Electronic Materials and Devices

5 Semiconductor

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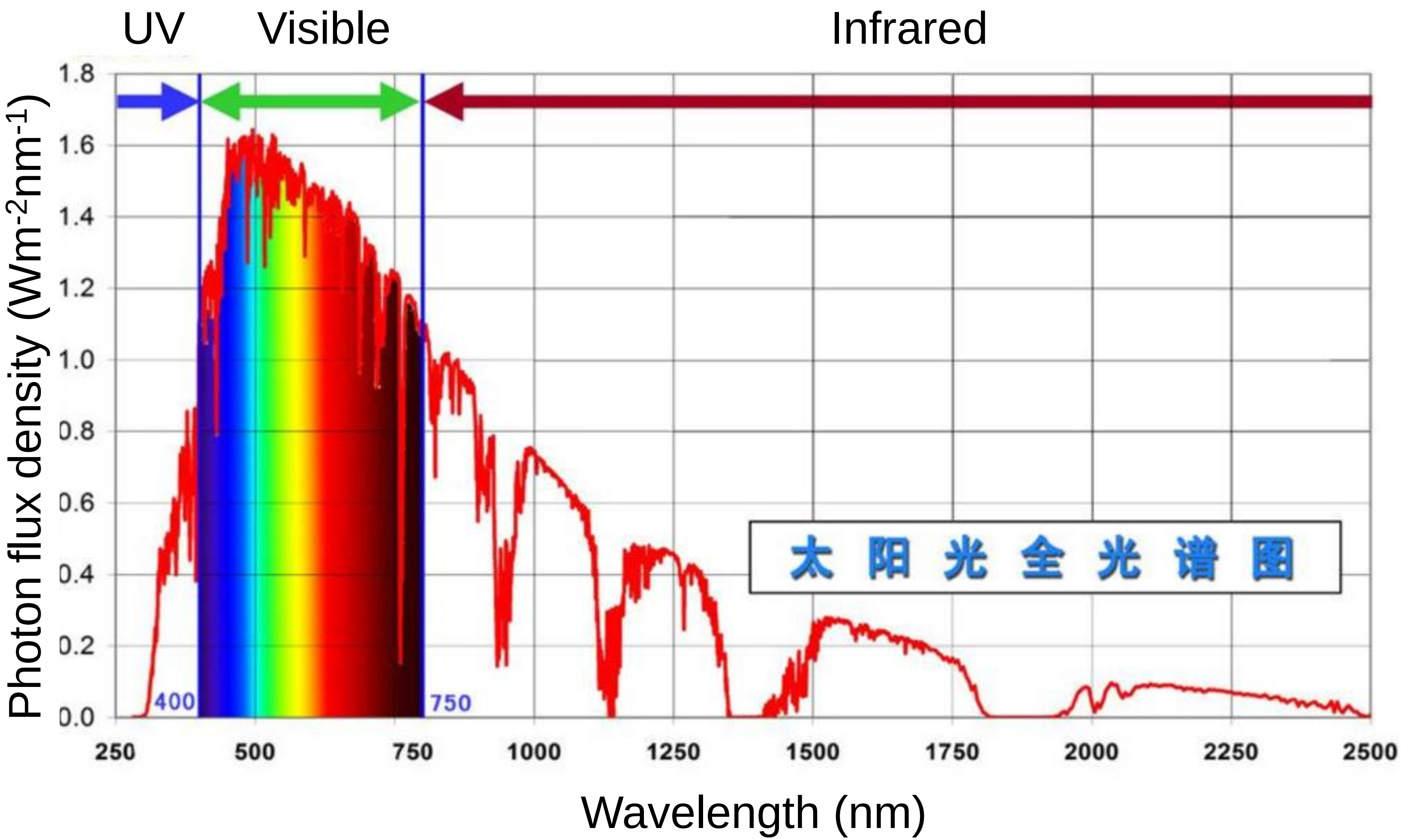
5.7 Solar cells

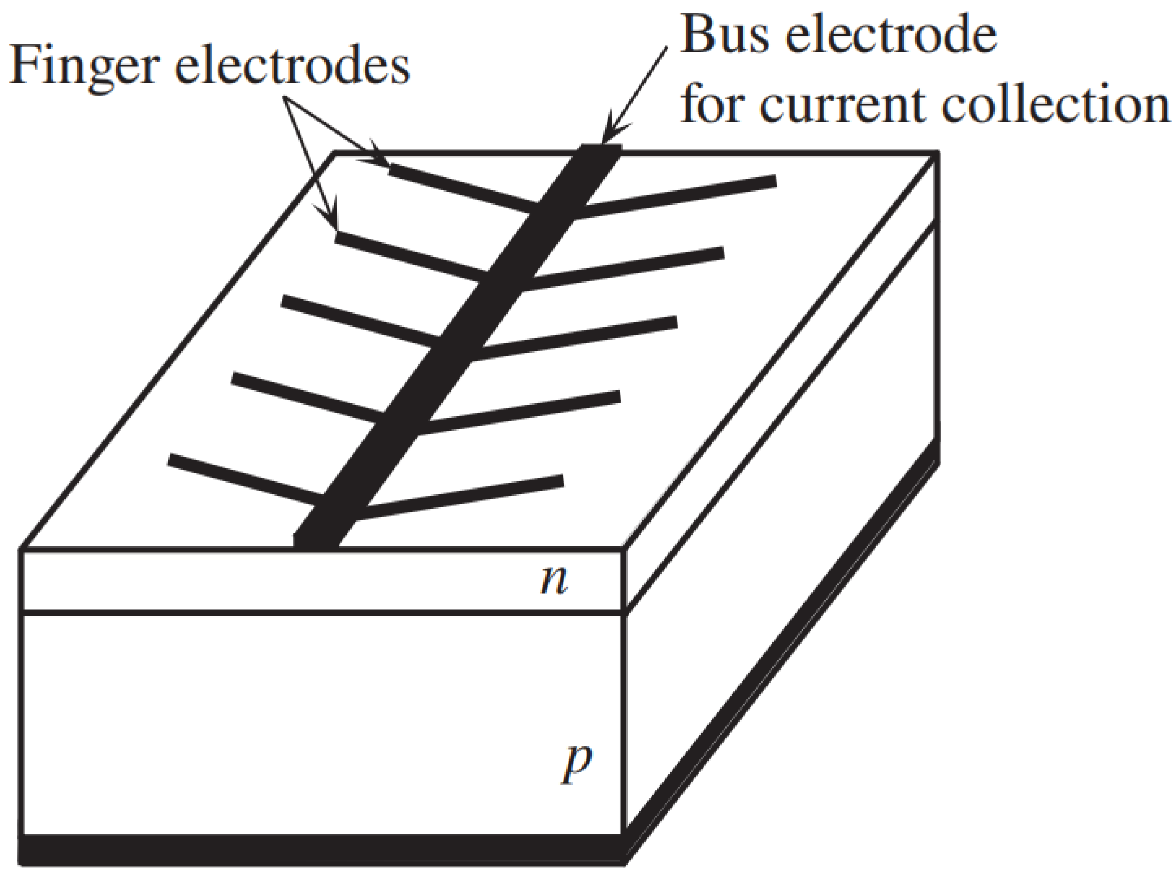
Green technology

Solar spectrum

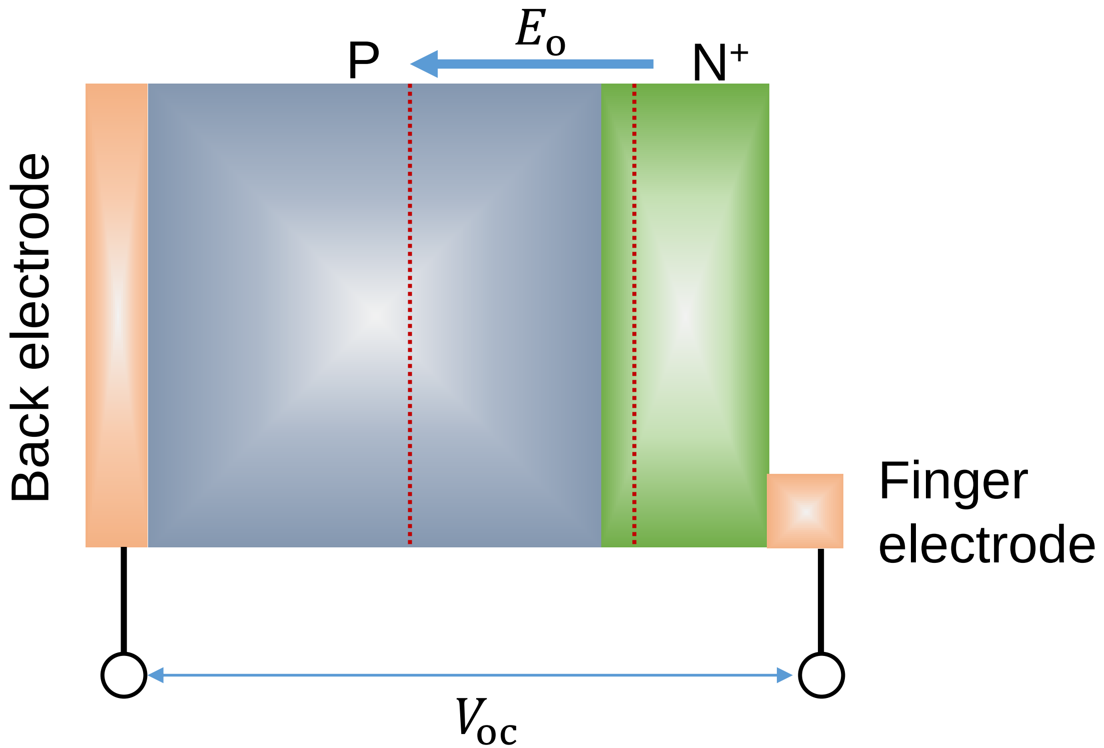


Bandgap for Silicon: 1.1 eV

Photovoltaic device principles

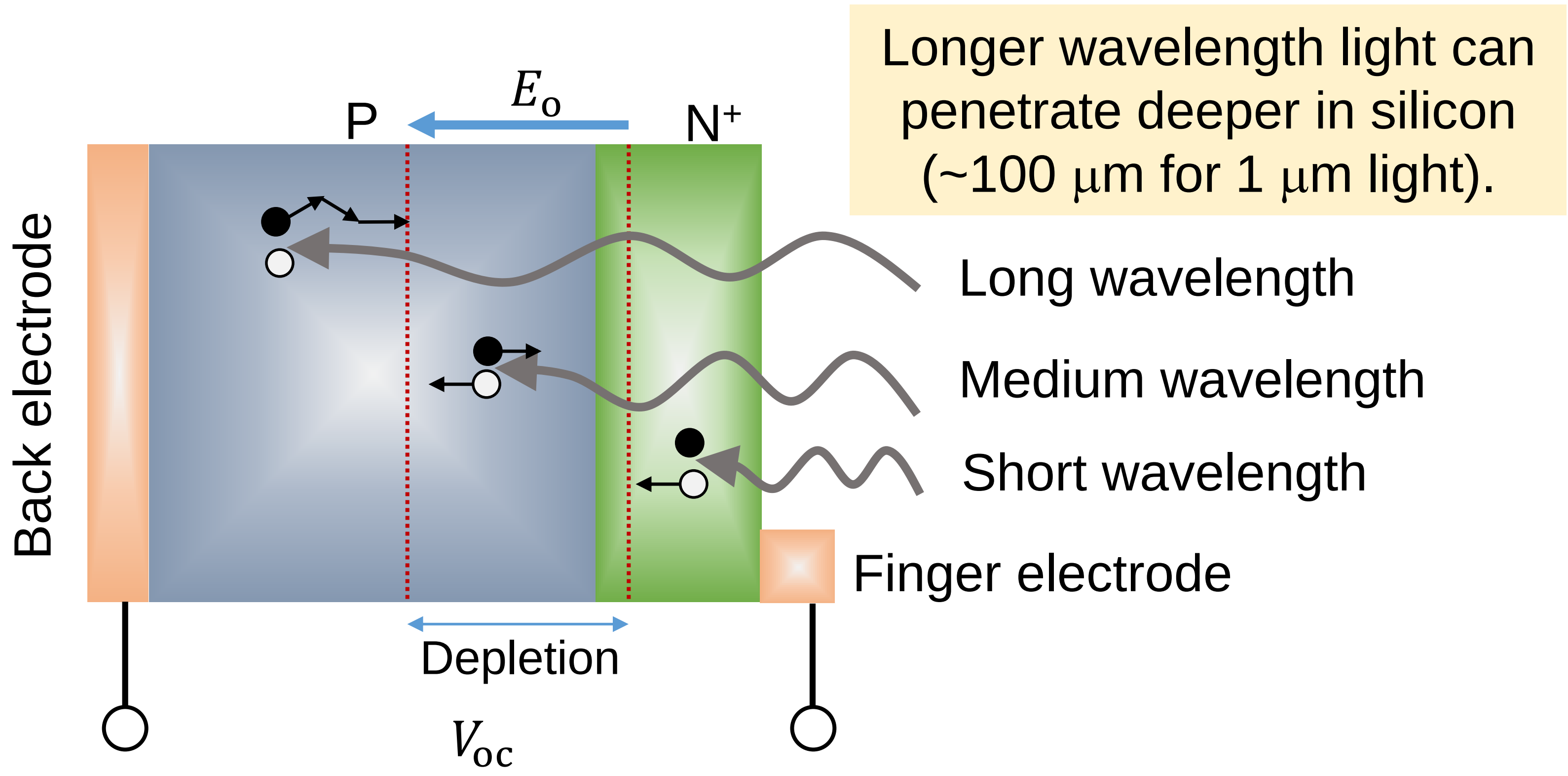


No incident light

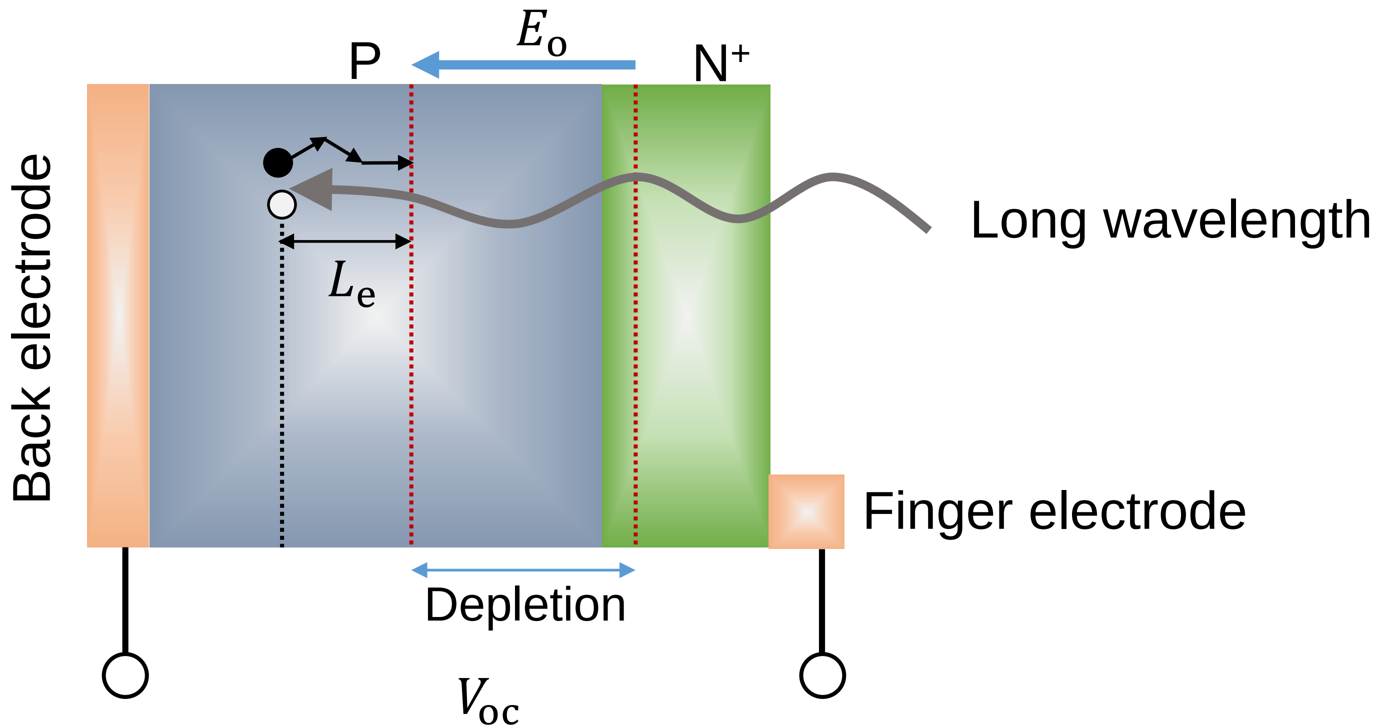


Open circuit voltage: $V_{oc} = 0V$

With incident light



In P-region

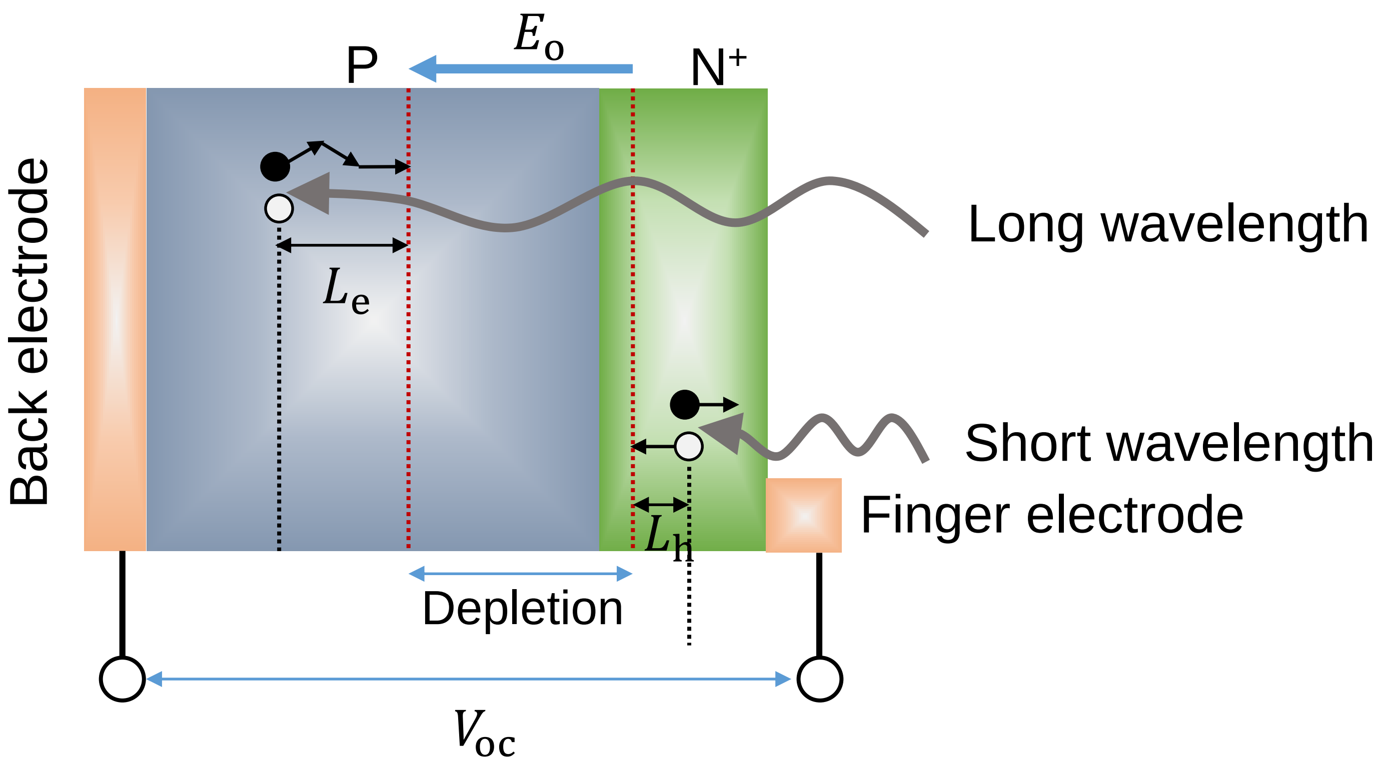


Electron recombination lifetime: τ_e

Electron mean diffusion length: $L_e = \sqrt{D_e \tau_e}$

Electrons generated within L_e can diffusive to depletion region and contribute to the current.

In N⁺-region

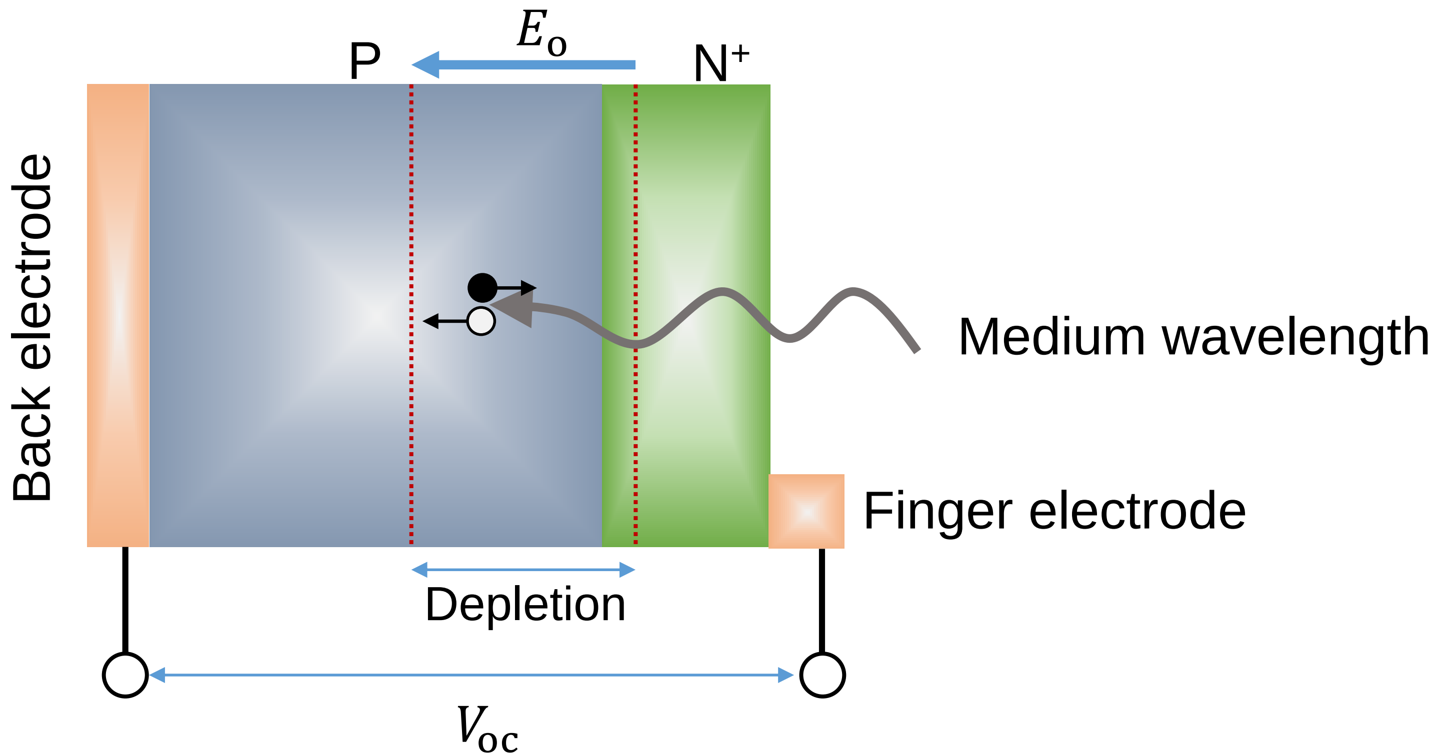


Hole recombination lifetime in N⁺ region: τ_h

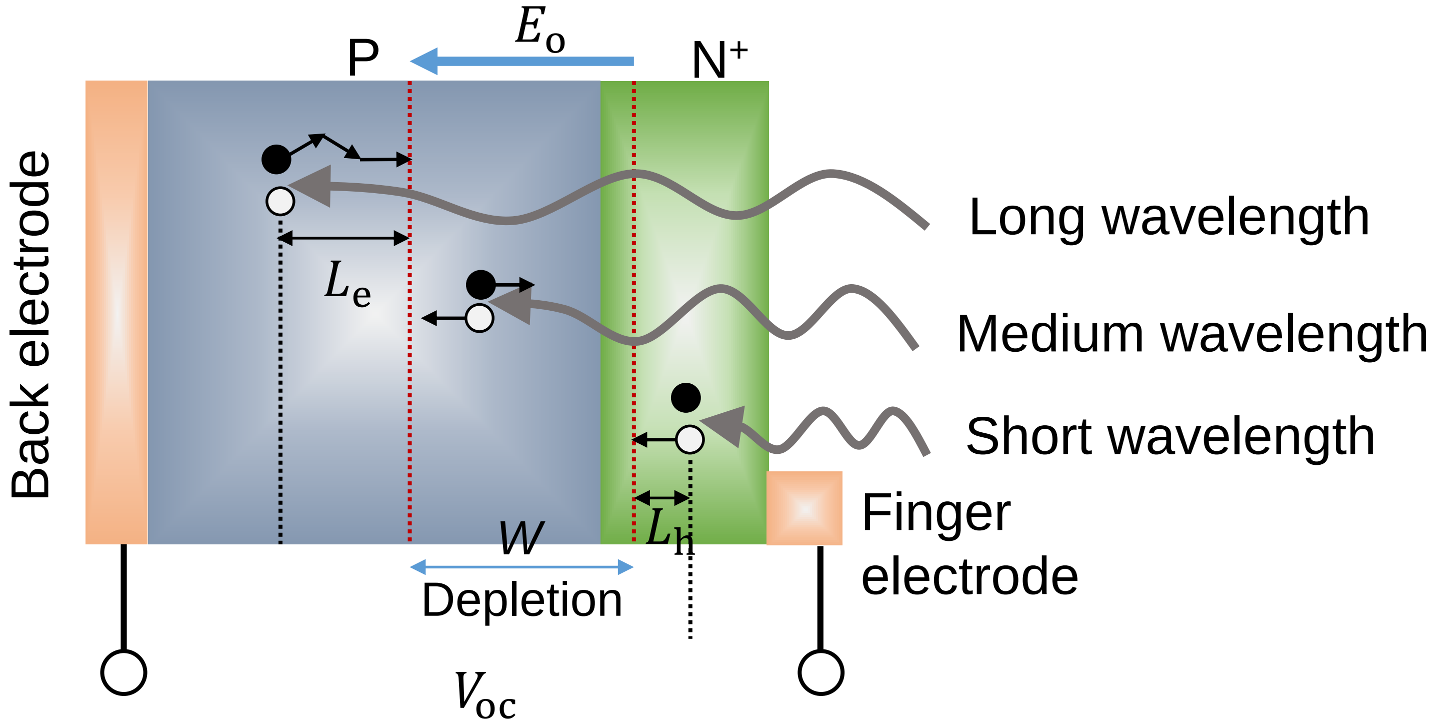
Hole mean diffusion length in N⁺ region : $L_h = \sqrt{D_h \tau_h}$

In silicon: $L_e \gg L_h$

In depletion region



Electrons and holes are separated and accelerated to N^+ and P region, respectively.

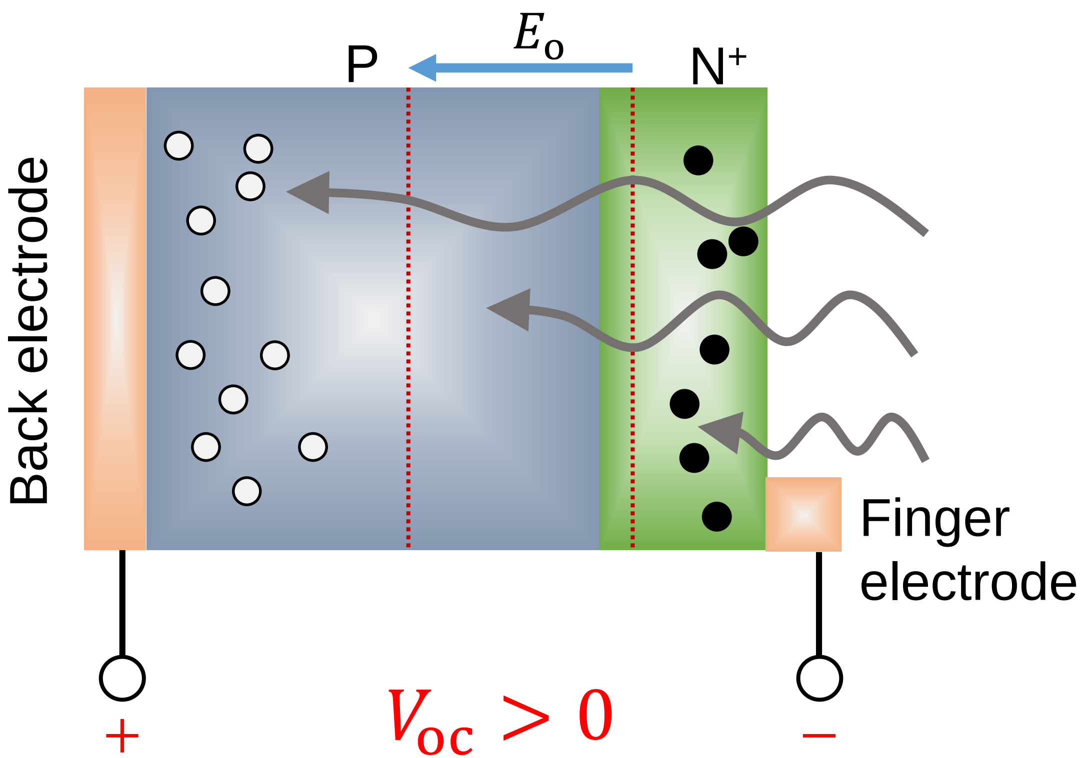


Photovoltaic effect occurs in region $L_e + W + L_h$

For 1-1.2μm infrared light, absorption depth in silicon is ~100 μm

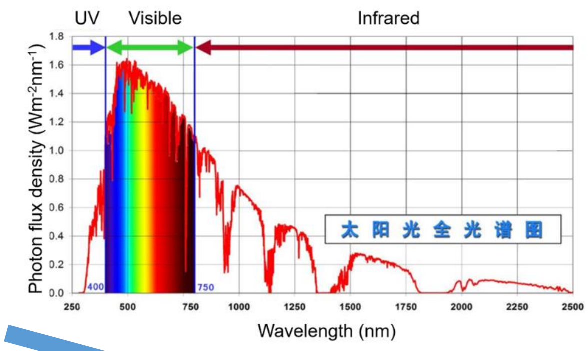
Thick P-region: 200-500 μm

Thin N^+-region: 0.2 μm



Electrons and holes will accumulated in N+ and P region, respectively, resulting in an open circuit voltage V_{OC}.

Silicon solar cell efficiency



Ideal efficiency: 100%

Bandgap limitation: <1.1 μm 75%

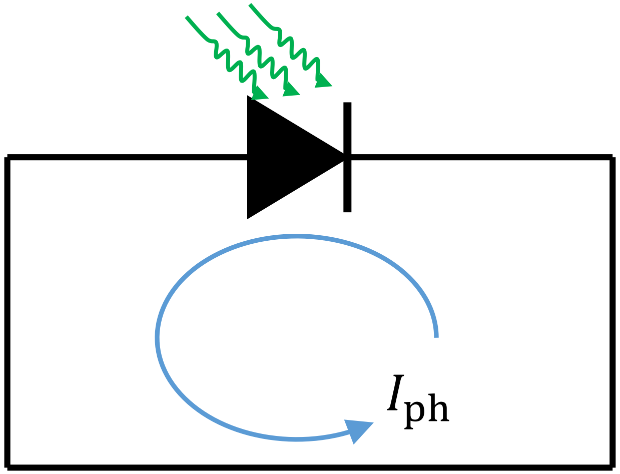
Surface recombination (defects) in N$^+$ region: 45%

Antireflection coating at surface is not perfect: 38%

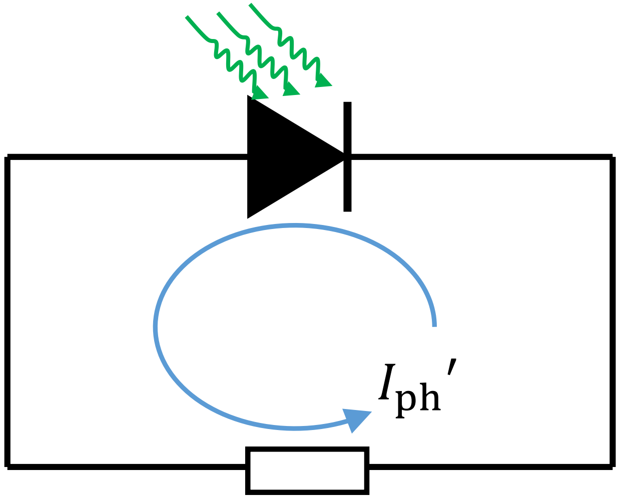
Limitation of load resistor: **25%**

Effect of load resistor

No load resistor: R=0

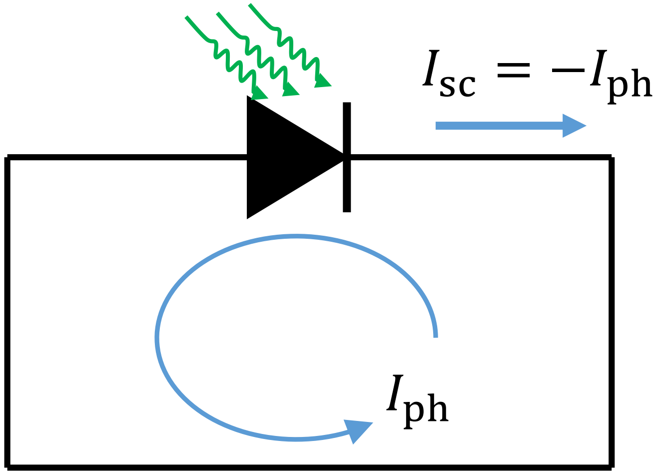


With load resistor: R



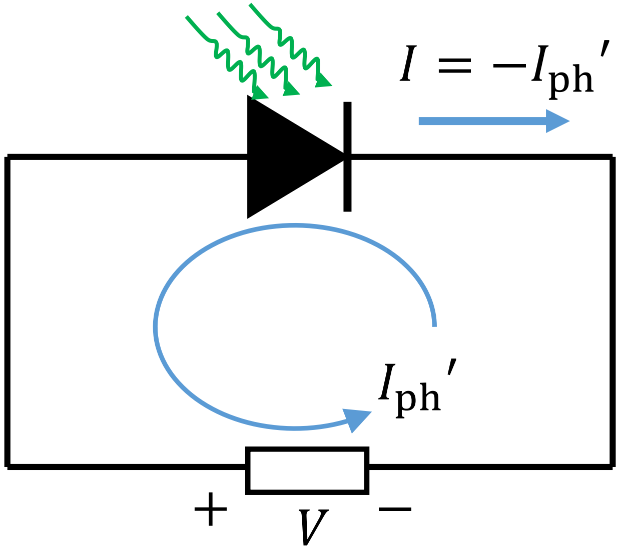
Q: $I_{\mathrm{ph}}' < I_{\mathrm{ph}}$ or $I_{\mathrm{ph}}' = I_{\mathrm{ph}}$ or $I_{\mathrm{ph}}' > I_{\mathrm{ph}}$?

No load resistor: R=0



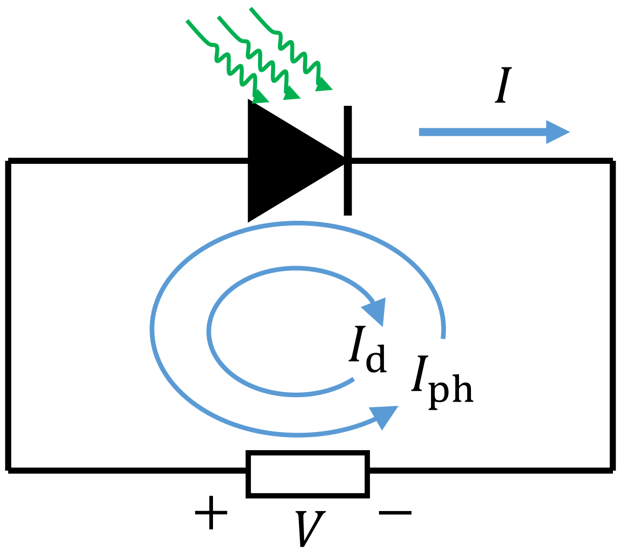
Voltage on diode is 0

With load resistor: R



Voltage on diode >0

With load resistor: R



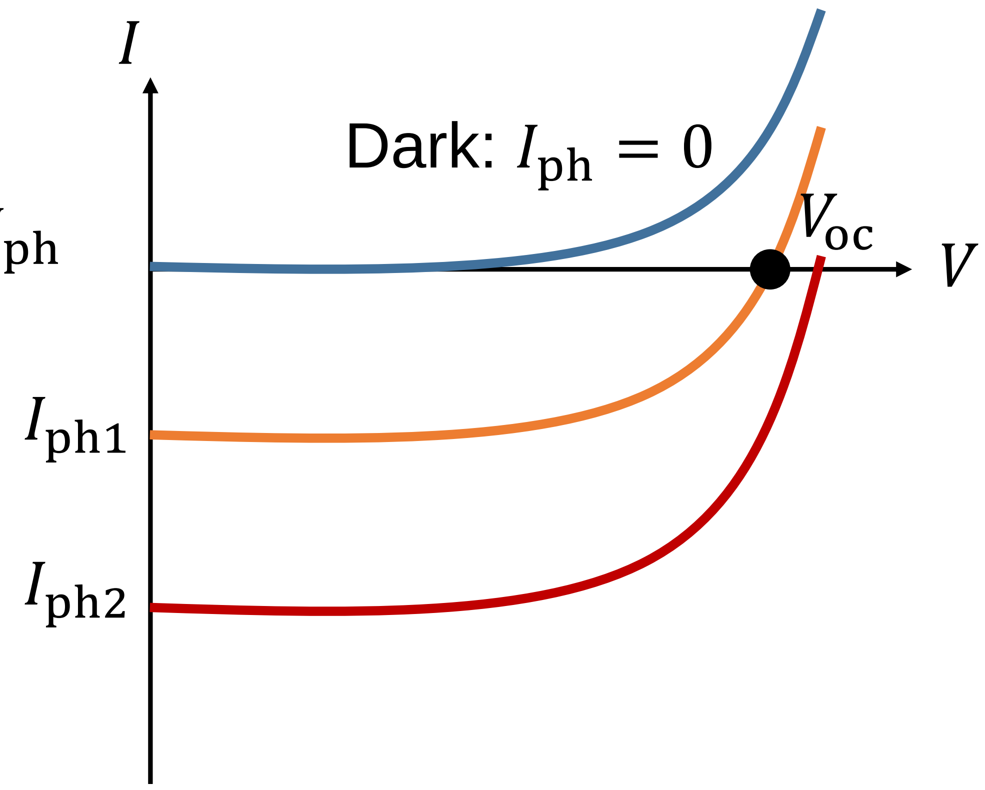
$$I = I_{\rm d} - I_{\rm ph}$$

$$I_{\rm d} = I_{\rm o}\left[\exp\left(\frac{eV}{\eta kT}\right) - 1\right]$$

$$\begin{cases} I = I_{\rm o}\left[\exp\left(\frac{eV}{\eta kT}\right) - 1\right] - I_{\rm ph} \\ I = -\frac{V}{R} \end{cases}$$

Use graphic method 图解法
to solve the equations.

$$\begin{cases} I = I_o \left[\exp\left(\dfrac{eV}{\eta kT} \right) - 1 \right] - I_{ph} \\ I = -\dfrac{V}{R} \end{cases}$$

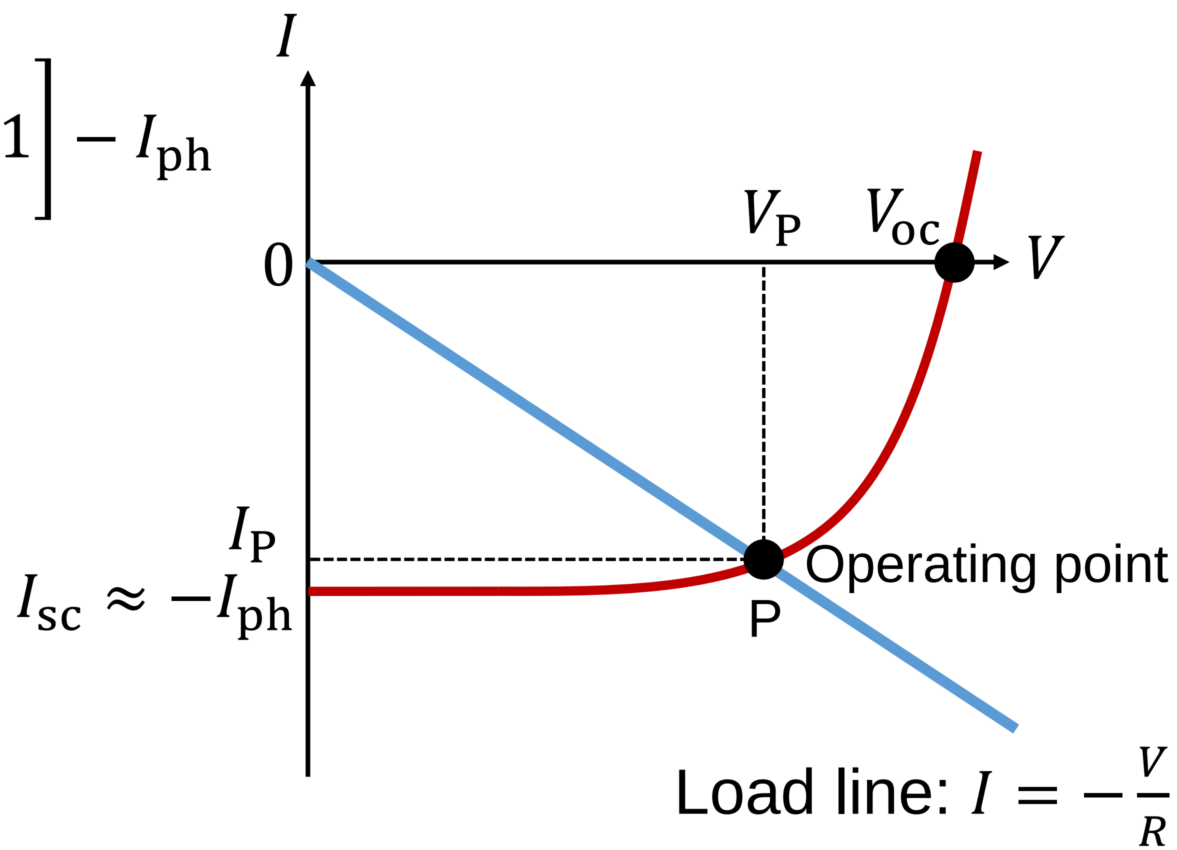


$$\begin{cases} I = I_o\left[\exp\left(\dfrac{eV}{\eta kT}\right) - 1\right] - I_{ph} \\[2ex] I = -\dfrac{V}{R} \end{cases}$$

$$|I_P| < |I_{sc}|$$

$$V_P < V_{oc}$$

Output power: $P = |V_P I_P|$



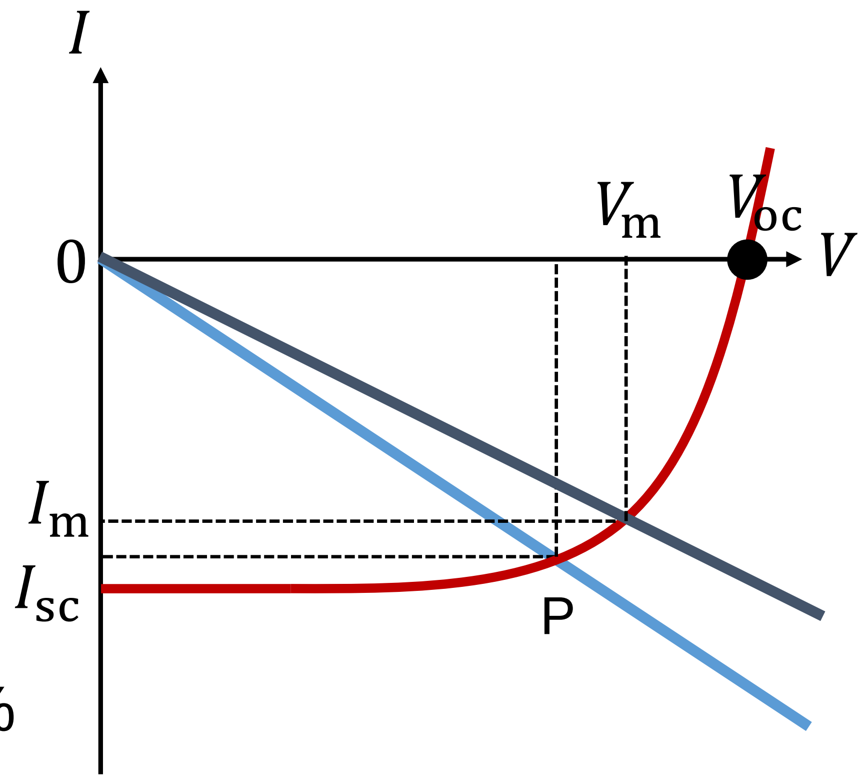
Maximum output power:

$$P = |V_\mathrm{m} I_\mathrm{m}|$$

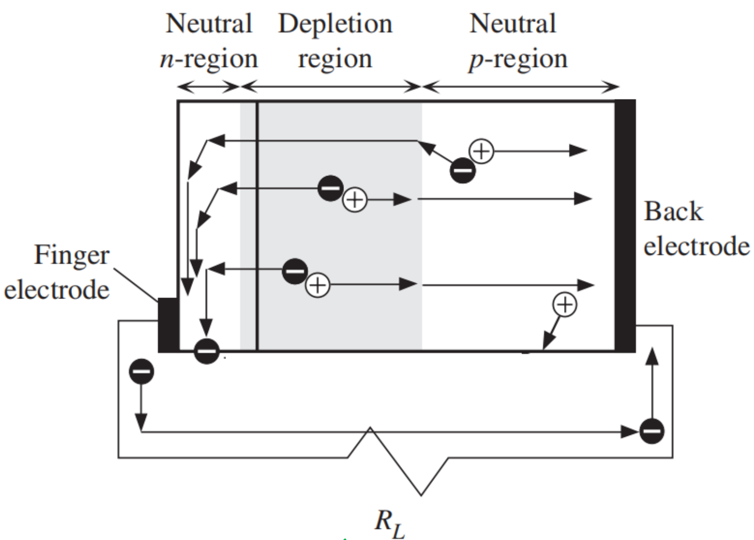
Fill factor:

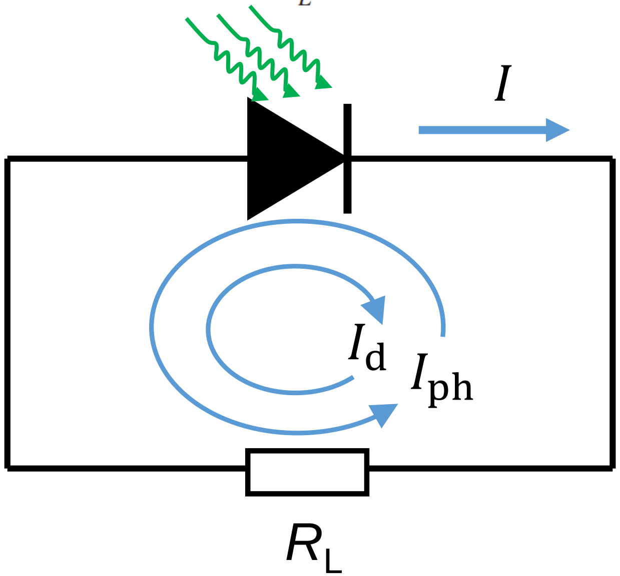
$$F = \frac{V_\mathrm{m} I_\mathrm{m}}{V_\mathrm{oc} I_\mathrm{sc}}$$

Fill factor is typically 70-85% in silicon solar cell.



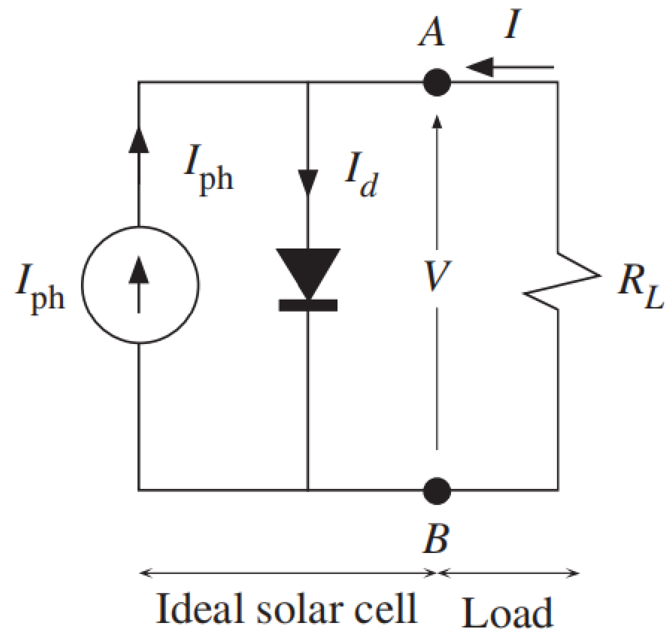
Ideal solar cell circuit model



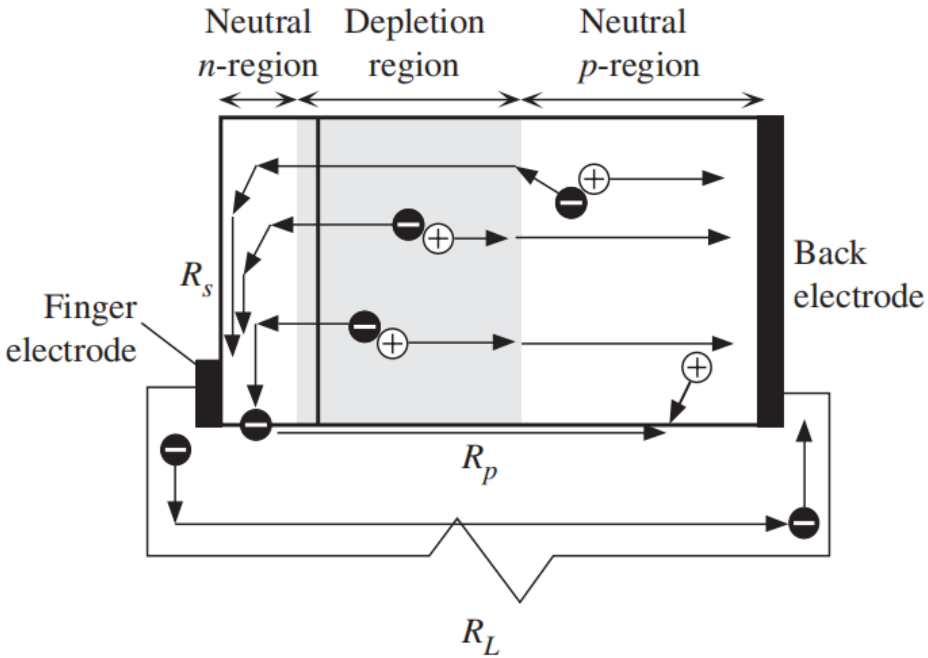


$$I = I_{\mathrm{d}} - I_{\mathrm{ph}}$$

Constant current source



Real solar cell circuit model

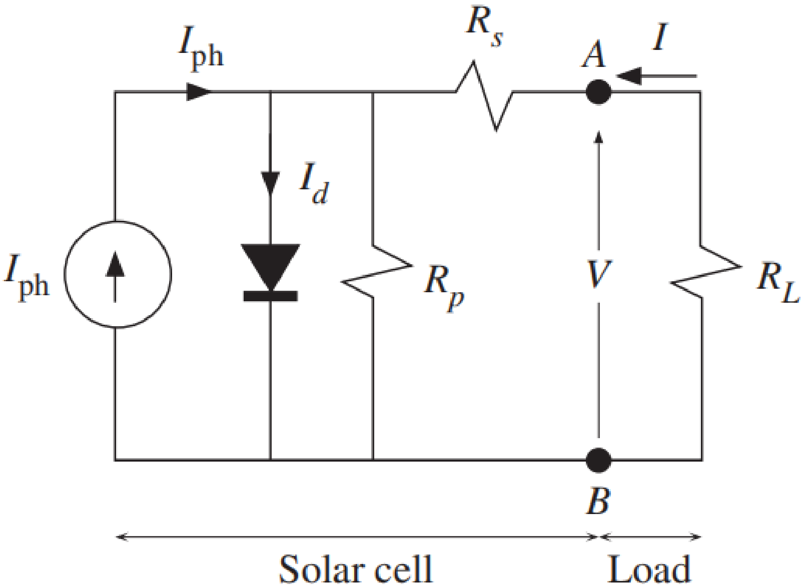


Series resistance R_s:

Resistance of electrode and contact resistance

Parallel resistance R_p:

Current flow through the crystal surface/grain boundary

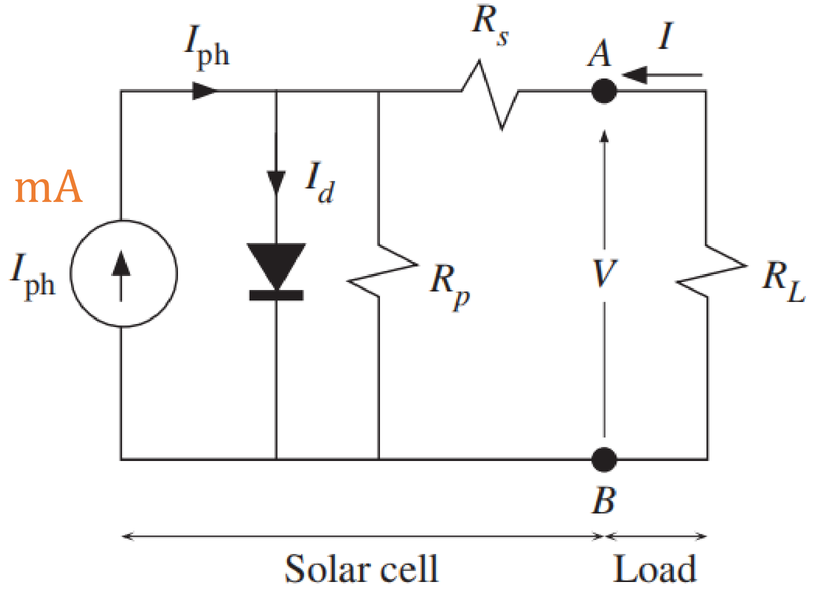


Practice: For a solar cell made from N⁺P diode: reverse current $I_o = 3.2 \times 10^{-6}\text{mA}$, ideality factor $\eta = 1.6$, parallel resistance $R_p \to \infty$. When the diode is under illumination and is short, the photocurrent $-I_{ph}$ is -10 mA, ask:

(1) When R_s=0, 20, and 50 Ω, draw the *IV* curves. (You can use any software, including origin, matlab, …).

(2) When R_s=0, 20, and 50 Ω, the value of *I* and *V* for load resistor 40 Ω (suggest you to use graphic method).

$I_{ph} = 10$ mA



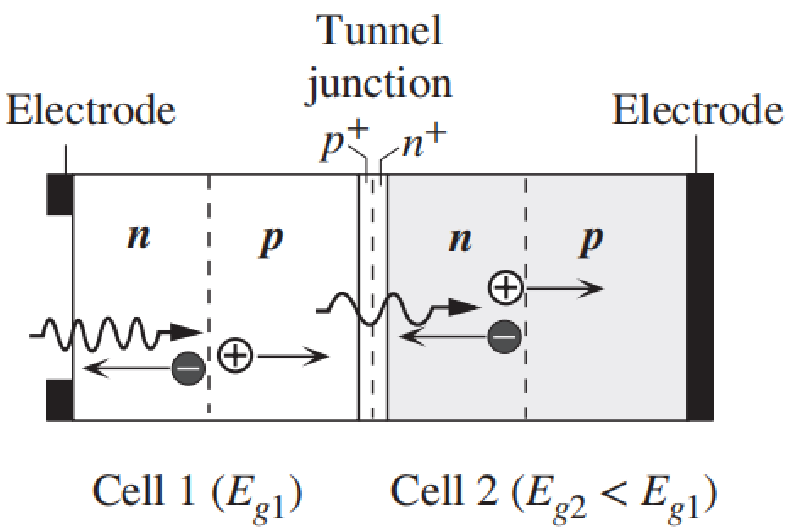
Solar cell materials

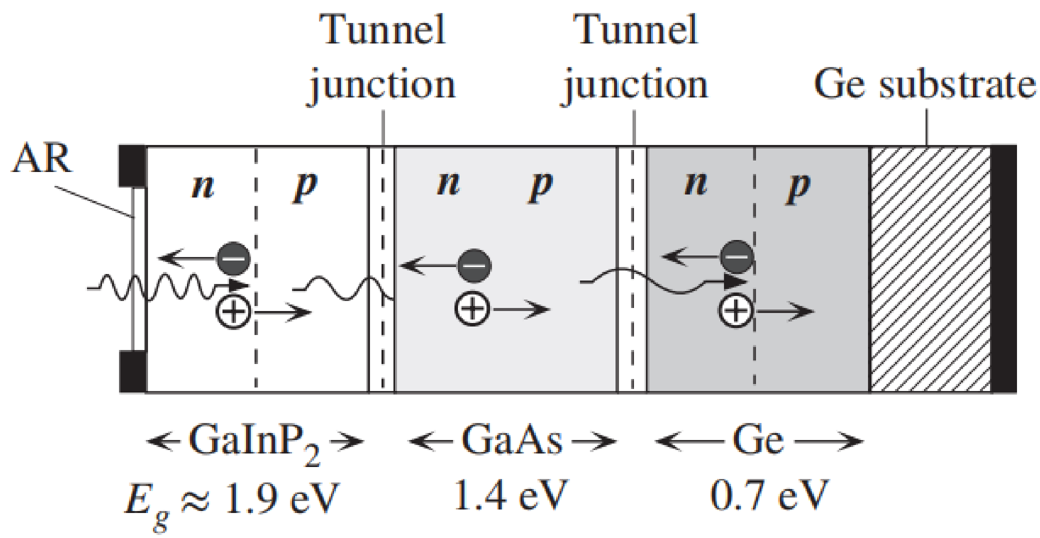
Table 6.5 Room temperature typical photovoltaic parameters for individual cells under AM1.5 illumination 1000 W m^{-2}

Semiconductor	E_g (eV)	V_{oc} (V)	J_{sc} (mA cm^{-2})	FF (%)	η (%)	Comment
Si, single crystal	1.1	0.706	42.7	82.8	25.6	Single crystal, PERL
Si, polycrystalline	1.1	0.663	39.0	80.9	20.4	
Si, c-Si/a-Si:H	1.1/1.7	0.750	41.8	83.2	25.6	Crystalline Si (c-Si)/a-Si:H heterojunction
Amorphous Si (a-Si:H)	1.7	0.896	16.36	69.8	10.2	Thin film
Amorphous Si:Ge:H film					8–13	Amorphous film with tandem structure. Convenient large area fabrication
GaAs, single crystal	1.42	1.030	29.8	86.0	26.4	High fill factor
GaAs, polycrystalline	1.42	0.757	23.2	79.7	18.4	Ge substrate
InP, single crystal	1.34	0.878	29.5	85.4	22.1	Epitaxial layer
CIGS	1.2–1.4	0.757	35.7	77.6	21.0	CIGS is $Cu(In_{1-x}Ga_x)Se_2$
CdTe, polycrystalline	1.5	0.84	26	75	16–17	Thin film
Perovoskite film		1.074	19.29	75.1	15.6	
Organic films		0.793	19.4	71.4	11.0	
$GaInP_2$/GaAs Tandem	1.9/1.4	2.488	14.22	85.6	30.3	Different bandgap materials in tandem increases absorption efficiency
$GaInP_2$/GaAs/Ge Tandem	1.9/1.4/0.7	2.622	14.37	85.0	32.0	Triple junction

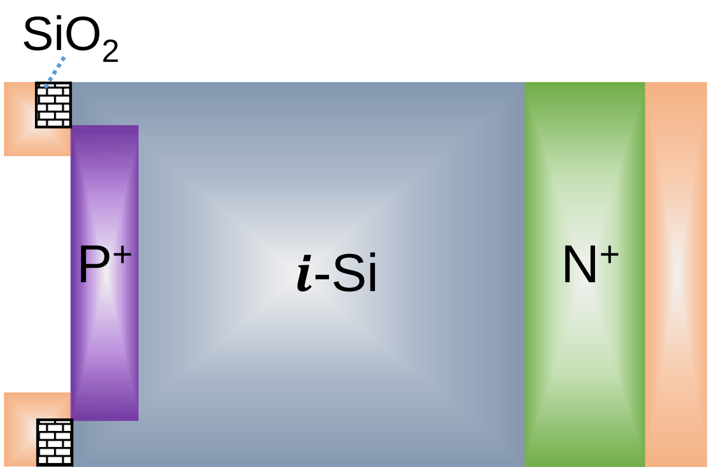
Data: year of 2010

Tandem (multijunction) solar cells 串联太阳能电池组





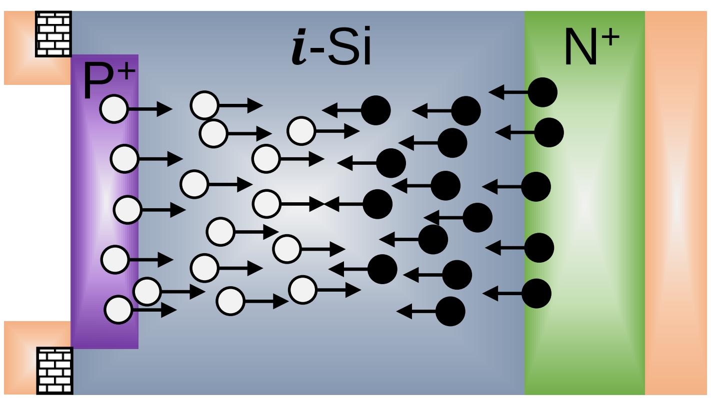
pin diodes, photodiodes, and solar cells



P^+-Si: heavily doped, thin

N^+-Si: heavily doped, thin

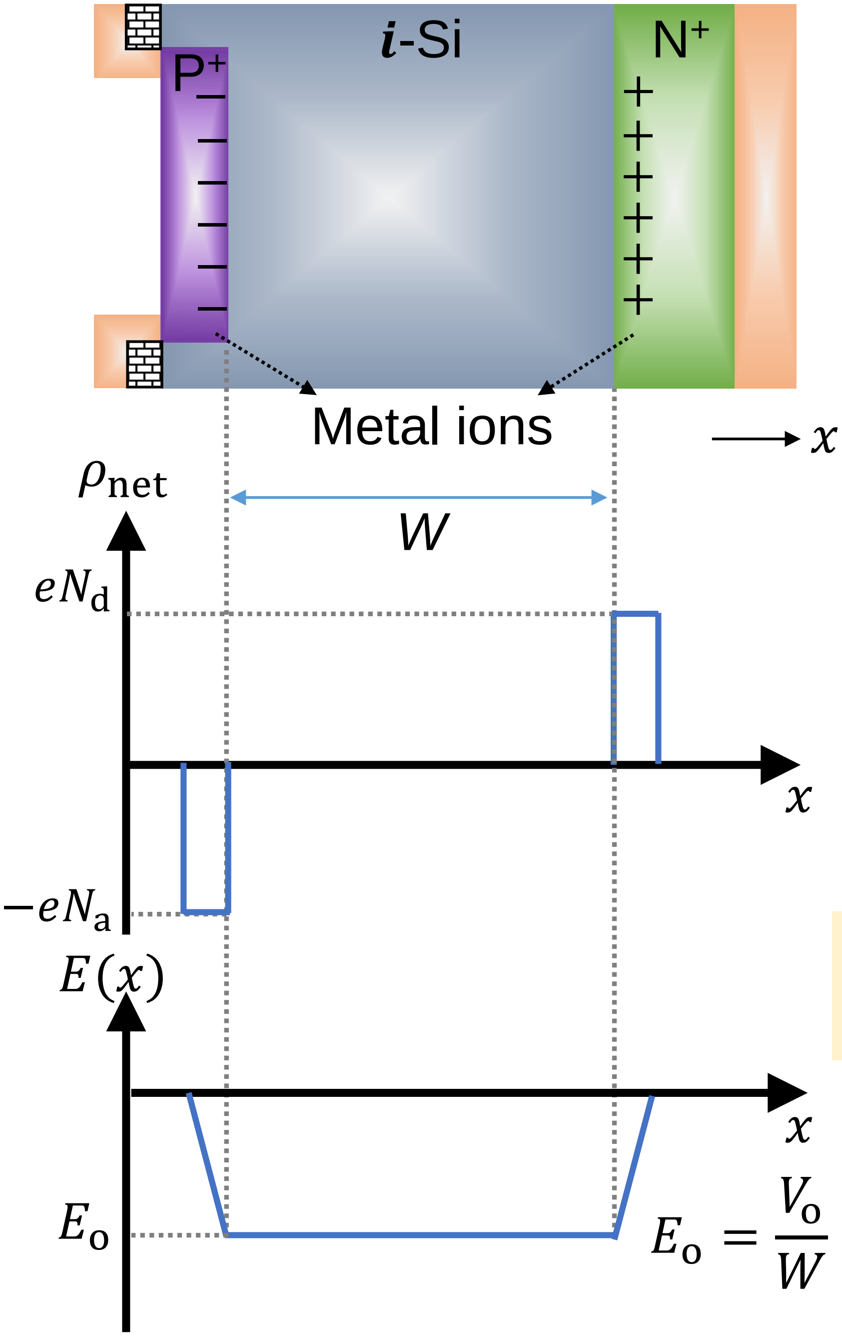
i-Si: intrinsic, thick 5-50 μm



Depletion region is very wide in ***i*** region

Holes diffusive from P^+ to ***i*** region

Electrons diffusive from N^+ to ***i*** region



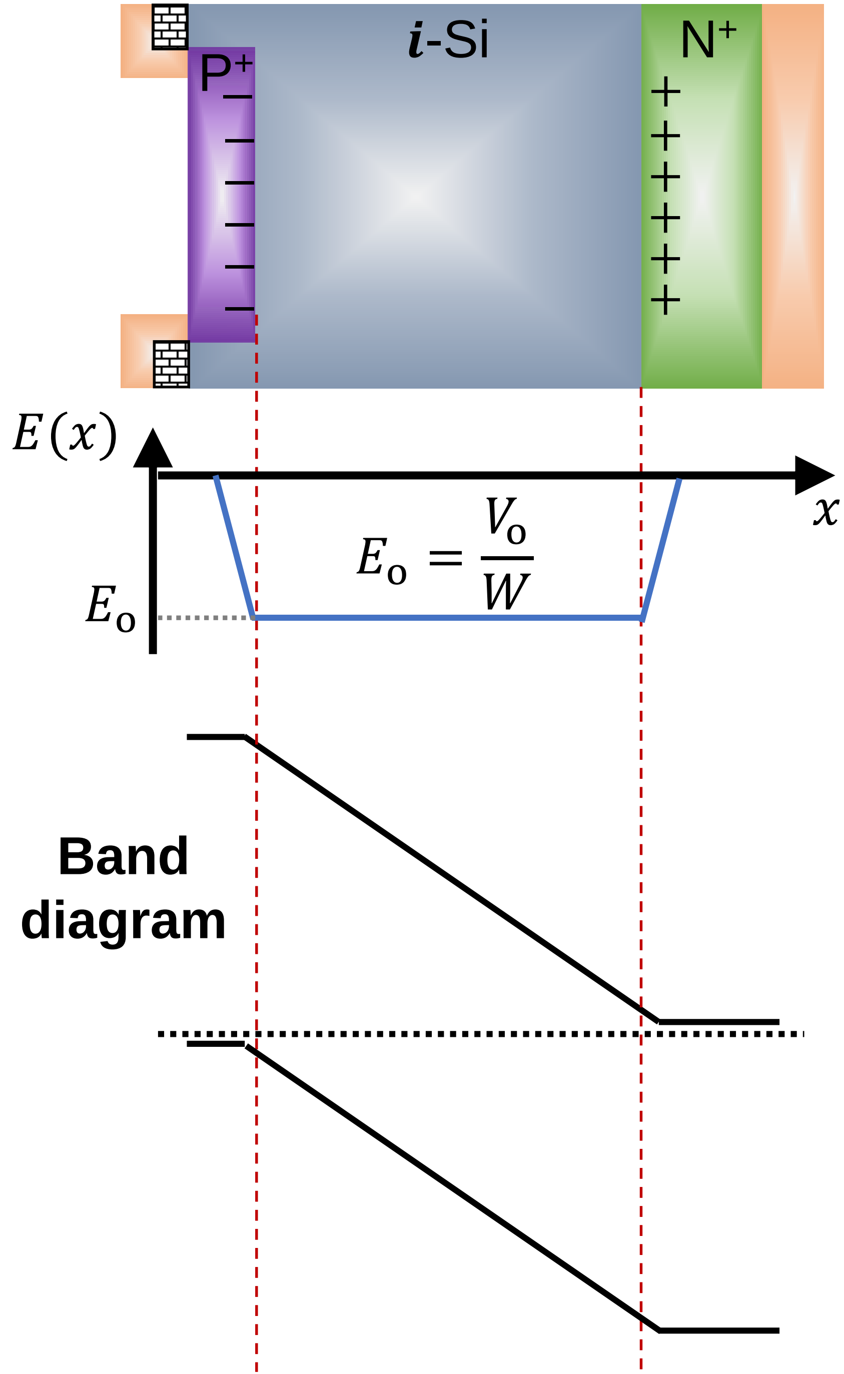
Electrons and holes recombine in $\boldsymbol{i}$ region

It's like a parallel-plate capacitor, the capacitance of $\boldsymbol{pin}$ junction:

$$C_{\mathrm{dep}} = \frac{\varepsilon_0 \varepsilon_{\mathrm{r}} A}{W}$$

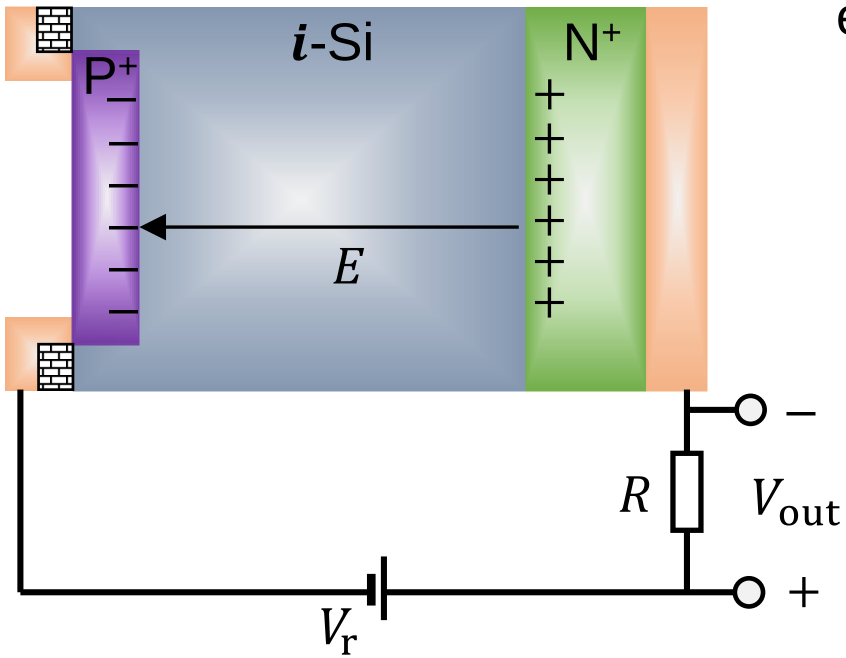
Because W can be at μm orders, C_{dep} can be very small ~pF. RC time constant of $\boldsymbol{pin}$ diode is very small ~ ps.

$\boldsymbol{pin}$ diode can be applied in high frequency circuits.



i-Si
P+
N+
$E(x)$
x
$E_o = \frac{V_o}{W}$
E_o
Band diagram

pin diodes operate as photodiodes/photodetectors



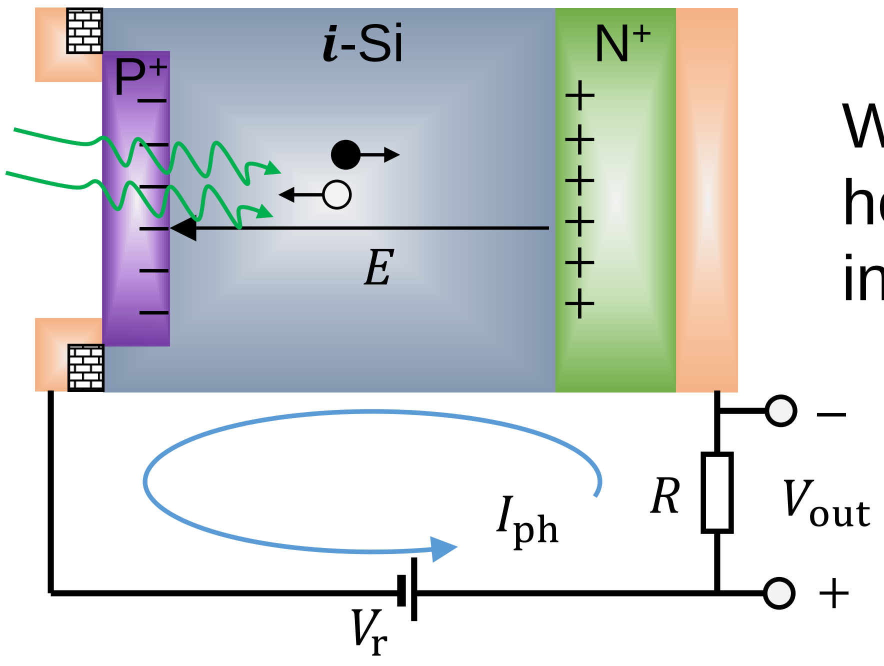
A reverse bias is applied, and internal electric field is enhanced:

$$E = \frac{V_0 + V_r}{R}$$

Resistance of i region is very large

Current in circuit ≈ 0

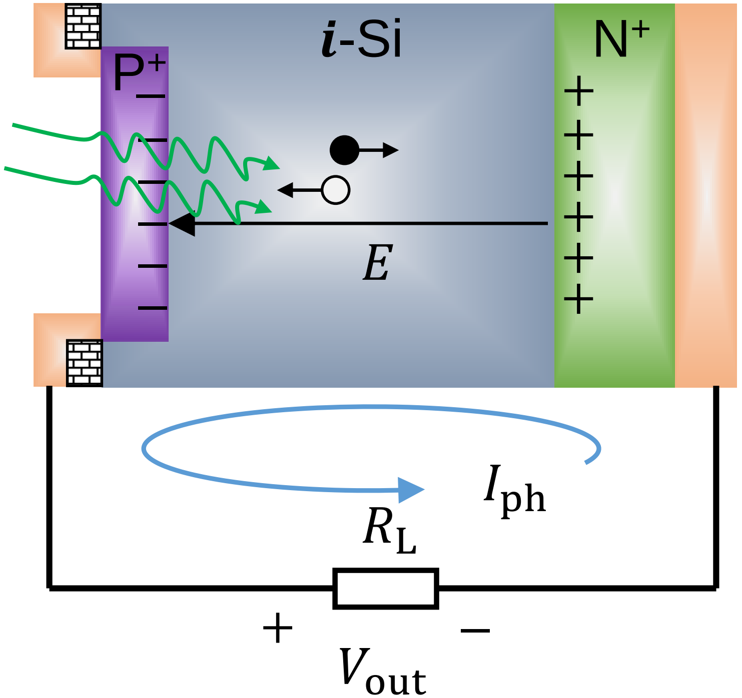
pin diodes operate as photodiodes/photodetectors



When there is light, electron and hole pairs are separated, resulting in a total photocurrent I_{ph}.

Output voltage: $V_{\mathrm{out}} = I_{\mathrm{ph}} R$

pin diodes operate as solar cells



When there is light, electron and hole pairs are separated, resulting in a total photocurrent I_{ph}.

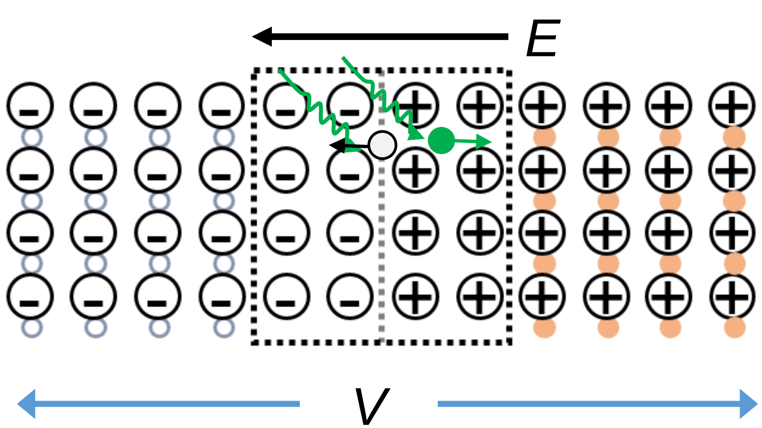
Output voltage: $V_{\mathrm{out}} = I_{\mathrm{ph}} R$

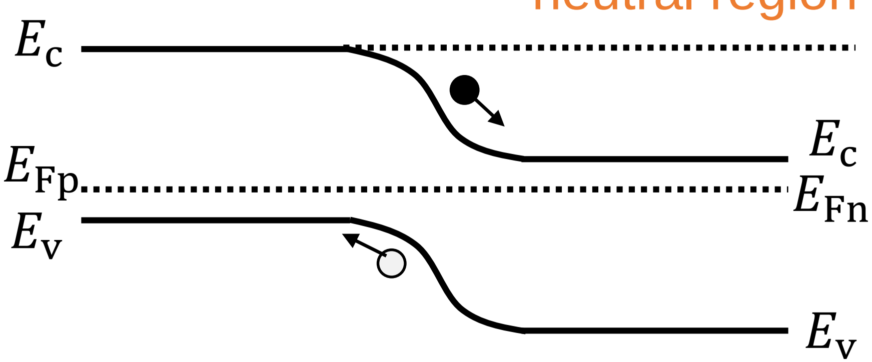
Classic mechanisms in photodetectors

1. Photovoltaic effect
2. Photoconductive effect
3. Photothermal effect
4. Bolometric effect

Photovoltaic effect

Photo-generated electron and hole pairs are separated by build-in electric field, resulting in a finite potential *V* across the sample.

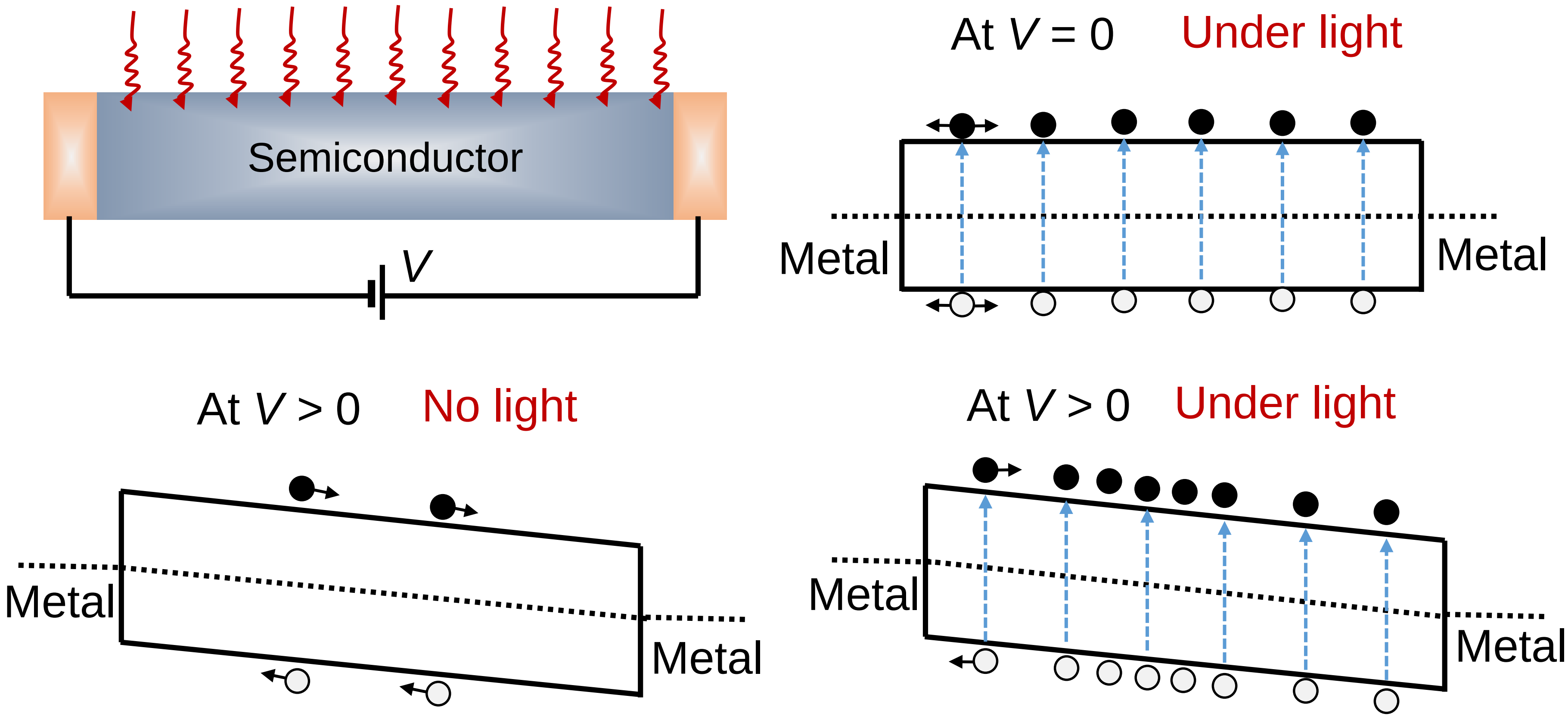




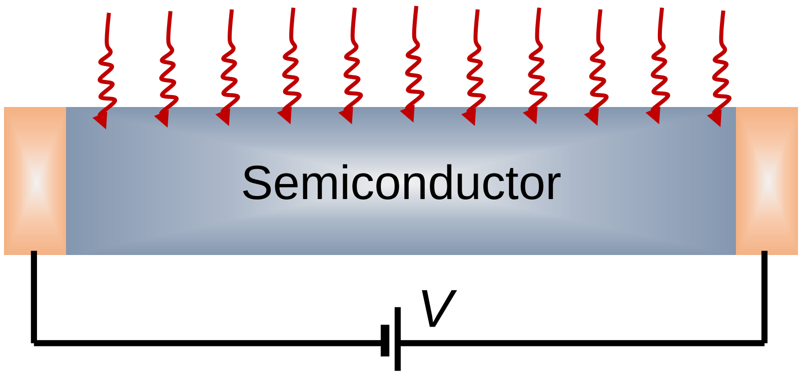
Photovoltaic effect: PN junction devices

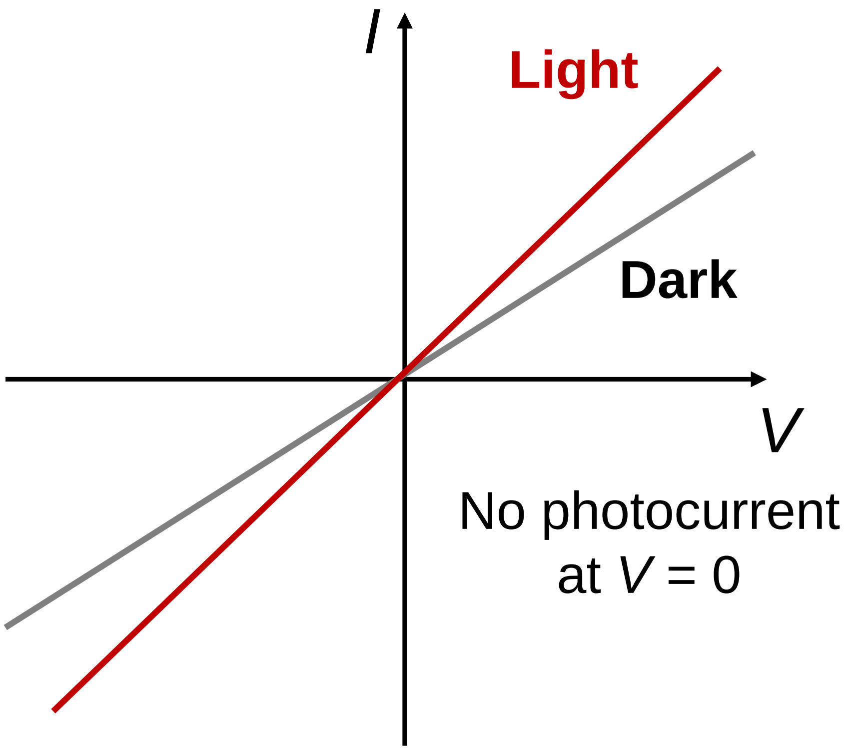
Photoconductive effect

Photo-generated electron and hole pairs changed the conductance/resistance of materials.



Photoconductive effect

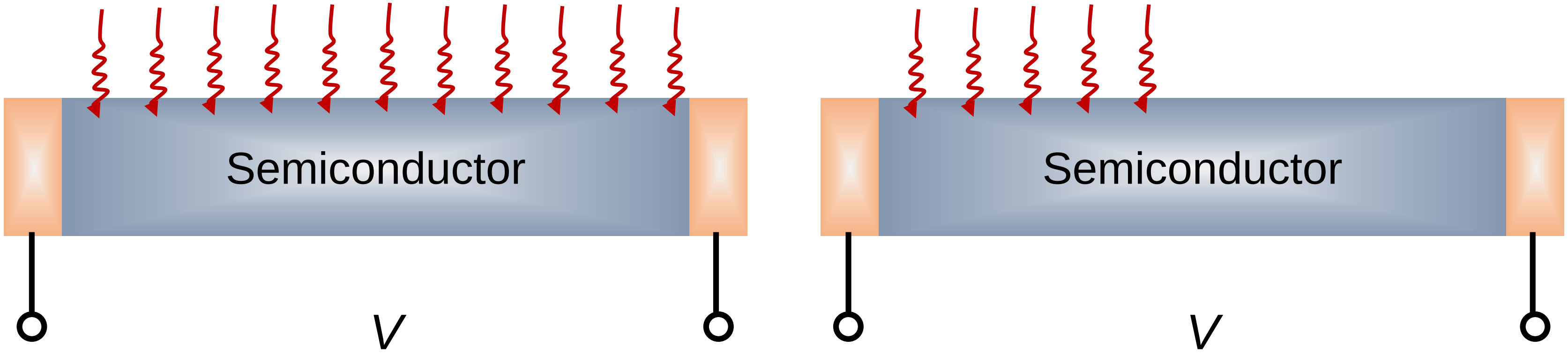


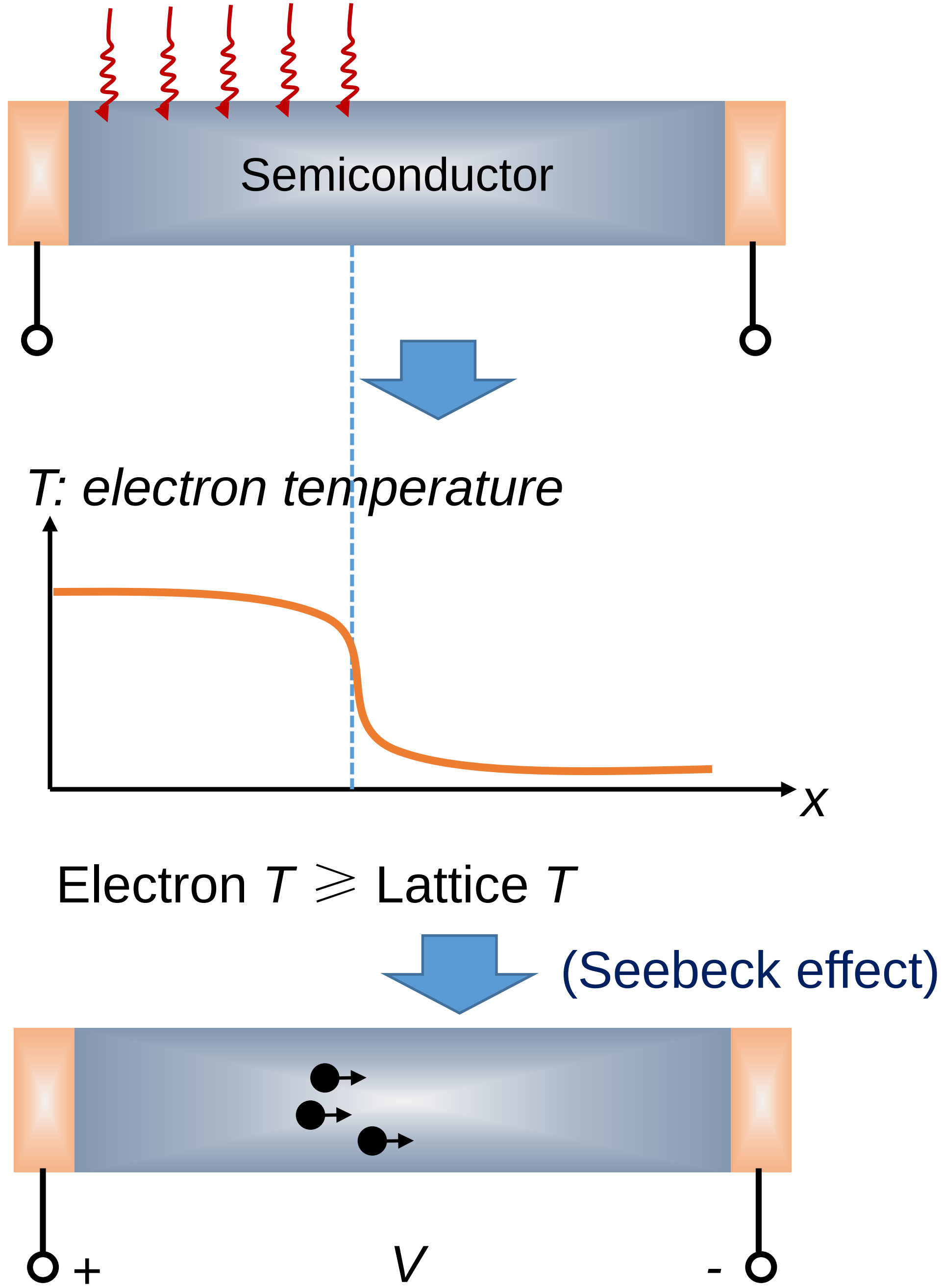


Photothermal effect

Light ⟶ **Thermal gradient (Seeback effect)** ⟶ **Photocurrent** **Photovoltage**

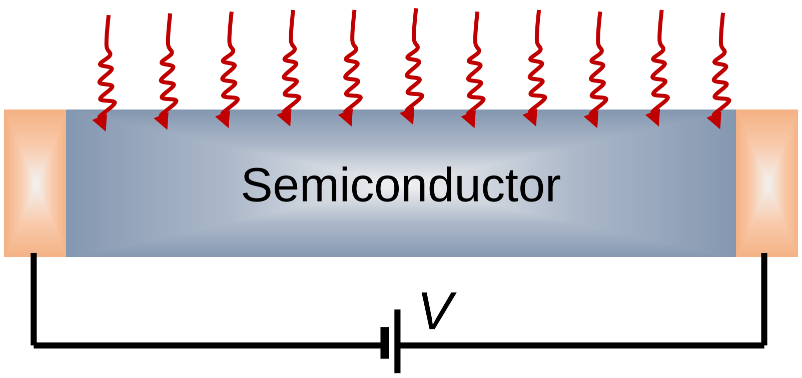
Q: Which *V* is nonzero? (Assume there is no Schottky barrier between metal and semiconductor)

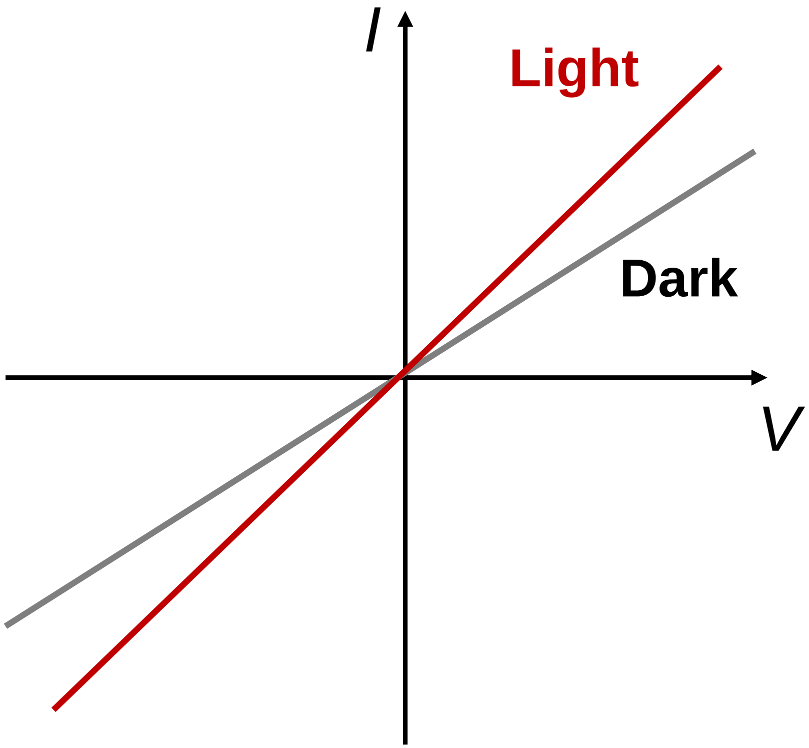



Semiconductor
T: electron temperature
x
Electron T ≫ Lattice T
(Seebeck effect)
+
V
-

Bolometric effect

Light ⟶ Thermal effect ⟶ Resistance change





Photocurrent ∝ 1/ΔR

Q: Difference between photoconductive, photothermal and bolometric effects?

Photoconductive

Light

$\downarrow$

Photo-excited carriers

$\downarrow$ (With bias *V*)

Photo-excited carriers are collected by electrodes

$\downarrow$

Photocurrent

Photothermal

Non uniform light

$\downarrow$

Photo-excited carriers

$\downarrow$

Transfer partially/all energy to lattice

$\downarrow$

Temperature gradient

$\downarrow$ (Seeback)

Photocurrent

Bolometric

Light

$\downarrow$

Photo-excited carriers

$\downarrow$

Transfer partially/all energy to lattice

$\downarrow$

Temperature change

$\downarrow$

Resistance change

$\downarrow$ (Bias *V*)

Current change