Opto-Electronics and Photonics

Lecture 24 : Semiconductor Photodetectors

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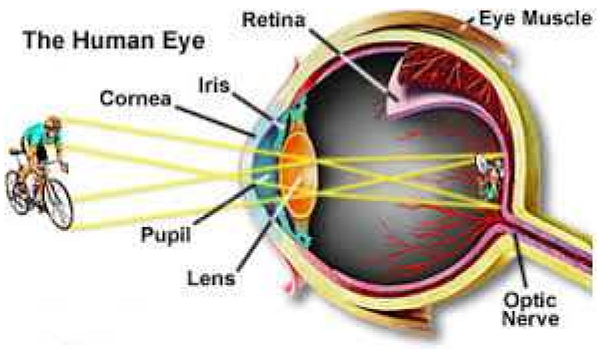
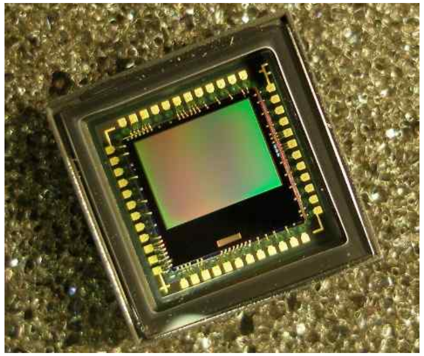
Lecture 24: Semiconductor Photodetectors

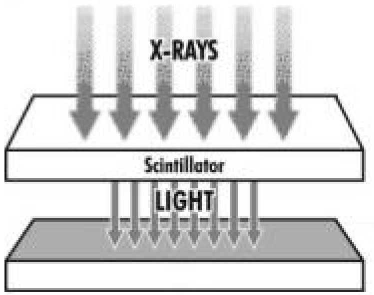
Many different types of photodetecting devices



CMOS Image Sensor (CIS)



X-ray sensor



Photomultiplier

Semiconductor-based Photodetectors

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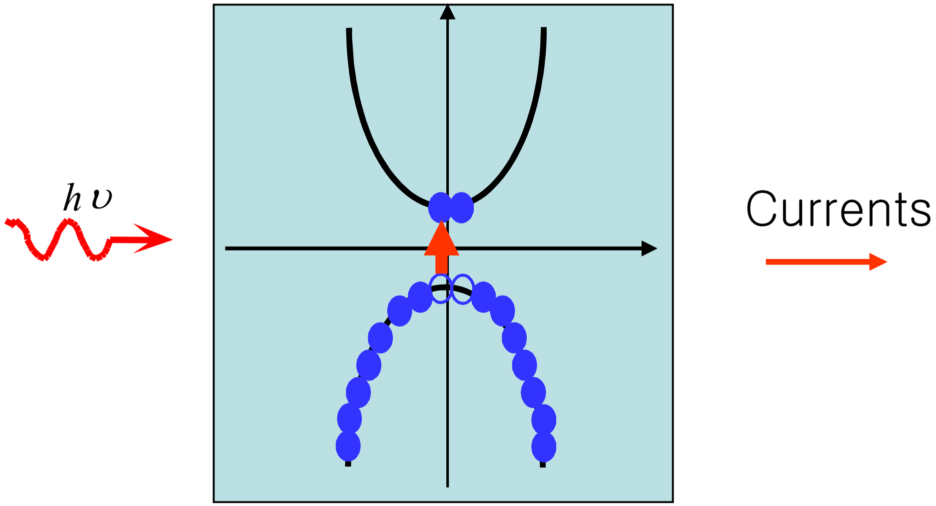
Photodetection in Semiconductor: Absorption ➔ Current Generation



Materials for photodetection: $E_g < h\nu$

Various methods for generating currents with photo-generated carriers:

Photoconductors, photodiodes, avalanche photodiodes …

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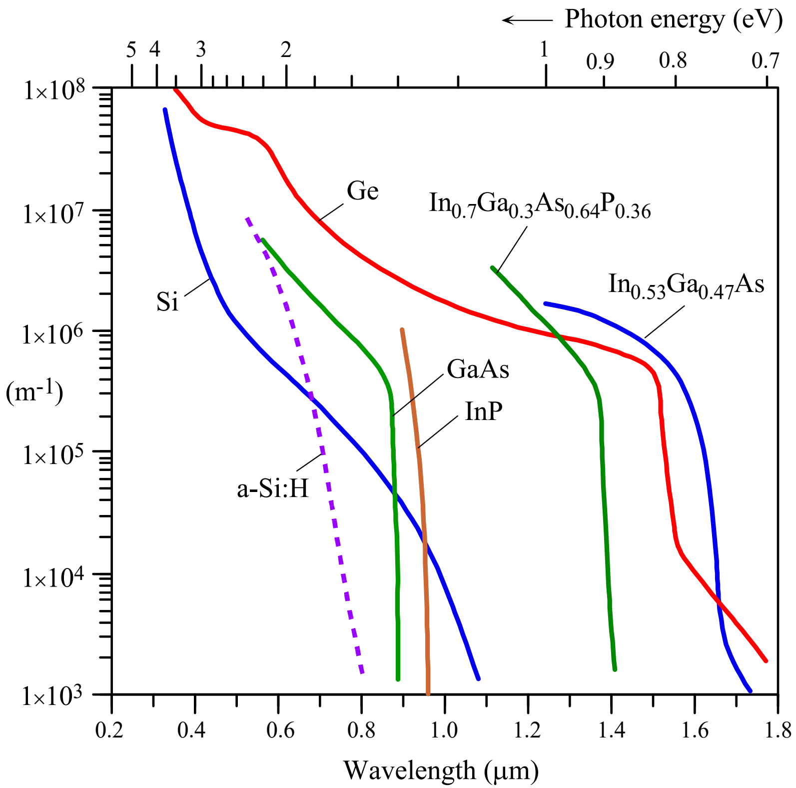
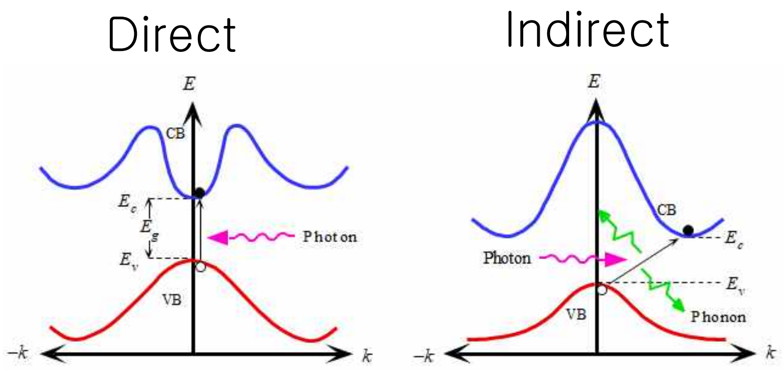


Sharp decrease in absorption for photon energy < E_g

$P_{out}/P_{in} = \exp(gL)$ $g < 0$ ➔ $\alpha = -g$

Indirect bandgap semiconductor can absorb



Indirect cannot efficiently satisfy k-conservation for emission process

Indirect can satisfy k-conservation for absorption process

➔ Indirect semiconductors used for photodetectors (solar cells, image sensors)

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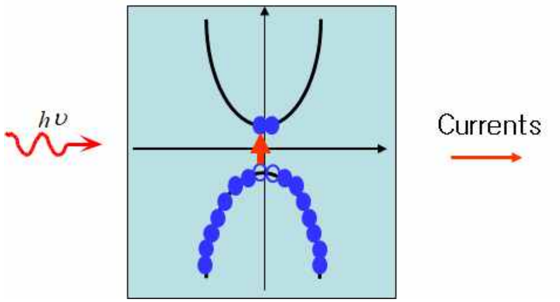
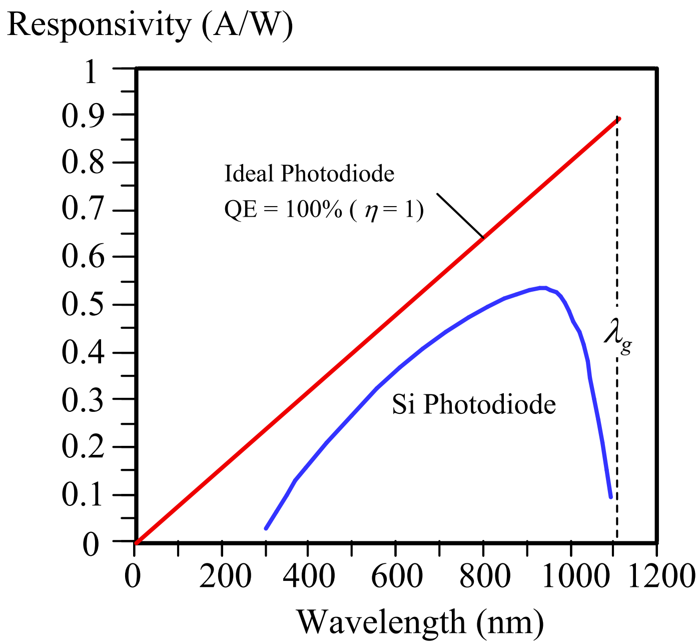


Photodetection efficiency $\quad R\ \text{(Responsivity)} = \frac{I}{P}$

$$\eta\ \text{(Quantum Efficiency)} = \frac{I/q}{P/h\nu} = R \cdot \frac{h\nu}{q}$$

$$R = \eta \cdot \frac{q}{h\nu} \qquad \frac{q}{h\nu} \sim \frac{\lambda[\mu\text{m}]}{1.24}[1/\text{V}]$$

$$\sim \eta \frac{\lambda[um]}{1.24}[1/V]$$



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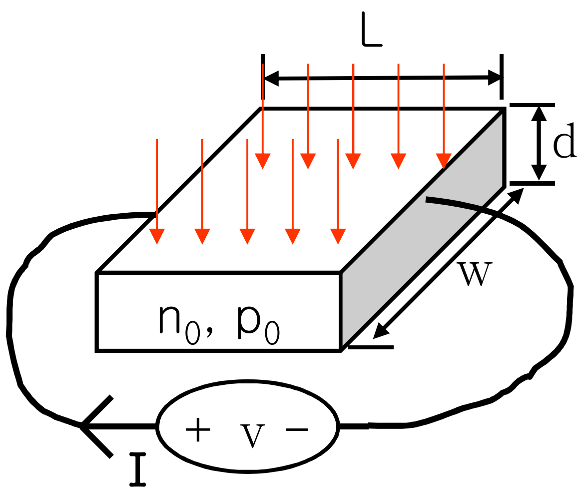
Photoconductor



$R = ?$

Without light,

Conductivity: $\sigma = q\mu_e n + q\mu_h p$

($\mu_{e,h}$: electron, hole mobility)

$$J = \sigma E \qquad I = wd\sigma\frac{V}{L}$$

With light,

$$n = n_0 + \Delta n,\ p = p_0 + \Delta p$$

$$\sigma + \Delta\sigma = q\mu_e(n + \Delta n) + q\mu_h(p_0 + \Delta p)$$

$$\Delta I = wd\cdot\Delta\sigma\cdot\frac{V}{L} = wd\cdot(q\mu_e\Delta n + q\mu_h\Delta p)\cdot\frac{V}{L}$$

Light → Change in R

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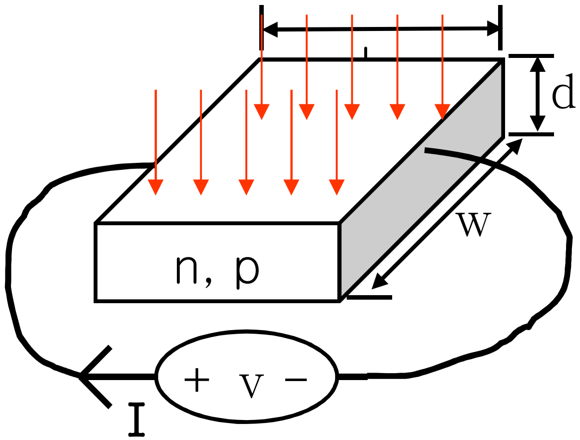

With light,

$$n = n_0 + \Delta n,\ p = p_0 + \Delta p$$

$$\sigma + \Delta\sigma = q\mu_e(n + \Delta n) + q\mu_h(p_0 + \Delta p)$$

$$\Delta I = \ wd\left(q\mu_e\Delta n + q\mu_h\Delta\right)\frac{V}{L}$$

Responsivity?

$$\Delta n = \Delta p \ = \eta_{\text{int}} \cdot \frac{P}{h\nu} \cdot \frac{\tau}{wLd} \quad \text{(Assume } \Delta n, \Delta p \text{ are uniform)}$$

τ : carrier lifetime

$$\Delta I = \ wd \cdot q\left(\mu_e + \mu_h\right) \cdot \eta_{\text{int}} \frac{P}{h\nu}\frac{\tau}{wLd} \cdot \frac{V}{L} = q\left(\mu_e + \mu_h\right) \cdot \eta_{\text{int}} \cdot \frac{P}{h\nu} \cdot \frac{\tau}{L^2} \cdot V$$

$$R = \frac{I}{P} \simeq \frac{\Delta I}{P} \text{ (Assume dark current is small)} \quad R = \frac{q}{h\nu}\left(\mu_e + \mu_h\right) \cdot \eta_{\text{int}} \cdot \frac{\tau}{L^2} \cdot V$$

$$R = G \cdot \eta_{\text{int}} \frac{q}{h\nu} \quad \text{where } G = \left(\mu_e + \mu_h\right) \cdot \frac{\tau}{L^2} \cdot V$$

Gain possible because
photogenerated carriers go through photoconductor several times before disappear

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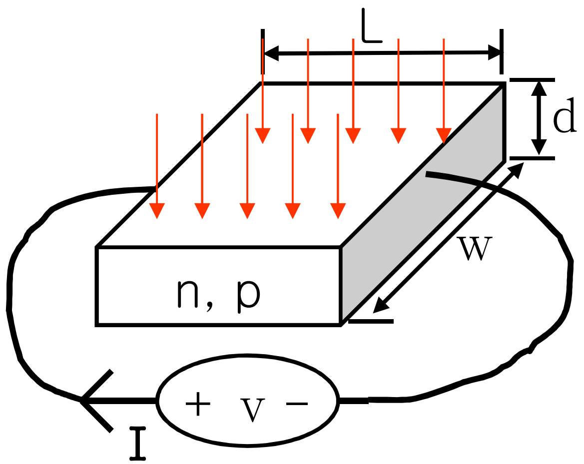
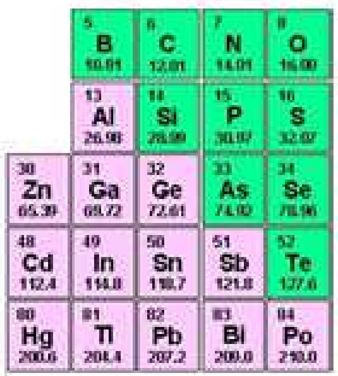


Photoconductor

- Very easy to make
- Large gain
- Speed limited by τ
- Dark currents can be large

Material	Spectral Range
Silicon (Si)	Visible to NIR
Germanium (Ge)	NIR
Gallium Phosphide (GaP)	UV to Visible
Indium Gallium Arsenide (InGaAs)	NIR
Indium Arsenide Antimonide (InAsSb)	NIR to MIR
Extended Range Indium Gallium Arsenide (InGaAs)	NIR
Mercury Cadmium Telluride (MCT, HgCdTe)	NIR to MIR



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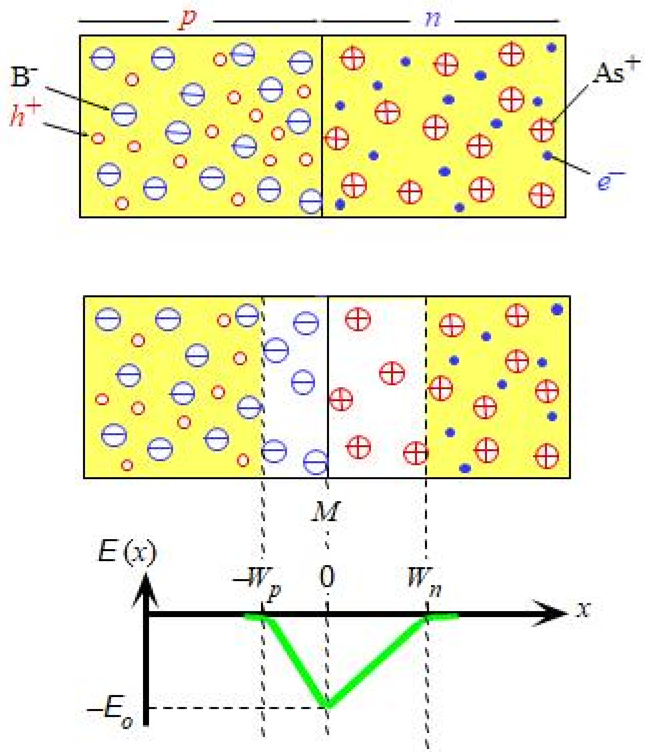
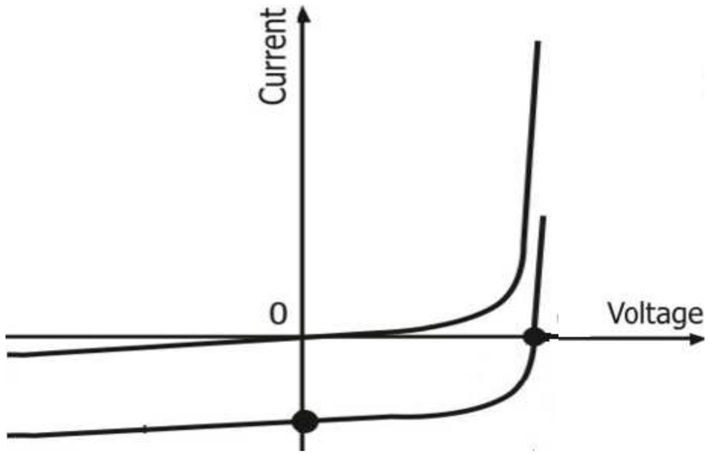
Photodiodes: PN junction



With light

$$I = I_s \exp(\frac{qV}{kT} - 1) - I_{ph}$$



I_{ph} depends on where the light is incident

➔ Larger if closer to depletion region

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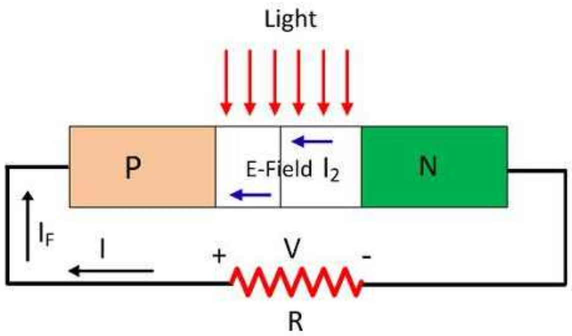
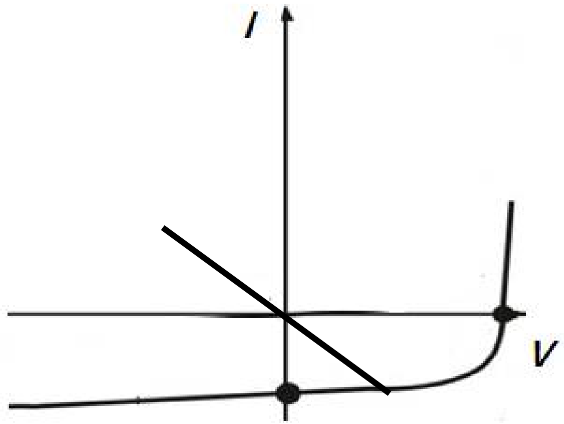
Photodiodes: PN junction

$$I = I_s \exp(\frac{qV}{kT} - 1) - I_{ph}$$





➔ Solar (Photovoltaic) Cell

Theoretically, max. conversion efficiency: 32.33%

Commercial solar cell conversion efficiency: < 20%

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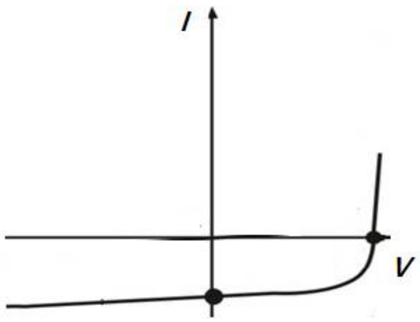
Photodiodes: PN junction

$$I = I_s \exp(\frac{qV}{kT} - 1) - I_{ph}$$

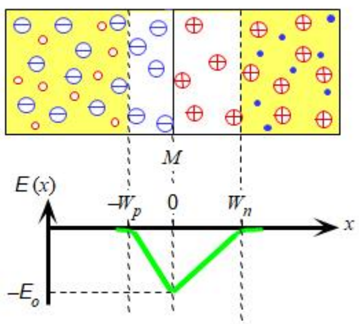


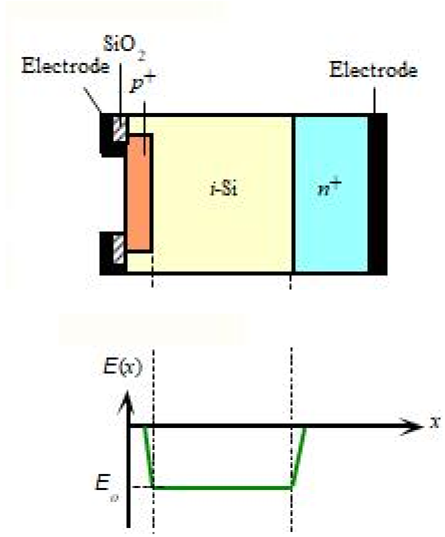
Larger I_{ph} if closer to depletion region

I_{ph} max. if all photons incident in depletion region due to built-in field

Typically, the depletion width is very small (< 1μm)

➔ Use PIN structure





$$I_{ph} = \eta_{\text{int}} \frac{P}{h\nu} q$$

➔ PIN PD

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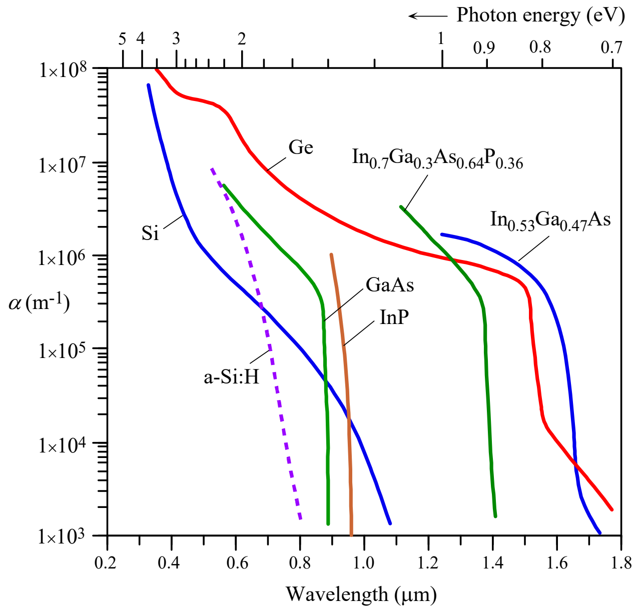
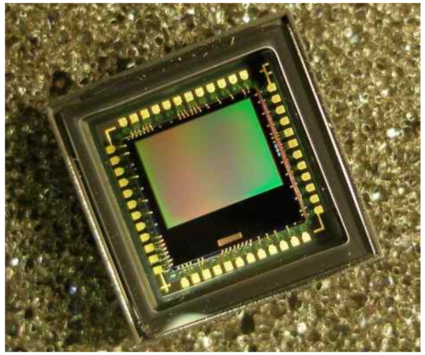
PIN PD



CMOS Image Sensor (CIS)



Galaxy Note 20 Ultra:

12,000 x 900, each pixel 0.8μm

InGaAs, Ge: Long-distance optical fiber comm.

GaAs: Short-distance optical fiber comm.

Si: Visible light detection

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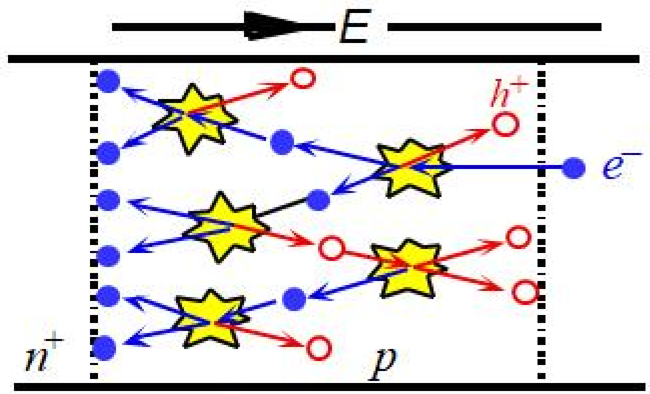
PIN PD with gain?

Avalanche Photodiode (APD)

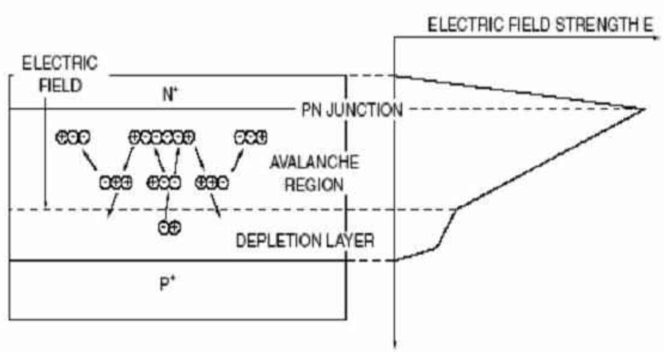
(avalanche: a large mass of snow, ice, earth, rock, or other material in swift motion down a mountainside)

➔ Gain by multiplying electrons and/or holes

Under high E-field, electrons and holes can have sufficiently high kinetic energies breaking bonds and creating new e-h pairs (Impact Ionization)



Avalanche region



➔ Very high sensitivity

(Single photon detection possible)

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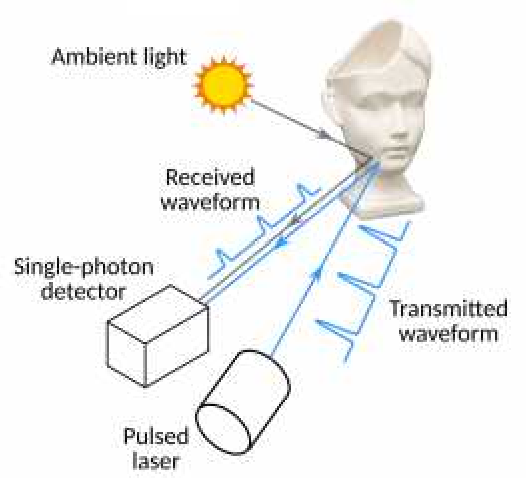
Applications: ➔ LIDAR (Light Detection And Ranging)



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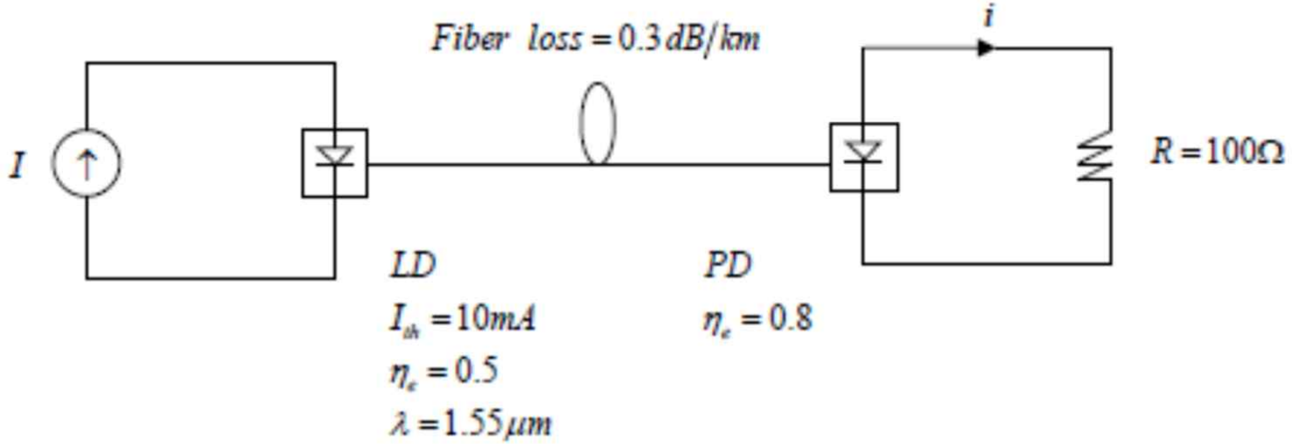
Homework: (Due 12/6)

Consider a simple optical fiber link which consists of a semiconductor laser transmitter, fiber, and a PIN receiver as shown below. The laser has a single mode lasing wavelength at 1.55 μm, the threshold current of 10 mA and the external quantum efficiency of 0.5. Assume the laser has only one output facet. The fiber has transmission power loss of 0.3dB/km. The PIN PD has the (external) quantum efficiency of 0.8. Assume there are no coupling losses between LD and fiber, and fiber and PD (all the powers from LD is coupled into fiber and from fiber to PD).



(a)How much optical power comes out of the laser if the laser driver current I =15mA?

(b)If the fiber length is 100Km, how much currents are produced at the receiver?

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● Goals:

Learn basic properties of light

Learn how to control the light property for useful applications

- Discussion Session: Dec. 7, Mon., 10 am
- Final Exam: Dec. 9, Wed., 10-12 am
- Final Exam Review: Dec. 14, Mon., 10 am