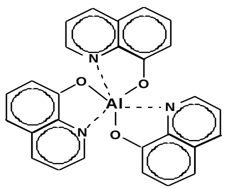
Organic Electronics: Motivations, Status and Promises

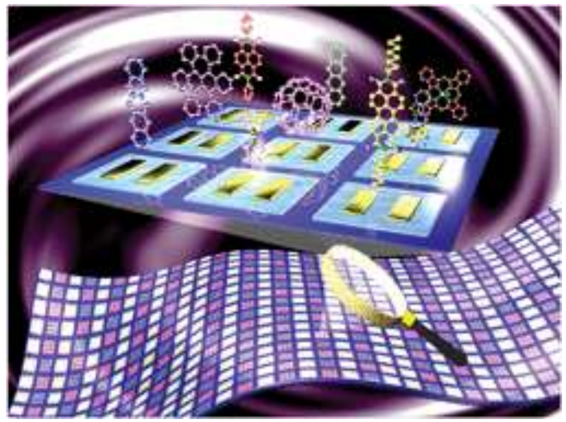
Antoine Kahn

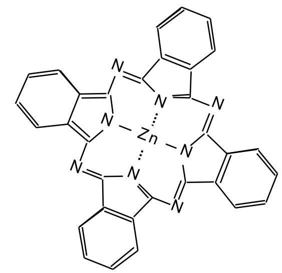
Department of Electrical and Computer Engineering
Princeton University, Princeton NJ, 08544, USA

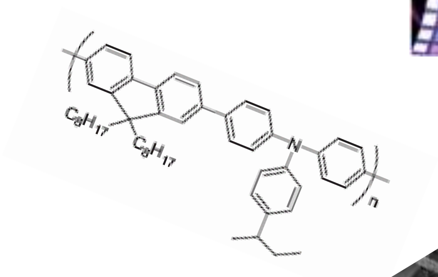
Israeli Vacuum Society
May 5, 2021

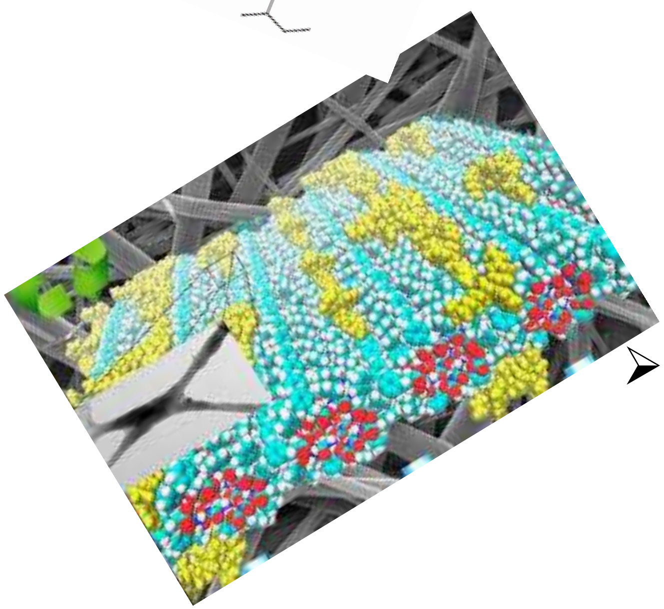
Organic electronics



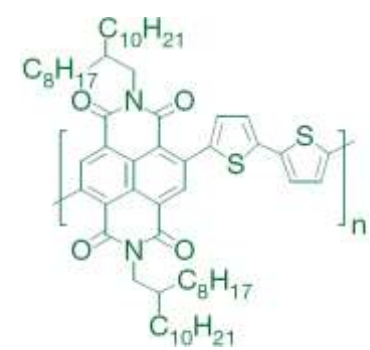


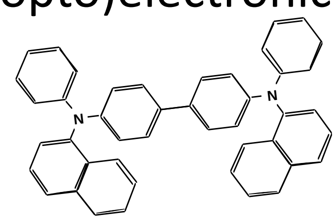






- **Organic electronics**: field of materials science concerning the design, synthesis, characterization, and application of **organic carbon-based** small molecules or polymers that show desirable **electronic** properties such as energy gap and conductivity.
- **Thin film** technology, for flexible, large area, low cost, (opto)electronic applications





Organic electronics today

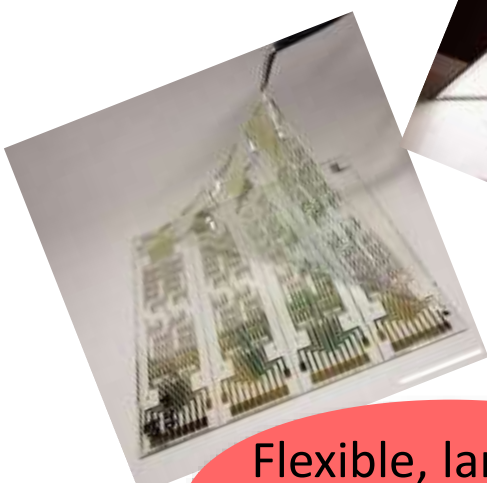
Photovoltaic cell

Light emission; lighting; displays

Light harvesting

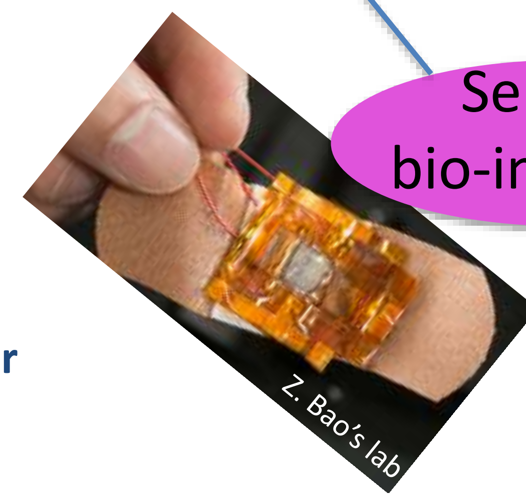
Light emitting diode

Organic Electronics



Flexible, large area electronics; logic; memory

Field effect transistor
Memory devices



Sensing; bio-interfaces

Field effect transistor
Photodetectors

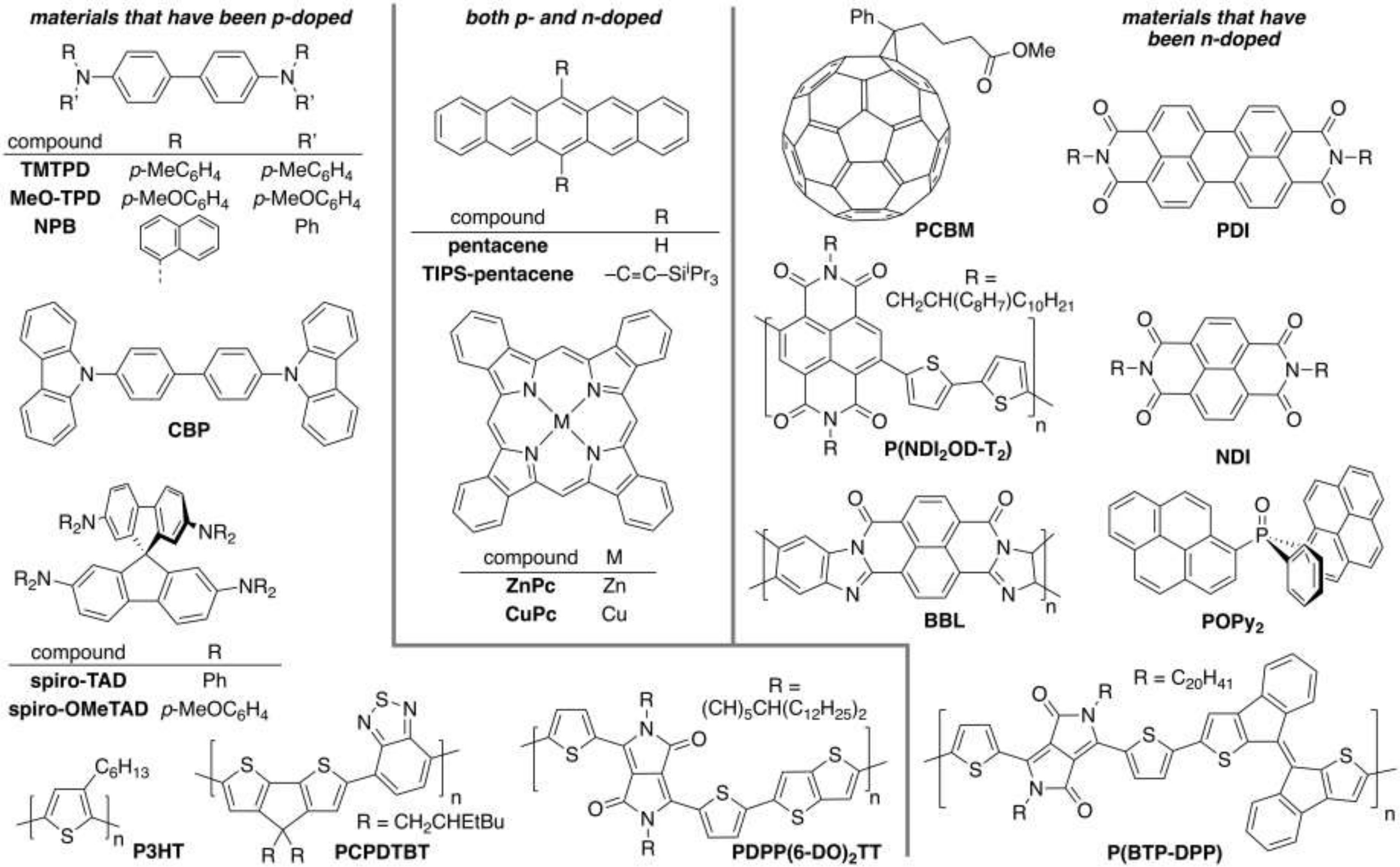
Outline

- Organic semiconductors
  - Quasi infinite choice of materials and energy levels
  - Basic considerations of electronic structure
  - Key enabling properties
- Light emission
  - Organic Light Emitting Diode: origin and evolution
  - Fundamental improvements
  - OLED displays and lighting
- Light harvesting
  - Organic Photovoltaic cell: key principles and materials
  - The non-fullerene acceptor revolution
- Electronics on plastics
  - Organic Field Effect Transistor: key principles and materials
  - Applications

Outline

- Organic semiconductors
  - Quasi infinite choice of materials and energy levels
  - Basic considerations of electronic structure
  - Key enabling properties
- Light emission
  - Organic Light Emitting Diode: origin and evolution
  - Fundamental improvements
  - OLED displays and lighting
- Light harvesting
  - Organic Photovoltaic cell: key principles and materials
  - The non-fullerene acceptor revolution
- Electronics on plastics
  - Organic Field Effect Transistor: key principles and materials
  - Applications

Organic semiconductors (OSC): quasi infinite space

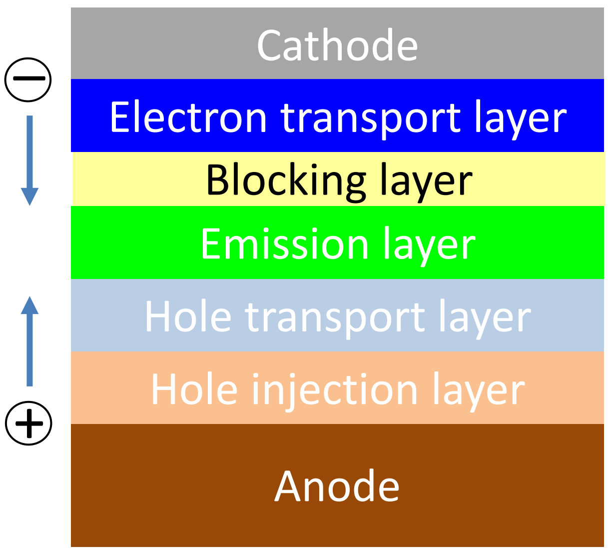


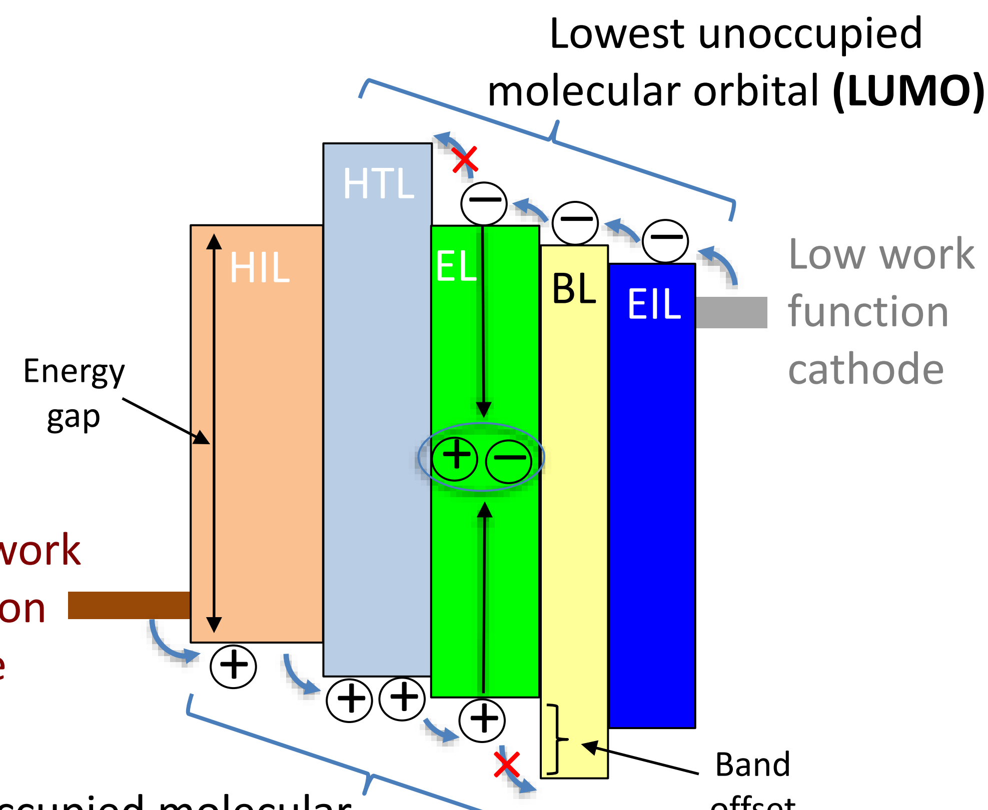
S. Barlow et al., *Handbook of Conducting Polymer* (2018)

OSC devices: charge injection / extraction

- OSCs have extremely low intrinsic carrier densities and are essentially insulators
- OSC devices function via charge carrier injection and extraction
- Energy levels for carrier (electrons and holes) injection and transport, i.e. **the frontier orbitals**, are of paramount importance

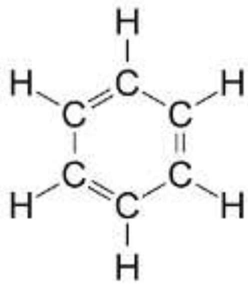
Standard generic OLED structure

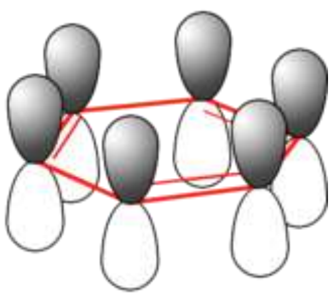




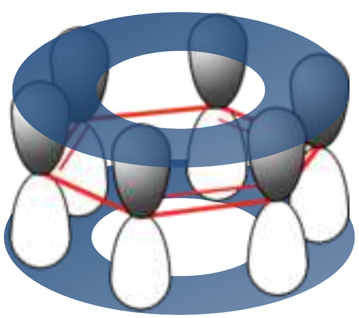
Conjugation and frontier energy levels in OSCs

Benzene





6 p-orbitals



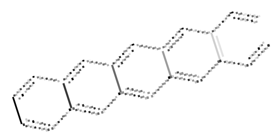
Delocalization

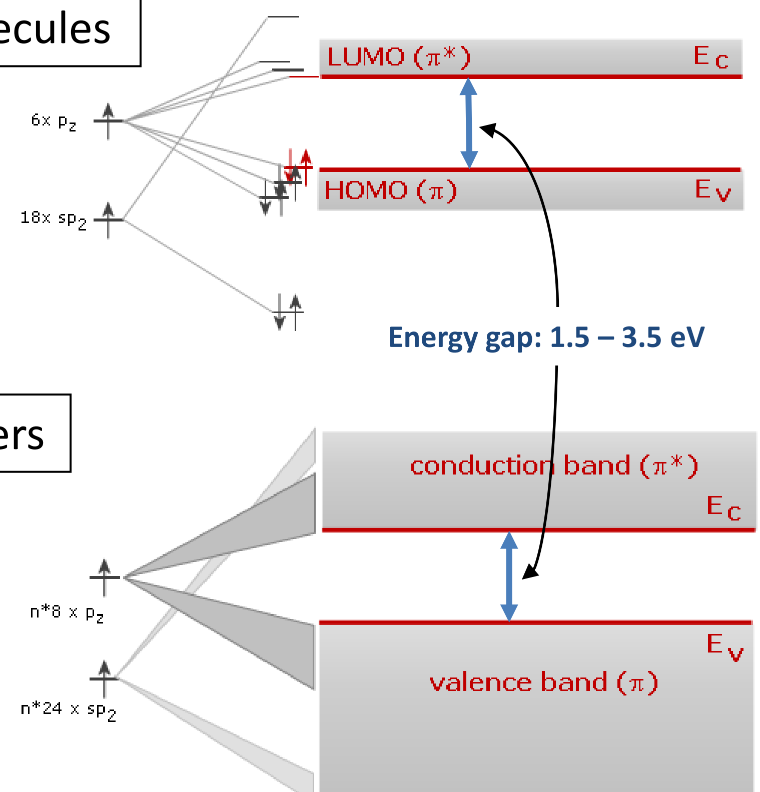
Conjugated system has connected p-orbitals, conventionally represented with alternating single and multiple (e.g. double) bonds

- **delocalization** of the electrons across all adjacent parallel aligned p−orbitals
- Increase stability; lower overall energy of the molecule

Small molecules

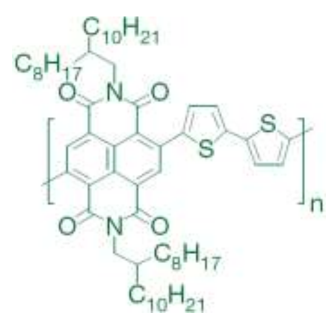
Pentacene





Polymers

P(NDI$_2$OD-T$_2$)



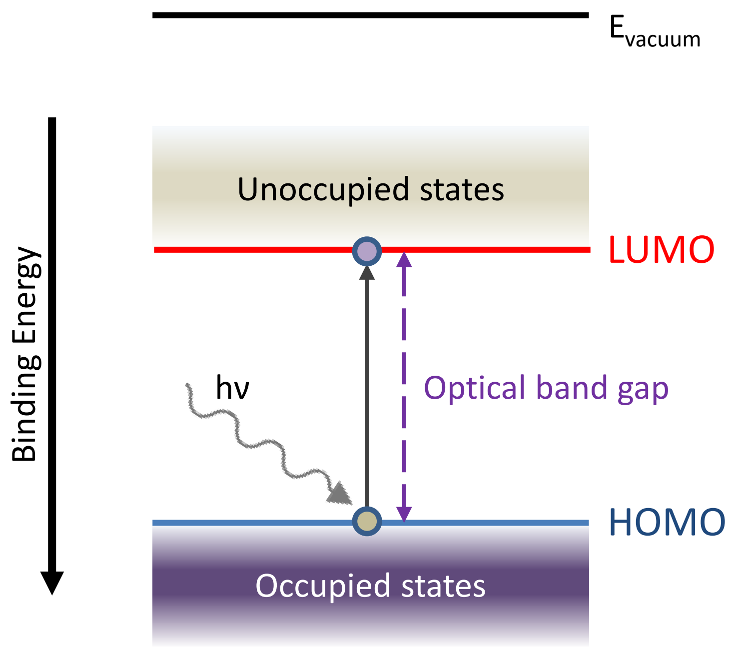
Mind the gap! What are we talking about?

J.-L. Bredas, *Mater. Horiz.*, ***17***, 1 (2014)

Single-particle (transport) gap vs. optical gap

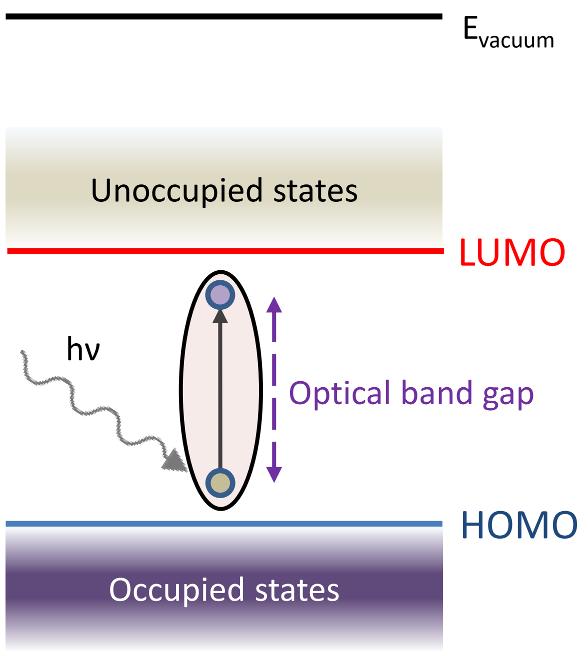
Inorganic SC; 3D perovskites; ….

- Exciton binding energy 10-20 meV
- Single particle gap ~ optical gap



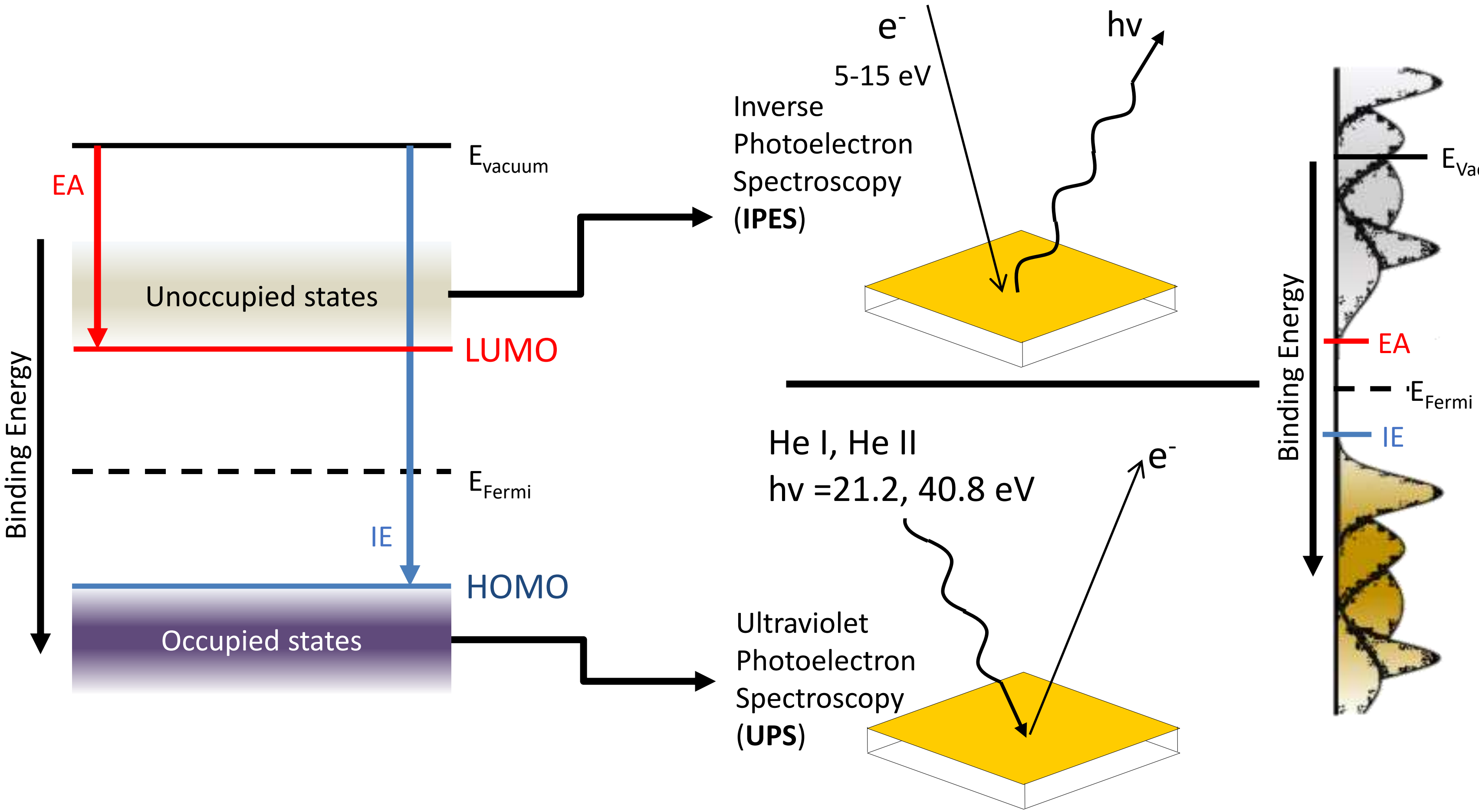
Organic SC; 2D perovskites (n=1, 2); ….

- Exciton binding energy 0.3-1 eV
- Single particle gap > optical gap



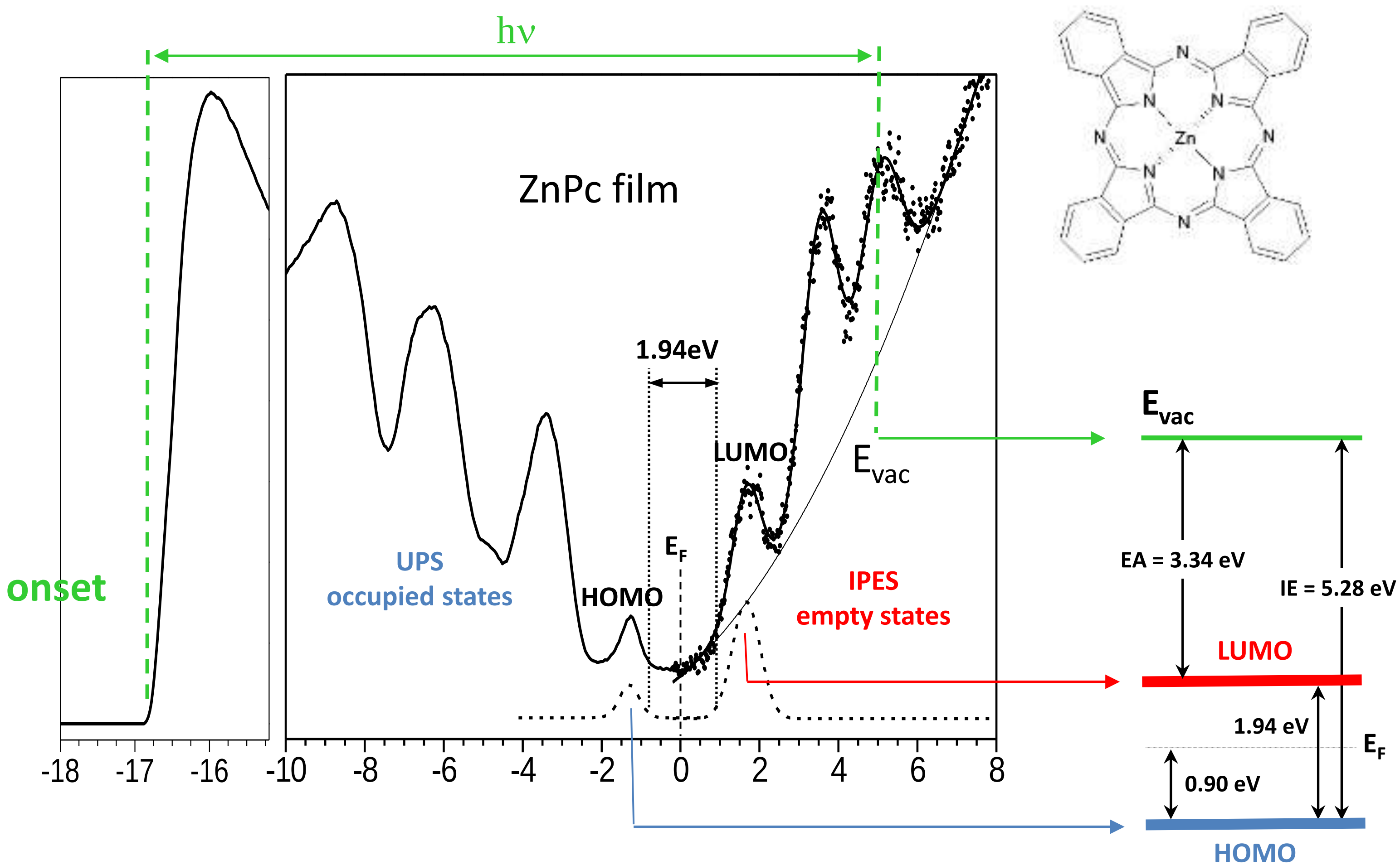
$$E_{B(exciton)} = E_{g(single\ particle)} - E_{g(optical)}$$

Measurement of single-particle (transport) levels



Composite UPS/IPES - complete electronic structure of ZnPc

Example of a film of the organic molecule zinc phthalocyanide (ZnPc)



UPS: hole transport level

IPES: electron transport level

W. Gao et al., *Org. Elect.* **3**, 53 (2002)

OSCs: key enabling properties

- Unlimited choice of organic (semiconductor) materials
  - Chemistry control → molecular structure → energy levels, photon absorption/emission, charge carrier transport, etc.
- Processibility: near room temperature film formation via vacuum or solution processing; printing; etc.
  - enables large area coverage
  - use of ultra-thin, flexible substrates (plastic) → ultra-thin, flexible electronics
- Ability to stack/mix unlike materials
  - no constraint of lattice matching, no thermal budget → unmatched flexibility in device engineering
  - Dopability (electrical; optical)
- Remarkable opto-electronic characteristics
  - Strong photo-emission and -absorption → excellent conditions for efficient LEDs, solar cells, photodetectors

OSCs: key enabling properties

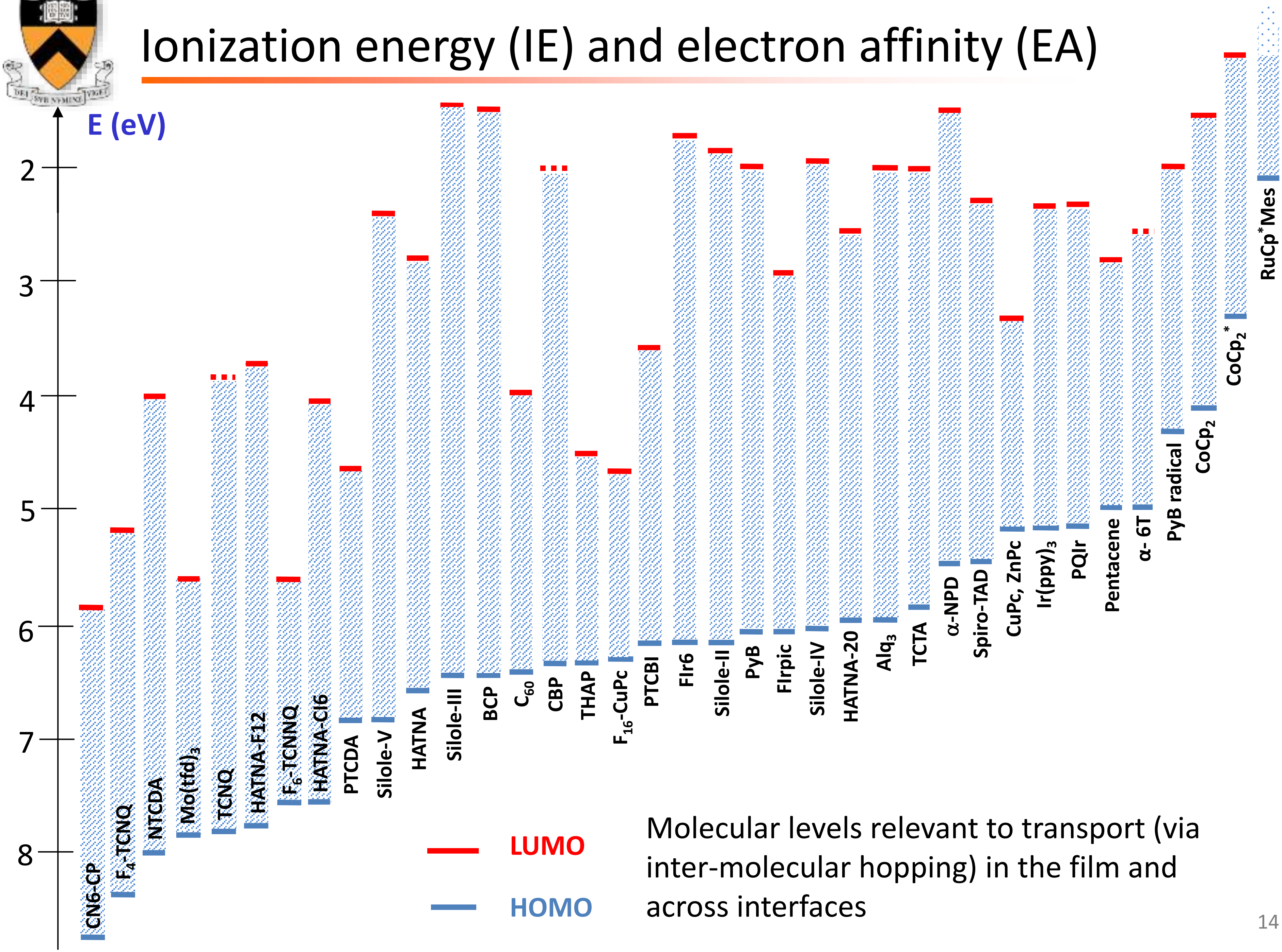
- Unlimited choice of organic (semiconductor) materials
  - Chemistry control → molecular structure → energy levels, photon absorption/emission, charge carrier transport, etc.

- Processibility: near room temperature film formation via vacuum or solution processing; printing; etc.
  - enables large area coverage
  - use of ultra-thin, flexible substrates (plastic) → ultra-thin, flexible electronics

- Ability to stack/mix unlike materials
  - no constraint of lattice matching, no thermal budget → unmatched flexibility in device engineering
  - Dopability (electrical; optical)

- Remarkable opto-electronic characteristics
  - Strong photo-emission and -absorption → excellent conditions for efficient LEDs, solar cells, photodetectors

Ionization energy (IE) and electron affinity (EA)

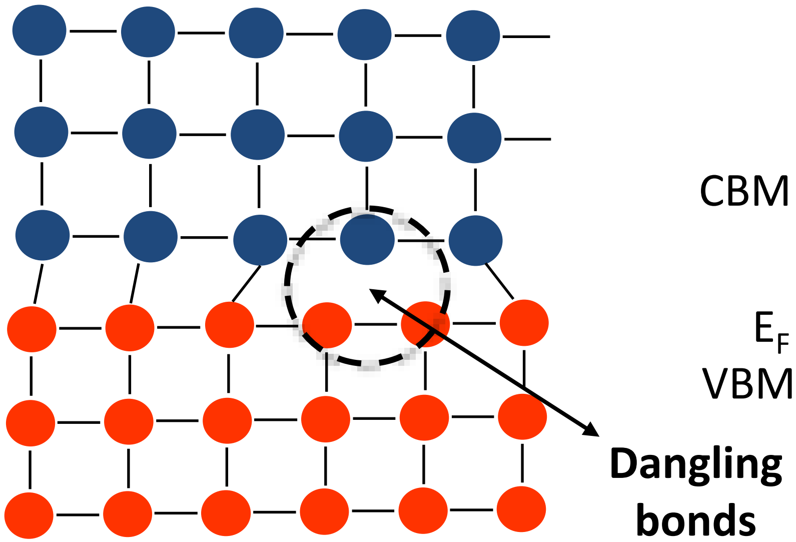


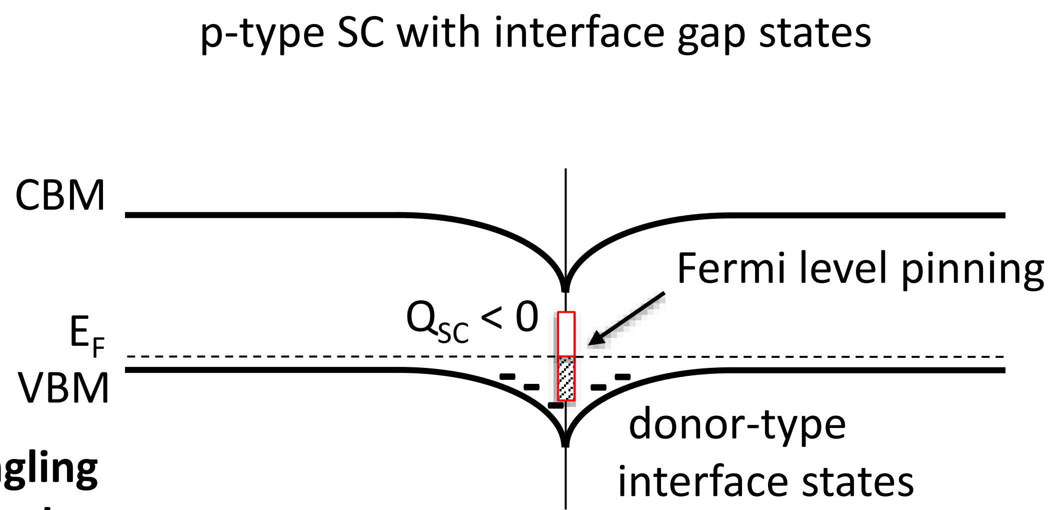
Molecular levels relevant to transport (via inter-molecular hopping) in the film and across interfaces

OSCs: key enabling properties

- Unlimited choice of organic (semiconductor) materials
  - Chemistry control → molecular structure → energy levels, photon absorption/emission, charge carrier transport, etc.
- Processibility: near room temperature film formation via vacuum or solution processing; printing; etc.
  - enables large area coverage
  - use of ultra-thin, flexible substrates (plastic) → ultra-thin, flexible electronics
- Ability to stack/mix unlike materials
  - no constraint of lattice matching, no thermal budget → unmatched flexibility in device engineering
  - Dopability (electrical; optical)
- Remarkable opto-electronic characteristics
  - Strong photo-emission and -absorption → excellent conditions for efficient LEDs, solar cells, photodetectors

Inorganic SC interfaces: impact of dangling bonds



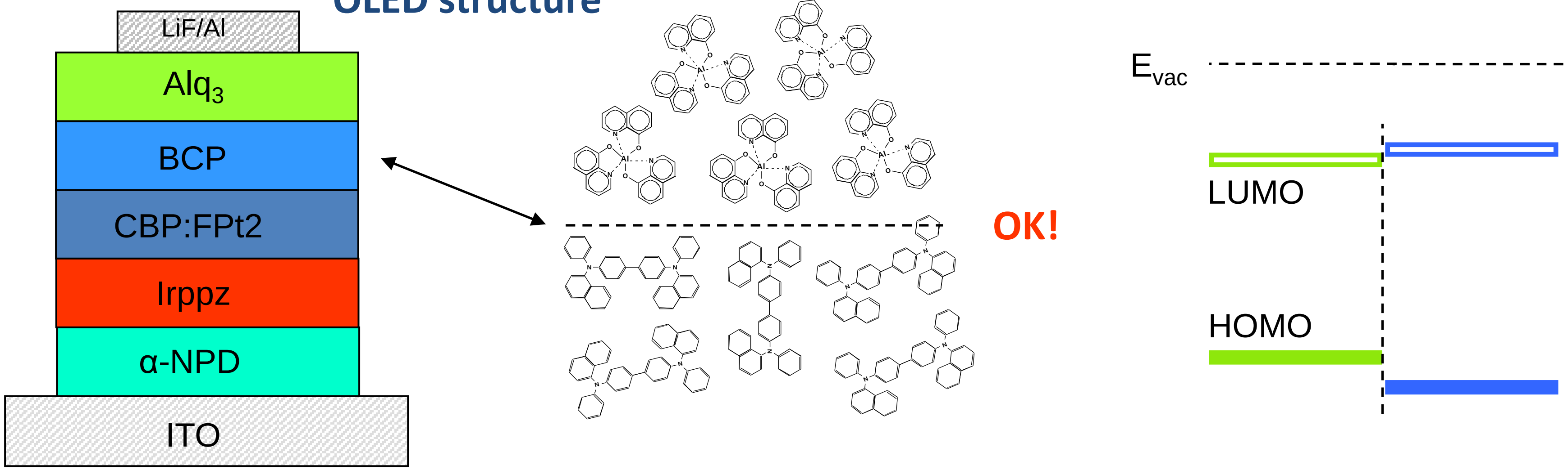


- Inorganic semiconductor interfaces include defects and/or dangling bonds that give rise to electronically active electronic gap states.
  → Fermi level pinning, internal band bending, recombination centers, etc.
- Paramount importance of lattice/thermal matching; heterojunctions dominated by interface states

OSC interfaces: far more tolerant

- Closed-shell molecular structure and weak van der Waals intermolecular bonds: **no dangling bonds**
- Possible to stack heterogeneous structures, leading to unique opportunities for innovation in material, device structure design and processes!

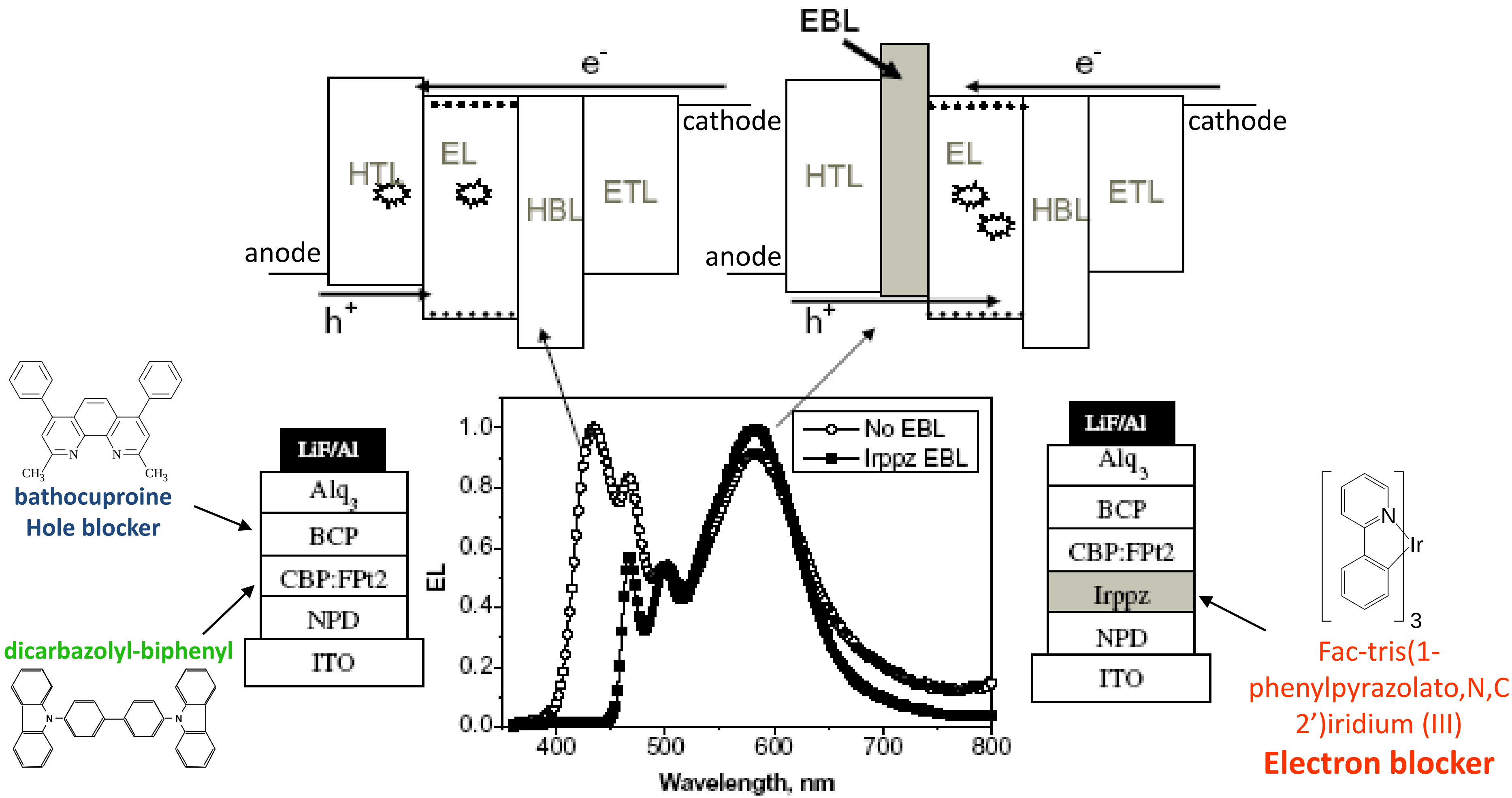
OLED structure



Property is a key enabler of organic electronics; allows unmatched flexibility in mixing and stacking different organic materials, leading to complex functional, optimized structures for OLEDs, OPV cells, etc..

Enormous flexibility in device design

Ex.: Introduction of an electron blocker

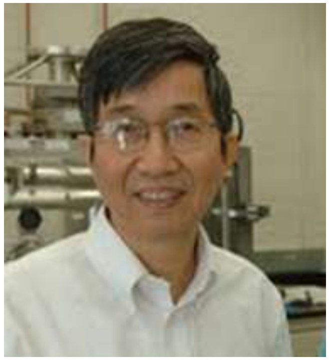


V. Adamovitch et al., *Org. Elec.* **4**, 77 (2003)

Outline

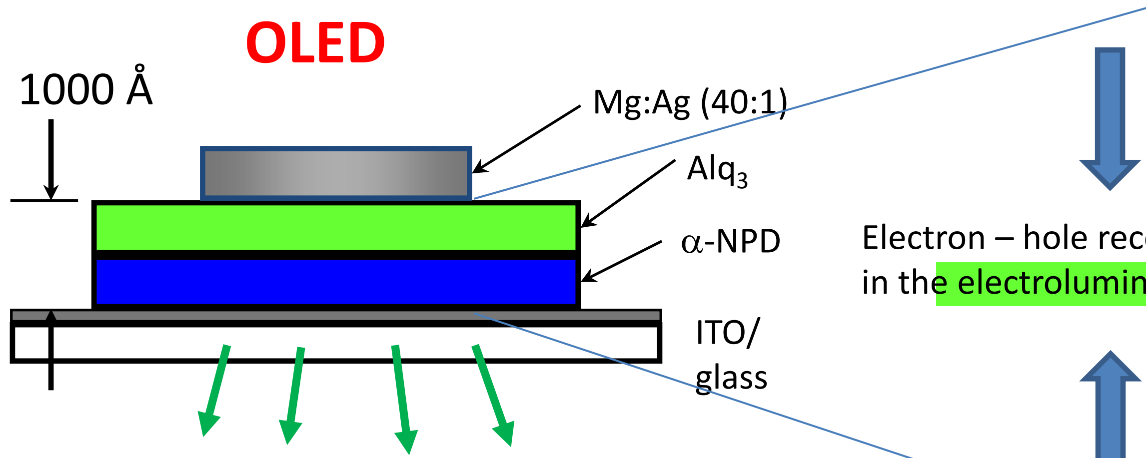
- Organic semiconductors
  - Quasi infinite choice of materials and energy levels
  - Basic considerations of electronic structure
  - Key enabling properties
- Light emission
  - Organic Light Emitting Diode: origin and evolution
  - Fundamental improvements
  - OLED displays and lighting
- Light harvesting
  - Organic Photovoltaic cell: key principles and materials
  - The non-fullerene acceptor revolution
- Electronics on plastics
  - Organic Field Effect Transistor: key principles and materials
  - Applications

The organic light emitting diode (OLED)



THE 2011 WOLF PRIZE IN CHEMISTRY

Wolf Foundation · קרן וולף



C.W. Tang et al., APL **51**, 913 (1987)

Organic electroluminescent diodes

C. W. Tang and S. A. VanSlyke
Research Laboratories, Corporate Research Group, Eastman Kodak Company, Rochester, New York 14650

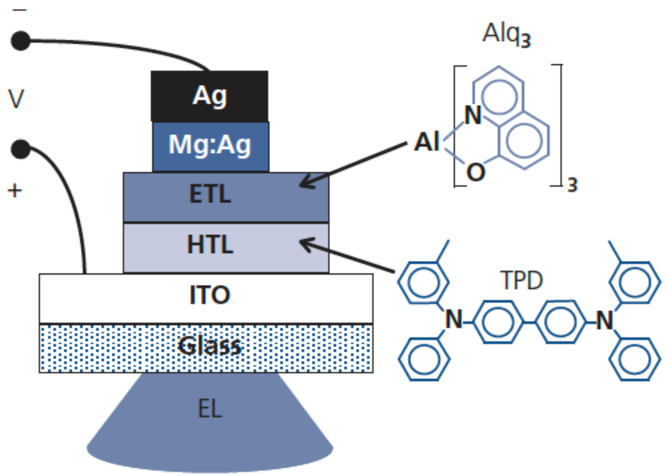
(Received 12 May 1987; accepted for publication 20 July 1987)

A novel electroluminescent device is constructed using organic materials as the emitting elements. The diode has a double-layer structure of organic thin films, prepared by vapor deposition. Efficient injection of holes and electrons is provided from an indium-tin-oxide

APL **51**, 913 (1987)
12,015 citations
(as of May 4, 2021)

Evolution toward a mature OLED technology

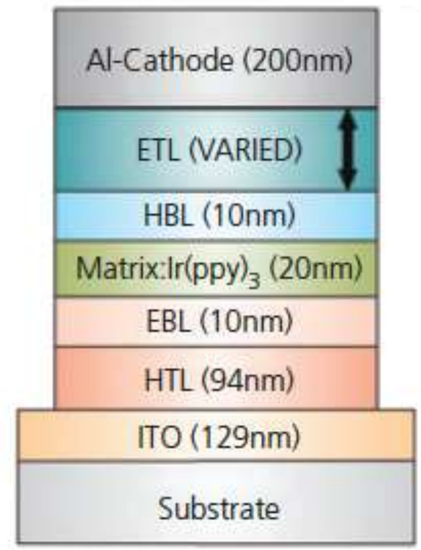
1st viable OLED



Tang and VanSlyke, *APL* 1987

Evolution

Generic structure of a high efficiency OLED

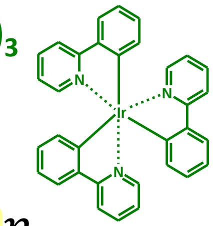


Numerous fundamental and technological advances have contributed to the development of a mature technology over the past 30 years:

- High efficiency R, G, B emitters
- Electron and hole transport / blocking materials with proper energetics
- Fundamental improvements in internal quantum efficiency
- Doping of transport layers to improve conductivity
- Technological development of light out-coupling
- Encapsulation
- ……………

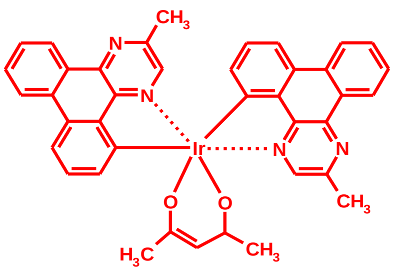
High efficiency **phosphorescent** OLED

$Ir(ppy)_3$



OLED external quantum efficiency = $\eta_{ext} = \eta_{int}\eta_{out} = \gamma\chi_{ST}\eta_{PL}\eta_{out}$

$Ir(MDQ)_2(acac)$



η_{int} = internal quantum efficiency

η_{out} = outcoupling efficiency

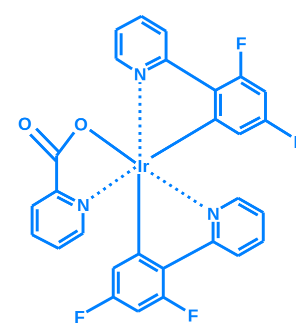
χ_{ST} = spin formation ratio

η_{PL} = quantum yield of the molecule

- **Problem:** random formation of singlet and triplet excitons due to pairing of uncorrelated spins of injected electrons and holes. Statistically, only 25% of singlet excitons for 75% of triplet excitons, limiting considerably the efficiency of fluorescent OLEDs, which only utilize singlets

- **Late 1990's:** introduction of emissive phosphorescent dopants containing heavy metal atoms (Pt, Ir, Ru, Re), whose spin orbit coupling promotes singlet/triplet mixing ⟹ nearly 100% energy transfer from both singlet and triplet states (M. Baldo et al., *Nature* ***395***, 151 (1998))

- Development of the **phosphorescent OLED (PHOLED)**



FIrpic

High efficiency OLED: lifetime performance

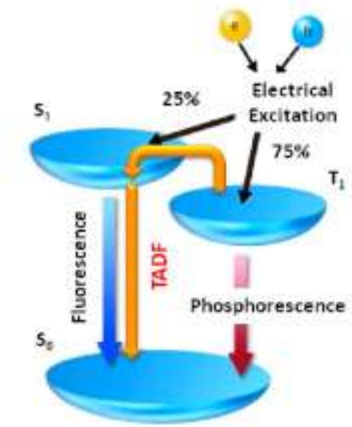
Table 1. Universal Display Corporation (UDC) OLED material performance[65].

Color \ OLED	PhOLEDs		Fluorescent OLED	
	1931 CIE coordinates	T_{50}^{*} [h]	1931 CIE coordinates	T_{50}^{*} [h]
Red	(0.64, 0.36)	900 000	(0.67, 0.33)	160 000
Green	(0.31, 0.63)	400 000	(0.31, 0.63)	200 000
Blue	–	< 100	(0.14, 0.12)	11 000

*T_{50}: time of decay to 50% of initial brightness

S. Sudheendran et al., *Adv. Sci.*, ***8***, 2002254 (2021)

High efficiency OLED from **delayed fluorescence**



ED external quantum efficiency = $\eta_{ext} = \eta_{int}\eta_{out} = \gamma\chi_{ST}\eta_{PL}\eta_{out}$

η_{int} = internal quantum efficiency

η_{out} = outcoupling efficiency

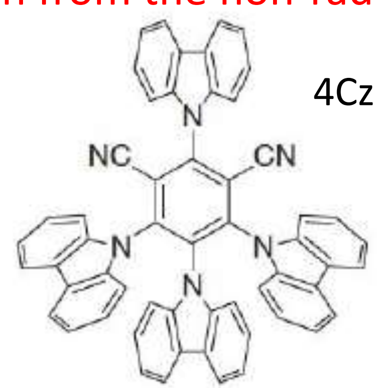
χ_{ST} = spin formation ratio

η_{PL} = quantum yield of the molecule

- **Problem:** random formation of singlet and triplet excitons due to pairing of uncorrelated spins of injected electrons and holes. Statistically, only 25% of singlet excitons for 75% of triplet excitons, limiting considerably the efficiency of fluorescent OLEDs, which only utilize singlets

- **2012:** introduction of a class of metal-free organic electroluminescent molecules in which the energy gap between singlet and triplet is minimized (10s meV) thereby promoting efficient spin up-conversion from the non-radiative triplet states to radiative singlet states
  (H. Uoyama et al., *Nature* ***492***, 234 (2012))

- Development of **OLEDs based on Thermally Activated Delayed Fluorescence (TADF)**



4CzIPN

OLED displays are here to stay!

Flexible displays (Visionox, China)

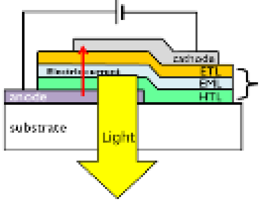
Apple

Samsung

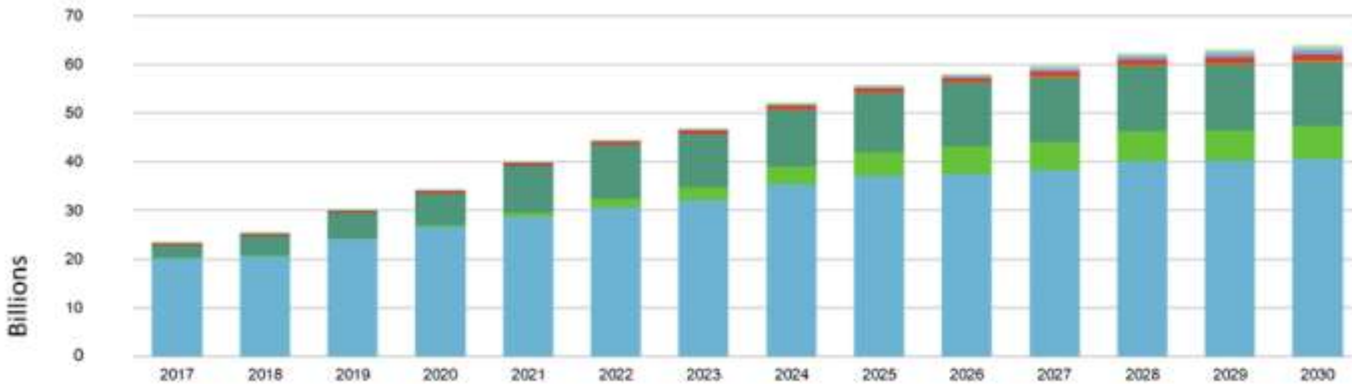
Google

LG grand display (Incheon Airport, S. Korea)

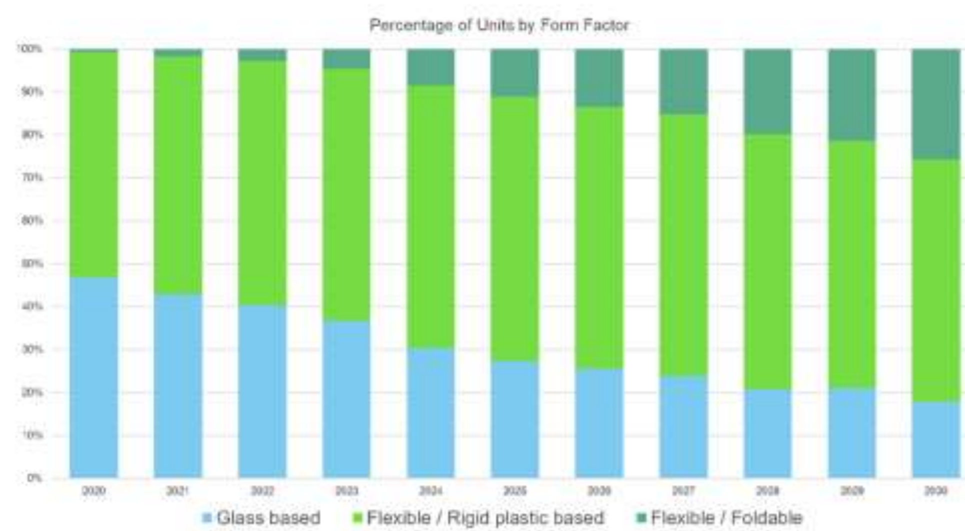
Active matrix (AM)OLED market share



OLED Display Forecasts 2017-2030 by Value $ Billions



Change in form factor of OLED Displays 2020-2030



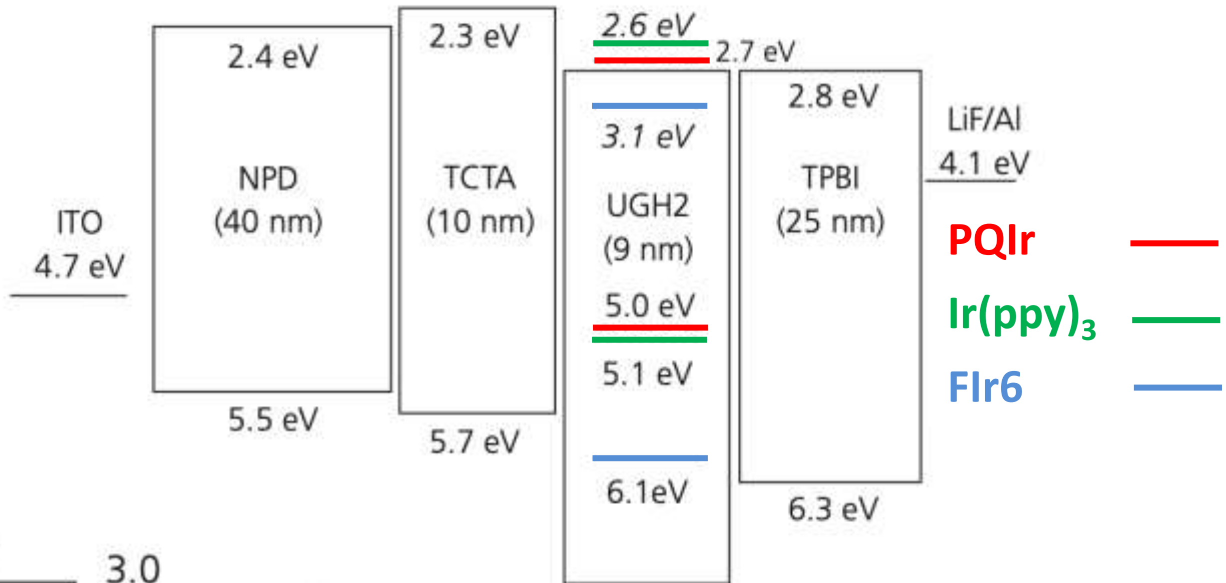
"Flexible, Printed OLED Displays 2020-2030: Forecasts, Markets, Technologies"
By Raghu Das and Xiaoxi He

Lighting, evolved

- compared to 6-8% today, solid-state lighting is expected to comprise 86% of installations by 2035
- energy savings equivalent to 45 million US homes today
- cumulative energy savings represent $630B
- thin-film solid-state lighting is poised to contribute to this mix

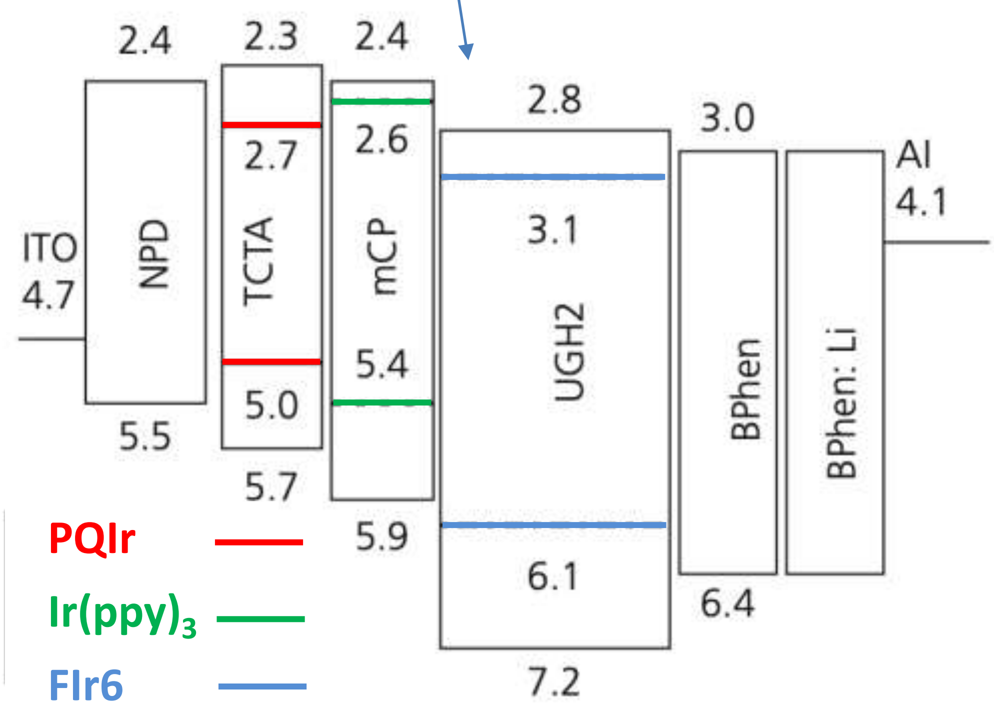
Courtesy of Barry Rand, Princeton

White organic light emitting diode (WOLED)



Triple phosphor / triple host WOLED

Sun et al., *Org. Electron. 9*, 994 (2008)



Three phosphor WOLED blended in a single thin (9 nm) wide energy gap host (UGH2)

D'Andrade et al., *Adv. Mater.* ***16***, 624 (2004)

Organic lighting

OLED lighting: lifetimes and other performance marks

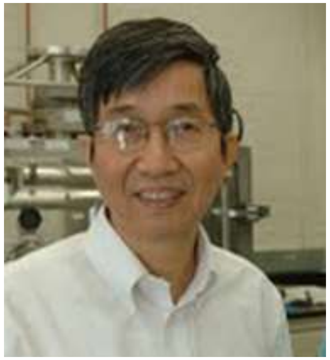
Comparison of OLED lighting with other commercially available lamps.

Particulars	OLED	LED	Fluorescent Lamp	Compact Fluorescent Lamp
Lighting technology	Fourth generation lighting system (Solid state lighting)	Fourth generation lighting system (Solid state lighting)	Third generation lighting system (1938)	Third generation lighting system (1976)
Types	Area Light. Soft diffused light, no glare. Generates uniform lighting. Heat naturally dispersed across the entire surface of the panel.	Point source. Requires optical diffusion to protect occupants from glare by a bright light source. Generates heat. Thermal management system mandatory	Point – Area light source. Requires fluorescent light diffuser	Point – Area light source. Sometimes require diffuser to cover warm and soften bright harsh light
Flexibility	Yes	None. Flexible LED strips are possible.	None	None
Efficiency	~60–90 lm/W	65–160 lm/W	>80 lm/W	50–70 lm/W
Color rendering index (CRI)	80–90	>65–95	>62–80	about 80
Color temperature	2700–5,400 K	2700–10,000 K	2700–6000 K	2700–6000 K
Mercury	No	No	Yes. Contain toxic mercury	Yes. Contain toxic mercury
Infrared radiation	No	No	Yes. A small amount of infrared (>700 nm) radiation	Yes. A small amount of infrared (>700 nm) radiation
UV radiations	No	No	Yes. Very low levels of UVB (280–315 nm), UVA (315–400 nm) radiations	Yes. Very low levels of UVB (280–315 nm), UVA (315–400 nm) radiations
Cost	Expensive. Lower cost in the future	Upfront cost relatively higher compared to CFL and fluorescent lamps	Affordable. Widely adopted	Affordable. Widely adopted.
Dimming	Dimmable when paired with dimming drivers	Very easy to dim	Often not suitable for dimming	CFL bulbs can be dimmed
Response time	Much faster about 10 μs (0.01 ms)	Fraction of a second (1/10th of ms)	Slight delay on turn-on and turn off.	Slight delay on turn-on and turn off.
Life time	5000–10,000 h. Expecting lifespan of 10,000 h at 100% brightness or 40,000 h at 25% brightness	50,000 to 100,000 h	7000–15,000 h	Rated service life of 6000–15,000 h
Acoustic noise	None	None	Ballast can make a buzzing sound	Buzzing sound is caused by a hum in the ballast

Outline

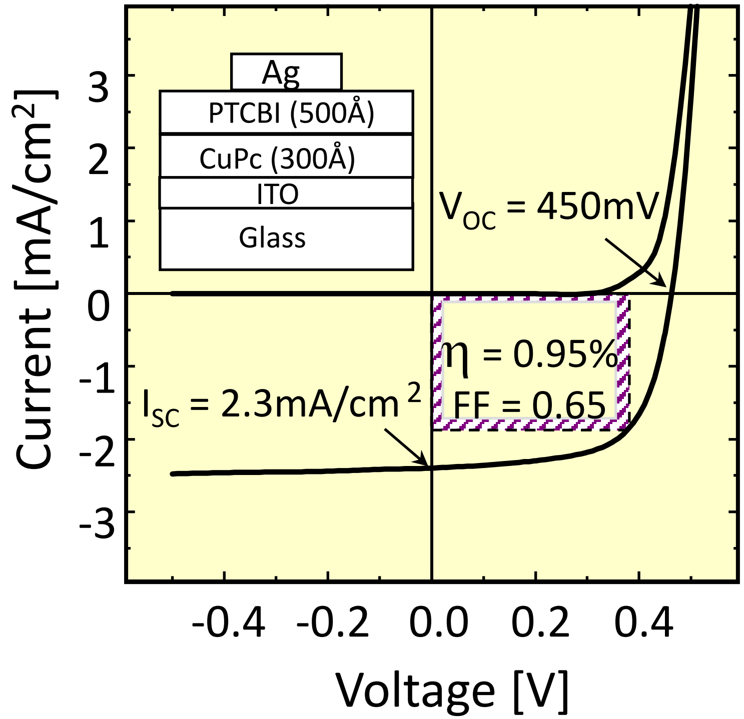
- Organic semiconductors
  - Quasi infinite choice of materials and energy levels
  - Basic considerations of electronic structure
  - Key enabling properties
- Light emission
  - Organic Light Emitting Diode: origin and evolution
  - Fundamental improvements
  - OLED displays and lighting
- Light harvesting
  - Organic Photovoltaic cell: key principles and materials
  - The non-fullerene acceptor revolution
- Electronics on plastics
  - Organic Field Effect Transistor: key principles and materials
  - Applications

Early OPV cell

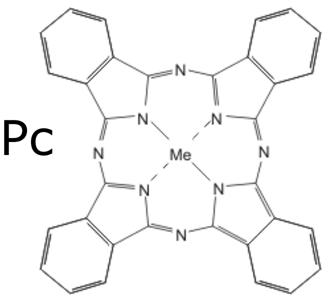


THE 2011 WOLF PRIZE IN CHEMISTRY

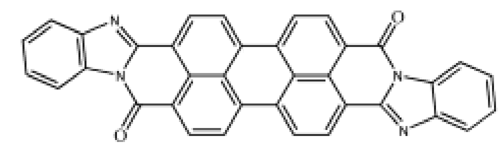
Wolf Foundation · קרן וולף



MePc



PTCBI



Two-layer organic photovoltaic cell

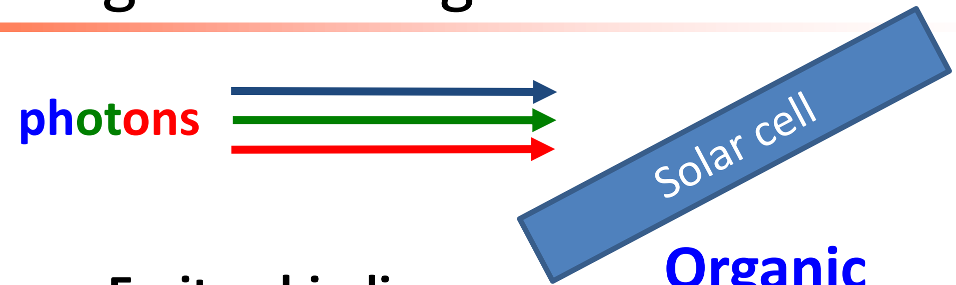
C. W. Tang
Research Laboratories, Eastman Kodak Company, Rochester, New York 14650

APL **48**, 183 (1986)
4,022 citations
(as of May 4, 2021)

(Received 28 August 1985; accepted for publication 31 October 1985)

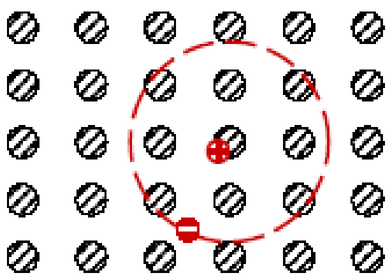
A thin-film, two-layer organic photovoltaic cell has been fabricated from copper phthalocyanine and a perylene tetracarboxylic derivative. A power conversion efficiency of about 1% has been

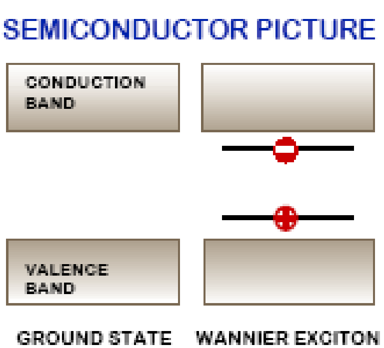
Excitons: inorganic vs. organic PV cell



Inorganic SC

Wannier exciton
(typical of inorganic semiconductors)

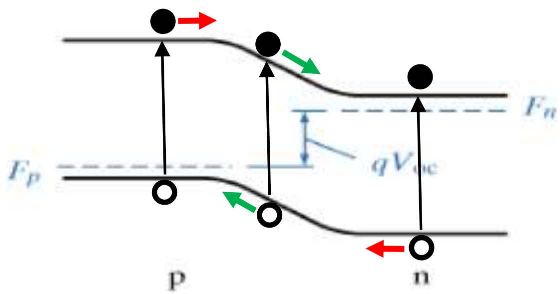




binding energy ~10meV
radius ~100Å

Exciton binding energy < kT

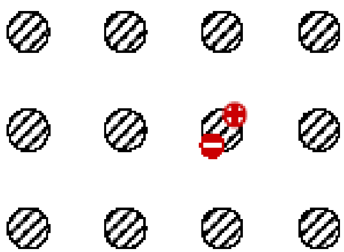
→ dissociation in both diffusion and space charge regions

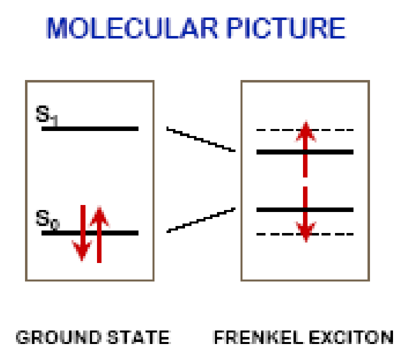


Diffusion **Drift**

Organic

Frenkel exciton
(typical of organic materials)

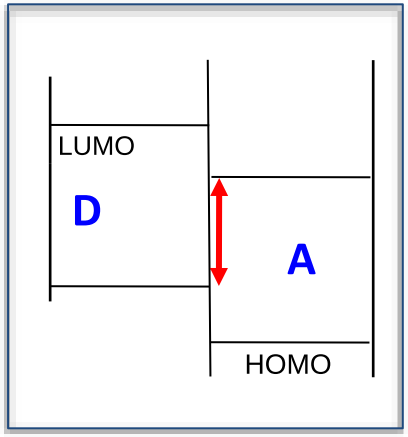




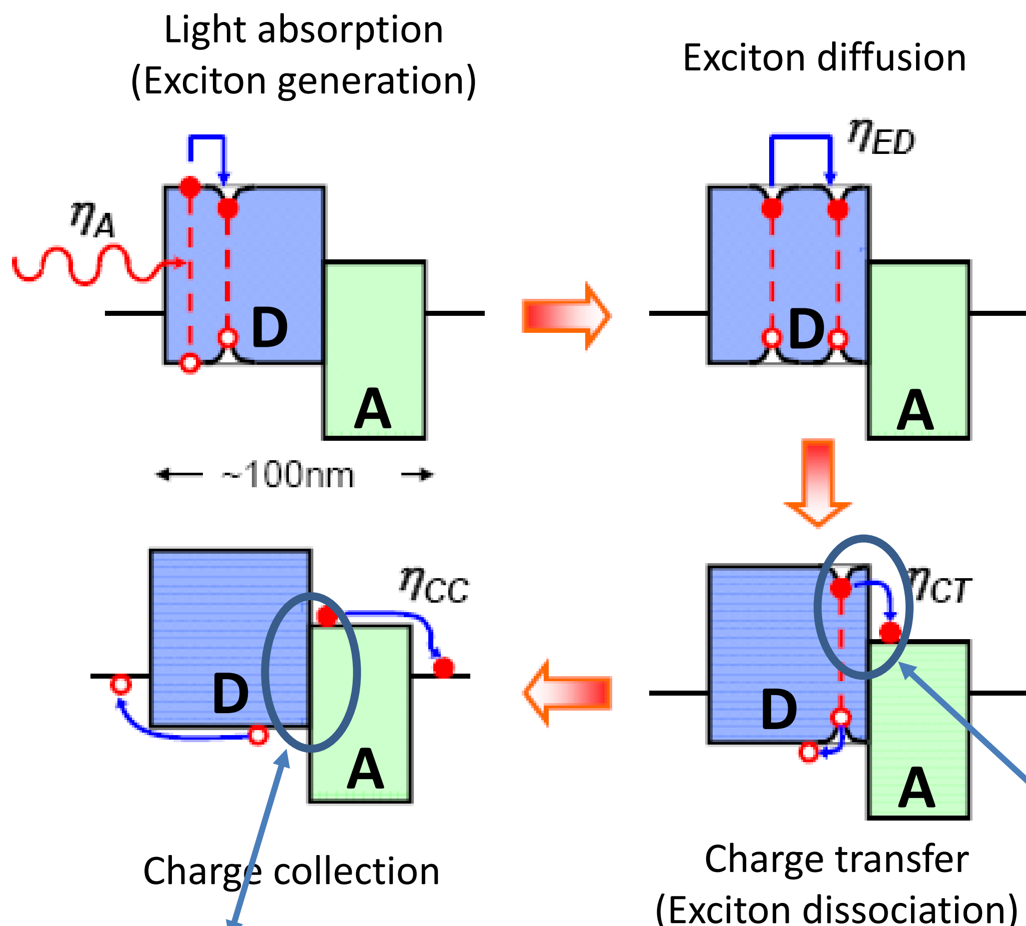
binding energy ~1eV
radius ~10Å

Exciton binding energy >> kT

→ requires a donor/acceptor (D/A) type of structure



Photocurrent generation at an organic heterojunction



$$\eta_{EQE} = \eta_A \times \eta_{ED} \times \eta_{CT} \times \eta_{CC}$$

η_A ~ 50% – 100%

η_{ED} ~ 10% – 50%

η_{CT} < 100%

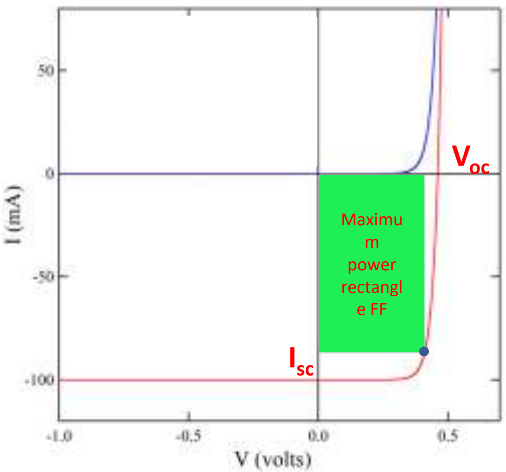
η_{CC} ~ 100%

Maximizing $LUMO_A$-$HOMO_D$ gap crucial to maintain large V_{OC}

Important for exciton dissociation process (although physics should be described in terms of excitonic states)

Courtesy of Steve Forrest; DOE BES Workshop, 2005

Origin of the short circuit current, J_{sc}



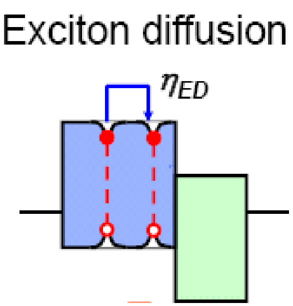
J_{sc} related to:

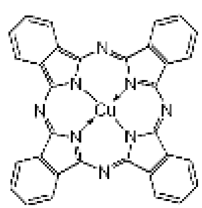
- number of absorbed photons → excitons
- conversion of exciton into e^- and h^+
- Efficiency of e^-/h^+ transport to, and collection at, electrodes

Necessary to dissociate excitons at the D/A heterojunction

Exciton diffusion length: 10 – 50 nm, depending on material

Planar heterojunction e.g. CuPc/C_{60}





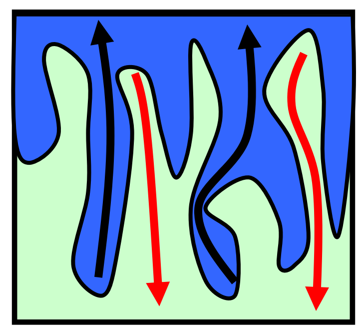
Copper phthalocyanine (CuPc)

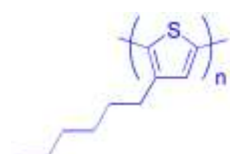
C_{60}

+ More control on structure
+ Simpler; better conduction path
+ Amenable to doping

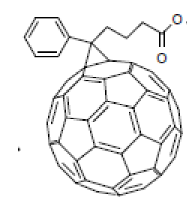
– Trade-off between thickness (photon absorption) and exciton diffusion length

Bulk heterojunction e.g. P3HT:PCBM





poly(3-hexylthiophene) (P3HT)



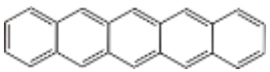
[6,6]-phenyl C_{61} butyric acid methyl ester) (PCBM)

+ Higher interface area
+ Shorter exciton diffusion path

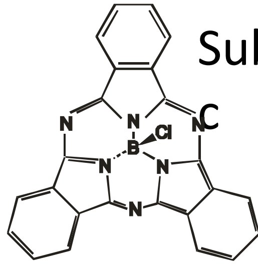
– Internal structure more difficult to control
– Connectivity/conduction path

Typical OPV materials

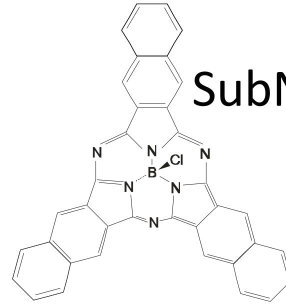
Donors



Pentacene

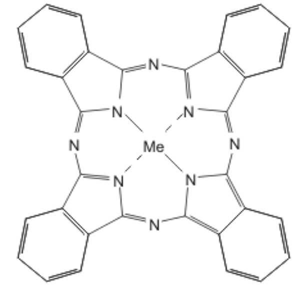


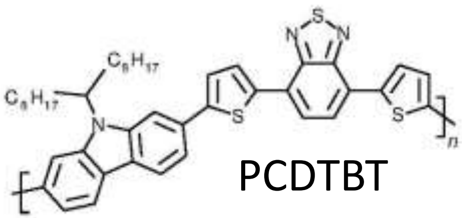
SubP



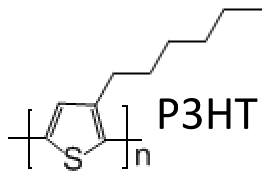
SubNc

MePc

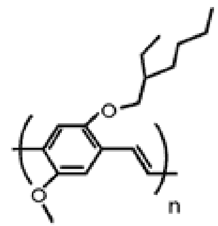




PCDTBT

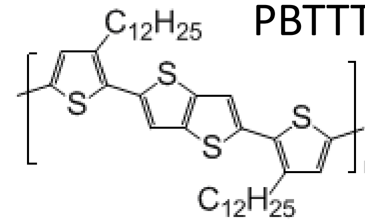


P3HT

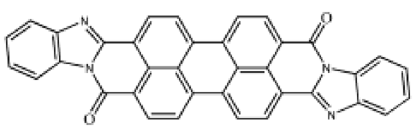


MEH-PPV

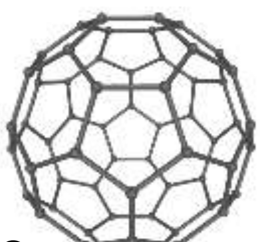
PBTTT-C_{12}



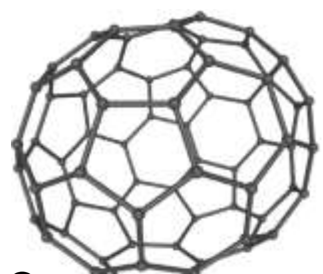
Acceptors (OPV acceptors dominated by fullerene derivatives till ~ 2015)



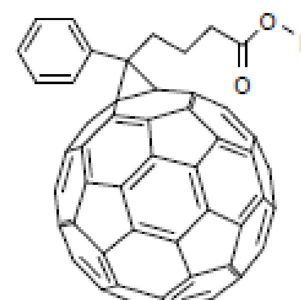
PTCBI



C_{60}



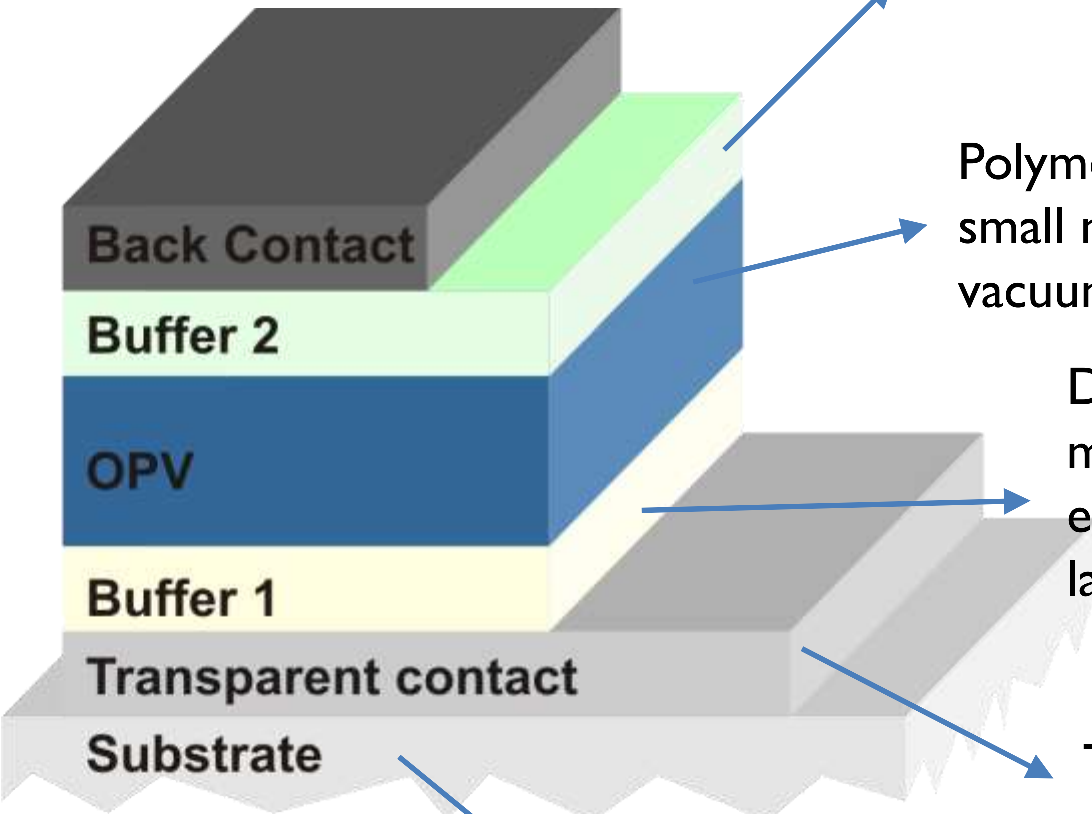
C_{70}



PCBM

Anatomy of a typical OPV cell

Carrier extraction/selective layer



Polymer-based (solution processed), small molecule-based (solution or vacuum)

Doped organic films (PEDOT:PSS), metal oxides (TiO_x, ZnO, MoO_x, etc.); carrier extraction/selective layer

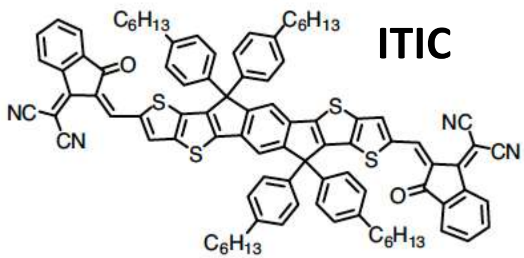
TCOs, thin metals, carbon, polymers, Ag nanowires

Glass, plastic foil

Rise of the non-fullerene acceptors (NFA)

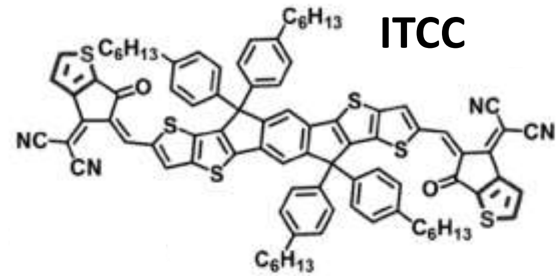
……. or the rebirth of the OPV field.

ITIC



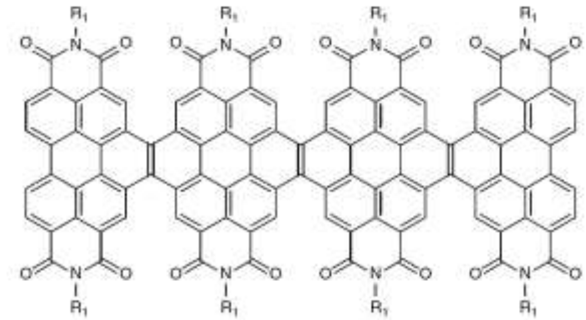
Lin et al. *Adv. Mater.* ***27***, 1170 (2015)

ITCC



Yao et al. *Adv. Mater.* ***29***, 1700254 (2017)

hPDI4



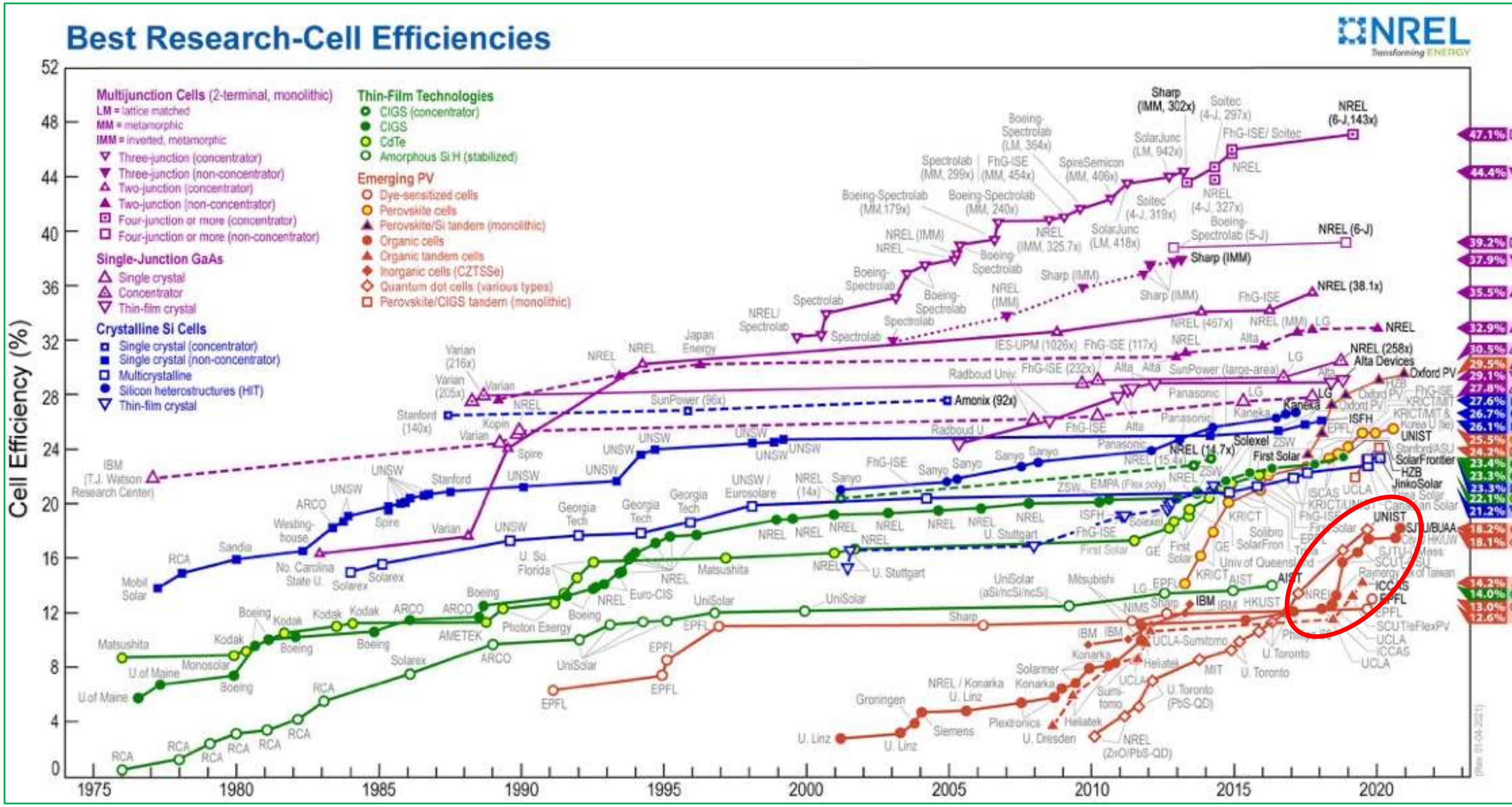
Zhong et al., *Nat. Comm.* ***6***, 8242 (2015)

2015 conception and development of a class of non-fullerene acceptors termed ‘‘fused ring electron acceptors (FREA), with ITIC as the benchmark molecule.

Advantages of NFAs over fullerene counterparts

- Stronger absorption in the visible → more active participation in current generation
- Much larger variability of electronic properties, → ability to tune energy levels by chemical means for better match with the donor
- Better stability of film morphology in bulk heterojunctions.

Photovoltaic conversion efficiencies vs. t

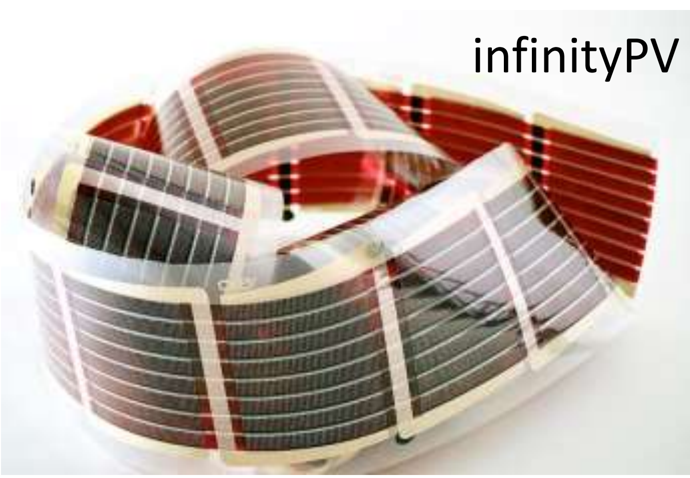


https://www.nrel.gov/pv/assets/pdfs/best-research-cell-efficiencies.20200104.pdf

Organic photovoltaics: niche to main stream application

Heliatek

Konarka
(defunct)



infinityPV

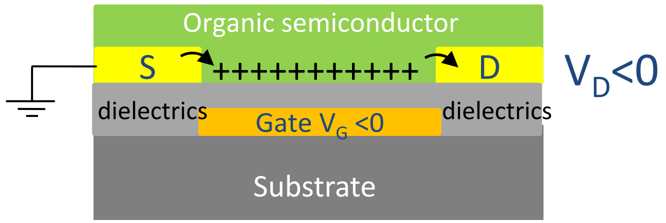
ORENgE

Outline

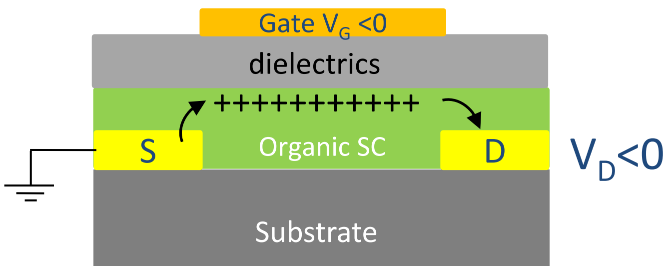
- Organic semiconductors
  - Quasi infinite choice of materials and energy levels
  - Basic considerations of electronic structure
  - Key enabling properties
- Light emission
  - Organic Light Emitting Diode: origin and evolution
  - Fundamental improvements
  - OLED displays and lighting
- Light harvesting
  - Organic Photovoltaic cell: key principles and materials
  - The non-fullerene acceptor revolution
- Electronics on plastics
  - Organic Field Effect Transistor: key principles and materials
  - Applications

The organic field effect transistor (OFET)

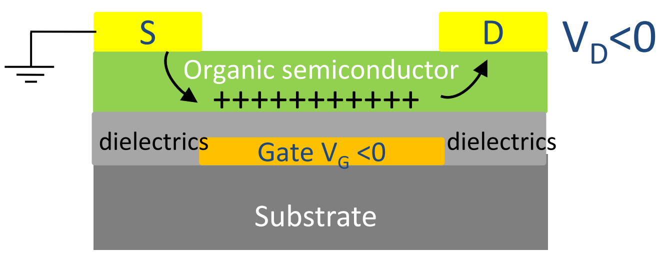
Bottom gate, bottom contact



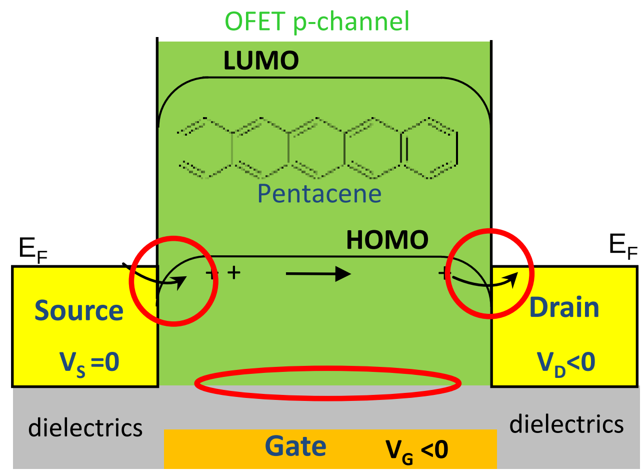
Top gate, bottom contact



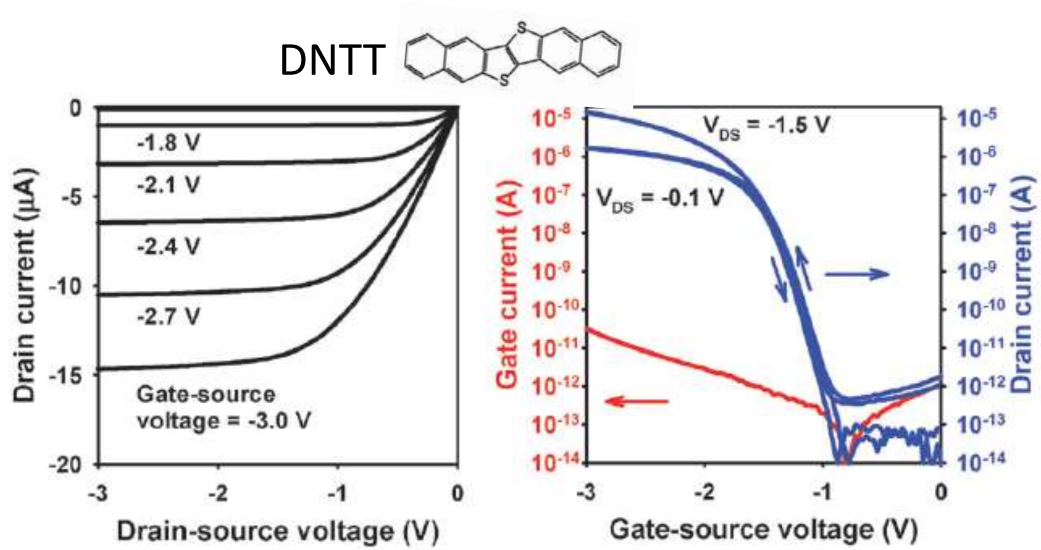
Bottom gate, top contact



- OFET typically operates in accumulation, with the channel right next to the dielectric interface



DNTT

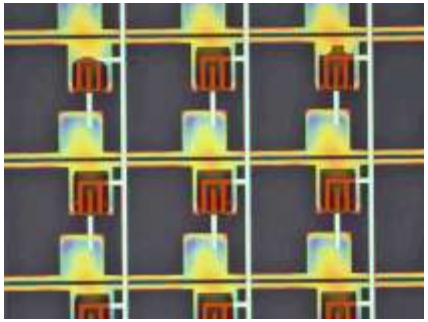


Hagen Klauk, Chem. Soc. Rev. **39**, 2643 (2010)

The organic field effect transistor (OFET)

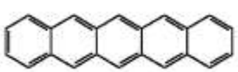
- Small molecules: best electron and hole mobility well above 5 $cm^2/V.s$
- Polymers: hole and electron mobility above 2 $cm^2/V.s$
- All solution processing; Flexible substrates
- @ few µA, OFET life-times above 100,000 hours
- Backplanes with half-million printed OFETs have been realized
- Increasing panoply of electron- and hole-transport semiconductors → complementary n- and p-channel OFETs

250 μm

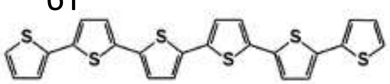


Vacuum-deposited **hole**-transport small molecules

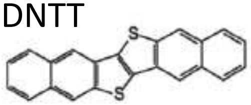
Pentacene



6T

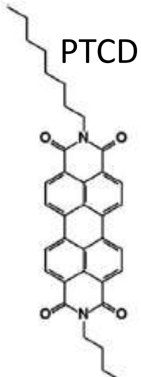


DNTT

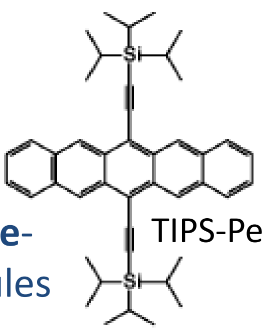


C_{60}

PTCDI-C8H17



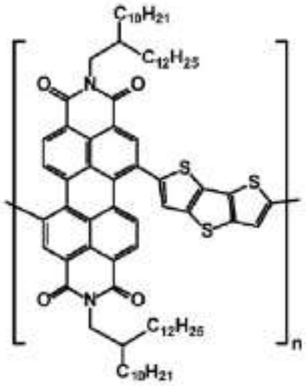
Vacuum-deposited **electron**-transport small molecules



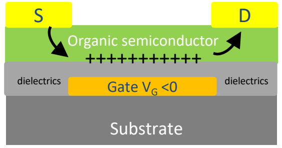
TIPS-Pentacene

Solution-deposited **hole**-transport small molecules

solution-deposited **electron**-transport polymers

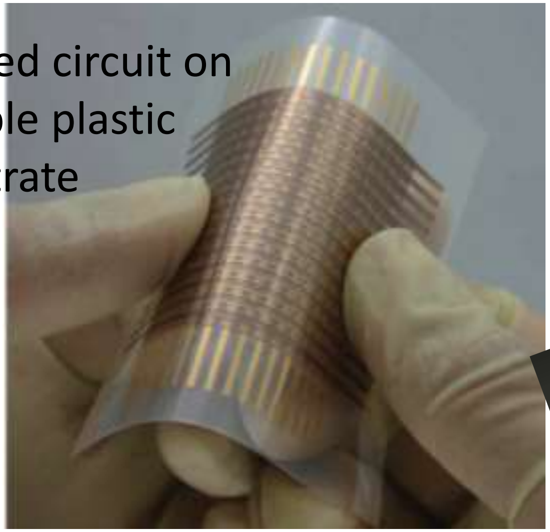


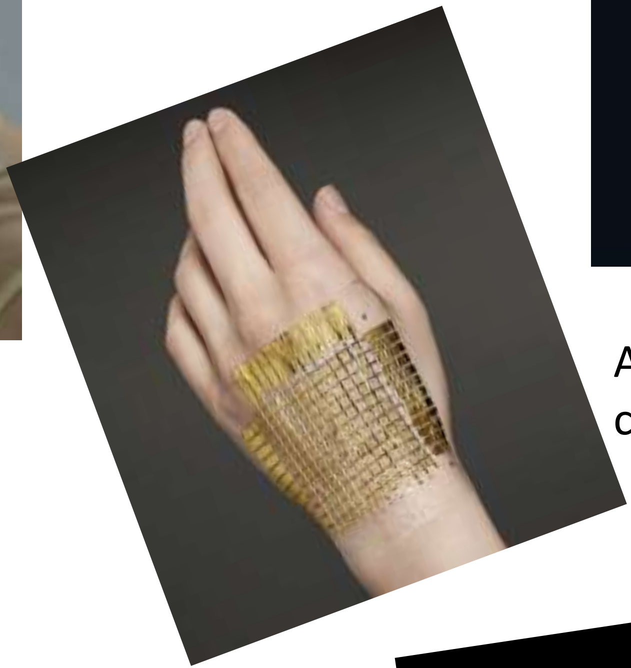
Flexible electronics: OFET on plastic

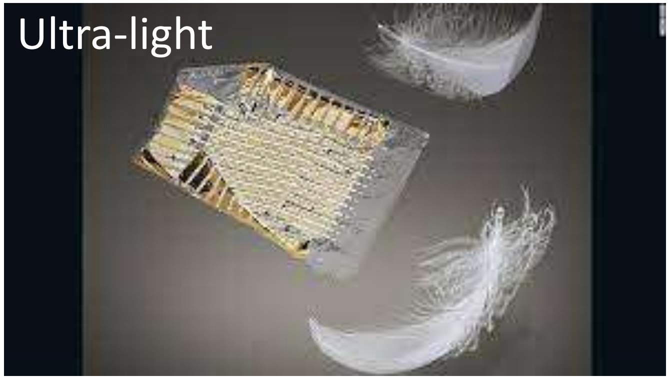


Circuits built on < 1 µm tick foil; sustains folding to radius of < 5 µm

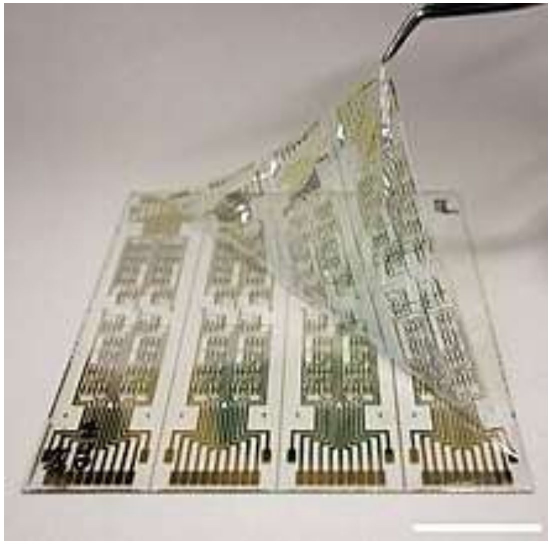
Printed circuit on flexible plastic substrate







Applications in wearable health-care monitoring systems



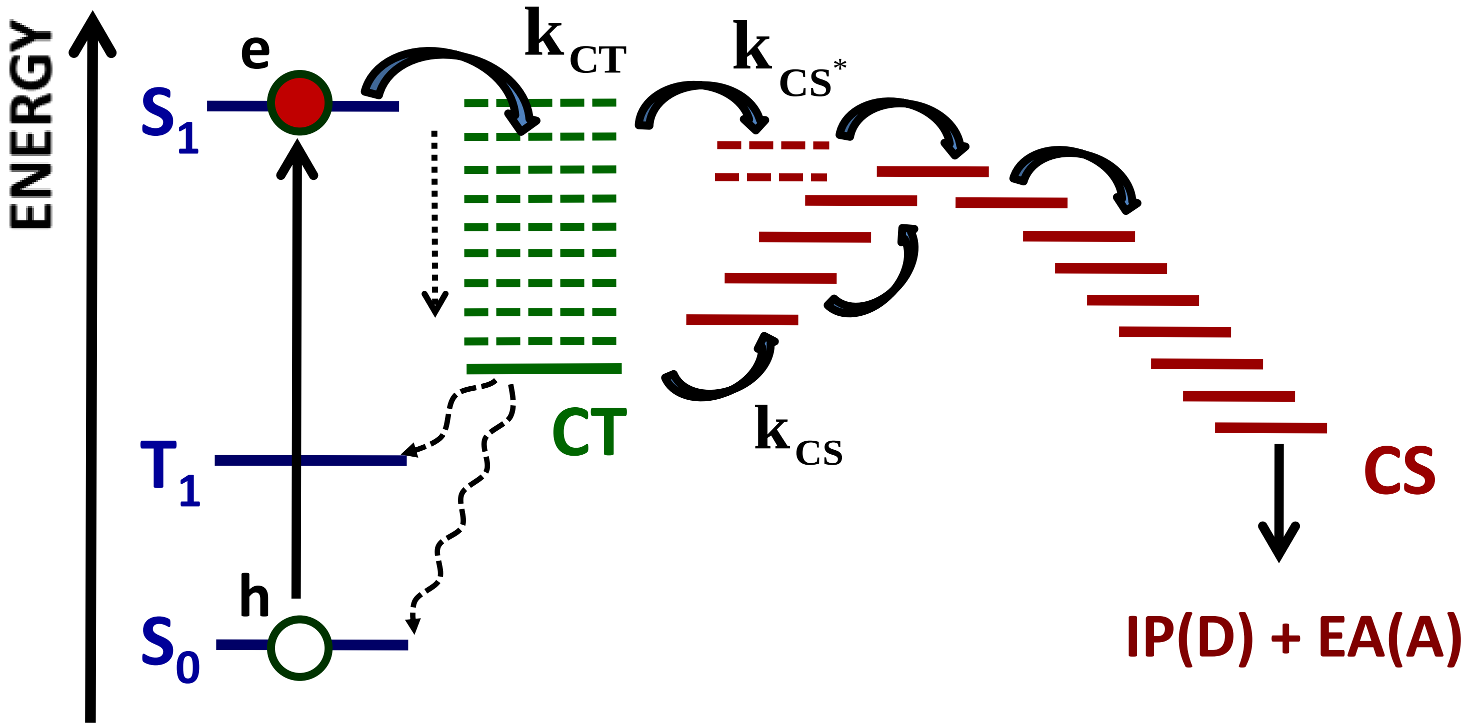
Bionic skin; sensing; robotics

Courtesy from T. Someya, Univ. of Tokyo.

.... a bright future for organic electronics

- Thirty years of high-level research on the unique physical and (opto)electronic properties of organic semiconductors and their interfaces
- Continuous flow of newly synthesized molecules and polymers
- Unique processing flexibility offered by organic semiconductors
- Ever expanding demand for high-resolution and inexpensive displays, flexible and wearable electronics and sensors, and large area solar energy conversion
- With continued innovation and strong link between research and development, the sky is the limit .....

Complexity of the charge separation mechanism

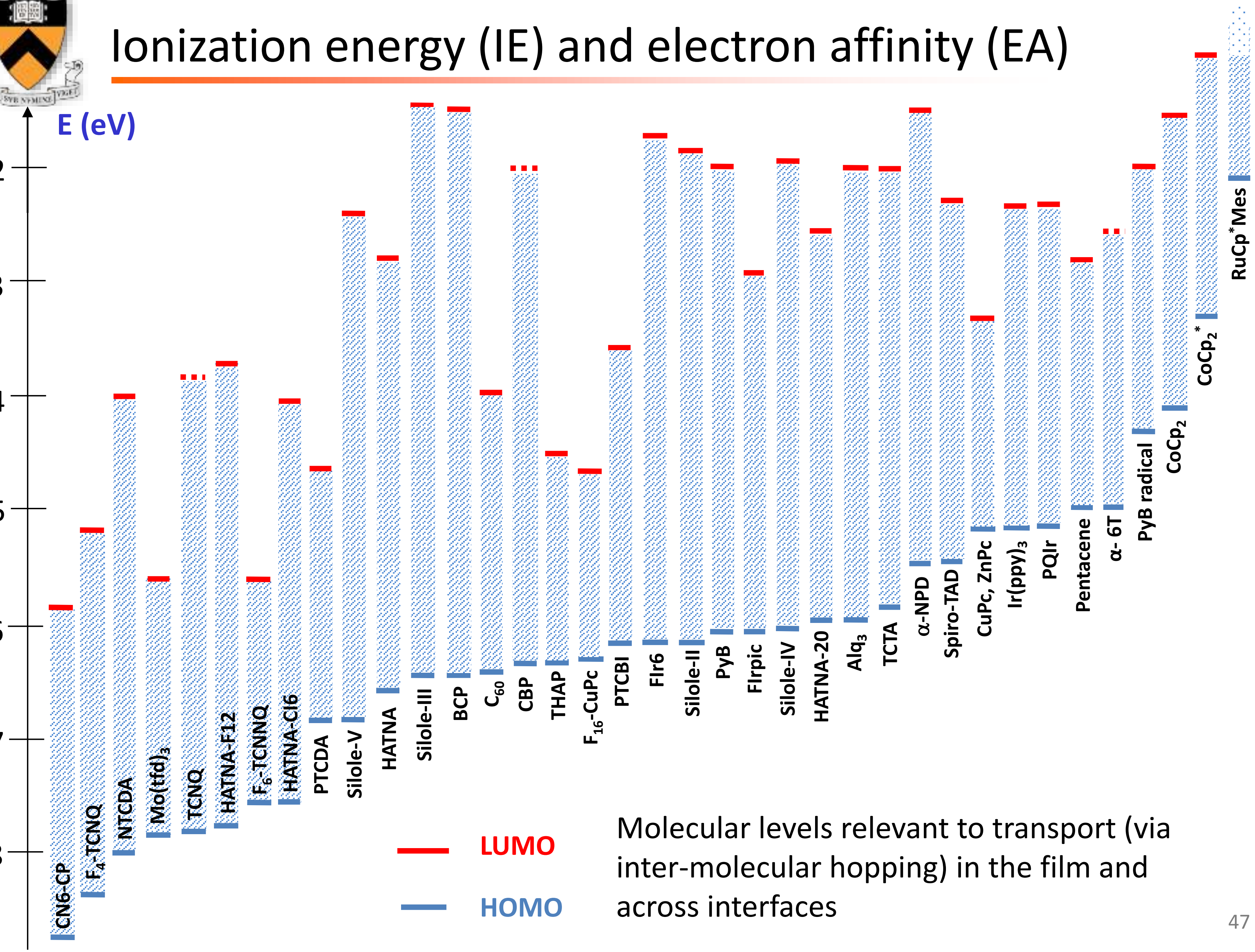


exciton → charge transfer → charge separation

B. Kippelen & JLB, Energy & Environmental Science 2, 251 (2009)
JLB, J. Norton, J. Cornil & V. Coropceanu, Acc. Chem. Res. 42, 1691 (2009)
J. Durrant *et al.*, Chem. Rev. (2009)

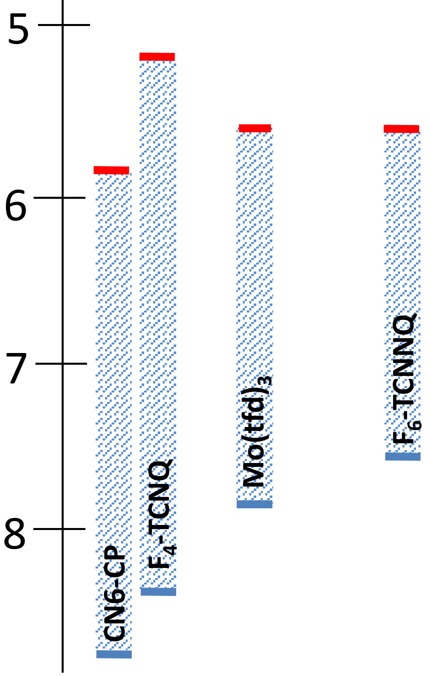
Courtesy of J.-L. Brédas, Georgia Tech

Ionization energy (IE) and electron affinity (EA)



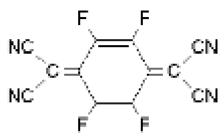
Molecular levels relevant to transport (via inter-molecular hopping) in the film and across interfaces

Some powerful n- and p-dopants

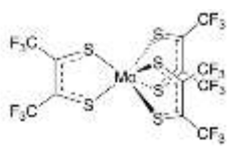


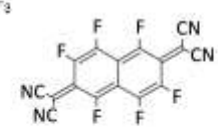
High electron affinity oxidizing molecules p-dopants

F$_4$-TCNQ
Tetrafluorotetracyano-quinodimethane

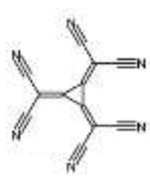


Mo(tfd)$_3$
Molybdenum tris[1,2-bis(trifluoromethyl) ethane-1,2-dithiolene]

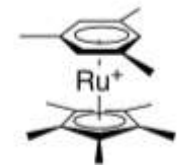




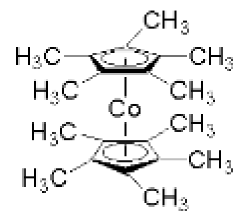
F$_6$-TCNNQ
2,2′-(perfluoronaphthalene-2,6-diylidene)dimalononitrile



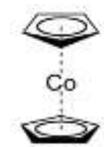
CN6-CP
Hexacyano-trimethylene-cyclopropane



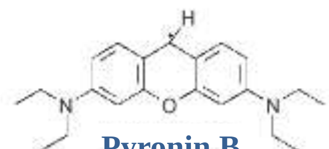
[RuCp*Mes]$_2$
(pentamethylcyclopentadienyl)(1,3,5-trimethylbenzene)ruthenium



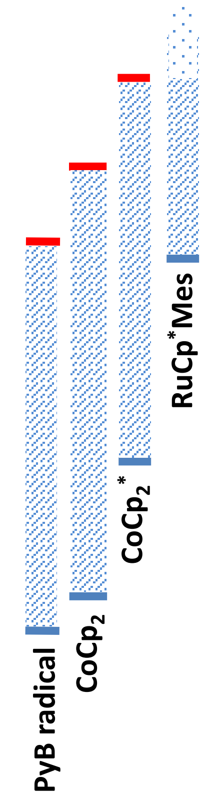
CoCp$_2^*$
Decamethyl-cobaltoscene



CoCp$_2$
cobaltocene



Pyronin B
Reduced radical



Low ionization energy reducing molecules n-dopants

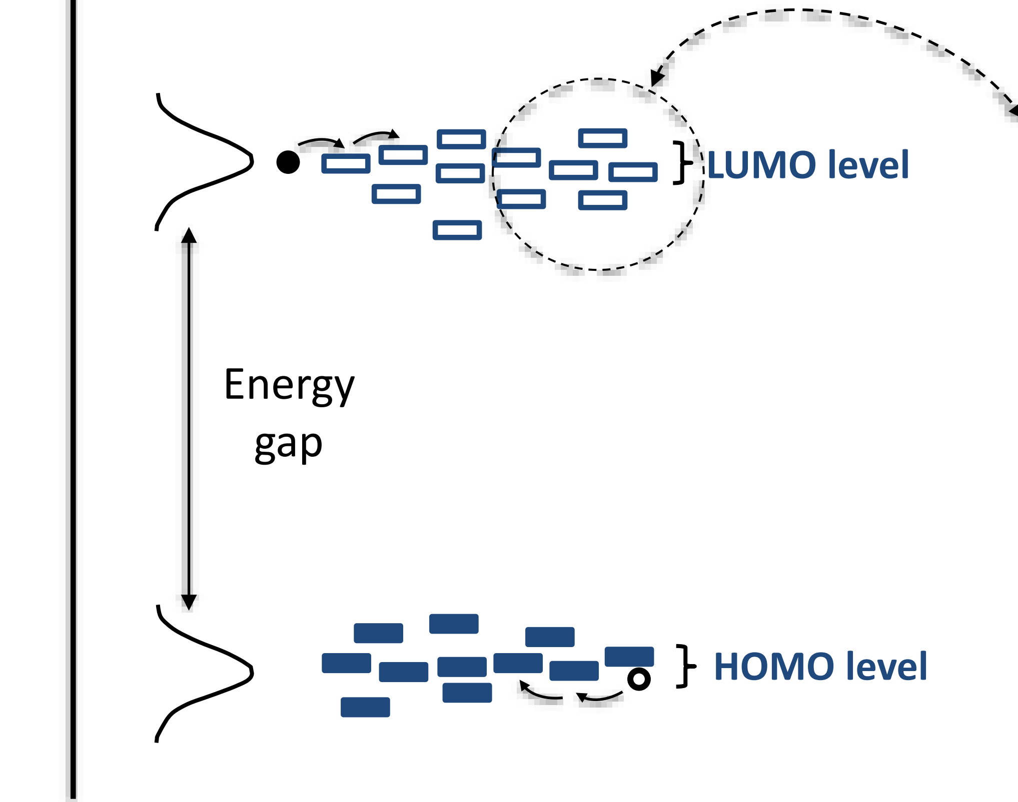
LUMO

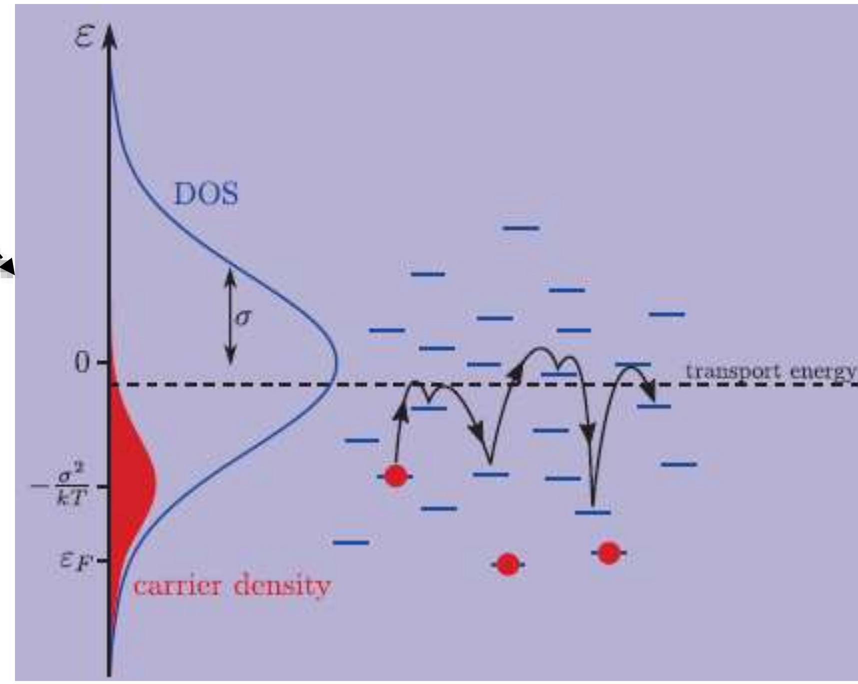
HOMO

Molecular levels relevant to transport (via inter-molecular hopping) in the film and across interfaces

Hopping transport in disordered solids

Energetic distribution due to static and dynamic structural disorder

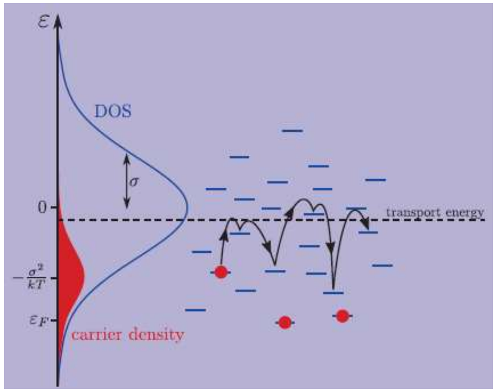




S.D. Baranovskii, Phys. Stat. Sol. 251, 487-525 (2014)

Hopping transport in disordered solids

- The jump rate between site *i* and *j* is described by the Miller-Abrahams relation



Electron transfer rate

$$\nu_{ij} = \begin{cases} \nu_0 exp(-\Gamma r_{ij}) exp(-\beta \Delta E_{ij}), \Delta E_{ij} \geq 0 \\ \nu_0 exp(-\Gamma r_{ij}), \Delta E_{ij} < 0 \end{cases}$$

A. Miller and E. Abrahams, Phys. Rev. **120**, 745 (1960)

where

$$\Delta E_{ij} = E_j - E_i + (field).r_{ij}$$

E_i and E_j are the carrier energies on sites *i* and *j*

Γ: inter-molecular coupling coefficient, inverse localization length (localization length ~ 10^{-8} cm)

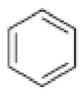
υ_0 is the attempt frequency, estimated as ~ phonon frequency for a thermally activated process (10^{12} s^{-1})

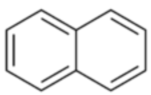
r_{ij} is the distance between localized states *i* and *j*

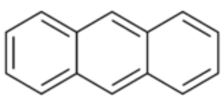
β = 1/kT

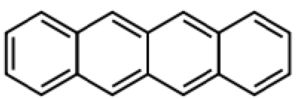
Unlimited choice of semiconductor parameters

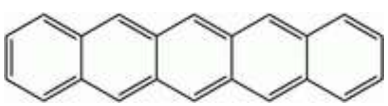
Polyacenes

Benzene  2550 Å (4.86 eV)

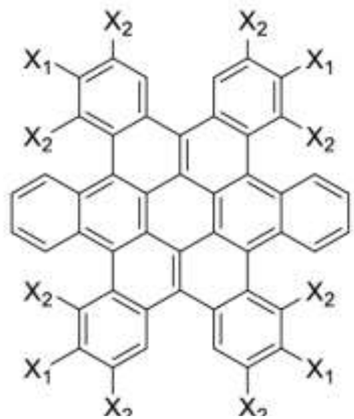
Naphthalene  3150 Å (3.93 eV)

Anthracene  3800 Å (3.2 eV)

Naphthacene or Tetracene  4800 Å (2.6 eV)

Pentacene  5800 Å (2.13 eV)

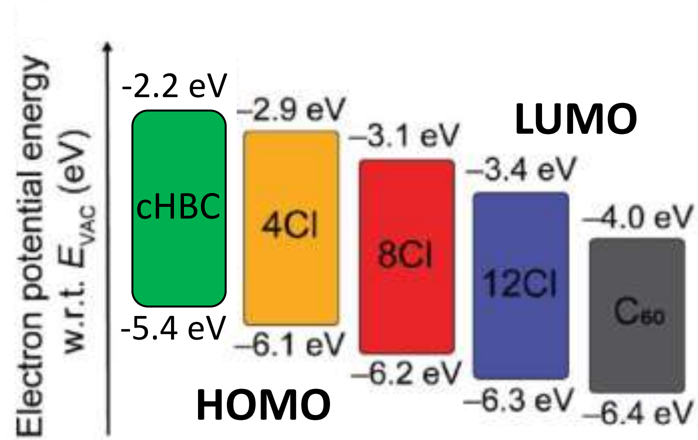
Contorted hexabenzocoronene (cHBC) + halogenated derivatives



4Cl, X_1 = Cl, X_2 = H

8Cl, X_1 = H, X_2 = Cl

12Cl, X_1 = X_2 = Cl



N.C. Davy et al., *Adv. Energy Mat.* ***9***, 1901649 (2019)

Where modern organic electronics started

THE 2011 WOLF PRIZE IN CHEMISTRY

Wolf Foundation · קרן וולף

Ching W. Tang
University of Rochester

Two-layer organic photovoltaic cell

C. W. Tang
Research Laboratories, Eastman Kodak Company, Rochester, New York 14650

APL **48**, 183 (1986)
4,022 citations
(as of May 4, 2021)

(Received 28 August 1985; accepted for publication 31 October 1985)

A thin-film, two-layer organic photovoltaic cell has been fabricated from copper phthalocyanine and a perylene tetracarboxylic derivative. A power conversion efficiency of about 1% has been

Organic electroluminescent diodes

C. W. Tang and S. A. VanSlyke
Research Laboratories, Corporate Research Group, Eastman Kodak Company, Rochester, New York 14650

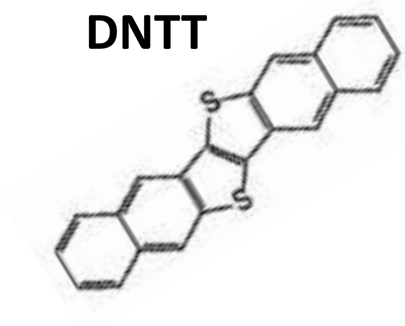
(Received 12 May 1987; accepted for publication 20 July 1987)

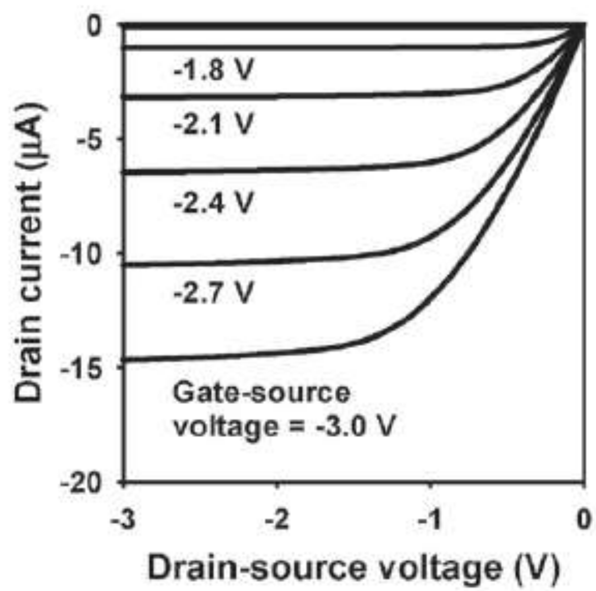
APL **51**, 913 (1987)
12,015 citations
(as of May 4, 2021)

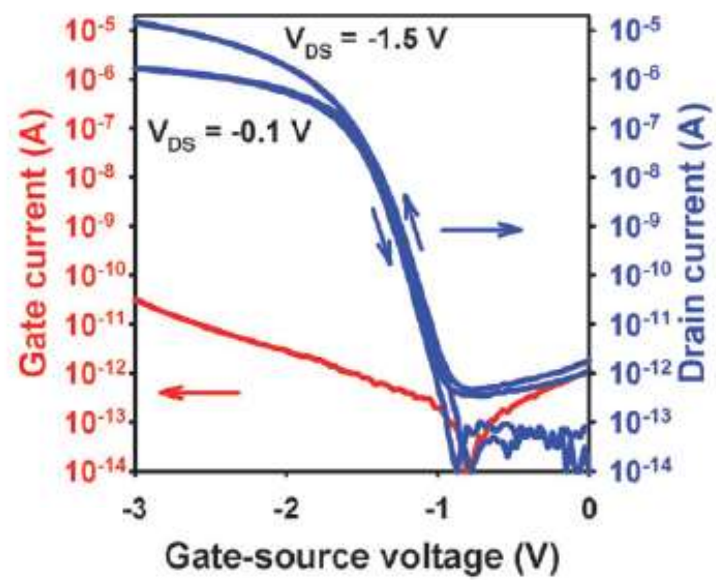
A novel electroluminescent device is constructed using organic materials as the emitting elements. The diode has a double-layer structure of organic thin films, prepared by vapor deposition. Efficient injection of holes and electrons is provided from an indium-tin-oxide

Characteristics of a hole-channel DNTT OFET

- Recall: in Si MOSFET, threshold voltage defined as the minimum gate-source voltage necessary to bring the SC in strong inversion
- OFETs do not operate in inversion, so strictly speaking, V_T cannot be defined. However, still very useful concept, since it is the minimum gate-source voltage required to obtain an appreciable drain current
- Switch-on voltage V_{SO} is V_{GS} when I_D reaches minimum (~-1 V here)







H. Klauk, *Chem. Soc. Rev.* ***39***, 2643 (2010)