Semiconductor Devices

1947 1st transistor invented
半導體元件 (Semiconductor Devices)

- 電子元件 (electronic devices)
  - 二極體 (diode)
    - 雙極電晶體 (bipolar junction transistor, BJT)
    - 場效電晶體 (field effect transistor, FET)

- 光電元件 (opto-electronic devices)
  - 通電發光：
    - 發光二極體 (light emitting diode, LED)
    - 雷射二極體 (laser diode)
  - 吸光發電：
    - 光檢測器 (photo-detector)
    - 太陽電池 (solar cell)
光電效應 (Photoelectric Effect):

C : metal plate, cathode (陰極)
A : anode (陽極), collector
V : retarding voltage
Ammeter : to measure photoelectron current

C : metal plate, cathode (真空管)
A : anode (真空管), collector
V : retarding voltage
Ammeter : to measure photoelectron current

( with the same light Intensity )

Stopping potential, $V_o \propto \nu$

Frequency, $\nu$

Cs
Cu
\( h\nu = E_k + E_b \),

\[ \begin{aligned}
E_k : & \text{ K.E. of the ejected electron} \\
E_b : & \text{ binding energy of the electron}
\end{aligned} \]

with fixed \( \nu \), if \( E_b \downarrow \rightarrow E_k \uparrow \)

\( \Rightarrow E_{k,\text{max}} = h\nu - \Phi \), \( \Phi : \text{ minimum binding energy} \)

\( \rightarrow \text{ work function of the metal} \)

• work function \( \rightarrow \) the energy difference between the vacuum level and the Fermi level

\[ \begin{aligned}
\phi_2 & \quad \text{Metal 2} \\
E_{F_2} & \\
\phi_1 & \quad \text{Metal 1} \\
E_{F_1} & \\
\end{aligned} \]

\[ \begin{aligned}
V_o & \propto \nu \\
\text{Cs} & \\
\text{Cu} & \\
\end{aligned} \]

( with the same \( I \) )

\[ \begin{aligned}
\text{Frequency}, \nu \\
\end{aligned} \]
• when two metals are placed in contact:
  e\textsuperscript{-} near E\textsubscript{F1} have higher energies
  \(\rightarrow\) net flow of e\textsuperscript{-} from metal 1 to metal 2
  \(\rightarrow\) until both metal have a common Fermi level

• metal 2 gains some e\textsuperscript{-} and becomes negatively charged,
  and metal 1 becomes positively charged due to e\textsuperscript{-} loss
  \(\rightarrow\) an electrical potential difference established across the junction
  \(\rightarrow\) contact potential V\textsubscript{c}

• a general principle: The Fermi levels of two conducting solids,
  including metals and semiconductors, in contact must be equal at
  equilibrium condition.
• net diffusion of e\textsuperscript{-} from n region into p region
  \rightarrow recombine with holes in the p region

• net diffusion of holes from p region into n region
  \rightarrow recombine with e\textsuperscript{-} in the n region

• the regions near both sides of the contact junction is depleted of free carriers, i.e. e\textsuperscript{-} and holes
  \rightarrow depletion region with high resistivity
depletion region, also called space charge region

\[ \rightarrow \{ \begin{align*} & \text{positively charged layer from ionized donors on } n\text{-side} \\ & \text{negatively charged layer from ionized acceptors on } p\text{-side} \end{align*} \]

\[ \rightarrow \text{an internal electrical field which prevent further carrier diffusion} \]

\[ \rightarrow \text{equilibrium established very quickly} \]
- charged layer → create a potential difference $V_c$ at the junction

This corresponds to an upward shift of the electronic energy bands in the p side.
- charged layer $\rightarrow$ create a potential difference $V_c$ at the junction
- $V_c$ is associated with the requirement that the Fermi level be the same on both sides of the junction:

![Diagram showing potential difference and energy bands](image)

- Corresponds to an upward shift of the electronic energy bands in the p side

![Diagram showing potential energy](image)
• charged layer $\rightarrow$ create a potential difference $V_c$ at the junction

• $V_c$ is associated with the requirement that the Fermi level be the same on both sides of the junction:

$$|e| V_c = E_{Fn} - E_{Fp}$$

![Diagram showing potential difference and Fermi levels across a junction.](image)

The diagram illustrates the shift of electronic energy bands in the p side, corresponding to an upward shift of the Fermi level in the p side, due to the potential difference $V_c$. The Fermi level $E_F$ is shown for both the n-side and p-side, with $E_{Fn}$ and $E_{Fp}$ indicating the Fermi levels for the n-type and p-type regions, respectively.
• charged layer → create a potential difference $V_c$ at the junction

• $V_c$ is associated with the requirement that the Fermi level be the same on both sides of the junction:

$$|e|V_c = E_{F_n} - E_{F_p}$$

• in a doped semiconductor, $E_F$ depends on impurity concentration and temp.
  $\rightarrow V_c$ depends on impurity conc. and temp.

• typical $V_c$ in Si: 0.6 ~ 0.9 eV @ room T
• Equilibrium currents:
  consider first the e\(^-\) flow
  ( case for holes flow is similar )

\[ N_e = N_c \exp \left[ - \frac{(E_g - E_F)}{k_B T} \right] \]

\[ i (p\rightarrow n) \propto N_e \]

\[ i (p\rightarrow n) = A \exp \left( - \frac{E_1}{k_B T} \right) \]

\[ i (n\rightarrow p) = A N_e f( E \geq |e| V_c ) \]

\[ f( E \geq |e| V_c ) = \exp \left( - \frac{|e| V_c}{k_B T} \right) \]

\[ i (n\rightarrow p) = A \exp \left[ - \frac{(E_2 + |e| V_c)}{k_B T} \right] = A \exp \left( - \frac{E_1}{k_B T} \right) = i (p\rightarrow n) \]

\[ i (n\rightarrow p) = i (p\rightarrow n) \Rightarrow \text{the net e}^- \text{ current is zero at equilibrium} \]

( similarly, the net hole current is also zero at equilibrium )

• \( i (p\rightarrow n) \) not affected by \( V_c \)

\[ i (n\rightarrow p) \propto \exp \left( - \frac{|e| V_c}{k_B T} \right) , \text{ and since} \]

\( V_c \) can be changed by externally applied voltages

\( \Rightarrow i (n\rightarrow p) \) can be changed by externally applied voltages
• Forward bias characteristics:
  depletion region has high resistance
  → $V_o$ appears almost entirely across the depletion region
  → junction potential barrier reduced to $V_c - V_o$
• Reverse bias characteristics:

  depletion region has high resistance
  \[ \rightarrow V_o \text{ appears almost entirely across the depletion region} \]
  \[ \rightarrow \text{junction potential barrier increased to } V_c + V_o \]
- Current-voltage (I-V) characteristics:

consider first only the e\(^{-}\) flow

\[ i = i(n \rightarrow p) - i(p \rightarrow n) \]

\[ i(n \rightarrow p) = A \exp \left( - \frac{E_2 + |e|(V_c - V_o)}{k_BT} \right) \]

\[ i(p \rightarrow n) = A \exp \left( - \frac{E_1}{k_BT} \right) \]

\[ i = A \exp \left( - \frac{E_2 - |e|(V_c - V_o)}{k_BT} \right) - A \exp \left( - \frac{E_1}{k_BT} \right) \]

\[ E_2 + |e|V_c = E_1 \]

\[ i = A \exp \left( - \frac{E_1 - |e|V_o}{k_BT} \right) - A \exp \left( - \frac{E_1}{k_BT} \right) \]

\[ = A \exp\left( - \frac{E_1}{k_BT} \right) \left\{ \exp(\frac{|e|V_o}{k_BT}) - 1 \right\} \]

\[ = i_o \left\{ \exp(\frac{|e|V_o}{k_BT}) - 1 \right\} \quad \leftarrow \text{diode equation} \]
Current-voltage (I-V) characteristics:

consider first only the e⁻ flow

\[ i = i(n\rightarrow p) - i(p\rightarrow n) \]

\[ i(n\rightarrow p) = A \exp \left( - \frac{E_2 + |e|(V_c - V_o)}{k_B T} \right) \]

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\[ E_2 + |e|V_c = E_1 \]

\[ i = A \exp \left( - \frac{E_1 - |e|V_o}{k_B T} \right) - A \exp \left( - \frac{E_1}{k_B T} \right) \]

\[ = A \exp(- \frac{E_1}{k_B T}) \left[ \exp\left( \frac{|e|V_o}{k_B T} \right) - 1 \right] \]

\[ = i_o \left[ \exp\left( \frac{|e|V_o}{k_B T} \right) - 1 \right] \leftarrow \text{diode equation} \]
• Current-voltage (I-V) characteristics:

 例 : @ room temp. \( \Rightarrow k_B T \approx 0.025 \text{ eV} \)
  when \( V_o = 0.1 \text{ V} \) reverse bias
  \( \Rightarrow i = i_o \left( e^{-4} - 1 \right) = -0.98 i_o \)
  when \( V_o = 0.1 \text{ V} \) forward bias
  \( \Rightarrow I = i_o \left( e^4 - 1 \right) = 54 i_o \)
  when \( V_o = 0.5 \text{ V} \) forward bias
  \( \Rightarrow I = i_o \left( e^{20} - 1 \right) = 4.8 \times 10^8 i_o \)

• in practice, other resistance in the circuit will limit the current at high forward bias voltage
  
  \( \Rightarrow \) In most circuits used in computers and other digital instruments, \( i \leq \) a few mA
  
  \( \Rightarrow \) for most Si diodes, \( V_o \) (操作電壓) \( \leq 0.6 \sim 0.7 \text{ V} \)
• base is very narrow (~ $10^{-6}$ m) & very lightly doped compared with the emitter

(a) Physical composition and electronic symbol of an $npn$ transistor. (b) Physical composition and electronic symbol of a $pnp$ transistor.

E : emitter
B : base
C : collector
• base is very narrow (~ 10^{-6} m) & very lightly doped compared with the emitter

(a) Physical composition and electronic symbol of an npn transistor. (b) Physical composition and electronic symbol of a pnp transistor.

E : emitter
B : base
C : collector

at thermal equilibrium and no bias
• common base configuration
• high resistance in depletion layers
  → applied voltages appear almost entirely across the junctions

E-B : forward biased diode
  ⇒ \( V_c \rightarrow (V_c - V_{BE}) \)
B-C : reverse biased diode
  ⇒ \( V_c \rightarrow (V_c + V_{CB}) \)
• e\(^{-}\) injected from E → B will diffuse across the base and reach the collector junction
  → then accelerated across the junction, and collected by the collector
• \( i_E = i_{eE} + i_{pE} \)
  
  since base doping << emitter doping
  
  \( \rightarrow i_{pE} << i_{eE} \rightarrow i_E \approx i_{eE} \)

• \( i_C = \alpha \cdot i_E + i_o \)
  
  \( i_o \): reverse saturation current across the C-B junction

\( \alpha \) depends on

(1) \( e^-\)'s minority carrier lifetime in the base, \( \tau_e \)

(2) \( e^-\)'s diffusion time across the base, \( \tau_D \)

with very lightly doped and very thin base

\( \rightarrow \alpha : 0.9 \sim 0.998 \)

\( \rightarrow \alpha i_E >> i_o \)

\( \Rightarrow i_C \approx \alpha i_E \)

\( i_C \) determined by \( i_E \) which is determined by \( V_{BE} \)
transistor as a voltage amplifier
transistor as a voltage amplifier
transistor as a voltage amplifier

• E-B remain forward biased
  
  \( R_1 \) usually small (e.g. 100 \( \Omega \))
  
  \( i_E \propto \frac{1}{(R_1 + R_e)} \)
  
  \( R_e \): effective resistance of the forward biased E-B junction
  
  \( \Delta i_E = \Delta V_1 / (R_1 + R_e) \)
  
• B-C remain reverse biased
  
  \( i_C = \alpha i_E + i_0 \approx \alpha i_E \)
  
  \( \Rightarrow \Delta i_C = \alpha \Delta i_E = \alpha \Delta V_1 / (R_1 + R_e) \)
  
  \( \Rightarrow \Delta V_2 = R_2 \Delta i_C \)
  
  \[ = \alpha \Delta V_1 \left[ \frac{R_2}{R_1 + R_e} \right] \]
  
  \[ \approx \Delta V_1 \left[ \frac{R_2}{R_1 + R_e} \right] \]
  
  \( R_e \) very small at forward bias (e.g. 10 \( \Omega \))
  
  \( R_2 \) usually \( >> R_1 \) (e.g. \( R_2 \sim 50 \text{k}\Omega \)) \( \Rightarrow \Delta V_2 = 455 \Delta V_1 \)
場效電晶體 ( Field Effect Transistor, FET )

例：金氧半場效電晶體 ( Metal-Oxide-Semiconductor FET, MOSFET )

- SiO₂ thickness ~ tens or hundreds of angstrom
- Eg of SiO₂ ~ 8.8 eV
  → insulator → MOS capacitor
  → Vg drop primarily across the thin oxide
- negative gate bias attract holes ( majority carriers ) to the oxide/Si interface
  → accumulation layer
- positive gate bias repels holes away from the oxide/Si interface
  → depletion region
- strong positive gate bias ( |Vg| > Vₜ, threshold ) attracts electrons ( minority carriers ) to the oxide/Si interface
  → inversion layer
- once the electron inversion layer is formed
  → an n-channel for $e^{-}$ flow from source to drain
  → $i_d$ appears in response to $V_d$

- $V_g \uparrow \rightarrow$ free $e^{-}$ in inversion layer $\uparrow$
  → $i_d \uparrow$

- at fixed $V_g$, when $V_d \geq V_g - V_t$
  → $(\text{gate voltage}) - (\text{channel voltage})$
    $$\leq V_g - (V_g - V_t) \leq V_t$$
  → voltage across the oxide not sufficient
to sustain the inversion layer
  → n-channel pinch-off
  → $i_d$ constant when $V_d \geq V_g - V_t$
• radiative recombination → photon
  non-radiative recombination → atom vibration, heat
• in Si → most recombinations are non-radiative
  → not suitable for opto-electronic devices

Fig. 1.5. (a) Radiative recombination of an electron-hole pair accompanied by the emission of a photon with energy \( h\nu = E_g \). (b) In non-radiative recombination events, the energy released during the electron-hole recombination is converted to phonons (adopted from Shockley, 1950).
• wavelength of the emitted light determined mainly by the bandgap of the material

\[ E_g = h\nu, \quad \nu \lambda = c \]

\[ \Rightarrow \lambda \approx \frac{1.24}{E_g (\text{eV})} \quad (\mu) \approx \frac{1240}{E_g (\text{eV})} \quad (\text{nm}) \]

e.g. 3 fundamental colors:

- \( \text{GaInN} \quad E_g \approx 2.65 \text{ eV} \)
  \[ \Rightarrow \lambda \approx 470 \text{ nm (blue)} \]
- \( \text{GaInN} \quad E_g \approx 2.35 \text{ eV} \)
  \[ \Rightarrow \lambda \approx 525 \text{ nm (green)} \]
- \( \text{AlGaInP} \quad E_g \approx 2.0 \text{ eV} \)
  \[ \Rightarrow \lambda \approx 625 \text{ nm (red)} \]
e.g. 3 fundamental colors:

GaInN $E_g \approx 2.65$ eV
$\rightarrow \lambda \approx 470$ nm (blue)
GaInN $E_g \approx 2.35$ eV
$\rightarrow \lambda \approx 525$ nm (green)
AlGaN$P \ E_g \approx 2.0$ eV
$\rightarrow \lambda \approx 625$ nm (red)
• 5 million cones in each eye
• density decreases with distance from fovea
• 3 kinds of color-sensitive pigments:
  L-cones, sensitive to red light (610 nm)
  M-cones, sensitive to green light (560 nm)
  S-cones, sensitive to blue light (430 nm)
Red + Green + Blue ⇒ White

another way to make white light: blue LED + yellow phosphor

(a) Structure of white LED consisting of a GaInN blue LED chip and a phosphor-containing epoxy encapsulating the semiconductor die. (b) Wavelength-converting phosphorescence and blue luminescence (after Nakamura and Fasol, 1997).
Luminous performance of visible LEDs versus time. Also shown is the luminous performance to other light sources (adopted from Craford, 1997, 1999, updated 2000).
雷射二極體 (Laser Diode)

reflecting mirror surfaces

http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html
雷射二極體 (Laser Diode)

reflecting mirror surfaces

more intense, highly directional, & monochromatic light

http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html
to generate population inversion
→ heavy doping
→ until $E_F$ lie within the conduction and the valence band
→ operate the device at forward bias
→ population inversion at the junction

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雷射二極體 ( Laser Diode )

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雷射二極體 (Laser Diode)

- LED：光学功率与波长的关系
  - Spontaneous emission
  - Optical Power vs. λ

- Laser：光学功率与波长的关系
  - Stimulated emission
  - Optical Power vs. λ

- Laser Threshold (I_th): 当电流达到阈值时，开始产生激光
• operated at reverse bias:

  photo-generated $e^-$ in the depletion region
  → swept to n-side (attracted by the positive voltage)

  photo-generated $h^+$ in the depletion region
  → swept to p-side (attracted by the negative voltage)

  ⇒ increase in reverse current magnitude

http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html
太陽電池 (Solar Cell)

負載電阻，load resistor

no light

dim light

bright light

solar cells operated in this region

photodiodes operated in this region
Charge Coupled Device, CCD
PN homojunction under (a) zero and (b) forward bias, and (c) heterojunction under forward bias. In homojunctions, carriers diffuse over the diffusion lengths $L_n$ and $L_p$ before recombining. In heterojunctions, carriers are confined by the heterojunction barriers.