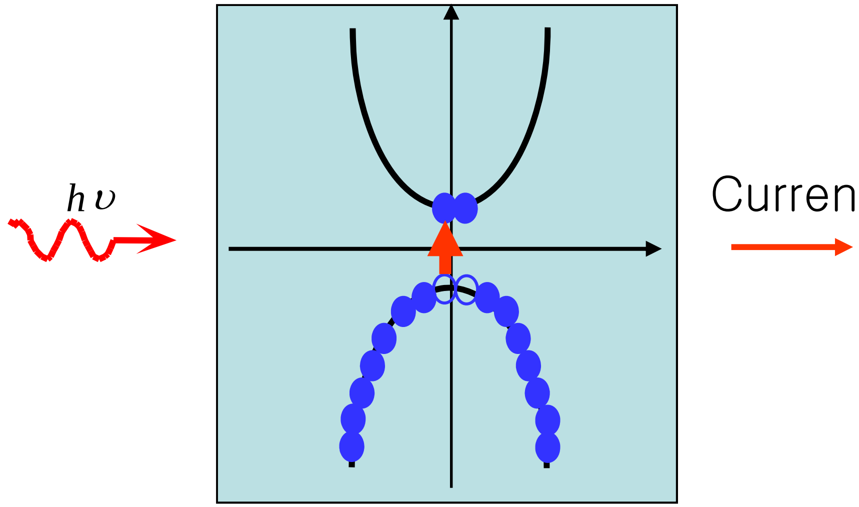
Lect. 10: Photodetectors

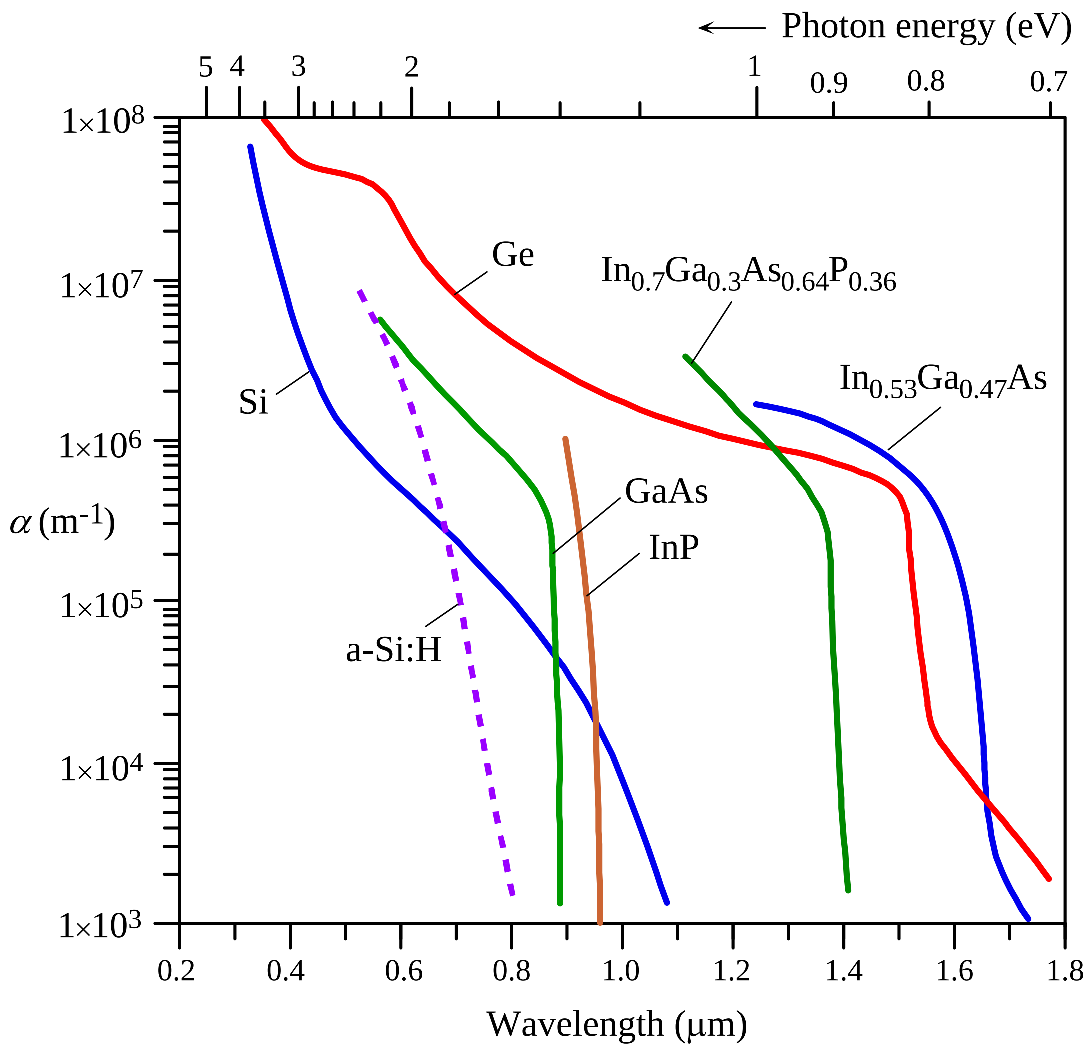
Photodetection: Absorption => Current Generation



Materials for photodetection: $E_g < h\nu$

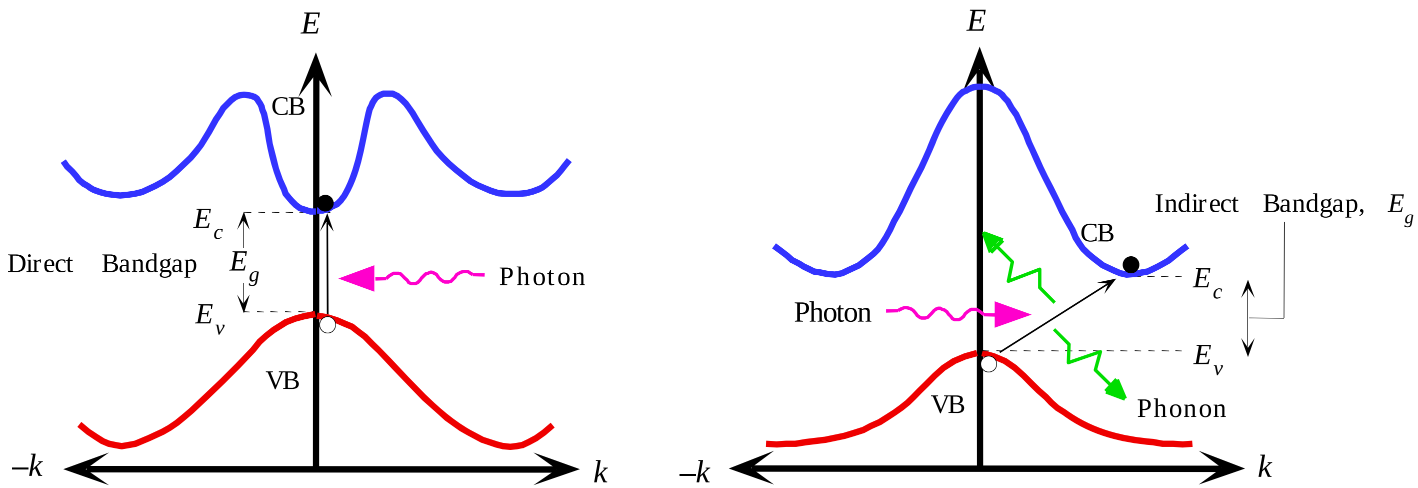
Various methods for generating currents with photo-generated carriers: photoconductors, photodiodes, avalanche photodiodes

Lect. 10: Photodetectors



- Sharp decrease in α for $\lambda > E_g$
- Photodetection for indirect bandgap materials?

– Photodetection for indirect bandgap materials?



(a) GaAs (Direct bandgap)

(b) Si (Indirect bandgap)

Unlike emission, absorption in indirect bandgap semiconductor is highly probable

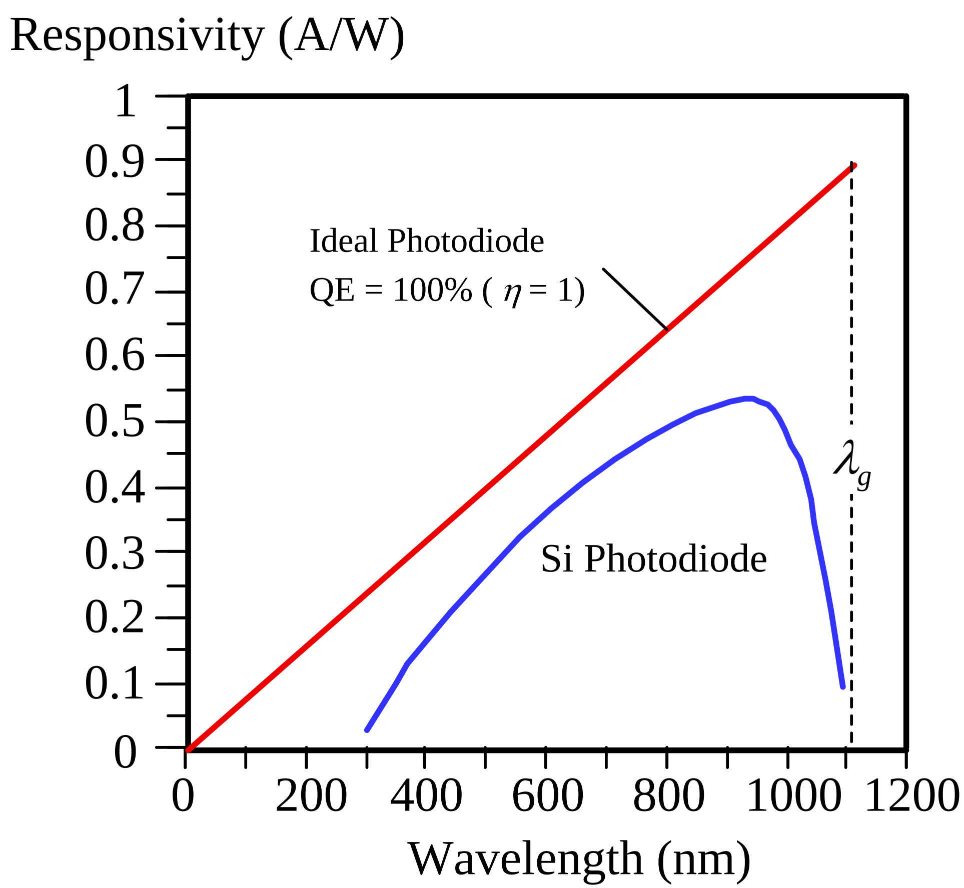
Photodetection efficiency

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

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

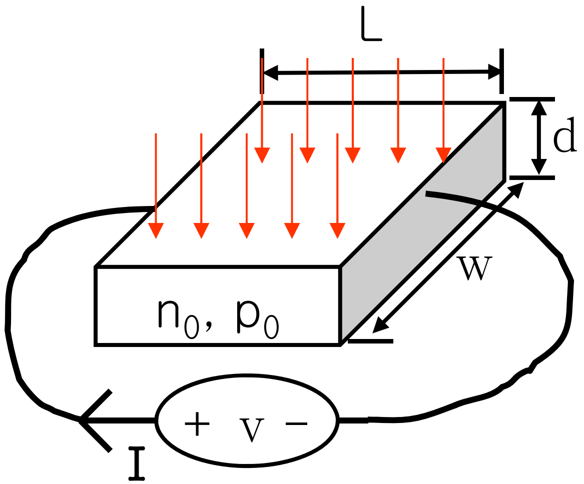
$$R = \eta \cdot \frac{q}{h\nu} \qquad h\nu[\text{eV}] = \frac{1.24}{\lambda[\mu\text{m}]}$$

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



Lect. 10: Photodetectors

Photoconductor



$$R = ?$$

Without light,

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

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

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

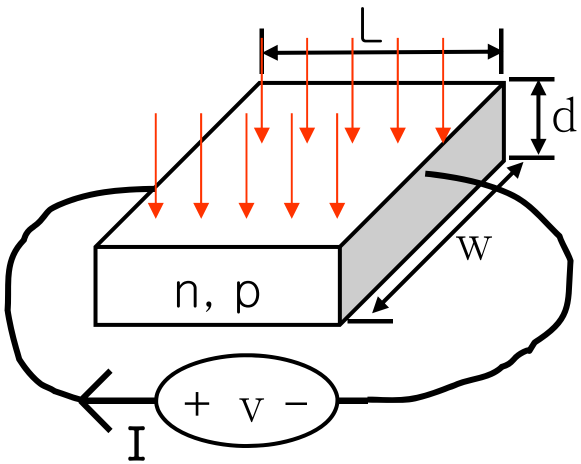
With light,

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

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

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

Lect. 10: Photodetectors



With light,

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

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

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

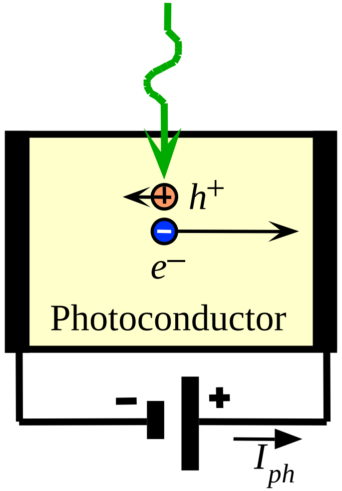
$$\Delta n = \Delta p = \eta_{\text{int}} \cdot \frac{P}{h\nu} \cdot \frac{\tau}{wLd} \text{ (Assume } \Delta n, \Delta p \text{ are uniform)}$$

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

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

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

Lect. 10: Photodetectors



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

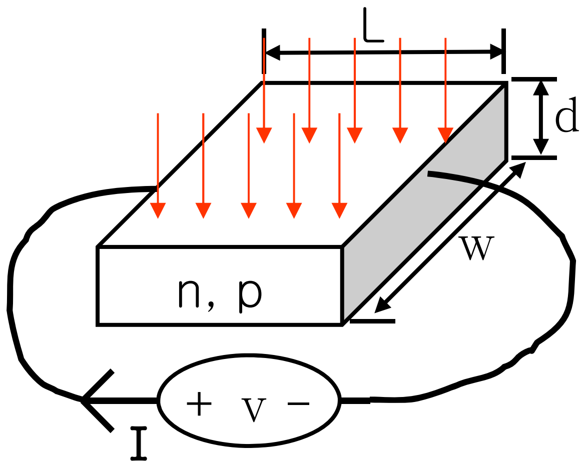
$\tau >> \tau_e$ ==> electrons circulate many time before recombination

With μ_h

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

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

Lect. 10: Photodetectors

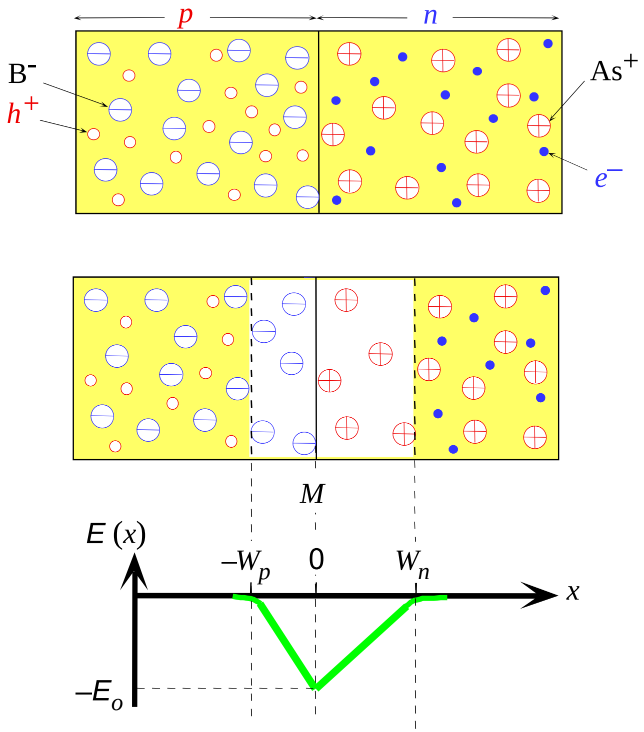


Photoconductors:

- Very easy to make
- Large gain
- But slow (speed limited by τ)
- Can have significant dark currents

Lect. 10: Photodetectors

Faster, less dark-current photodetectors?   photodiode

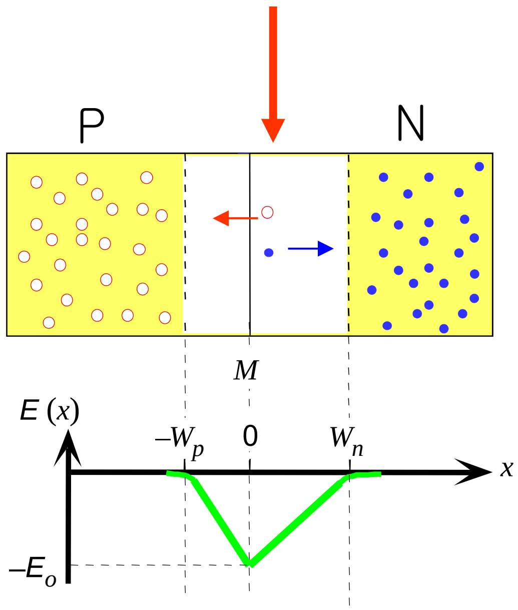


PN junction in reverse bias

- No significant current flow=> small dark currents

- Photo-generated carriers are removed
  by built-in field in depletion region
  (space charge region)

Lect. 10: Photodetectors



– Photo-generated carriers drift into P (holes) and N (electrons) regions generating currents

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

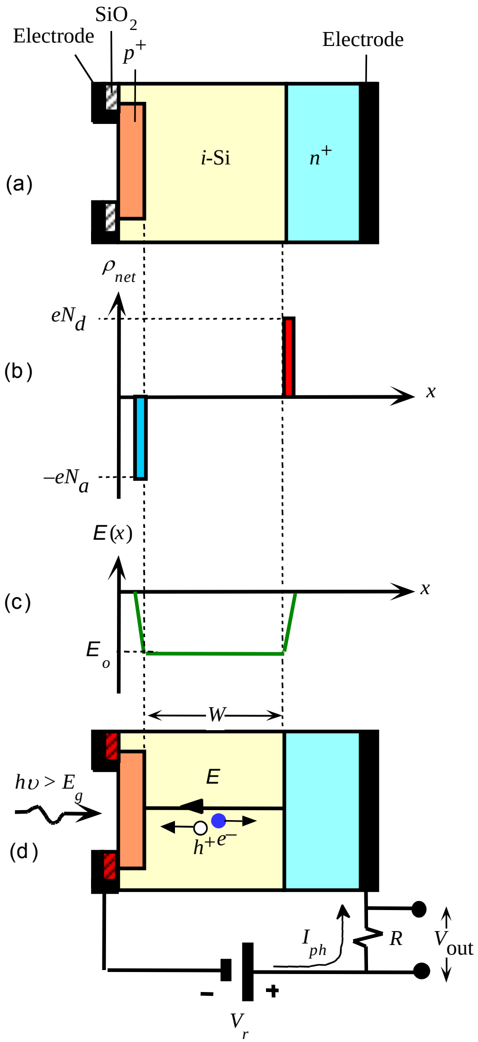
– One photon creates a pair of electron and hole

– Problem: depletion region is very thin (< 1 μm)

➔ η_{int} is very small

=> Use PIN structure

Lect. 10: Photodetectors



PIN Photodiode

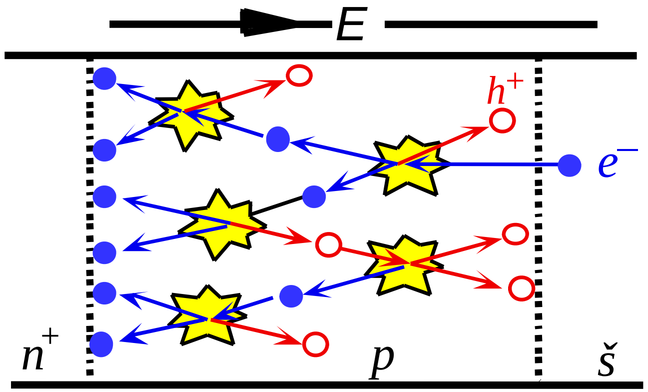
Lect. 10: Photodetectors

PD with gain?

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

Achieve gain by multiplying electrons and/or holes.

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



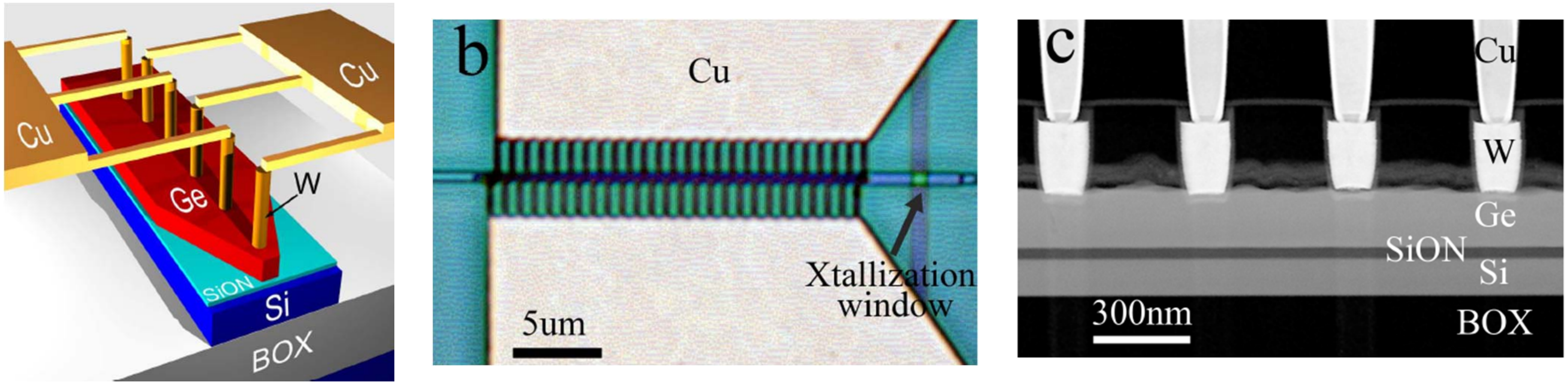
Avalanche region

It is preferred only one type of carrier (either electron or hole) causes impact Ionization

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

Lect. 10: Photodetectors

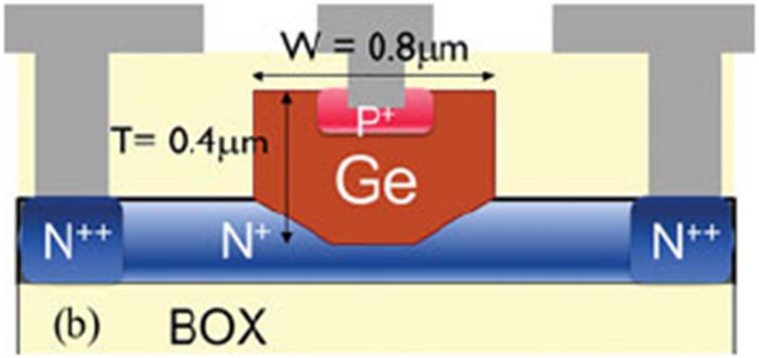
- Metal-Semiconductor-Metal (MSM) Ge PD
  - Low responsivity due to metal shadow (surface illuminated type)
  - Large dark current (low schottky barrier, quality of Ge grown on Si)
  - Electrode distance ➔ photodetection bandwidth

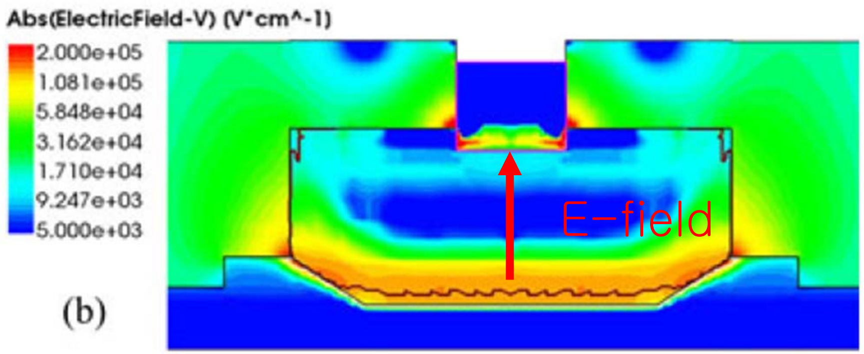


Type	Responsivity	OE bandwidth	Dark current	Ge thickness
WG MSM	0.14 A/W @ -1V	40 GHz @ -2V	90 uA @ -1V	100 nm

Ref) 2010, OE, CMOS-integrated high-speed MSM germanium waveguide photodetector, IBM

- Vertical PIN Ge PD
  - Thickness of intrinsic Ge: tradeoff between transit time and junction cap
  - *RC* time and transit time ➔ photodetection bandwidth

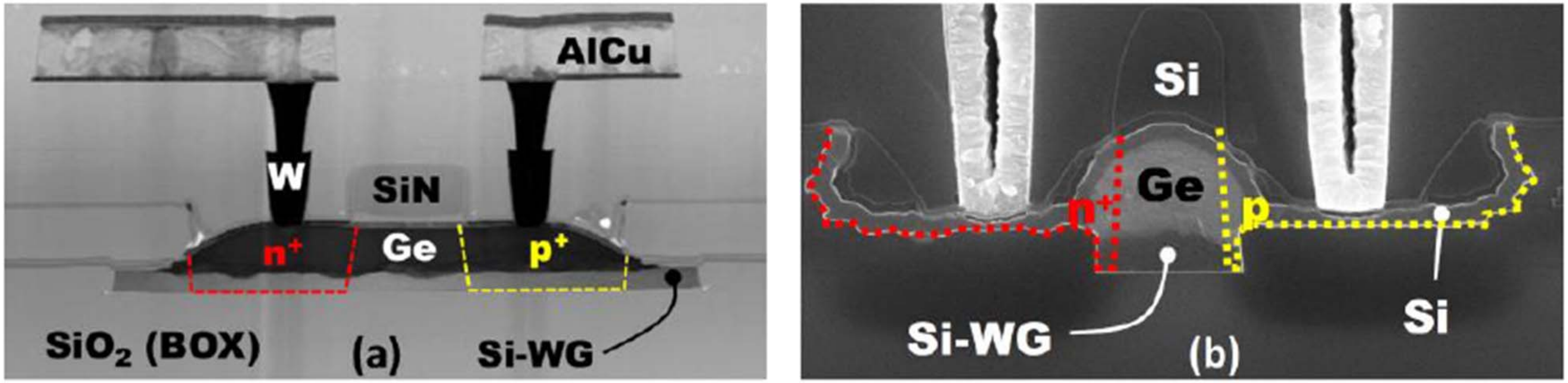




Type	Responsivity	OE bandwidth	Dark current	Ge thickness
WG Vertical PIN	0.5 A/W @ −1V	50 GHz @ −1V	50 nA @ −1V	400 nm

Ref) 2015, JLT, High-responsivity low-voltage 28-Gb/s Ge p-i-n photodetector with silicon contacts, IMEC

- Lateral PIN Ge PD
  - Lower minority carrier diffusion length ➔ increase photodetection bandwidth

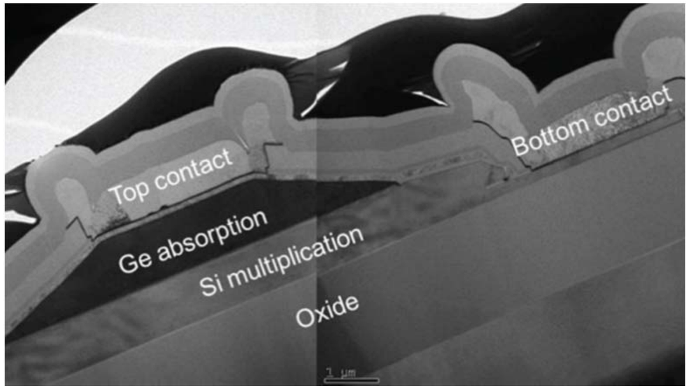


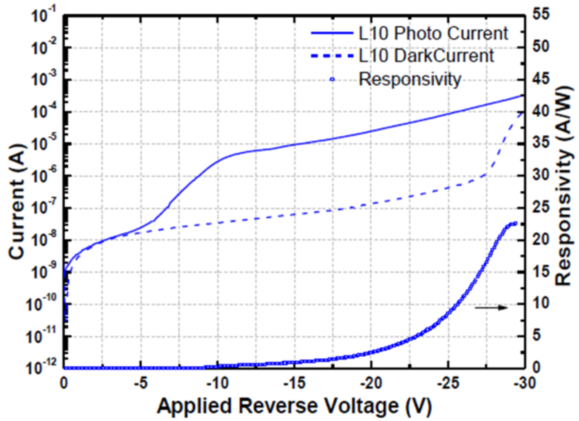
Type	Responsivity	OE bandwidth	Dark current	Ge thickness
WG Lateral PIN	> 1 A/W @ −1V	> 70 GHz @ −1V	100 nA @ −1V	500 nm

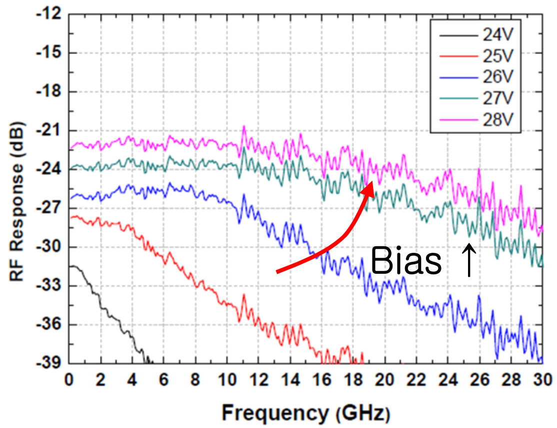
Ref) 2015, OE, High bandwidth, high responsivity waveguide-coupled germanium p-i-n photodiode, IHP

Lect. 10: Photodetectors

- Separate-Absorption-Charge-Multiplication (SACM) PD (Ge/Si APD)
  - Si's low noise property & Ge's strong absorption near 1.55 μm wavelength
  - Low k_{eff} (k ~ 0.09, ratio of ionization coefficients of electrons and holes)
    ➔ high gain-bandwidth products, low noise
  - Need large reverse bias for avalanche ➔ high dark current







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