Electronic Materials and Devices

5 Semiconductor

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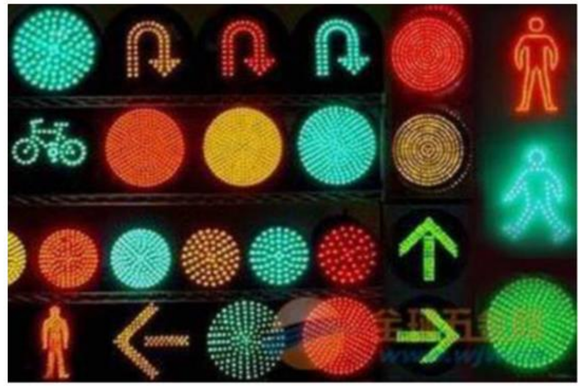
5.6 Light emitting diode 发光二极管

LED is widely used in every aspects of our life.

Indicator board

Traffic lights



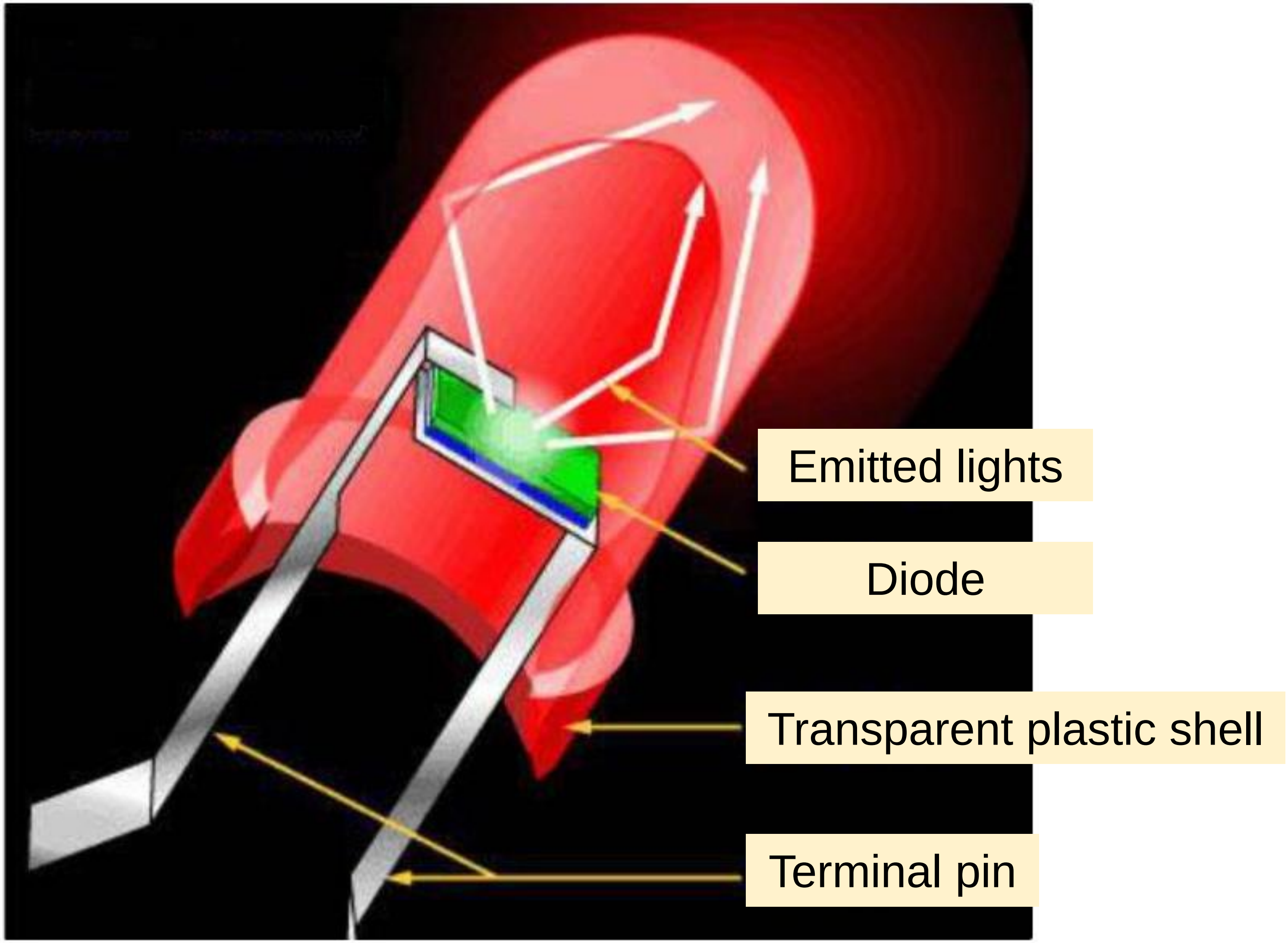
LED screen

Illumination

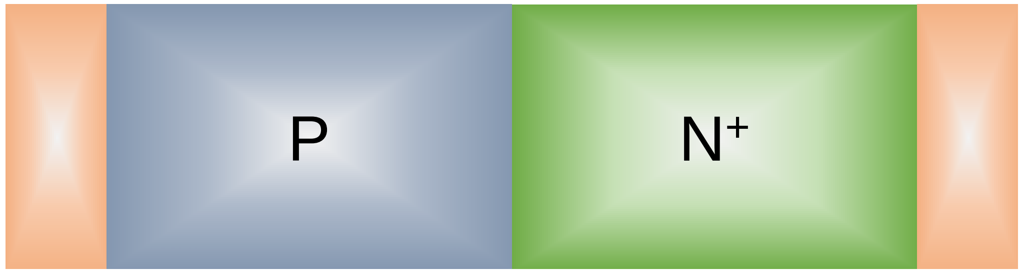
Car lights

Decoration

Structure of a LED product

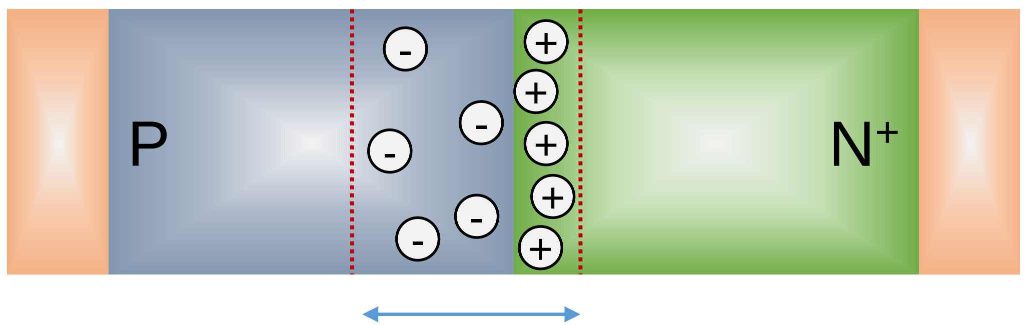


Working principle of LED



Electrode

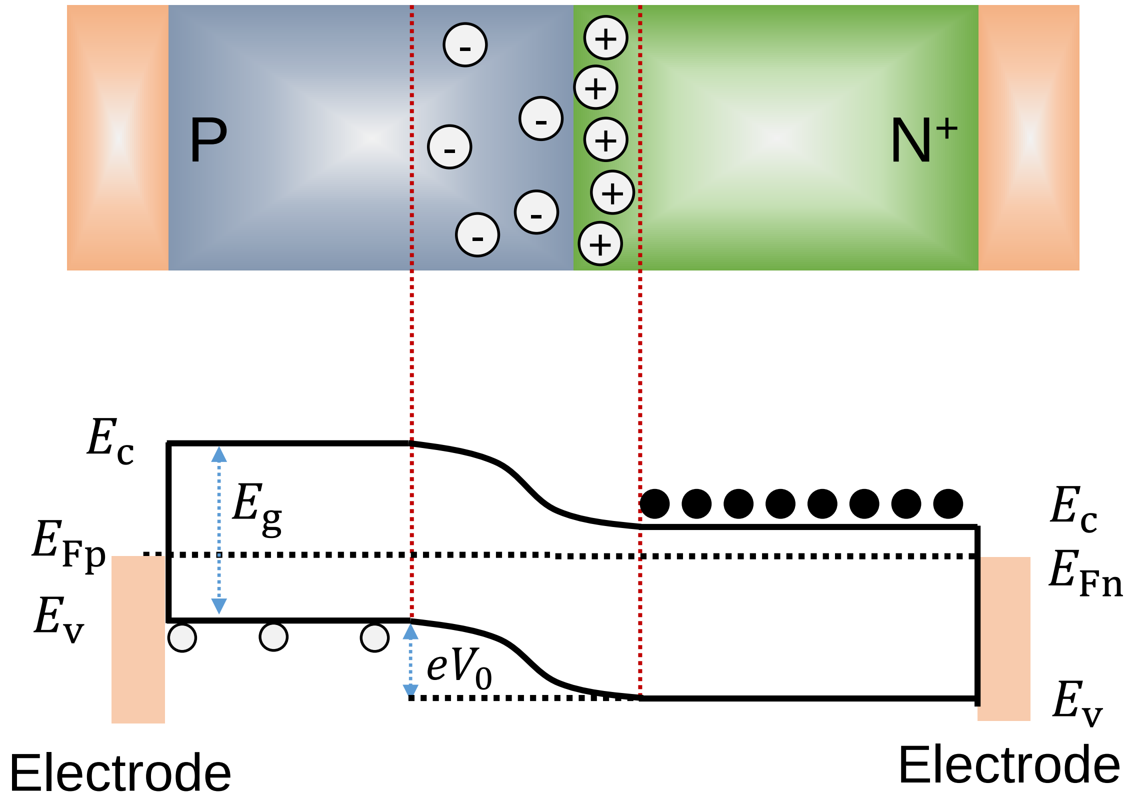
Electrode



Space charge layer (SCL)

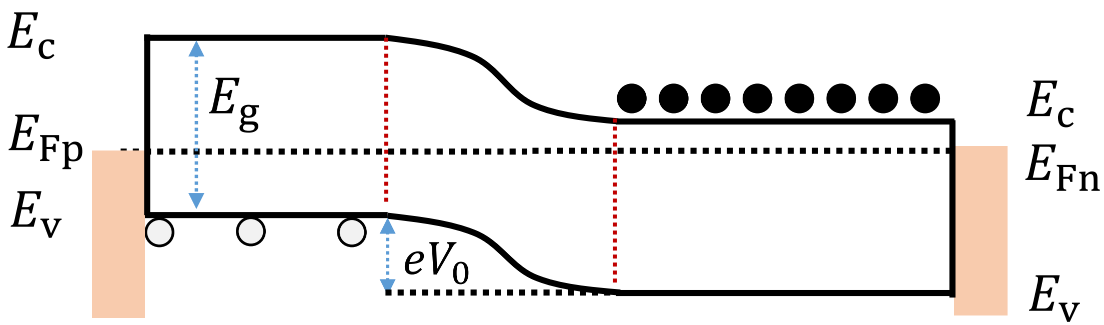
Depletion layer

Working principle of LED

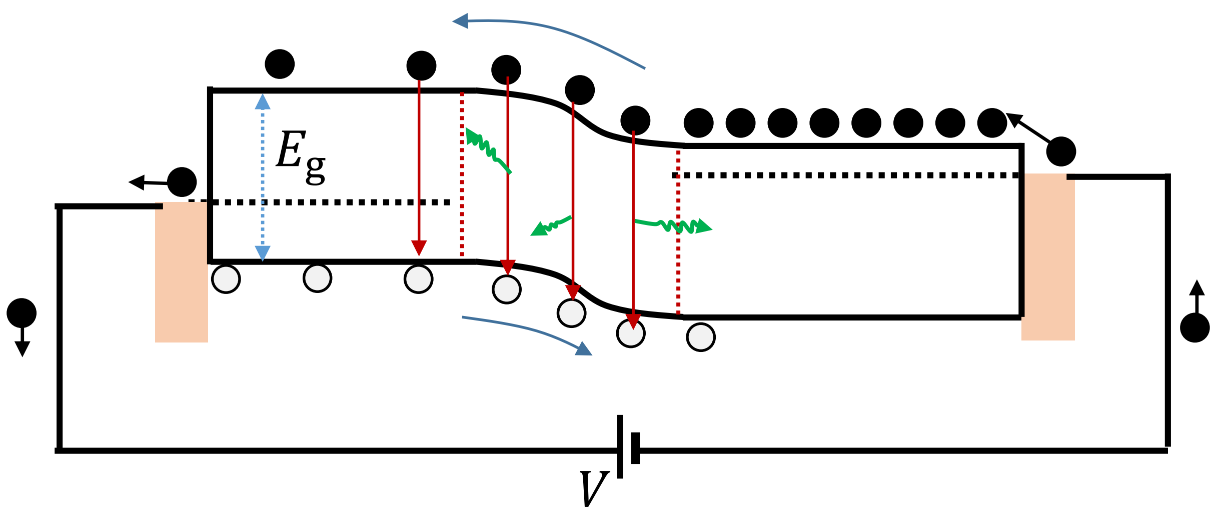


Working principle of LED

No voltage bias

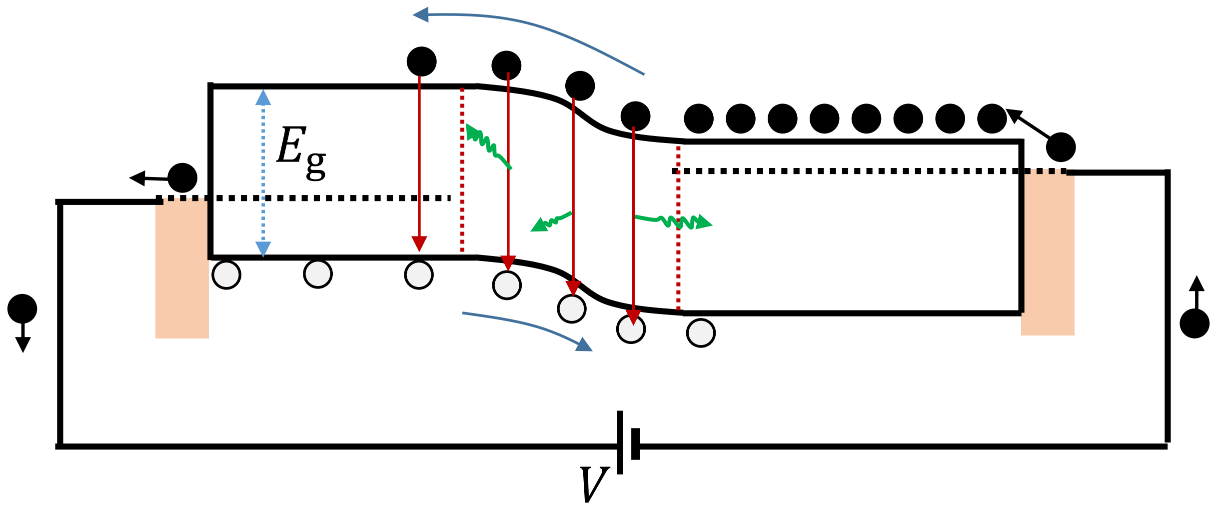


Forward bias



Electron and hole can recombine over an diffusion length L_e inside p-region.

Working principle of LED



Photon energy ≈ E_g

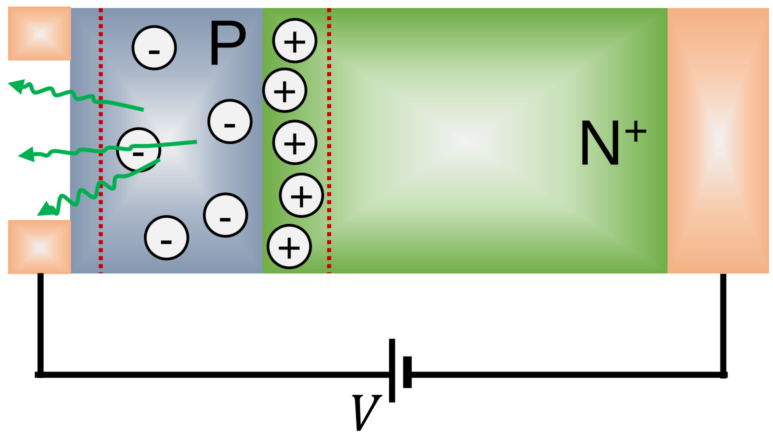
Photons are emitted in random directions.

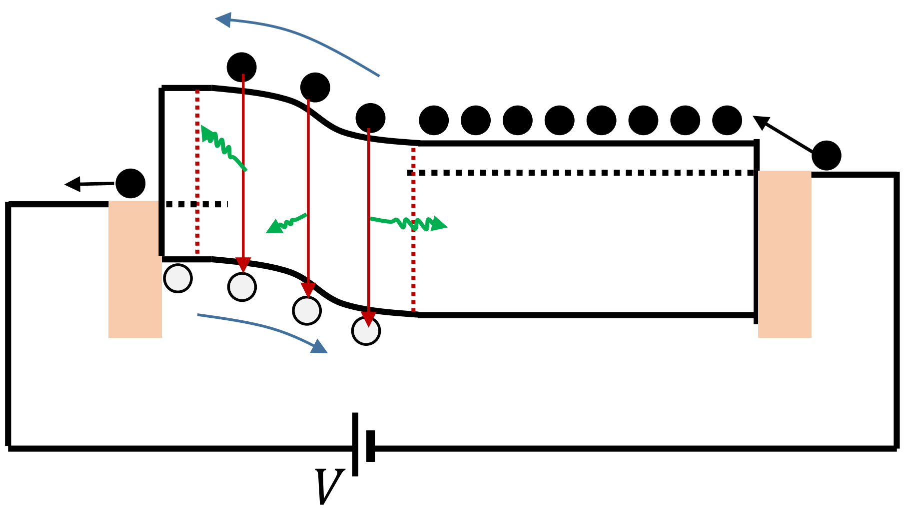
To have a higher brightness of LED, the structure of LED should be improved:

Electrode should be transparent.

P-region should be thin.

Improved LED structure

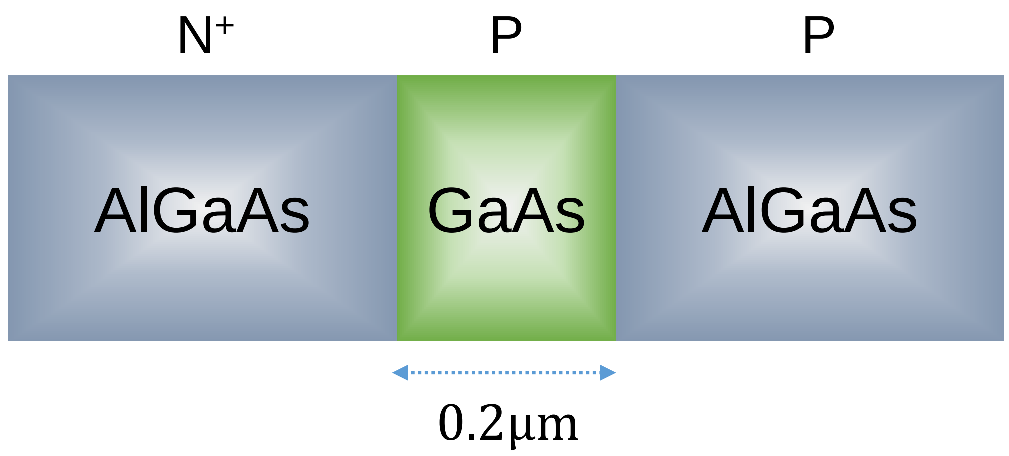


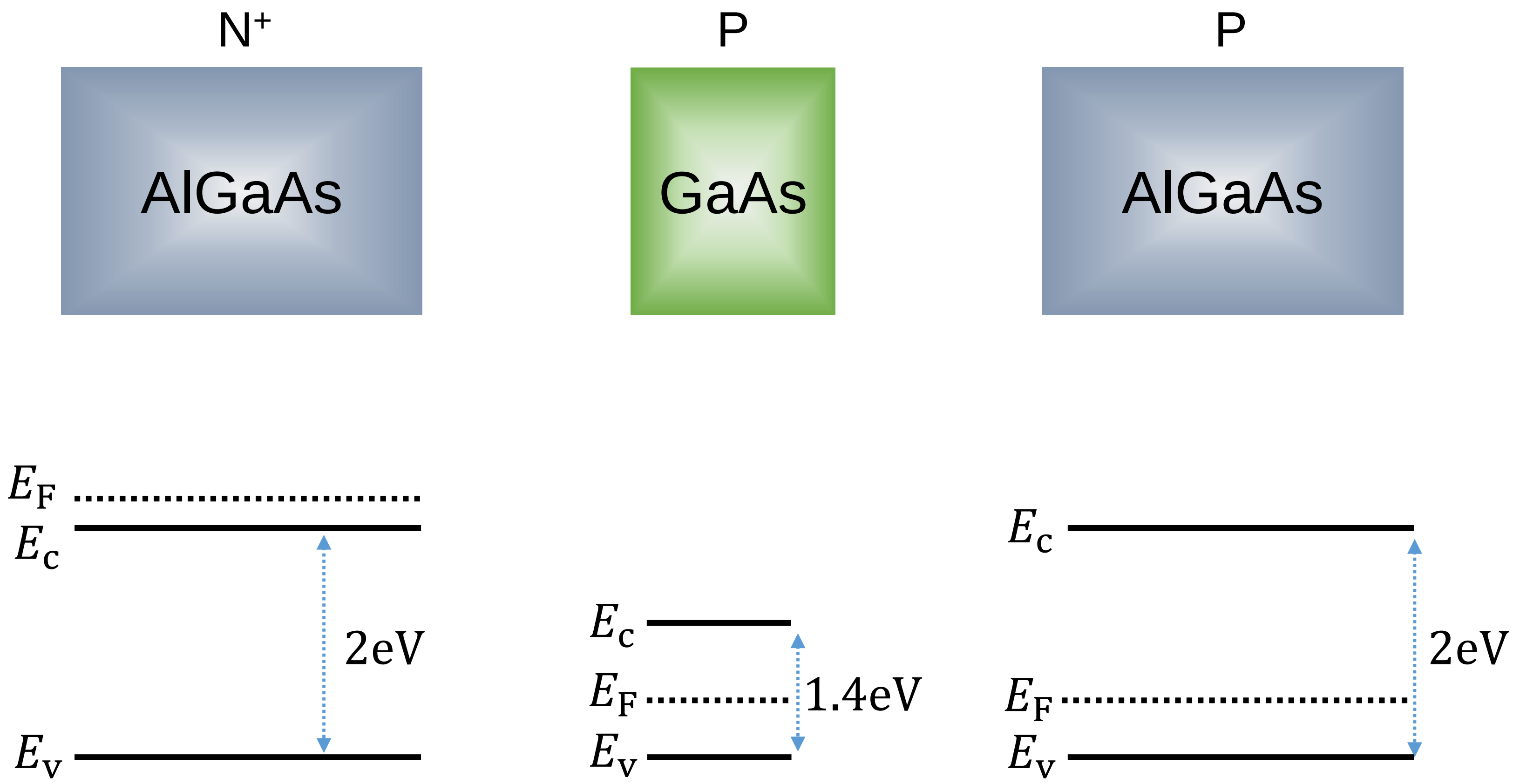


Heterojunction high-intensity LEDs

Junction between two differently doped semiconductors that are of the same material, that is, the same bandgap E_g, is called a **homojunction** 单质结. (Silicon PN junction)

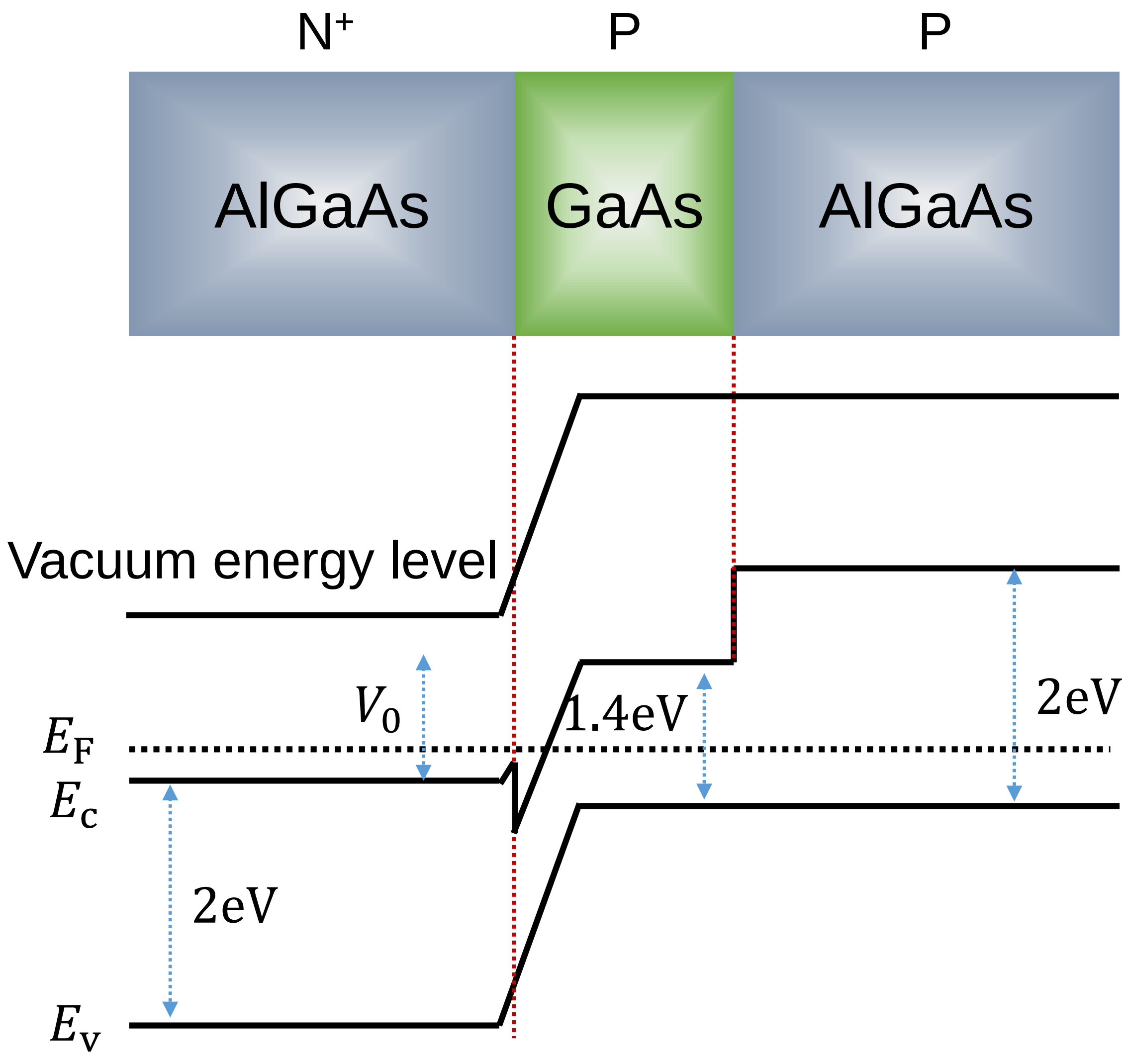
Junction between two different bandgap semiconductors is called a **heterojunction** 异质结.



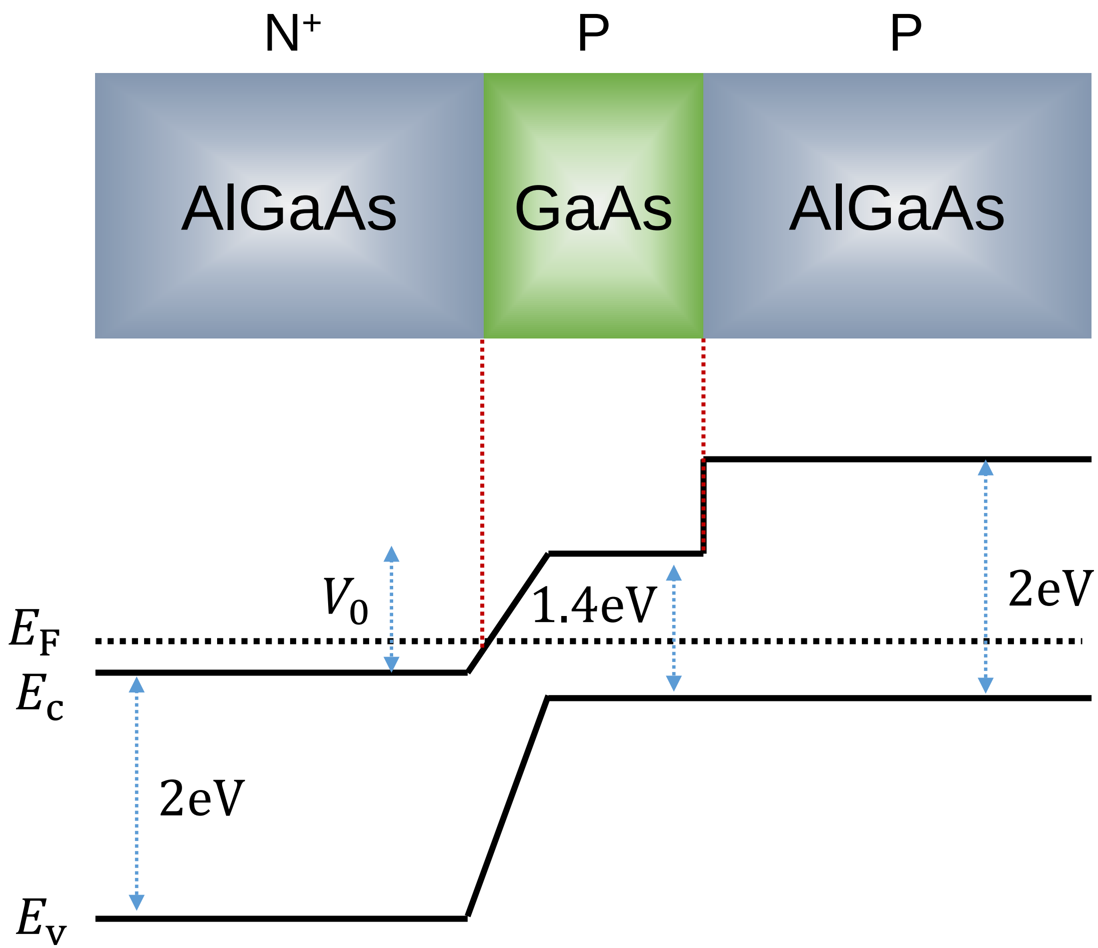


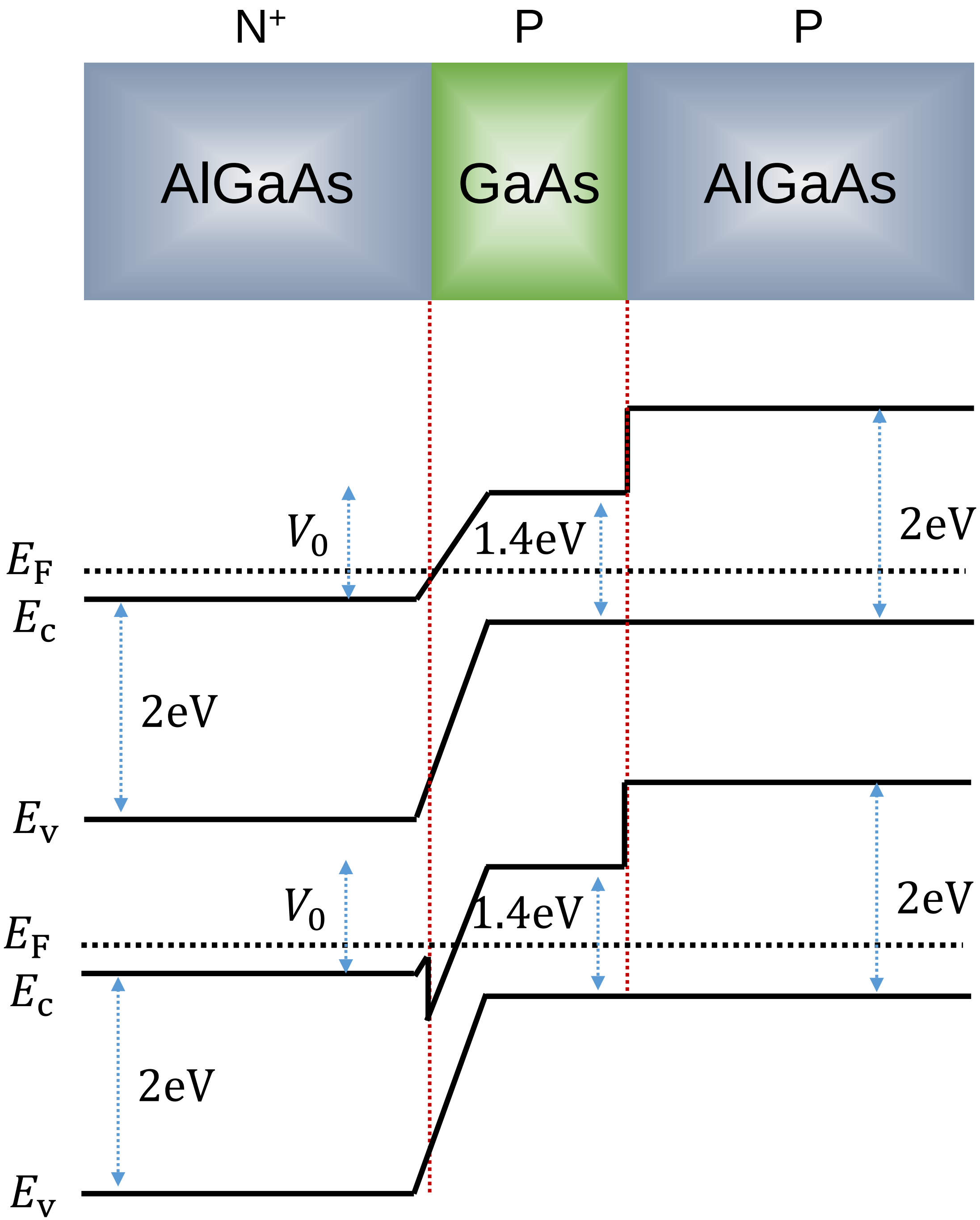
N+
P
P
AlGaAs
GaAs
AlGaAs
E_F
E_c
2eV
E_v
E_c
E_F
1.4eV
E_v
E_c
2eV
E_F
E_v

Band diagram



Simplified band diagram shown in the textbook

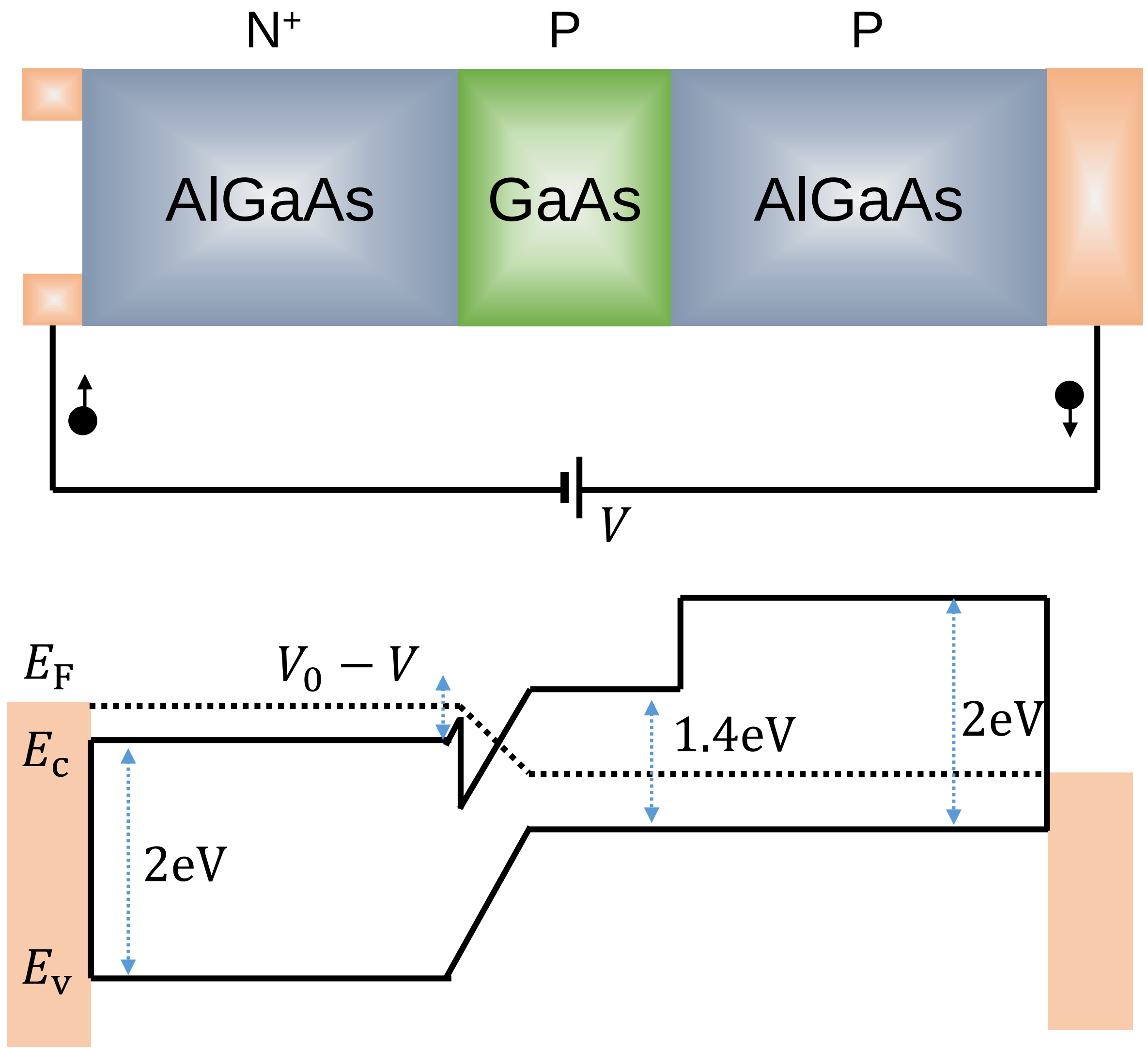




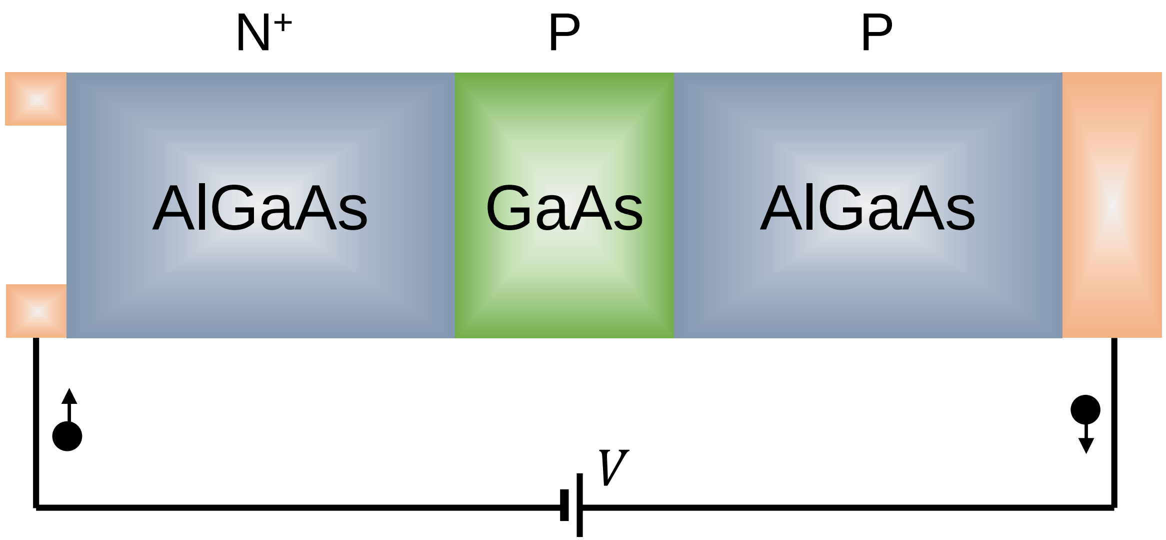
Simplified band diagram

Exact band diagram

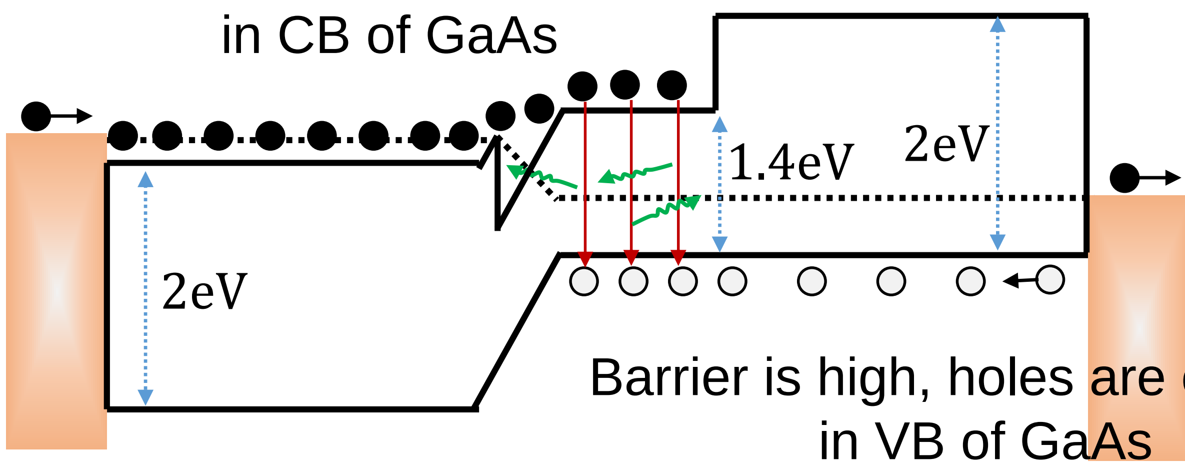
Band diagram



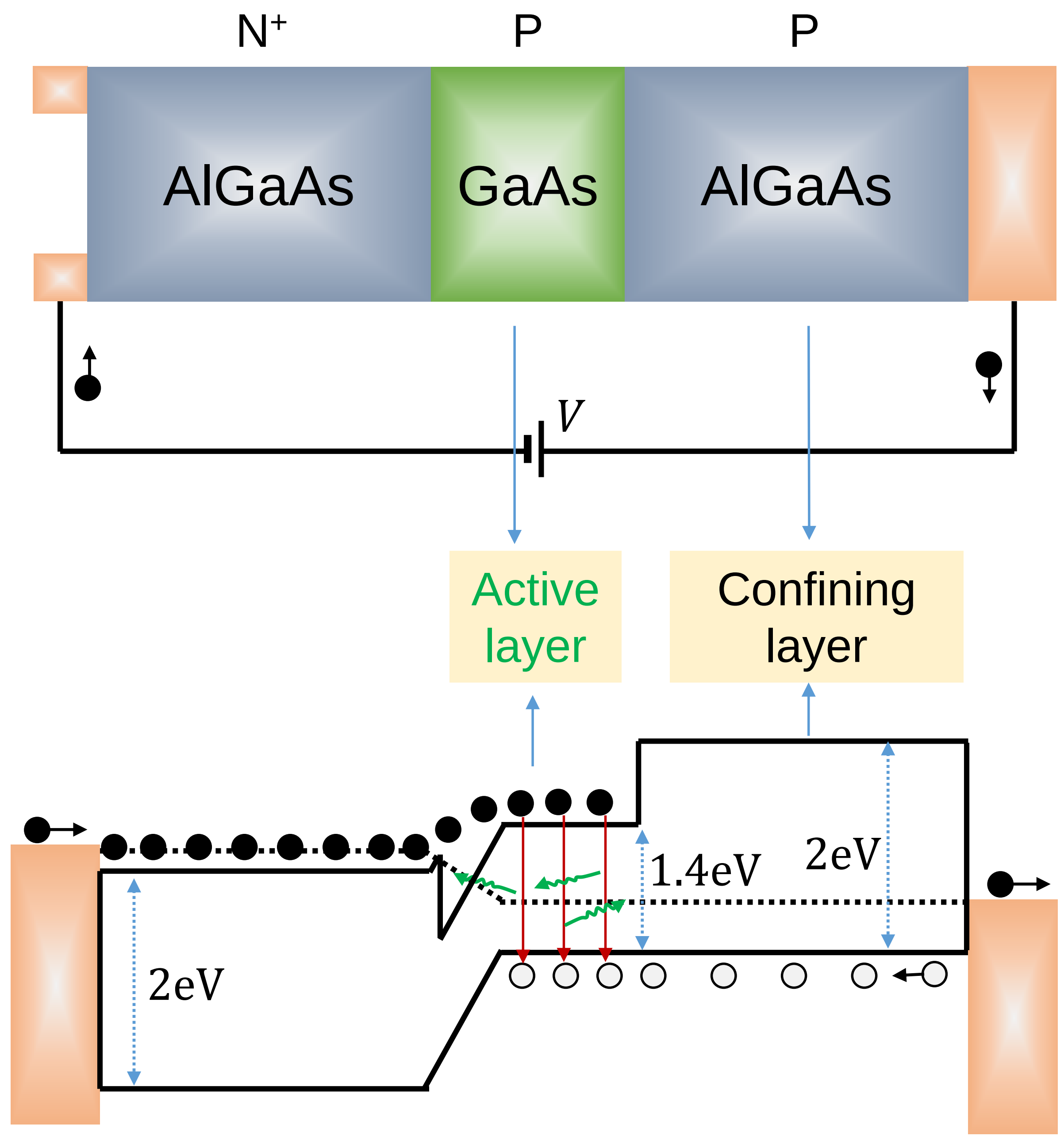
Heterojunction high-intensity LEDs



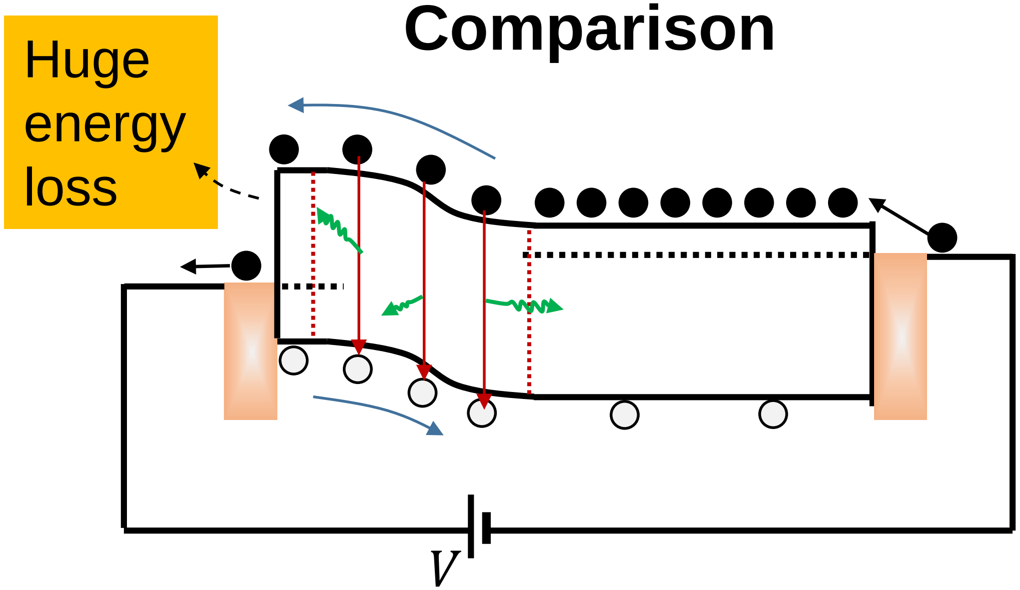
Electrons are confined in CB of GaAs



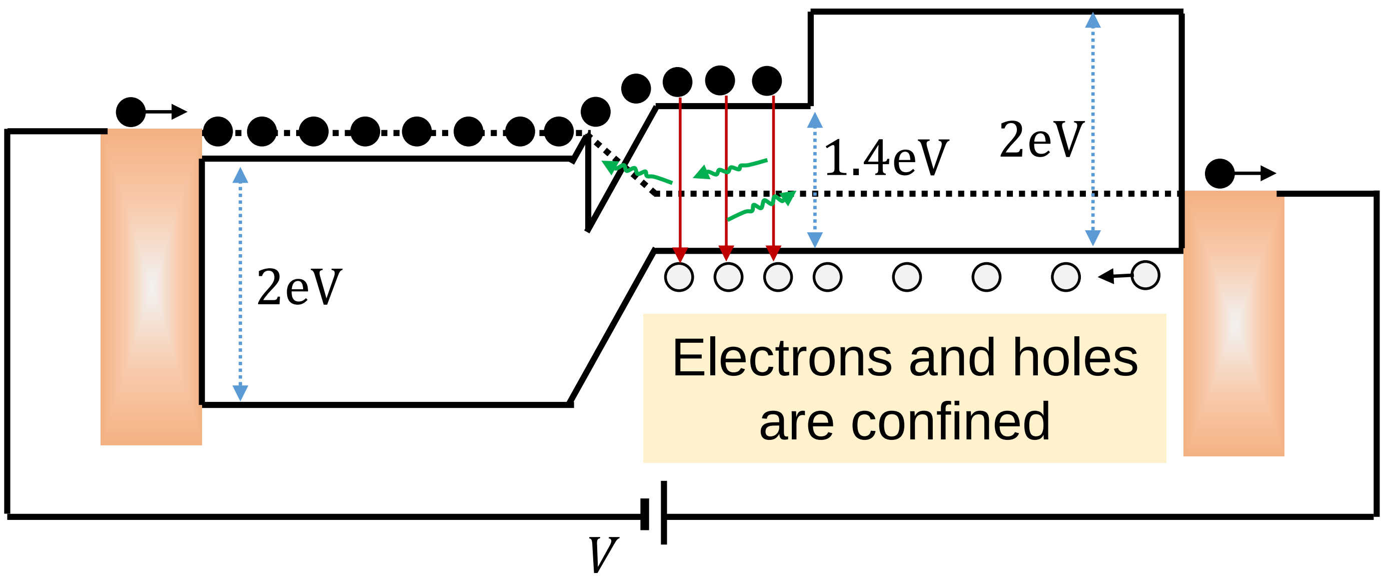
Barrier is high, holes are confined in VB of GaAs


N+
P
P
AlGaAs
GaAs
AlGaAs
V
Active layer
Confining layer
1.4eV
2eV
2eV

Comparison

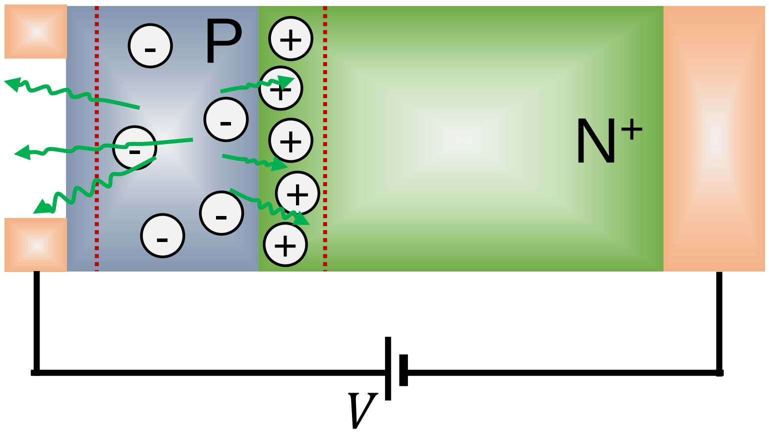


Huge energy loss
V

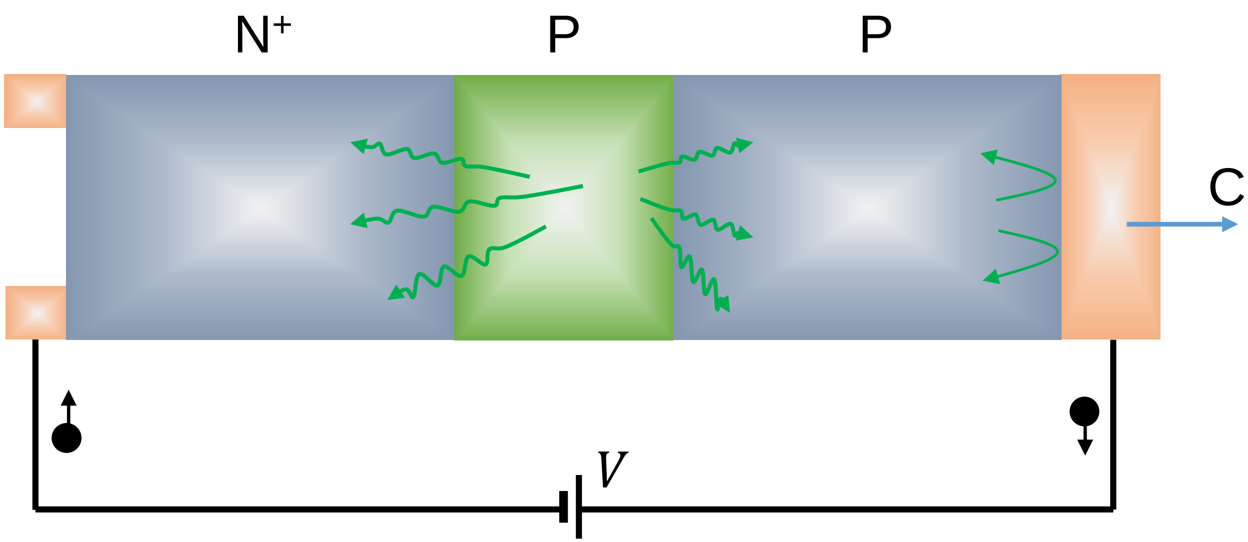


2eV
1.4eV
2eV
Electrons and holes are confined
V

Comparison

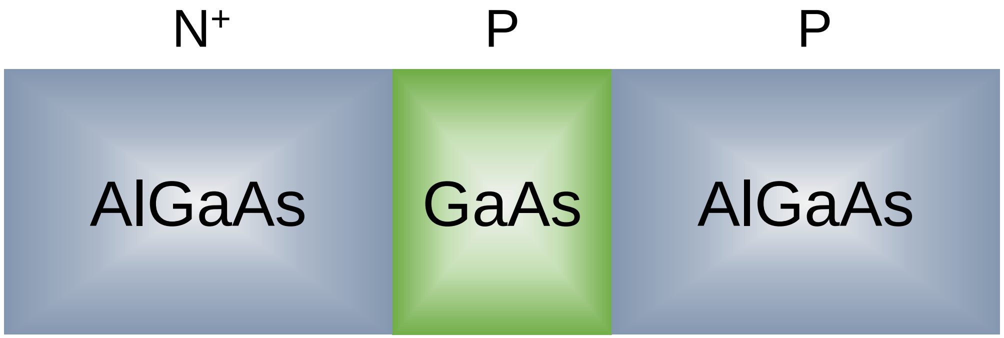


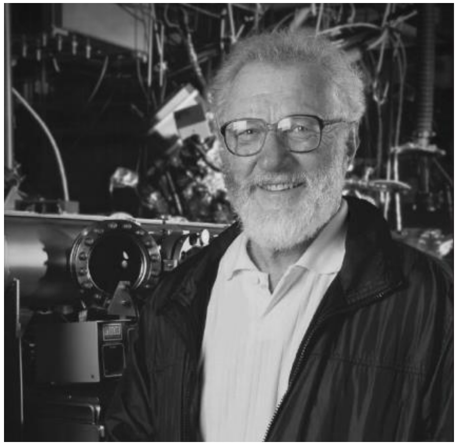
Light in right direction is absorbed by N$^+$ region.



Can also act as a mirror to reflect back light.

Growth of the heterostructure





Herbert Kroemer

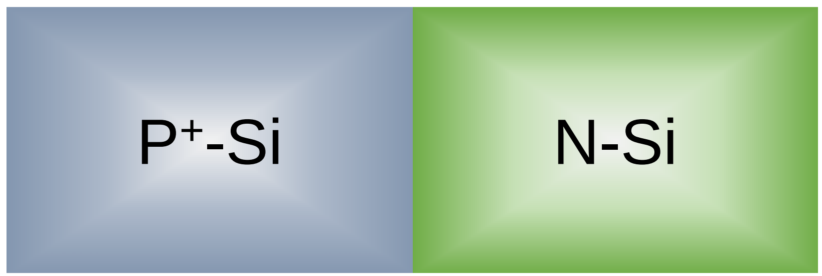
Molecular Beam epitaxy (MBE)

分子外延生长

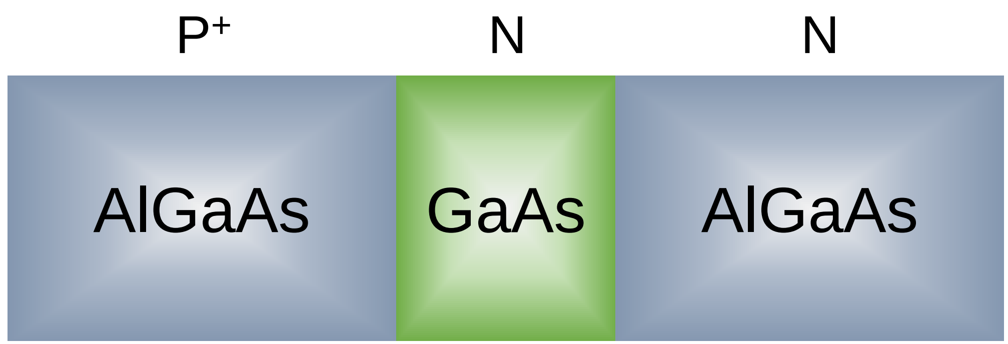
Small lattice mismatch between AlGaAs and GaAs

Homework 1-4: the band diagram and working principle of following LEDs (don’t use the simplified band diagram for heterostructure).

(1)

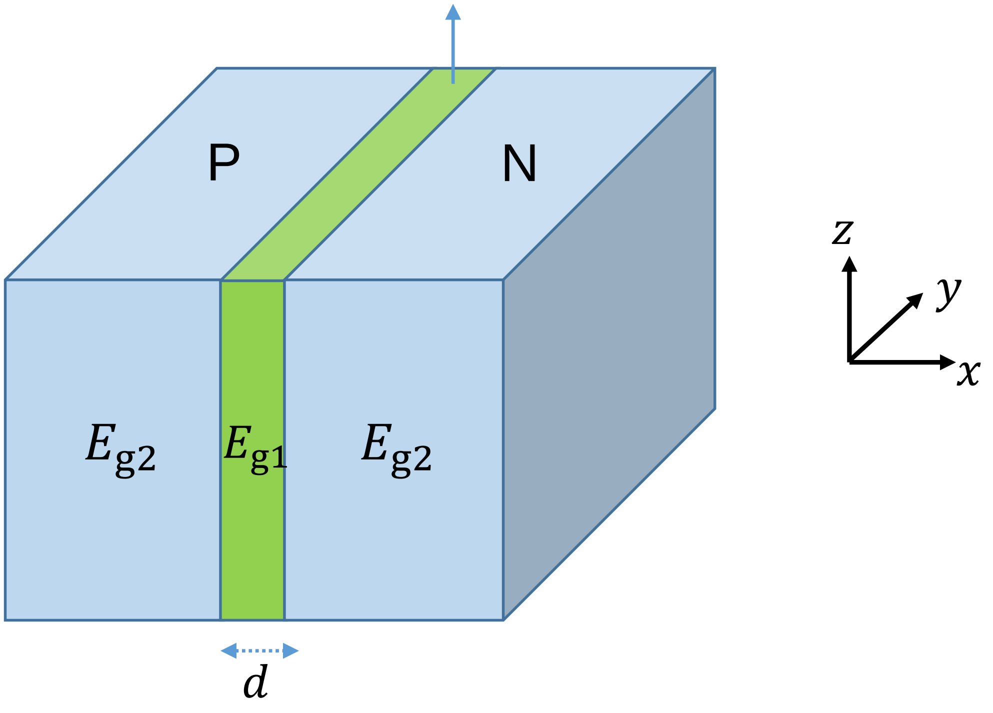


(2)



Quantum well high-intensity LEDs

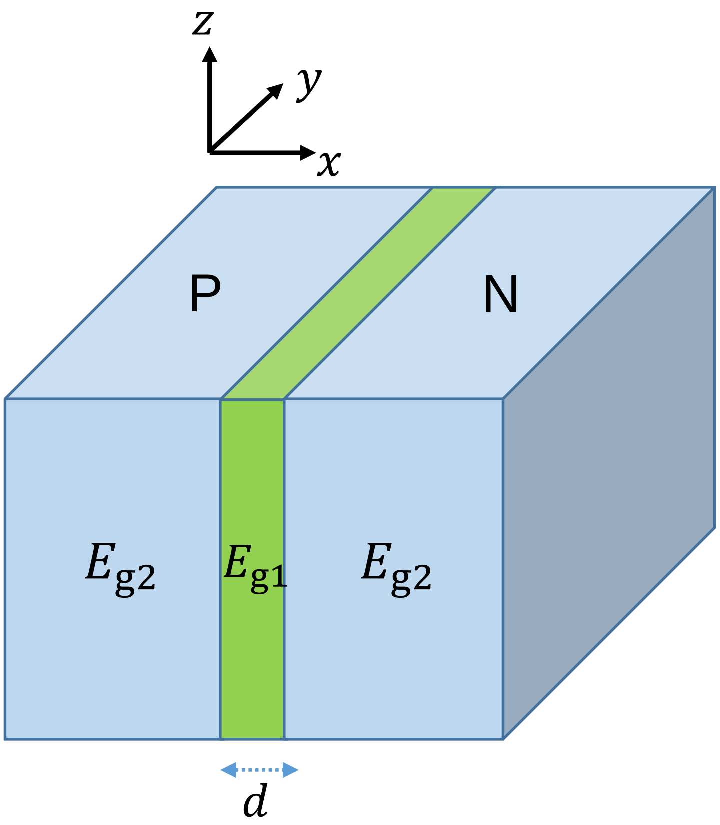
(Quasi-) two-dimensional plane

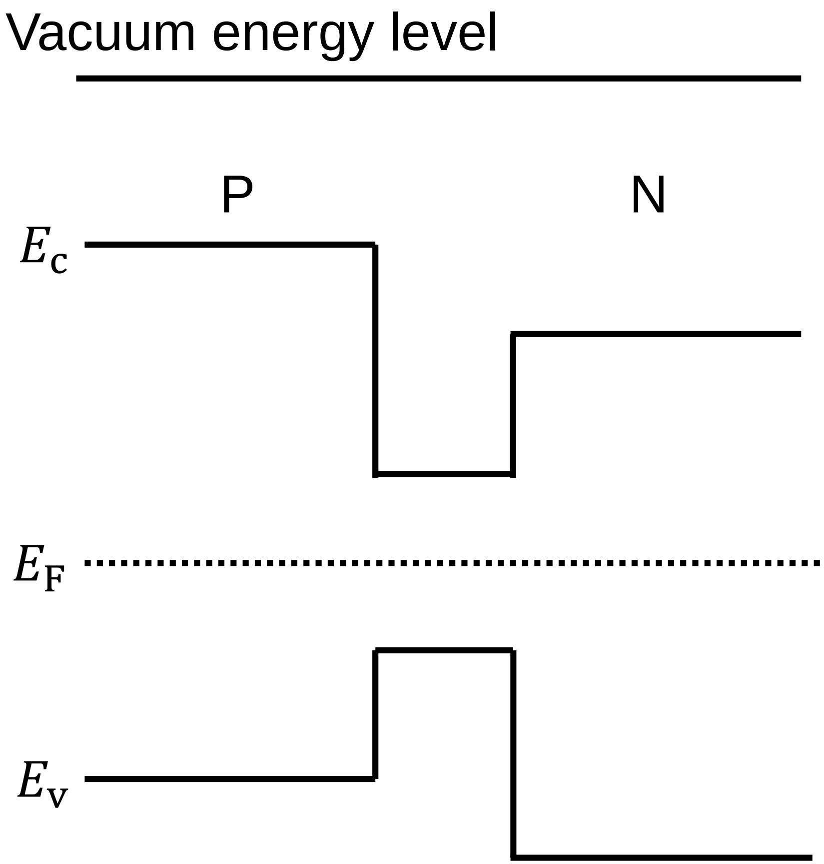


Very thin active layer: *d*<10 nm

$E_{g2} > E_{g1}$

Quantum well high-intensity LEDs

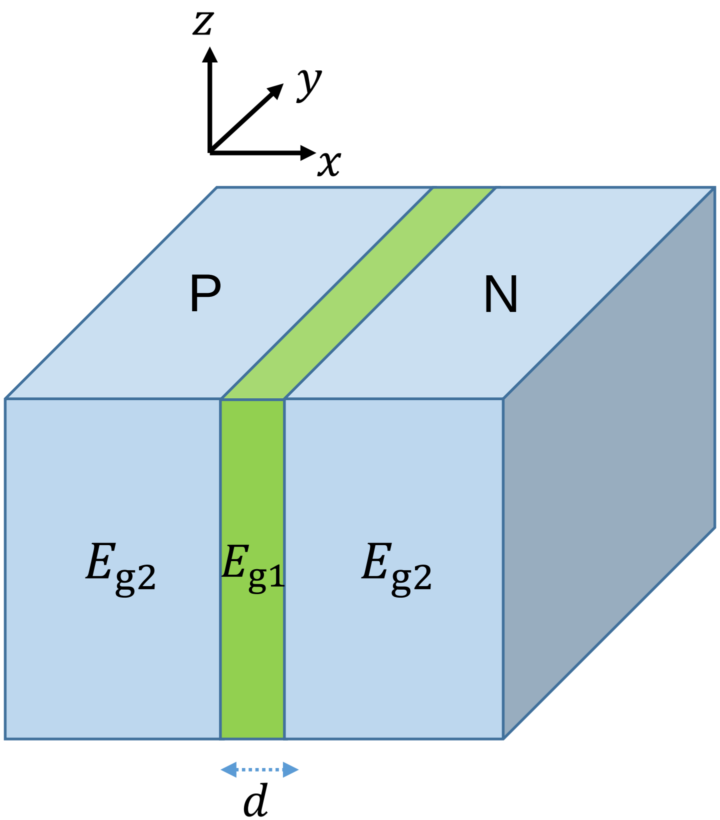


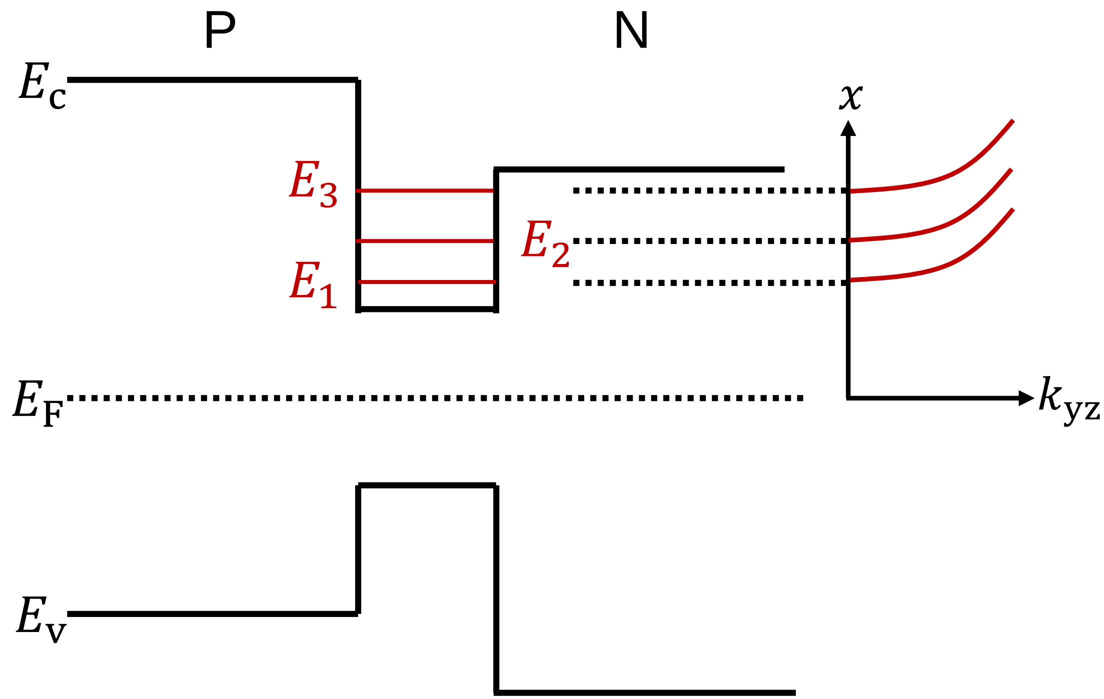


Quantum well high-intensity LEDs

Electron energy in CB of quantum well

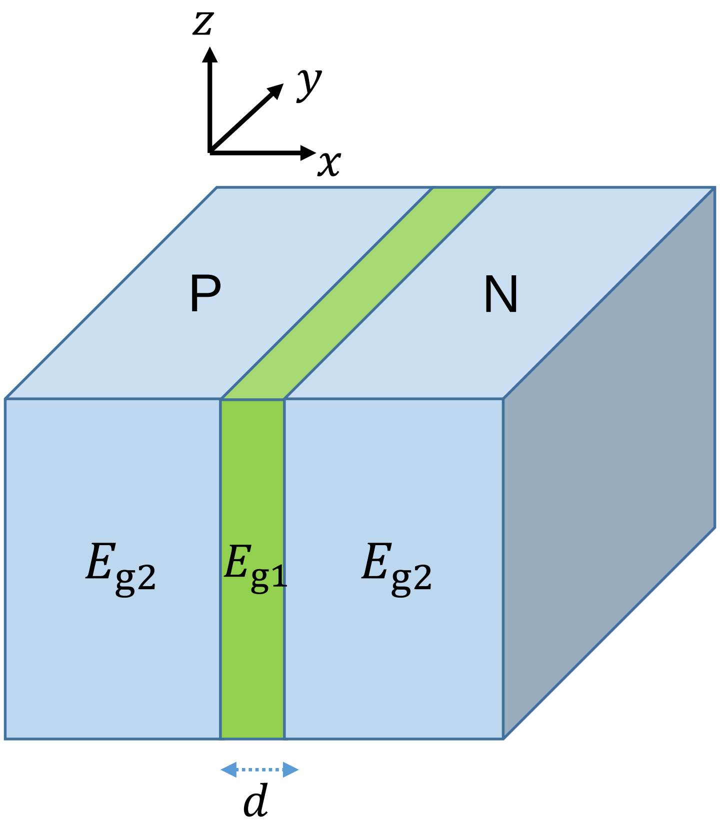
$$E_n = E_c + \frac{\hbar^2 n^2}{8 m_e^* d^2} + \frac{\hbar^2 k_y^2}{2 m_e^*} + \frac{\hbar^2 k_z^2}{2 m_e^*}$$





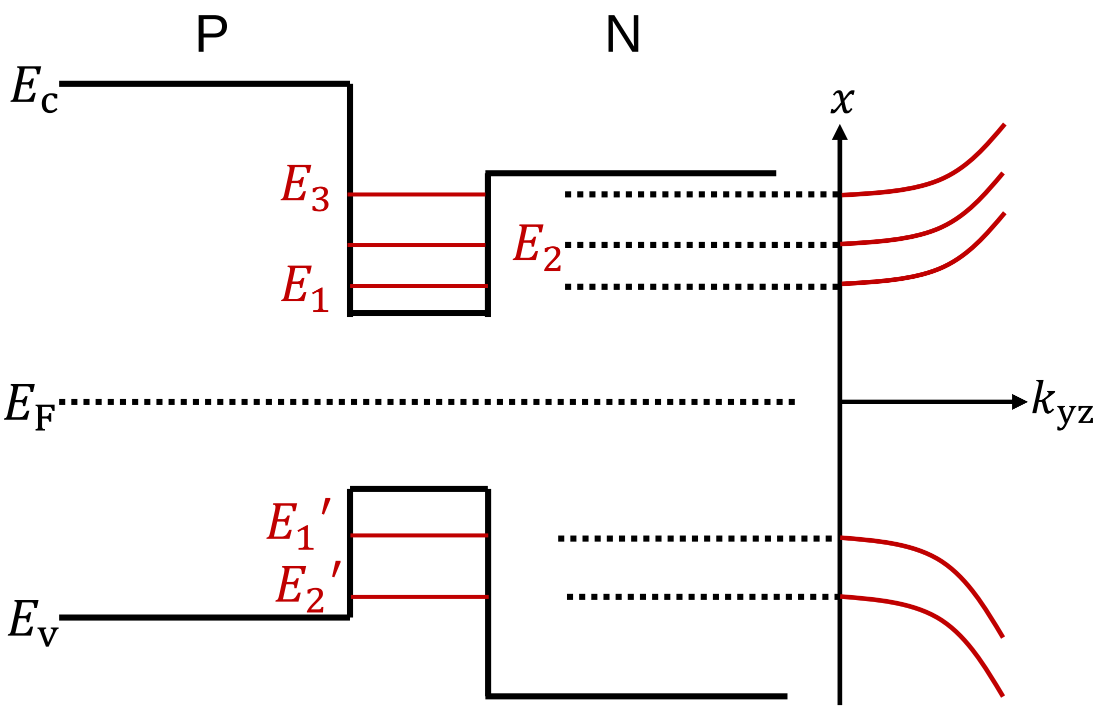
This is also called **two-dimensional electron gas.**

Quantum well high-intensity LEDs

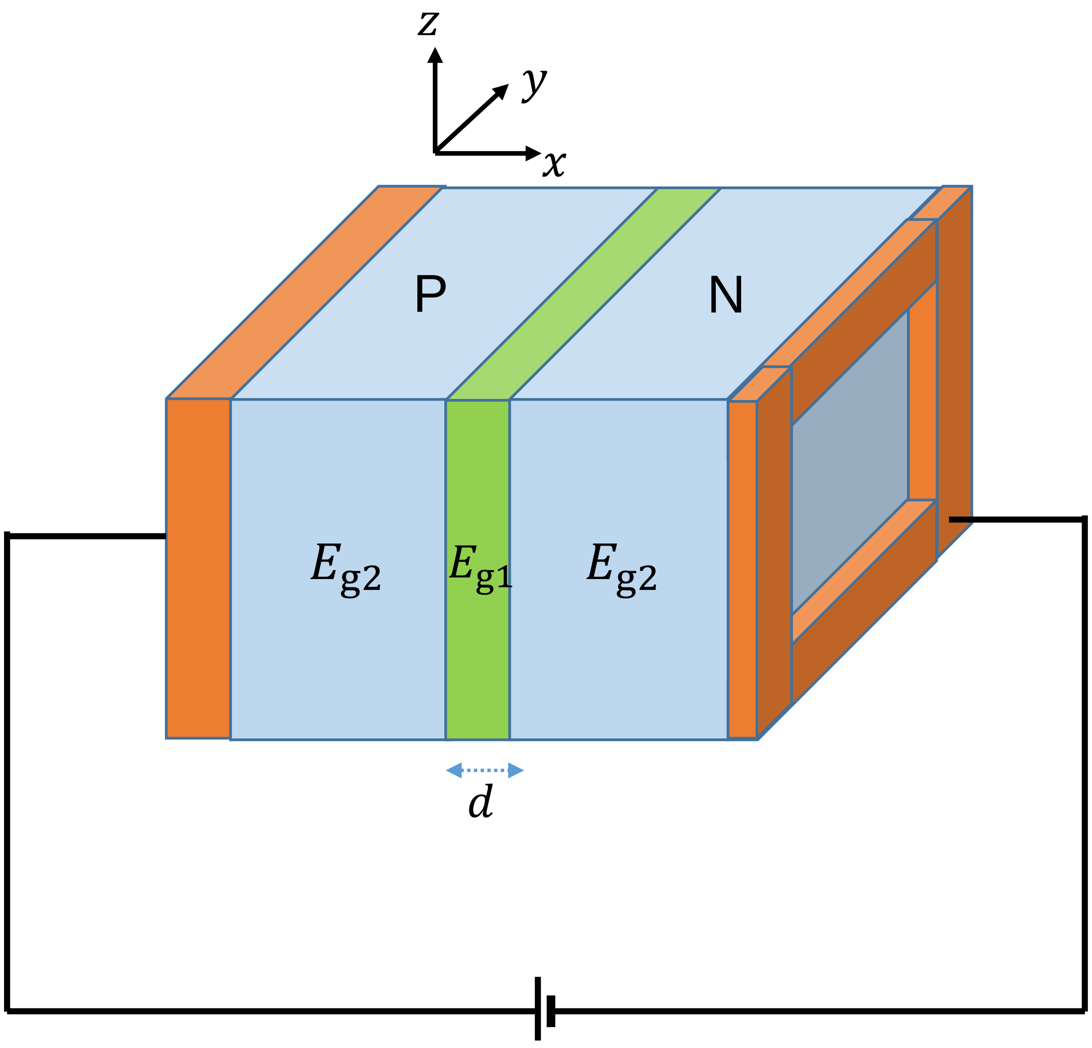


Hole energy in VB of quantum well

$$E_h = E_v - \frac{\hbar^2 n^2}{8m_h^* d^2} - \frac{\hbar^2 k_y^2}{2m_h^*} - \frac{\hbar^2 k_z^2}{2m_h^*}$$

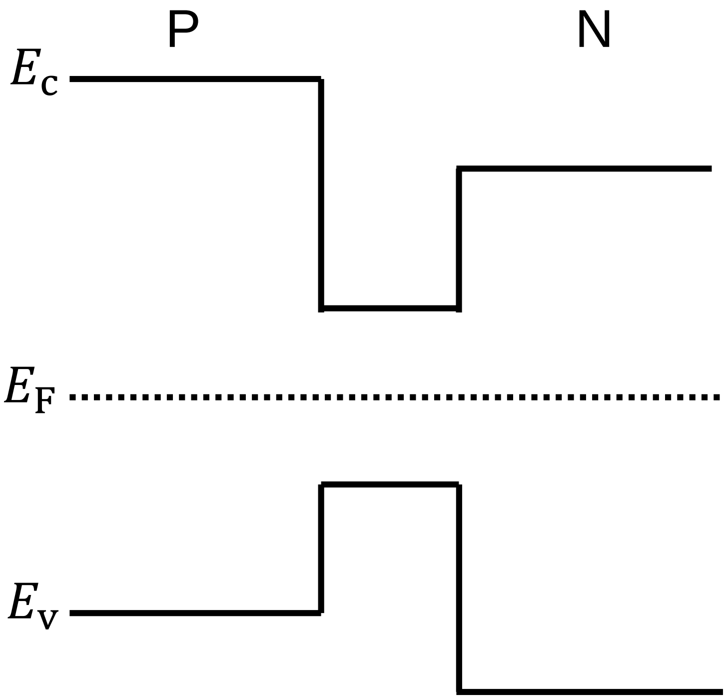


Working principle

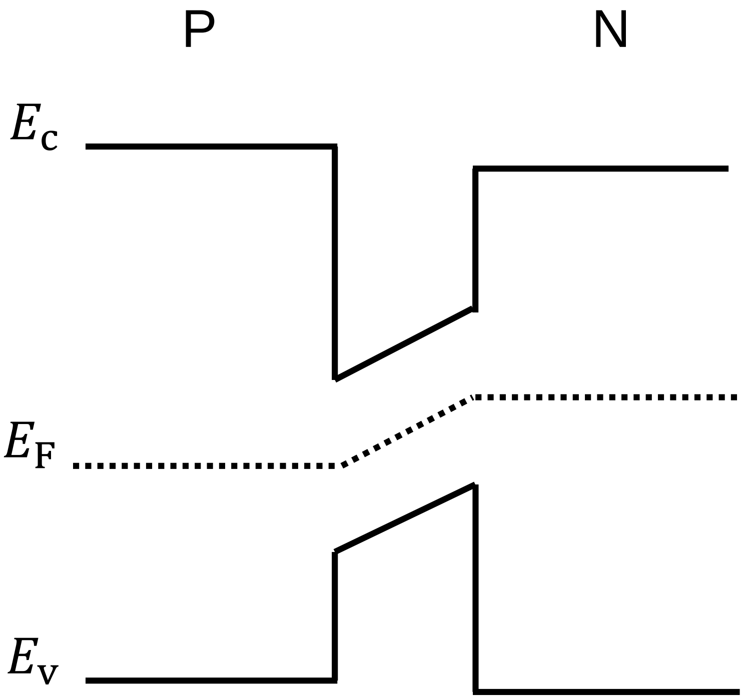


Working principle

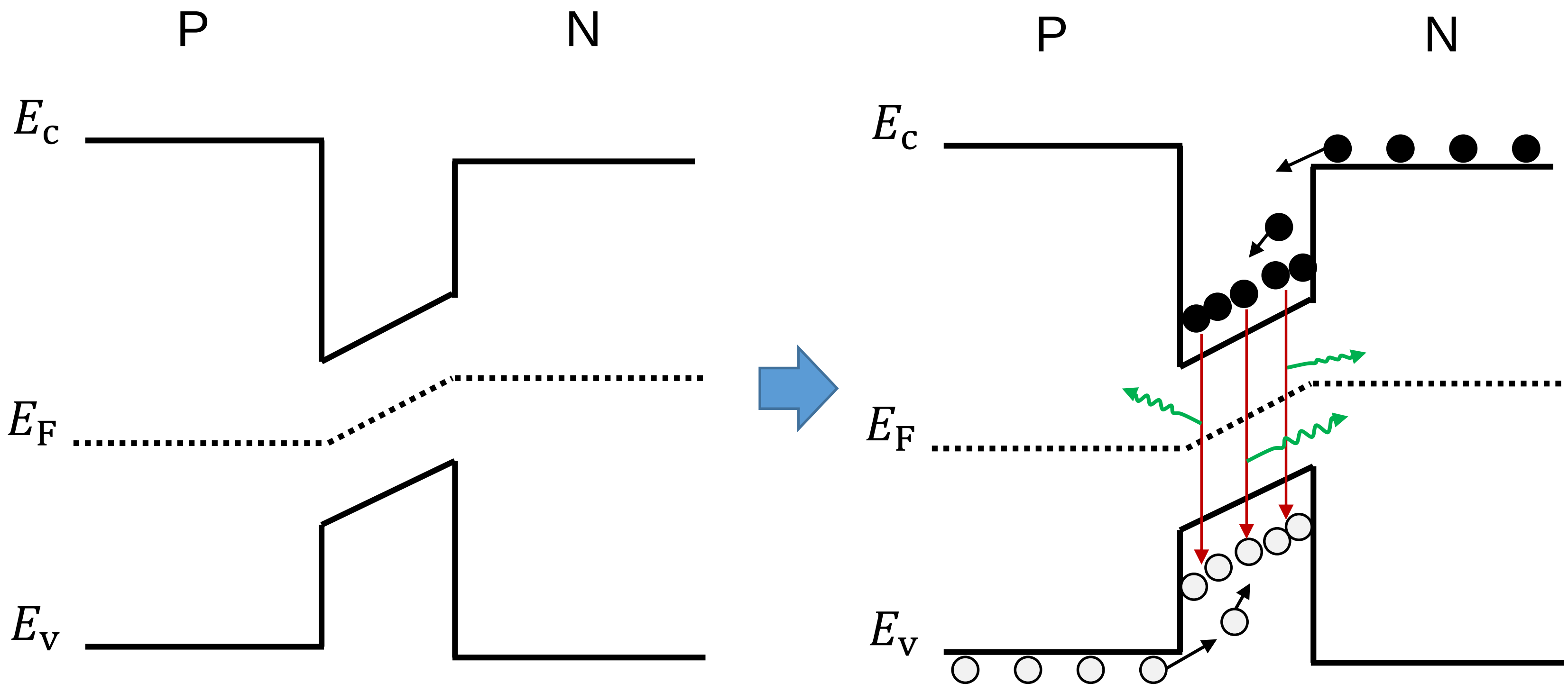
No forward bias



With forward bias



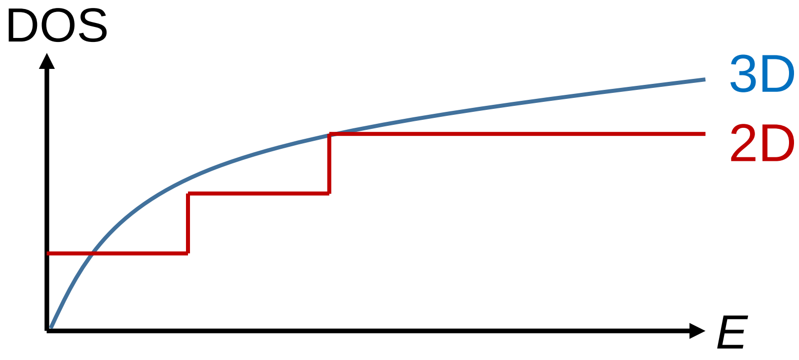
Working principle



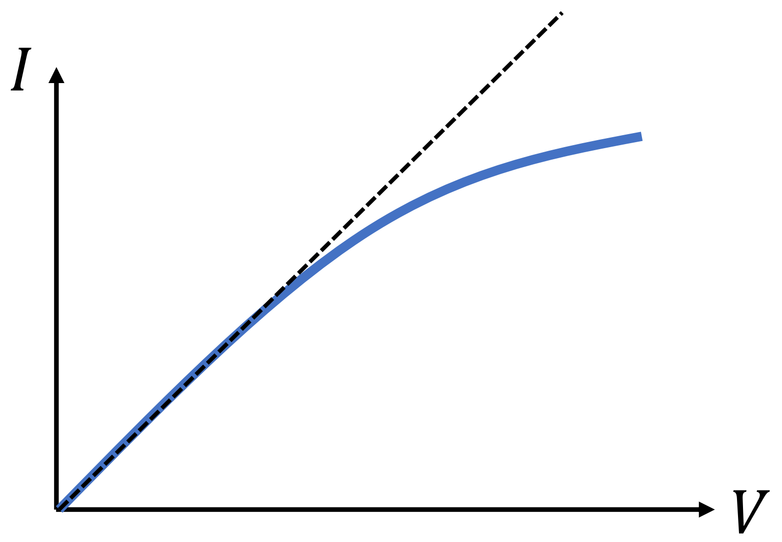
Merits of quantum well LEDs

- Electrons and holes are confined in a very narrow space, and hence unable to avoid each other, which encourages recombination.

- 2D electron gas: large density of states (constant) at lowest energies E_1 and E_1'; For 3D: $DOS \propto \sqrt{E}$

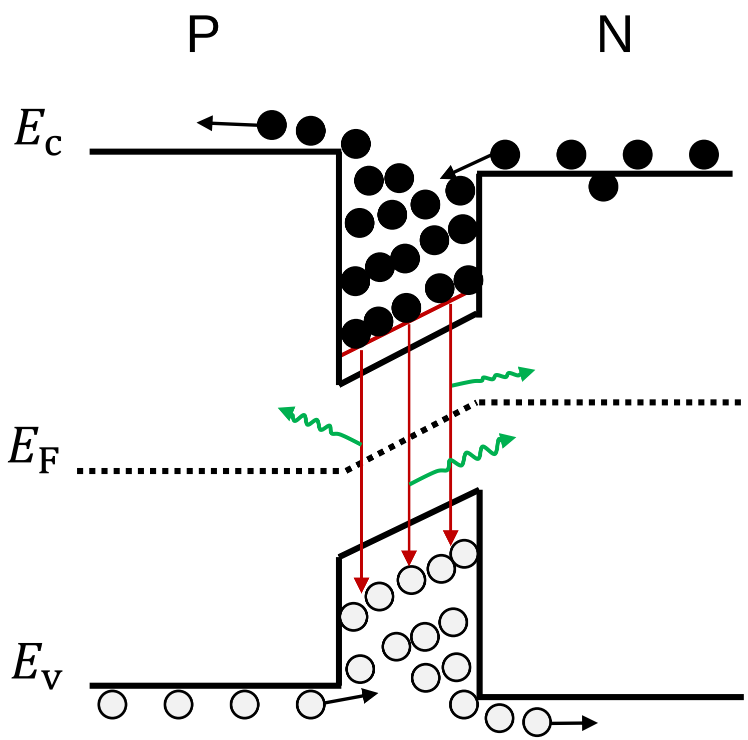


Ampere-voltage characteristics of quantum well LEDs



- At low bias: linear dependence of I-V
- At High bias: current becomes saturated

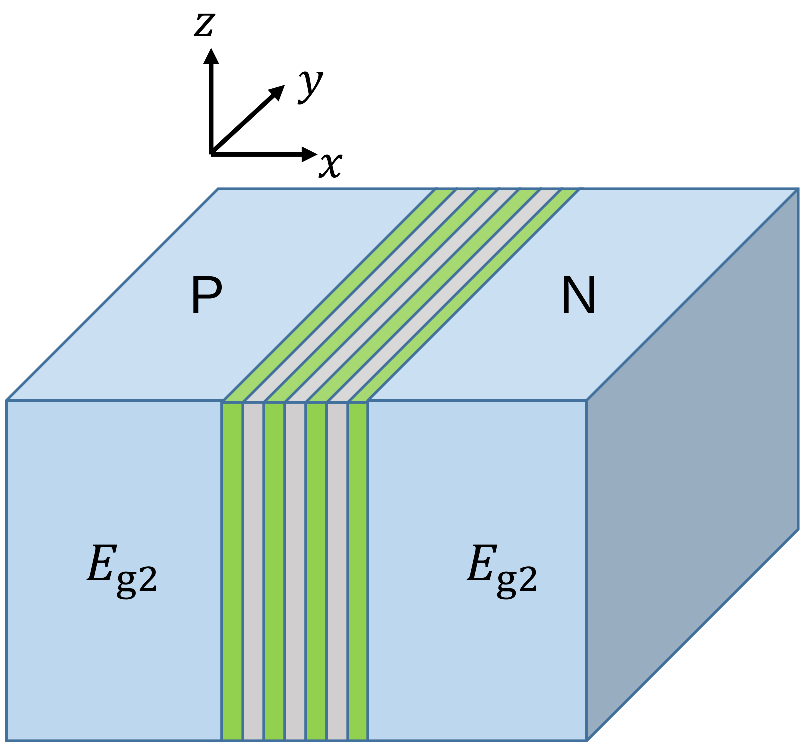
At high voltage bias

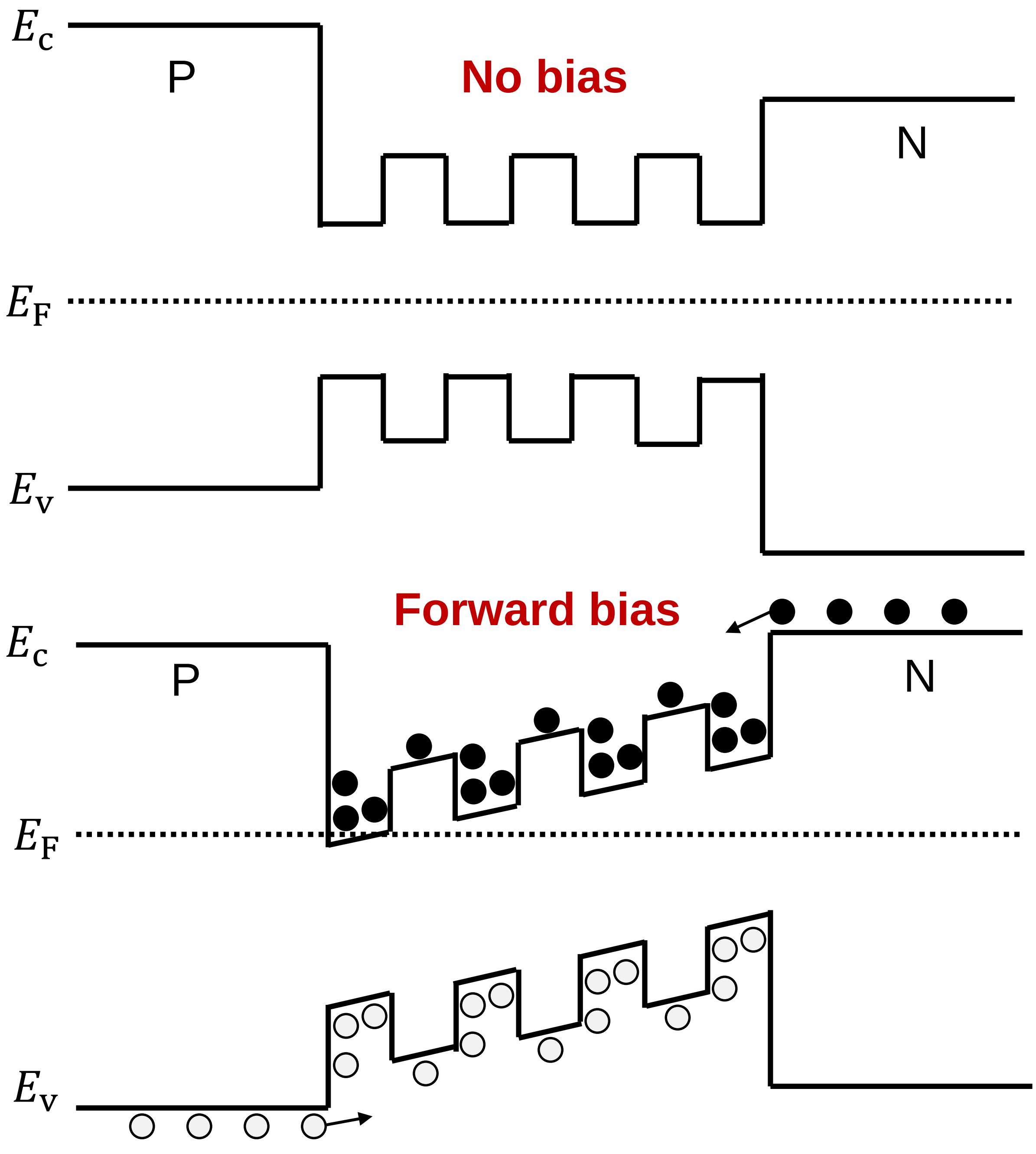


Quantum well are overflowed with electrons and holes.

How to solve/reduce this effect?

Multiple quantum well LEDs

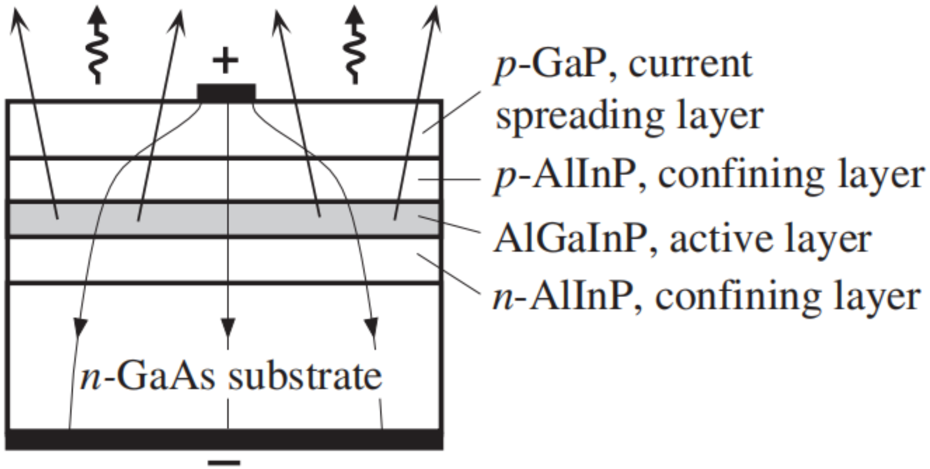




E_c
P
No bias
N
E_F
E_v
Forward bias
E_c
P
N
E_F
E_v

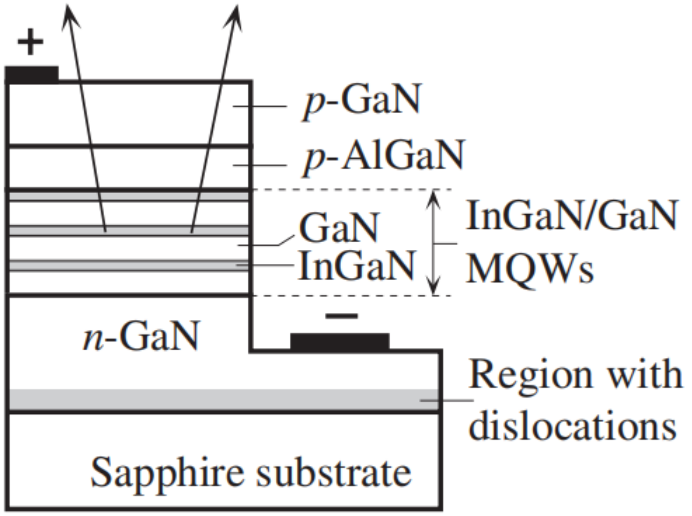
LED structure and materials

AlGaInP high intensity heterostructures



(a)

Multiple quantum well III-Nitride based LED



(b)

LED structure and materials

Table 6.4 Selected LED semiconductor materials

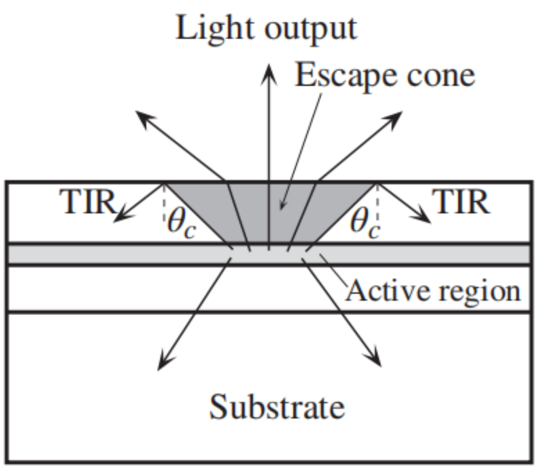
Semiconductor Active Layer	Structure	D or I	λ (nm)	PCE (%)	Comment
GaAs	DH	D	870–900	10	Infrared (IR)
$Al_xGa_{1-x}As$ ($0 < x < 0.4$)	DH	D	640–870	3–20	Red to IR
$In_{1-x}Ga_xAs_yP_{1-y}$ ($y \approx 2.20x$, $0 < x < 0.47$)	DH	D	1–1.6 μm	>10	LEDs in communications
$Al_xGa_{0.51-x}In_{0.49}P$	DH	D	570–630	>10	Amber, green, red. High luminous intensity
InGaN/GaN	MQW	D	450–530	5–20	Blue–green
AlGaN/GaN	MQW	D	240–360	1–30	UV
$GaAs_{1-y}P_y$ ($y < 0.45$)	HJ	D	630–870	<1	Red–IR
$GaAs_{1-y}P_y$ ($y > 0.45$) (N or Zn, O doping)	HJ	I	560–700	<1	Red, orange, yellow
SiC (doped)	HJ	I	460–470	0.02	Blue. Low efficiency
GaP (Zn-O)	HJ	I	700	<2	Red
GaP (N)	HJ	I	565	<1	Green

DH: double heterostructure

HJ: Homojunction

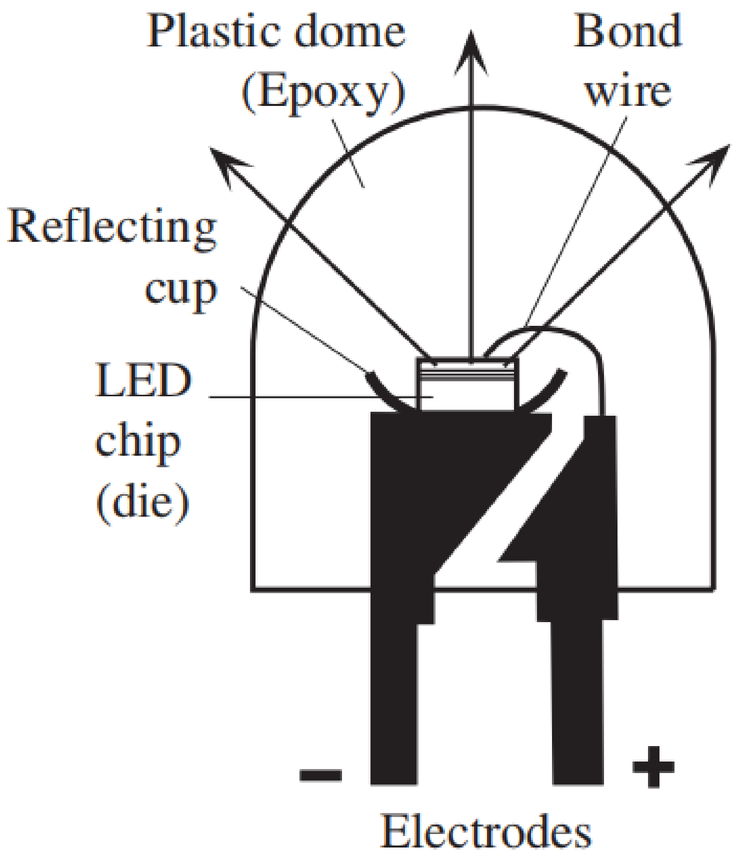
MQW: Multiple quantum well

LED structure and materials



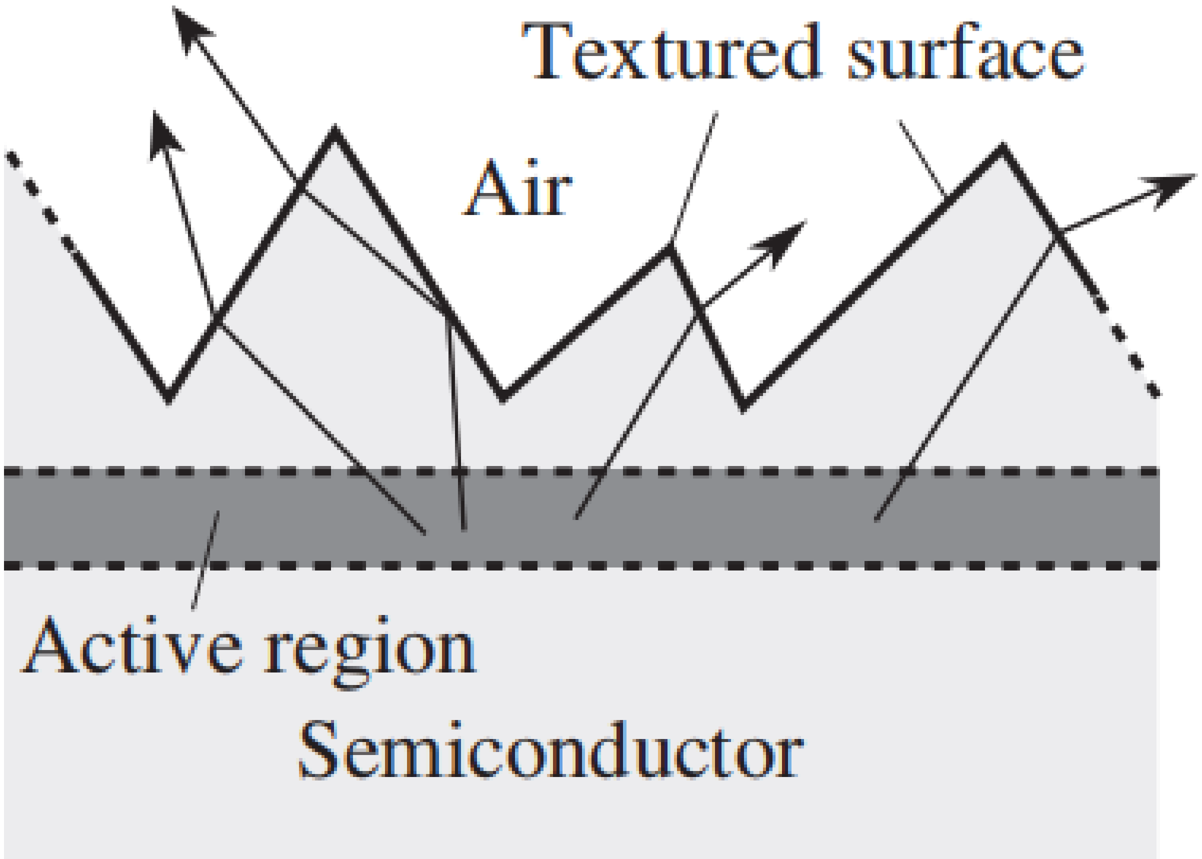
TIR: total internal reflection

Emitted light with angle larger than θ_c will be reflected



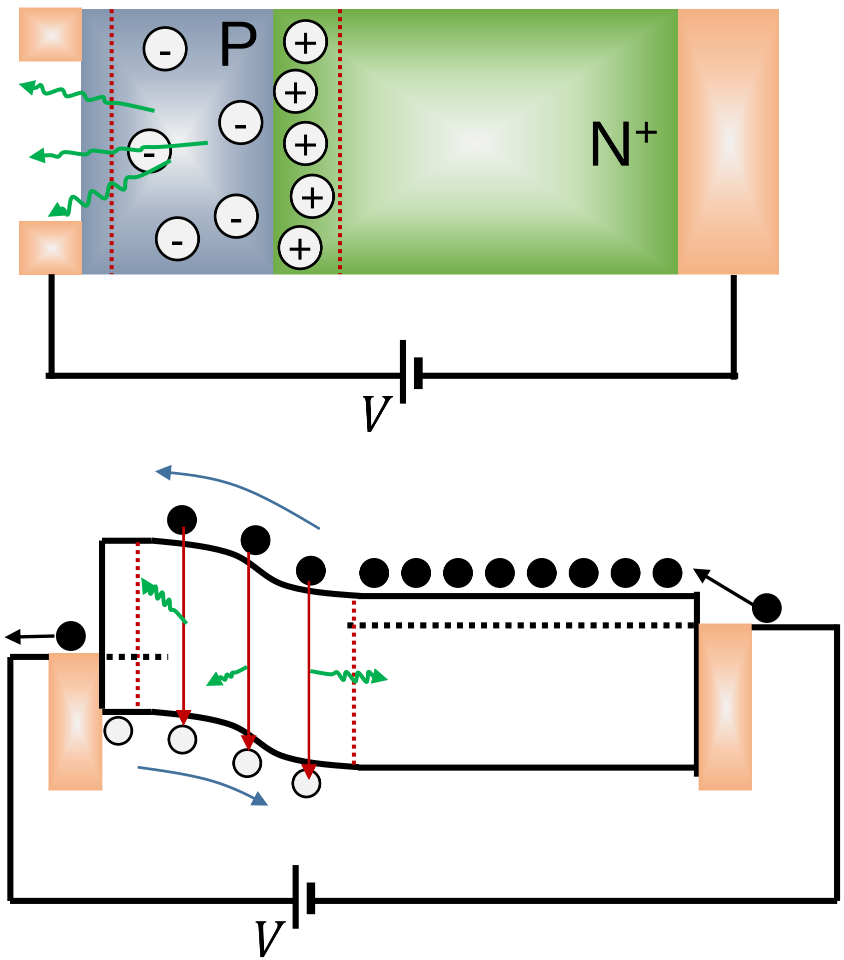
- Epoxy: high refractive index and domed surface

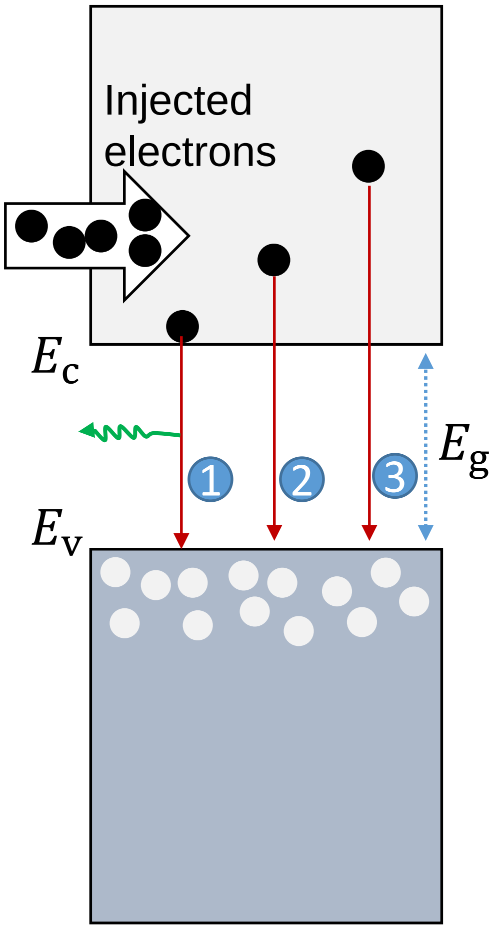
Textured surface to decrease TIR

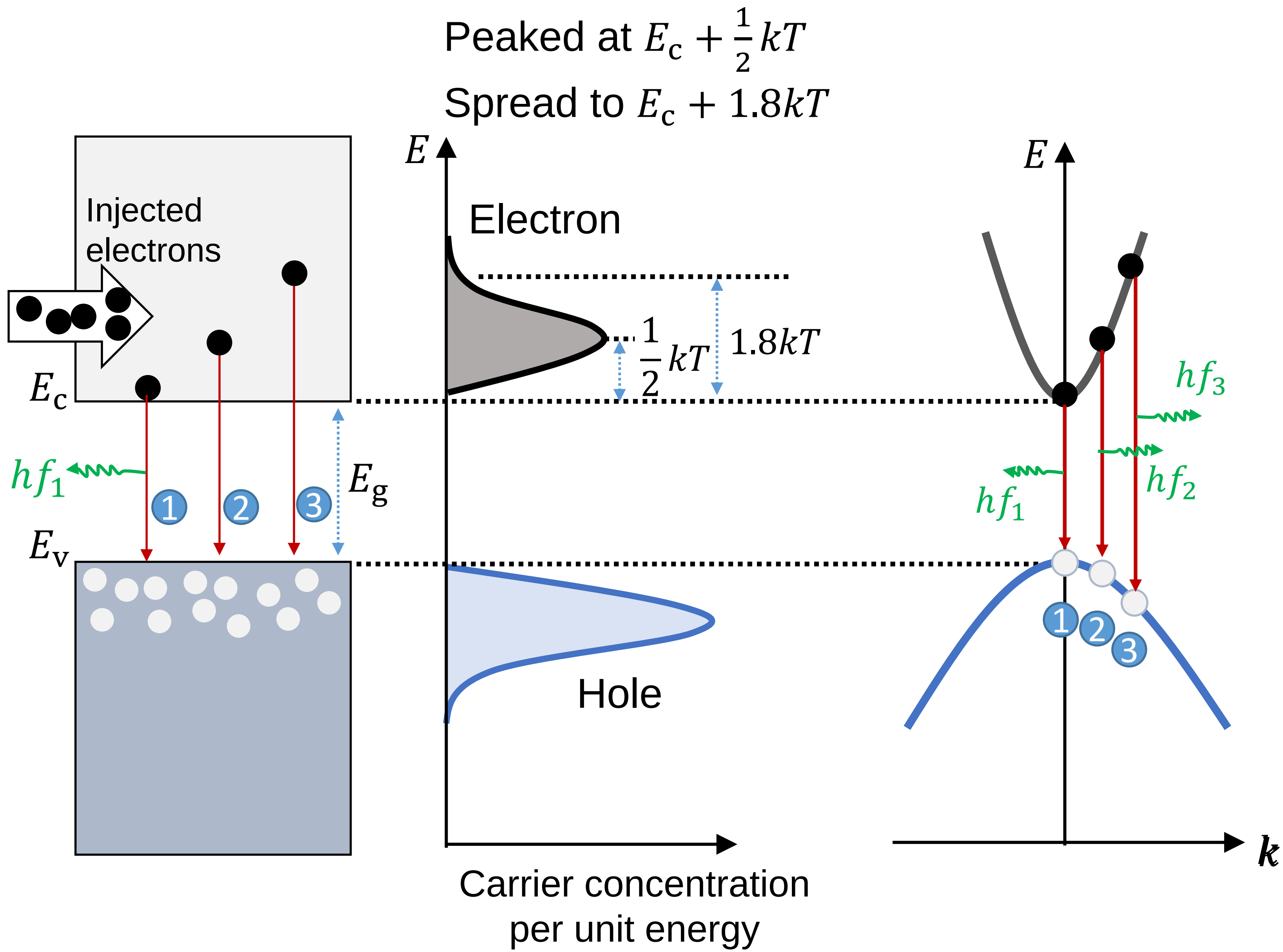


LED output spectrum

The emitted photon energy from an LED is not simply equal to the bandgap energy E_g.



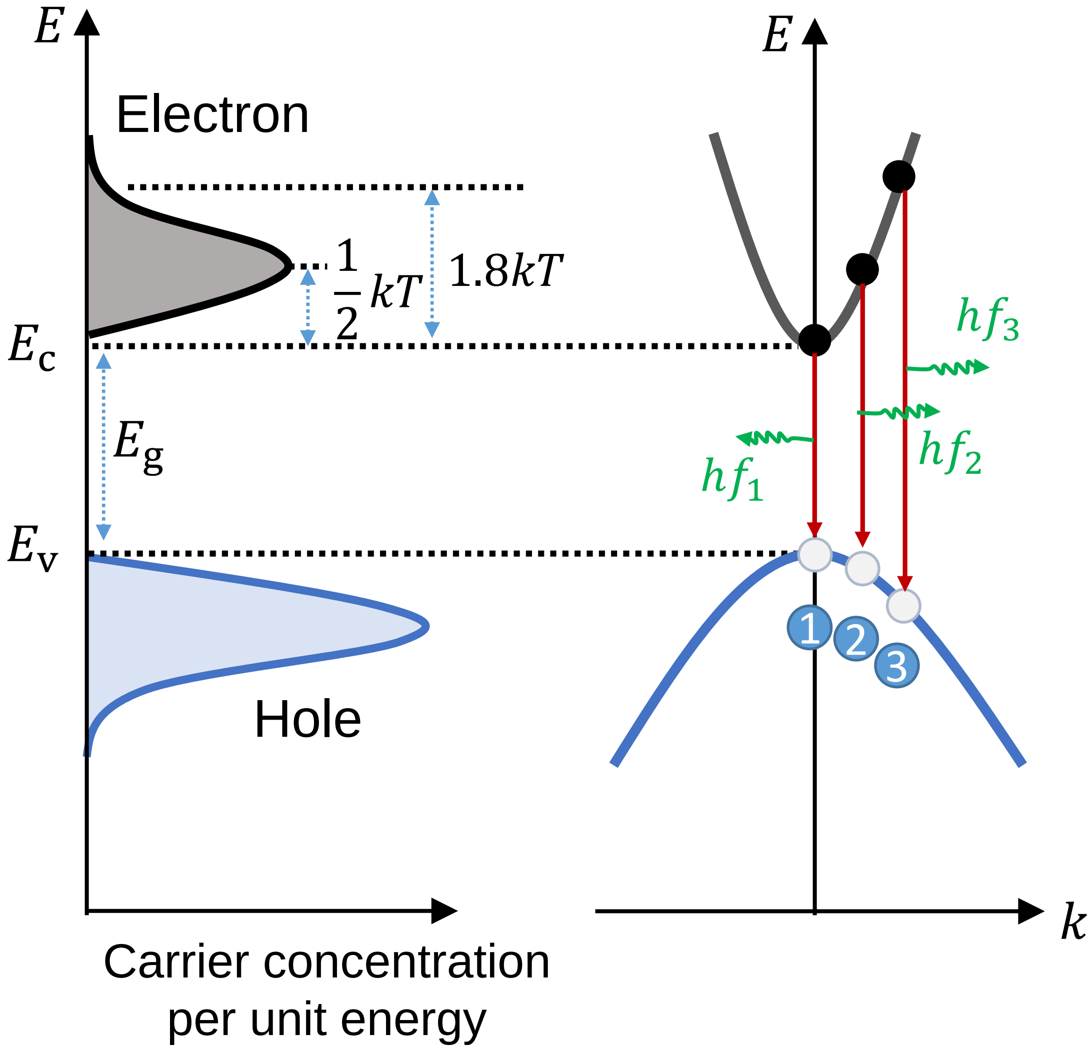


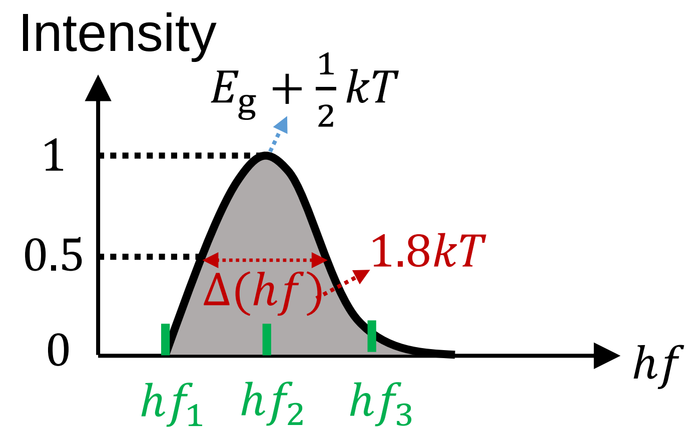


Peaked at $E_c + \frac{1}{2}kT$
Spread to $E_c + 1.8kT$
Injected electrons
E_c
E_v
hf_1
1
2
3
E_g
E
Electron
$\frac{1}{2}kT$
$1.8kT$
Hole
Carrier concentration per unit energy
E
hf_3
hf_2
hf_1
k

Peaked at $E_c + \frac{1}{2}kT$

Spread to $E_c + 1.8kT$

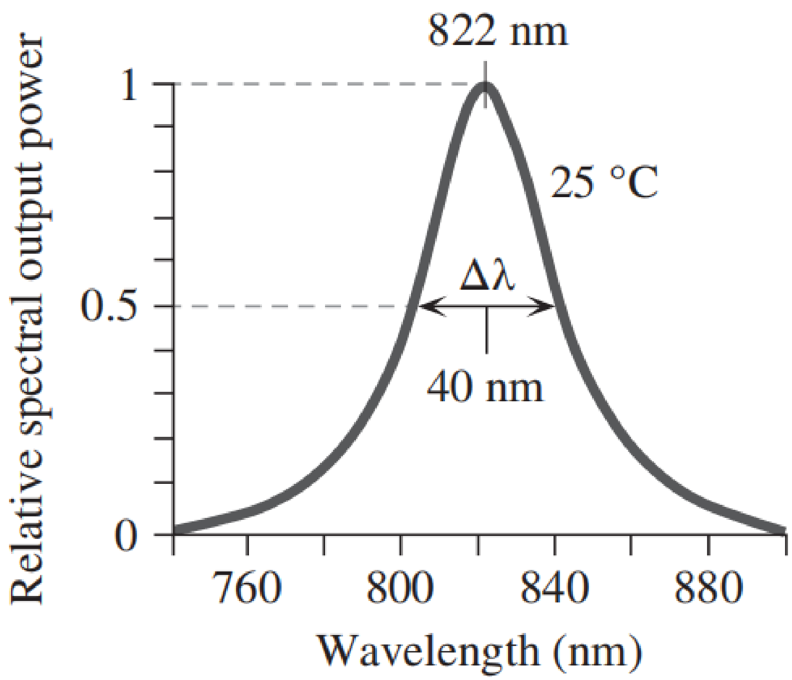




$$hf_1 = E_g$$

Δf or $\Delta\lambda$:
Full-width at half-maximum (FWHM)

Output spectral of AlGaAs IR LED



$$hf_0 = E_g + \frac{1}{2}kT$$

$$\Delta f = mkT$$

Theoretical value *m*=1.8

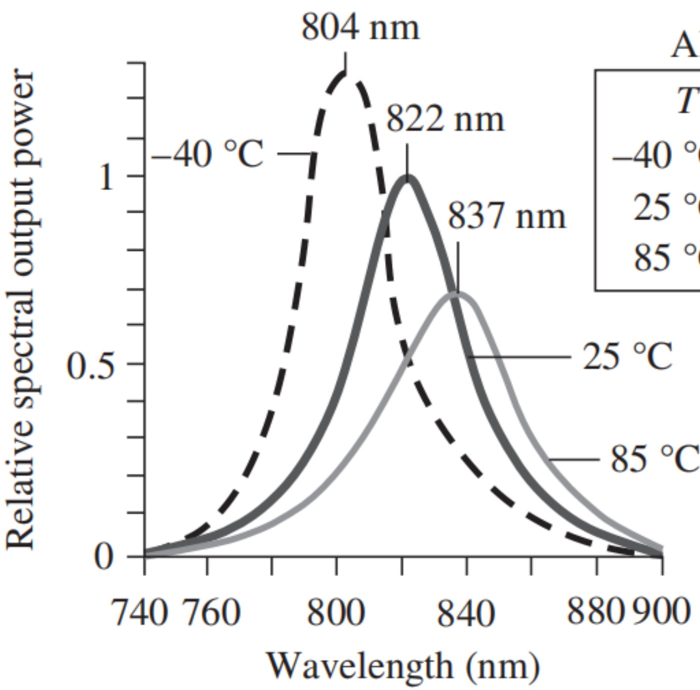
$$\Delta\lambda = {\lambda_0}^2 \frac{mkT}{hc}$$

Output spectral is less asymmetric:

Higher energy photons can be reabsorbed and emitted at lower energies.

Band edge in doped semiconductor is not sharp.

Output spectral of AlGaAs IR LED



$$hf_0 = E_g + \frac{1}{2}kT$$

Varshni equation
for semiconductors:

$$E_g = E_{g0} - \frac{AT^2}{B+T},$$

$$E_{g0} = E_g(T = 0K)$$

$$hf_0 = E_{g0} - \frac{AT^2}{B+T} + \frac{1}{2}kT$$

Brightness and efficiency of LEDs

Power conversion efficiency/external efficiency: η_{PCE}

$$\eta_{\mathrm{PCE}} = \frac{\text{Optical output power}}{\text{Electrical input power}} = \frac{P_{\mathrm{o}}}{IV}$$

Internal quantum efficiency: η_{IQE}

$$\eta_{\mathrm{IQE}} = \frac{\text{Rate of radiative recombination}}{\text{Total rate of recombination (radiative + nonradiative)}}$$

τ_{r}^{-1}: Mean life time of an electron before it recombines radiatively.

τ_{nr}^{-1}: Mean life time of an electron before it recombines nonradiatively.

$$\eta_{\mathrm{IQE}} = \frac{\tau_{\mathrm{r}}^{-1}}{\tau_{\mathrm{r}}^{-1} + \tau_{\mathrm{nr}}^{-1}}$$

Extraction efficiency: η_{EE}

$$\eta_{\text{EE}} = \frac{\text{Photons emitted externally from the device}}{\text{Photons generated internally by recombination}}$$

External quantum efficiency: η_{EQE}

$$\eta_{\text{EQE}} = \frac{\text{Photons emitted externally per seconds(Photon flux)}}{\text{Electrons flowing into the device per seconds}}$$

$$= \frac{P_{\text{o}}/hf}{I/e}$$

Relation between η_{EQE}, η_{IQE}, and η_{EE}:

$$\eta_{\text{EQE}} = \eta_{\text{IQE}} \times \eta_{\text{EE}}$$

Q: $\eta_{\mathrm{EQE}} \geq \eta_{\mathrm{PCE}}$ or $\eta_{\mathrm{EQE}} \leq \eta_{\mathrm{PCE}}$ or ...?

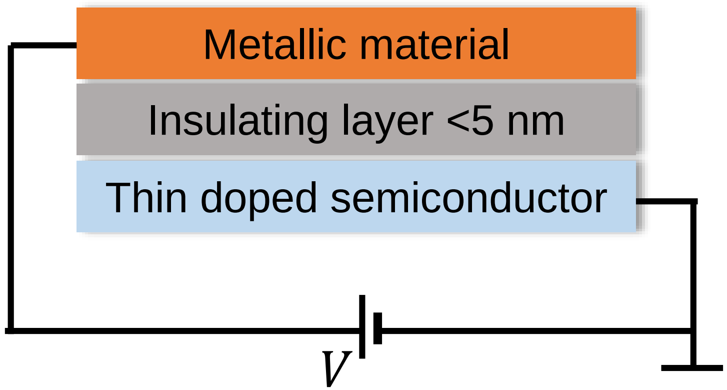
External quantum efficiency: η_{EQE}

$$\eta_{\mathrm{EQE}} = \frac{\text{Photons emitted externally per seconds (Photon flux)}}{\text{Electrons flowing into the device per seconds}} = \frac{P_{\mathrm{o}}/hf}{I/e}$$

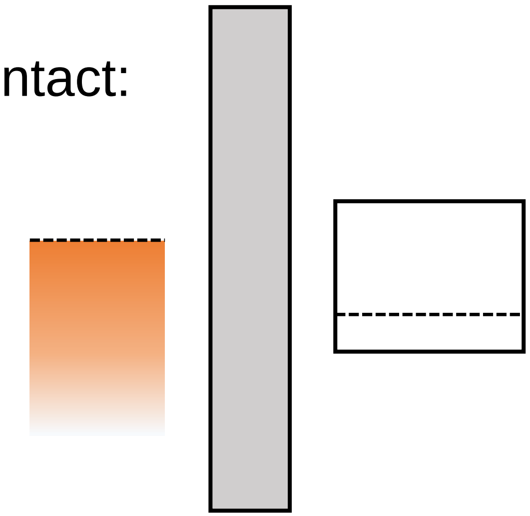
Power conversion efficiency/external efficiency: η_{PCE}

$$\eta_{\mathrm{PCE}} = \frac{\text{Optical output power}}{\text{Electrical output power}} = \frac{P_{\mathrm{o}}}{IV}$$

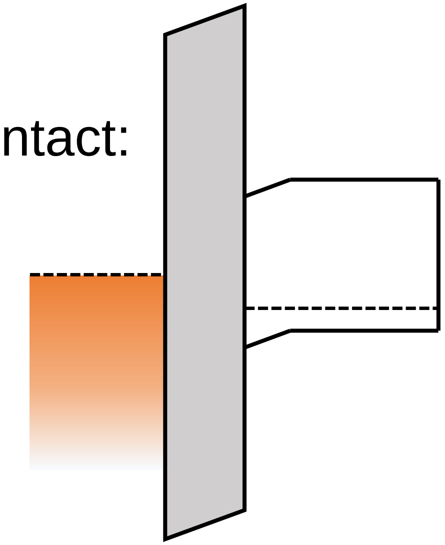
Tunneling LEDs 隧穿发光二极管

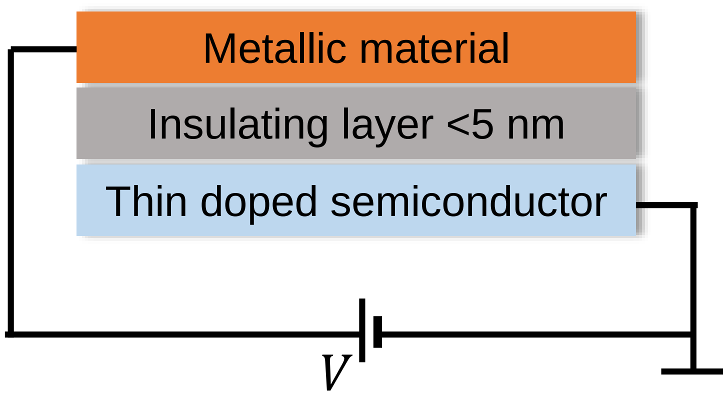


Before contact:

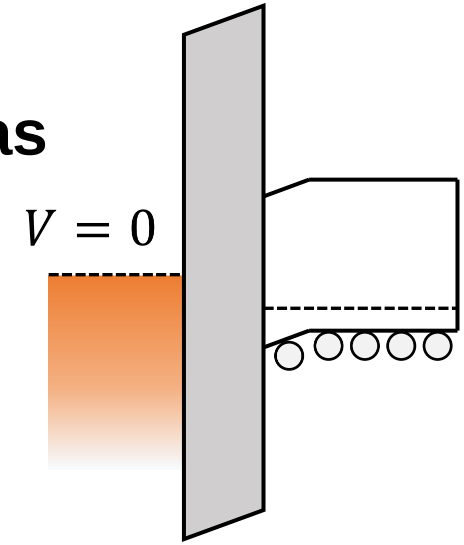


In contact:

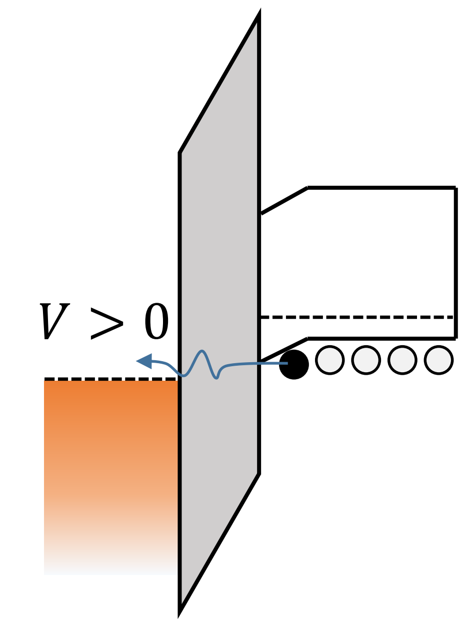


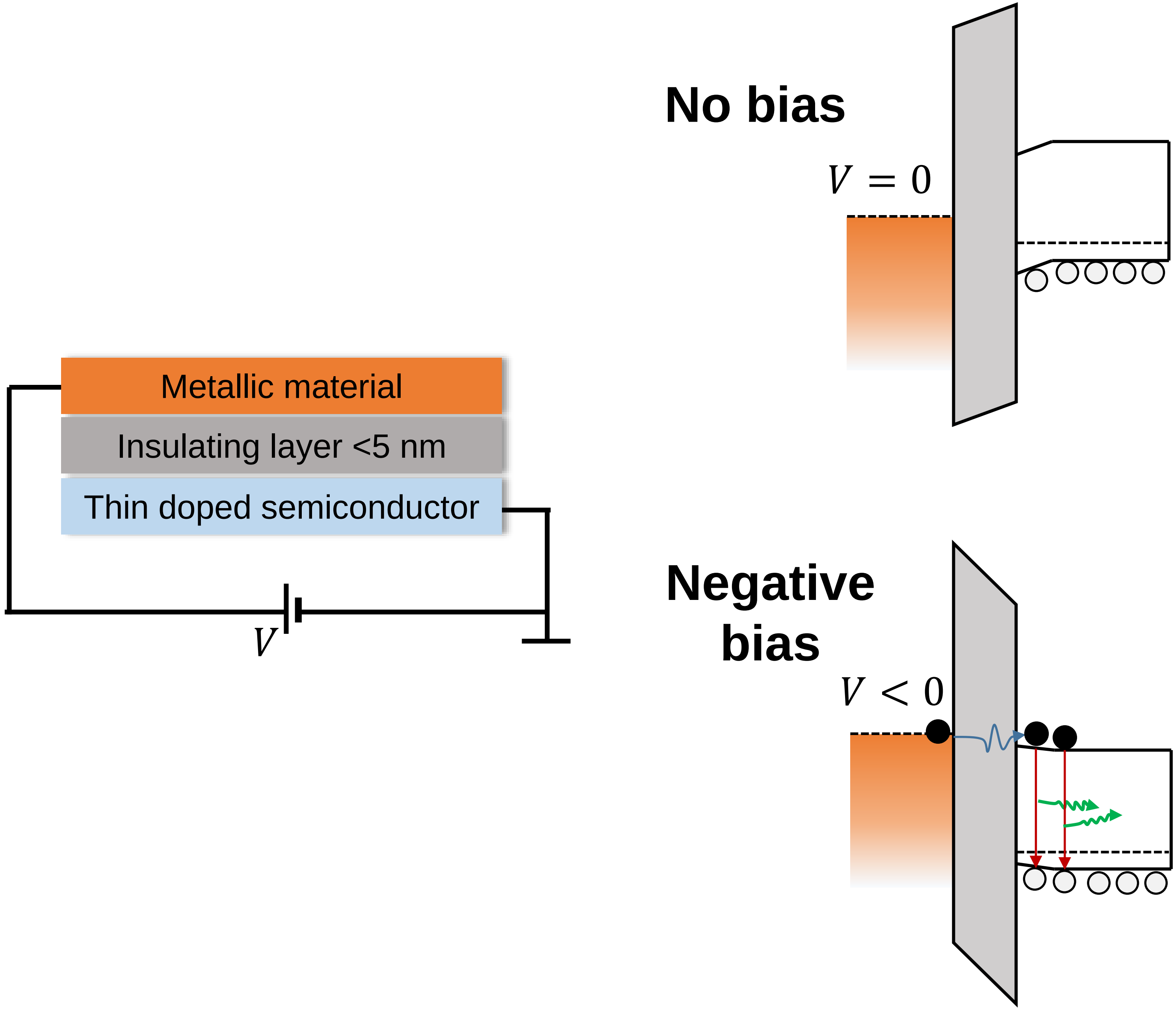


No bias



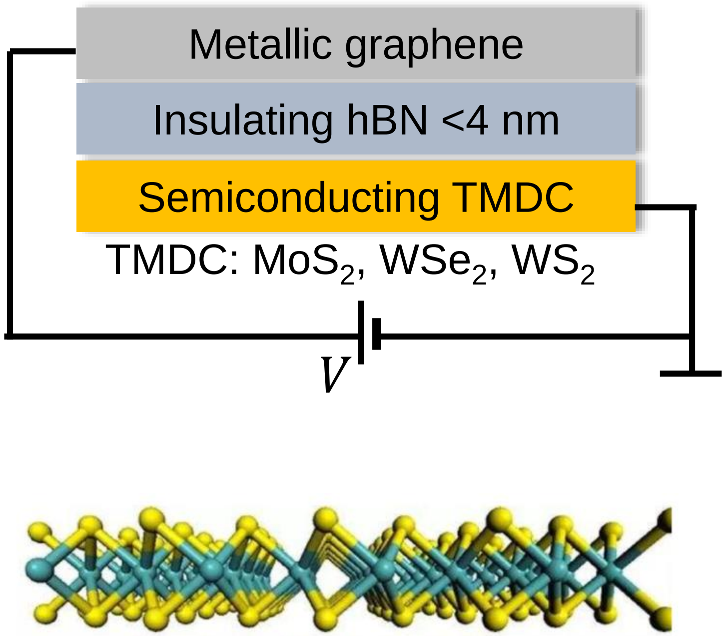
Positive bias

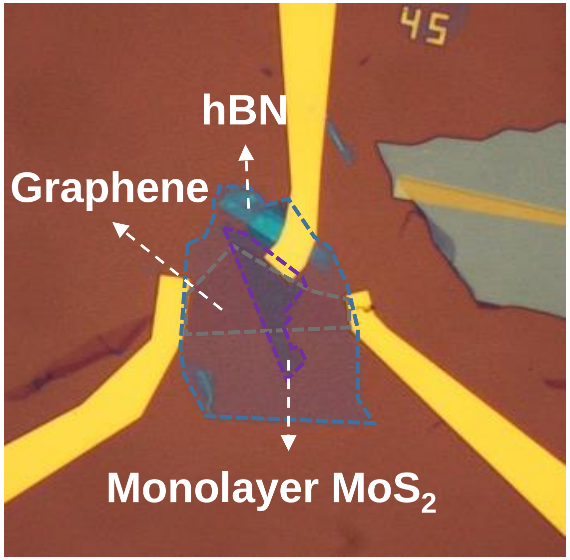


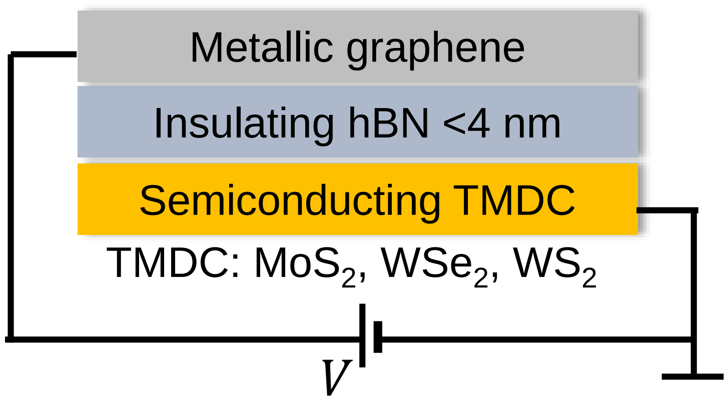


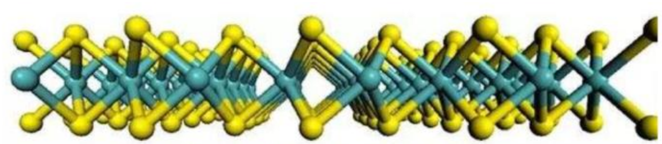
Metallic material
Insulating layer <5 nm
Thin doped semiconductor
V
No bias
V = 0
Negative bias
V < 0

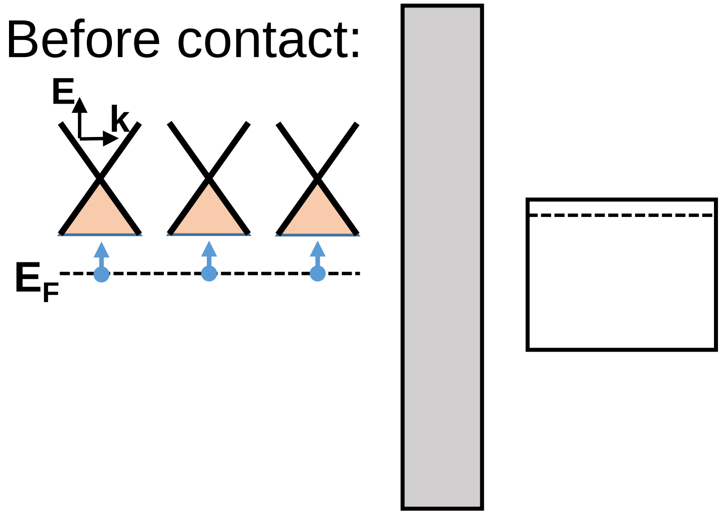
Tunneling LEDs made from two-dimensional materials

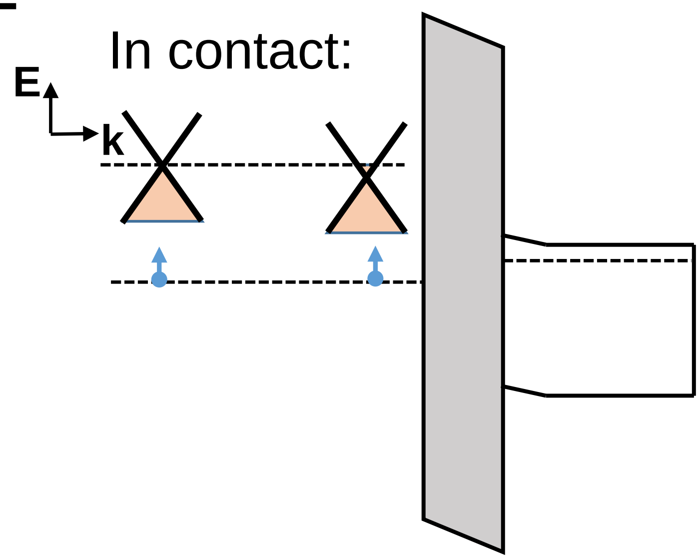


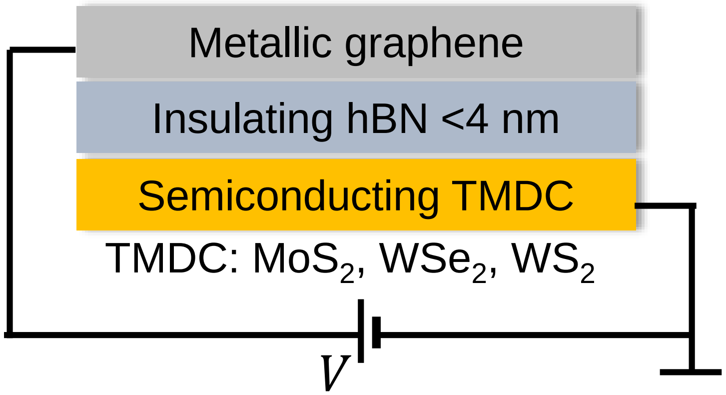


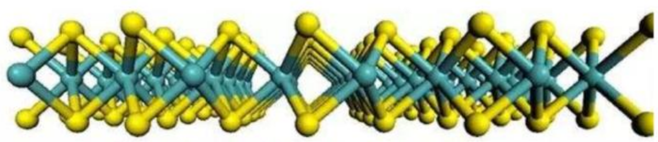

Metallic graphene
Insulating hBN <4 nm
Semiconducting TMDC
TMDC: MoS2, WSe2, WS2
V



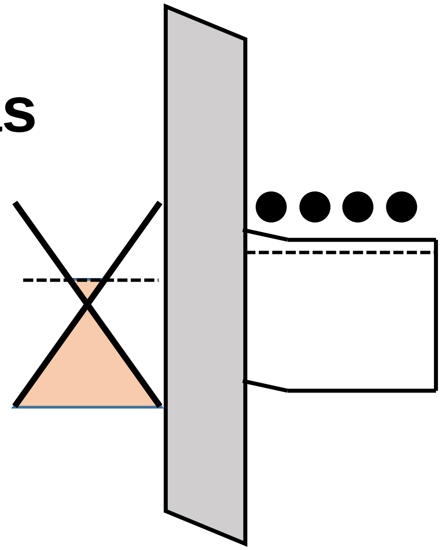

Before contact:
E
k
EF


In contact:
E
k

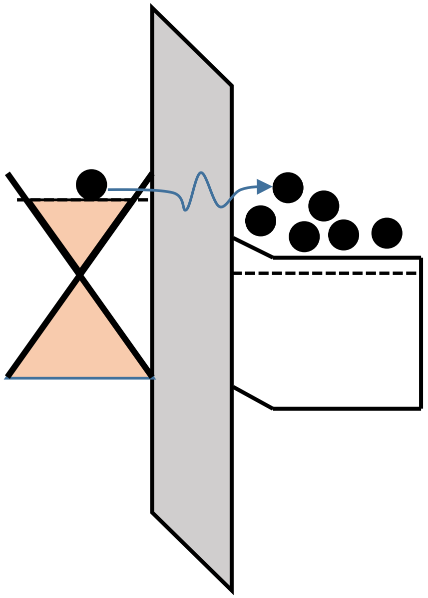


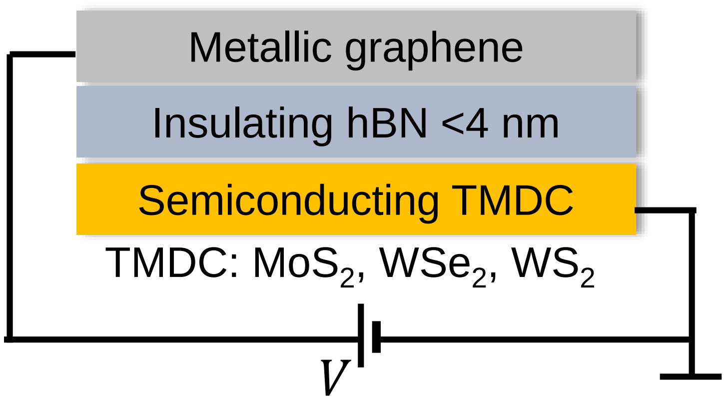


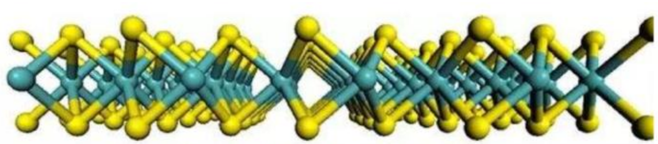
No bias



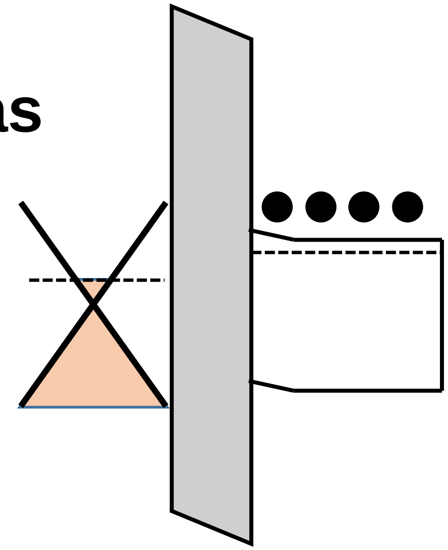
Negative bias



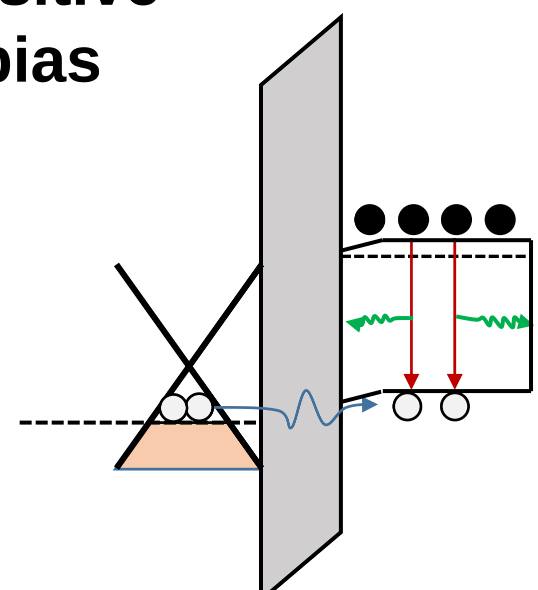




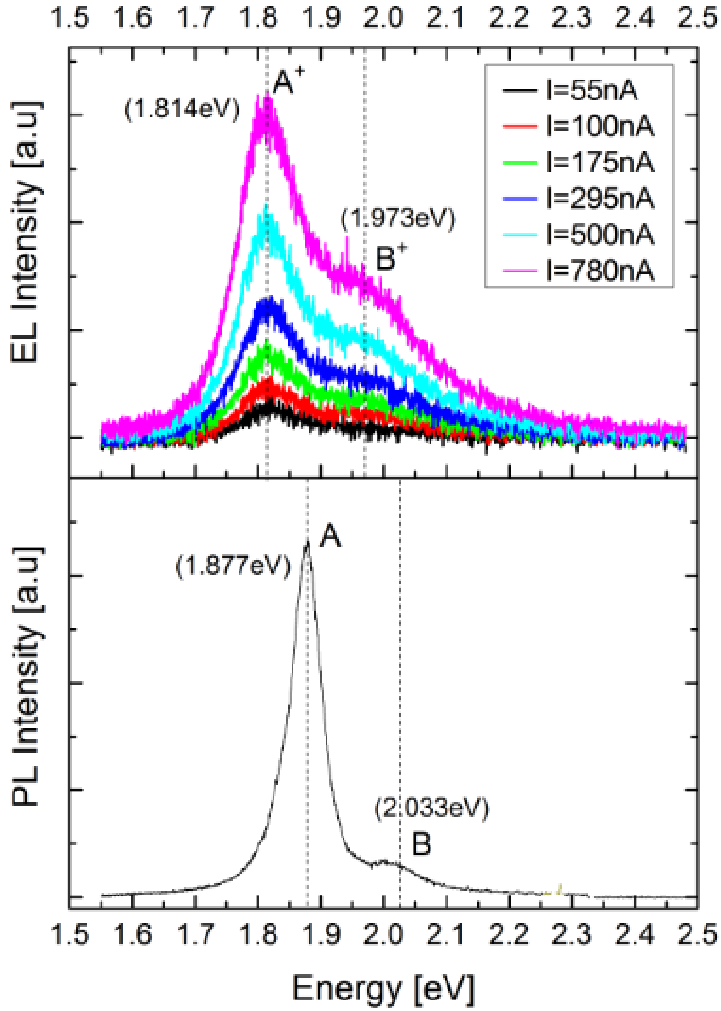
No bias



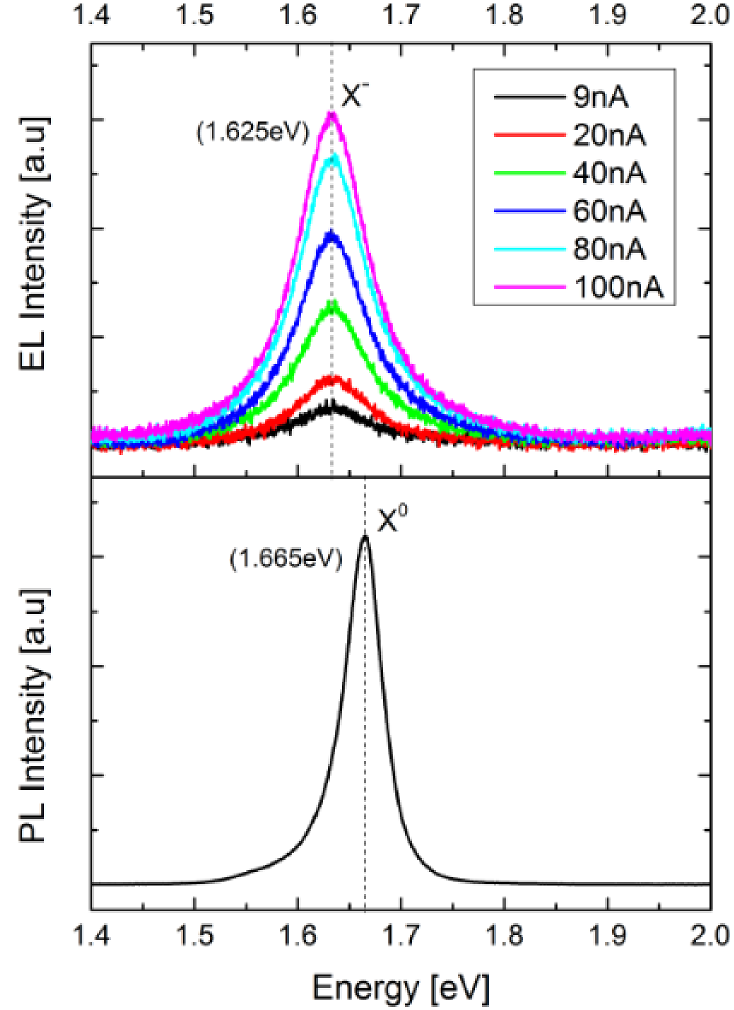
Positive bias



MoS_2-based LED



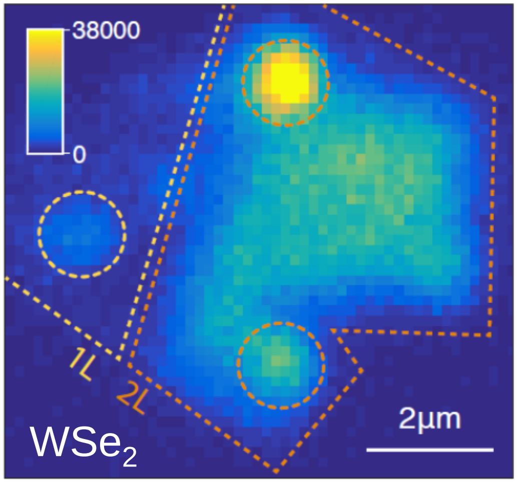
WSe_2-based LED



Quantum LED/ Single photon light source

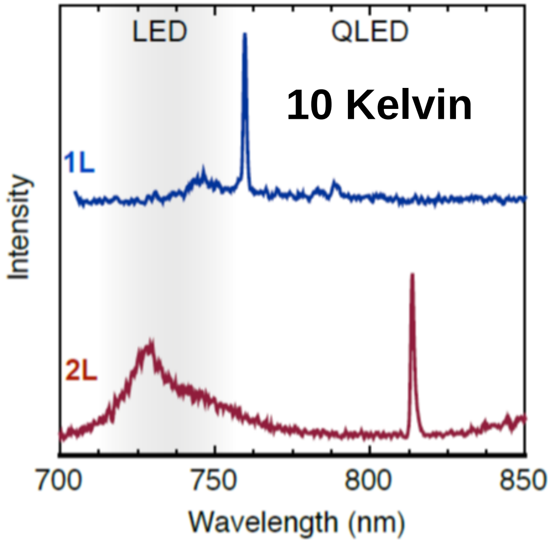
Send the device to low temperature: 10 Kelvin

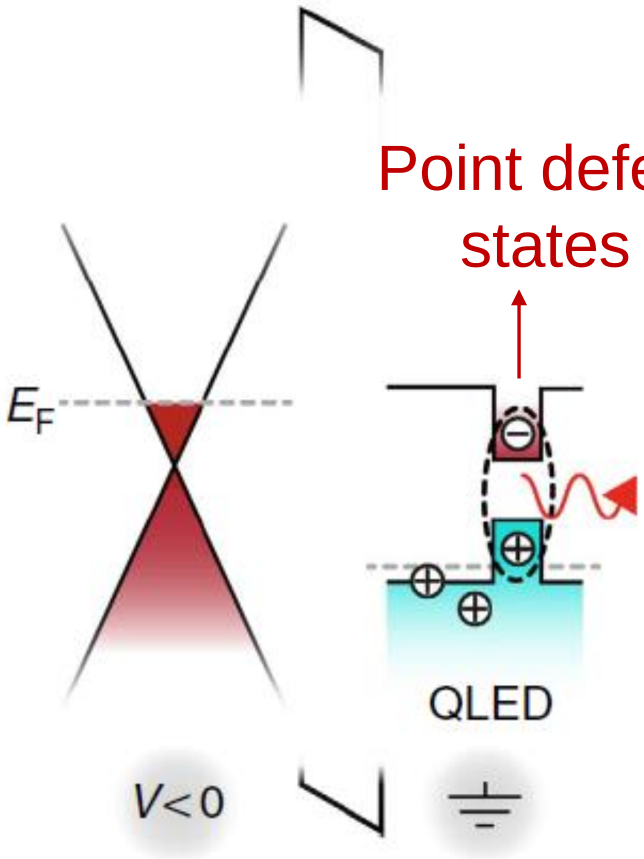
EL mapping



10 Kelvin

FWHM: 0.8 and 3 nm





Point defect states

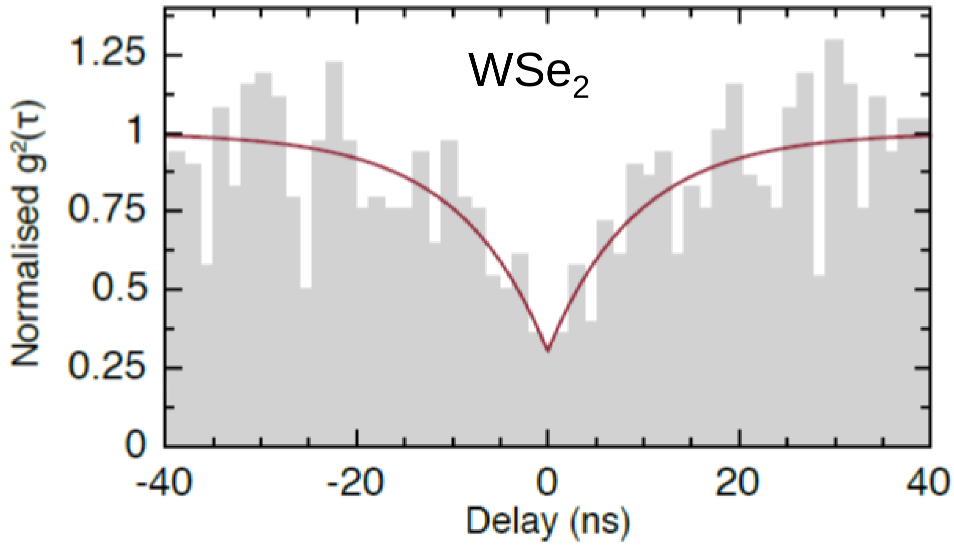
Density of states: 1

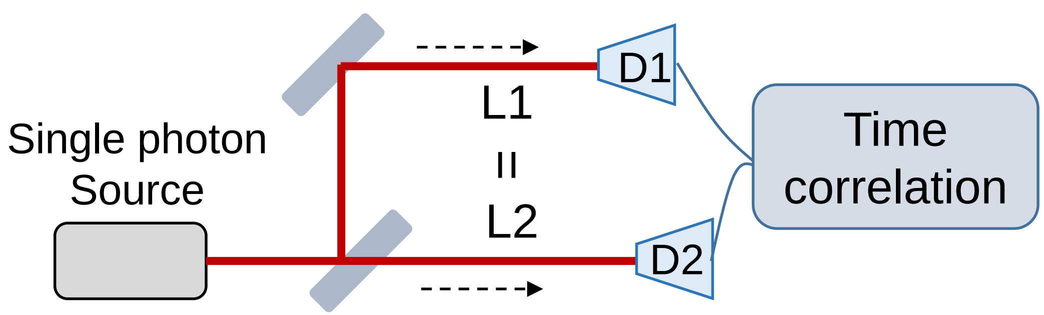
At each time, only one electron can fill the state.

Only one photon can emit at each time.

Phase of photons are all the same.

Intensity-correlation $g^2(\tau)$ measurement





Quantum communication/computation needs single photon light source.

量子通信和量子计算需要单光子源。