콜로이드 양자점의 물성 제어 및 소자 응용

Control of Physical Properties and Device Applications of Colloidal Quantum Dots

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2026.05.21

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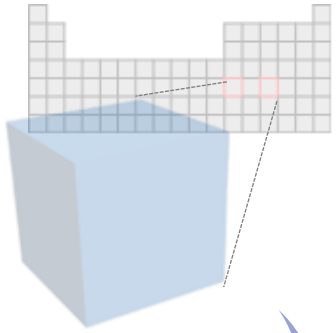
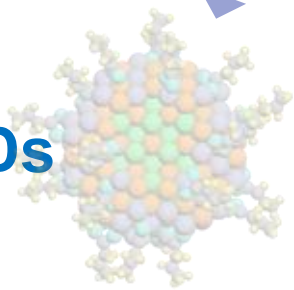
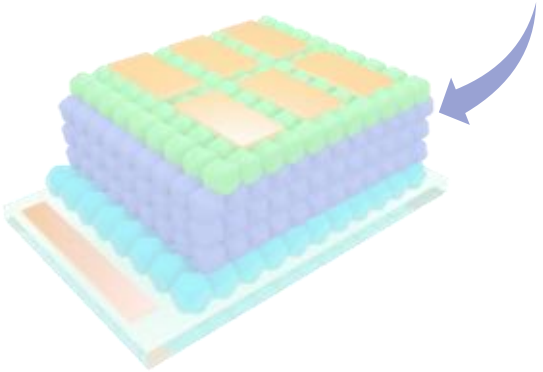
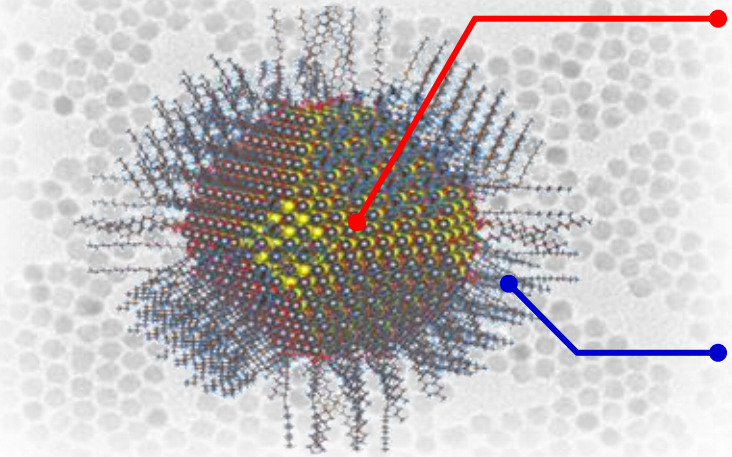




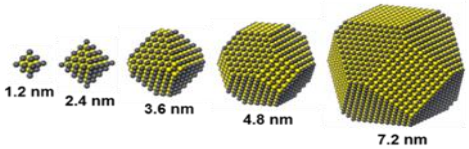


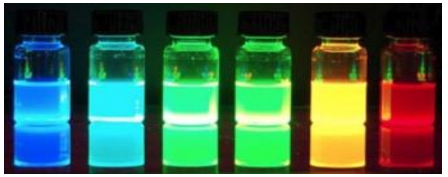
What is quantum dot?

콜로이드 **양자점** 소재 → **태양전지**, FET, LED 소자 적용

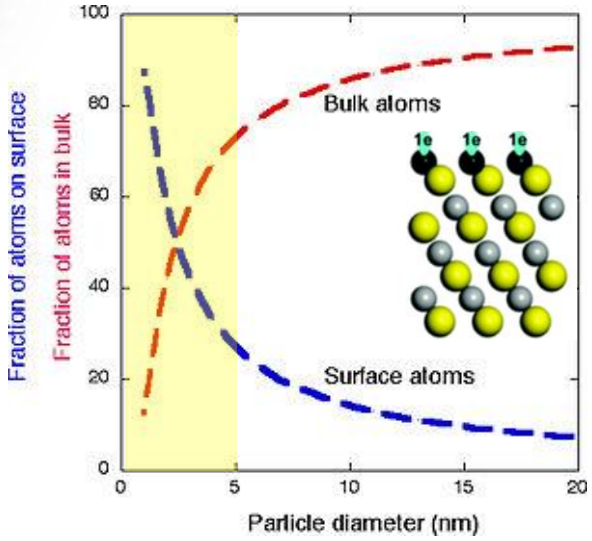


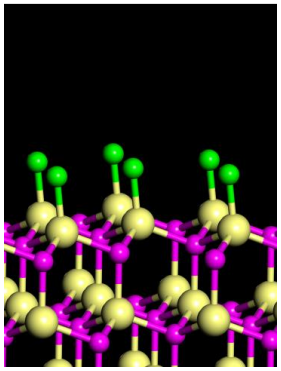
무기 반도체 코어





표면 리간드



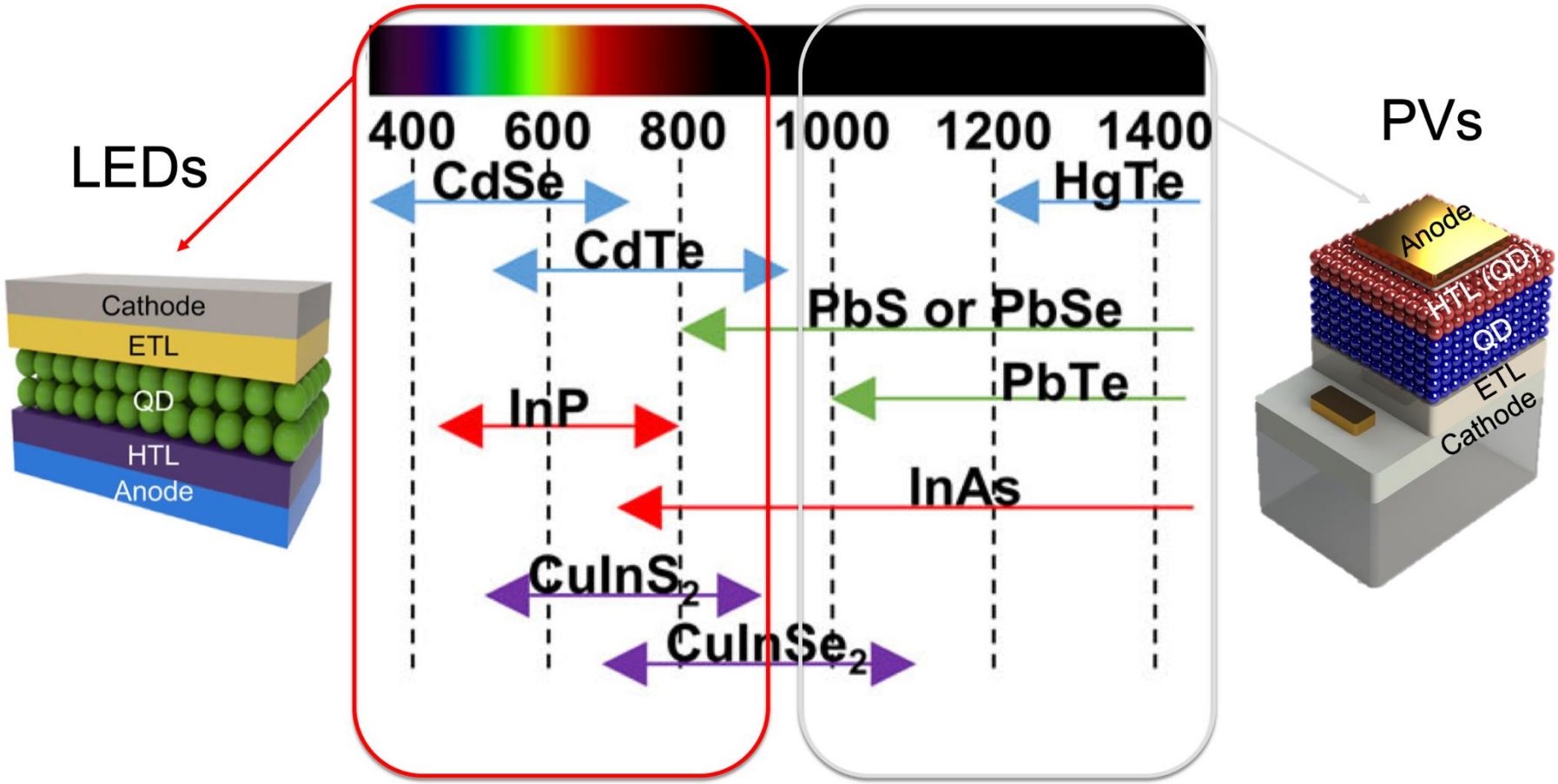


기본물성을 정의하는 최소 단위

- 용액 합성 공정 (저가 공정 가능)
- 표면 기능화를 통한 다양한 물성 제어 가능

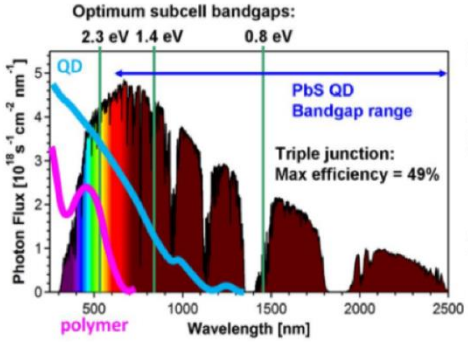
What is quantum dot?

Spectral range of CQDs with various semiconductor materials

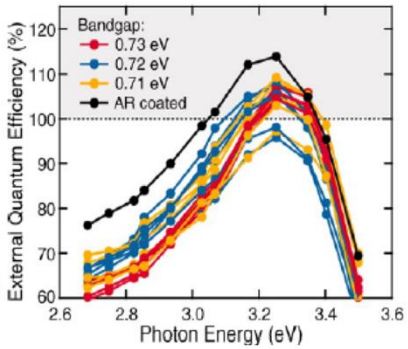


Potential for Optoelectronic Applications

Photovoltaics

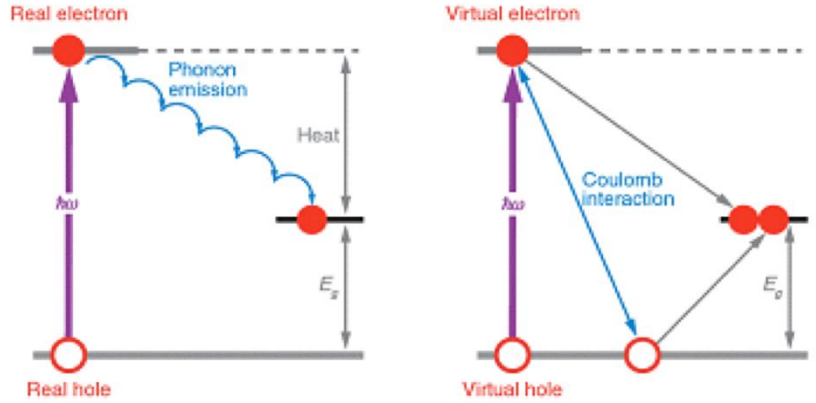


Bawendi group webpage



A. J. Nozik, and M. C. Beard, et al., *Science* 334, 1530 (2011)

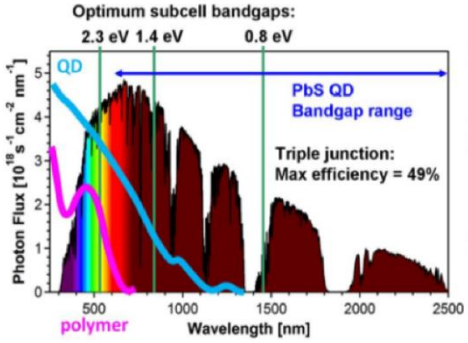
✓ **Promise efficiency boost *via* minimizing thermal loss (hot carrier utilization)**



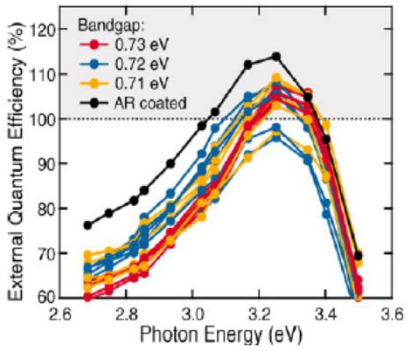
R. D. Schaller, and V. I. Klimov, *Phys. Rev. Lett.*, 92, 186601 (2014)

Potential for Optoelectronic Applications

Photovoltaics

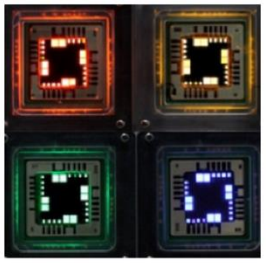


Bawendi group webpage

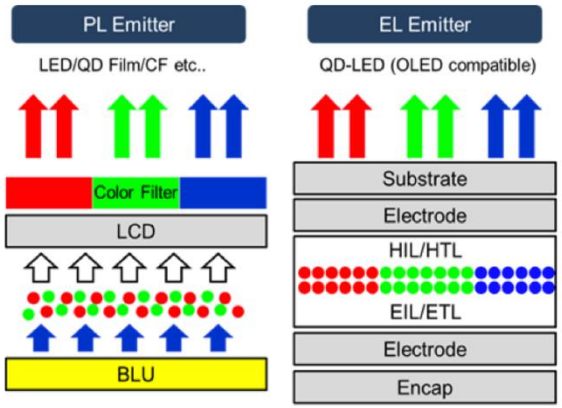


A. J. Nozik, and M. C. Beard, et al., *Science* 334, 1530 (2011)

LED/Display

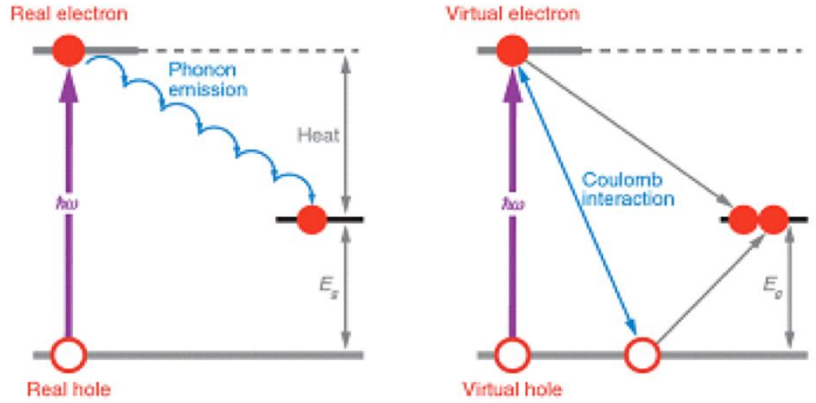


QD Vision

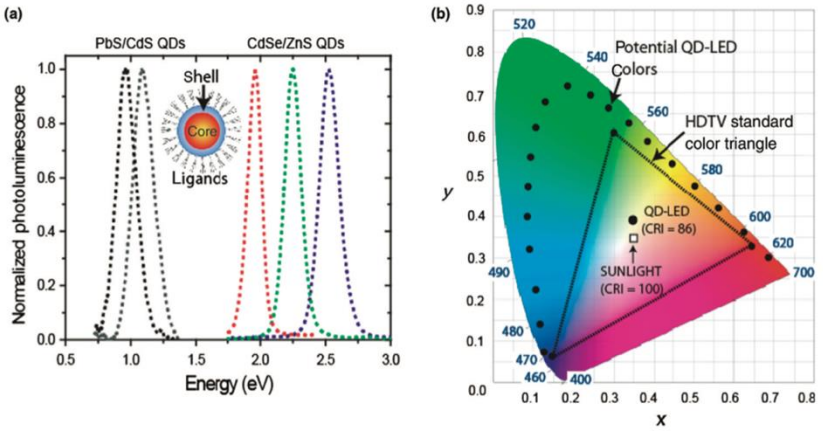


✓ **Promise efficiency boost *via* minimizing thermal loss (hot carrier utilization)**

✓ **Promise color purity *via* size monodispersity**



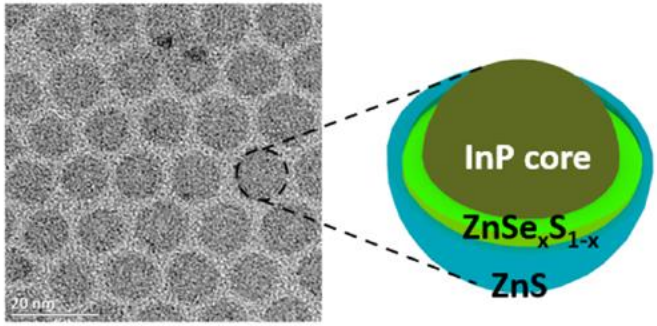
R. D. Schaller, and V. I. Klimov, *Phys. Rev. Lett.*, 92, 186601 (2014)



V. wood, and V. Bulovic, *Nano Review*, 1, 5202 (2010)

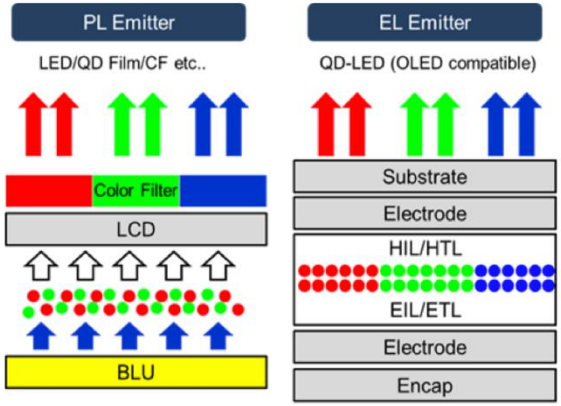
Potential for Optoelectronic Applications

InP QDs

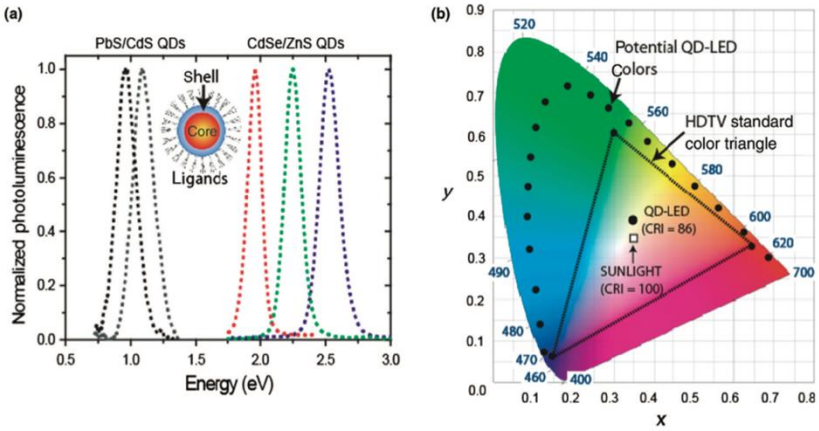


LED/Display

QD Vision



✓ **Promise color purity *via* size monodispersity**



V. wood, and V. Bulovic, *Nano Review*, 1, 5202 (2010)

Research Field

NOBELPRISET I KEMI 2023
THE NOBEL PRIZE IN CHEMISTRY 2023

KUNGL. VETENSKAPS-AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

Moungi Bawendi
Massachusetts Institute of Technology (MIT)
USA

Louis Brus
Columbia University
USA

Alexei Ekimov
Nanocrystals Technology Inc.
USA

"för upptäckt och syntes av kvantprickar"

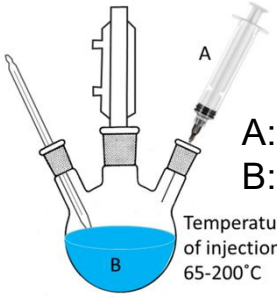
"for the discovery and synthesis of quantum dots"

Research Field

Synthesis

CIGS, AIGS, InP , CdSe, $AgBiS_2$, PbS, PbSe

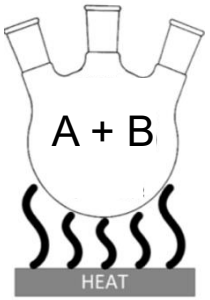
- Hot injection



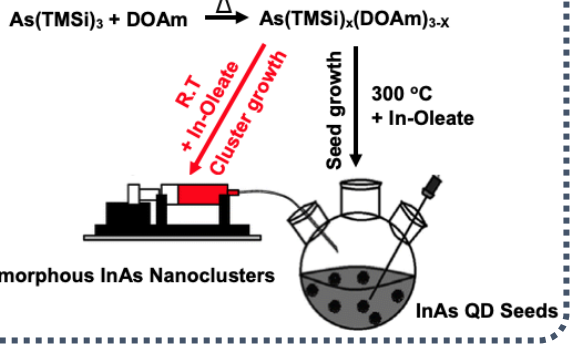
A: anion precursor
B: cation precursor

- Heat-up

A: anion precursor
B: cation precursor

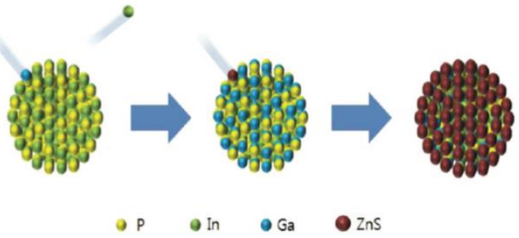


- Continuous injection

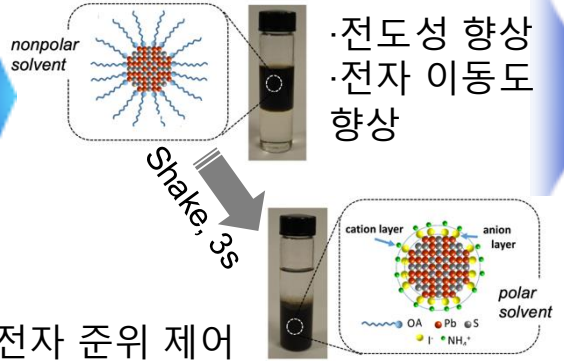


Surface Modification

- Core-shell (InP/GaP/ZnS)



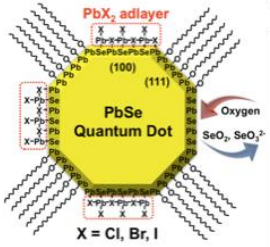
- Ligand exchange (ink)

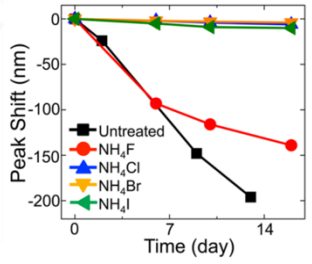


·전도성 향상
·전자 이동도 향상

· 전자 준위 제어
· 페르미 준위 제어

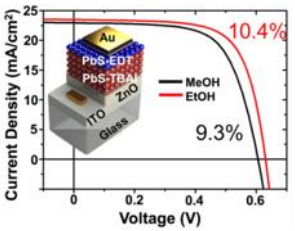
- Selective adlayer formation (대기 안정성 증대)

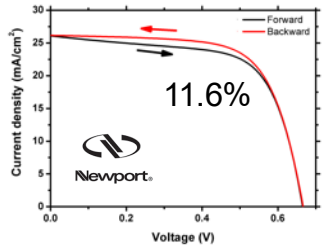




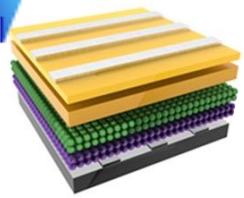
Device Applications

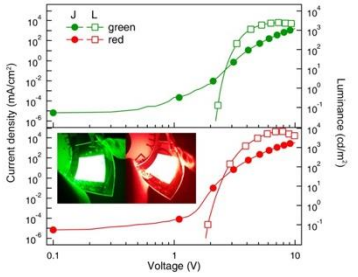
- PVs, PDs



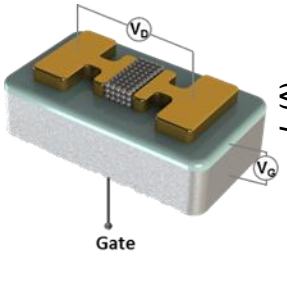


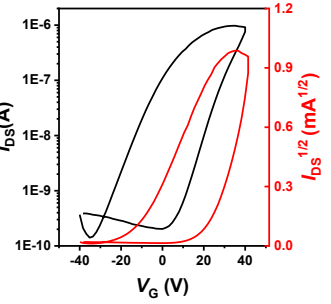
- LEDs





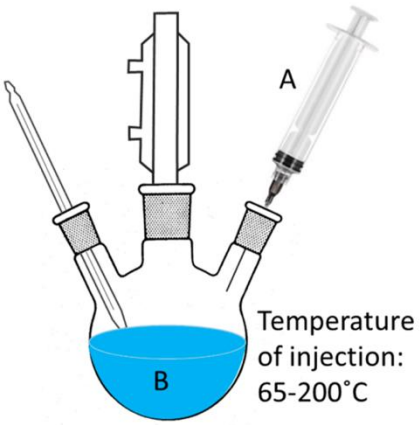
- FETs





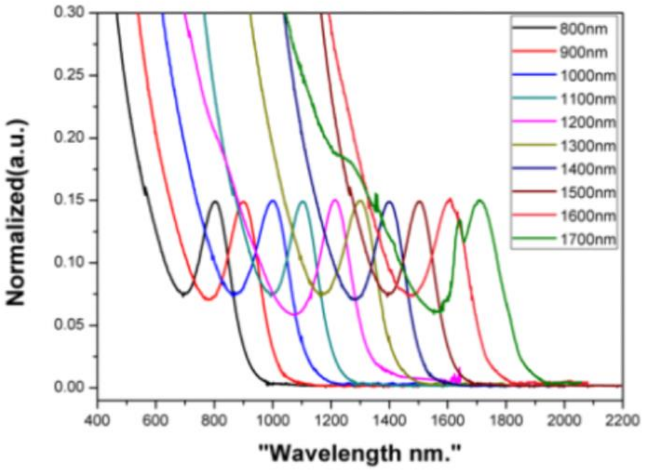
Colloidal Quantum Dot Synthesis

Hot injection

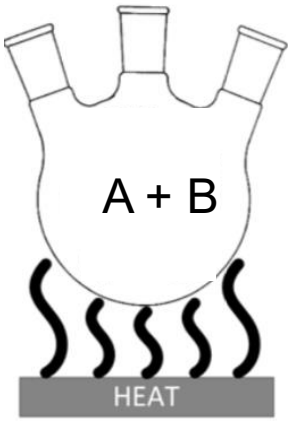


A: anion precursor
B: cation precursor

PbS, $AgBiS_2$, $CuInGaSe_2$

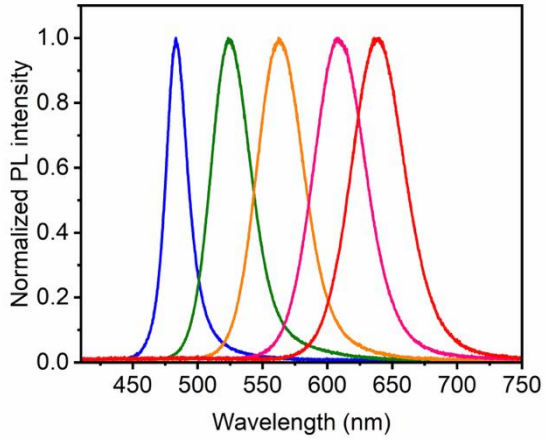


Heat-up



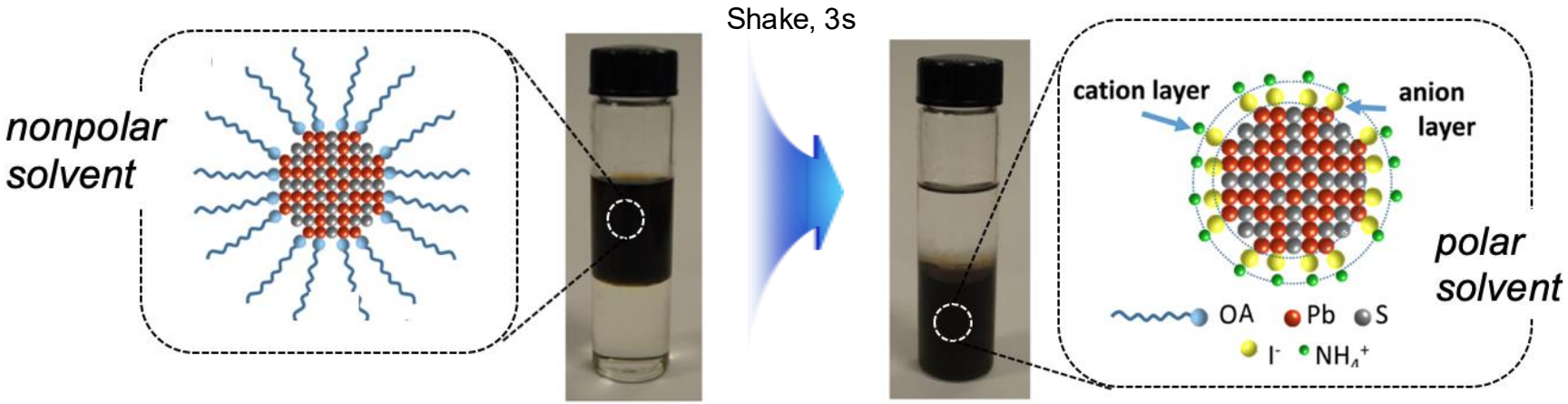
A: anion precursor
B: cation precursor

$AgInGaS_2$, InP

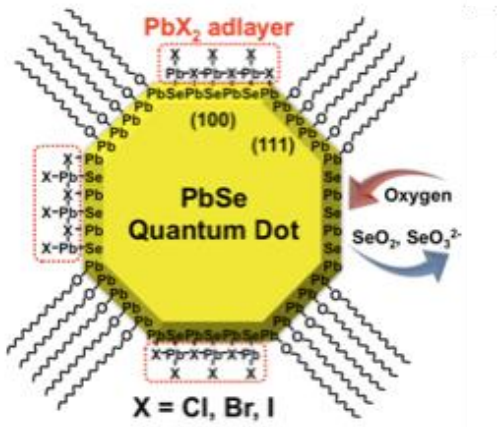


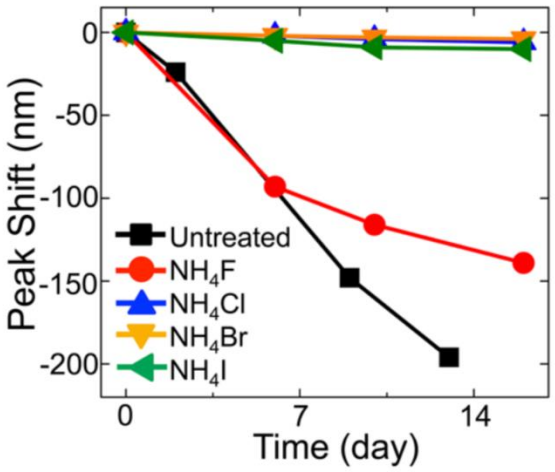
Surface Modification

Ligand exchange



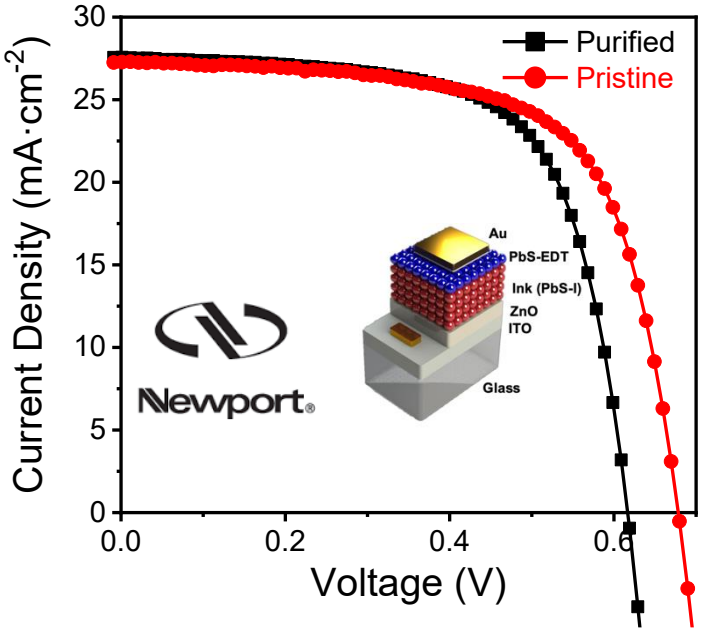
Adlayer formation (Core-shell)



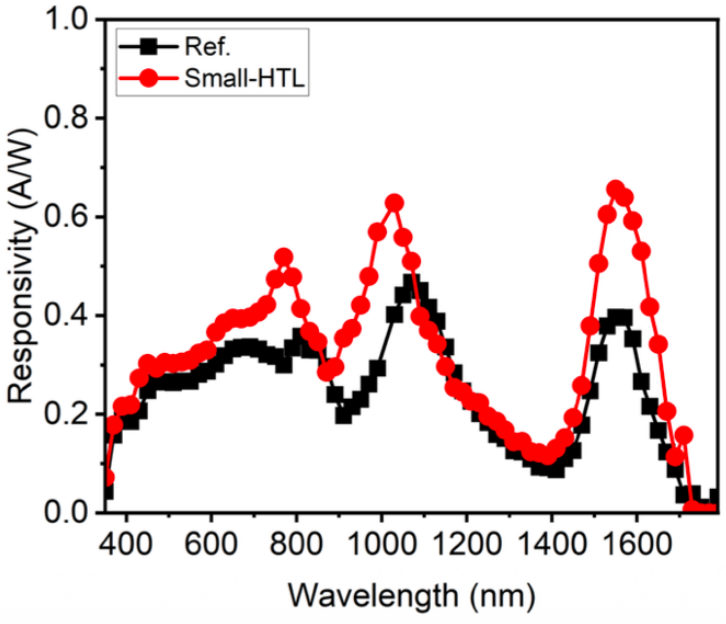


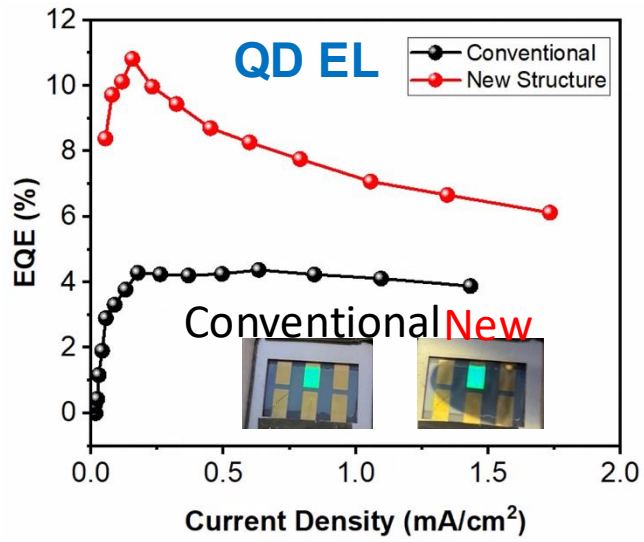
Optoelectronic Applications

Photovoltaics

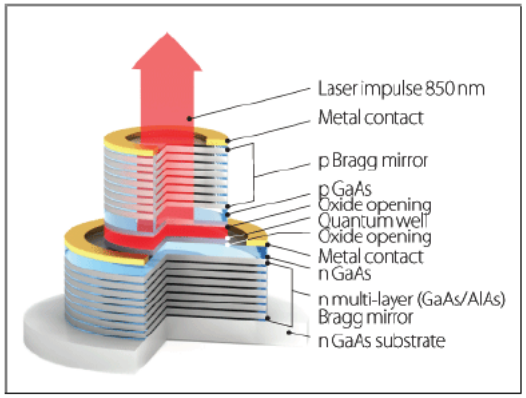


Photodiodes

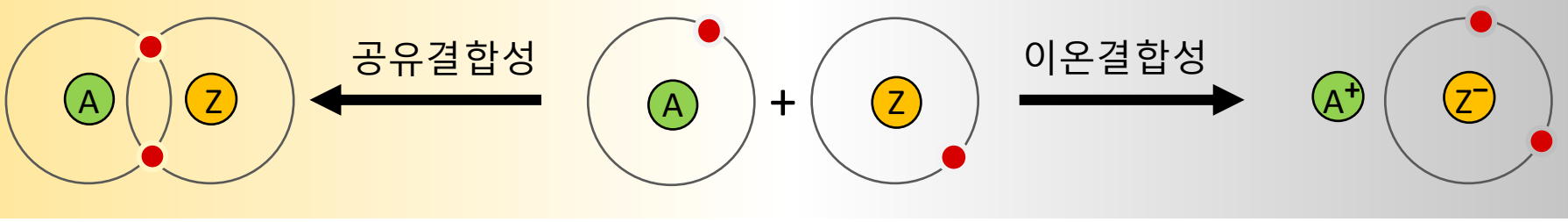




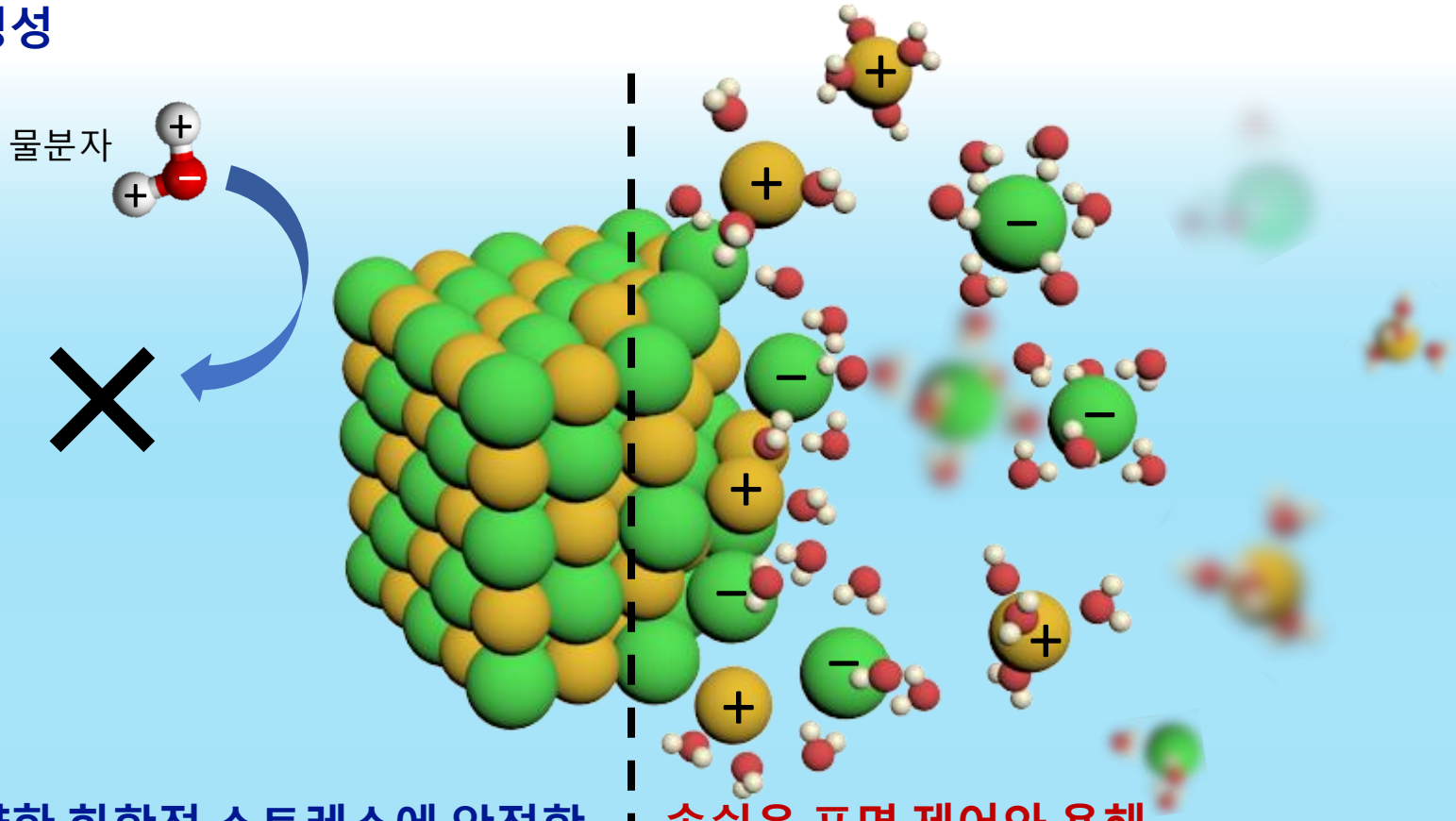
LASER



Quantum Dots with Ionic Crystal



화학적 안정성



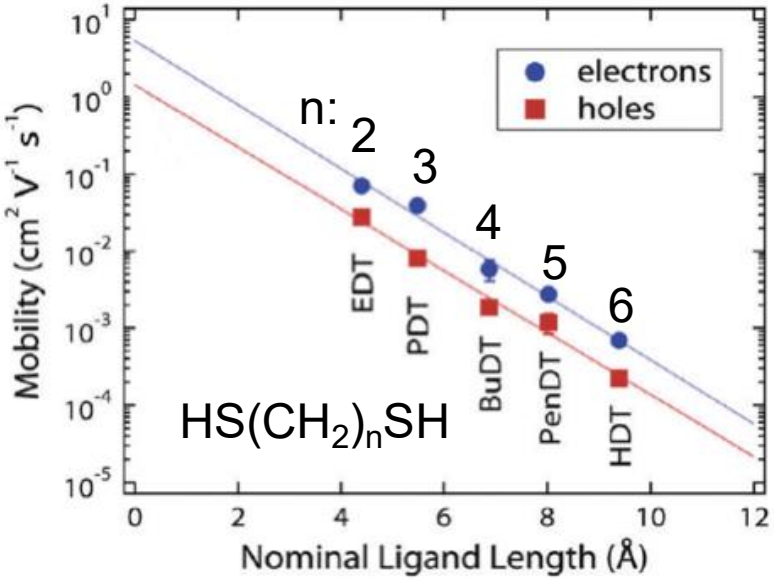
다양한 화학적 스트레스에 안정함
안정한 저독성 소재 ←

손쉬운 표면 제어와 용해
→ 안정성 및 생체 독성 문제

Properties Depending on Surface Modification

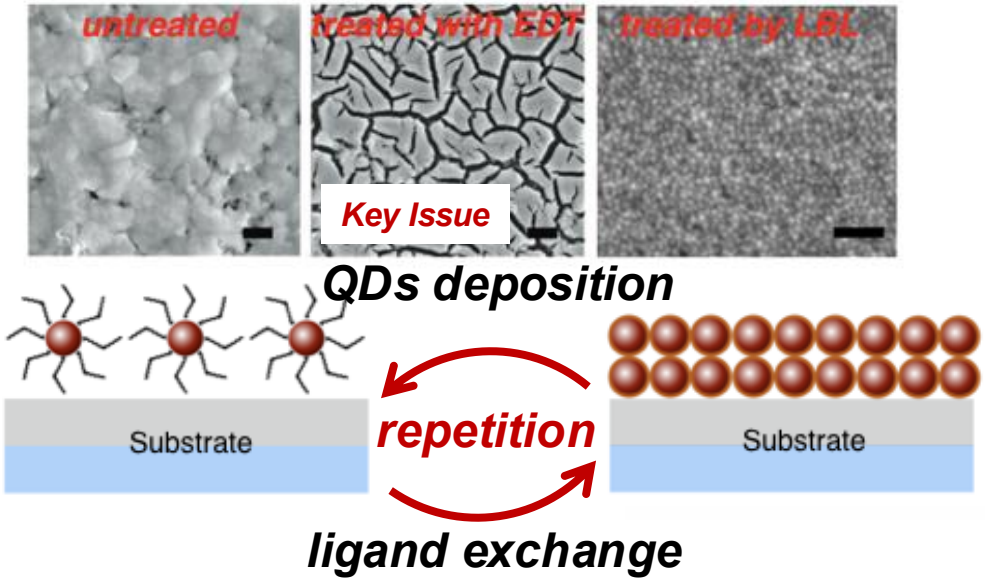
Ligand-dependent Mobility

Liu et al., Nano Lett., 2009, 10, 1960



Layer-by-layer (LBL) Process

Luther et al., ACS Nano, 2008, 2, 271

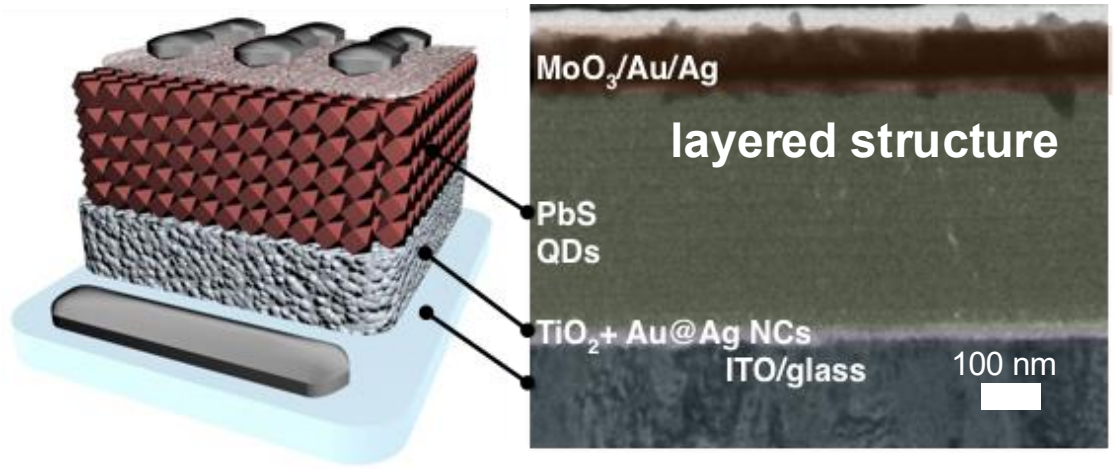


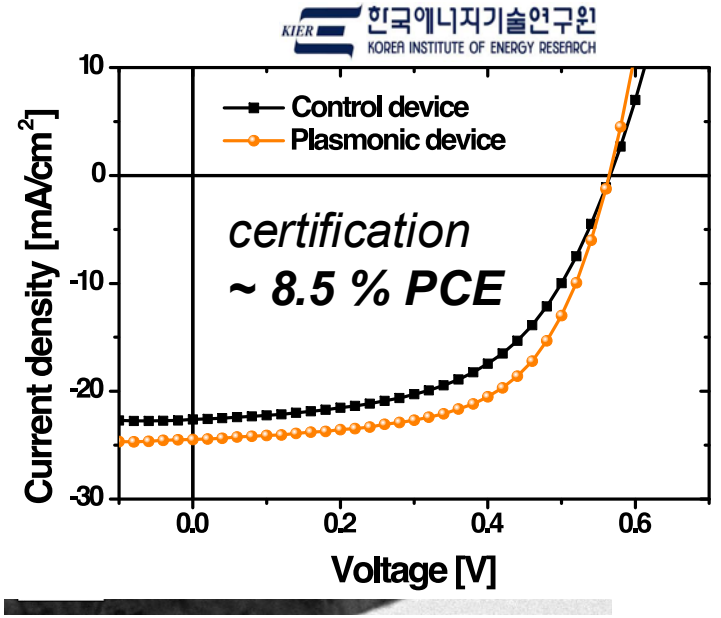
- 양자점 기반 응용소자의 동작 원리에 따라 물성 제어 필요
- 수광소자 (태양전지 및 광센서)의 경우 높은 전도도 요구
- 짧은 리간드로 교환 시, 박막의 갈라짐 발생

Properties Depending on Surface Modification

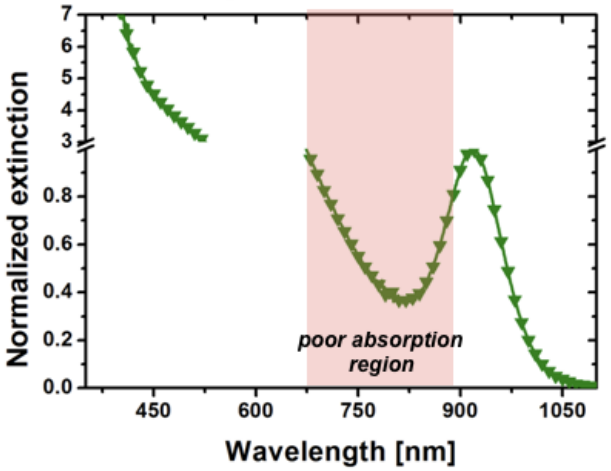
CQD Solar Cell using LBL Process

J. H. Song, et al., *Adv. Mater.,* 2015, 27, 8102

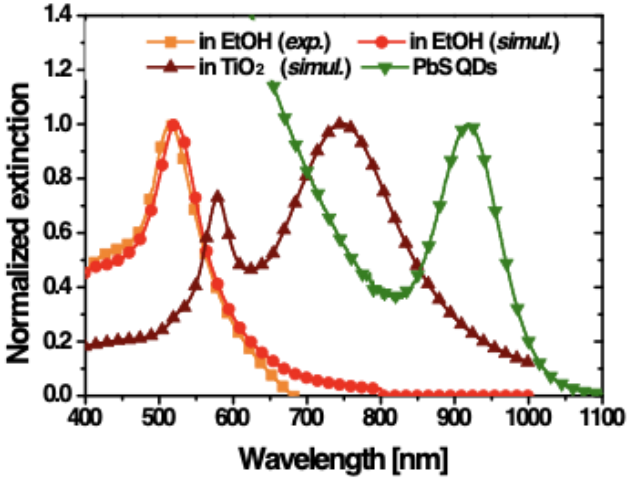




External quantum efficiency & absorption in solar cells

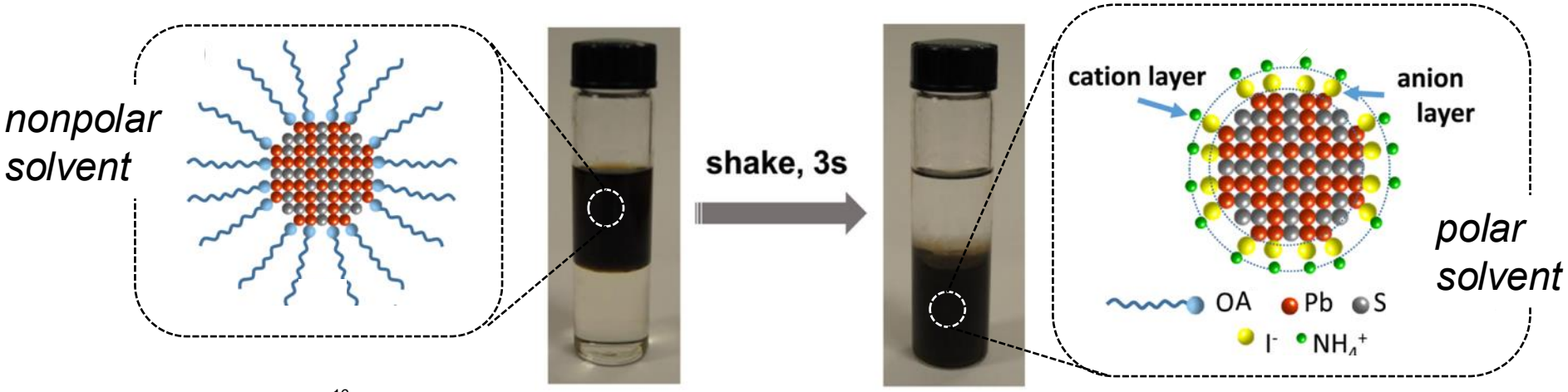


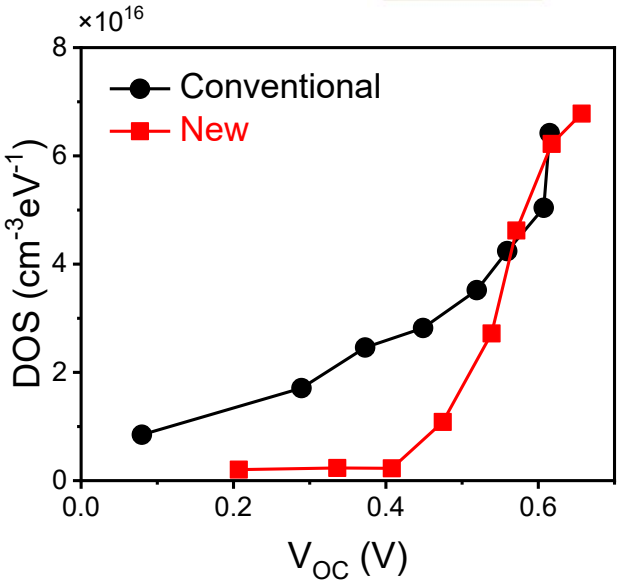
NCs scattering in TiO_2 & QD abs.

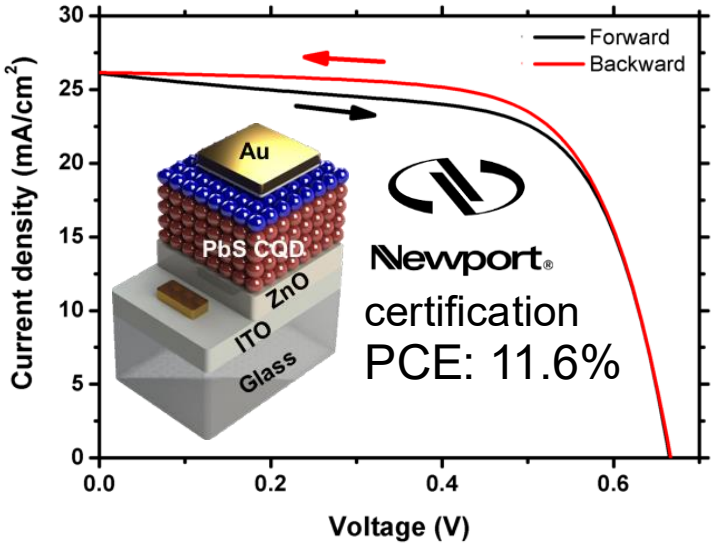


Surface Modifications for Efficient PVs (trap density)

Control of surface defects by solution phase ligand exchange (**Diffusion length**)



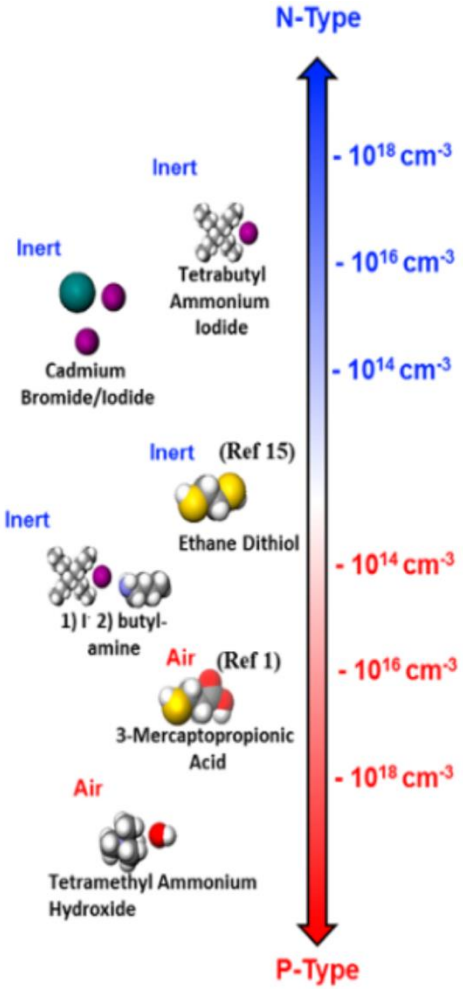




Properties Depending on Surface Modification

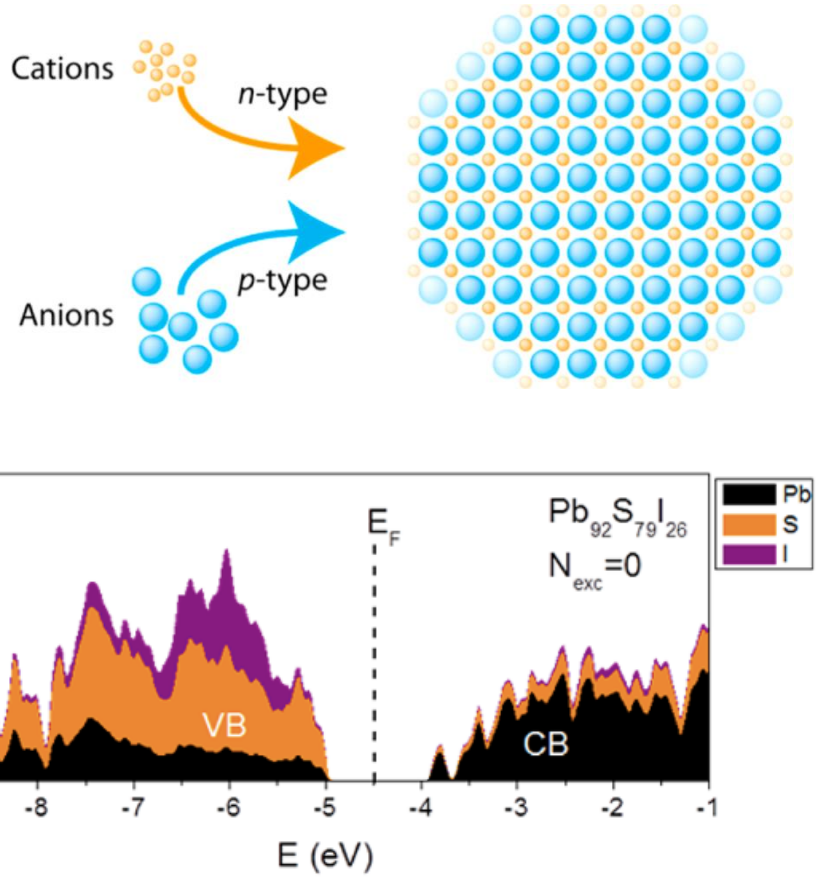
Ligand-dependent Doping

Voznyy et al., *ACS Nano*, 2012, 6, 8448



Stoichiometry Doping

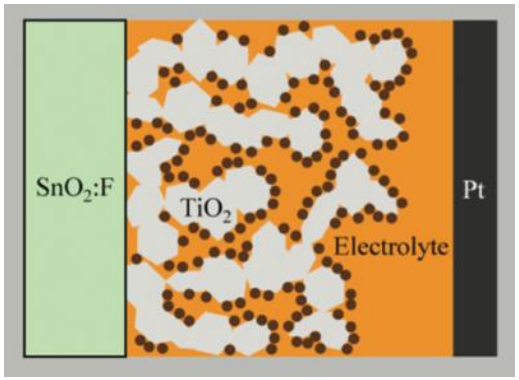
Bozyigit et al. *Nat. Commun.* 2015, 6, 6180



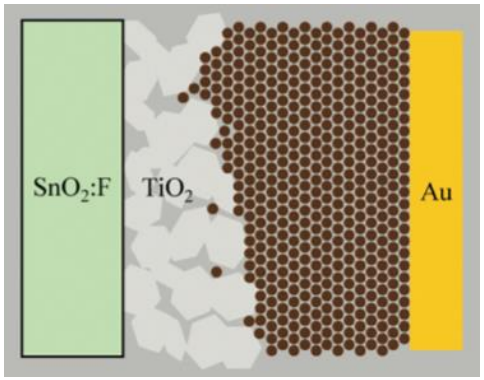
Surface Modifications for efficient PVs (doping)

Various structures of quantum dot solar cells

CQD-sensitized solar cell
(LED 소자와 동작 원리 유사)



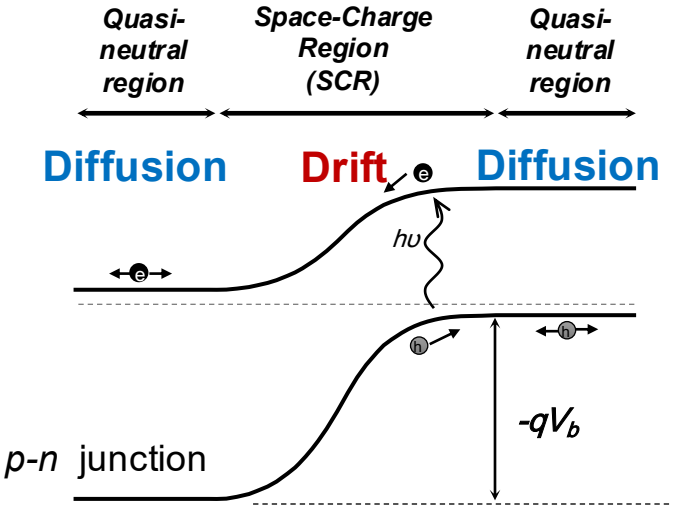
CQD thin film solar cell



장점
우수한 광 흡수

단점
양자점들간 전하 이동 고려 (전기적 물성 제어 필수)

Operating principle of thin-film quantum dot solar cell



전하의 이동

- **Drift** region : Doping concentration, Energy level *etc.*
- **Diffusion** region : Trap density, Mobility, *etc.*

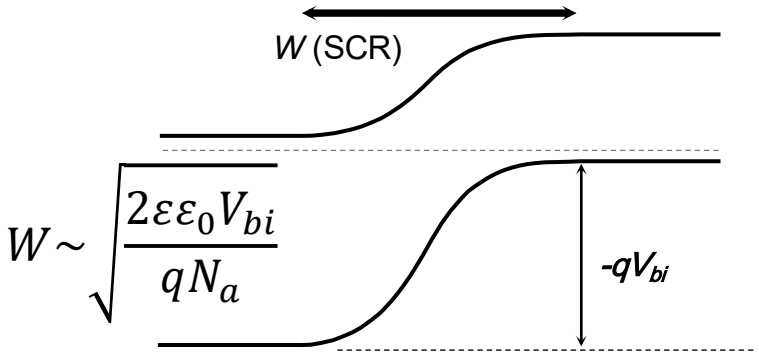
박막형 양자점 태양전지 → **Drift solar cells***

Drift region (~300 nm) > **Diffusion** region (~100 nm)

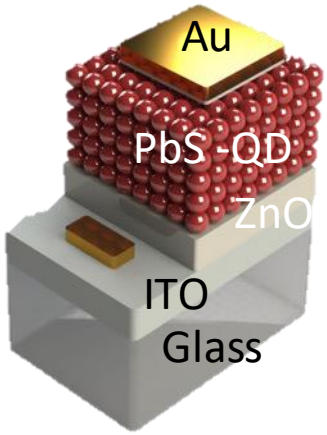
Surface Modifications for efficient PVs (doping)

Space charge region increase by doping concentration (**Drift region**)

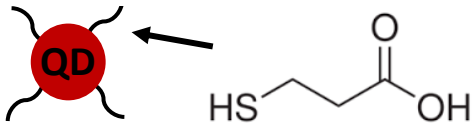
표면 리간드에 따른 도핑 농도 및 SCR 영역 변화



넓은 SCR 영역 ~ 낮은 도핑 농도



Mercaptopropionic acid



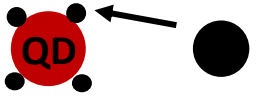
p: ~ 10^{17} cm^{-3}

W: ~ 150 nm

MPA

Iodide

(tetrabutylammonium iodide)

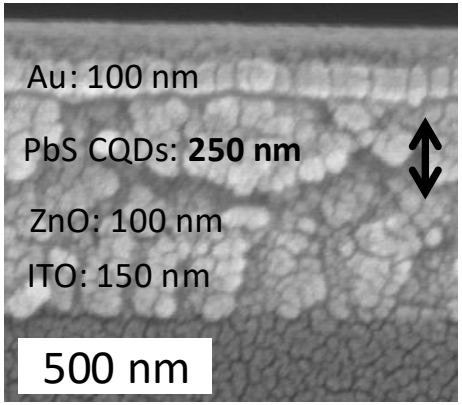


p: ~ 10^{16} cm^{-3}

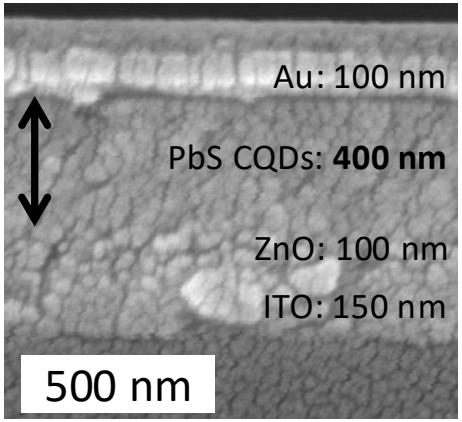
W: ~ 300 nm

TBAI

MPA

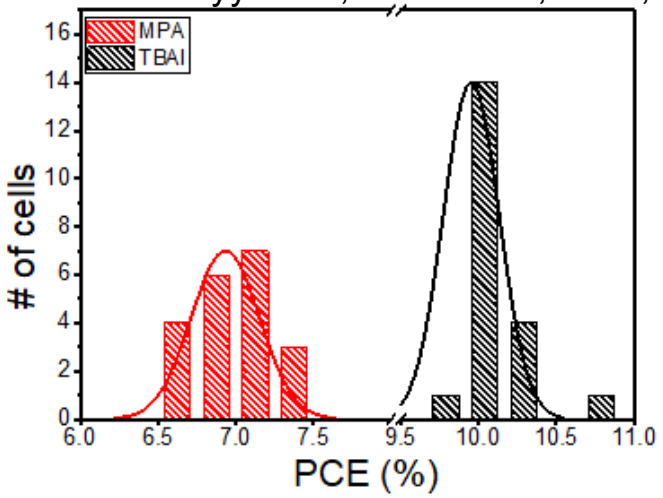


TBAI



J. H. Song et al. *Adv. Mater.*, 2015, 27, 8102

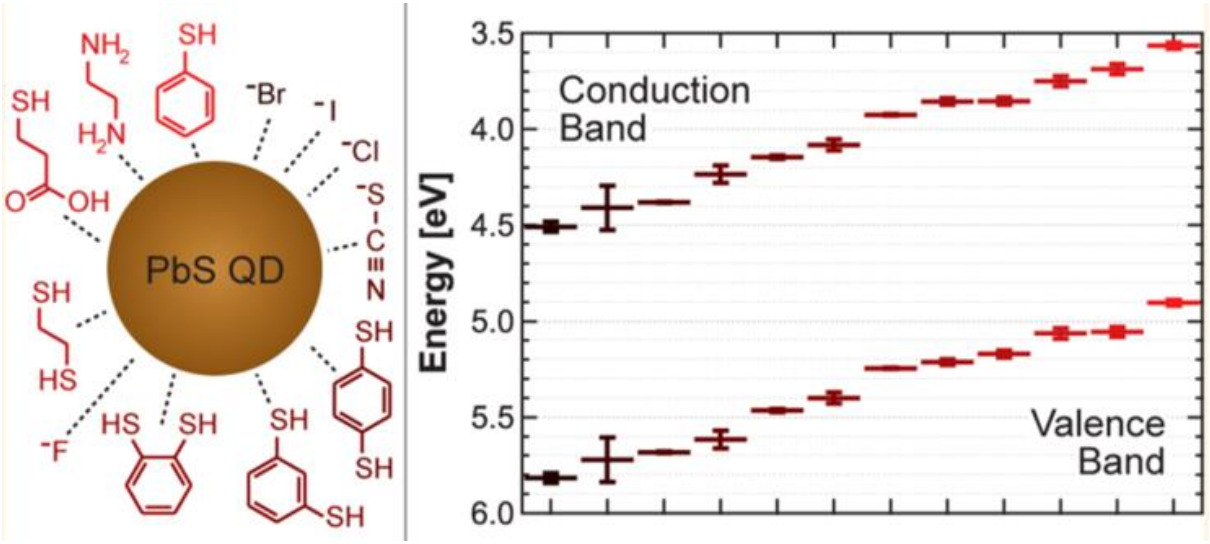
Voznyy et al., *ACS Nano*, 2012, 6, 8448

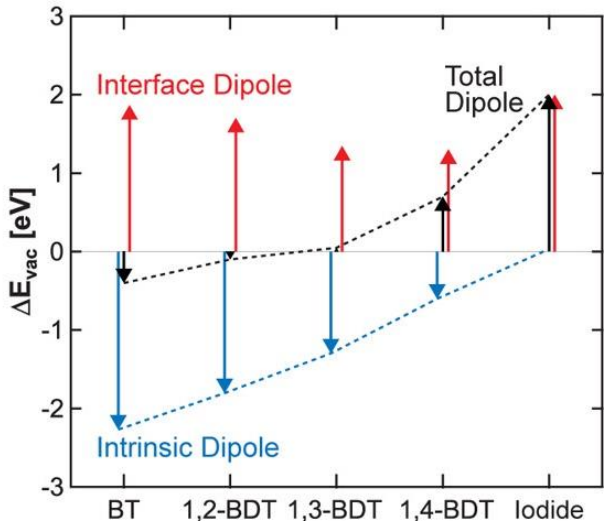


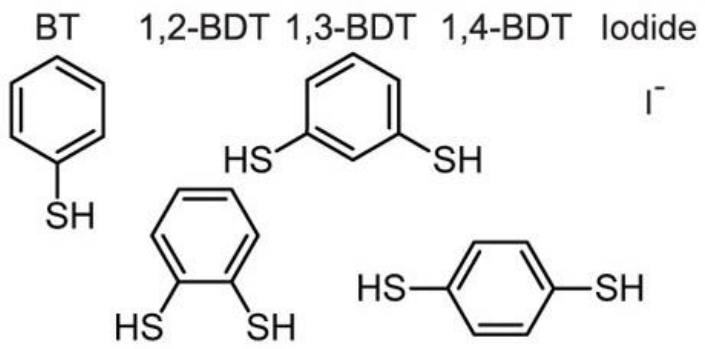
Properties Depending on Surface Modification

Ligand-dependent Energy Level

Brown et al., ACS Nano, 2014, 8, 5863







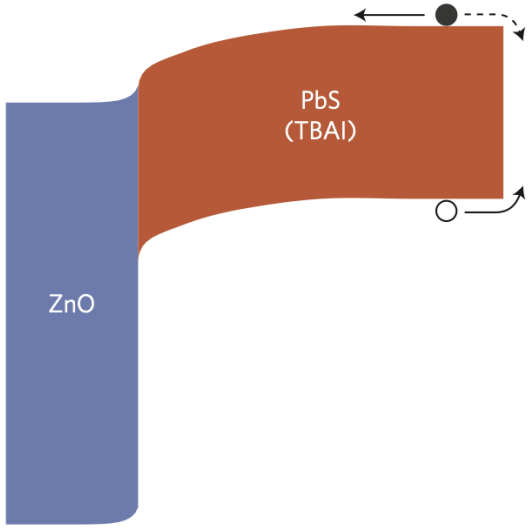
- 표면 리간드 결합에 의한 전자 재분포

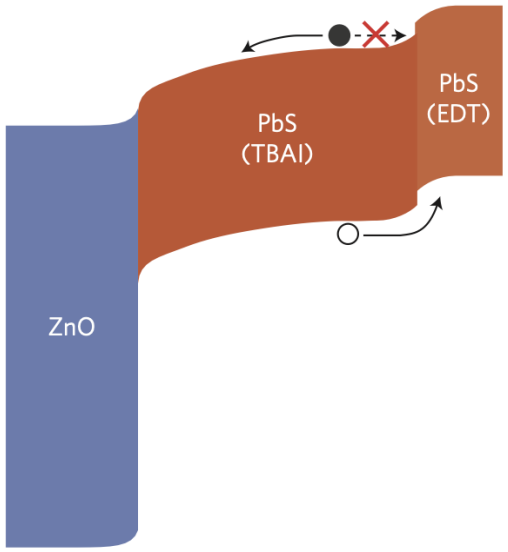
  → surface dipole moment

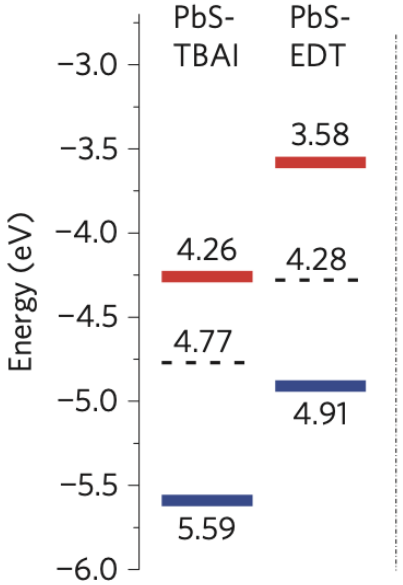
Properties Depending on Surface Modification

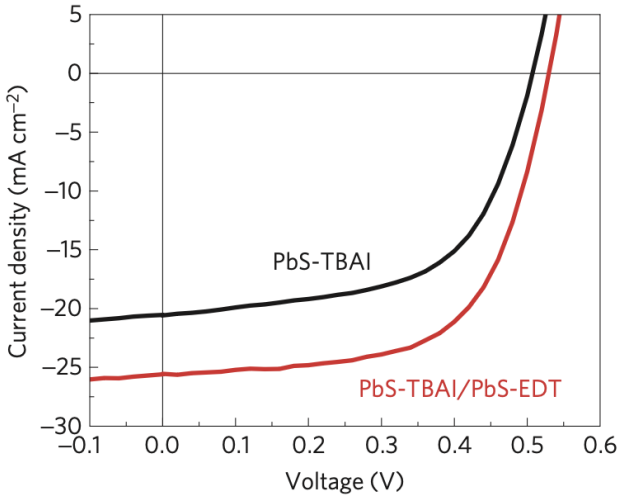
Improved performance through band alignment engineering

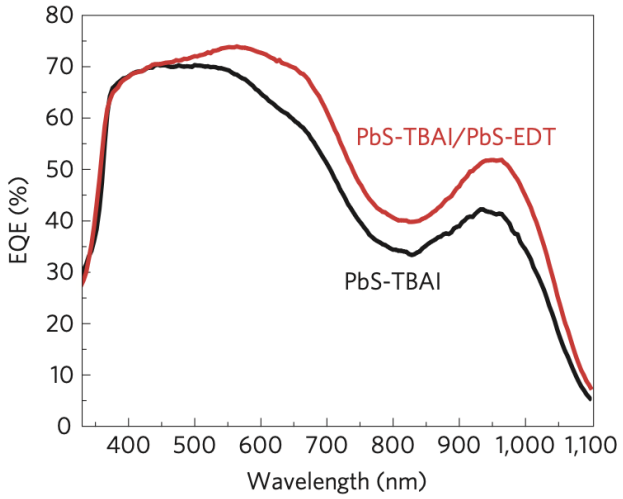
C. M. Chuang et al., Nat. Mater., 2014, 13, 796



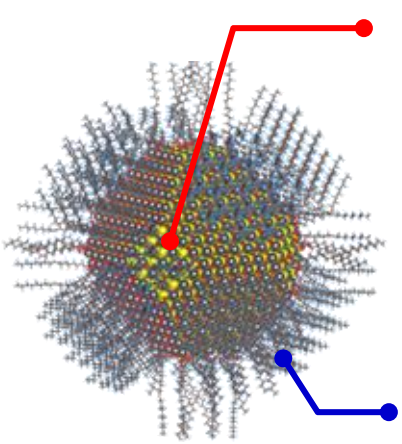


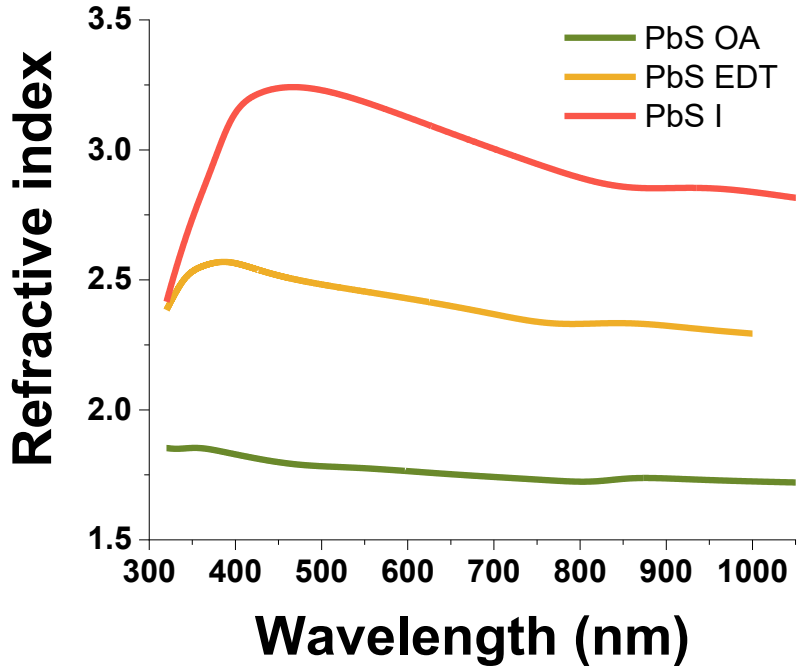




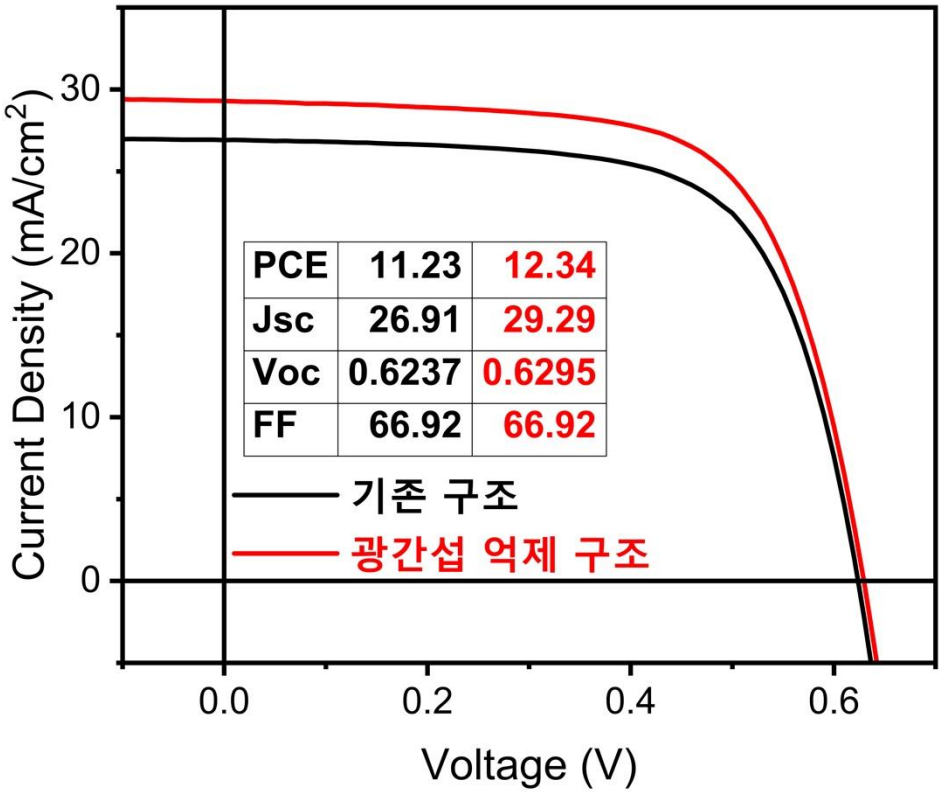


Control of optical Properties by Surface Modification



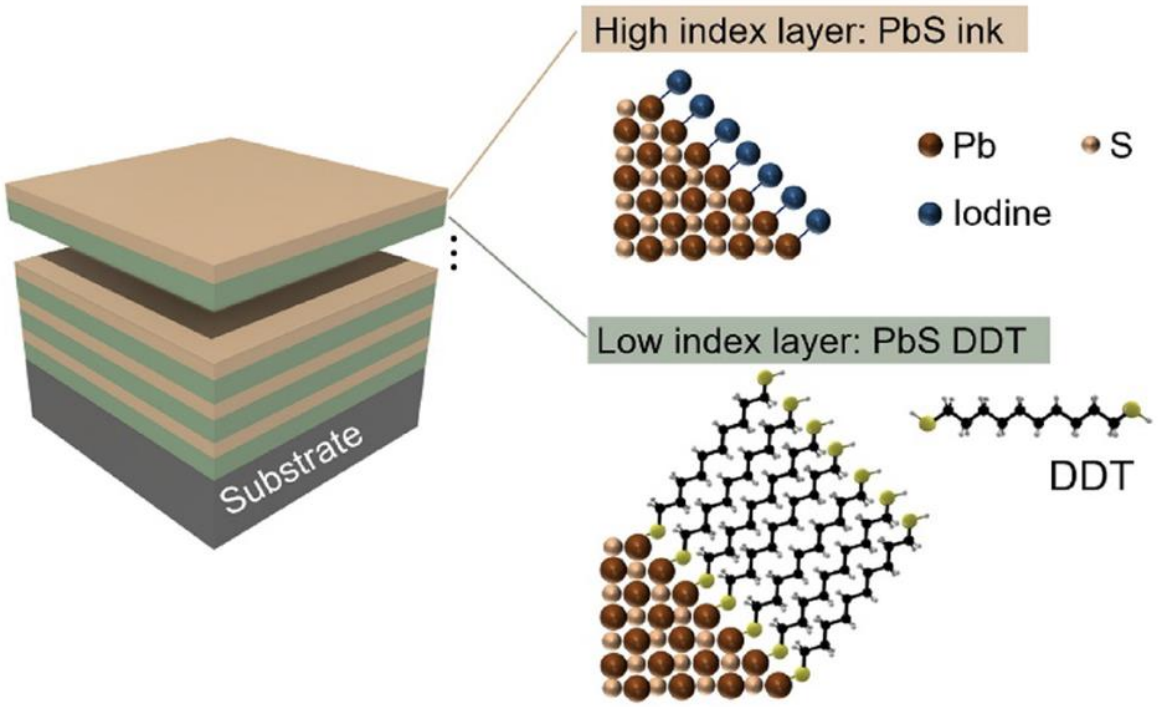


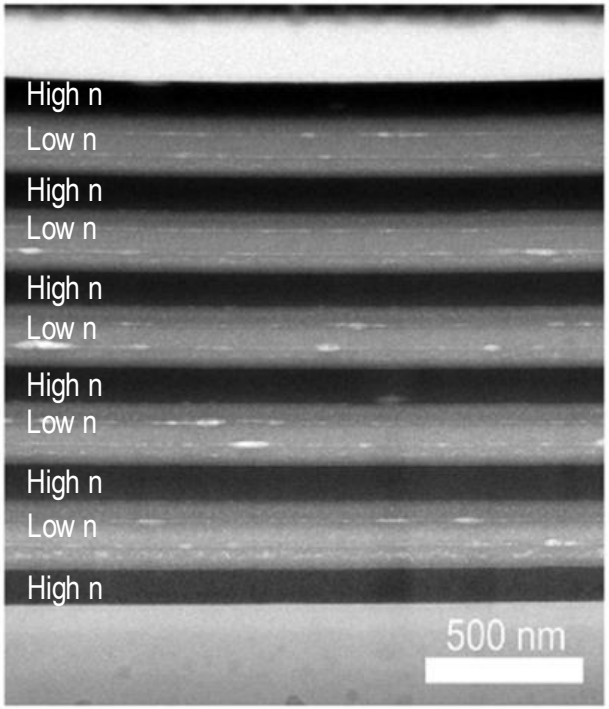
Reflection suppression structure
using refractive index control of QDs



Paper** in **preparation

Control of optical Properties by Surface Modification





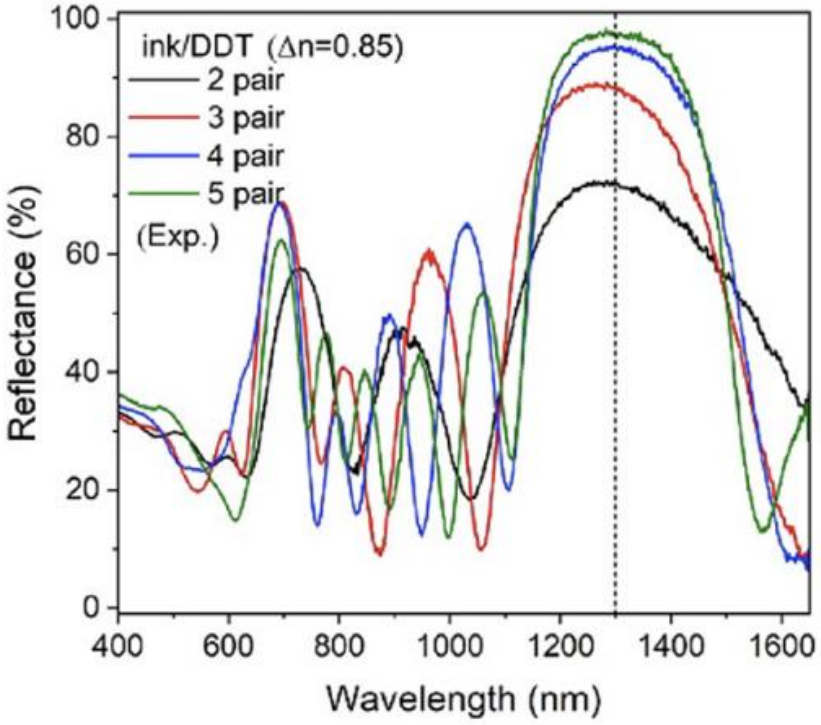
$n_H d_H + n_L d_L = \frac{\lambda_C}{2} \rightarrow \lambda_C = 1300\, nm$

$d_H \sim 121\, nm$

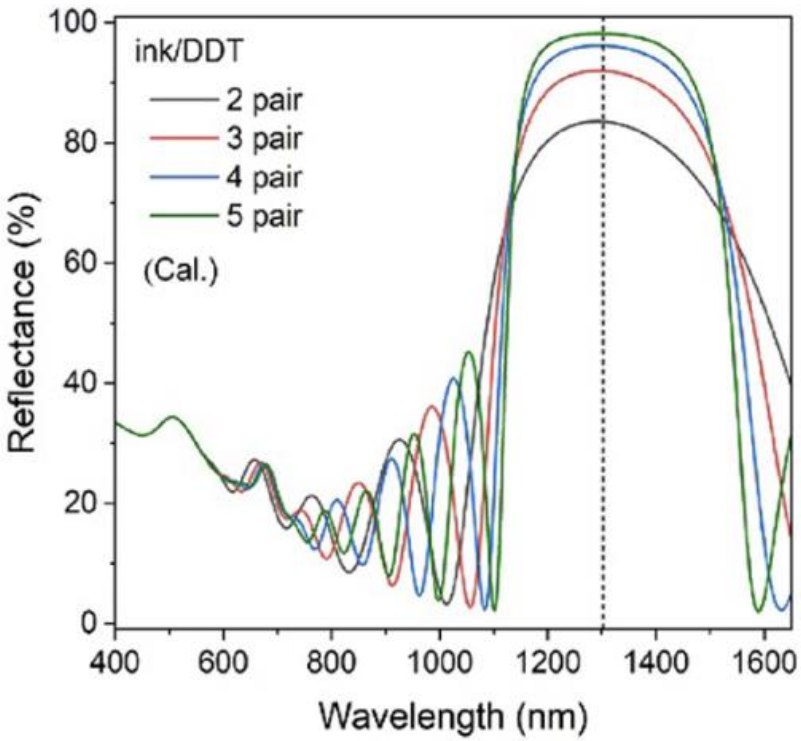
$d_L \sim 177\, nm$

Fabrication of Quantum Dot DBR

Experimental Results



Calculation Results



Ink/DDT → $\Delta n = 0.85$

$n_H d_H + n_L d_L = \frac{\lambda_C}{2} \rightarrow \lambda_C = 1300\, nm$

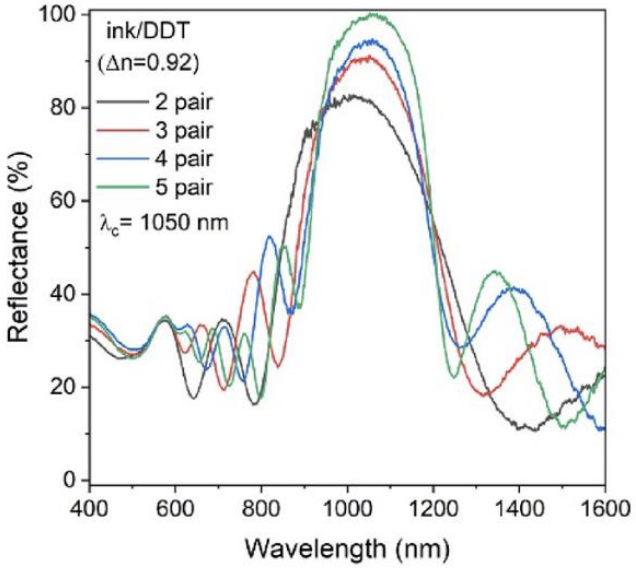
$d_H \sim 121\, nm$

$d_L \sim 177\, nm$

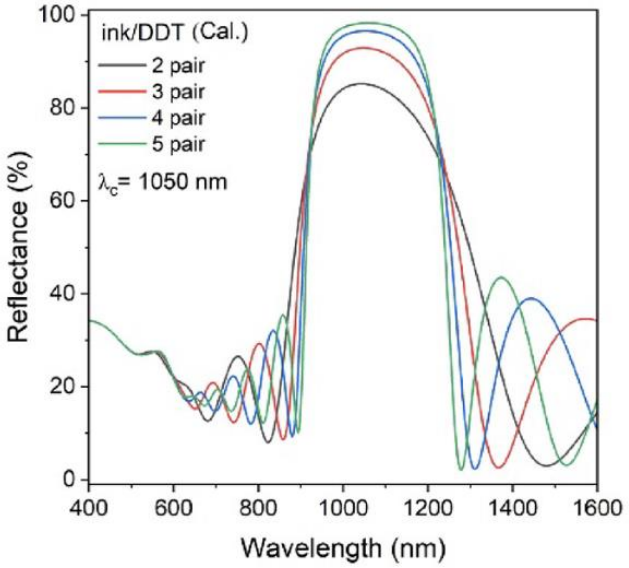
Fabrication of Quantum Dot DBR

$\lambda_C = 1050\ nm$
Ink/DDT ($\Delta n = 0.92$)

Experimental Results

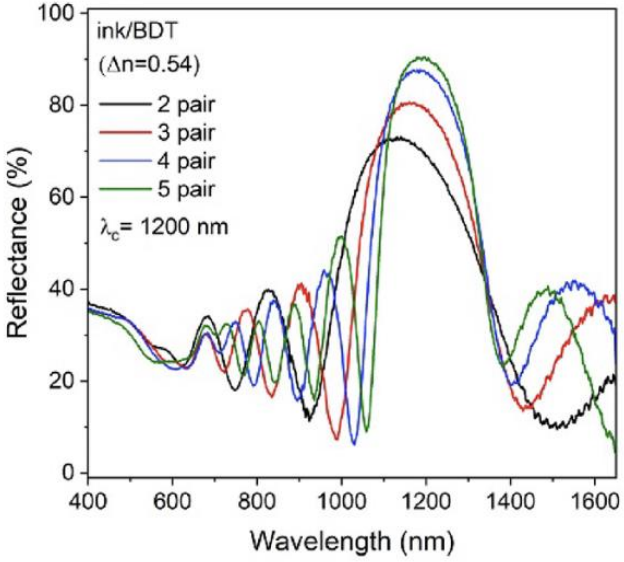


Calculation Results

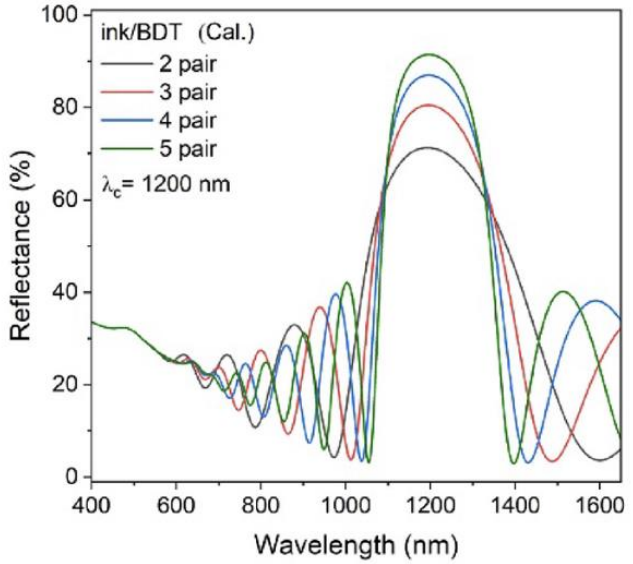


$\lambda_C = 1200\ nm$
Ink/BDT ($\Delta n = 0.54$)

Experimental Results



Calculation Results



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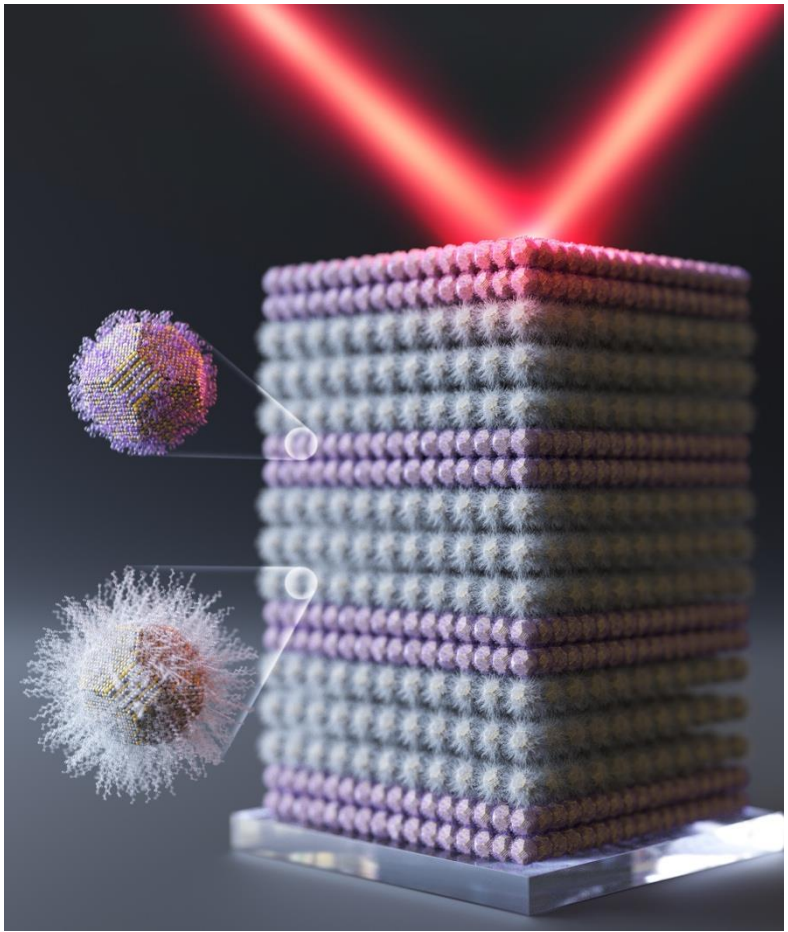
Tunable Infrared Bragg Reflectors of Entirely Ligand-Engineered Lead Sulfide Quantum Dot Layers

Jung Hoon Song, Jugyoung Kim, Moses Kim, Jung-Gyu Park, and Jang-Won Kang*

Cite This: https://doi.org/10.1021/acs.jpcc.5c06300 Read Online

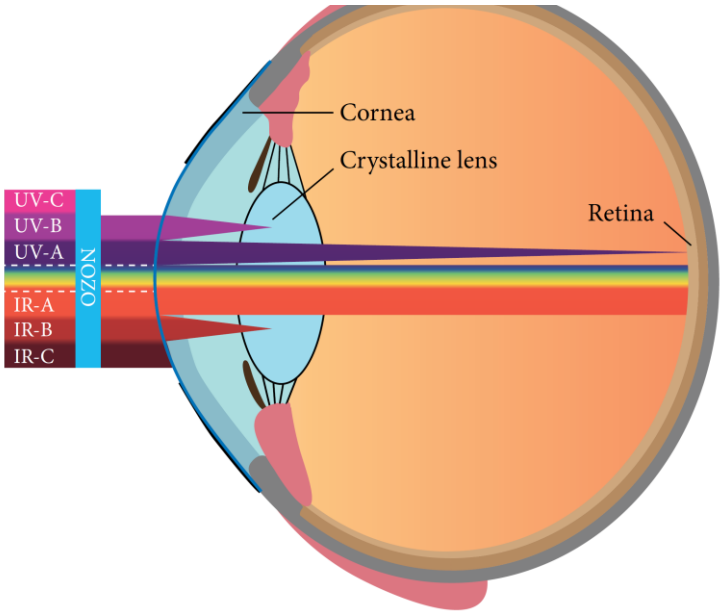


Emerging Applications of CQD Devices

Wireless Charging Systems

Eye-Safety Sensor Systems

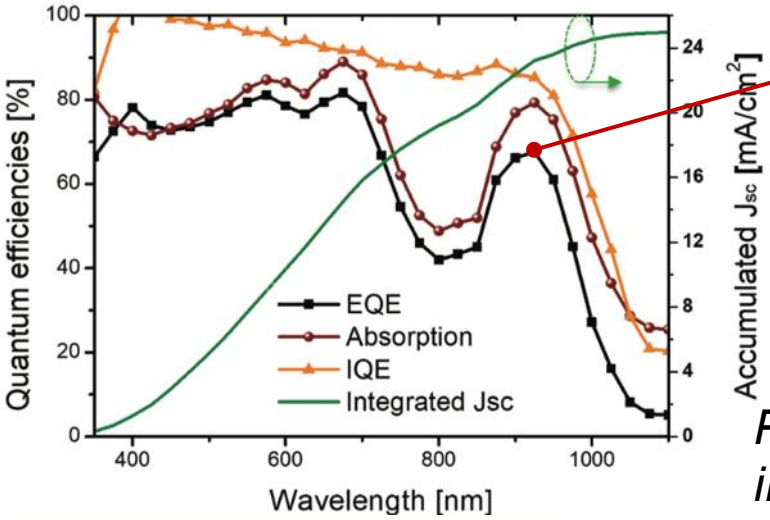
Short-Wave IR (**SWIR**)
1400 ~ 2500 nm



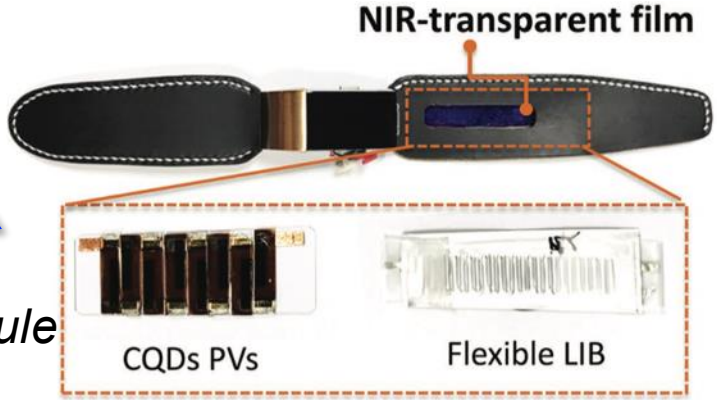
Near IR (**NIR**)
750 ~ 1400 nm

Emerging Applications of CQD Devices

Wireless Charging System Using NIR

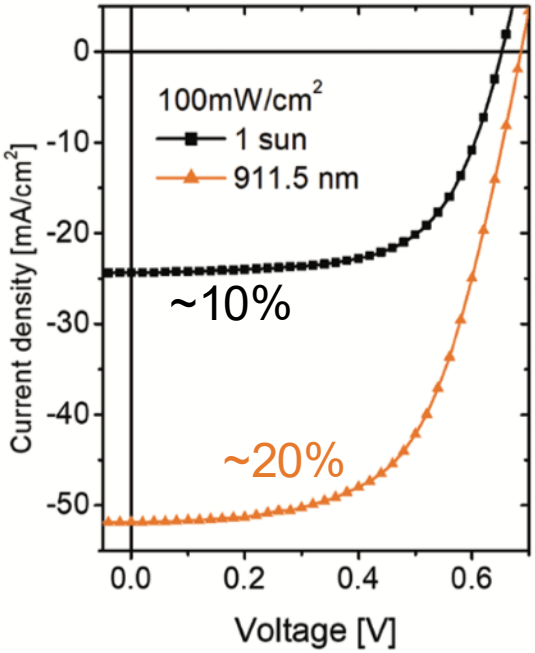


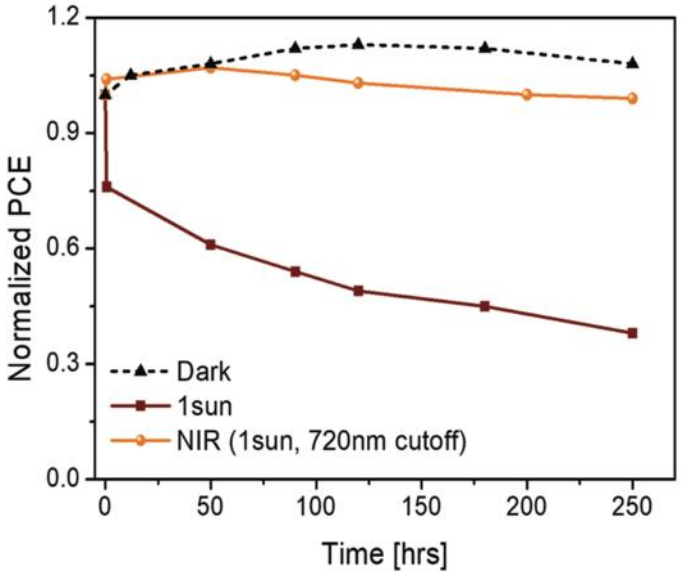
target: ~ 910nm

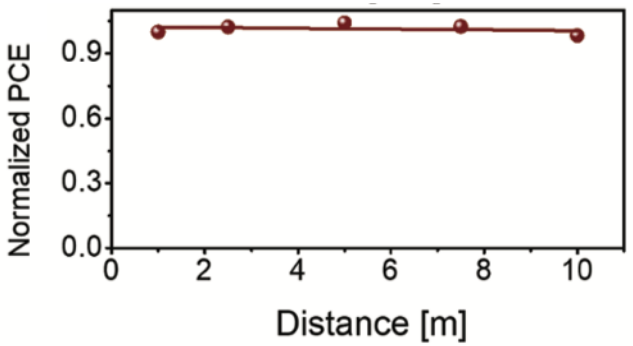


Photovoltaics module integrating 8 cells

New structure





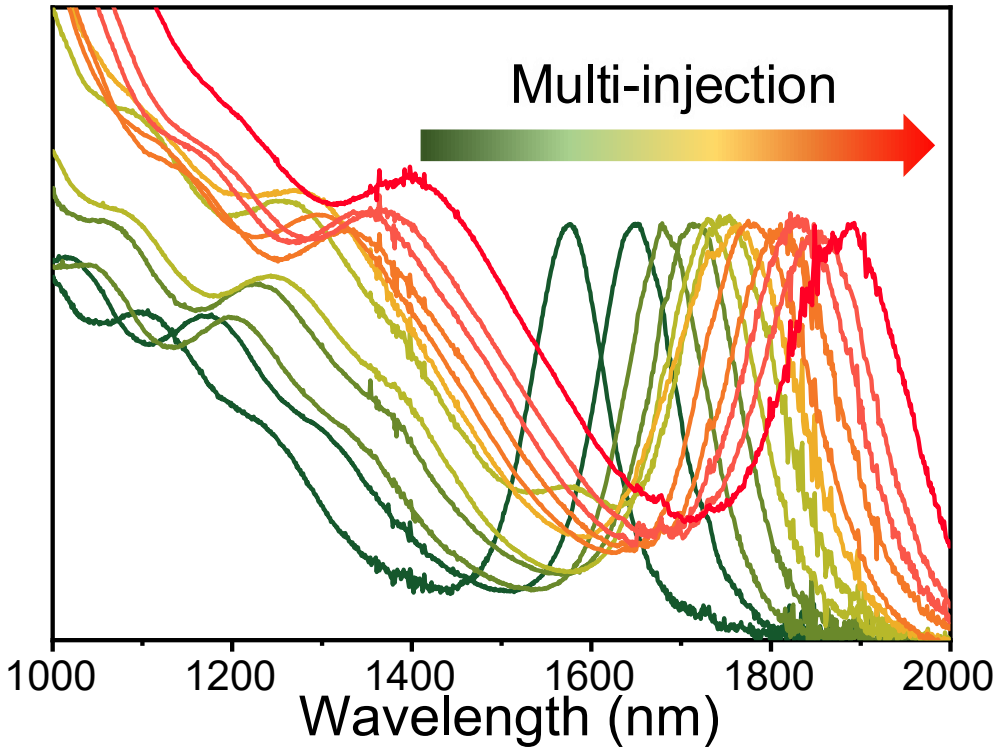


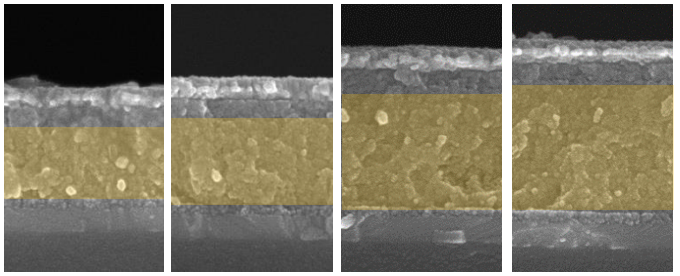
Efficient & Stable operation in NIR

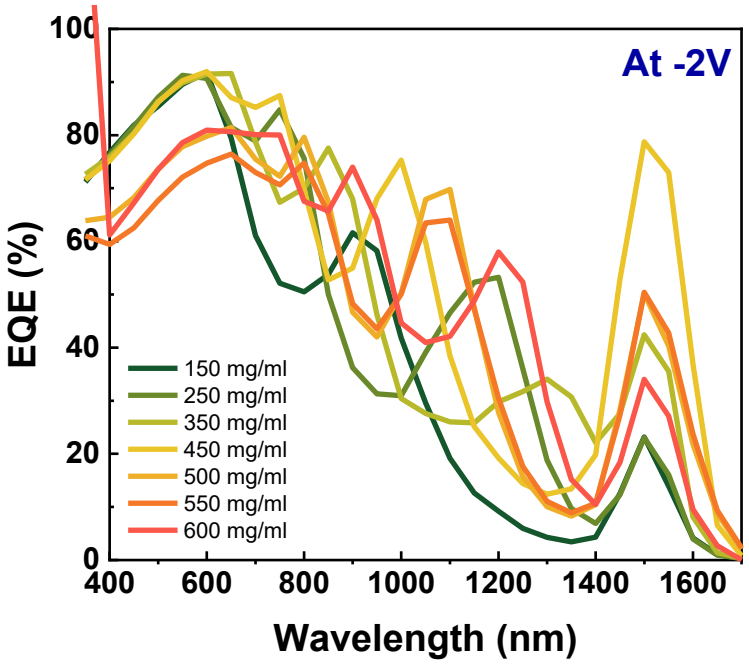
S.-W. Baek et al. *Adv. Mater.*, 2018, 1707224

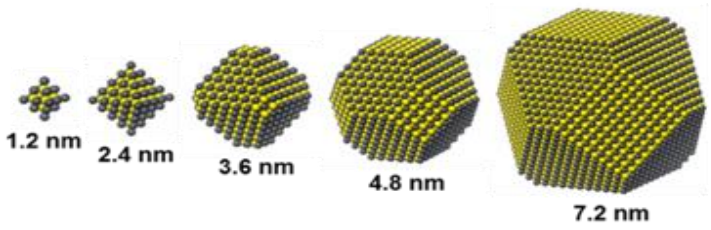
Emerging Applications of CQD Devices

Eye-Safety Sensor System Using CQDs



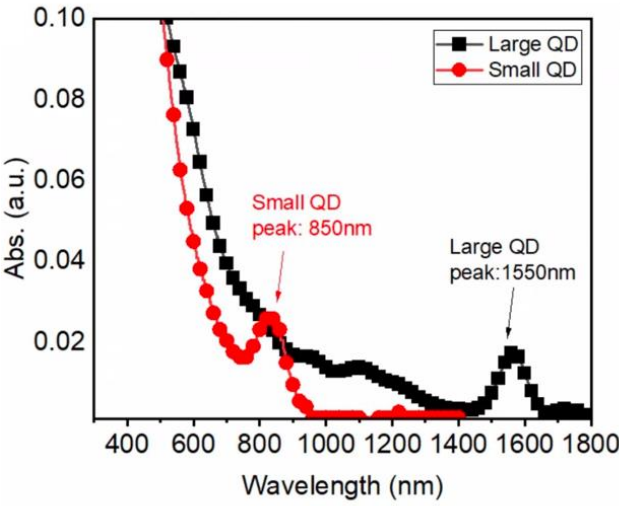


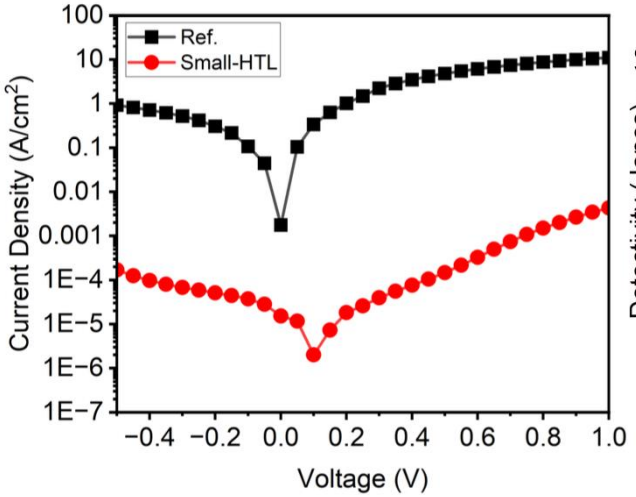


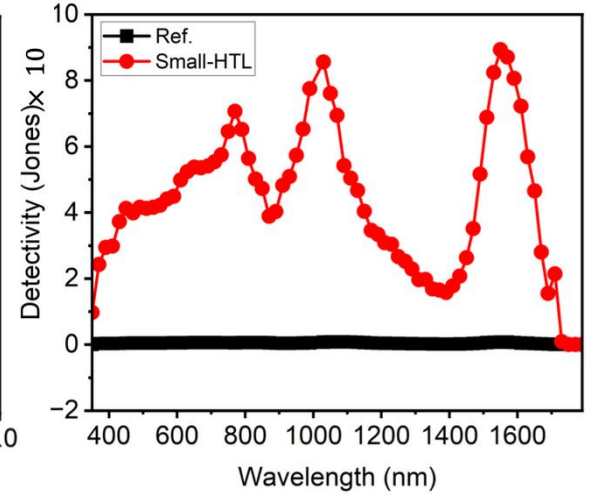


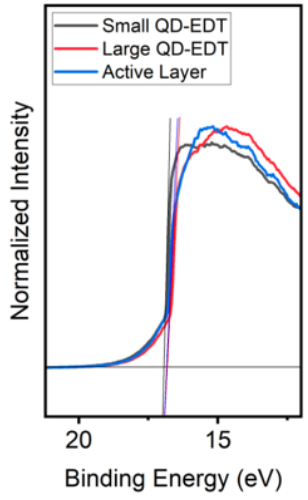
Band Alignment Engineering

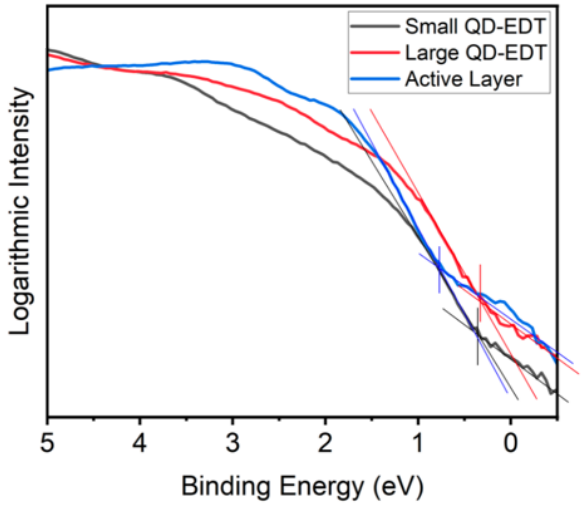
Improved Performance through Ligand-dependent Energy Level

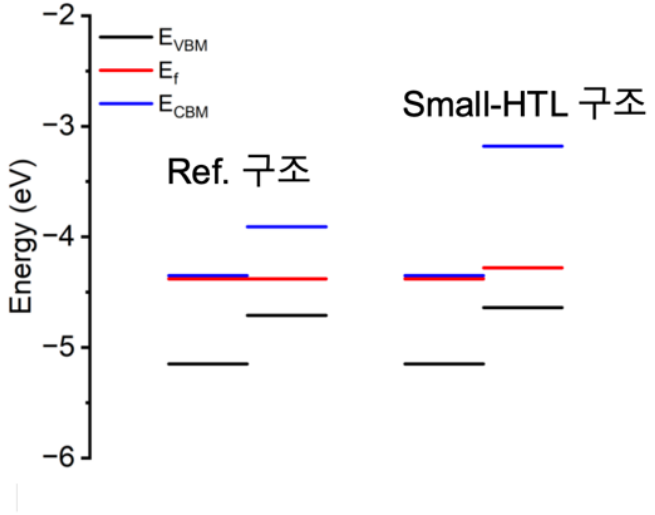






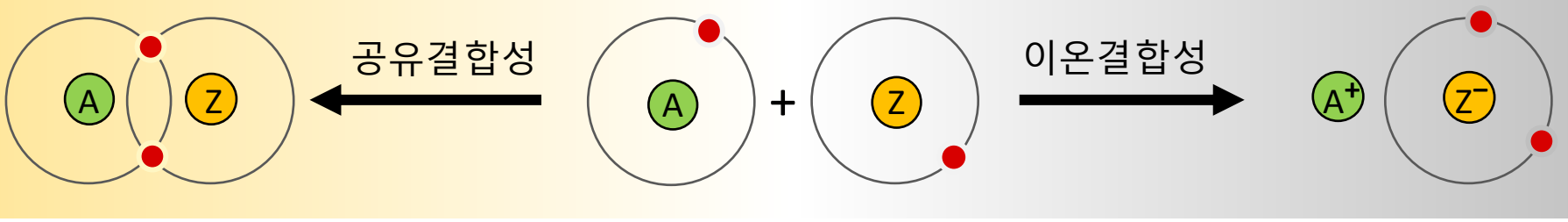




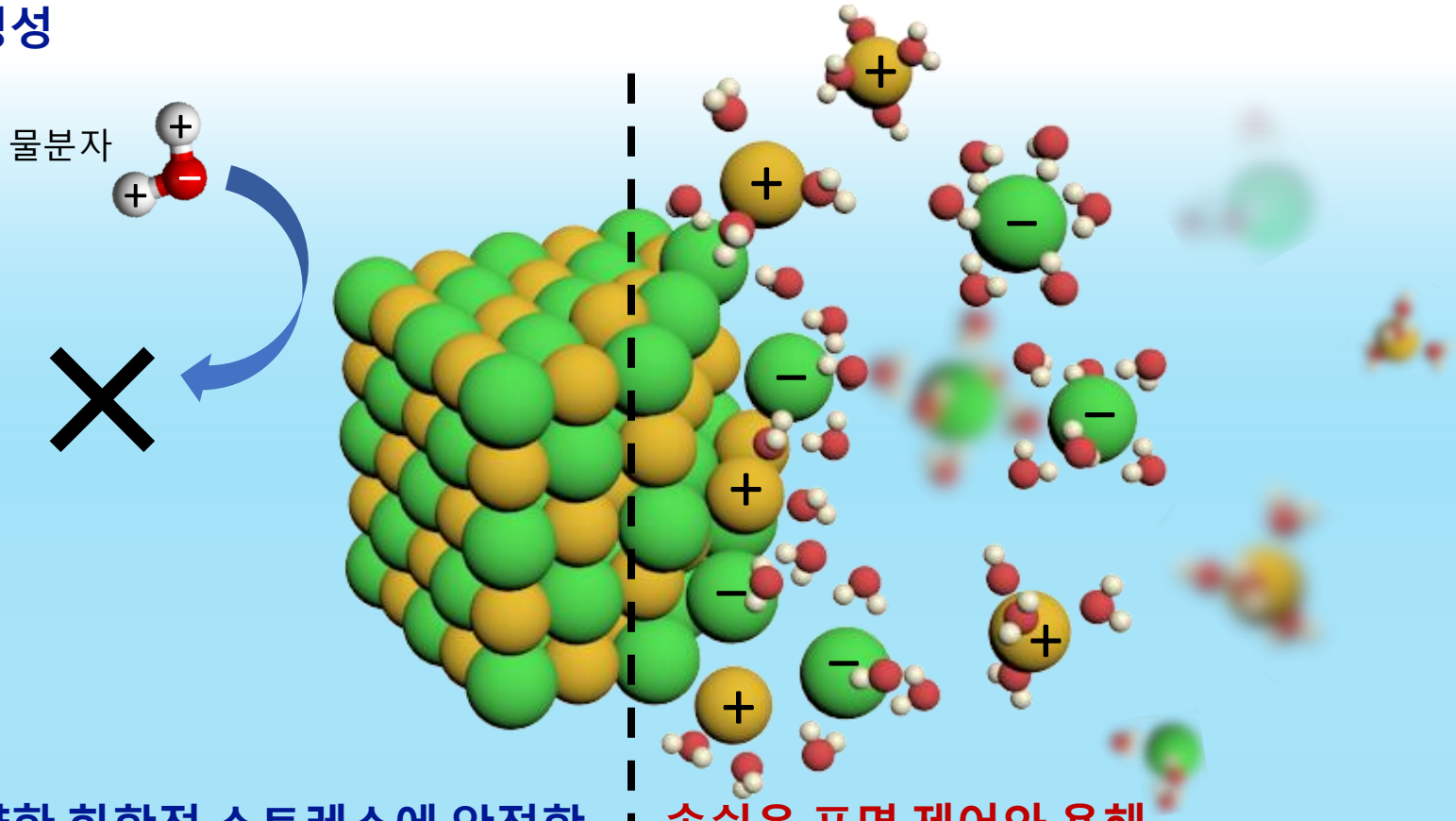


Paper preparation

Quantum Dots with Covalent Crystal



화학적 안정성

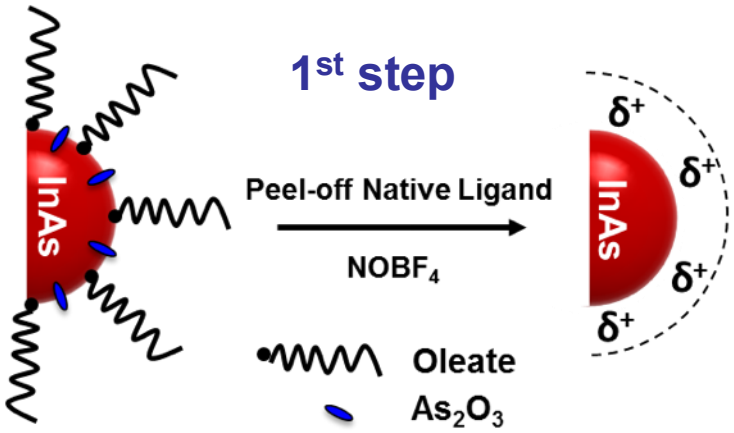


다양한 화학적 스트레스에 안정함
안정한 저독성 소재 ←

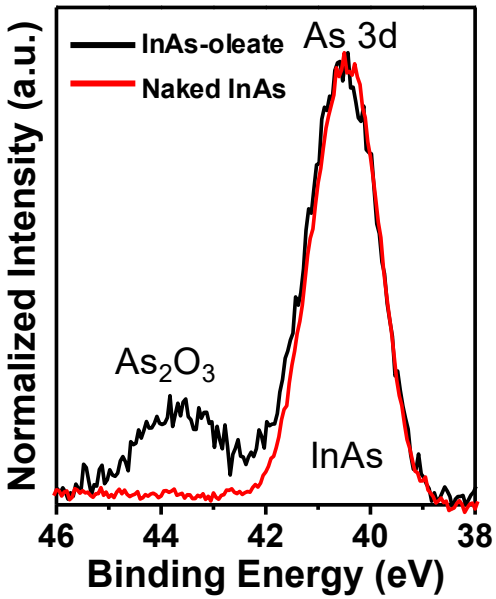
손쉬운 표면 제어와 용해
→ 안정성 및 생체 독성 문제

Surface Modifications of Covalent Crystal QDs

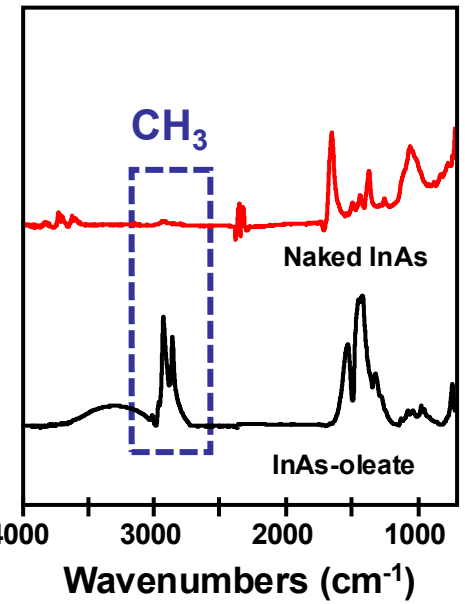
2단계 표면개질 (Two step surface modification) 기술 개발



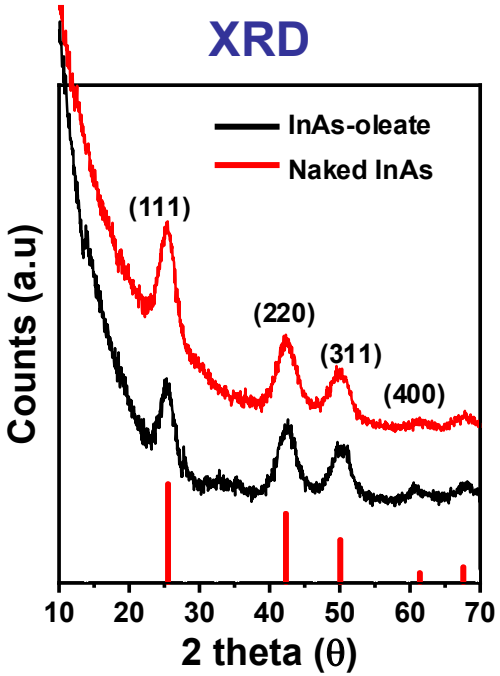
XPS



FT-IR



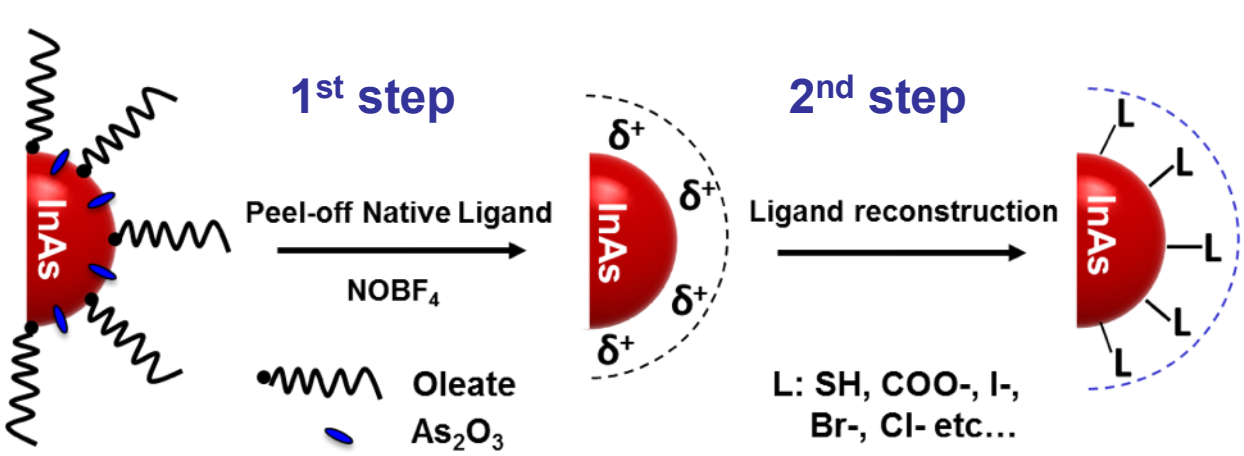
XRD

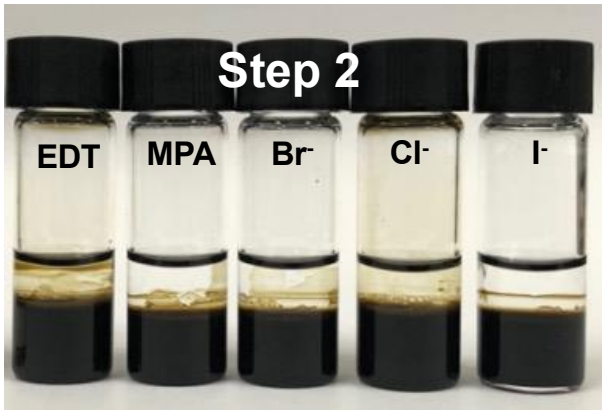


J. H. Song et al. *Nat. Commun.*, 2018, 9, 4267

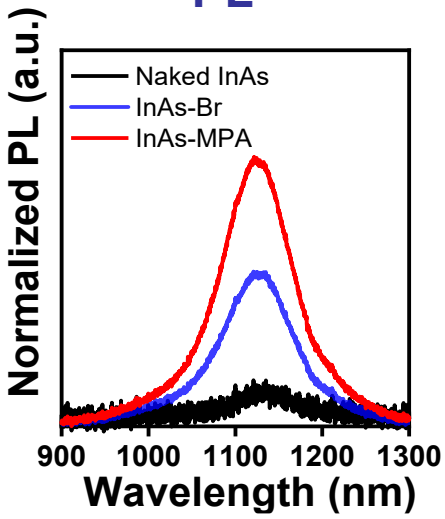
Surface Modifications of Covalent Crystal QDs

2단계 표면개질 (Two step surface modification) 기술 개발

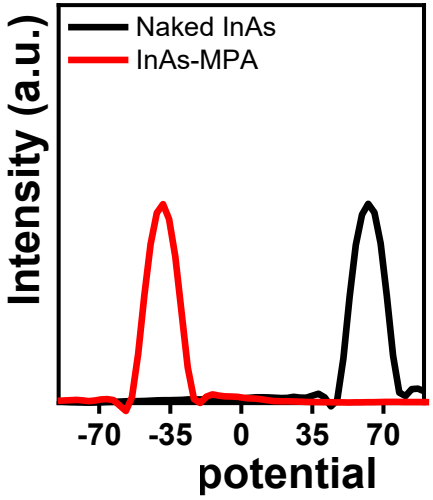




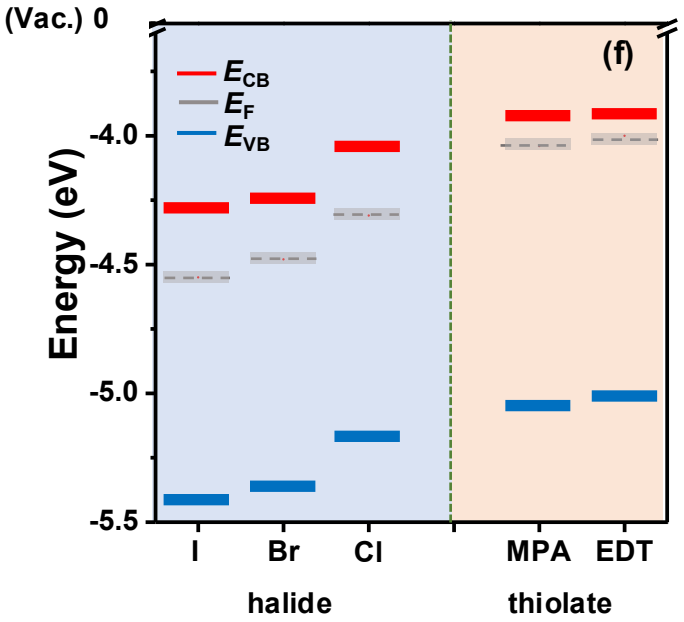
PL



Zeta potential



UPS



J. H. Song et al. *Nat. Commun.*, 2018, 9, 4267

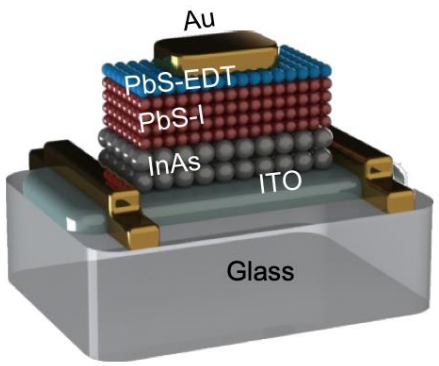
Fabrication of Solar Cells using Covalent Crystal QD

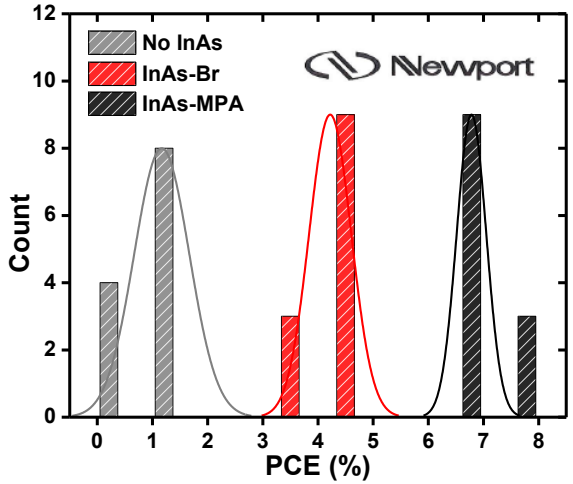
Analysis of physical properties of covalent crystal QDs

Materials	Mobility ($cm^2 V^{-1} s^{-1}$)	Carrier Concentration (cm^{-3})	Trap Density (cm^{-3})	Diffusion Length (nm)
InAs–Br	1.55×10^{-3} (FET) 1.34×10^{-3} (3D PL)	2.77×10^{16} (FET) 4.65×10^{16} (*C–V*)	3.32×10^{17} (3D PL)	30 (3D PL)
InAs–MPA	2.25×10^{-3} (FET) 1.78×10^{-3} (3D PL)	1.28×10^{17} (FET) 1.27×10^{17} (*C–V*)	1.24×10^{17} (3D PL)	60 (3D PL)

Device for Covalent Crystal QD Applications

Key Issue:
- *High doping concentration*
- *Only n-type doping polarity*
- *Short diffusion length*

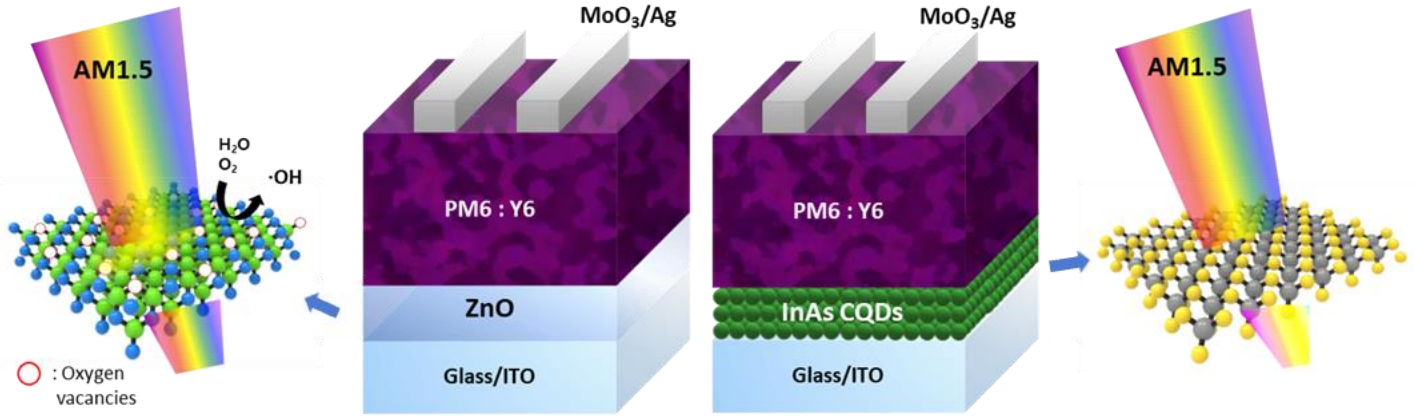


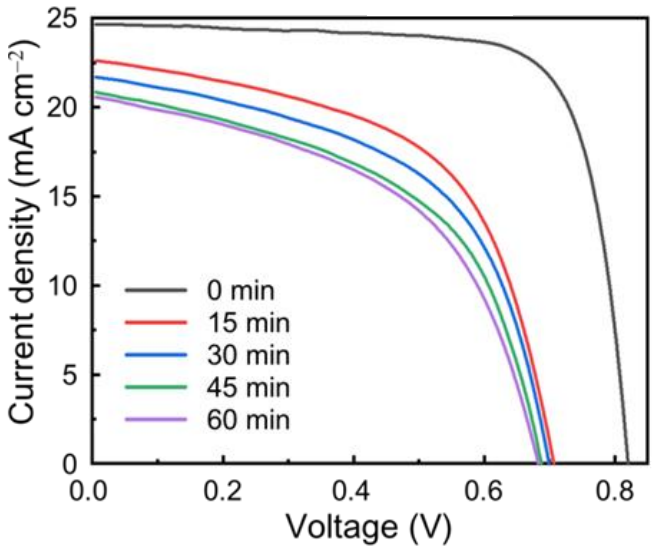


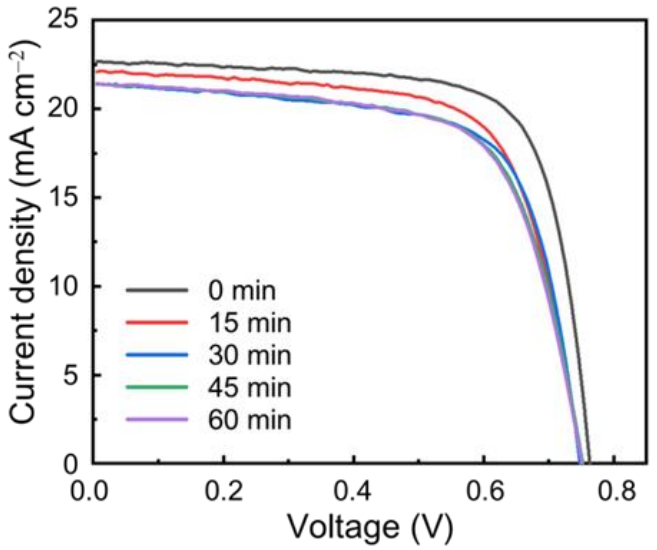
J. H. Song et al. *Nat. Commun.*, 2018, 9, 4267

Fabrication of Solar Cells using Covalent Crystal QD

Charge-Selective, Narrow-Gap InAs QD for Highly Stable and Efficient Organic Photovoltaics

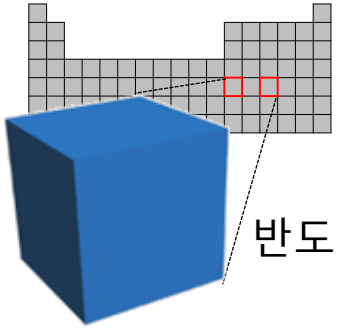






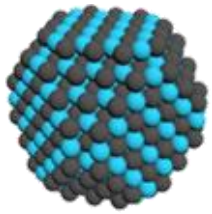
Y. Park et al. *Adv. Mater.*, 2022, 12, 2104018

Conclusion



반도체 소재 AZ

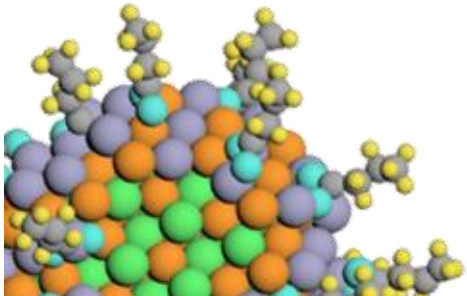
양자점 합성
소재의 저차원화



양자점 소재

표면 개질
최외각 껍질층 제어

전범위에 걸친 전자준위의 자유로운 조절:
전자의 형성, 천이, 분리, 이동을 자유자재로 제어



양자점 소재의 전자 구조 연속 제어

→ 양자점 합성과 표면개질의 조합을 통해 자유로운 물성 제어 가능 → 전자소자의 특성 극대화

Acknowledgement

Keit
한국산업기술평가관리원

시장 주도형 K-센서기술개발
(저가형 eye-safe 대역 SWIR 센서)

OLED 한계 돌파형 사용화 제품을 위한 기술개발
(QD-OLED 시장 확대를 위한 광변환층용 고흡수/고신뢰성 양자점재료 개발)

SAMSUNG
삼성디스플레이

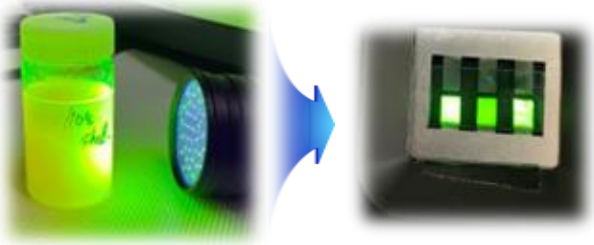
Post-InP QD 개발

소자제작 (용액공정)

양자점 합성

소자제작 (전극 및 박막제작)

LED



PD, PV

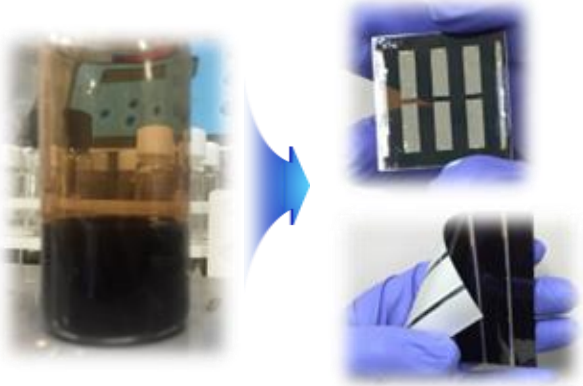
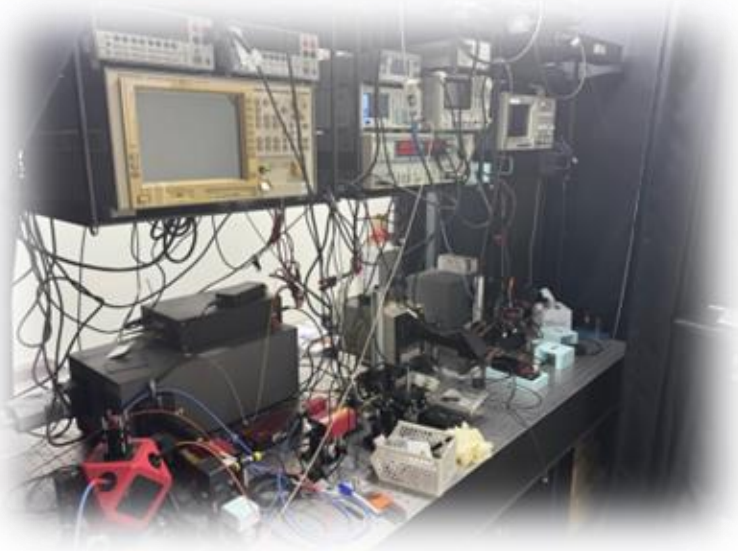


Photo & E-beam Lithography

양자점 소재 특성 분석



양자점 소재 분석 종류

- 흡광 & 발광 분석

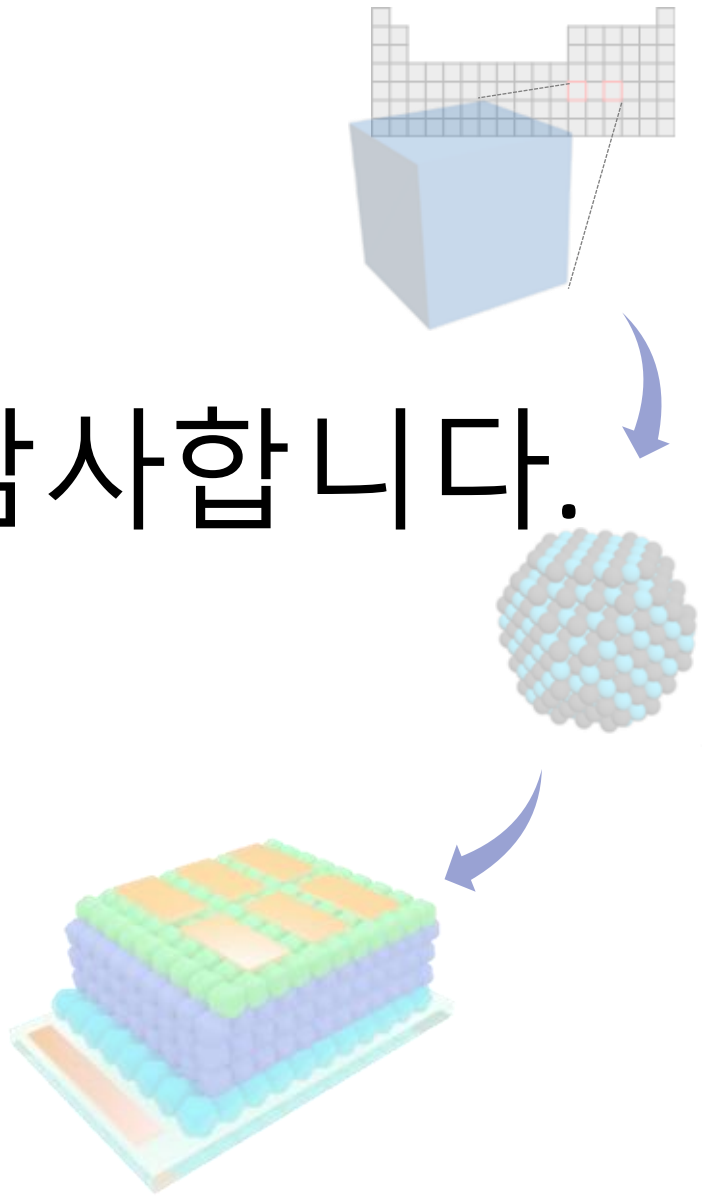
405nm, 450nm, 630nm, 1550nm 레이져

양자점 소자 특성 분석

양자점 소자 분석 종류

- IV 특성 분석
- Solar cell: PCE 분석
- LED: L-I-V 특성 분석
- ToF 분석
- Photo CELIV 분석
- EQE & Resonsivity 분석
- C-V 특성 분석

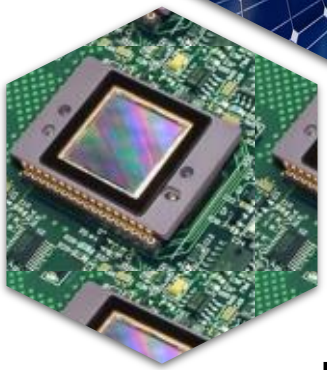
경청해 주셔서 감사합니다.



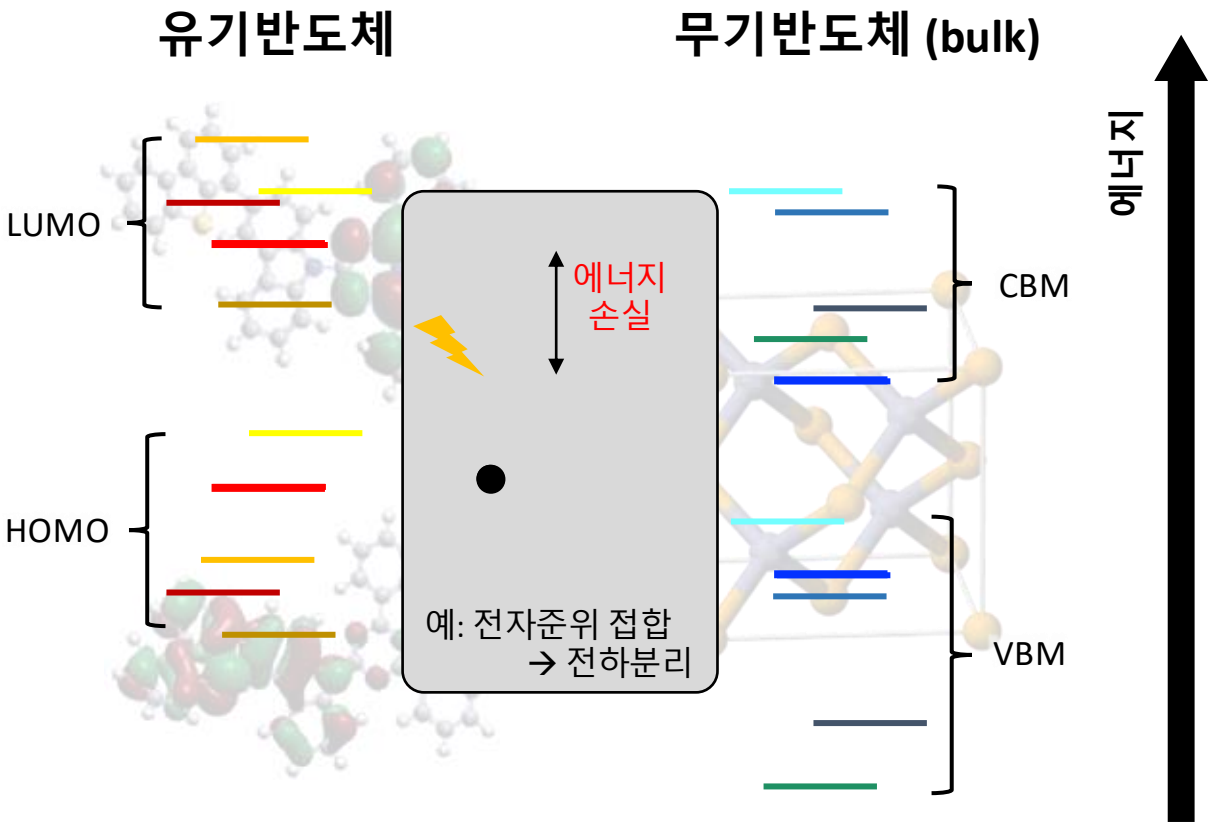
Conclusion

발광소자

태양전지



검출소자



반도체는 현대 전자부품의 핵심 소재

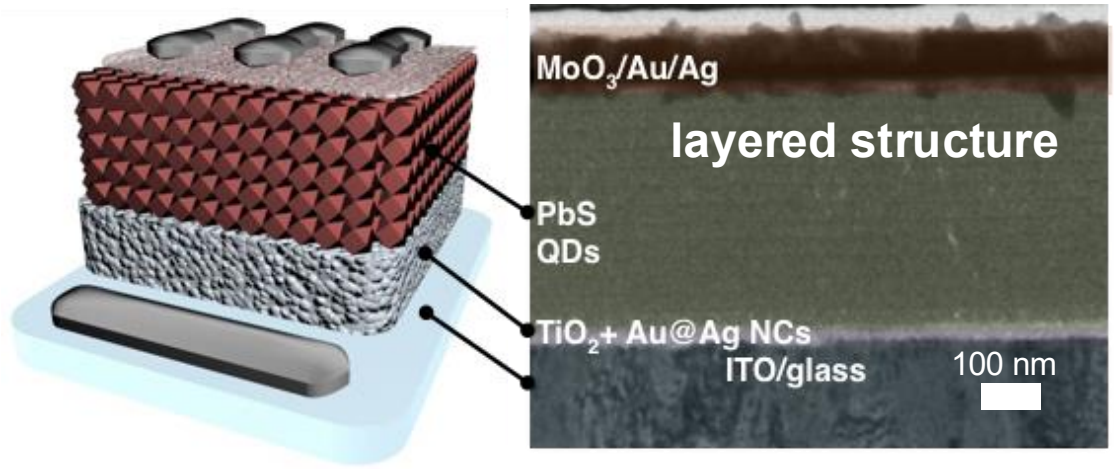
- 다양한 전자준위의 조합을 통한 광/전기/화학적 특성 발현
- 전하의 이동에서 전자준위의 차이는 에너지의 손실로 이어짐

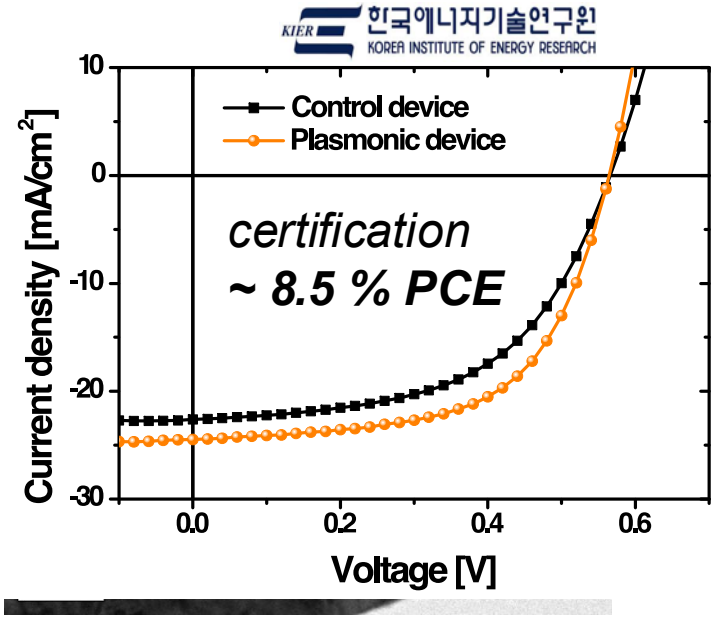
→ 표면 개질을 이용한 **전자준위의 연속적인 제어**

Properties Depending on Surface Modification

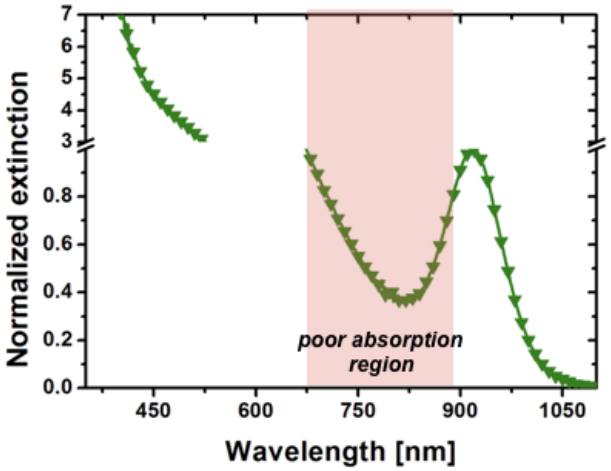
CQD Solar Cell using LBL Process

J. H. Song, et al., *Adv. Mater.,* 2015, 27, 8102

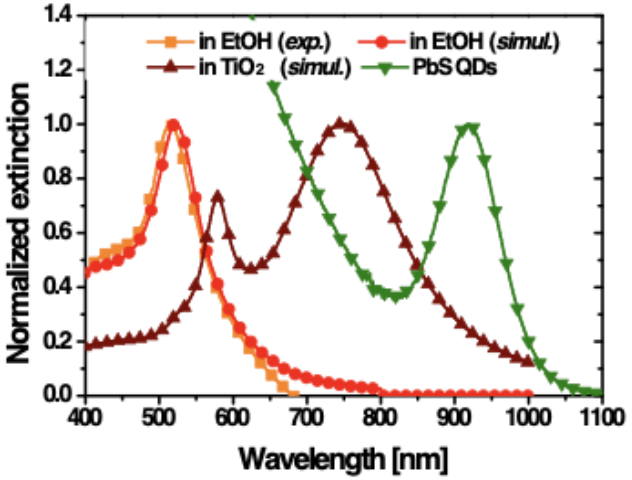




External quantum efficiency & absorption in solar cells



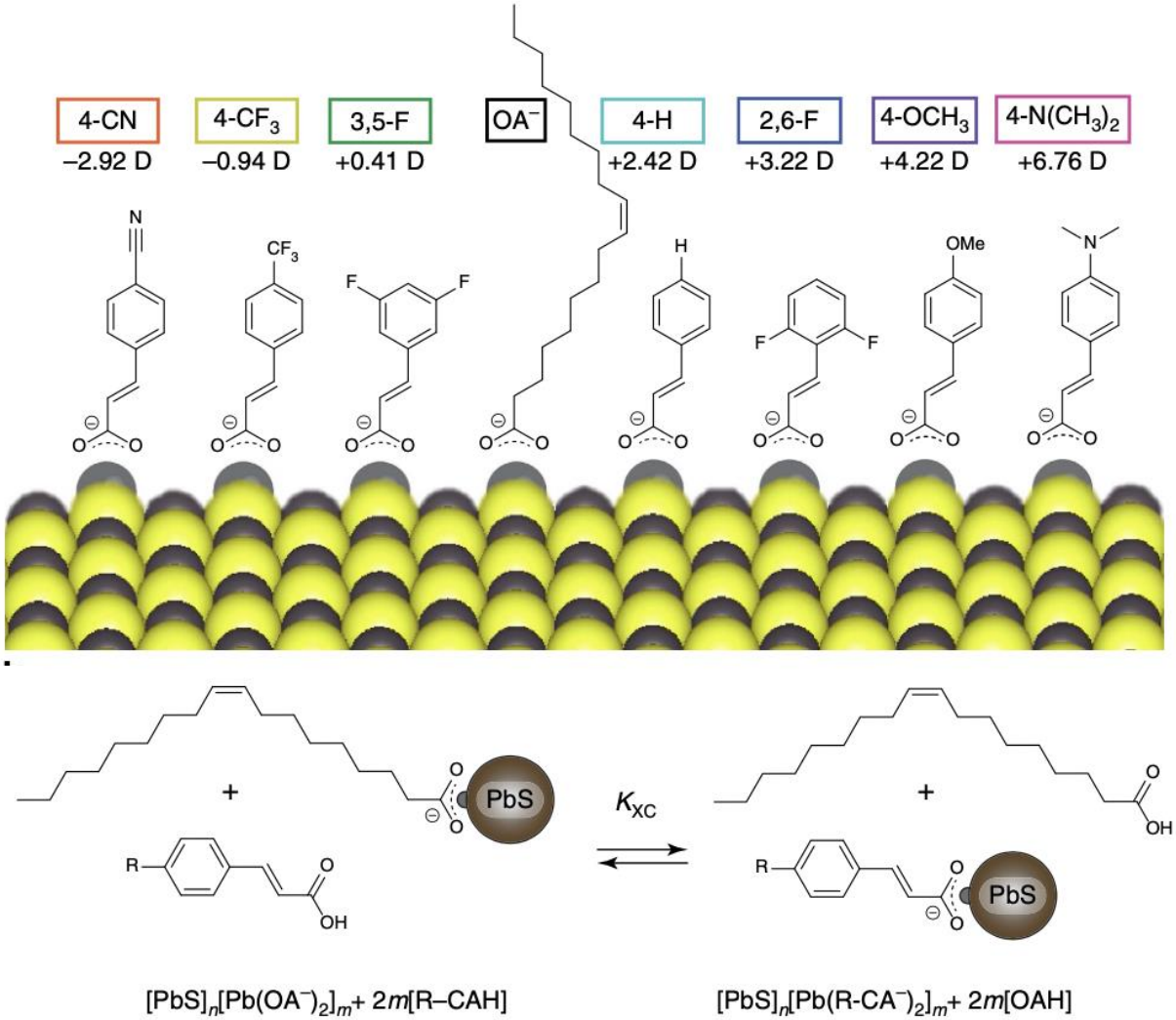
NCs scattering in TiO_2 & QD abs.



Properties Depending on Surface Modification

Ligand-dependent Energy Level

D. M. Kroupa et al., Nat. Commun., 2017, 8, 15257



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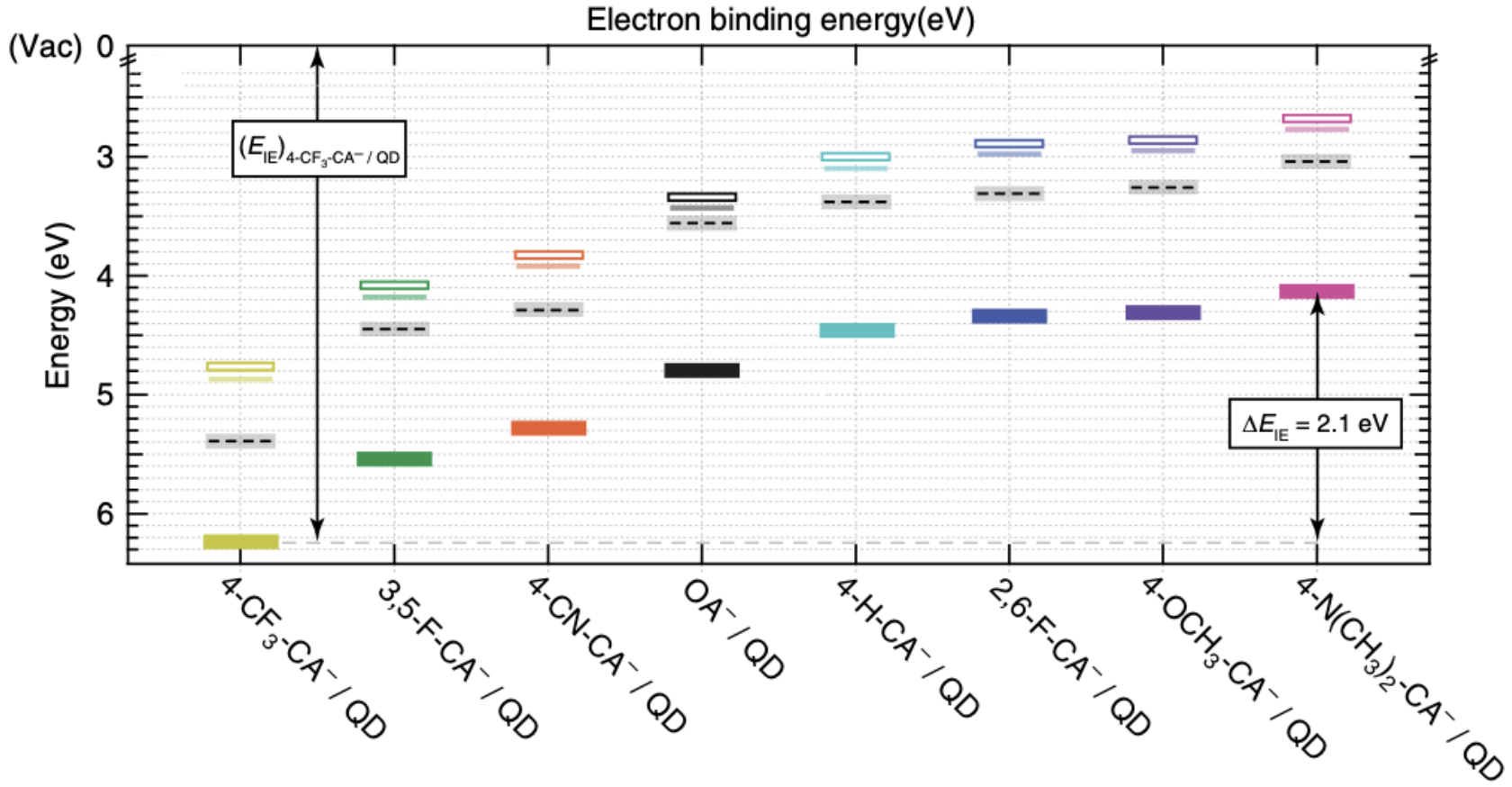
Ligand-dependent Energy Level

D. M. Kroupa et al., Nat. Commun., 2017, 8, 15257



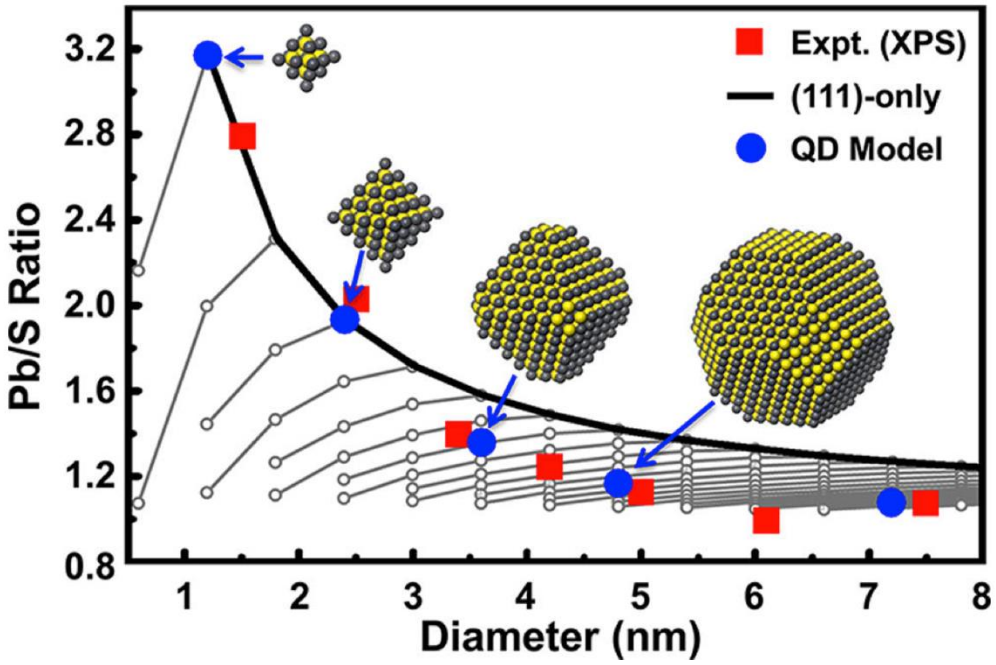
Properties Depending on Surface Modification

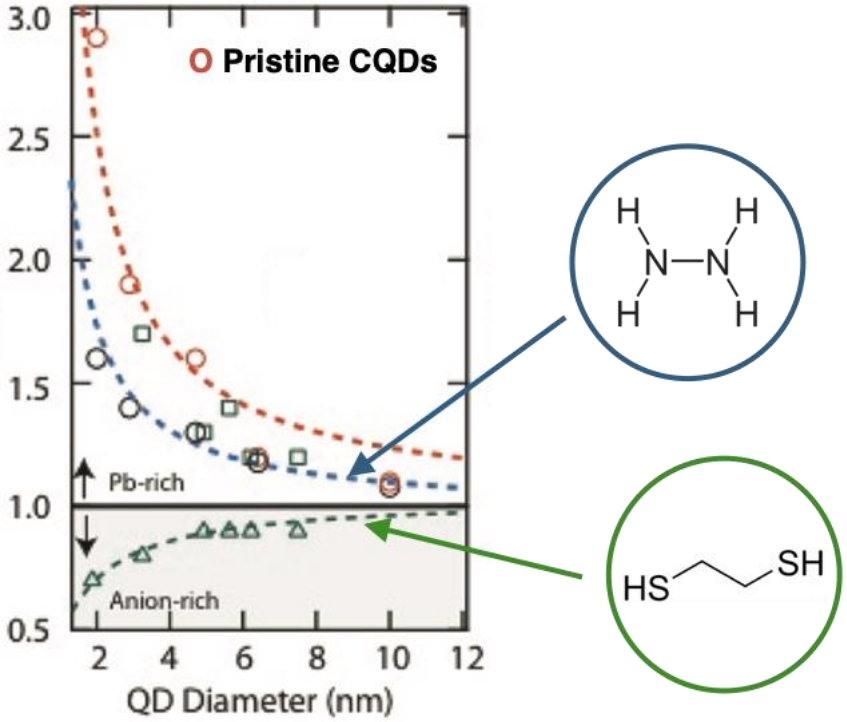
Intrinsic non-stoichiometry

Choi et al. *J. Am. Che. Soc.* 135, 5278 (2013)

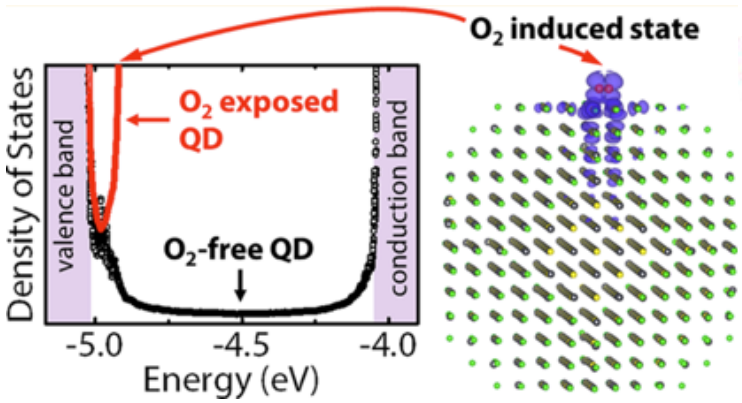
Ligand-induced non-stoichiometry

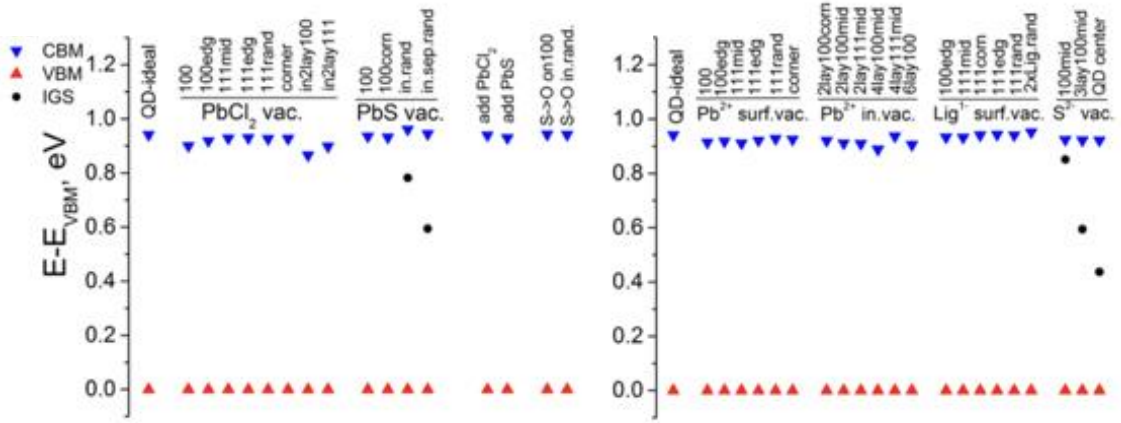
Hughes et al. *ACS Nano* 6, 5498 (2012)



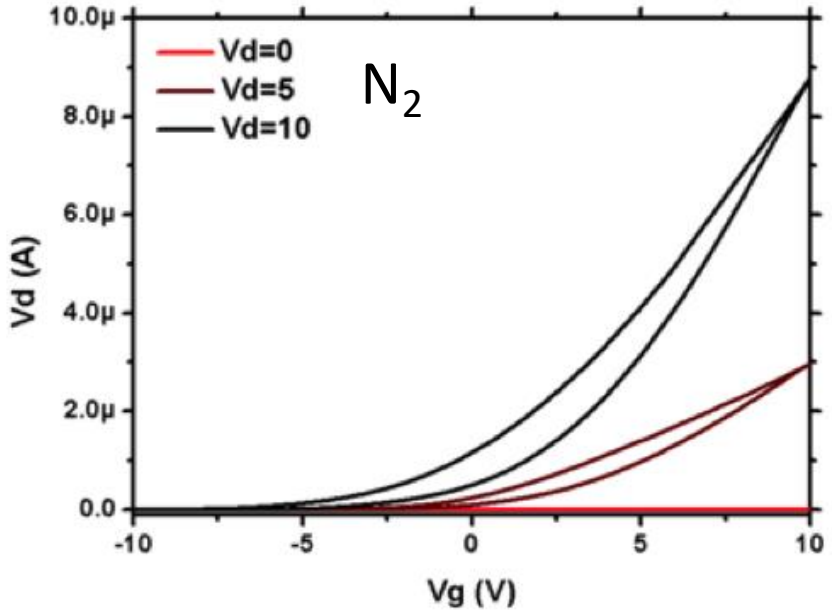


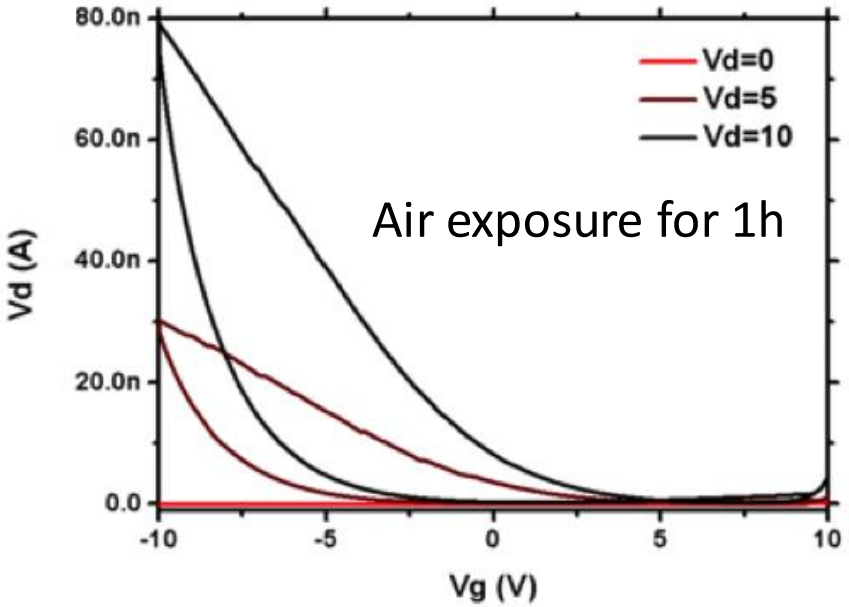
Doping by Physical Adsorption of Oxygen Molecules





Y. Zhang, et al. *ACS Nano*, 2015, 9, 10445

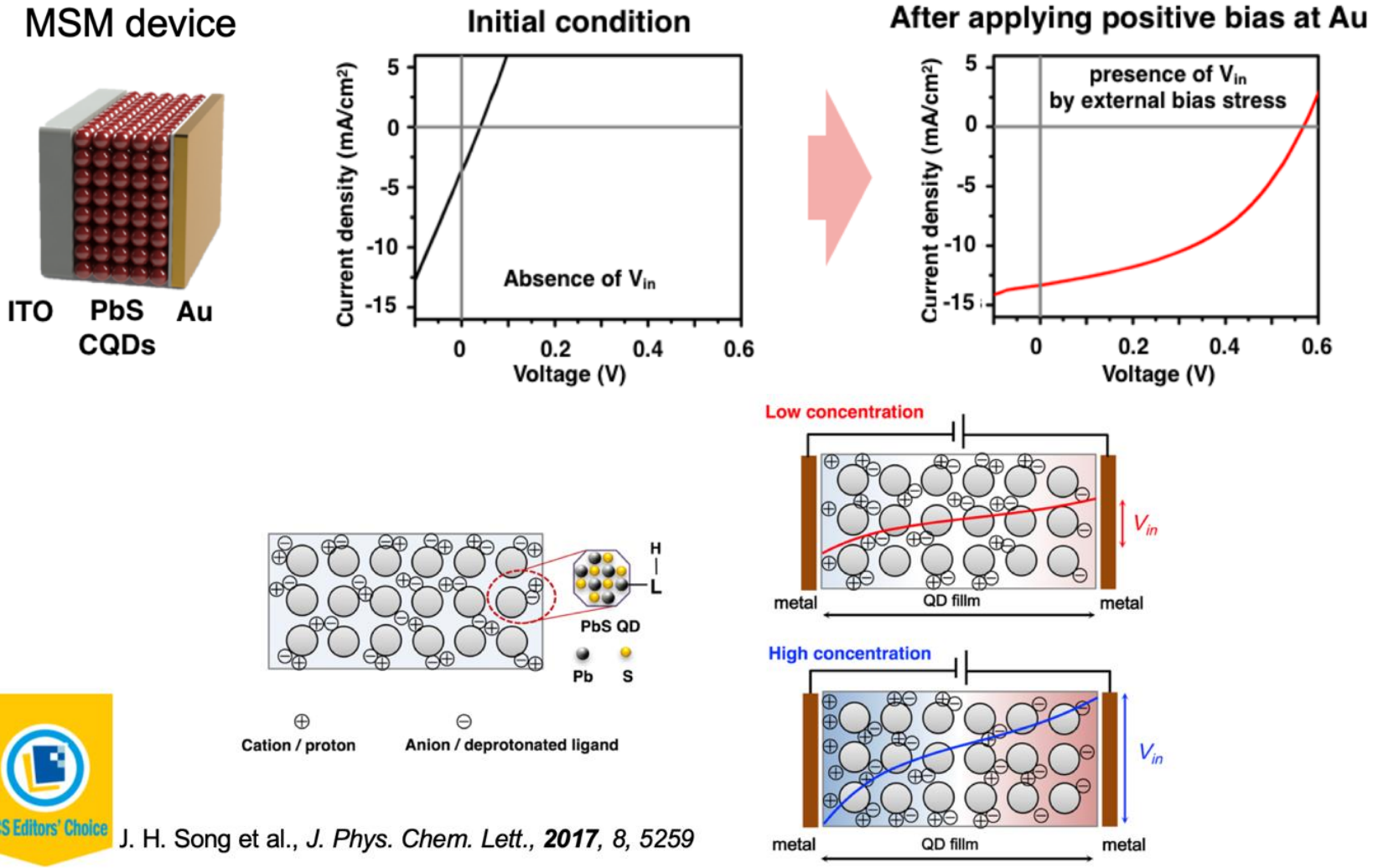




J. H. Song et al. Nat. Commun., 2018, 9, 4267

Properties Depending on Surface Modification

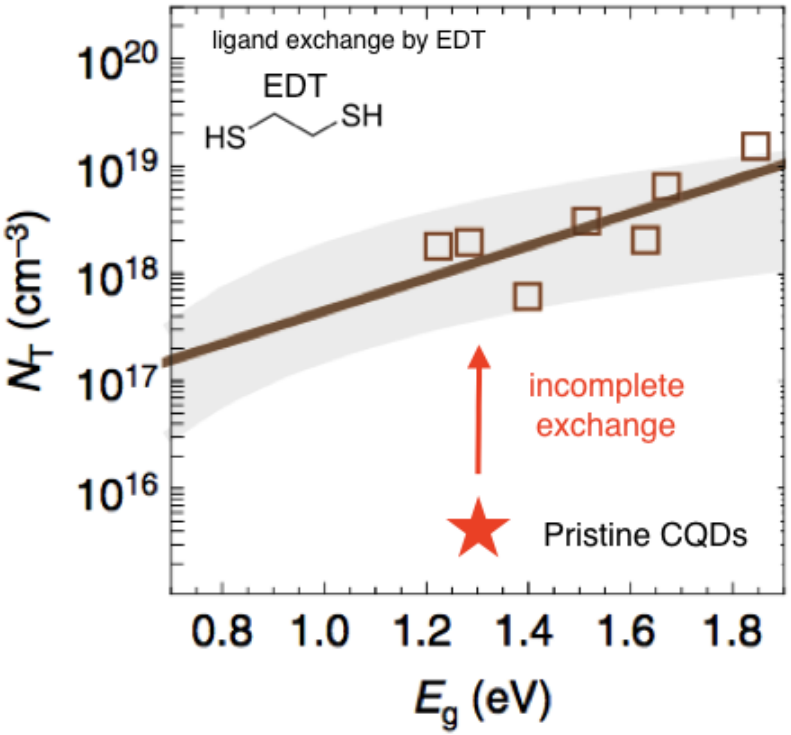
Surface modification and induced photovoltaic effect due to external bias



J. H. Song et al., *J. Phys. Chem. Lett.*, **2017**, *8*, 5259

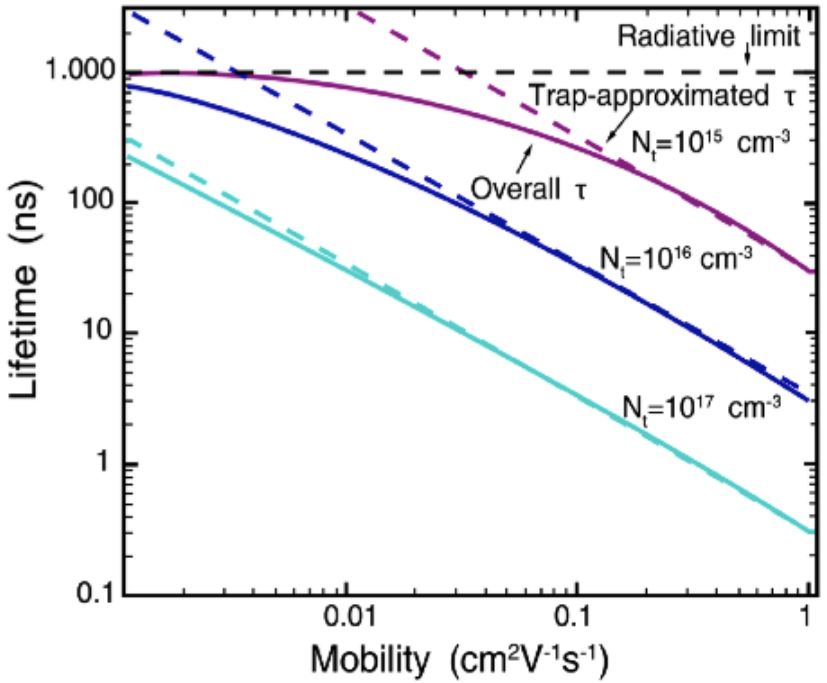
Defect Concentration Depending on QD Size

Size-dependent trap density



Bozyigit et al. *Nat. Commun.* **6**, 6180 (2015)
★ Zhitomirsky et al. *ACS Nano* **6**, 5282 (2013)

Lifetime and trap density



Zhitomirsky et al. *Nat. Commun*, **2,** 5498 (2014)

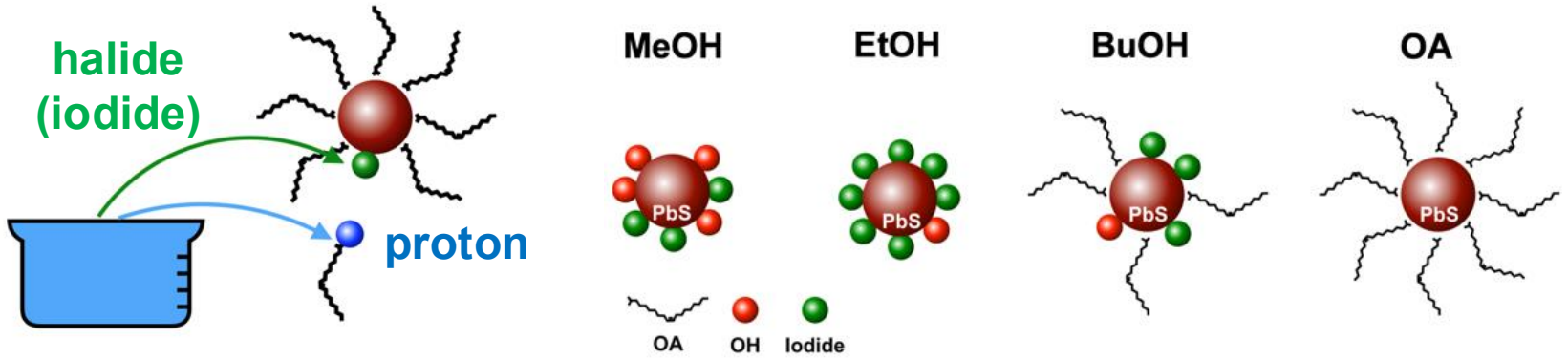
Diffusion Length (L_D) ⟶ $\sqrt{Lifetime \cdot mobility \cdot \frac{k_B T}{e}}$

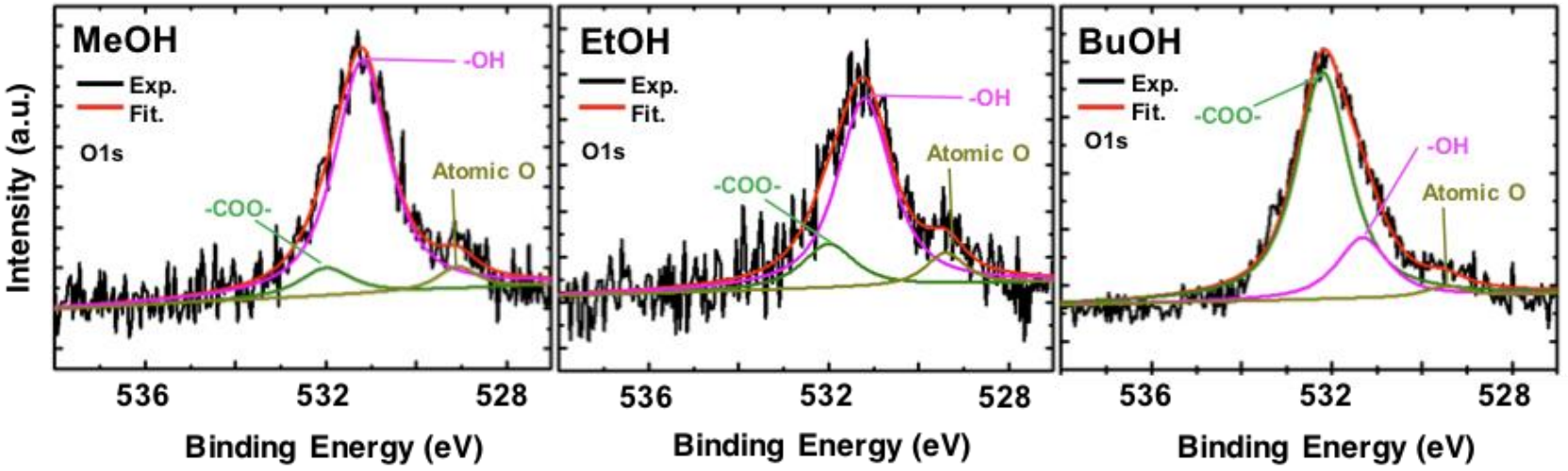
Short diffusion length: low mobility & high trap density

Surface Modifications for Efficient PVs (trap density)

Surface defect control through effective surface ligand exchange (**Diffusion length**)

리간드 교환 반응의 원리 규명 및 리간드 교환 반응성 제어



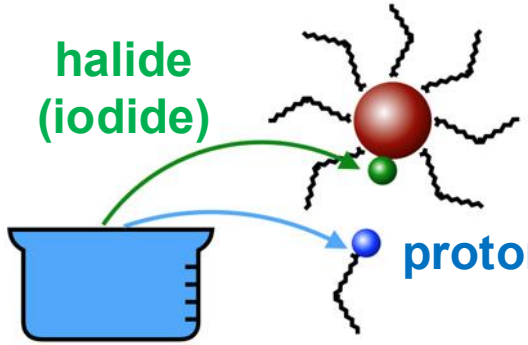


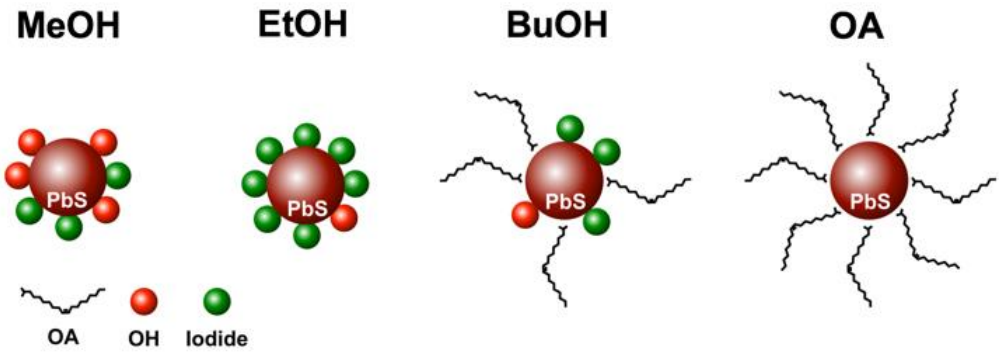
J. H. Song et al. *Adv. Energy Mater.*, 2017, 1700301

Surface Modifications for Efficient PVs (trap density)

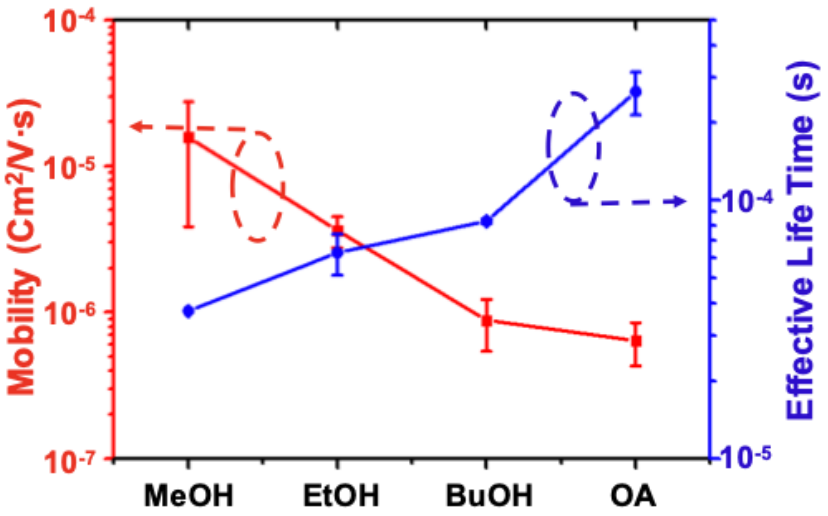
Surface defect control through effective surface ligand exchange (**Diffusion length**)

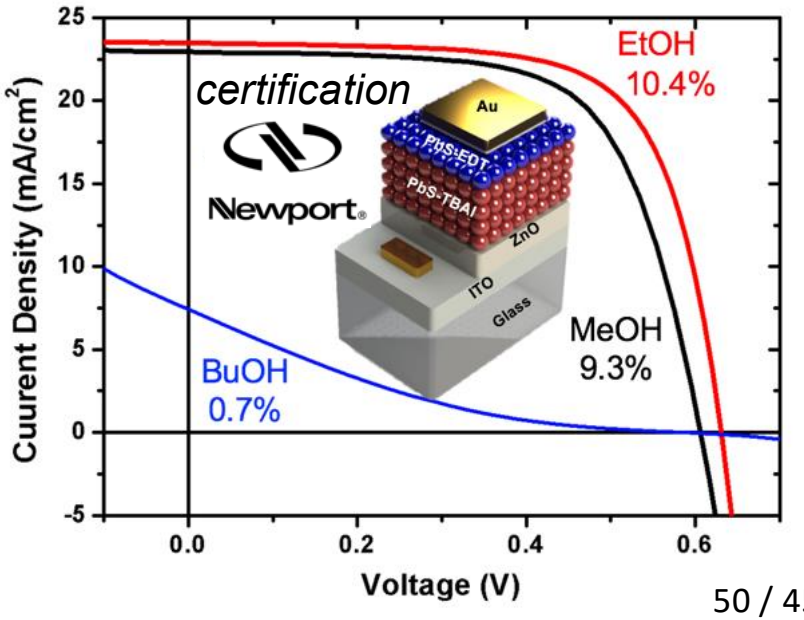
리간드 교환 반응의 원리 규명 및 리간드 교환 반응성 제어





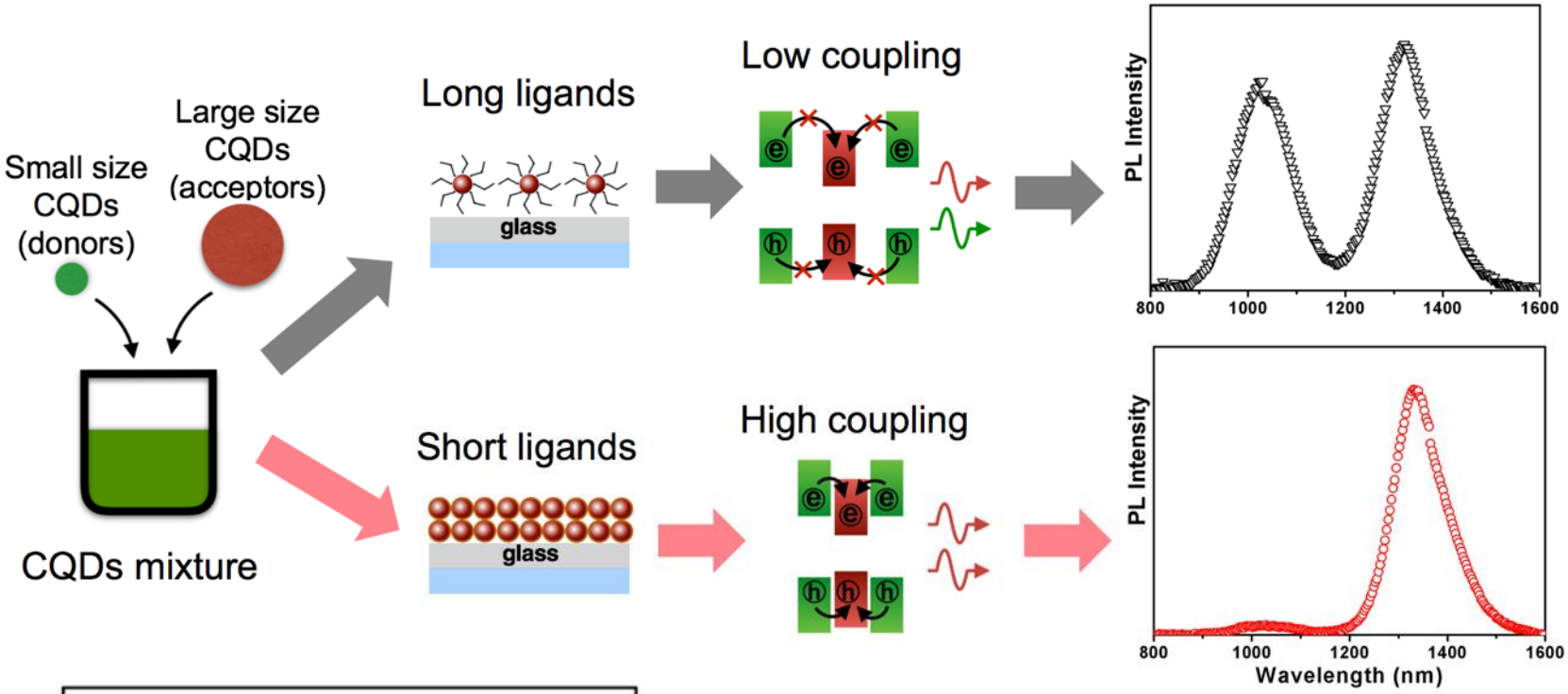
protic solvent (halide salt)

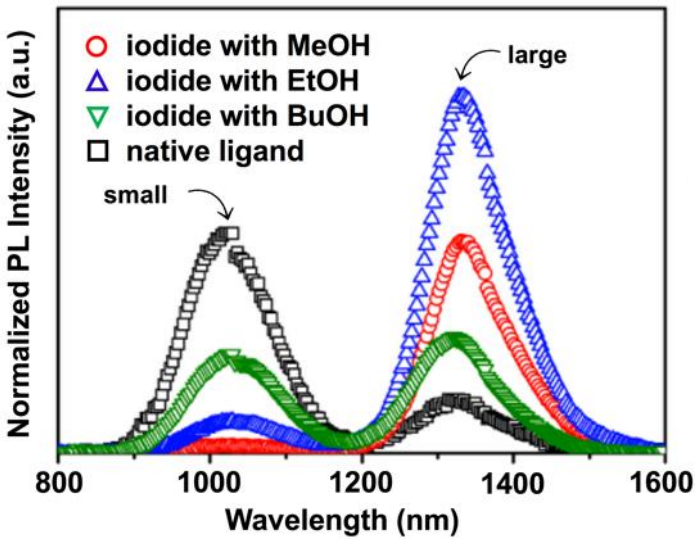


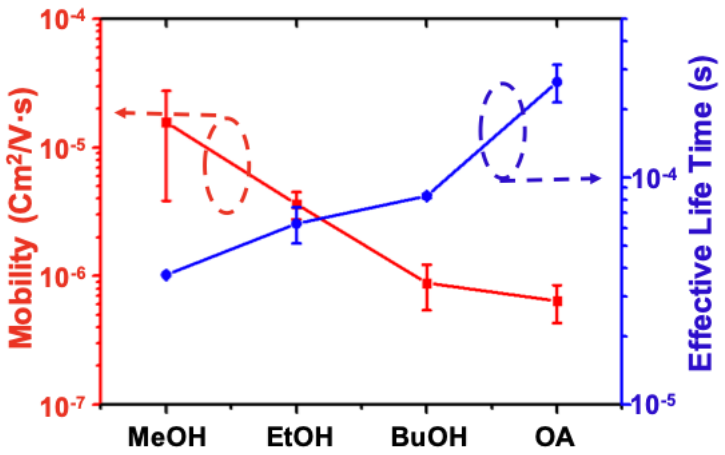


J. H. Song et al. *Adv. Energy Mater.*, 2017, 1700301

Supplementary Information – 3D PL Measurement

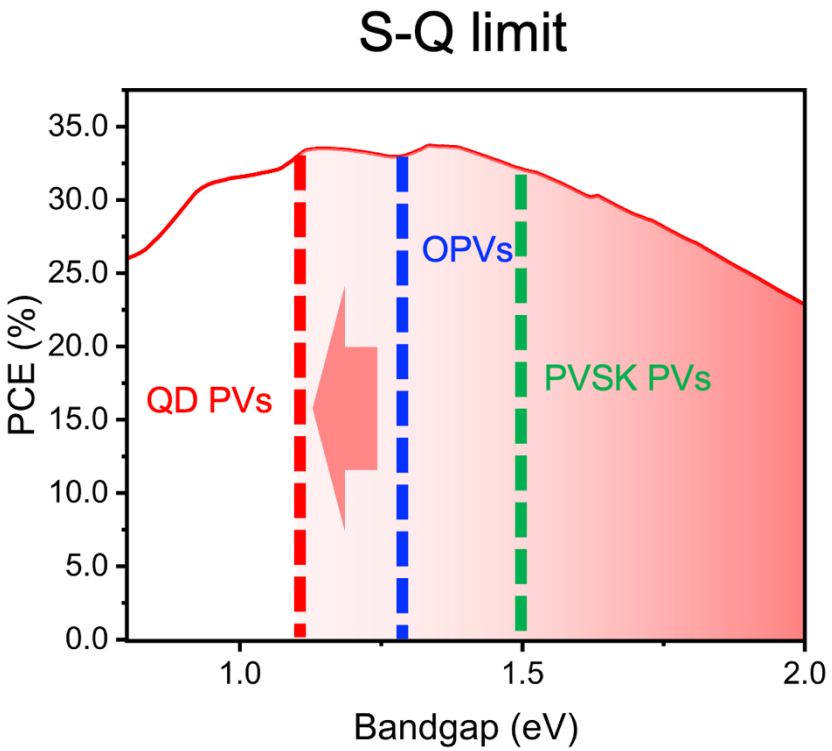




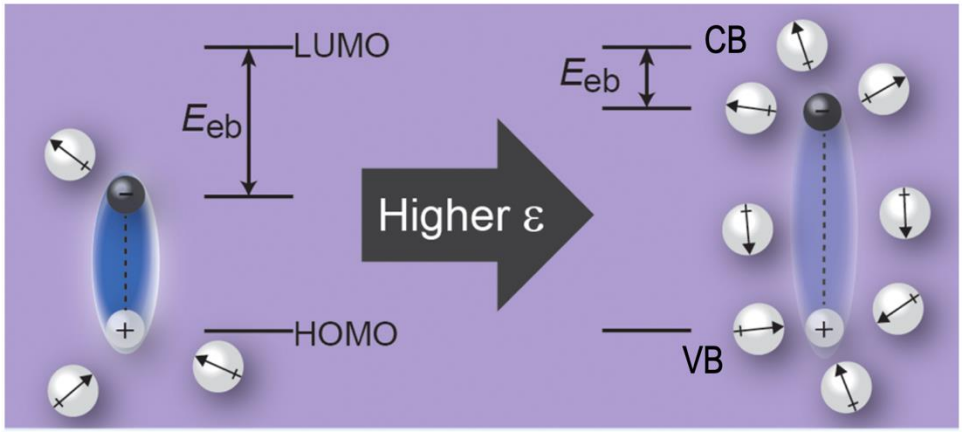


Strategy for High-Efficiency Quantum Dot Solar Cells

Absorption of Long-Wavelength Light



Quantum Dots with a High Dielectric Constant



Effective Long-Wavelength Light Absorption

→ Thin-film quantum dot solar cells

→ Low exciton binding energy

→ High refractive index PbS CQDs

W. Shockley, H. J. Queisser *J. Appl. Phys.* **32**, 510–519 (**1961**)

Strategy for High-Efficiency Quantum Dot Solar Cells

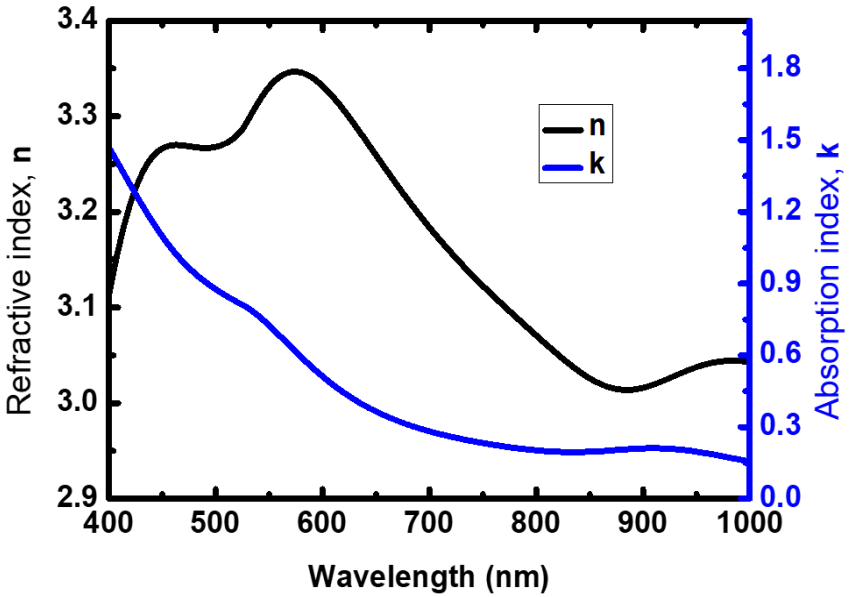
Effective long-wavelength light absorption

→ Thicker active layer

→ Enhanced space charge region through doping control

+ Extended diffusion length through improved material quality

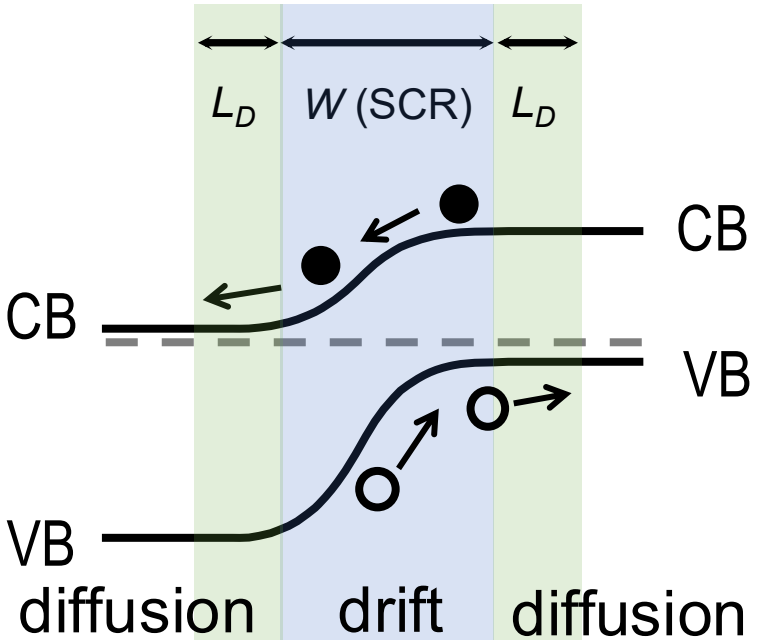
PbS quantum dot optical properties



$\varepsilon_r \sim 10$ (PbS QDs)

$E_b \sim 25\ meV$ (PbS QDs)

Charge extraction
(drift + diffusion)

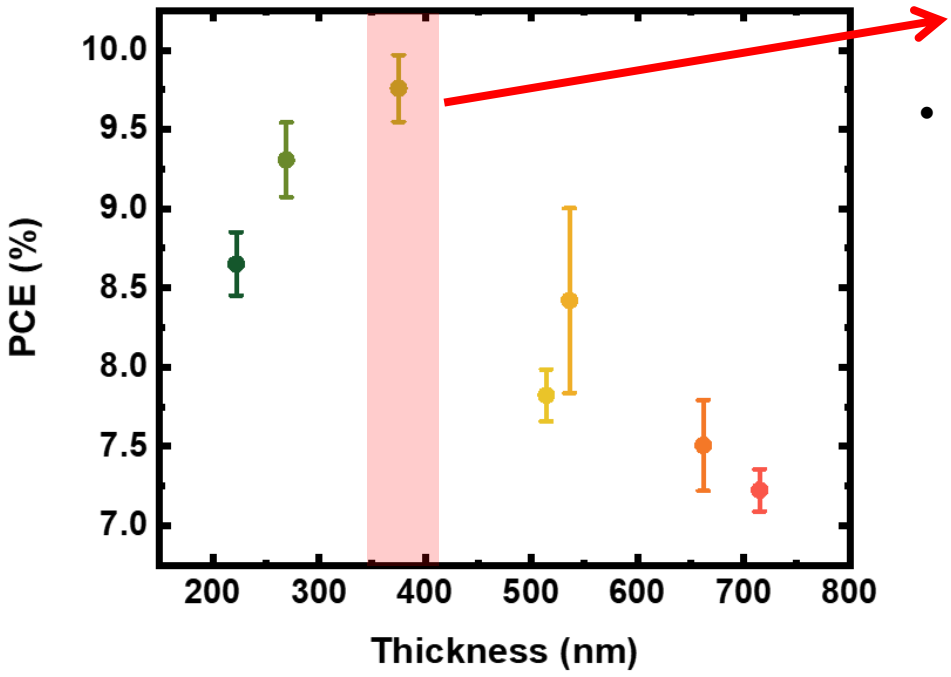


$$W \sim \sqrt{\frac{2\varepsilon\varepsilon_0 V_{bi}}{q}\left(\frac{1}{N_a}+\frac{1}{N_d}\right)} \qquad L_D \propto \sqrt{\mu\tau}$$

Weeraddana, T. M. *et al. j. Phys. Chem. Lett.* **13**, 7756–7761 (**2022**)

Optimized QD Solar Cell Structure

PCE variation with PbS quantum dot thickness



General optimization process

- **Charge extraction efficiency decreases** at thickness near 400nm
- The optimized thickness of the active layer is approximately **400 nm**

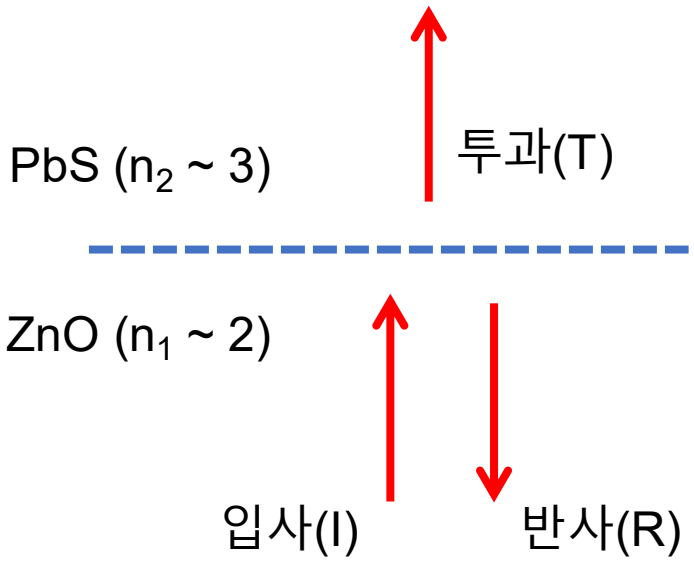
a high refractive index

- Light absorption decreases due to **optical interference**.
- The optimized thickness of the acti ve optical layer can exceed 400 nm

T. Kim, X. Jin, J. H. Song *et al. ACS Energy Lett.* **5**, 248–251 (**2020**)

Fresnel reflection and internal reflection

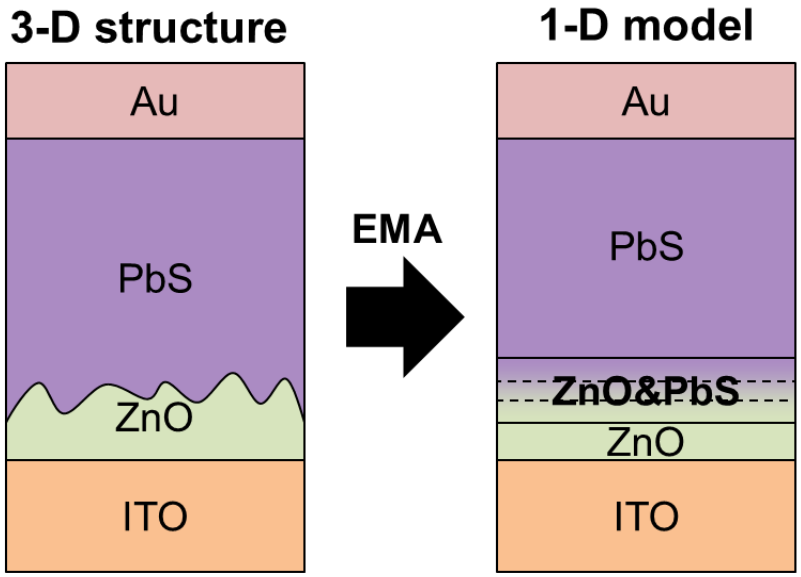
Internal reflection in solar cells (Fresnel reflection)



$$R = \left(\frac{n_2 - n_1}{n_2 + n_1}\right)^2$$

$$R + T = 1$$

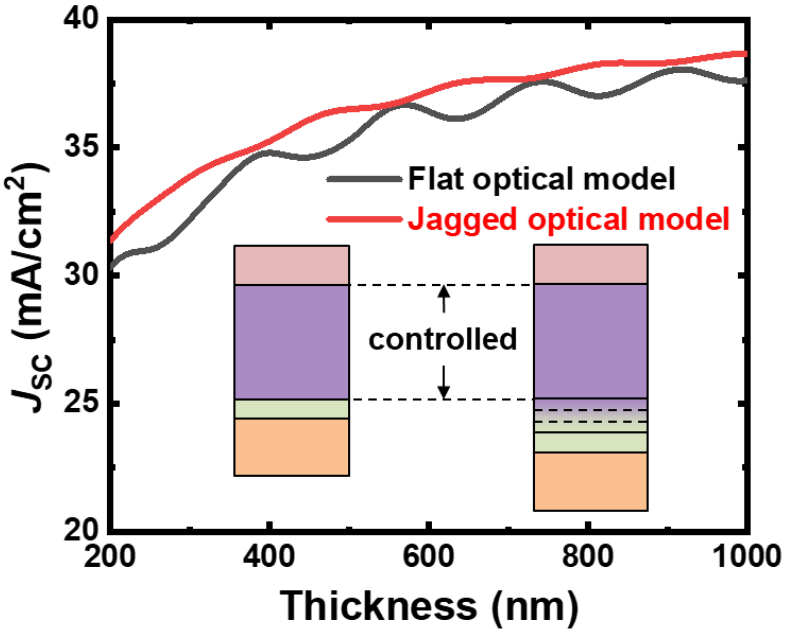
Proposed structure to suppress internal reflection

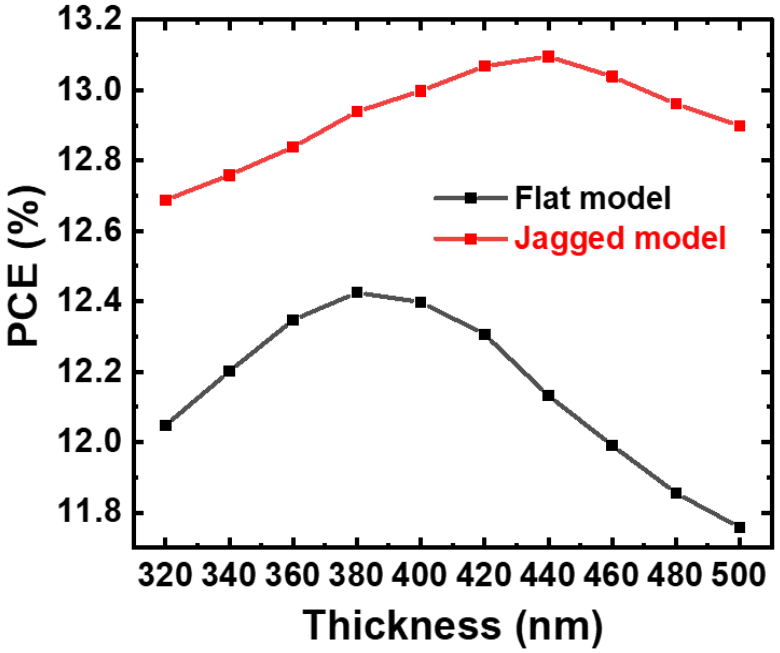


Fresnel reflection and internal reflection

Internal reflection in solar cells (Fresnel reflection)

Proposed structure to suppress internal reflection

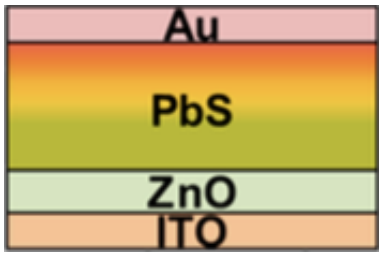


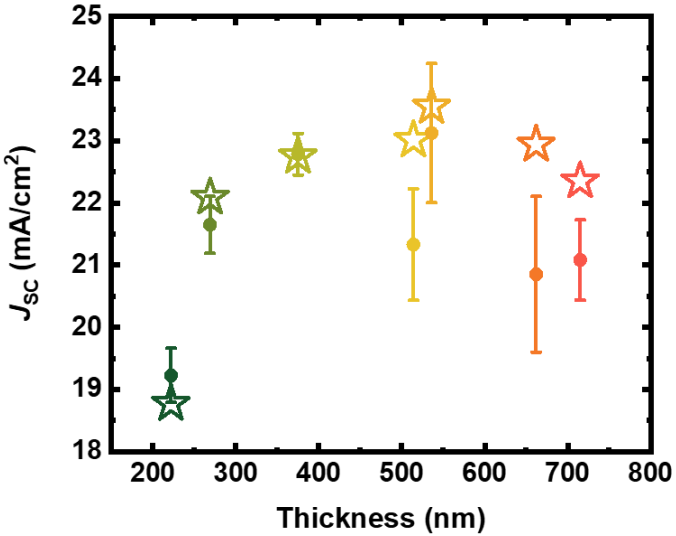


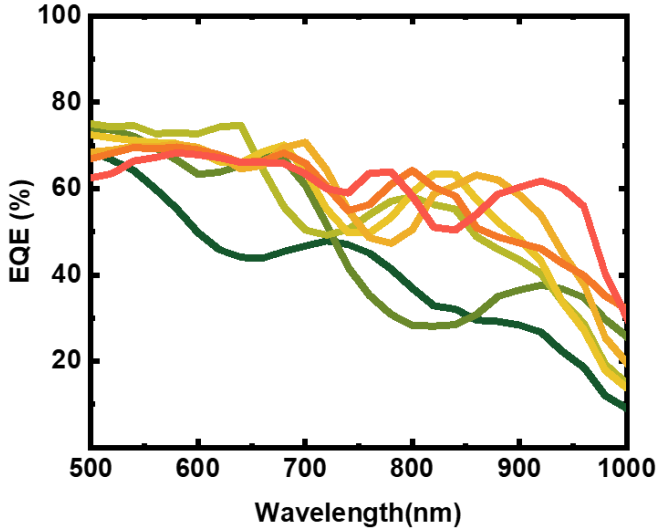
Effects of optical interference on QD solar cells

J_{SC} and external quantum efficiency characteristics of a planar device

planar device

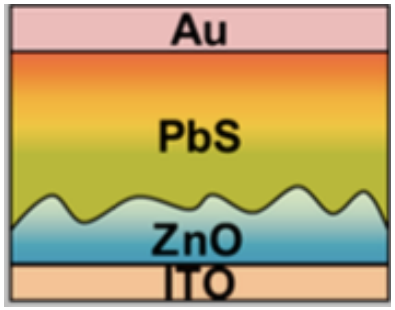


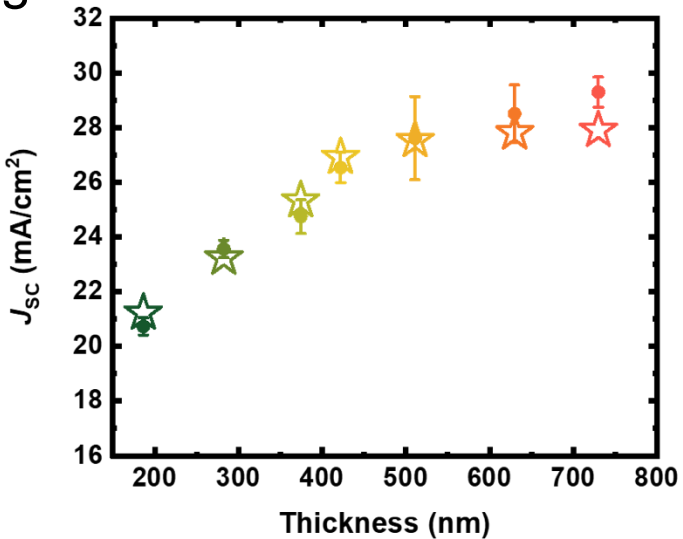


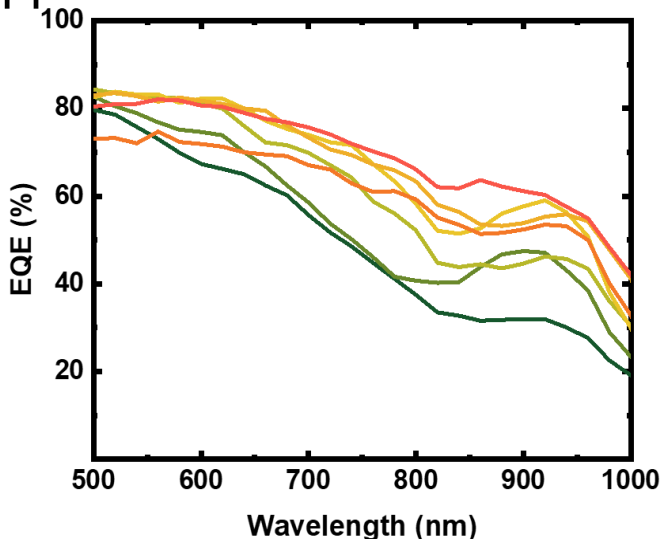


J_{SC} and external quantum efficiency characteristics of a Device with a Jagged Structure for Reflection Suppression

jagged device

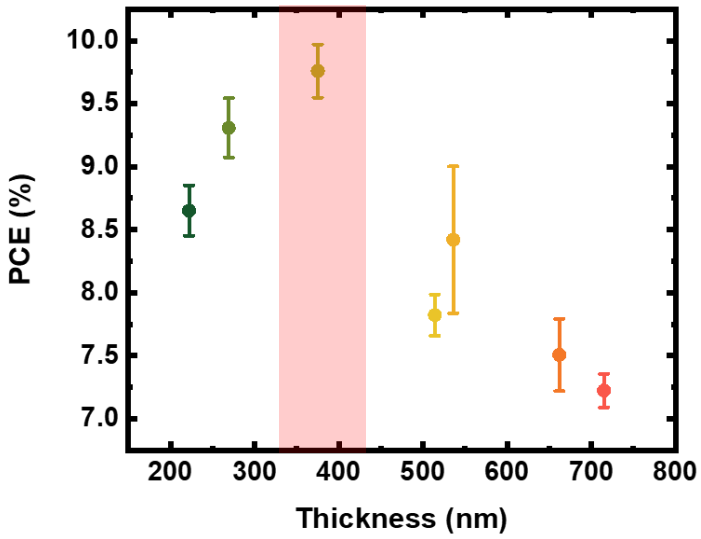


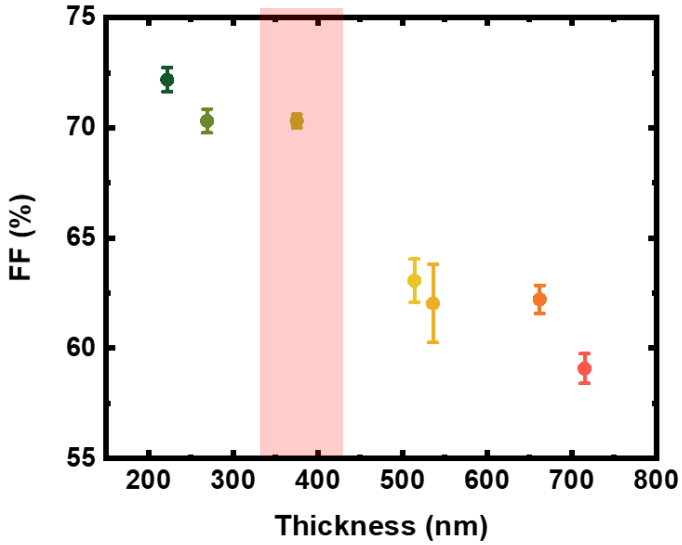




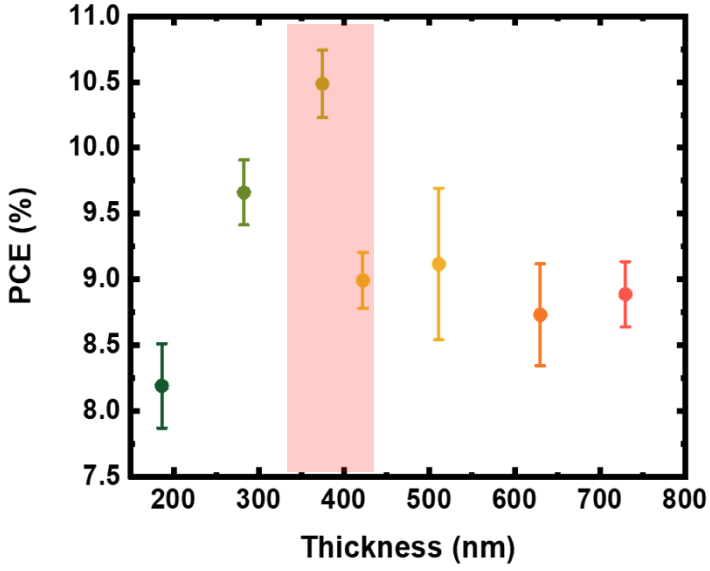
Effects of optical interference on QD solar cells

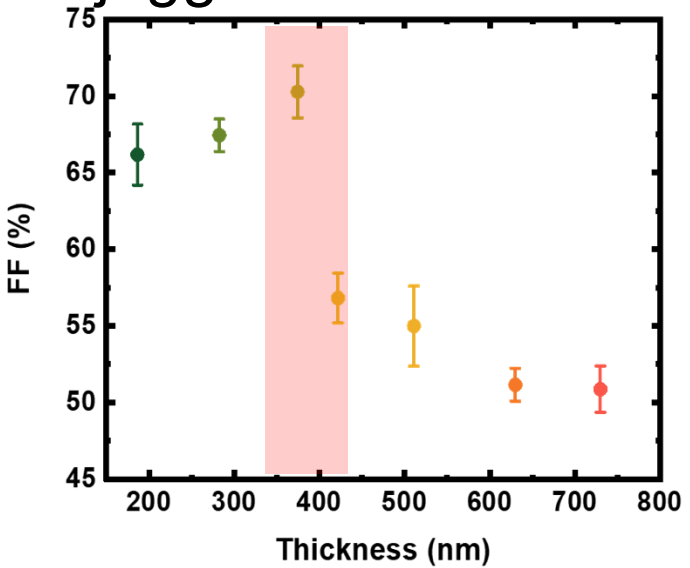
PCE and fill factor for flat devices





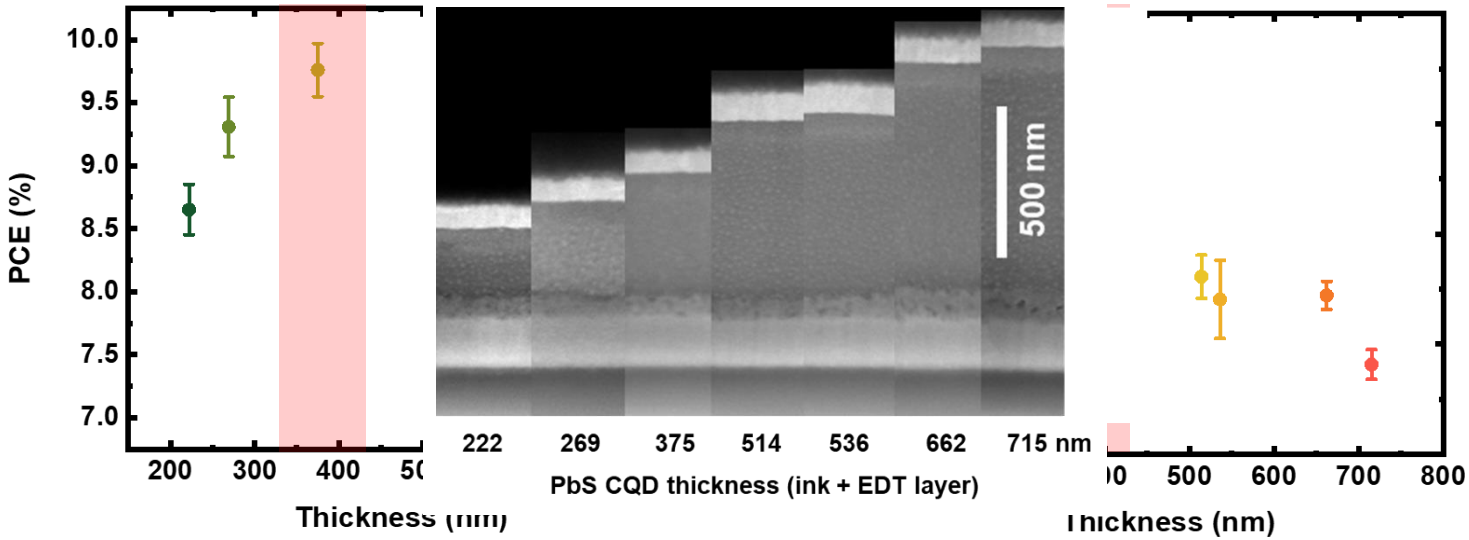
PCE and fill factor for jagged devices





Effects of optical interference on QD solar cells

PCE and fill factor for flat devices



PCE and fill factor for jagged devices