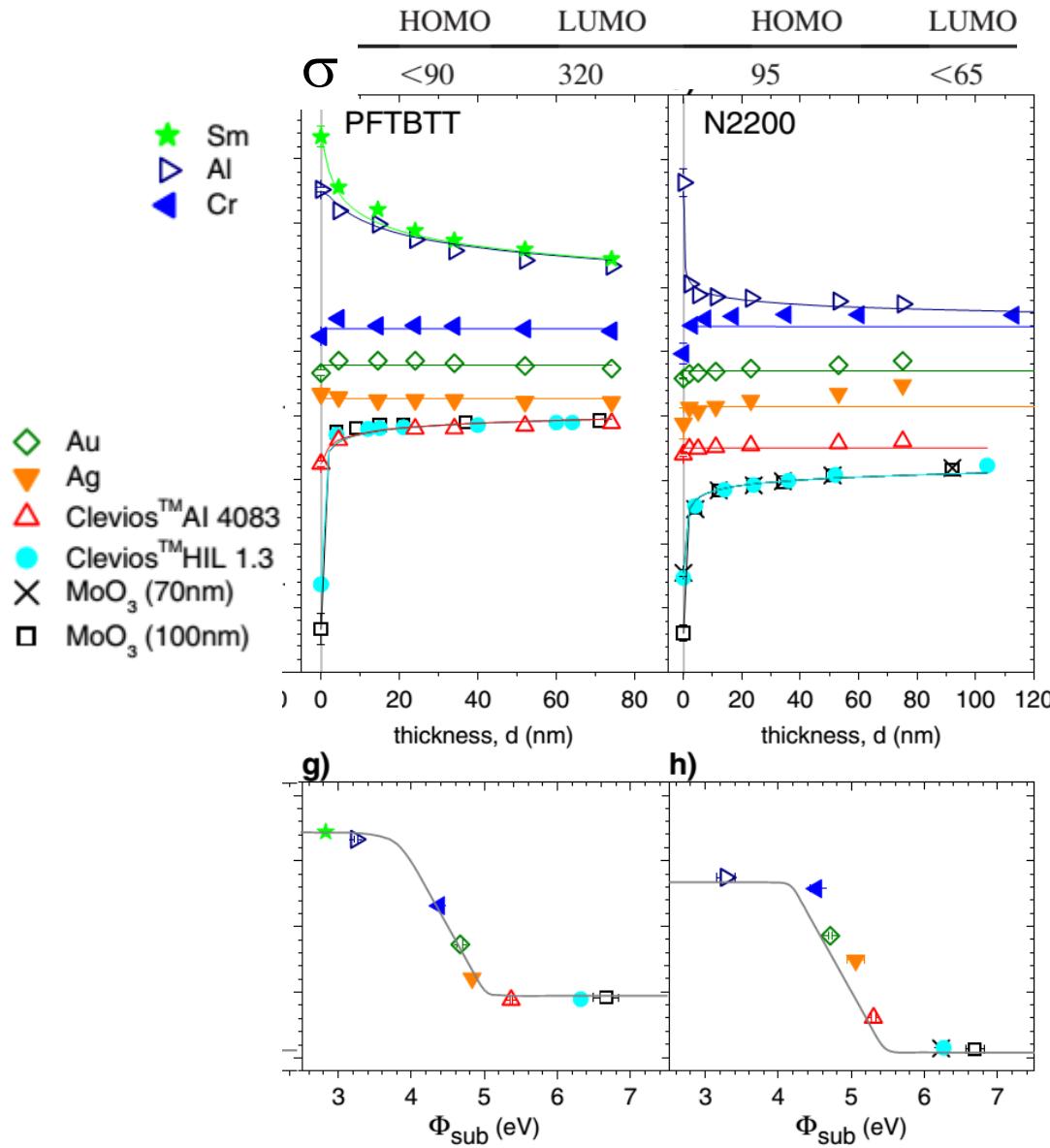
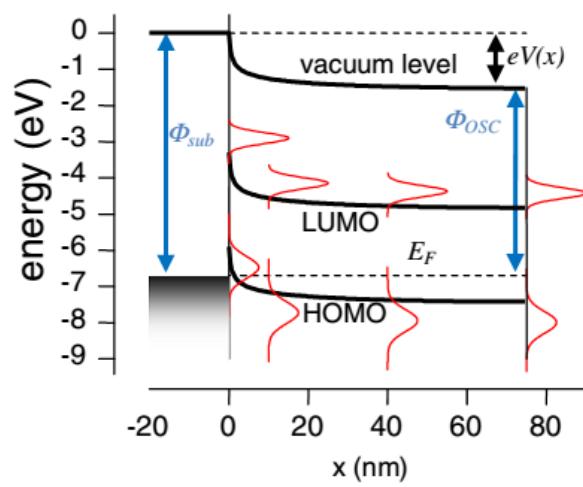


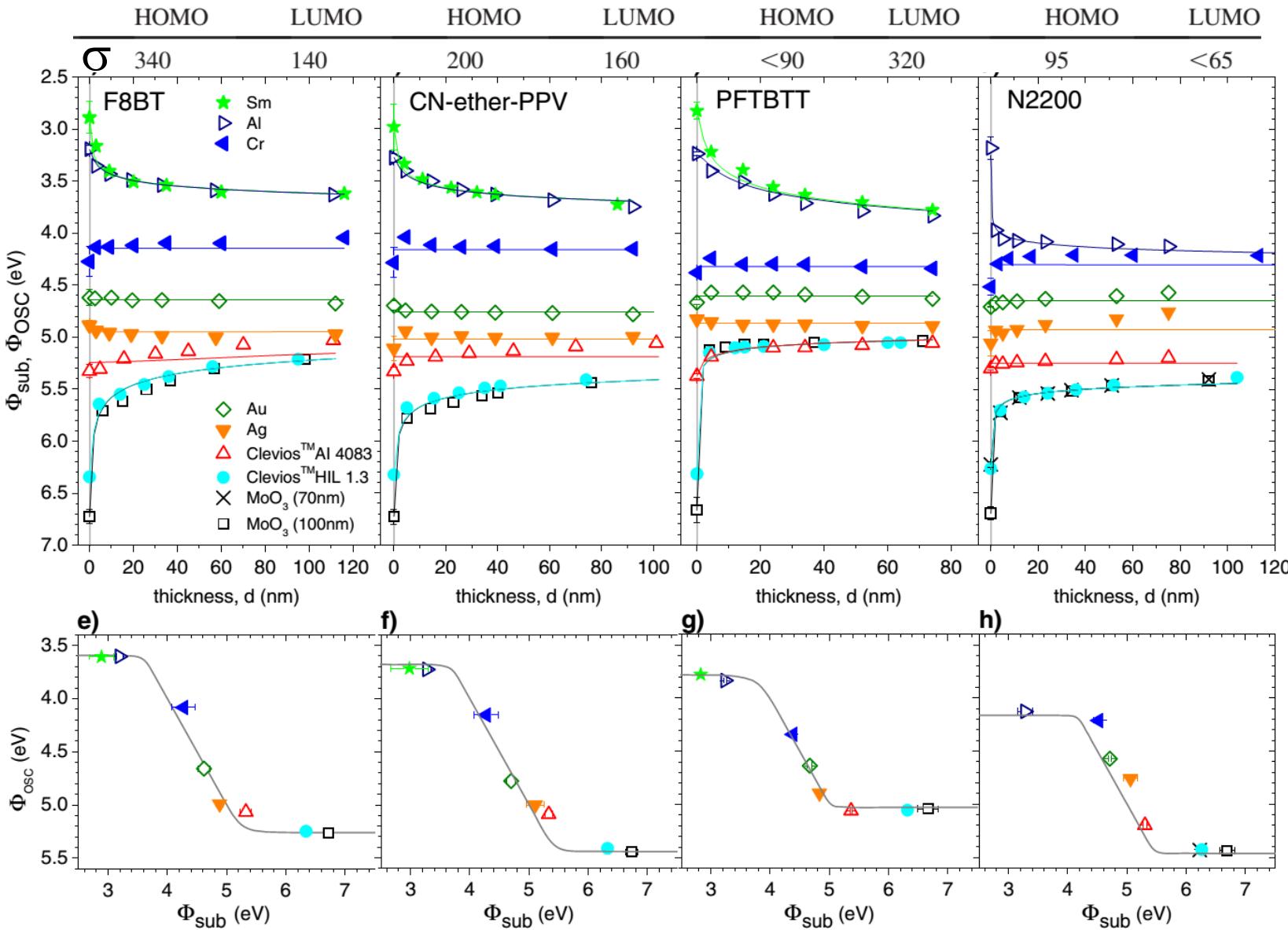
Fig. 8.3. Density of electrons and rise in potential near an Ohmic contact.
 L_1 is the Debye length for the density n_1 .

Interaction strength	Example of interface	Interaction type	Refs.
Weak	Surfaces of similar materials or different materials with low interaction energy	Precipitation, desorption, or charge transfer	10, 41-43
Medium	Surfaces with intermediate interaction energy	Precipitation, possible image formation, desorption, or charge transfer	22, 68
Strong	Surfaces with high interaction energy	Work function change, possible surface diffusion	23, 30
Very strong	Surfaces with very high interaction energy	Energy, desorption, adsorption, and work, spillover	30
Extremely strong	(Incompatible mixture with reaction products) Surfaces with close interaction energy	Strong adsorption, desorption, and work, and metal-surface dipole	34, 37

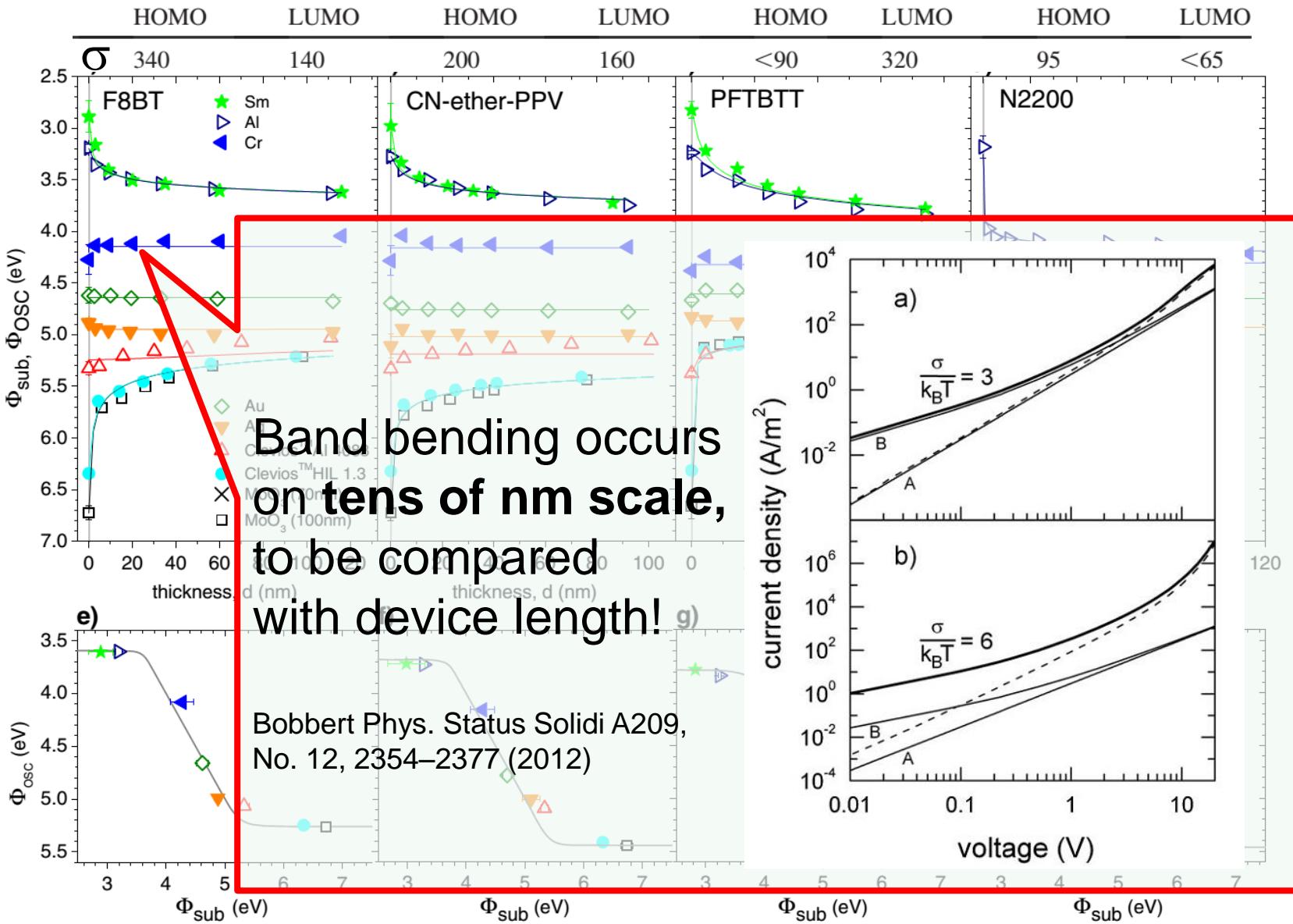
Physisorptive regime:



Physisorptive regime: effect of disorder

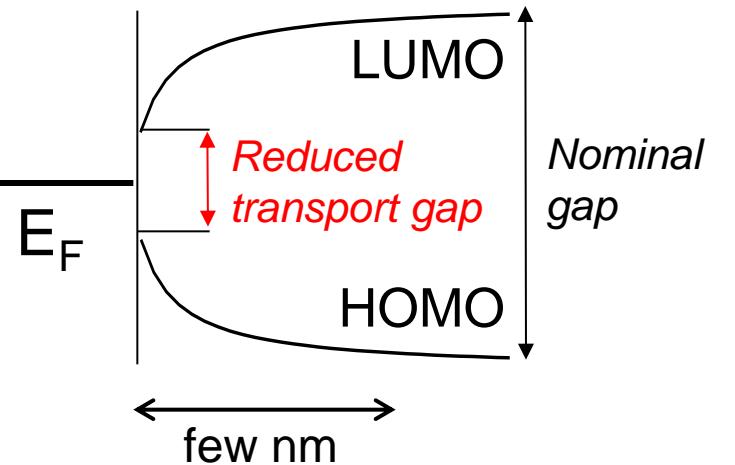


Physisorptive regime: effect of disorder



Physisorptive regime: image charge

Weak	Example of interface	Interaction type	Ref(s)
Weak	Surfaces with some or certain interactions on one total surface	Physisorption, adhesion, or charge transfer	31,41-43
Investigated	Includes all possible interactions between two total surfaces	Physisorption, possible image charge, possible dipole-dipole	22,48
Strong	Surfaces with strong interactions on one total surface	Chemisorption, covalent bonding	23,49
Strong	Surfaces with strong interactions on one total surface	Work function, possible dipole-dipole	31,49
Strong	Surfaces with strong interactions on one total surface	Energy, adsorption, desorption, and work, spiciness	30
Strong	Surfaces with strong interactions on one total surface	Strong adsorption, desorption, and work, dipole-dipole	34,47



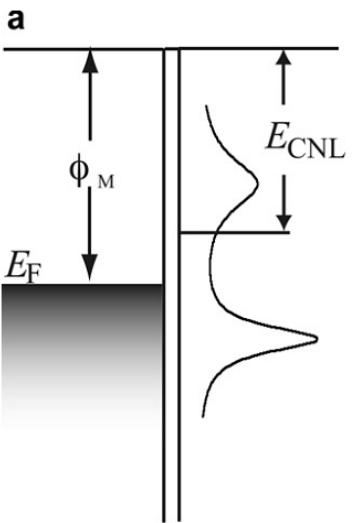
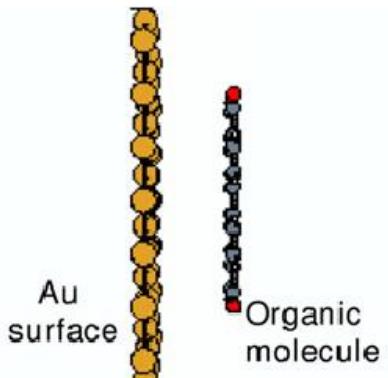
Clean Metal/molecule interfaces: weak chemisorption



Interaction strength	Example of interface	Interaction type	Refs.
Weak	Noble gas atoms or saturated hydrocarbons on clean metal surfaces	Physisorption, absence of charge transfer	59, 61-63
	π -conjugated molecules and polymers on organic or passivated metal surfaces	Physisorption, possible integer electron charge transfer through tunneling	22, 68
	π -conjugated molecules on non-reactive clean metal surfaces	Weak chemisorption, possible partial charge transfer	21, 80
	(π -conjugated) molecules on reactive clean metal surfaces	Strong chemisorption, covalent bonding between molecule and metal, (partial) charge transfer	20
Strong	(π -conjugated) molecules with intrinsic dipole and anchoring groups on clean metal surfaces	Strong chemisorption, covalent bond at specific sites of the molecule and metal, (partial) charge transfer, surface dipole	24, 97

Weak	Interaction type	Ref.
Nitro or amine or nitroso substituted surfaces	Pseudopotential, absence of interaction	59,63
Alkyl substituted methoxides and alkoxides as ligand at transition metal surface	Pseudopotential, possible large electron density change transfer	22,28
Ketone group, methoxides, or alkoxides as ligand at transition metal surface	Pseudopotential, possible large electron density change transfer	1,38
Alkyl, alkenyl, alkynyl, and aryl groups as ligand at transition metal surface	Using ab initio, pseudopotential calculations	20
Alkyl, alkenyl, alkynyl, and aryl groups as ligand at transition metal surface	Using ab initio, pseudopotential calculations	24,49

Induced Density of states model



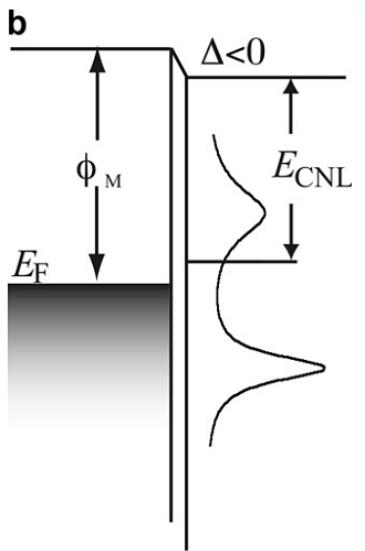
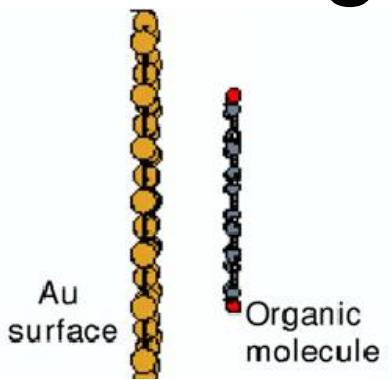
Charge Neutrality Level

In organic molecule CNL accounts for:

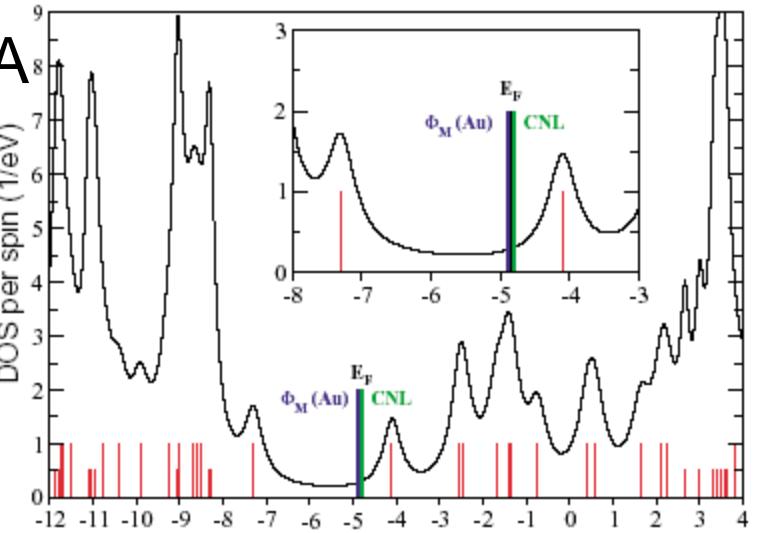
- all Molecular Orbitals
- Metal induced orbitals broadening-> midgap states

Charge Neutrality Level

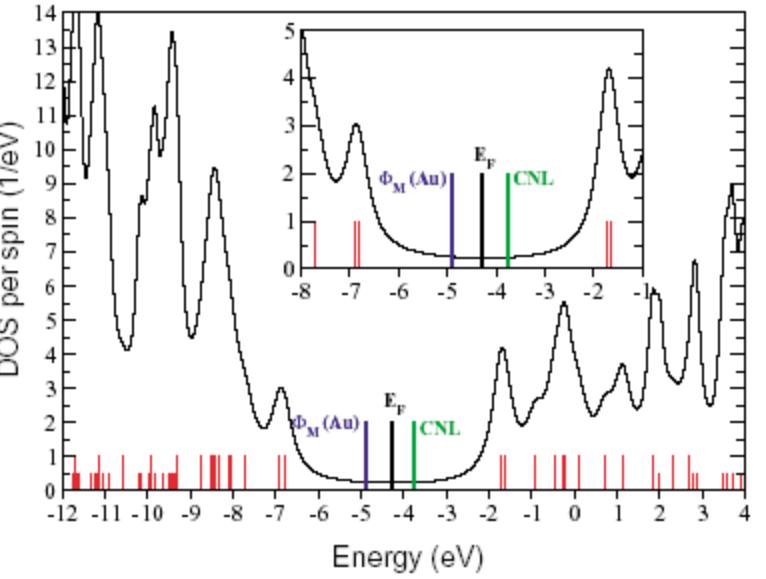
Interaction strength	Example of interface	Interaction type	Ref.
Weak	None or neutral interaction between molecules and surface	Polarization, absence of charge transfer	59,63
Medium	Long-range interactions between molecules and surface	Polarization, possible large dipoles, charge transfer	22,28
Strong	Local interactions between molecules or atoms	Hydrogen bonding, covalent bonding, ionic bonding	1,38
Very strong	Very strong interaction on metal/molecule surface	Strong adsorption, specific bond formation	20
Extremely strong	Extremely strong interaction with surface dipole and resulting strong polarization	Very strong adsorption, specific bond at specific site, strong dipole-dipole effect	34,49



PTCDA

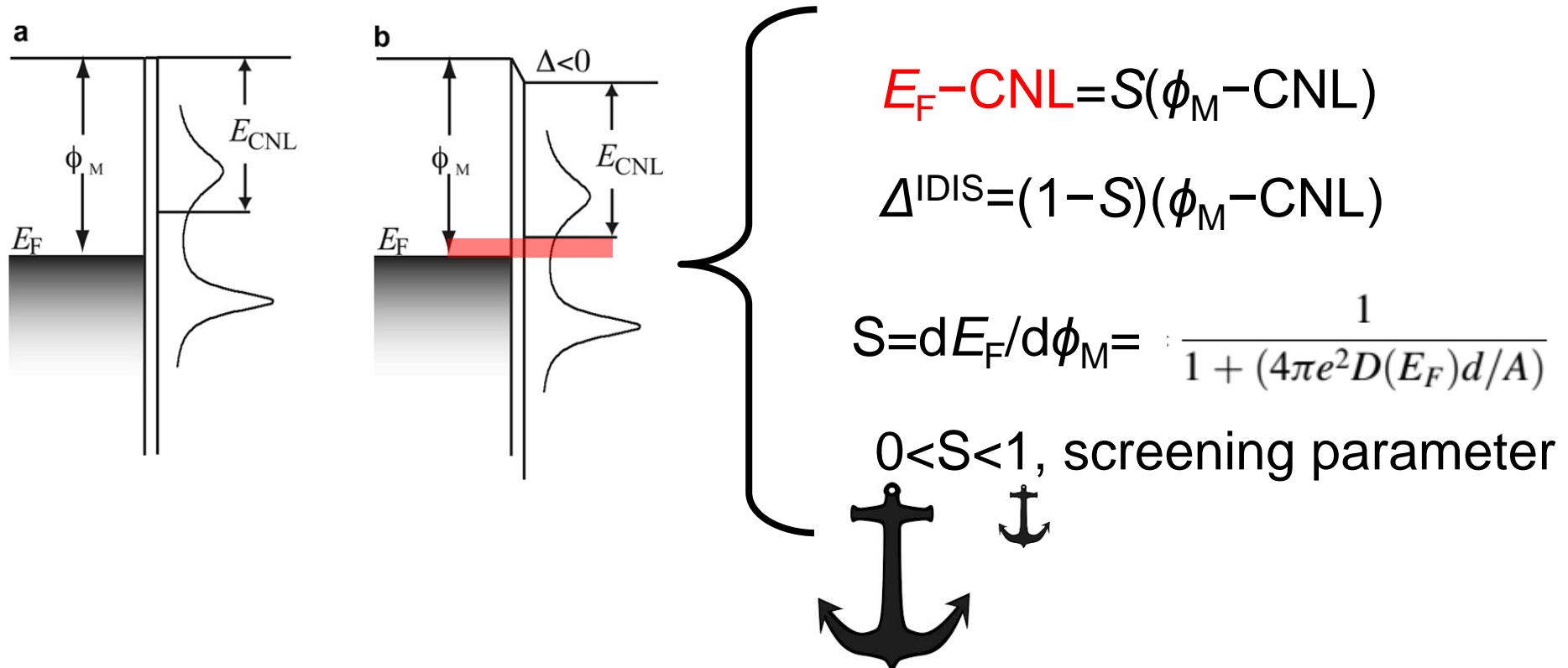


CBP



Interaction strength	Example of interface	Interaction type	Ref.
Weak	Wetting on smooth hydrophobic surface	Precipitation, absence of wetting	59,63
Medium	Langmuir monolayers and proteins on rigid surfaces	Precipitation, possible large droplets, charge transfer	22,28
Strong	Keratogel monolayers or proteins on flexible surfaces	Wetting, desorption, spreading	1,38
Very strong	Proteins in aqueous droplets	Wetting, desorption, spreading	20
Extremely strong	Proteins at specific sites and binding sites on the surface	Wetting, desorption, spreading	74,97

Charge Neutrality Level

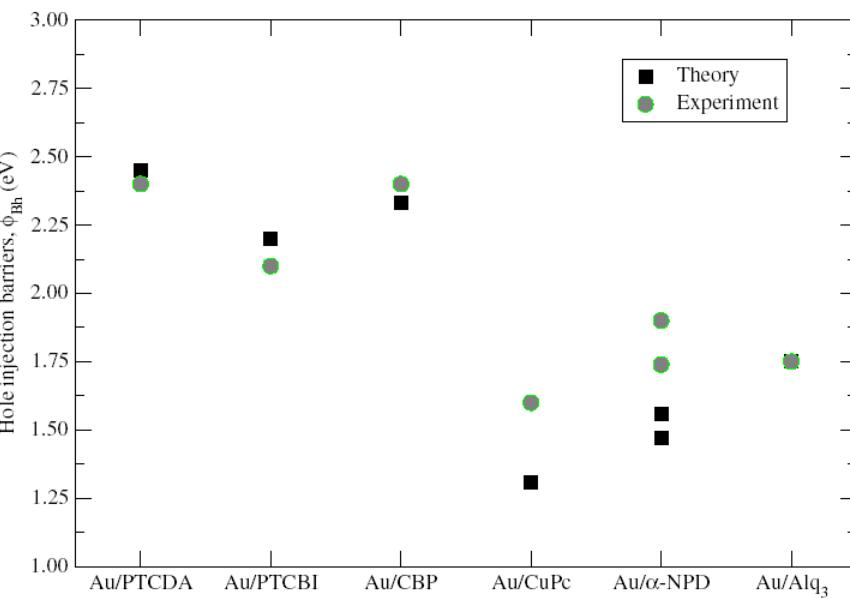
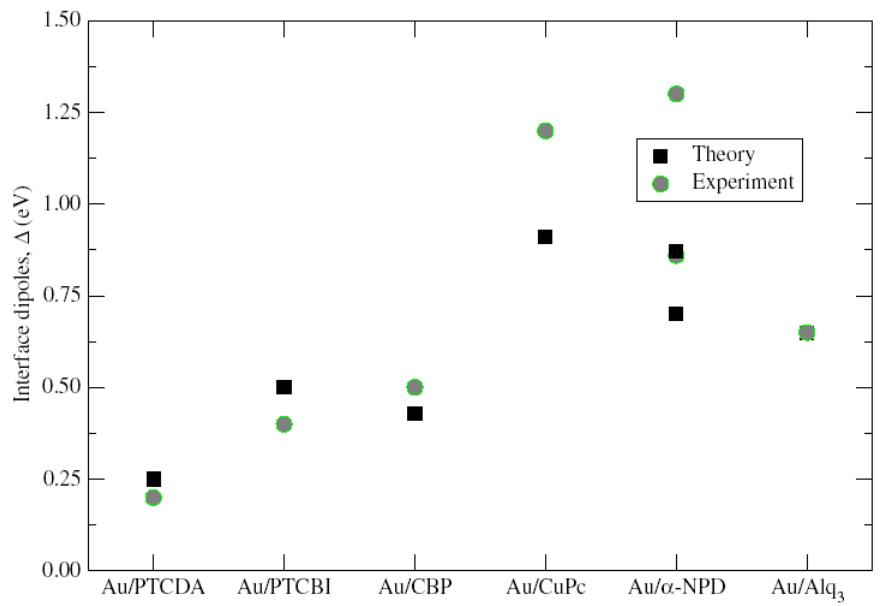


S describes the degree of pinning of the Fermi level at the interface

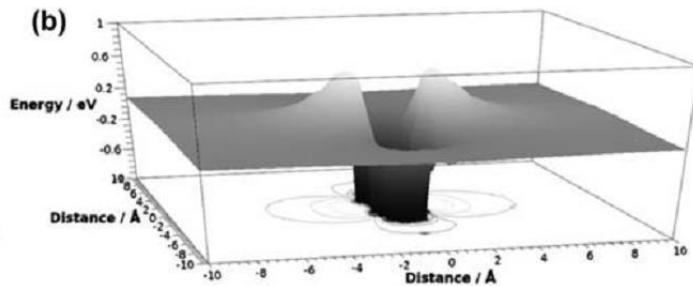
Interaction strength	Example of interface	Interaction type	Ref.
Weak	Ndoped p-type or undoped n-type silicon	Pi-Pi interaction, absence of charge transfer	59,63
Medium	Aluminum electrodes and polyimide as insulator	Pi-Pi interaction, possible charge transfer	22,28
Strong	Kapton electrodes or carbon nanotubes	Weak electron transfer, electron hole transfer	1,38
Very strong	Aluminum electrodes and polyimide as insulator	Strong electron transfer, electron hole transfer	20
Extremely strong	Titanium electrodes and polyimide as insulator	Very strong electron transfer, electron hole transfer	34,49

CNL: Theory vs Experiment

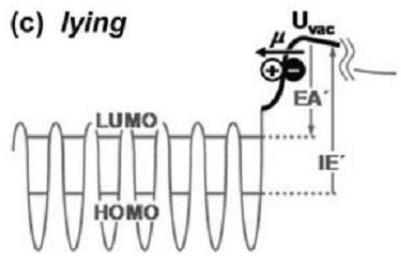
	-CNL	-IE	$-\phi_M$	S (theoretical)	Δ (theoretical)	Δ (experimental)	ϕ_{Bh} (theoretical)	ϕ_{Bh} (experimental)
PTCDA	4.8	7.3 (6.8)	5.1 [6]	0.16	0.25	0.2 [6]	2.45	2.40 [6]
PTCBI	4.4	6.7 (6.2)	5.0 [7]	0.16	0.50	0.4 [7]	2.20	2.10 [7]
CBP	4.05	6.8 (6.3)	4.9 [10]	0.50	0.43	0.5 [10]	2.33	2.40 [10]
CuPc	4.0	5.7 (5.2)	5.3 [31]	0.30	0.91	1.2 [31]	1.31	1.60 [31]
α -NPD	4.1	6.0 (5.5)	5.14 [32]	0.33	0.70	0.86 [32]	1.56	1.74 [32]
			5.4 [33]		0.87	1.3 [33]	1.47	1.9 [33]
Alq ₃	3.65	6.3 (5.8)	5.2 [6]	0.58	0.65	0.65 [6]	1.75	1.75 [6]
BCP	3.65	6.9(6.4)	–	0.42	–	–	–	–



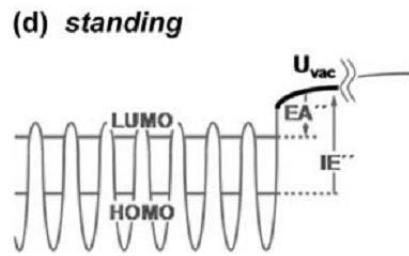
Metal/ordered molecule interfaces: n-poles



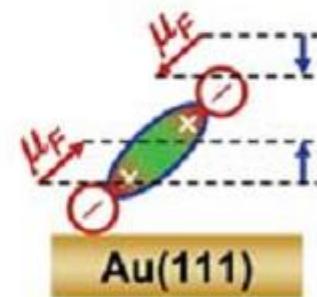
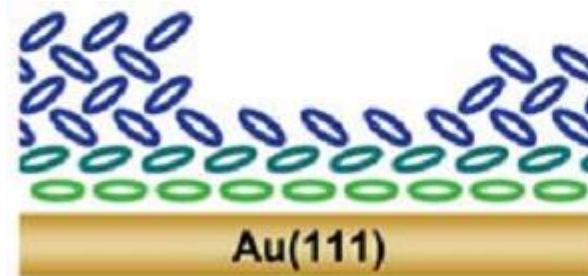
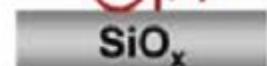
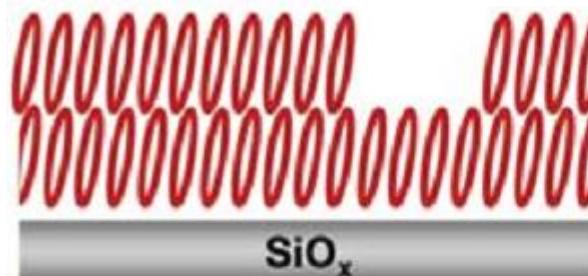
(c) lying



(d) standing



Quadrupoles
and intrinsic dipoles

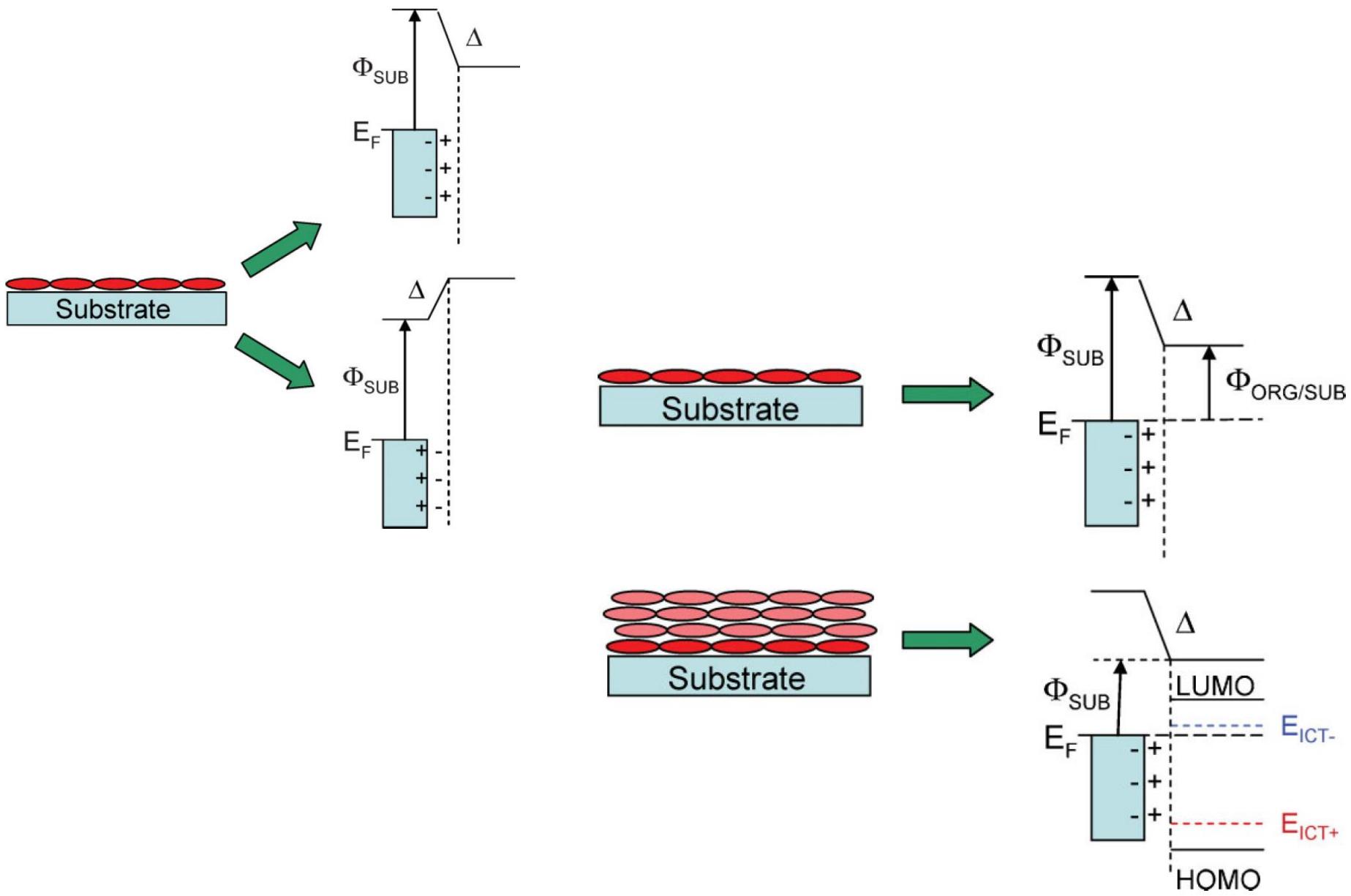


Strong chemical interaction @ Interface



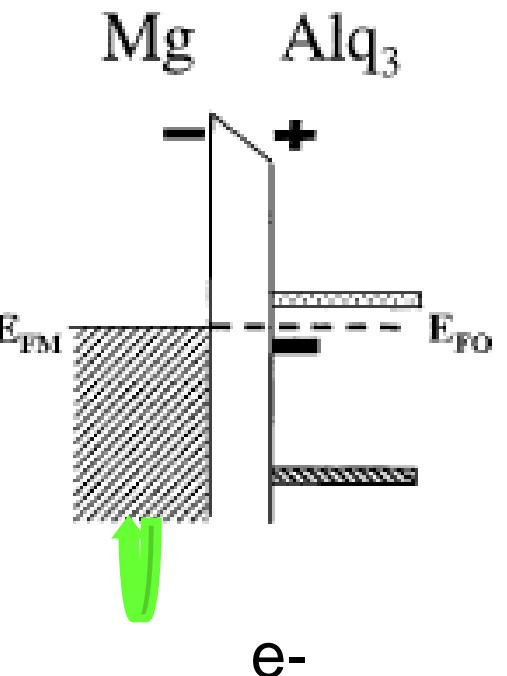
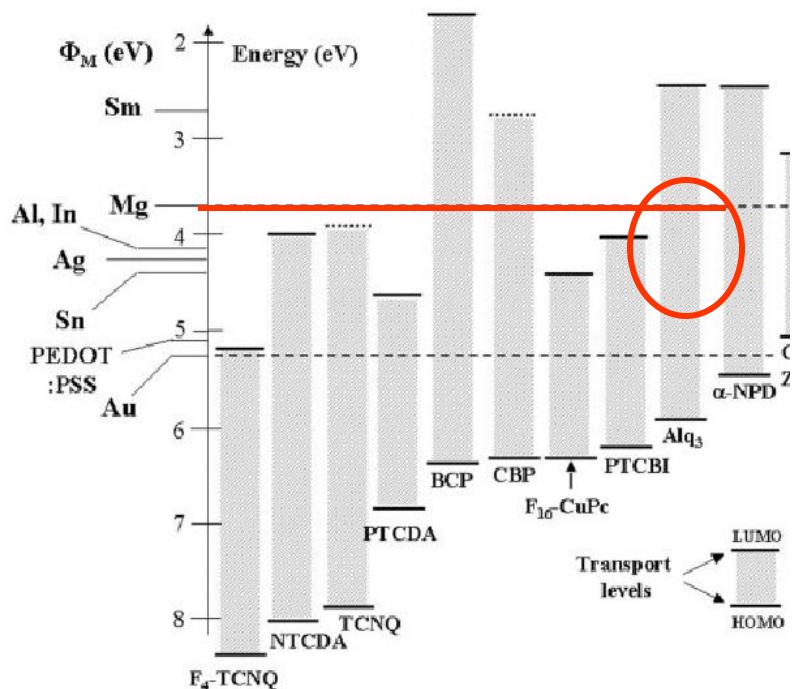
Interaction strength	Example of interface	Interaction type	Ref.s.
Weak	Noble gas atoms or saturated hydrocarbons on clean metal surfaces	Physisorption, absence of charge transfer	59, 61-63
	π -conjugated molecules and polymers on organic or passivated metal surfaces	Physisorption, possible integer electron charge transfer through tunneling	22, 68
	π -conjugated molecules on non-reactive clean metal surfaces	Weak chemisorption, possible partial charge transfer	21, 80
	(π -conjugated) molecules on reactive clean metal surfaces	Strong chemisorption, covalent bonding between molecule and metal, (partial) charge transfer	20
Strong	(π -conjugated) molecules with intrinsic dipole and anchoring groups on clean metal surfaces	Strong chemisorption, covalent bond at specific sites of the molecule and metal, (partial) charge transfer, surface dipole	24, 97

Chemisorption

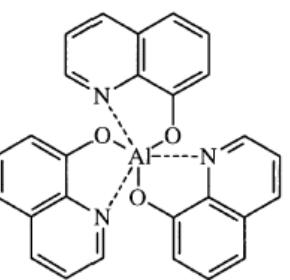


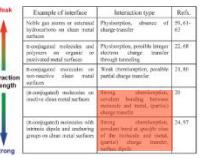
Weak	Example of interface	Interaction type	Ref.
Weak	No hydrogen or other interactions at close contact	Physisorption, absence of charge transfer	21, 43
Medium	Long-range van der Waals interaction between polarized solid surfaces	Physisorption, possible longer range interactions through bridging	22, 68
Strong	Polarization of molecules and surfaces by electron transfer	Chemisorption, possibly metal charge transfer	23, 46
Very strong	(Excessive) inclusion in lattice sites and surface	Strong chemisorption, possibly adsorption and metal charge transfer	24, 47

Chemisorption: Alq₃/Mg (1)

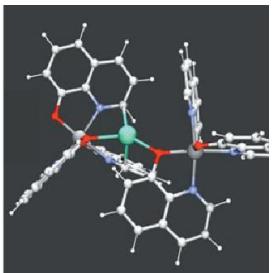
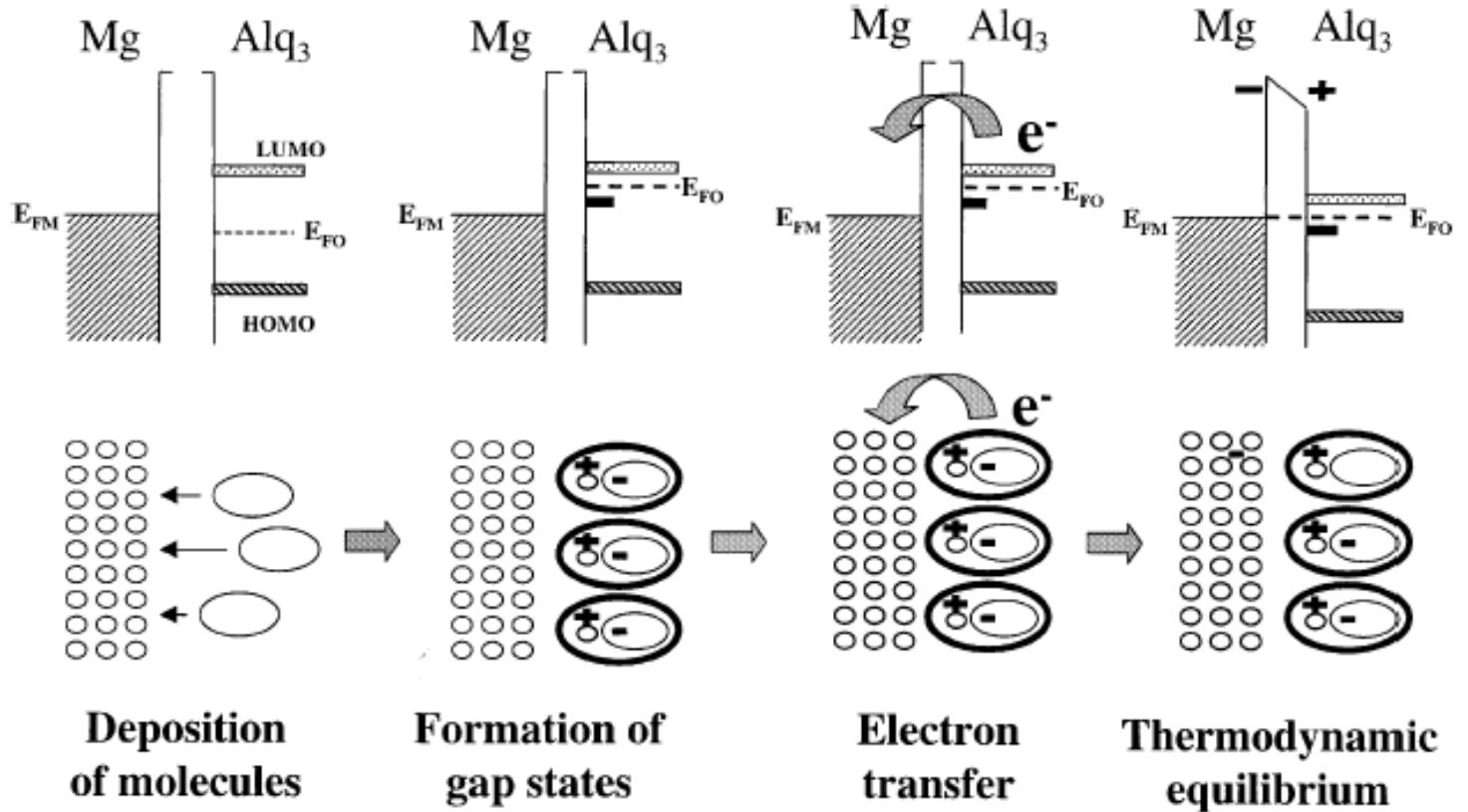


Unexpected electron flow!!





Chemisorption: Alq₃/Mg (2)



Chemistry induced electronic states formation:
a new Mg:Alq₃ organometallic complex

Interface energetics: summary

Weak
Interaction strength
Strong

Example of interface	Interaction type
Noble gas atoms or saturated hydrocarbons on clean metal surfaces	Physisorption, absence of charge transfer
π -conjugated molecules and polymers on organic or passivated metal surfaces	Physisorption, possible integer electron charge transfer through tunneling
π -conjugated molecules on non-reactive clean metal surfaces	Weak chemisorption, possible partial charge transfer
(π -conjugated) molecules on reactive clean metal surfaces	Strong chemisorption, covalent bonding between molecule and metal, (partial) charge transfer
(π -conjugated) molecules with intrinsic dipole and anchoring groups on clean metal surfaces	Strong chemisorption, covalent bond at <i>specific</i> sites of the molecule and metal, (partial) charge transfer, surface dipole

Integer charge transfer

IDIS and partial C.T.

Chemical reactions
@ interface

Polymers on metal



Weak	Example of interface	Interaction type	
	Noble gas atoms or saturated hydrocarbons on clean metal surfaces	Physisorption, absence of charge transfer	Integer charge transfer
	π -conjugated molecules and polymers on organic or passivated metal surfaces	Physisorption, possible integer electron charge transfer through tunneling	
Interaction strength	π -conjugated molecules on non-reactive clean metal surfaces	Weak chemisorption, possible partial charge transfer	IDIS and partial C.T.
	(π -conjugated) molecules on reactive clean metal surfaces	Strong chemisorption, covalent bonding between molecule and metal, (partial) charge transfer	
Strong	(π -conjugated) molecules with intrinsic dipole and anchoring groups on clean metal surfaces	Strong chemisorption, covalent bond at <i>specific</i> sites of the molecule and metal, (partial) charge transfer, surface dipole	Chemical reactions @ interface

Solvents “**passivates**” metals-> no *intimate* metal organic contact
-> no IDIS nor chemical reaction

Metal on *Polymers*

Weak
Interaction strength
Strong

Example of interface	Interaction type
Noble gas atoms or saturated hydrocarbons on clean metal surfaces	Physisorption, absence of charge transfer
π -conjugated molecules and polymers on organic or passivated metal surfaces	Physisorption, possible integer electron charge transfer through tunneling
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(π -conjugated) molecules with intrinsic dipole and anchoring groups on clean metal surfaces	Strong chemisorption, covalent bond at <i>specific</i> sites of the molecule and metal, (partial) charge transfer, surface dipole

Integer charge transfer

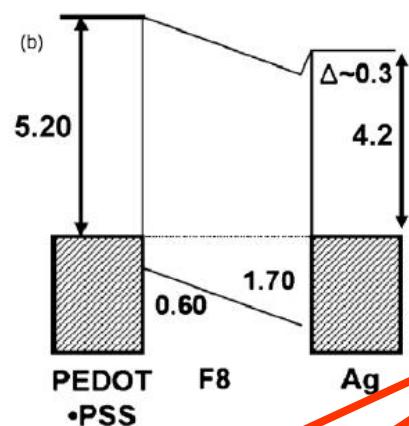
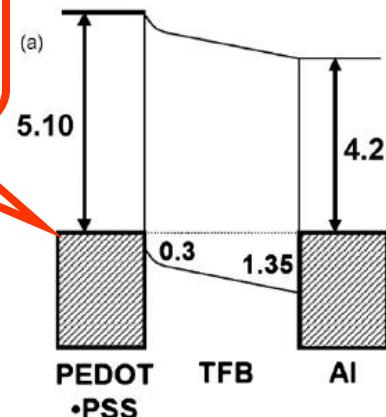
IDIS and partial C.T.

Chemical reactions
@ interface

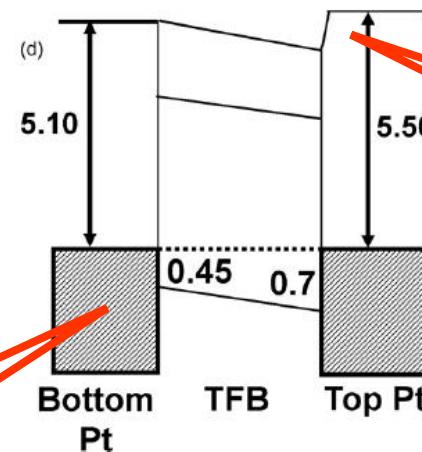
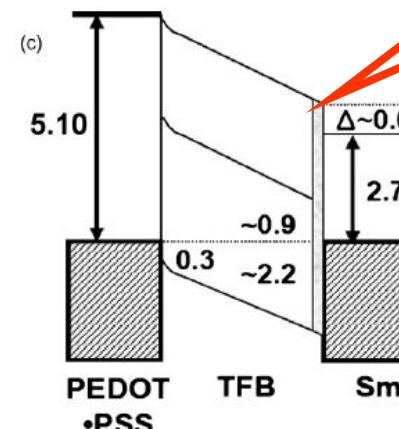
Intimate metal organic contact is possible
due to (Ultra) High Vacuum metal evaporation

Metal-Polymers-Metal interfaces

ICT
barriers < 0.3/0.4 eV
Band bending?



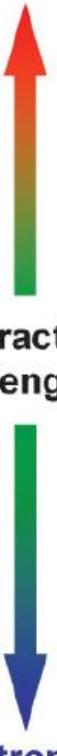
Pushback:
Pt Ef=5.65eV



Chemical reaction

IDIS dipole

[Metal/Small molecule] – [Small molecule/metal] interfaces

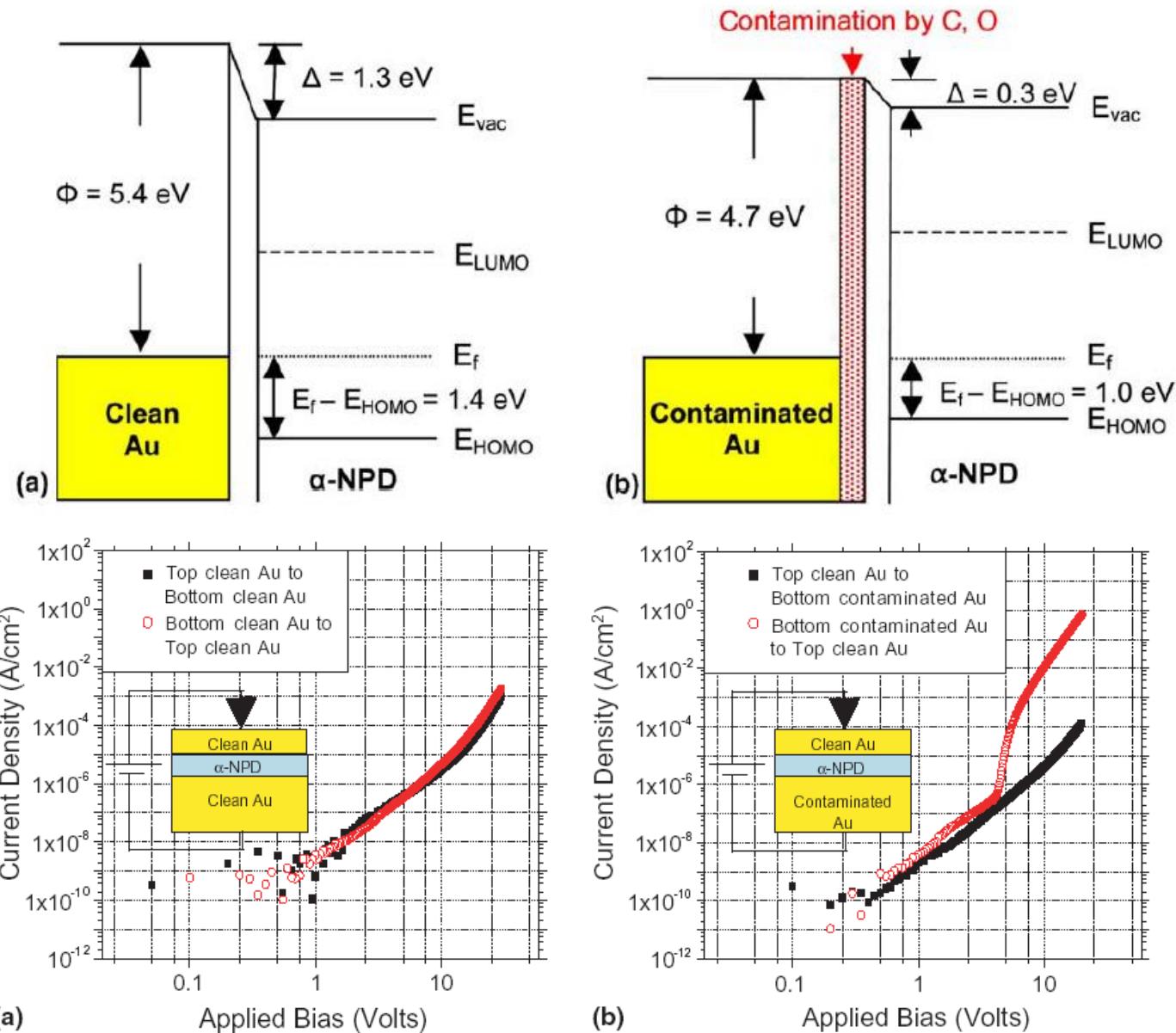
Weak  Strong Interaction strength	Example of interface	Interaction type	
	Noble gas atoms or saturated hydrocarbons on clean metal surfaces	Physisorption, absence of charge transfer	Integer charge transfer
	π -conjugated molecules and polymers on organic or passivated metal surfaces	Physisorption, possible integer electron charge transfer through tunneling	
	π -conjugated molecules on non-reactive clean metal surfaces	Weak chemisorption, possible partial charge transfer	IDIS and partial C.T.
	(π -conjugated) molecules on reactive clean metal surfaces	Strong chemisorption, covalent bonding between molecule and metal, (partial) charge transfer	
	(π -conjugated) molecules with intrinsic dipole and anchoring groups on clean metal surfaces	Strong chemisorption, covalent bond at <i>specific</i> sites of the molecule and metal, (partial) charge transfer, surface dipole	Chemical reactions @ interface

Intimate metal organic contact is possible
due to (Ultra) High Vacuum **metal and molecule** evaporation

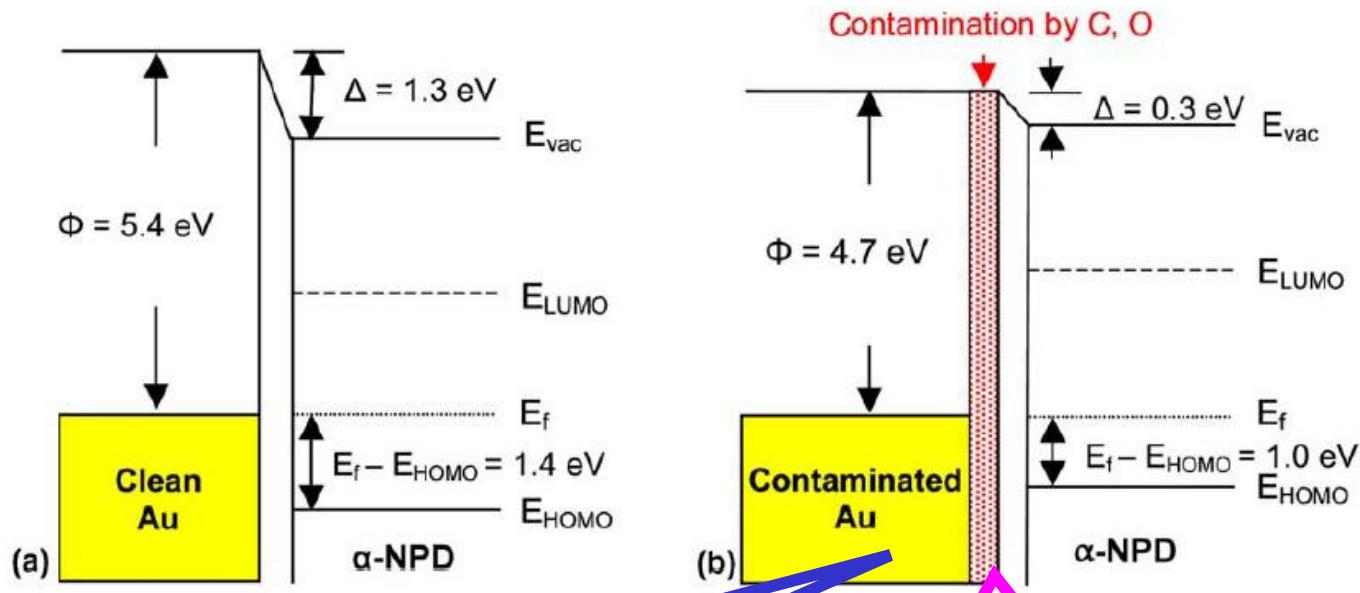


Molecules: Clean Vs. contaminated metal

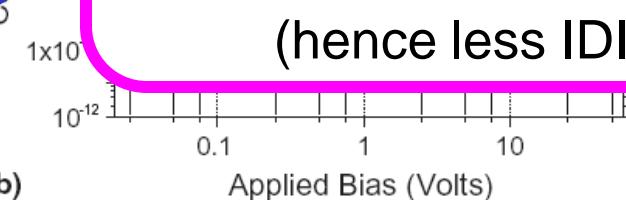
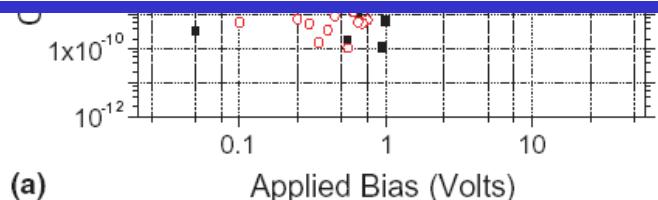
A. Wan et Organic Electronics 6 (2005) 47–54



Molecules: Clean Vs. contaminated metal



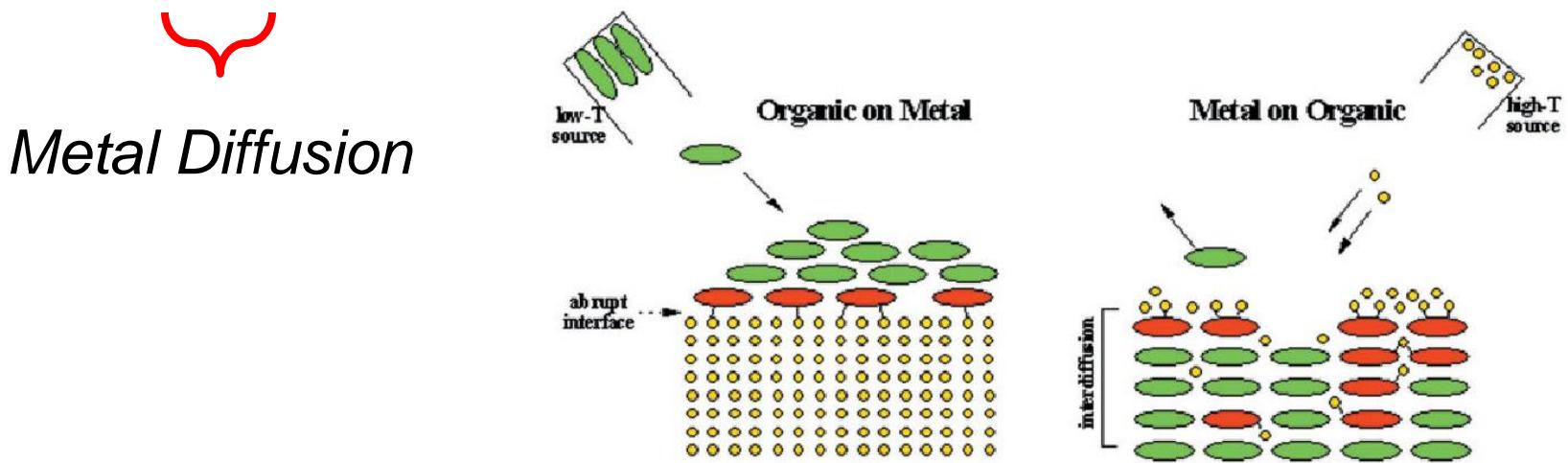
counter-intuitively
The contaminated metal has the
smaller work function BUT
yields the *lower hole barrier*



Contaminants give:
a pushback effect
but also
a less intimate contact
(hence less IDIS)

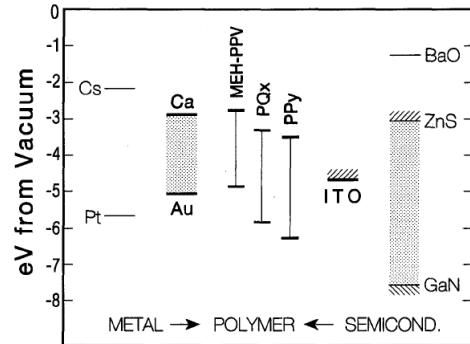
Effect of deposition technique

- Vacuum deposited **vs** liquid phase deposition:
solvents/air passivates interfaces
- Metal upon Organics **vs** Organics upon Metal



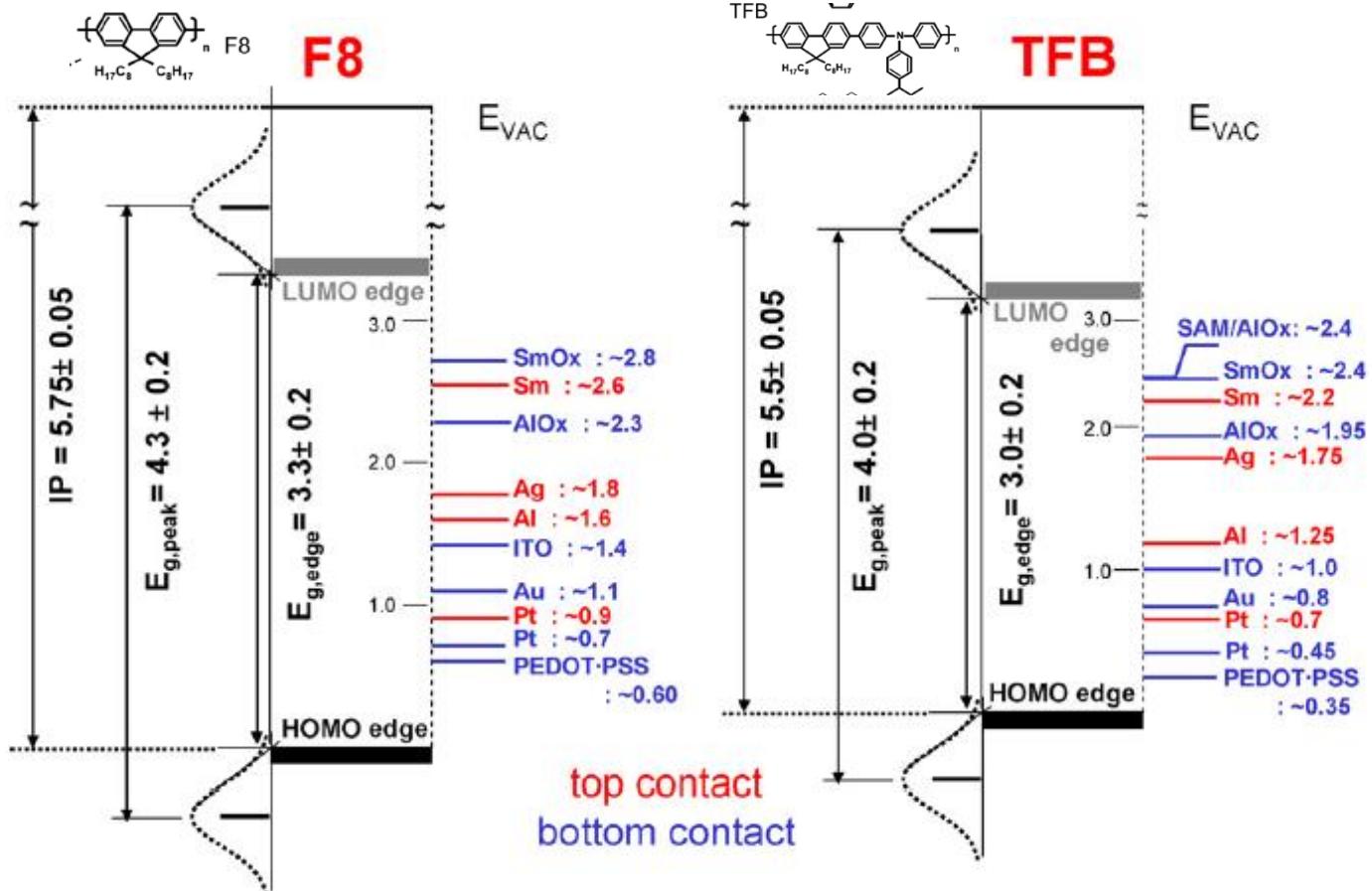
But often this does not give different electrical behavior...

Materials

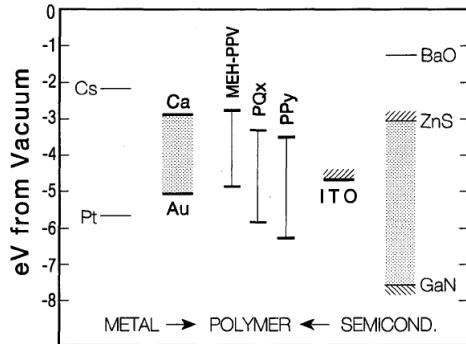


Theory...

practice...

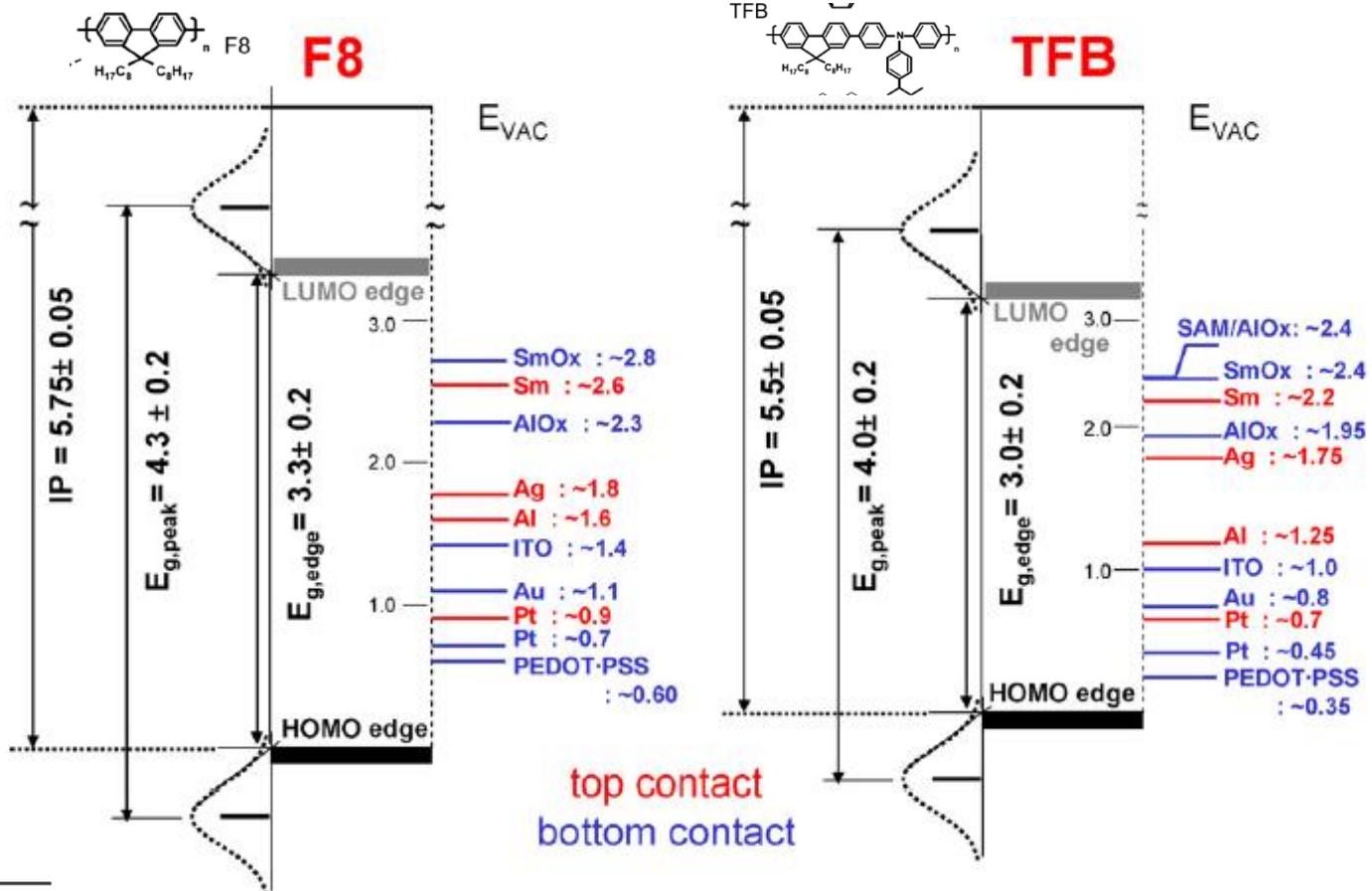


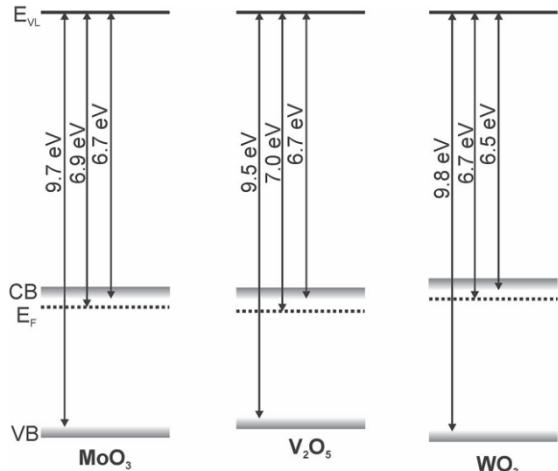
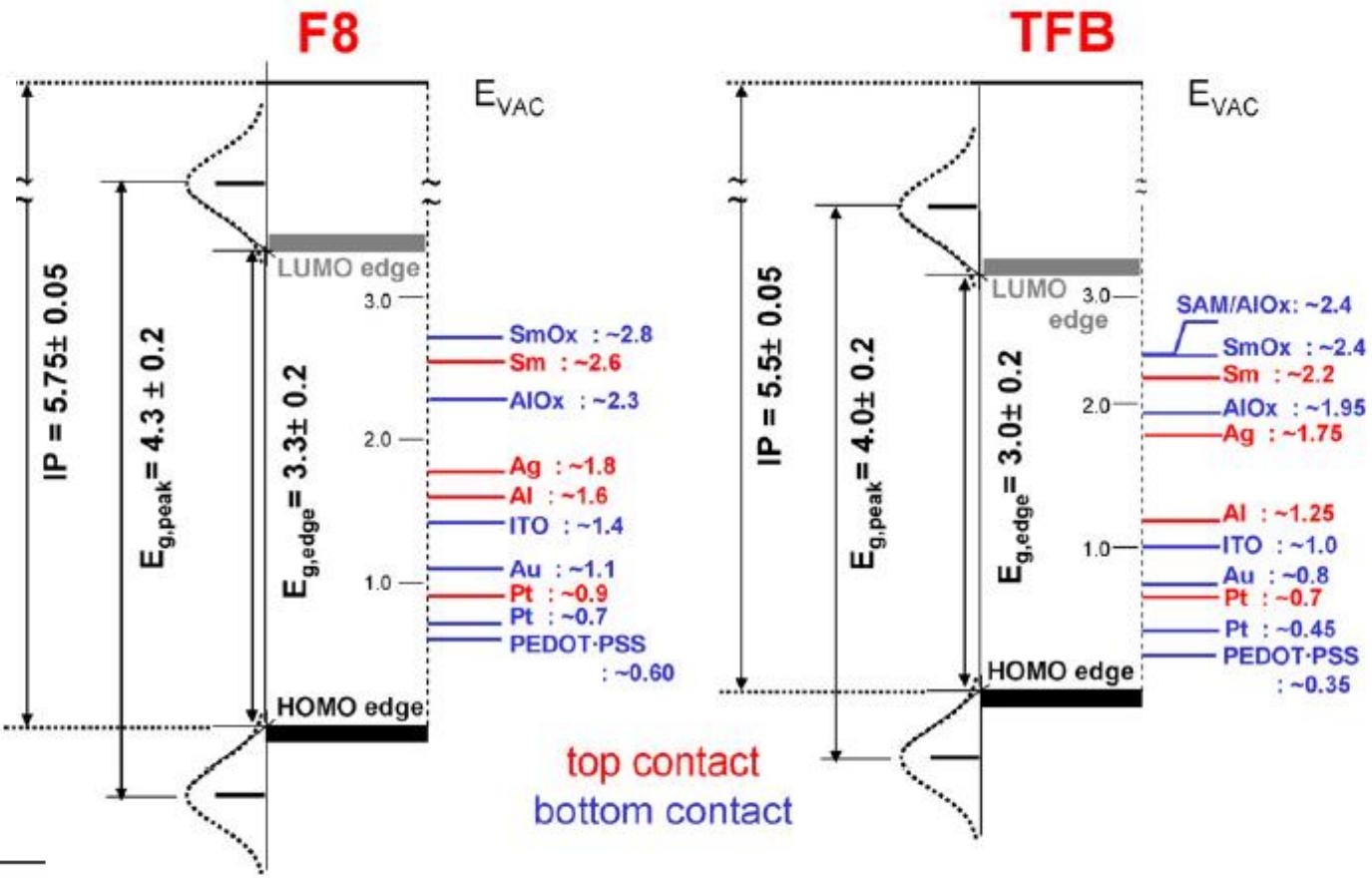
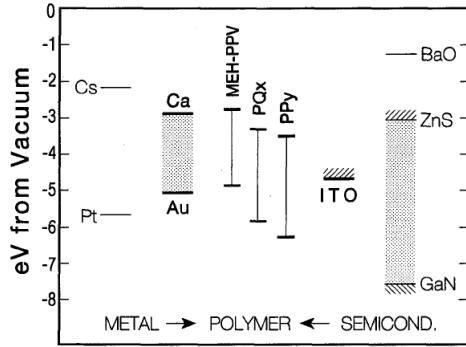
Materials



Theory...

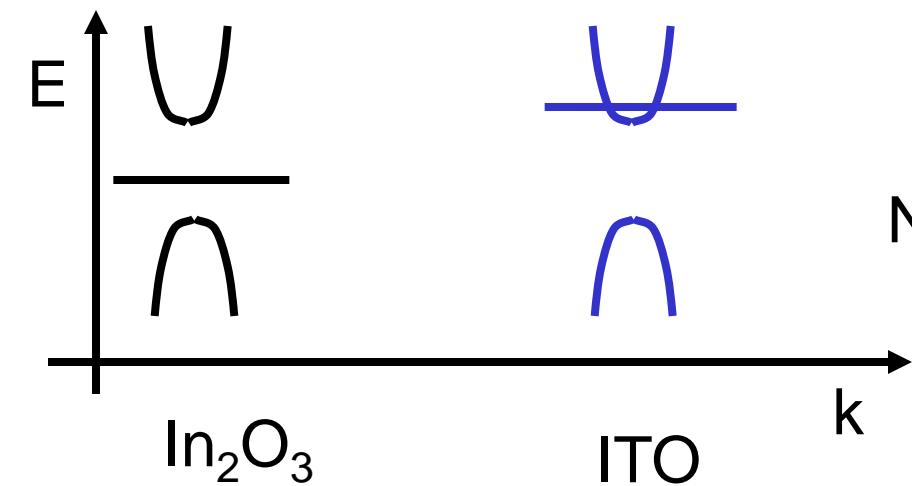
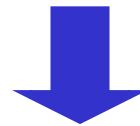
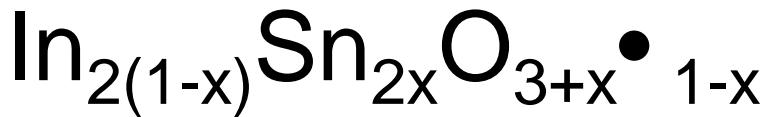
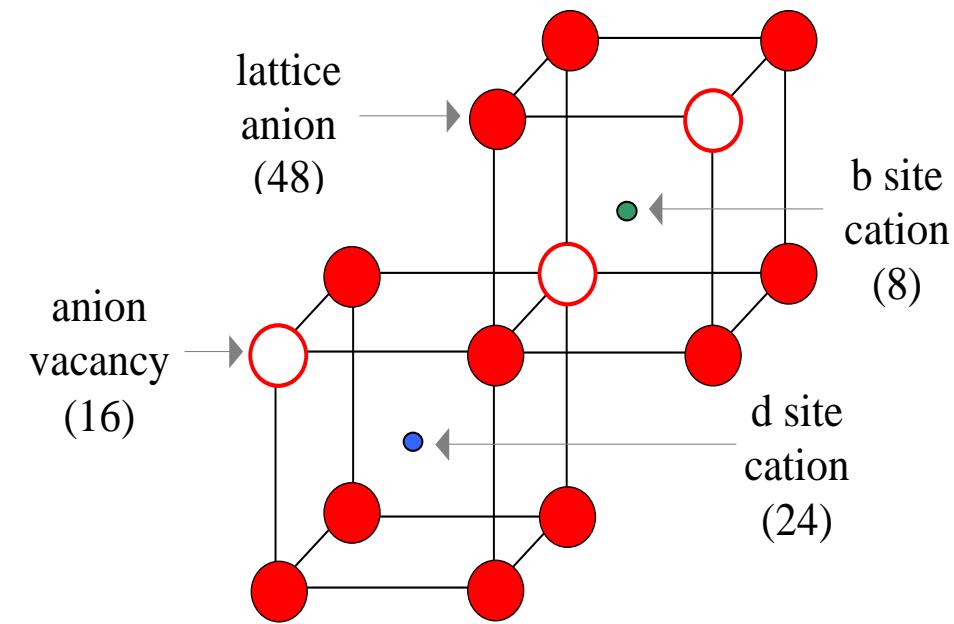
practice...





Transition metal oxides:
n-type semiconductors with low-lying CB,
are useful hole inj./extr. layers

ITO (I)



N-type degenerate semiconductor

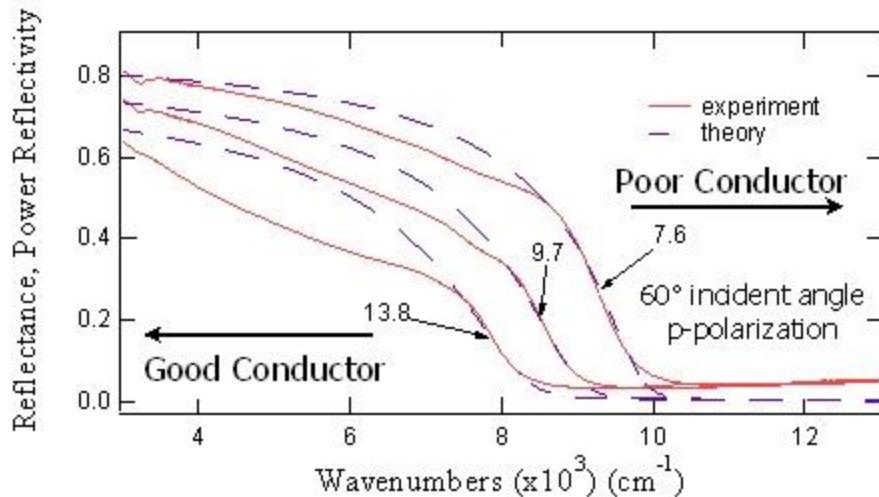
ITO (II)

$$\varepsilon = 1 - \left(\frac{\omega_p}{\omega} \right)^2, \omega_p = \left(\frac{n e^2}{\epsilon_0 m} \right)^{1/2}$$

$\omega > \omega_p, \varepsilon > 0$
 $\omega < \omega_p, \varepsilon < 0$

→

transparent insulator
reflective conductor

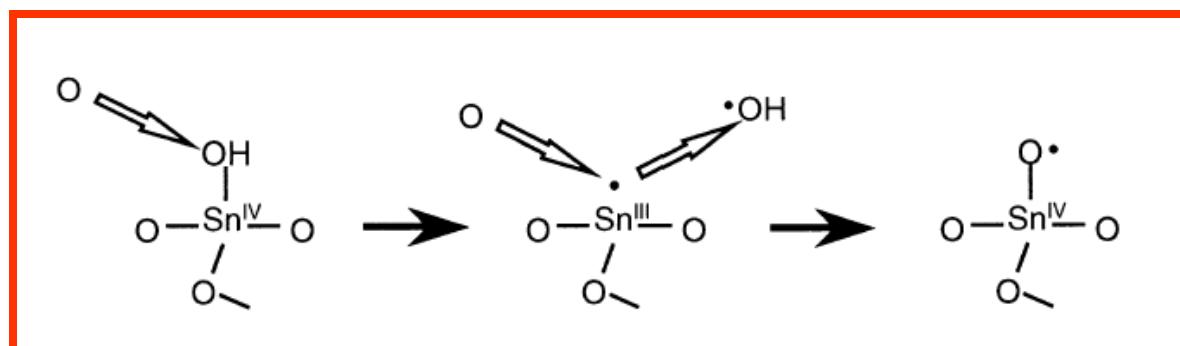


ω_p ITO ≈ 900 nm

Interface functionalization

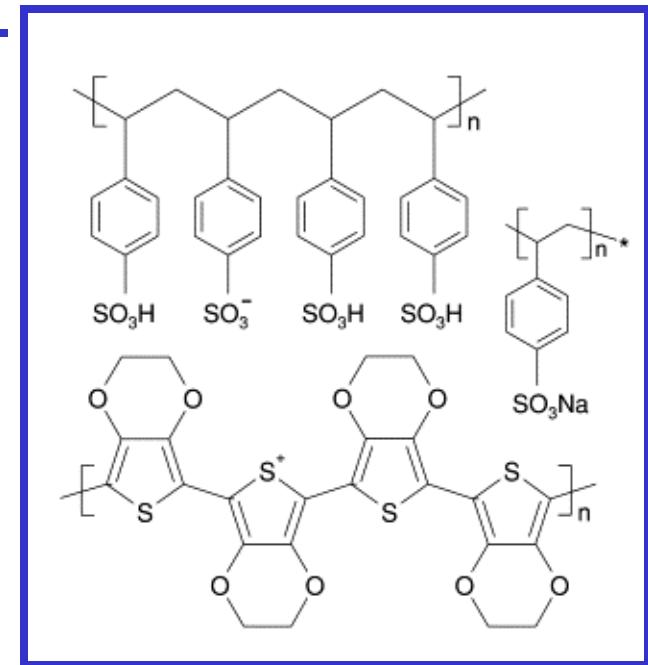
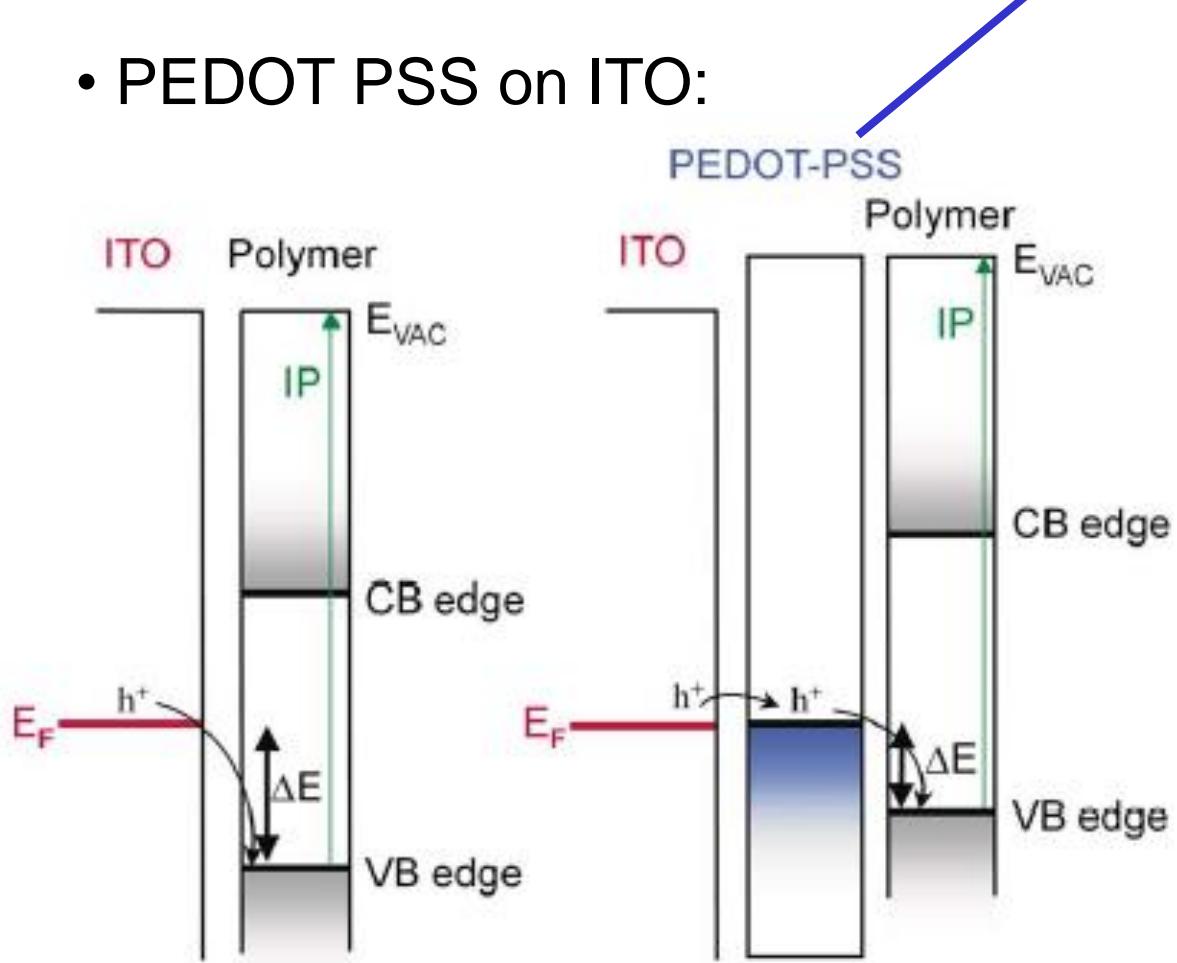
TABLE I. Work function, sheet resistance, and root-mean-square (rms) surface roughness of ITO for the different surface treatments.

	Surface treatment	Work function (eV)	Sheet resistance (Ω/sq)	Surface roughness (nm)
	As-received	4.5	16.1	2.6
(a) Mechanical	Paper rubbing	4.2	16.3	2.3
	Teflon rubbing	4.2	16.5	2.4
(b) Wet cleaning	Ultrasonic	4.35	15.5	3.4
	RCA (no IPA)	4.35	19.6	2.4
(c) Dry cleaning	Aquaregia (10'/20'/30')	4.6/4.3/4.7	18.5/23.5/28.6	3.8/8.4/8.8
	O ₂ plasma (5'/10'/15')	4.35/4.75/4.65	16.4/15.0/16.4	1.4/1.4/2.1
	Ar plasma (5'/10'/15')	4.5/4.5/4.55	16.7/17.3/17.0	10.9/15.4/23.0
(d) Combined*	Aquaregia (20')/O ₂ plasma (10')	4.6	27.7	6.0
	O ₂ plasma (10')/aquaregia (20')	4.7	>30.0	1.8



Interface functionalization

- PEDOT PSS on ITO:



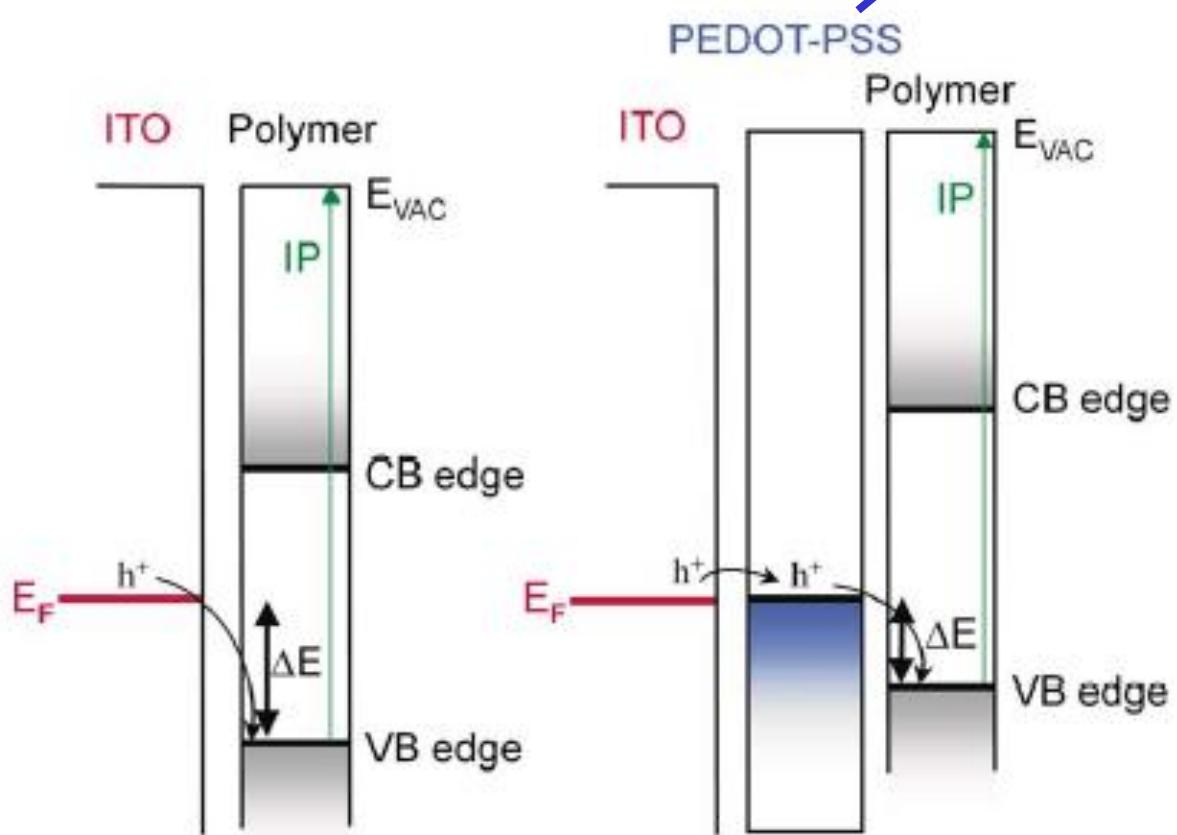
$10^{-5} - 100 \text{ S/cm}$
depending on
processing and
composition

Large ΔE , varies with ITO(E_F)

Smaller ΔE , independent of ITO(E_F)

Interface functionalization

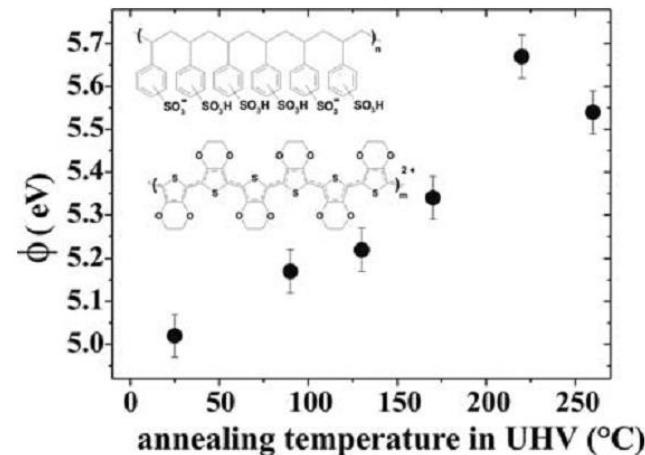
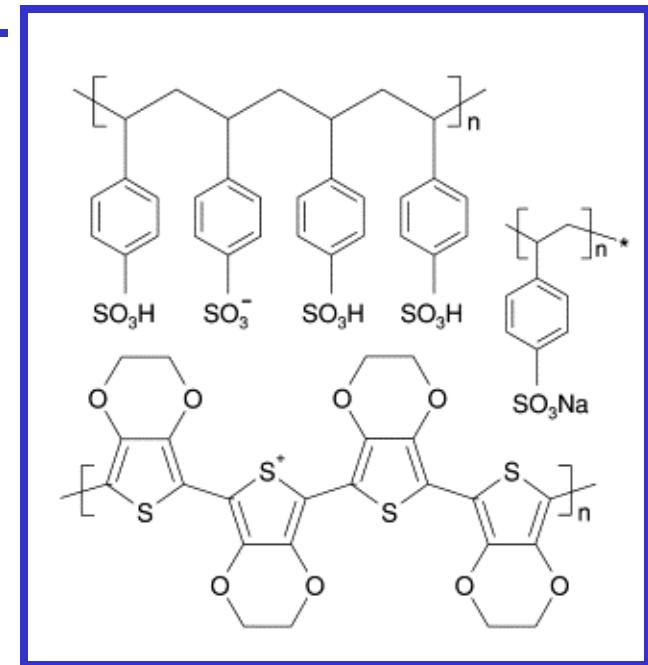
- PEDOT PSS on ITO:



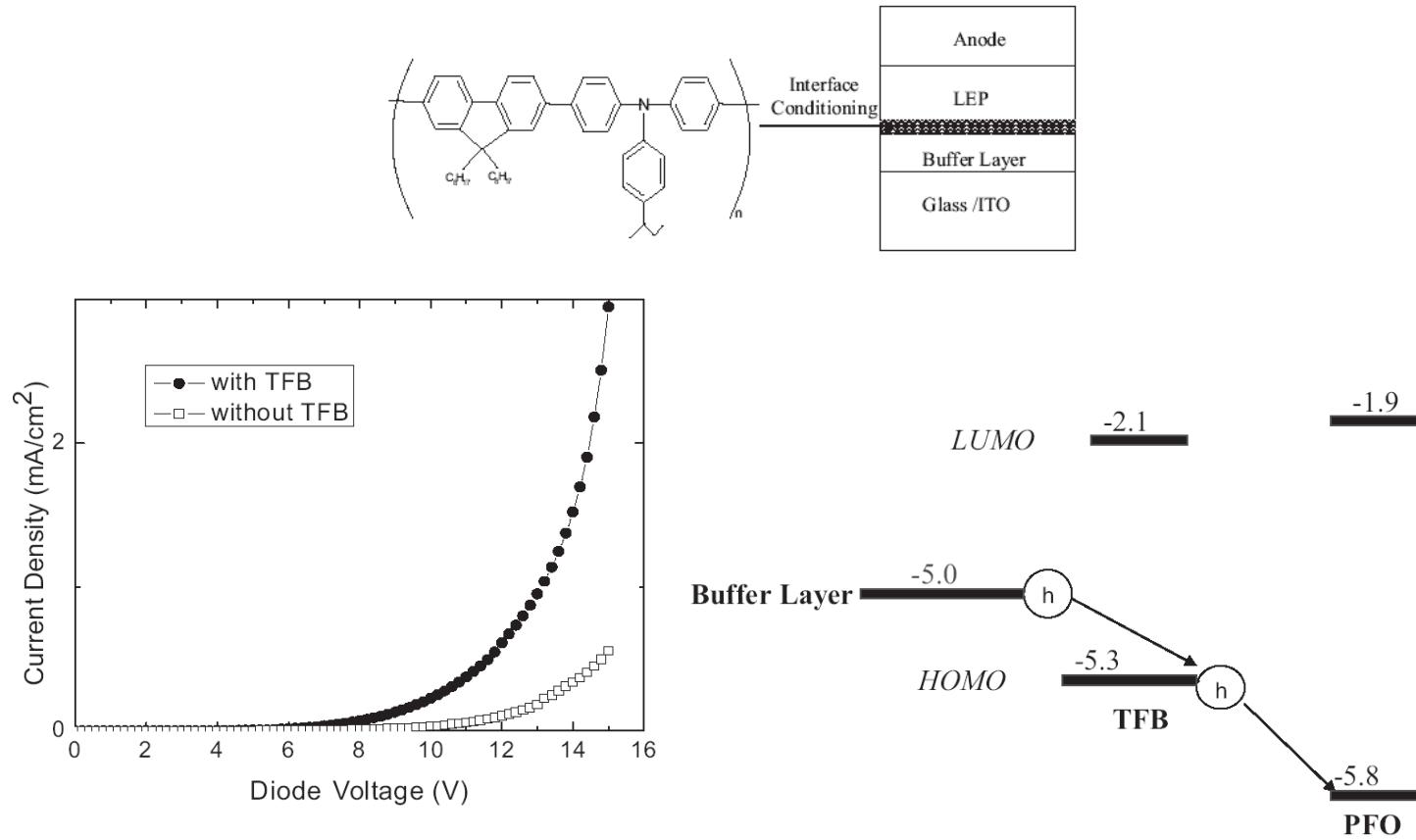
Large ΔE , varies with ITO(E_F)

Phys. Status Solidi RRL 6, No. 7 (2012)

Smaller ΔE , independent of ITO(E_F)



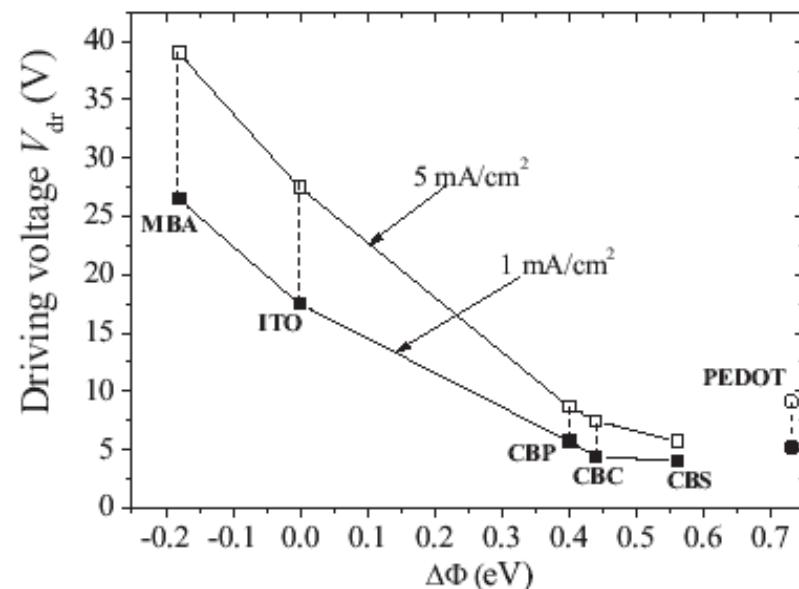
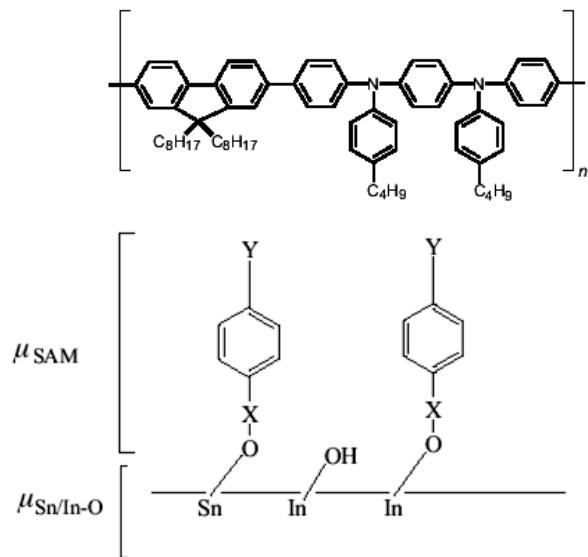
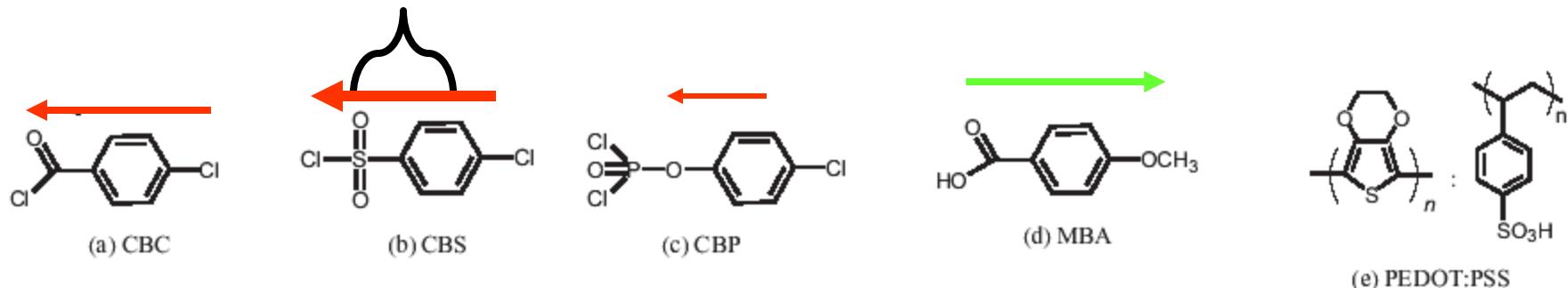
Interface functionalization: multilayer



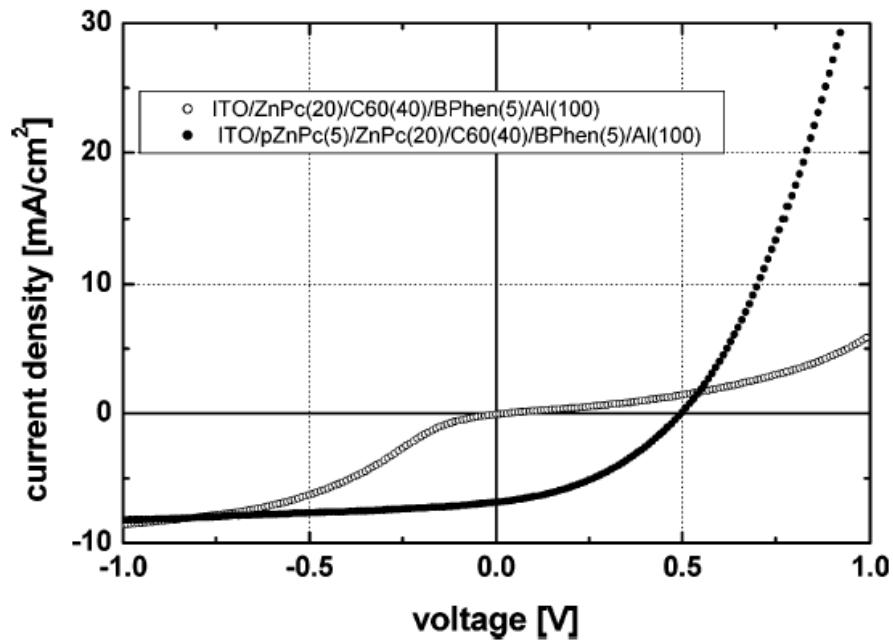
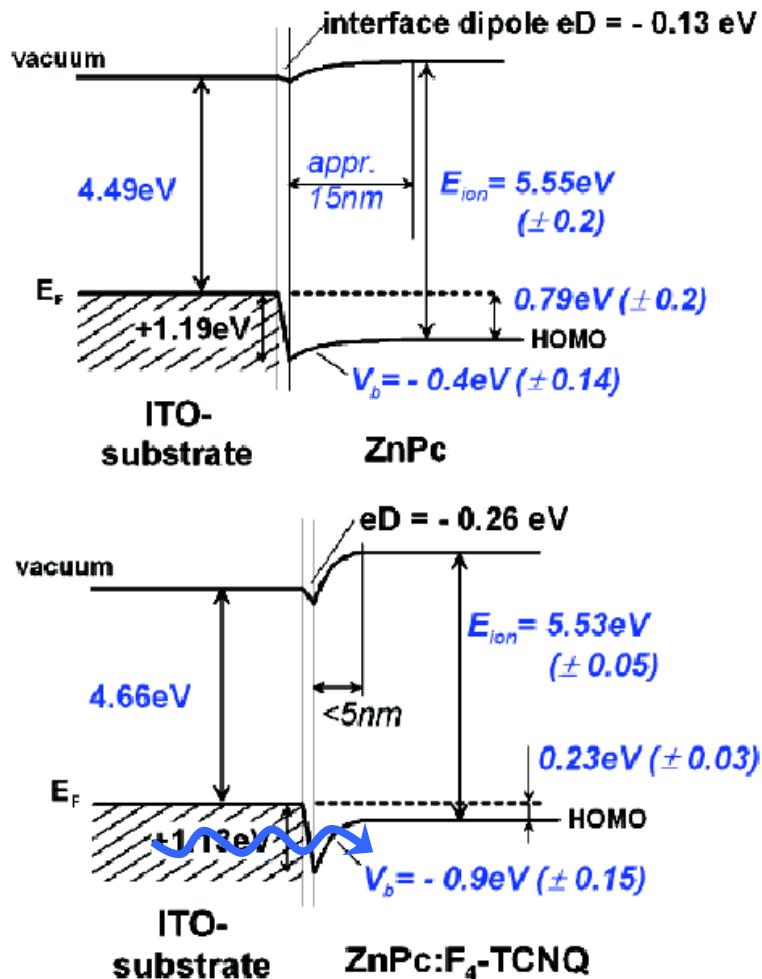
From single large Φ_B to many smaller Φ_{Bi}

Interface functionalization(4)

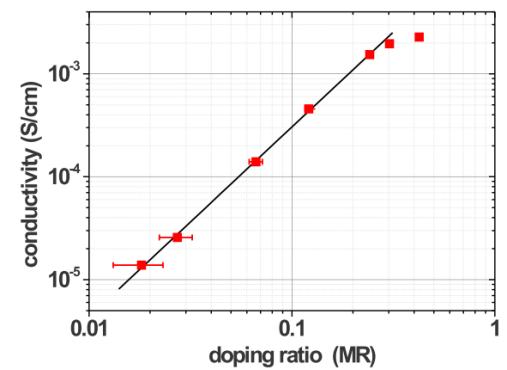
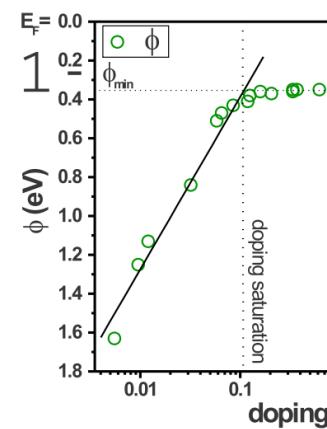
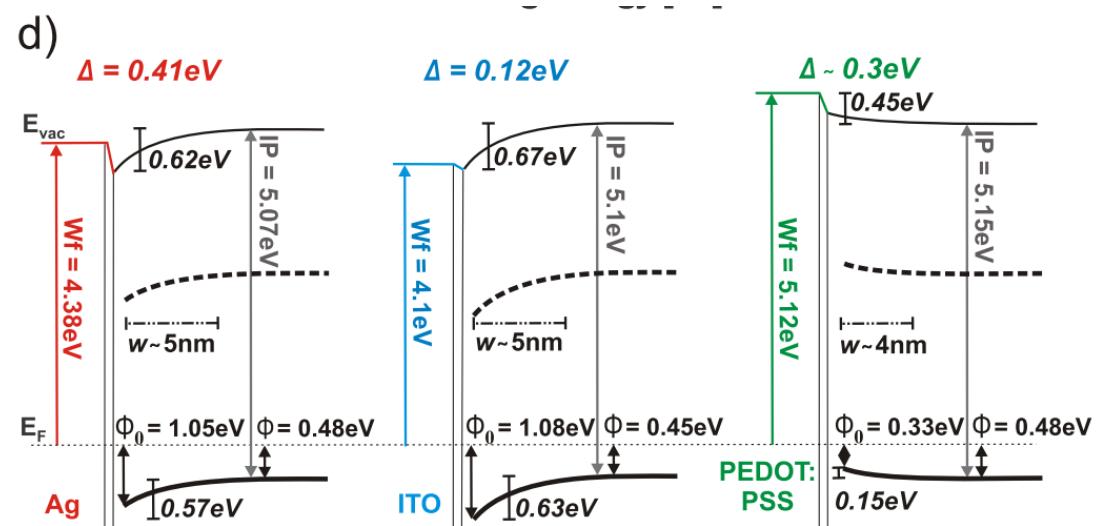
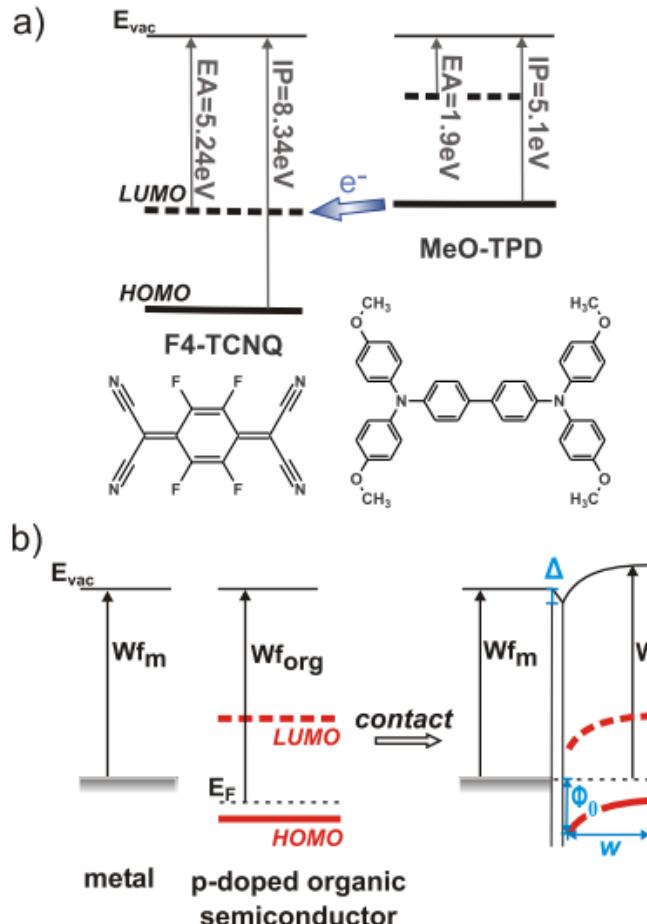
polar SAM on ITO



Doping

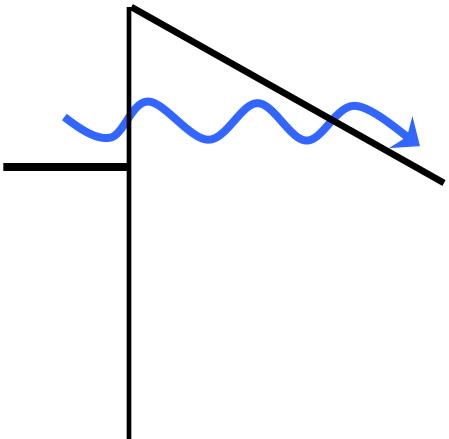


Doping



Charge injection

Classic models

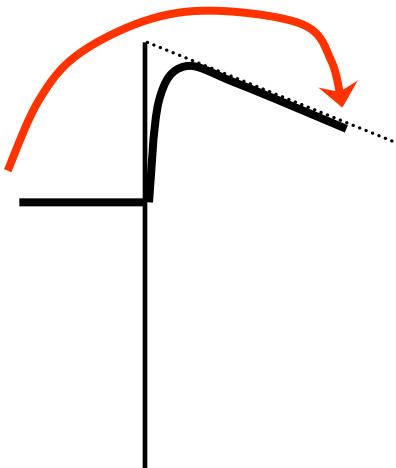


Through the barrier:

Fowler-Nordheim

$$J = BF^2 \exp\left(-\frac{b}{F}\right)$$

Needs bands and triangular barrier



Over the barrier:

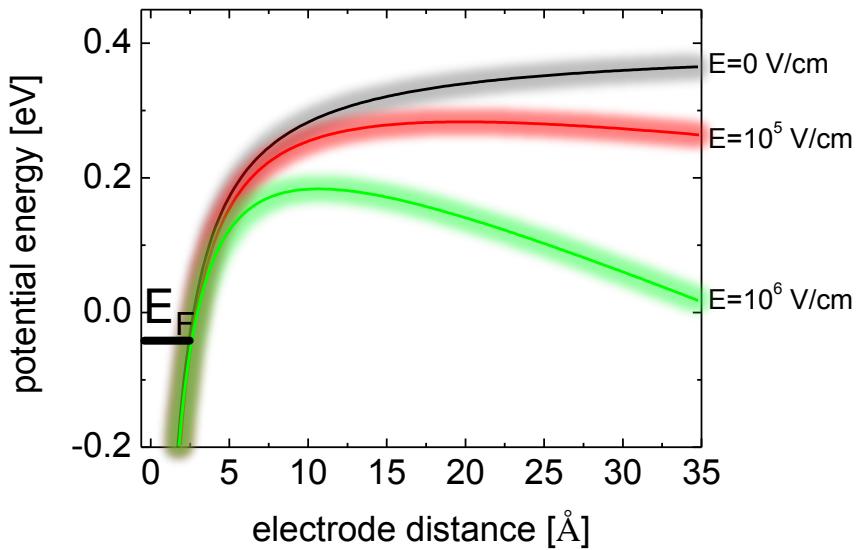
Richardson-Schottky

$$J = A^* T^2 \exp\left(-\frac{\Delta - cF^{1/2}}{kT}\right)$$

Does not take hopping into account



Injection in organics



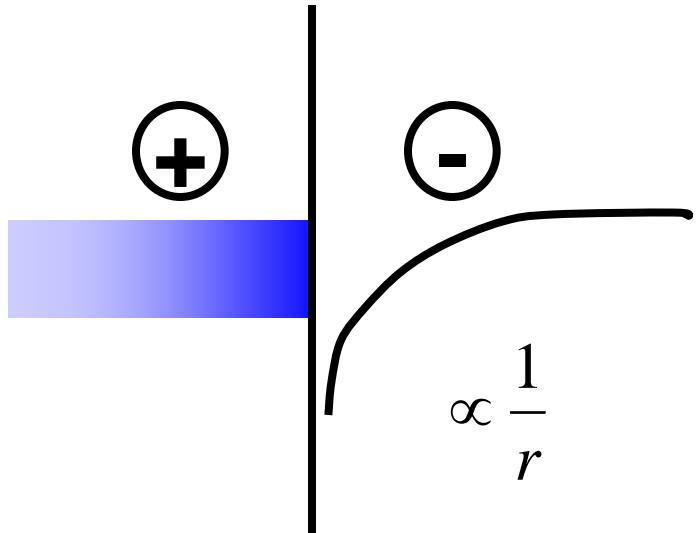
Ingredients:

- hopping transport
- Schottky effect
- Energetic disorder

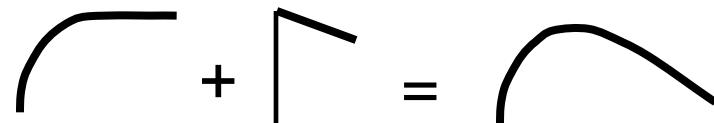
Schottky effect(1)

Ingredients:

- hopping transport
- **Schottky effect**
- Energetic disorder

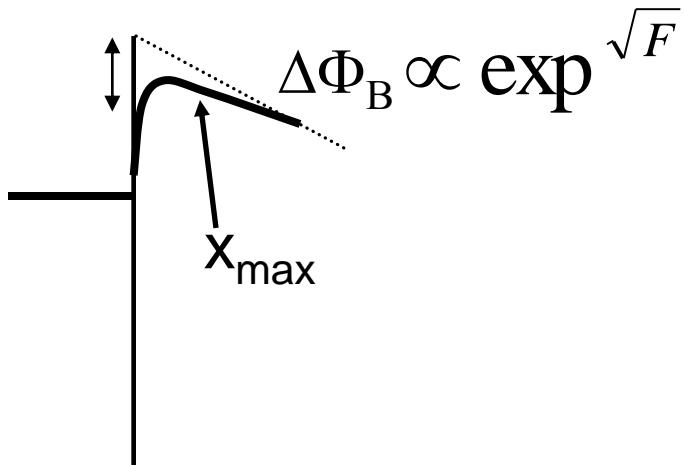


$$\propto \frac{1}{r}$$



Schottky ΔV

Barrier
lowering

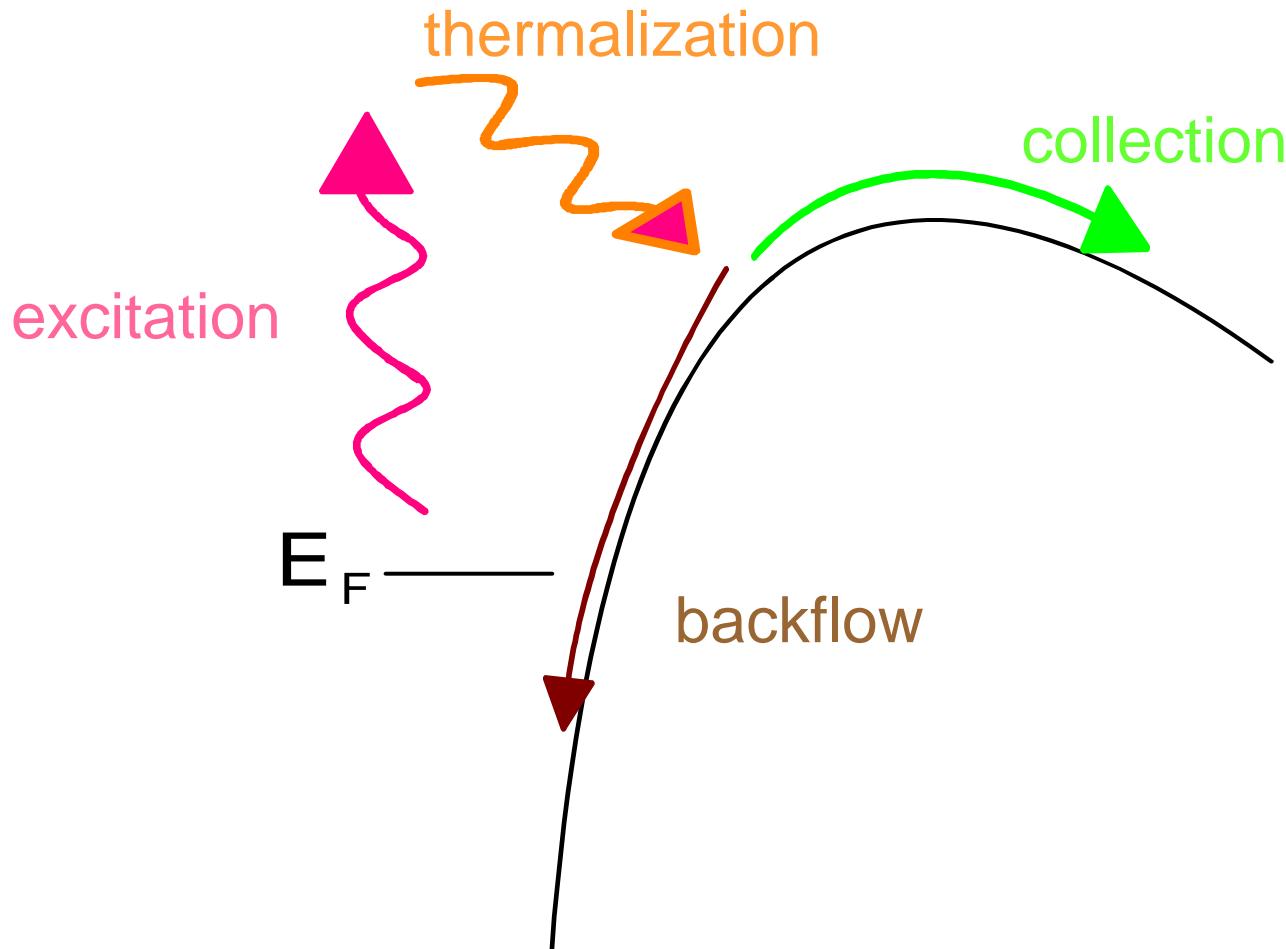


$F:$	$10^5 \text{ V/cm} \rightarrow 2 \times 10^6 \text{ V/cm}$
$V:$	$1 \text{ V} \rightarrow 20 \text{ V su } 100 \text{ nm}$
$\Delta\Phi_B:$	$0.06 \text{ V} \rightarrow 0.28 \text{ V}$
$X_{max}:$	$3.2 \text{ nm} \rightarrow 0.7 \text{ nm}$

Hopping & image potential

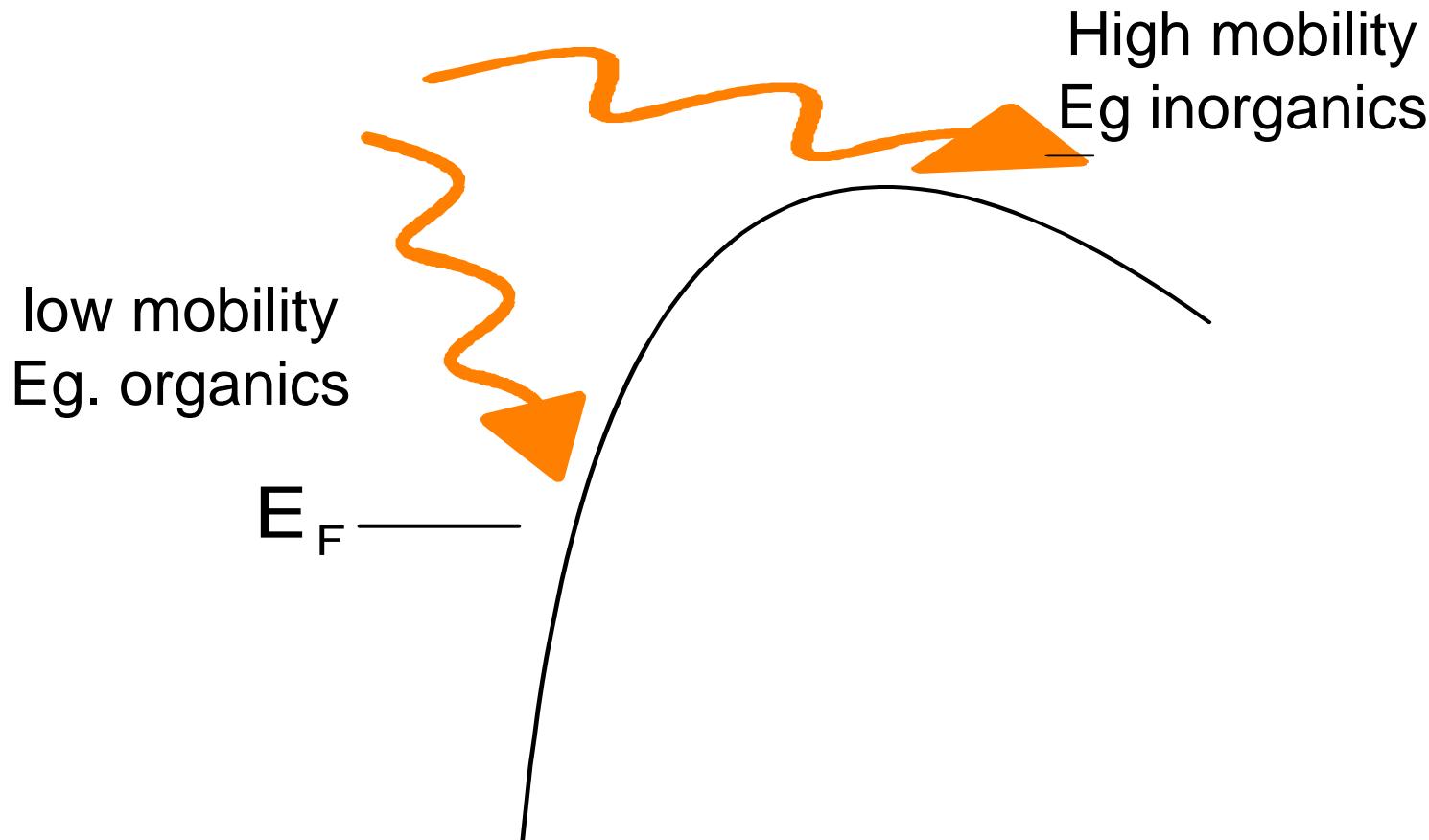
Ingredients:

- hopping transport
- Schottky effect
- Energetic disorder



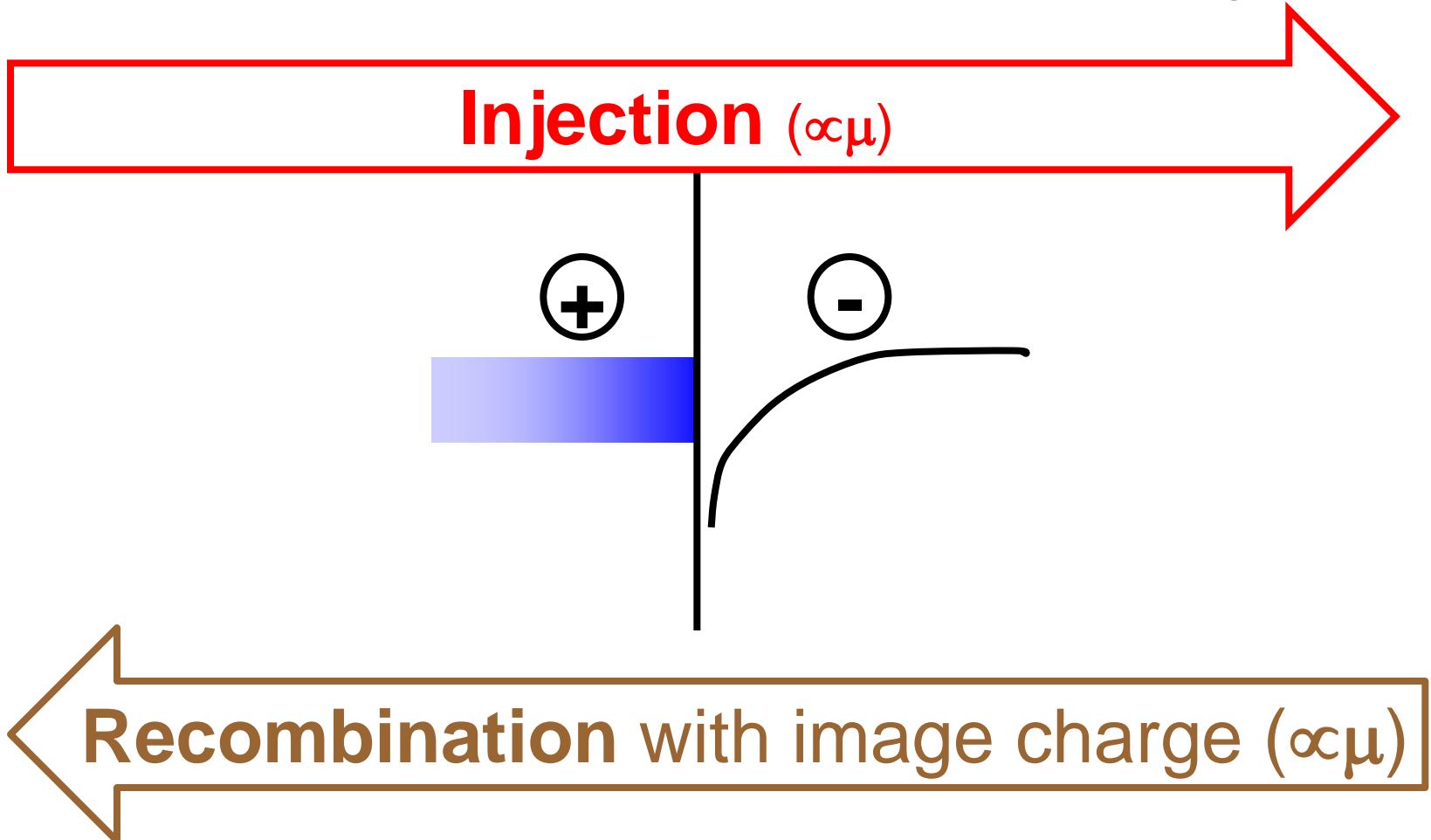
Thermalization length

- Ingredients:
- hopping transport
 - Schottky effect
 - Energetic disorder



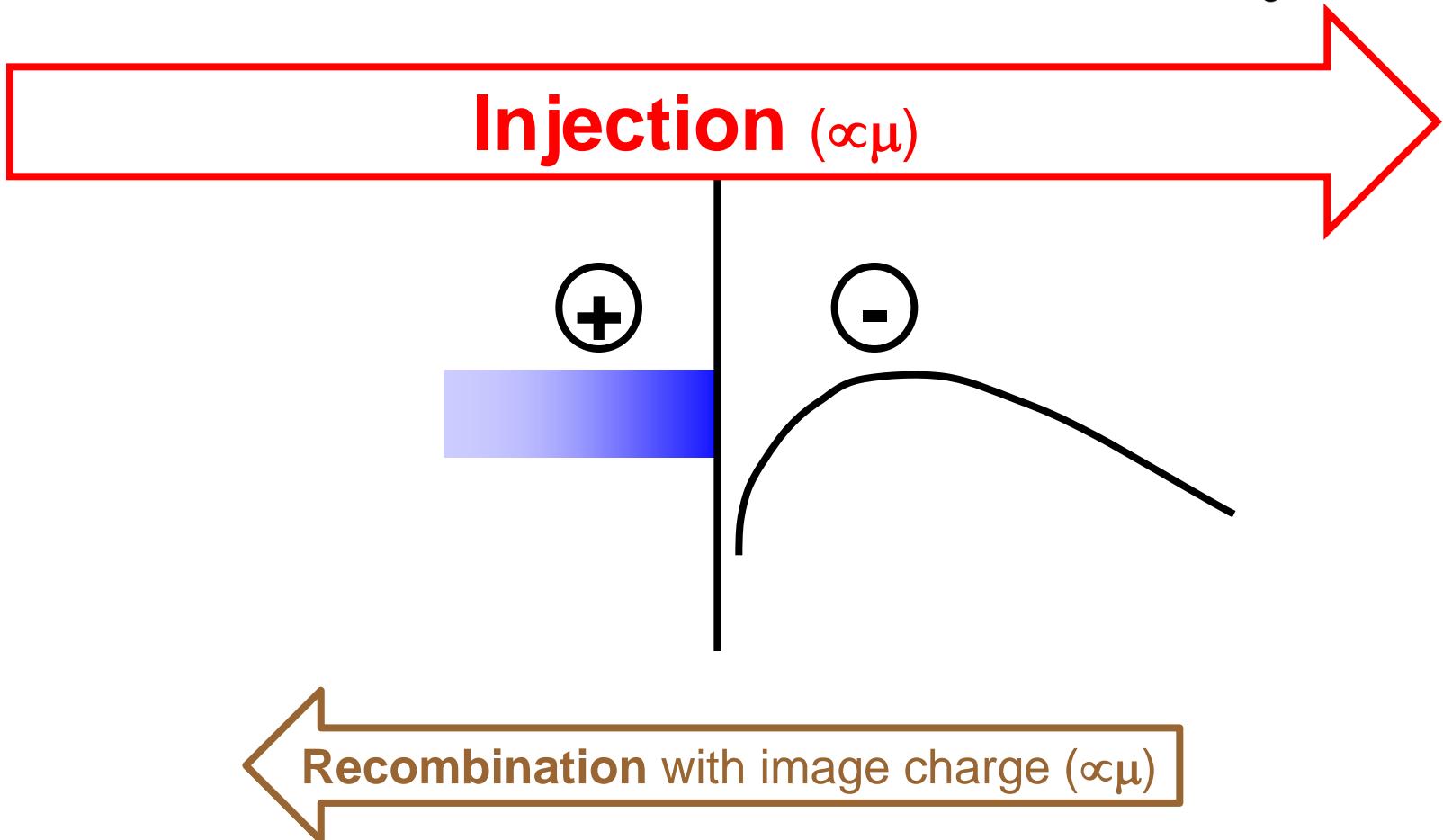
Under thermal equilibrium

- Ingredients:
- hopping transport
 - Schottky effect
 - Energetic disorder

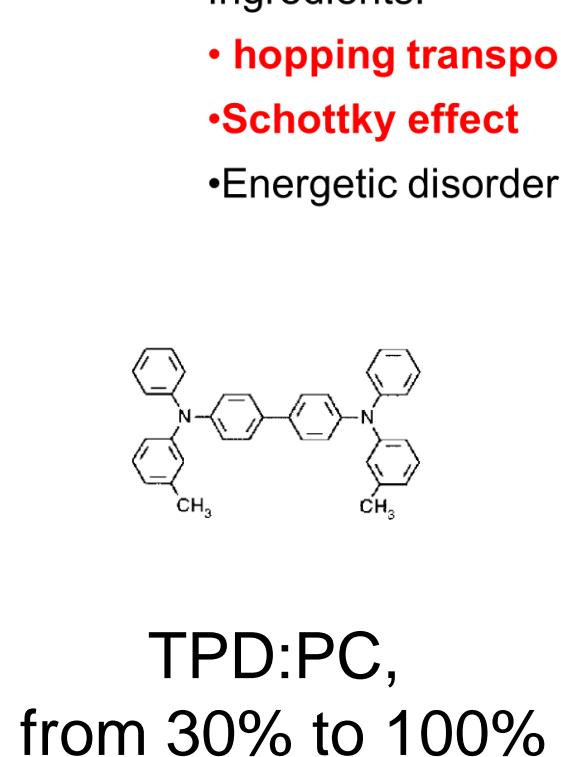
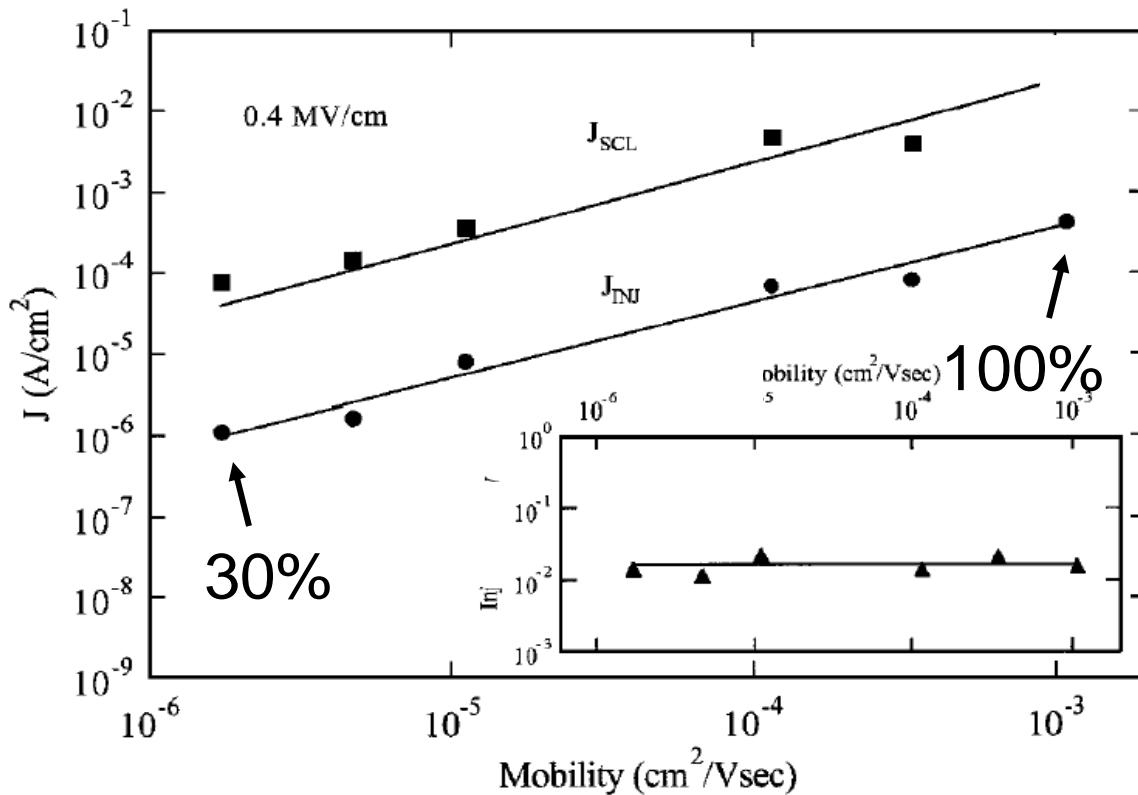


Under Applied voltage

- Ingredients:
- hopping transport
 - Schottky effect
 - Energetic disorder



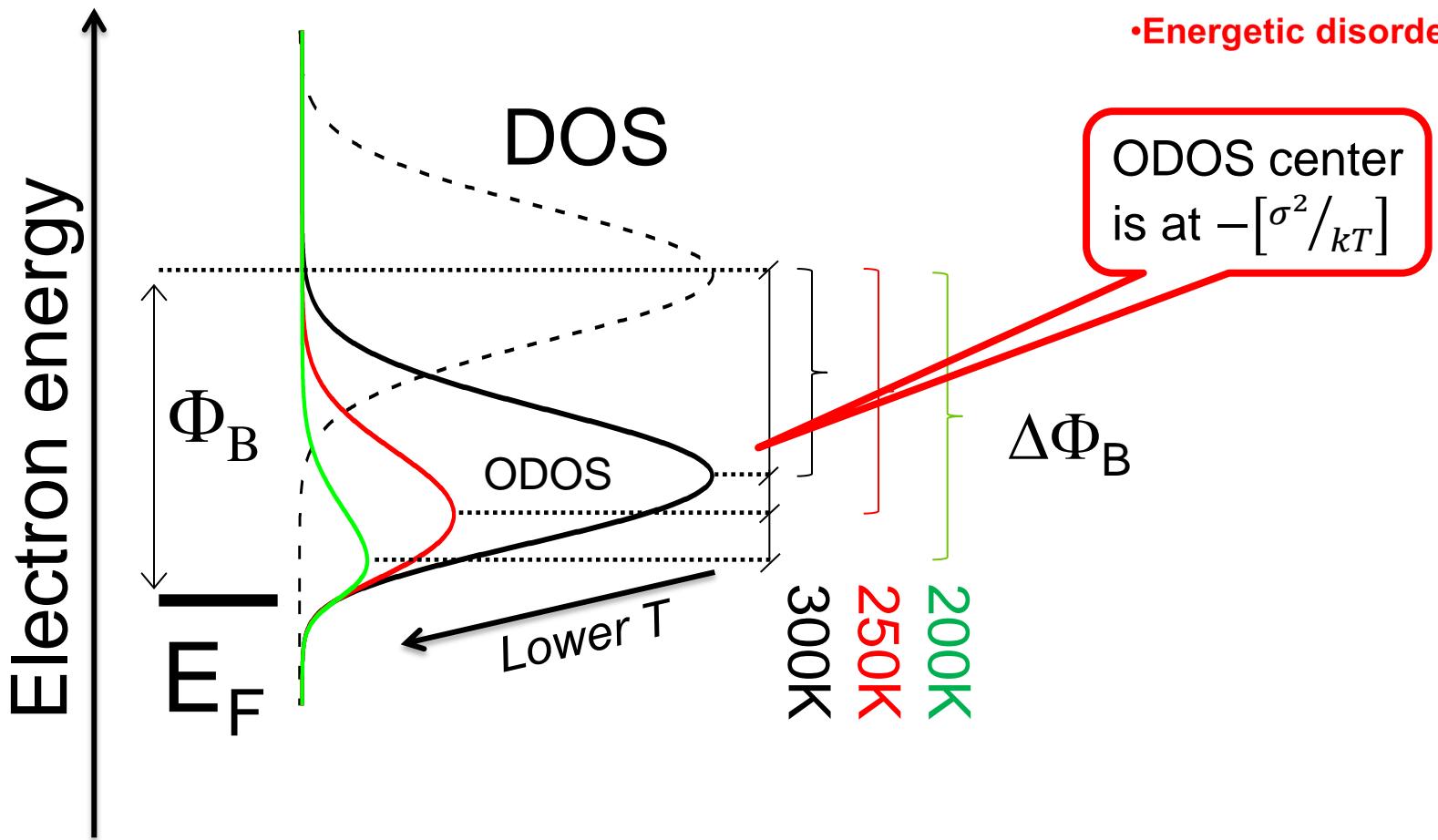
- Ingredients:
- hopping transport
 - Schottky effect
 - Energetic disorder



For a given energetics, the larger the mobility,
the higher the injection efficiency

- Ingredients:
- hopping transport
 - Schottky effect
 - Energetic disorder

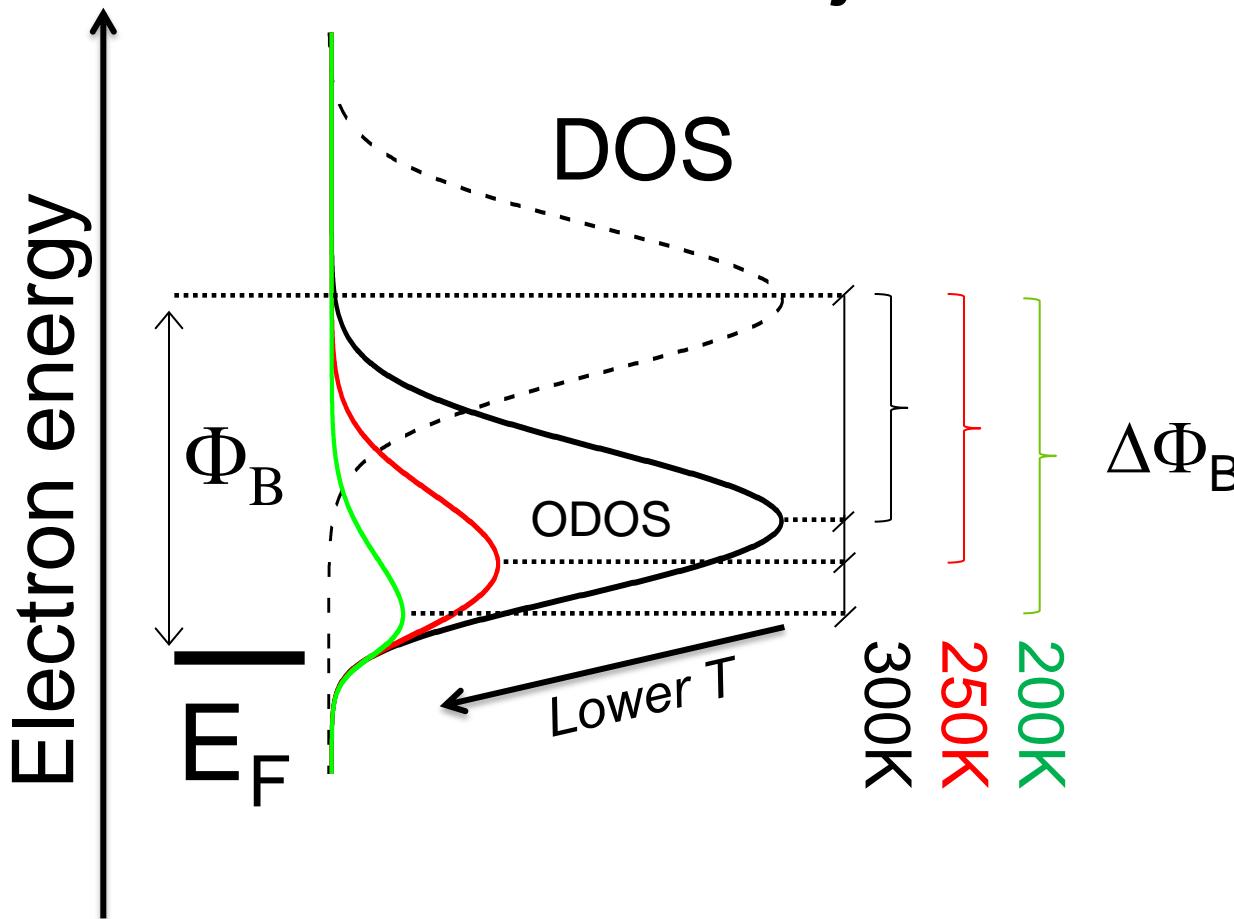
Disorder & injection



The higher the disorder, the lower Φ_B

- Ingredients:
- hopping transport
 - Schottky effect
 - Energetic disorder

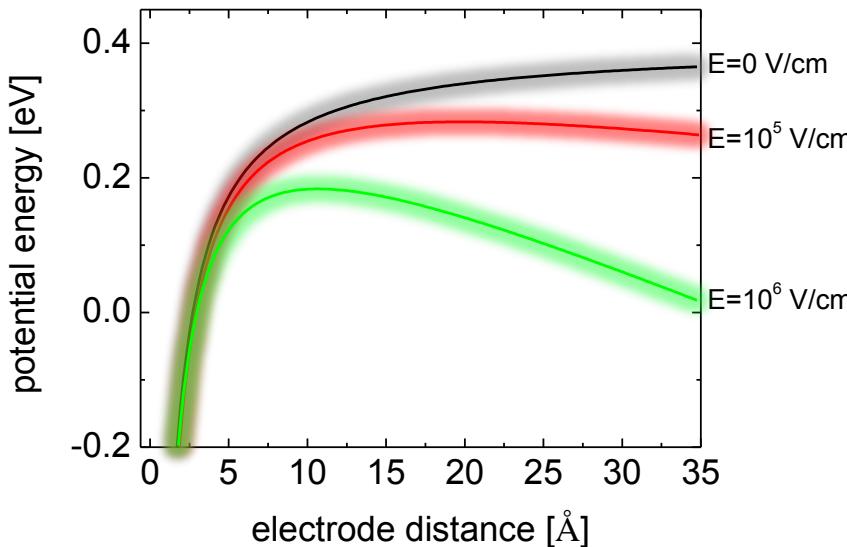
Disorder & injection



$$J = q\mu N_0 F \exp \left(- \frac{\Phi_B - \frac{1}{2} \frac{\sigma^2}{kT}}{kT} + \beta_s \sqrt{F} \right) \Psi(F)$$

- Ingredients:
- hopping transport
 - Schottky effect
 - Energetic disorder

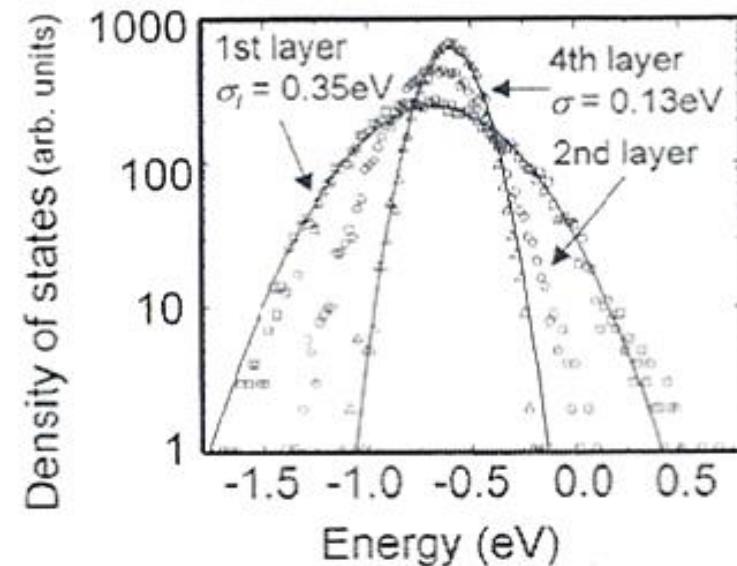
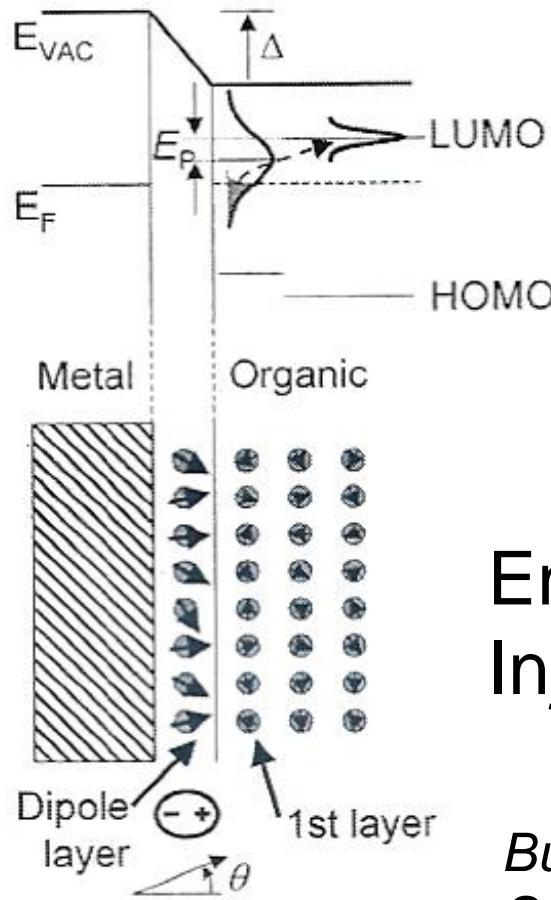
Disorder & injection



$$J = q\mu N_0 F \exp \left[- \frac{\Phi_B}{kT} - \frac{1}{2} \frac{\sigma^2}{kT} + (\beta_s + \beta_\sigma) \sqrt{F} \right] \Psi(F)$$

$\beta_\sigma = 2^{3/2} / 3 [q\alpha\sigma^2/(kT)^3]^{0.5}$

Disorder & injection



Enhanced disorder at interface:
Injection **is not** the most difficult step

*But! Image charge attenuates interface disorder....
So what?!*

Organic Organic interfaces

- Low charge density -> no pillow effect
- Active forces:
 - Van der –waals
 - Electrostatic interaction
 - Repulsion forces
- Degree of interaction
 - CT@gnd state (eg. *alkyl chains prevent intimate contact*)
 - Orbital mixing @gnd state (short range interaction)
 - Polarizations (long range interaction)

} **INTERFACE
DIPOLE!**

The End