Advanced Energy Conversion

Photovoltaic cells (solar cells)

– for space application –

Hiroyuki KOIZUMI

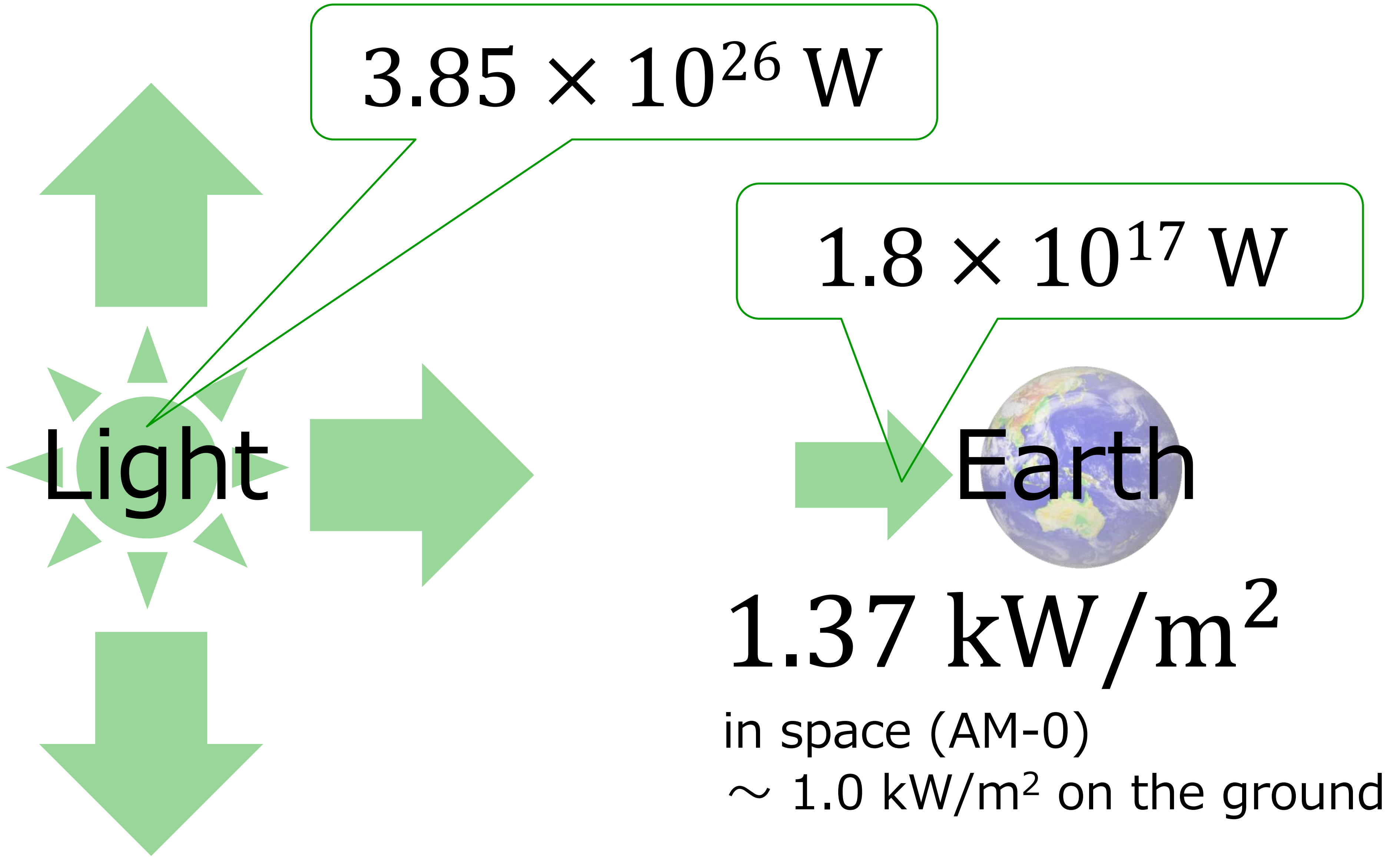
0. Introduction

1. Principle

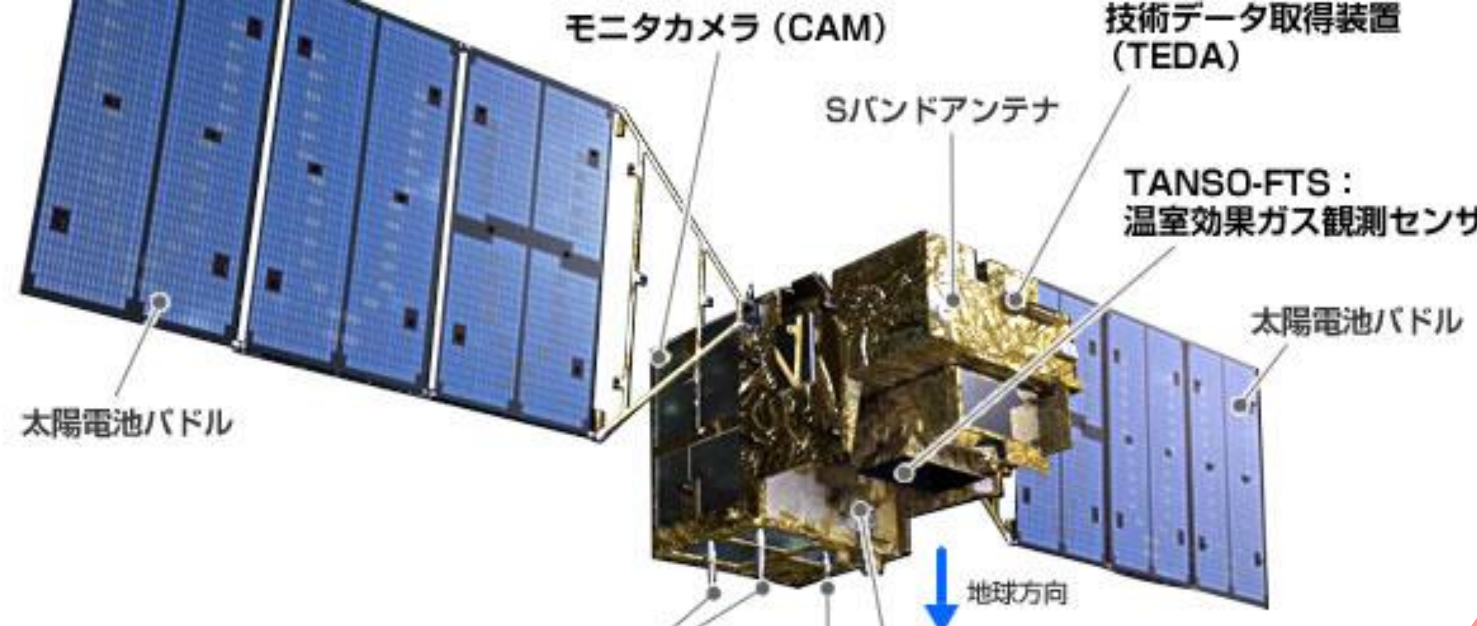
2. Higher efficiency
    - Wavelength & Bandgap
    - Multi-junction cells
    - Concentrator photovoltaic
    - Others

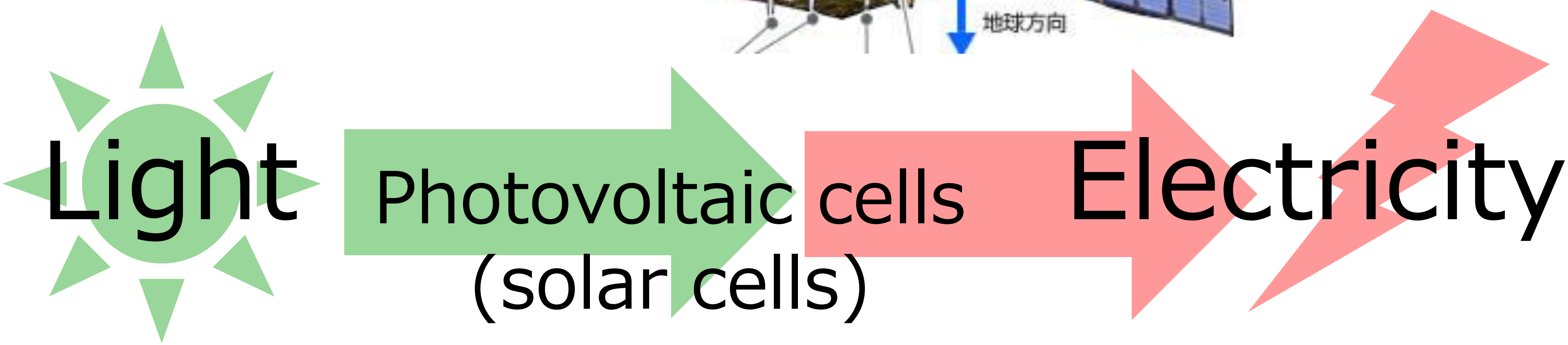
3. Solar cells of spacecraft
    - ISS, DS1, Hayabusa-1, DAWN

0. Introduction



3.85×10^{26} W
1.8×10^{17} W
Light
Earth
1.37 kW/m^2
in space (AM-0)
$\sim$ 1.0 kW/m^2 on the ground


モニタカメラ（CAM）
技術データ取得装置
（TEDA）
Sバンドアンテナ
TANSO-FTS：
温室効果ガス観測センサ
太陽電池パドル
太陽電池パドル
地球方向

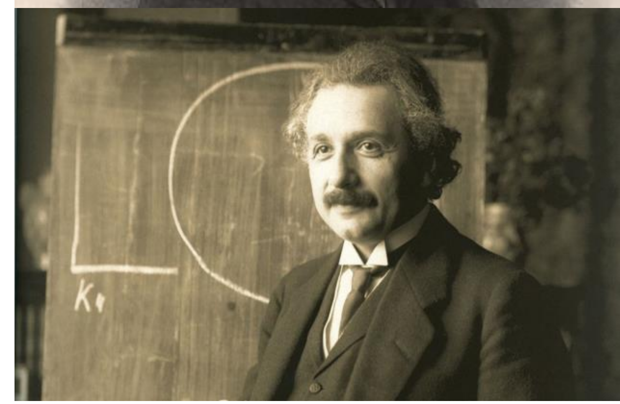

Light
Photovoltaic cells
(solar cells)
Electricity

1839; The photovoltaic effect

was experimentally demonstrated first by Edmond Becquerel

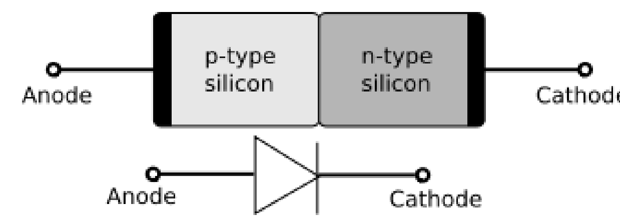
1905; A quantum theory

was proposed to explain the photoelectric effect by Albert Einstein



1941; P-N-junctions

was discovered in Cu_2O and silver sulphide protocells by Vadim Lashkaryov

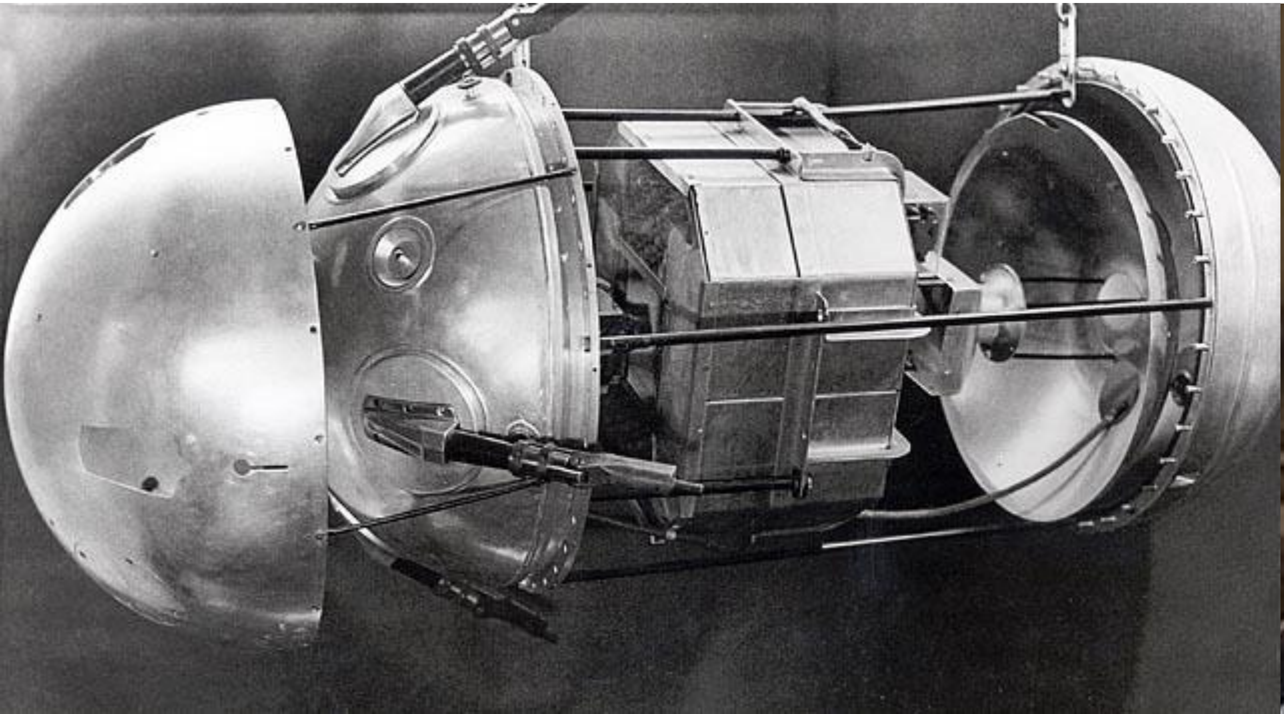


1954; The first practical solar cell

was publicly demonstrated at Bell Laboratories.

Sputnik-1

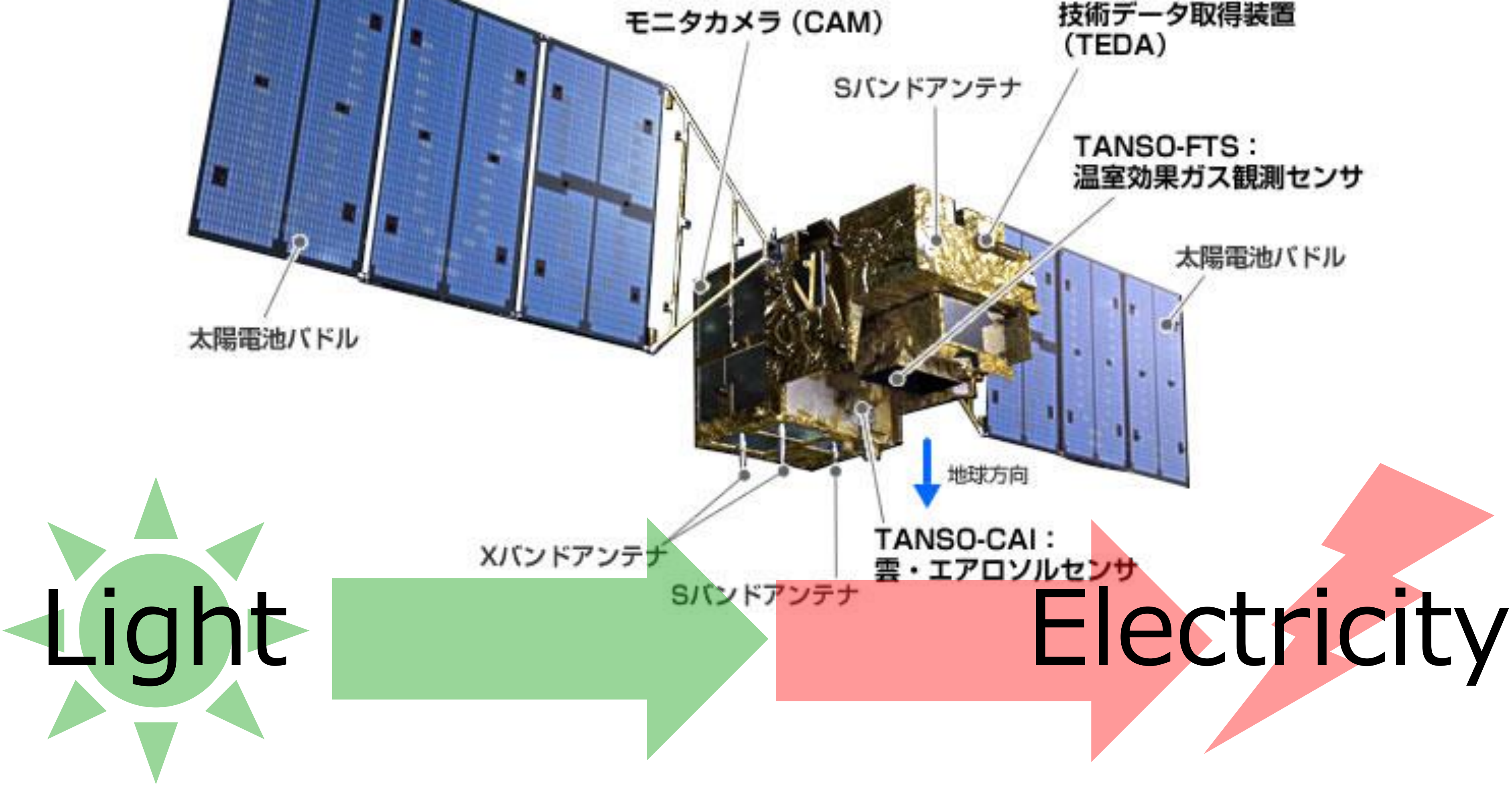
(1957)
The first artificial satellite
83 kg
Battery (20 days)

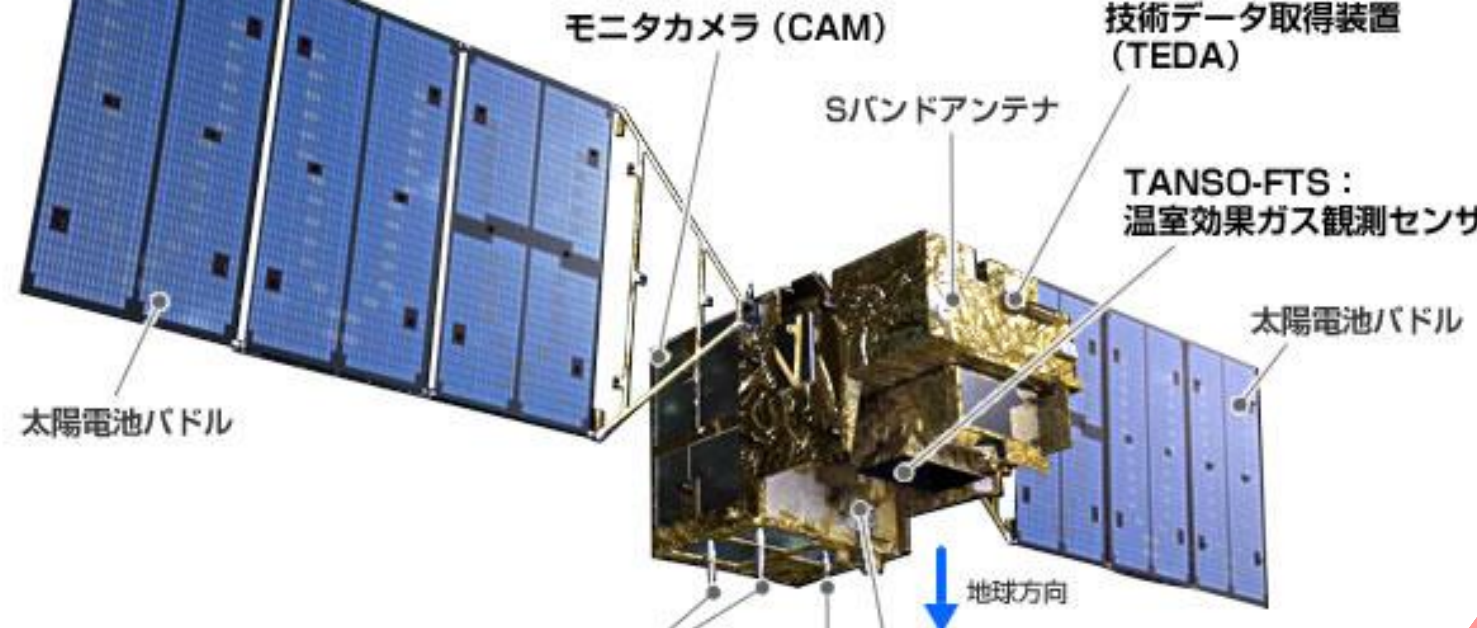


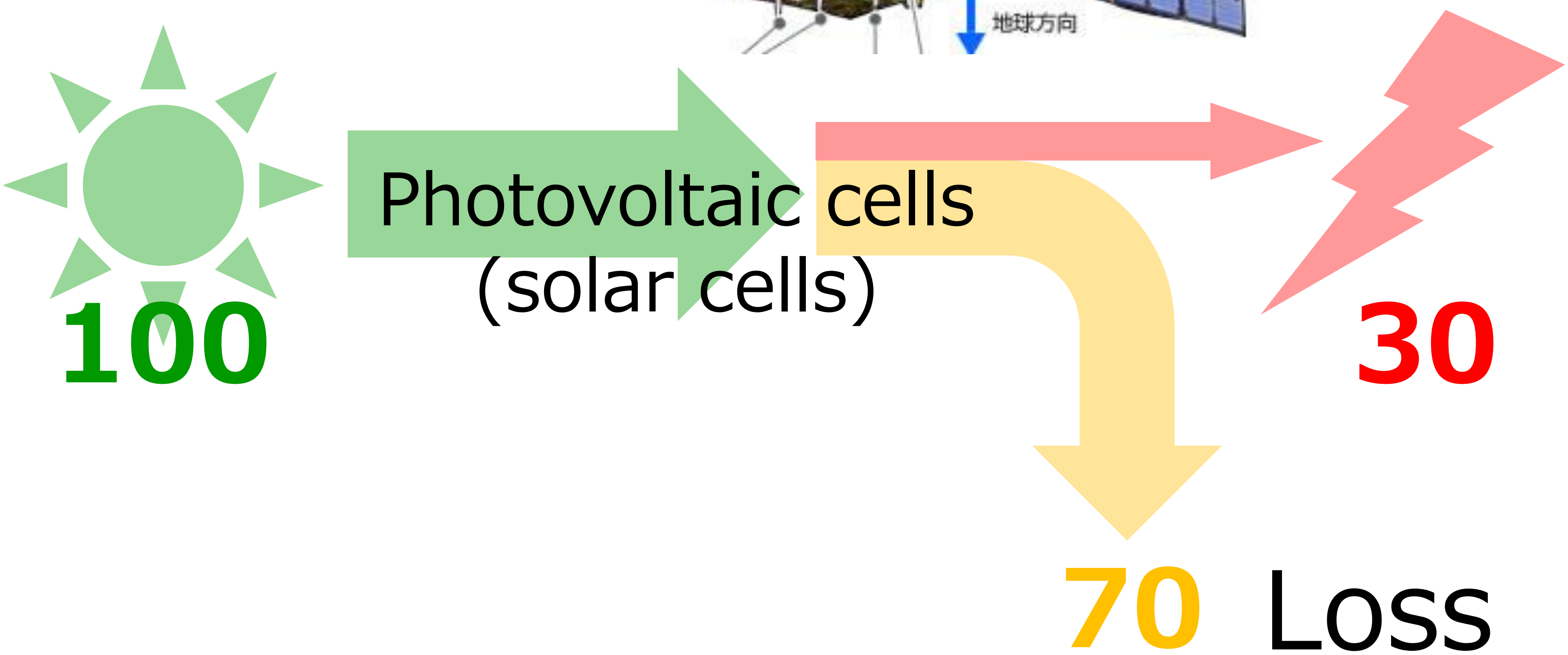
Vanguard-1

(1958)
The fourth artificial satellite
1.46 kg
The first solar powered
(worked for 6 years)

The cells were single crystal silicon and produced a total of about 1 Watt with 10% efficiency at 28 C.


モニタカメラ（CAM）
技術データ取得装置
（TEDA）
Sバンドアンテナ
TANSO-FTS：
温室効果ガス観測センサ
太陽電池パドル
太陽電池パドル
地球方向
Xバンドアンテナ
Sバンドアンテナ
TANSO-CAI：
雲・エアロソルセンサ
Light
Electricity

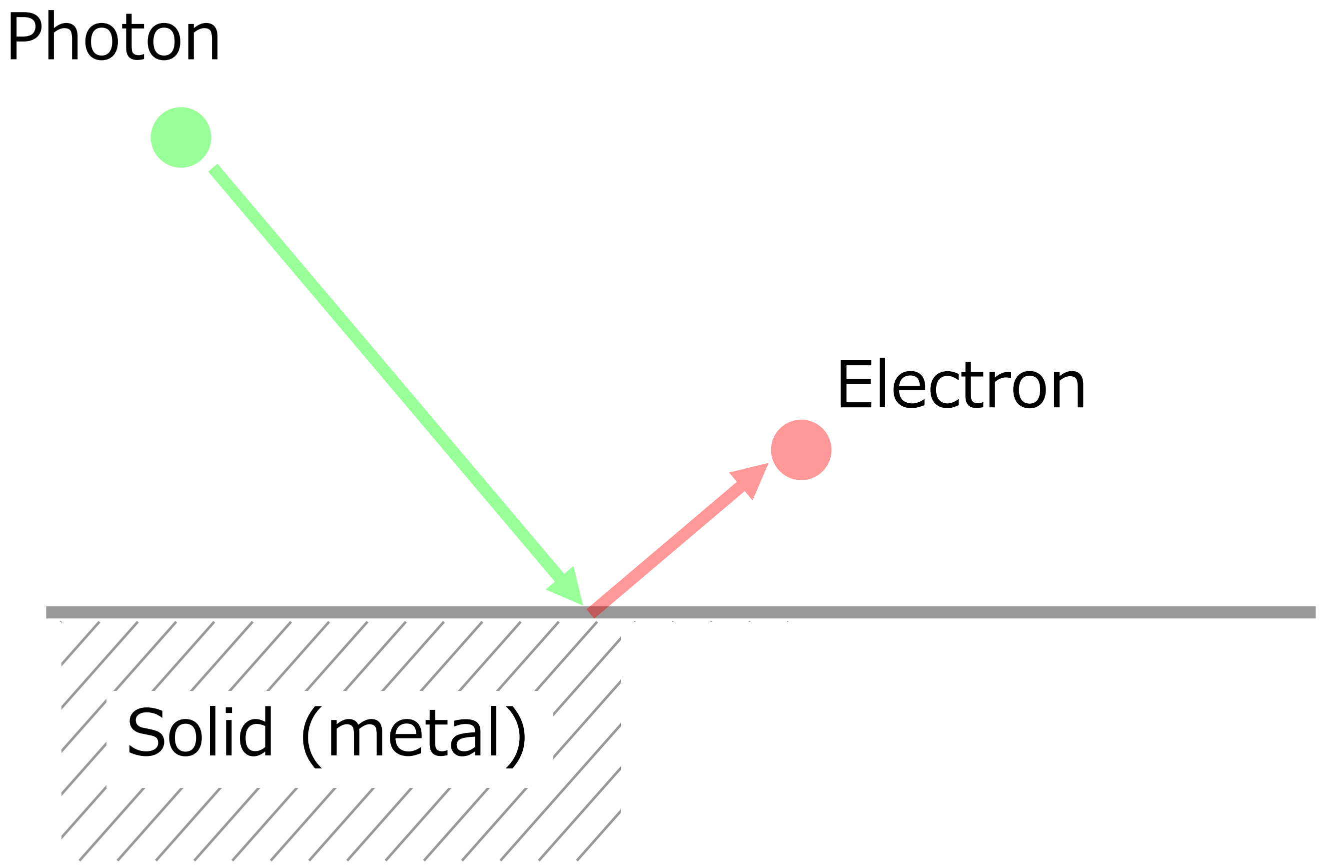

モニタカメラ（CAM）
技術データ取得装置
（TEDA）
Sバンドアンテナ
TANSO-FTS：
温室効果ガス観測センサ
太陽電池パドル
太陽電池パドル
地球方向


100
Photovoltaic cells
(solar cells)
30
70 Loss

1. Principle

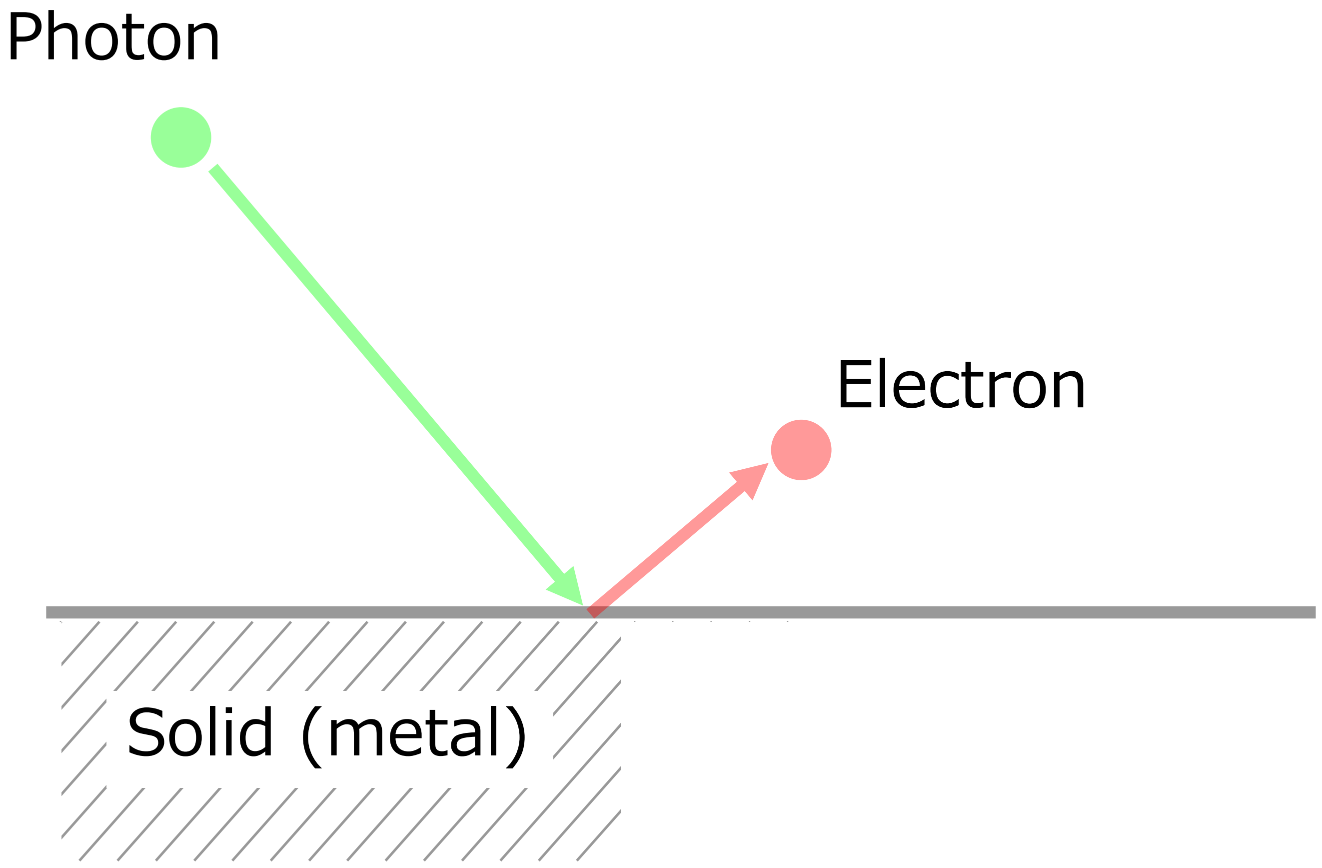
Photoelectric effect

electrons are emitted only by the impingement of photons when those photons reach or exceed a threshold frequency

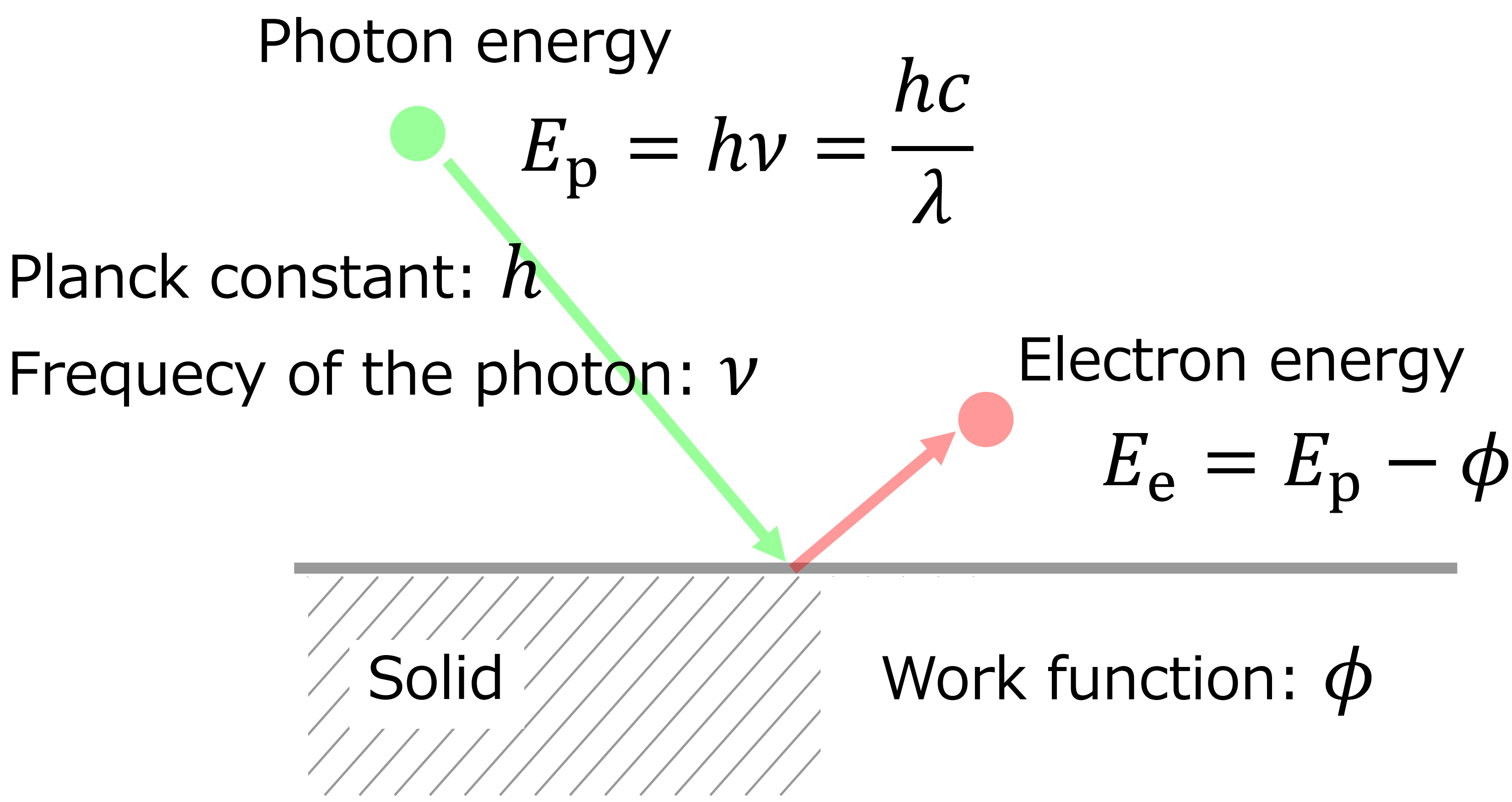


Photoelectric effect

electrons are emitted only by the impingement of photons when those photons reach or exceed a threshold frequency

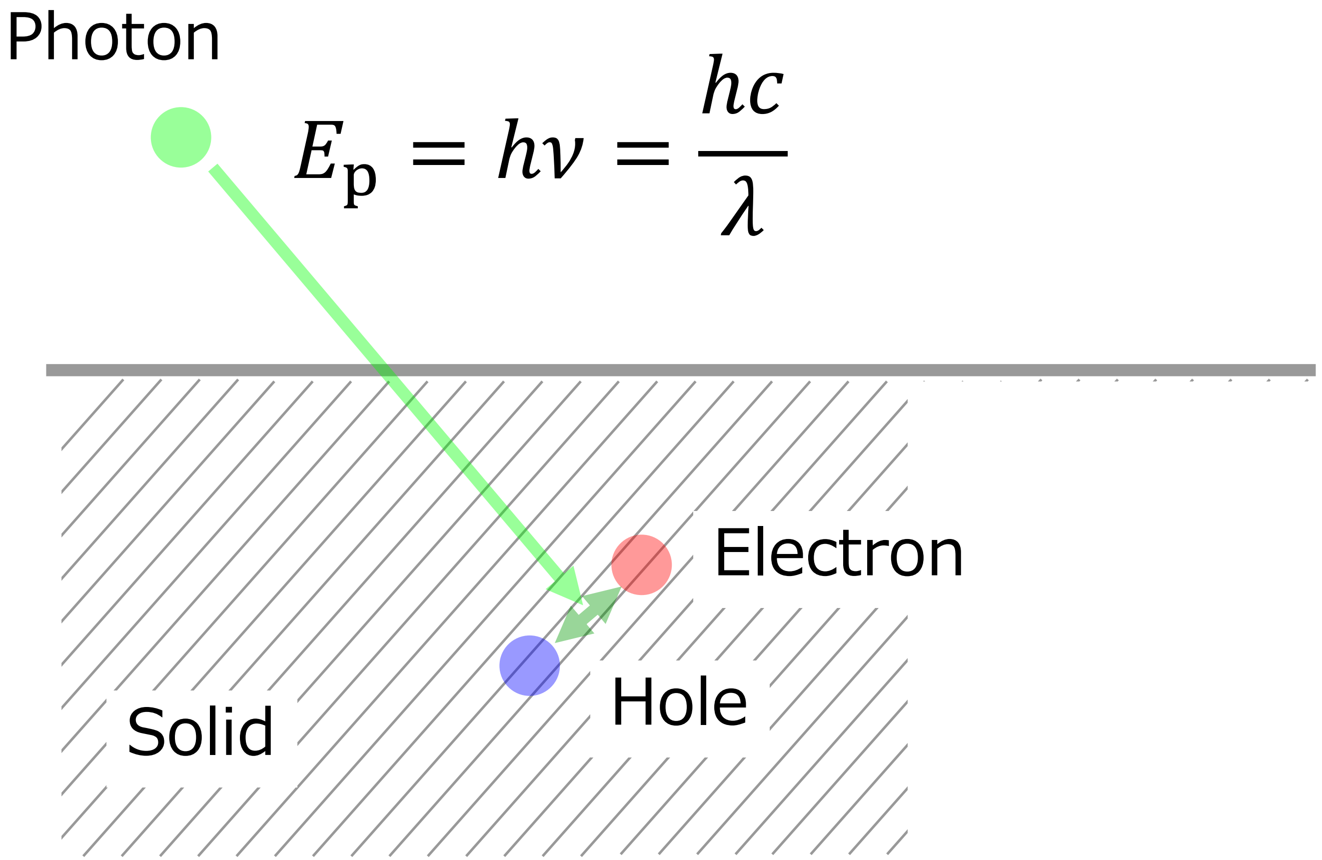


Photoelectric effect



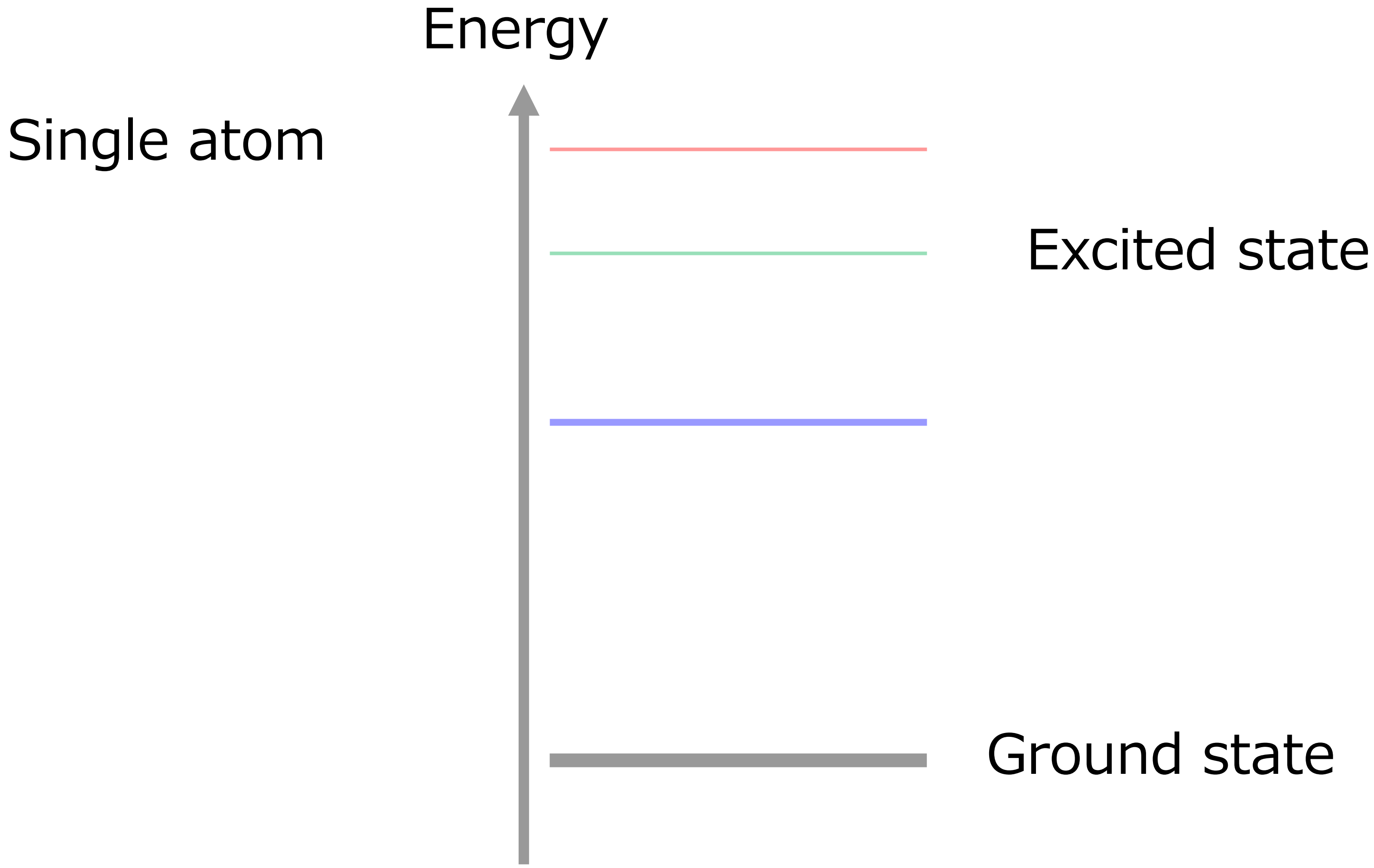
Photovoltaic effect

(internal photoelectric effect)
excitation of an electron to a higher-energy state



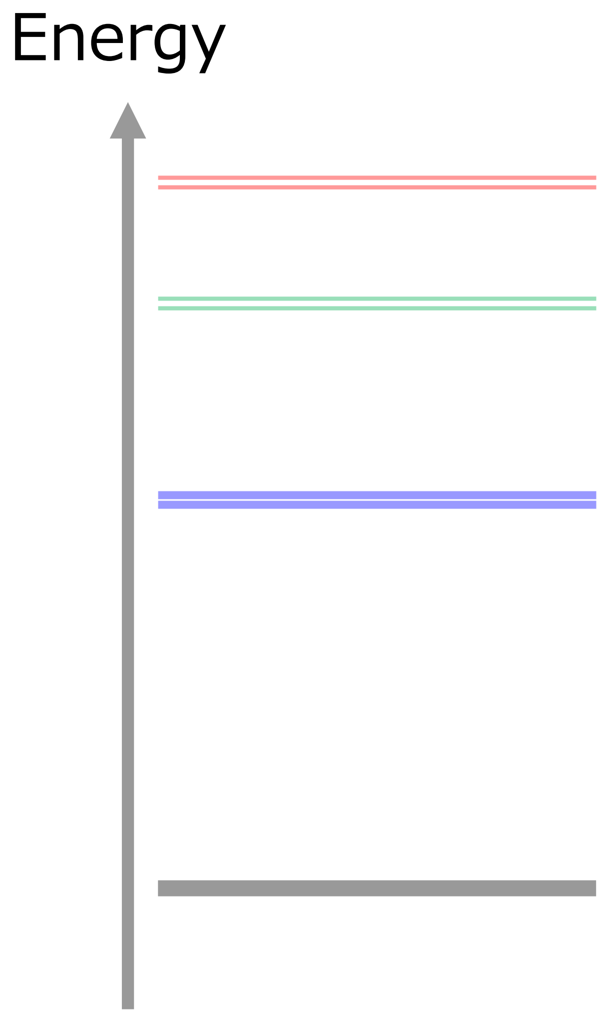
$$E_p = h\nu = \frac{hc}{\lambda}$$

Electron energy levels



Electron energy levels

Two atoms
(molecule)



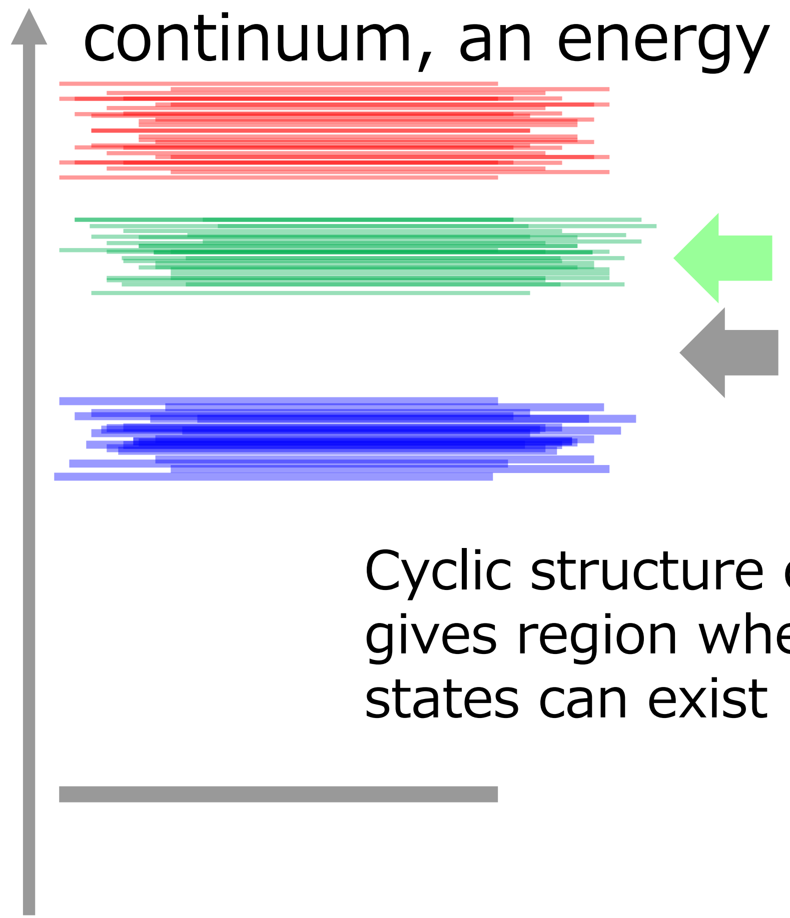
Each levels splits
into two levels
(Pauli exclusion
principle)

Ground state

Electron energy ~~levels~~ bands

Levels are so many (10^{22}) and so close, they can be considered as a continuum, an energy band.

N identical atoms (crystal lattice)

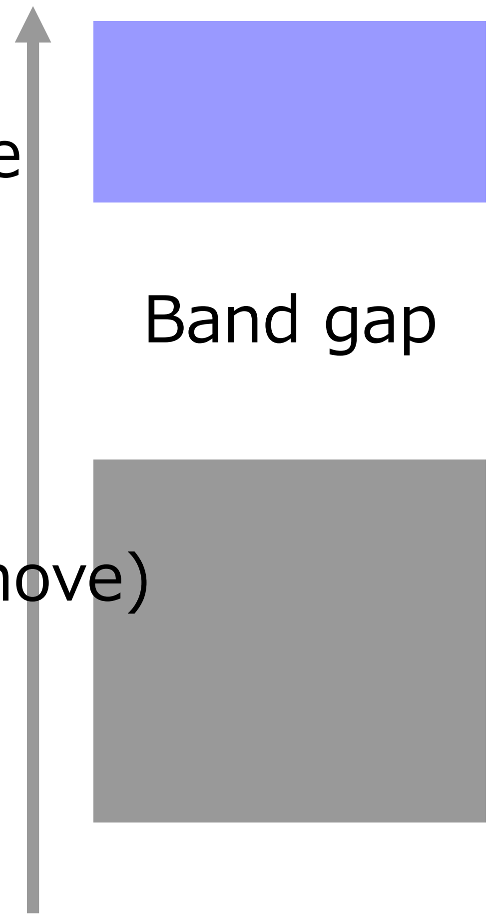


Cyclic structure of a crystal gives region where no electron states can exist

Semiconductor band structure

Unfilled band
(electrons can move
if they exist)

Conduction band
伝導帯



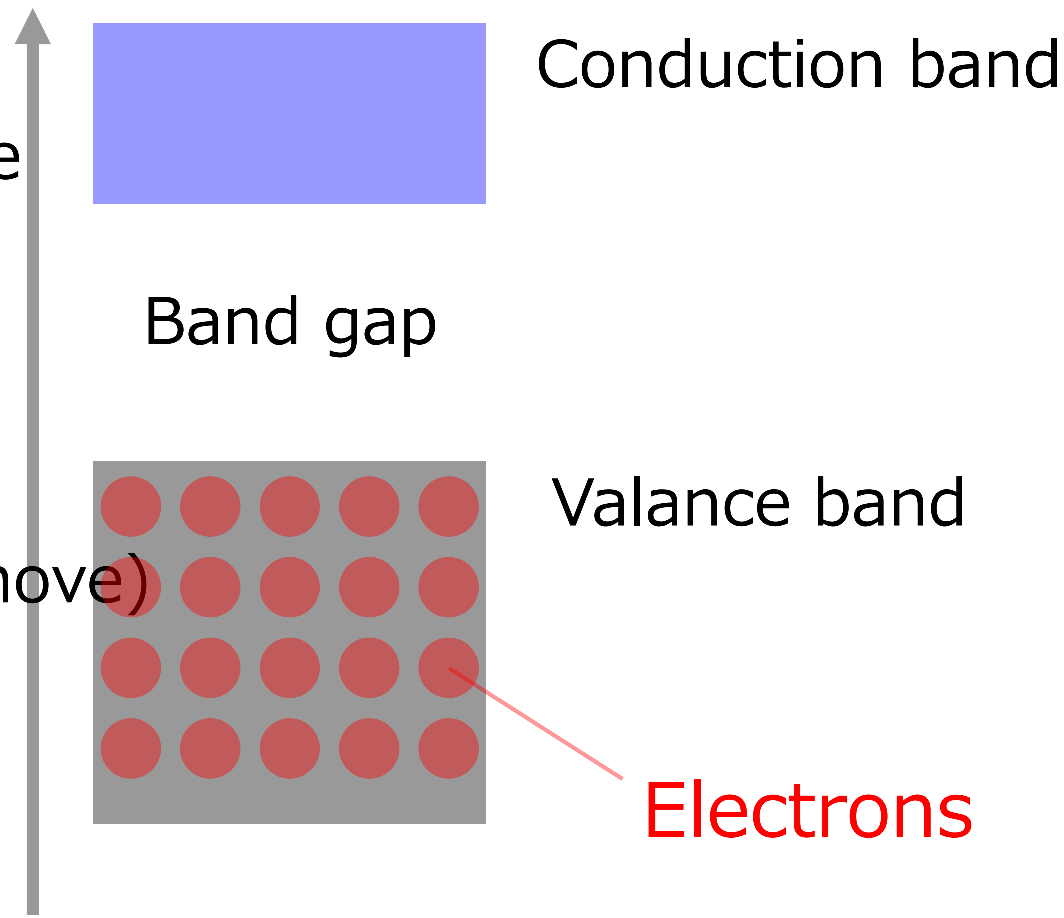
Filled by electrons
(electrons cannot move)

Valance band
価電子帯

Semiconductor band structure

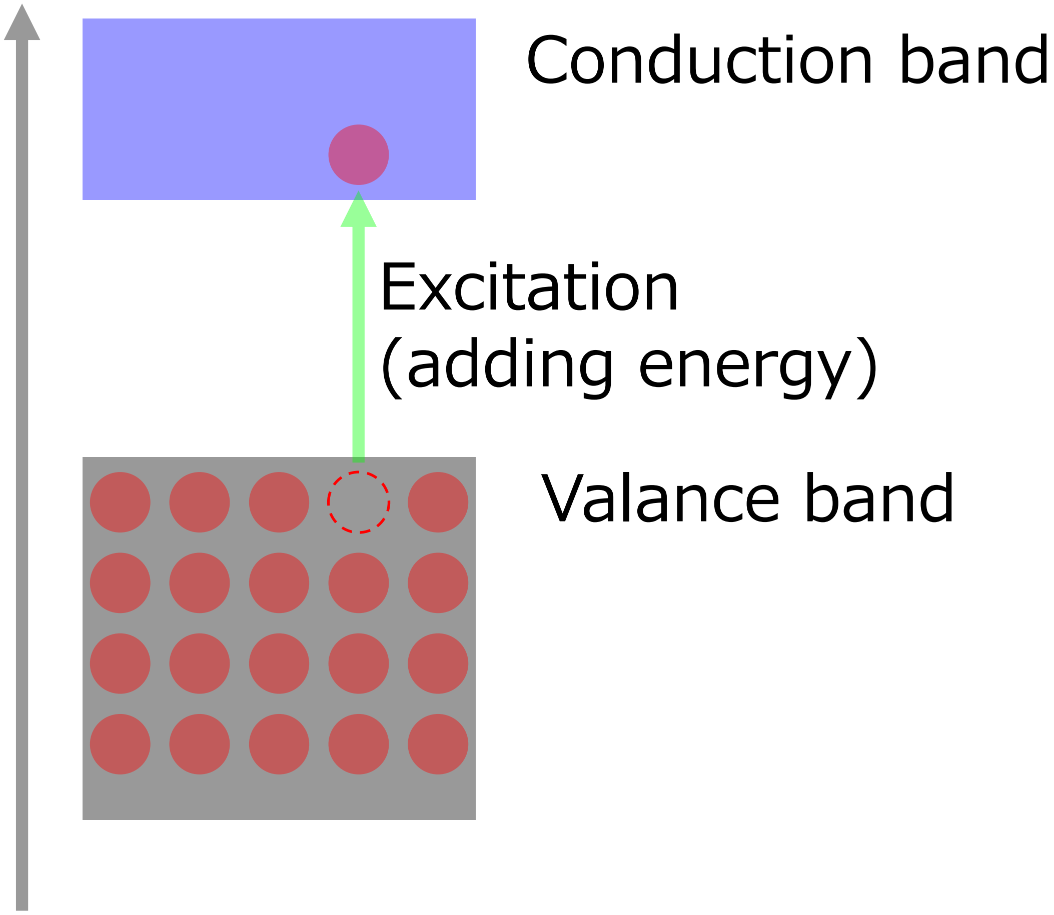
Unfilled band
(electrons can move
if they exist)

Filled by electrons
(electrons cannot move)



Semiconductor band structure

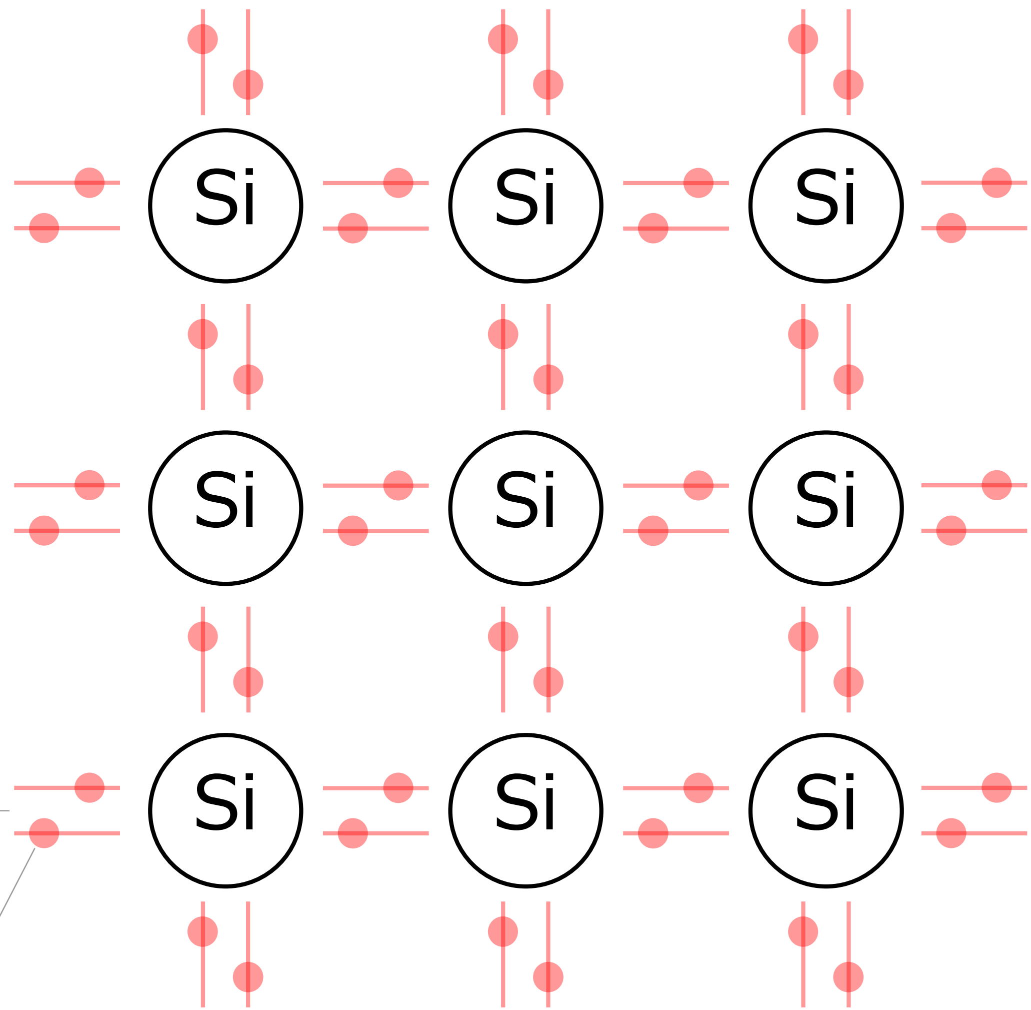
If an electron is excited from valance to conduction band, it becomes current carrier.



Semiconductor crystal

Valance electron
(価電子)

Si: 4



Covalent bond
共有結合

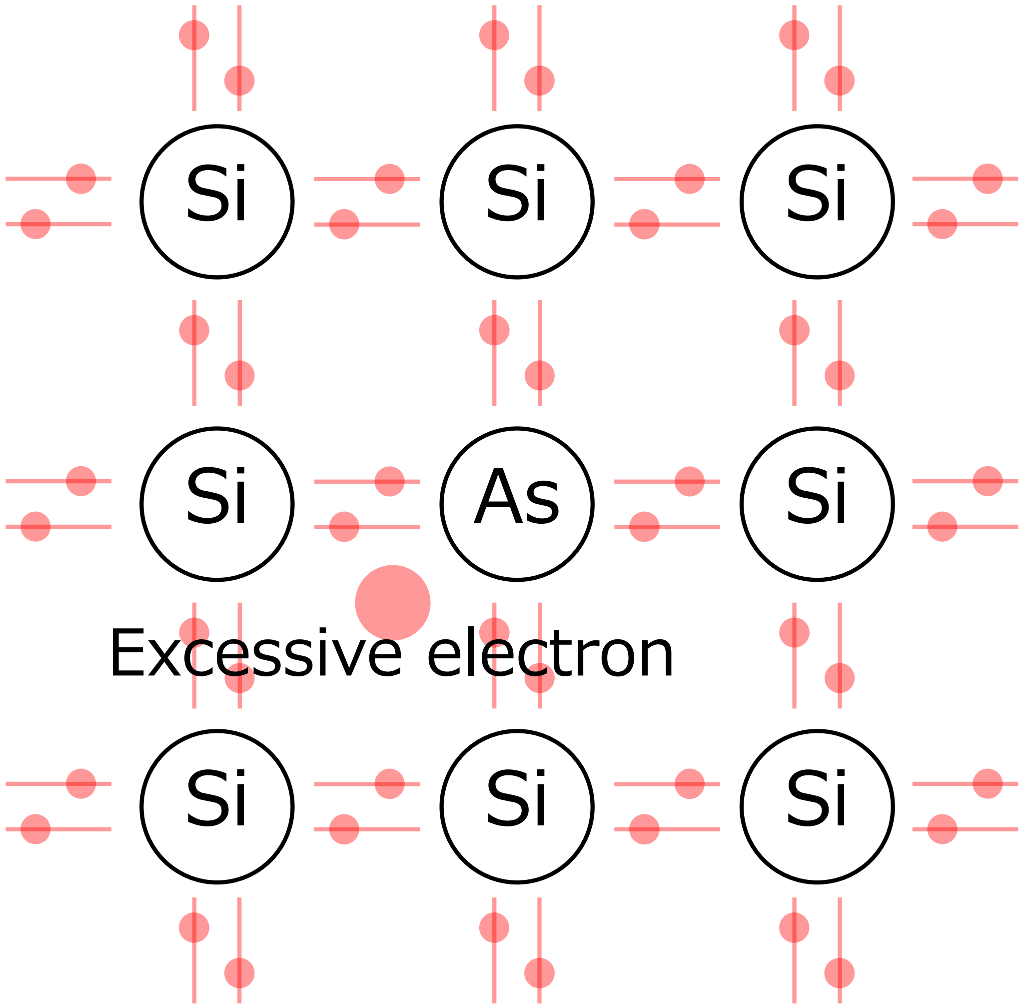
valance electron

Extrinsic (doped) Semiconductor

Valance electron
(価電子)

Si: 4

As: 5



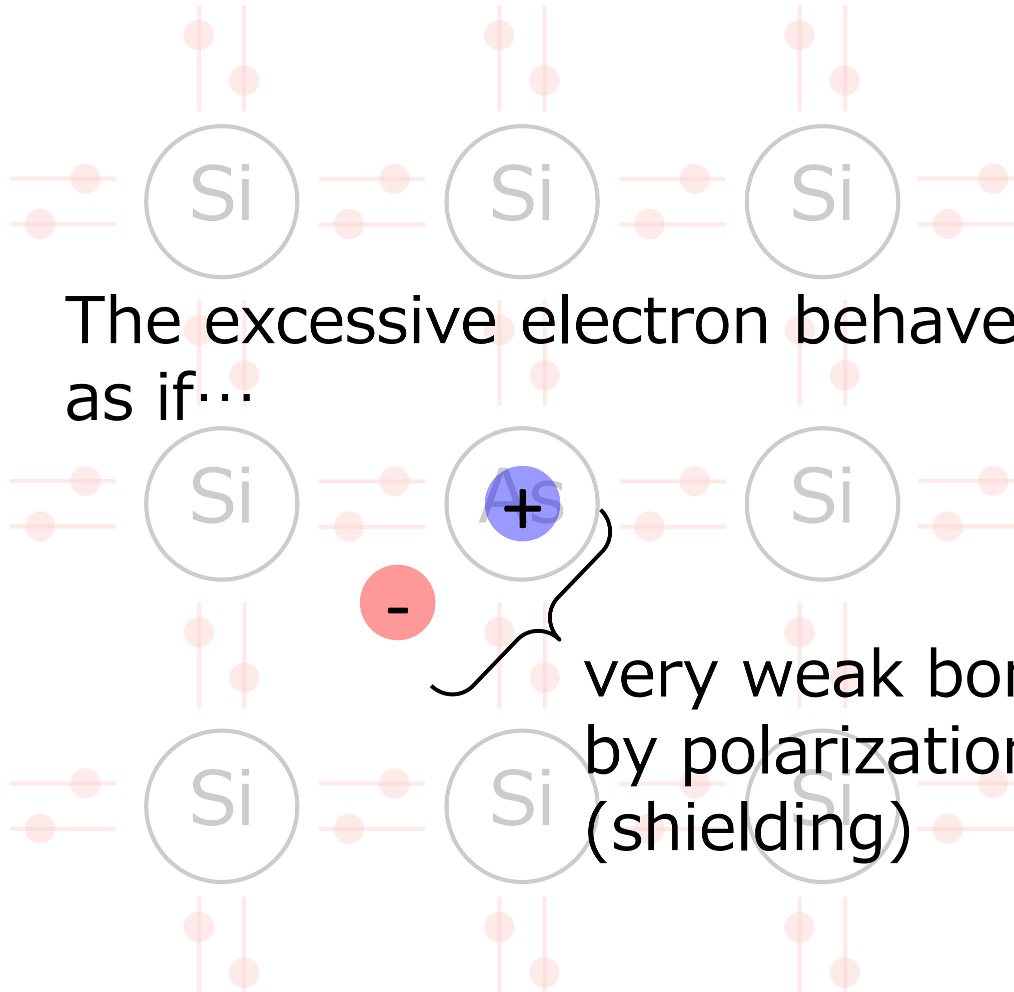
Extrinsic (doped) Semiconductor

Valance electron
(価電子)

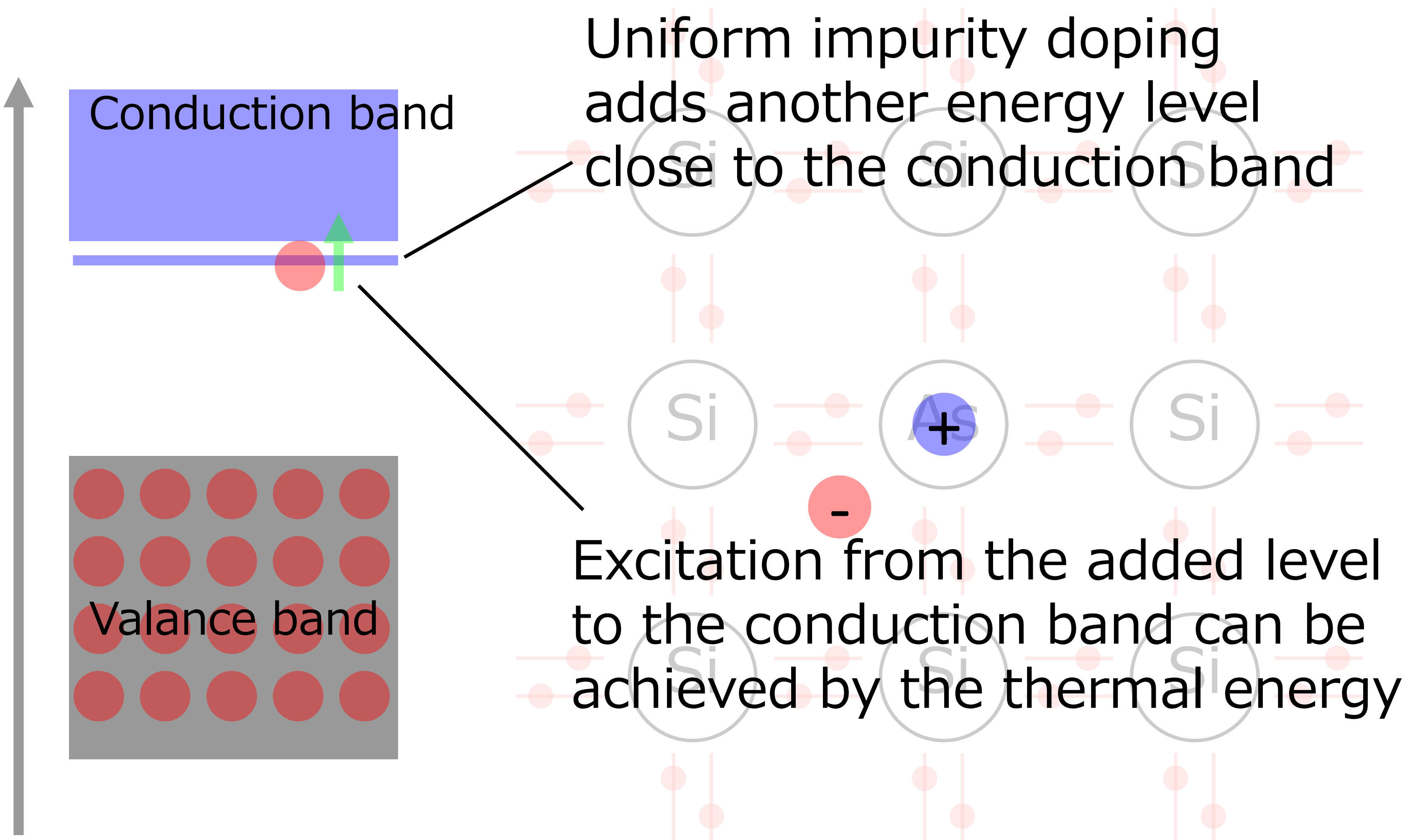
Si: 4

As: 5

The excessive electron behaves as if…



N-type Semiconductor



Uniform impurity doping adds another energy level close to the conduction band

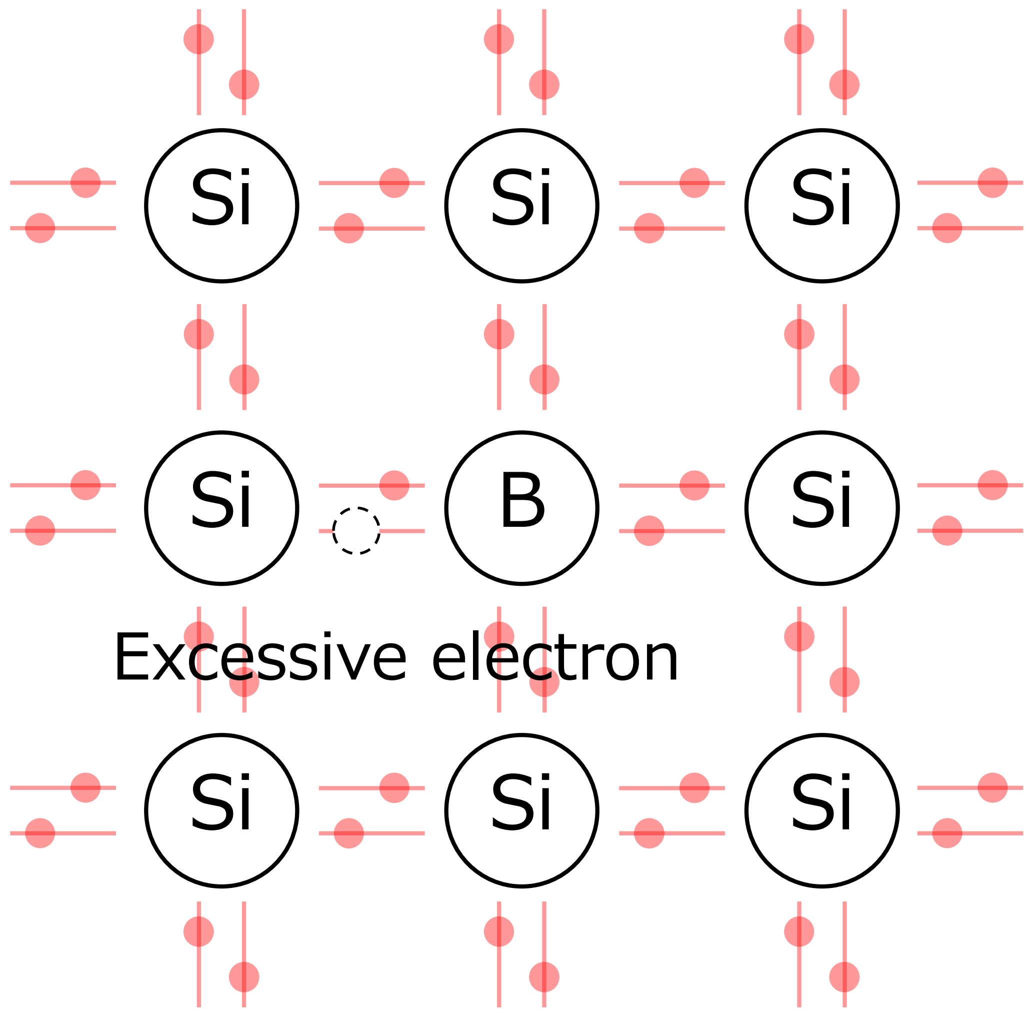
Excitation from the added level to the conduction band can be achieved by the thermal energy

P-type Semiconductor

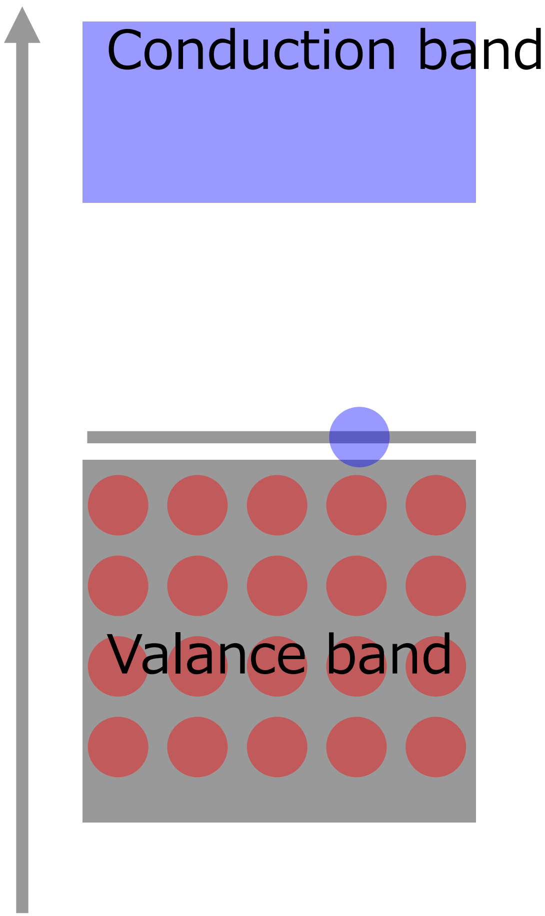
Valance electron
(価電子)

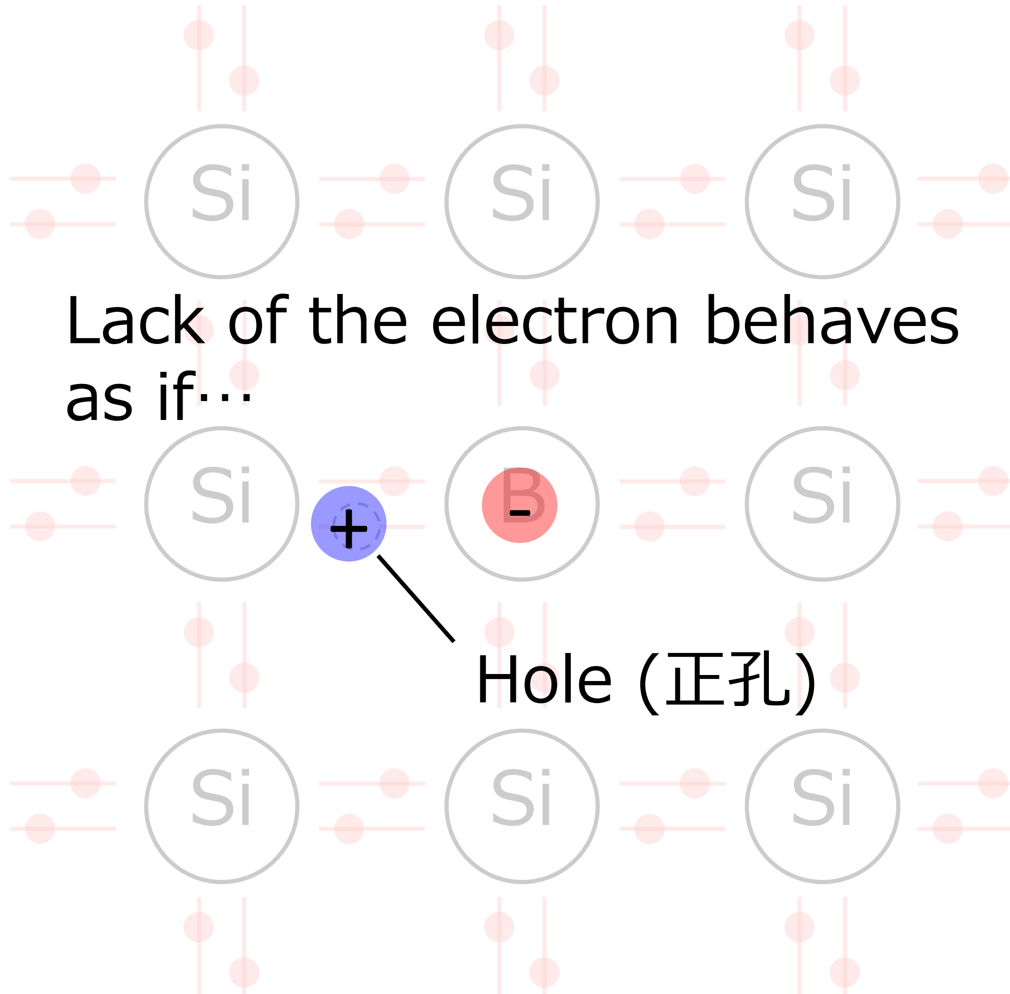
Si: 4

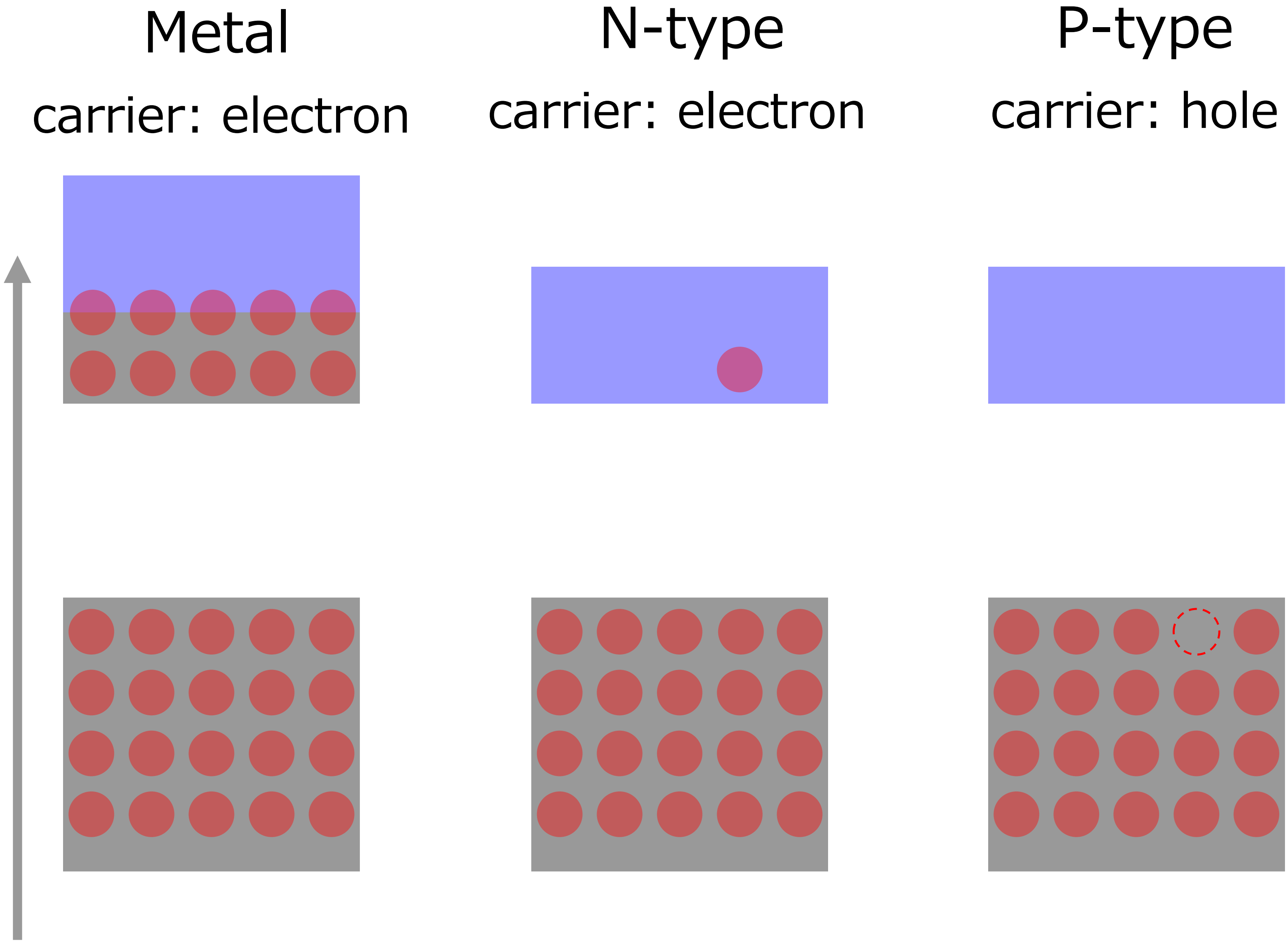
B: 3



P-type Semiconductor






Metal
carrier: electron
N-type
carrier: electron
P-type
carrier: hole

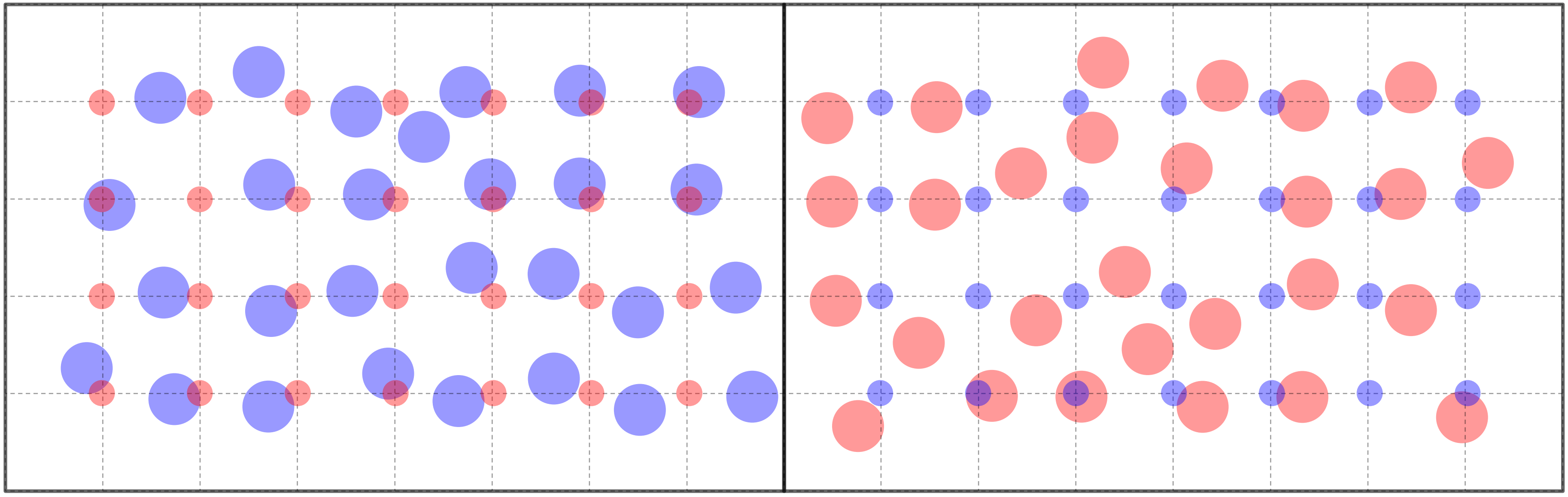
P-N junction

P

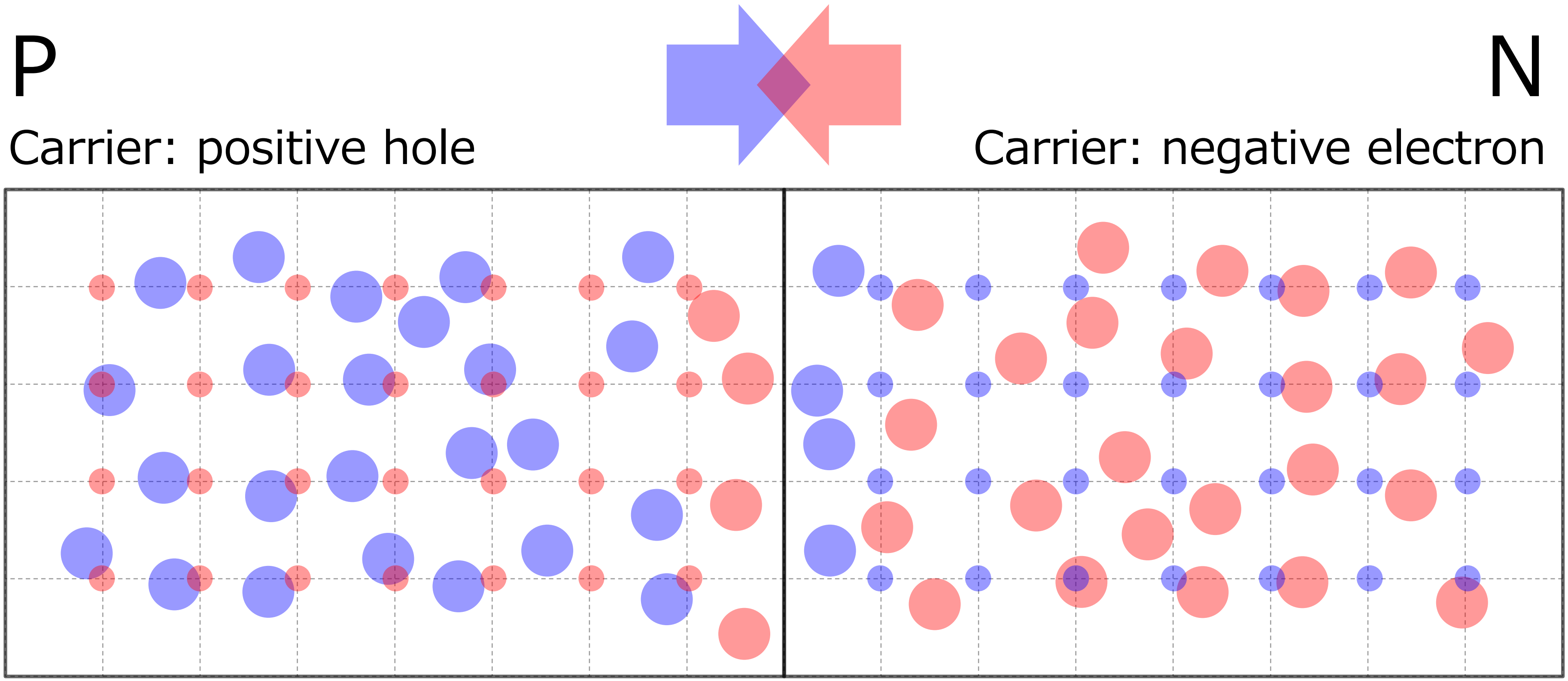
N

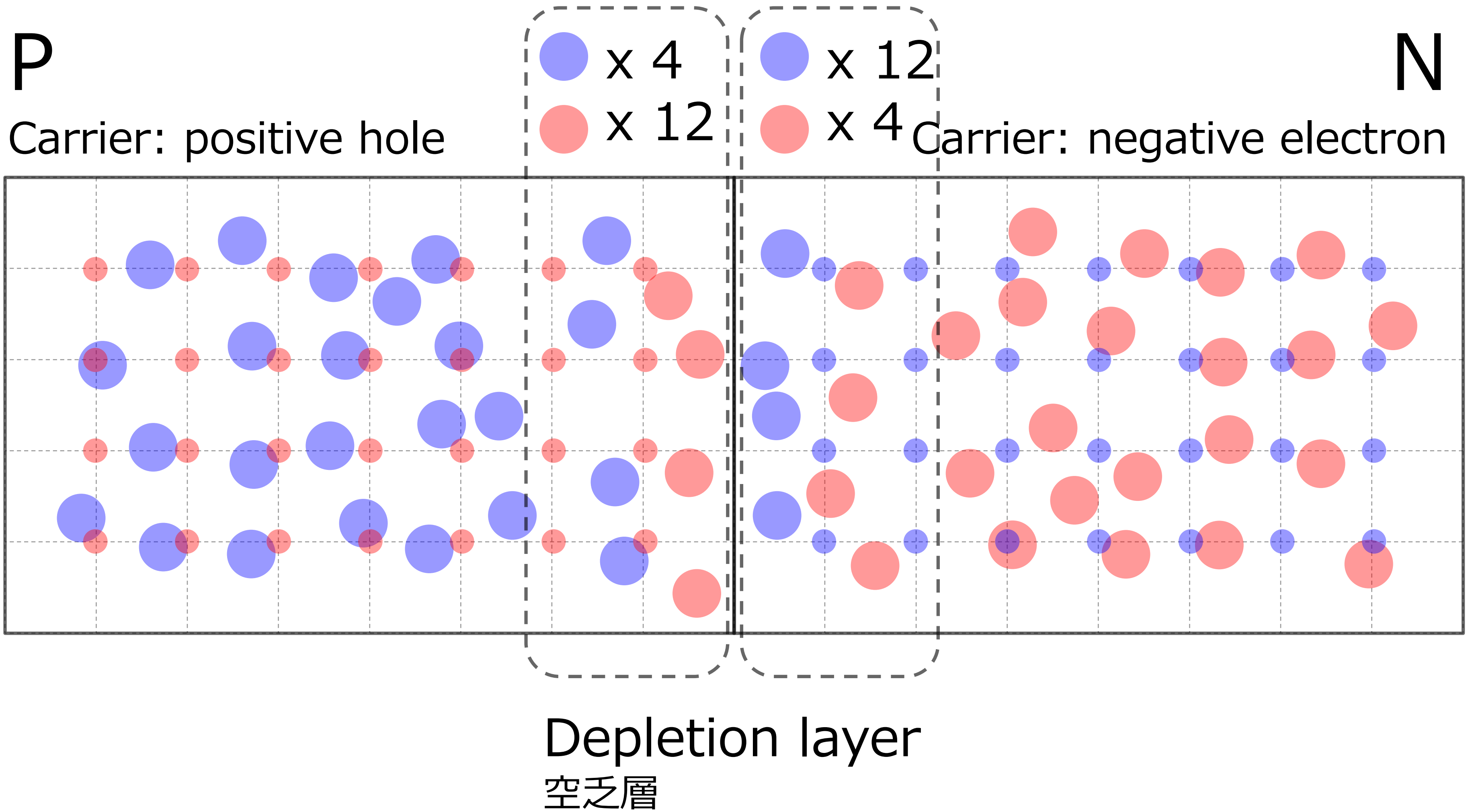
Carrier: positive hole

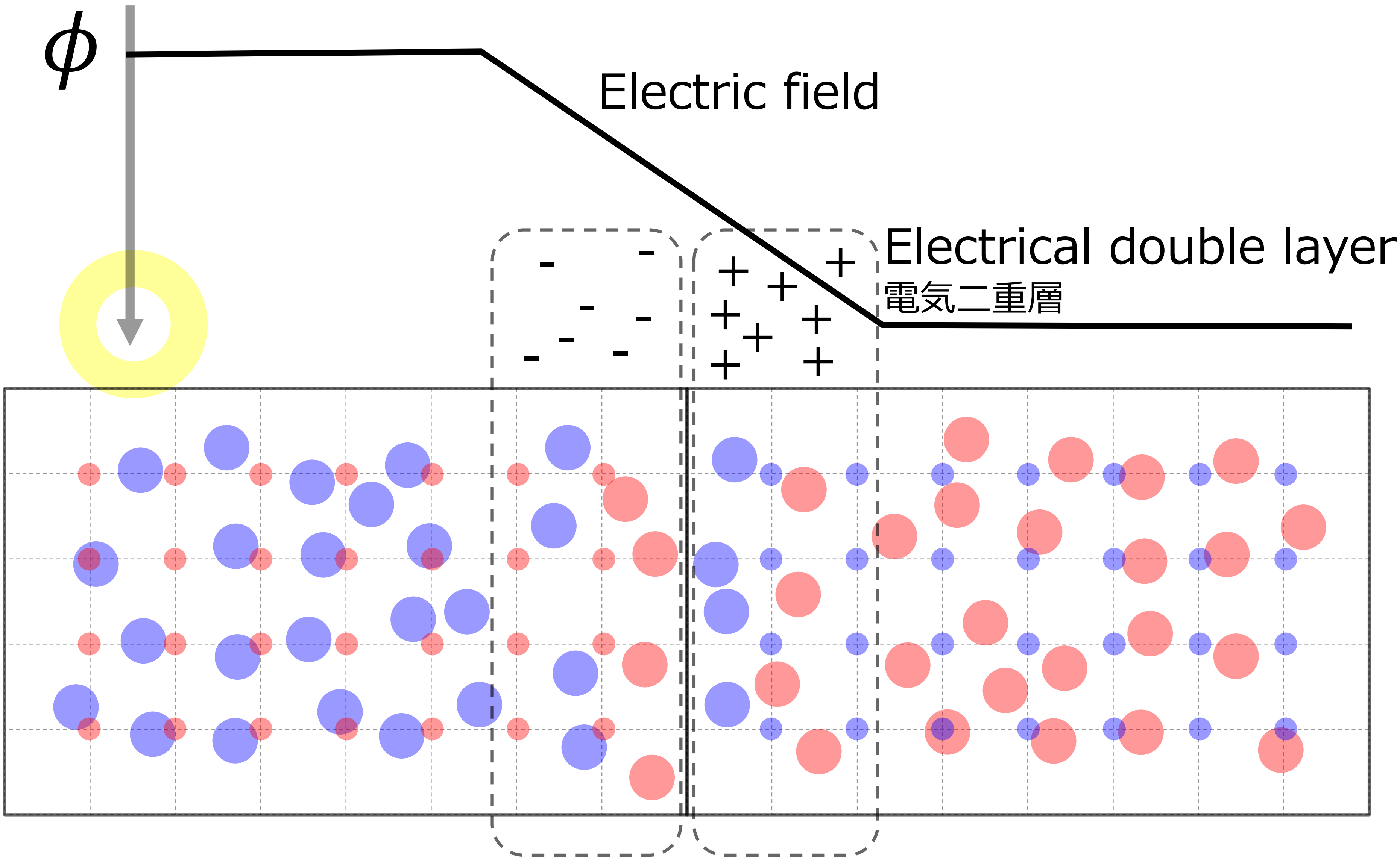
Carrier: negative electron



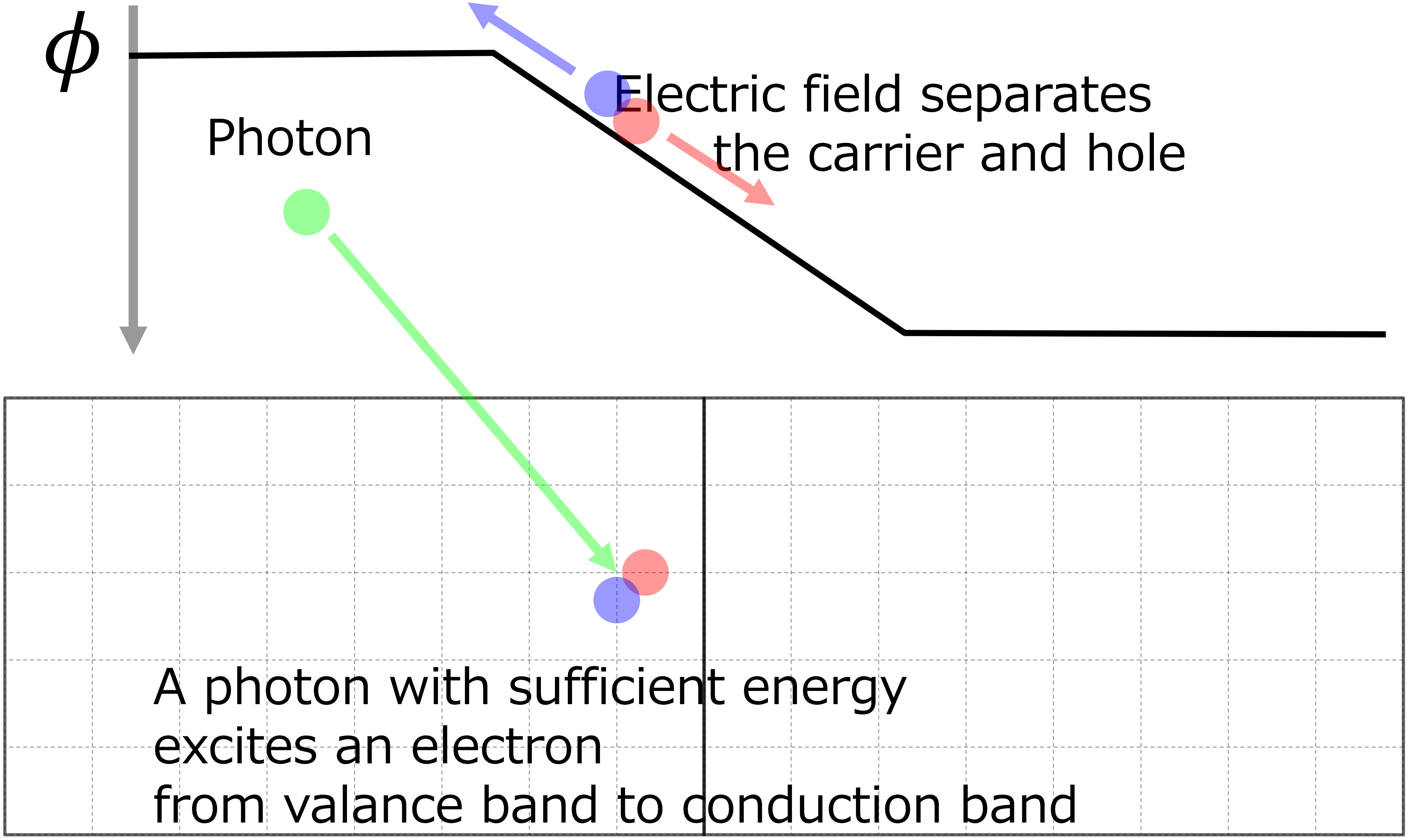
Diffusion of electrons and holes

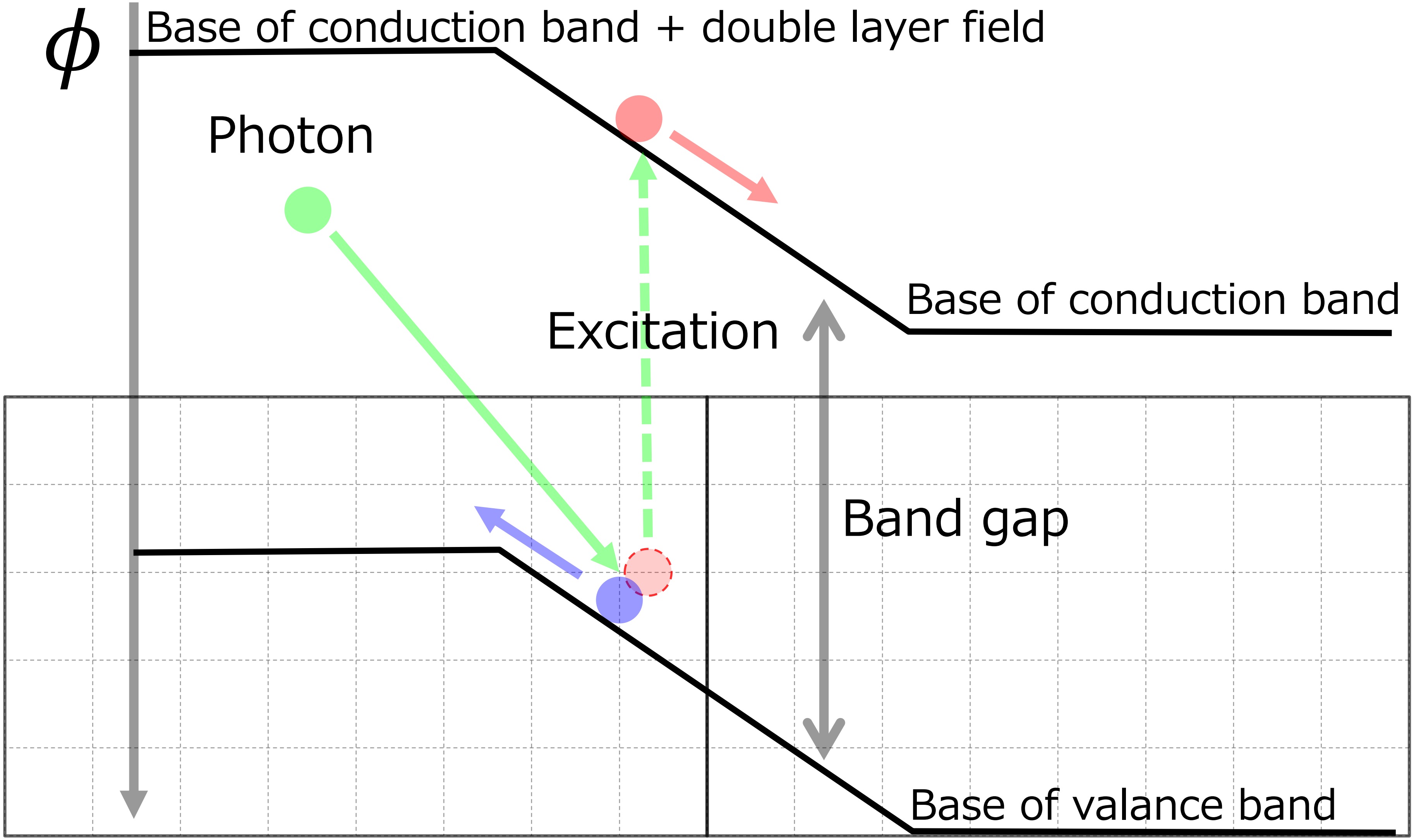


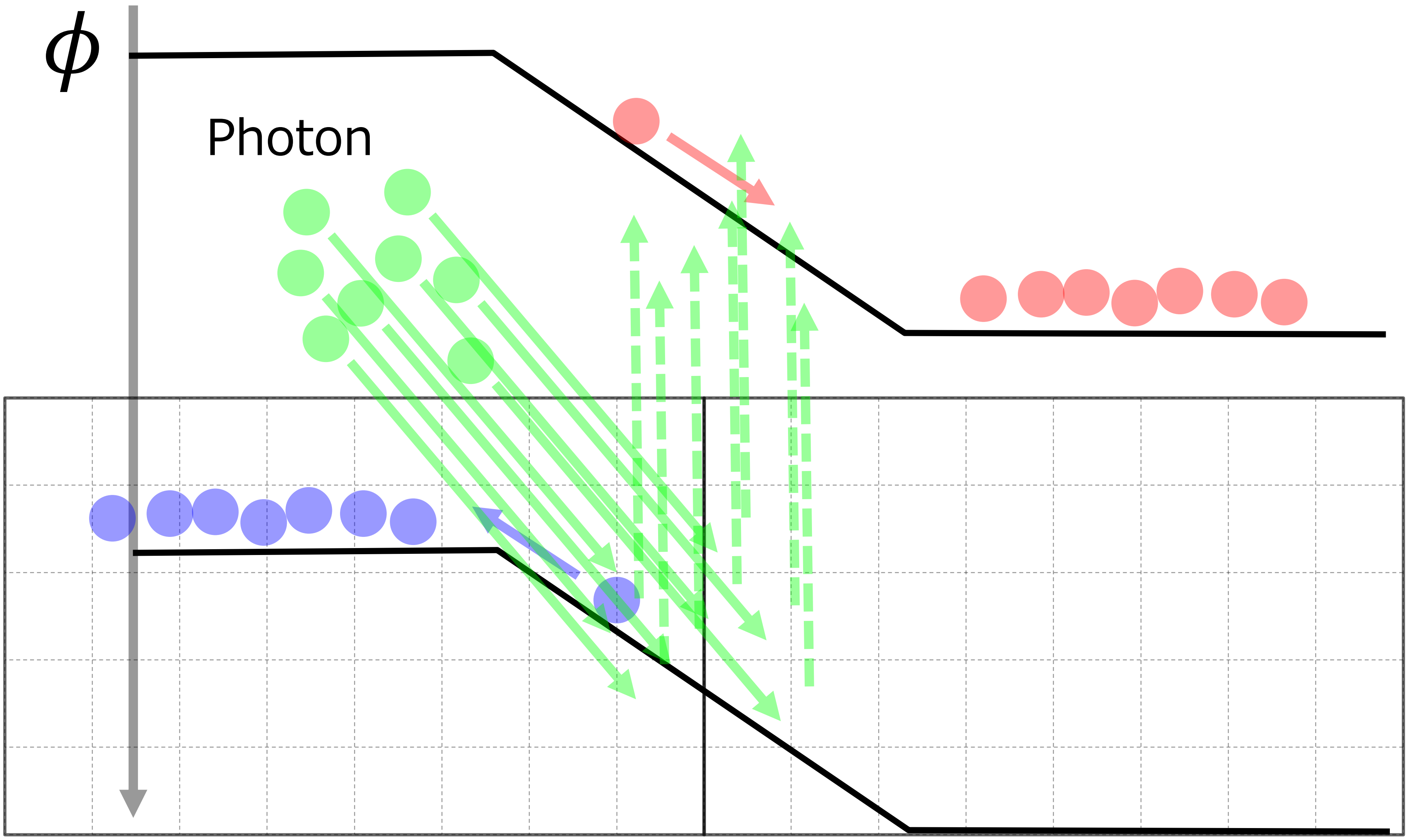

P
Carrier: positive hole
x 4
x 12
x 12
x 4
N
Carrier: negative electron
Depletion layer
空乏層

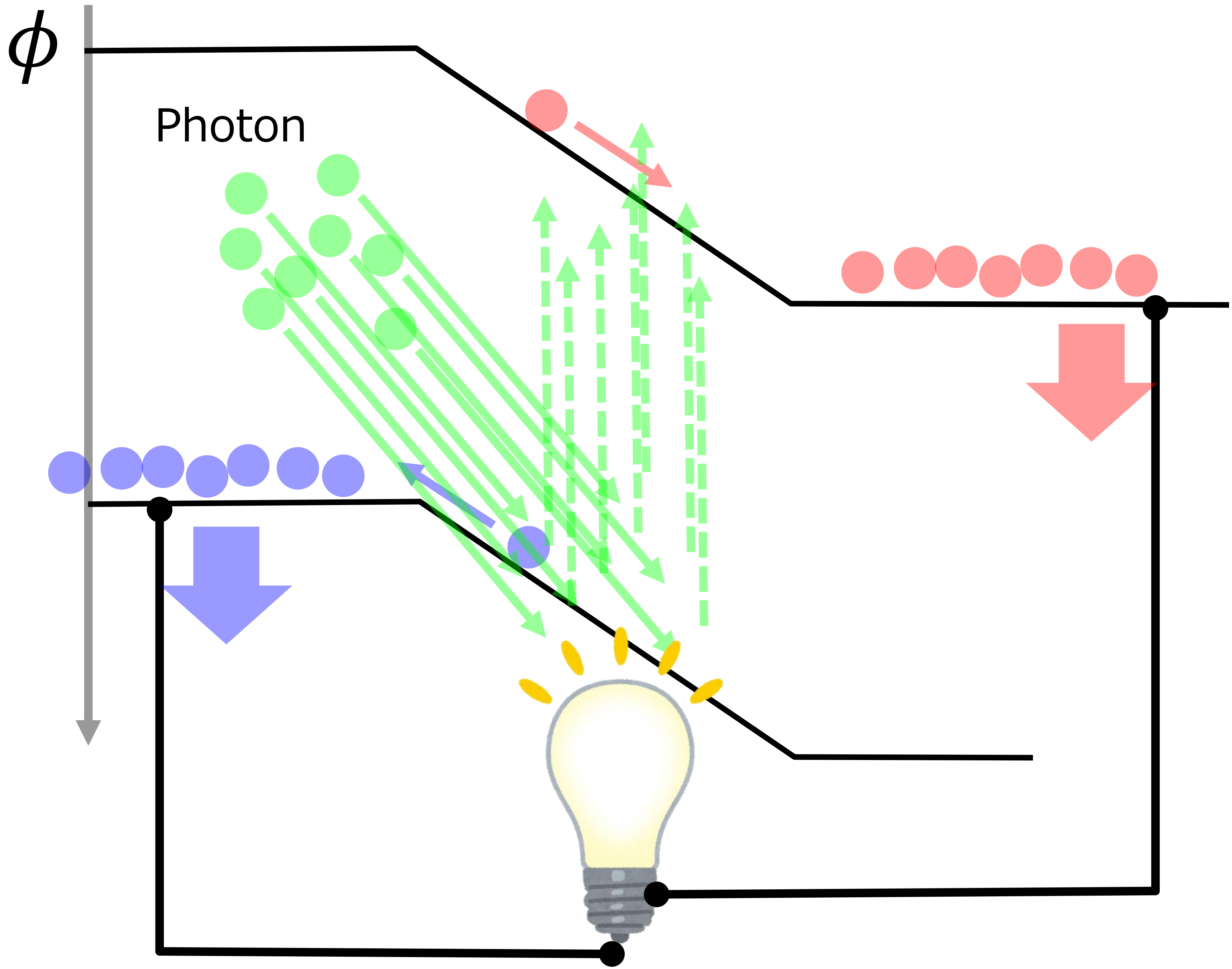


ϕ
Electric field
Electrical double layer
電気二重層

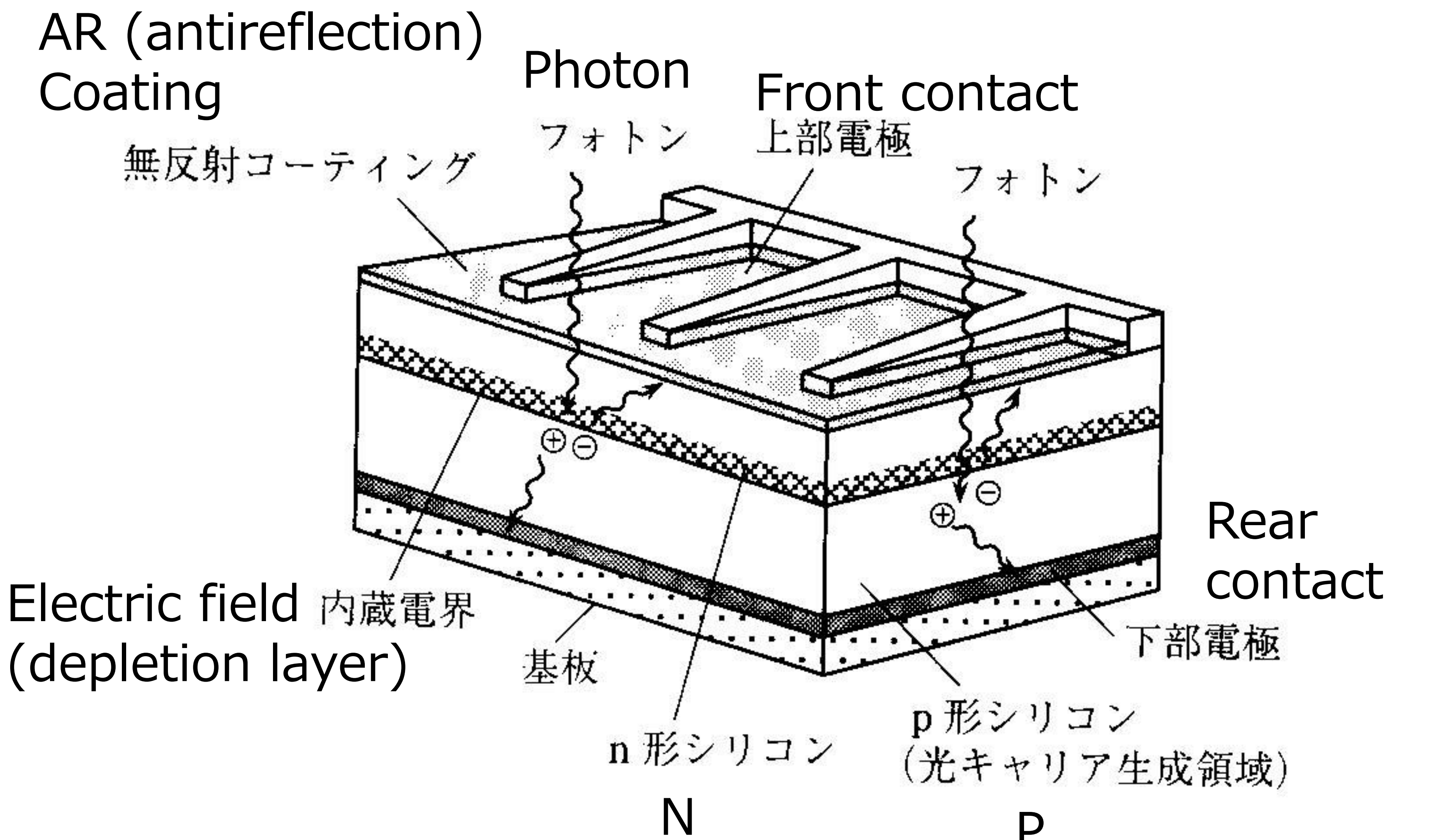

ϕ
Photon
Electric field separates
the carrier and hole
A photon with sufficient energy
excites an electron
from valance band to conduction band


ϕ
Base of conduction band + double layer field
Photon
Excitation
Base of conduction band
Band gap
Base of valance band


ϕ
Photon

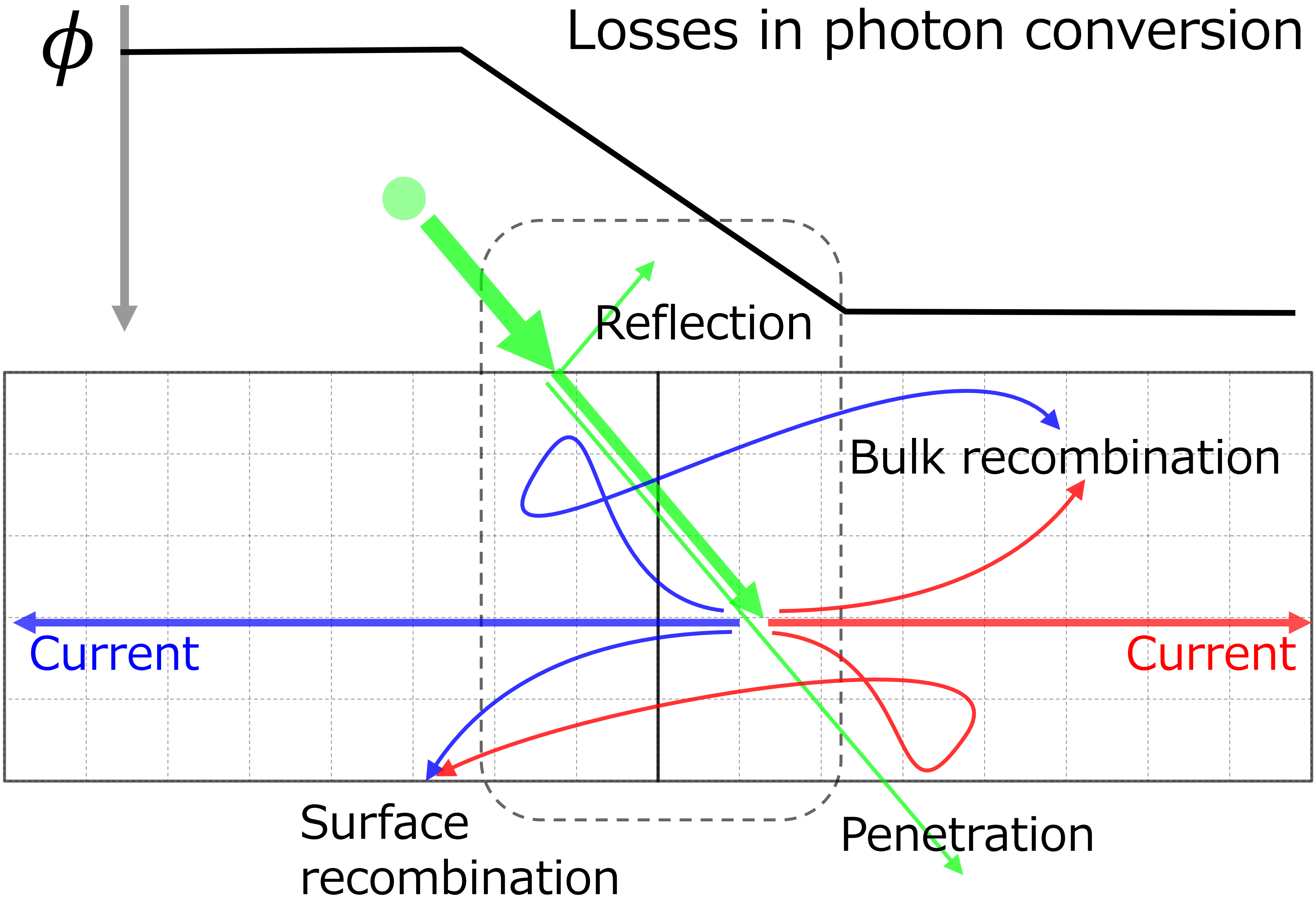


ϕ
Photon


AR (antireflection)
Coating
無反射コーティング
Photon
フォトン
Front contact
上部電極
フォトン
Rear
contact
下部電極
Electric field
(depletion layer)
内蔵電界
基板
n 形シリコン
N
p 形シリコン
(光キャリア生成領域)
P

2. Higher efficiency

What causes losses of the energy?



ϕ
Losses in photon conversion
Reflection
Bulk recombination
Current
Current
Surface
recombination
Penetration

$$I_{\mathrm{PV}} = eA \int_0^{\infty} (1 - r_{\lambda})a_{\lambda}\Phi_{\lambda}(1 - R_{\lambda})\, d\lambda$$

Photon number flux: $\Phi(\lambda)$

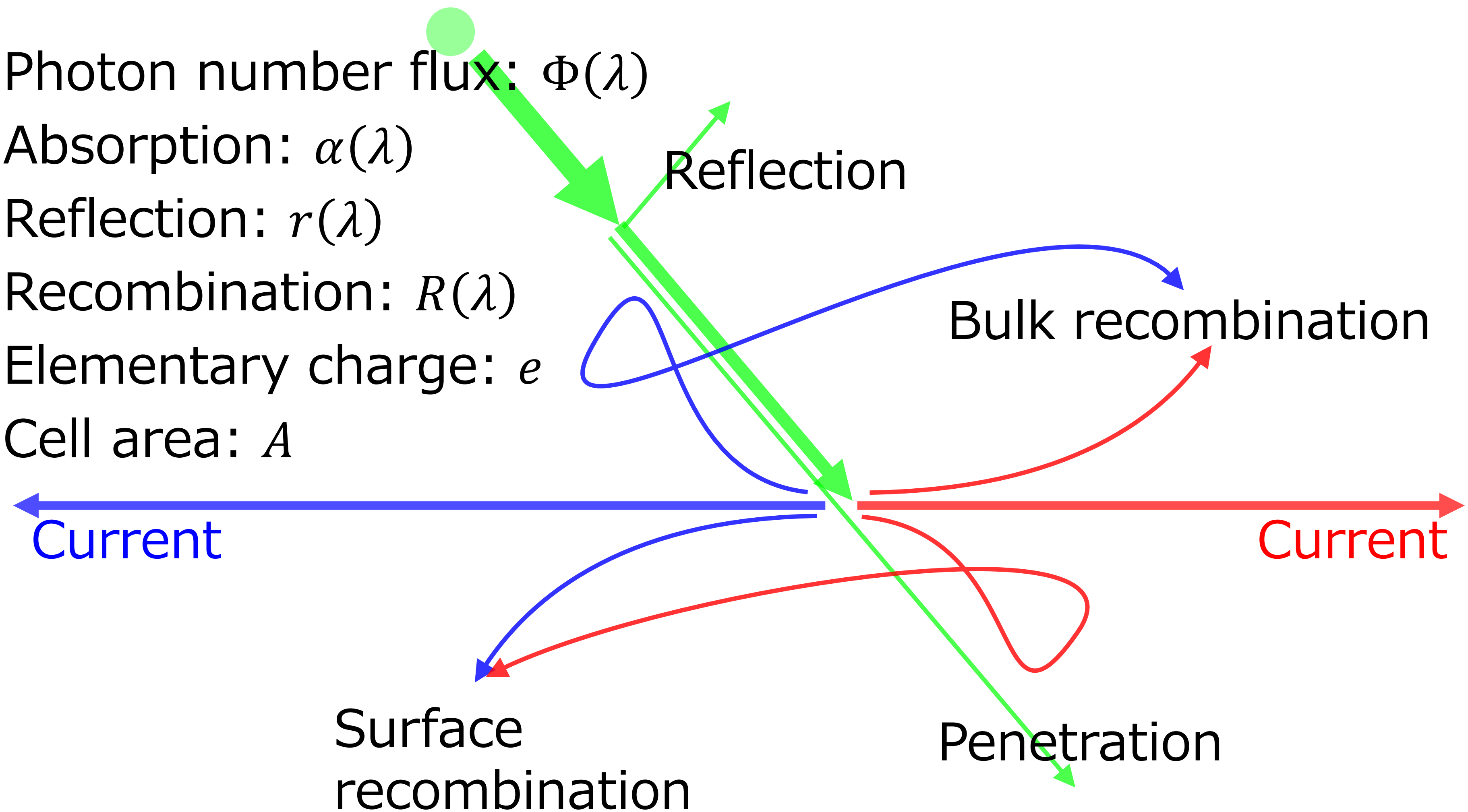
Absorption: $\alpha(\lambda)$

Reflection: $r(\lambda)$

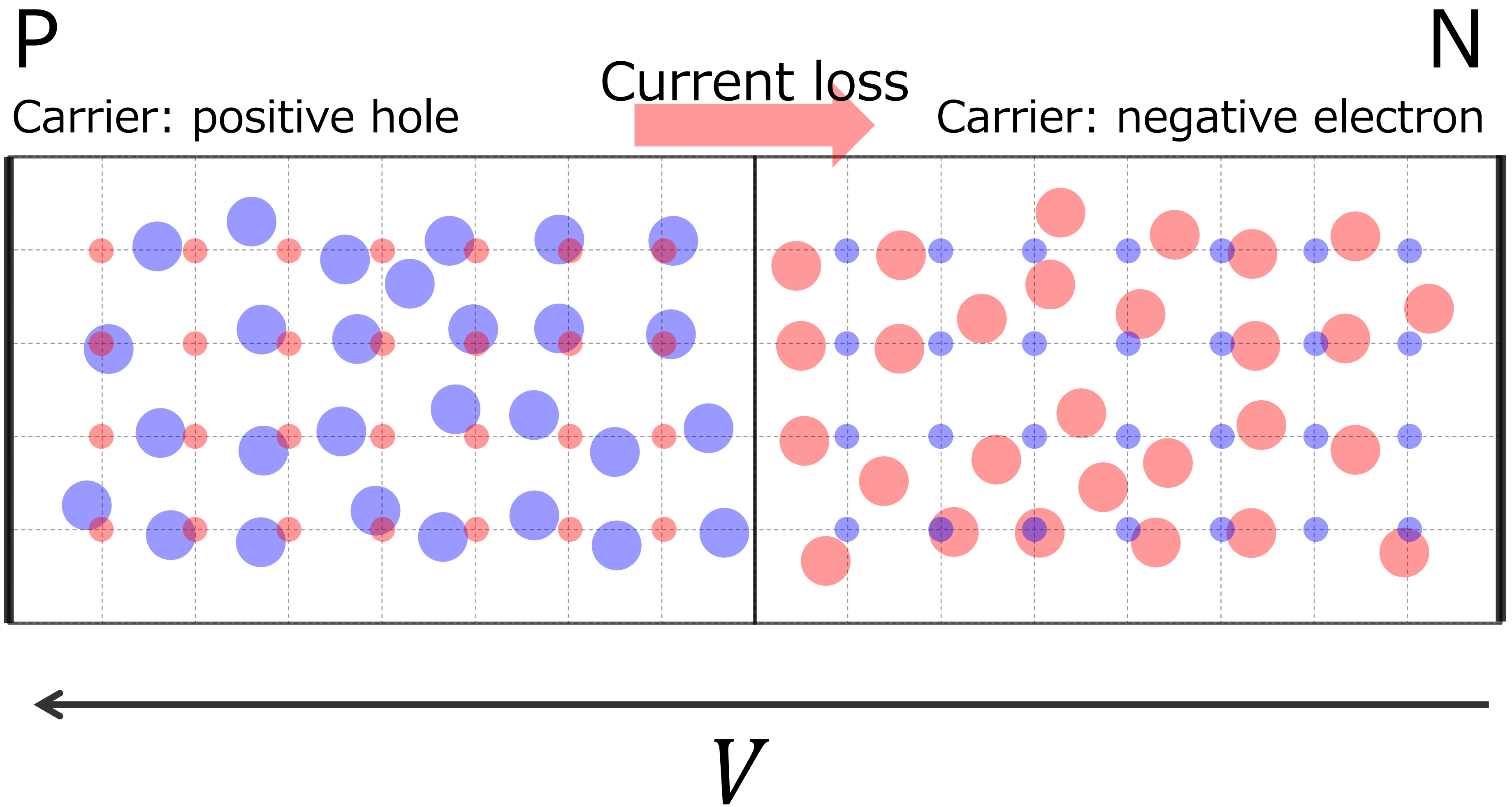
Recombination: $R(\lambda)$

Elementary charge: e

Cell area: A



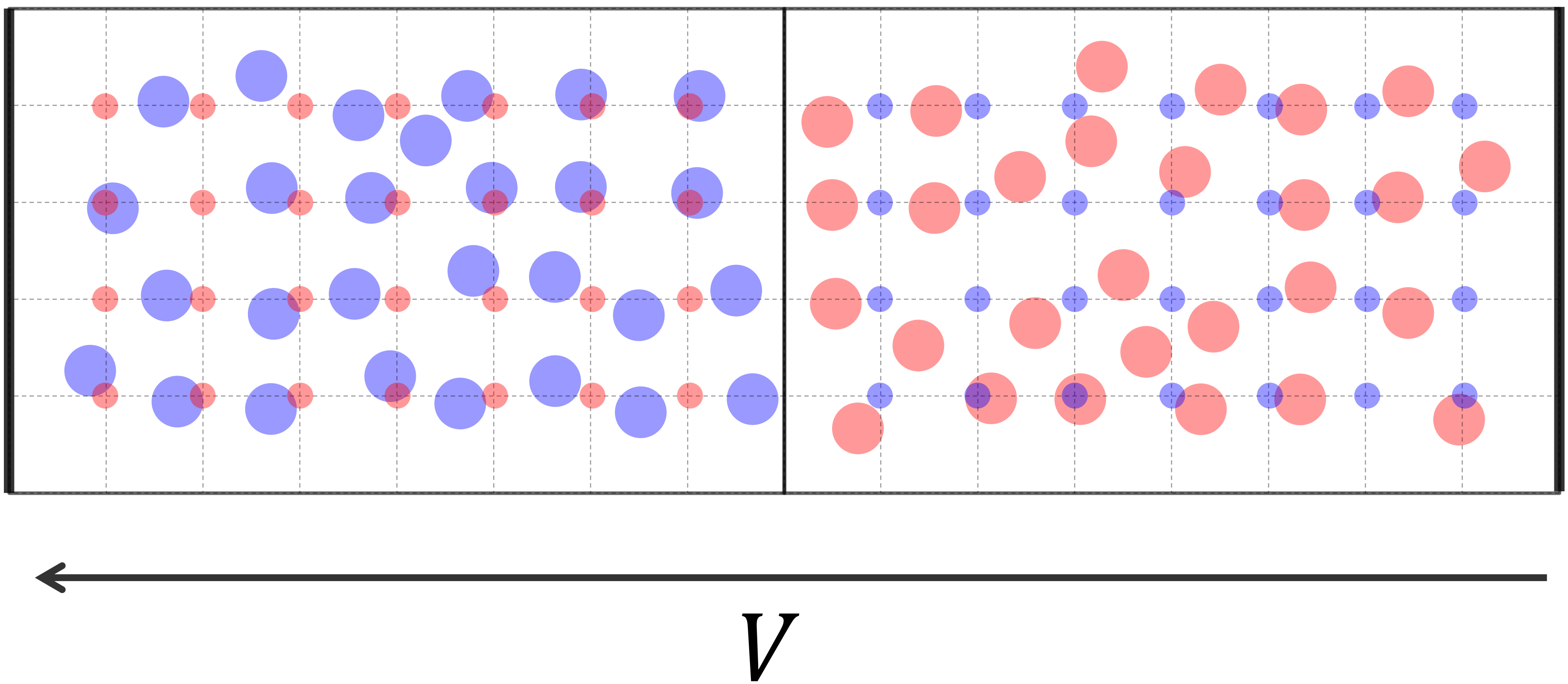
This is a diode



$$I_{\mathrm{dark}} = I_0 \left\{ \exp\left(\frac{eV}{nkT} \right) - 1 \right\}$$

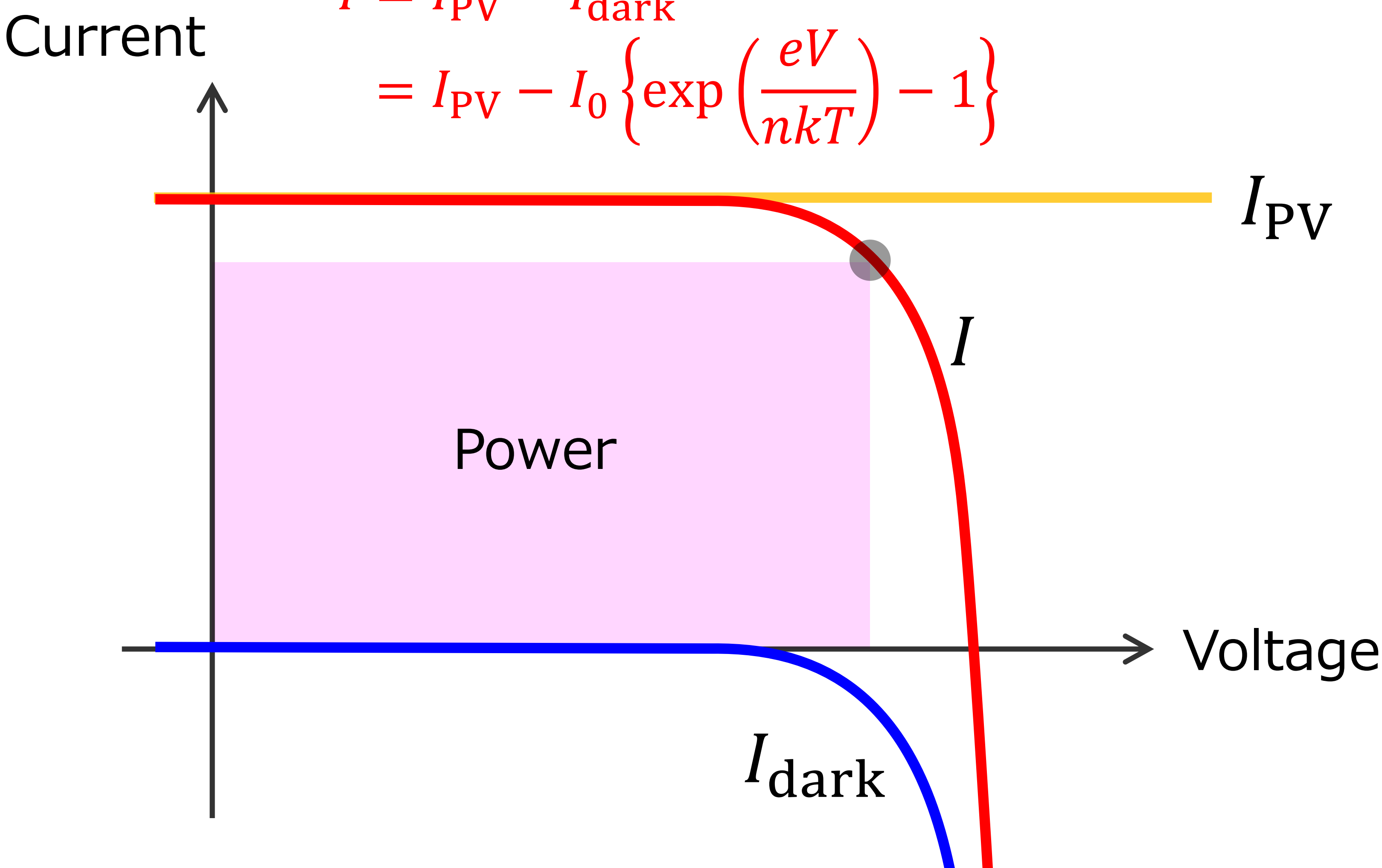
Reverse saturation current: I_0

Ideally factor: n

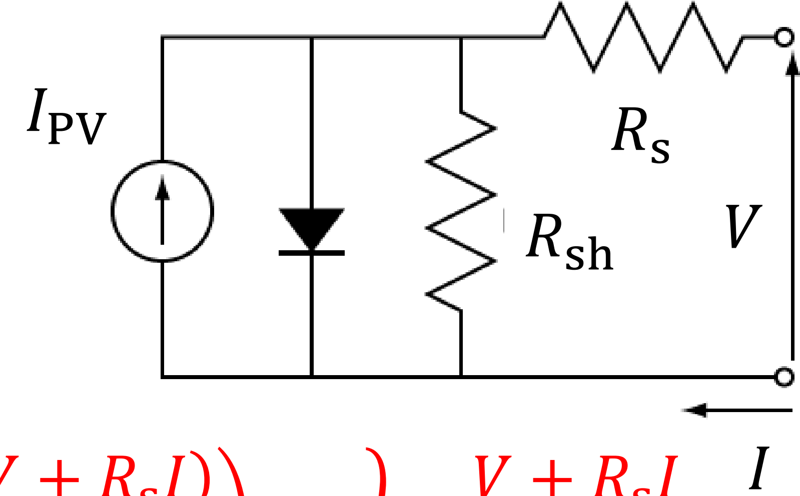


Photovoltaic current
(the simplest expression)

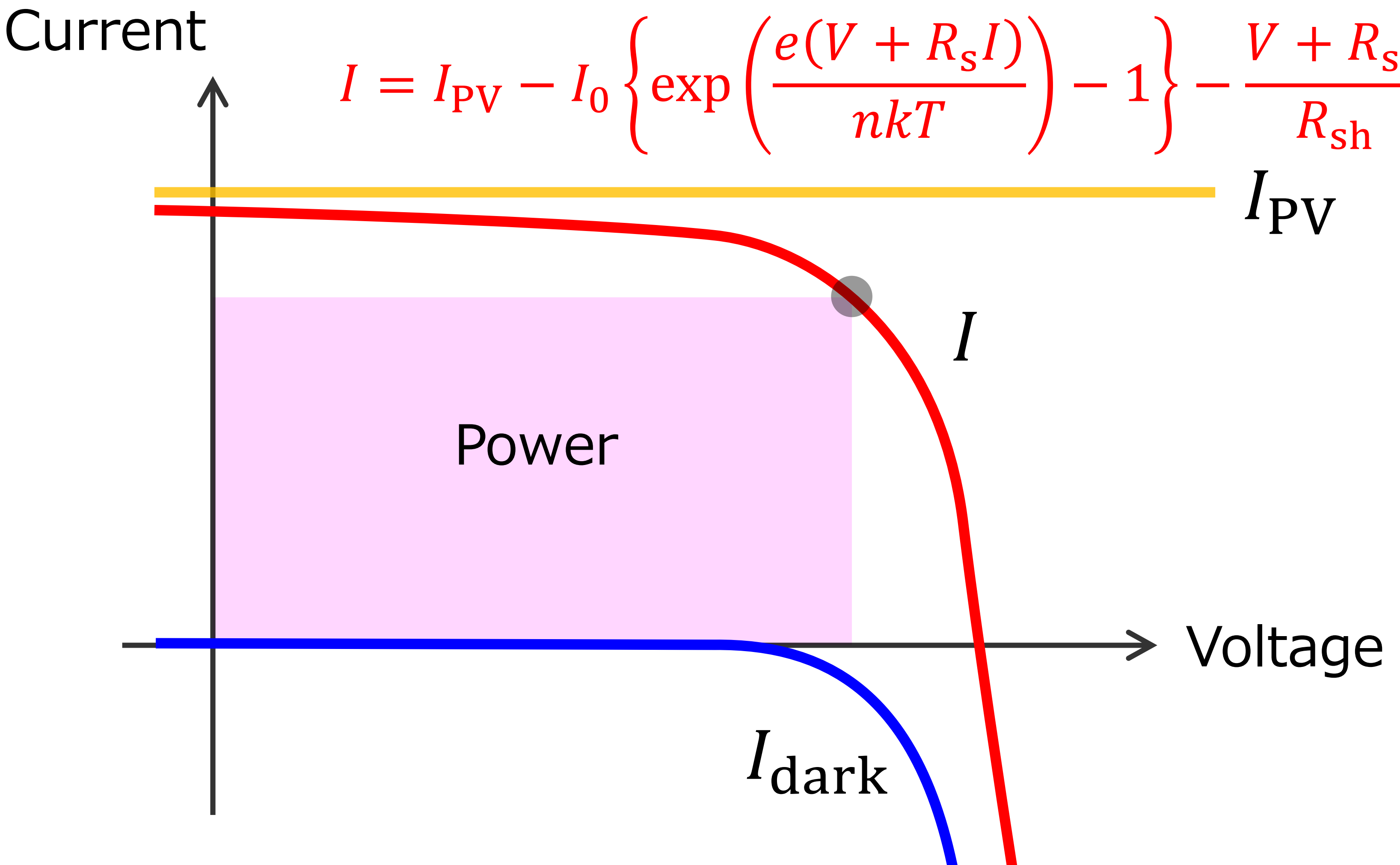
$$I = I_{\mathrm{PV}} - I_{\mathrm{dark}}$$
$$= I_{\mathrm{PV}} - I_0 \left\{ \exp\left(\frac{eV}{nkT} \right) - 1 \right\}$$



Photovoltaic current
(more practical expression)



$$I = I_{\mathrm{PV}} - I_0\left\{\exp\left(\frac{e(V + R_s I)}{nkT}\right) - 1\right\} - \frac{V + R_s I}{R_{\mathrm{sh}}}$$



Photovoltaic efficiency

Power input: $$P_{\mathrm{in}} = \int_0^{\infty} \frac{hc}{\lambda} \Phi_\lambda \, d\lambda$$

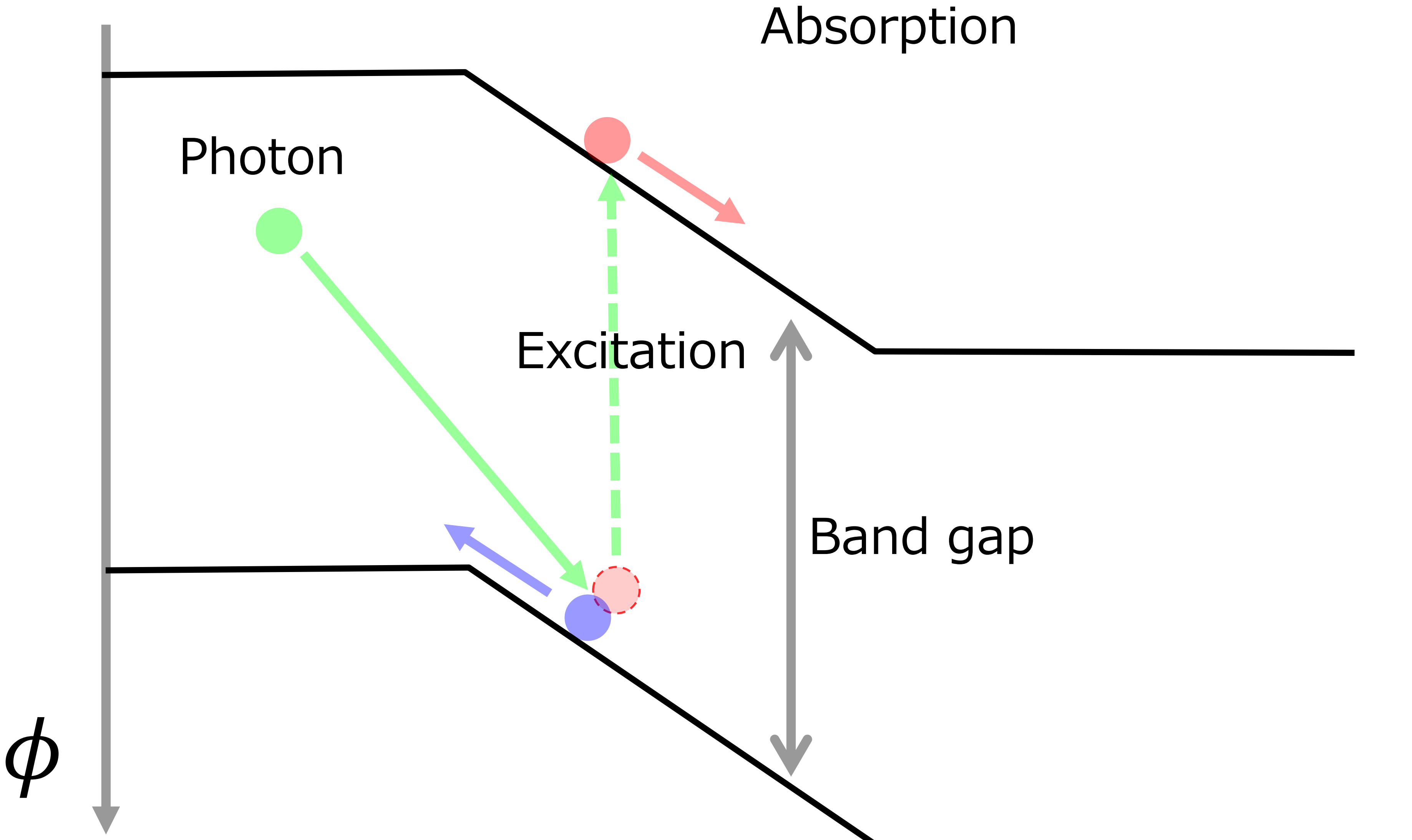
Power output: $$P_{\mathrm{out}} = (I_{\mathrm{SC}} - I_{\mathrm{dark}})V$$

$$I_{\mathrm{SC}} = eA \int_0^{\infty} (1 - r_\lambda) a_\lambda \Phi_\lambda (1 - R_\lambda) \, d\lambda$$

Efficiency: $$\eta = \frac{P_{\mathrm{out}}}{P_{\mathrm{IN}}}$$

Wavelength and bandgap matching

$$I_{SC} = eA \int_0^\infty (1 - r_\lambda) a_\lambda \Phi_\lambda (1 - R_\lambda)\, d\lambda$$



$$I_{SC} = eA \int_0^{\infty} (1 - r_\lambda) a_\lambda \Phi_\lambda (1 - R_\lambda)\, d\lambda$$

Absorption

If photon energy < band gap ($h\nu < E_g$),

No excitation
(no carrier increase) → $a_\lambda = 0$

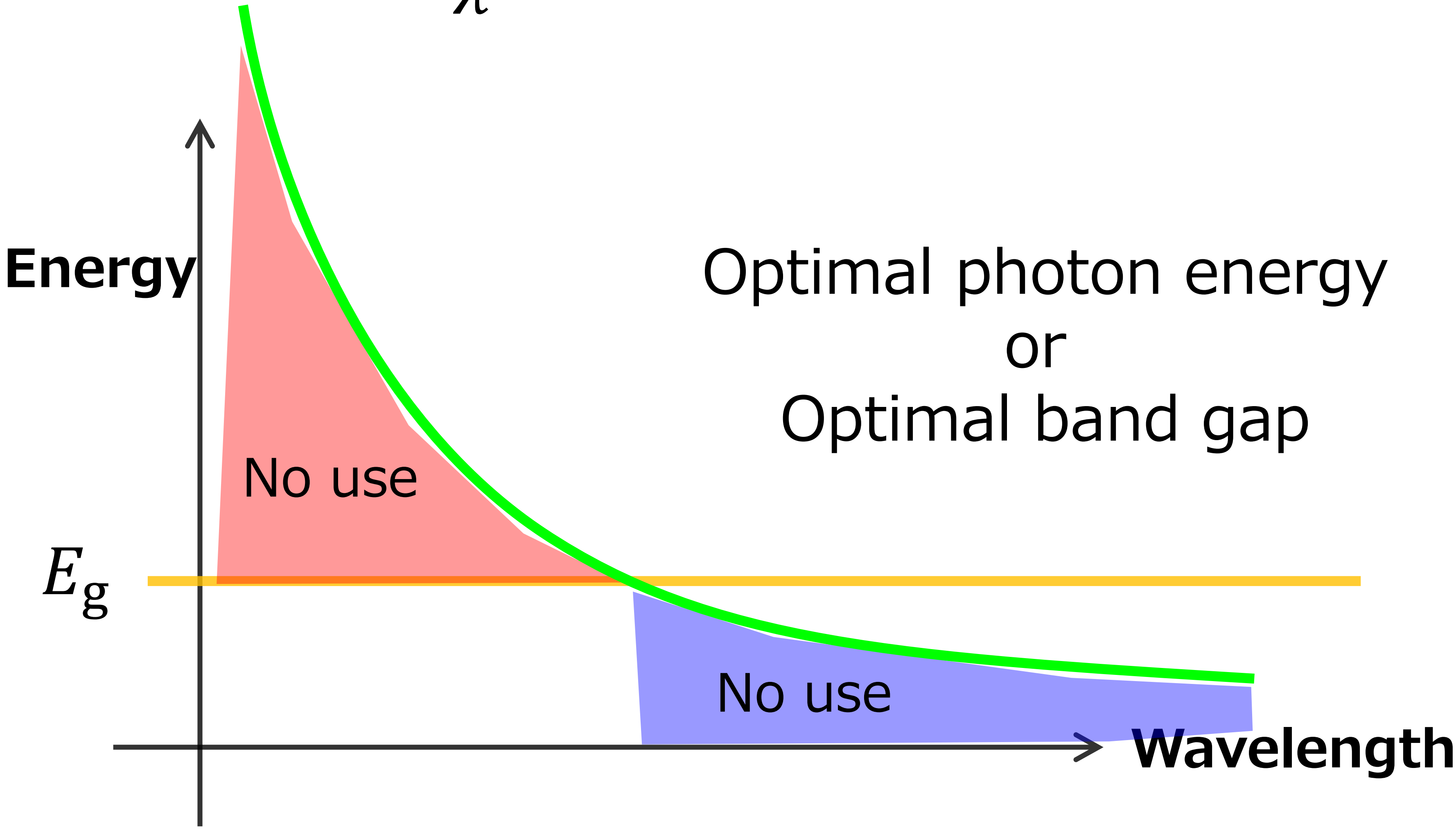
If photon energy > band gap ($h\nu > E_g$),

Excitation
(carrier increase) → $a_\lambda > 0$

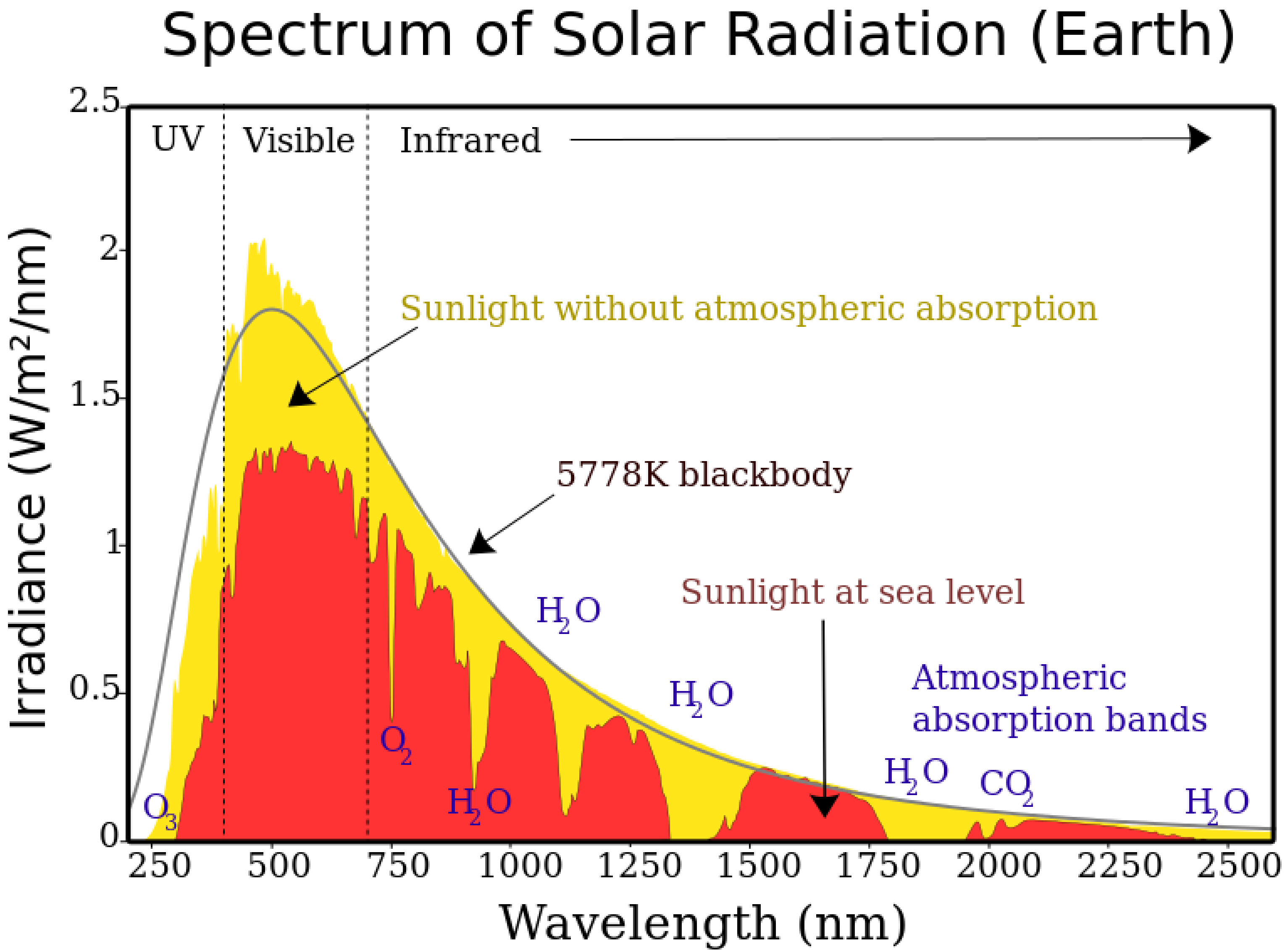
$h\nu - E_g$ dissipates
as thermal energy

Solar spectrum is important

$$E_{\mathrm{PV}} = h\nu = \frac{hc}{\lambda}$$

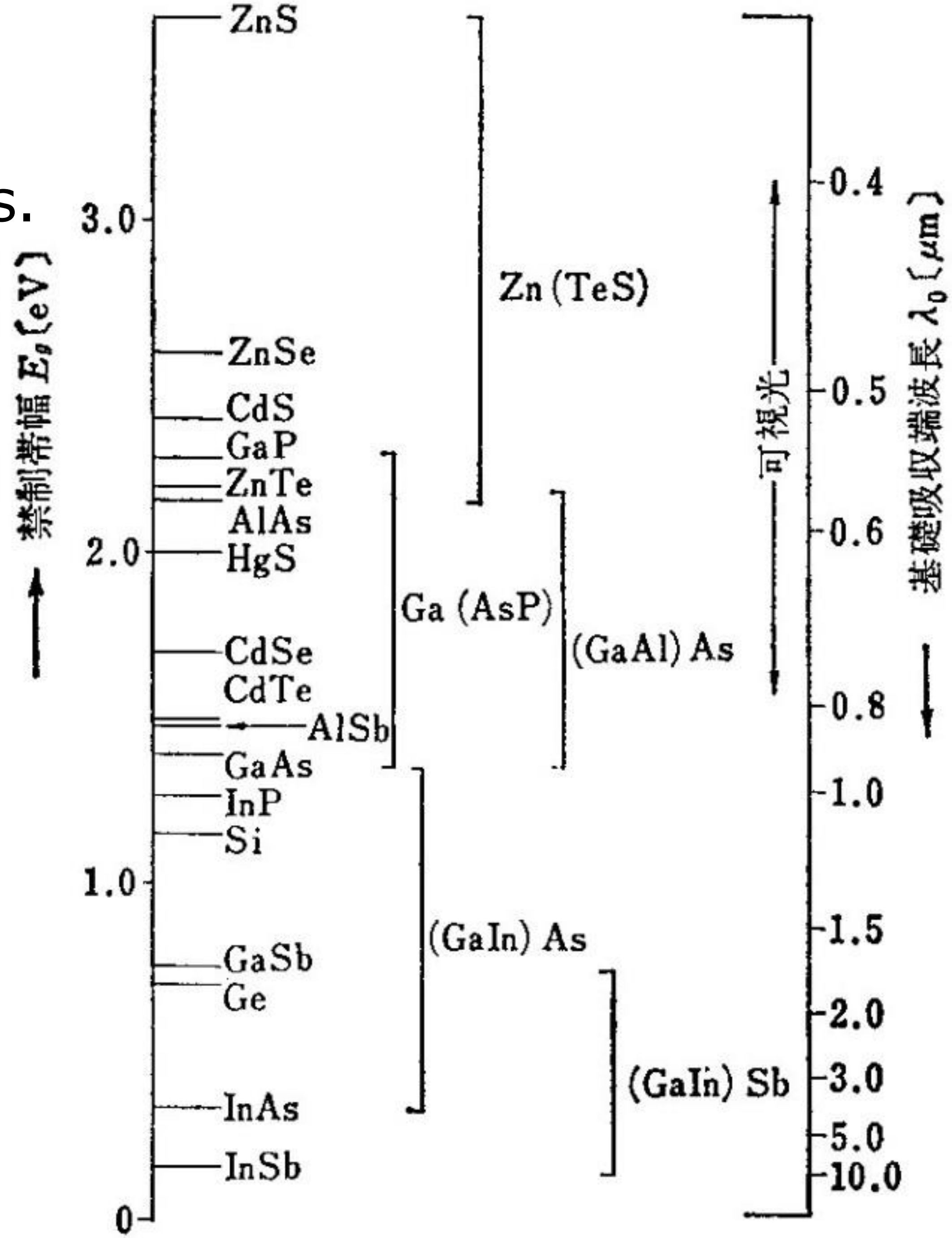


Optimal photon energy
or
Optimal band gap



Spectrum of Solar Radiation (Earth)
UV
Visible
Infrared
Sunlight without atmospheric absorption
5778K blackbody
Sunlight at sea level
Atmospheric absorption bands
O_3
O_2
H_2O
H_2O
H_2O
H_2O
CO_2
H_2O
Irradiance (W/m²/nm)
Wavelength (nm)
0
0.5
1
1.5
2
2.5
250
500
750
1000
1250
1500
1750
2000
2250
2500

Wavelength of intrinsic absorption edge in various semiconductors.



Effective power

Low energy photon can not be used

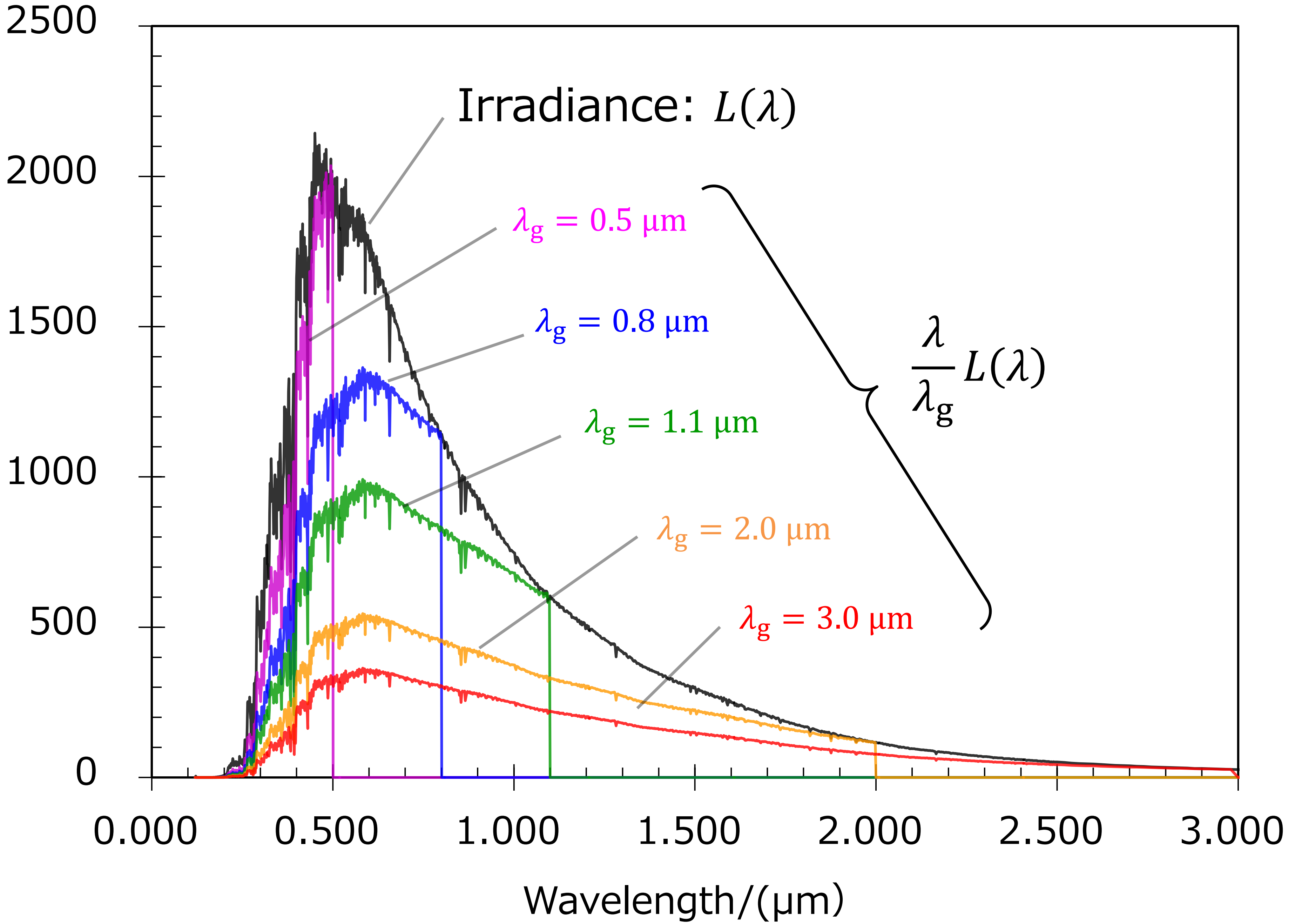
$$P_{\mathrm{eff}} = \int_0^{\lambda_{\mathrm{g}}} E_{\mathrm{g}} \Phi(\lambda)\, d\lambda = \int_0^{\lambda_{\mathrm{g}}} \frac{\lambda}{\lambda_{\mathrm{g}}} L(\lambda)\, d\lambda$$

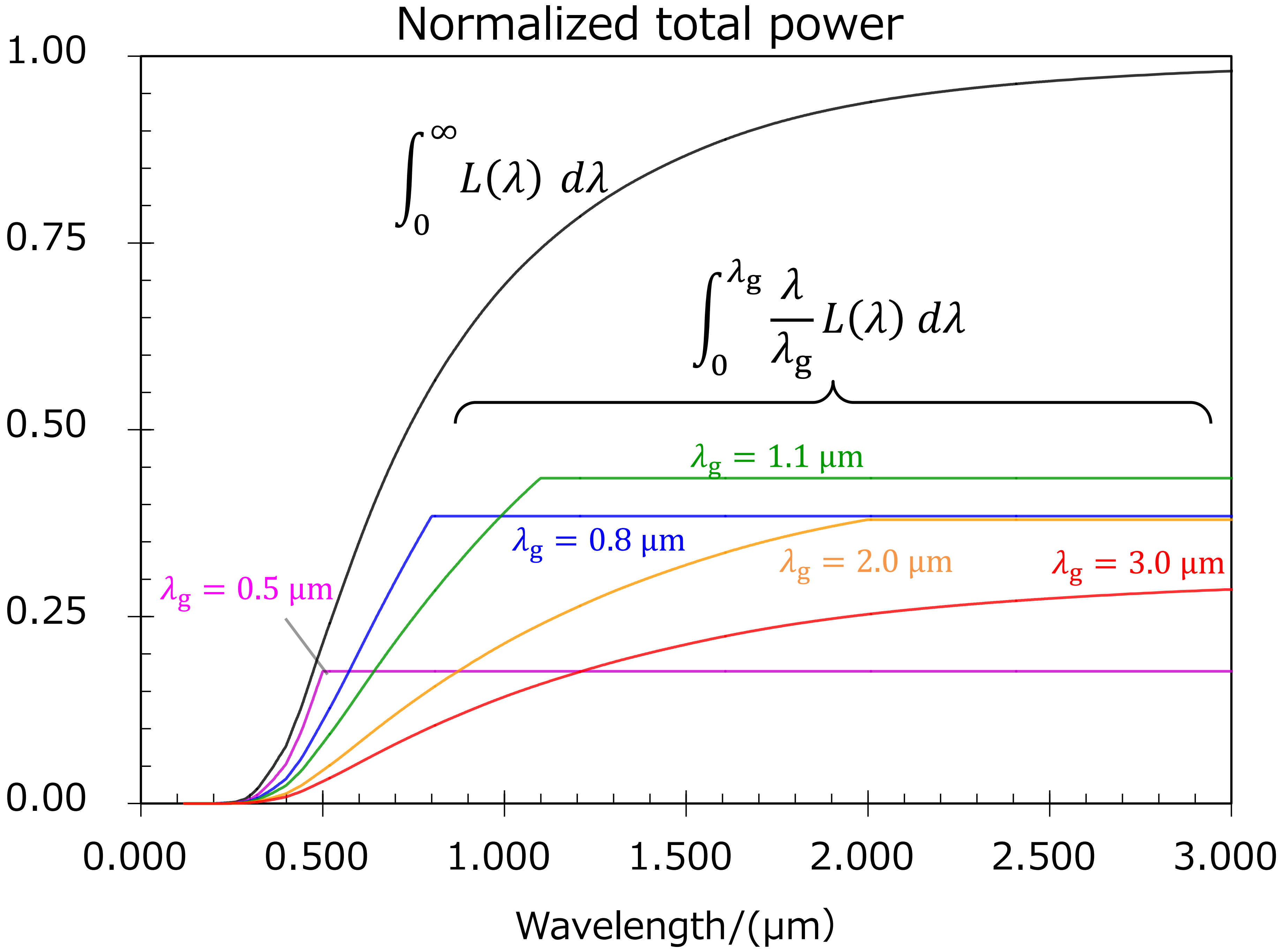
Only band gap energy can be used

Irradiance: $L(\lambda)$
Power per unit area, unit wavelength

Photon flux: $\Phi(\lambda)$
Photon number flux per unit area, unit wavelength

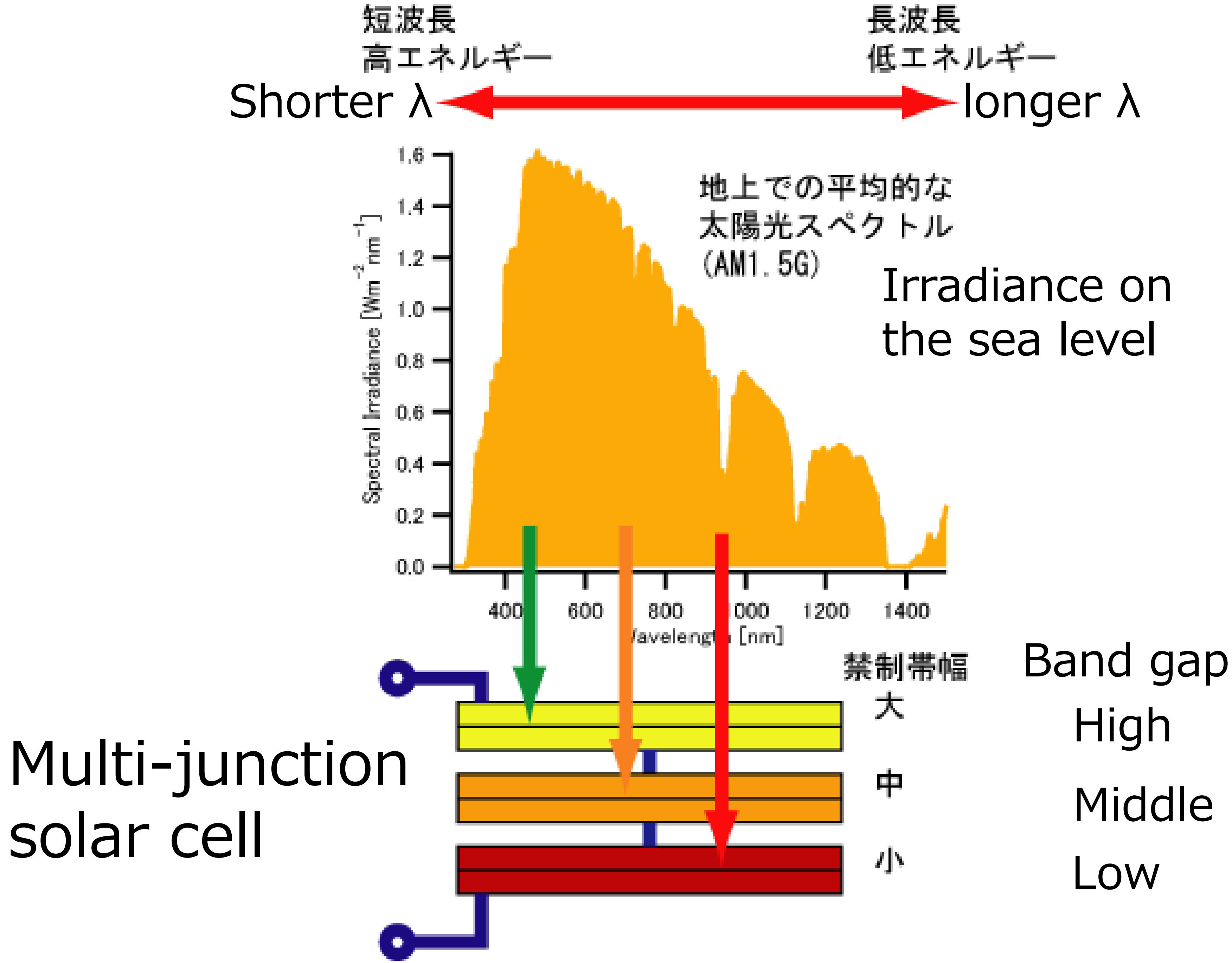
$$L(\lambda) = h\nu\Phi(\lambda) = \frac{hc}{\lambda}\Phi(\lambda)$$

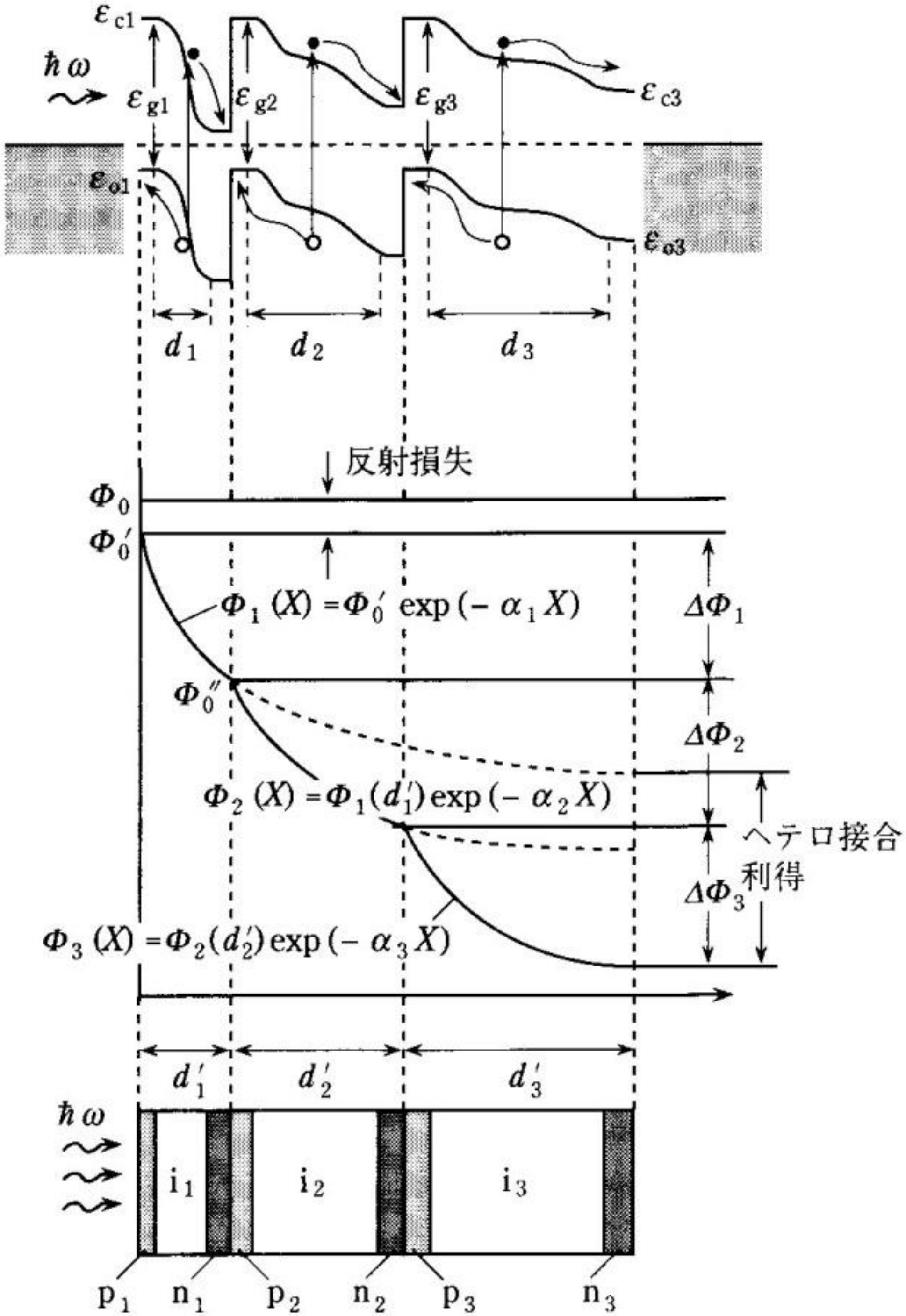

2500
2000
1500
1000
500
0
Irradiance: $L(\lambda)$
$\lambda_g = 0.5\ \mu m$
$\lambda_g = 0.8\ \mu m$
$\lambda_g = 1.1\ \mu m$
$\lambda_g = 2.0\ \mu m$
$\lambda_g = 3.0\ \mu m$
$\frac{\lambda}{\lambda_g} L(\lambda)$
0.000
0.500
1.000
1.500
2.000
2.500
3.000
Wavelength/(μm)



Normalized total power
1.00
0.75
0.50
0.25
0.00
0.000
0.500
1.000
1.500
2.000
2.500
3.000
Wavelength/(μm)
$\int_0^\infty L(\lambda)\ d\lambda$
$\int_0^{\lambda_g} \frac{\lambda}{\lambda_g} L(\lambda)\ d\lambda$
$\lambda_g = 1.1$ μm
$\lambda_g = 0.8$ μm
$\lambda_g = 2.0$ μm
$\lambda_g = 3.0$ μm
$\lambda_g = 0.5$ μm

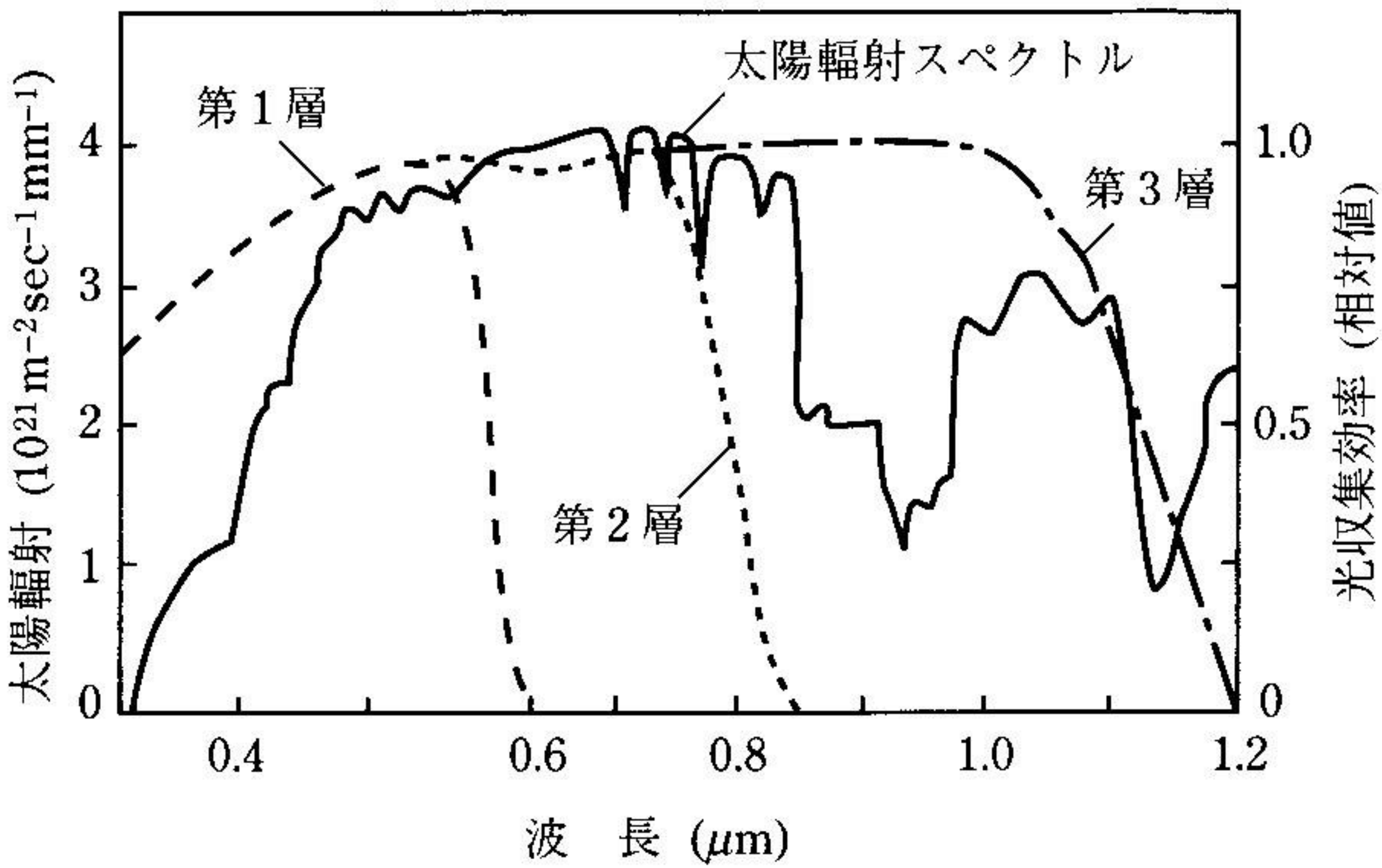
Multi-junction solar cells


短波長
高エネルギー
Shorter λ
長波長
低エネルギー
longer λ
地上での平均的な
太陽光スペクトル
(AM1.5G)
Irradiance on
the sea level
Spectral Irradiance [Wm⁻² nm⁻¹]
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
400
600
800
1000
1200
1400
Wavelength [nm]
禁制帯幅
Band gap
大
High
中
Middle
小
Low
Multi-junction
solar cell



High E_g, to low E_g

High energy
=short wavelength
=short absorption length



太陽輻射スペクトル
第1層
第2層
第3層
太陽輻射 (10^{21} m^{-2}sec^{-1}mm^{-1})
光収集効率（相対値）
波　長 (μm)
0
1
2
3
4
0.4
0.6
0.8
1.0
1.2
0.5

Concentrator photovoltaics

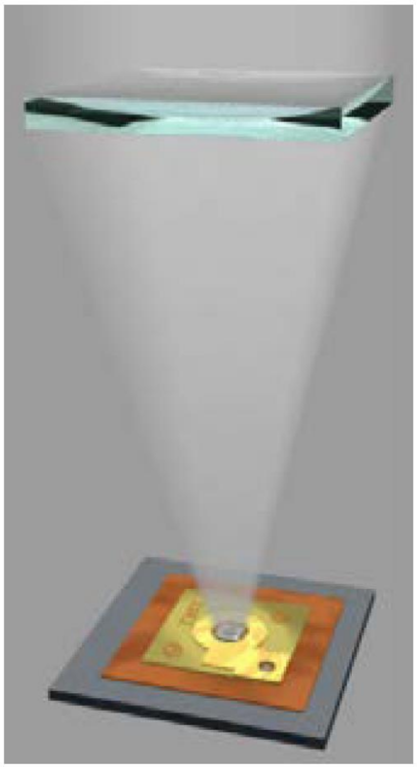
Concentrator Photovoltaic

Figure 1: Left and middle: Example of a CPV system using Fresnel lenses to concentrate the sunlight: FLATCON® concept originally developed at Fraunhofer ISE. Right: Example of a mirror-based system developed by the University of Arizona, USA [7].

Current Status of Concentrator Photovoltaic Technology, Fraunhofer ISE and NREL, 2016

Concentrator Photovoltaic

- Higher Efficiency
- Lower cost

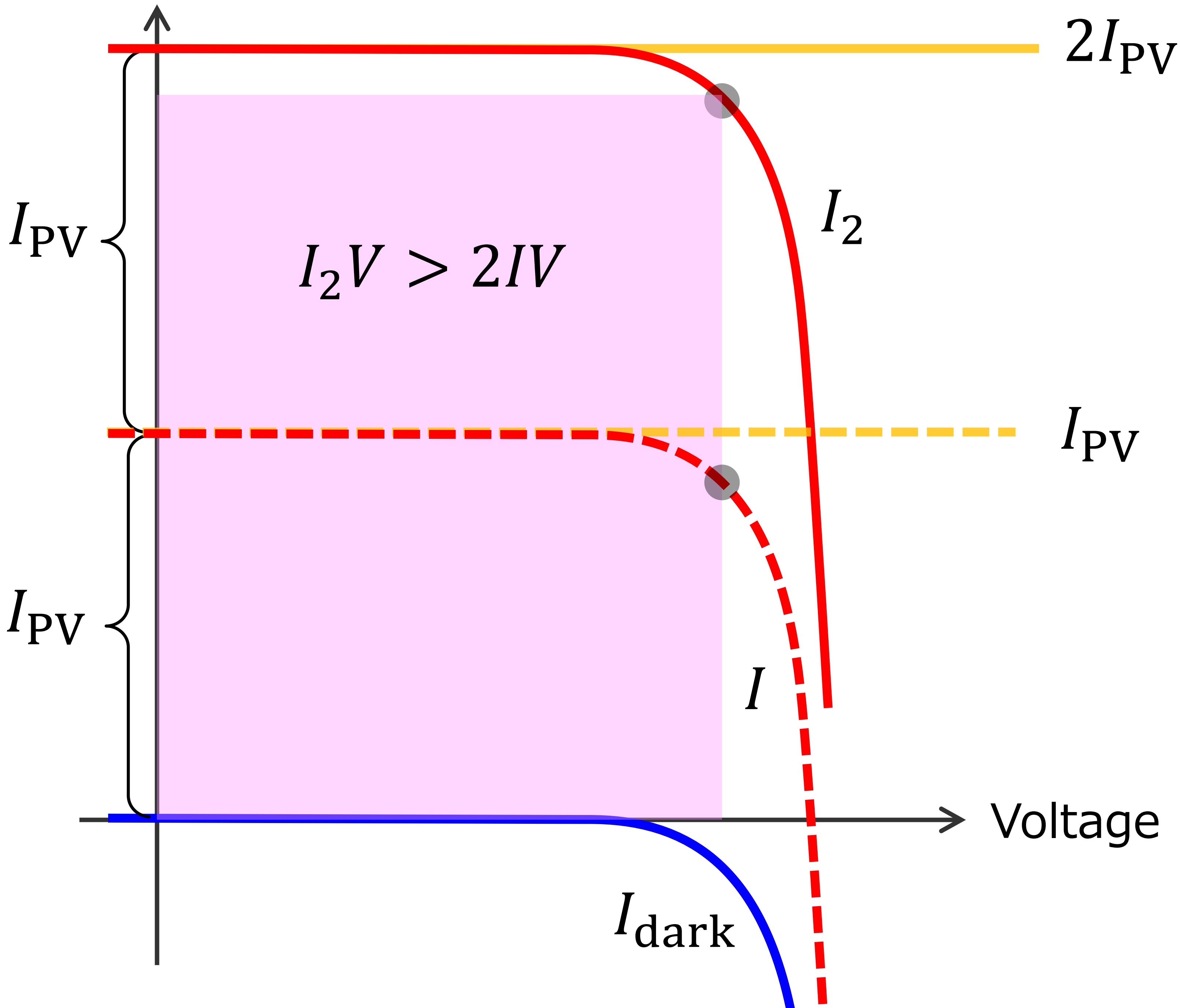


Available photons are the same

Higher irradiation

Smaller semiconductor
(reducing expensive minor metal)

Current Status of Concentrator Photovoltaic Technology, Fraunhofer ISE and NREL, 2016



$2I_{PV}$
I_{PV}
I_2
$I_2V > 2IV$
I_{PV}
I_{PV}
I
Voltage
I_{dark}

Concentrator Photovoltaic

- Higher Efficiency
- Lower cost

- Need sunlight tracking
- No use of diffuse light
- Optical losses

Reflection loss on the semiconductor surface

→ AR coating, texture structure, BSR (Back Surface Reflection)

Surface recombination loss

→ BSF (Back Surface Field) structure

Bulk recombination loss

→ Wide gap window, drift effect

Series resistance loss

→ Optimization of electrode pattern

Other techniques

Reflection loss on the semiconductor surface

- AR coating
- Surface texturing
- BSR (Back Surface Reflection)

Surface recombination loss

- Passivation
- BSF (Back Surface Field) structure

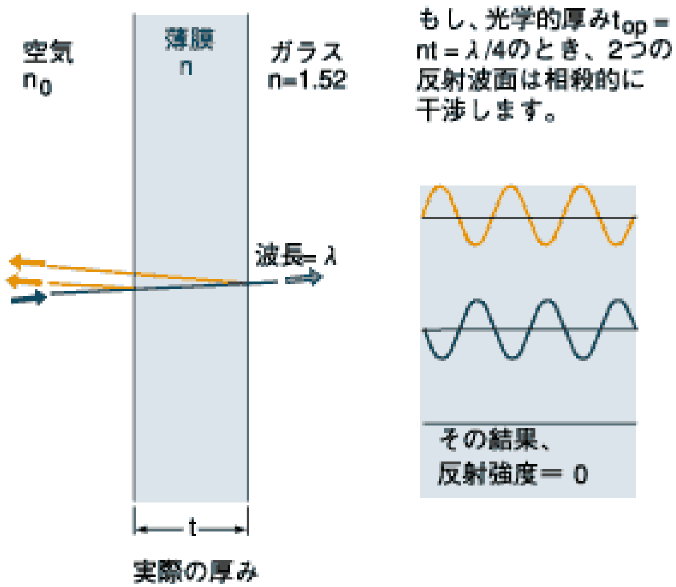
Series resistance loss

- Optimization of electrode pattern

Anti-reflective (AR) coating

optical coating to reduce reflection
commonly-used technique for optical elements

Si refractive index is as high as n_{Si}=3.5～6 (λ=1100～400 nm)
-> high refraction loss of 34%-54%.



Anti-phase interference

Anti-phase condition(coating thickness *d*)

$$d = (2N+1)\lambda/4 \qquad (18)$$

Equi-strength condition for the reflections from the two junction planes

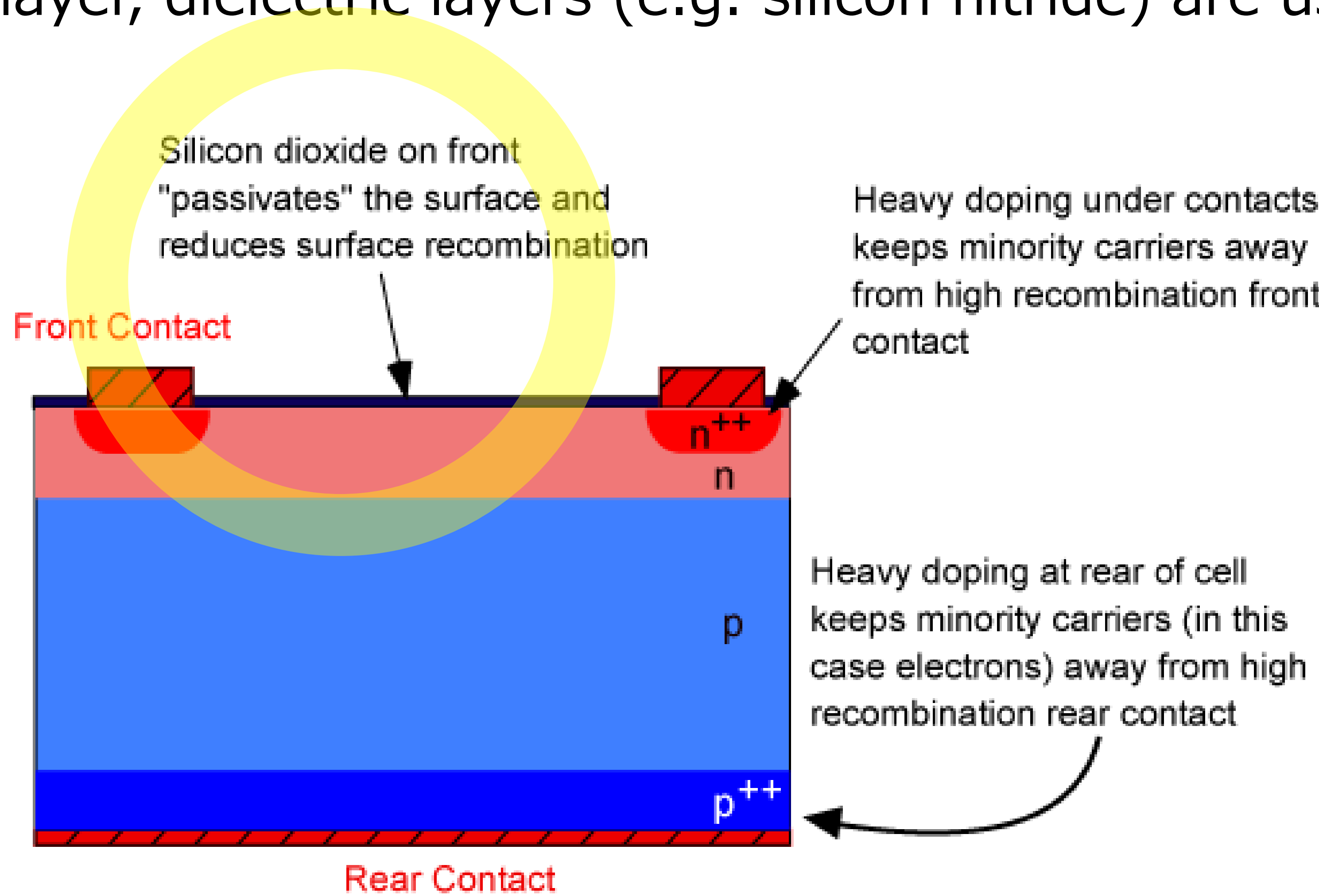
$$\frac{n_0}{n} = \frac{n}{n_{Si}} \qquad (19)$$

n_0=1, then refractive index of coating material should be

$$n = \sqrt{n_{Si}} = \sqrt{3.5-6} = 1.9-2.5 \qquad (20)$$

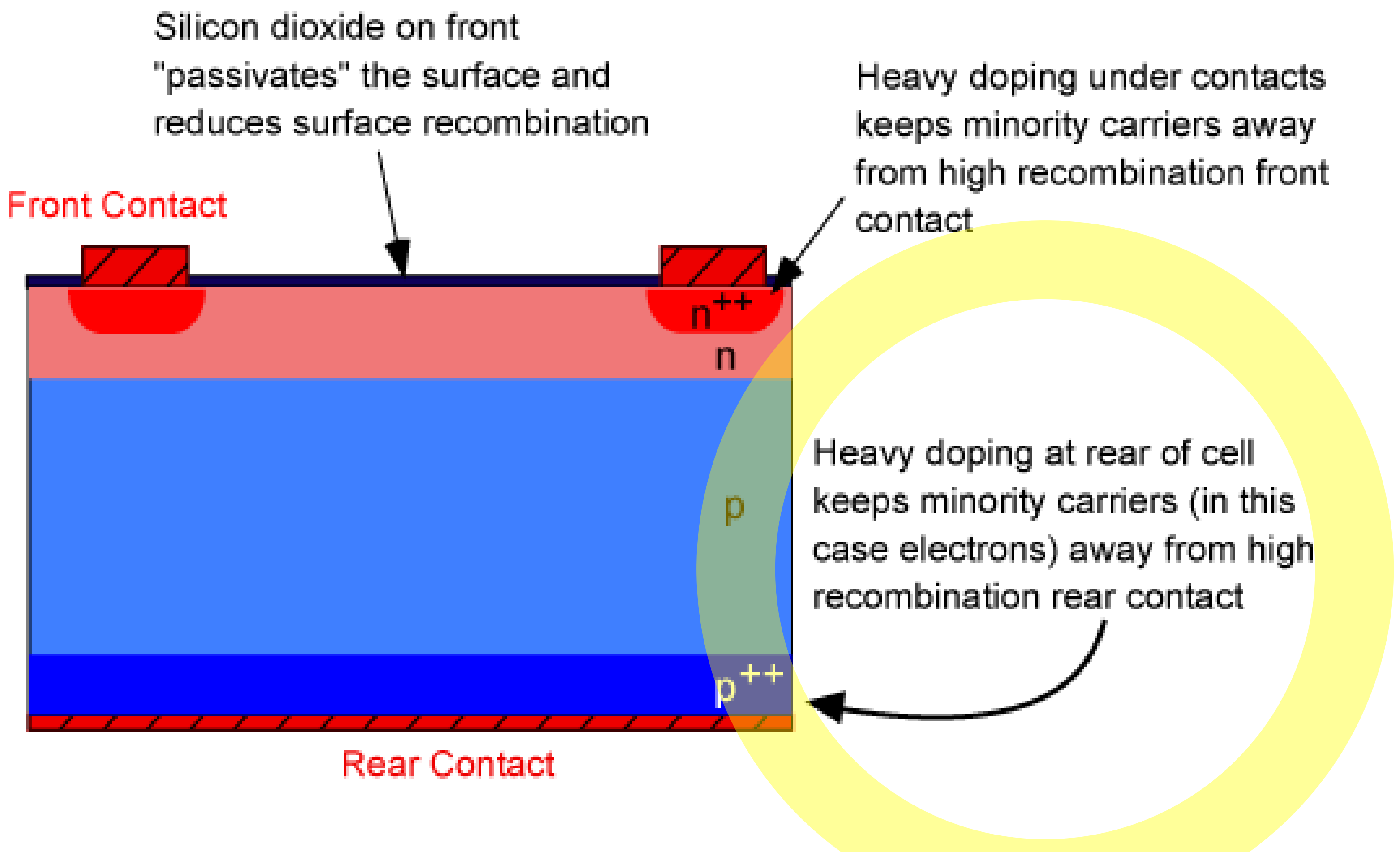
Passivation

to reduce the surface recombination. silicon dioxide layer, dielectric layers (e.g. silicon nitride) are used



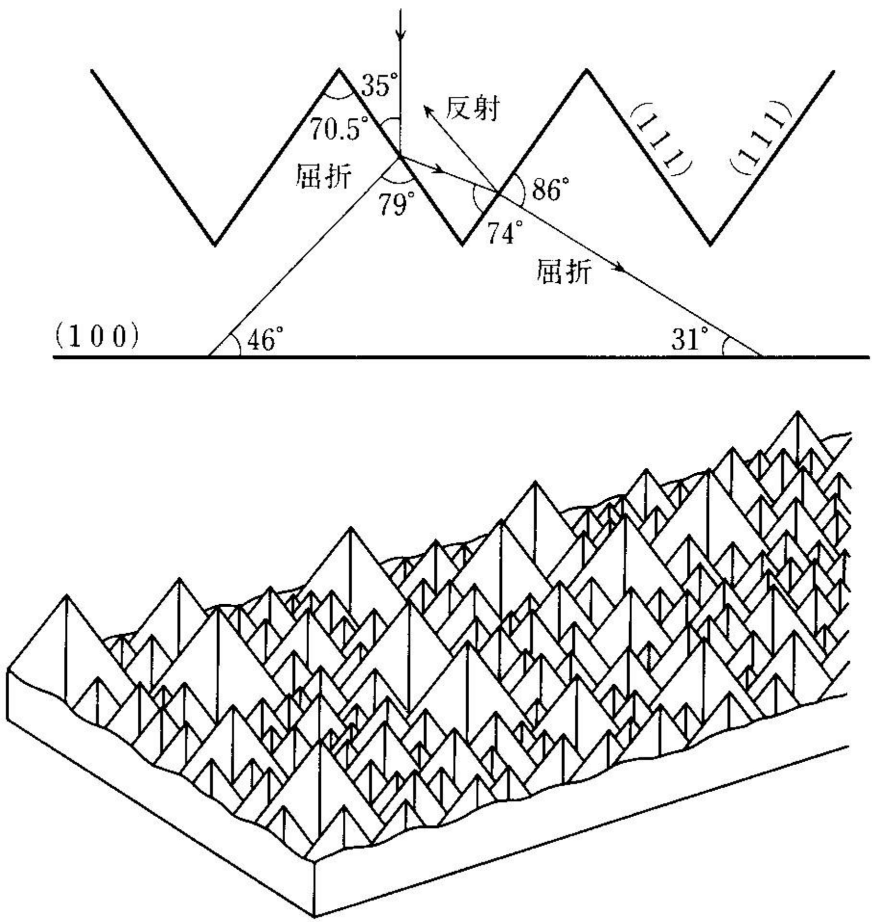
BSF (Back Surface Field) structure

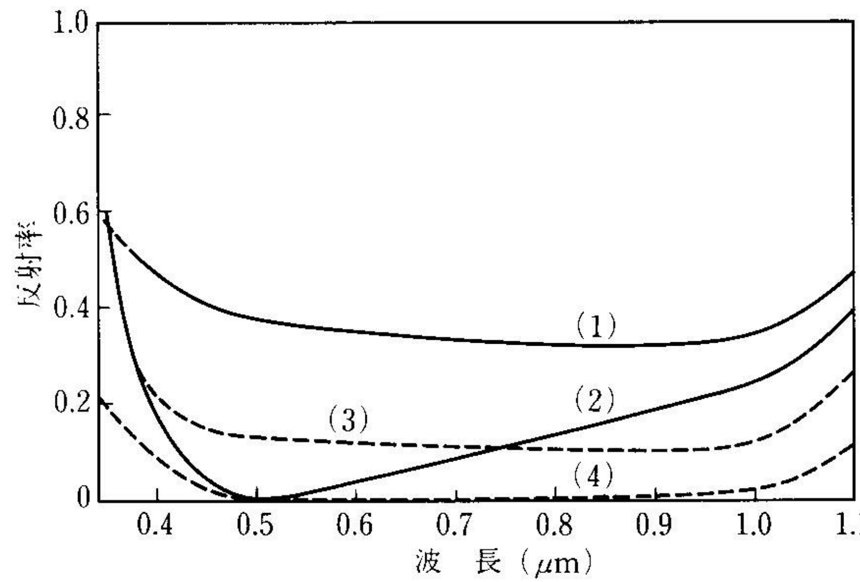
a higher doped region at the rear surface of the solar cell a a barrier to minority carrier flow to the rear surface



Surface Texturing

increasing the chances of reflected light bouncing back in combination with an anti-reflection coating





Reflectivity on a crystalline Si cell

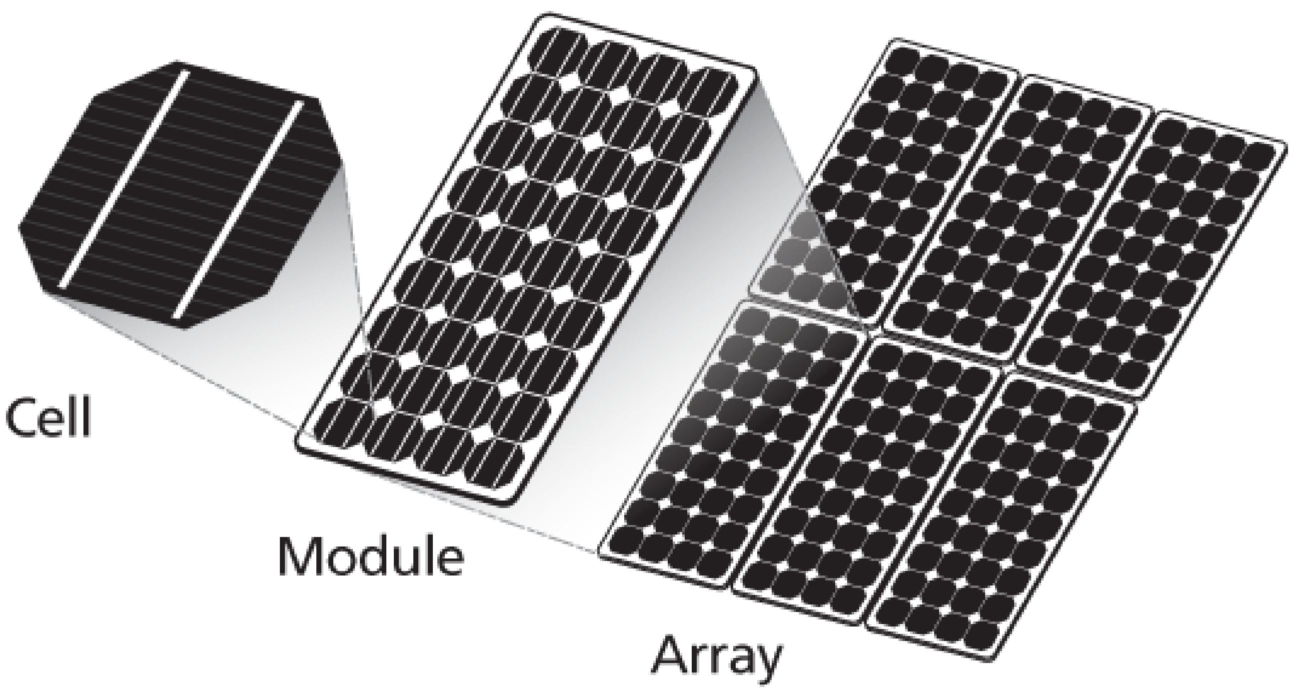
(1)no facing (2)AR coating (3)texture facing (4) AR coating + texture facing

Cell, module, array

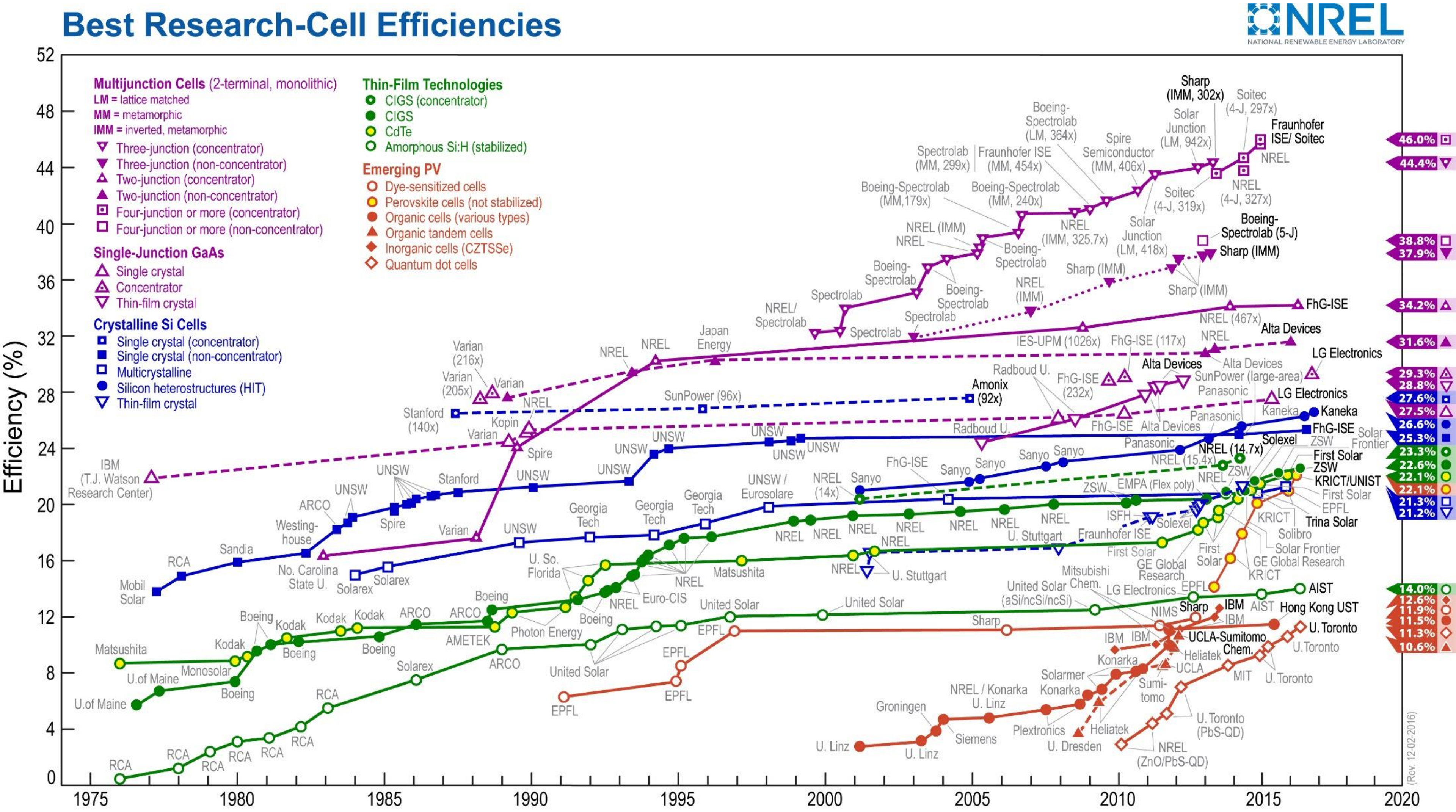
Low photovoltaic voltage (Si: 0.8 V)

PV cells are wired in series and parallel to achieve the desired voltage and current

Optimization of electrode pattern



http://www.nrel.gov/pv/



3. Solar cells of spacecraf

International Space Station

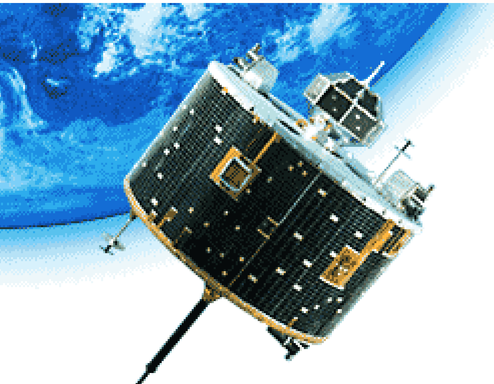
International Space Station

ISS One Blanket properties

No. of Solar Array Wings	8
Area of a SAW	35m x 12m
Cells on a SAW	33,000
Power capacity of a SAW	16 kW
Specific power	32W/kg
Generation voltage	160V
Supply voltage	124V

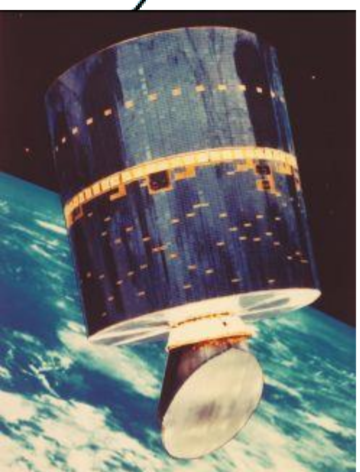
8cm x 8cm Si cell (efficiency 14.2%)
400 cells are connected in series.

Solar Powered Satellites



InP

on Hagoromo
Hiten & Hagoromo （ISAS,1980）



GaAs

The world first GaAs cell on a practical satellite
Sakura（CS-3, NASDA, 1988）

GaAs

Radiation tests on GTO
Tsubasa (MDS-1,2002-2005, NASDA)

Deep space 1 (DS1)

**The Scarlet Solar Array:
Technology Validation and Flight Results**

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www.aec-able.com

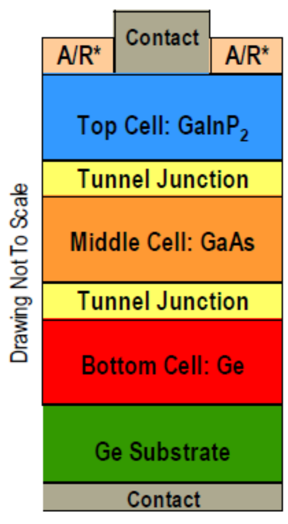
Tel: 805.685.2262

The first electric propulsion
for deep space exploration
(technology demonstrator for DAWN)

SCARLET array for DS1

Concentrator PV

GaInP2/GaAs/Ge multi-junction
22.6 % by ×7.5 concentration
Made by TECSTAR



*A/R: Anti-Reflective Coating

The information contained on this sheet is for reference only. Specifications subject to change without notice.
Revised 5/20/2010

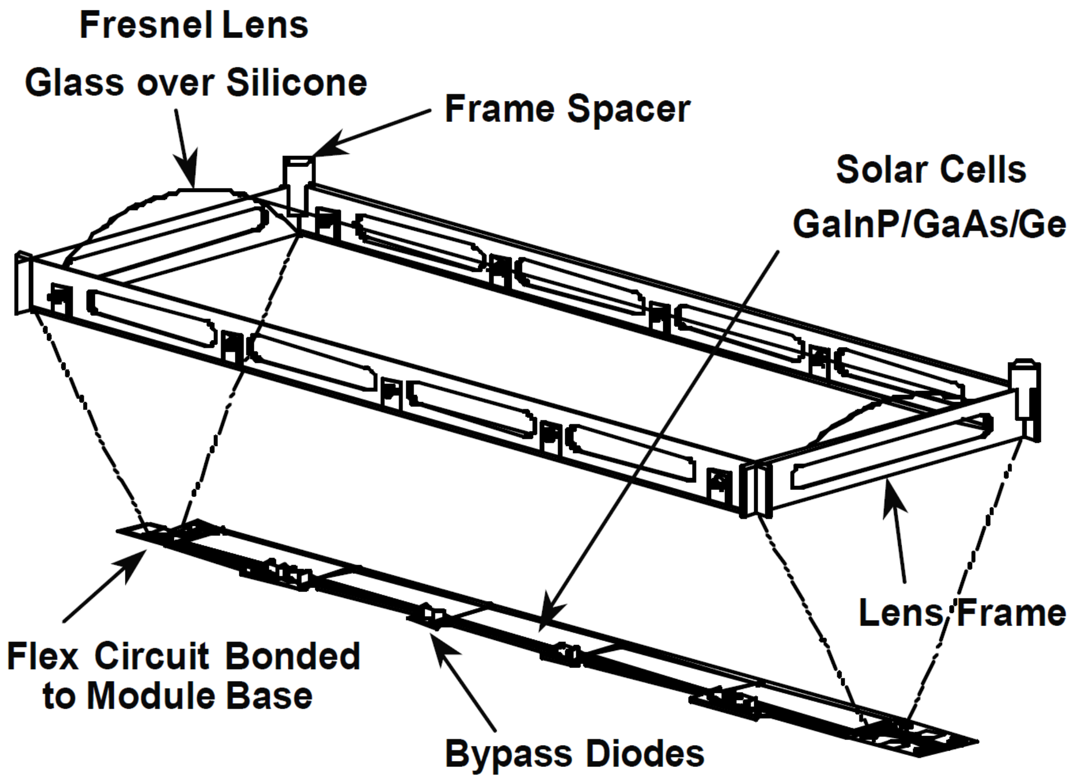
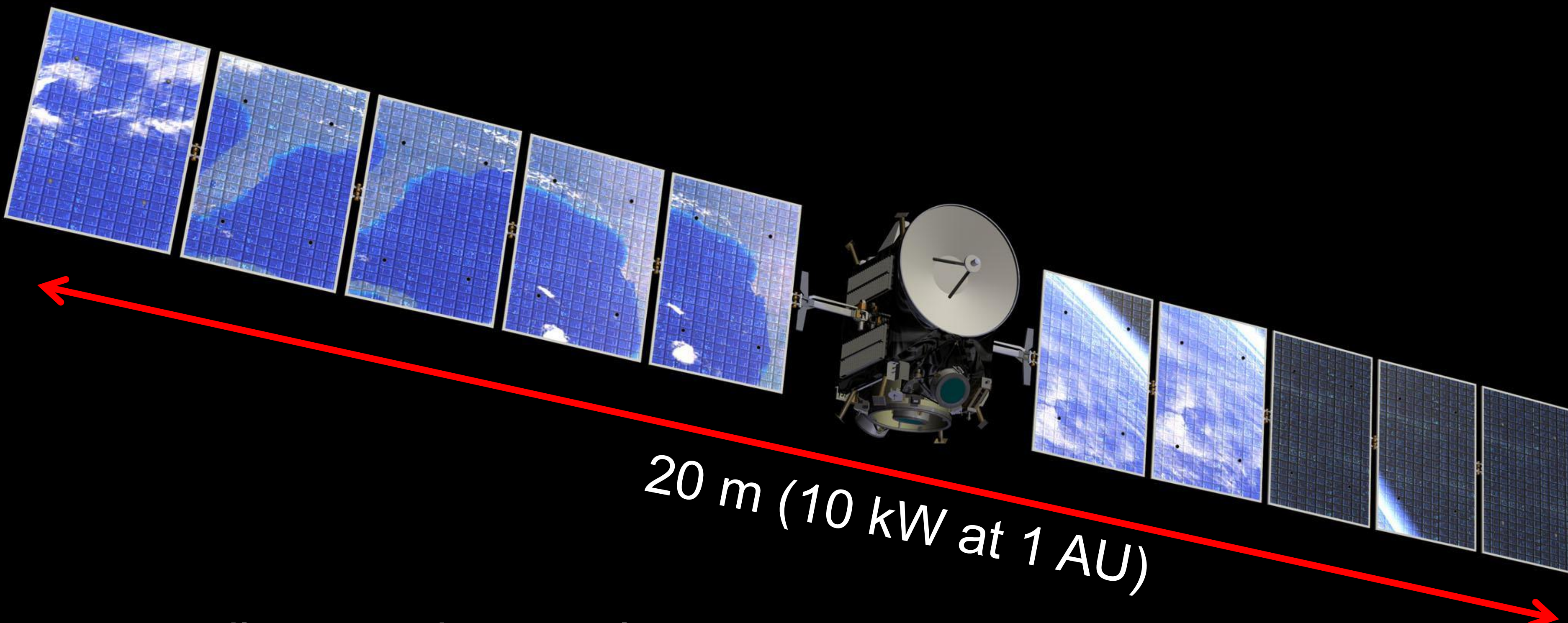


Figure 4. ***Scarlet*** **Module: Lens and Receiver**

HAYABUSA-1

GaInP2/GaAs/Ge Multi-Junction
Efficiency 26.0%
Made by EMCORE（former TECSTAR, USA)

DAWN (ドーン) by NASA JPL



InGaP/InGaAs/Ge multi-junction
Efficiency > 27.6 %
Made by Airbus (Dutch Space)
10 kW by 36.4 m^2

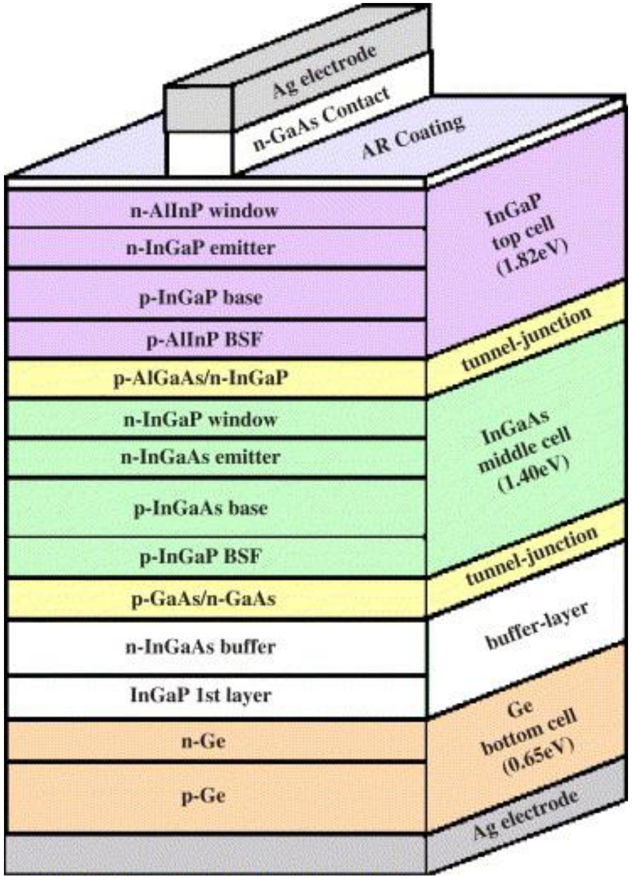


Fig. 1. Schematic of an InGaP/InGaAs/Ge triple-junction solar cell.

Kensuke Nishioka, Tatsuya Takamoto, Takaaki Agui, Minoru Kaneiwa, Yukiharu Uraoka, Takashi Fuyuki

Evaluation of InGaP/InGaAs/Ge triple-junction solar cell and optimization of solar cell's structure focusing on series resistance for high-efficiency concentrator photovoltaic systems

Solar Energy Materials and Solar Cells, Volume 90, Issue 9, 2006, 1308–1321

http://dx.doi.org/10.1016/j.solmat.2005.08.003

Thank you