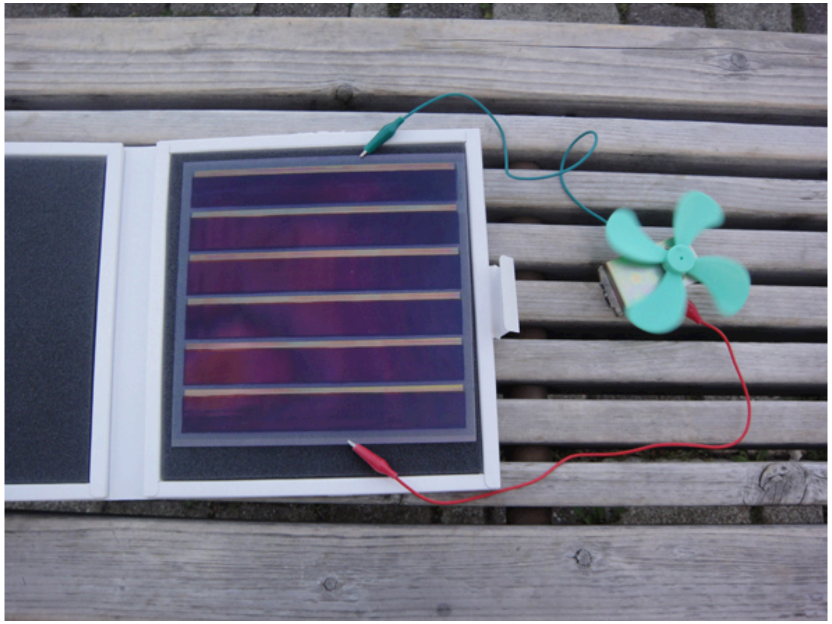
Organic Semiconductor and Organic Solar Cells
(Next generation solar cells using nanomaterials)



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The University of Tokyo

2016.10.11

– General Overview of Solar Cells –

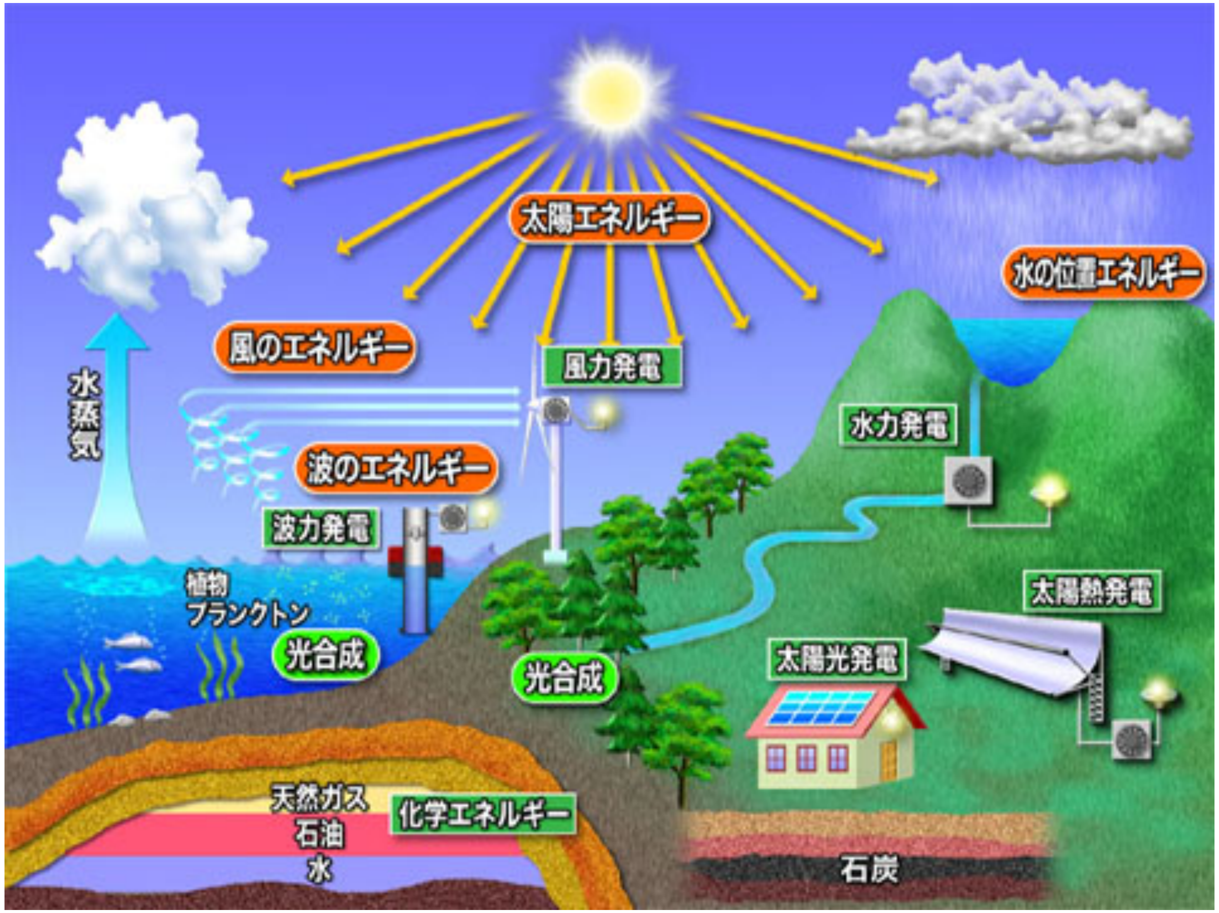
Solar Energy

potential energy of water

wind power

wave power

photo-synthesis



solar power
solar thermal

chemical energy

- natural gas 63 years
- petroleum 41 years
- coal 147 years

reverse-production ratio

Solar Cells

History:

1839 Becquerel, recognition of photovoltaic effect
1884 Fritts, the first solar cell (selenium/gold)
1954 AT&T Bell Lab., single crystal silicon solar cells
1991~ intensive research of dye-sensitized solar cells
2000~ intensive research of organic thin-film solar cells

World market of solar cells:

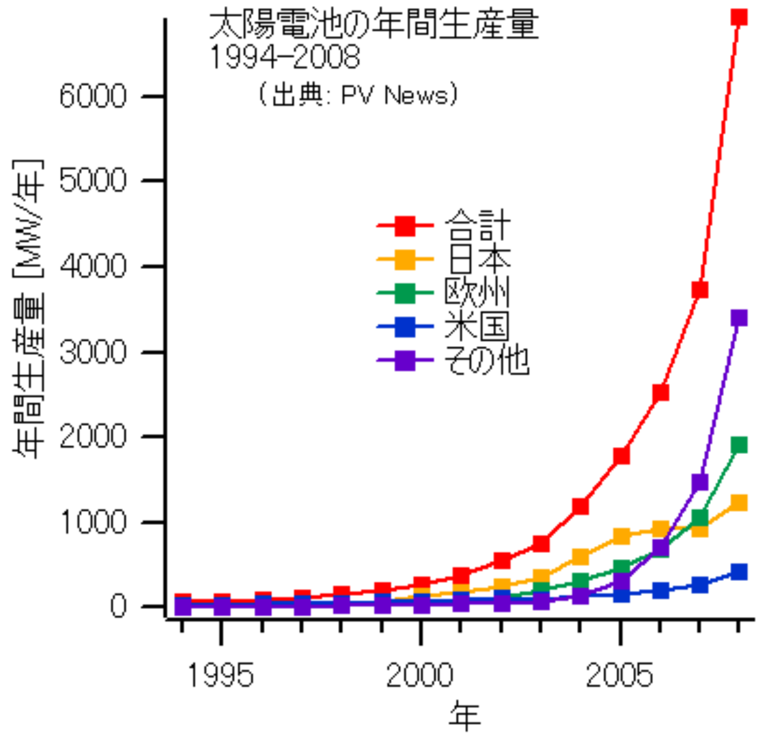
2007, $12,008,000,000 (1兆2008億円)
2012, $46,700,000,000 (4兆6700億円)
(expected)

Annual production of solar cells

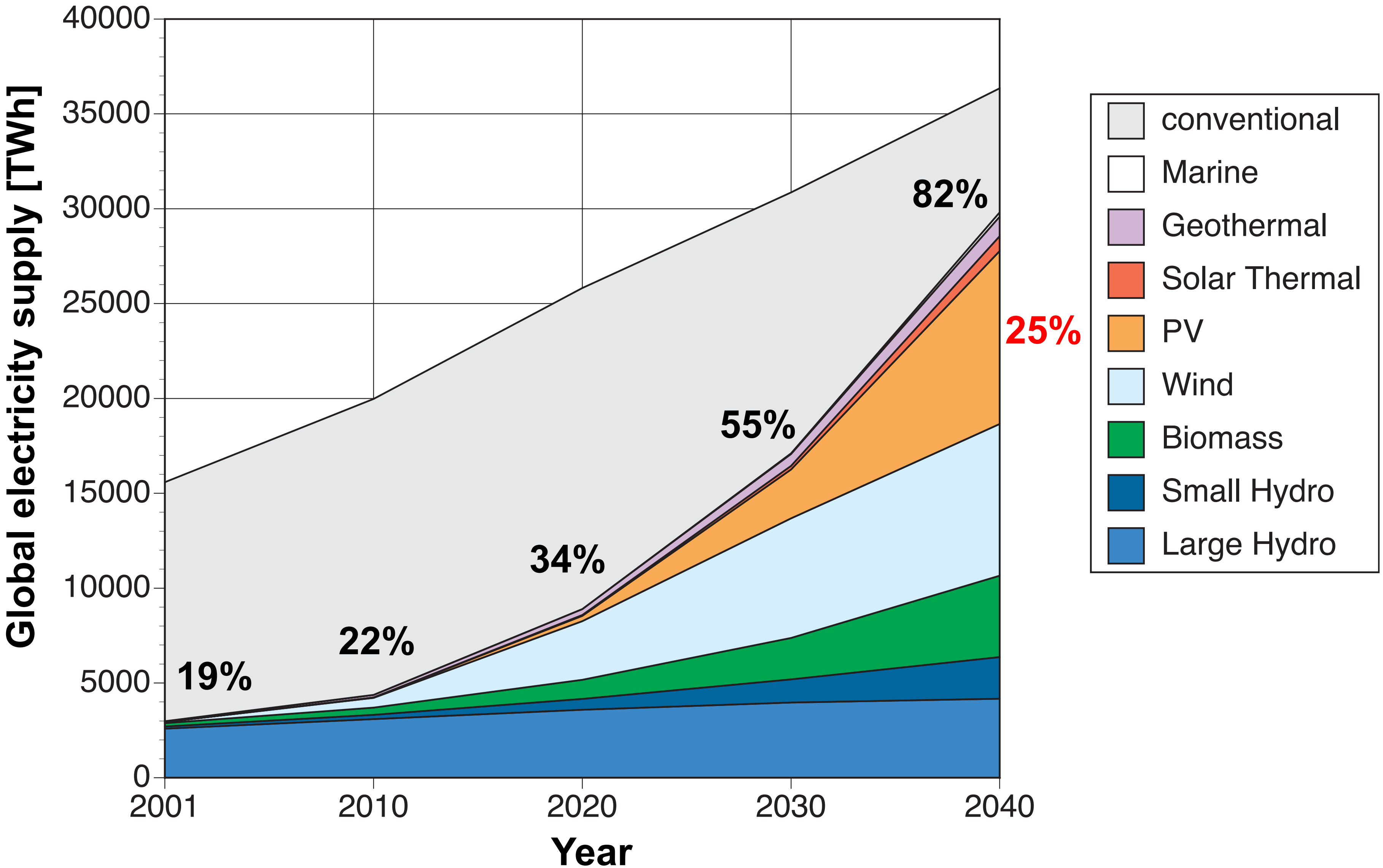
2006, 2.5 GW/year
2007, 3.5 GW/year
2008, 6.9 GW/year

cf. nuclear power generation: 1GW/plant·year

annual production [MW/year]



Renewable Energy



Source: European Renewable Energy Council

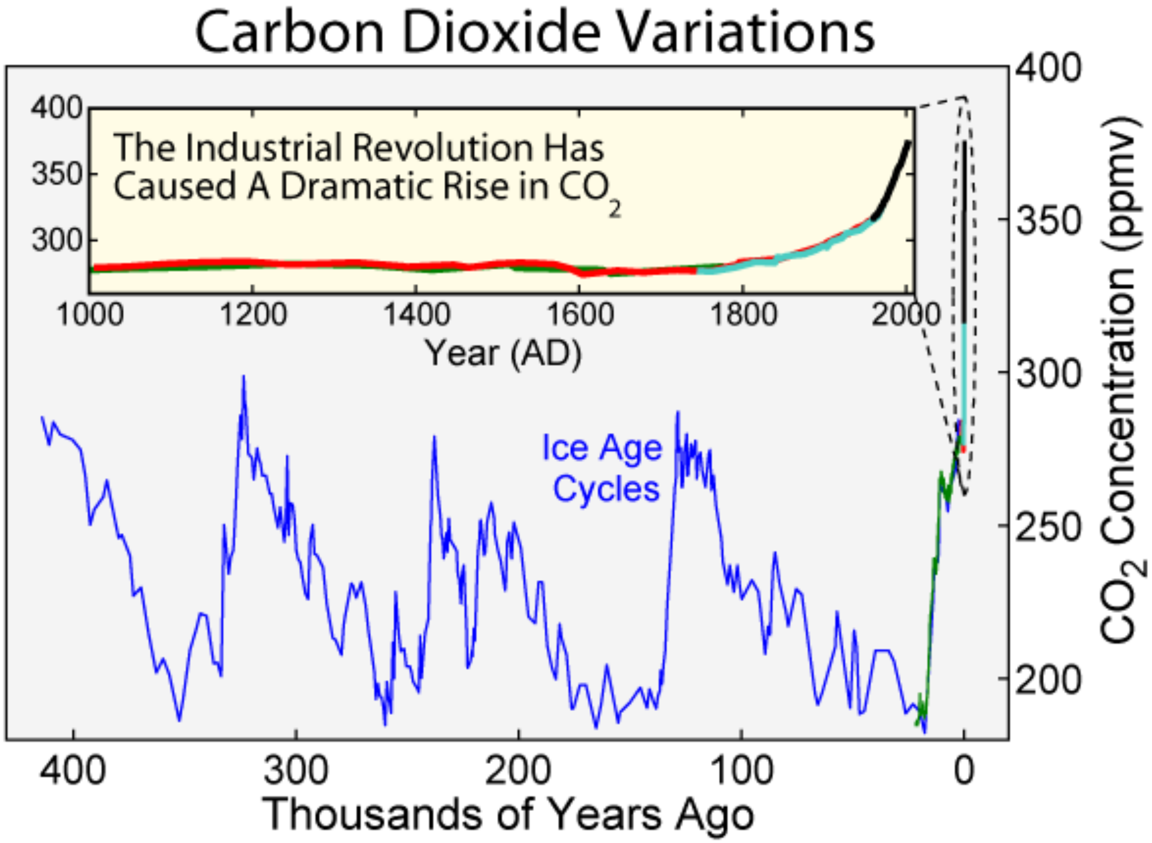
Low CO_2 Emission of Solar Cells

CO_2 Emission:

solar cells: 25–80 g-CO_2/kWh

fossil fuels: 600–700 g-CO_2/kWh

Global Warming:



Energy and Money Balance

Energy Payback Time (EPT):

$$EPT = \frac{E_{input}}{E_{producing}} = \frac{\text{energy used in solar cell production}}{\text{annual energy production (/ year)}}$$

- polycrystalline silicon solar cell: 1.5 (year)
- amorphous silicon solar cell: 1.1 (year)
- CIS solar cell: 0.9 (year)
- (wind power: 0.3 year)

Money Payback Time (MPT):

$$MPT = \frac{M_{input}}{M_{producing}}$$

Cost of Solar Cells

Power Cost (発電コスト):

Cost for Manufacturing（製造コスト）
Installation
Operation
Decommissioning

- Si solar cell: 45–65 yen / kWh
- Oil-thermal power: ca. 10 yen / kWh
- Wind power: 10–14 yen / kWh
- (cf.) electricity price at home: 15–30 yen / kWh

Production and purification of Si:

$$SiO_2 \xrightarrow[\text{}]{\text{C (コークス)}} \text{crude Si} \xrightarrow{Cl_2} SiCl_4 \rightarrow \text{pure Si}$$

(Siemens method)

Various Solar Cells

Inorganic

silicon solar cells

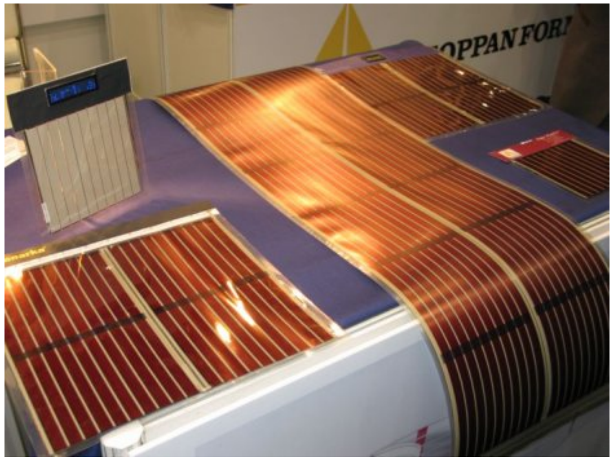
compound semiconductor solar cells

CIGS (CIS) solar cells

C: copper
I: indium
G: gallium
S: diselenide
(selenium)

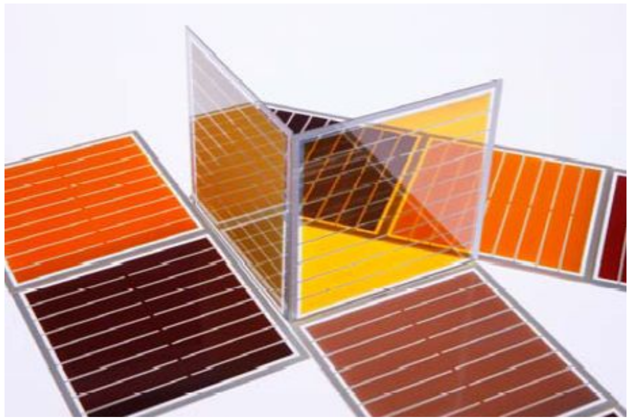
Organic

organic photovoltaic cells



Konarka Technologies

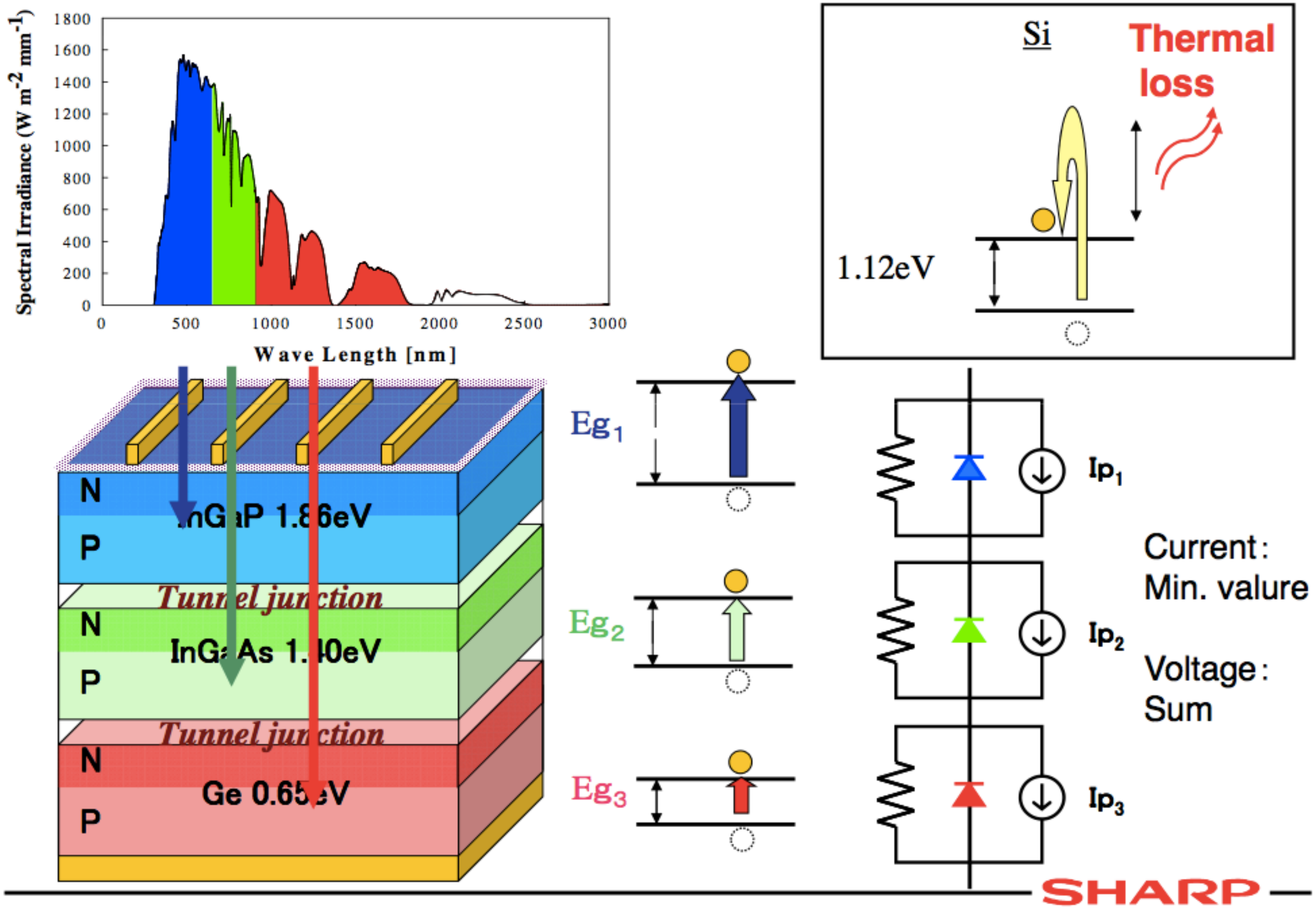
dye-sensitized solar cells



potential low-cost, lightweight, flexible, wide area

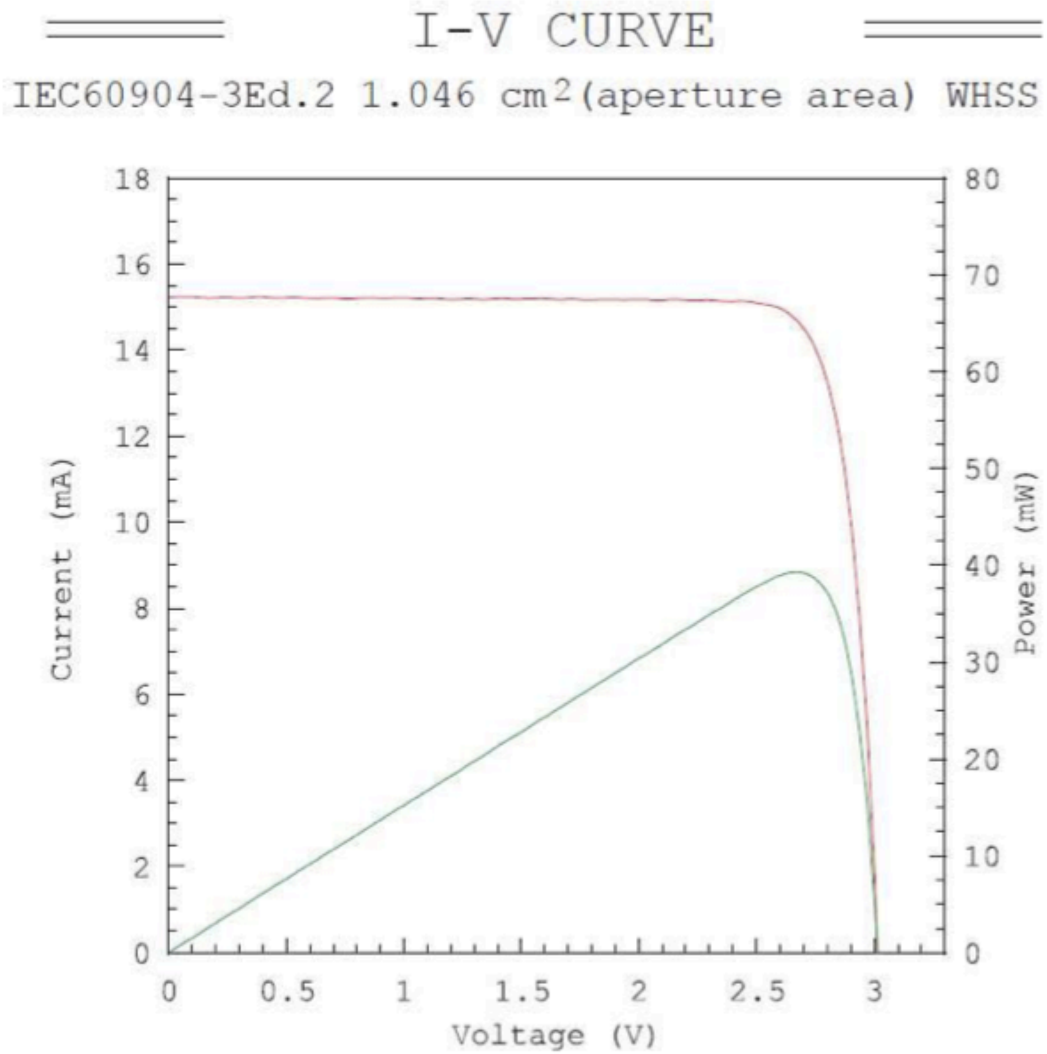
Highest Power Conversion Efficiency

InGaAs-based three-layer solar cells：37.5％



シャープ，2012年12月5日発表

Highest Power Conversion Efficiency



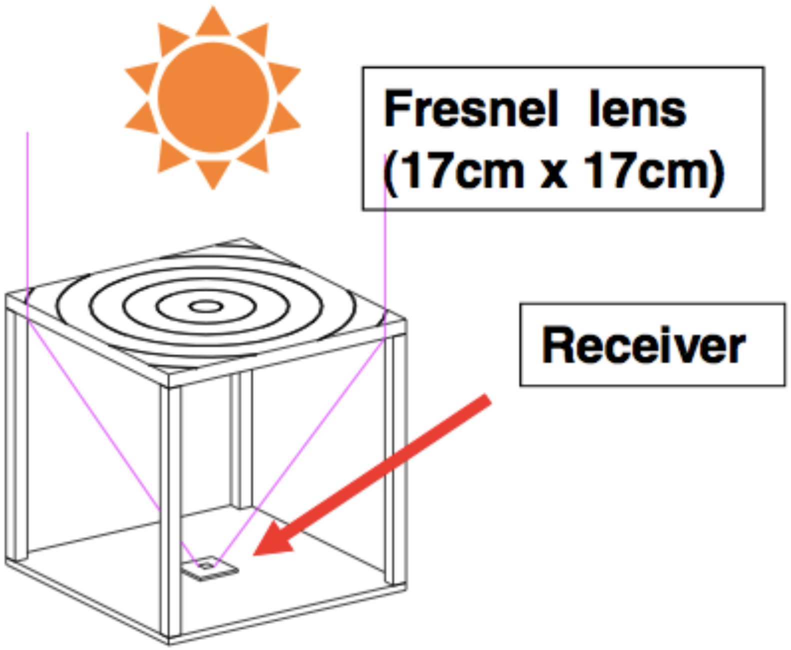
Date : 03 Feb 2012
Data No :
SC1270-01
Sample No :
SC1270
Repeat Times : 9

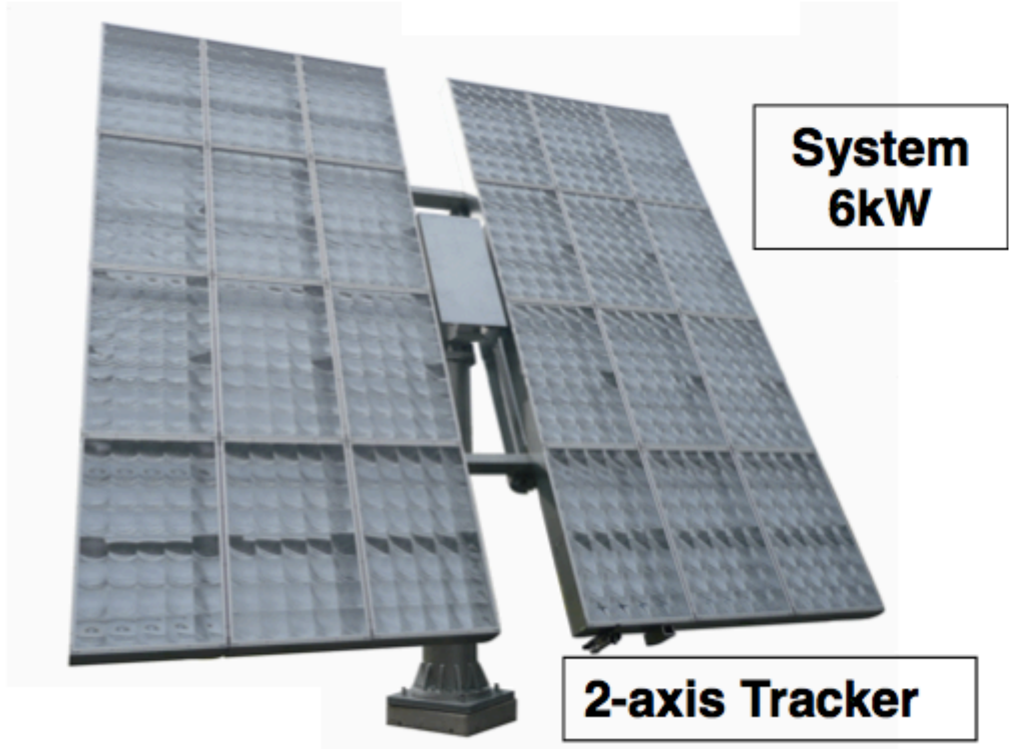
I_{sc}	15.23	mA
V_{oc}	3.015	V
P_{max}	39.26	mW
I_{pmax}	14.65	mA
V_{pmax}	2.680	V
F.F.	85.5	%
Eff(ap)	37.5	%
DTemp.	25.0	℃
MTemp.	25.0	℃
DIrr.	100.0	mW/cm^2
MIrr.	100.5	mW/cm^2 (top)
	99.4	mW/cm^2 (middle)
	100.9	mW/cm^2 (bottom)

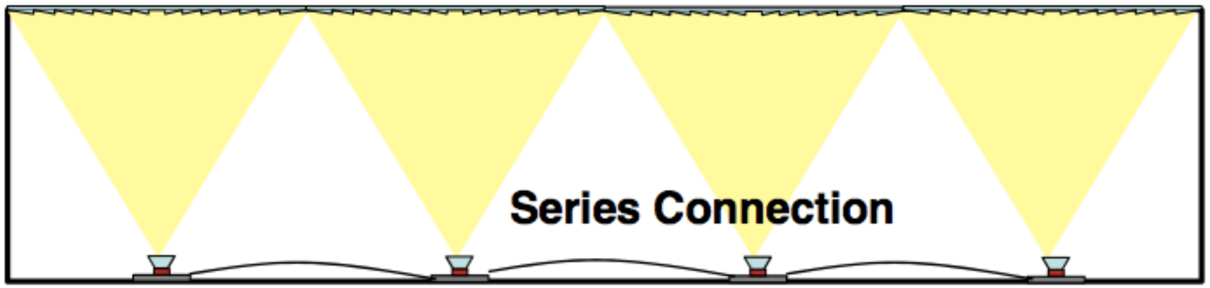
Scan Mode
I_{sc} to V_{oc}

シャープ，2012年12月5日発

Concentrator Cells

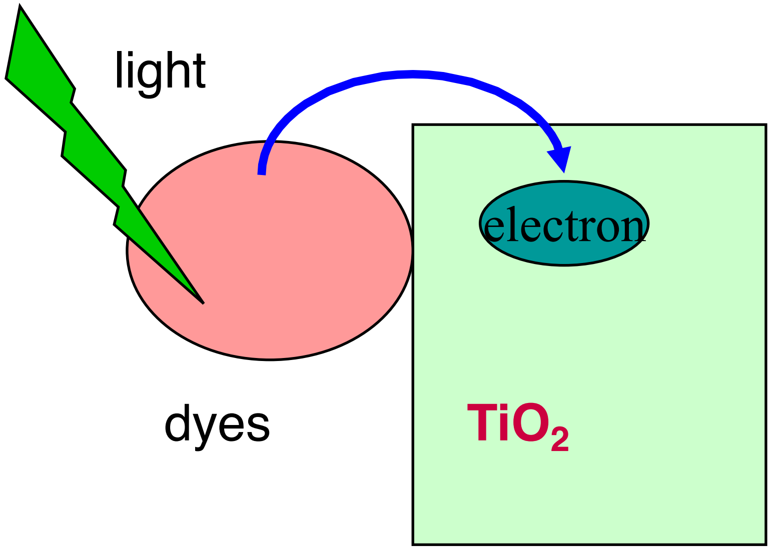


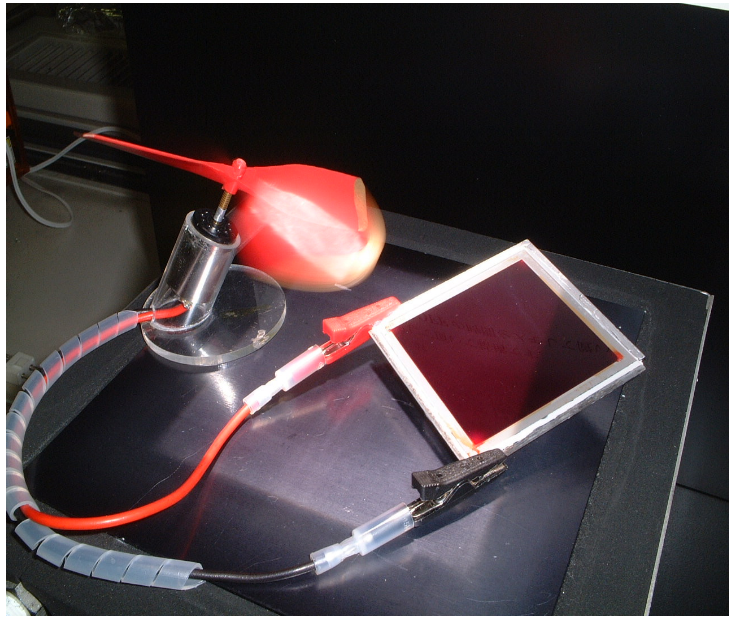


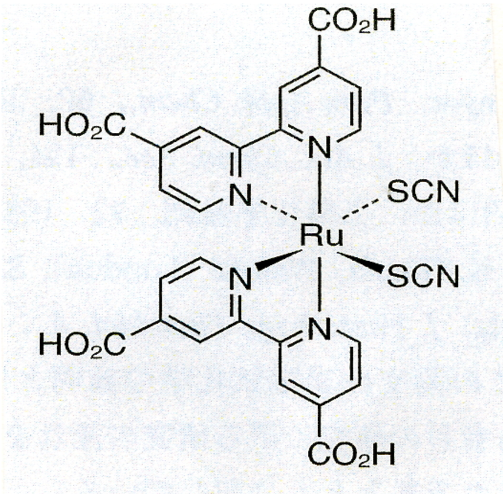


Sharp,
PCE = 43.5%

Dye-sensitized Solar Cells

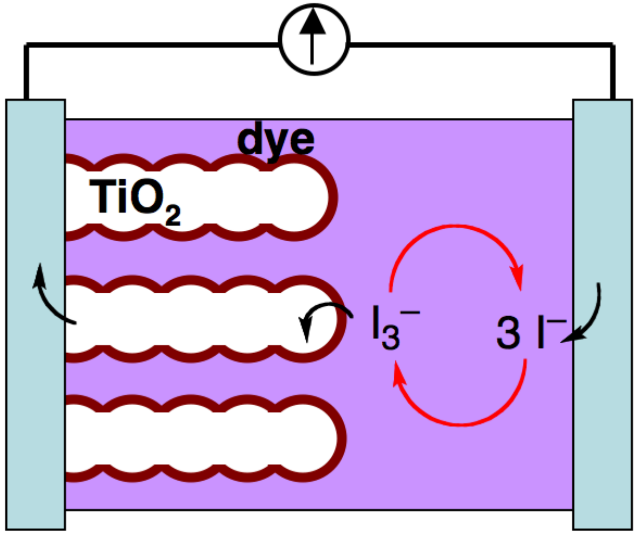






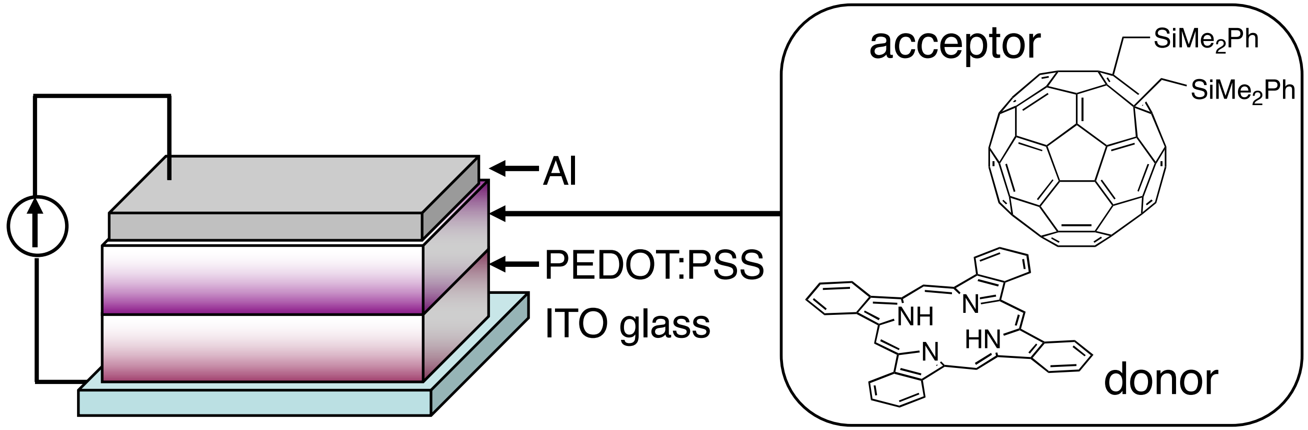
N-3: $Ru(dcbpy)_2(SCN)_2$

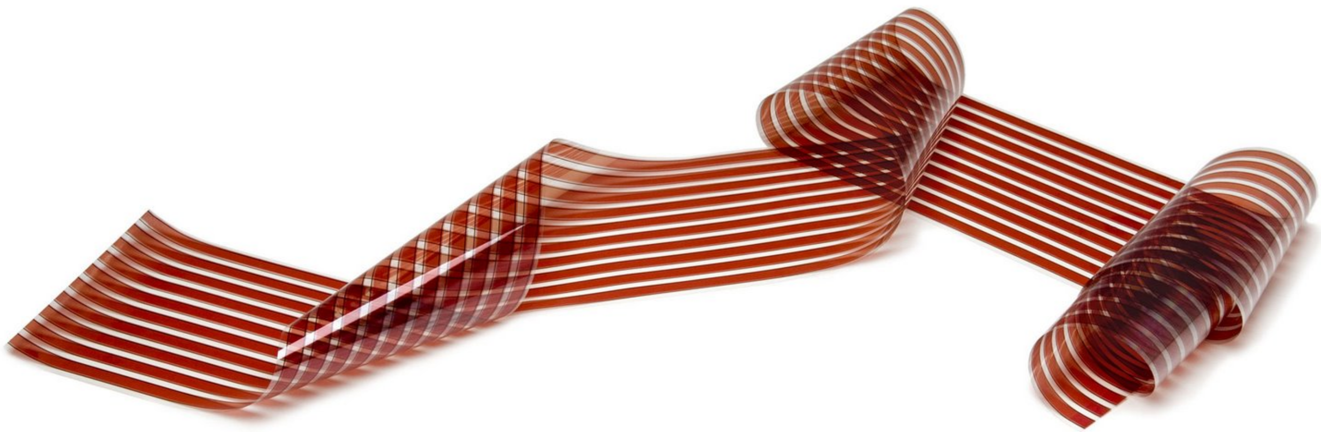
PCE
10%



Grätzel, *et al. Nature* **1991**, 353, 737.

Organic Thin-film Solar Cells



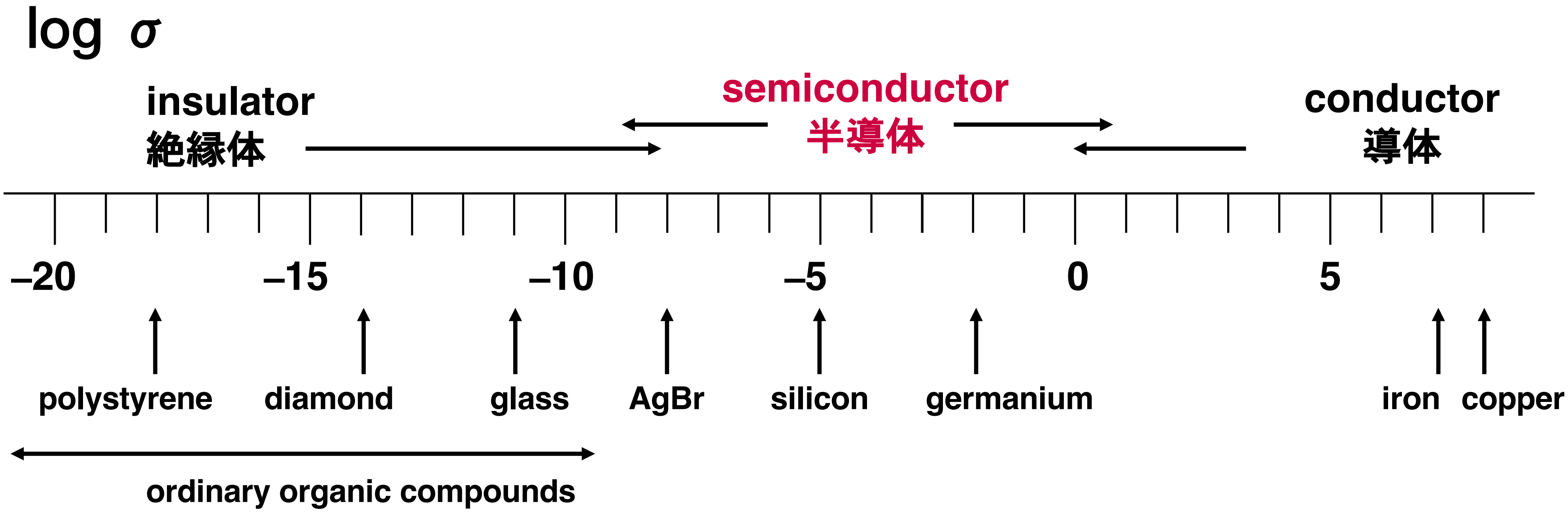


Potential low-cost, large area, light weight, flexible substrate

– History of Organic Semiconductors –

Semiconductors

σ : conductance (電気伝導度，導電率) [S·m^{-1}] (Ω^{-1}·m^{-1})



Characteristics of semiconductor

- variable conductance controlled with outer electric field: transistors
- two charges (electron, hole) for two carriers (n-type, p-type): diodes

The First Organic Semiconductors

(*Reprinted from Nature, Vol.* 173, *p.* 168, *January* 23, 1954)

Electrical Conductivity of the Perylene–Bromine Complex

WE have found that some complexes between polycyclic aromatic compounds and halogens, in the solid state, have fairly good electrical conductivity ($\sim$ 1–10^{-3} ohm^{-1}-cm.$^{-1}$). Nevertheless, many of them are not stable and do not keep this property for long.

Among them, the perylene–bromine complex is relatively stable and has very good electrical conductance. This complex has been made as a precipitate from a benzene solution of perylene by adding bromine (method of Brass and Clar[1]), or by the direct absorption of bromine vapour by perylene (method of Zinke and Pongratz[2]). In the latter case,

. . .

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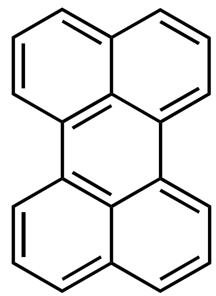
University of Tokyo.



perylene

+ Br_2

Nature **1954**, *173*, 168.

Perylene:Bromine Complexes

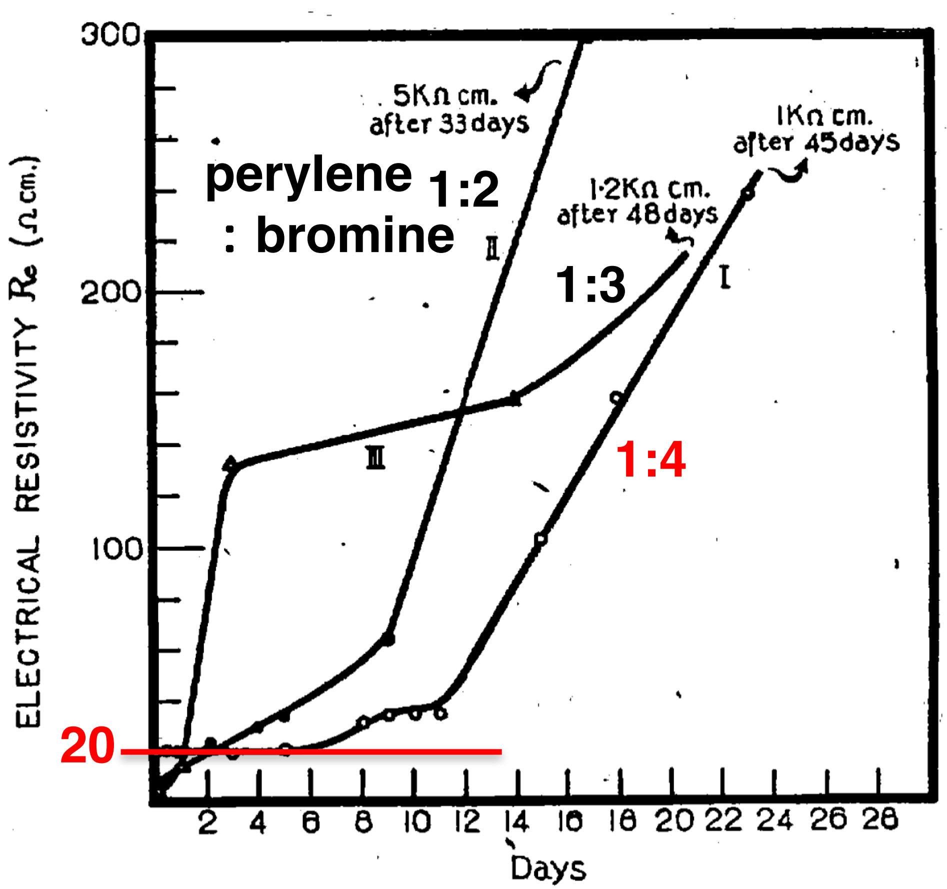


Fig. 2. Electrical resistivity (R_e) of (I) perylene–bromine complex (1 : 4); (II), perylene–bromine complex (1 : 3); (III), dibromo-perylene–bromine complex (1 : 2)

resistivity (電気抵抗率) 20 [Ω·cm]

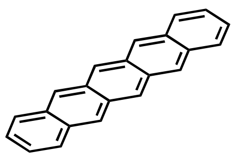
conductivity 電気伝導度（導電率） $= \dfrac{1}{\text{resistivity}}$

Organic Semiconducting Materials

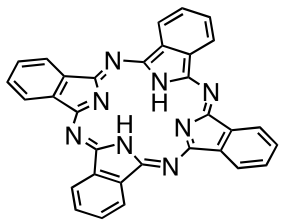
Organic compounds having semiconducting property

（charge can be transported in organic materials => organic semiconductors）

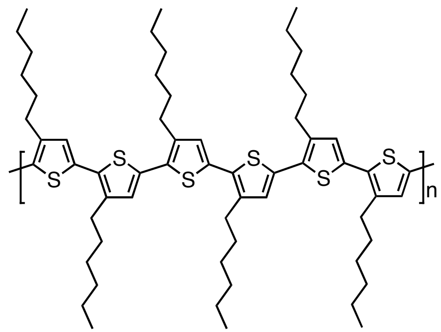
p-type organic semiconductors (electron donors): hole transporting



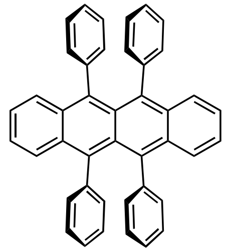
Acenes



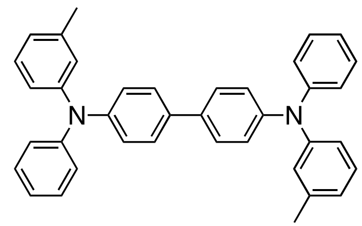
phthalocyanine



polythiophene

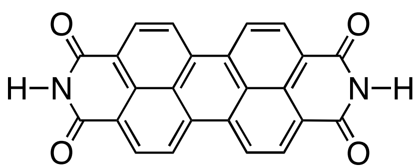


rubrene

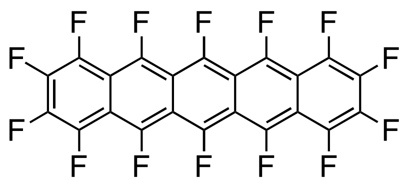


triarylamines

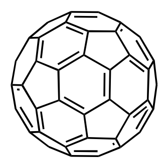
n-type organic semiconductors (electron acceptors): electron transporting



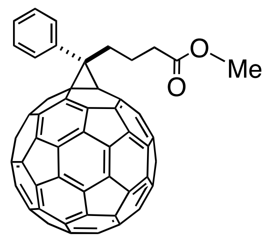
perylene diimide



perfluoro acenes



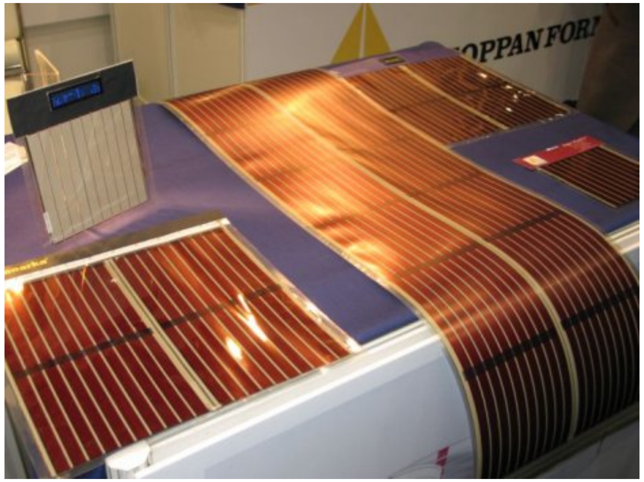
fullerene



fullerene derivatives

Features of Organic Semiconductor Devices

- Potential low-cost
- Lightweight
- Flexible
- Wide area devices
- Low-temperature, low-energy processes



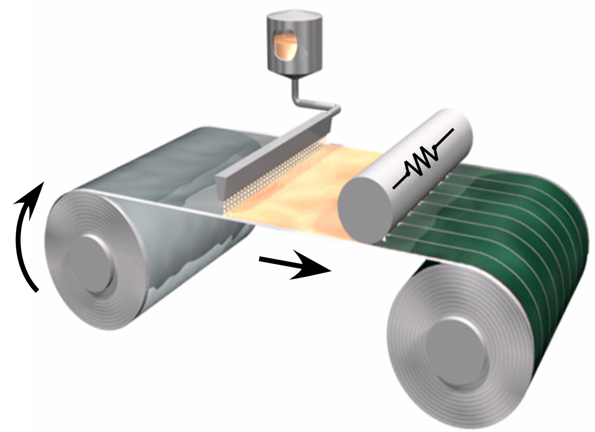
Molecular Design

Electronic, photo-electronic, and thermal properties

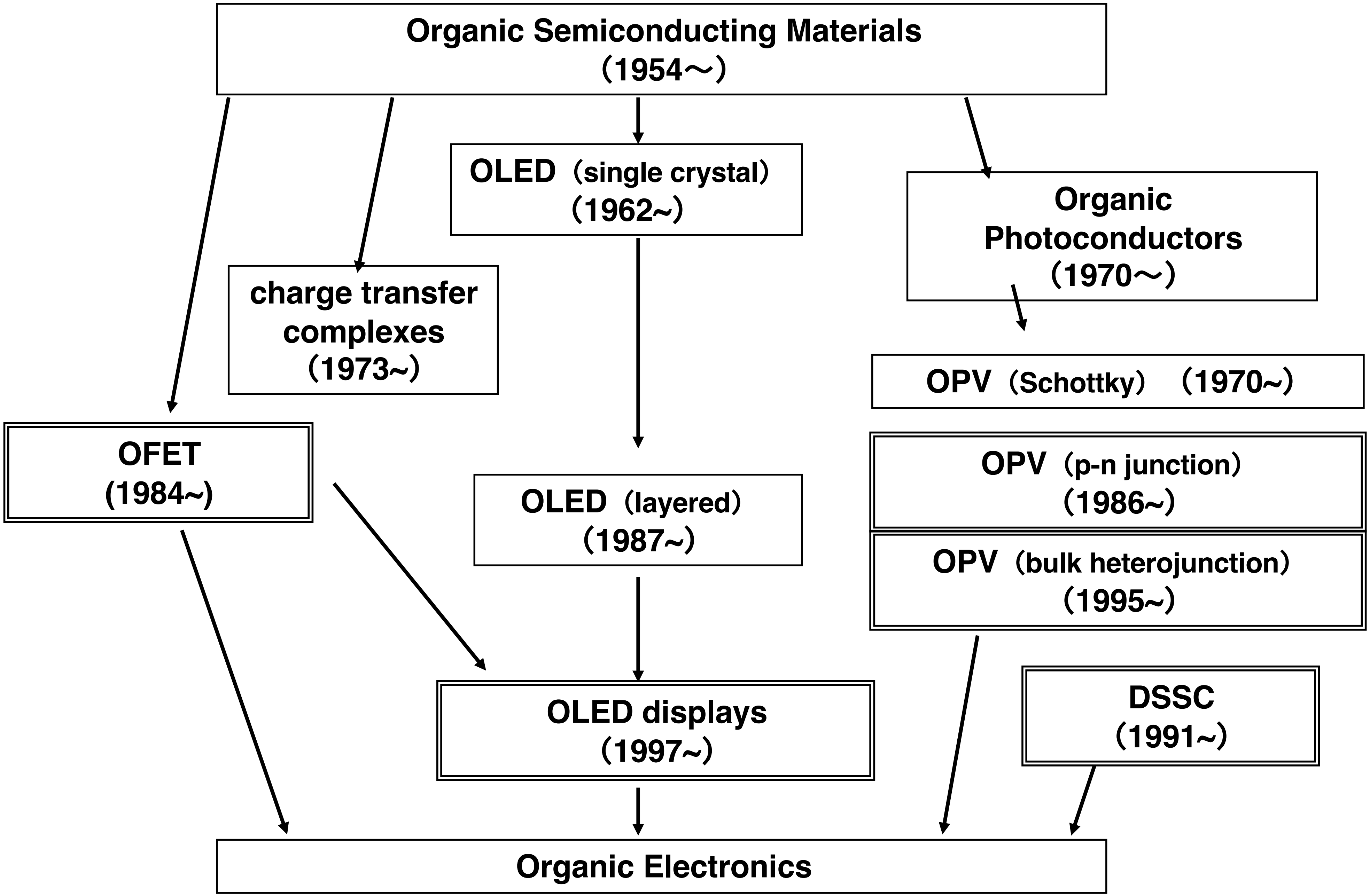
Processes

Solution process (wet process)

Printing technology

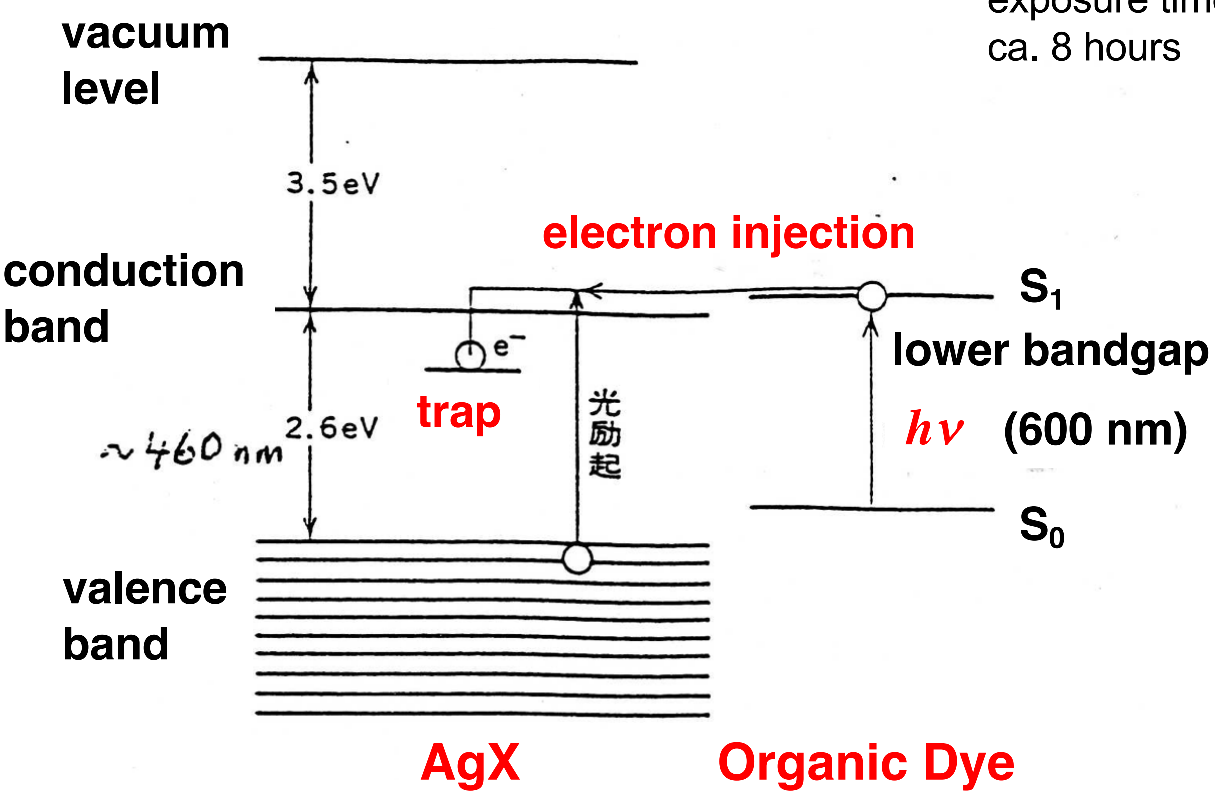


History of Organic Semiconducting Devices

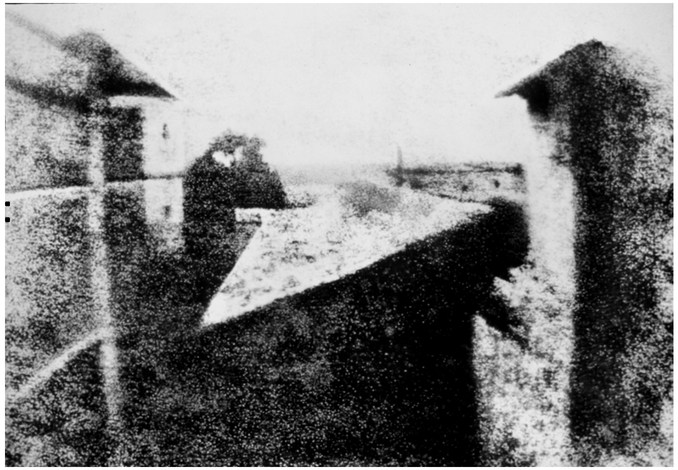


Silver Halide Photography

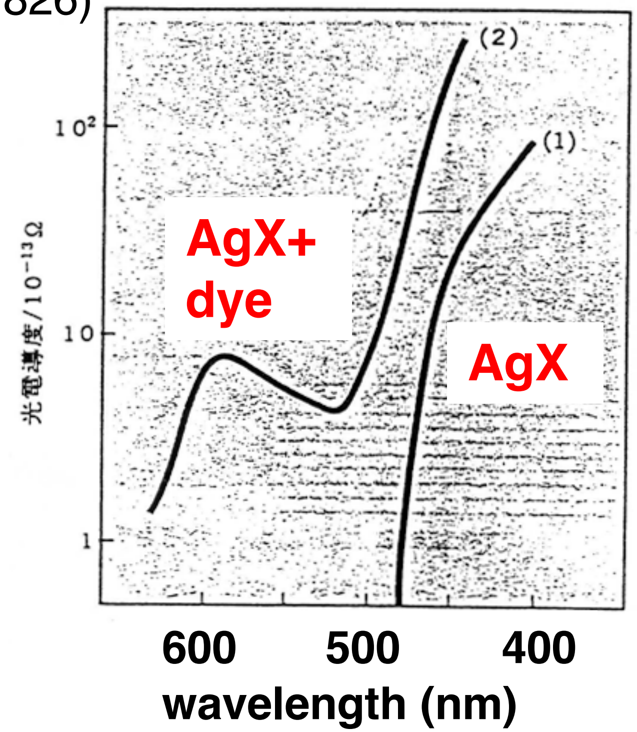
$$AgX \xrightarrow{h\nu} Ag + 1/2\ X_2$$



exposure time : ca. 8 hours

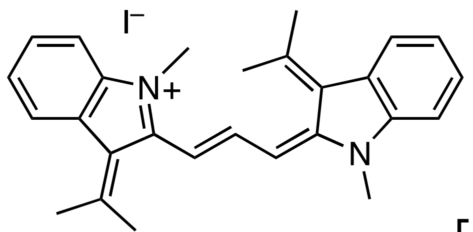


The first photograph by Niepce (1826)



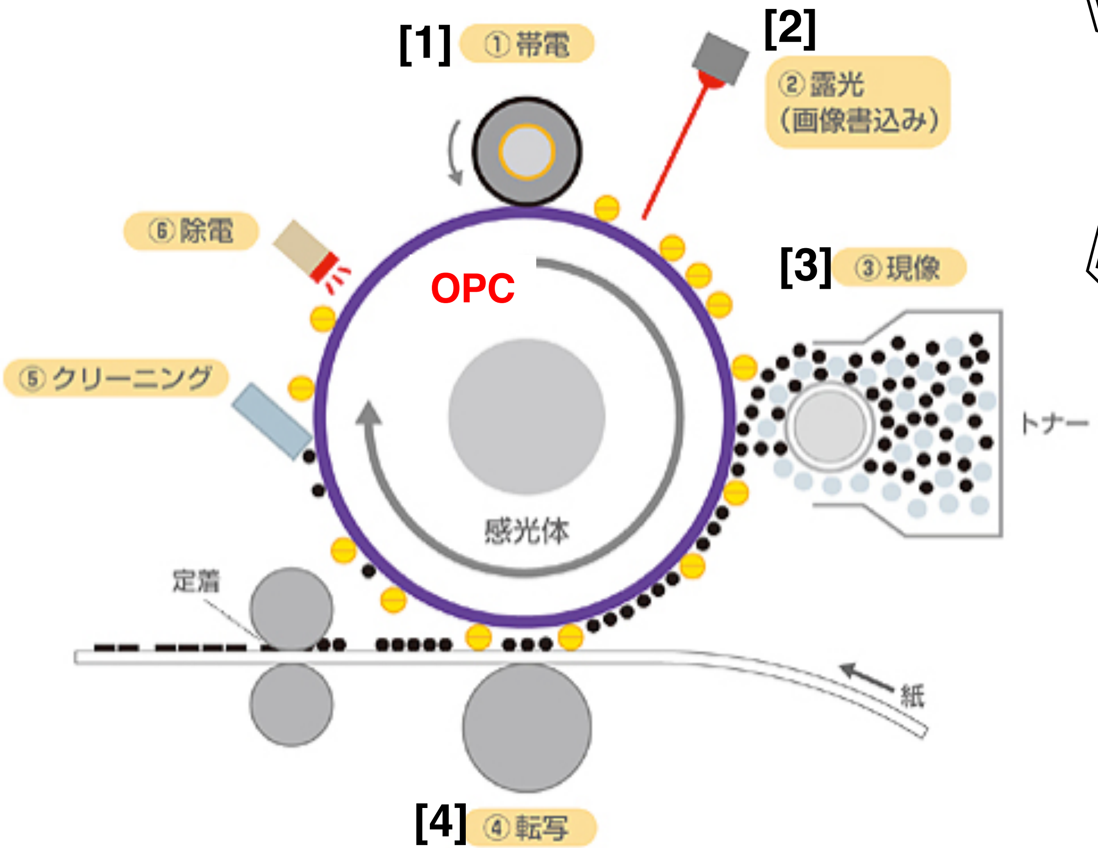
[亀山直人、福本務、工化, 42, 489 (1939)]

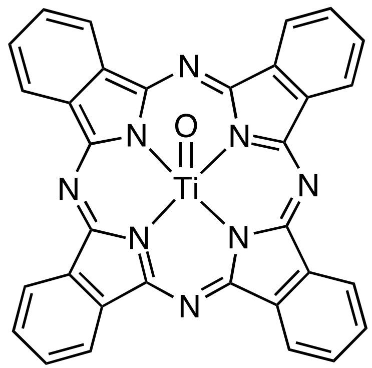
dye-sensitizing:
H. W. Vogel (1873)



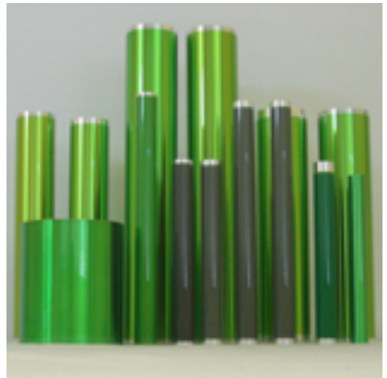
Organic Photoconductors (OPC)

Laser printer, Copy machine:

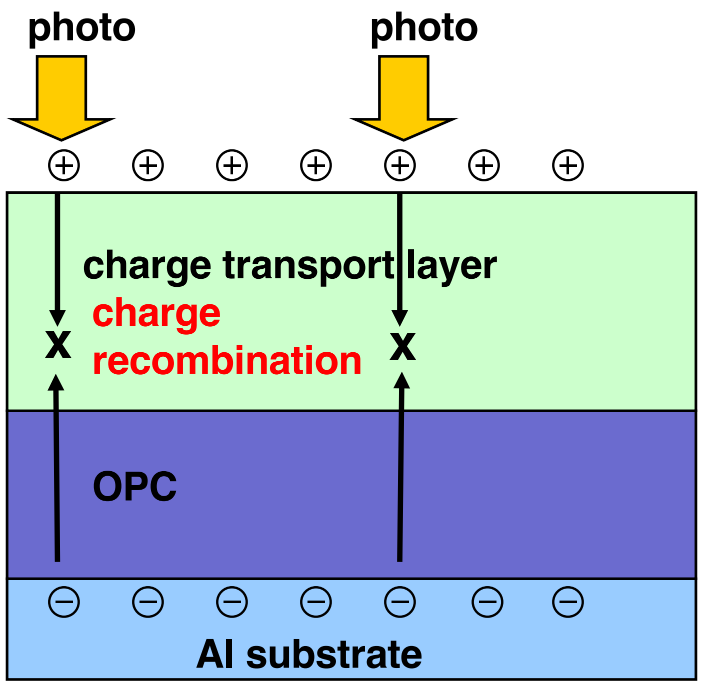




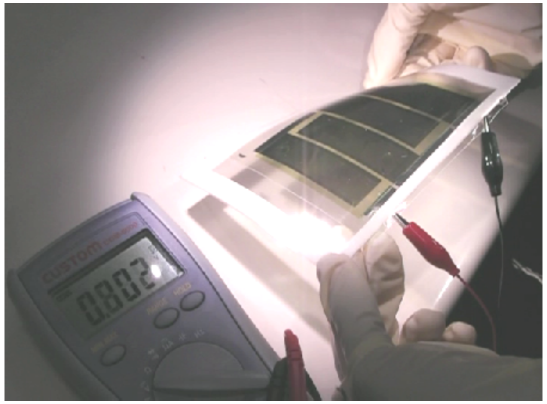
TiOPc



1. Electric charge
2. Exposure, Charge recombination
3. Setting toner on the charged parts
4. Transcription, Printing

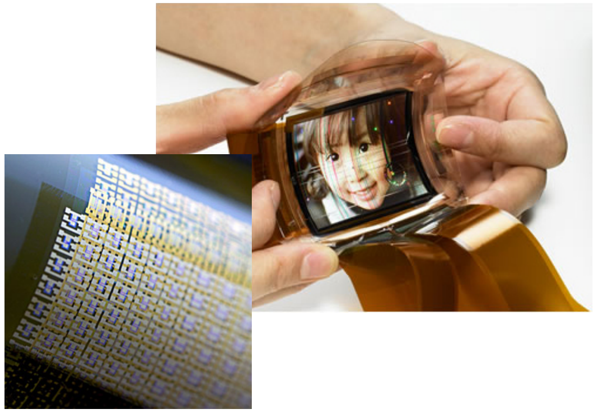


From Organic Semiconductors toward Organic Electronics Devices



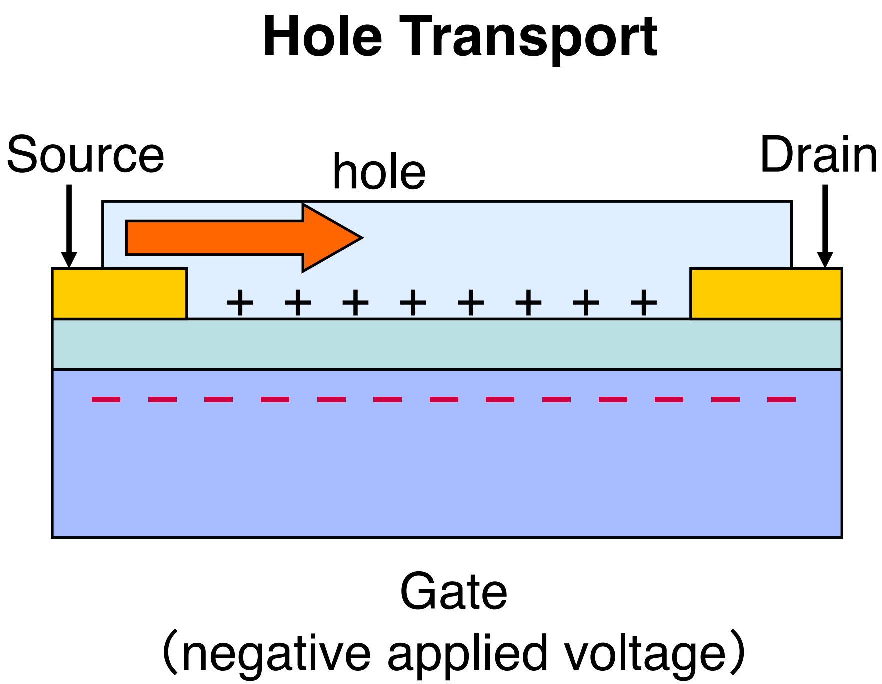
organic solar cells

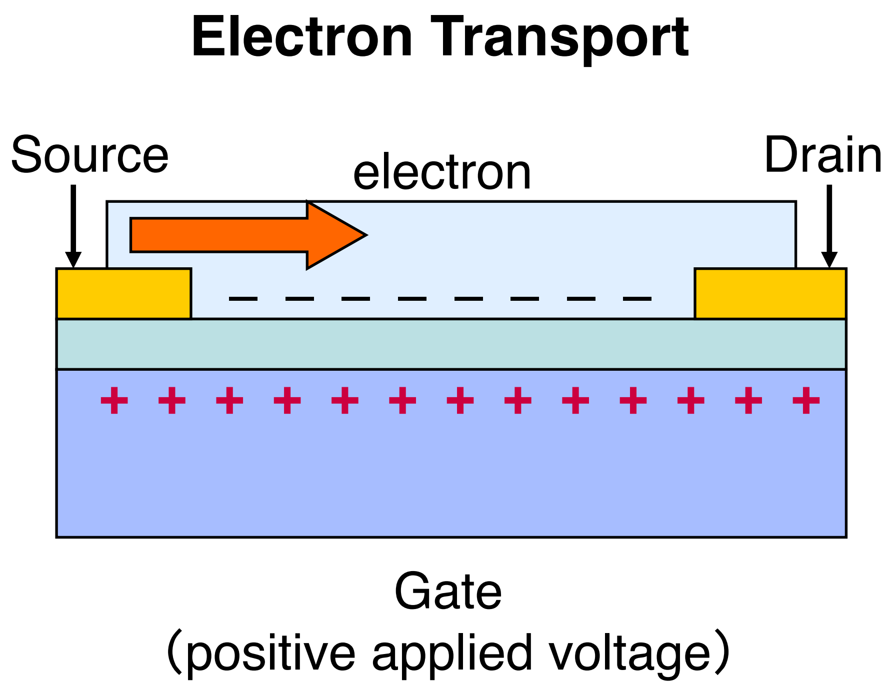
organic light emitting diodes



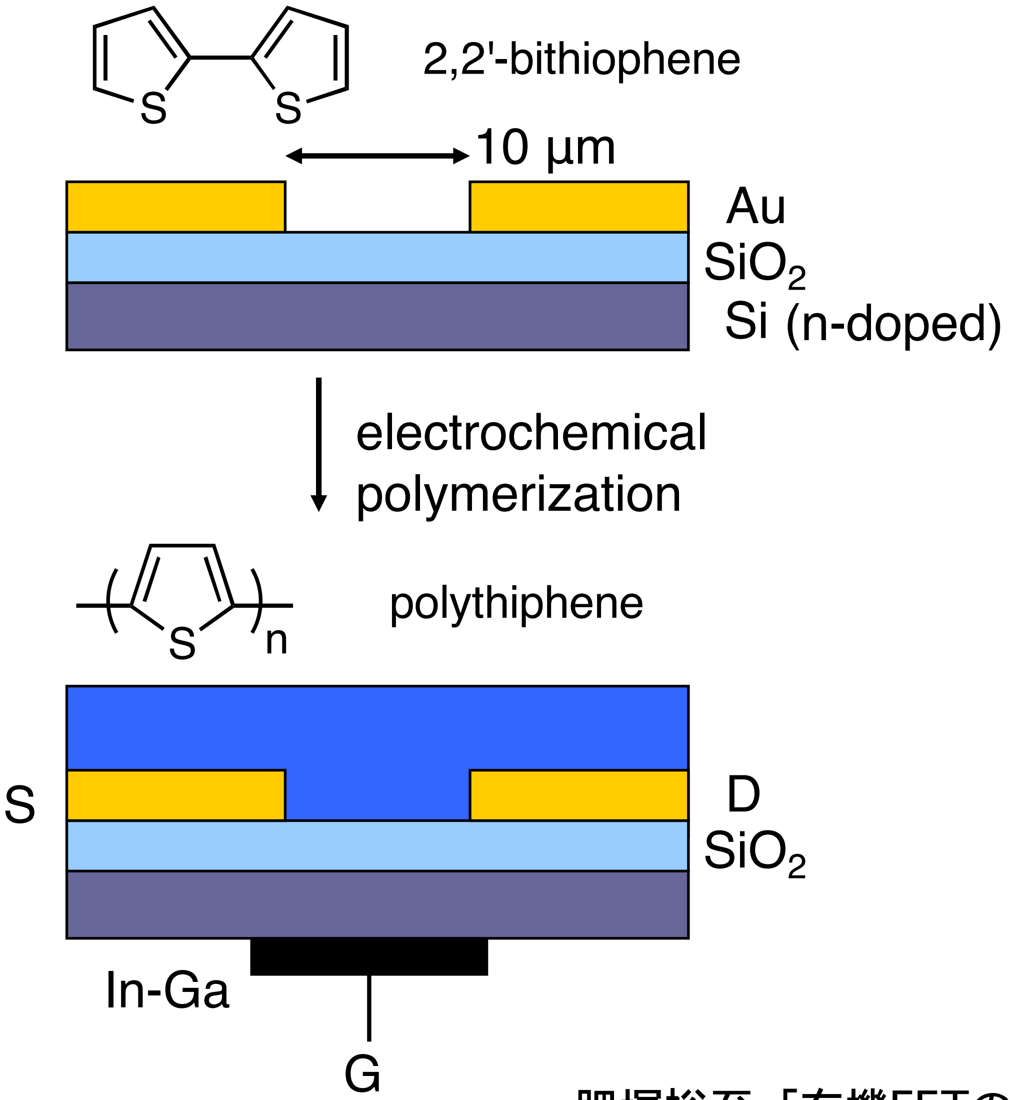
organic transistors

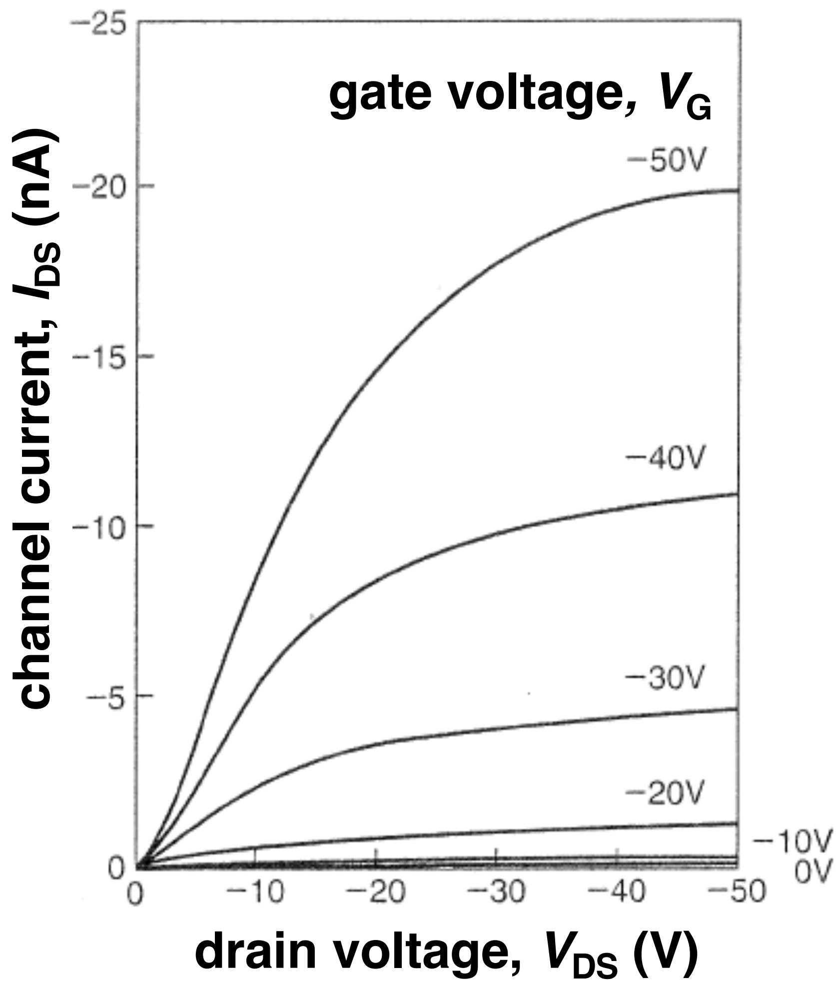
Organic Field Effect Transistor





The First Organic FET



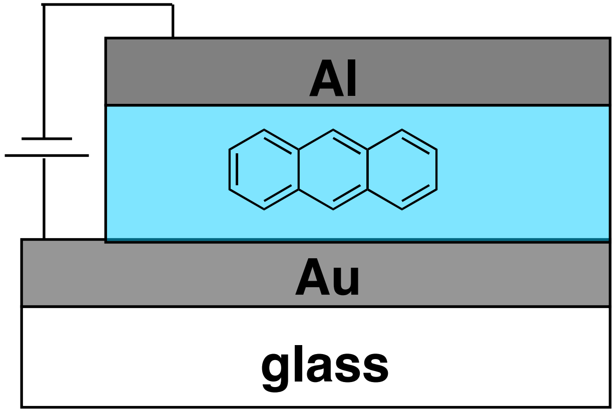


肥塚裕至「有機FETのルーツは日本にあった！：導電性ポリマーから超伝導まで」化学 2001年10月号

A. Tsumura, H. Koezuka, T. Ando, *Appl. Phys. Lett.* **1986**, *49*, 1210.

OLED (Monolayer, Thin-Film)

Anthracene Thin-Film

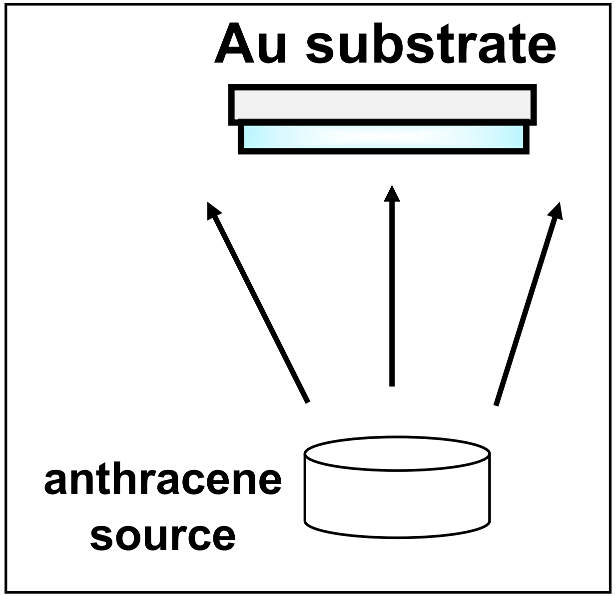


cathode

light emitting layer (0.4–0.6 μm)

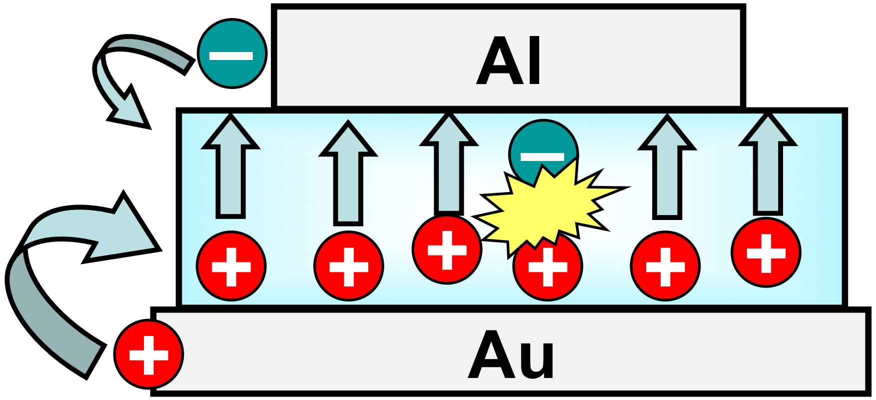
anode

Vacuum Deposition



Vacuum chamber

operation voltage : 30 V
external quantum efficiency : 0.03％

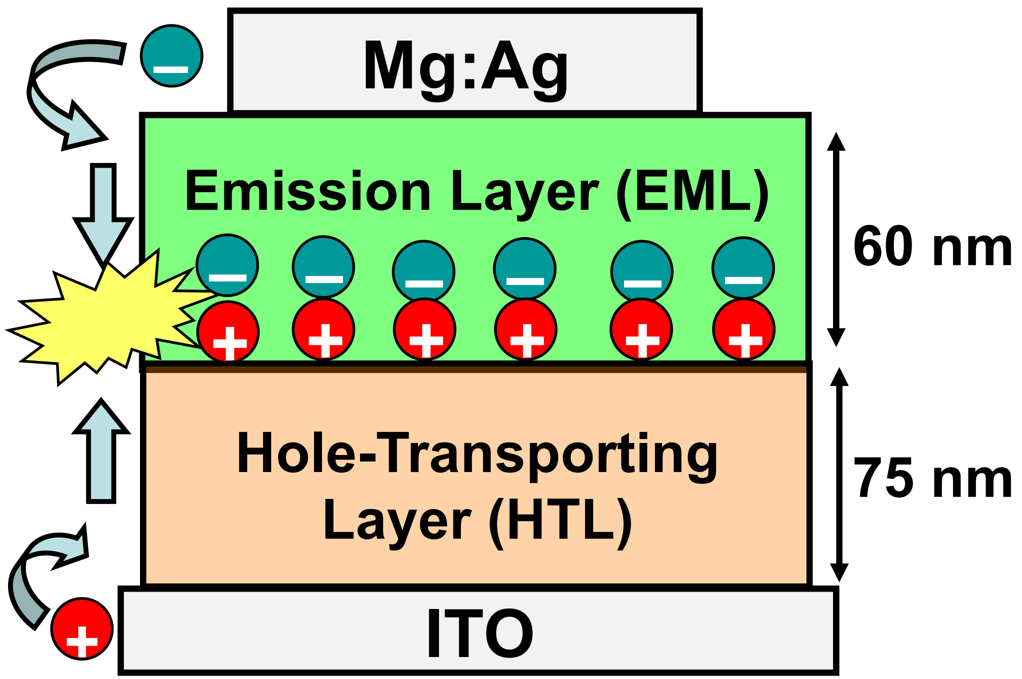


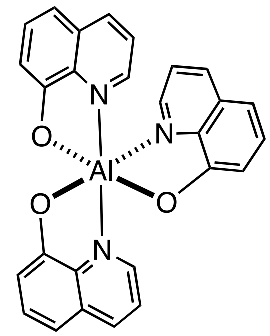
hole injection: good

electron injection: bad

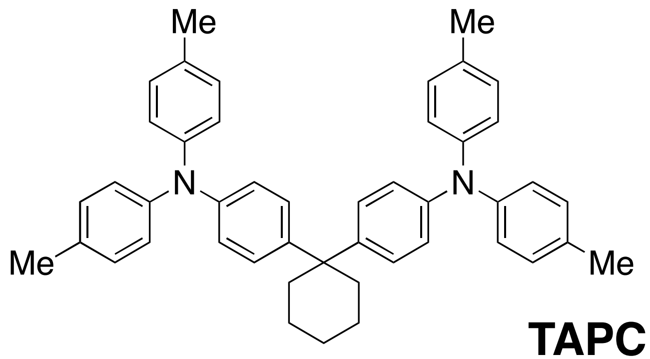
P. S. Vincett *et al.*, *Thin Solid Film* **1982**, *94*, 171.

OLED (Bilayer)





Alq_3

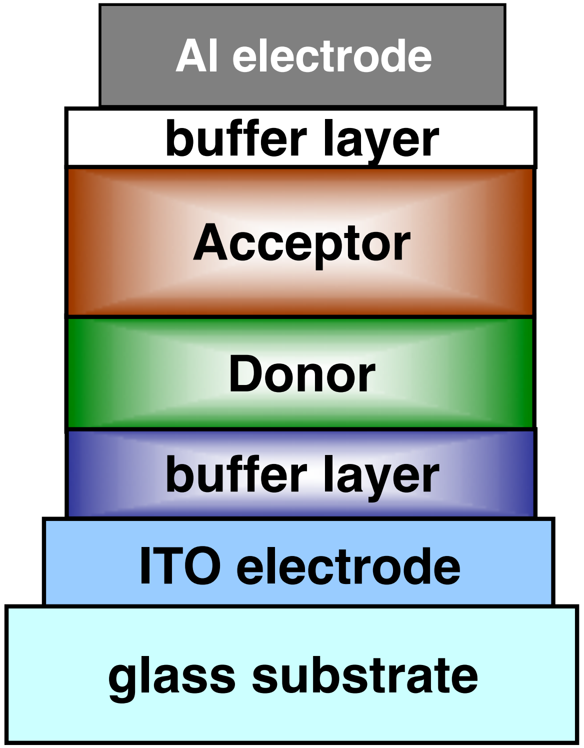


TAPC

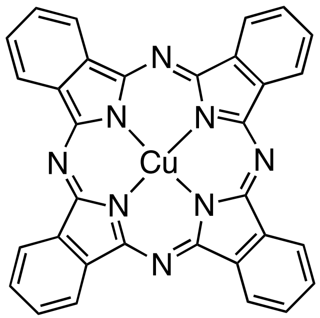
- good hole and electron injection balance
- green emission of Alq_3 (540 nm)
- emission starting from 3 V
- operation voltage 8 V, current density 100 mA/cm^2, luminance 1000 cd/m^2
- external quantum efficiency 1%

Organic Electroluminescent Diodes
C. W. Tang and S. A. Van Slyke, *Appl. Phys. Lett.* **1987**, *51*, 913.

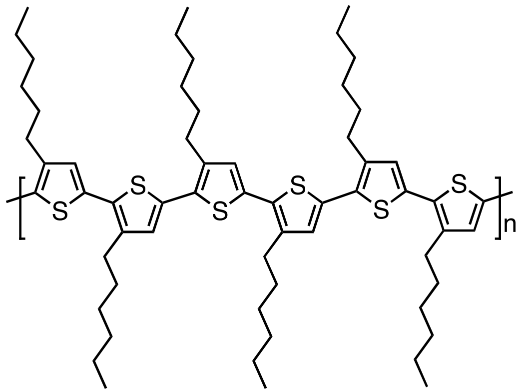
Organic Solar Cells



Organic Electron Donors:

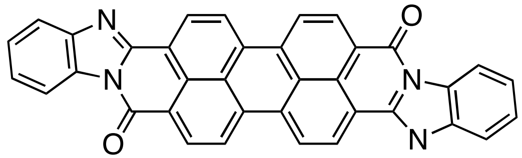


CuPc

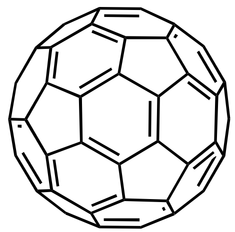


polythiophene

Organic Electron Acceptors:



PTCBI



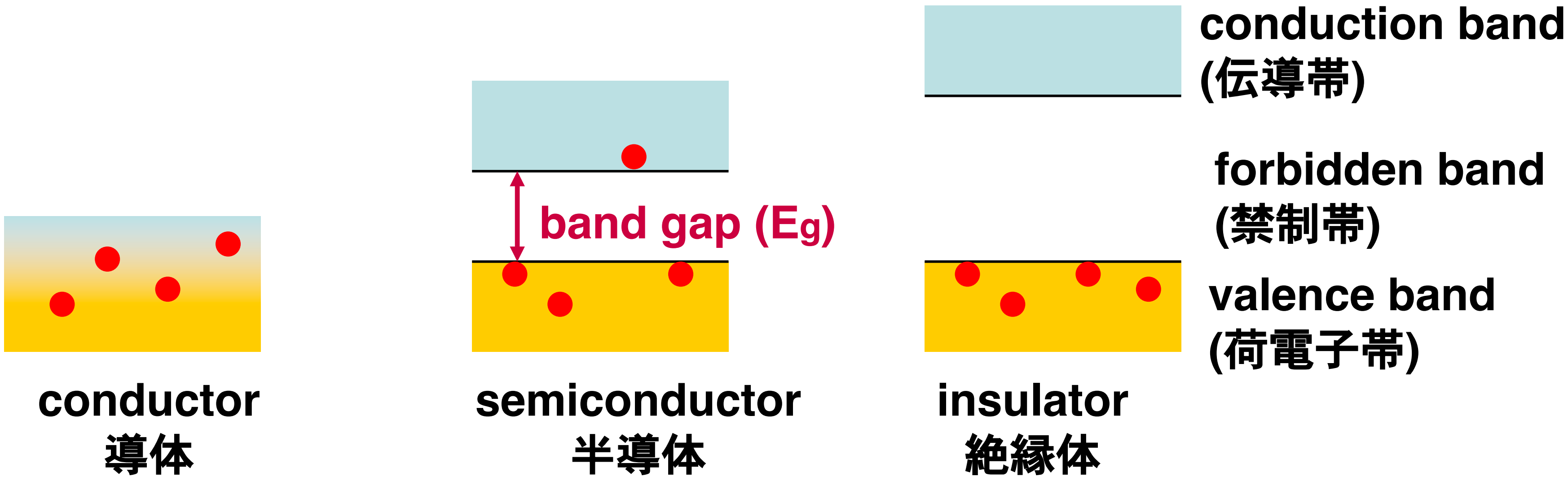
C_{60}

C. W. Tang, *Appl. Phys. Lett.* **1986**, *48*, 183; U. S. Patent (1979).

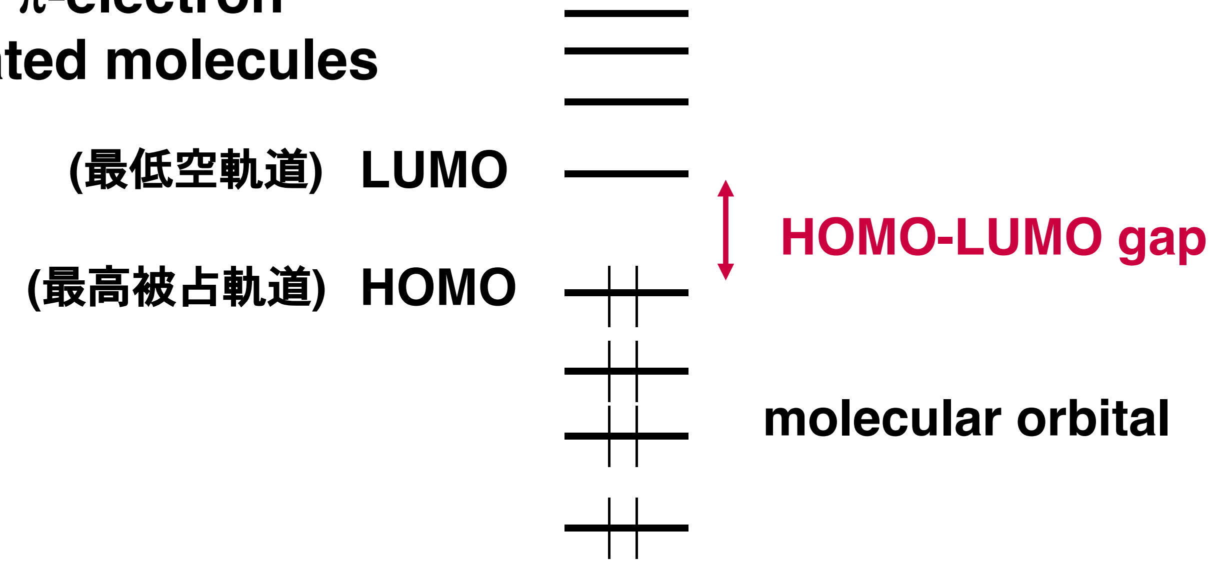
– Physical Properties of Organic Semiconducting Materials –

Molecular Orbital vs. Solid State Physics

Solid State Physics



Organic π-electron conjugated molecules

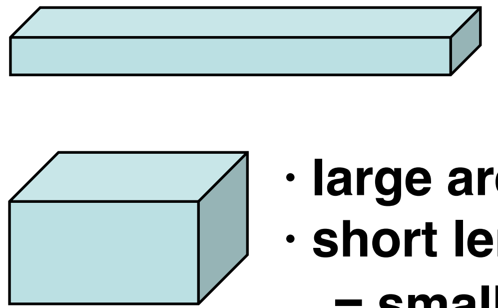


Properties of Organic Semiconductor

Carrier Mobility	OFET, OLED, OPV
Ionization Potential (HOMO Levels)	OFET, OLED, OPV
Electron Affinity (LUMO Levels)	OFET, OLED, OPV
Light Absorption	OPV
Light Emission	OLED

Carrier Mobility, Carrier Density

・Depending on Sample Size
試料サイズによる



$$\text{Resistance } [\Omega] = \frac{\text{Voltage [V], 電圧}}{\text{Current [A], 電流}}$$
電気抵抗

・large area
・short length
= small resistance

・Independent of Sample Size, Inherent Parameter for Materials
試料サイズによらない，物質固有のパラメータ

$$\text{Resistivity}（\rho）[\Omega\cdot\mathrm{m}] = \frac{\text{Resistance } [\Omega]\text{, 電気抵抗}}{\text{Length [m], 長さ}} \times \text{Area } [\mathrm{m}^2]$$
抵抗率 ... 面積

・Conductivity 伝導率（σ）： inverse of Resistivity
(導体，半導体，絶縁体を区別)

$$\text{Conductivity}（\sigma）[\Omega^{-1}\cdot\mathrm{m}^{-1}] = \frac{1}{\text{Resistivity}（\rho）[\Omega\cdot\mathrm{m}]}$$
伝導率 ([S/m]) ... 抵抗率

Carrier Mobility, Carrier Density

Conductivity（σ）is proportional to charge of carrier, carrier density（n）, and carrier mobility （μ）

キャリアのもつ電荷（＝電気素量）　電荷密度　電荷移動度

Conductivity（σ） [$\Omega^{-1} \cdot m^{-1}$] ＝
elementary charge [C] x carrier density（n） [m^{-3}] x carrier mobility（μ）

電気素量

$$\text{dimension of mobility}: \frac{[\Omega^{-1} \cdot m^{-1}]}{[C]\,[m^{-3}]} = \frac{[A \cdot V^{-1} \cdot m^{-1}]}{[A \cdot s]\,[m^{-3}]} = [m^2/Vs]$$

Carrier Density（n） : valuable for each devices (c.f., doping)

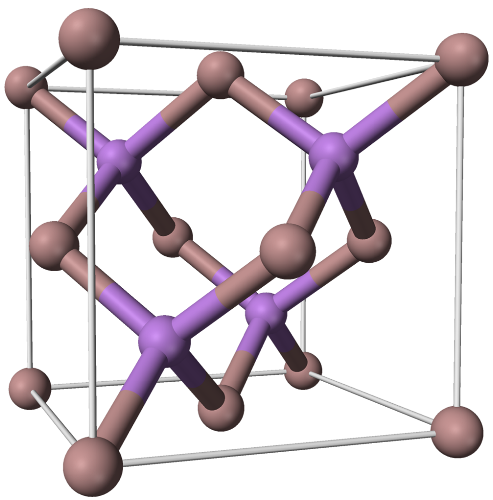
Carrier Mobility（μ） : fundamental value for each materials

Carrier Mobility

Mobility (cm^2/Vs) at room temperature

Inorganic Semiconductors

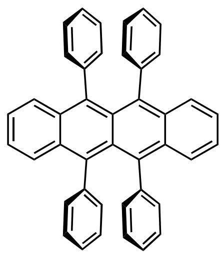
GaAs (single crystal, electron)	7500
GaAs (single crystal, hole)	400
Si (single crystal, electron)	1500
Si (single crystal, hole)	450
Si (polycrystalline, electron)	500
Si (amorphous, hole)	1
ITO (hole)	100

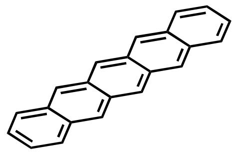


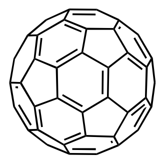
gallium arsenide

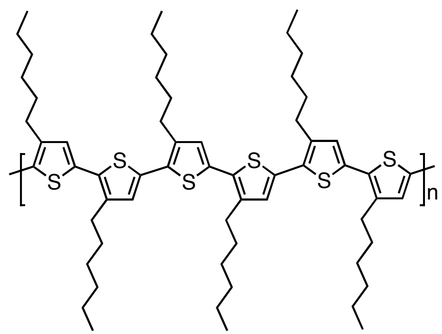
Organic Semiconductors

rubrene (single crystal, hole)	40
pentacene (film, hole)	1.5
C_{60} (film, electron)	1.4
semiconducting polymers (hole)	0.1

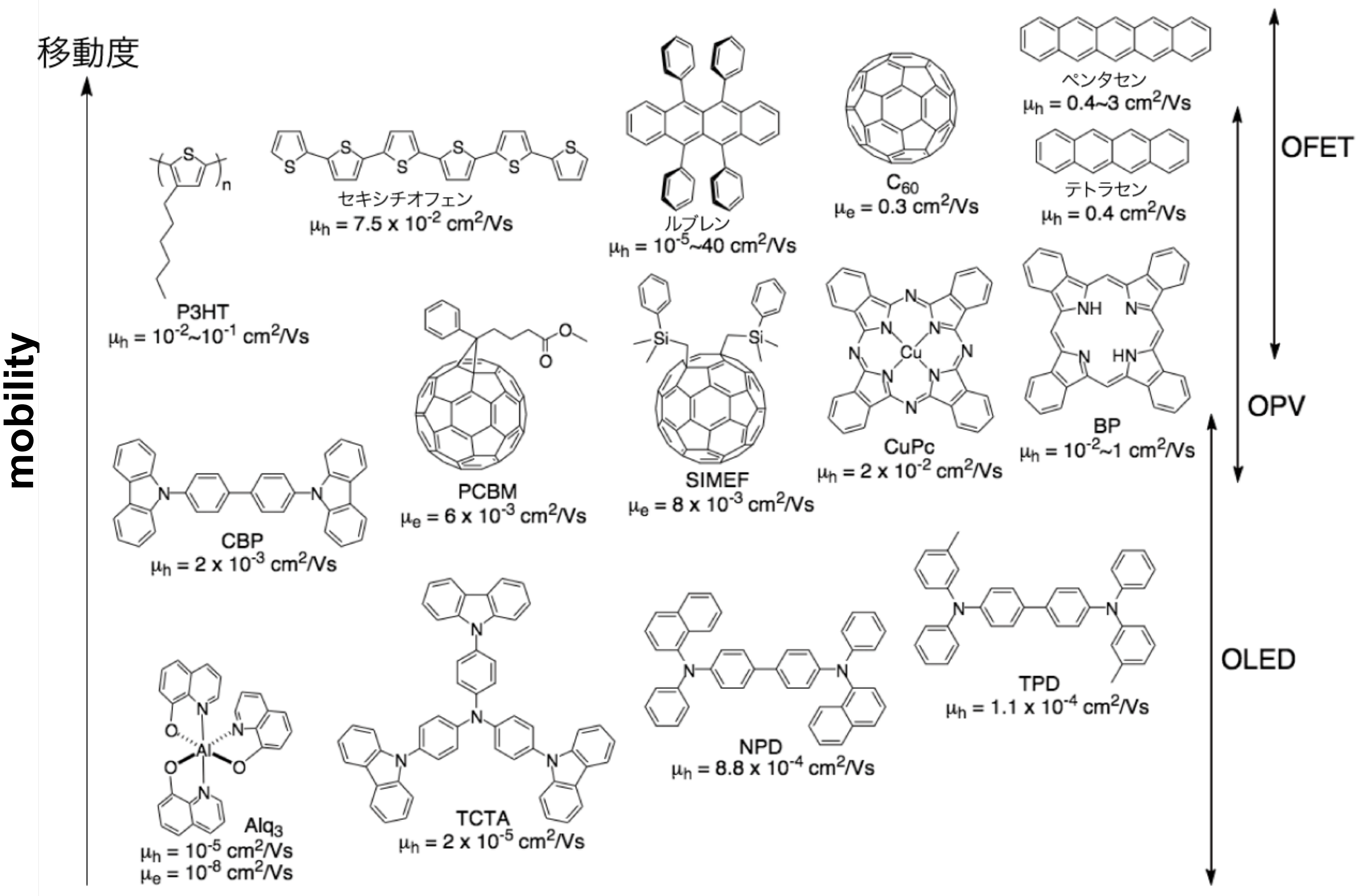






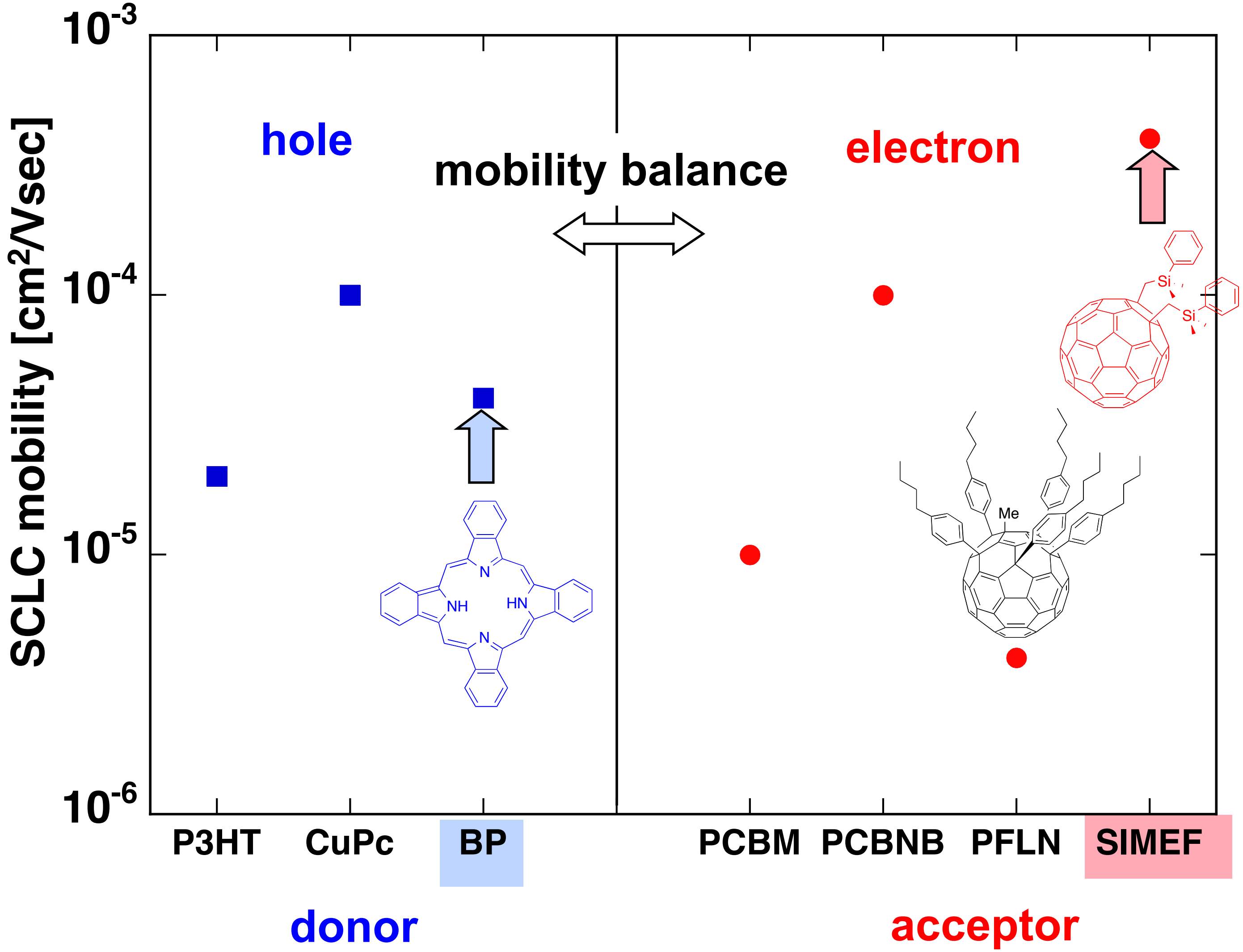


Mobility



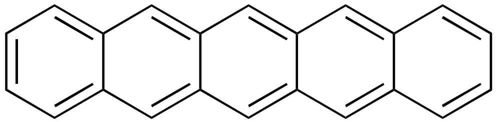
移動度
mobility
P3HT
μh = 10-2~10-1 cm2/Vs
セキシチオフェン
μh = 7.5 x 10-2 cm2/Vs
ルブレン
μh = 10-5~40 cm2/Vs
C60
μe = 0.3 cm2/Vs
ペンタセン
μh = 0.4~3 cm2/Vs
テトラセン
μh = 0.4 cm2/Vs
OFET
OPV
OLED
PCBM
μe = 6 x 10-3 cm2/Vs
SIMEF
μe = 8 x 10-3 cm2/Vs
CuPc
μh = 2 x 10-2 cm2/Vs
BP
μh = 10-2~1 cm2/Vs
CBP
μh = 2 x 10-3 cm2/Vs
TPD
μh = 1.1 x 10-4 cm2/Vs
NPD
μh = 8.8 x 10-4 cm2/Vs
Alq3
μh = 10-5 cm2/Vs
μe = 10-8 cm2/Vs
TCTA
μh = 2 x 10-5 cm2/Vs

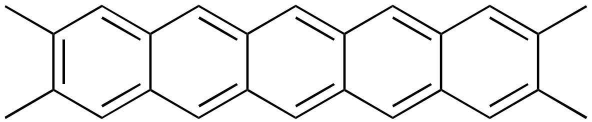
Mobility Balance



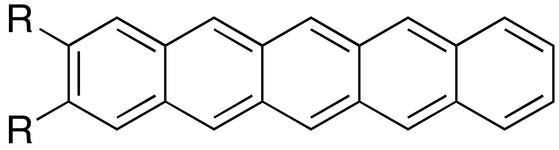
(High Mobility Materials)

Materials for OFET



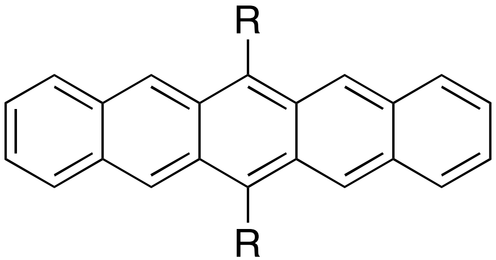


Bao



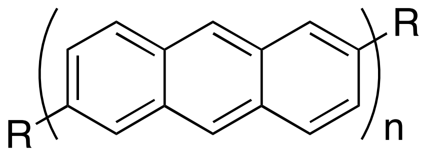
R = Br, CN, CF_3

Bao 0.3 cm^2/Vs



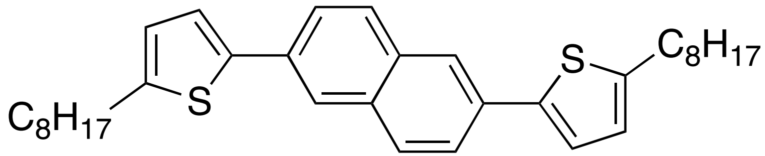
R = SMe, n-Pr, silylalkynyl

Kobayashi, Takahashi, Anthony

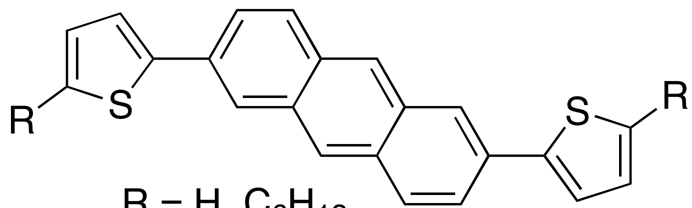


n = 2–3 R = H, C_6H_{13}

Suzuki 0.18 cm^2/Vs

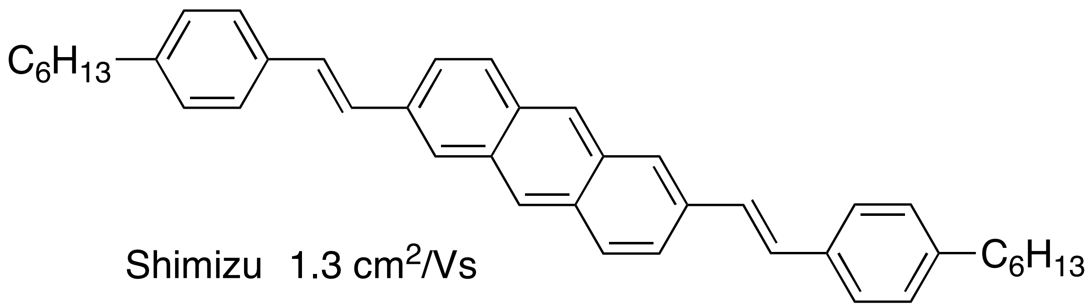


Shimizu 0.1 cm^2/Vs

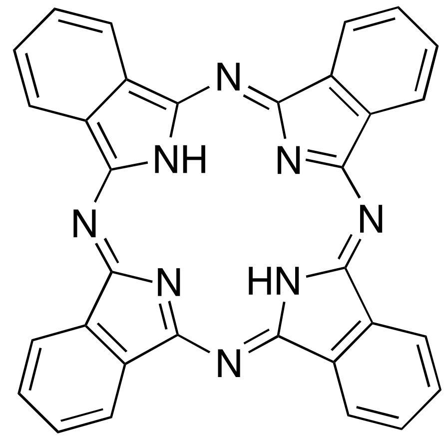


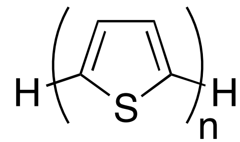
R = H, C_6H_{13}

Shimizu 0.5 cm^2/Vs



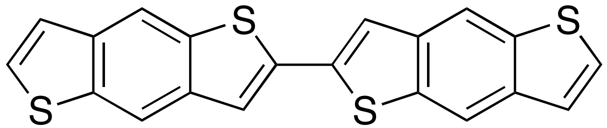
Shimizu 1.3 cm^2/Vs



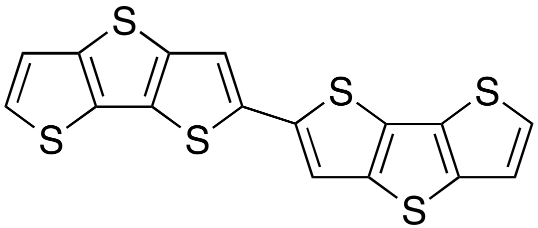


n = 4–8

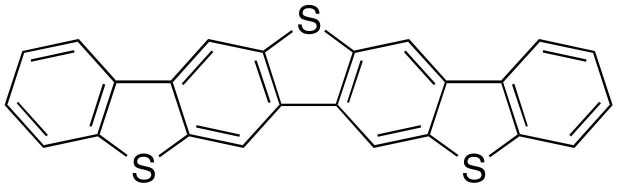
Materials for OFET



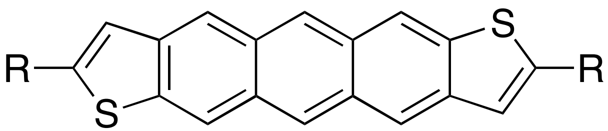
Katz 0.04 cm²/Vs



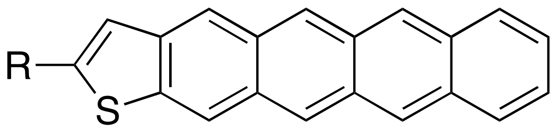
Katz 0.05 cm²/Vs



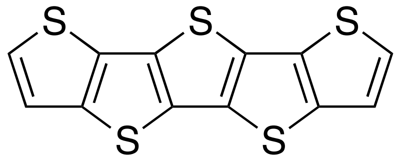
Katz 0.15 cm²/Vs



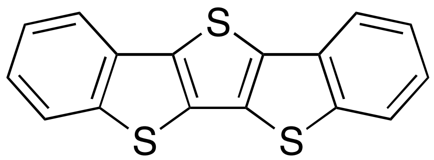
Katz



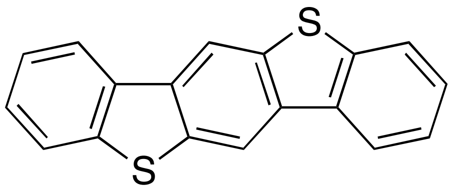
Bao, Valiyev 0.1 cm²/Vs



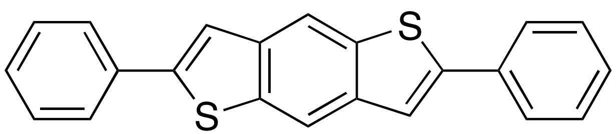
Zhu 0.045 cm²/Vs



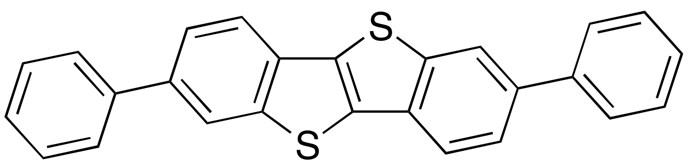
Yamaguchi 0.51 cm²/Vs



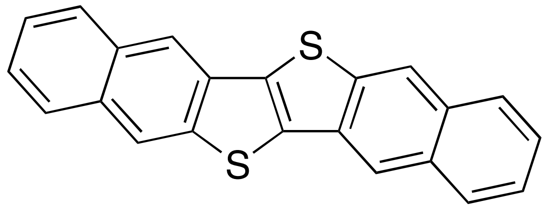
Takimiya 10^{-3} cm²/Vs



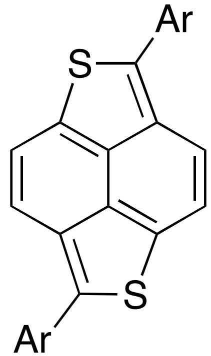
Takimiya 0.2 cm²/Vs



Takimiya 0.3 cm²/Vs

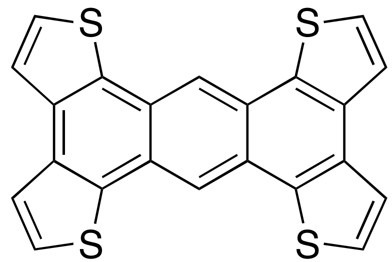


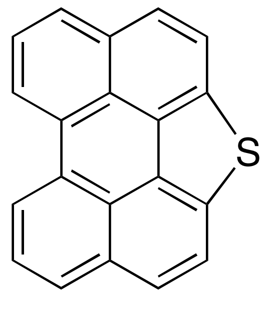
Takimiya 2.9 cm²/Vs



Takimiya

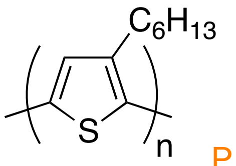
0.1 cm²/Vs





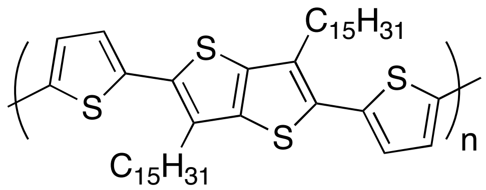
0.8 cm²/Vs

Polymer Materials for OFET



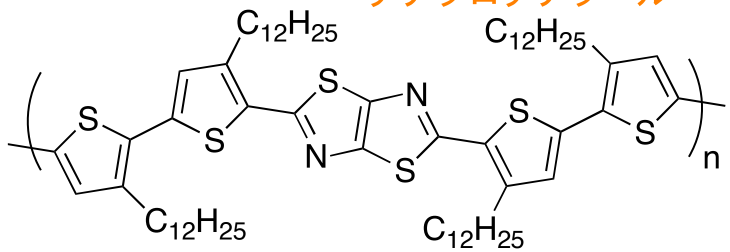
P 3 H T

0.1 cm^2/Vs
Science **1998**, *280*, 1741.

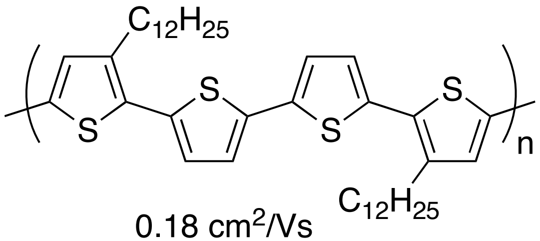


0.25 cm^2/Vs
Adv. Mater. **2006**, *18*, 3029.

チアゾロチアゾール

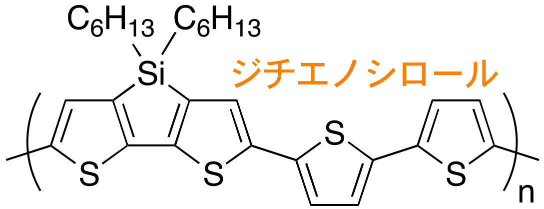


0.14 cm^2/Vs
Adv. Mater. **2007**, *19*, 4160.

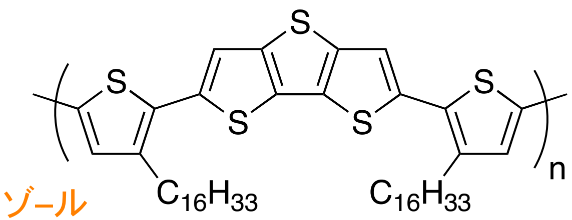


0.18 cm^2/Vs
APL **2005**, *86*, 142102.

ジチエノシロール

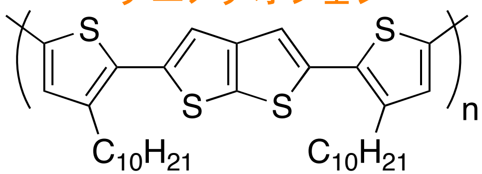


0.06 cm^2/Vs
JACS **2006**, *128*, 9035.



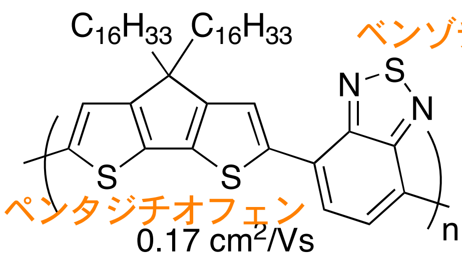
0.27 cm^2/Vs
S. Tokito

チエノチオフェン



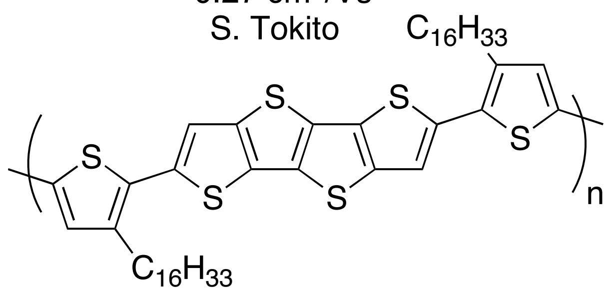
0.15 cm^2/Vs
JACS **2005**, *127*, 1078.

ベンゾチアジアゾール

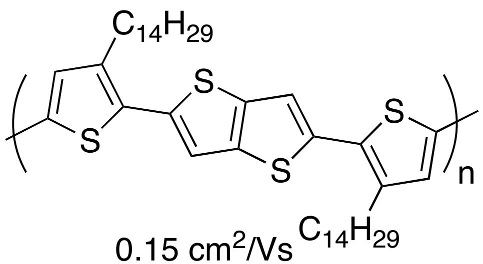


シクロペンタジチオフェン

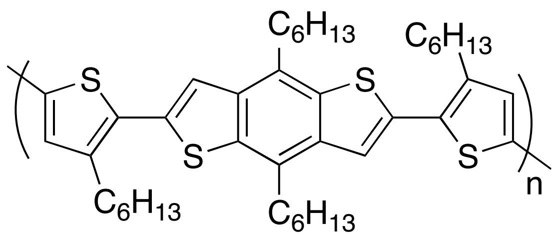
0.17 cm^2/Vs
JACS **2007**, *129*, 3472.



0.06 cm^2/Vs
S. Tokito



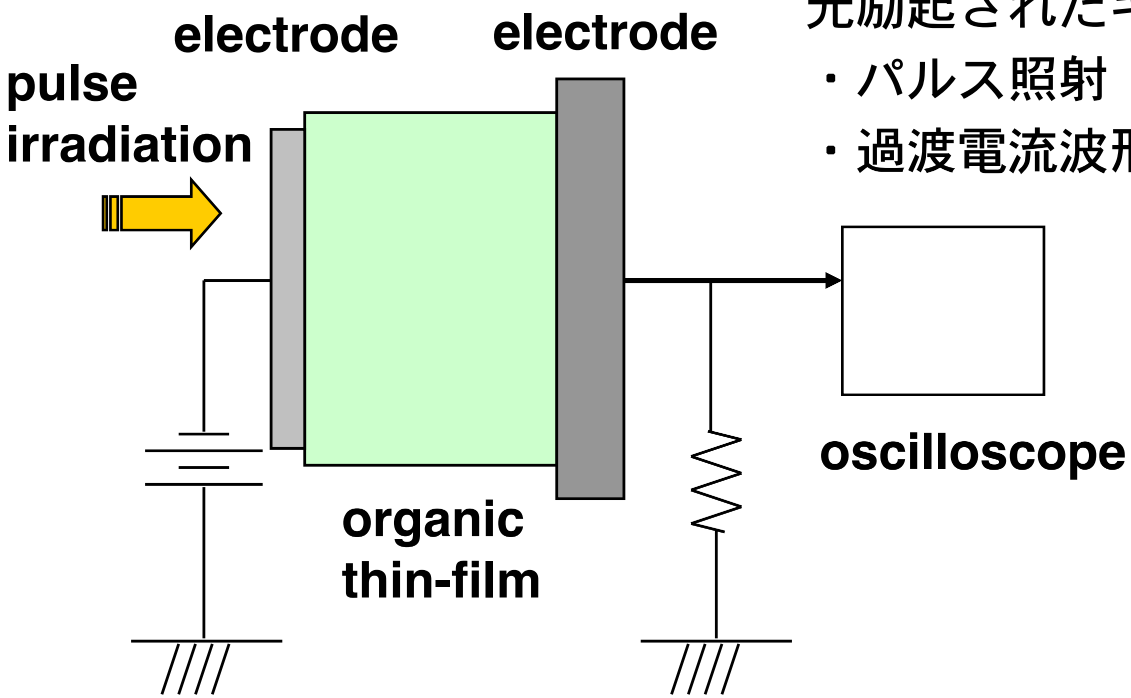
0.15 cm^2/Vs
Nat. Mater. **2006**, *5*, 328.



0.25 cm^2/Vs
JACS **2007**, *129*, 4112.

Evaluation of Carrier Mobility (1)

TOF (Time-of-Flight) method



光励起されたキャリアの膜厚方向の移動度を測定

・パルス照射（窒素レーザ光，400ps）

・過渡電流波形を測定，ドリフトタイムがわかる.

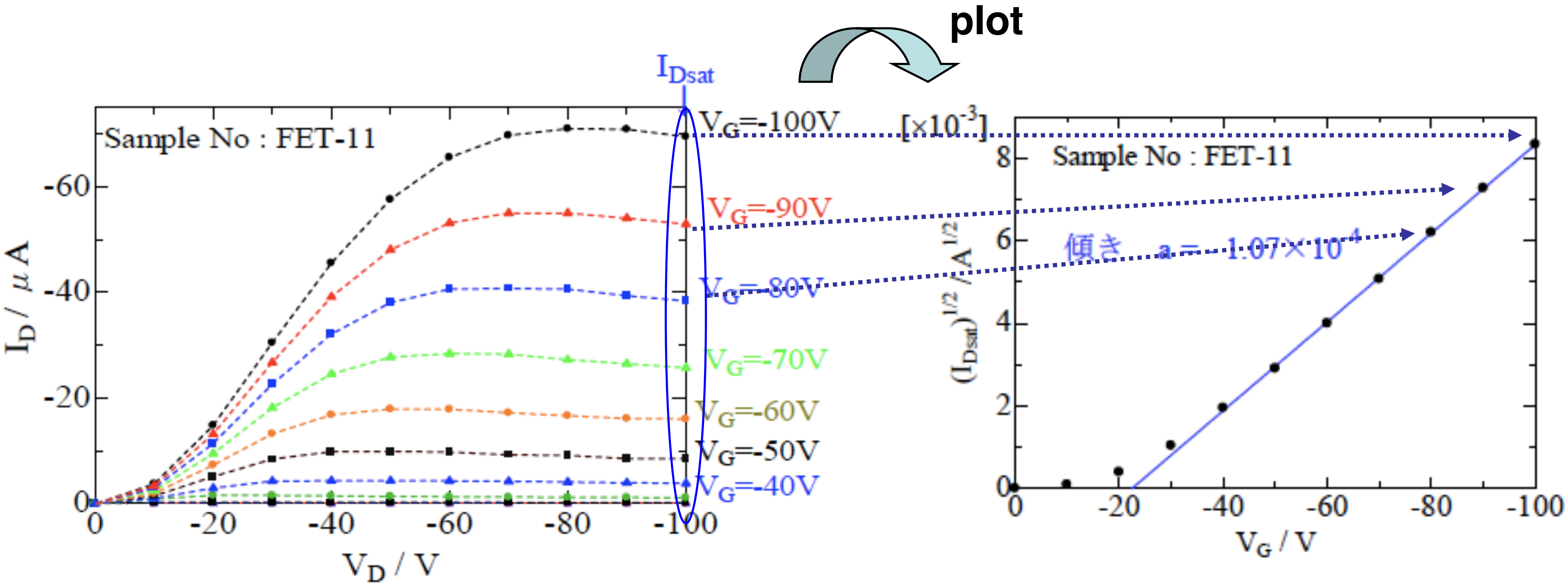
mobility（μ）[cm^2/Vs]＝ drift speed per unit electric field

単位電界あたりの電荷の移動速度(距離/時間)

$$= \frac{\text{drift length, 移動距離（thickness, 膜厚）} L \text{ [cm]}}{\text{electric field, 電界強度 } E \text{ (V/d) [V/cm]} \times \text{ drift time, ドリフトタイム } t \text{ [s]}}$$

Evaluation of Carrier Mobility (2)

FET (field effect transistor)

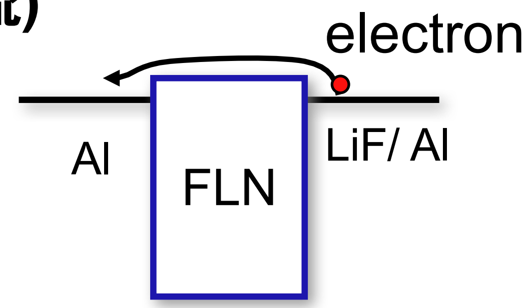


$I_{Dsat} = (W\mu C/2L)x(V_G–V_t)^2$ (slope)^2 ＝$W\mu C/2L$

W: channel width, チャネル幅; L: channel length, チャネル長
C: capacitance per unit area (insulator), 絶縁膜の単位面積あたりの静電容量
I_{Dsat}: saturated drain current, 飽和ドレイン電流
V_G: gate voltage, ゲート電圧; V_t: threshold voltage, しきい値電圧
μ: mobility, 移動度

Evaluation of Carrier Mobility (3)

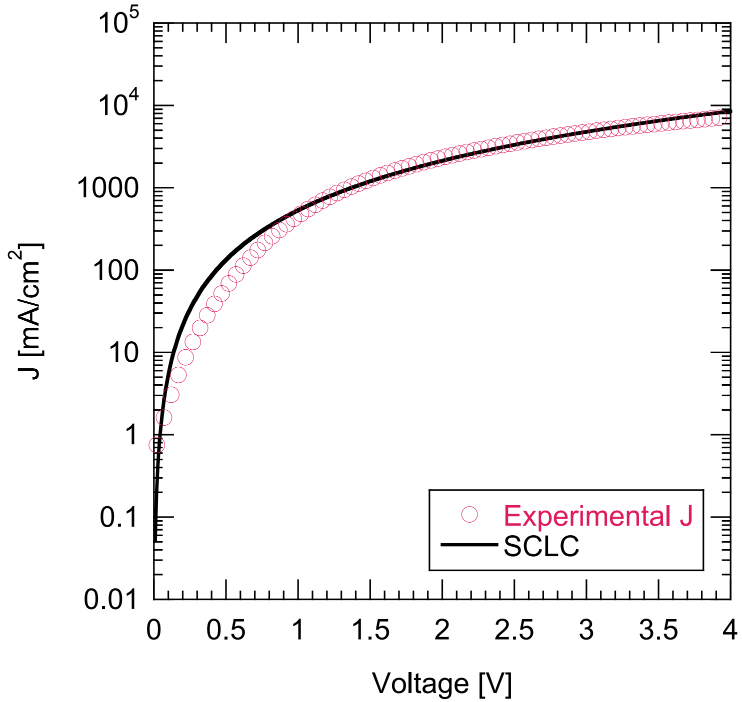
SCLC model
(Space Charge Limited Current, 空間電荷制限電流)



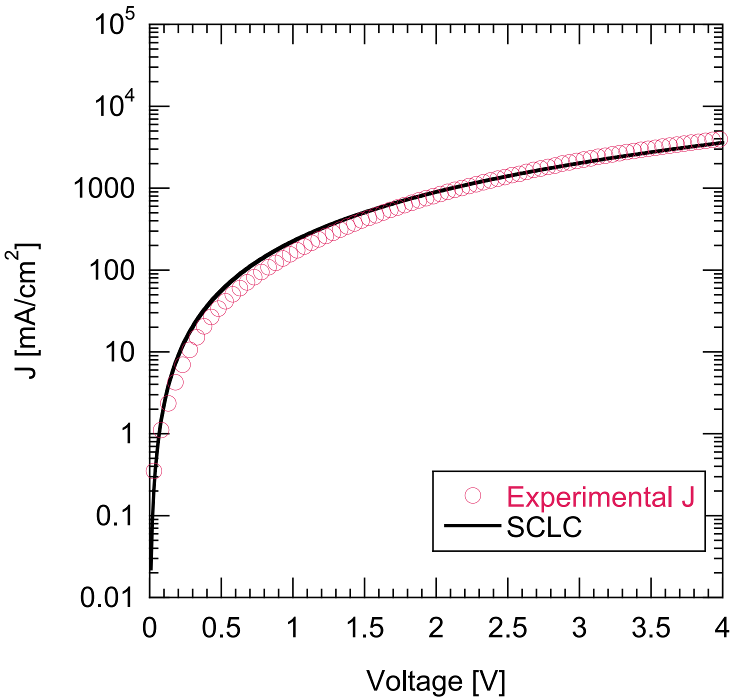
Aluminum / FLN (SIMEF or PCBM) / LiF / Aluminum

(film thickness = 220 nm fabricated from 1.25 wt% solution)

$$J_{SCLC} = 9/8 \cdot \varepsilon_r \varepsilon_0 \mu \cdot V^2/L^3$$



SIMEF: 8 × 10^{-3} [cm^2/Vs]



PCBM: 6 × 10^{-3} [cm^2/Vs]

Evaluation of Carrier Mobility (3)

SCLCモデル
(Space Charge Limited Current, 空間電荷制限電流)

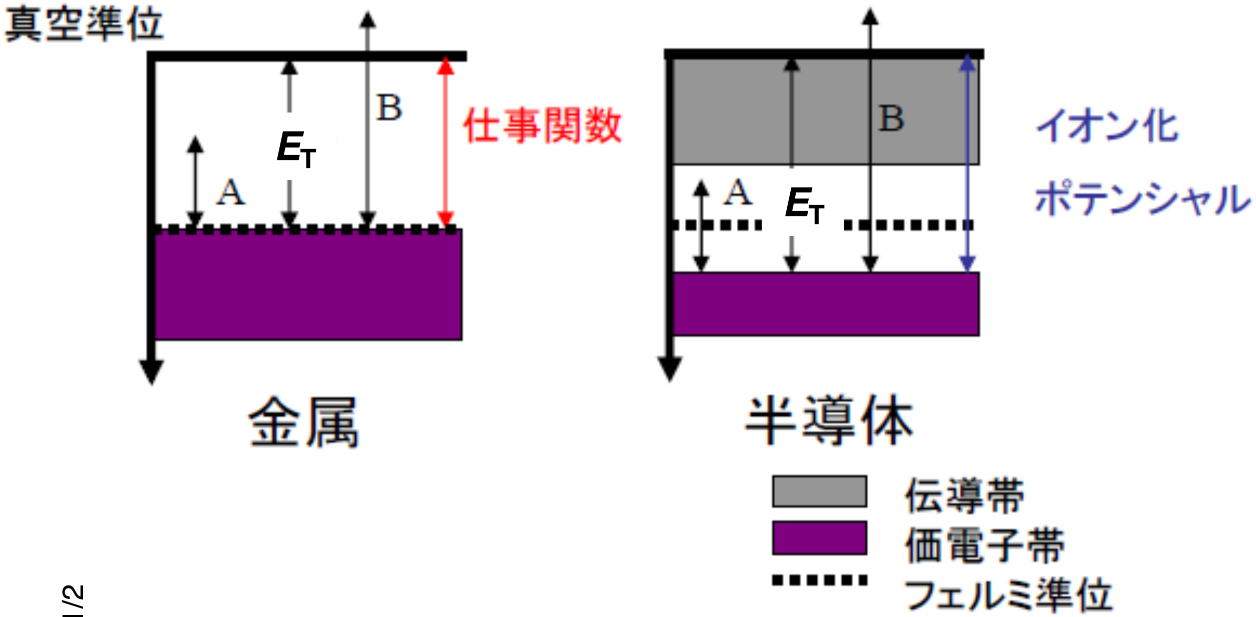
$$J = \frac{9}{8} \varepsilon_r \varepsilon_0 \mu \frac{V^2}{L^3}$$

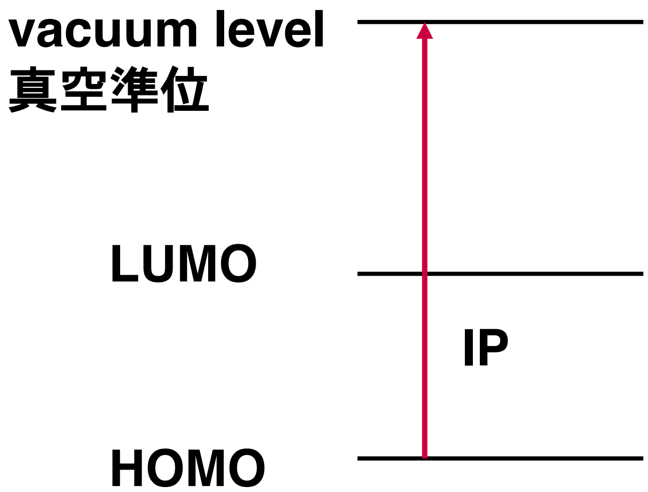
J: current density, 電流密度 [A/m^2]
V: voltage, 電圧 [V]
L: thickness, 膜厚 [m]
ε_r: relative permittivity, 比誘電率 [dimensionless, 無次元量]
ε_0: electric constant, 真空の誘電率 (8.854×10^{-12} [F/m] ([A·m/V·s])**)**
($\varepsilon_r = \varepsilon/\varepsilon_0$, ε: permittivity, 誘電率)
μ: mobility, 移動度 [m^2/V·s]

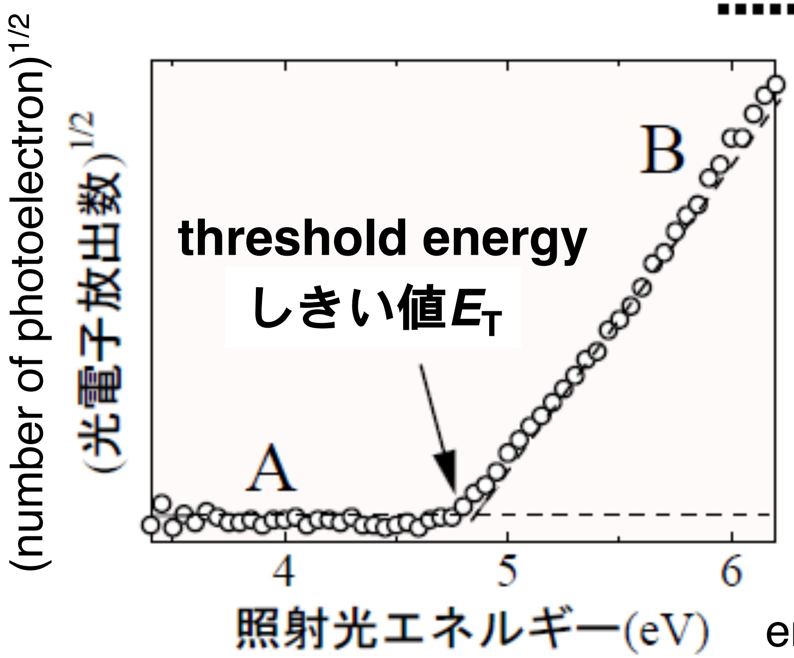
P. E. Burrows, Z. Shen, V. Bulovic, D. M. McCarty, S. R. Forrest, J. A. Cronin, S. R. Forrest, *J. Appl. Phys.* **1996**, *79*, 7991.

Evaluation of Ionization Potential (1)

光電子分析法（電子計数方式，大気中）, photoelectron counting at normal pressure





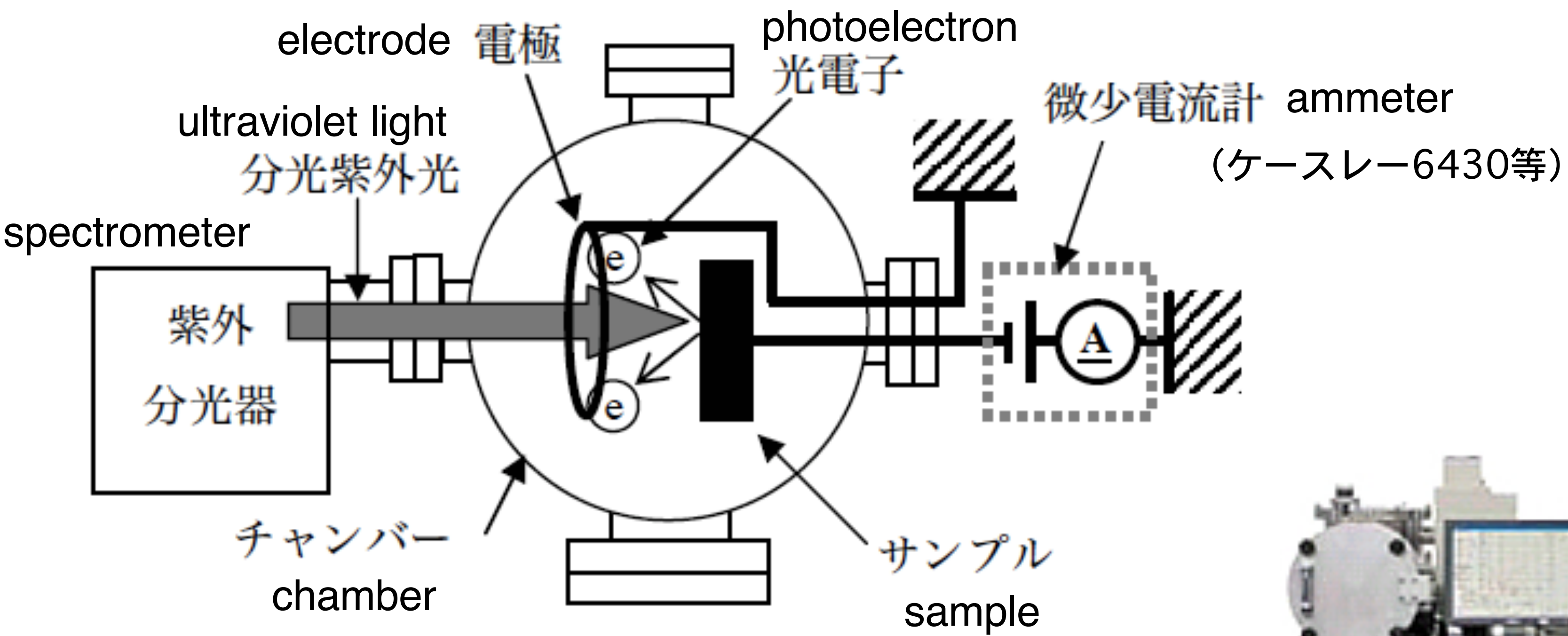


理研計器
AC-1, AC-2, AC-3

Evaluation of Ionization Potential (2)

光電子収量分光 (PYS, Photoelectron Yield Spectroscopy)，真空中，大気中

in vacuo and at normal pressure



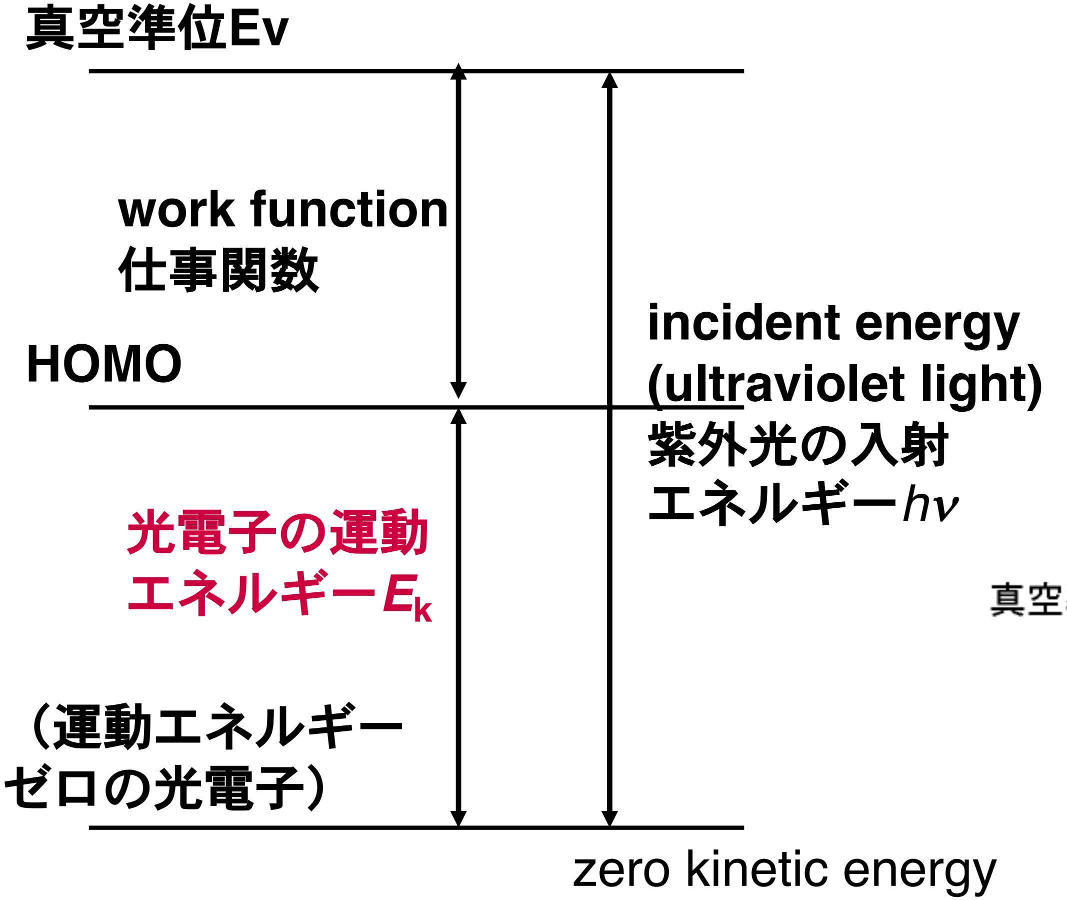
・飛び出た電子を補償する電流を測定
（光電子計数方式よりシンプル）

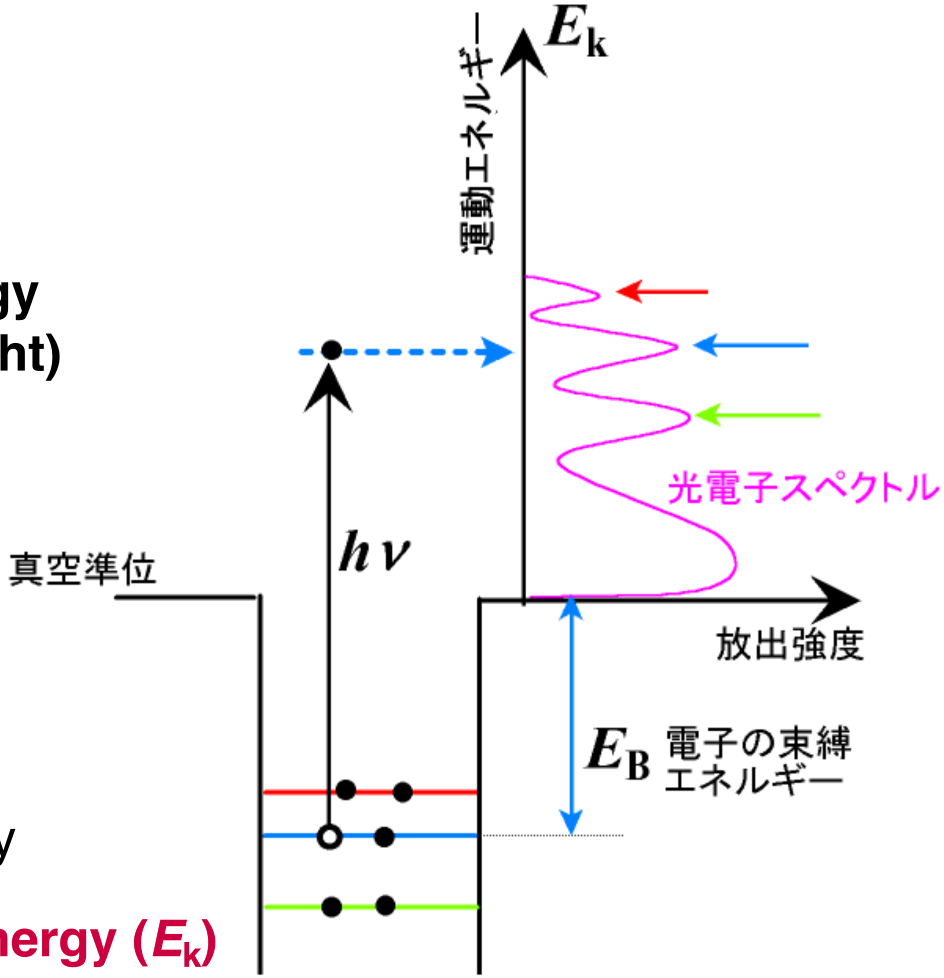
・サンプルにわずかに負電圧を印加し，
電子が飛び出し易いようにする

住友重工・PYS-201

Evaluation of Ionization Potential (3)

紫外光電子分光（UPS, Ultraviolet Photoelectron Spectroscopy），超高真空下



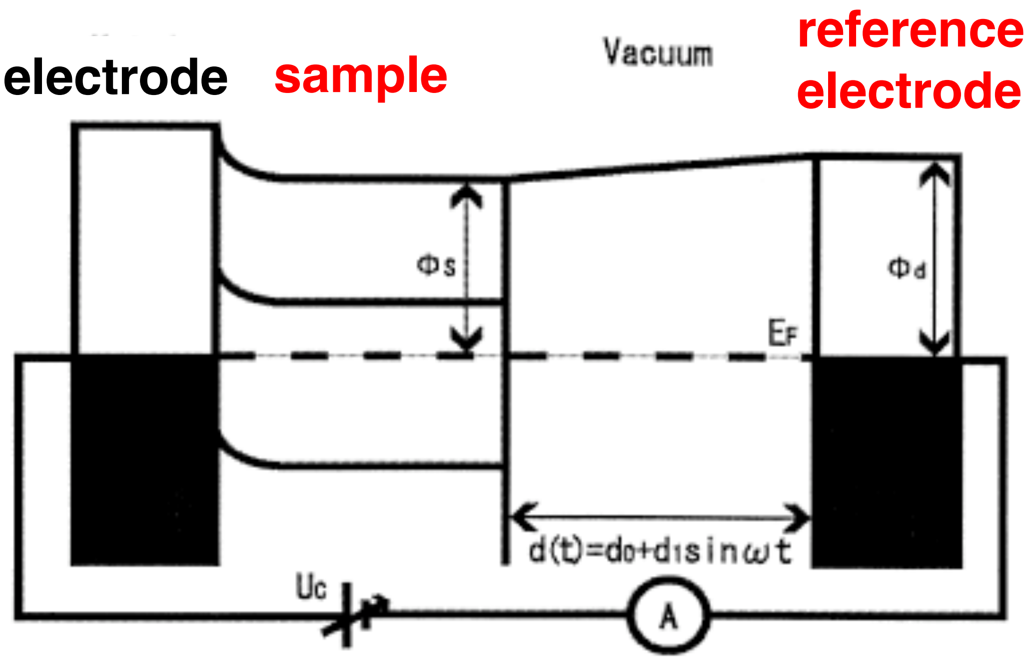


measurement of photoelectron kinetic energy (E_k)

光電子の運動エネルギーE_kを測定

Evaluation of Ionization Potential (4)

Kelvin Probe Method (KPM)



· This measurement gave a Fermi level of organic semiconductors rather than ionization potential of them.

· Oscillation of two materials having different work function (WF) affords alternating current AC.

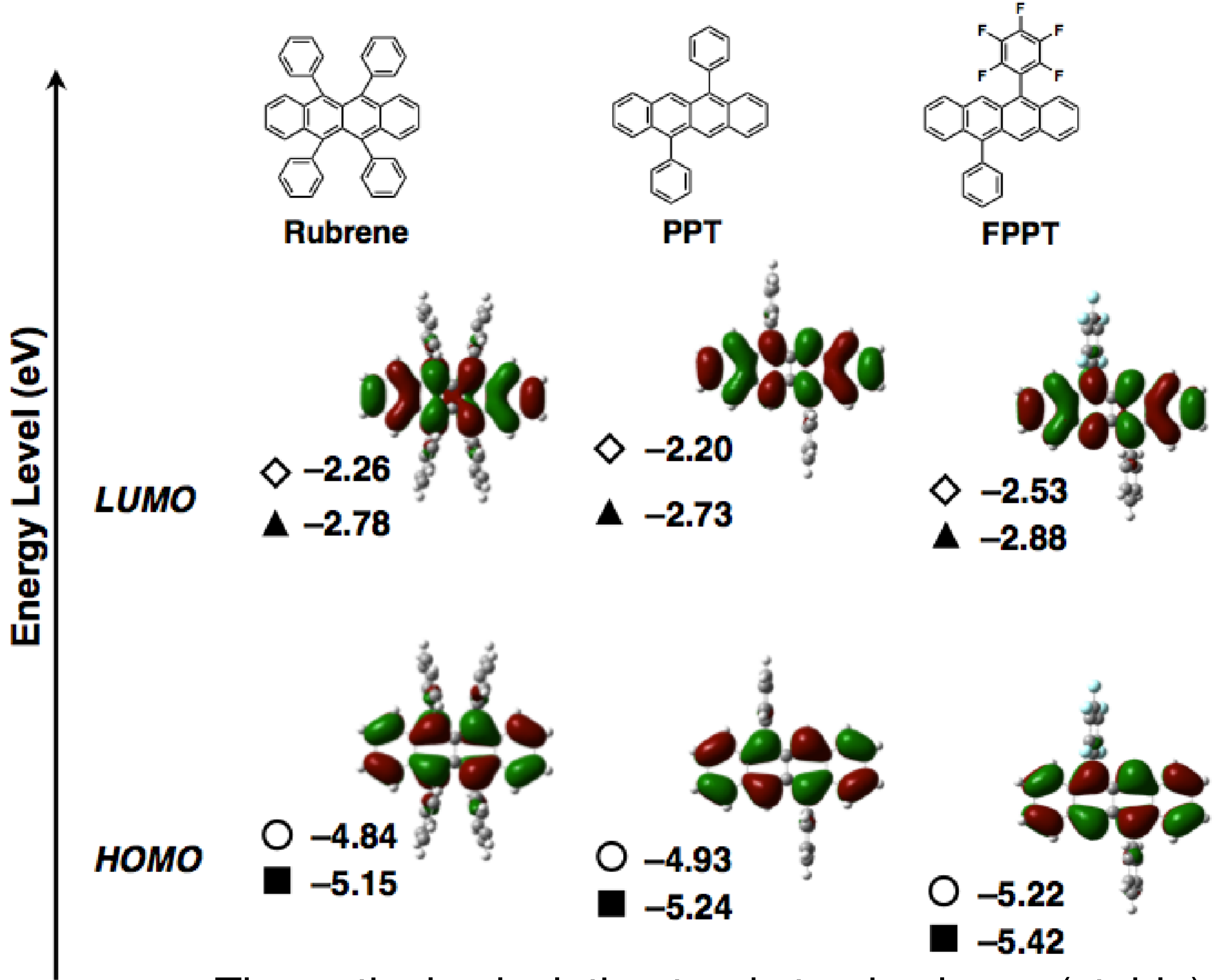
· To cancel the generated AC, offset voltage is applied.

· WF (Fermi level) of the sample = WF of the reference electrode – offset voltage

表面科学 2002, Vol. 23, No. 7, 455.

Evaluation of Ionization Potential (5)

Quantum Chemical Calculation



◇, ○ : electrochemical

▲, ■ : theoretical

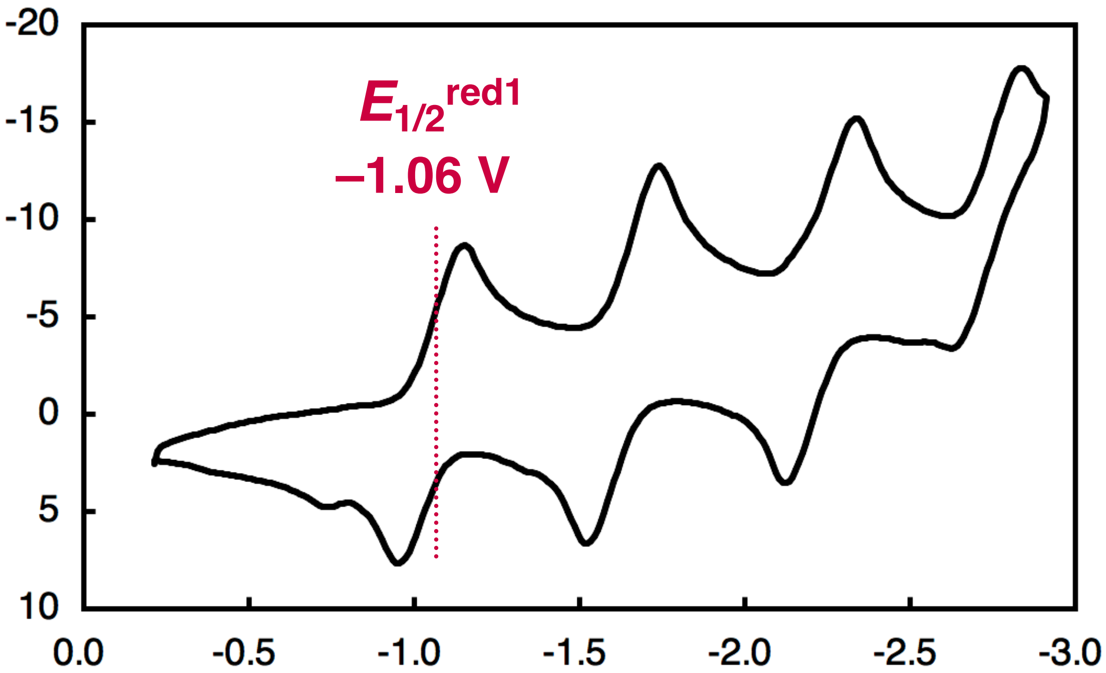
B3LYP/6-31g*

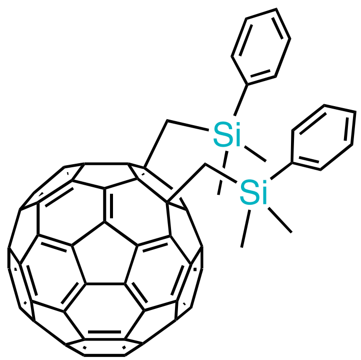
Theoretical calculation tends to give lower (stable) energy levels.

Chem. Mater. **2011**, *23*, 1646.

Evaluation of Electron Affinity

Electrochemical Study (Cyclic Voltammetry)





$E_{LUMO} = -(4.8 - 1.06)$

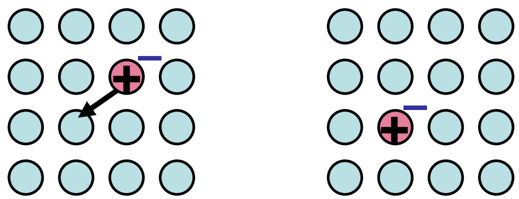
$= -3.74$ [eV]

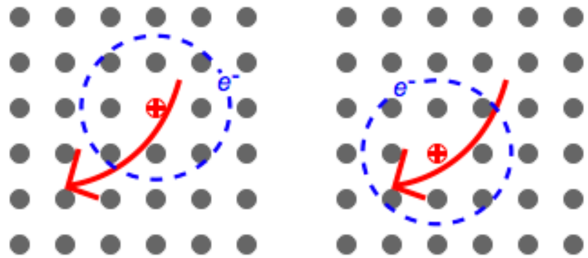
E_{LUMO} [eV] = $-(E_{1/2}^{red1}$ [V vs. Fc/Fc^+] + 4.8)

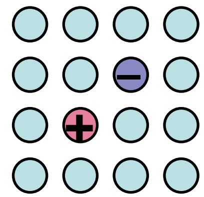
R. S. Ashraf *et al., Macromol. Rapid Commun.* **2006**, *27*, 1454.
W.-Y. Wong *et al., Nat. Mater.* **2007**, *6*, 521.
Y. Matsuo *et al. J. Am. Chem. Soc.* **2008**, *130*, 15429.

Exciton, エキシトン（励起子）

An electron/hole pair of　the excitation state







Frenkel exciton
（フレンケル励起子）

Mott-Wannier exciton
（ワニエ励起子）

(charge transfer)
（電荷移動型）

organic semiconductors　　**silicon, inorganic semiconductor**

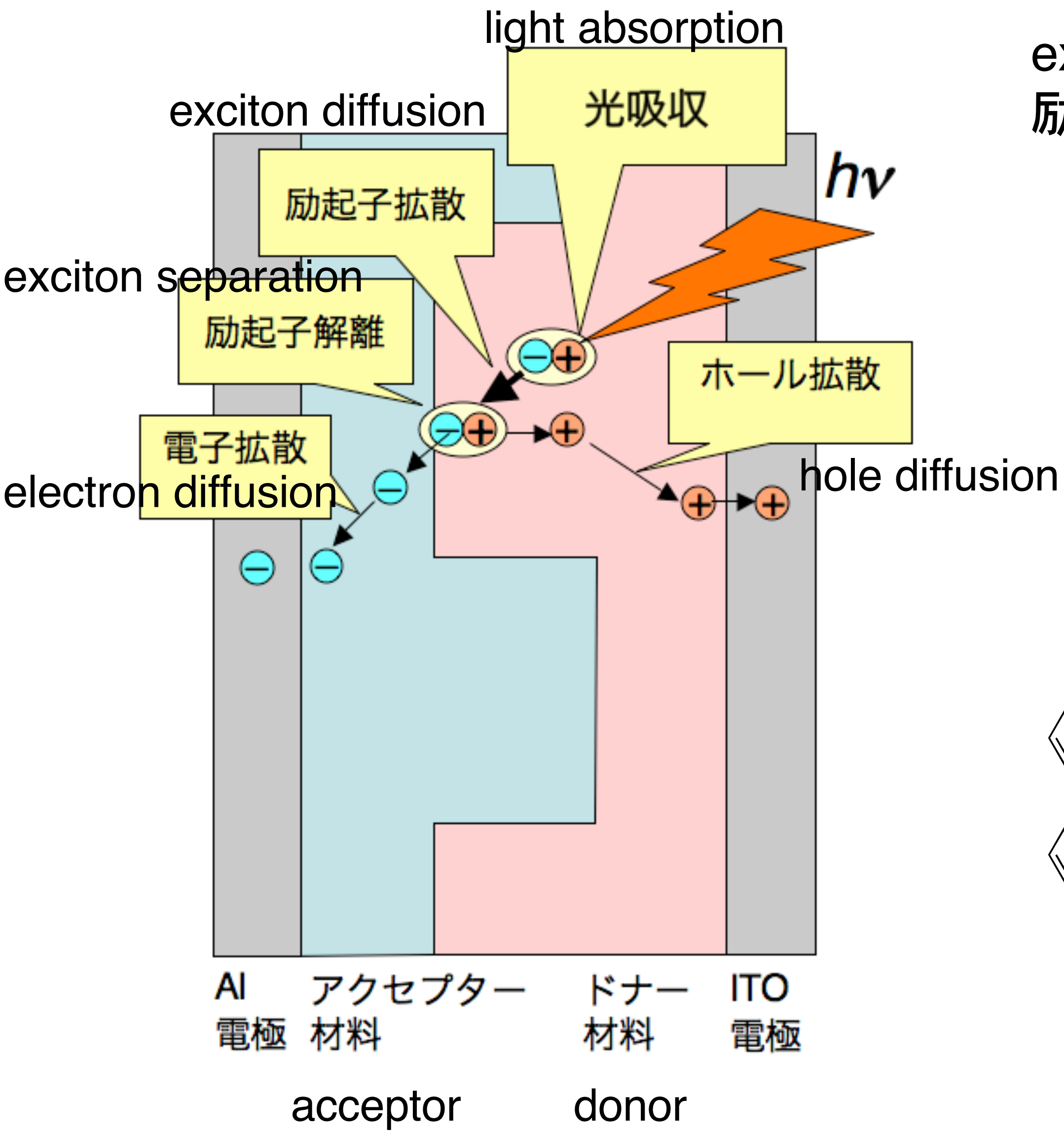
closed electron and hole (~1 nm)

separated electron and hole (~10 nm)

OELD: charge recombination of hole and electron generates exciton.

OPV: light absorption of organic molecules generates exciton.

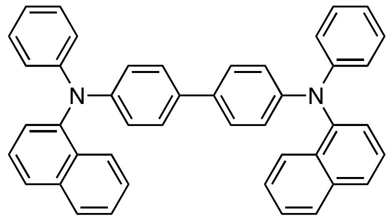
Exciton Diffusion Length, 励起子の拡散距離



exciton diffusion length, L_D
励起子の拡散距離：ca.10 nm

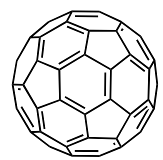
triplet excitation state:
ca.10～30 nm

P. Peumans, A. Yakimov, S. R. Forrest, *J. Appl. Phys.* **2003**, *93*, 3693-3723.



L_D = 6.5 nm

α-NPD



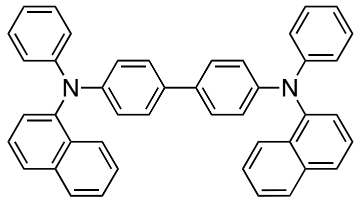
L_D = 13 nm

C_{60}

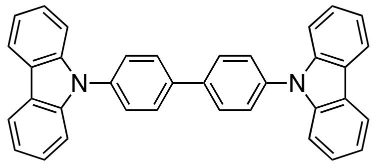
Exciton Diffusion Length, Doping

Doping Triplet Materials

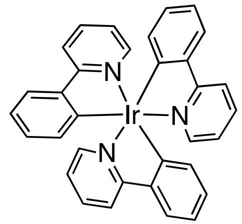
	L_D
NPD	6.5±0.3 nm
NPD +1wt% $Ir(ppy)_3$	9.4±0.5 nm
NPD +5wt% $Ir(ppy)_3$	11.8±0.6 nm



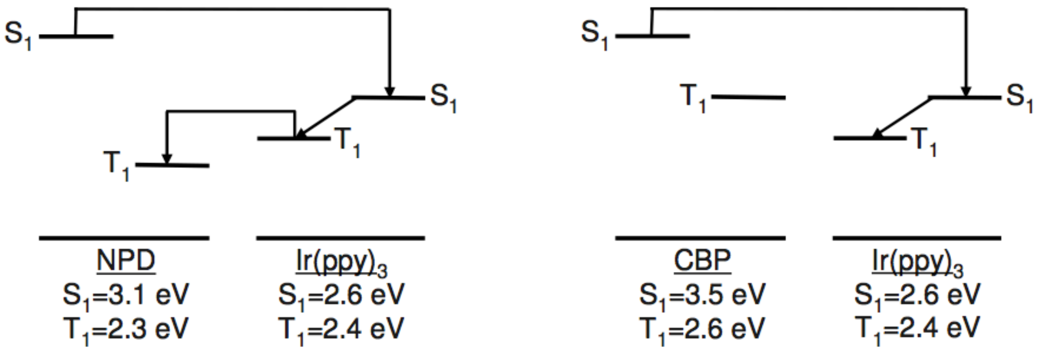
NPD

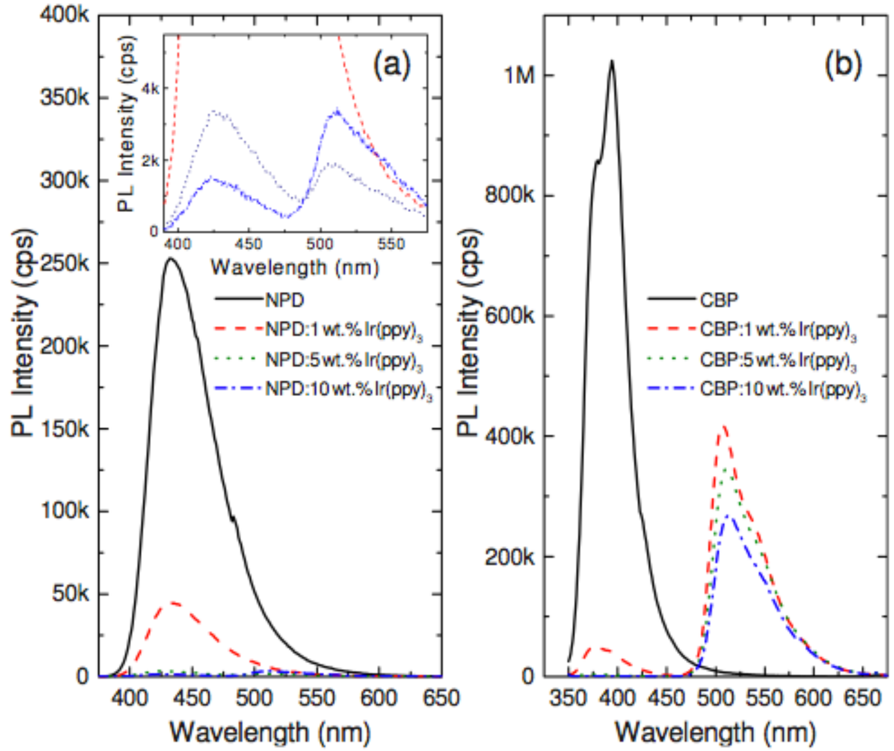


CBP



$Ir(ppy)_3$

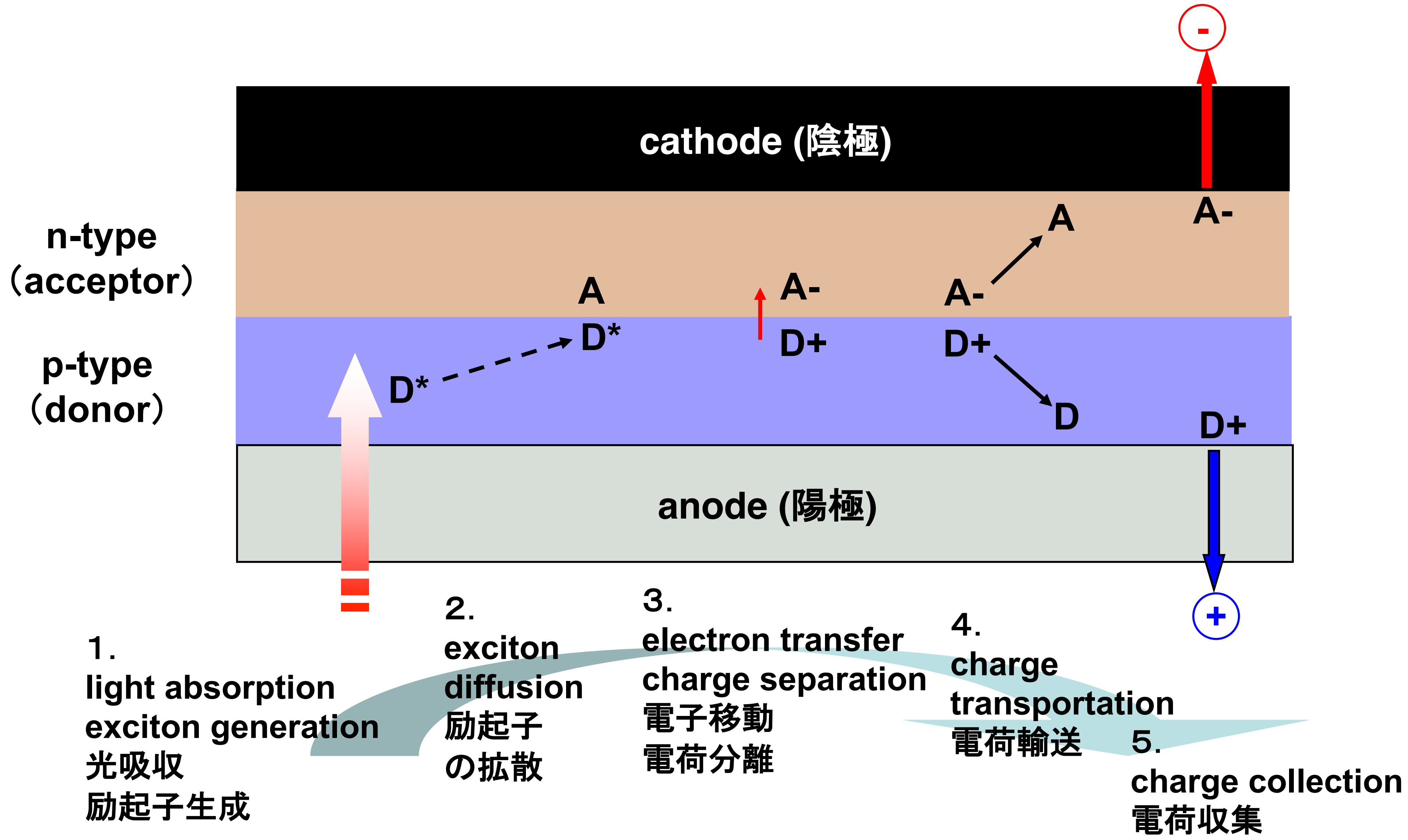




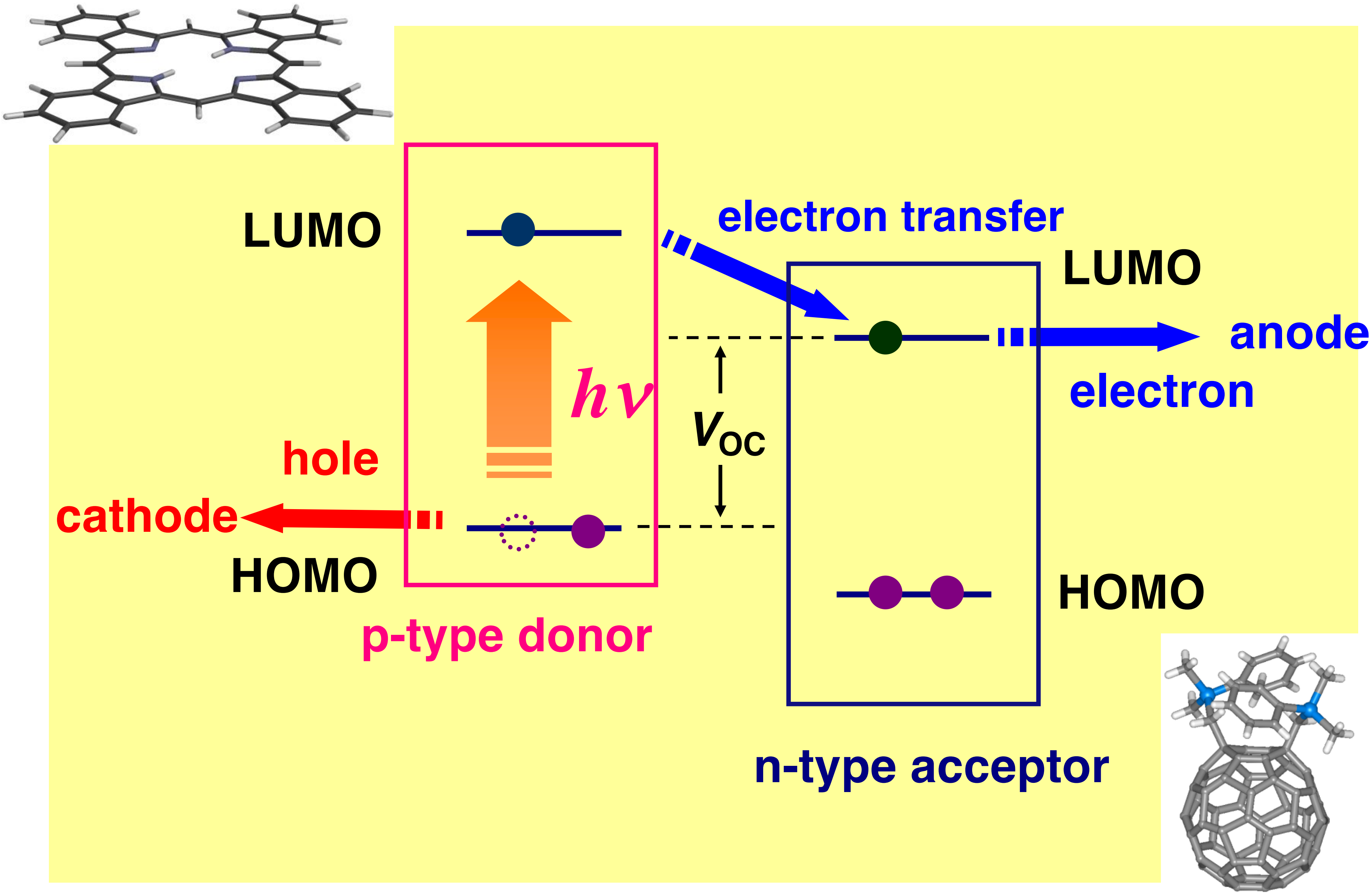
W. A. Luhman, R. J. Holmes, *Appl. Phys. Lett.* **2009**, *94*, 153304.

– Basics of Organic Solar Cells –

Photovoltaic Mechanism

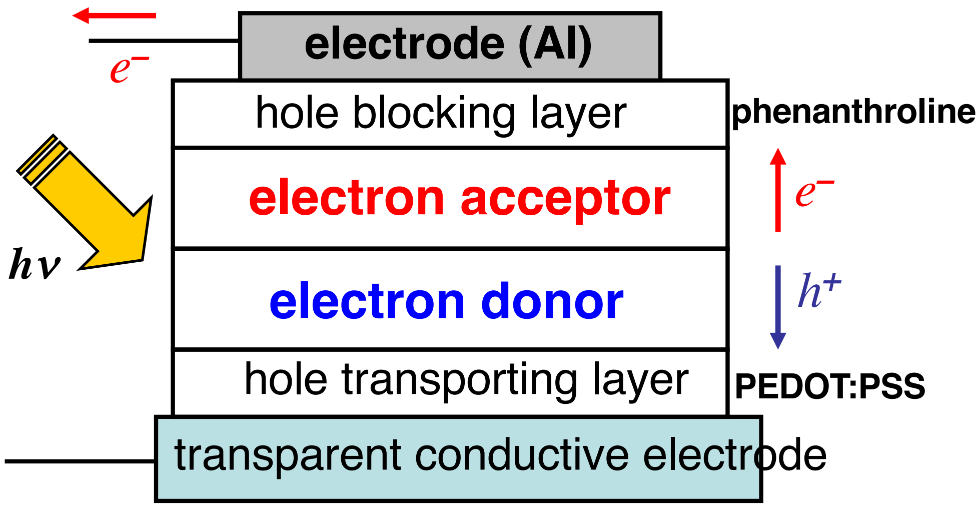


Photovoltaic Mechanism

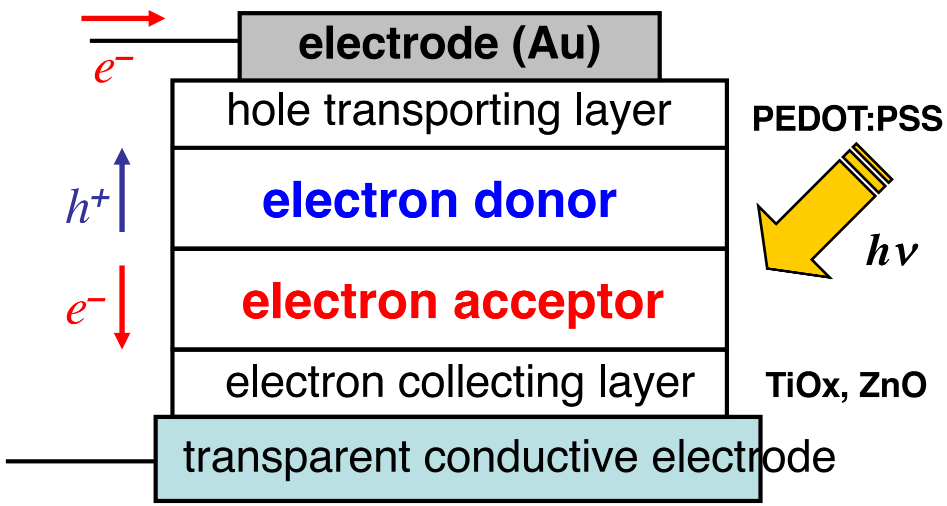


Device Configuration of Organic Solar Cells

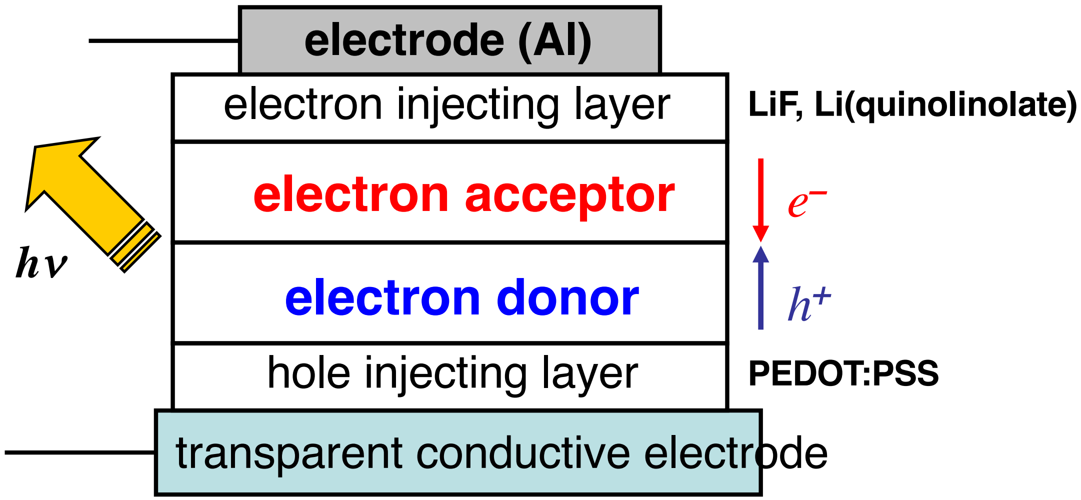
Normal structure



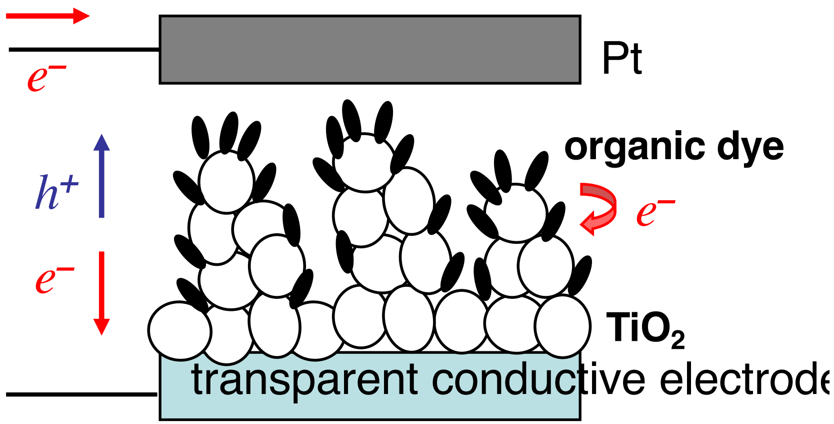
Inverted structure



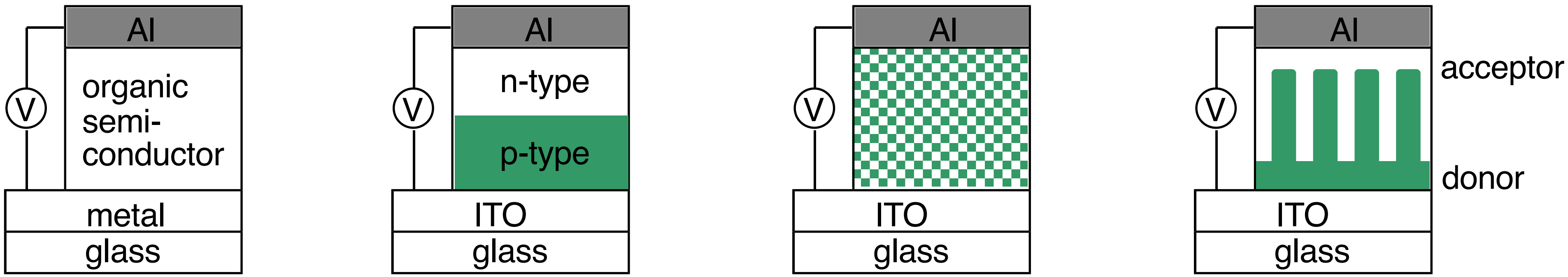
cf. Organic light emitting diodes



cf. Dye-sensitized Solar cells



Structures of Active Layers



Schottky junction
(Calvin cell)
1958
PCE = 0.01%

pn heterojunction
(Tang cell)
1986
PCE = 1%

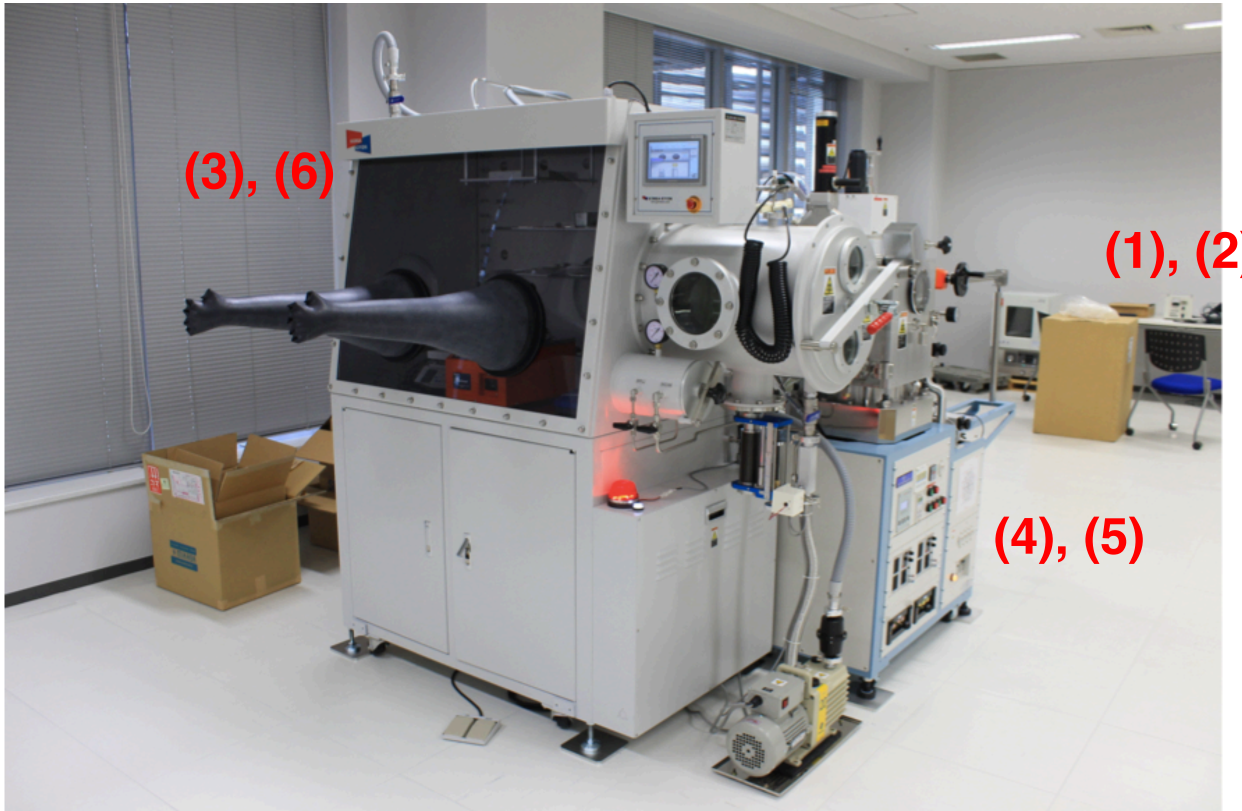
bulk heterojunction
(Sariciftci cell)
1995
PCE = 5%

- **good carrier formation**
- **bad carrier transport**

interpenetrating
nanostructure cell
2009
PCE > 7%

- **good carrier formation**
- **good carrier transport**

Fabrication of Organic Solar Cells



1. Cleaning of ITO glass (UV/ozone cleaner)
2. Spin-coating of PEDOT:PSS (hole transport material) in air, then baking
3. Spin-coating of the active layer in glovebox, then thermal annealing
4. Vacuum deposition of the hole blocking layer
5. Vacuum deposition of the back electrode
6. Encapsulation of the device in glovebox

Fabrication of Inverted Organic Solar Cells

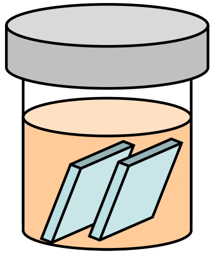
spin coater and hot plate

Patterned ITO

↓

Sol-gel or chemical bath deposition process for making inorganic metal oxide layer

↓



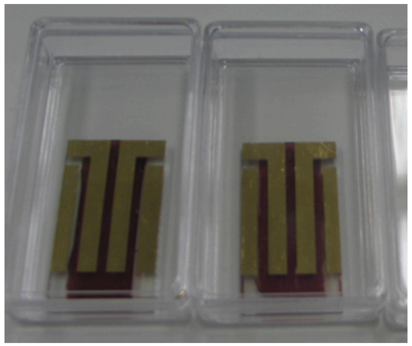
Spin coating of the active layer

↓

Spin coating of the PEDOT:PSS layer

vacuum deposition coater

↓

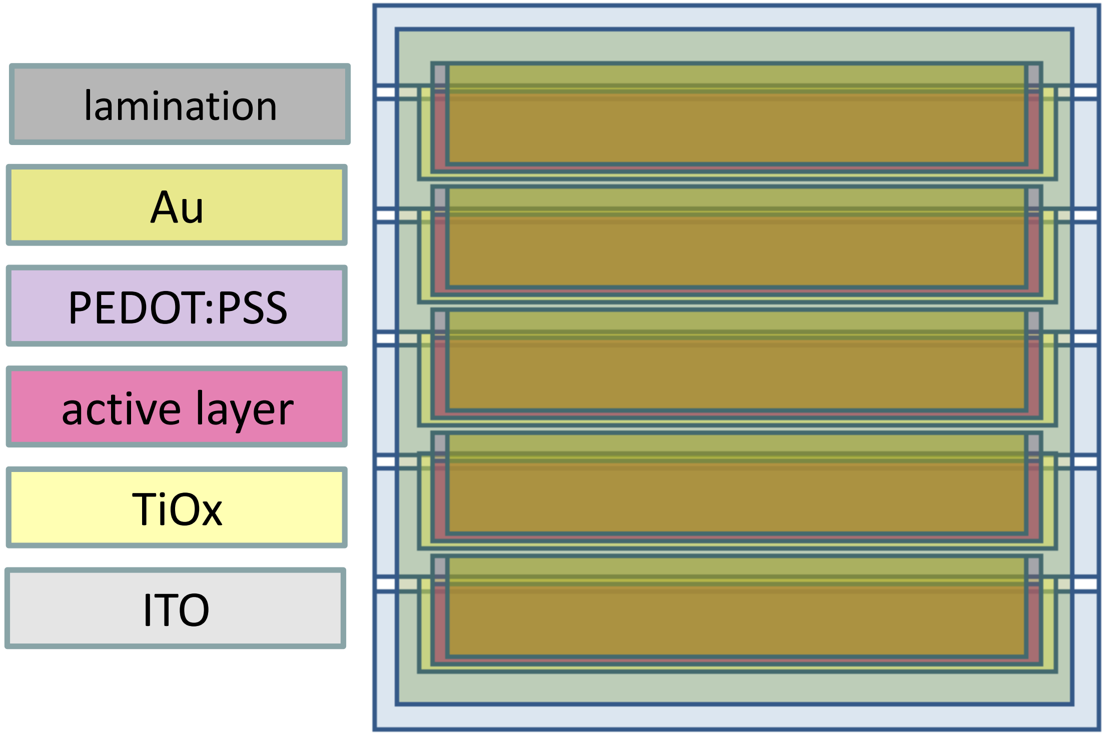


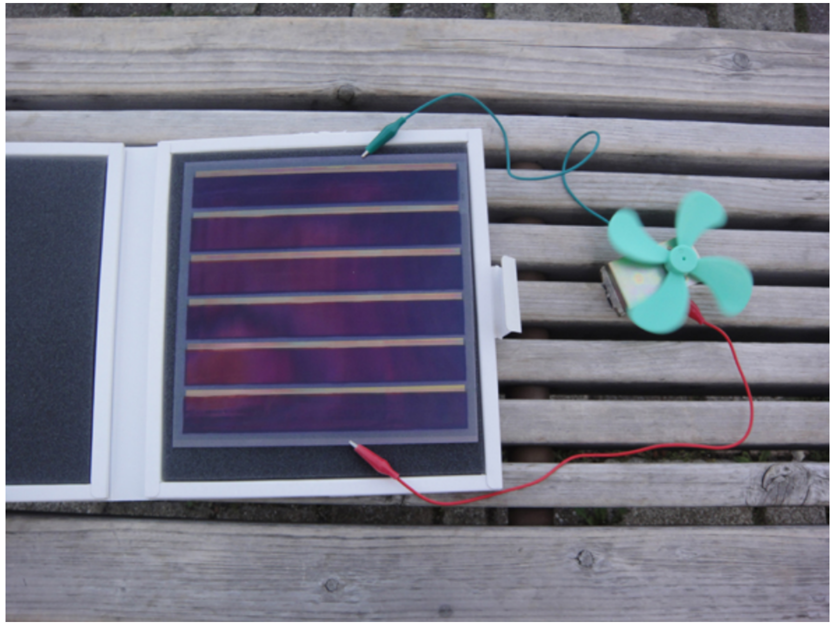
Thermal annealing

↓

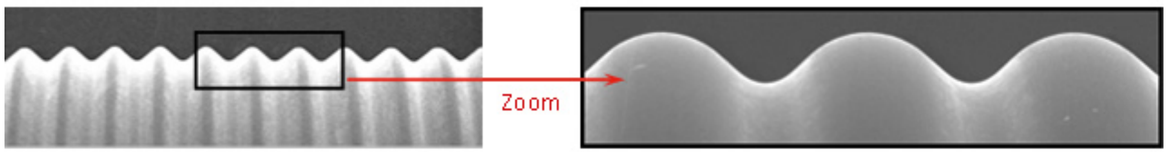
Vacuum deposition of gold electrode

Fabrication of Large-Area Organic Solar Cells

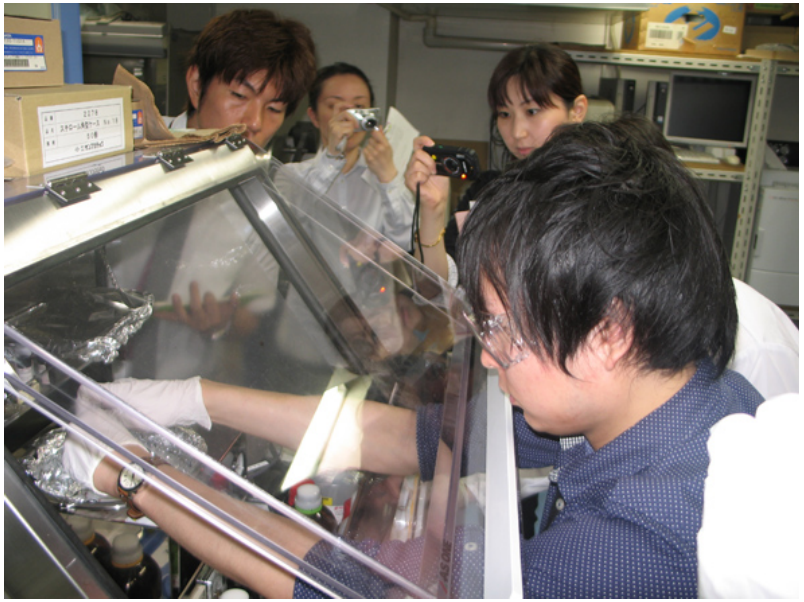




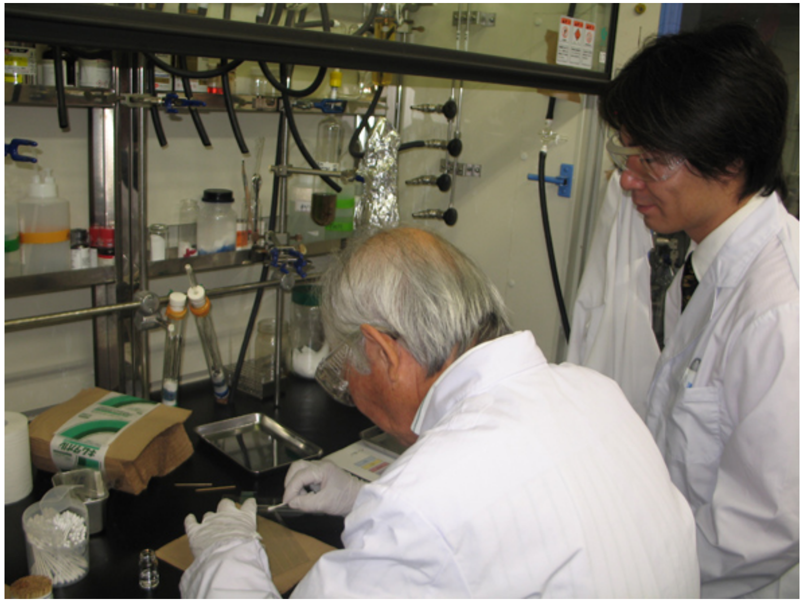
bar coater



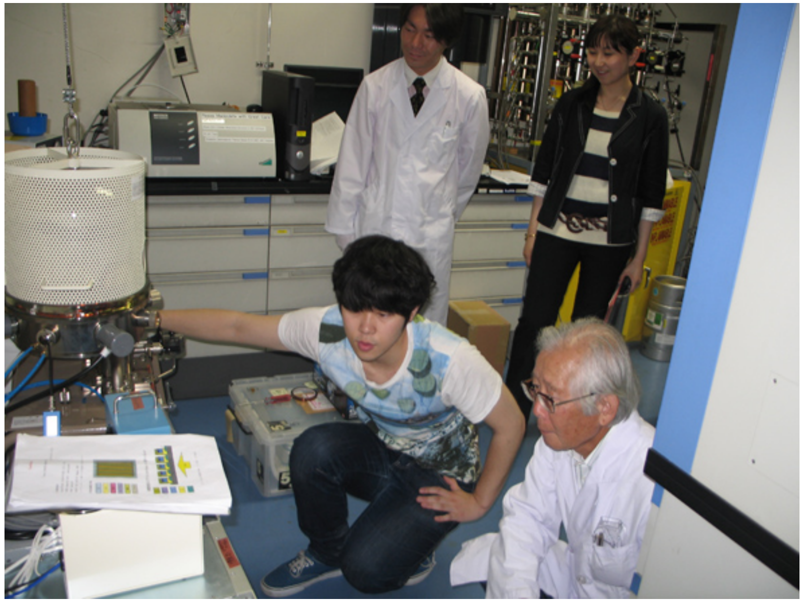
Fabrication of Large-Area Organic Solar Cells



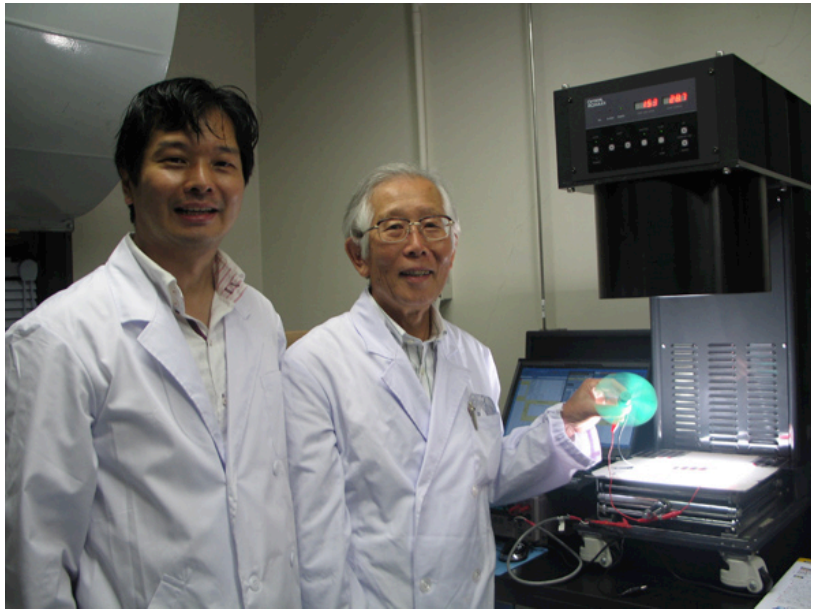
1. Spin-coating to form organic thin-films



2. Scribing with cotton swab



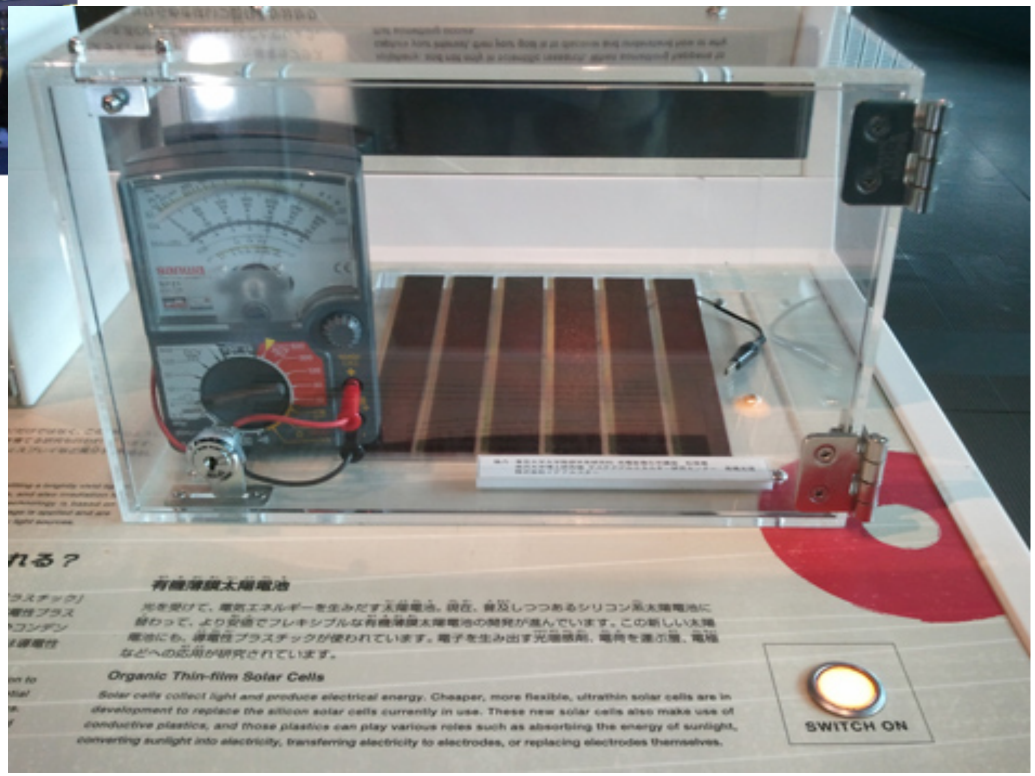
3. Vacuum deposition of back electrode



4. Completion

Fabrication of Large-Area Organic Solar Cells

Miraikan Museum (Odaiba)



Exhibition next to the poly(acetylene) film

Roll-to-Roll Process on Flexible Plastic Substrate

PET-ITO film

↓

ZnO nanoparticle, slot dye coating
(stabilizer: methylethylacetic acid; solvent: acetone)

↓

Active layer, slot dye coating
(P3HT:PCBM in chlorobenzene)

↓

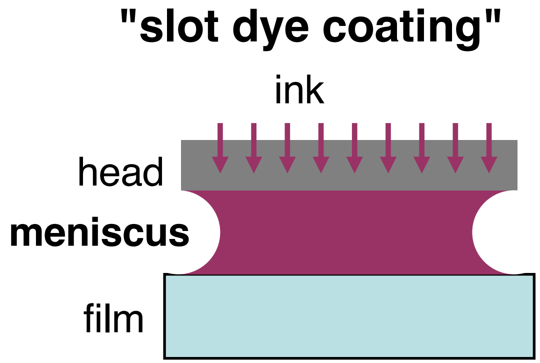
PEDOT:PSS, slot dye coating

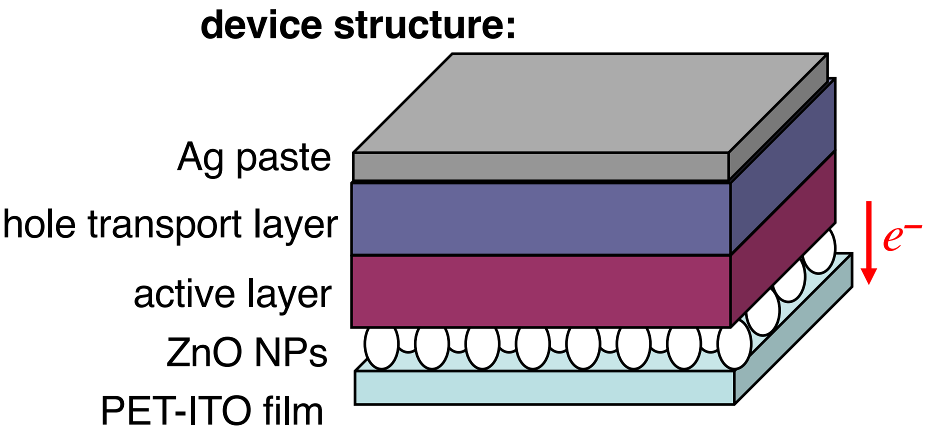
↓

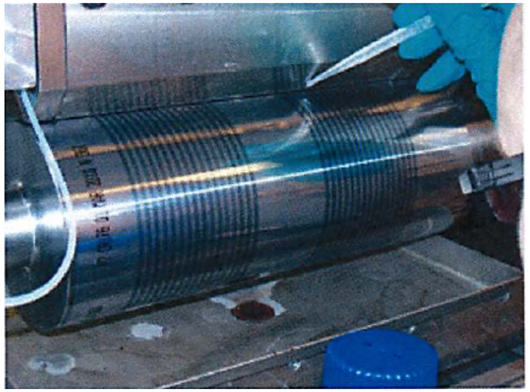
Silver paste, screen printing

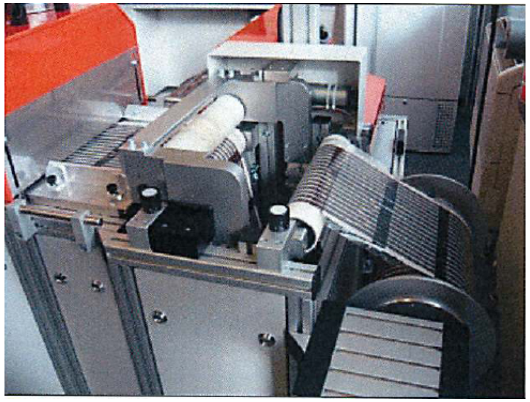
↓

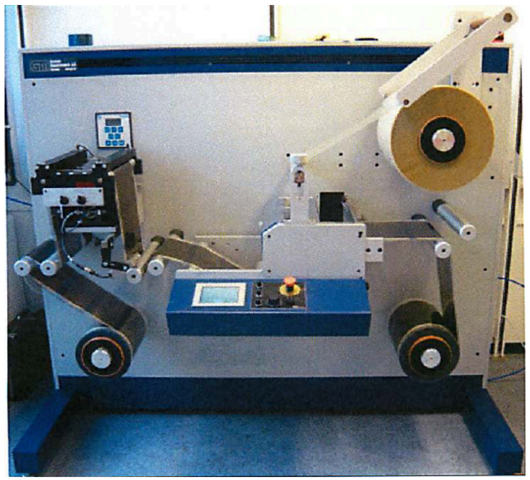
Cold lamination



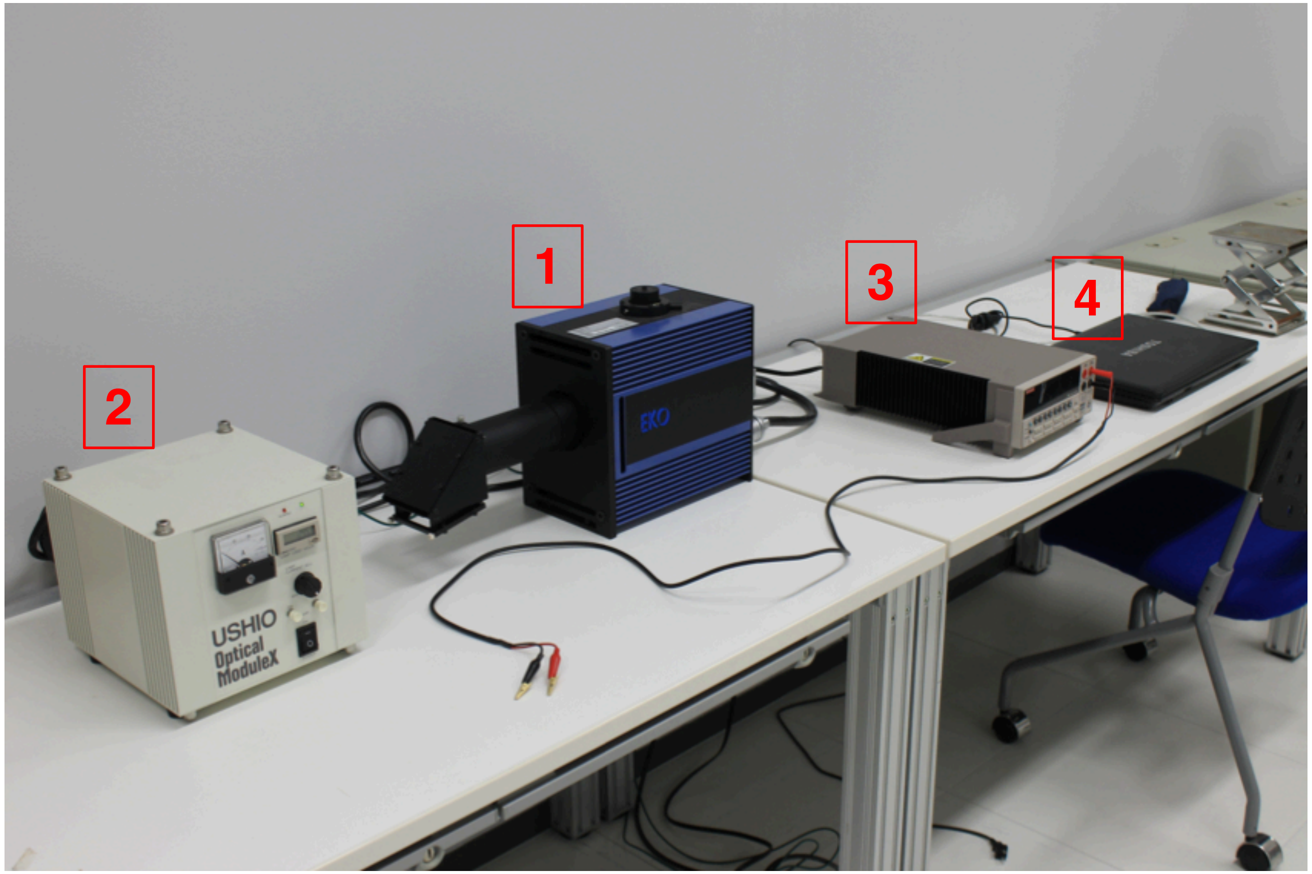








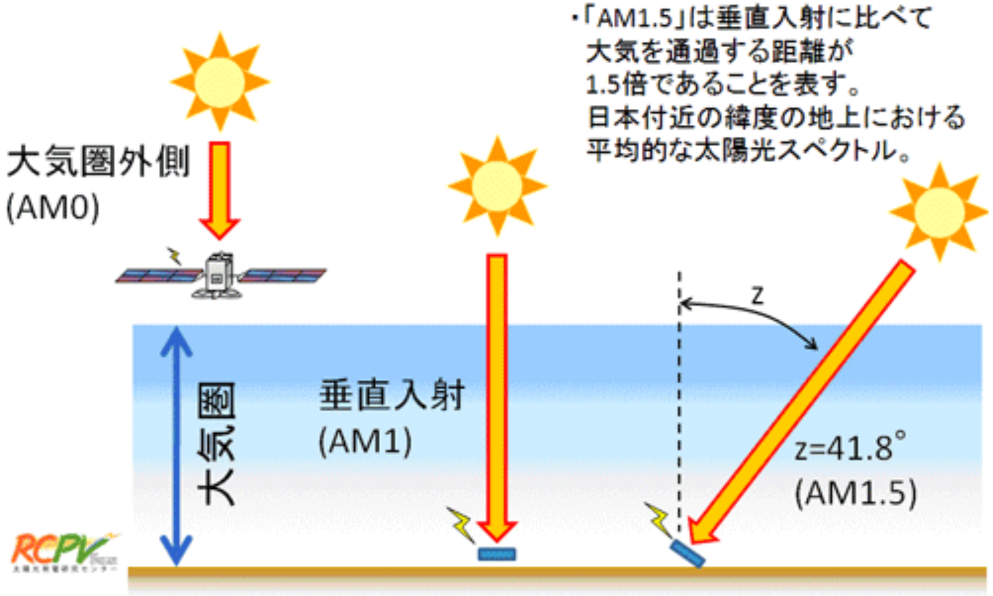
Evaluation of Performance

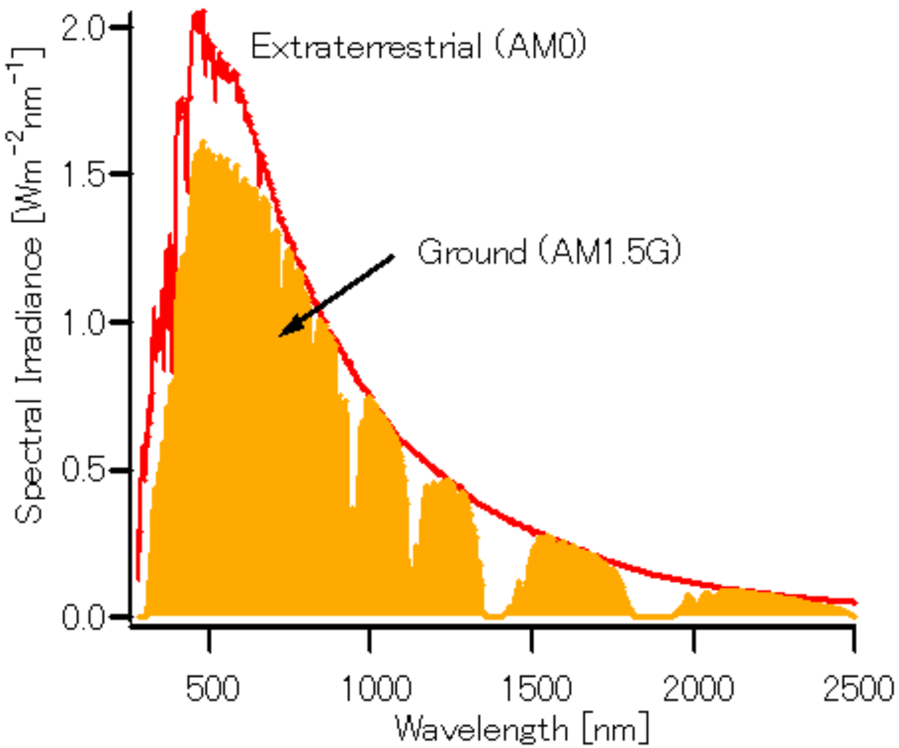


1. Solar Simulator: Xenon Lump and Air Mass (AM) Filter
2. Power Source: For Xenon Lump
3. Source Meter Unit: Output=Voltage, Input=Current
4. PC: Control, Data Reduction
5. Photon Counter: For Data Calibration

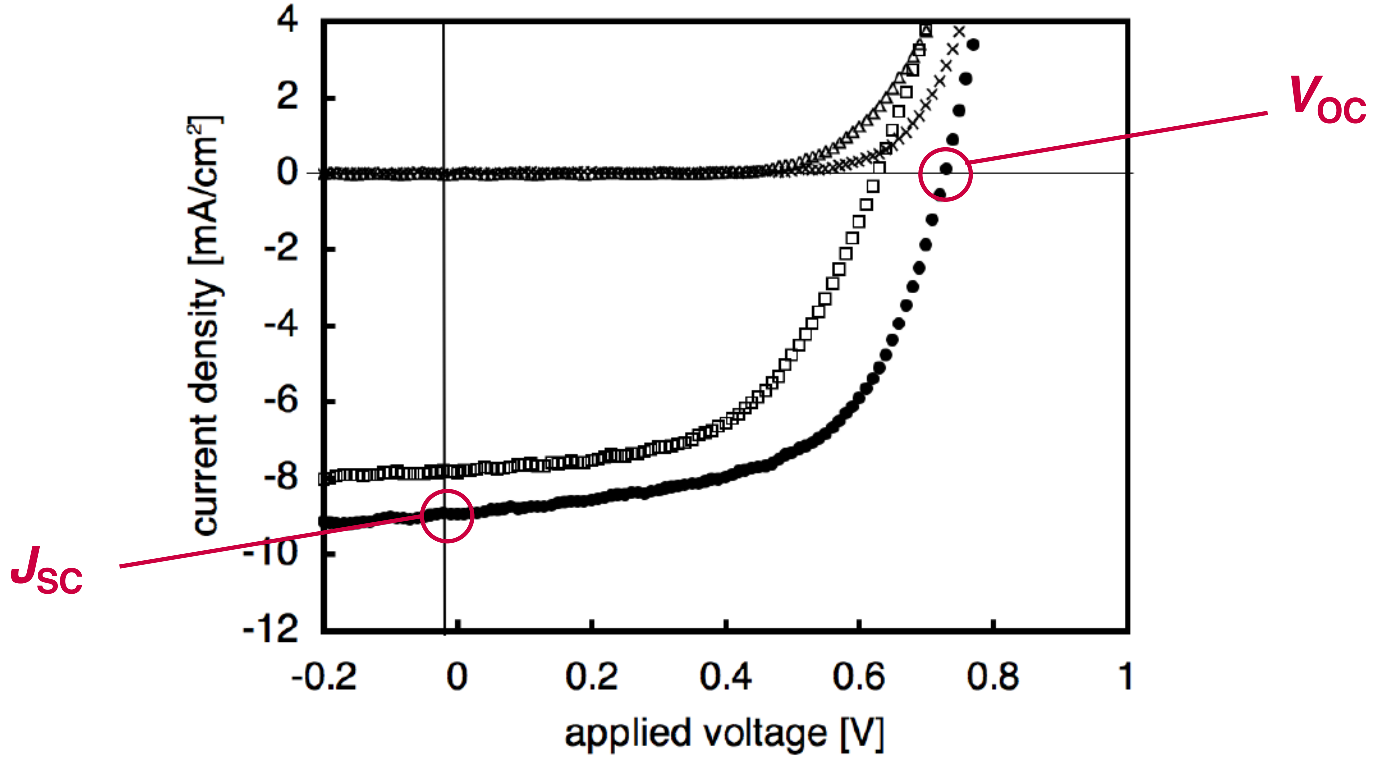
Artificial Sun Light

Air Mass (AM)





Characteristic of Organic Photovoltaic Devices



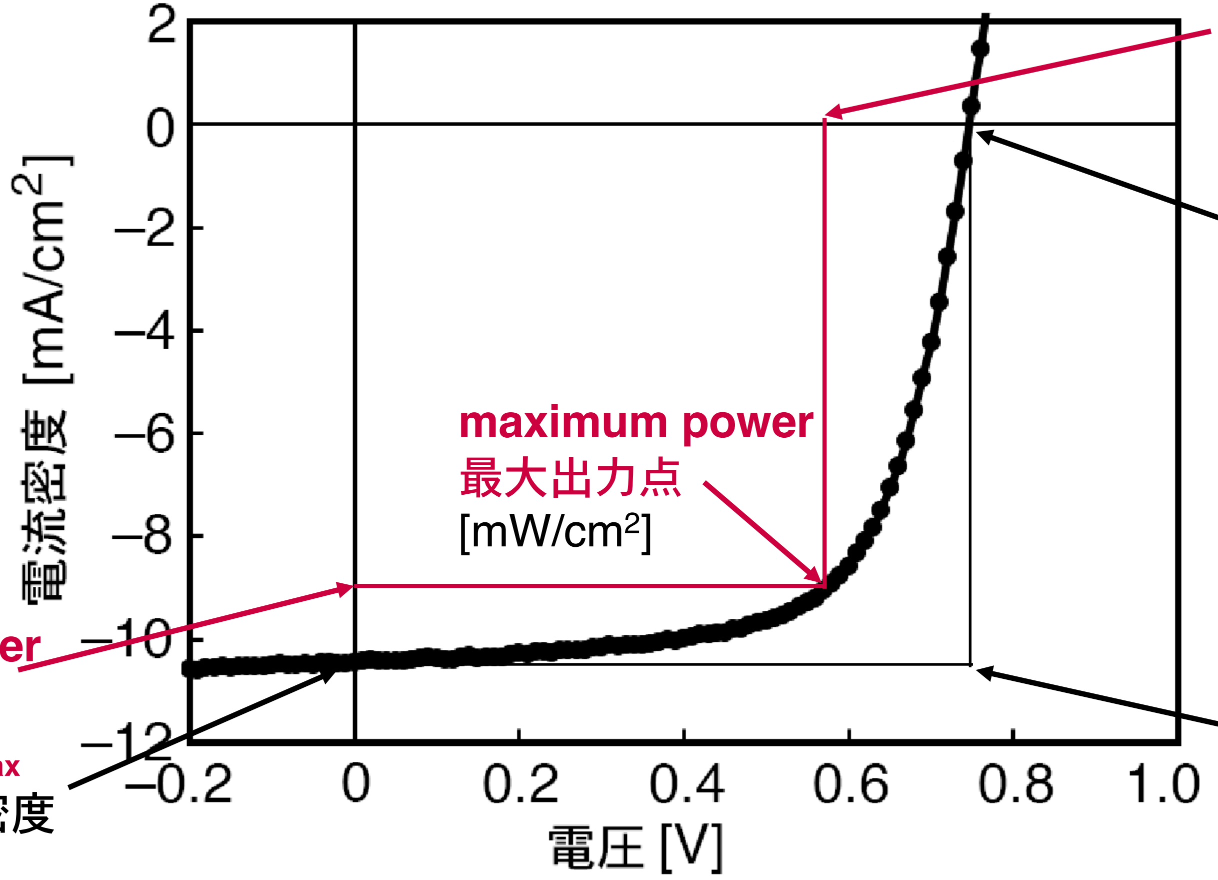
Open Circuit Voltage（V_{OC}: 開放電圧）[V]

太陽電池に何もつながない状態で、太陽電池の両端に発生する電圧

Short-Circuit Current Density（J_{SC}: 短絡電流密度）[mA/cm^2]

太陽電池の両端をショートさせた状態で、ショートして流れる電流
それを受光面積で割ったもの

Characteristic of Organic Photovoltaic Devices



FF (フィルファクタ，曲線因子) = $\dfrac{V_{max} \cdot J_{max}}{V_{OC} \cdot J_{SC}}$

PCE (エネルギー変換効率)
(power conversion efficiency)

$$= \frac{V_{max} \cdot J_{max} \ \text{(max. power [mW/cm}^2\text{])}}{\textbf{incident energy} \ \text{(100 [mW/cm}^2\text{])}} \times 100 = V_{OC} \cdot J_{SC} \cdot \mathrm{FF}$$

入射光のエネルギー

IQE and EQE

Internal Quantum efficiency (IQE), 内部量子効率

$$\textbf{IQE} = \frac{\textbf{number of electrons on external circuit}\text{, 外部回路を流れる電子数}}{\textbf{number of absorbed photons}\text{, 吸収した光子数}}$$

= exciton diffusion efficiency x charge transfer efficiency x charge collection efficiency
エキシトン拡散効率 x 電荷移動効率 x 電荷捕集効率

External Quantum efficiency (EQE), 外部量子効率

$$\textbf{EQE} = \frac{\textbf{number of electrons on external circuit}\text{, 外部回路を流れる電子数}}{\textbf{number of incident photons}\text{, 入射した光子数}}$$

= light absorption efficiency of incident light at active layer x IQE
活性層における入射光の吸収効率 x IQE

Measurement of EQE

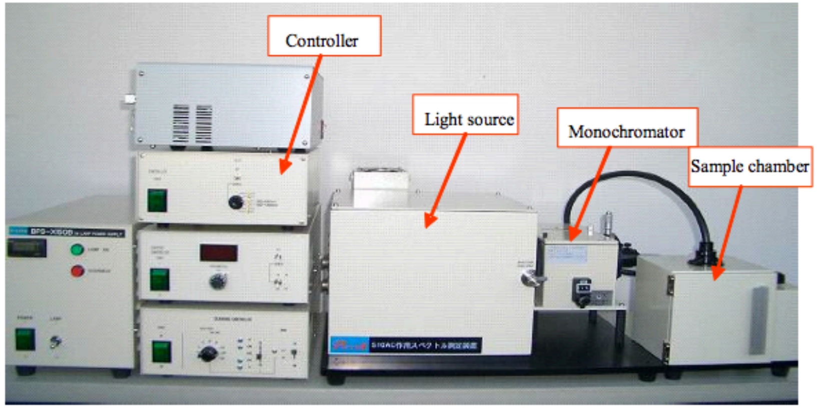
Incident Photon to Current Efficiency (IPCE)

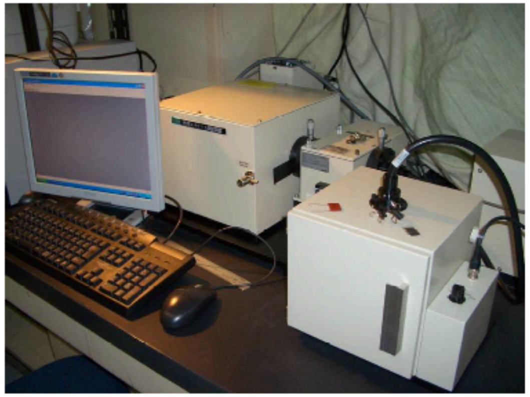
at certain wavelength irradiation

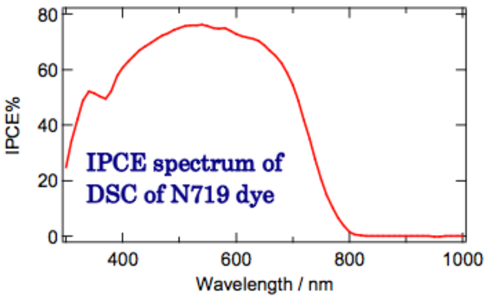
$$\mathrm{IPCE} = \frac{\text{number of electrons}}{\text{number of incident photons}} = \frac{J_{SC}}{P_{inc}} \, \frac{1240}{\lambda} \times 100$$

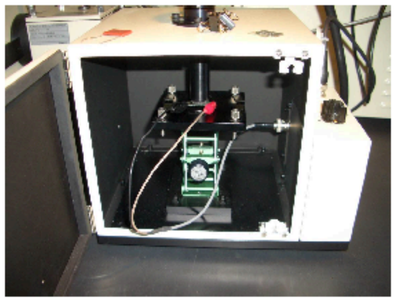
J_{SC}: 短絡電流密度 [A/cm^2]
λ: 波長 [nm]
P_{inc}: 入射光のパワー [W/cm^2]

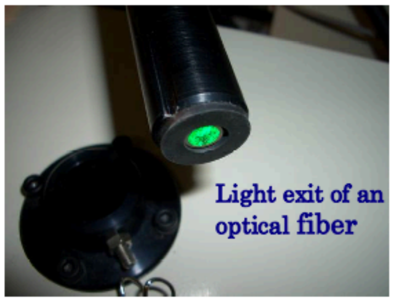
(1240を< 光の波長[nm] >で割ると，
<光のエネルギー [eV] >)



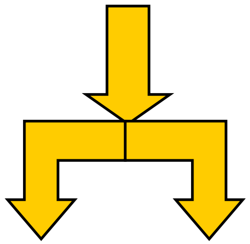








monochromic incident light



power measurement (w/ photon counter)

photo-current measure-ment

IPCE Spectrum