Si Photonics

Lecture 14 : Photodetectors

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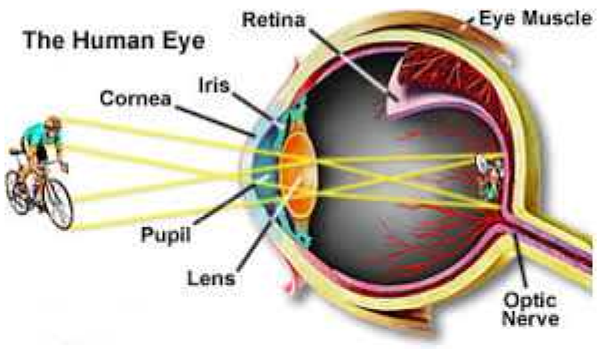
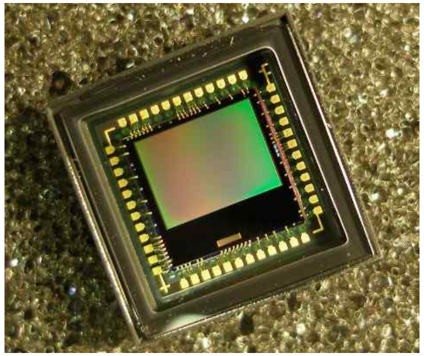
Lecture 14: Photodetectors

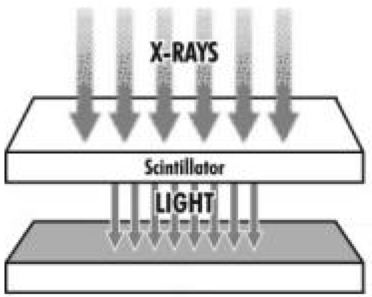
Many different types of photodetecting devices



CMOS Image Sensor (CIS)



X-ray sensor



Photomultiplier

Semiconductor-based Photodetectors

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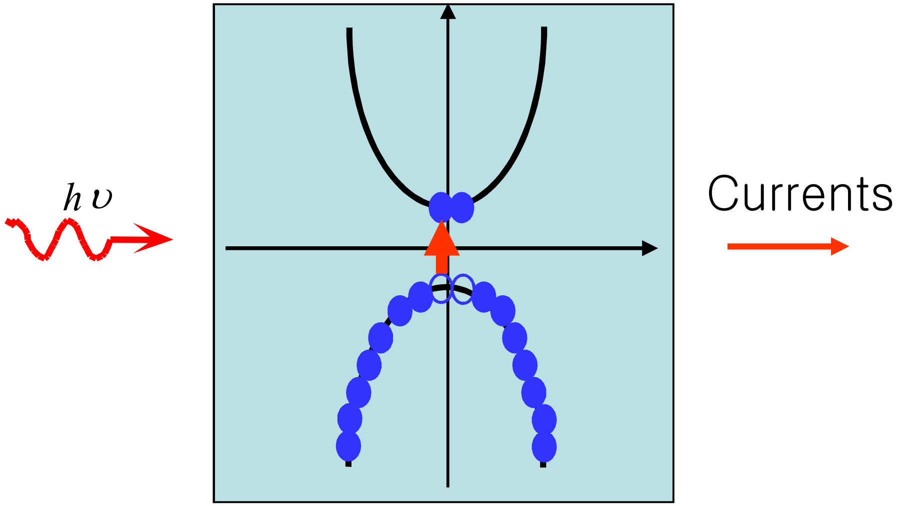
Photodetection in Semiconductor



Absorption of incident light

Convenient to view light as a particle (photon)

=> 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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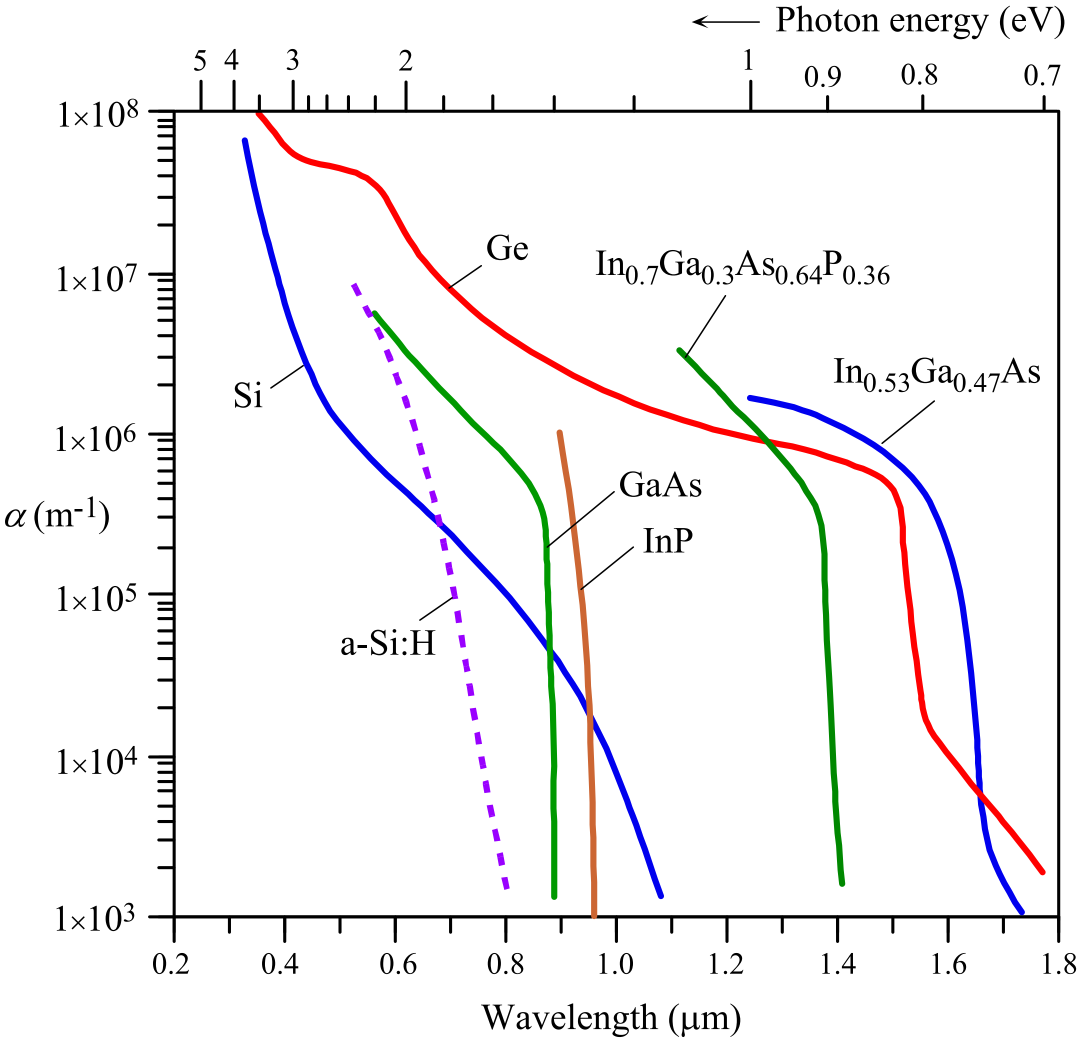
Semiconductor materials for photodetection



- Sharp decrease in α for $\lambda > E_g$
- Si cannot detect 1.3~1.5 μm light
- Ge on Si

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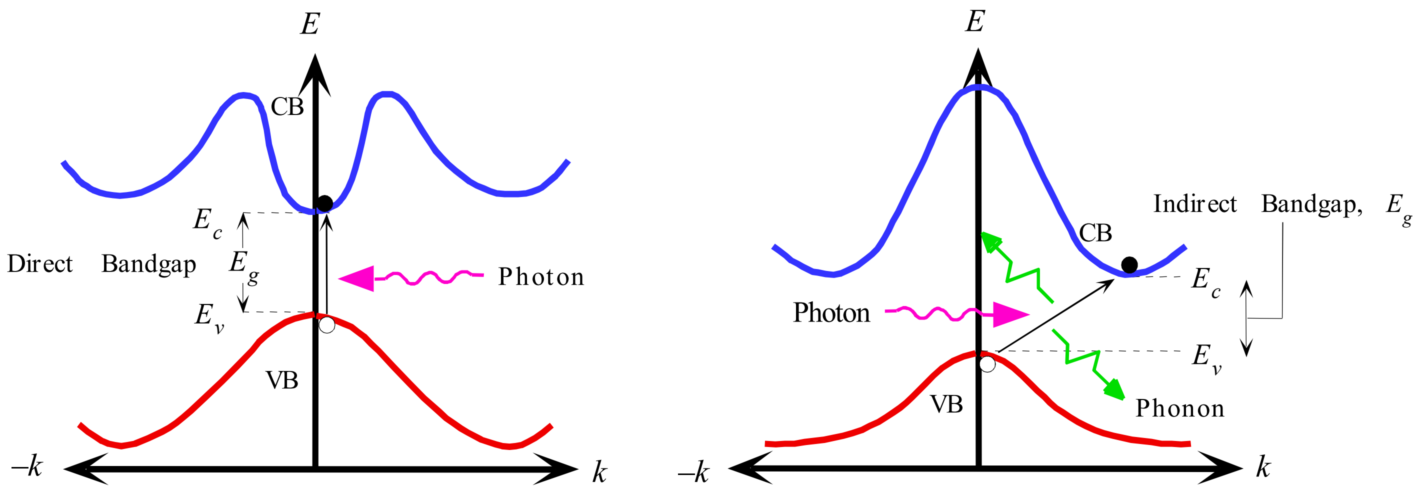
- Photodetection for indirect bandgap materials?



(a) GaAs (Direct bandgap)

(b) Si (Indirect bandgap)

Unlike emission, absorption in indirect bandgap semiconductor is highly probable

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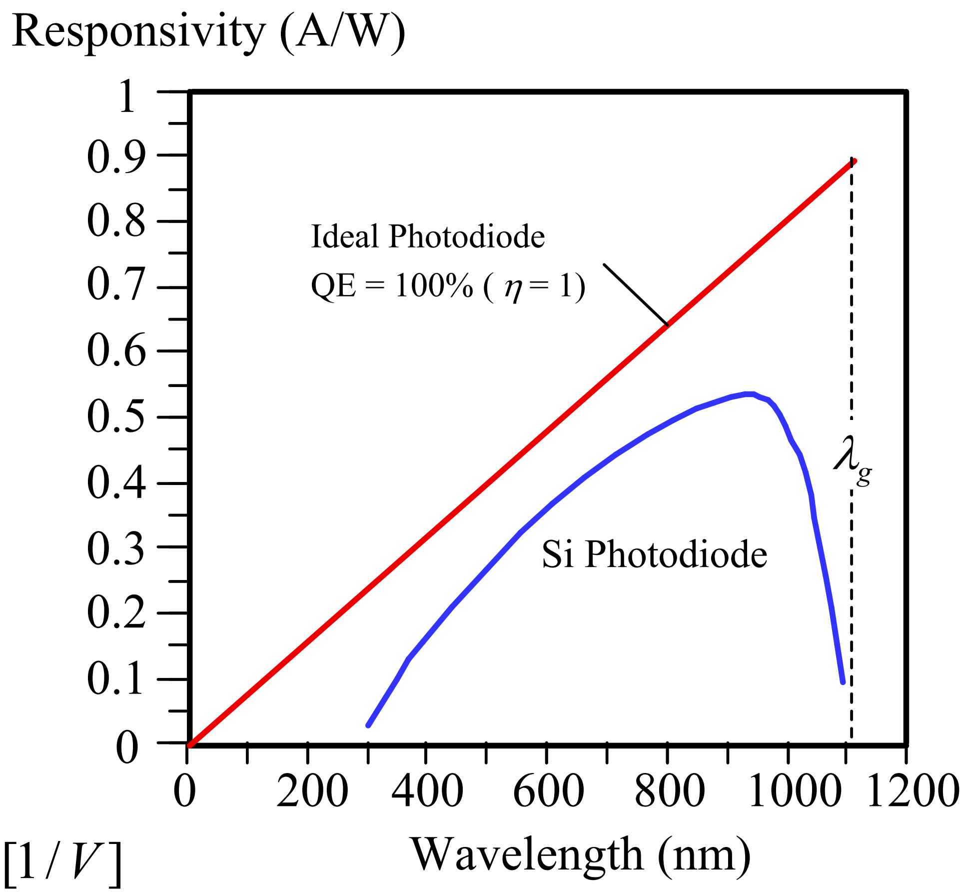
Photodetection efficiency

$$R\text{ (Responsivity)} = \frac{I}{P}\left[\frac{A}{W} = \frac{1}{V}\right]$$

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

$$R = \eta \cdot \frac{q}{h\nu} \qquad h\nu[\text{eV}] = \frac{1.24}{\lambda(\text{in }\mu\text{m})}$$

$$R = \eta \cdot q[C] \cdot \frac{\lambda}{1.24}[1/eV] \quad = \eta \cdot \frac{\lambda}{1.24}[1/V]$$



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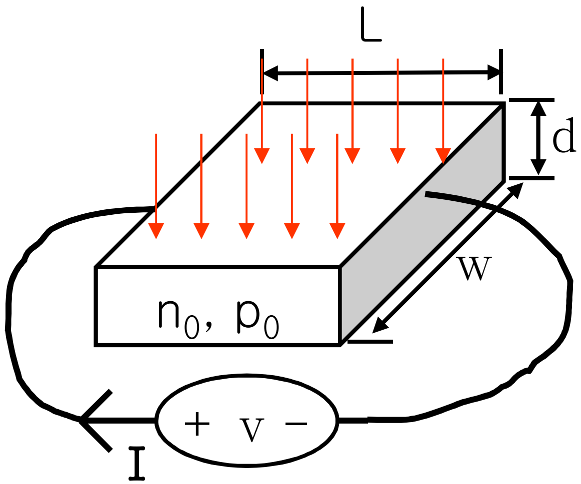
Photoconductor



$R = ?$

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,

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

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

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

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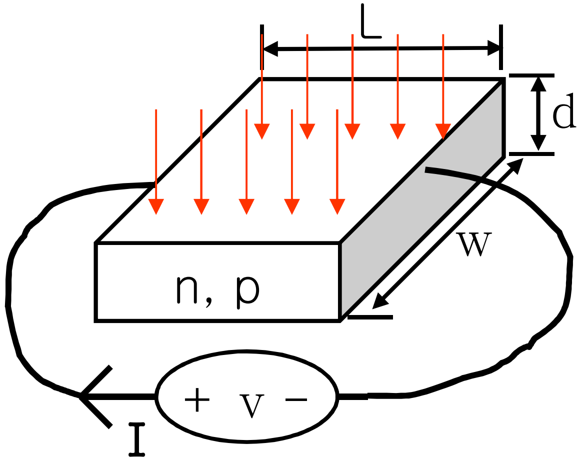

With light,

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

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

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

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

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

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

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

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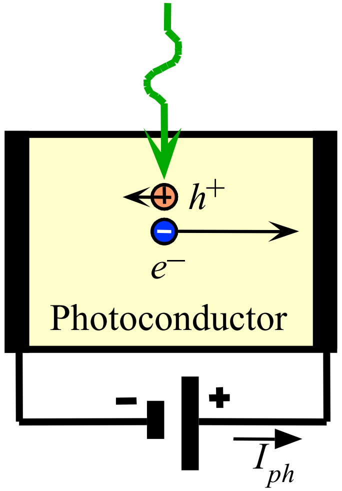

Gain: $G = (\mu_e + \mu_h) \cdot \frac{\tau}{L^2} \cdot V$

Assuming $\mu_e >> \mu_h$, $G = \mu_e \cdot \frac{\tau}{L^2} \cdot V = \frac{\tau}{L^2 / \mu_e \cdot V} = \frac{\tau}{\tau_e}$

$\tau_e = \frac{L}{\mu_e \cdot \frac{V}{L}} = \frac{L}{\mu_e \cdot E} = \frac{L}{v}$; Time for travelling distance L

$\tau >> \tau_e$ ==> electrons circulate many time before recombination

With μ_h

$$G = \frac{\tau}{L^2 / (\mu_e + \mu_h) \cdot V} = \frac{\tau}{\tau_{eh}}$$

$$\tau_{eh} = \frac{L}{(\mu_e + \mu_h) \cdot \frac{V}{L}} = \frac{L}{(\mu_e + \mu_h) \cdot E} = \frac{L}{v_e + v_h} = \frac{1}{\frac{v_e + v_h}{L}} = \frac{1}{\frac{1}{\tau_e} + \frac{1}{\tau_h}} = \frac{\tau_e \cdot \tau_h}{(\tau_e + \tau_h)}$$

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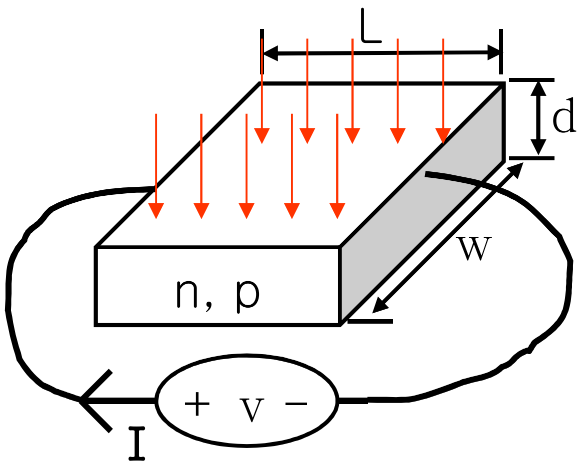
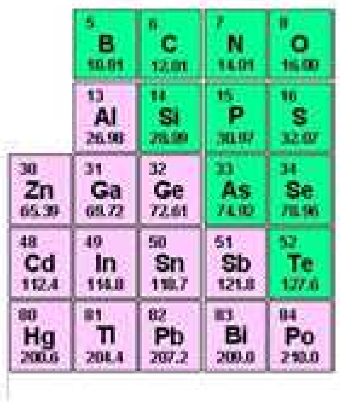


Photoconductor

- 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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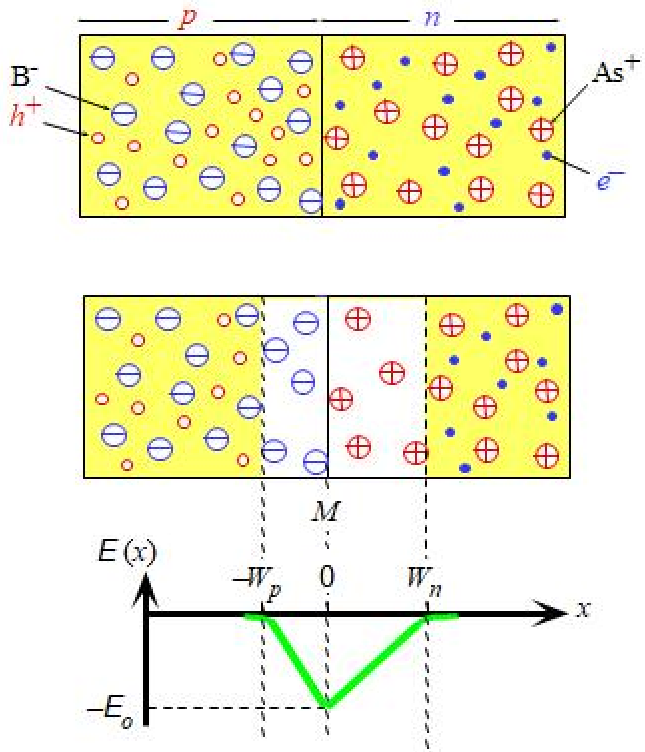
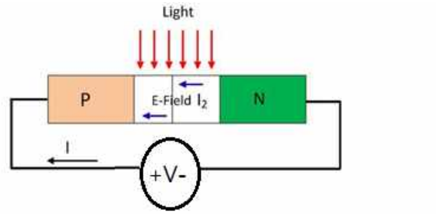
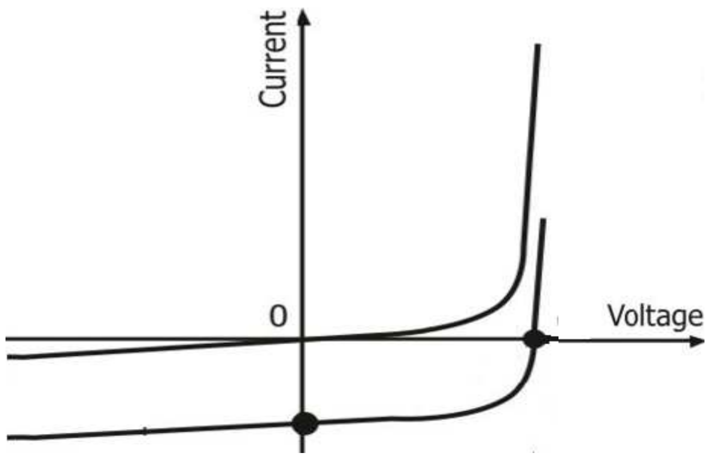
Photodiodes: PN junction



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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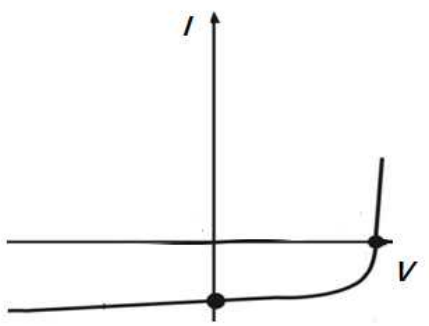
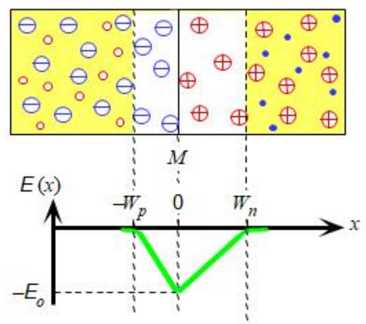
Photodiodes: PN junction

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



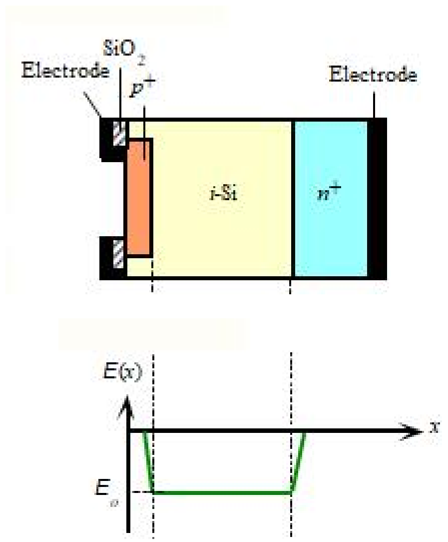


Larger I_{ph} if closer to depletion region

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



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

➔ PIN PD

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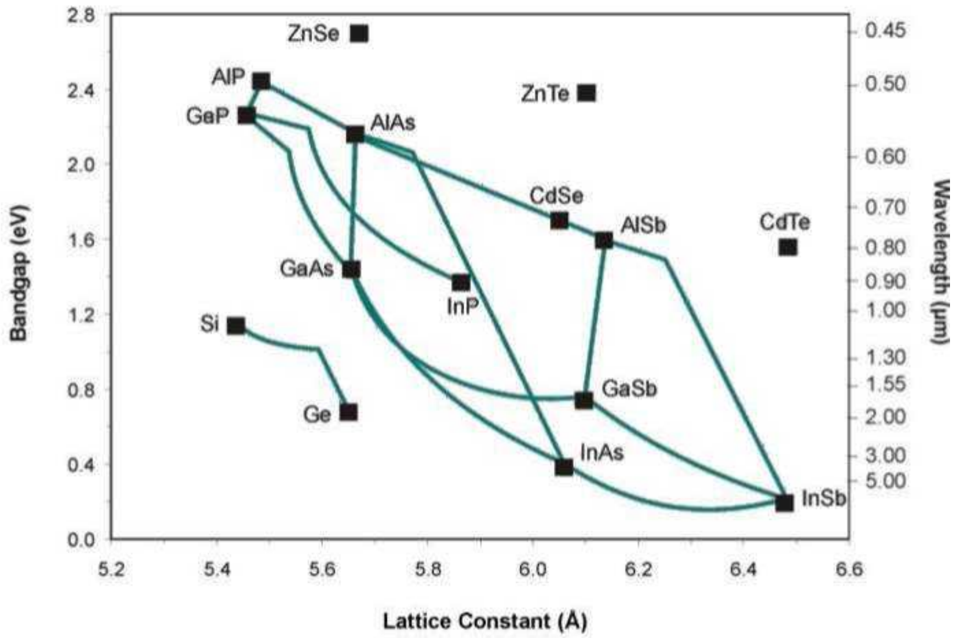
How to realize 1.3-1.5μm photodetectors for Si photonics?



About 4% lattice constant mismatch between Si and Ge

Advanced CVD technique can be used for reasonable quality Ge layers on Si

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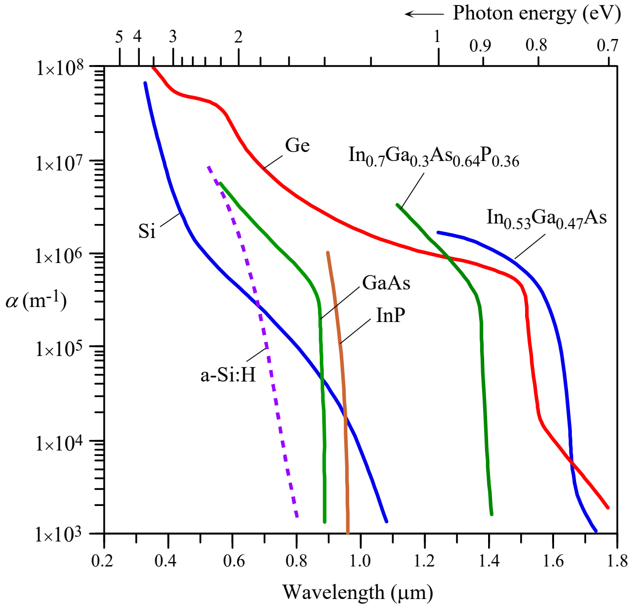
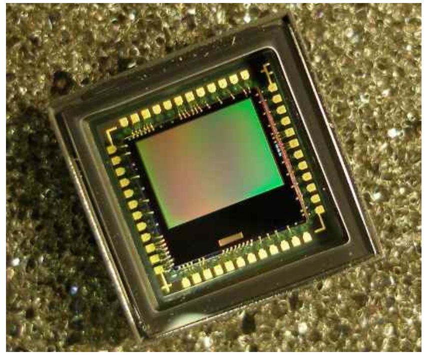
PIN PD



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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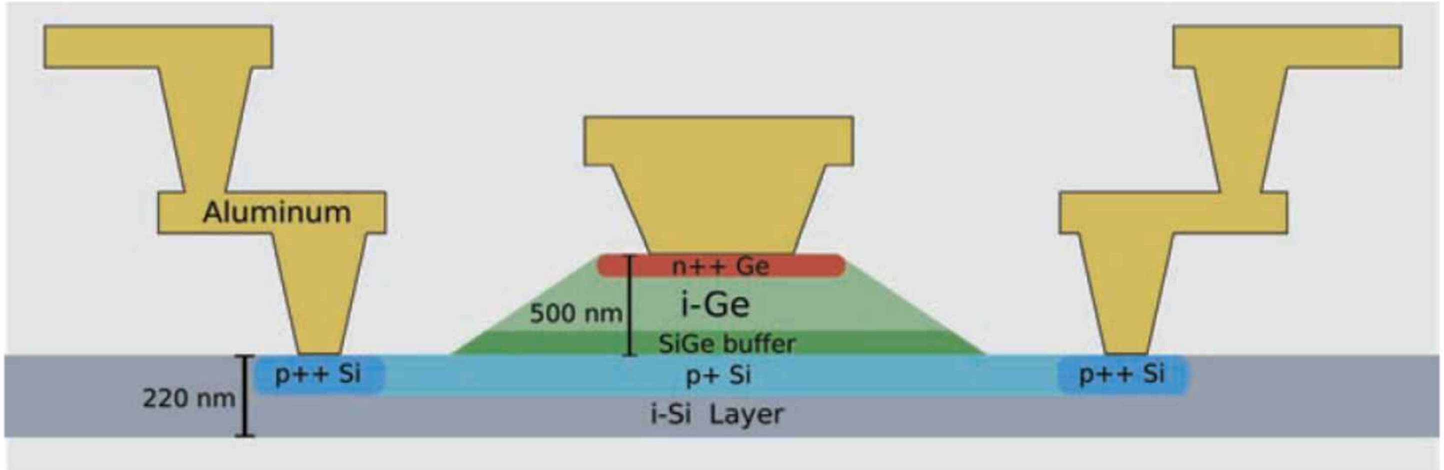
Ge PIN PD on Si



Optimal thickness for i-Ge layer?

Trade-off between responsibility and detection bandwidth

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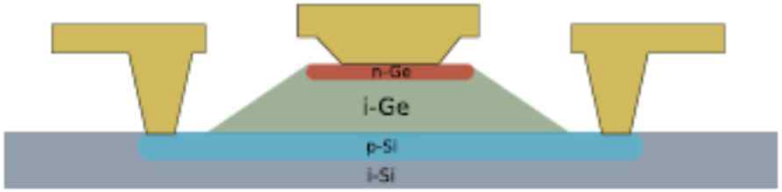
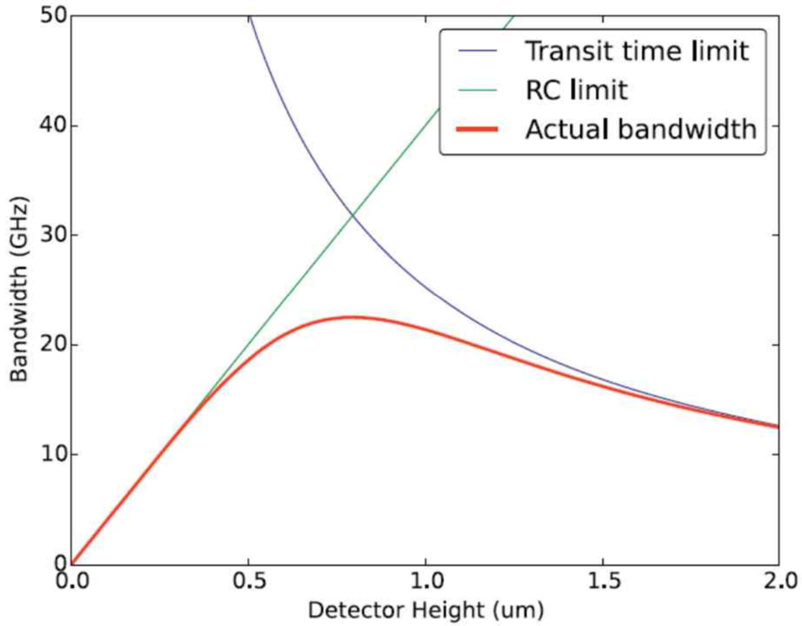
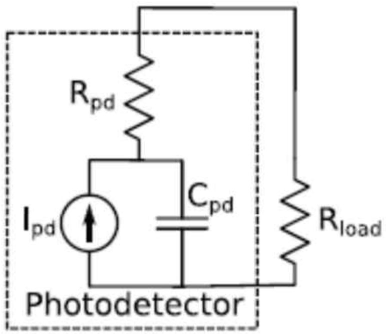
- What determines the Ge-on-Si PIN PD detection bandwidth?

- Transit time





- RC time constant



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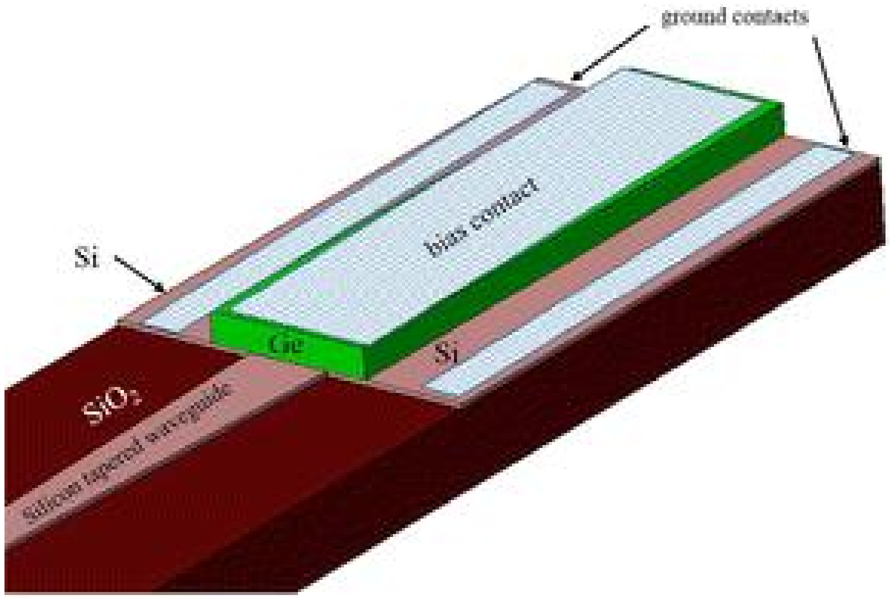
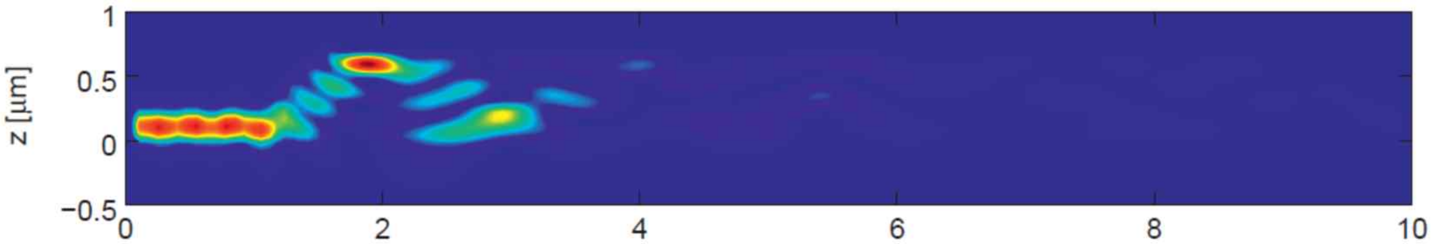
Waveguide PD



Minimize Ge intrinsic layer thickness
for transit-time reduction

Maximize responsivity
by waveguide configuration



Simulated carrier generation rates in waveguide Ge PIN PD

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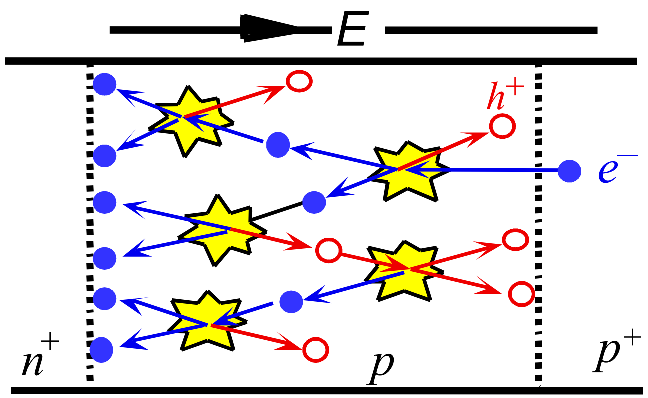
PD with gain?

Avalanche Photodiode (APD)

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

Gain by multiplication of electrons and/or holes

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



Avalanche region

It is preferred only one type of carrier (either electron or hole) causes impact Ionization ➔ higher bandwidth and less noises

k: ratio of ionization coefficients (= hole/electron)

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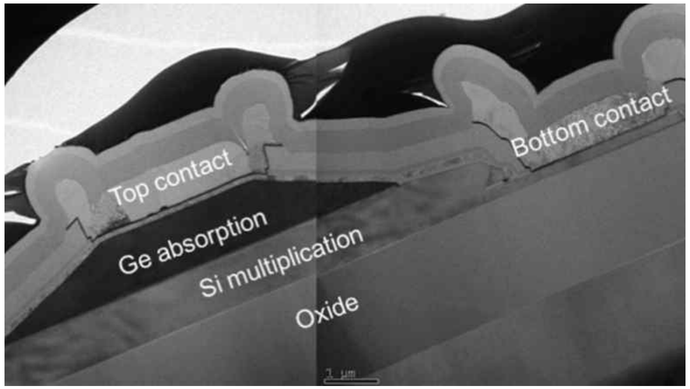
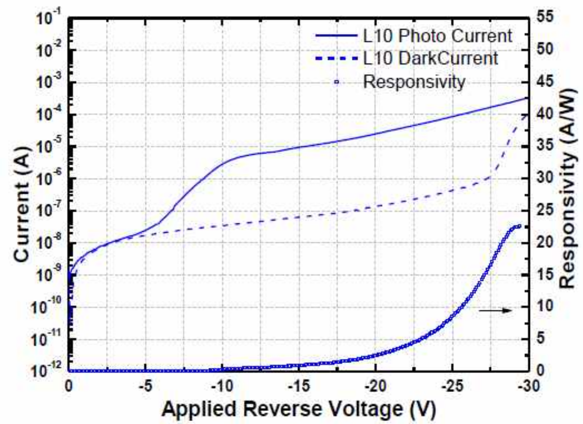
- Separate-Absorption-Charge-Multiplication (SACM) PD (Ge/Si APD)
  - Ge for absorption
  - Si for multiplication as Si has low k (~ 0.09)

  (Impact ionization by only electronics)



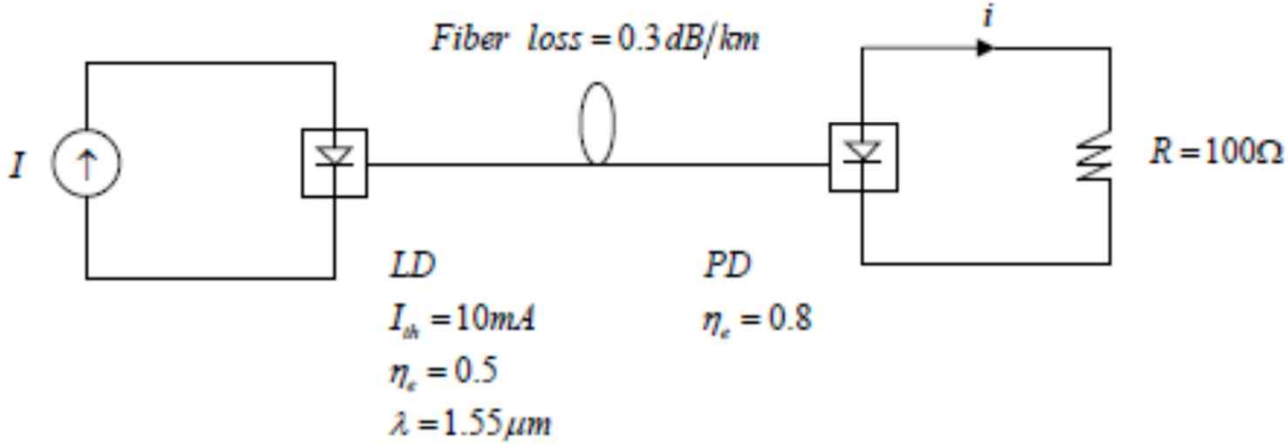


Type	Responsivity	OE bandwidth	Dark current	Ge thickness
WG SACM APD	22 A/W @ −27V	20 GHz @ −27V	10 μA @ −27V	1 μm

Ref) 2013, OFC, High speed waveguide-integrated Ge/Si avalanche photodetector, IME

Homework

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?