Solar Cells:

From DSSC to PSSC

Eric Wei-Guang Diau（刁維光）

Department of Applied Chemistry

Institute of Molecular Science

National Yang-Min Chiao-Tung University (NYCU)

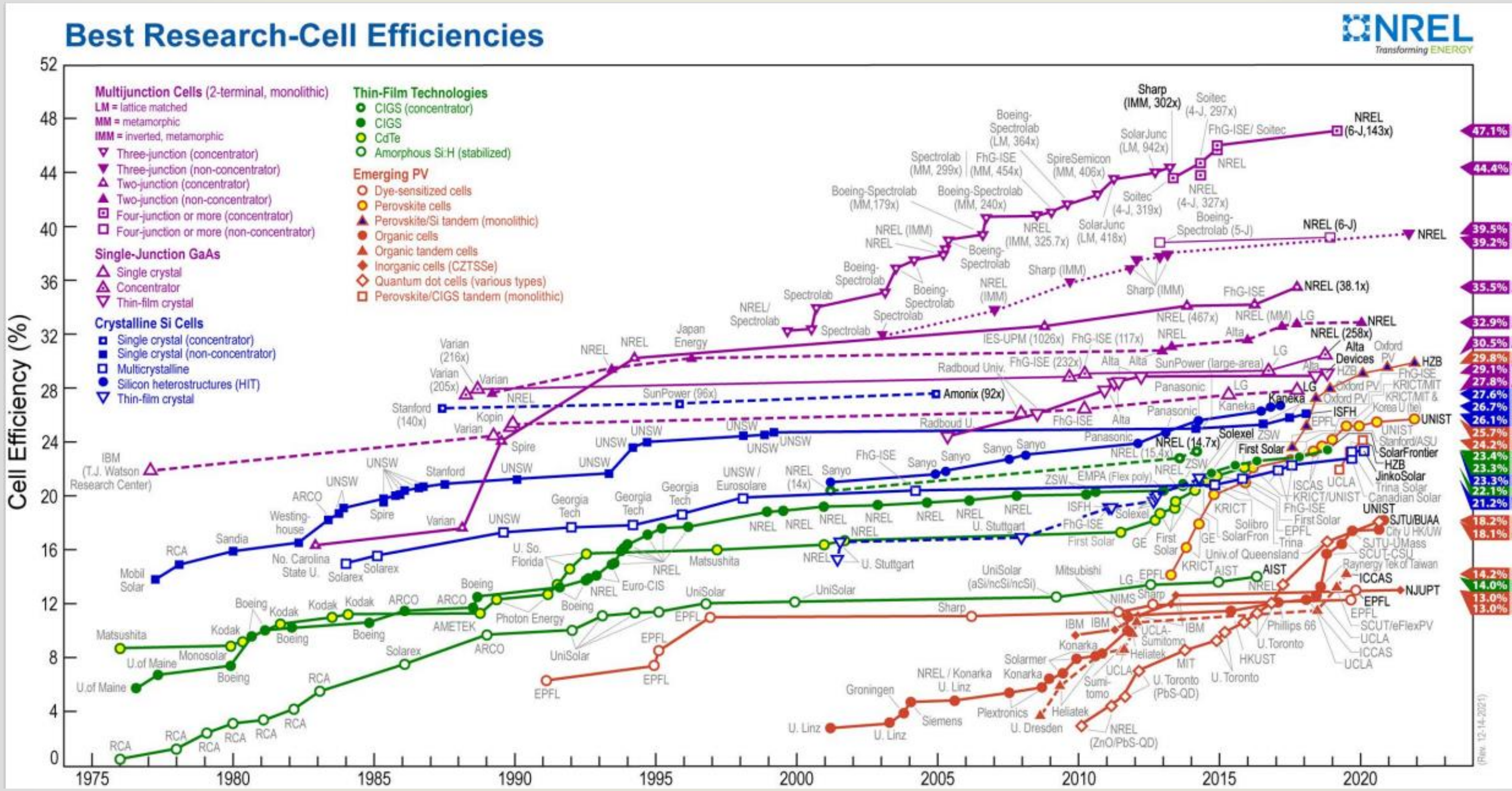
Hsinchu, Taiwan

Renewable Energy and Solar Cells

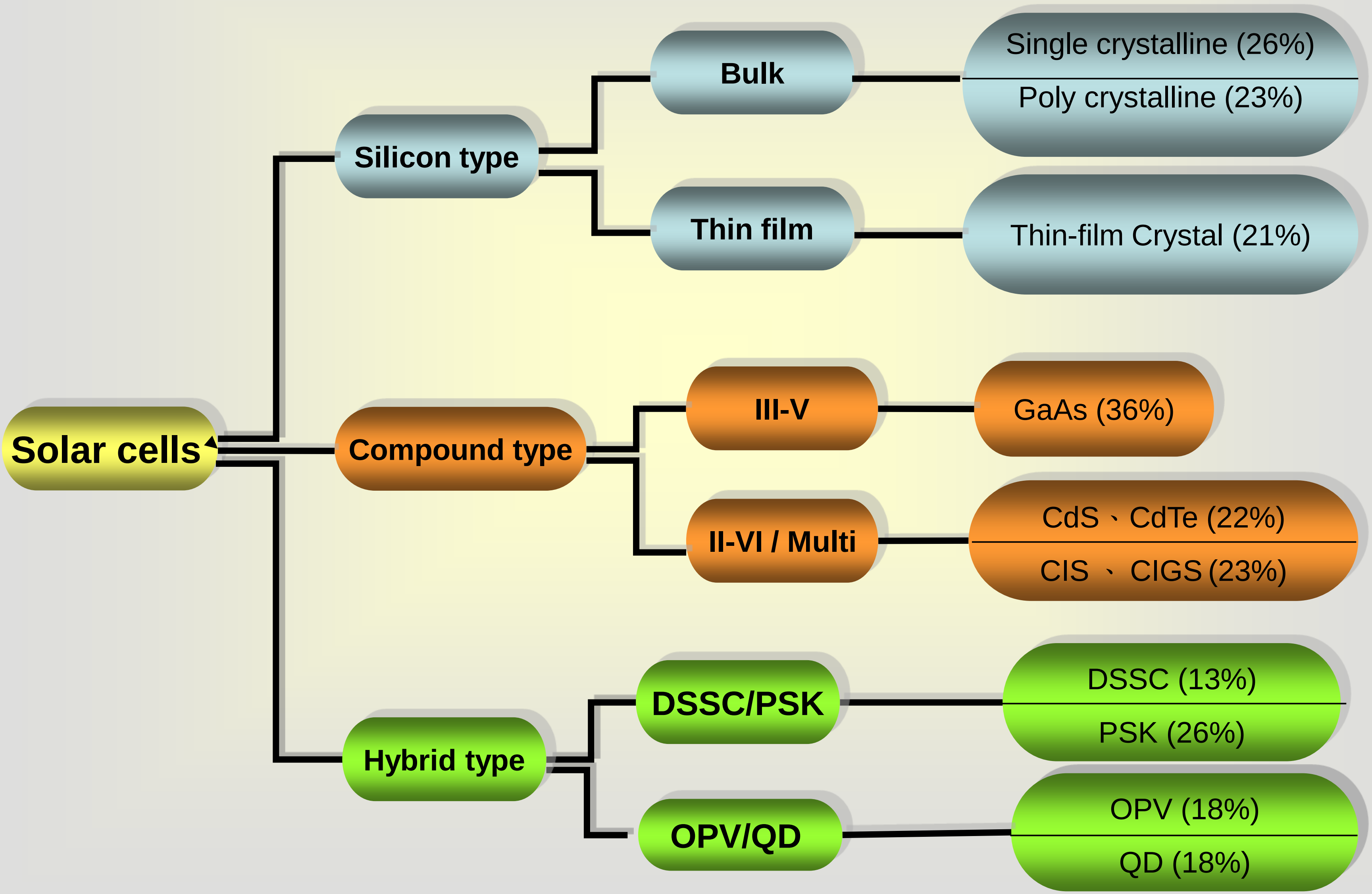
- Fossil fuels – coal, oil and gas – when burned to produce energy, cause harmful greenhouse gas emissions, such as carbon dioxide that make crisis of climate changes.
- Renewable energy is energy derived from natural sources that are replenished at a higher rate than they are consumed.
- Generating renewable energy creates far lower emissions than burning fossil fuels, and it is important to achieve the NET zero carbon policy in 2050.
- Renewable energies include solar energy (太陽能), wind energy (風力), geothermal energy (地熱), hydropower (水力), ocean energy (洋流) and bioenergy (生質能).
- Solar energy is the most abundant of all

Introduction to Solar Cells

Solar Cell Performance Progress up to 2022

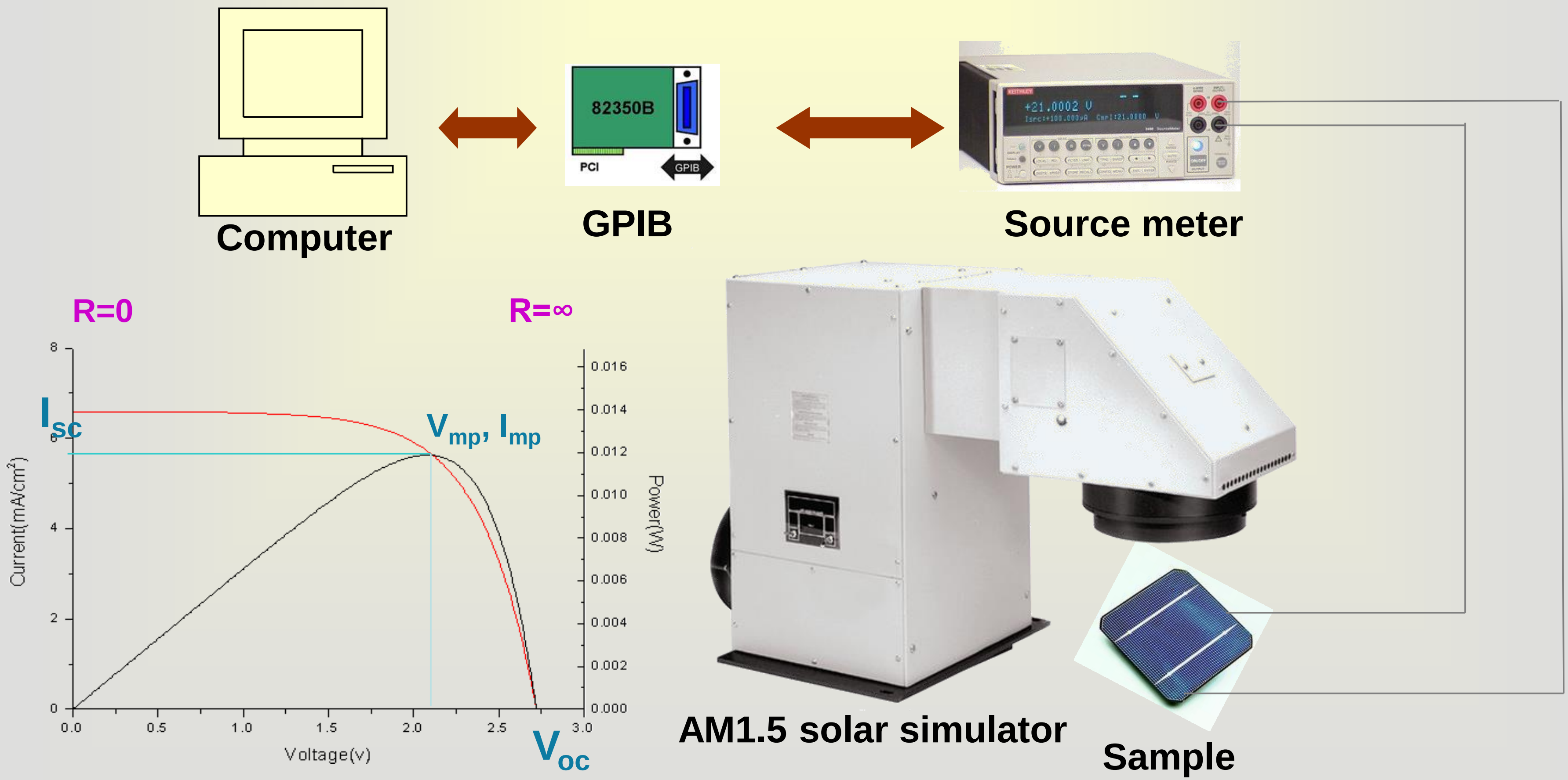


Classification of Common Solar Cells



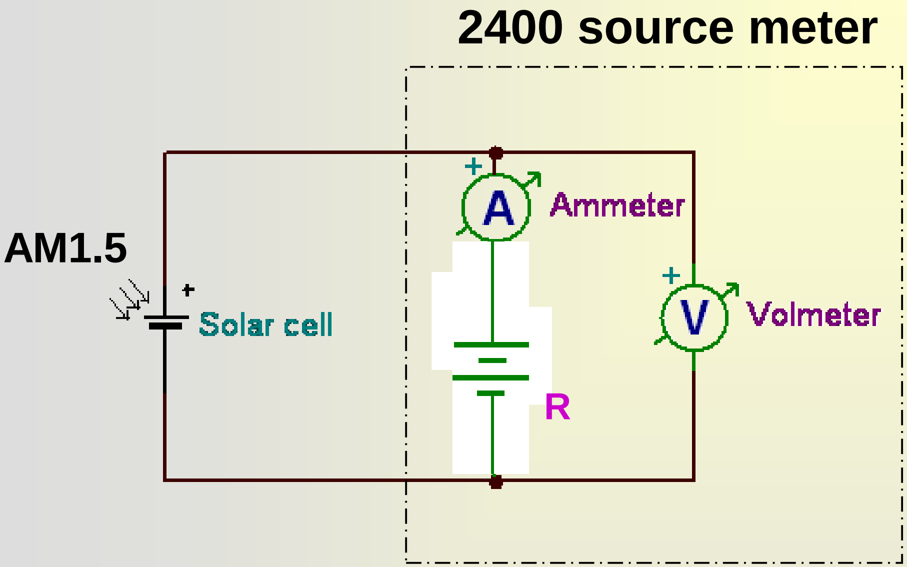
How to Determine the Performance of a Solar Cell

IV-curve Measurements

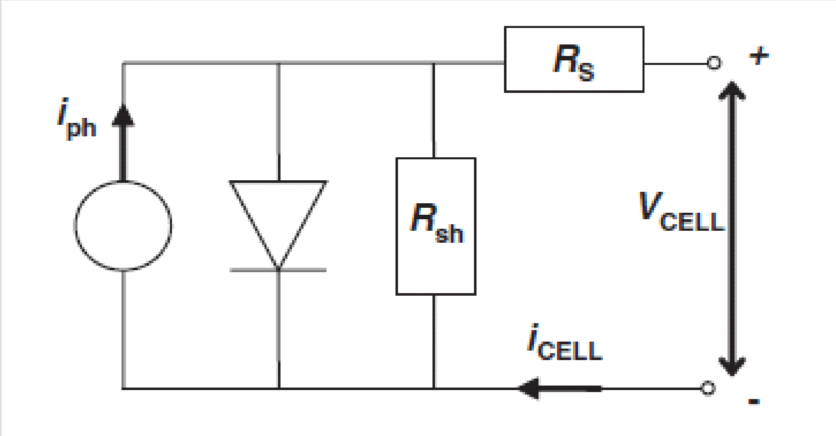


IV curve

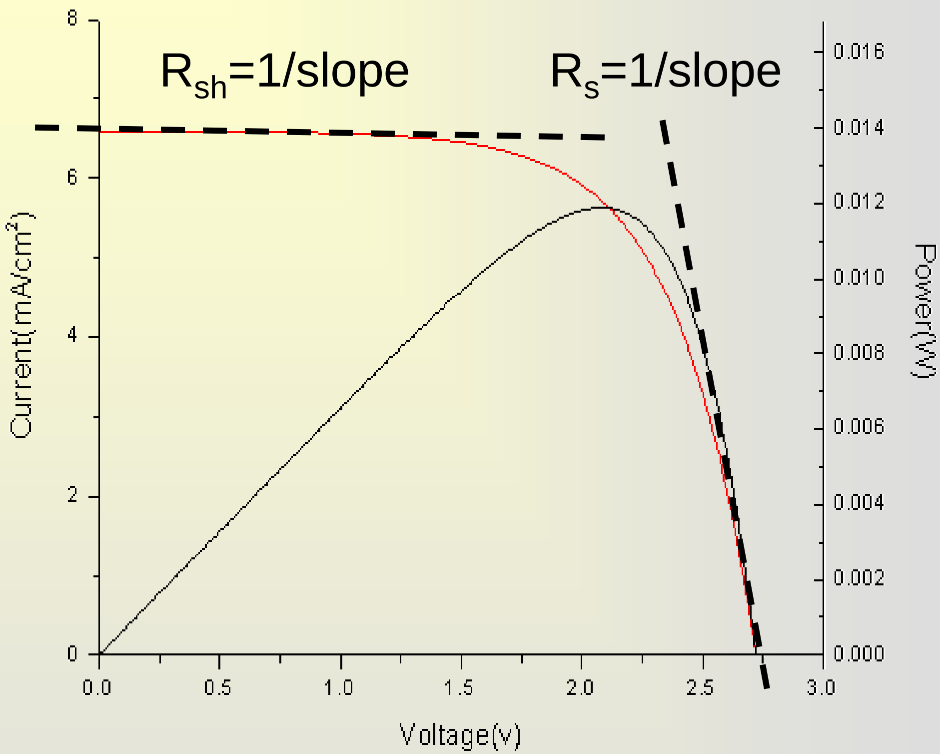
Principle of IV-curve measurements



Equivalent circuit



Basic diode equivalent circuit model of a solar cell.



R_s: Series resistance 串聯電阻

R_{sh}: Shunt resistance 並聯電阻

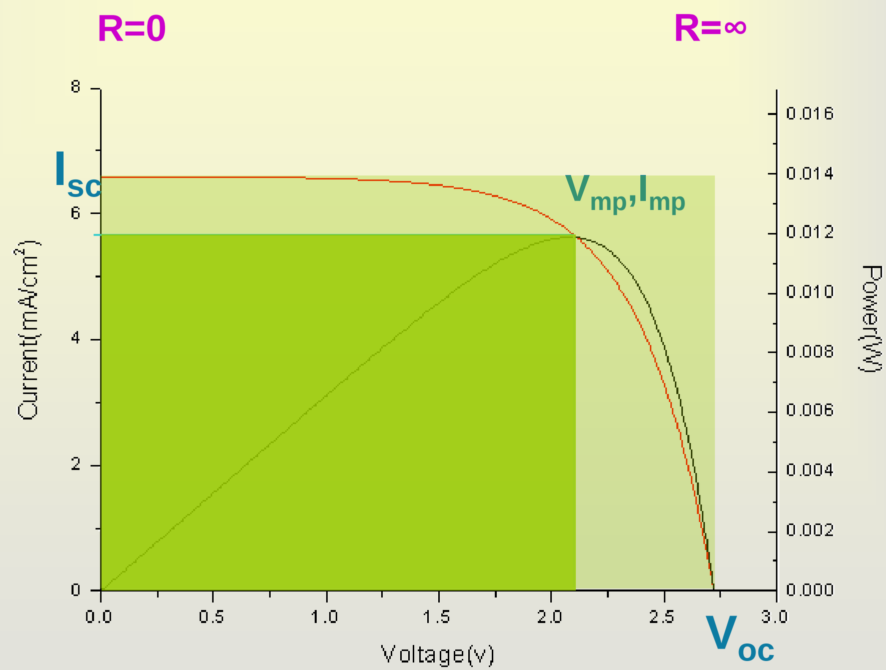
Power Conversion Efficiency (η)

V_{oc} I_{sc} $FF(fill\ factor)$

$\eta(conversion\ efficiency)$

$$FF = \frac{I_{mp} \cdot V_{mp}}{I_{sc} \cdot V_{oc}}$$

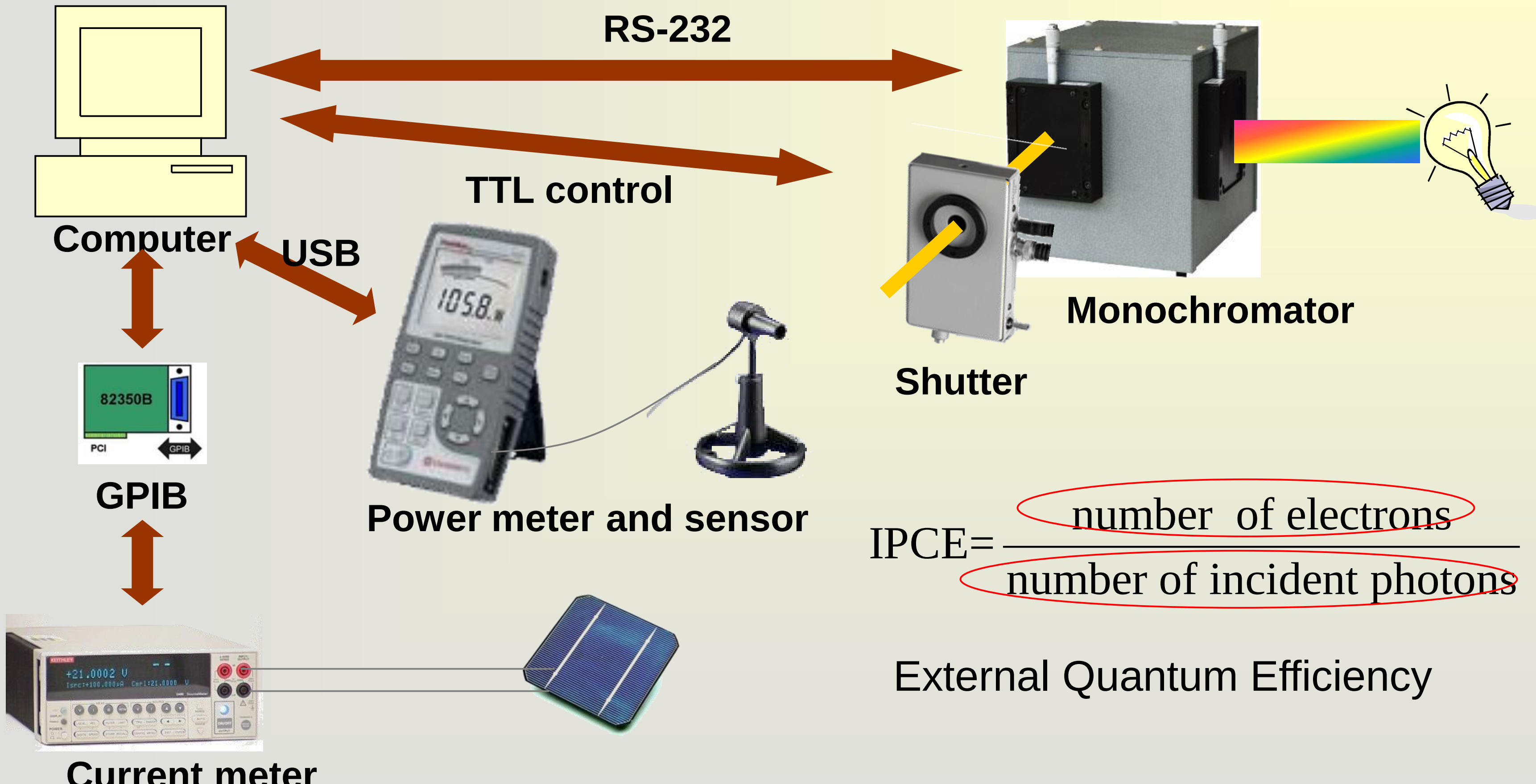
$$\eta = \frac{I_{mp} \cdot V_{mp}}{P_{in}} = \frac{I_{sc} \cdot V_{oc} \cdot FF}{P_{in}}$$



IV curve and electric power

IPCE measurements

(Incident monochromatic photon-to-current conversion efficiency)



$$\text{IPCE} = \frac{\text{number of electrons}}{\text{number of incident photons}}$$

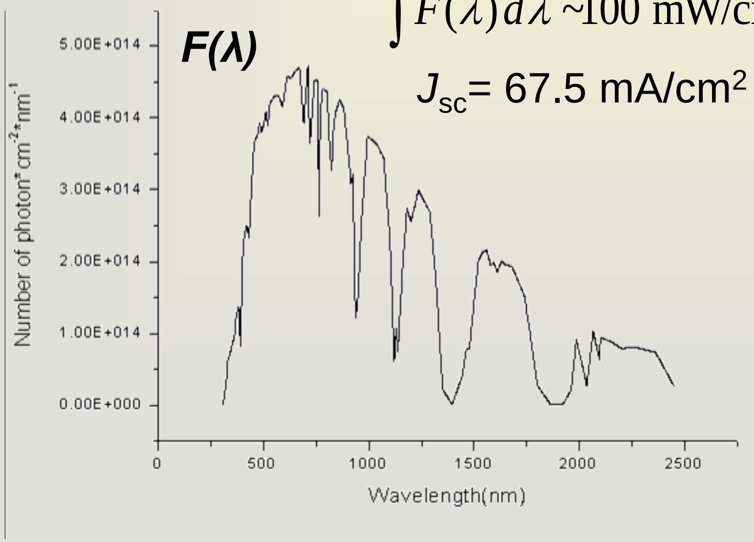
External Quantum Efficiency

$$IPCE(\lambda) = \frac{1240 \times I(mA \times cm^{-2})}{\lambda(nm) \times P(mW \times cm^{-2})} = LHE(\lambda) \times \Phi_{inj} \times \eta_{CC}$$

IPCE can be converted to J_{sc}

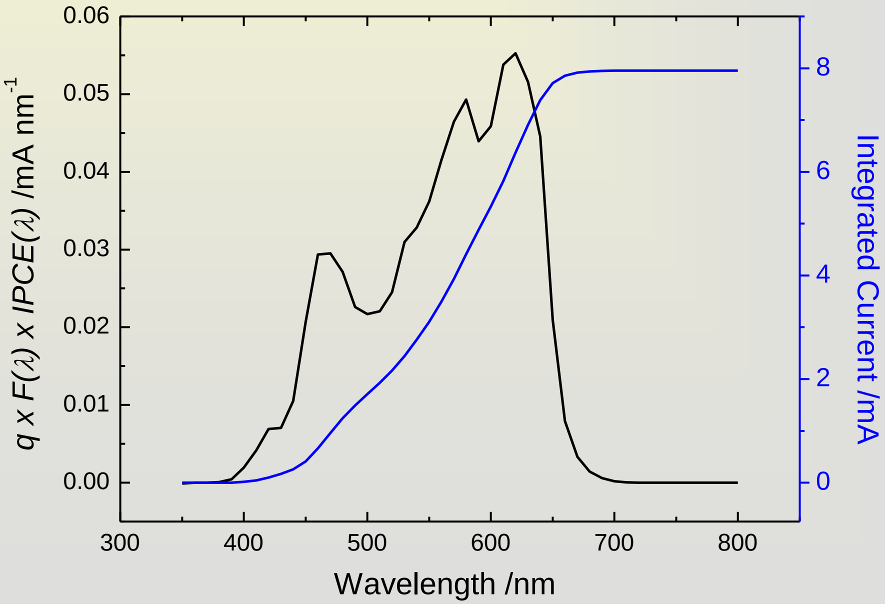
$$I_{sc} = \int q \cdot F(\lambda) \cdot IPCE(\lambda) \cdot d\lambda$$

q **: the electron charge**
F(λ) **: incident photon flux density**
IPCE(λ) **: incident photon to current efficiency**



$\int F(\lambda)\, d\lambda$ ~100 mW/cm^2

J_{sc}= 67.5 mA/cm^2

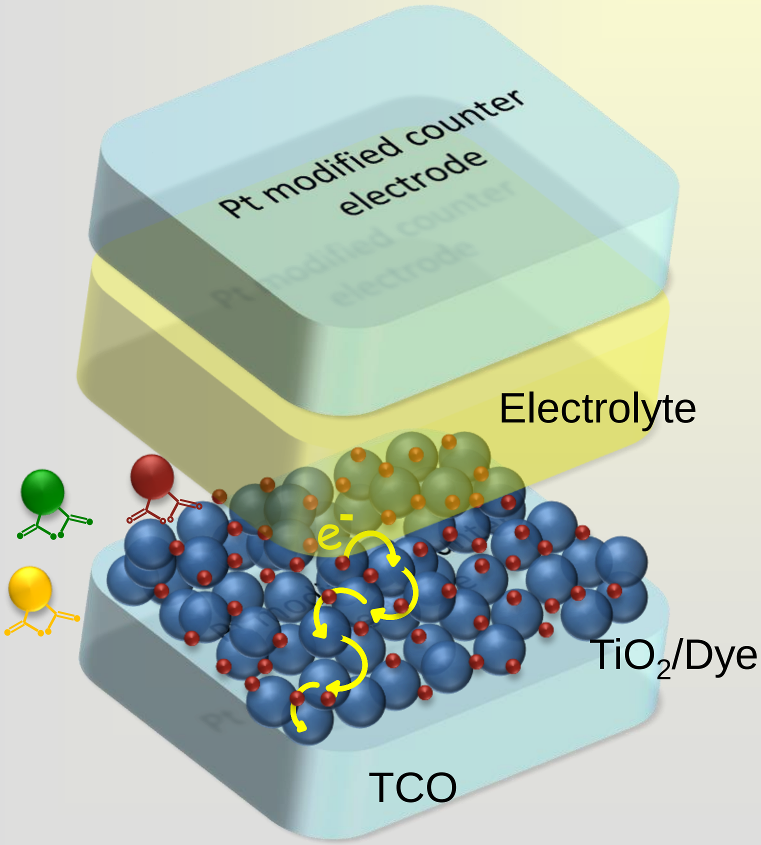


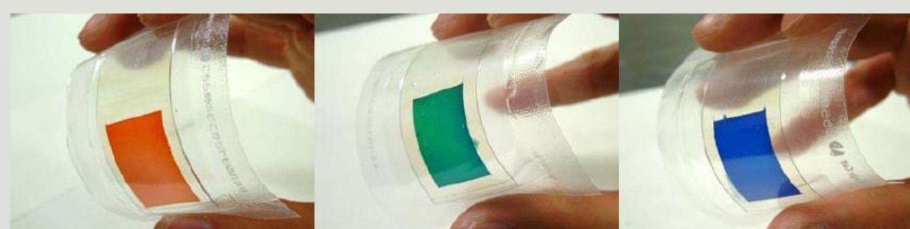
Dye-Sensitized Solar Cells (DSSC)

Why DSSC?

A new paradigm: Mesoscopic solar cells based on interpenetrating network (bulk) junctions

- Low fabrication cost
- Simple wet-chemistry processing
- Not sensitive to light level : indoor use
- Materials are environmental friendly & low cost
- ***Colorful & semi-transparent***
- Can be flexible





Dye sensitized nanocrystalline solar cells lead the new PV generation

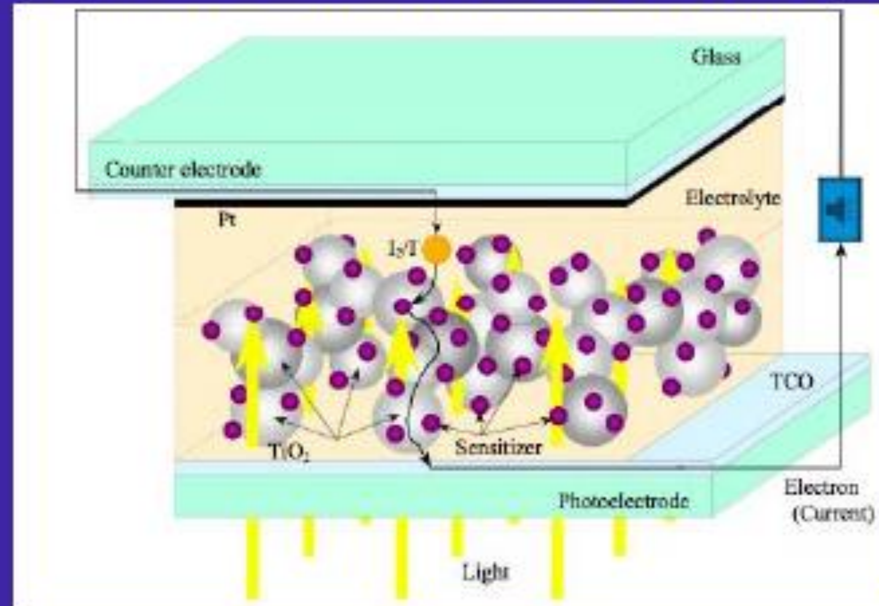
A low-cost, high-efficiency solar cell based on dye-sensitized colloidal TiO_2 films

Brian O'Regan* & Michael Grätzel†

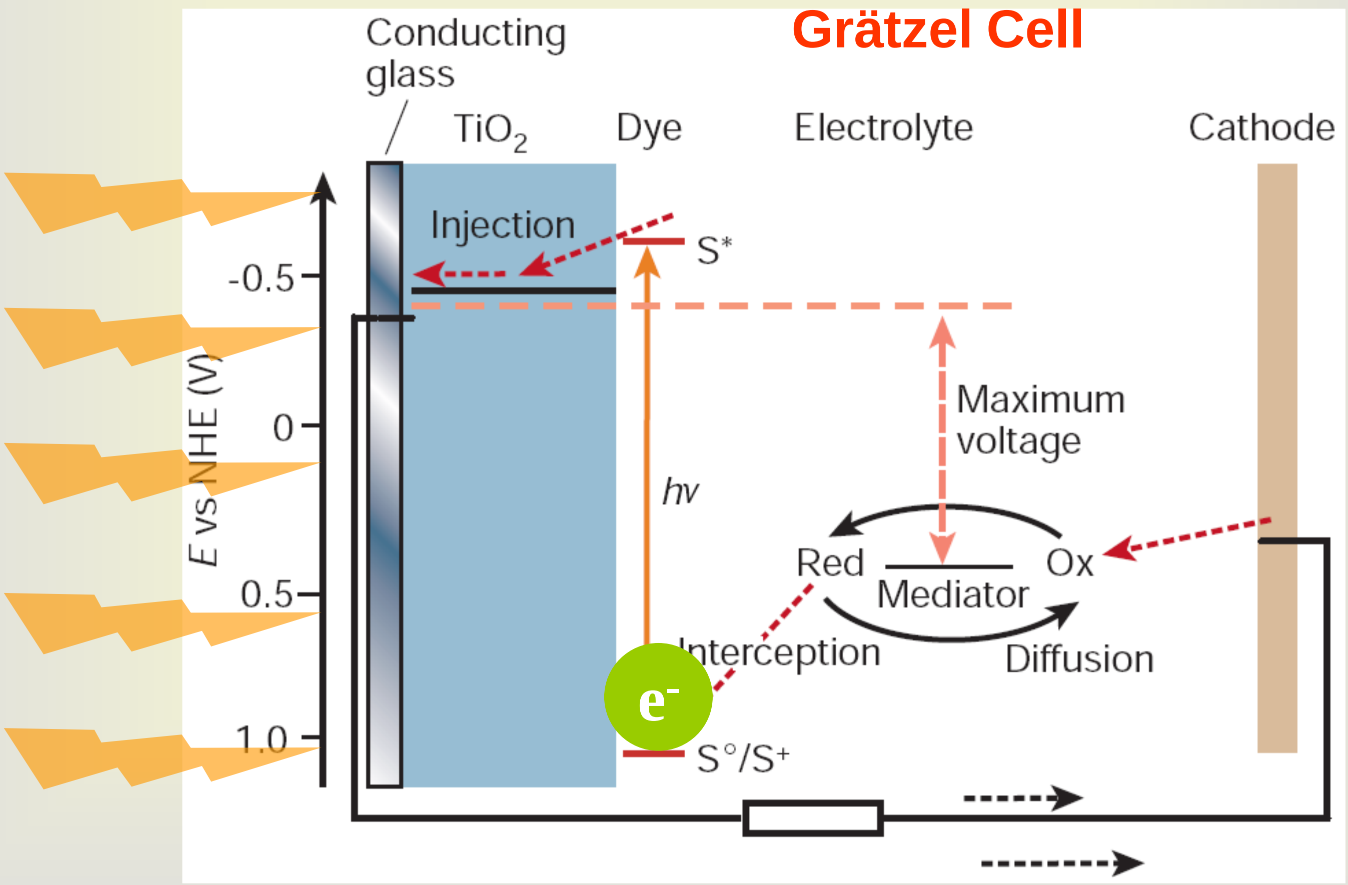
Institute of Physical Chemistry, Swiss Federal Institute of Technology, CH-1015 Lausanne, Switzerland

THE large-scale use of photovoltaic devices for electricity generation is prohibitively expensive at present: generation from existing commercial devices costs about ten times more than conventional methods[1]. Here we describe a photovoltaic cell, created from low- to medium-purity materials through low-cost processes, which exhibits a commercially realistic energy-conversion efficiency. The device is based on a 10-μm-thick, optically transparent film of titanium dioxide particles a few nanometres in size, coated with a monolayer of a charge-transfer dye to sensitize the film for light harvesting. Because of the high surface area of the semiconductor film and the ideal spectral characteristics of the dye, the device harvests a high proportion of the incident solar energy flux (46%) and shows exceptionally high efficiencies for the conversion of incident photons to electrical current (more than 80%). The overall light-to-electric energy conversion yield is 7.1–7.9% in simulated solar light and 12% in diffuse daylight. The large current densities (greater than 12 mA cm^{-2}) and exceptional stability (sustaining at least five million turnovers without decomposition), as well as the low cost, make practical applications feasible.

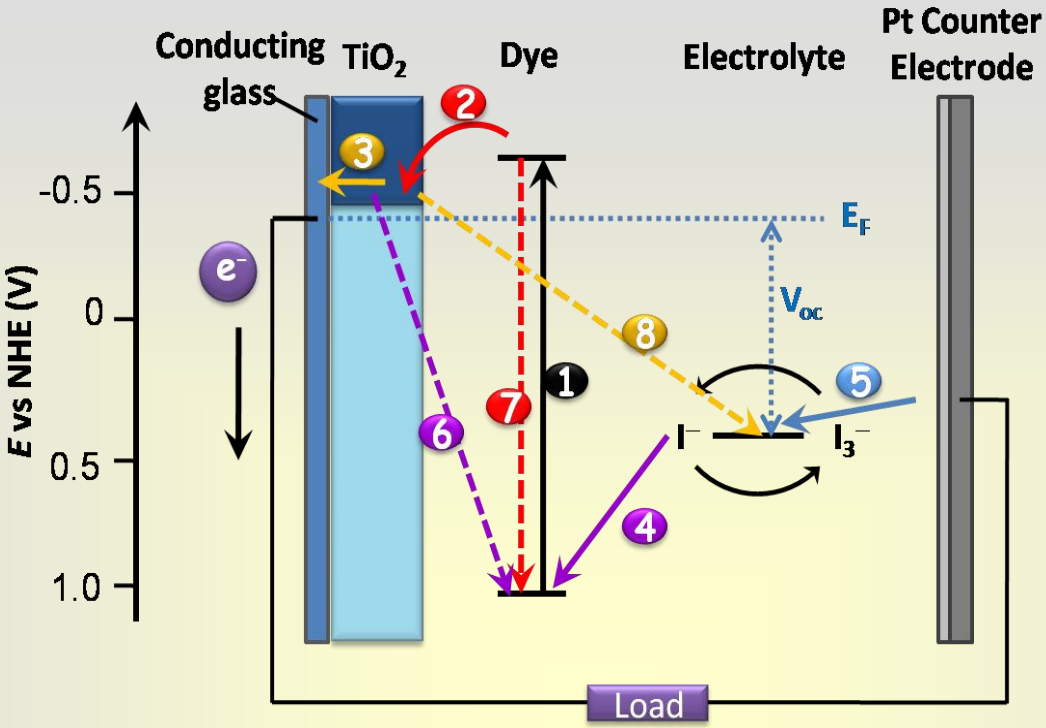
* Present address: Department of Chemistry, University of Washington, Seattle, Washington 98195, USA.
† To whom correspondence should be addressed.



DSSC Working Principle



Grätzel, M. *Nature* **2001**, *414*, 338-344



Anode

Cathode

❶ Photoexciation

Dye + hν → Dye*

❷ Electron injection

Dye* → Dye^+ + $e^-(TiO_2)$

❸ Electron diffusion

❹ Dye regeneration

2Dye+ + $3I^-$ → 2Dye + I_3^-

❺ Redox couple regeneration

I_3^- + 2e– → $3I^-$

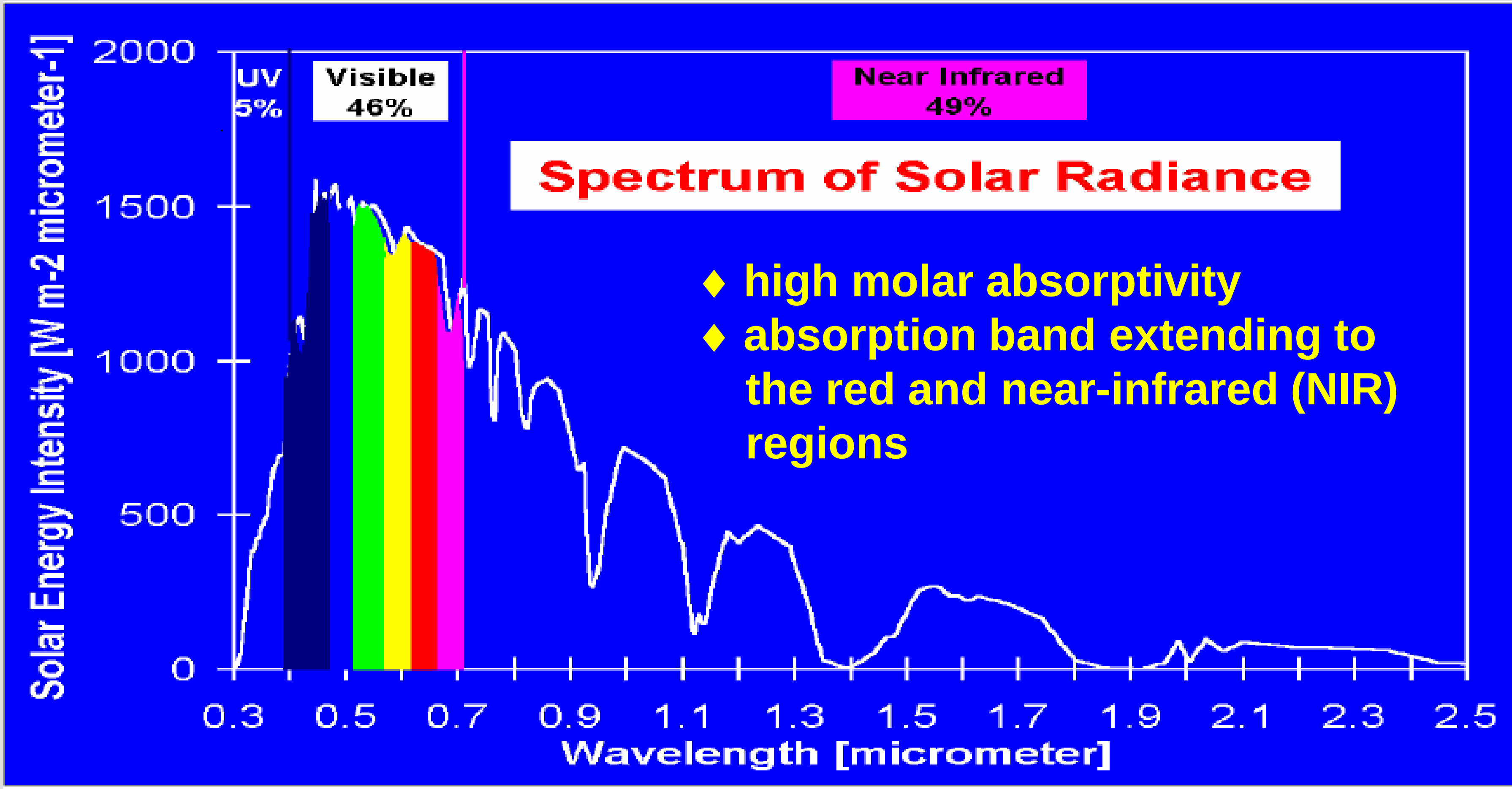
❻ charge recombination

❼ non-radiative relaxation

❽ back electron transfer

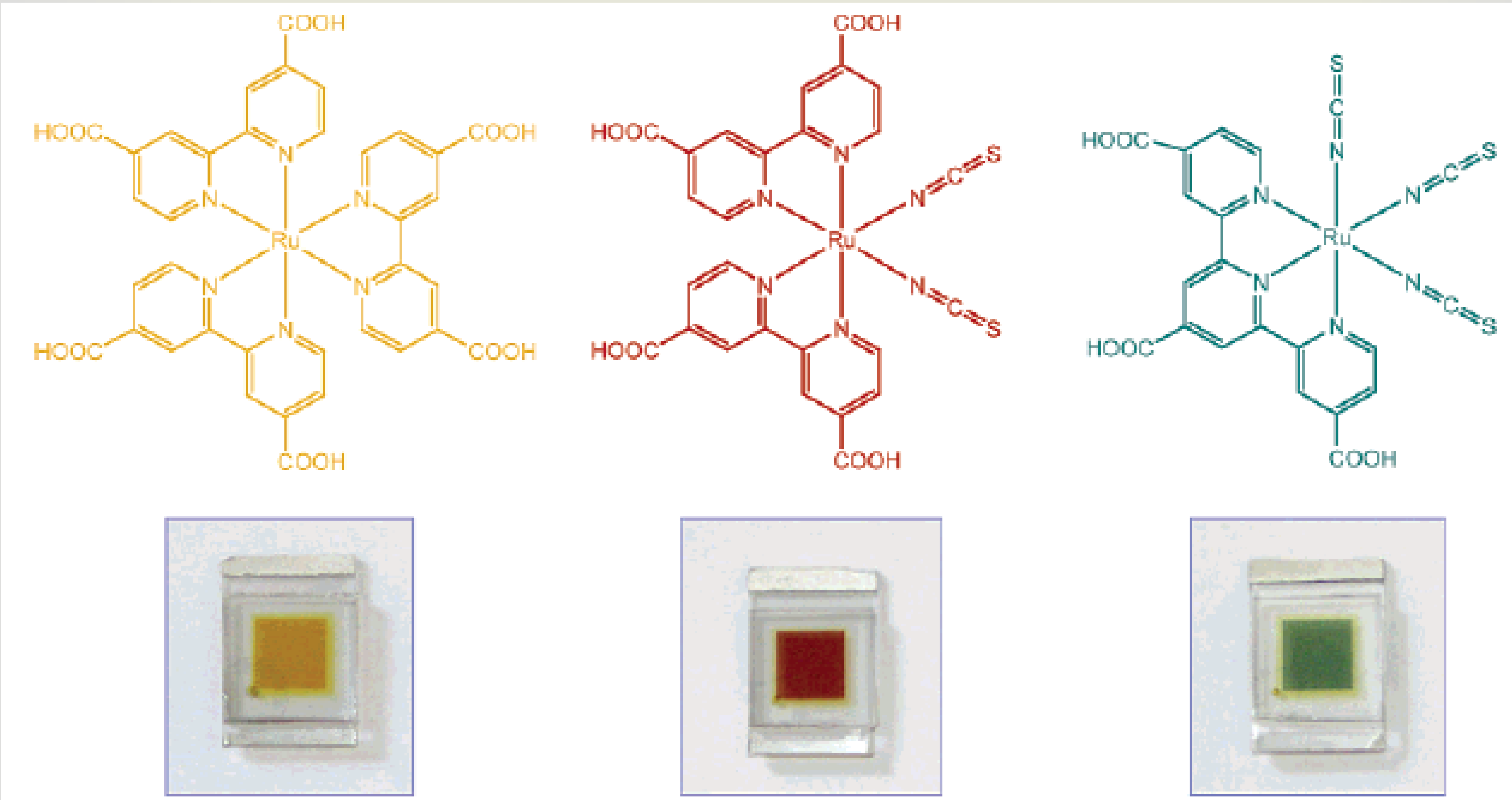
$2e^-(TiO_2) + I_3^- \rightarrow 3I^-$

Solar Spectrum



- ♦ high molar absorptivity
- ♦ absorption band extending to the red and near-infrared (NIR) regions

Traditional Ru-complex Sensitizers in DSSC



Ru(dcbpy)$_3$

N3

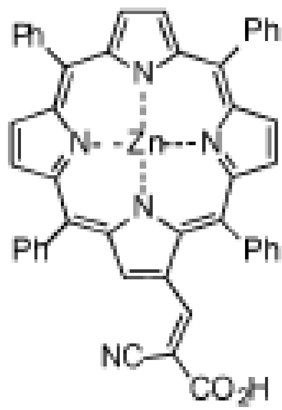
N719
(2COO$^-$TBA$^+$)

Black dye
(2COO$^-$TBA$^+$)

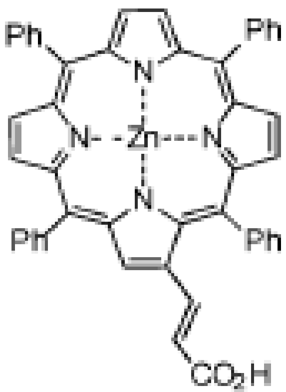
Grätzel, M. *Inorg. Chem.* **2005**, *44*, 6841-6851

Porphyrin-Sensitized Solar Cells (PSSC)

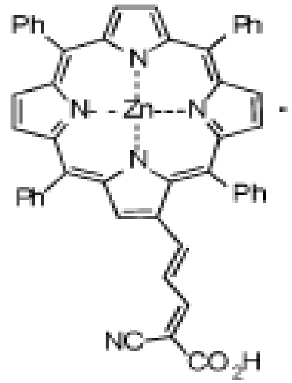
Using Porphyrins as Potential Sensitizers



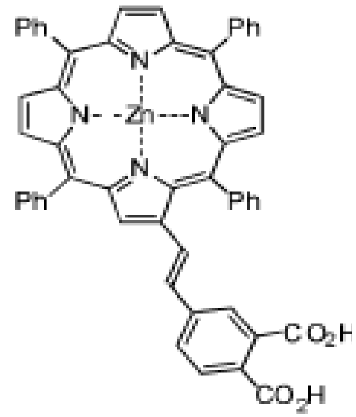
Zn-3



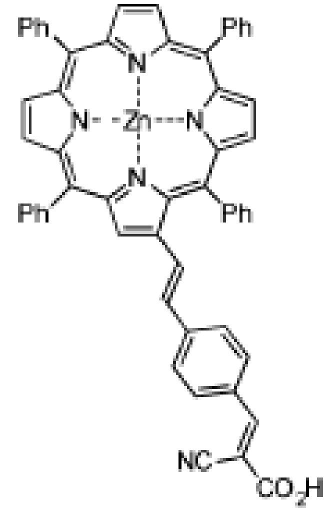
Zn-5



Zn-8



Zn-11



Zn-13

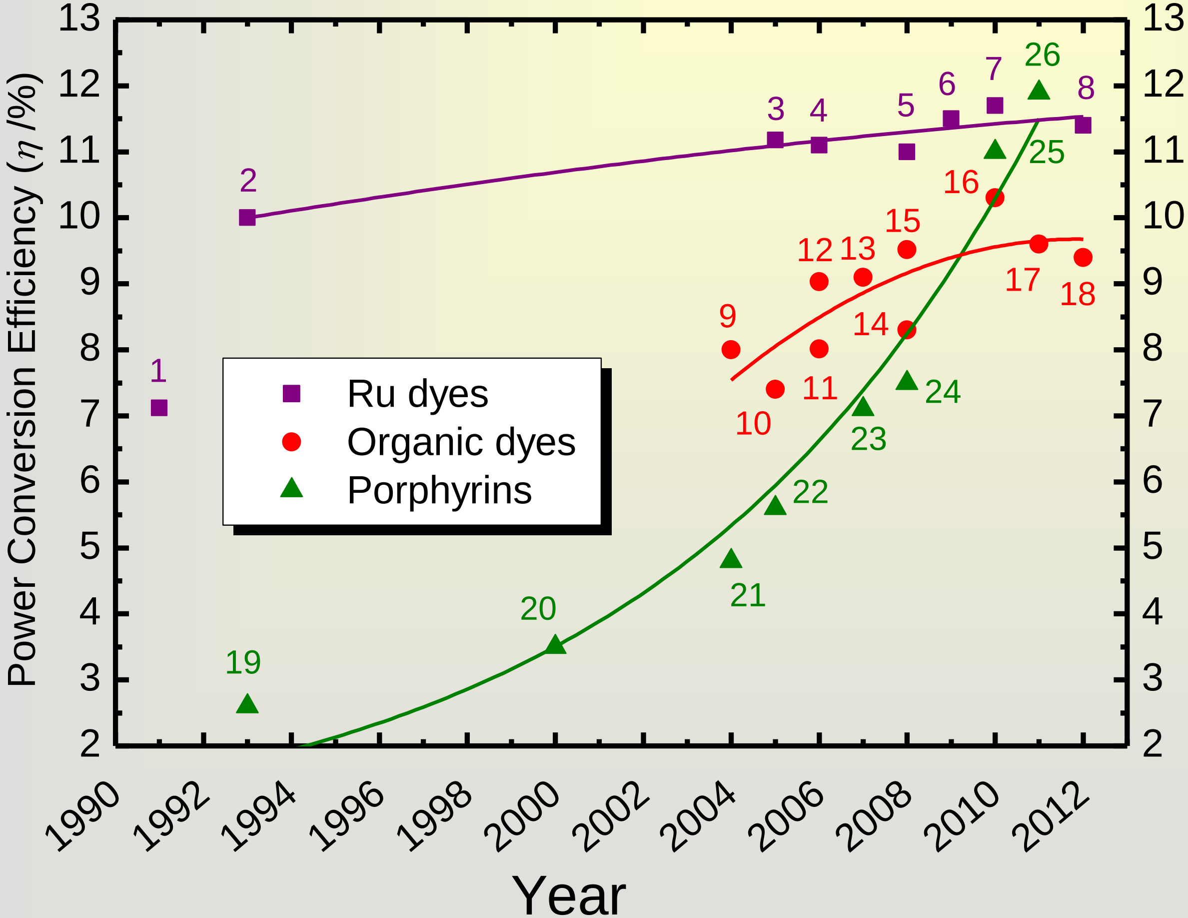
metalloporphyrin	V_{oc}, mV	J_{sc}, mA/cm^2	η, %
Zn-3	566	13.5	5.2
Zn-5	555	10.9	4.0
Zn-8	535	11.4	4.0
Zn-11	509	7.2	2.4
Zn-13	530	11.0	3.7

Electrolyte : 0.6 M *N*-methyl-*N*-butyl imidazolium iodide(BMII), 0.05 M iodine, 0.1 M LiI, 0.05 M*tert*-butylpyridine in a 15/85 (v/v) mixture of valeronitrile and acetonitrile.

J. Phys. Chem. B, **2005,** *109*, 15405

From Officer's Lab in NZ and Grätzel's Lab in Switzerland

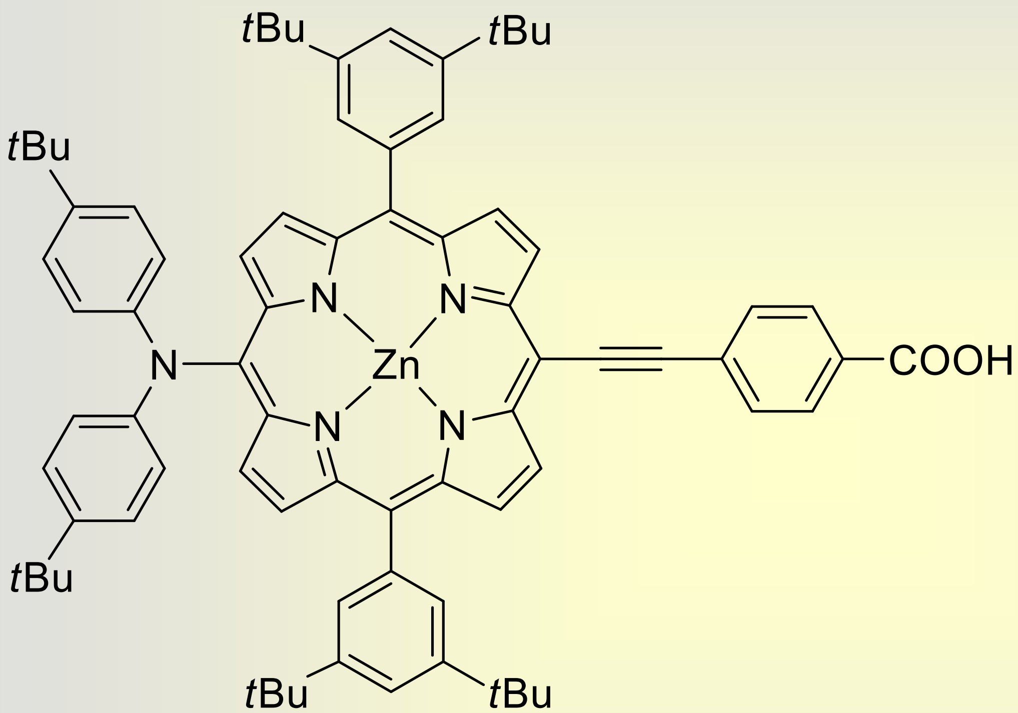
Progress on Photosensitizers

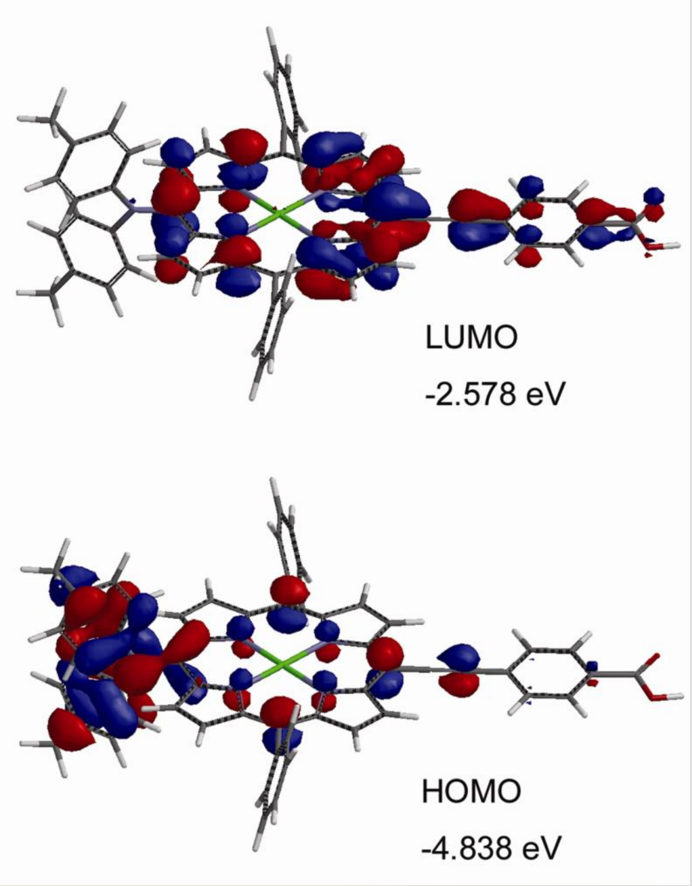


(1) trinuclear Ru dye,[1] (2) N3,[2] (3) N3,[6] (4) N719,[7] (5) C101,[25] (6) CYC-B11,[8] (7) **C106**,[10] (8) black dye,[11]
(9) indoline dye,[26] (10) NKX-2677,[27] (11) JK2,[28] (12) D149,[29] (13) TA-St-CA,[30] (14) MK-2,[31] (15) D205,[32] (16) **C219**,[33] (17) Y123,[34] (18) C218,[35]
(19) Cu-2-a-oxymesoisochlorin,[36] (20) TCPP,[37] (21) Zn-1a,[38] (22) Zn-3,[39] (23) GD2,[40] (24) tda-2b-bd-Zn,[41] (25) YD-2,[42] (26) **YD2-oC8**.[24]

Chem. Soc. Rev. **2013**, *42*, 291-304.

Design of Highly Efficient Green Dye (YD1)





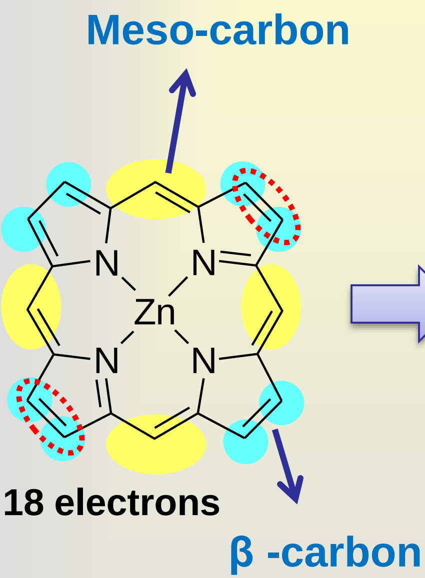
Donor (D) | Porphyrin core (P) | Bridge (B) | Anchor (A)

B3LYP/6-31G(d)

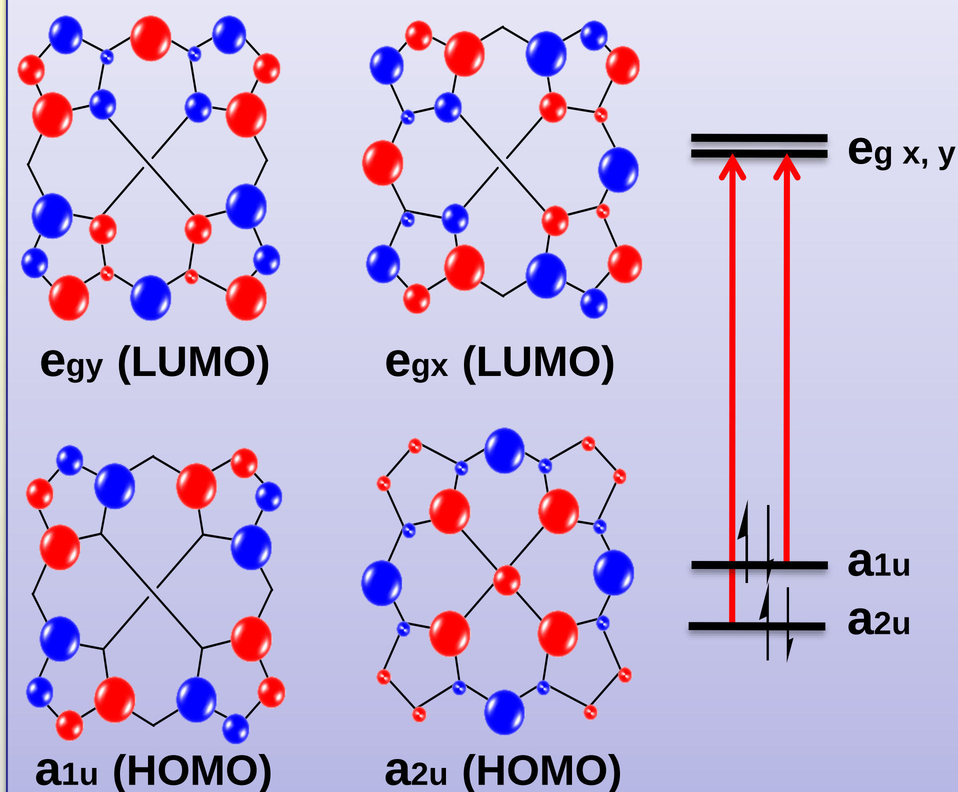
η= 6.0 % (~98 % of N3 dye)

Chem. Eur. J. **2009**, 115, 1403-1412.

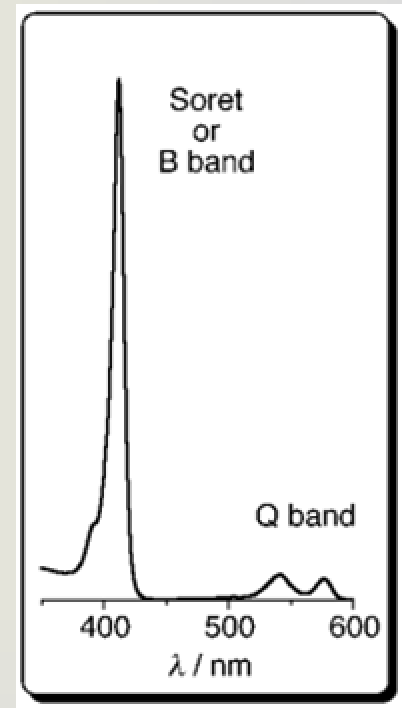
Gouterman Four Orbital Model



Molecular Structure

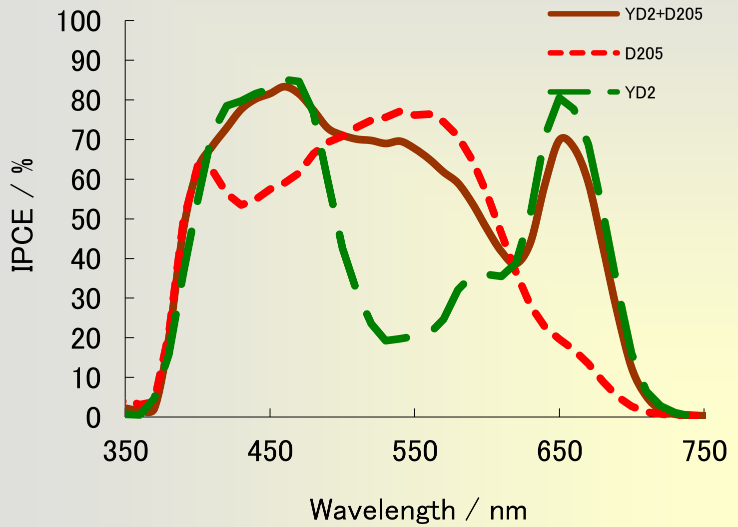


Molecular Orbitals (D_{4h})

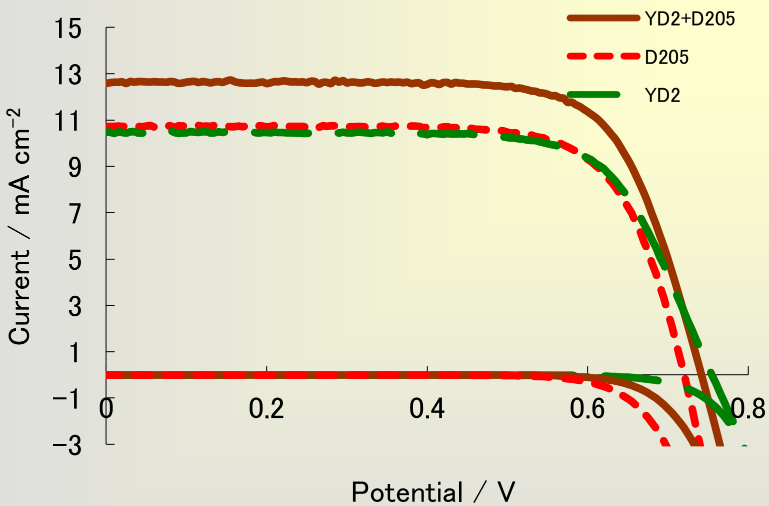


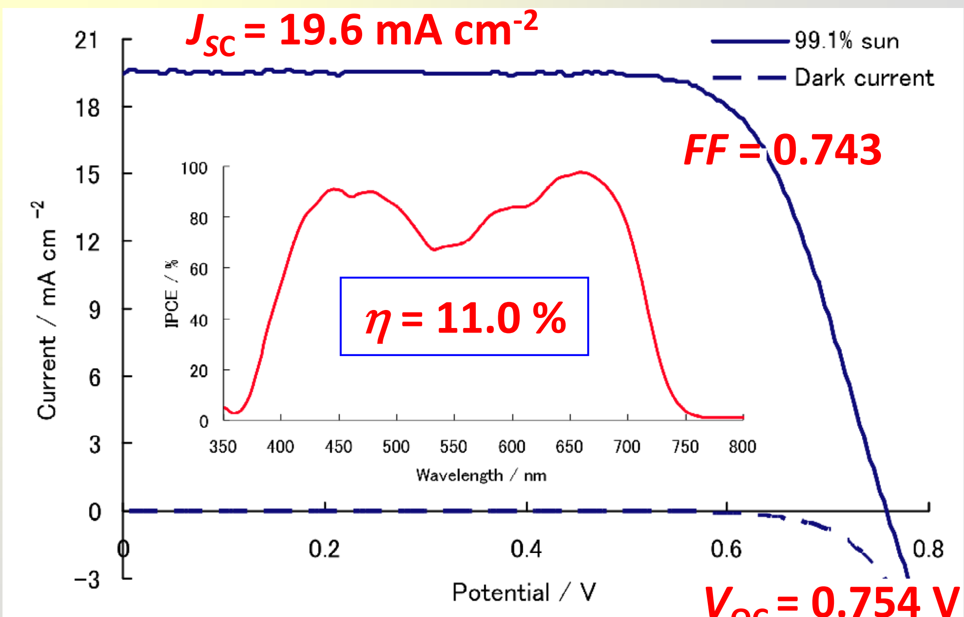
Absorption Spectrum

YD2-based DSSC Has Achieved 11 %



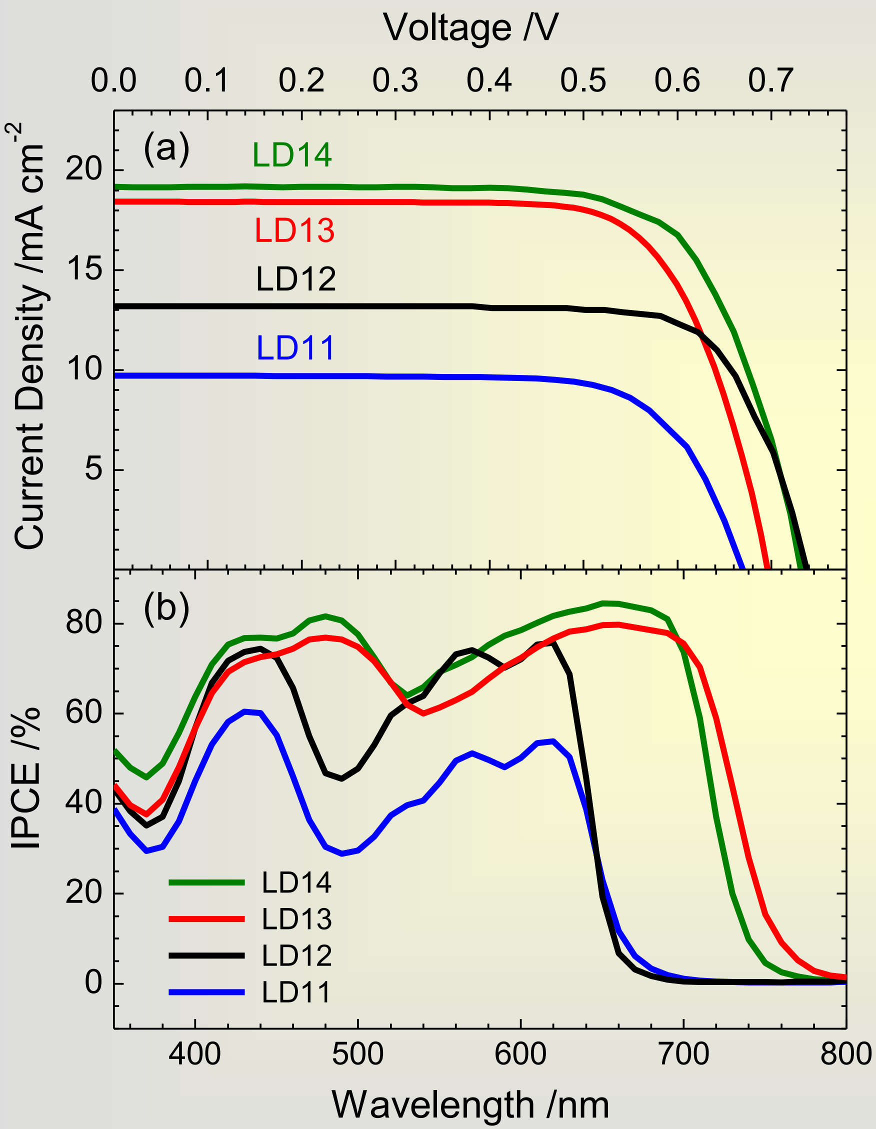
Sensitizers	V_{OC} /mV	J_{SC} /mA cm^{-2}	FF / %	η / %
YD-2+D-205	742	12.6	73.2	6.9
D-205	720	10.8	73.2	5.7
YD-2	755	10.5	71.2	5.6



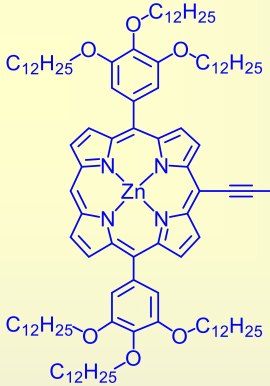


Angew. Chem. Int. Ed. **2010**, *49*, 6646-6649.

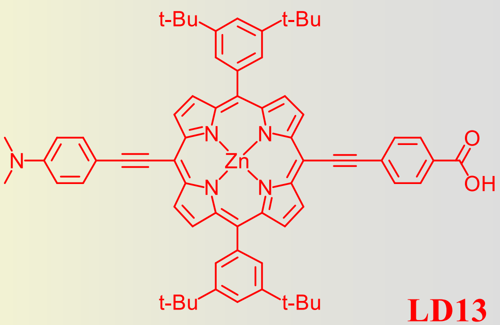
Photovoltaic Performance of LD11-LD14



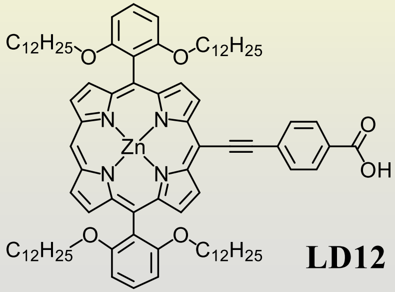
Dye	J_{SC} /mA cm^{-2}	V_{OC} /mV	FF	η /%
LD11	9.735	674	0.728	4.78
LD12	13.235	741	0.758	7.43
LD13	18.438	697	0.727	9.34
LD14	19.167	736	0.721	10.17



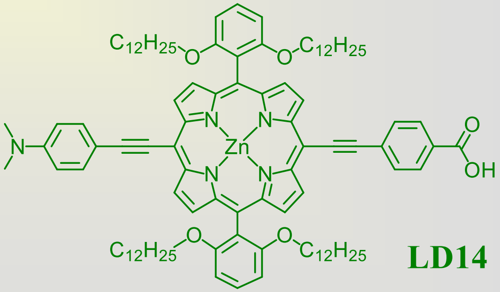
LD11



LD13



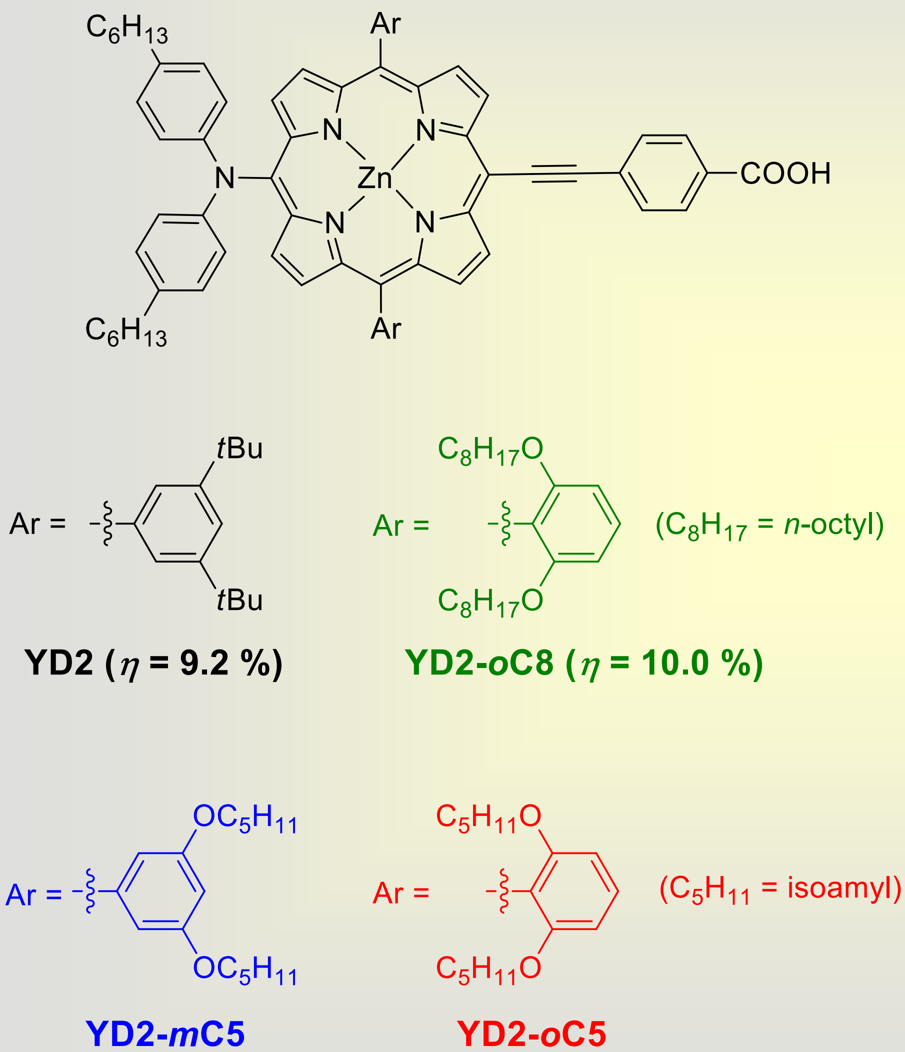
LD12

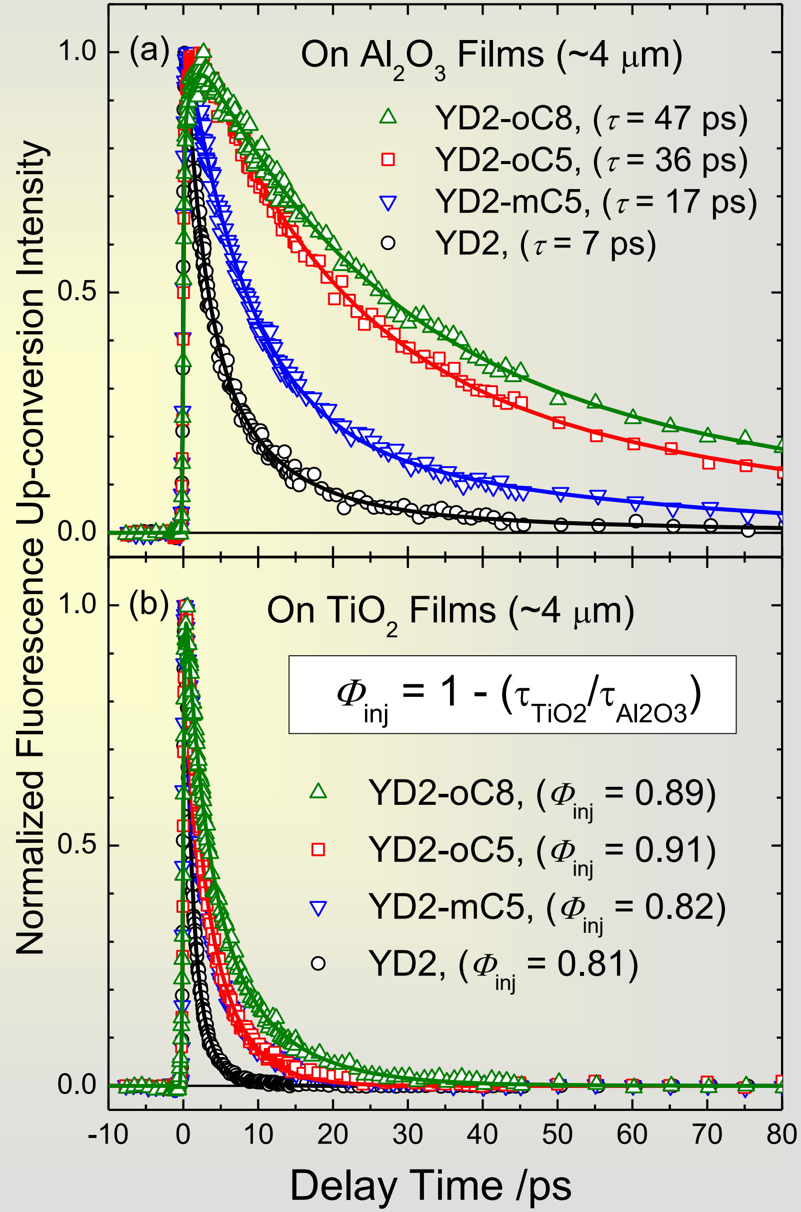


LD14

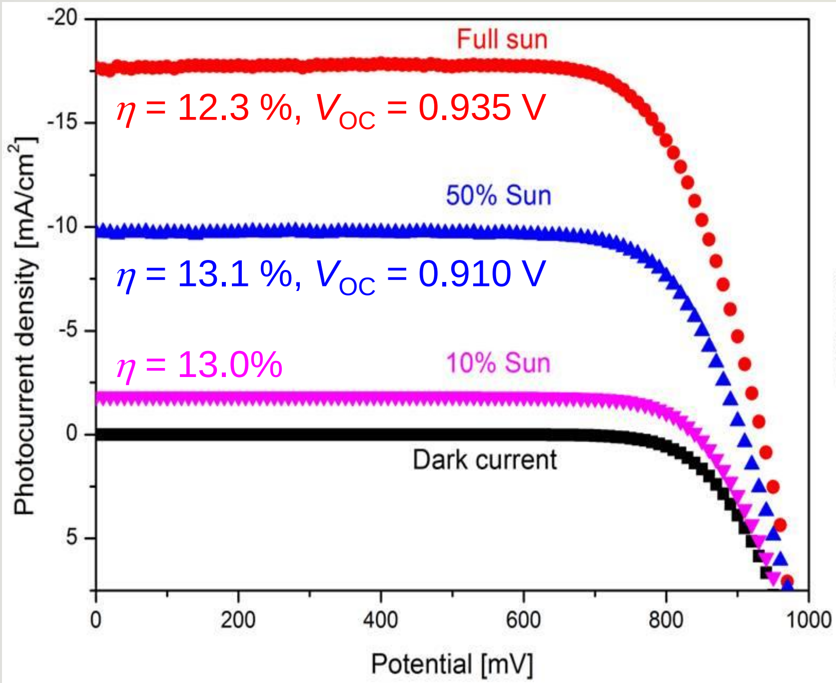
Chem Comm **2011**, *47*, 8910-8912.

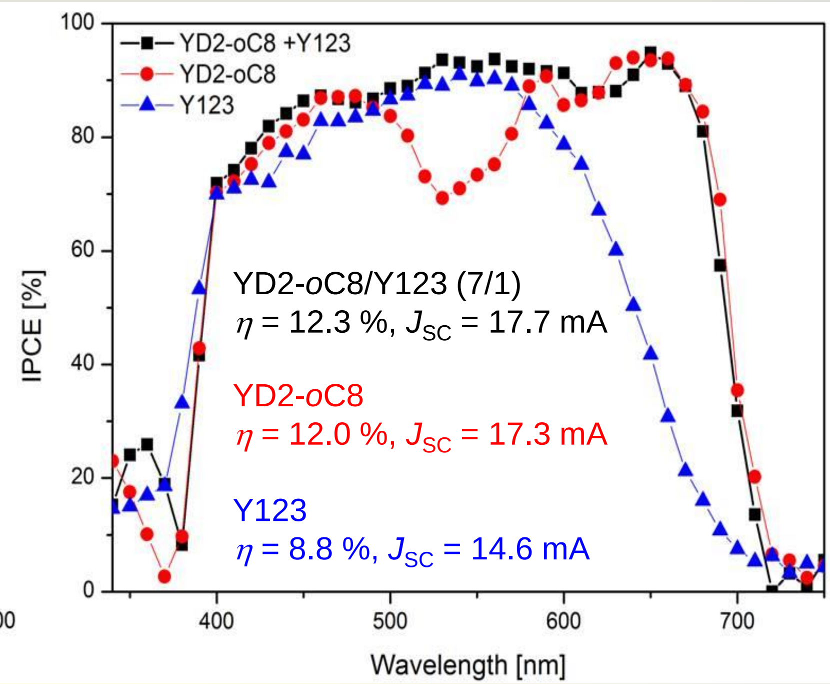
Electron Injections forYD2-series Porphyrins





A Promising PSSC (YD2-oC8) with PCE 12.3 %



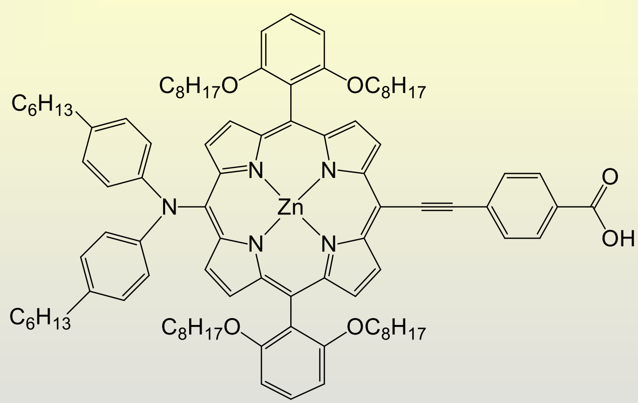


Michael Grätzel

(EPFL)

Chen-Yu Yeh

(NCHU, Taiwan)



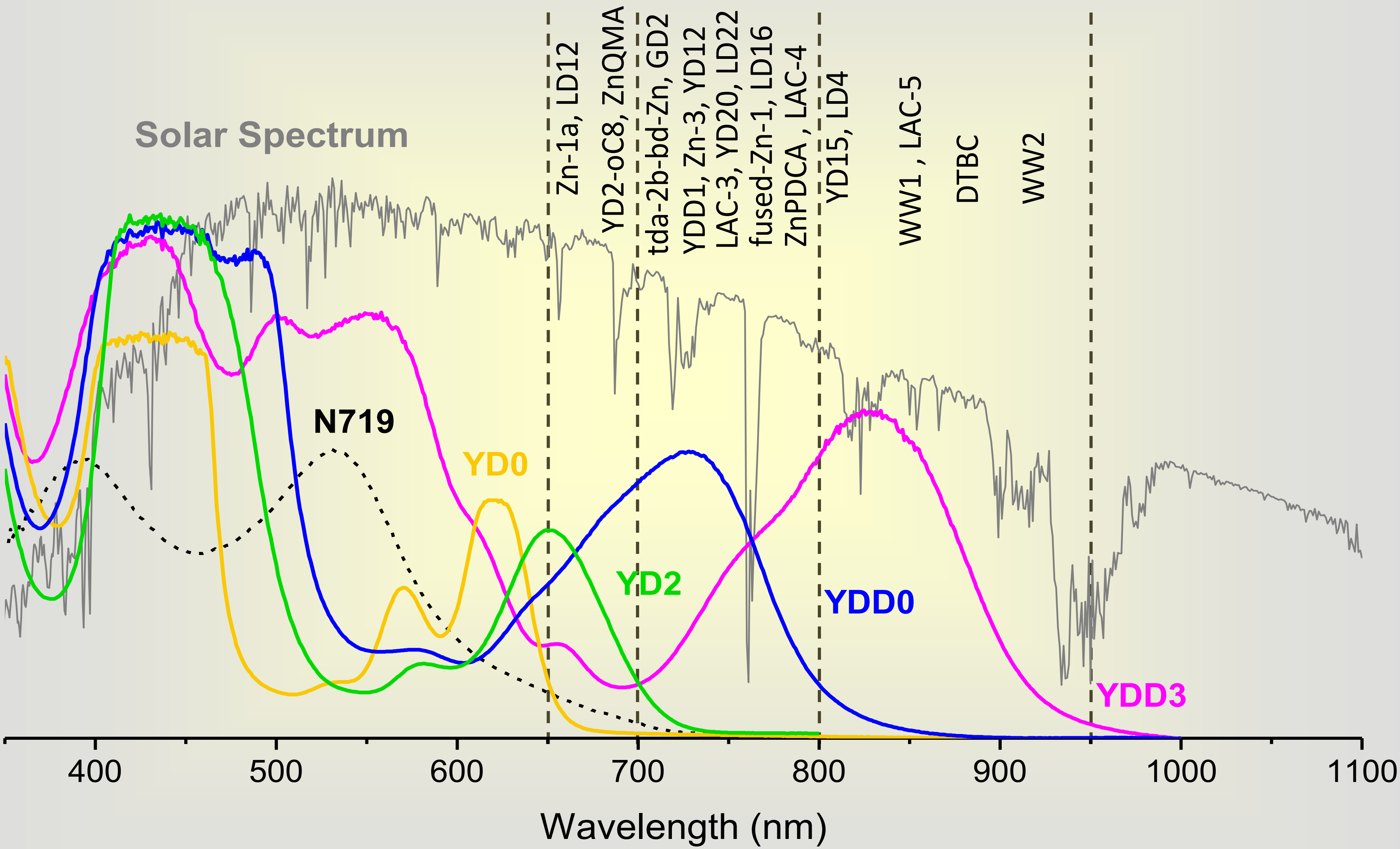
YD2-*o*C8

AY1 electrolyte:
0.165 M $[Co(bpy)_3](B(CN)_4)_2$
0.045 M $[Co(bpy)_3](B(CN)_4)_3$
0.8 M TBP
0.1 M $LiClO_4$
in CH_3CN

Science **2011**, *334*, 629-634.
(No. of citations is over 6500 upto 2022)

Co-Sensitization

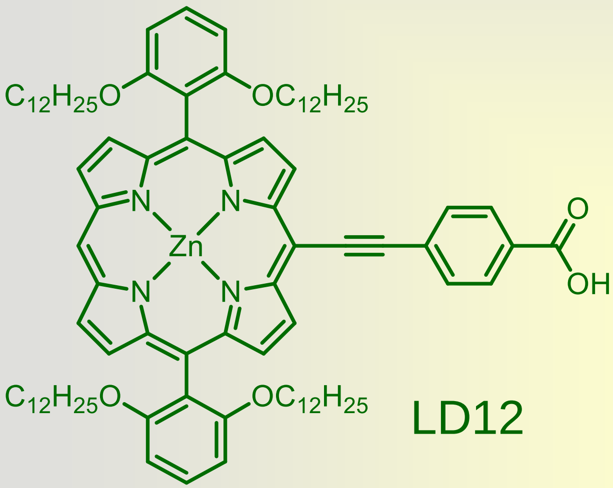
The Issue of Light Harvesting in PSSC



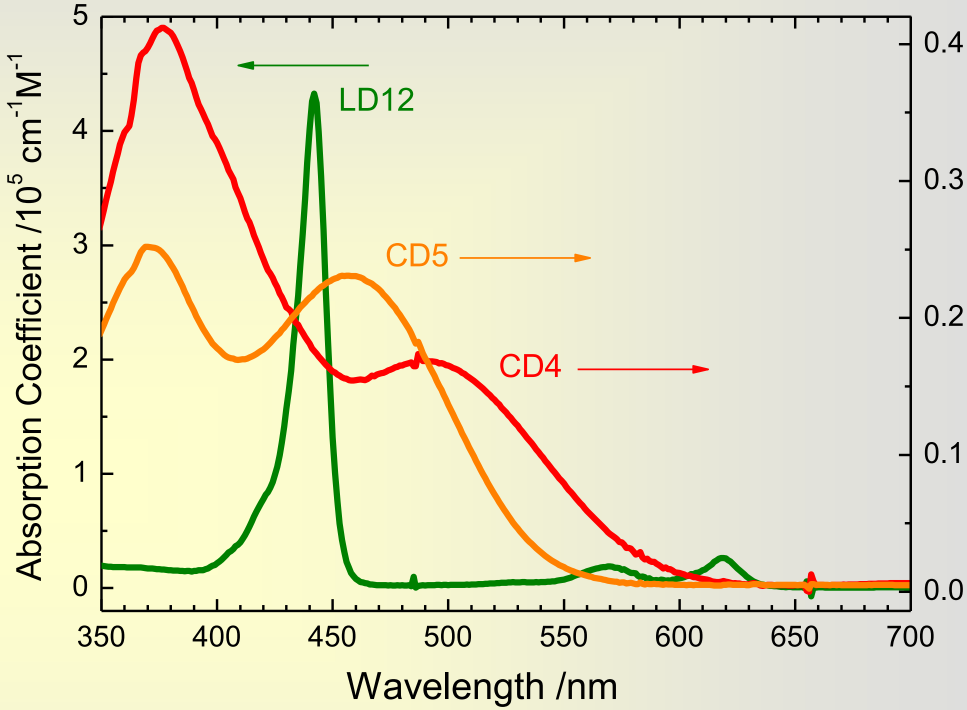
Chem. Soc. Rev. **2013**, *42*, 291-304.

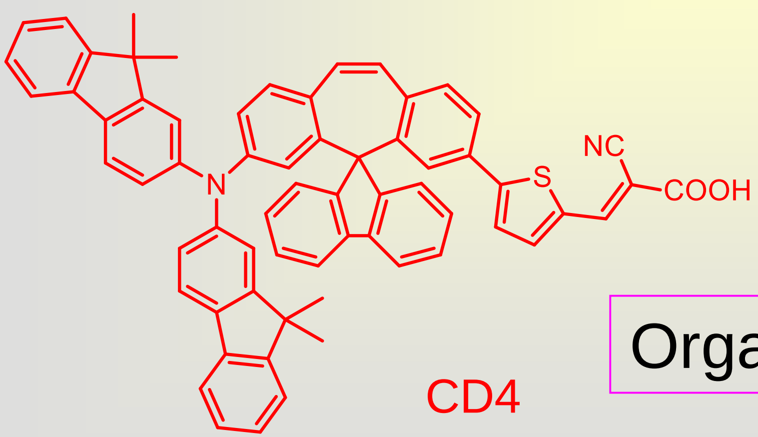
Design of Co-sensitization Systems

Porphyrins



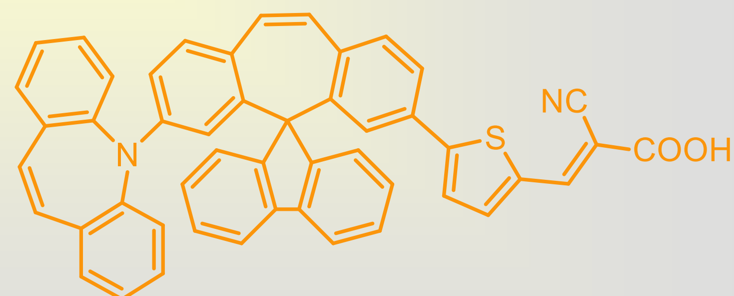
LD12





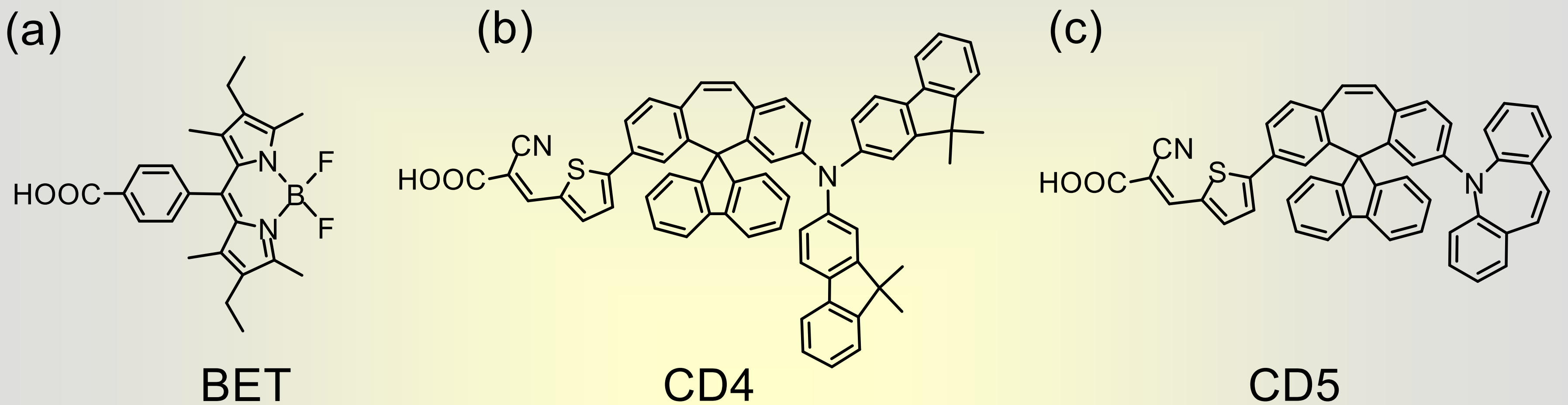
CD4

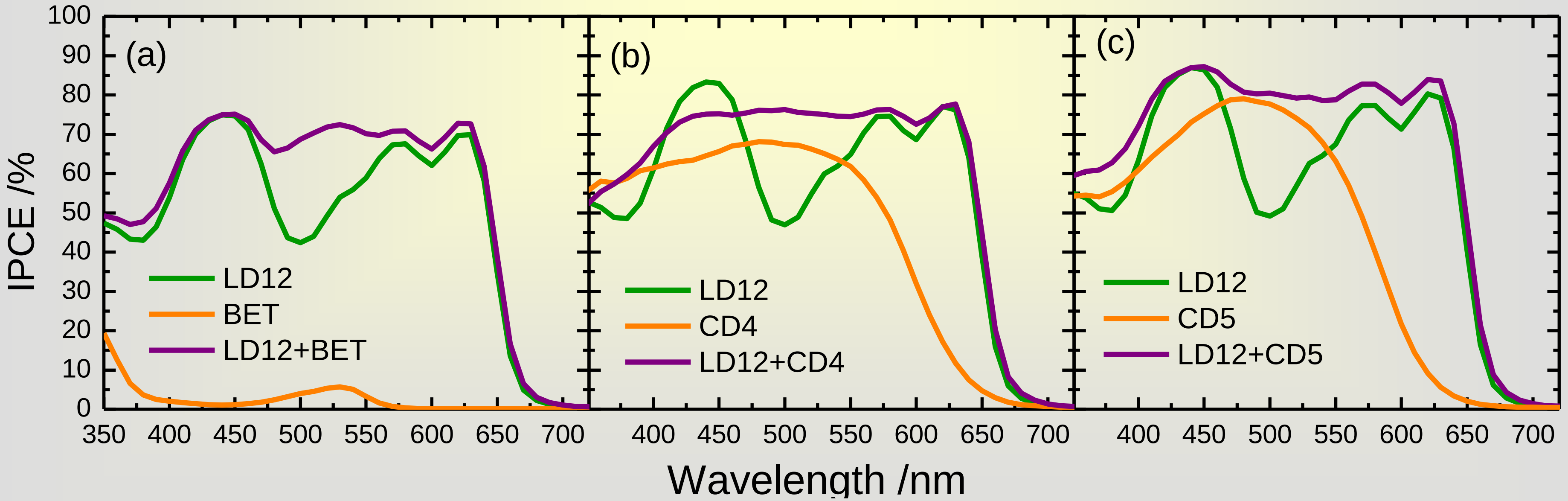
Organic Dyes



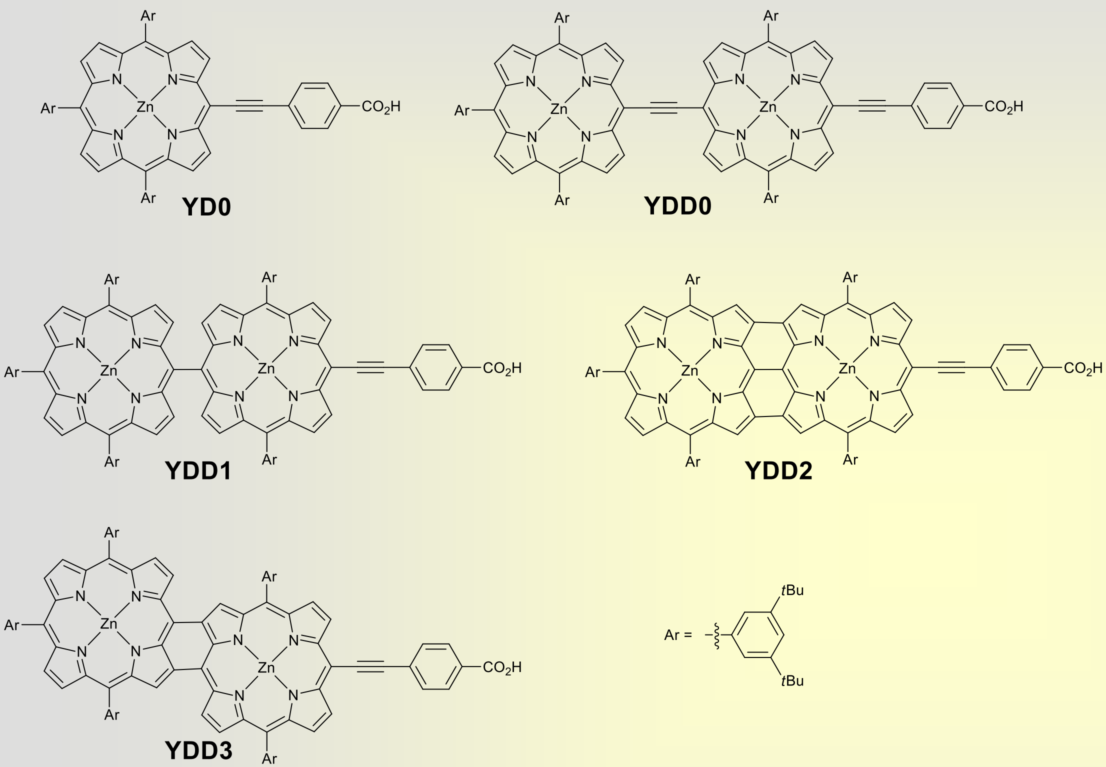
CD5

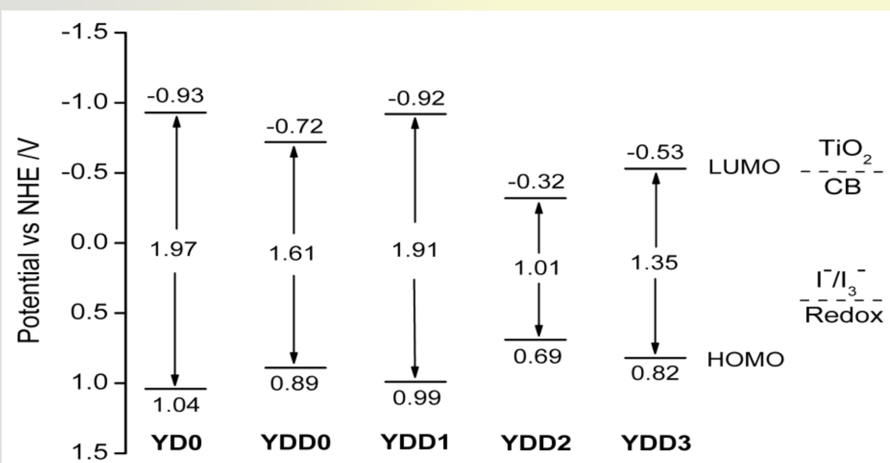
Photovoltaic Performance

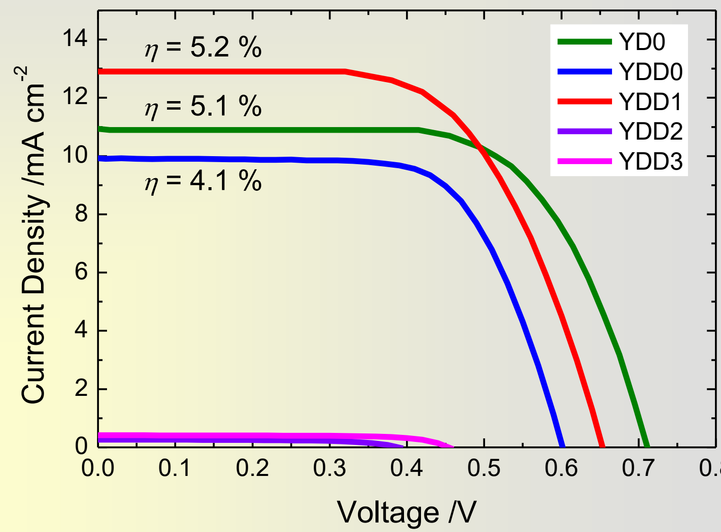


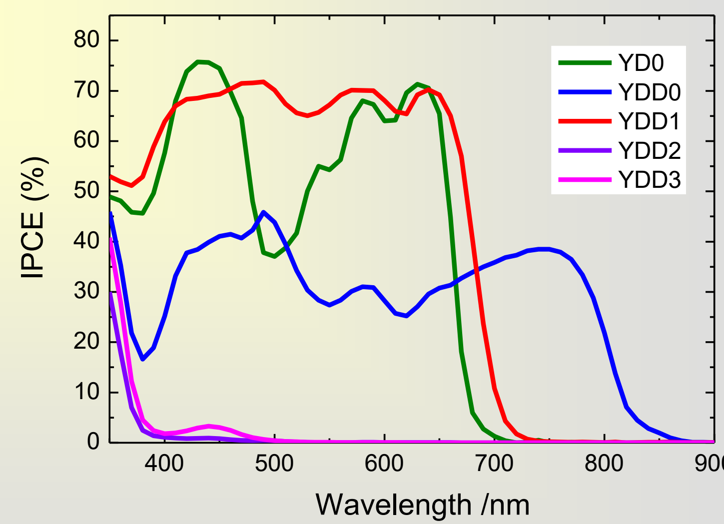


Using Porphyrin-dimers as Sensitizers



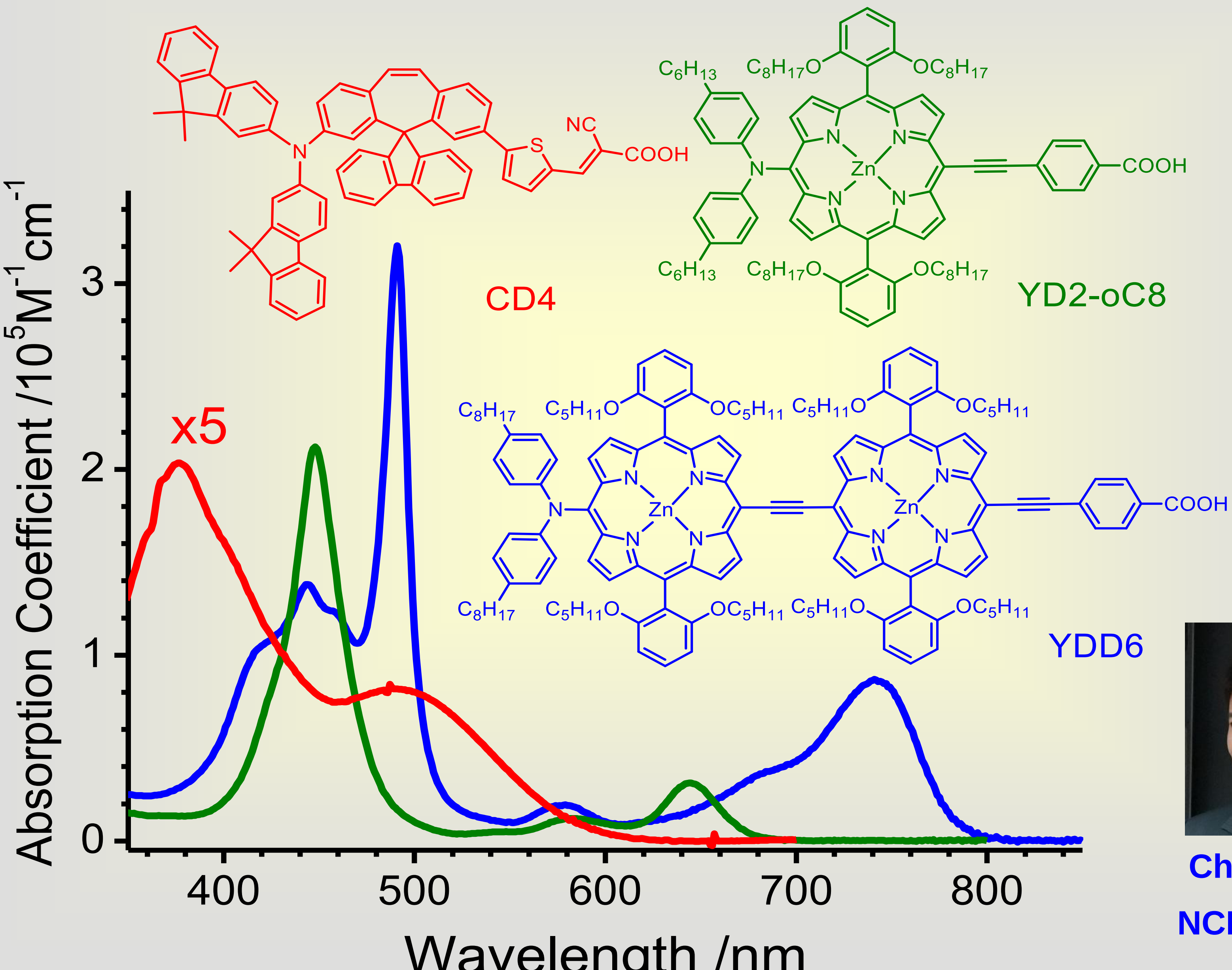






Chem. Commun. **2010**, *46, 809-811.*

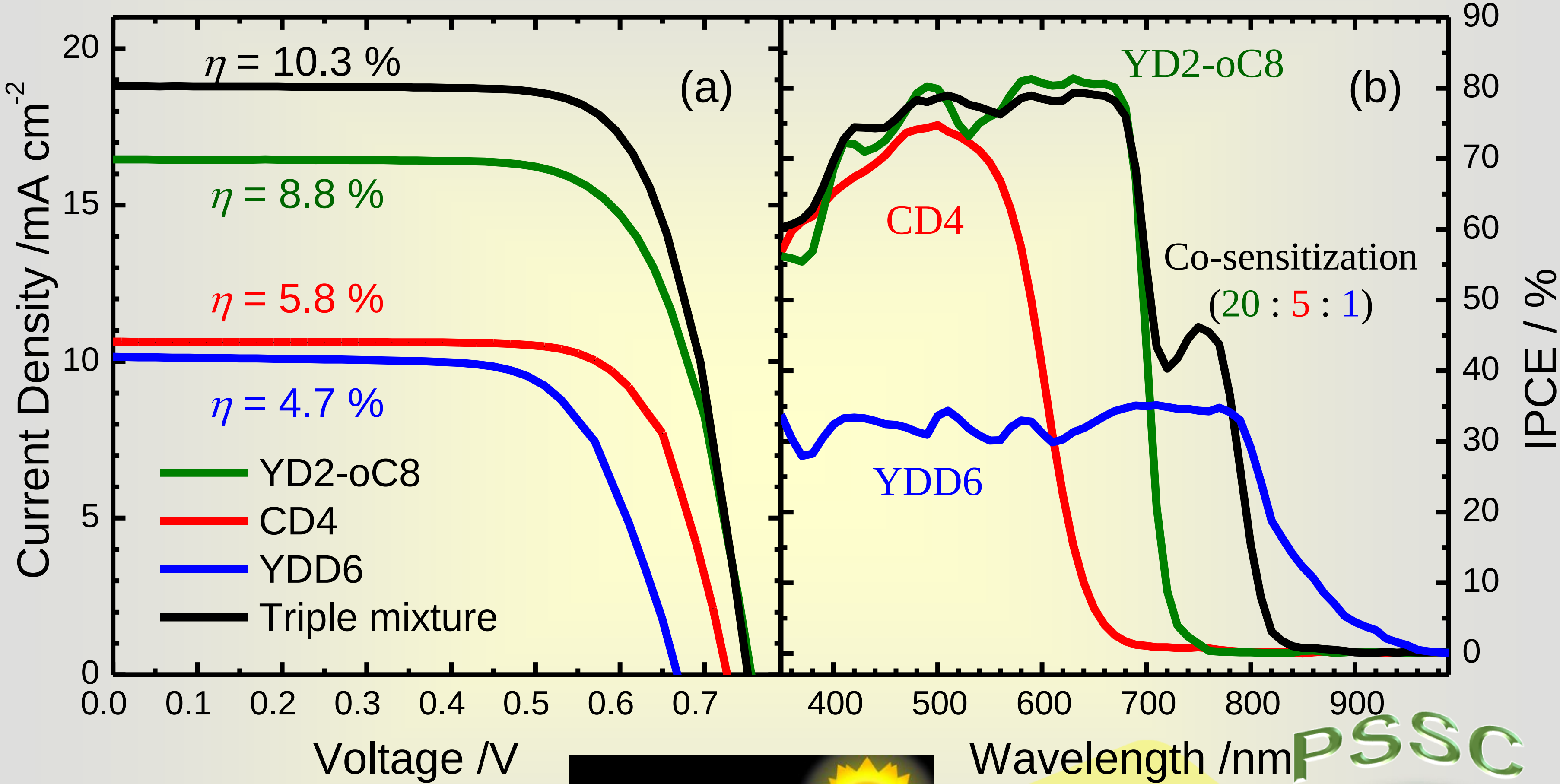
Design of Near-IR Porphyrin Dimer

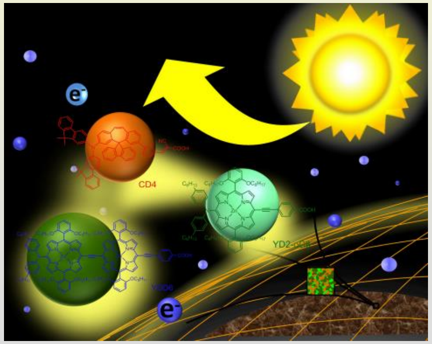


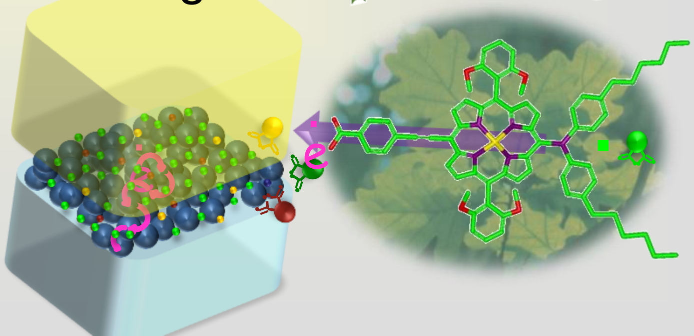
Chen-Yu Yeh

NCHU, Taiwan

Cocktail Molecular Co-sensitization

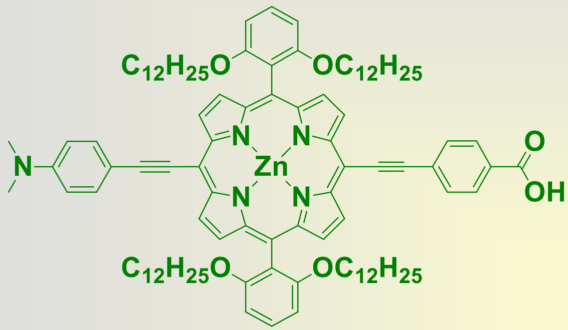




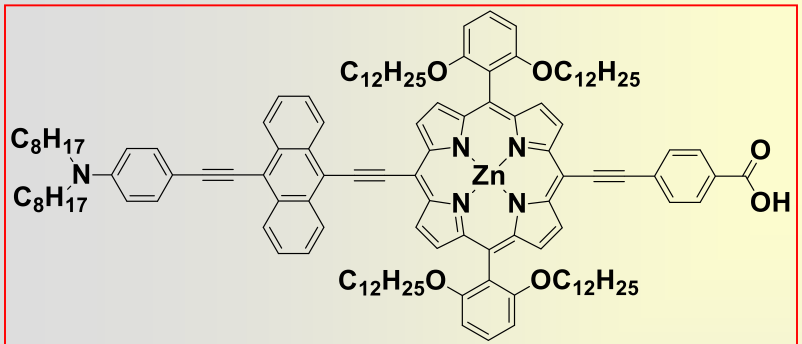


Energy Environ. Sci. **2012**, 5, 9843-9848; selected as cover story in issue 12.

Design of Near-IR Porphyrin Monomer



LD14



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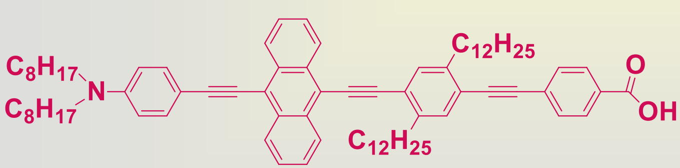
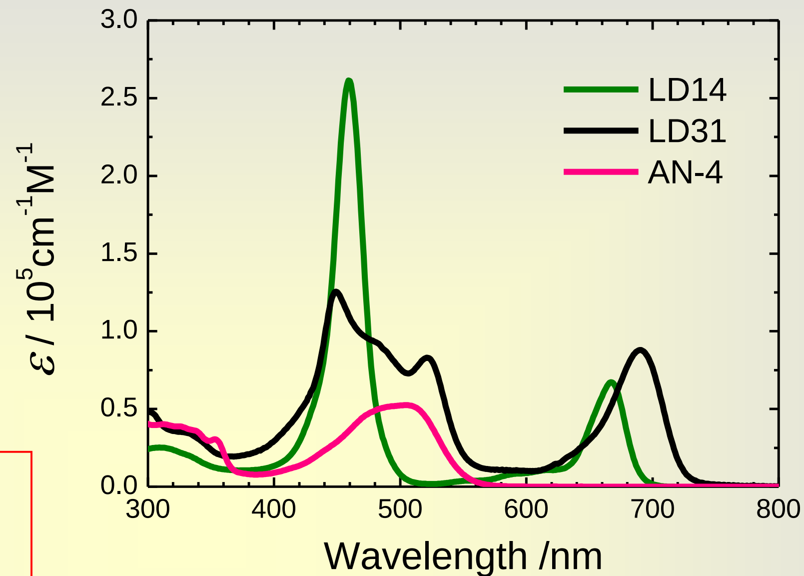


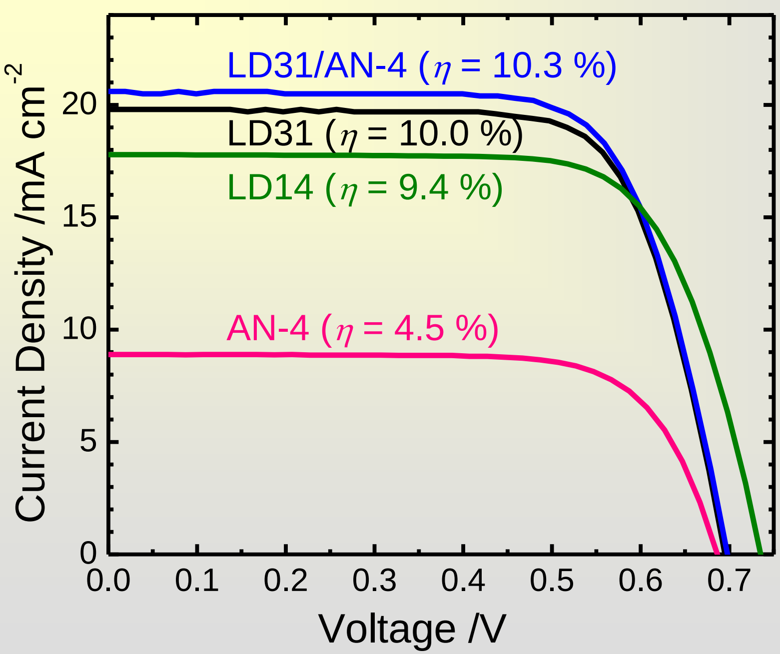
AN-4

Energy Environ. Sci. **2014**, *7*, 1392-1396.

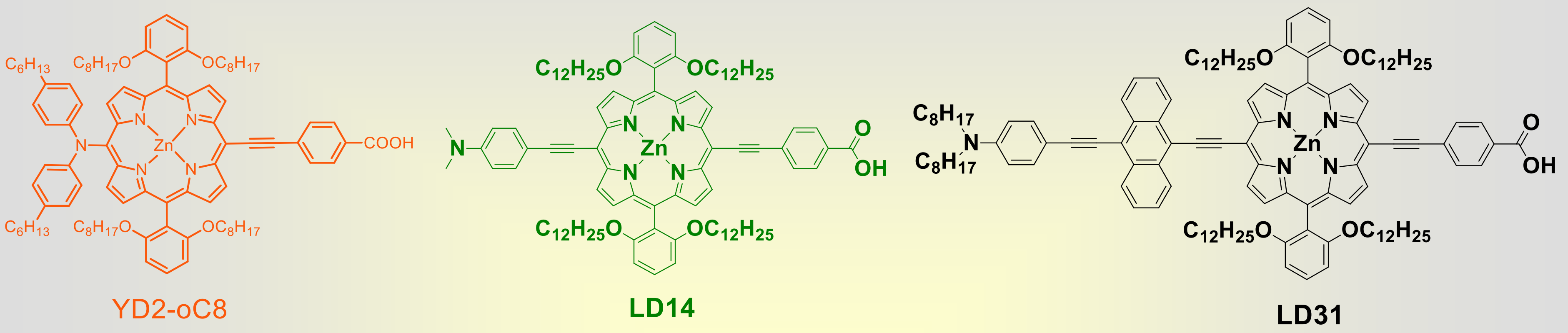


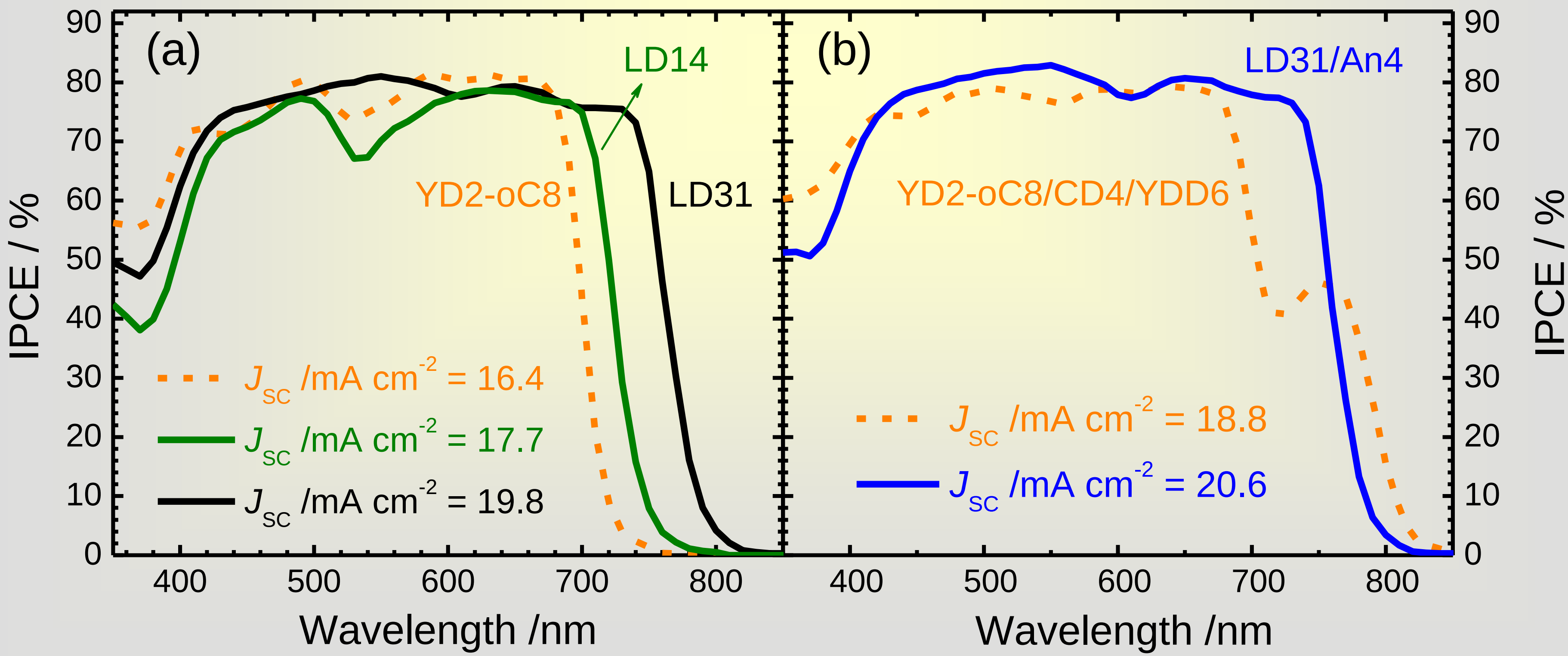
Ching-Yao Lin

(NCNU, Taiwan)

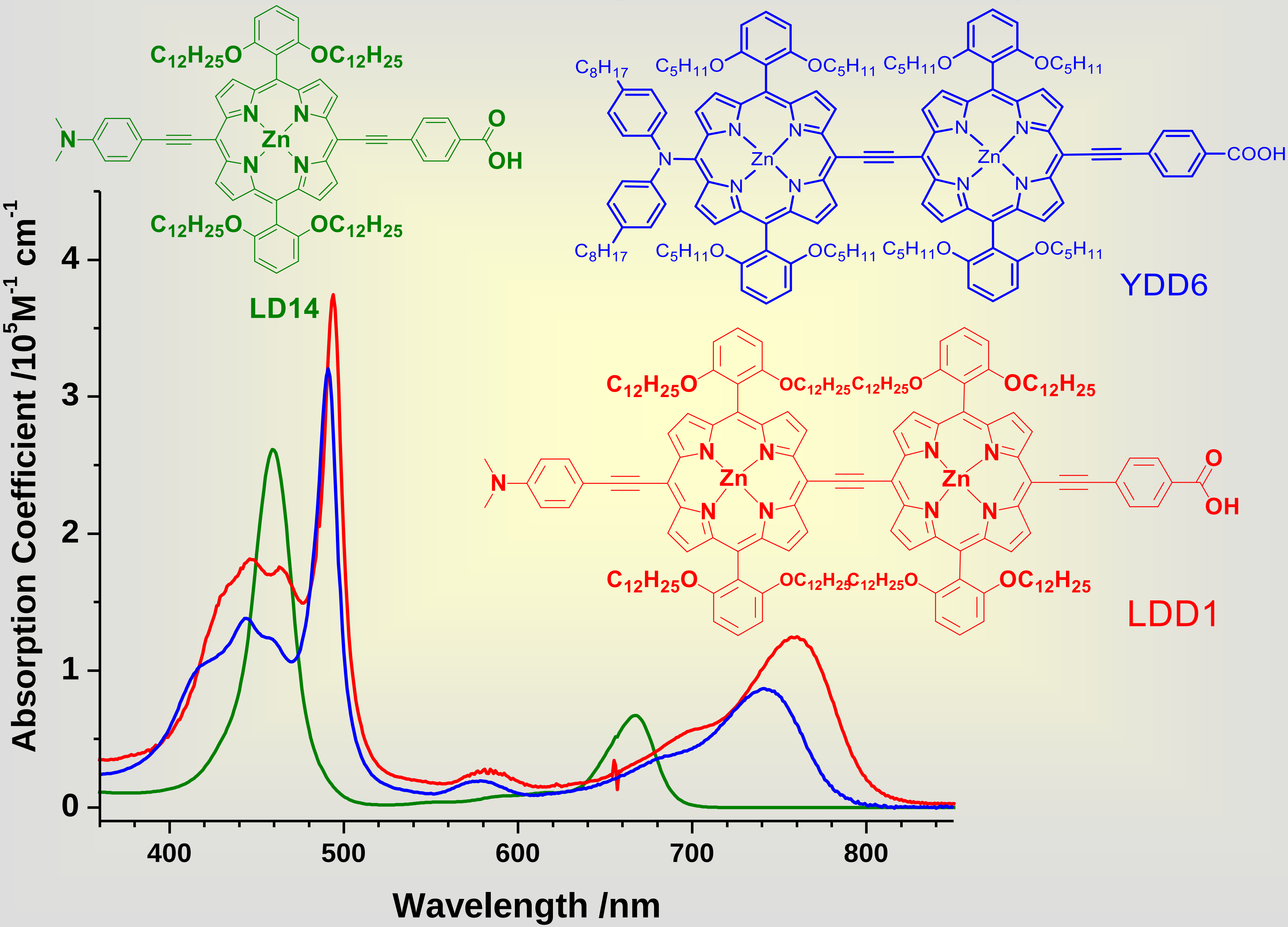


Comparison of Light Harvesting Abilities

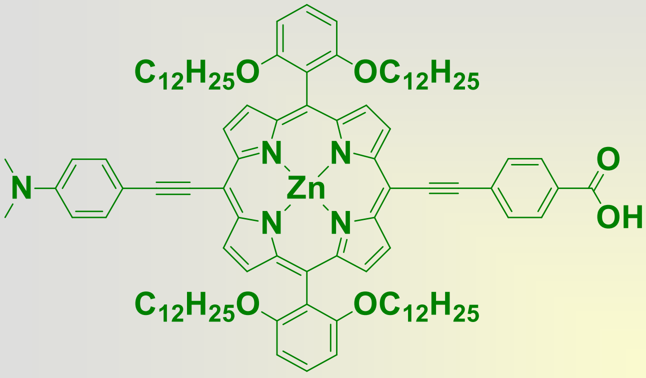




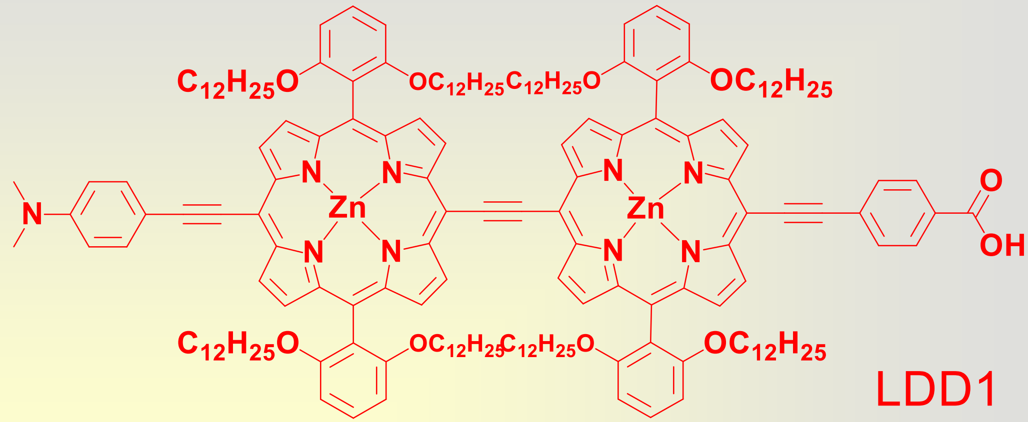
Another Promising NIR Porphyrin Dimer



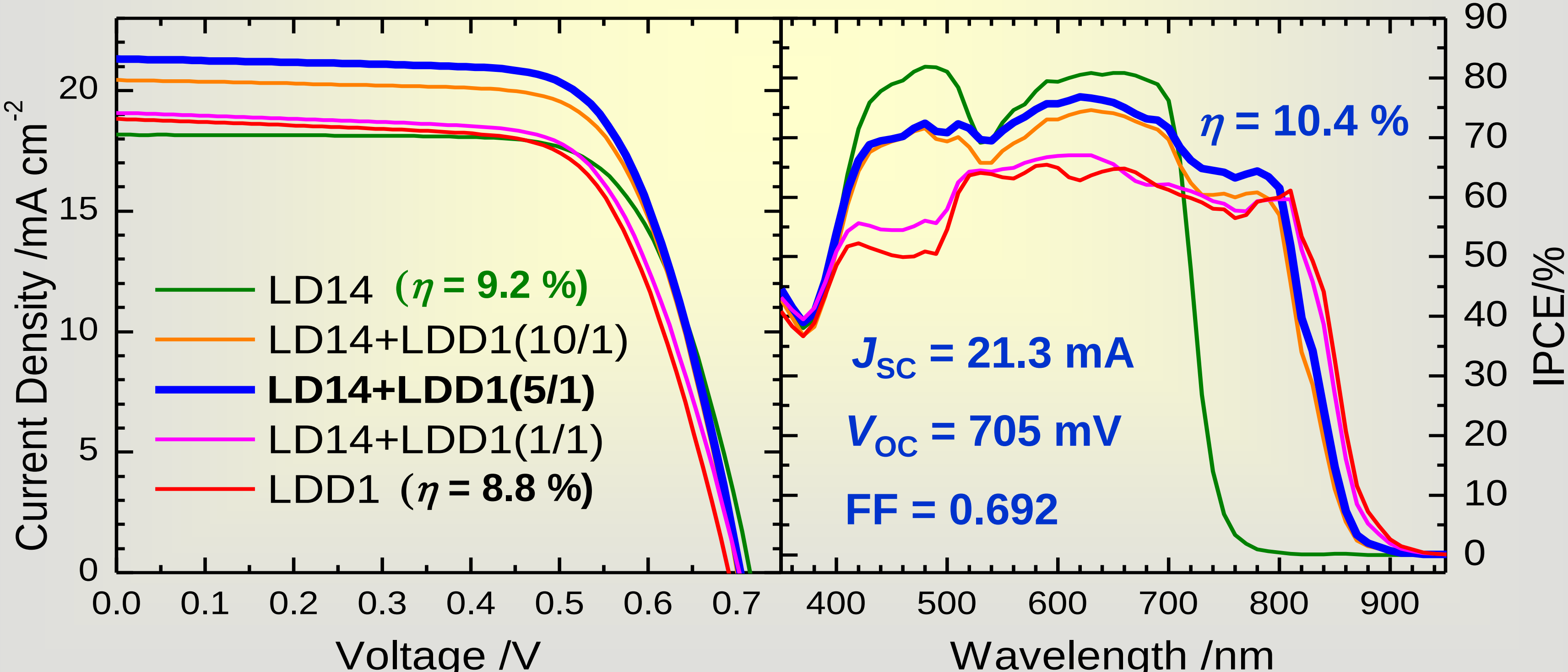
Co-sensitization of LDD1 with LD14



LD14

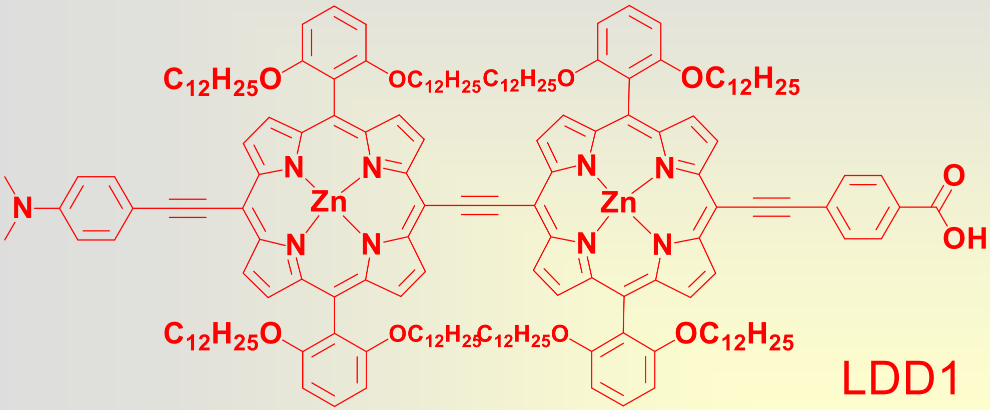


LDD1

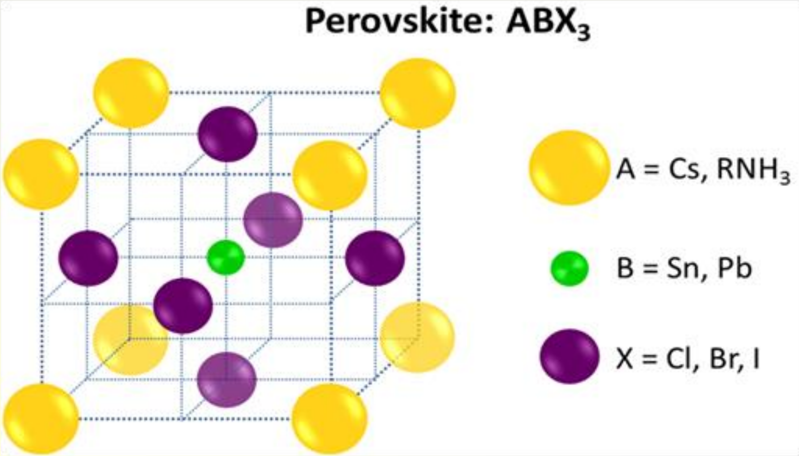


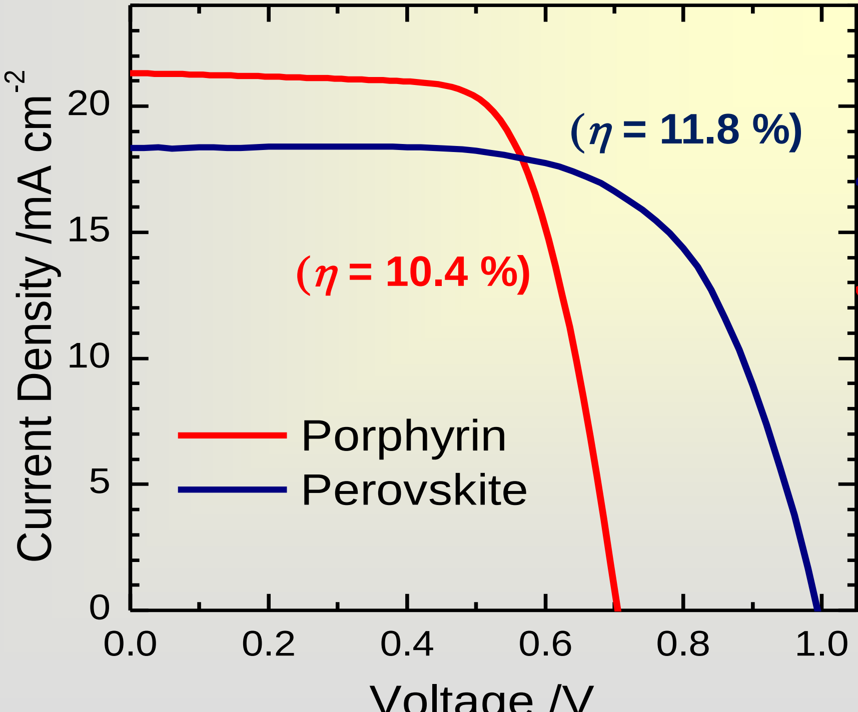
JMCA **2015**, *3*, 1417-1420.

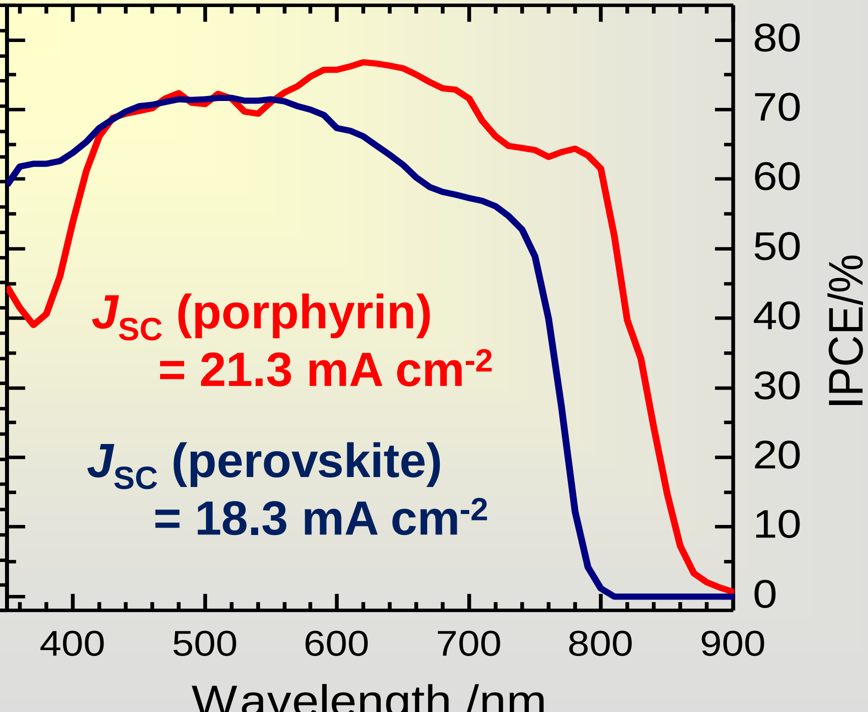
Porphyrin versus Perovskite



JMCA **2015**, *3*, 1417-1420.








(C)fuul
Thanks