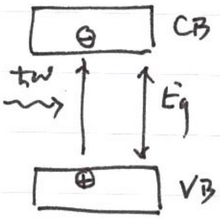
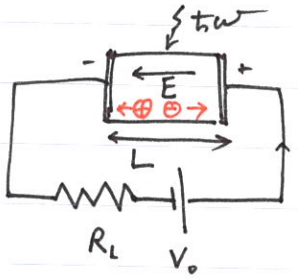
CH.14 Photodiode Detectors

- Problems in photoconductive Detectors
  1. Poor time response
  2. Shot noise due to high dark current

A. photoconductive Detectors (CH.13)



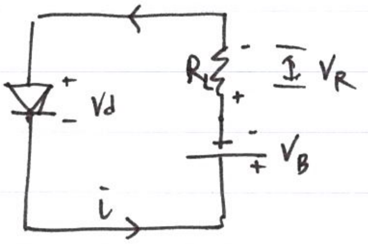
- Absorption of light $\hbar\omega$
  $\rightarrow e^-$ in CB : photoconductivity
  $\longrightarrow$ photocell



- $E = \dfrac{V_o}{L}$
- Due e-h pair generation,
  i_s created : $i_s = \dfrac{V_o}{R_L}$
- i_s drops V_o
- Drawback : background current i_o even w/o $\hbar\omega$.
  due to thermally generated e-h pairs. (inside the cell)
- Practically $i_o > i_s$

* photoconductive mode : p-n junction
(not photoconductive detector)

(i) photoconductive mode



(Fig. 14-2)

· Loop law (Kirchhoff)

→ $V_d + V_B + V_R = 0$

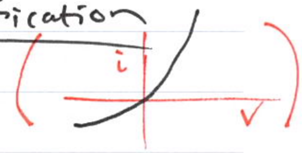
$V_R = iR_L$

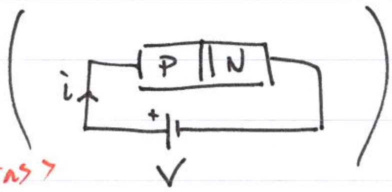
$\therefore i = -\frac{1}{R}(V_d + V_B)$

(load line)

· In p-n junction diode, ~~~~ rectification

$i = i_0\left(e^{\frac{eV}{\beta k_B T}} - 1\right)$ (10-21)





<reverse bias>

* why V applied : to balance the metal-semiconductor voltage drop in the circuit

· photocurrent i_λ : from e-h pairs generation via light absorption

$$i_\lambda = \frac{P_{in}}{hf} e\eta$$

$$\rightarrow i = i_0\left(e^{\frac{eV}{\beta k_B T}} - 1\right) - i_\lambda$$

. shockly diode Eq.

. i_0: dark current

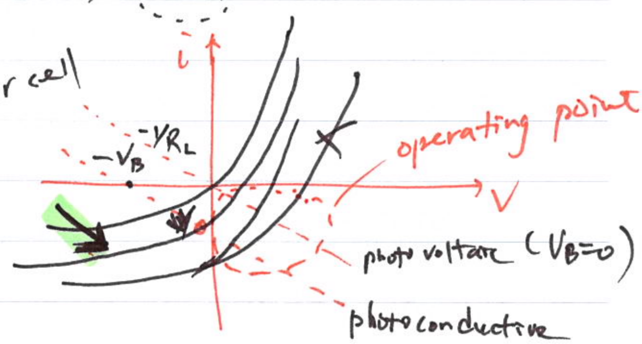
. $V_T = \frac{k_B T}{e}$

(14-3)

· for no light

1. photovoltaic : $i = 0$ → solar cell
2. photoconductive : $i < 0$ ($i = -i_0$)

→ dark current i_0 → noisy



<Load line analysis>

PAGE
DATE

· Application

1. photovoltaic → solar cell

$$P_{elec} = i^2 R_L \quad , \quad V_d = -iR$$

for $i_\lambda \gg i_0$,

• $i \sim i_0 e^{\left(\frac{-eiR_L}{\beta k_B T}\right)} - i_\lambda$: solar cell current

Efficiency

• $\eta_{sc} = \frac{P_{elec}}{P_{in}} = \frac{i^2 R_L}{P_{in}}$ (max must be optimized by R_L)

ex) Si solar cell area : $4\ cm^2$

reverse saturation current density : $1.5\times10^{-8}\ A/cm^2$

diode ideal factor β : $\beta = 1$

light intensity : $1000\ W/m^2$

$\lambda = 500\ nm$

$\eta_{abs} = 80\%$

Q. What is optimum R_L & power conversion efficiency in a solar cell ?

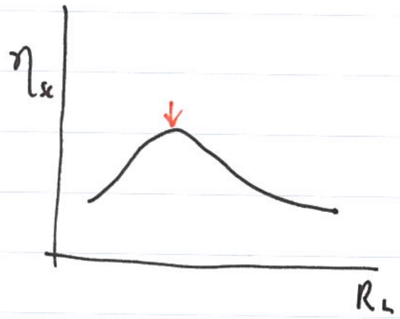
Sol) $i_\lambda = \frac{P_{in}/}{hf} e\eta_{ab} = \frac{P_{in}\lambda}{hc} e\eta_{ab} = \frac{(0.4\cdot10^{-4})(1000)(5\cdot10^{-7})(1.6\times10^{-19})(0.8)}{(6.63\times10^{-34})(3\cdot10^{8})} = 0.129\ A$

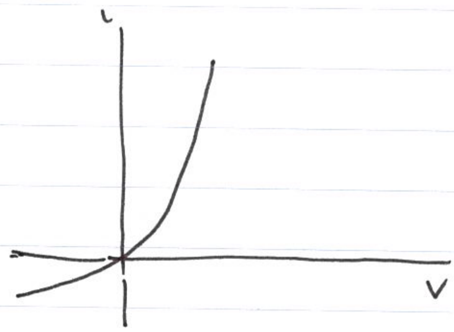
$V_T = \frac{k_B T}{e} = \frac{(1.38\times10^{-23})(293)}{1.6\times10^{-19}} = 0.0253\ V$ at $T = 20°C = 293K$

$\therefore i = i_0 e^{*\left(\frac{-eiR_L}{\beta k_B T}\right)} - i_\lambda = (6\times10^{-8}) e^{-\frac{iR_L}{0.0253}} - 0.129$

* → need numerical calculation to find R_L for maximum efficiency ($\eta_{sc} = i^2 R_L / P_{in}$)

For Your Alpha — AST®





14-2 Output Saturation

(ii) Photo voltaic mode

$$i = i_o\left[e^{\left(-\frac{V_d}{\beta V_T}\right)} - 1\right] - i_\lambda , \qquad V_T = \frac{k_B T}{e}$$

for $R_L \gg 1$, $\quad i \to 0 \quad$ (from I-V curve)

$$\therefore V_d = \beta V_T \ln\left(1 + \frac{i_\lambda}{i_o}\right) , \qquad i_\lambda = \frac{P_{in}}{hf} e\eta_{ab}$$

① If $i_\lambda \gg i_o$,

$$V_d \sim \beta V_T \ln\left(\frac{P_{in} e\eta_{ab}}{i_o hf}\right)$$

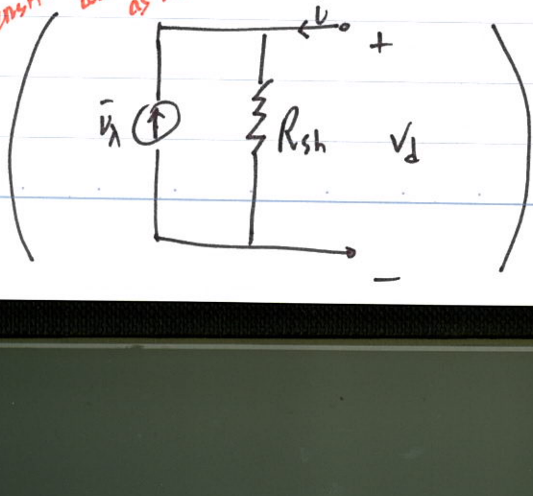
② If $i_\lambda \ll i_o$,

Talyer Expansion : $\ln(1+x) = x - \frac{x^2}{2} + \frac{x^3}{3} - \cdots$

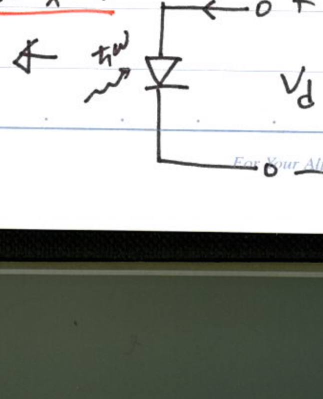
$$V_d \sim \beta V_T \frac{P_{in} e\eta_{ab}}{i_o hf}$$

$$= R_{sh} i_\lambda , \qquad R_{sh} = \frac{\beta V_T}{i_o} \quad \text{(shunt resistance)}$$

* more sensitive to weak light as $R_{sh}\uparrow$



for $i_\lambda \ll i_o$



PAGE
DATE

14.3 Response time

$$V_{out} = V_{max}(1 - e^{-t/RC}), \quad RC = \tau \text{ : time const.}$$

· Rise time t_r, (t_r : 10% → 90% for V_{out})

$$t_r = (\ln 9) RC = 2.2 RC$$

→ determines the response time to modulation.

· Bandwidth B, (3-dB electrical bandwidth)

$$B = \frac{1}{2\pi RC}$$

$$= \frac{2.2}{2\pi t_r} = \frac{0.35}{t_r} \quad \text{(3-dB bandwidth).}$$

Analysis:
The smaller C, the larger B.

To reduce C,

Techniques: ① Reverse bias V_B increase
→ photoconductive mode ($V_B > 0$)

② decrease the junction area
→ smaller detector area
→ Sensitivity vs. Speed trade off

③ Density of donor decreases

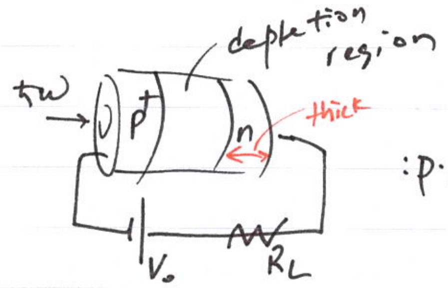
④ lower R_L
→ lower detector sensitivity, too.

14-4 Types of photodiodes (PD)

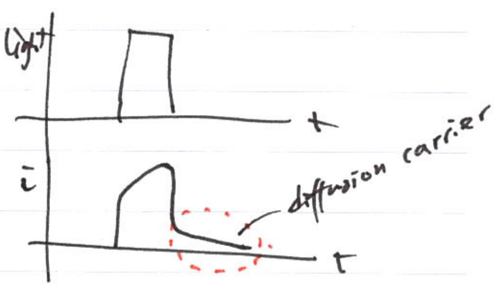
1. PIN PD

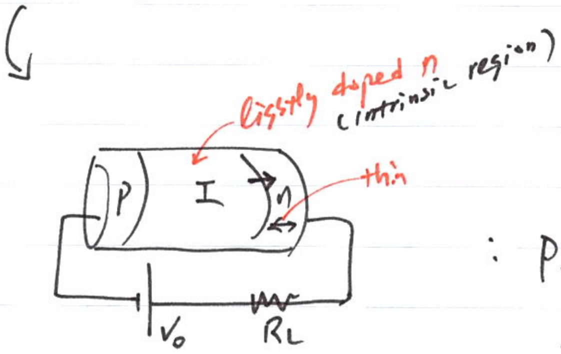
· To solve diffusion carriers

→ donor concentration decrease in n-region



: p-N





: PIN

— most common today

(drift ~ diffusion)

ex) Si-PIN, Intrinsic region thickness : 0.1 mm
What is minimum t_r , B , ~~V (reverse Bias)~~ ?

Sol) $v_s = 10^5$ m/s,

$$t_r = \frac{d}{v_s} = \frac{10^{-4}}{10^5} = 10^{-9}\ s = 1\ ns$$

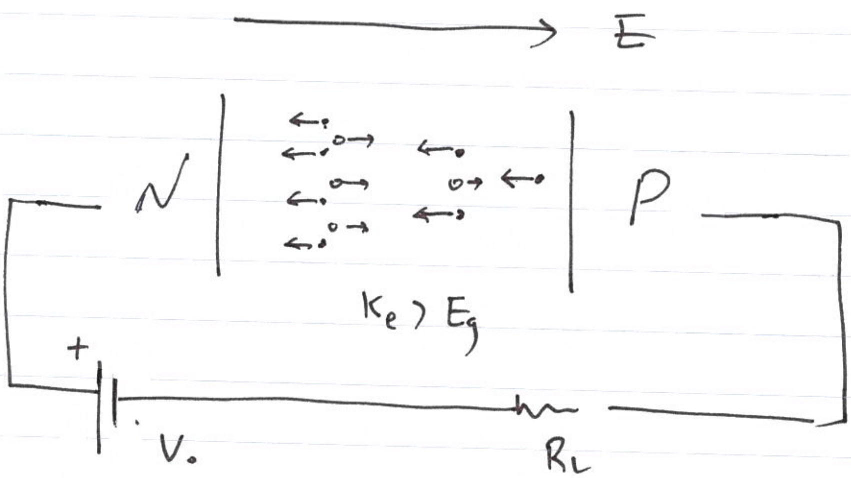
$$B = \frac{0.35}{t_r} = \frac{0.35}{10^{-9}} = 350\ MHz$$

2. Avalanche PD

- PIN : small R_L for high speed
  → small signal

Sol) multiplication in the depletion region
— analog of e^- multiplication in PMT.

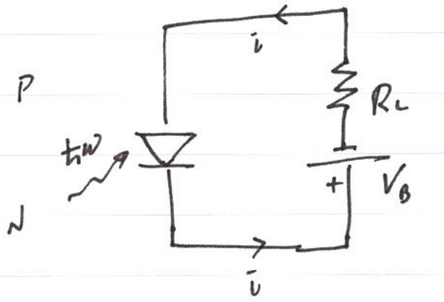
→ In a P-N junction applied by a reverse bias V_0,
e^-s whose kinetic energy is enough generate additional e^-s via impact ionization process.
→ avalanche photomultiplication



① For Δx moving, e^- lose potential energy by $\Delta x E \cdot e$, but gains kinetic energy K $(K > E_g)$

② If $K > E_g$, e^- creates e-h pair by collision

14-5 Signal to Noise ratio



(Reverse p-n)

$$\cdot\ P_{sig} = \bar{i}_\lambda^2 R_L = \left(\frac{P_{in}\,\eta_{ab}\,e}{hf}\right)^2 R_L ,$$

$$i_\lambda = \frac{P_{in}}{hf} e\eta_{ab} \qquad (14-2)$$

※ Signal current (i_λ)
: measured current − dark current i_0

(i) Shot noise induced electrical noise power :

$$P_{shot} = (i_N)^2 R_L = 2e(i_\lambda + i_0)BR_L ,$$

$$i_N = \sqrt{2e\bar{i}B} \qquad (13-29)$$

(ii) Thermal noise induced electrical noise power :

$$P_{therm} = \frac{V_N^2}{R_L} = 4k_BTB ,$$

$$V_N = \sqrt{4k_BTR_LB} \qquad (13-33)$$

Due to R_L dependence on the shot noise,

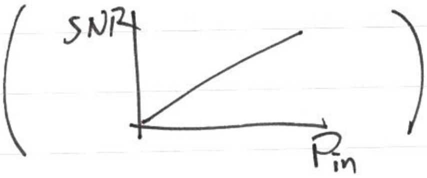
- P_{shot} becomes a dominant noise source for large R_L,
- P_{therm} 〃 for small R_L.

$$\cdot\ SNR \equiv \frac{P_{sig}}{P_{shot} + P_{therm}} = \frac{\bar{i}_\lambda^2 R_L}{2e(i_\lambda + i_0)BR_L + 4k_BTB}$$

$\cdot\ \sqrt{SNR}$ ⇒ Amplitude version.

(i) Large Sig : $\bar{i}_\lambda \gg i_0$ & $\bar{i}_\lambda R_L \gg V_T$, $V_T = \frac{k_B T}{e}$

· $SNR \sim \frac{\bar{i}_\lambda^2 R_L}{2e\bar{i}_\lambda B R_L} = \frac{\bar{i}_\lambda}{2eB}$ (shot noise dominant)



(ii) Small Sig , small R_L : $\bar{i}_\lambda \ll i_0$ & $i_0 R_L \ll V_T$

· $SNR \sim \frac{\bar{i}_\lambda^2 R_L}{4 k_B T B}$

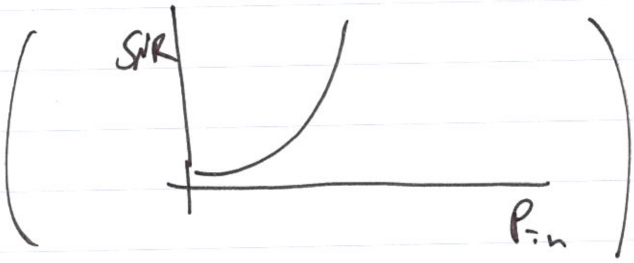
→ trade-off btwn response time and SNR

As $R_L \uparrow$, response time $\uparrow$ (degrades in B)
(due to RC)

(iii) Small Sig, large R_L : $\bar{i}_\lambda \ll i_0$ & $i_0 R_L \gg V_T$

· $SNR \sim \frac{\bar{i}_\lambda^2 R_L}{2e i_0 B R_L} = \frac{\bar{i}_\lambda^2}{2e i_0 B}$

→ limited by shot noise from dark current i_0



- Noise equivalent power : SNR = 1
(NEP)

· dBm : dB → 1 mW to denote optical power in mW

PAGE
DATE

· Optical power in dBm $= 10 \log_{10}\left(\frac{P}{1mW}\right)$

ex) $P = -20$ dBm

$\rightarrow -20 = 10 \log_{10}\left(\frac{P}{mW}\right)$

$P(mW) = 10^{-2} = 0.01\,(mW)$

$P = +20$ dBm

$\rightarrow 20 = 10 \log_{10}(P)$

$P(mW) = 10^{2} = 100\,(mW)$