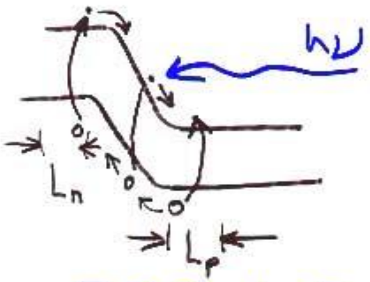
6. Photodiodes — Recall that semiconductors are photoconductors: change $\sigma \propto g_{op}$ with light

Chapter 8

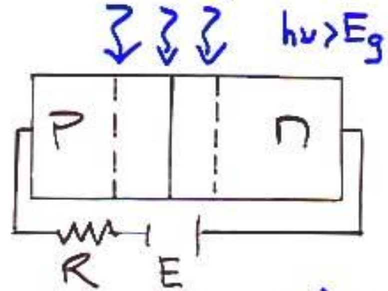
– Junction device improves speed and sensitivity to absorbed light.

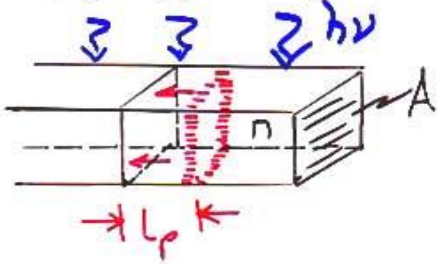


Thermal and optical generation

L_p = average distance traveled before hole recombines

L_n = " " " " electron ".





$\delta P_{op} =$ $\boxed{}$

$I_{op} = q\, g_{op} \int dV$ (volume)

$I_{op}^{h} = q\, g_{op} A L_p$ (n-side)

= current resulting from collection of these optically generated carriers

Likewise, for electrons,

$$I_{op}^{e} = q\, g_{op} A L_n \quad \text{(p-side)}$$

$$I_{op} = qA g_{op} (L_p + W + L_n)$$

Diode Equation (5-36) is now:

$$I = I_0 (e^{qV/kT} - 1) - I_{op}$$

Thermal

optical

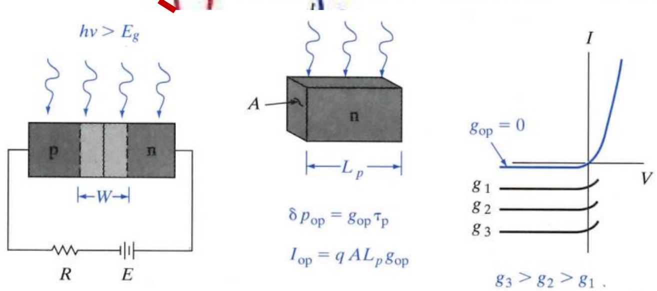
$$= I_{th} (e^{qV/kT} - 1) - I_{op}$$

$$I = qA\left(\frac{L_p}{\tau_p} p_n + \frac{L_n}{\tau_n} n_p\right)(e^{qV/kT} - 1) - qA g_{op}(L_p + W + L_n)$$

$$\left(\frac{D_p}{L_p} = \frac{L_p}{\tau_p}\right)$$

so g_{op} lowers I-V curve!

So g_{op} lowers I-V curve.



We'll use this again for BJT's.

Short Circuit: $V=0 \rightarrow$ First Terms Cancel

With light on: $I =$

Open Circuit: $I=0$, $V = V_{oc}$

$$V_{oc} = \frac{kT}{q}\ln\left[\frac{I_{op}}{I_{th}}+1\right]$$

$$= \frac{kT}{q}\ln\left[\frac{L_p+W+L_n}{\left(\frac{L_p}{\tau_p}p_n+\frac{L_n}{\tau_n}n_p\right)}\cdot g_{op}+1\right]$$

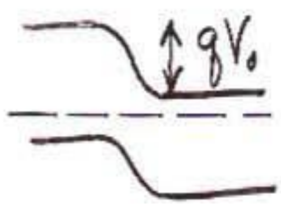
For special case of symmetric junction, $p_n = n_p$ and $\tau_p = \tau_n$, can rewrite equation in terms of $p_n/\tau_n = g_{th}$ and g_{op}. Neglecting generation in W,

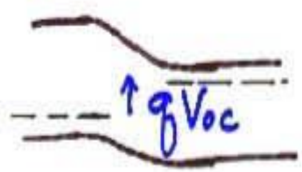
$$V_{oc} \simeq \frac{kT}{q} \ln \frac{g_{op}}{g_{th}} \quad \text{for } g_{op} \gg g_{th}$$

Limit to V_{oc}? τ decreases with more light

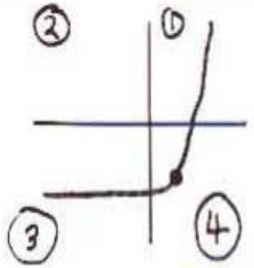
(more recombination since more electron-hole pairs than near equilibrium)

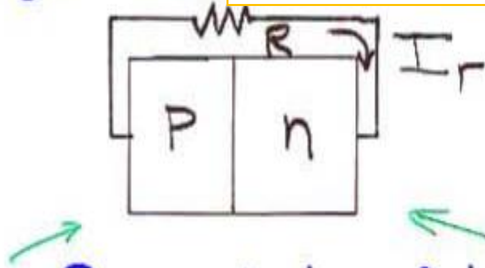
V_{oc} limit is contact potential V_0.





Forward Voltage V_{oc} =

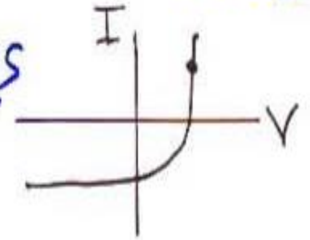


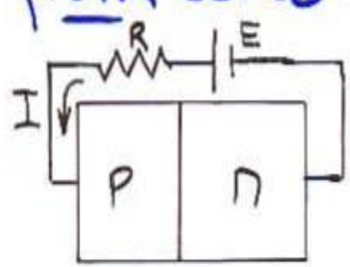


Voltage +
Current −

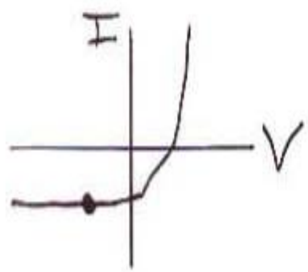
Power from device: Solar cell.

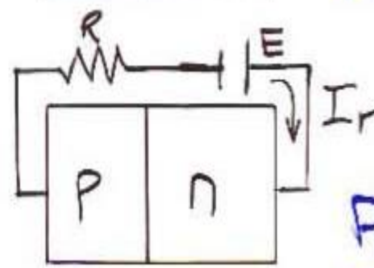
versus





Power to Device

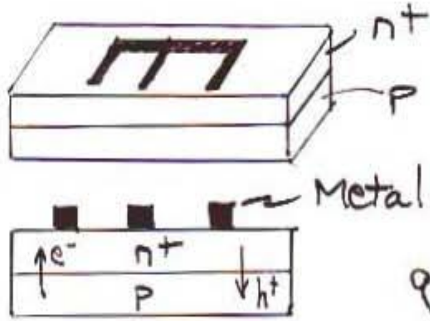


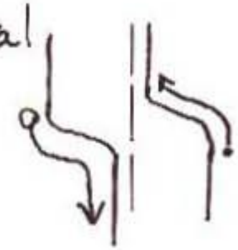


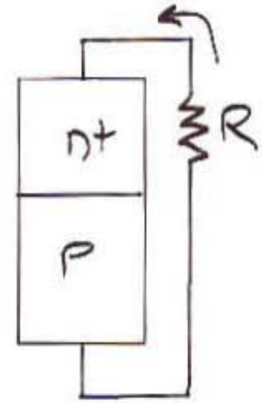
Power to Device: Photodetector

6.1 Solar Cells (Photodiode example)

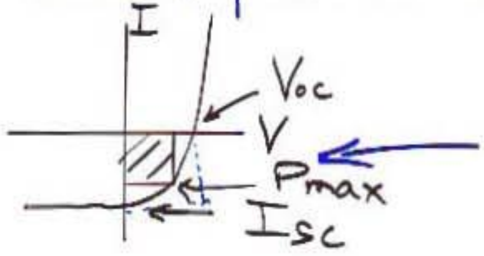
Two main goals: - absorb light
- collect photogenerated carriers







Current from n to p



Max Power Rectangle

$P_{max} = I_m V_m$

"Fill Factor" $= I_m V_m / I_{sc} V_{oc}$

FF ⇒ figure of merit

solar cell efficiency = $\frac{P_{out}}{P_{In}} = \frac{I_{sc} \cdot V_{oc} \cdot FF}{P_{In}}$ (i.e., solar energy)

Typical efficiency: Si (22%), GaAs (25%)

Space, Terrestrial, consumer power applications

Sun Power (P_{In}) ~ 1kW/m^2

25% $\longrightarrow$ 250 W/m^2 max

Design Rules

1) Match E_g to solar spectrum (absorb)

2) Long L_n, L_p to collect photogenerated carriers

3) Low resistance to reduce I^2R heat loss

4) Low cost, low weight

5) Match lengths $\frac{1}{\alpha}$, L_n, L_p to thickness of cell.

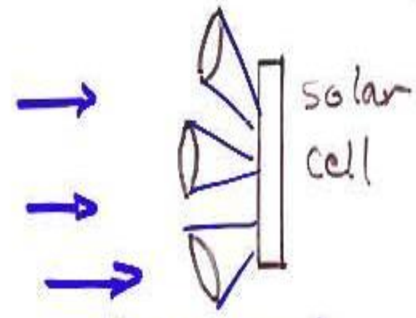
6) Use semi transparent electrodes (antireflection, low surface recombination velocity too)

→ Graded bandgap solar cells

→ Thin film solar cells

→ Multijunction solar cells

→ Concentrator solar cells

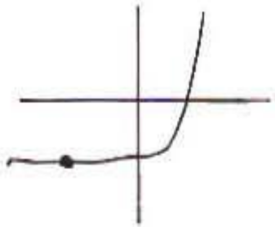


Increases flux and therefore current

S&B Chapter 8

6.2 Photodetectors

operates in third quadrant



$I \neq I(V)$

but $I \propto g_{op}$

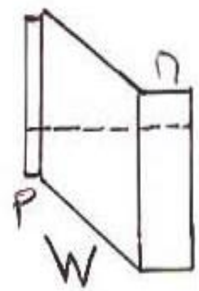
so can use to measure illumination intensity

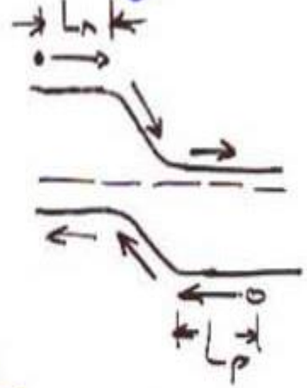
- convert time-varying optical signals
  to " " electrical "

Response time critical:

Need carriers to diffuse to junction and be swept across in $t <$ pulse width

Absorb in depletion (high field) region as much as possible

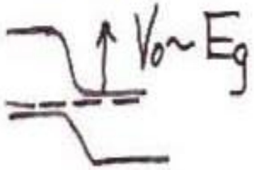




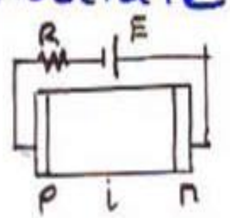
Depletion layer photodiode (if lightly doped) Also C, RC smaller

But, also want large $V_{oc} \sim V_o$ (contact potential)

so want moderate to high n and p doping.



Solution?



speed increases <u>and</u> V_{oc} high.

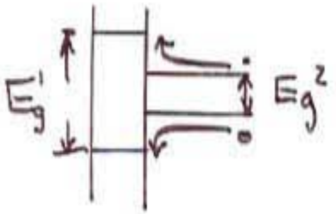
Design Rules

- Match semiconductor E_g to λ range of interest

Infrared: Ge, InGaAs, Si

Visible: AlGaAs

- Reduce surface recombination velocity – wide gap "window" – keep minority carriers away



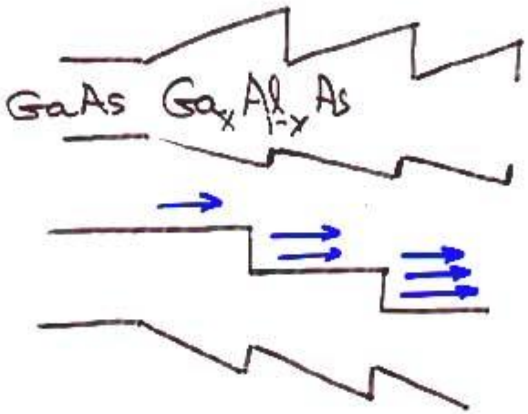
- Add multiplication – operate in avalanche mode

· Separate absorption and multiplication
  - small E_g for absorption
  - large E_g for multiplication (less leakage in reverse bias mode)

Increase Gain - Bandwidth product (figure of merit)
  - High gain → maximize lifetime/transit time
  - High bandwidth → minimize lifetime

Tradeoff!

Get around tradeoff with avalanche multiplication



No bias

Importance of heterojunctions

Bias

Impact Ionization

Reduce random dark current (Johnson noise) via <u>unequal</u> electron and hole ionization rates

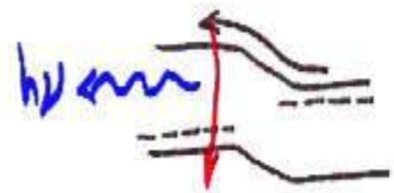
(Johnson noise versus shot, or thermal, noise)

Makes very sensitive detector!

6.3 Diodes for Light Emitters

- LEDs (light emitting diodes)
- lasers (light amplification by stimulated emission of radiation)

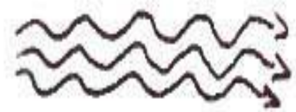
Forward bias injection: Electroluminescence



Laser → Narrower linewidth emission ("monochromatic")

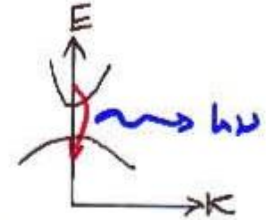
→ Directional

→ Coherent (plane waves in phase)

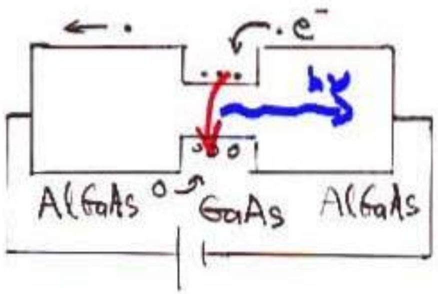
 vs. 

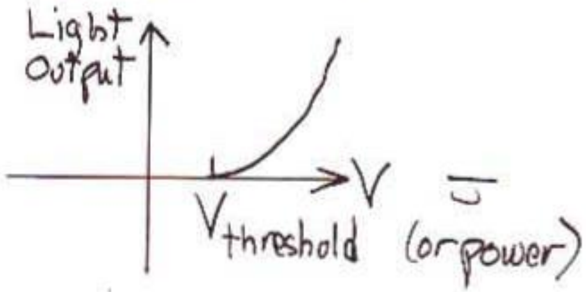
Semiconductors for lasers need:

· Direct gap (efficient recombination)



· Match λ to low absorption for fibers.





Reduce $V_{Threshold}$ or $J_{threshold}$

to shrink power supply required