What causes voltage loss in solar cells?

Optimization of quantum structure for high efficiency triple junction solar cells based on voltage loss analysis

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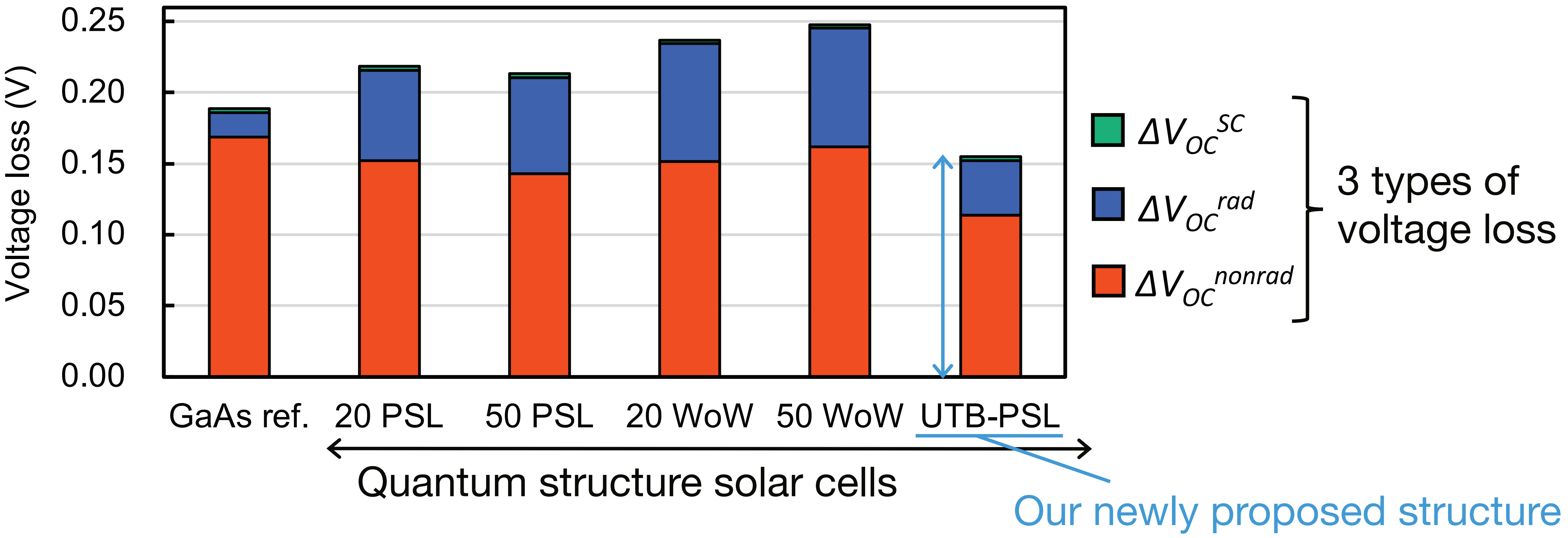
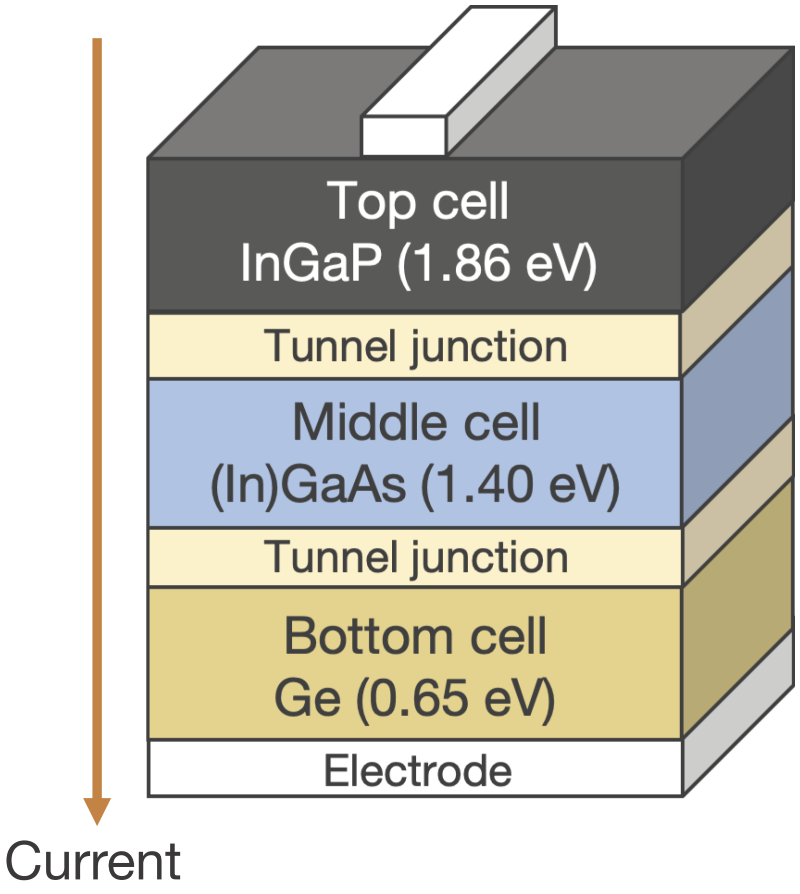
Abstract

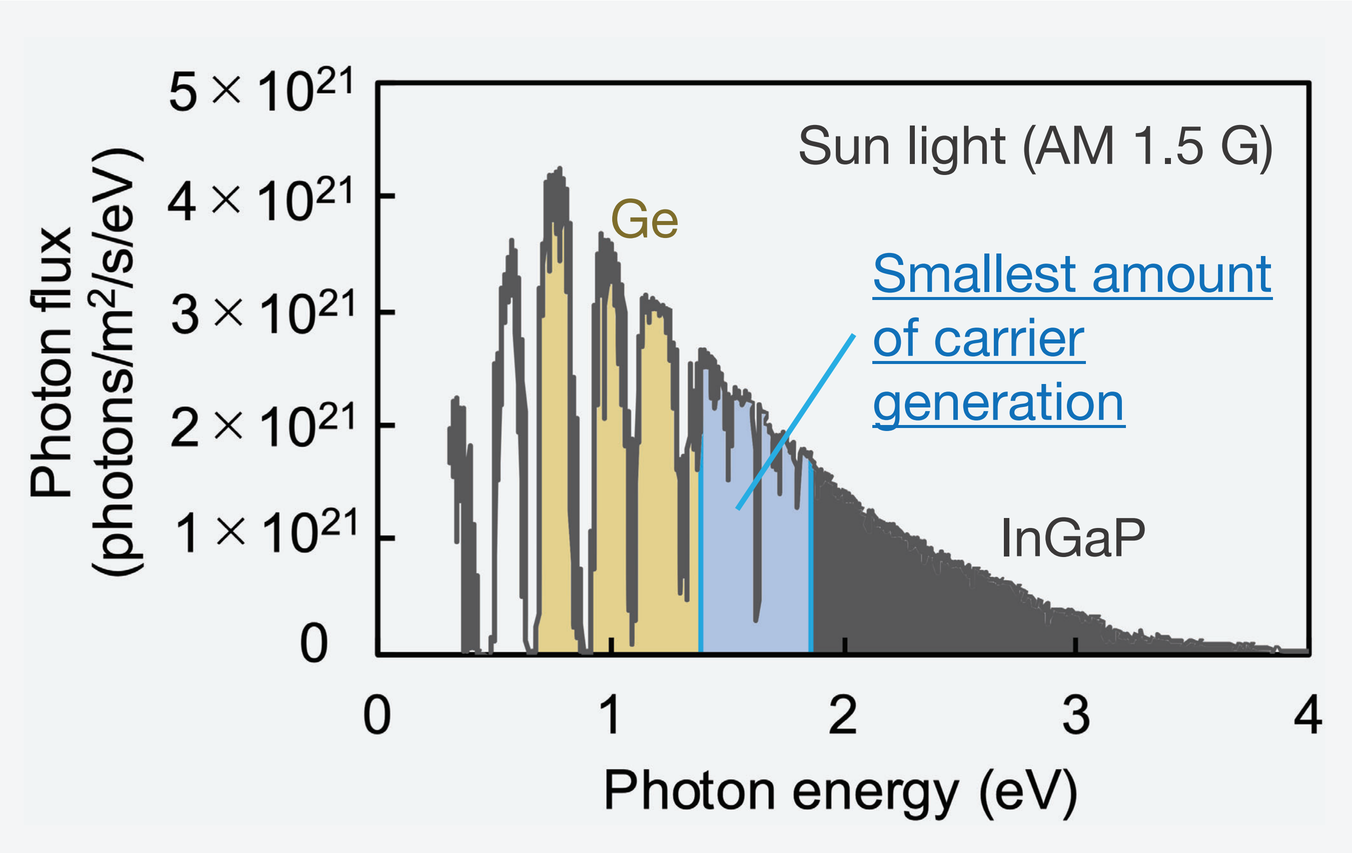


The **lowest voltage loss** was achieved by our new quantum structure solar cell

Outline

1-1 Background: Multi-junction solar cells

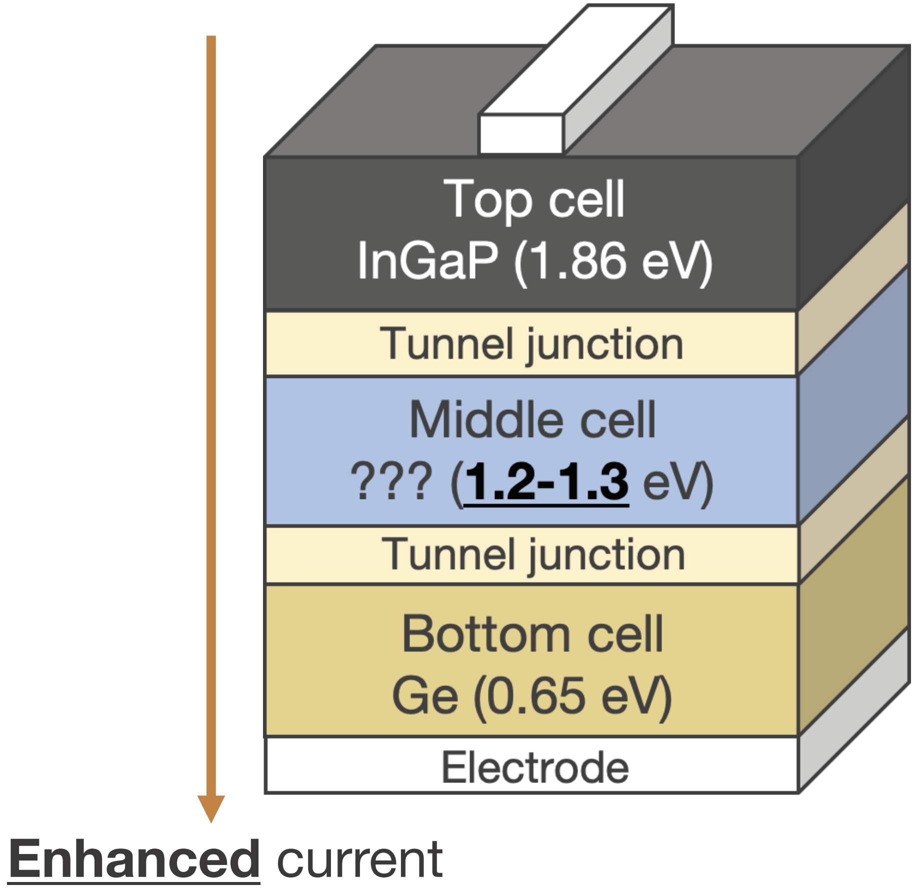


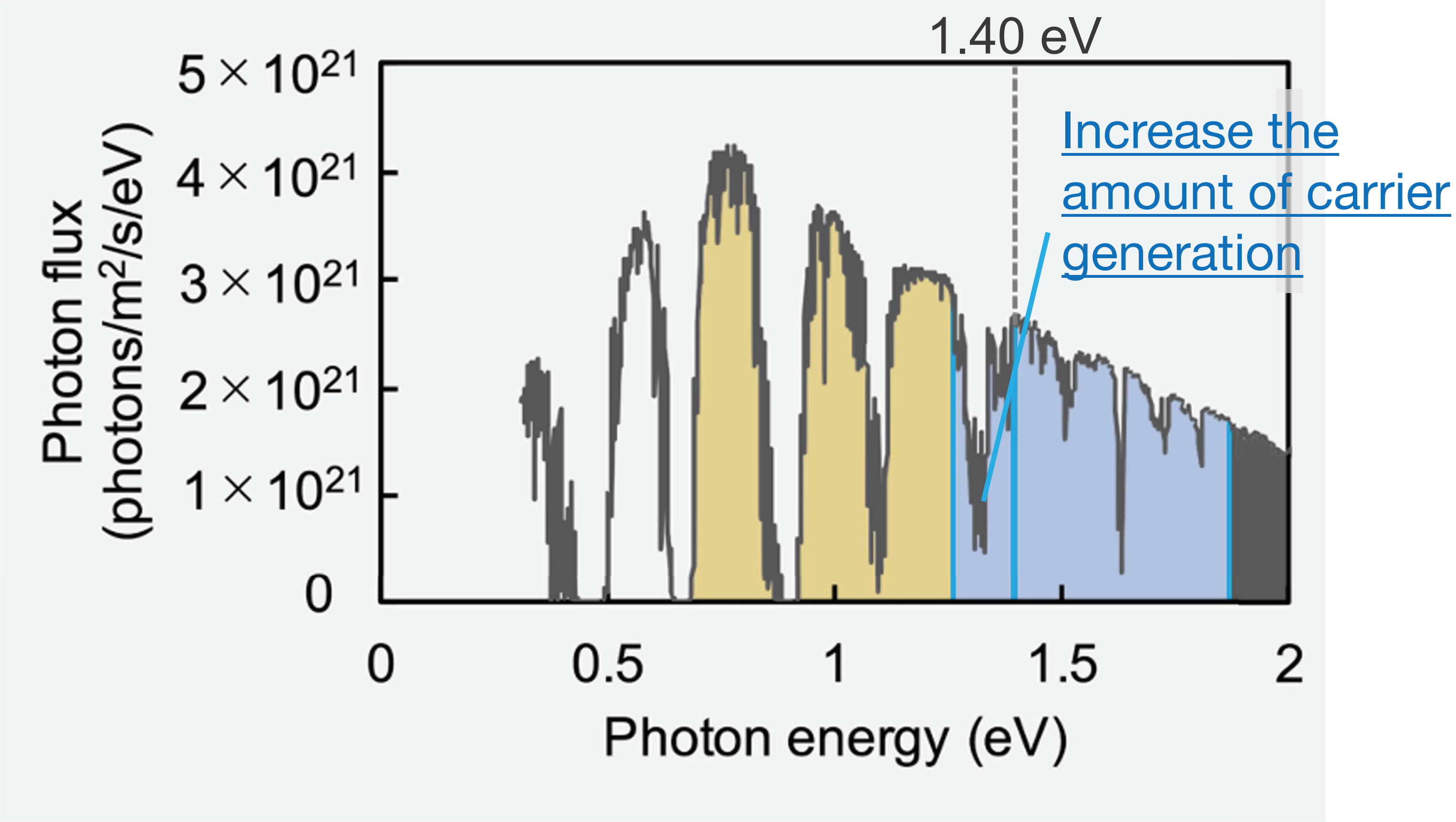


Current is restricted by **the middle cell** due to the excessively high bandgap, **1.40** eV.

M. Yamaguchi *et al.*, *Solar Energy* **79**, 2005.

1-1 Background: Multi-junction solar cells

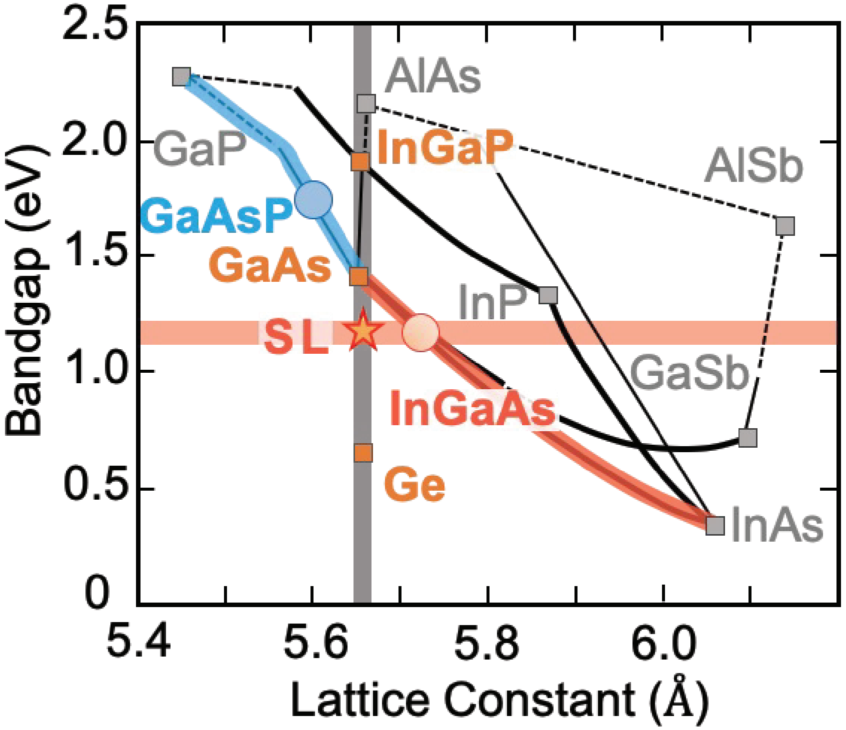


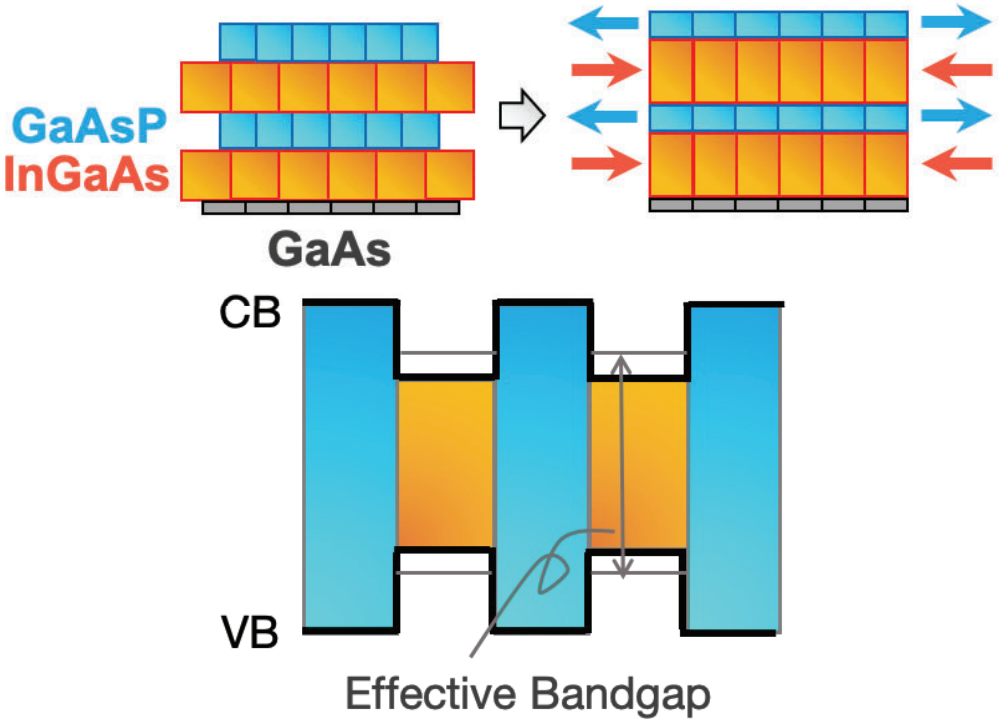


Solution: **Lattice-matched material** whose bandgap is **1.20-1.35** eV

Efficiency 30% → **45**%

1-1 Background: Bandgap adjustor





<u>Strain-balanced</u> superlattice (**<u>SB-SL</u>**)

☺ Superlattice (SL): **InGaAs** that has **narrower bandgap** than GaAs can be used.

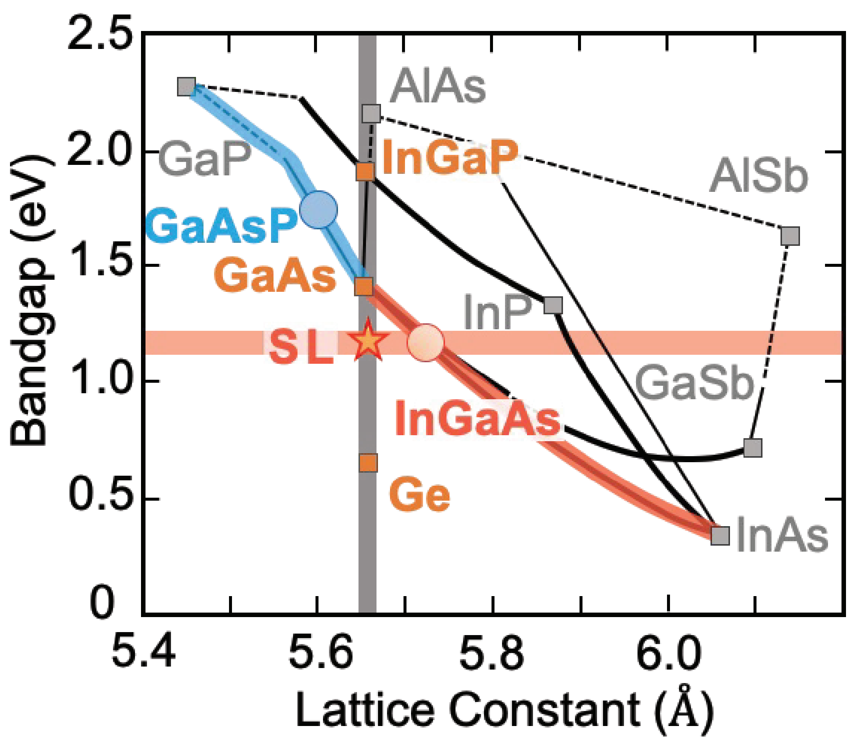
☺ **Crystal strain is compensated** by growing InGaAs and GaAsP thinly and alternately.

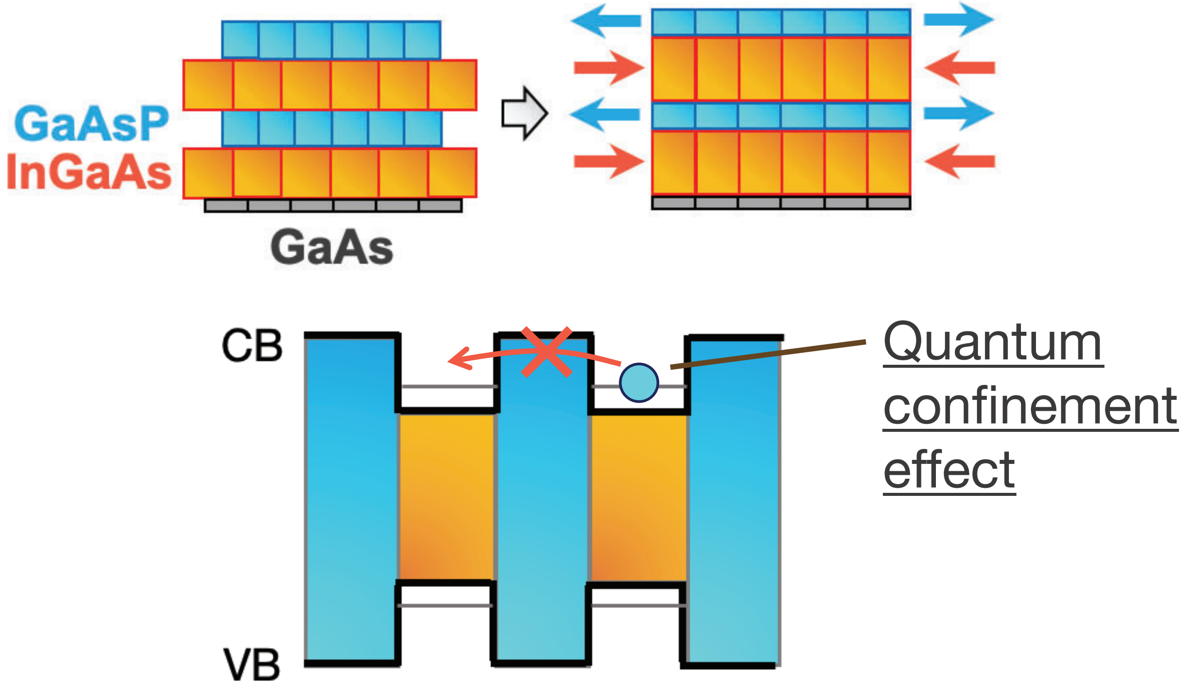
Effective bandgap **1.20-1.35** eV

N. J. Ekins-Daukes *et al.*, *Solar Energy* **68**, 2001.

I. Sayed, *IEEE JPV* **9**, 2019.

1-1 Background: Bandgap adjustor





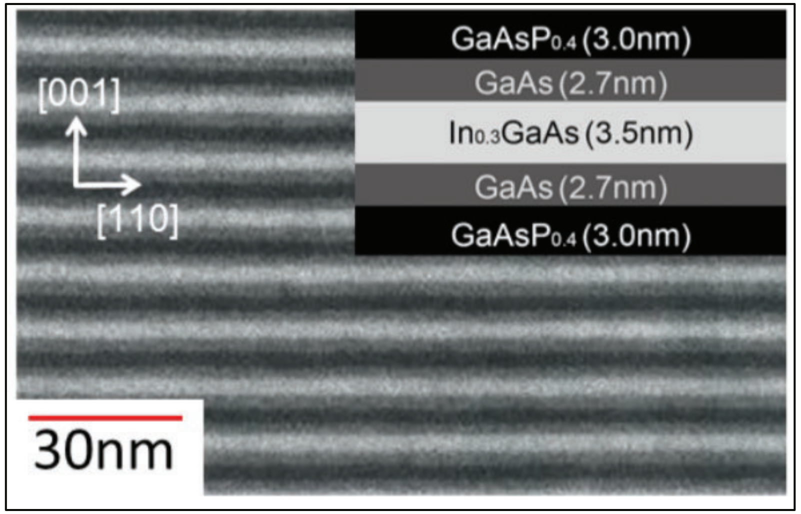
☹ **Quantum confinement effect** hinders carrier extraction.

→ **Low current density**

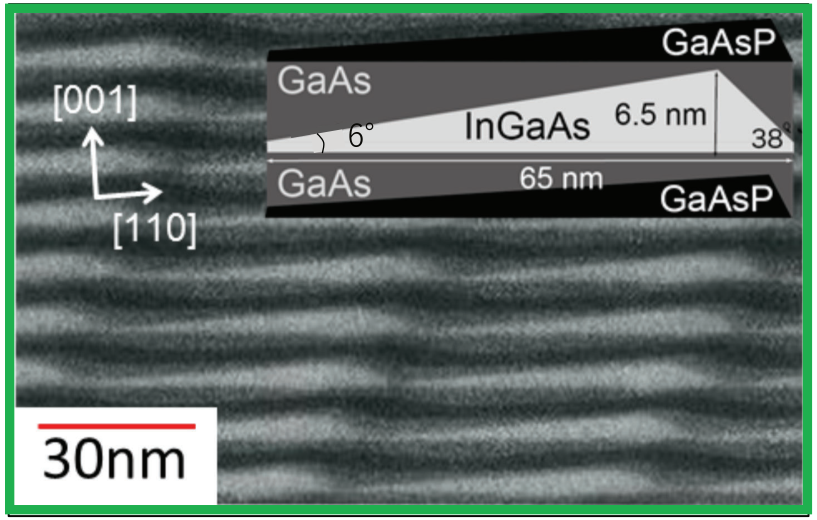
M. Sugiyama *et al.*, *J. Phys. D: Appl. Phys.* **46**, 2012.

1-1 Background: Undulated superlattice (WoW)

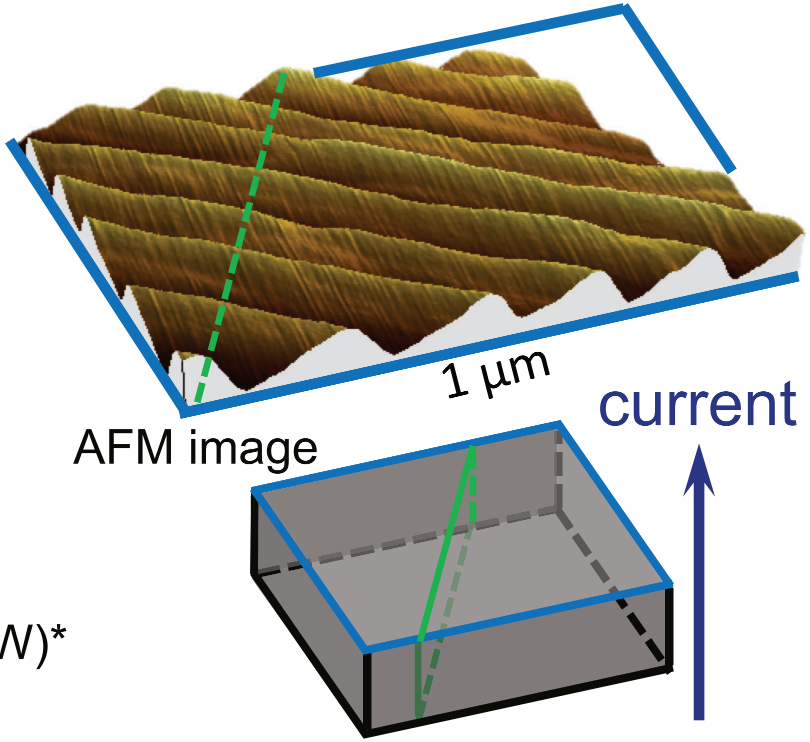
direction of crystal growth and current



STEM image of Planar Superlattice (PSL)*



STEM image of Wire on Well (WoW)*



- WoW is grown on a 6°misoriented GaAs (0 0 1) substrate at relatively low temperature (530~550°C)
- PSL is grown on a GaAs (0 0 1) substrate

*M. Sugiyama *et al*., *Prog. Photovolt: Res. Appl.* **24**, 2016.

1-1 Background: Undulated superlattice (WoW)

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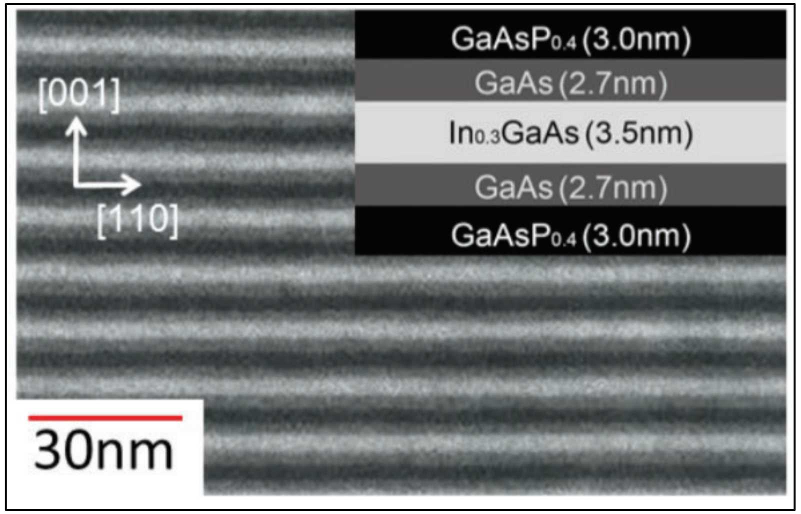

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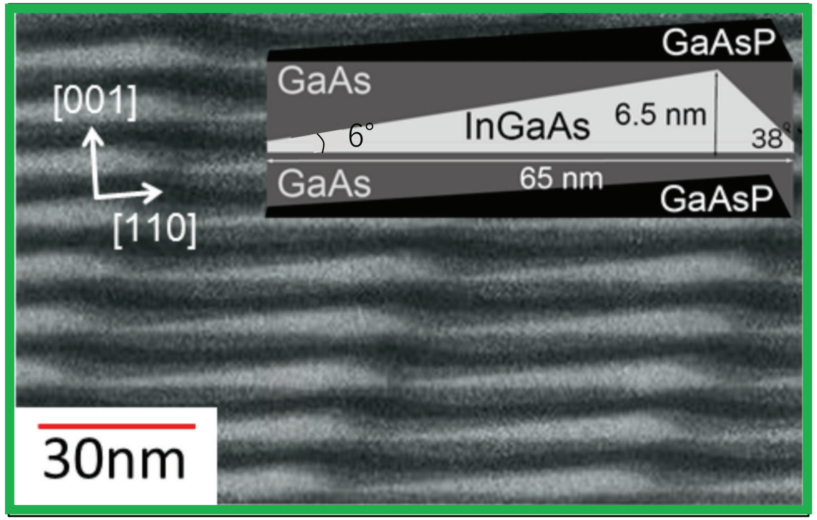

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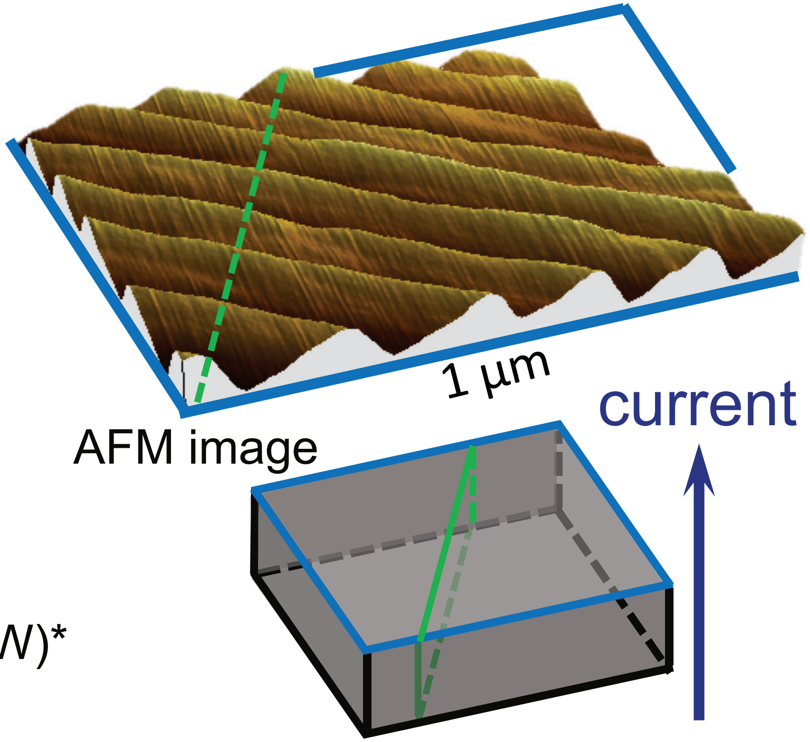
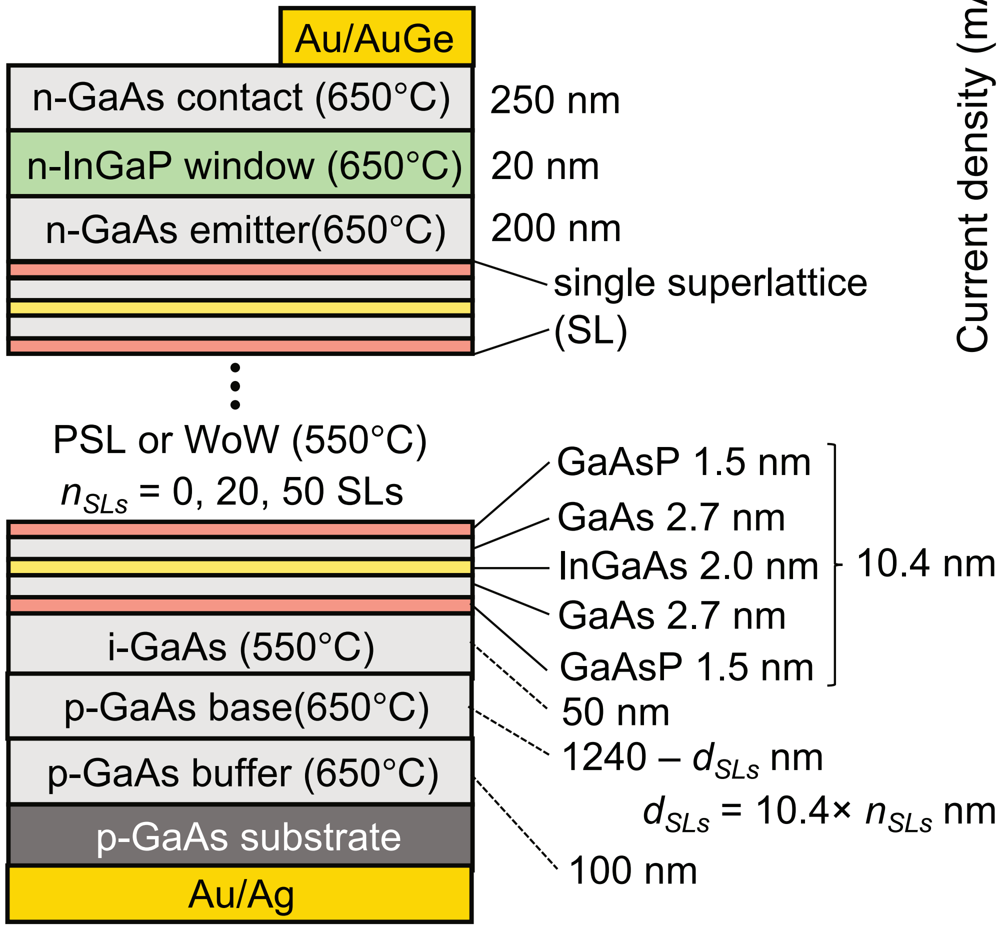


- We expected that Wire on Well can achieve better carrier collection, since there are locally thin quantum barrier areas
→ Carrier tunneling effect can be enhanced at thin barrier

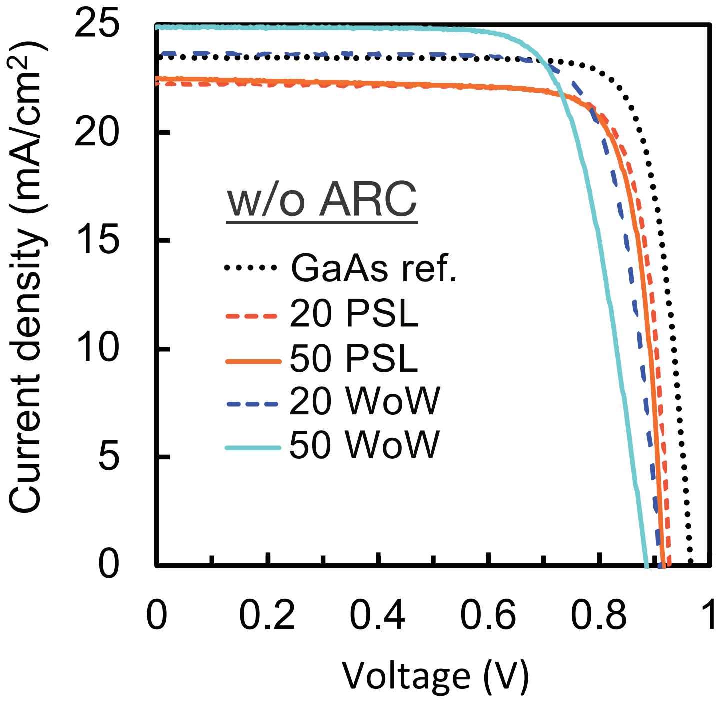
*M. Sugiyama *et al.*, *Prog. Photovolt: Res. Appl.* **24**, 2016.

1-1 Background: Voltage of WoW SC is low

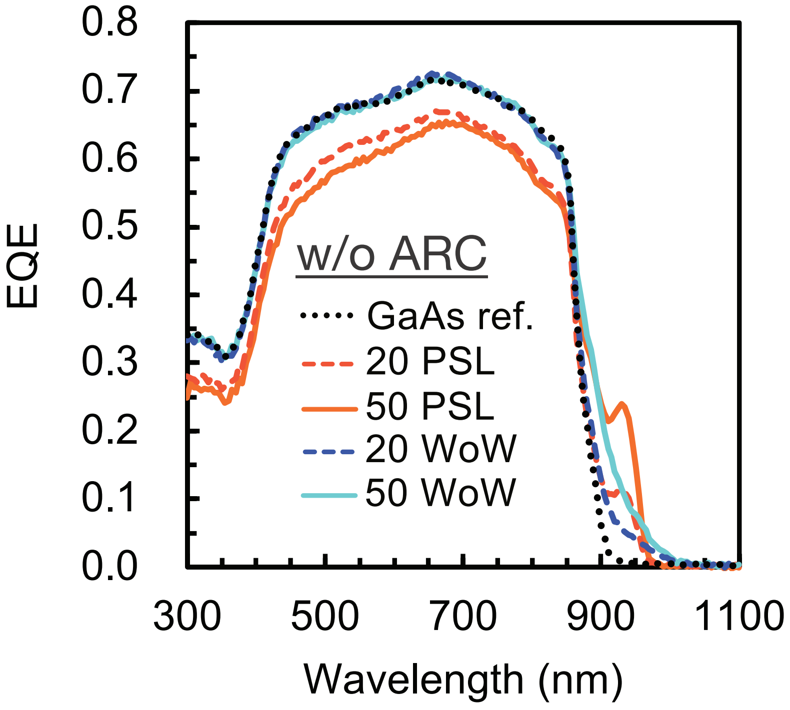


Au/AuGe
n-GaAs contact (650°C) 250 nm
n-InGaP window (650°C) 20 nm
n-GaAs emitter(650°C) 200 nm
single superlattice (SL)
PSL or WoW (550°C)
n_{SLs} = 0, 20, 50 SLs
GaAsP 1.5 nm
GaAs 2.7 nm
InGaAs 2.0 nm
GaAs 2.7 nm
GaAsP 1.5 nm
10.4 nm
i-GaAs (550°C) 50 nm
p-GaAs base(650°C) 1240 – d_{SLs} nm
d_{SLs} = 10.4× n_{SLs} nm
p-GaAs buffer (650°C) 100 nm
p-GaAs substrate
Au/Ag

Structure of samples



J-V curve



EQE results

Labels	J_{SC} (mA/cm²)	V_{OC} (V)	*FF*
GaAs ref.	23.47	0.966	0.814
20 PSL	22.20	0.927	0.813
50 PSL	22.50	0.916	0.803
20 WoW	23.65	0.910	0.779
50 WoW	24.87	0.886	0.736

M. Asami *et al.*, *IEEE JPV* **13**, 2023.

1-1 Background: Voltage of WoW SC is low

[*]	Carrier Mobility [cm^2/Vs]		
	electron μ_n	hole μ_p	average $\langle\mu\rangle=(\mu_n+\mu_p)/2$
WoW	5.10	2.67	3.89
PSL	1.21	1.45	1.33

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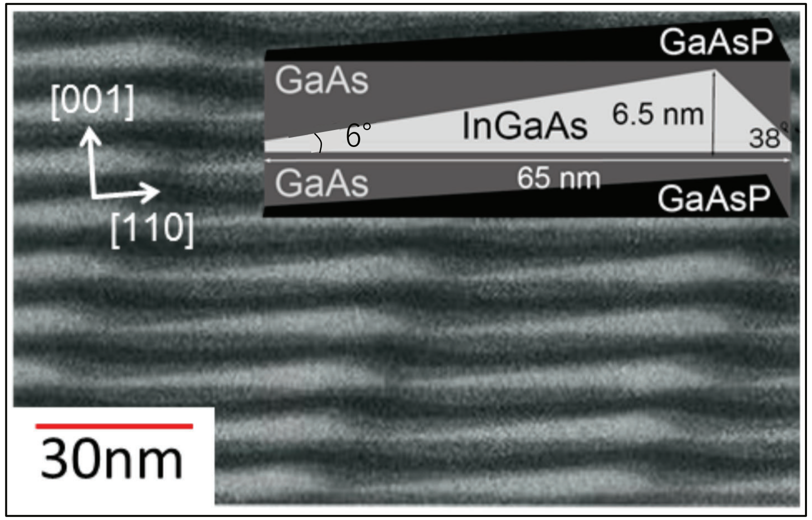

- Thinner barrier area may have boosted the tunneling probability of photo-generated carriers

→WoW solar cells achieved **high current density**

→However, **open circuit voltage of WoW solar cells is low**

[*] M. Asami *et al.*, *IEEE JPV* **10**, 2020.

1-1 Background: Voltage of WoW SC is low

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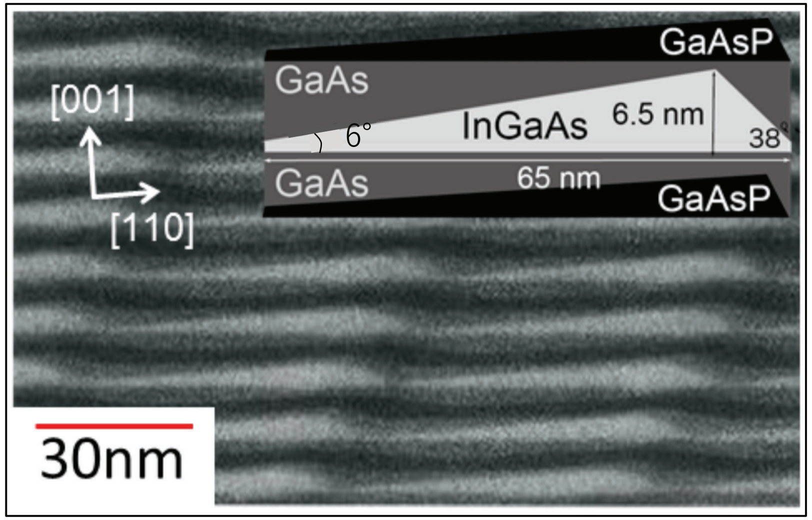


Why is the **open circuit voltage of WoW solar cells low?**

[*] M. Asami *et al.*, *IEEE JPV* **10**, 2020.

1-1 Why do we need an accurate voltage-loss analysis technique?

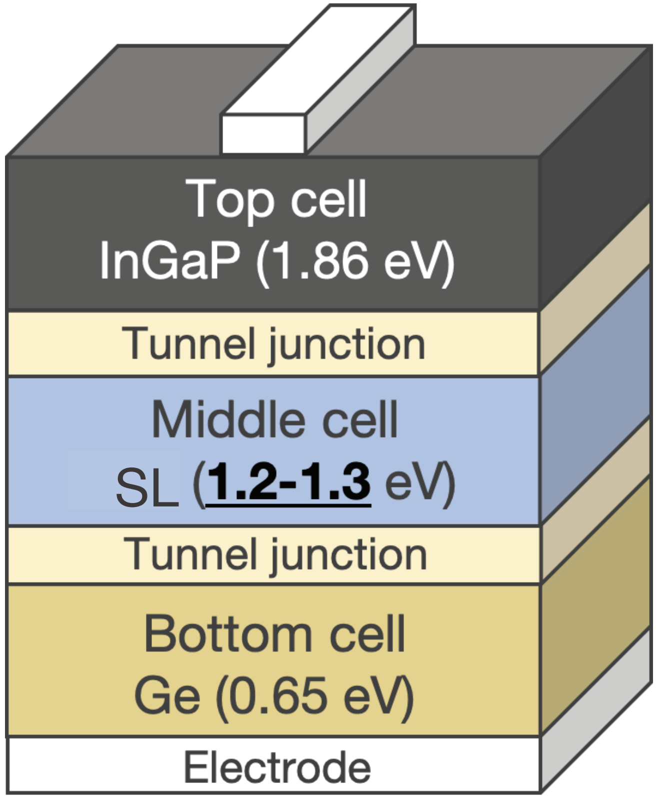
V_{OC} = 0.5 V　V_{OC} = 0.8 V　V_{OC} = 1.0 V　V_{OC} = 1.4 V

High?　Low?　So-so?

Without the information of **bandgap**,
we cannot evaluate the **“quality” of voltage**

ambiguous

For the development of solar cells,
voltage loss must be evaluated accurately
and the cause of the loss must be clarified



Top cell
InGaP (1.86 eV)

Tunnel junction

Middle cell
SL (**1.2-1.3** eV)

Tunnel junction

Bottom cell
Ge (0.65 eV)

Electrode

SL: Superlattice

Various combinations of bandgap

1-2 Background: How can we evaluate *V* loss?

Several voltage loss analysis techniques have been proposed in preceding studies

Bandgap offset $W_{OC} = \frac{E_g}{q} - V_{OC}$

☹ W_{OC} <u>must not be applied to quantum structure solar cells [*]</u>

We found that

voltage loss analysis based on **detailed balance theory** can be **applied to quantum structure solar cells**

[*] N. Ekins-Daukes, and A. Pusch, *EUPVSEC*, **1AO.1.3**, 2018.

1-2 Voltage loss analysis based on detailed balance theory

$$\underline{\underline{V_{OC}^{SQ}}} - \underline{\underline{V_{OC}}} = \underline{\underline{\frac{kT}{q}\ln\frac{J_{SC}^{SQ}}{J_{em,0}^{SQ}}}} - \underline{\underline{\frac{kT}{q}\ln\frac{J_{SC}-J_{nr}}{J_{em,0}}}} = -\frac{kT}{q}\ln\frac{J_{em,0}^{SQ}}{J_{SC}^{SQ}}\times\frac{J_{SC}-J_{nr}}{J_{em,0}} = -\frac{kT}{q}\ln\frac{J_{SC}}{J_{SC}^{SQ}}\times\frac{J_{em,0}^{SQ}}{J_{em,0}}\times\frac{J_{SC}-J_{nr}}{J_{SC}}$$

$$= \underline{\underline{\left(-\frac{kT}{q}\ln\frac{J_{SC}}{J_{SC}^{SQ}}\right)}} + \underline{\underline{\left(-\frac{kT}{q}\ln\frac{J_{em,0}^{SQ}}{J_{em,0}}\right)}} + \underline{\underline{\left(-\frac{kT}{q}\ln\frac{J_{SC}-J_{nr}}{J_{SC}}\right)}} = \underline{\underline{\Delta V_{OC}^{SC}}} + \underline{\underline{\Delta V_{OC}^{rad}}} + \underline{\underline{\Delta V_{OC}^{nonrad}}}$$

<u>Open circuit voltage at Shockley-Queisser (SQ) limit calculated from</u> E_g ⇨ $V_{OC}^{SQ} = \frac{kT}{q}\ln\frac{\int_{E_g}^{\infty} 1\times\phi_{sun}\,dE}{\int_{E_g}^{\infty} 1\times\phi_{bb}\,dE}$

J_{SC}^{SQ}: SC current at SQ limit, $J_{em,0}^{SQ}$: diode saturation current at SQ limit

$$J = 0 = J_{SC} - J_{em,0}\left(\exp\left(\frac{qV_{OC}}{kT}\right) - 1\right) - J_{nr}$$

$$\therefore \underline{\underline{V_{OC}}} = \frac{kT}{q}\ln\frac{J_{SC}-J_{nr}}{J_{em,0}}$$

$J_{em,0}$: diode saturation current, J_{nr}: non-radiative recombination current

Three types of voltage loss

Short circuit current voltage loss

radiative recombination voltage loss

non-radiative recombination voltage loss

U. Rau *et al*., Physical Review Applied 7, 2017.

ϕ_{sun}: Photon flux of sunlight, ϕ_{bb}: Photon flux of black body radiation

1-2 Voltage loss analysis based on detailed balance theory

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$$= \underline{\underline{\left(-\frac{kT}{q}\ln\frac{J_{SC}}{J_{SC}^{SQ}}\right)}} + \underline{\underline{\left(-\frac{kT}{q}\ln\frac{J_{em,0}^{SQ}}{J_{em,0}}\right)}} + \underline{\underline{\left(-\frac{kT}{q}\ln\frac{J_{SC}-J_{nr}}{J_{SC}}\right)}} = \underline{\underline{\Delta V_{OC}^{SC}}} + \underline{\underline{\Delta V_{OC}^{rad}}} + \underline{\underline{\Delta V_{OC}^{nonrad}}}$$

For the calculation of open circuit voltage at SQ limit, we have to define ***effective* *bandgap*** E_g of solar cells

Three types of voltage loss

Short circuit current voltage loss

radiative recombination voltage loss

non-radiative recombination voltage loss

U. Rau *et al*., Physical Review Applied 7, 2017.

Outline

0. Abstract

1. Background, preceding studies

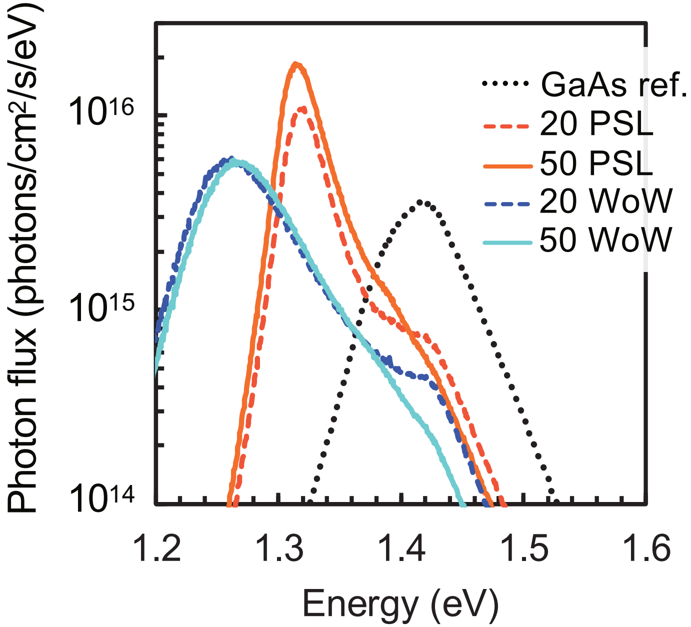
- 1-1. Why do we need an accurate voltage-loss analysis technique?
- 1-2. Voltage loss analysis based on detailed balance theory

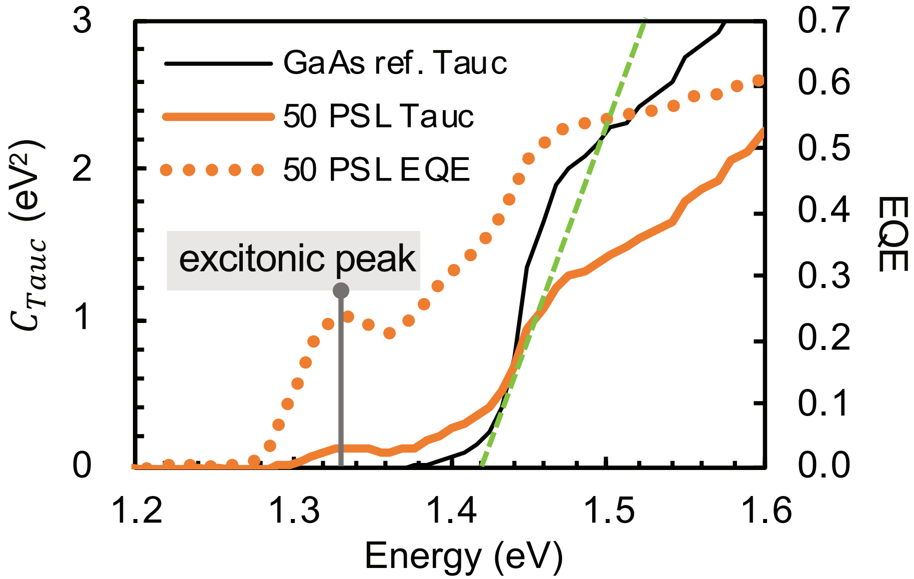
2. Our work

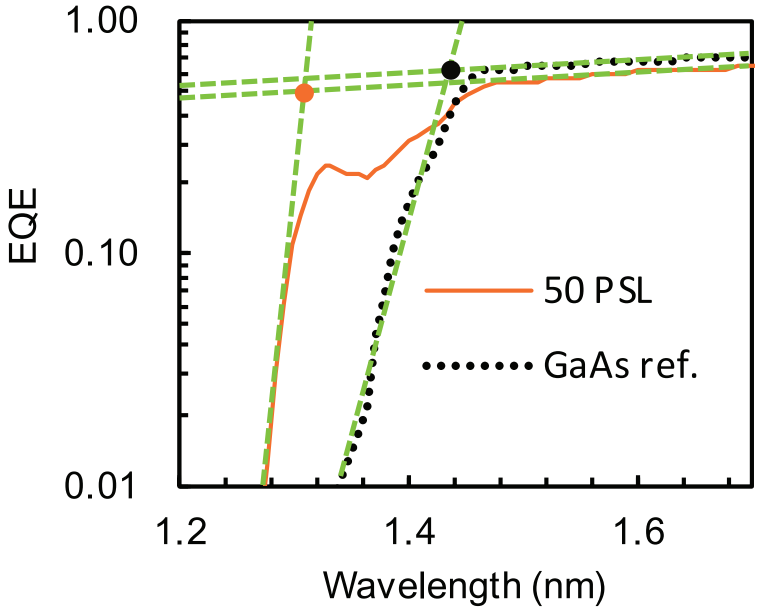
- 2-1. Definition of “bandgap” of quantum structure solar cells
- 2-2. Voltage loss analysis on quantum structure solar cells
- 2-3. How to reduce the voltage loss in quantum structure solar cells

3. Conclusion

2-1 Definition of “bandgap” of quantum structure solar cells





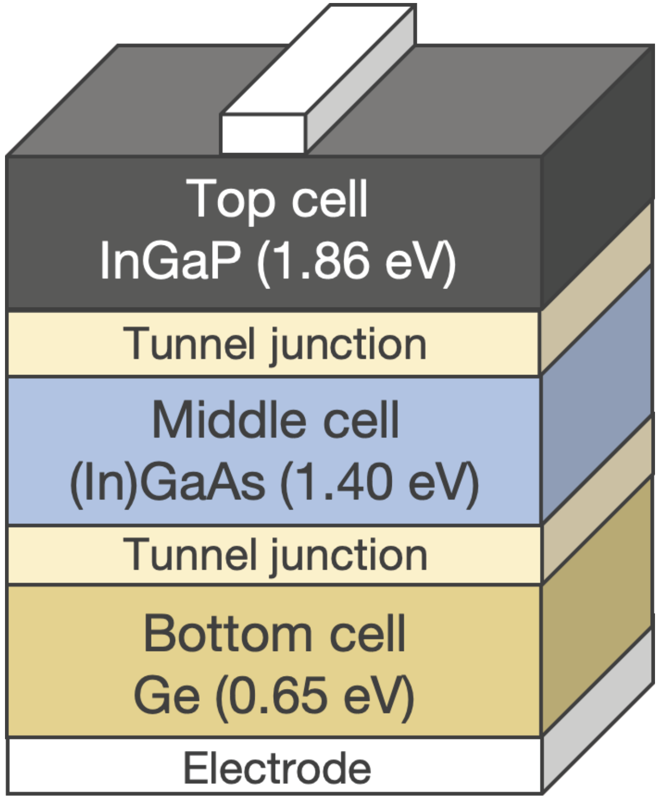


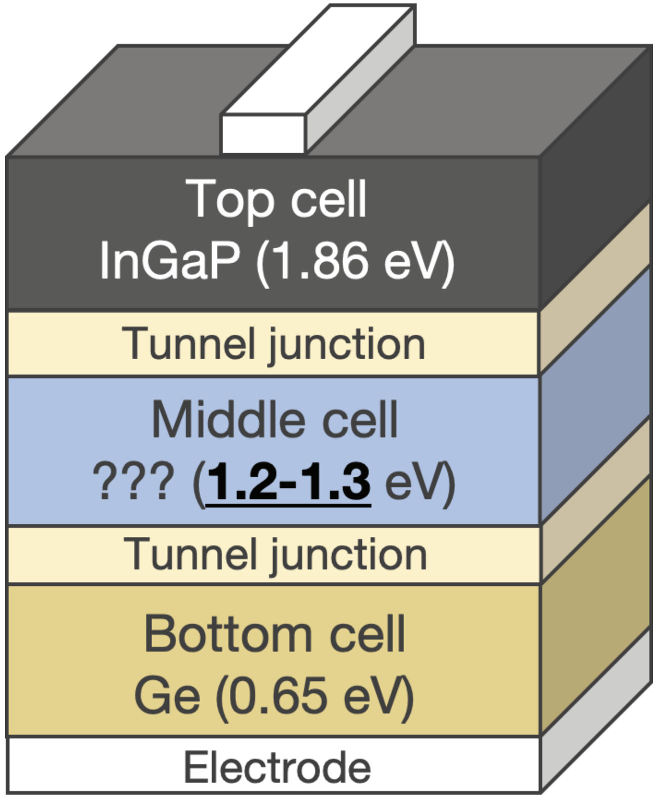
All of these methods are not applicable to quantum solar cells

cf. M. Asami *et al*., *IEEE JPV* **13**, 2023.

We propose a new method to define the “bandgap” of quantum structure solar cells

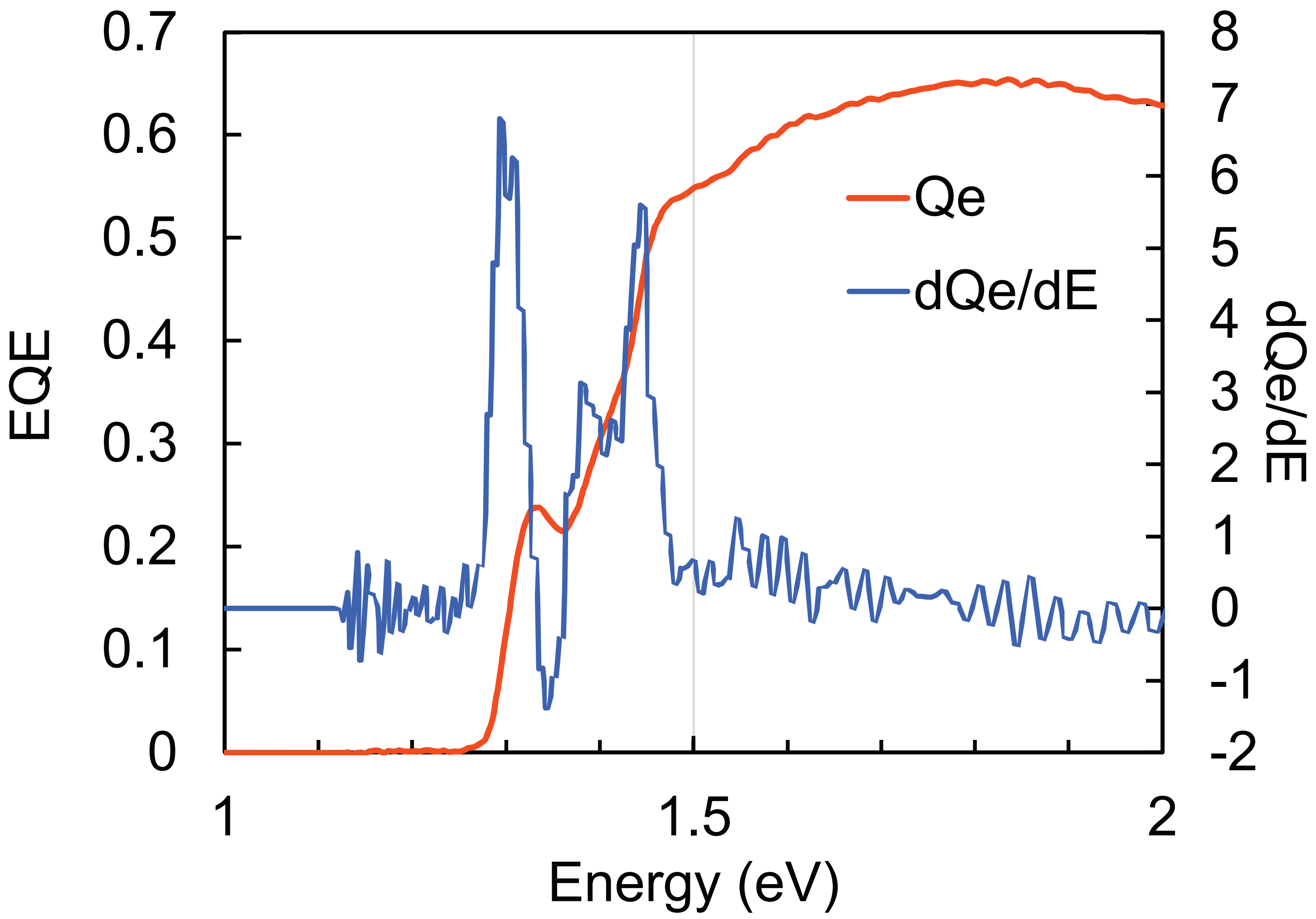
2-1 Definition of “bandgap” of quantum structure solar cells





The main objective of lowering the bandgap of the middle cell is to enhance current density

2-1 Definition of “bandgap” of quantum structure solar cells



Main objective

Increasing current density

<u>Expanding absorption edge</u>

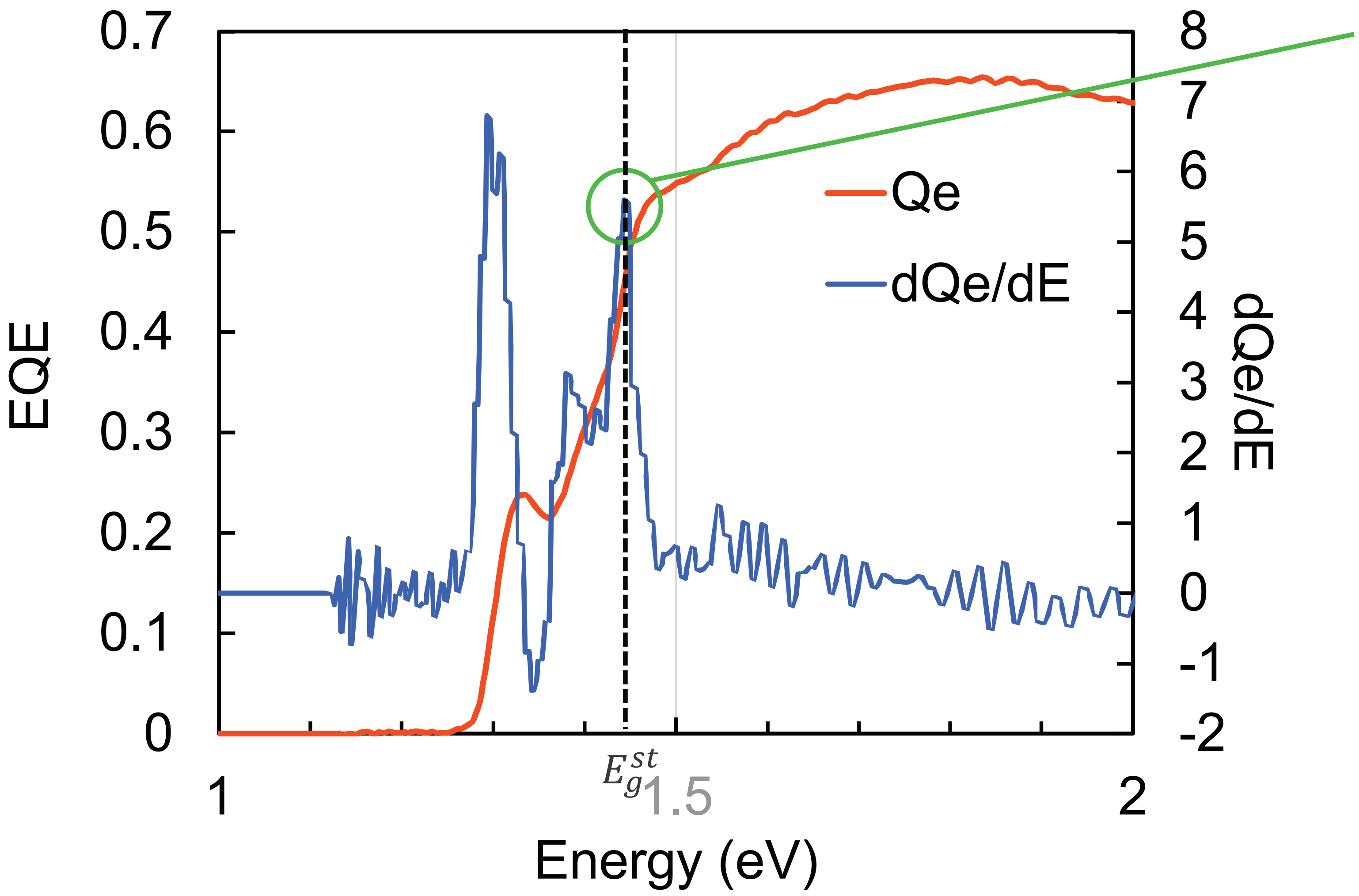
<u>Drawback</u>

Decreasing voltage

<u>Ideal material and structure</u>

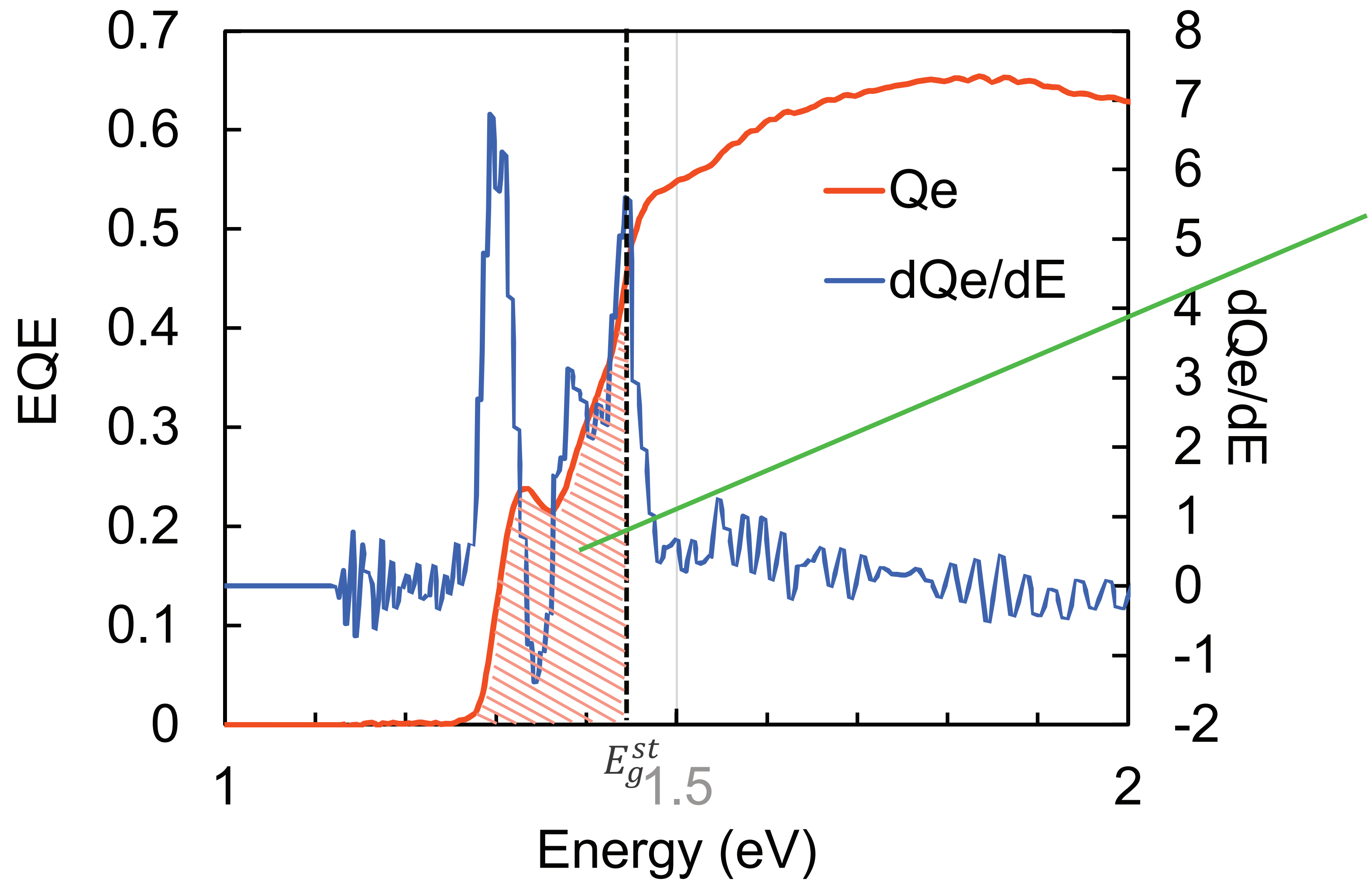
Increasing photo-generated carriers with minimized expansion of absorption edge

2-1 Definition of “bandgap” of quantum structure solar cells



1. A peak at the highest energy is regarded as a standard bandgap E_g^{st}

2-1 Definition of "bandgap" of quantum structure solar cells

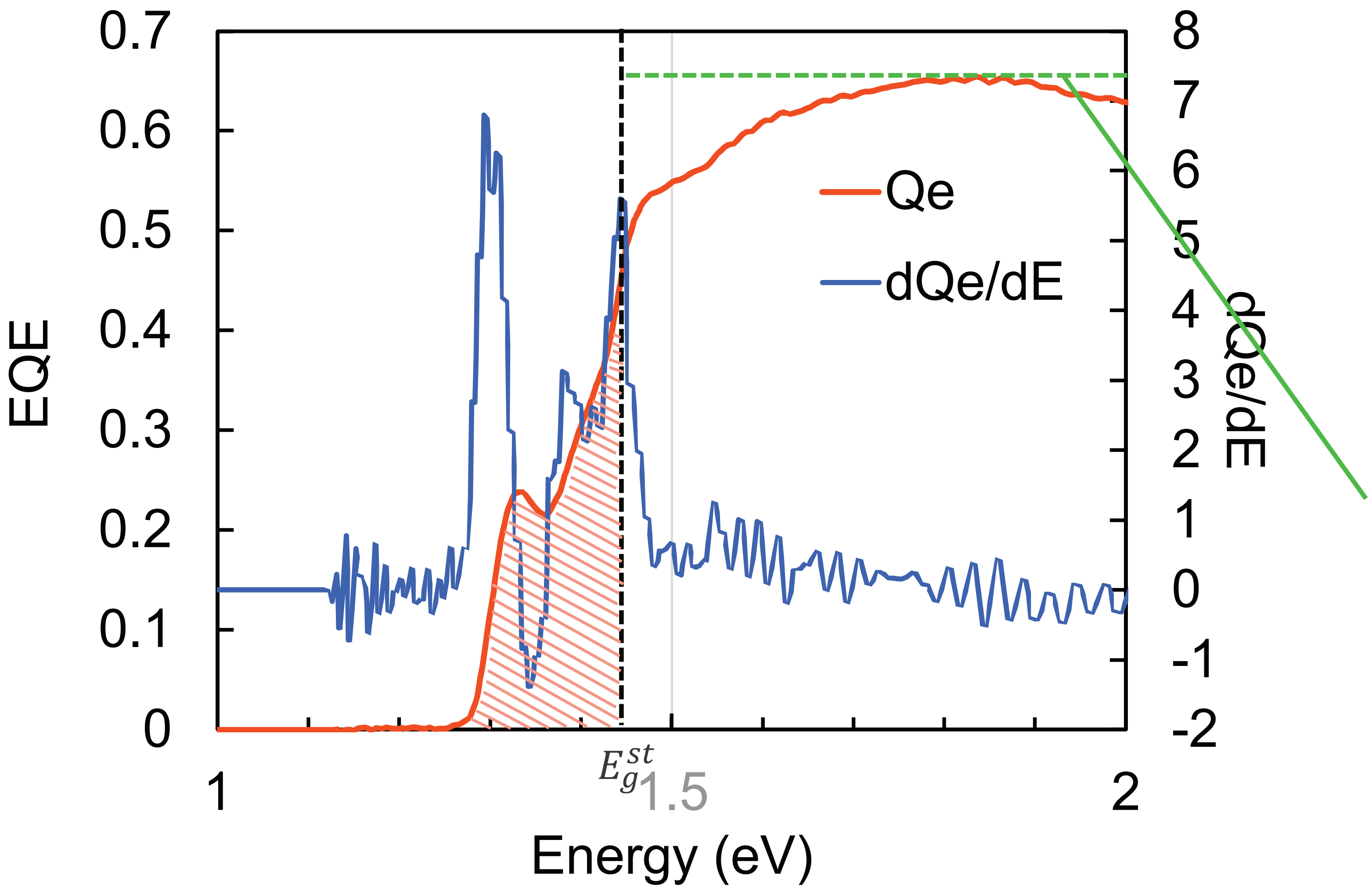


1. A peak at the highest energy is regarded as a standard bandgap E_g^{st}
2. Calculate the increased current density J_{exp} by expanding absorption edge from the standard bandgap to lower energy

$$J_{exp} = q \int_0^{E_g^{st}} Q_e \phi_{sun} dE$$

ϕ_{sun}: Photon flux of sun light

2-1 Definition of “bandgap” of quantum structure solar cells



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3. Maximum value of EQE

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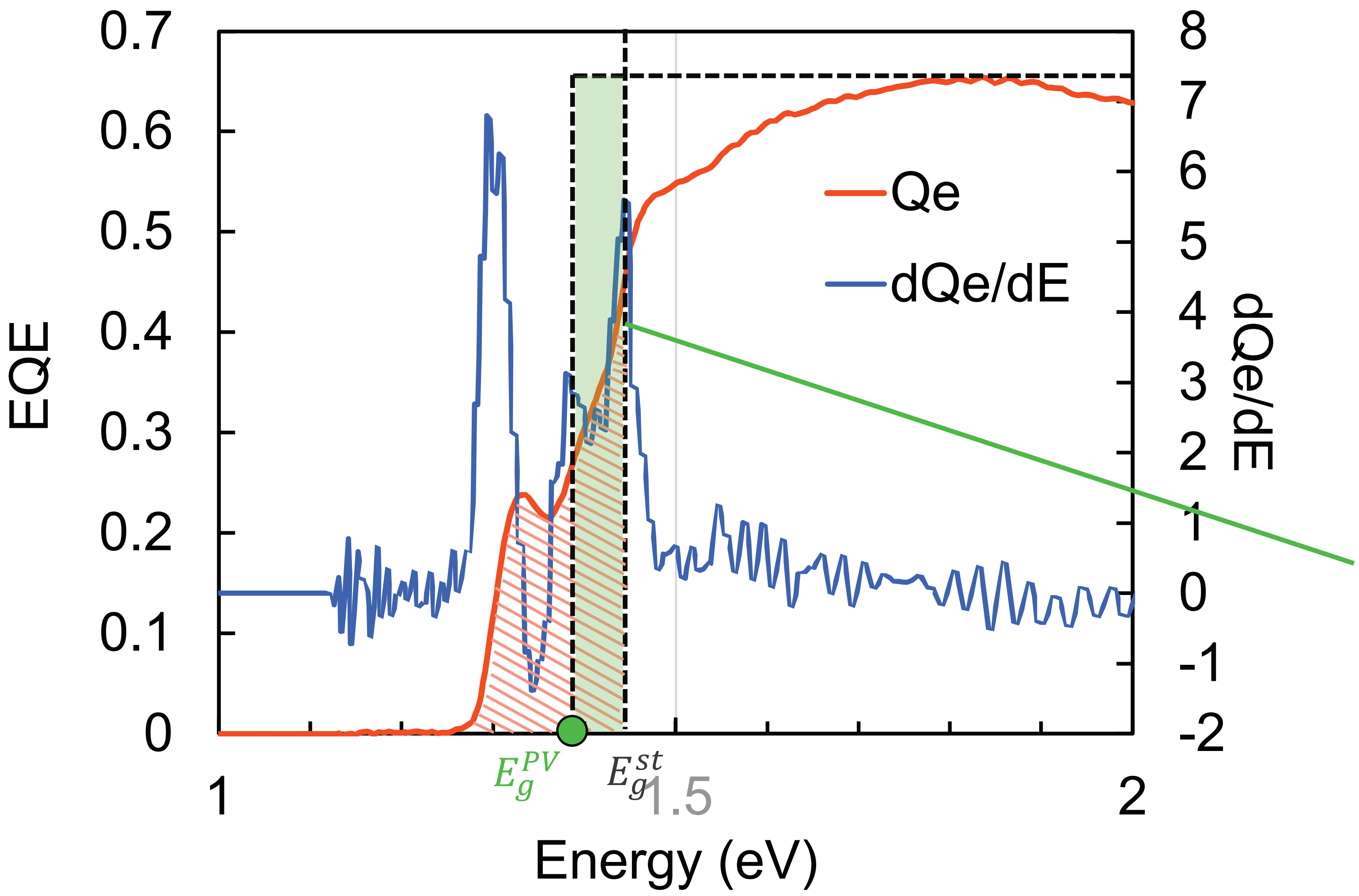

1. A peak at the highest energy is regarded as a standard bandgap E_g^{st}
2. Calculate the increased current density J_{exp} by expanding absorption edge from the standard bandgap to lower energy
3. Maximum value of EQE
4. Calculate E_g^{PV} from

$$q\int_{E_g^{PV}}^{E_g^{st}} \max\{Q_e\}\,\phi_{sun}\,dE = J_{exp}$$

$$\int 🟩\ \phi_{sun}\,dE = \int ▨\ \phi_{sun}\,dE$$

1-2 Voltage loss analysis based on detailed balance theory

$$\underline{\underline{V_{OC}^{SQ}}} - \underline{\underline{V_{OC}}} = \underline{\underline{\frac{kT}{q}\ln\frac{J_{SC}^{SQ}}{J_{em,0}^{SQ}}}} - \underline{\underline{\frac{kT}{q}\ln\frac{J_{SC}-J_{nr}}{J_{em,0}}}} = -\frac{kT}{q}\ln\frac{J_{em,0}^{SQ}}{J_{SC}^{SQ}}\times\frac{J_{SC}-J_{nr}}{J_{em,0}} = -\frac{kT}{q}\ln\frac{J_{SC}}{J_{SC}^{SQ}}\times\frac{J_{em,0}^{SQ}}{J_{em,0}}\times\frac{J_{SC}-J_{nr}}{J_{SC}}$$

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Open circuit voltage at Shockley-Queisser (SQ) limit calculated from E_g ⇨ $V_{OC}^{SQ} = \frac{kT}{q}\ln\frac{\int_{E_g}^{\infty} 1\times\phi_{sun}\,dE}{\int_{E_g}^{\infty} 1\times\phi_{bb}\,dE}$

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$$J = 0 = J_{SC} - J_{em,0}\left(\exp\left(\frac{qV_{OC}}{kT}\right) - 1\right) - J_{nr}$$

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$$V_{OC}^{SQ} = \frac{kT}{q}\ln\frac{\int_{E_g}^{\infty} 1\times\phi_{sun}\,dE}{\int_{E_g}^{\infty} 1\times\phi_{bb}\,dE} = \underbrace{\frac{kT}{q}\ln\frac{\int_{E_g}^{\infty} \max\{Q_e\}\times\phi_{sun}\,dE}{\int_{E_g}^{\infty} \max\{Q_e\}\times\phi_{bb}\,dE} = \frac{kT}{q}\ln\frac{J_{SC}^{max}}{J_{em,0}^{max}}}$$

We modified the conventional method

$$\underline{\Delta V_{OC}^{SC}} \equiv -\frac{kT}{q}\ln\frac{J_{SC}}{J_{SC}^{max}},\ \underline{\Delta V_{OC}^{rad}} \equiv -\frac{kT}{q}\ln\frac{J_{em,0}^{max}}{J_{em,0}},\ \underline{\Delta V_{OC}^{nonrad}} \equiv -\frac{kT}{q}\ln\frac{J_{SC}-J_{nr}}{J_{SC}}$$

Three types of voltage loss

Short circuit current voltage loss

radiative recombination voltage loss

non-radiative recombination voltage loss

ϕ_{sun}: Photon flux of sunlight, ϕ_{bb}: Photon flux of black body radiation

2-2 Voltage loss analysis on quantum structure solar cells

This modification is needed for low EQE samples.

Without this modification, ΔV_{OC}^{rad} sometimes becomes negative value (unphysical situation)

$$V_{OC}^{SQ} = \frac{kT}{q}\ln\frac{\int_{E_g}^{\infty} 1\times\phi_{sun}dE}{\int_{E_g}^{\infty} 1\times\phi_{bb}\,dE} = \underbrace{\frac{kT}{q}\ln\frac{\int_{E_g}^{\infty}\max\{Q_e\}\times\phi_{sun}dE}{\int_{E_g}^{\infty}\max\{Q_e\}\times\phi_{bb}\,dE} = \frac{kT}{q}\ln\frac{J_{SC}^{max}}{J_{em,0}^{max}}}$$

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Three types of voltage loss

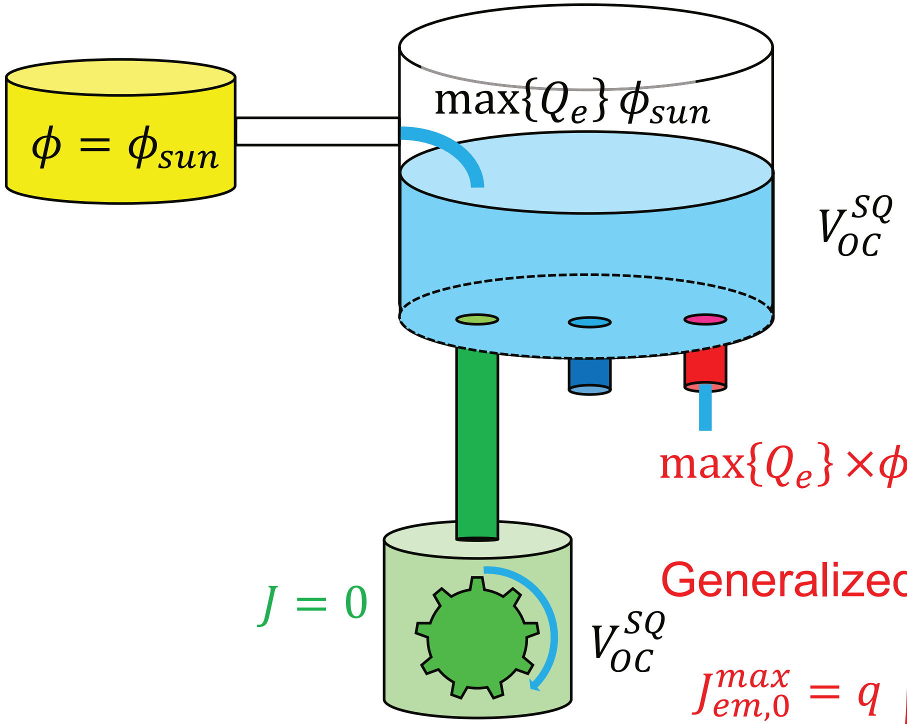
Short circuit current voltage loss

radiative recombination voltage loss

non-radiative recombination voltage loss

ϕ_{sun}: Photon flux of sunlight, ϕ_{bb}: Photon flux of black body radiation

2-2 Intuitive way to understand each voltage loss

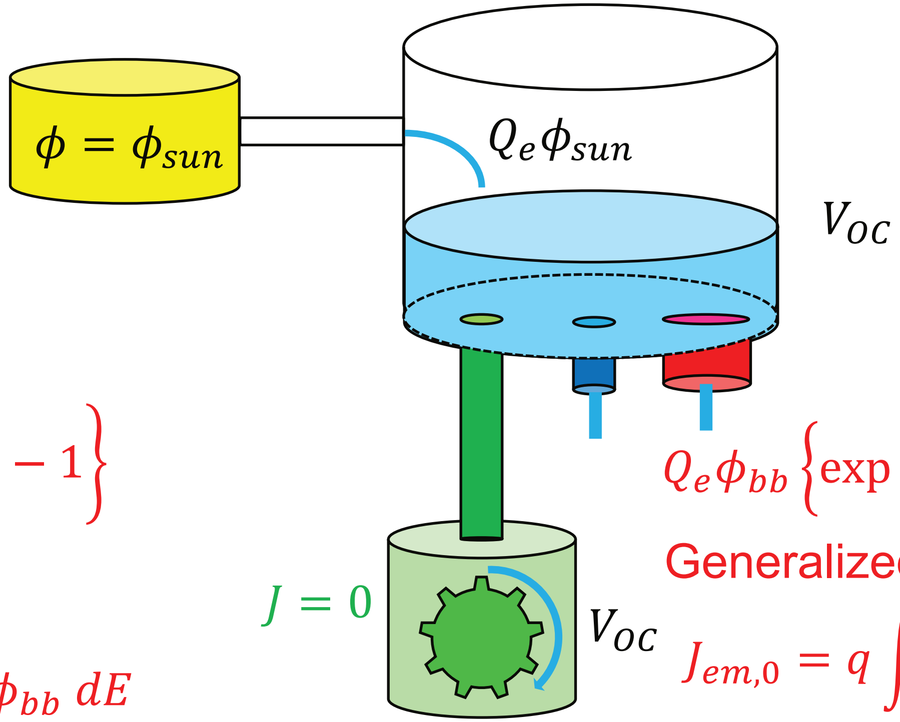


$$\max\{Q_e\} \times \phi_{bb} \left\{ \exp\left(\frac{qV_{OC}^{SQ}}{kT} \right) - 1 \right\}$$

Generalized Planck's law

$$J_{em,0}^{max} = q \int_0^{E_g^{PV}} \max\{Q_e\} \times \phi_{bb} \, dE$$

An ideal solar cell



$$Q_e \phi_{bb} \left\{ \exp\left(\frac{qV_{OC}}{kT} \right) - 1 \right\}$$

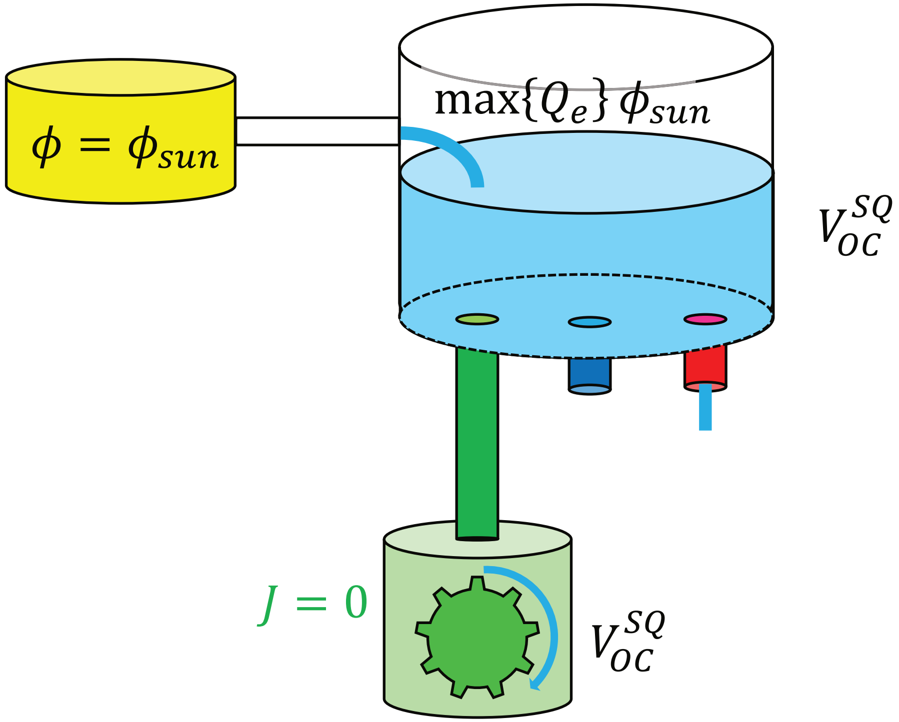
Generalized Planck's law

$$J_{em,0} = q \int_0^{\infty} Q_e \phi_{bb} \, dE$$

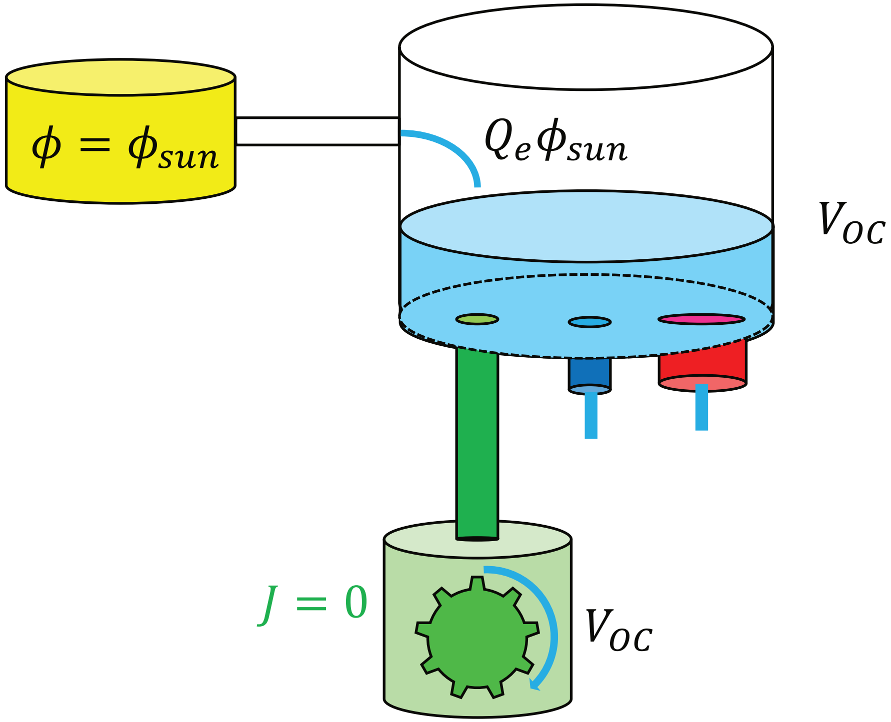
A quantum structure solar cell

generated current
non-radiative recombination
radiative recombination

2-2 Short circuit current voltage loss



An ideal solar cell



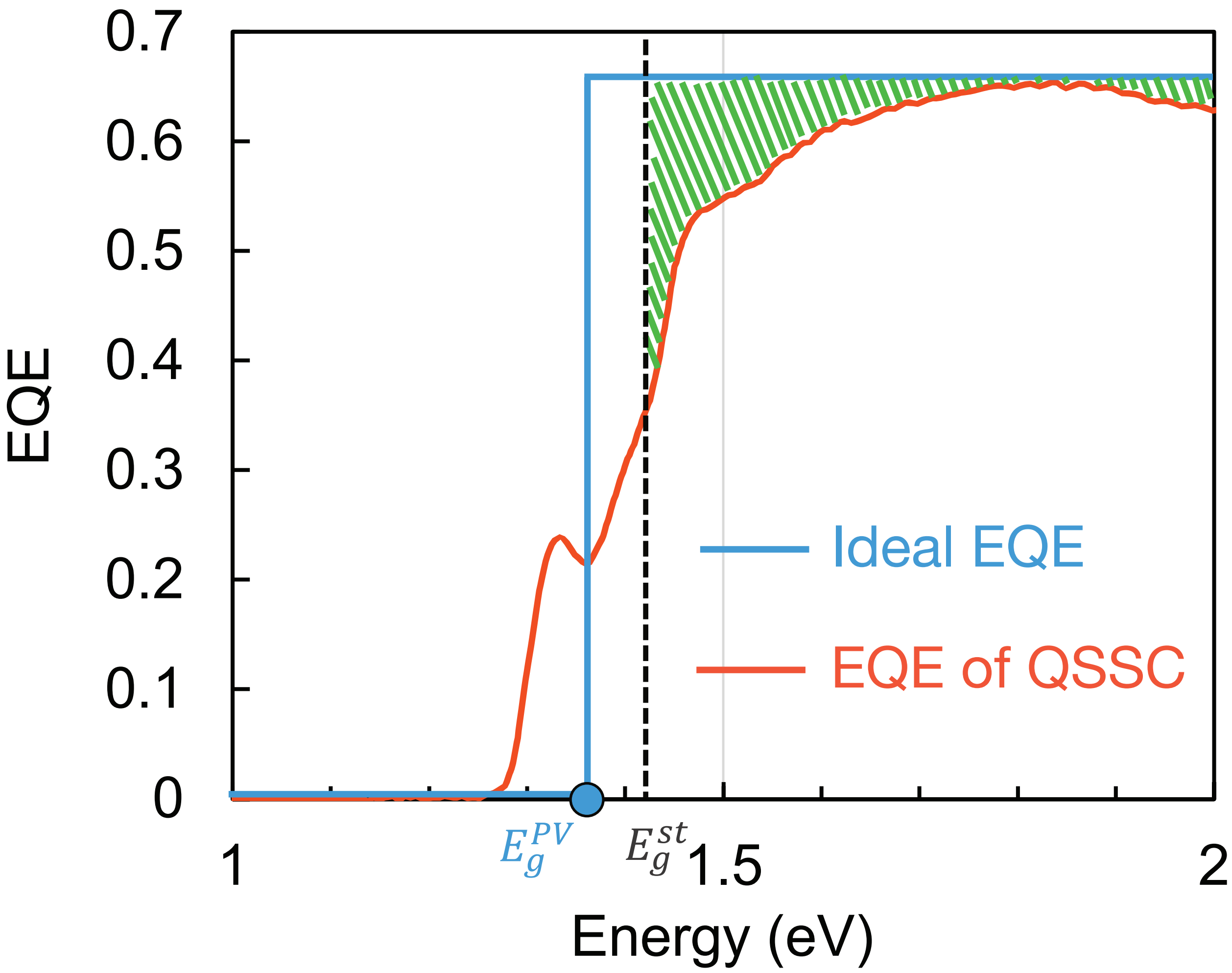
A quantum structure solar cell

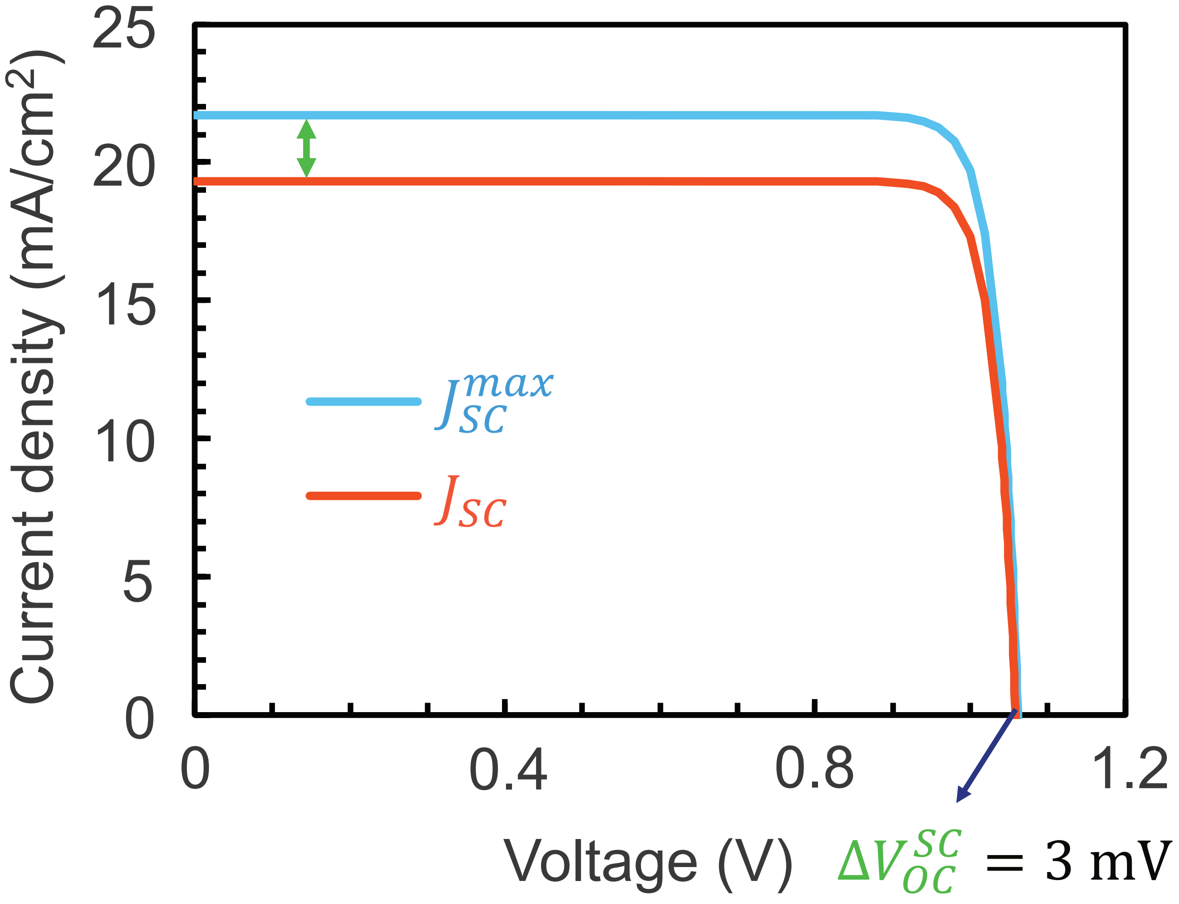
generated current

non-radiative recombination

radiative recombination

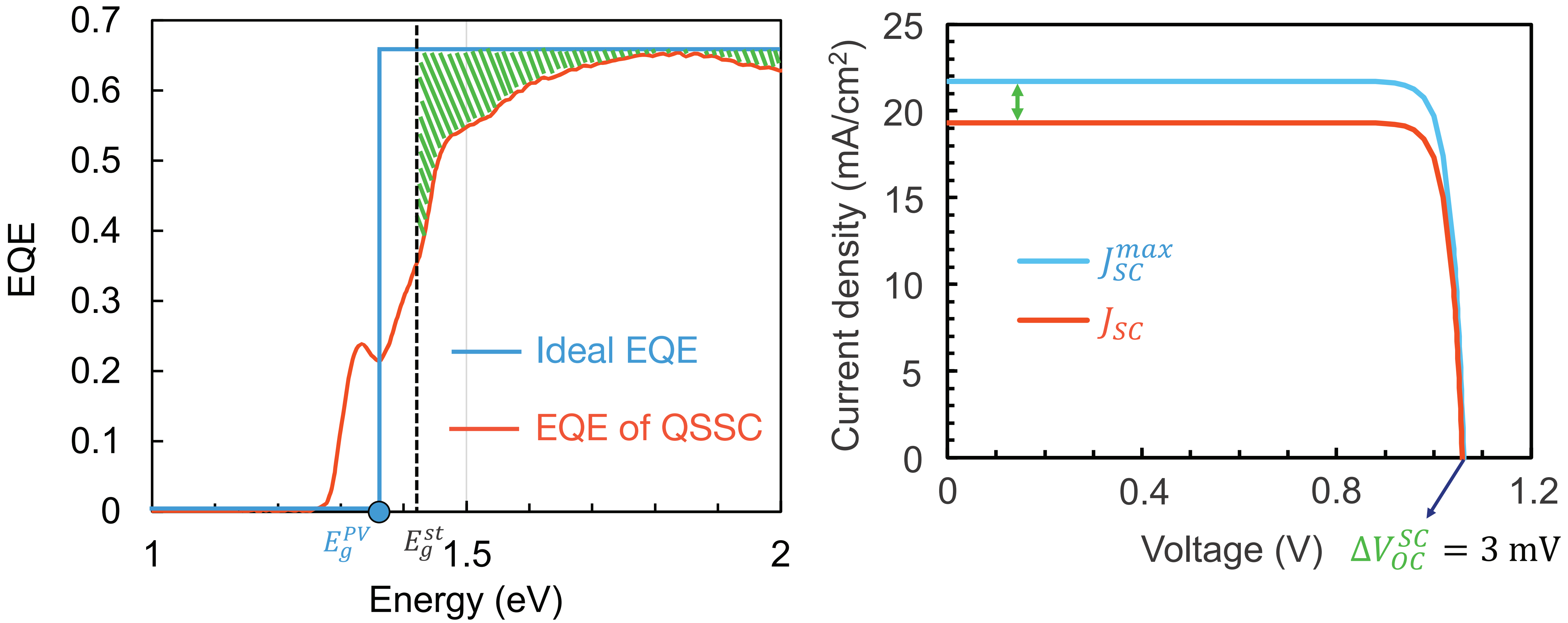
2-2 Short circuit current voltage loss





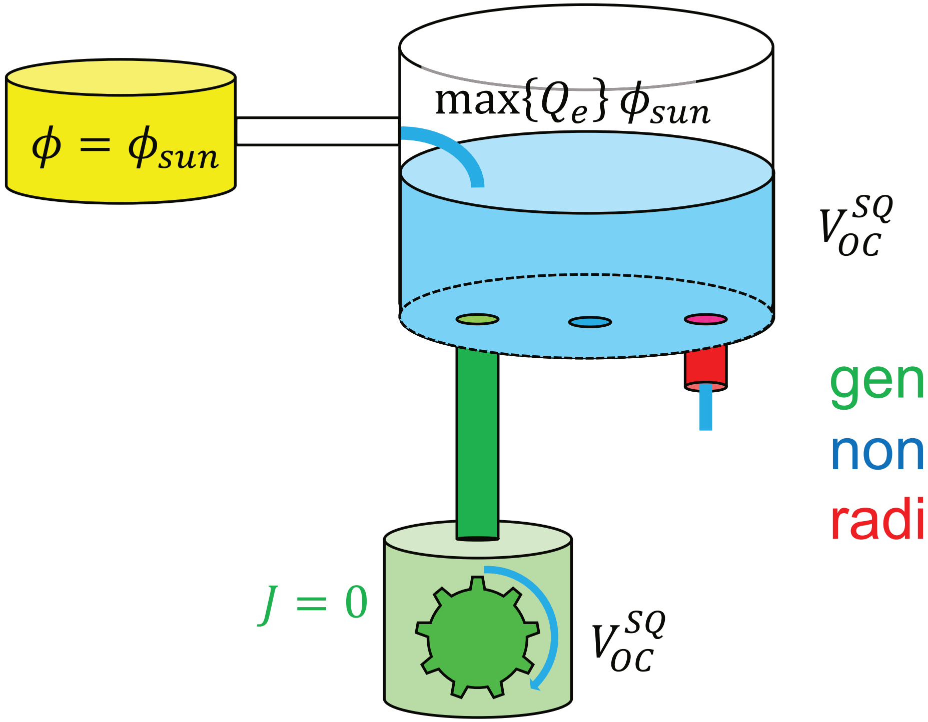
Short circuit current voltage loss is usually **negligibly small**

2-2 Short circuit current voltage loss



$$\Delta V_{OC}^{SC} \equiv -\frac{kT}{q}\ln\frac{J_{SC}}{J_{SC}^{max}}, \Delta V_{OC}^{rad} \equiv -\frac{kT}{q}\ln\frac{J_{em,0}^{max}}{J_{em,0}}, \Delta V_{OC}^{nonrad} \equiv -\frac{kT}{q}\ln\frac{J_{SC}-J_{nr}}{J_{SC}}$$

2-2 Non-radiative recombination voltage loss

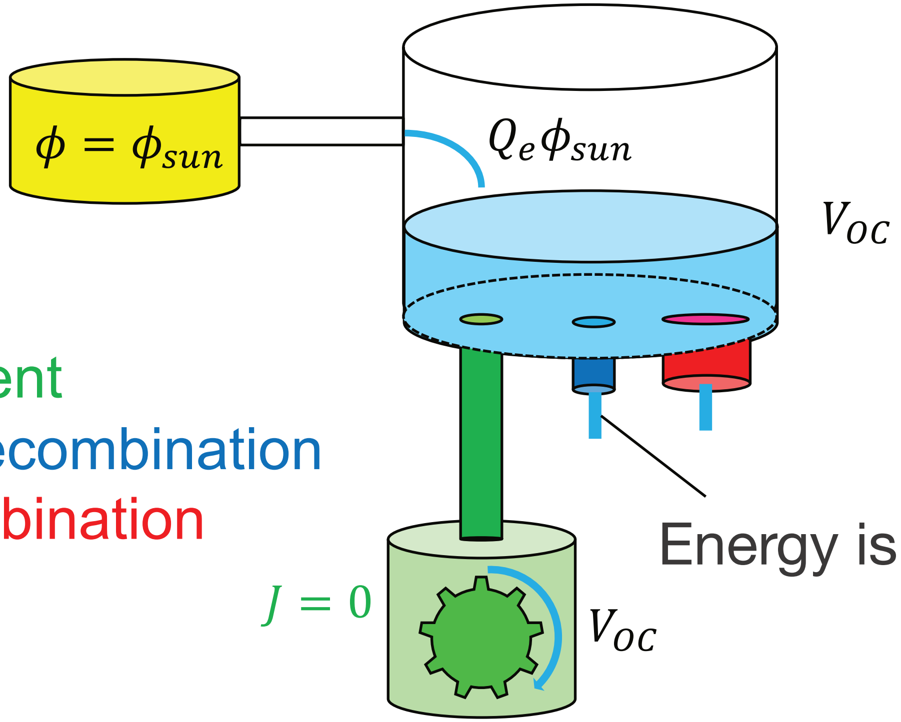


generated current

non-radiative recombination

radiative recombination

An ideal solar cell

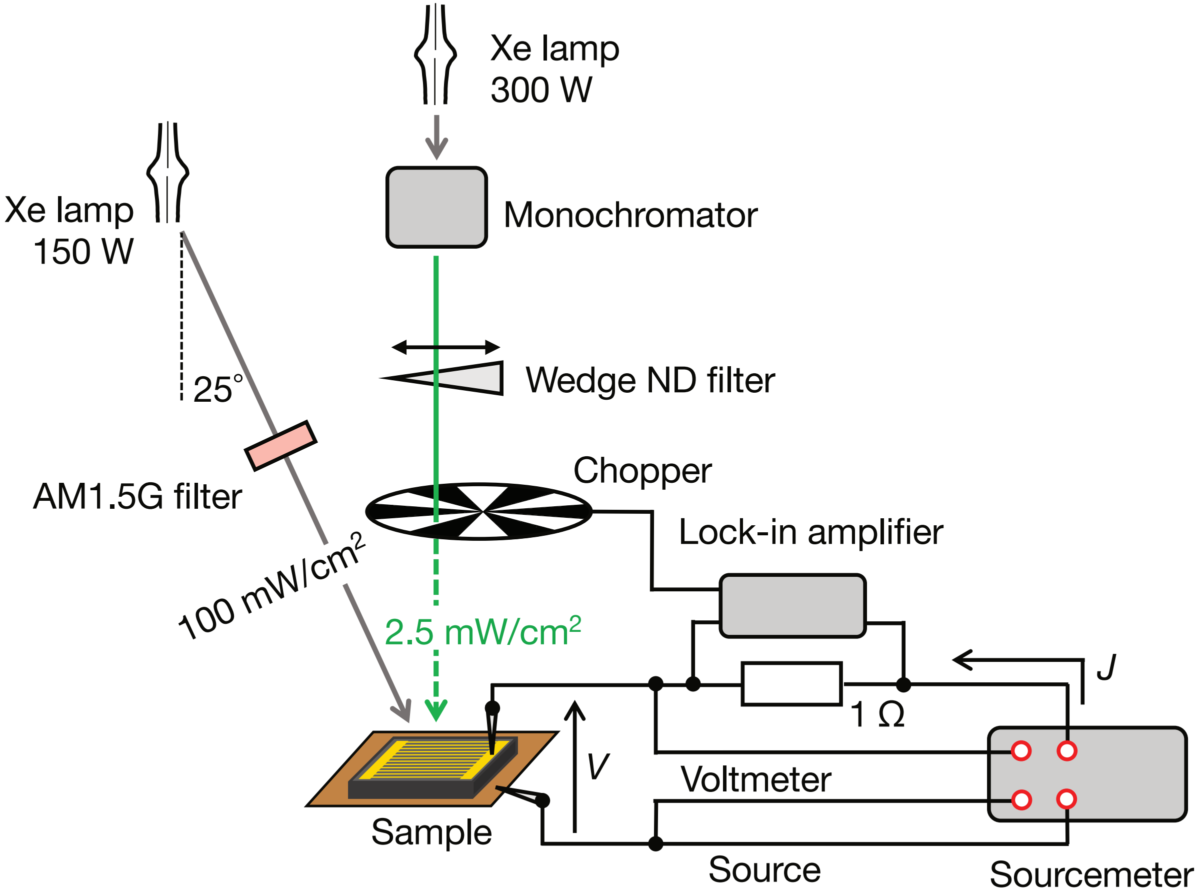


Energy is lost as **heat**

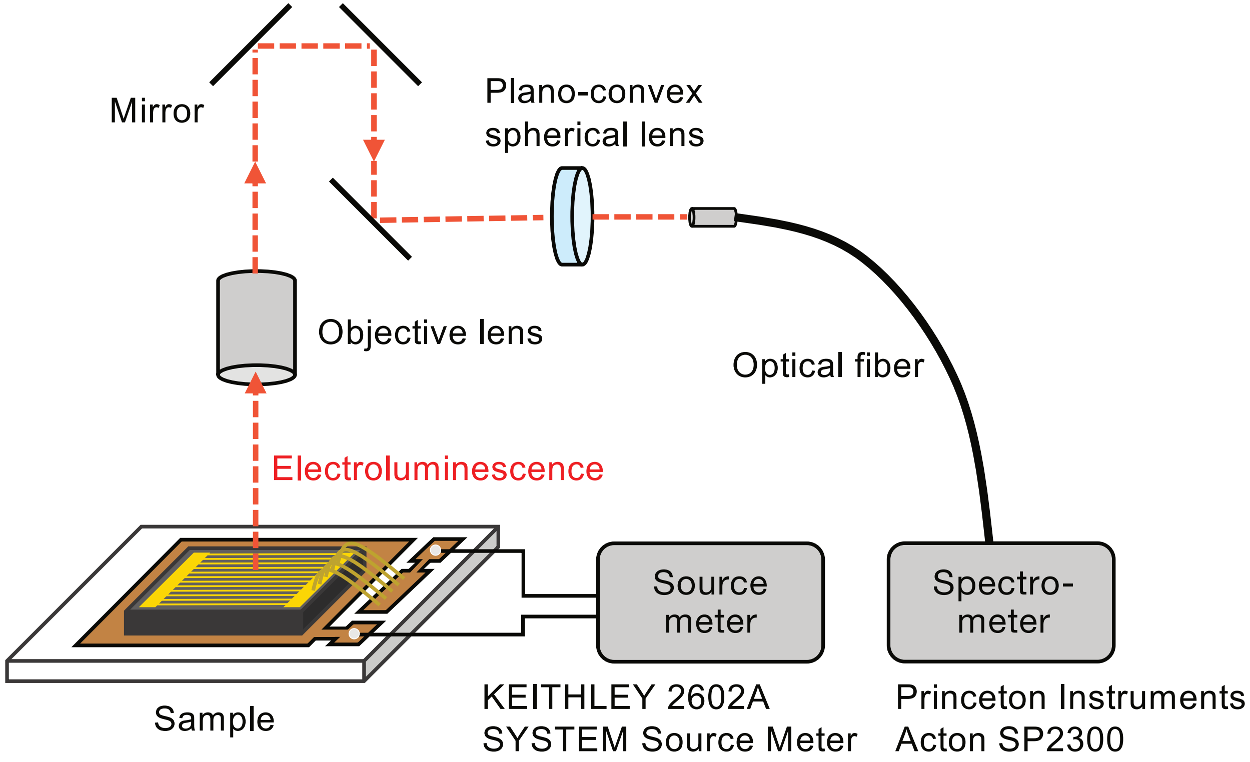
A quantum structure solar cell

An ideal solar cell does not have any non-radiative recombination voltage loss

2-2 Non-radiative recombination voltage loss



EQE measurement setup

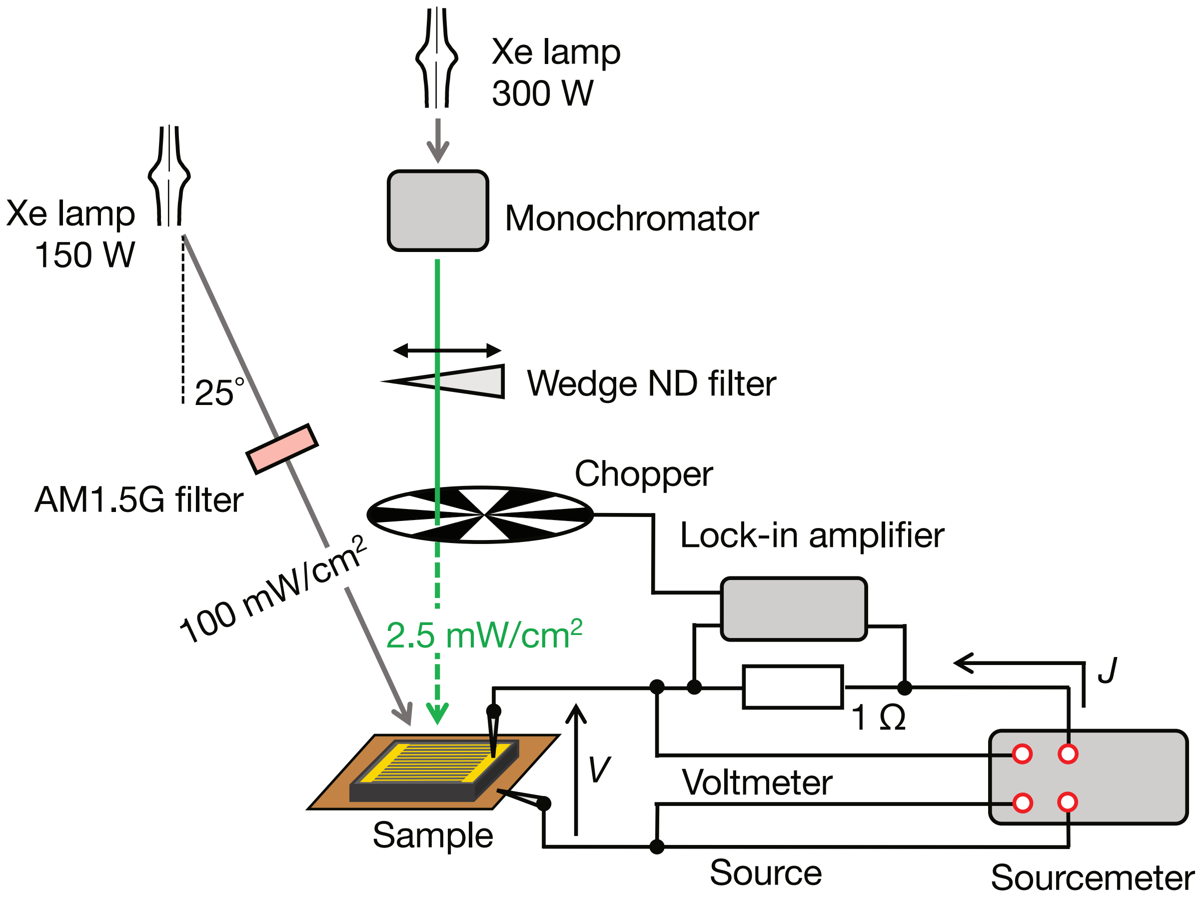


EL measurement setup

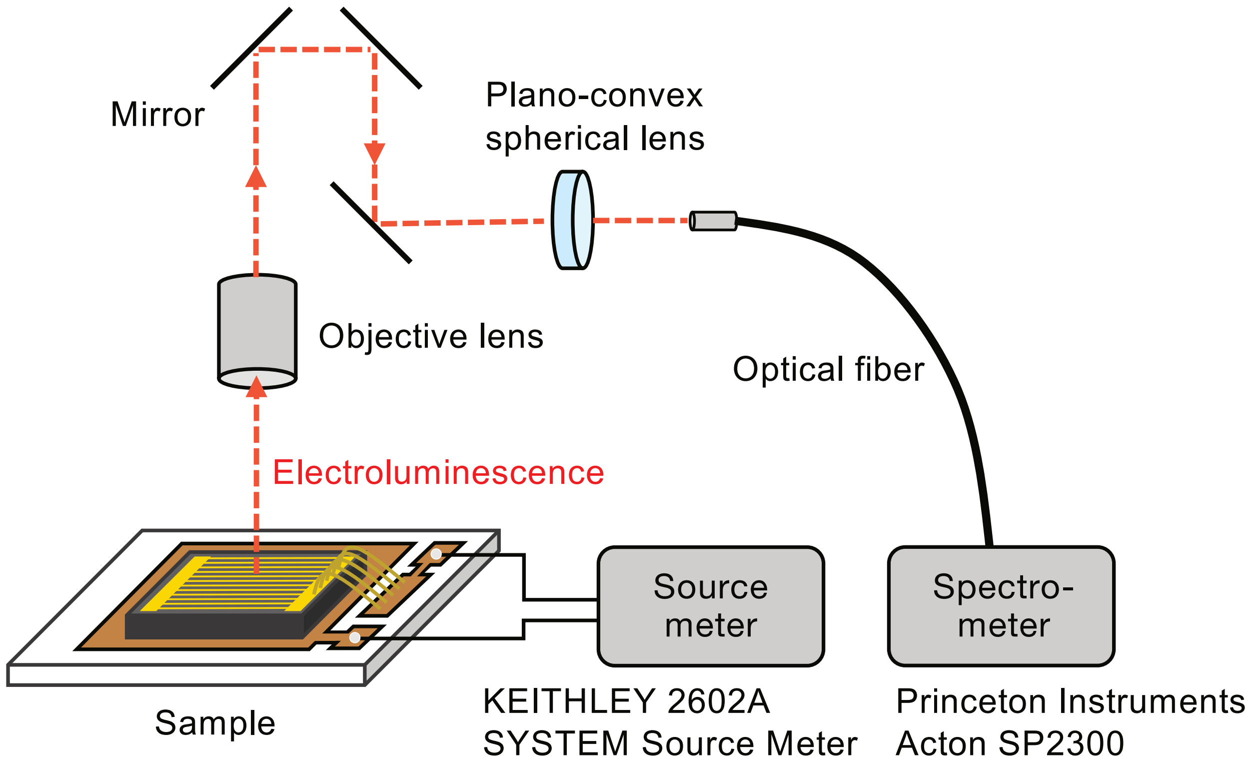
Non-radiative recombination voltage loss can be evaluated by either EQE or EL measurements [*]

[*] M. Asami *et al.*, *IEEE JPV* **13**, 2023.

2-2 Non-radiative recombination voltage loss



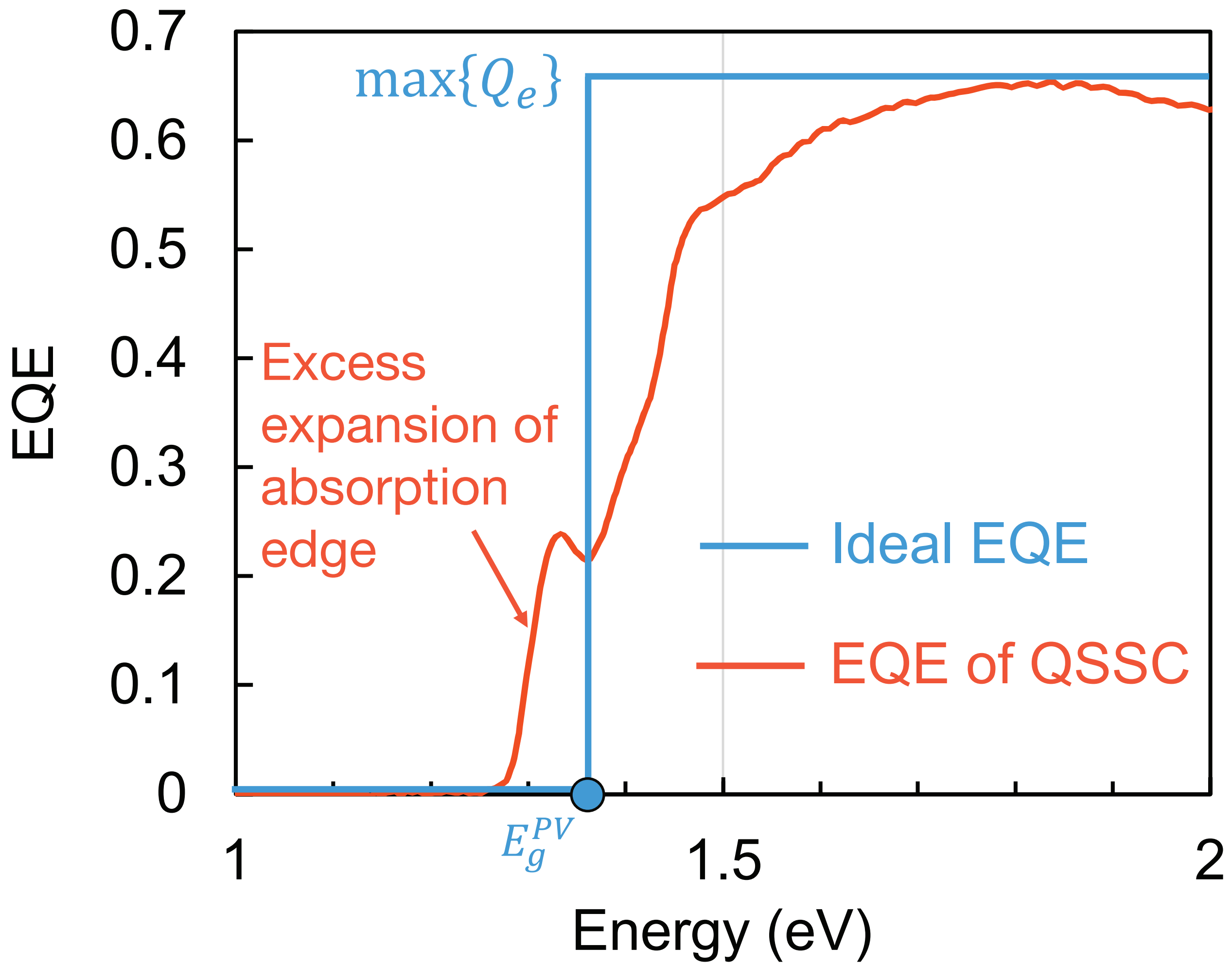
EQE measurement setup



EL measurement setup

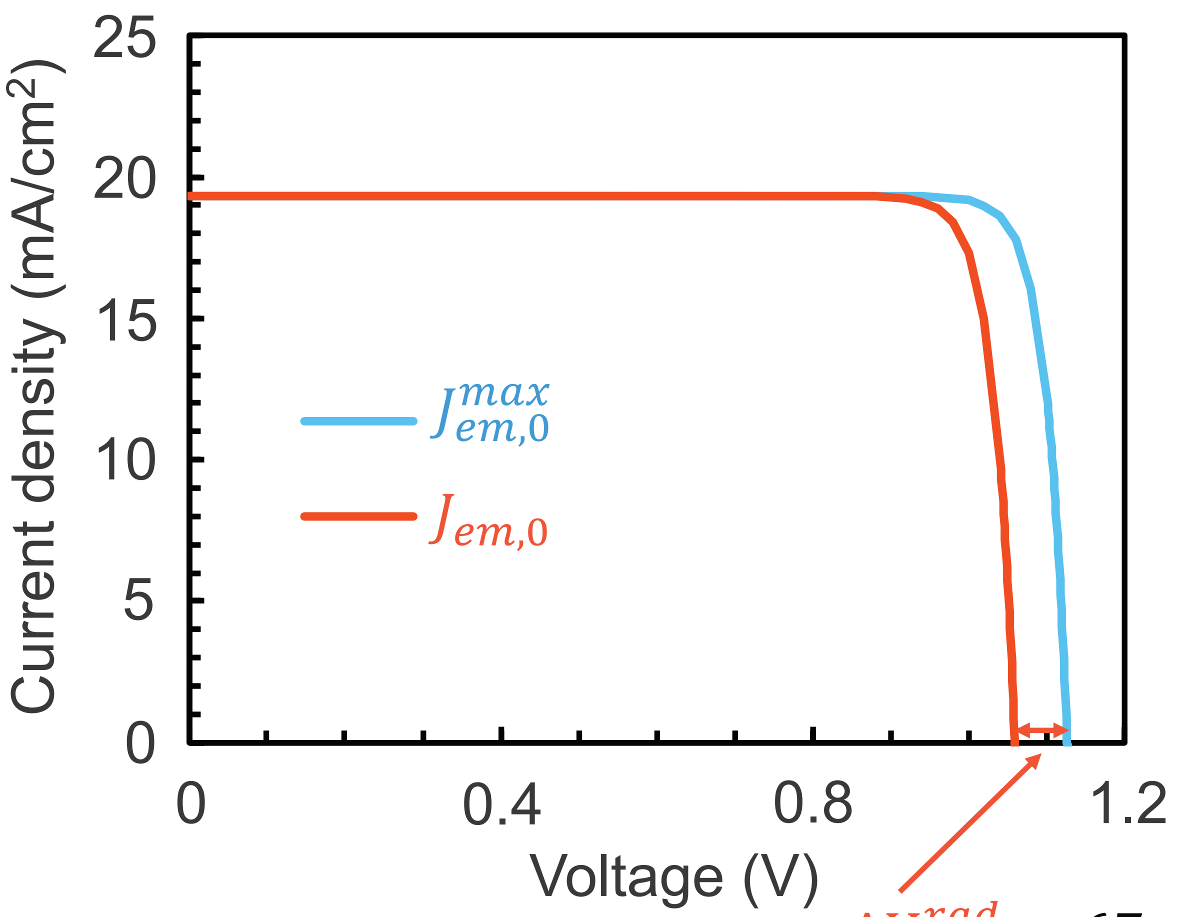
$$\Delta V_{OC}^{SC} \equiv -\frac{kT}{q}\ln\frac{J_{SC}}{J_{SC}^{max}}, \Delta V_{OC}^{rad} \equiv -\frac{kT}{q}\ln\frac{J_{em,0}^{max}}{J_{em,0}}, \Delta V_{OC}^{nonrad} \equiv -\frac{kT}{q}\ln\frac{J_{SC}-J_{nr}}{J_{SC}}$$

2-2 Radiative recombination voltage loss



Excess expansion of absorption edge

$$\Delta V_{OC}^{rad} \equiv -\frac{kT}{q}\ln\frac{J_{em,0}^{max}}{J_{em,0}} = -\frac{kT}{q}\ln\frac{\int_{E_g}^{\infty}\max\{Q_e\}\times\phi_{bb}\,dE}{\int_{0}^{\infty}Q_e\times\phi_{bb}\,dE}$$



$\Delta V_{OC}^{rad} = 67\ \text{mV}$

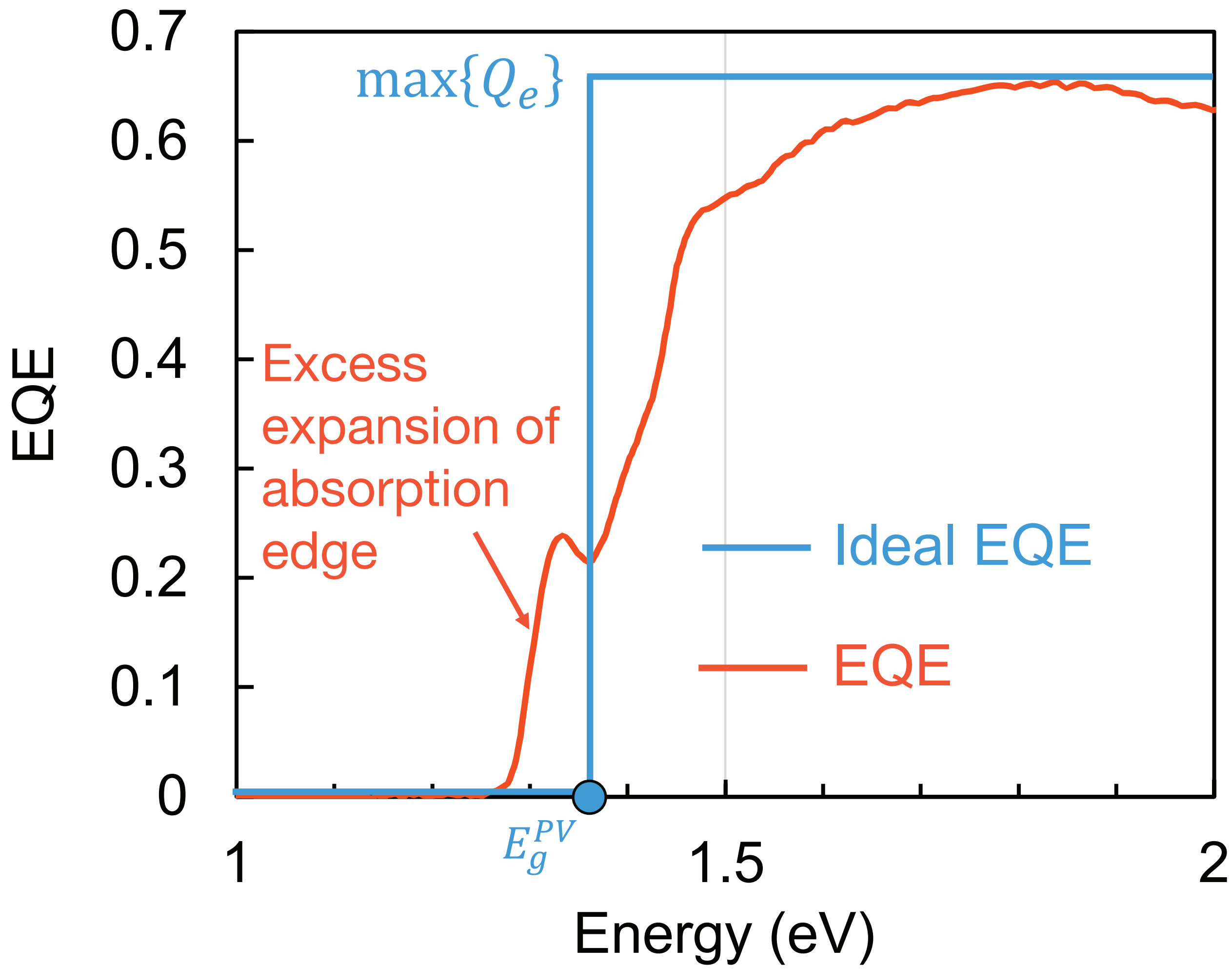
Energy conversion eff. (w/o ARC)

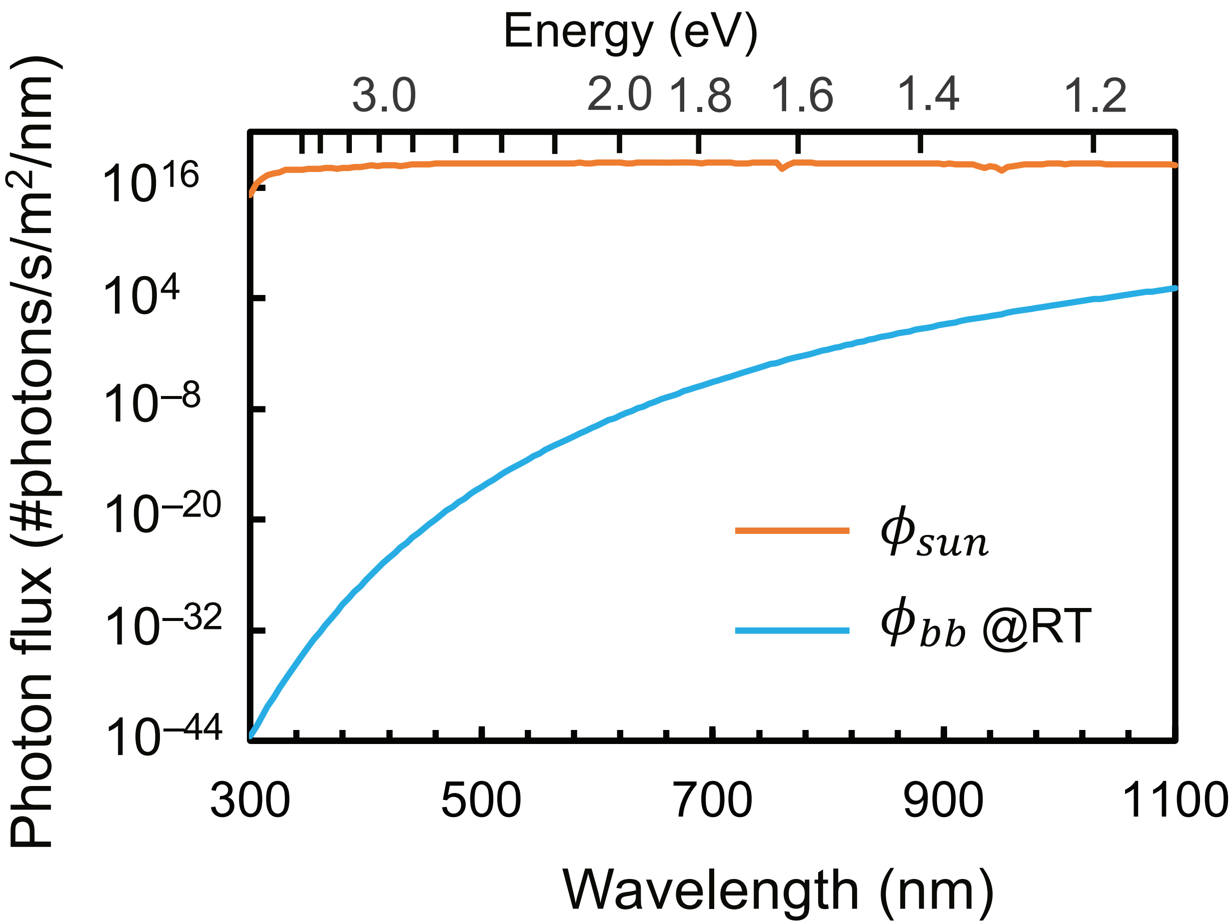
19.4% – 18.1% = 1.3 pt

~2 pt (w/ ARC)

ϕ_{bb}: Photon flux of black body radiation

2-2 Radiative recombination voltage loss



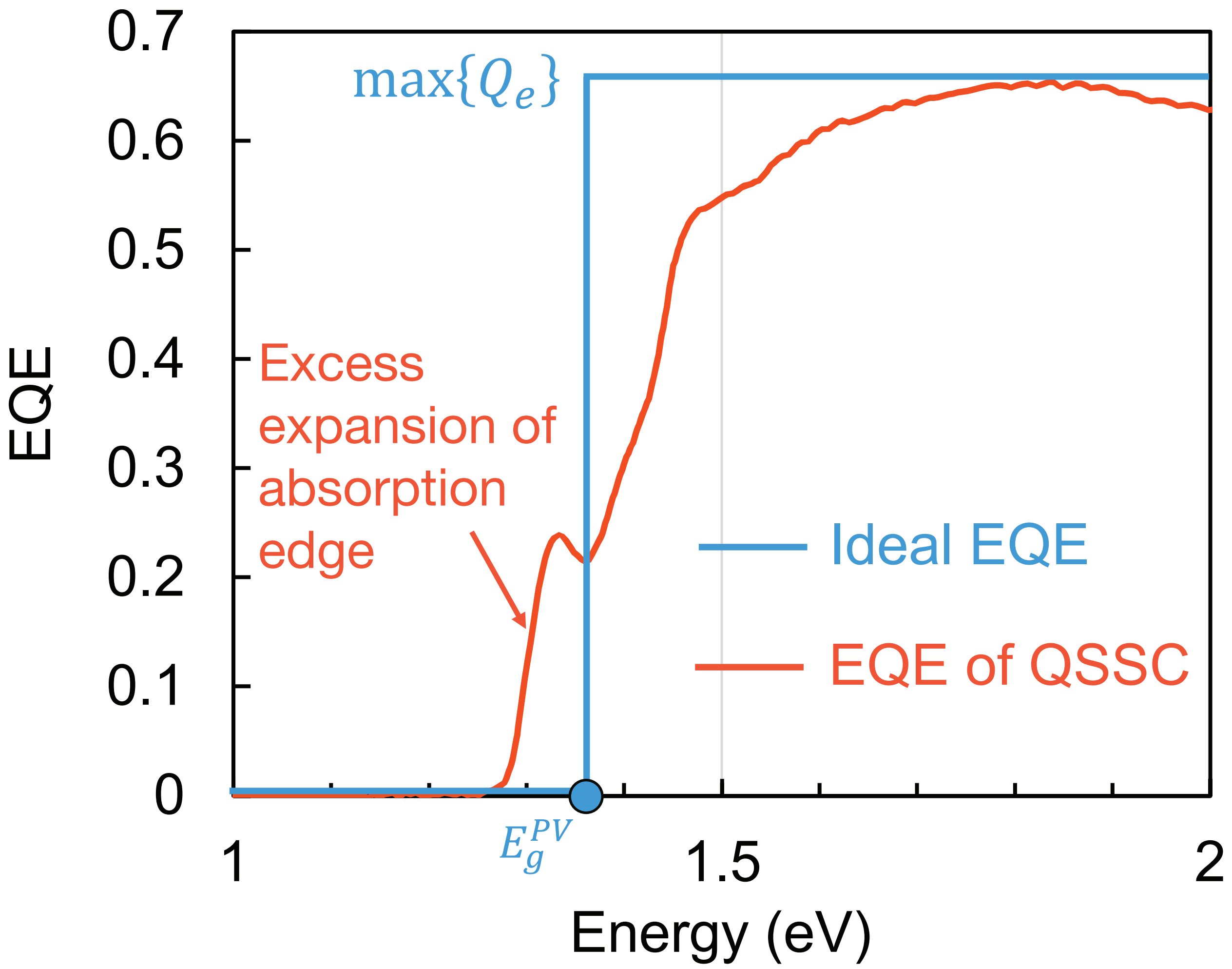


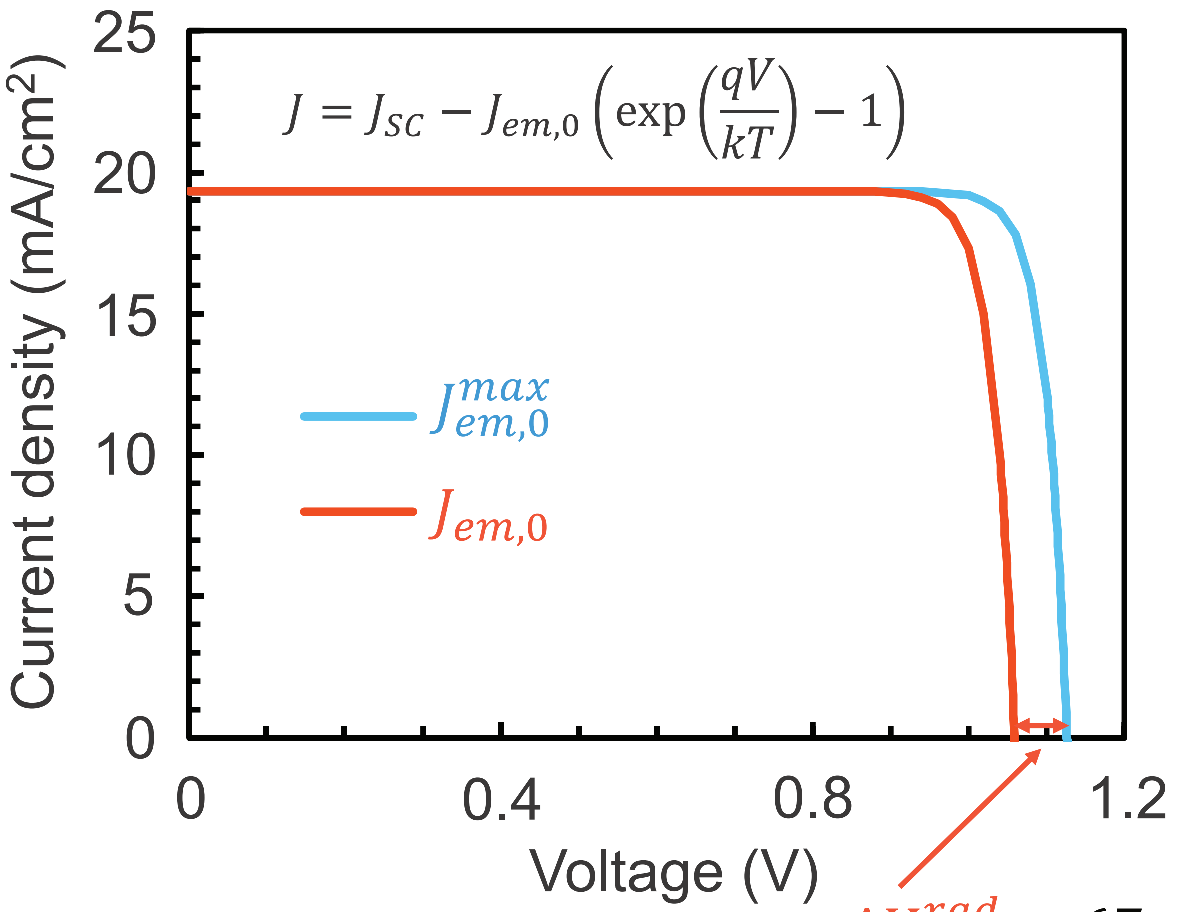
$$\Delta V_{OC}^{rad} \equiv -\frac{kT}{q}\ln\frac{J_{em,0}^{max}}{J_{em,0}} = -\frac{kT}{q}\ln\frac{\int_{E_g}^{\infty}\max\{Q_e\}\times\phi_{bb}\,dE}{\int_{0}^{\infty}Q_e\times\phi_{bb}\,dE}$$

ϕ_{bb} at lower energy is much higher

ϕ_{bb}: Photon flux of black body radiation

2-2 Radiative recombination voltage loss





$$J = J_{SC} - J_{em,0}\left(\exp\left(\frac{qV}{kT}\right) - 1\right)$$

$\Delta V_{OC}^{rad} = 67$ mV

$$\Delta V_{OC}^{rad} \equiv -\frac{kT}{q}\ln\frac{J_{em,0}^{max}}{J_{em,0}} = -\frac{kT}{q}\ln\frac{\int_{E_g}^{\infty}\max\{Q_e\}\times\phi_{bb}\,dE}{\int_{0}^{\infty}Q_e\times\phi_{bb}\,dE}$$

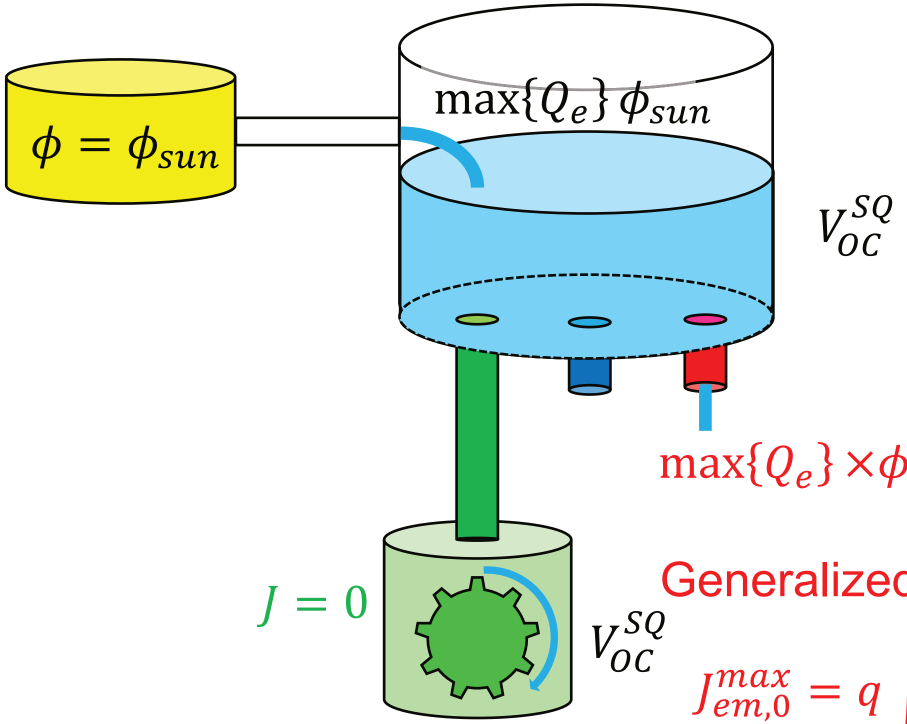
×8.6

$$J_{em,0}^{max} = 5.46\times10^{-18}\ \mathrm{mA/cm^{-2}}$$

$$J_{em,0} = 4.67\times10^{-17}\ \mathrm{mA/cm^{-2}}$$

ϕ_{bb}: Photon flux of black body radiation

2-2 Radiative recombination voltage loss

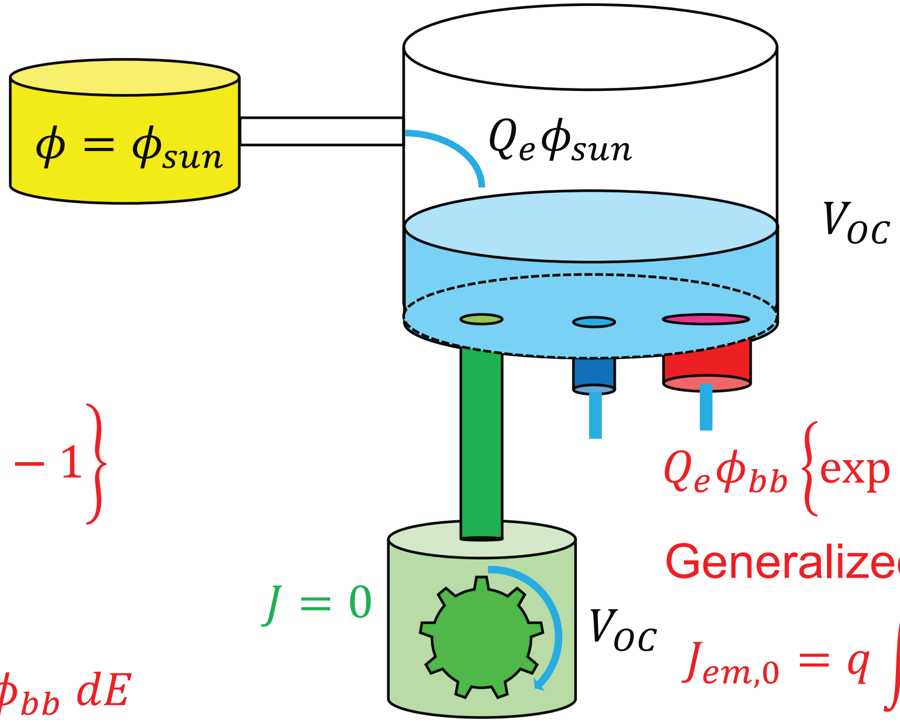


$$\max\{Q_e\} \times \phi_{bb} \left\{ \exp\left(\frac{qV_{OC}^{SQ}}{kT} \right) - 1 \right\}$$

Generalized Planck's law

$$J_{em,0}^{max} = q \int_0^{E_g^{PV}} \max\{Q_e\} \times \phi_{bb}\, dE$$

An ideal solar cell



$$Q_e \phi_{bb} \left\{ \exp\left(\frac{qV_{OC}}{kT} \right) - 1 \right\}$$

Generalized Planck's law

$$J_{em,0} = q \int_0^{\infty} Q_e \phi_{bb}\, dE$$

A quantum structure solar cell

generated current

non-radiative recombination

radiative recombination

Outline

0. Abstract

1. Background, preceding studies

  1-1. Why do we need an accurate voltage-loss analysis technique?

  1-2. Voltage loss analysis based on detailed balance theory

2. Our work

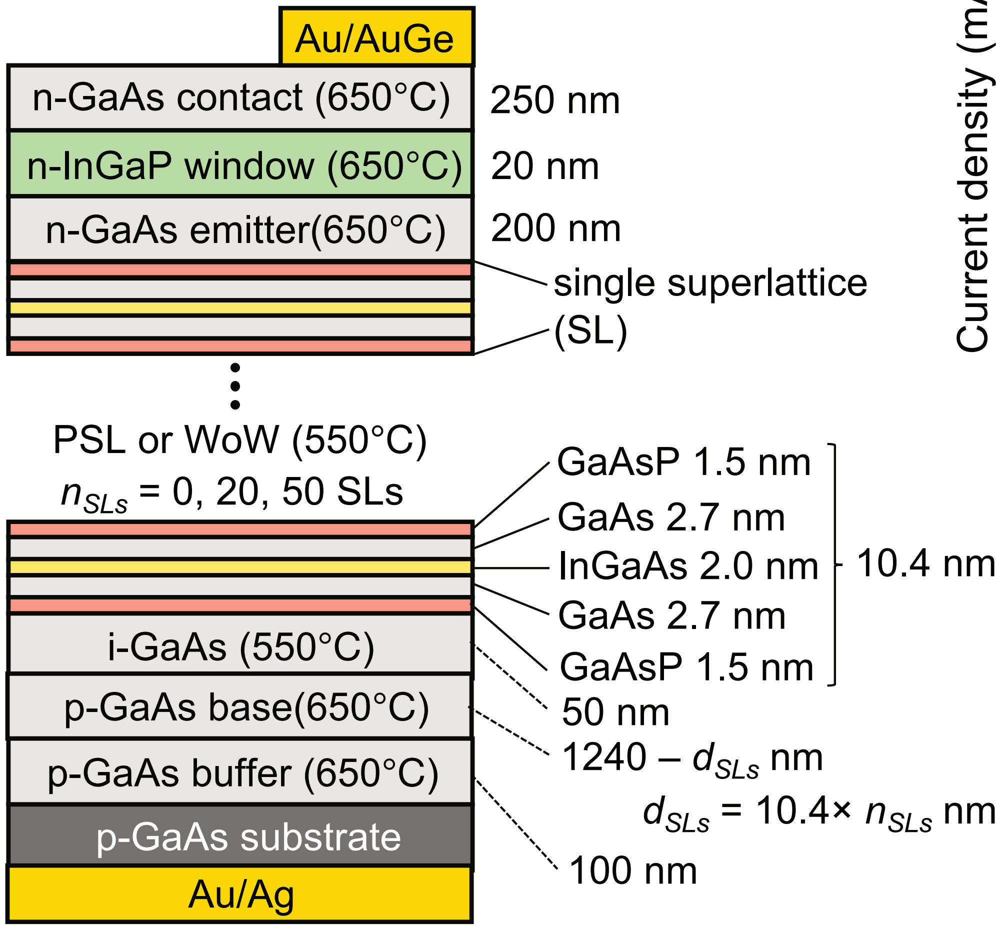
  2-1. Definition of “bandgap” of quantum structure solar cells

  2-2. Voltage loss analysis on quantum structure solar cells

  2-3. How to reduce the voltage loss in quantum structure solar cells

3. Conclusion

1-1 Background: Voltage of WoW SC is low



Au/AuGe

n-GaAs contact (650°C) 250 nm

n-InGaP window (650°C) 20 nm

n-GaAs emitter(650°C) 200 nm

single superlattice (SL)

PSL or WoW (550°C)

n_{SLs} = 0, 20, 50 SLs

GaAsP 1.5 nm

GaAs 2.7 nm

InGaAs 2.0 nm

GaAs 2.7 nm

GaAsP 1.5 nm

10.4 nm

i-GaAs (550°C) 50 nm

p-GaAs base(650°C) 1240 – d_{SLs} nm

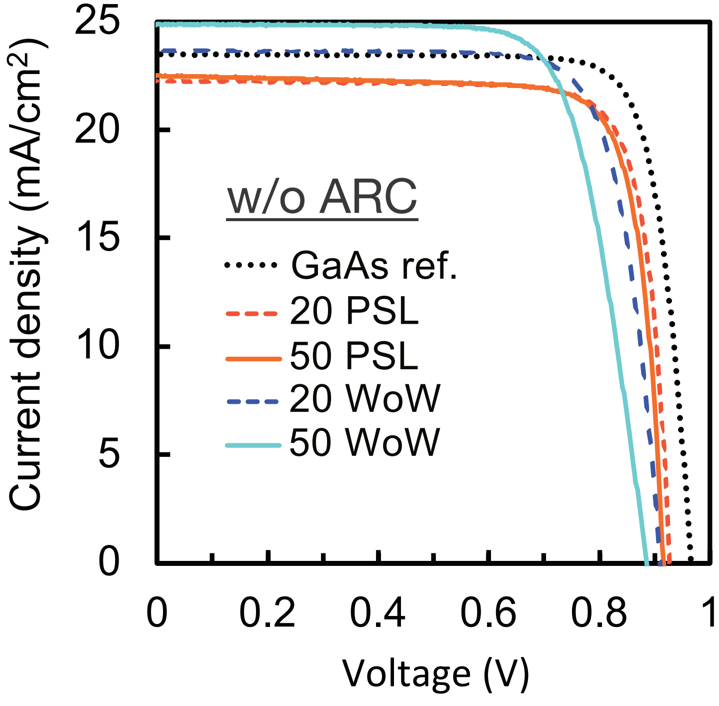
d_{SLs} = 10.4× n_{SLs} nm

p-GaAs buffer (650°C) 100 nm

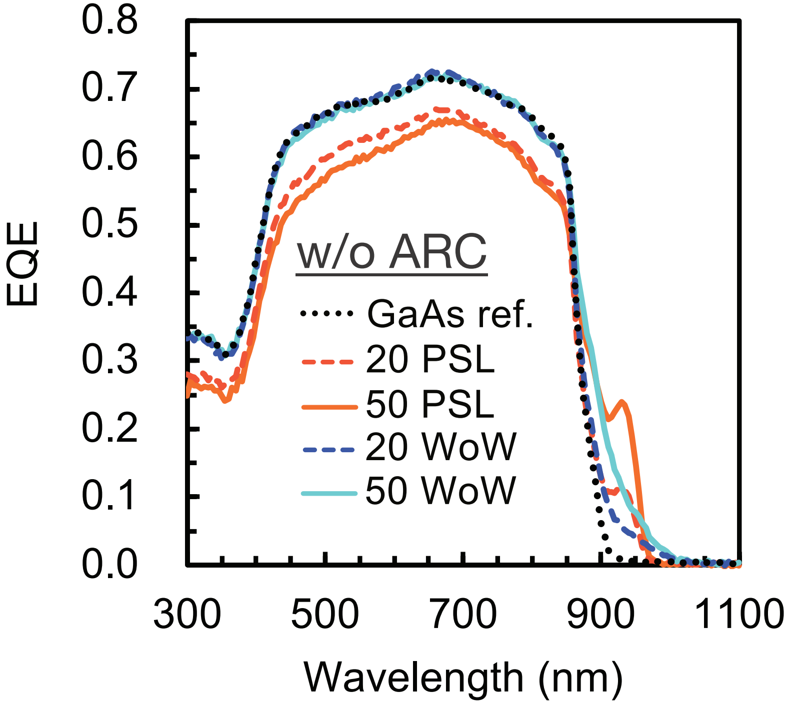
p-GaAs substrate

Au/Ag

Structure of samples



J-V curve

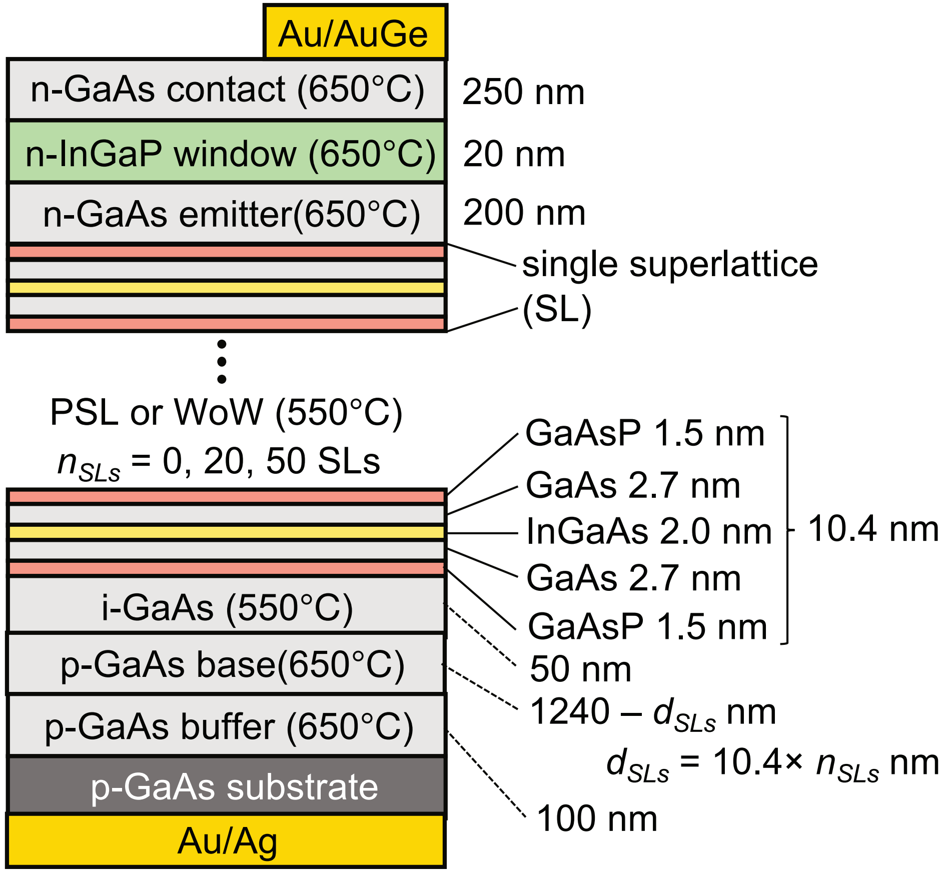


EQE results

Labels	J_{SC} (mA/cm^2)	V_{OC} (V)	*FF*
GaAs ref.	23.47	0.966	0.814
20 PSL	22.20	0.927	0.813
50 PSL	22.50	0.916	0.803
20 WoW	23.65	0.910	0.779
50 WoW	24.87	0.886	0.736

M. Asami *et al.*, *IEEE JPV* **13**, 2023.

2-2 Voltage loss in quantum structure solar cells



Au/AuGe

n-GaAs contact (650°C) 250 nm

n-InGaP window (650°C) 20 nm

n-GaAs emitter(650°C) 200 nm

single superlattice (SL)

PSL or WoW (550°C)

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GaAs 2.7 nm

InGaAs 2.0 nm

GaAs 2.7 nm

GaAsP 1.5 nm

10.4 nm

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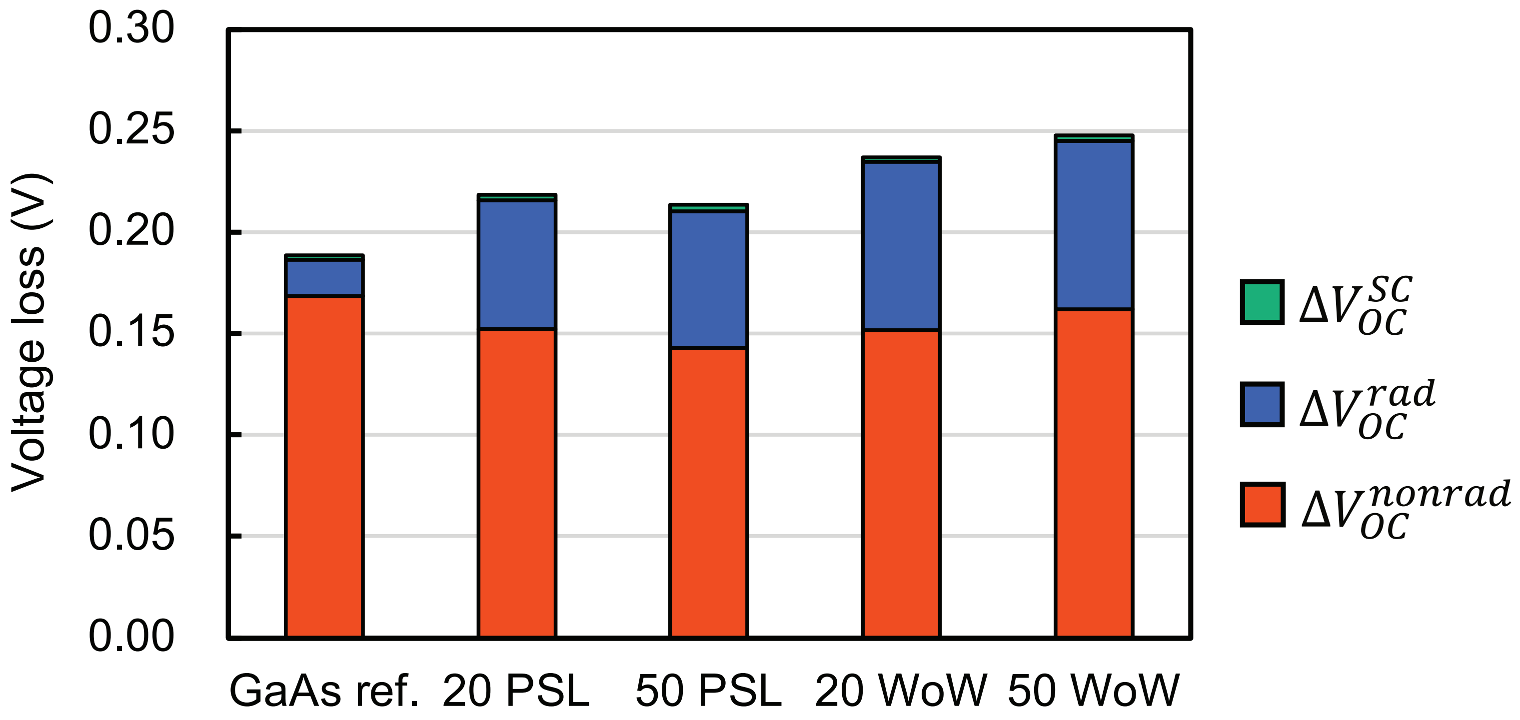
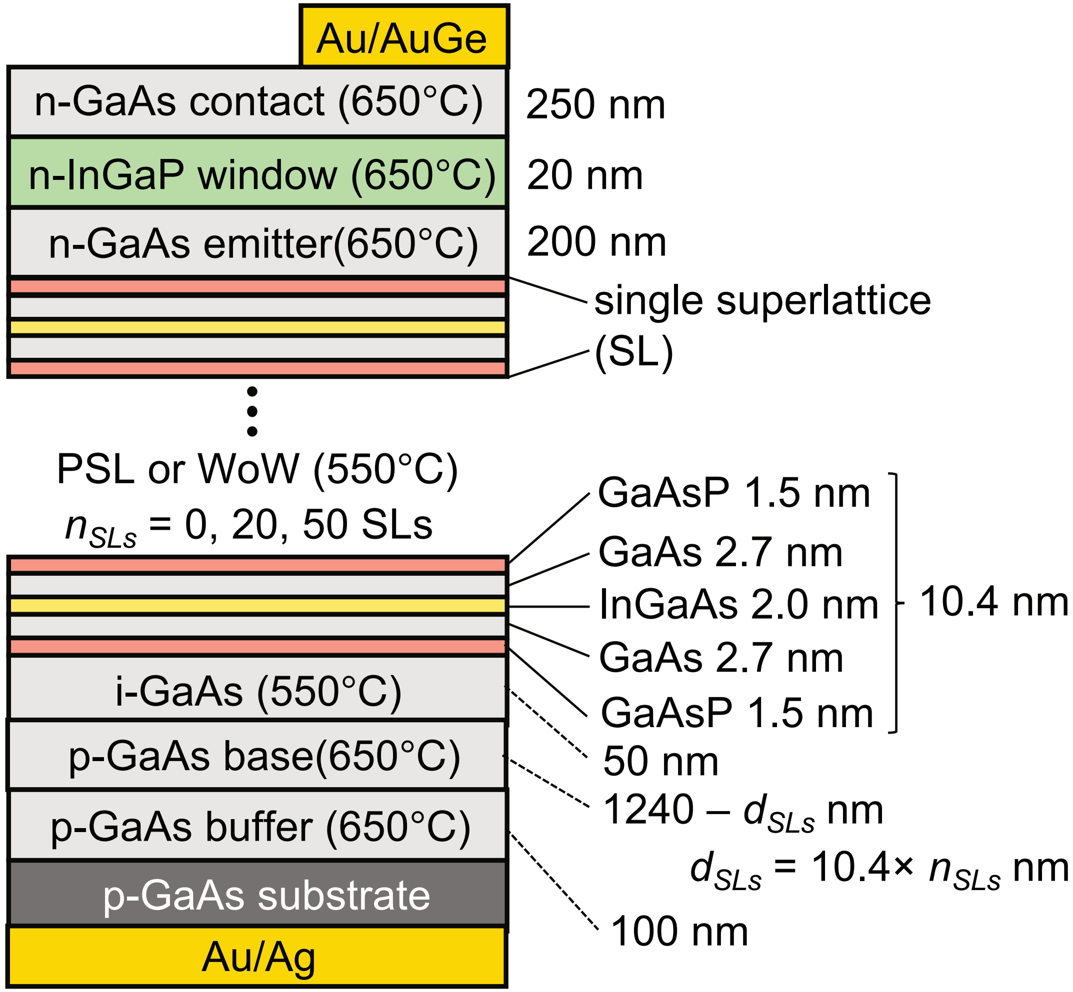
p-GaAs substrate

Au/Ag



Quantum structure solar cells have large voltage loss

2-2 Voltage loss in quantum structure solar cells



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n_{SLs} = 0, 20, 50 SLs

GaAsP 1.5 nm
GaAs 2.7 nm
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GaAs 2.7 nm
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10.4 nm

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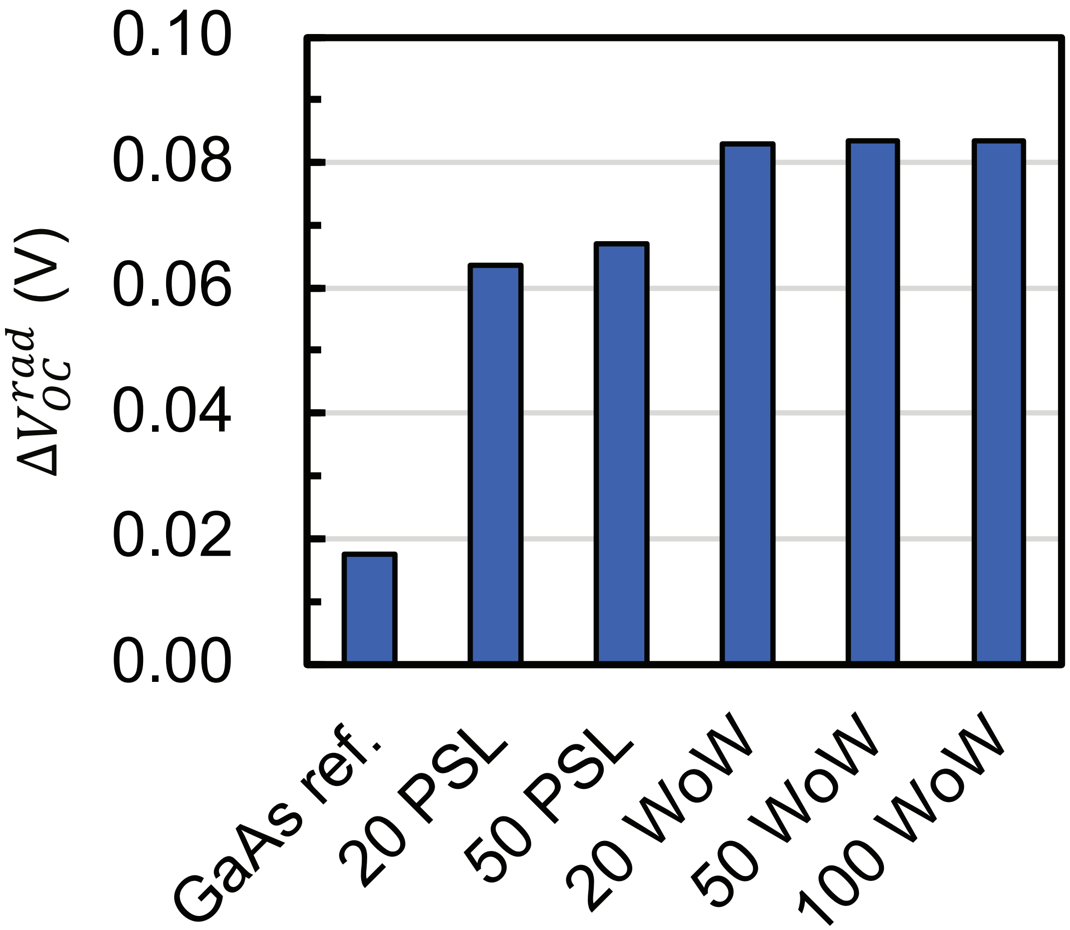
Au/Ag



We need to design new quantum structure to reduce radiative voltage loss

Outline

0. Abstract

1. Background, preceding studies

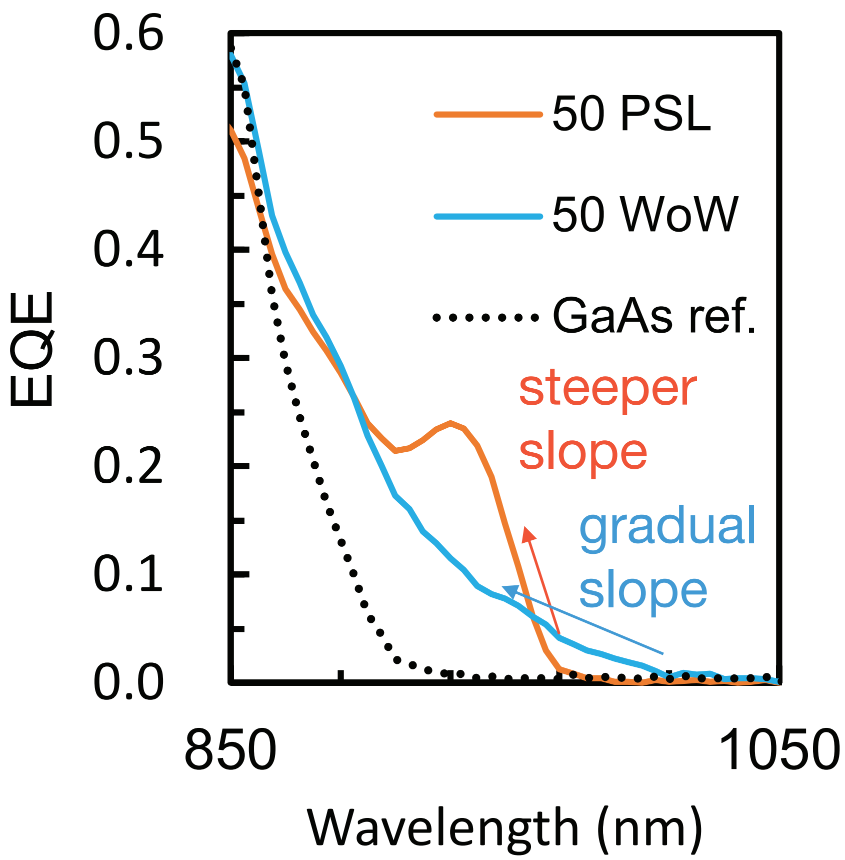
- 1-1. Why do we need an accurate voltage-loss analysis technique?
- 1-2. Voltage loss analysis based on detailed balance theory

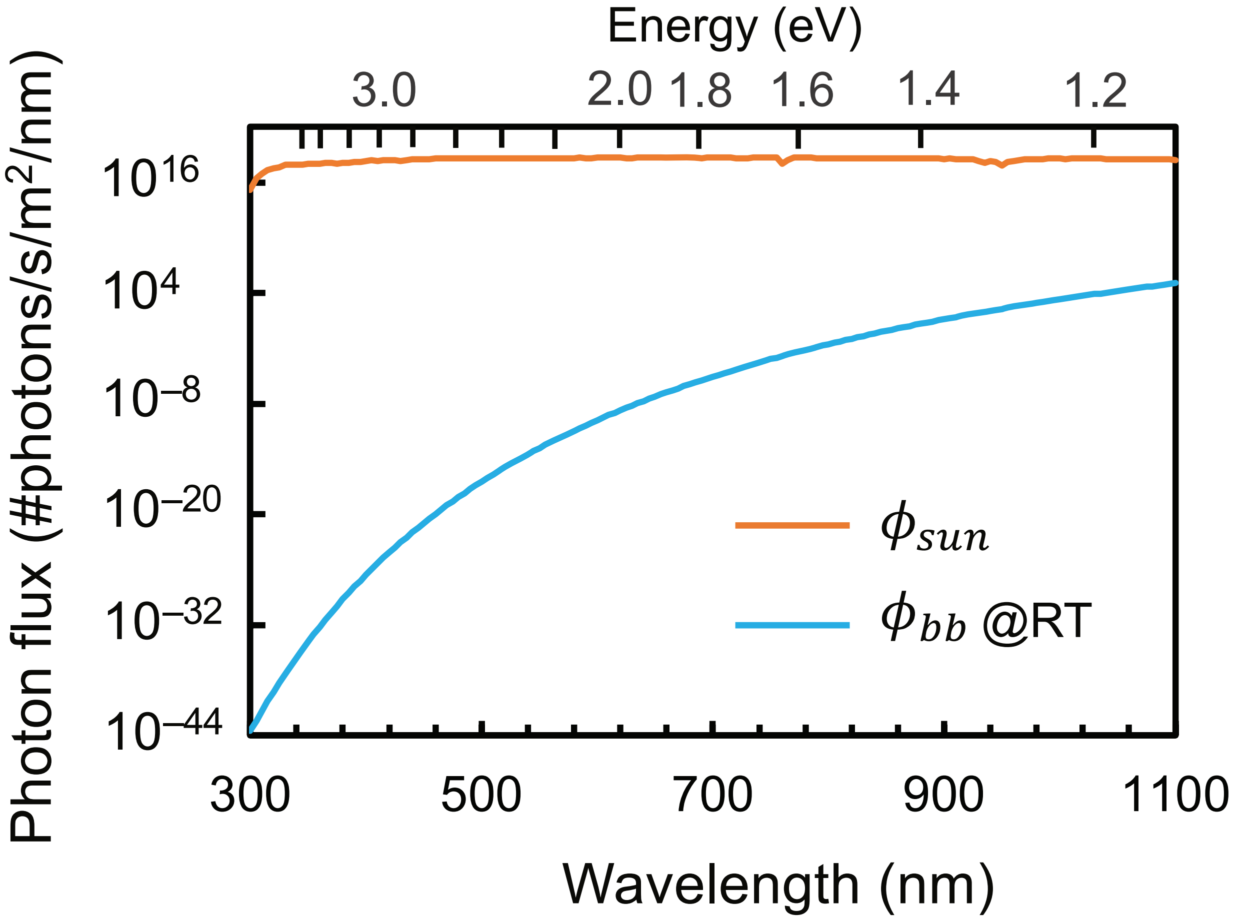
2. Our work

- 2-1. Definition of “bandgap” of quantum structure solar cells
- 2-2. Voltage loss analysis on quantum structure solar cells
- 2-3. How to reduce the voltage loss in quantum structure solar cells

3. Conclusion

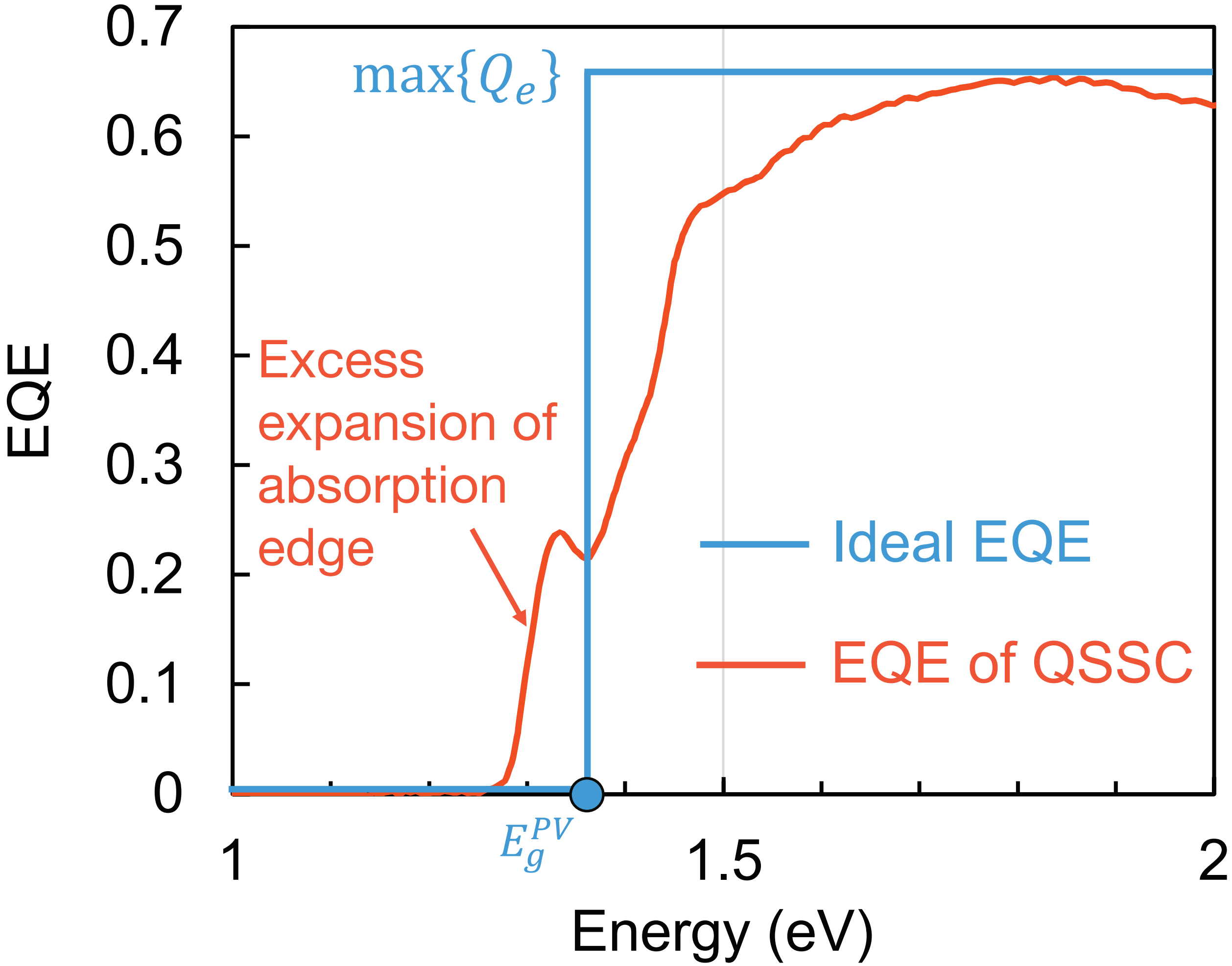
2-3 How to suppress radiative recombination voltage loss

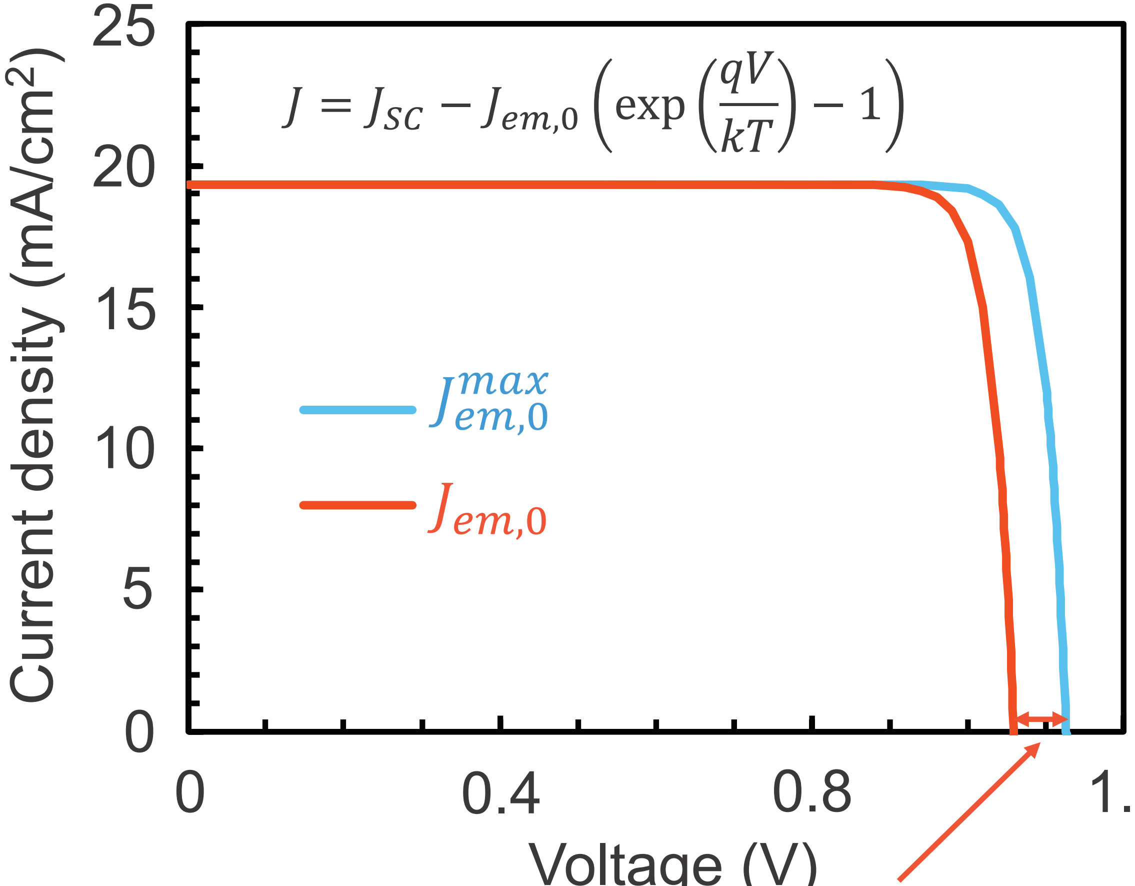




Steep absorption edge is indispensable for low radiative recombination voltage loss

2-2 Radiative recombination voltage loss




$$J = J_{SC} - J_{em,0}\left(\exp\left(\frac{qV}{kT}\right) - 1\right)$$

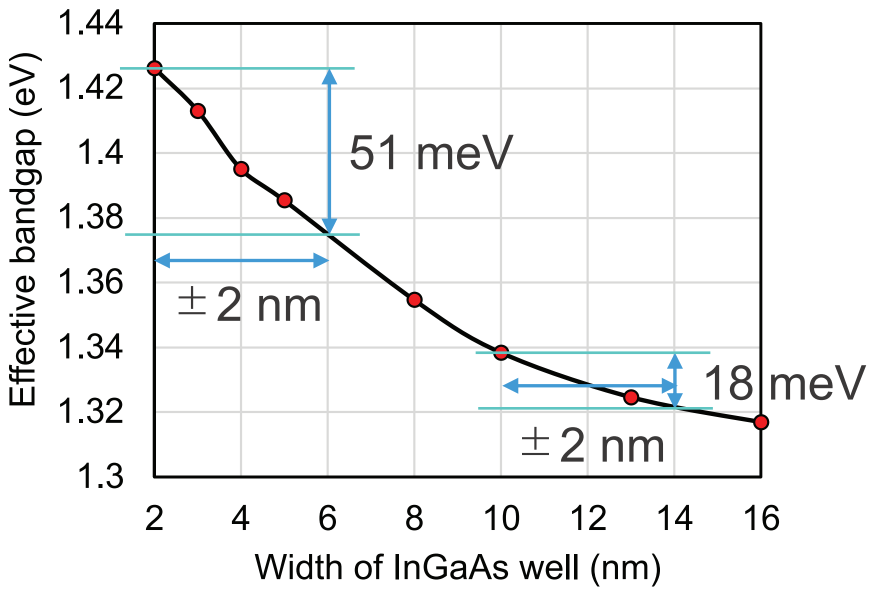
$\Delta V_{OC}^{rad} = 67$ mV

$$\Delta V_{OC}^{rad} \equiv -\frac{kT}{q}\ln\frac{J_{em,0}^{max}}{J_{em,0}} = -\frac{kT}{q}\ln\frac{\int_{E_g}^{\infty}\max\{Q_e\}\times\phi_{bb}\,dE}{\int_0^{\infty}Q_e\times\phi_{bb}\,dE}$$

$$\times 8.6 \left(\begin{array}{l} J_{em,0}^{max} = 5.46\times10^{-18}\ \mathrm{mA/cm^{-2}} \\ J_{em,0} = 4.67\times10^{-17}\ \mathrm{mA/cm^{-2}} \end{array} \right.$$

ϕ_{bb}: Photon flux of black body radiation

2-3 How to reduce radiative recombination voltage loss

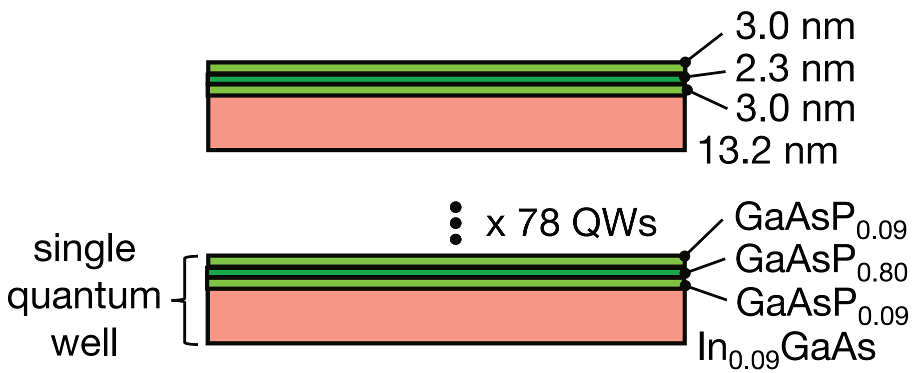


Quantum structure used in the simulation

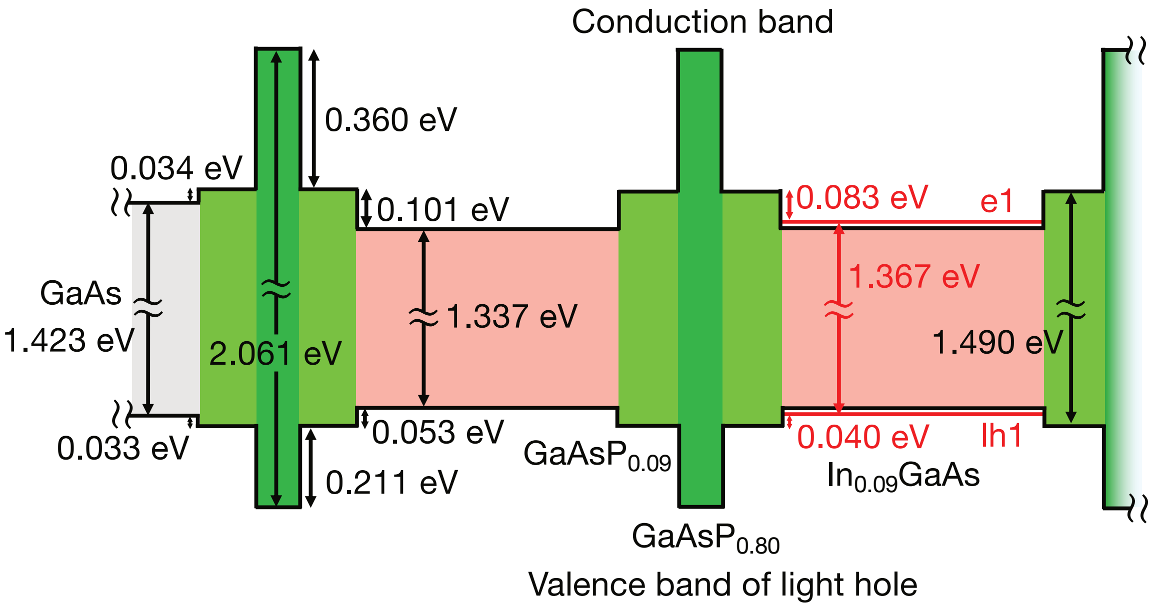
$In_{0.085}GaAs$ x nm
$GaAsP_{0.8}$ 3 nm

Advantage of thick InGaAs well

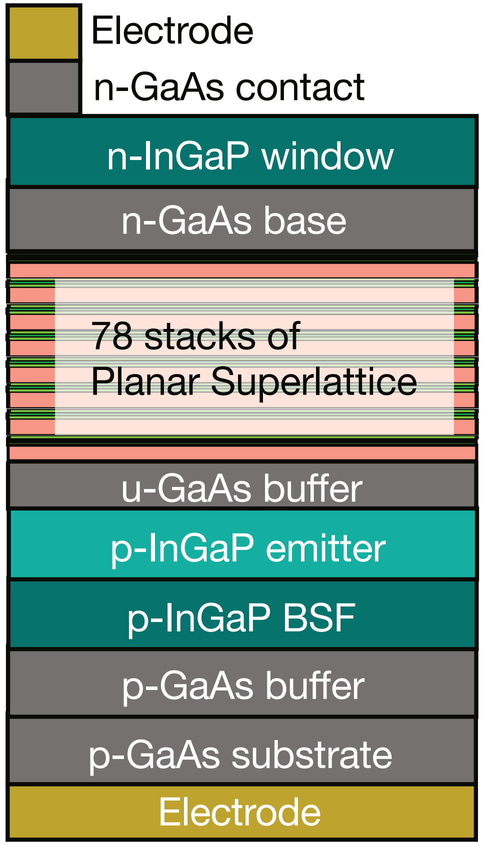
- Robust to the undulation
- Narrower effective bandgap

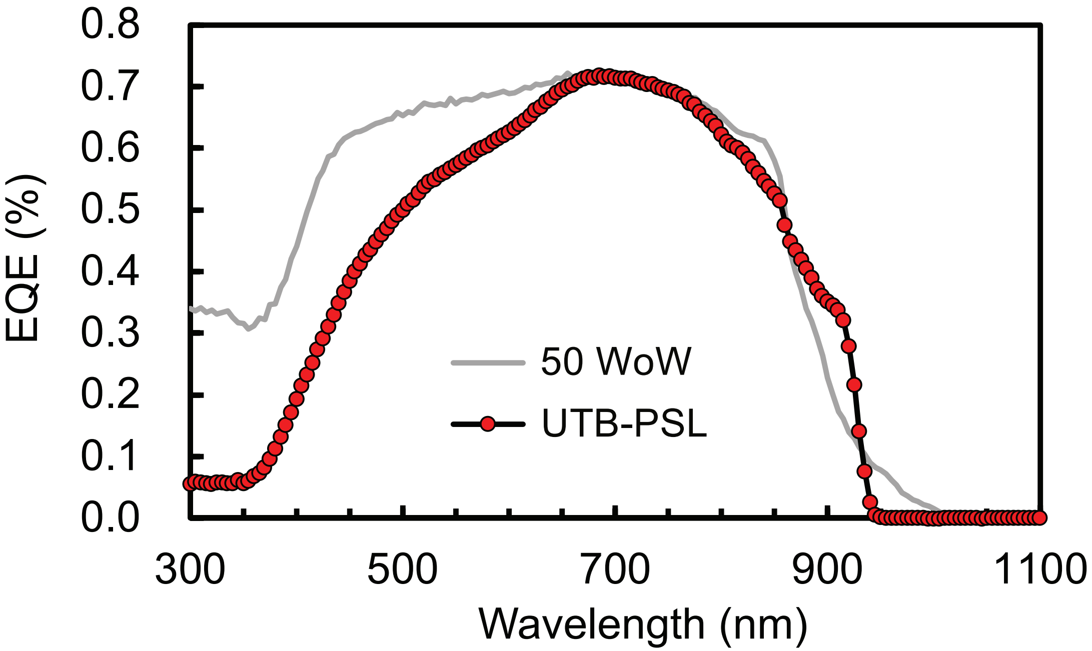


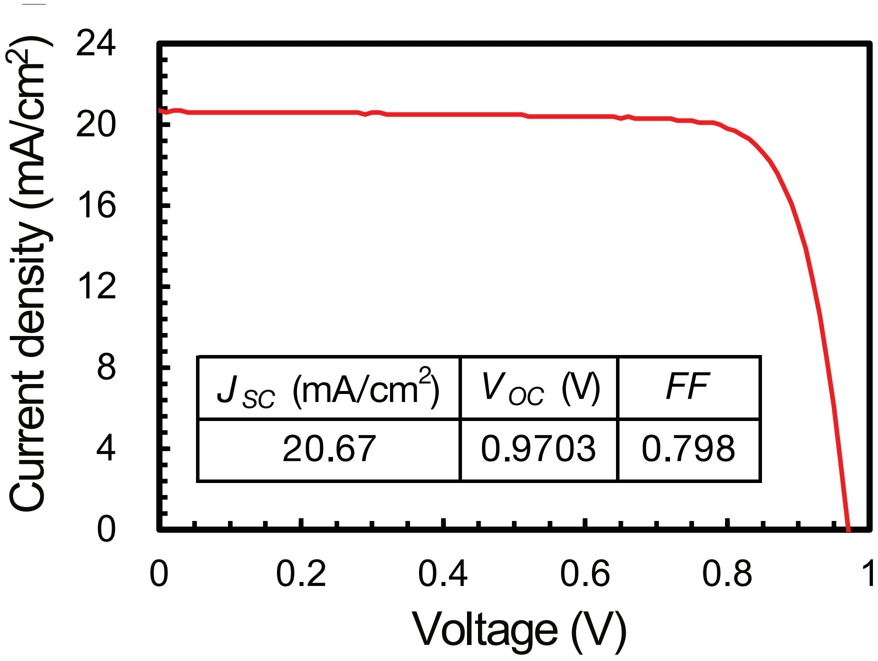
- Low P composition GaAsP interlayer was inserted to suppress the formation of interfacial crystal defects
- High P composition ultra thin GaAsP barrier



2-3 Characteristics of new quantum structure solar cell



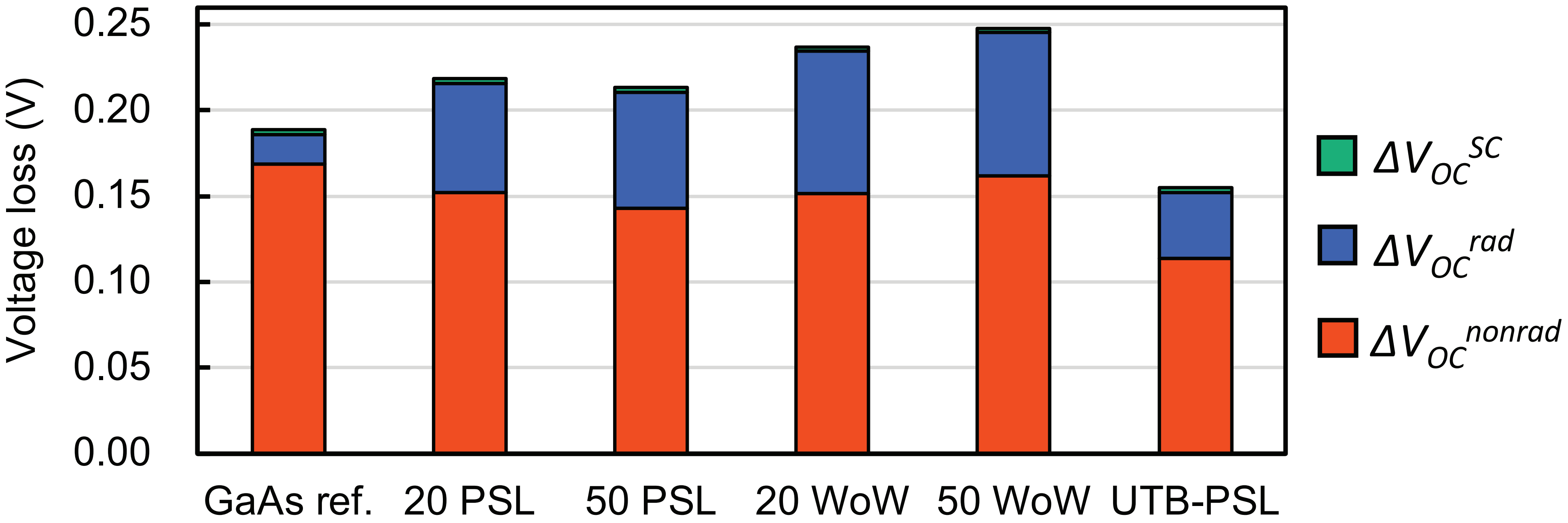




J_{SC} (mA/cm^2)	V_{OC} (V)	*FF*
20.67	0.9703	0.798

Steep absorption edge and high open circuit voltage are realized

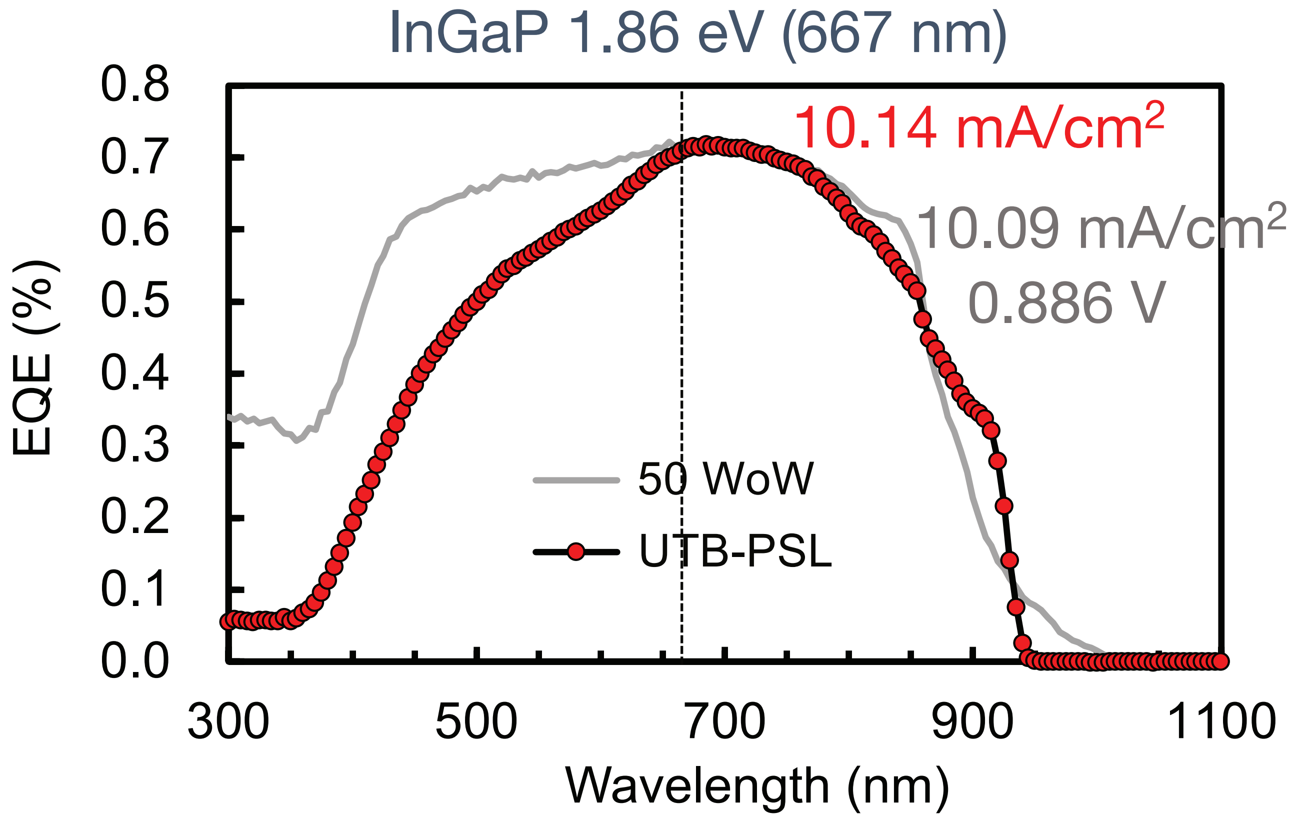
2-3 Low voltage loss is achieved by new structure

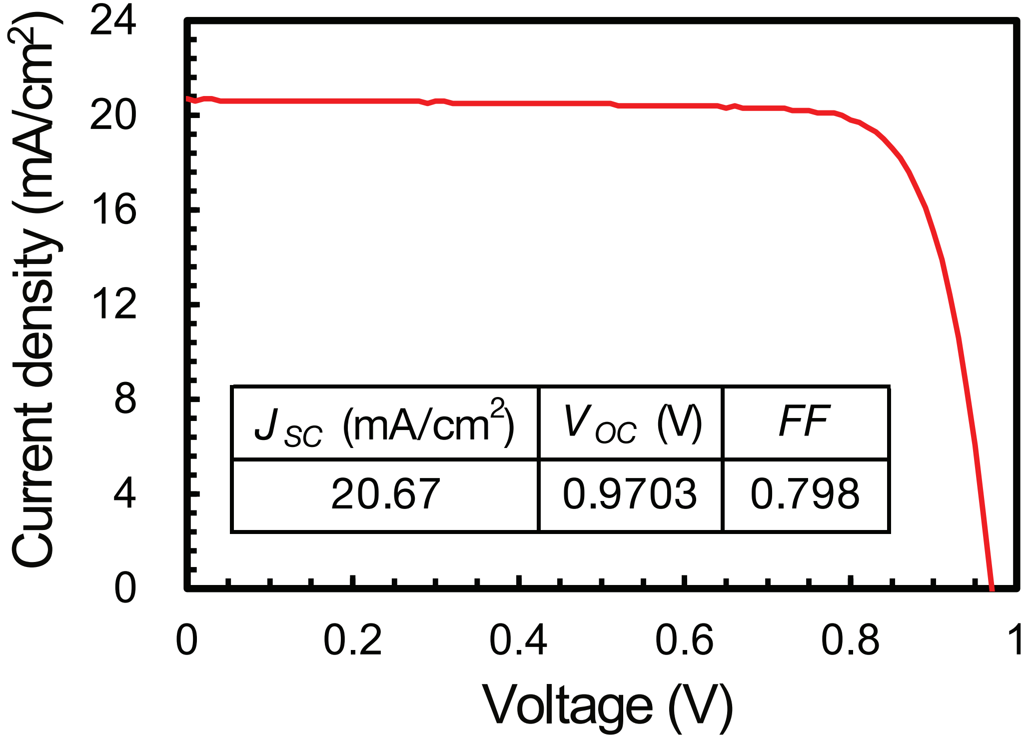


- Steep absorption edge successfully suppressed radiative voltage loss
- Low indium composition thick quantum well layer enhanced crystal quality and reduced nonradiative voltage loss

UTB-PSL: Ultra Thin Barrier Planar Superlattice

2-3 Improvement of energy conversion efficiency





J_{SC} (mA/cm^2)	V_{OC} (V)	*FF*
20.67	0.9703	0.798

Energy conversion efficiency can be increased to

30.9% (conventional[*] ; 29.5%)

UTB-PSL: Ultra Thin Barrier Planar Superlattice

[*] K. Nishioka *et al*., *Solar Energy* **90**, 2006

Conclusion

☐ **Accurate and easily available voltage metrics for the evaluation of quantum structure solar cells** were proposed

→We revealed the importance of radiative recombination voltage loss in quantum structure solar cells

→This voltage loss analysis can be applied to other type of solar cells such as CIGS and perovskite solar cells

☐ **Based on the voltage loss analysis, we proposed new quantum structure**

→Steep absorption edge is important for suppressing radiative recombination voltage loss

→New quantum structure solar cell successfully achieved low voltage loss

→New quantum structure solar cell can enhance the energy conversion efficiency of conventional Ge-based triple junction solar cells from 29.5% to 30.9%

Publication list

Journals

1. Meita Asami, Kasidit Toprasertpong, Kentaroh Watanabe, Yoshiaki Nakano, Yoshitaka Okada, Masakazu Sugiyama, “Comparison of Effective Carrier Mobility between Wire on Well and Planar Superlattice using Time of Flight Measurement,” *IEEE Journal of Photovoltaics*, vol. 10, issue 4, pp. 1008-1014, 2020.

2. Meita Asami, Kentaroh Watanabe, Yoshiaki Nakano, Masakazu Sugiyama, “Smooth Surface Morphology and Long Carrier Lifetime of InGaP Realized by Low-temperature-grown Cover Layer,” *Physica Status Solidi B*, vol. 259, issue 2, 2100305, 2022.

3. Meita Asami, Kentaroh Watanabe, Yoshiaki Nakano, Masakazu Sugiyama, “Comparison of Various Voltage Metrics for the Evaluation of the Nonradiative Voltage Loss in Quantum-Structure Solar Cells,” *IEEE Journal of Photovoltaics*, vol. 13, issue 1, pp. 95–104, 2023.