ETI Annual Workshop 2019, Nov. 5-6, Atlanta, GA

Organic photodiodes: towards large-area, low-cost photon counting platforms

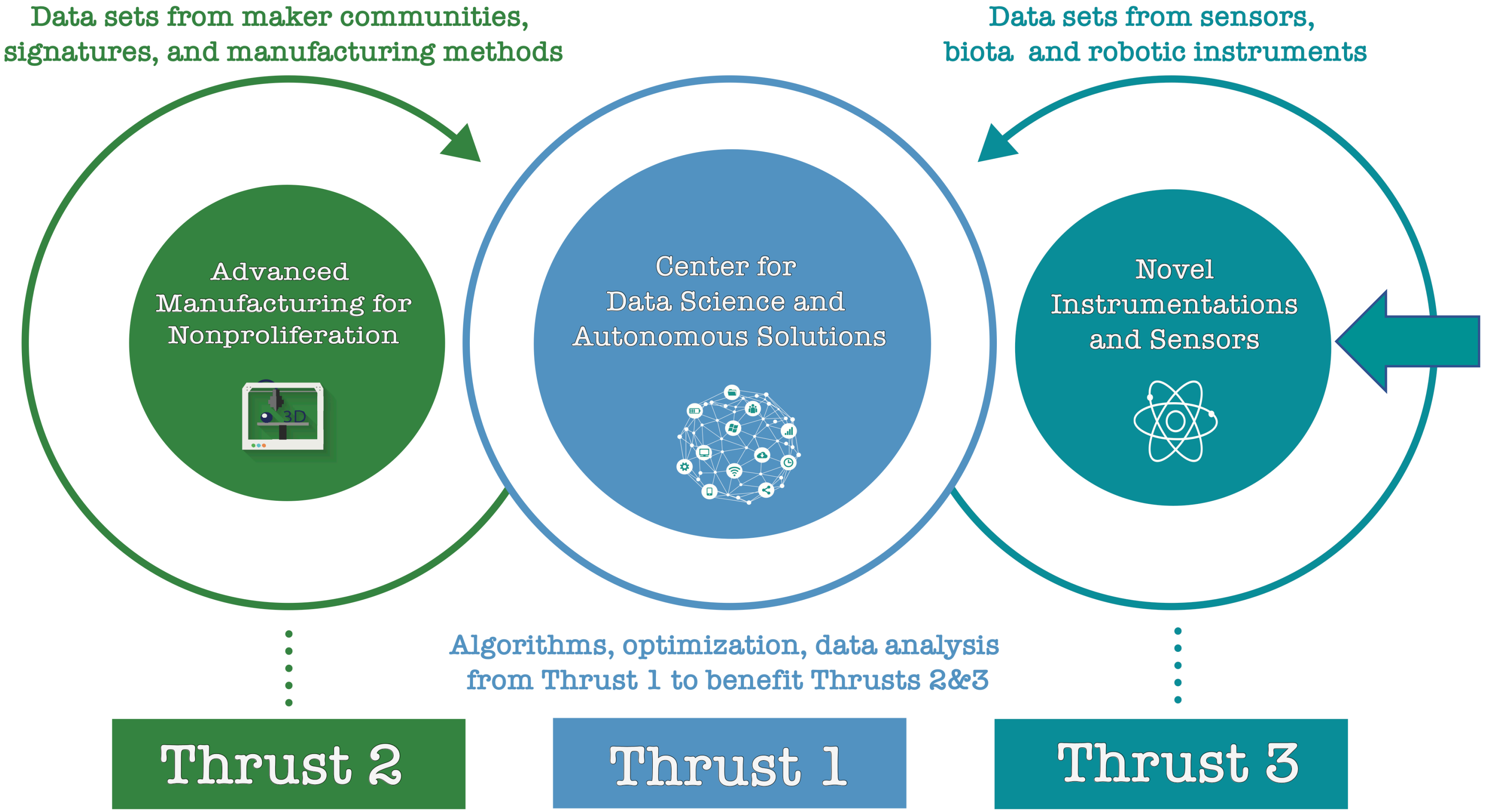
Kippelen Research Group

School of Electrical and Computer Engineering

Georgia Tech

Consortium for ENABLING TECHNOLOGIES & INNOVATION

Thrust 3: Novel instrumentation and sensors



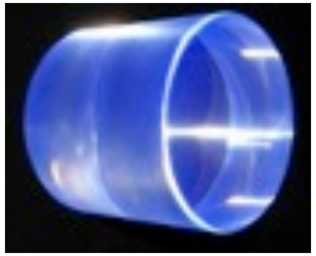
Light collection and materials

Light collection and materials

Sources

α, β, γ, n

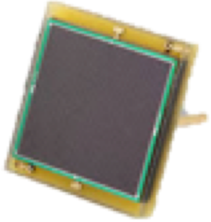
Conversion



Scintillators

Light collection and detection

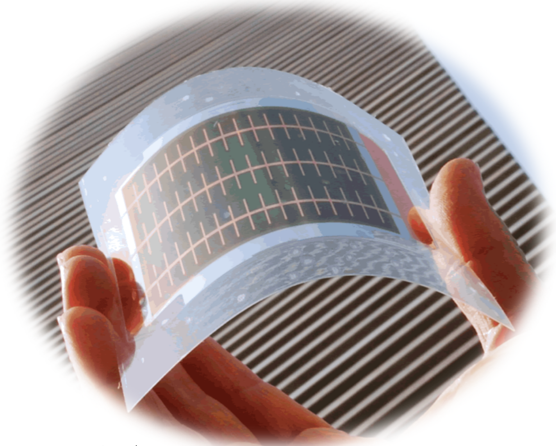
PMTs



Si-PMs

LEGACY TECHNOLOGY

NEXT GENERATION:



Georgia Tech

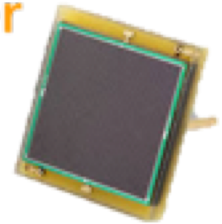
Organic/hybrid photodiodes and scintillators

Solid-state photodetectors: cost, size, performance

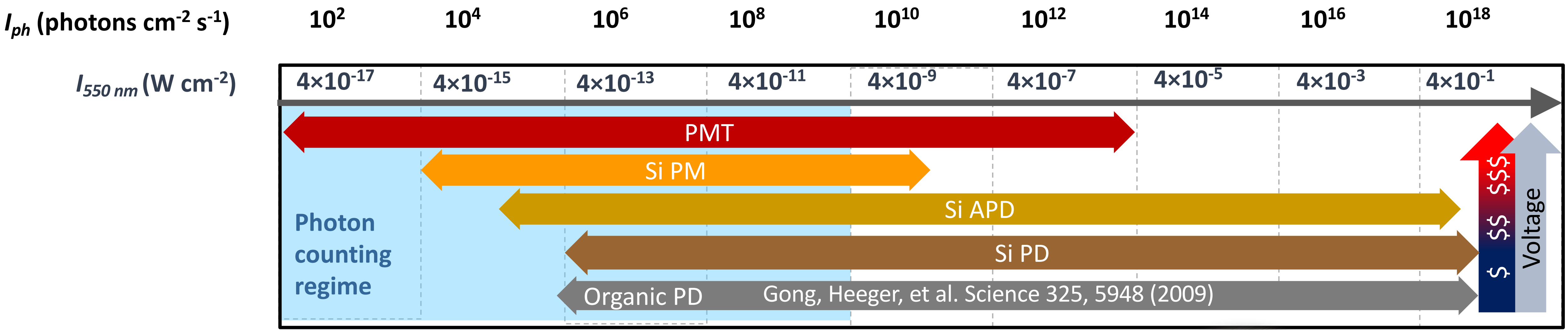
Photomultiplier tube (PMT)

$ 1000 – 10,000
1 – 4 cm^2

Si-photomultiplier (Si PM)



$ 100 – 1000
0.1 – 10 cm^2



Adapted from Hamamatsu

$ 10 – 100
0.01 – 1 cm^2

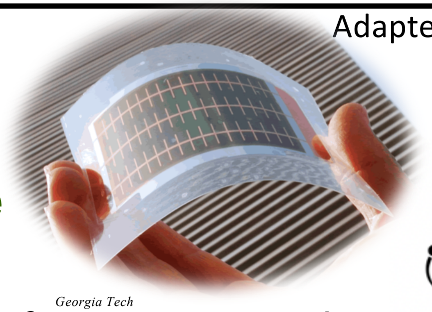
Si avalanche photodiode (Si APD)

$ 10 – 100
0.01 – 1 cm^2

Si-photodiode (Si PD)

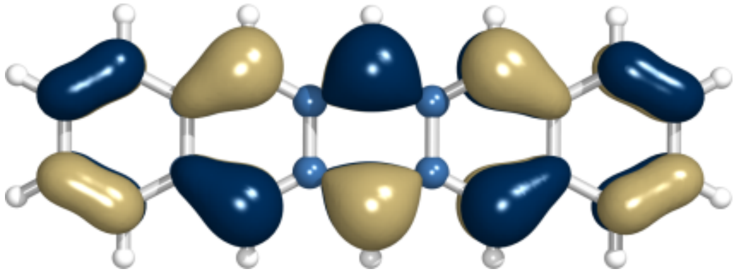
Organic photodiode (OPD)

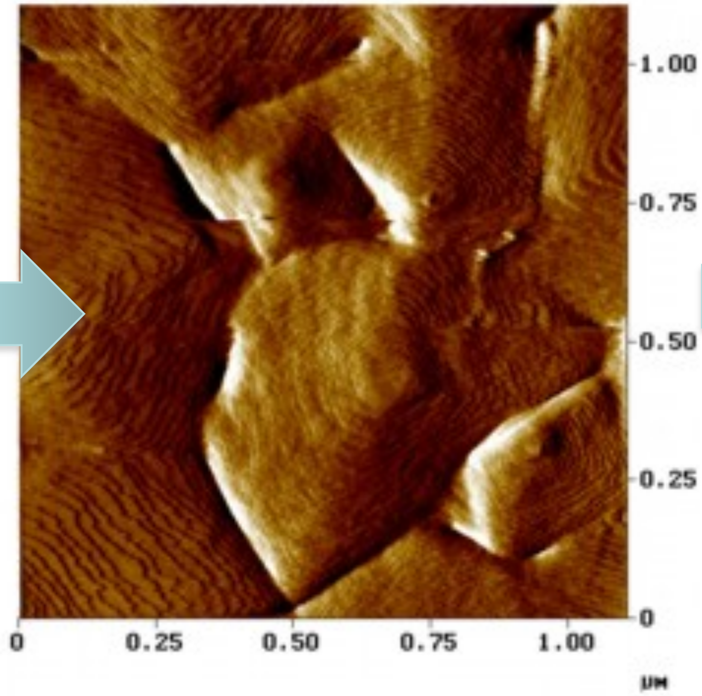
< $ 0.5 per cm^2



Organic semiconductors for printed electronics

large area, flexible, light weight, AND high performance

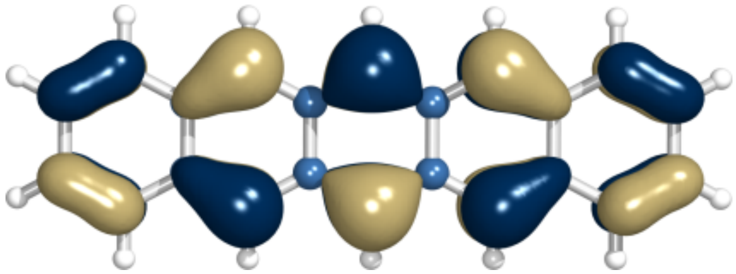




Processing at room temperature onto any substrate:
foil, plastic films, paper, elastomers

Semiconductors: organic and inorganic

Molecular properties



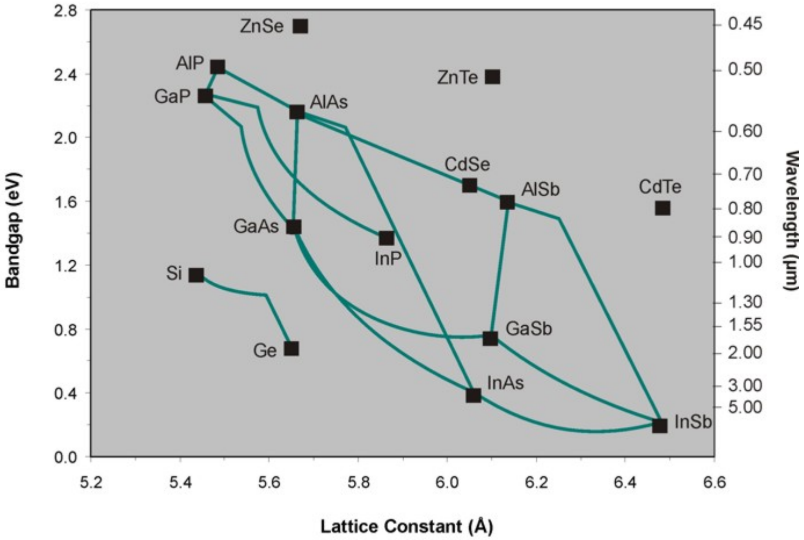
Courtesy of C. Risko

Highly <u>localized</u> electronic excitations

Morphology and structure difficult to define, disordered structures

Tolerant to defects

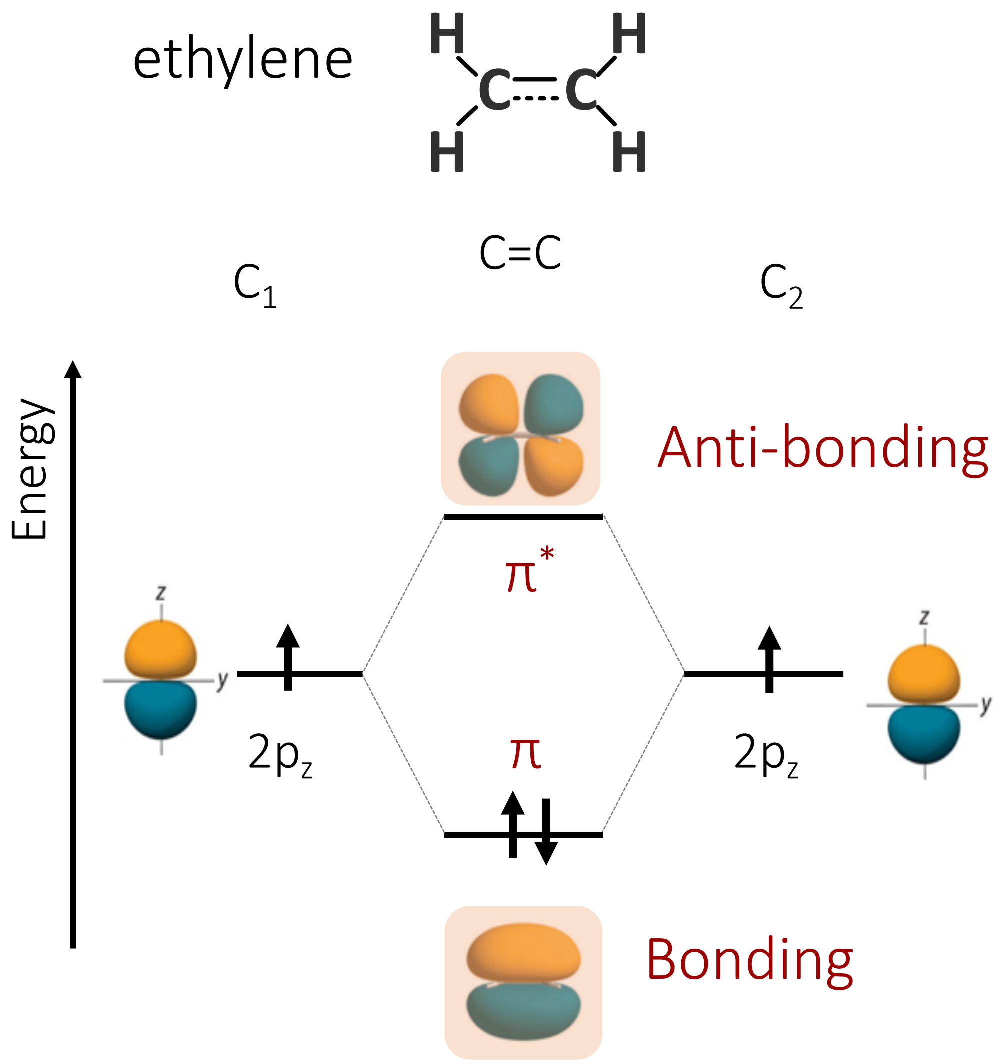
Lattice driven properties

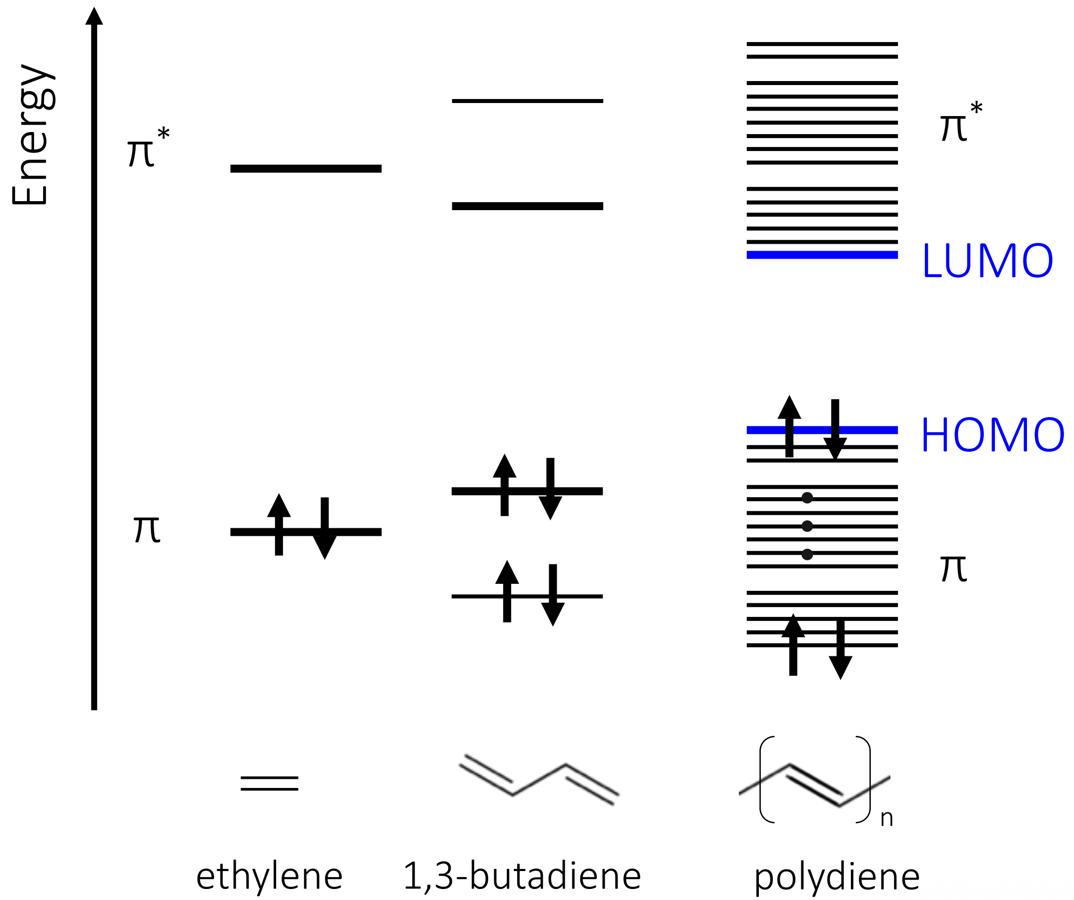


Highly <u>delocalized</u> electronic excitations

Periodic lattice leads to well defined band structures

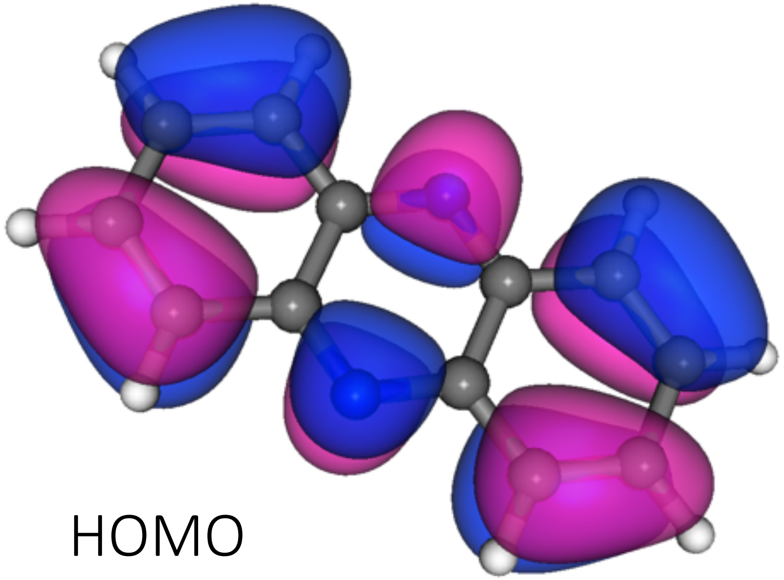
Frontier molecular orbitals



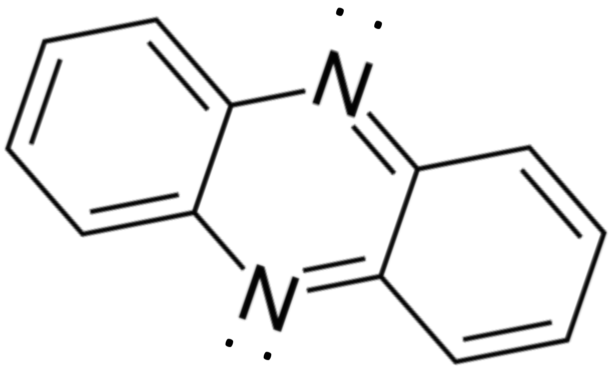


Examples of Molecular Orbitals

π orbital

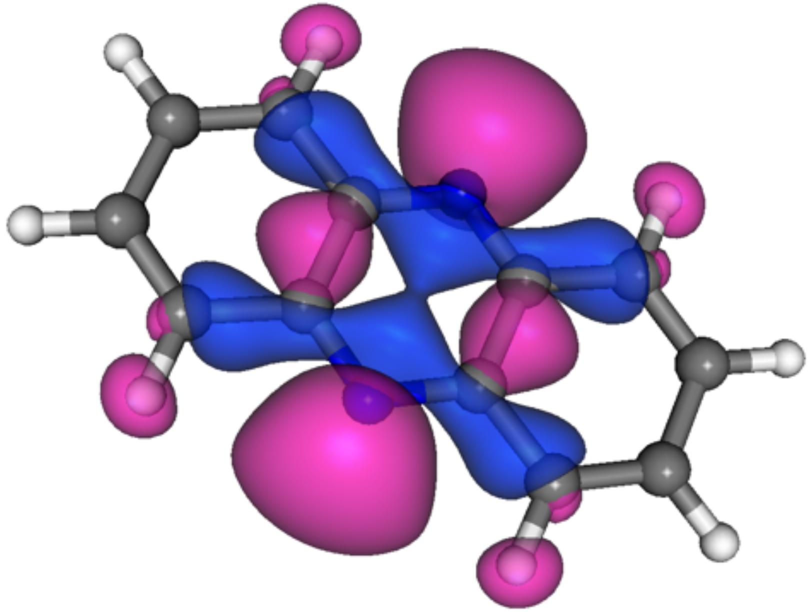


HOMO



Phenazine

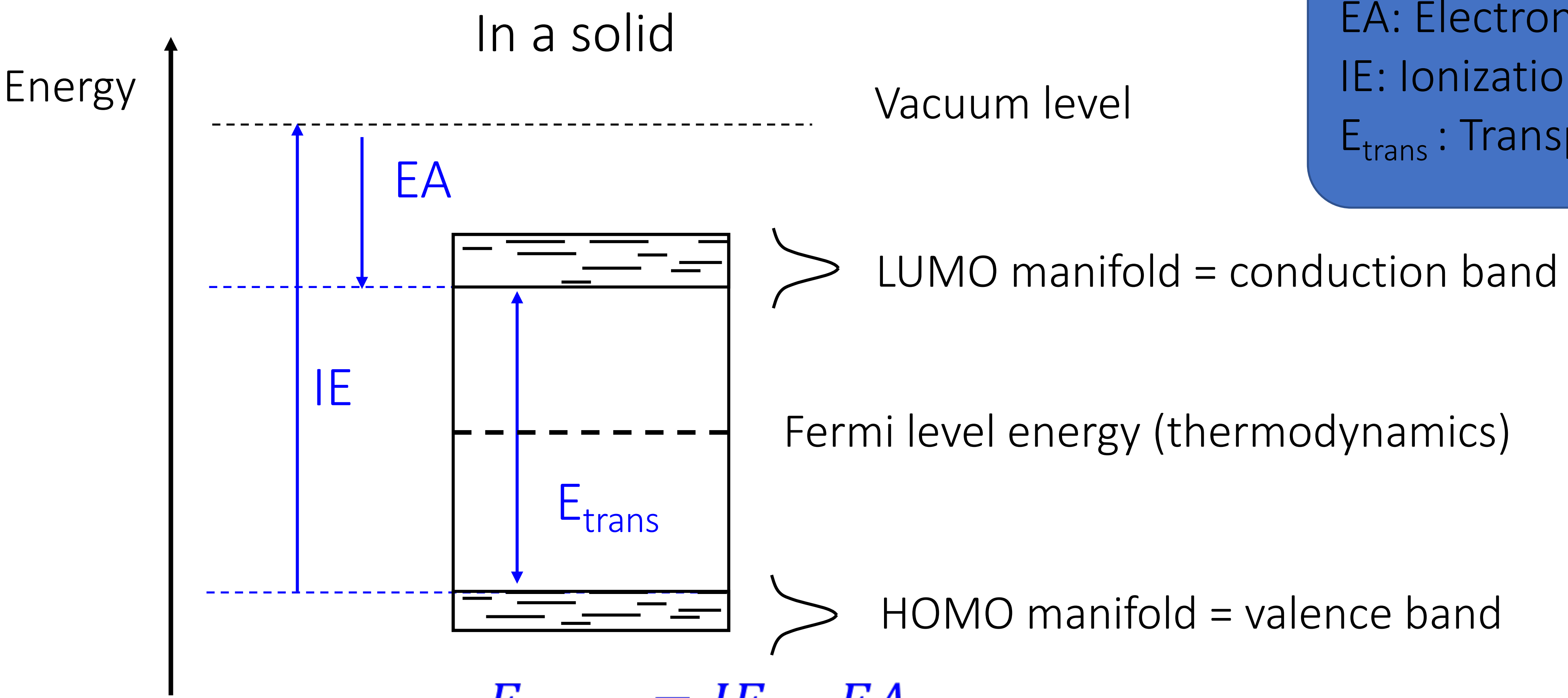
n orbital



HOMO-1

Drawings: courtesy of Wolfram Ratzke, Lupton Group, Univ. of Regensburg

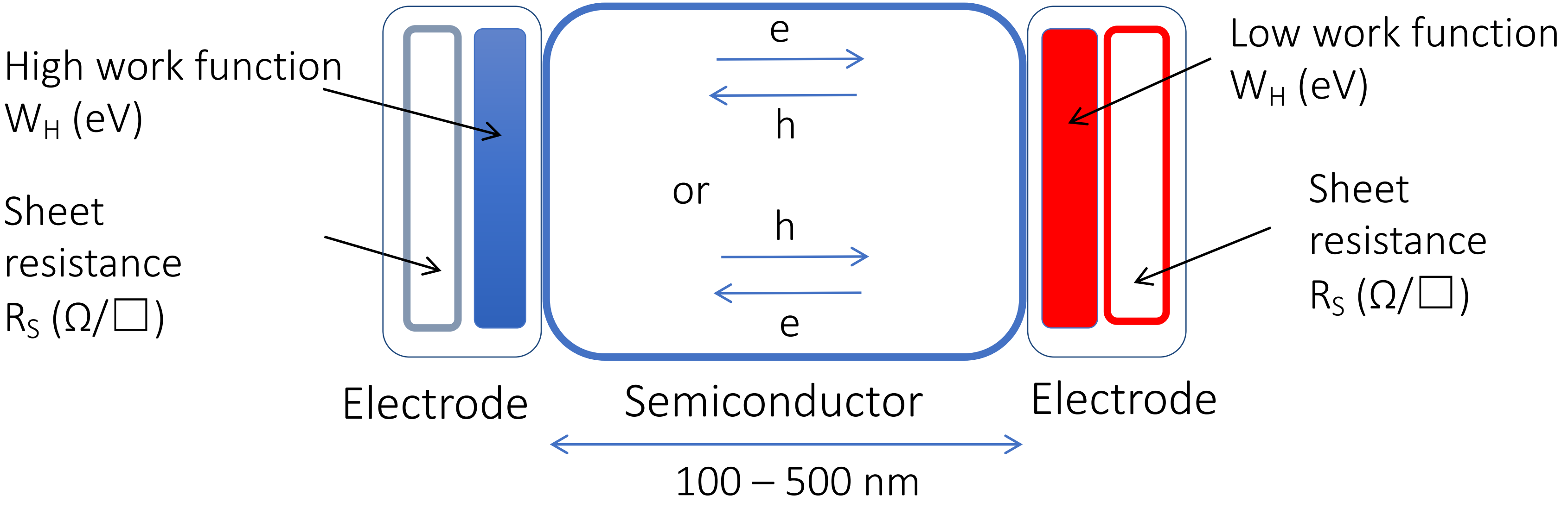
Organic semiconductors: transport Levels

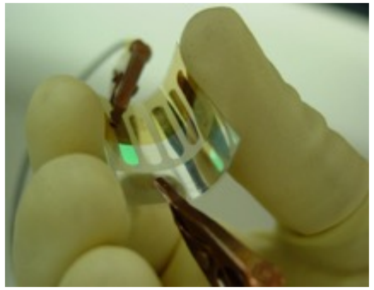


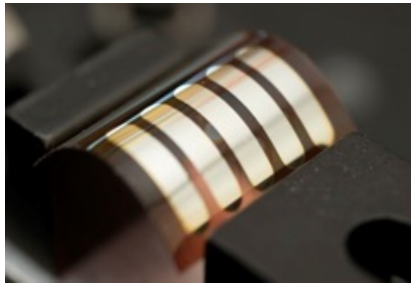
EA: Electron affinity
IE: Ionization energy
E_{trans} : Transport gap

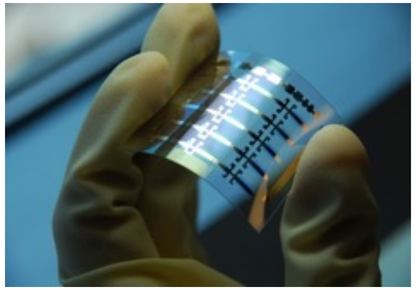
$$E_{trans} = IE - EA$$

Solid-state organic optoelectronic devices



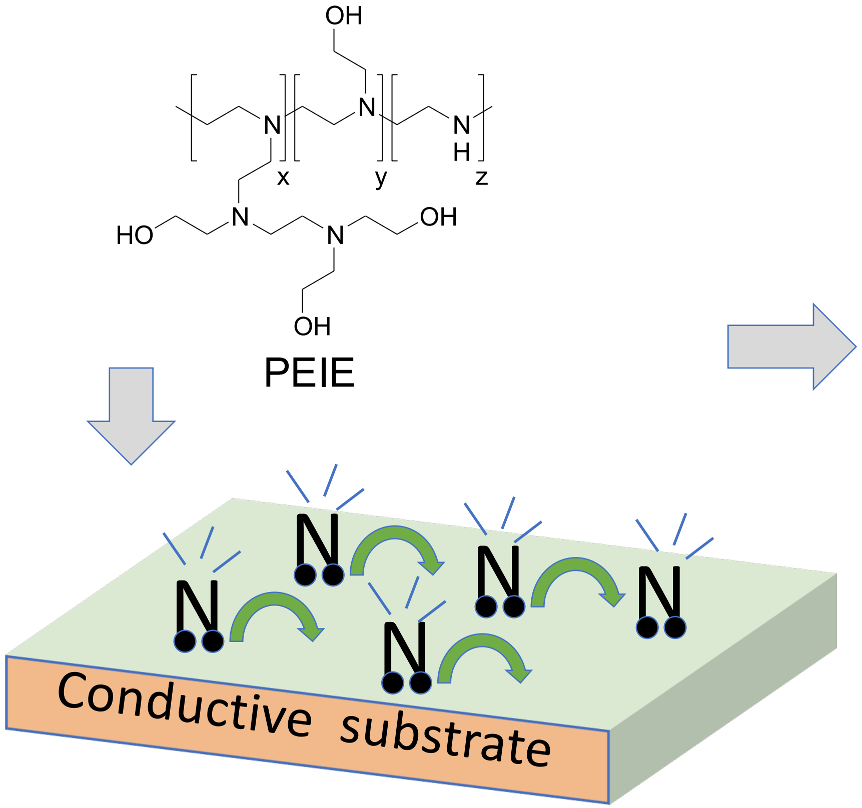


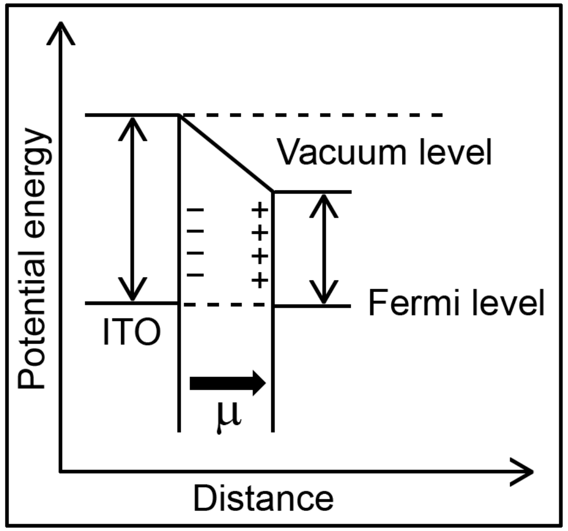


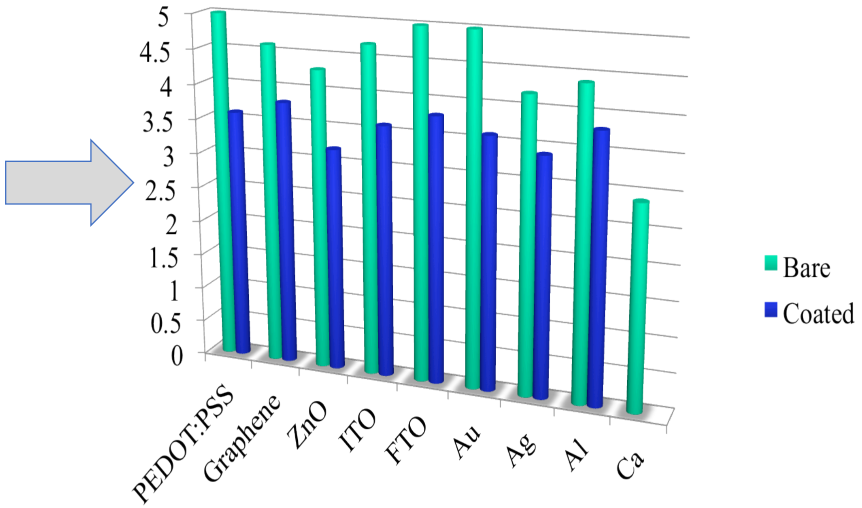


Electrodes for charge injection (OLED, OFET) or charge collection (OPV) are essential device-enabling building blocks

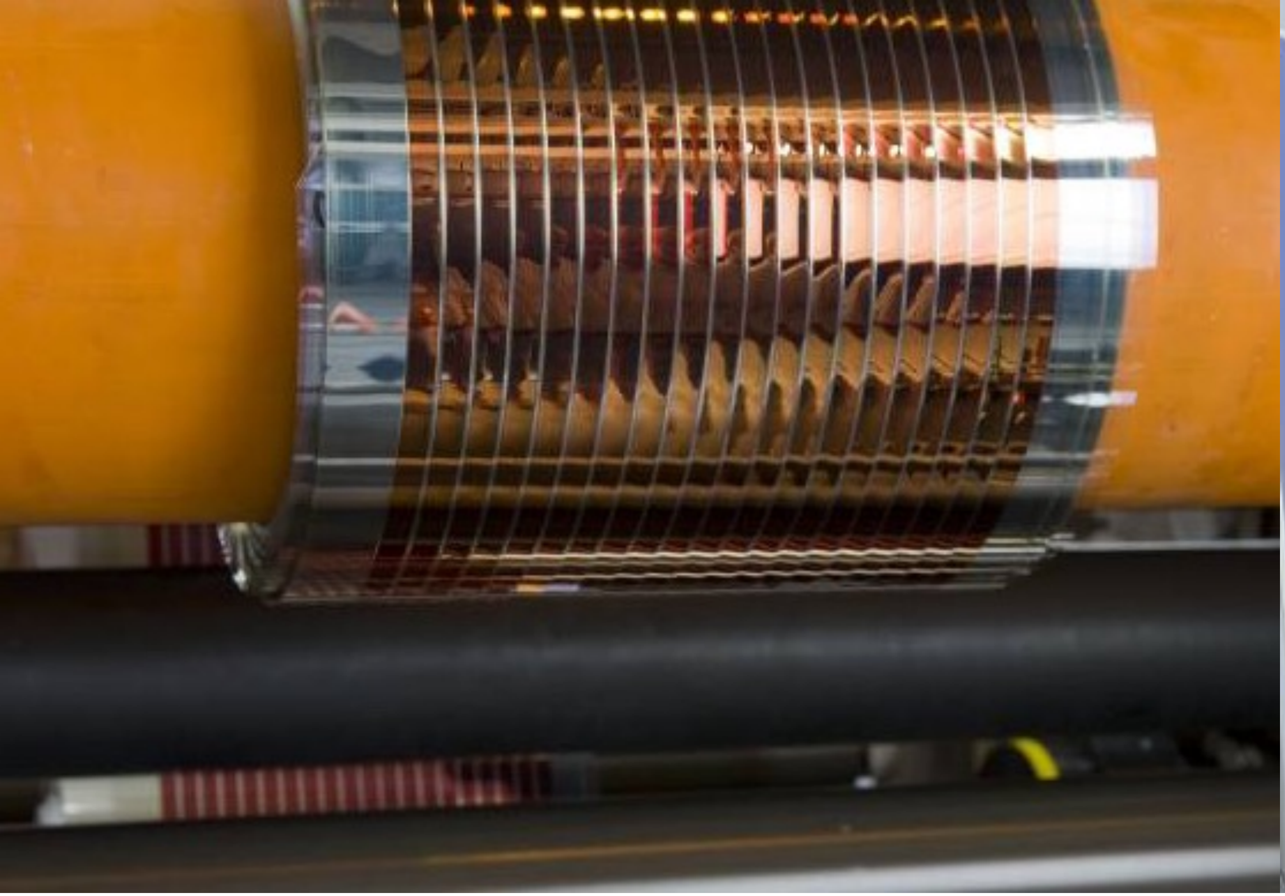
Enabling technology: air-stable low work-function electrodes







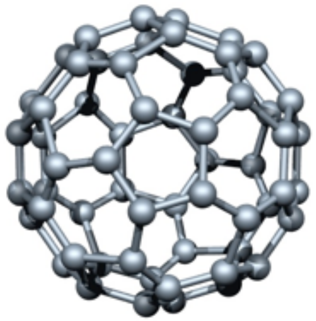
Y. Zhou, S.R. Marder, J.L. Bredas, S. Graham, A. Kahn, B. Kippelen et al.
Science, 336, 327 April 20 (2012).



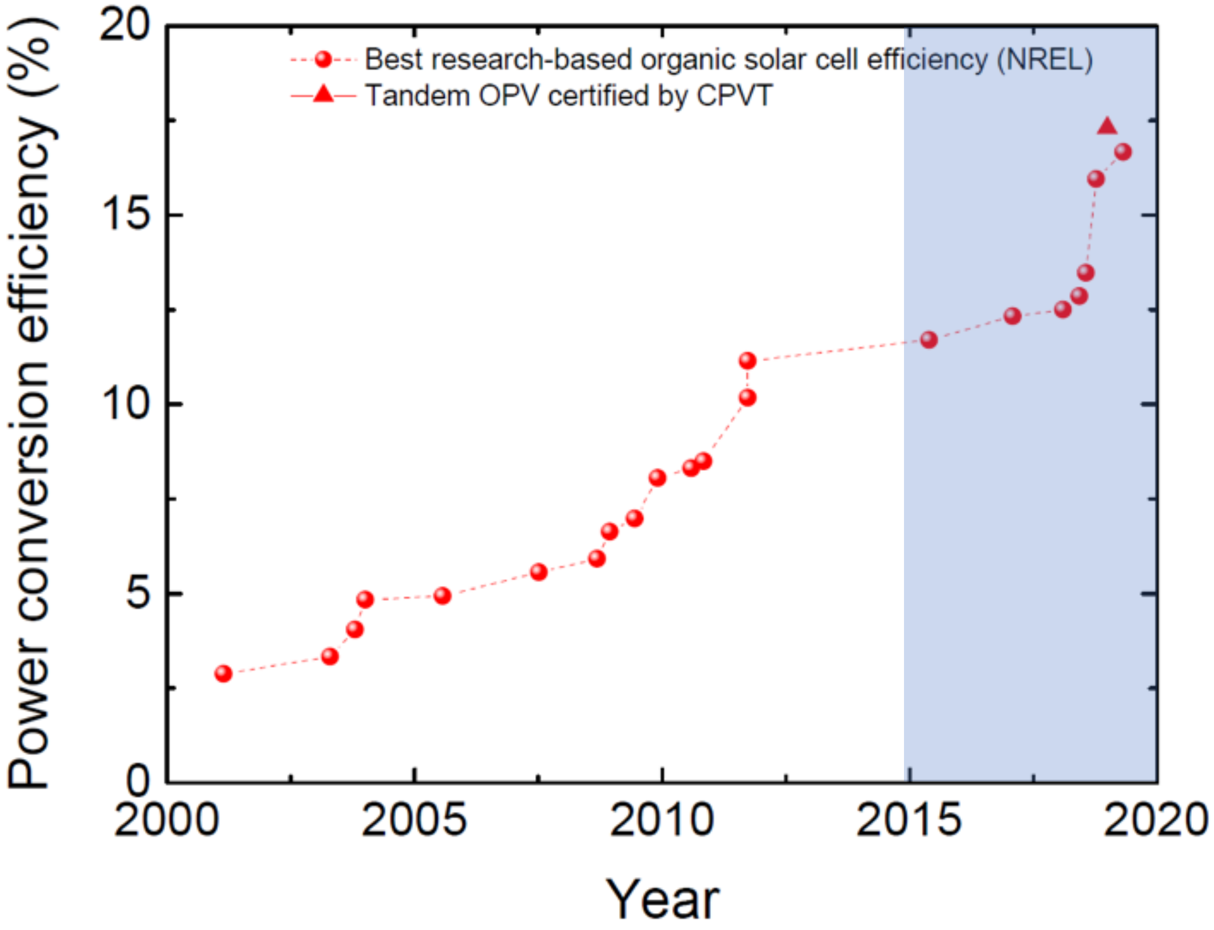

Organic Photovoltaics: Untethered Power

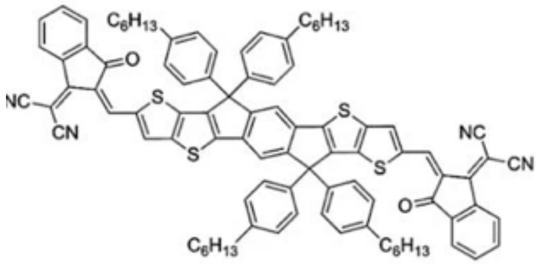
Power conversion efficiencies of 17% demonstrated

17.3%



Fullerene acceptor





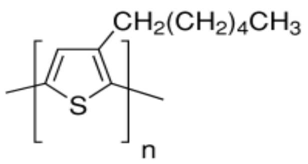
ITIC

Meng et al., Science 361, 1094–1098, 14 September (2018)

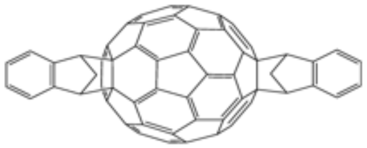
Organic photodiodes: beyond Si

OPD

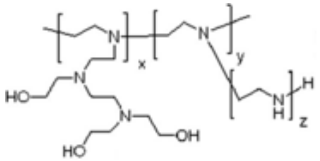
Materials



P3HT (donor)

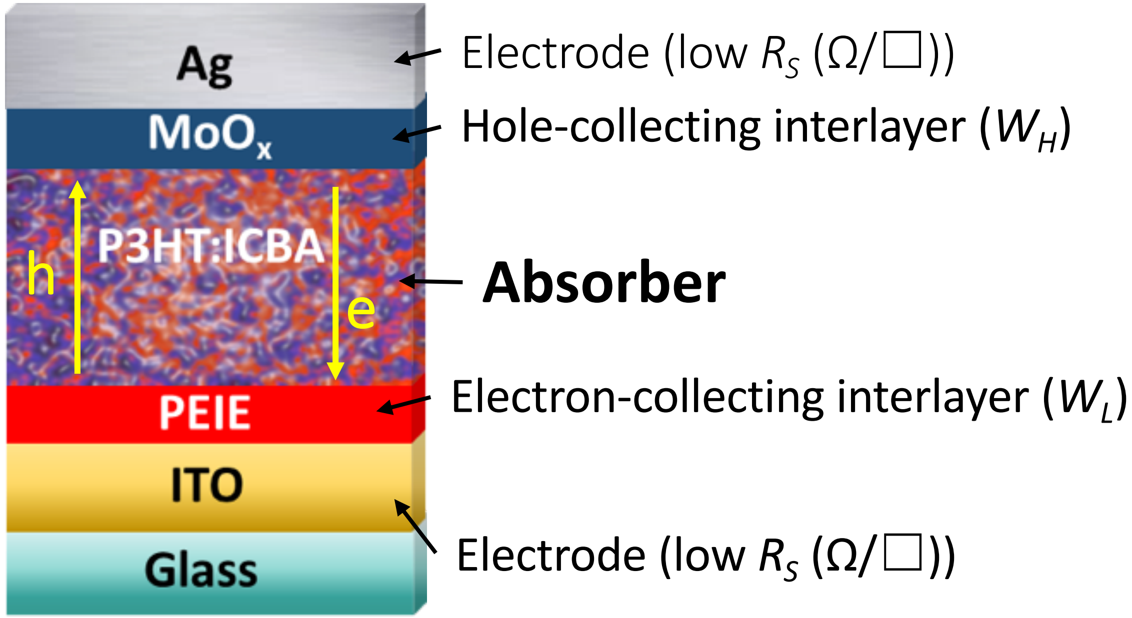


ICBA (acceptor)



PEIE

Device Architecture

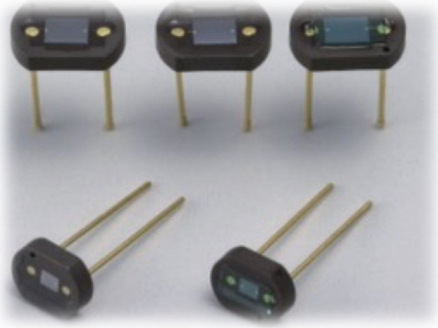


Y. Zhou et al., Science 336, 327–332 (2012)

Si PD

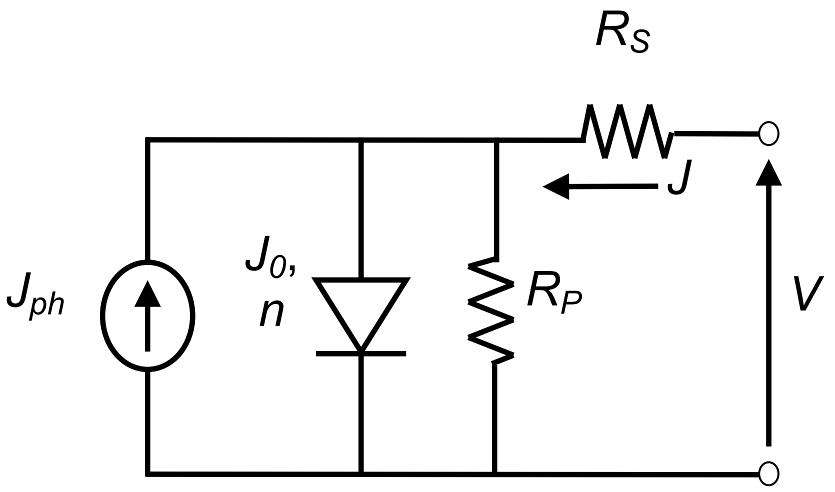
Hamamatsu S1133

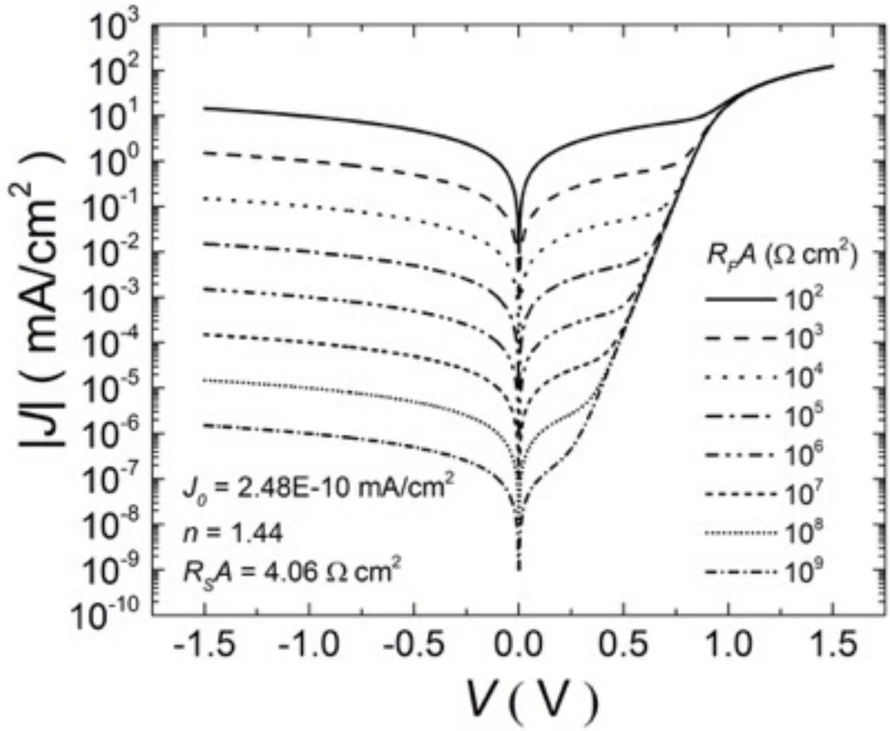
(state-of-the-art low-noise Si PD)



Modeling of organic photodiodes

Devices are not perfect diodes: current in reverse bias limited by shunt resistance

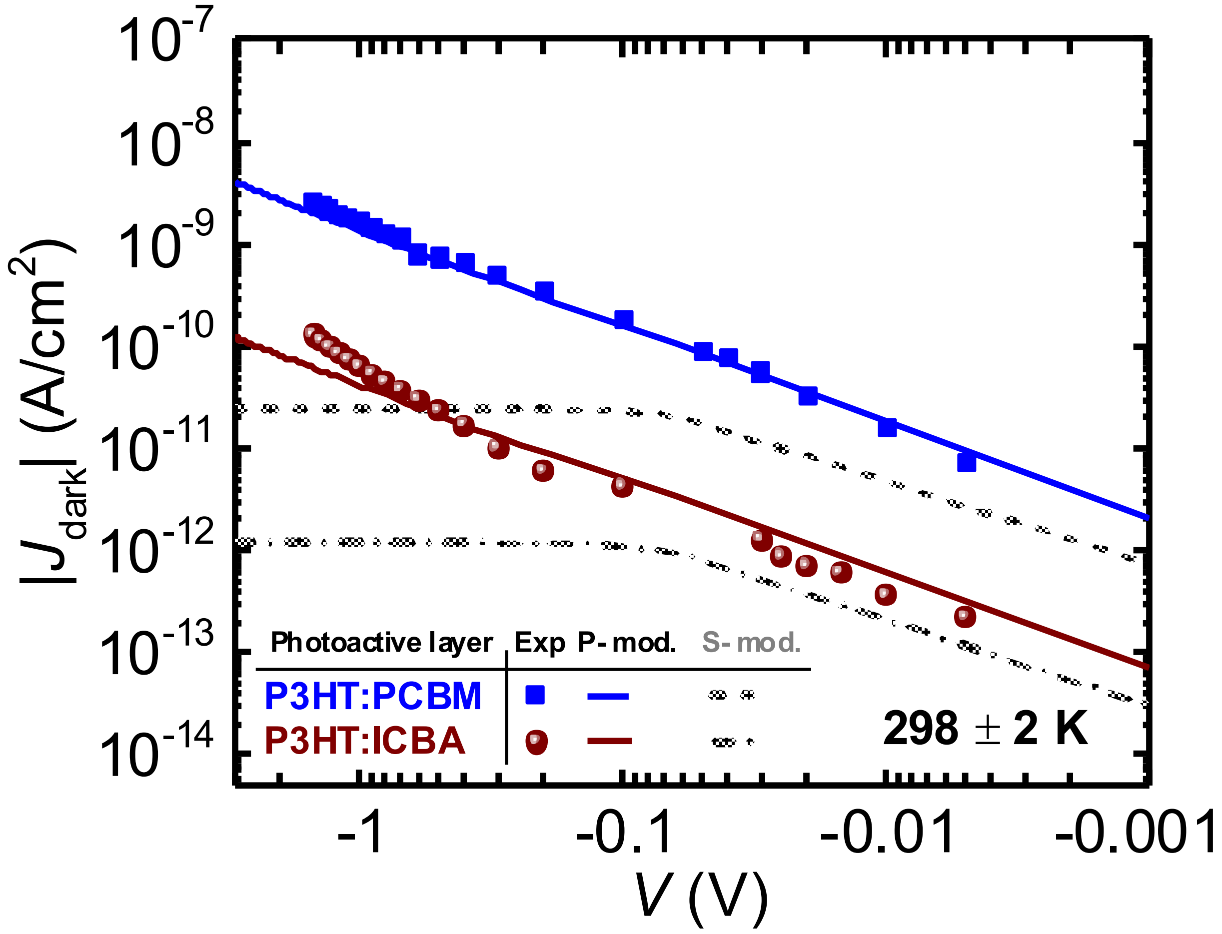




$$J = \frac{1}{1 + R_S / R_P} \left[J_0 \left\{ \exp\left(\frac{V - JR_S A}{nV_T} \right) - 1 \right\} - \left(J_{ph} - \frac{V}{R_P A} \right) \right]$$

M.B. Prince, *J. Appl. Phys.* 26, 534 (1955).

Dark current at low voltage



National Nuclear Security Administration

CNEC Consortium for Nonproliferation Enabling Capabilities

Conclusion and outlook

Recent results demonstrate that organic photodiodes have reached a level of performance that rivals that of silicon in all metrics except response time.

BUT WITH LARGE AREA AND LOWER COST

Future work will focus an amplification using impact ionization.