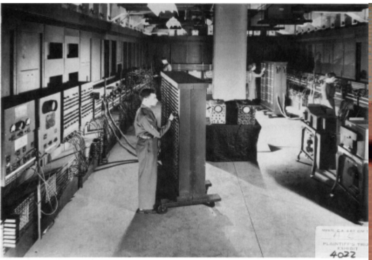
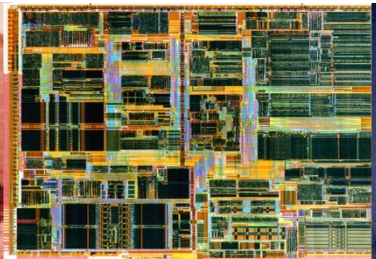
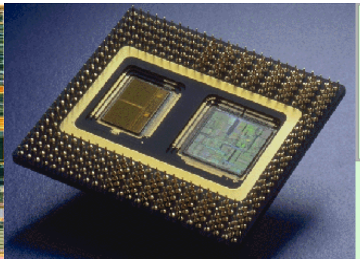
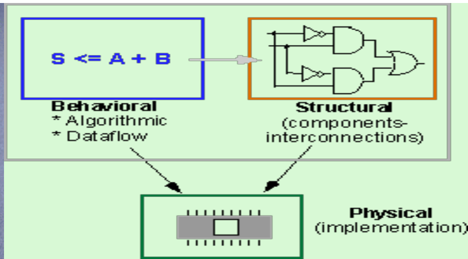
Lecture 6
Optoelectronic Devices

Bryan Ackland
Department of Electrical and Computer Engineering
Stevens Institute of Technology
Hoboken, NJ 07030

Adapted from Modern Semiconductor Devices for Integrated Circuits, Chenming Hu, 2010



Photons and Semiconductors

- Semiconductors can also be used to:
  - convert optical energy (light) into electronic energy
    - video & still cameras
    - optical communication receivers
    - solar cells
  - convert electronic energy into optical energy
    - light emitting diodes
    - semiconductor lasers
- Quantum mechanics teaches us light sometimes behaves as waves, and sometimes behaves as particles (photons)
- Energy of a single photon:

$$E_{ph} = h.\upsilon = \frac{h.c}{\lambda}$$

where υ = frequency

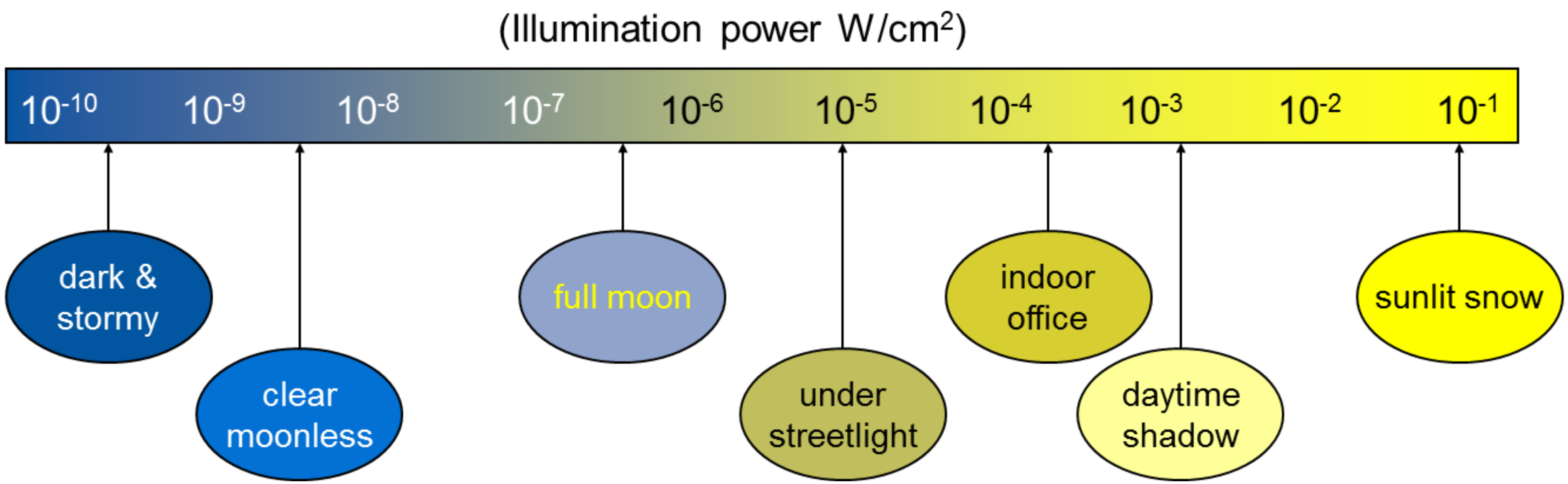
h (plank's constant) $= 6.63 \times 10^{-34}\ J.s$

$$E_{ph}(eV) = \frac{h.c}{\lambda.q} \approx \frac{1.24}{\lambda(\mu m)}$$

$$\lambda(\mu m) \approx \frac{1.24}{E_{ph}\,(eV)}$$

Optical Power

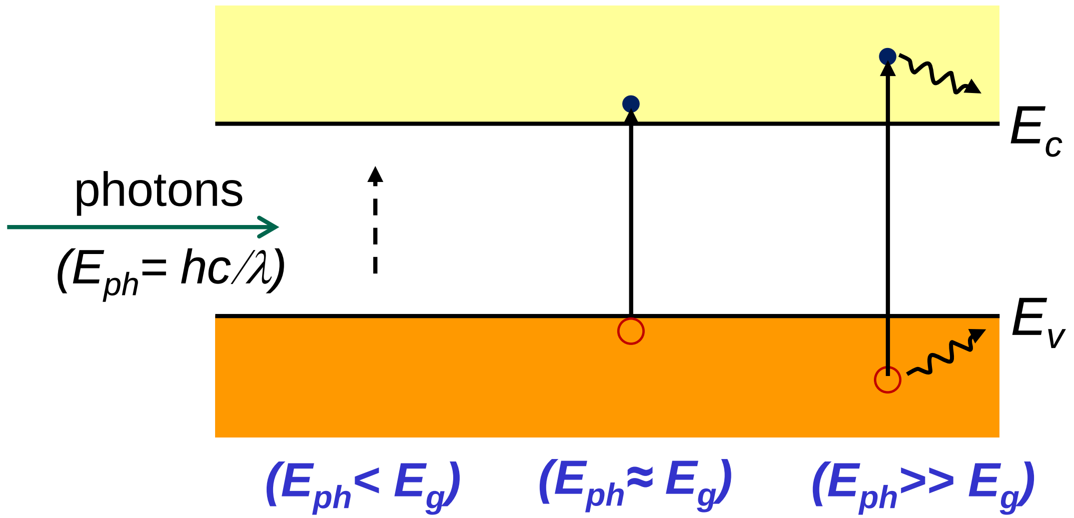
- Large range of optical illumination



- Illumination sometime measured in *lux*
  - lux is a photometric unit that biases different wavelengths according to sensitivity of eye
  - At *550 nm (green)*, *1 lux = 1.46 mW/m²* *= 146 nW/cm²*
    - *At 450 nm (blue), 1 lux = 31.1 mW/m²*
    - *At 650 nm (red), 1 lux = 13.7 mW/m²*
  - How many photons per cm^2 per sec is 1 lux @ 550nm ?

Photon Electron Interaction

- When a semiconductor is illuminated with light:
- If $E_{ph} < E_g$, photons are not readily absorbed
  - light is transmitted through material – appears transparent
- If $E_{ph} > E_g$, photon can interact with valence electron and elevate it into conduction band (creates an electron-hole pair)
- If $E_{ph} \gg E_g$, excess energy will be turned into additional electron or hole kinetic energy (dissipated as heat)

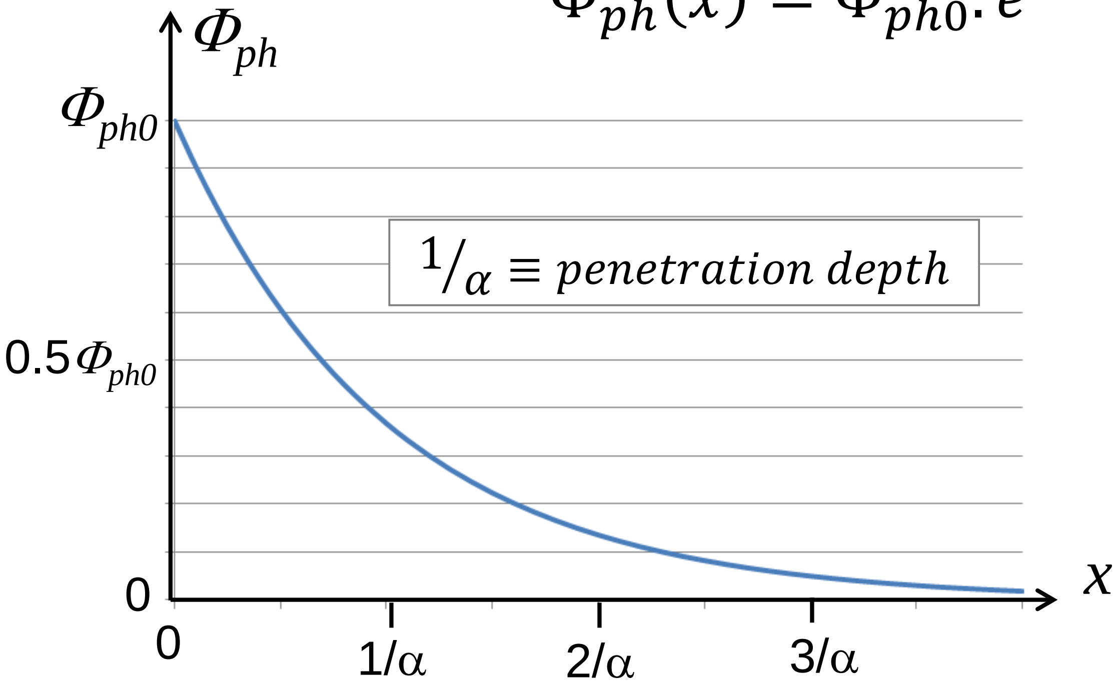


Photon Absorption Coefficient

- $\Phi_{ph} \equiv$ photon flux $(photons/cm^2.s)$
- Absorption is characterized by α : relative number of photons absorbed per unit distance

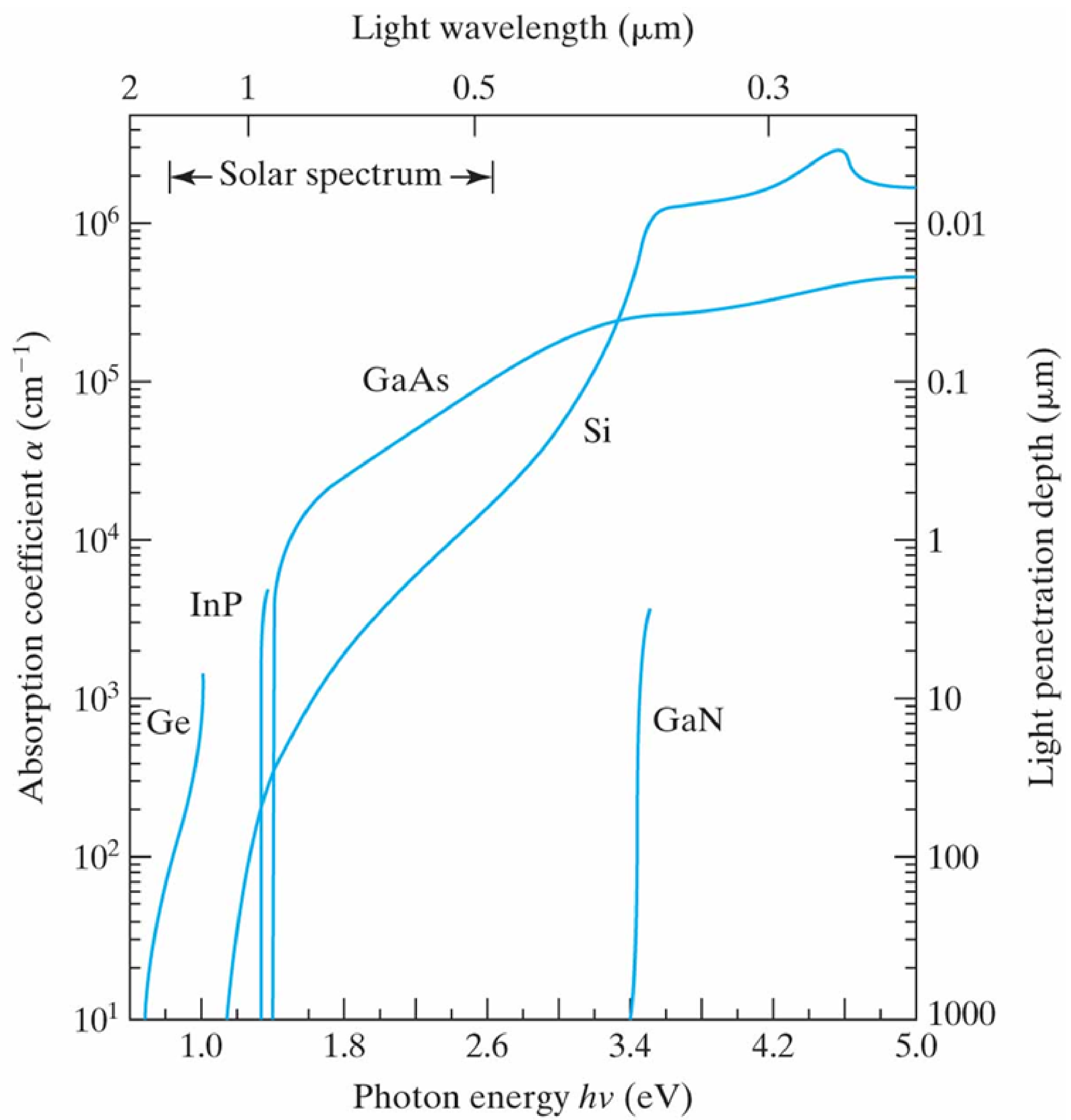
$$\frac{d\Phi_{ph}(x)}{dx} = -\alpha.\Phi_{ph}(x)$$

$$\Phi_{ph}(x) = \Phi_{ph0}.e^{-\alpha.x}$$



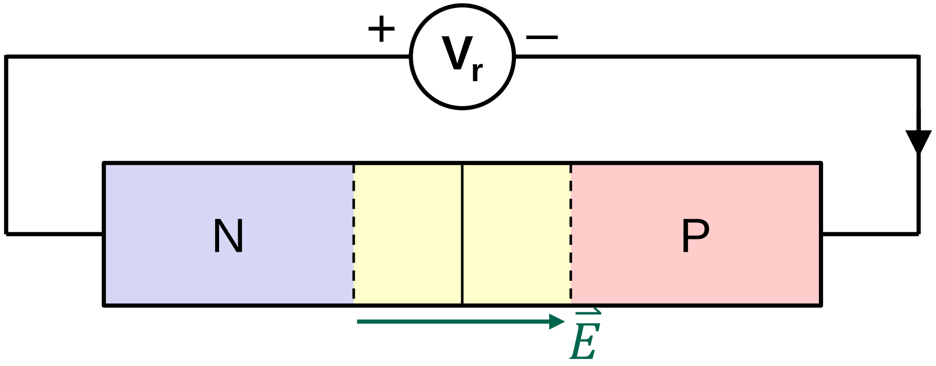
Photon flux decreases exponentially with distance through semiconductor material

Absorption Coefficient *vs.* Photon Energy



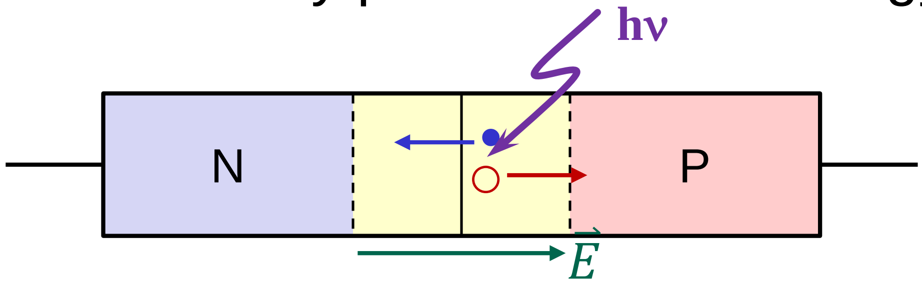
Photodiode

- Consider PN photodiode under reverse bias



$$I = I_0\left(e^{qV/kT} - 1\right)$$

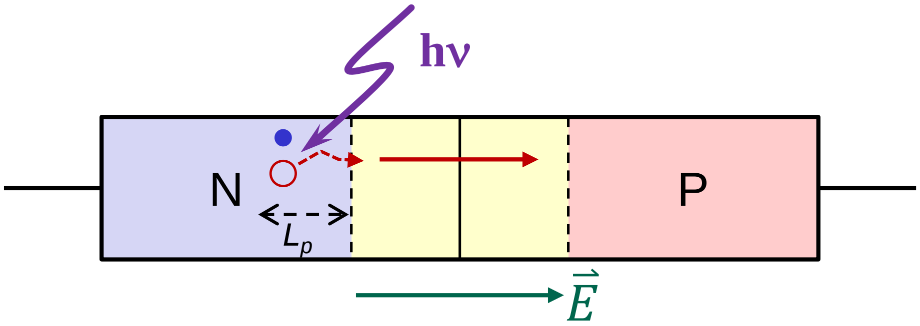
- Small reverse (dark) current flows due to minority carriers being swept across junction by electric field
- When illuminated by photons whose energy > E_g



- Photon is absorbed and generates electron-hole pair
- If absorbed in depletion region, electric field accelerates electron towards to N region and hole towards P region

Photo-diode

- If electron-hole pair is created in neutral N region within L_p of depletion region, hole may diffuse toward depletion region



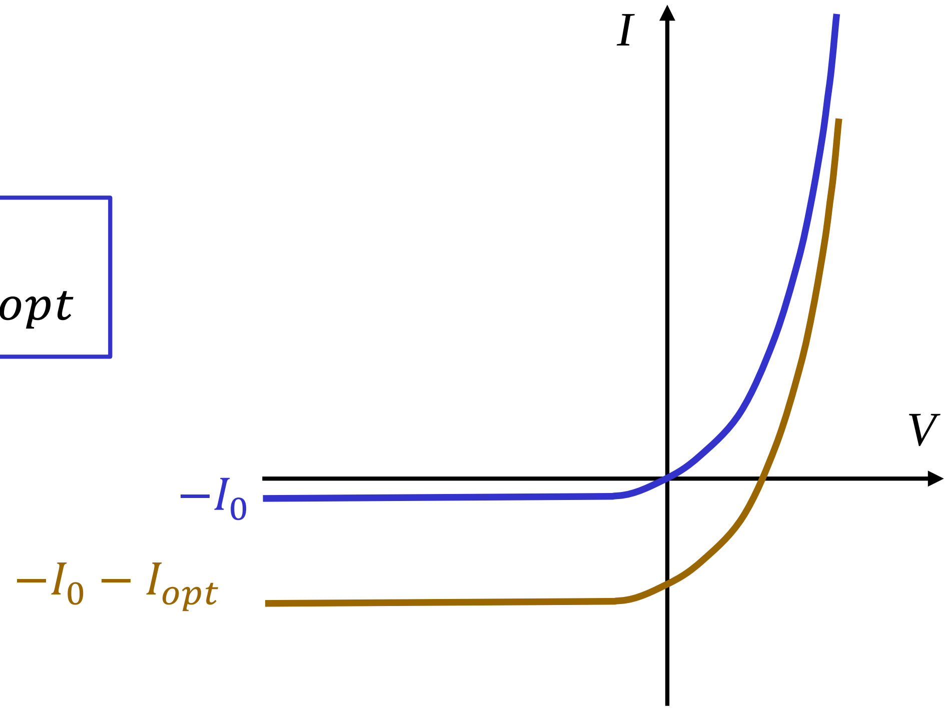
- Similarly for electrons generated in P region

- Electron-hole pairs created far from depletion region will usually recombine before reaching depletion region

- All carriers that make it to high-field depletion region will contribute to an optical current
  - total reverse current will be dark current plus optical current

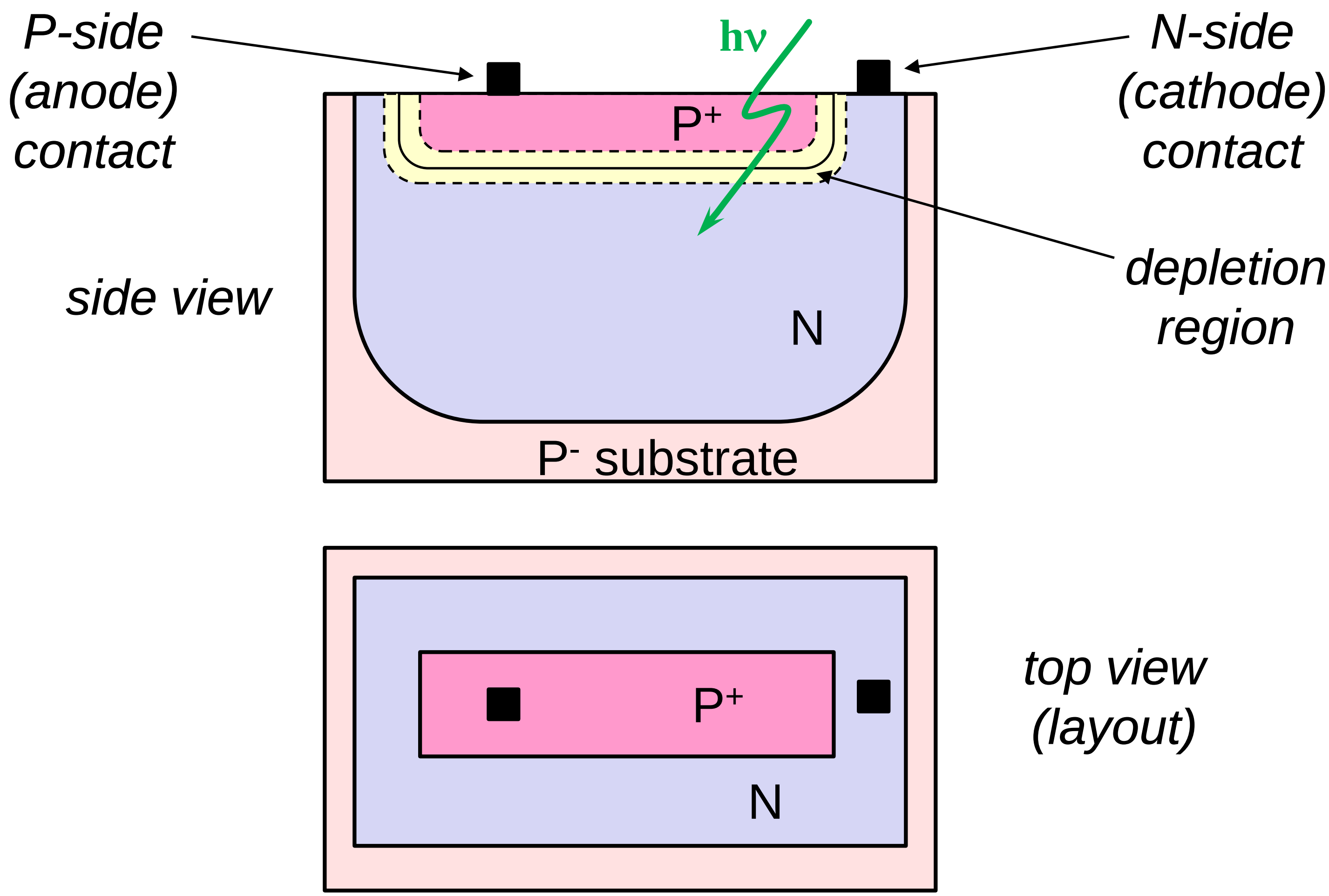
Photo-current

$$I = I_0\left(e^{qV/kT} - 1\right) - I_{opt}$$



- Optical current is negative (same direction as dark current)
- I_{opt} depends on number of excess carriers generated and is independent of V

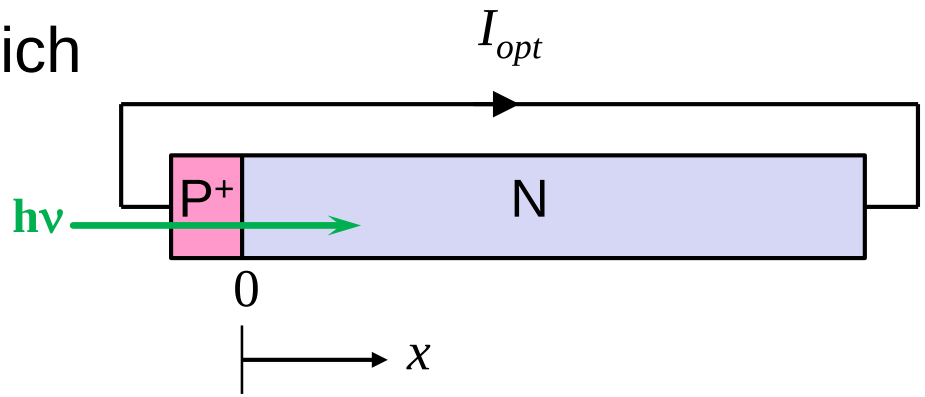
Photo-diode structure



- Assume shallow P^+ region contained in deep N region
  - $P_{depth} < 1/\alpha$ ⇨ most photons penetrate into N region

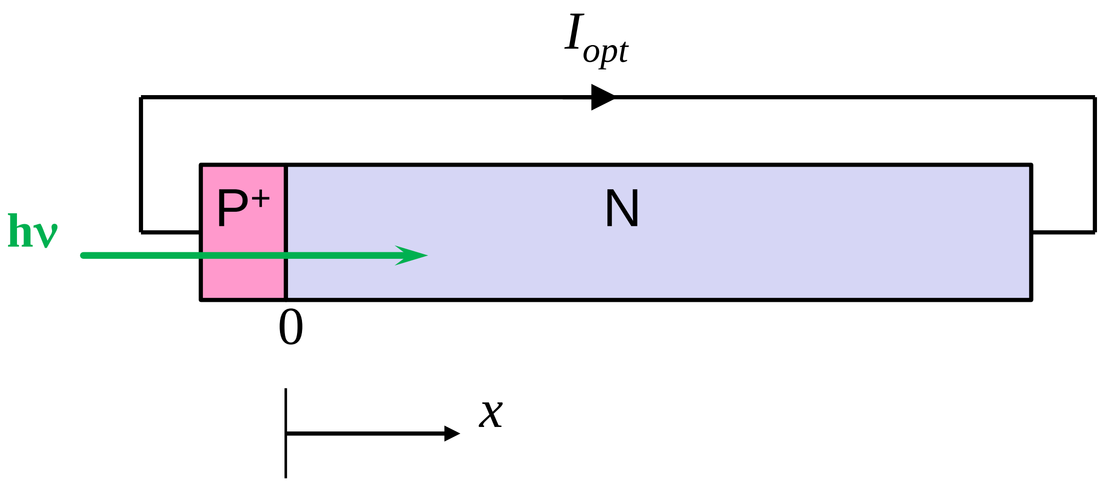
Photo-generated Minority Carriers

- Consider a photodiode in which most photons penetrate into neutral N region
  - $P^{+}_{depth} \ll 1/\alpha$
  - $W_{depletion} \ll 1/\alpha$



- To determine optical current in neutral N region, we need to know concentration of excess minority holes
- Can be determined from diffusion equation but its solution is complicated by:
  - Need for optical generation term G_L $holes\ cm^{-3}s^{-1}$
  - G_L is not uniform due to absorption: $G_L(x) = G_{L_0}.e^{-\alpha x}$
  - Finite length of diode
- To simplify solution, we will assume:
  - G_L is constant (independent of x – implies small absorption coeff.)
  - Diode is of infinite length

Diffusion Equation with Photogeneration



- With optical generation, continuity equation becomes:

$$-\frac{1}{q}.\frac{dJ_p}{dx} = \frac{p'}{\tau_p} - G_L$$

where G_L is optical hole generation rate

- This transforms Diffusion Equation to:

$$\frac{d^2p'}{dx^2} = \frac{p'}{{L_p}^2} - \frac{G_L}{D_p}$$

Excess Carrier Distribution

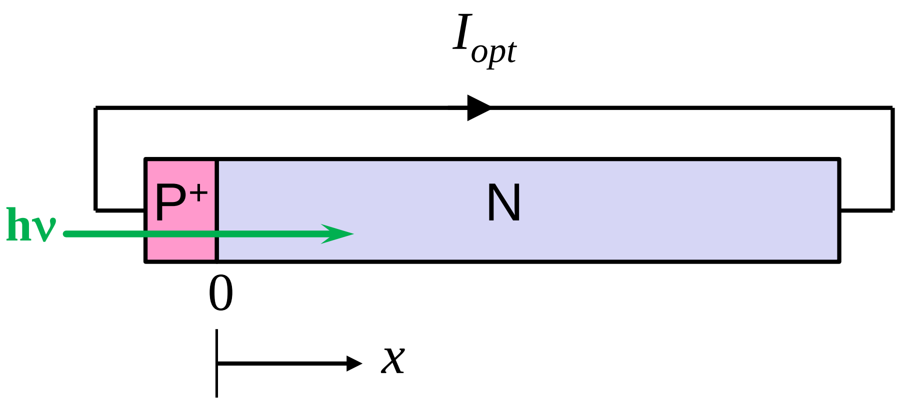
- Solve diffusion equation under boundary conditions:

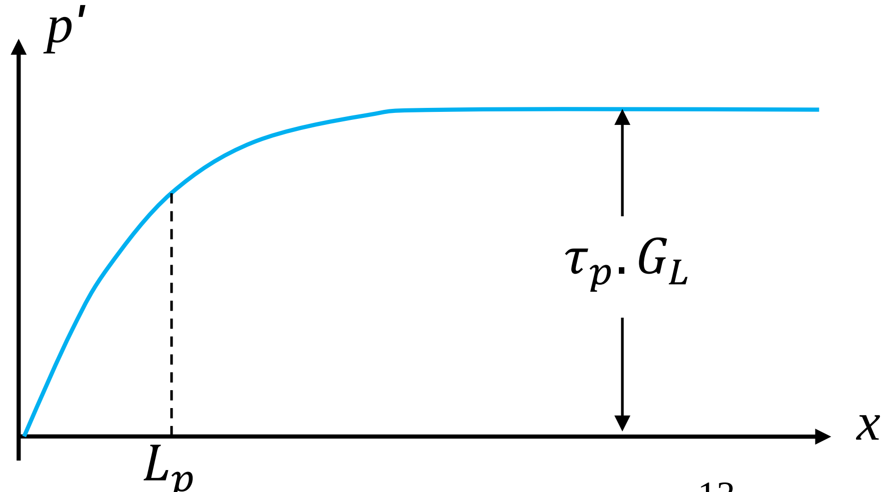
$$p'(0) = p_{N0}\left(e^{qV/kT} - 1\right) \approx 0$$

$$p'(\infty) = L_p{}^2 . \frac{G_L}{D_p} = \tau_p . G_L \qquad \left(\text{since } \frac{d^2p'}{dx^2} = 0 \; at \; x = \infty\right)$$

- yields:

$$p'(x) = G_L . \tau_p\left(1 - e^{-x/L_p}\right)$$





Long Diode Optical Current

$$J_p = -q.D_p.\frac{dp'}{dx} = -q.\frac{D_p.\tau_p}{L_p}.G_L.e^{-x/L_p}$$

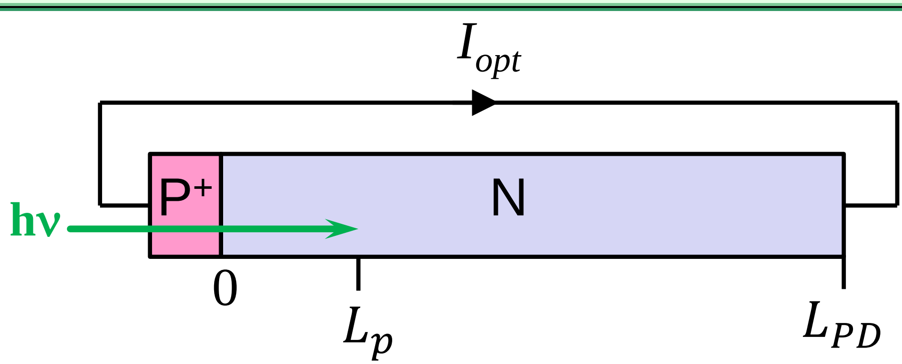
$$I_{opt} = A.J_p(0) = -q.A.G_L.L_p$$

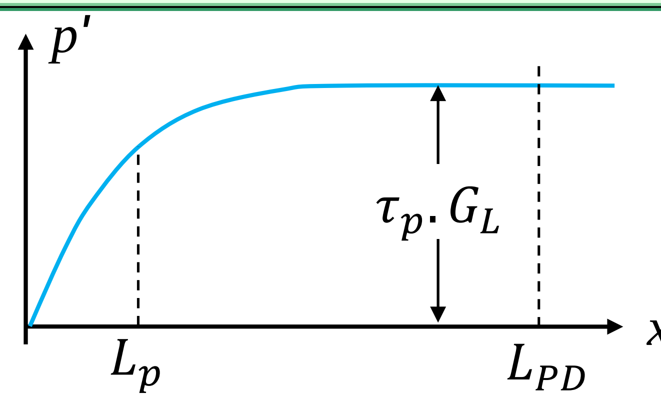
- As if all holes within a distance L_p of the junction are collected (to create optical current) and all holes beyond L_p recombine
- In the more general case where photons are absorbed in P and N regions and also in the depletion region:

$$I_{opt} = -q.A.G_L.(W_{dep} + L_p + L_n)$$

  - Note that optical current is always negative

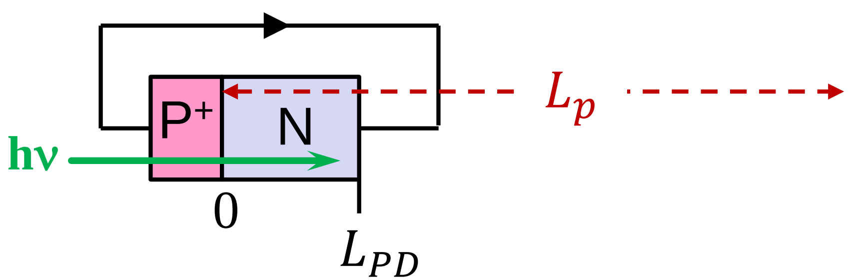
Short Photodiodes





$I_{opt} = -q. A. G_L. L_p$ assumes length of photodiode $L_{PD} \gg L_p$

- Integrated photodiodes often have $L_{PD} \ll L_p$



- We can then assume that all photo-generated holes make it to the high field depletion region

which gives: $I_{opt} = -q. A. G_L. L_{PD}$

Photodiode Quantum Efficiency

- Ideally, each photon entering photodiode creates a minority carrier which reaches the junction before recombination
- Define quantum efficiency η_{pd} =

$$\frac{\#optically\ generated\ minority\ carriers/sec\ to\ reach\ junction}{\#of\ photons/sec\ incident\ on\ photodiode}$$

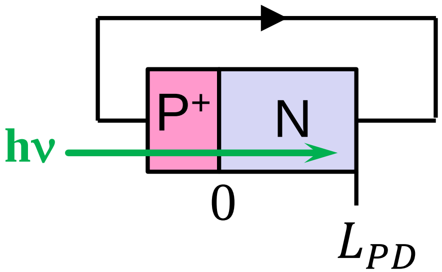
- We can then say:

$$I_{opt} = q.A.\eta_{pd}.\Phi_{ph0}$$

- η_{pd} is degraded by
  - reflections at surface
  - photons pass through not absorbed (absorption coefficient)
  - generated carriers that recombine

Short Photodiode Quantum Efficiency

- In a short photodiode, we assume that all generated carriers contribute to the optical current
- For short diode, we can use $G_L(x)$
  - i.e. account for absorption



$$G_L(x) = \alpha . \Phi_{ph}(x) = \alpha . \Phi_{ph0} e^{-\alpha x}$$

where Φ_{ph0} = incident photon flux
α = absorption coefficient

- Because all carriers contribute to photo current, we can say:

$$I_{opt} = A.q \int_0^{L_{PD}} G_L(x).dx = A.q.\alpha \int_0^{L_{PD}} e^{-\alpha x} dx$$

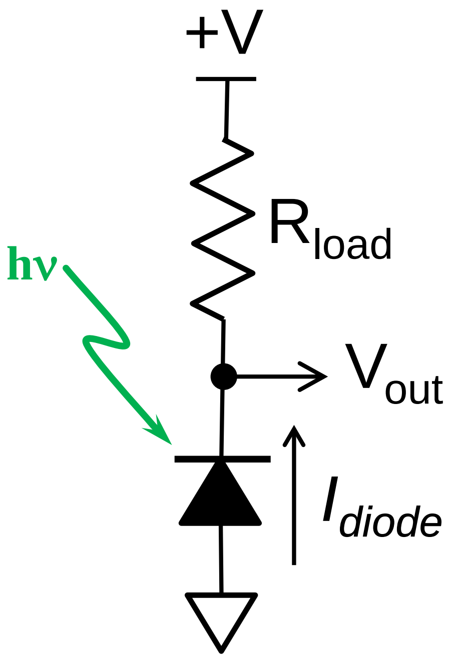
$$which\ gives \quad I_{opt} = A.q.\Phi_{ph0}(1 - e^{-\alpha . L_{PD}})$$

- So, for a short diode, ignoring reflection & other optical losses:

$$\eta_{pd} = 1 - e^{-\alpha . L_{PD}}$$

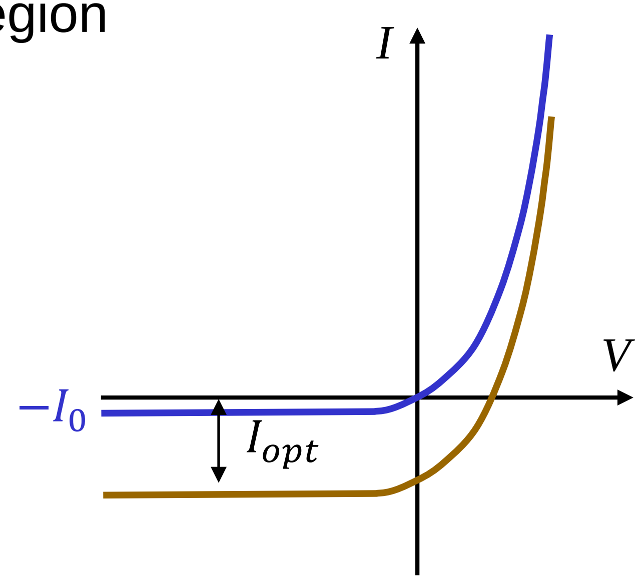
Photodiode Operation

- Photodiodes are normally operated in reverse bias:
  - gives a small, predictable dark current
  - wider depletion region to capture photons
  - reduced depletion capacitance
  - stronger electric field across depletion region



$$I_{diode} = I_{dark} - I_{opt}$$

$$I_{revbias} = -I_0 - I_{opt}$$



Photodiode Example

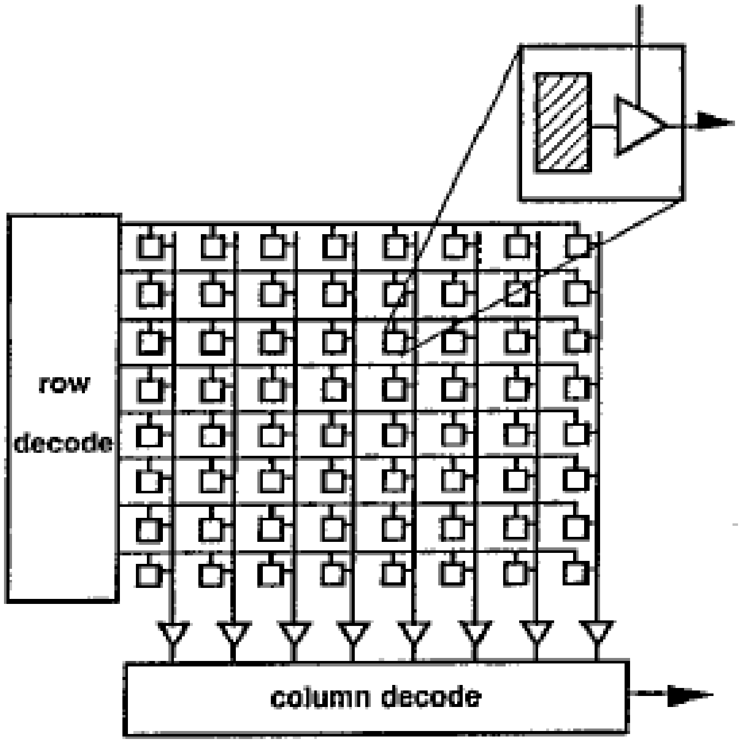
- A vertically illuminated P^+N silicon diode has a cross-section of 100μm x 100μm and a total depth (P plus N) of 1.5 μm. Carrier diffusion lengths are L_n=15μm and L_p=10μm. The diode is illuminated by green (550nm) light with an intensity of 100 lux. If the absorption factor in silicon at 550nm is 10^4 cm^{-1} ,

a) What will be the quantum efficiency of the photodiode?

b) What will be the optical current?

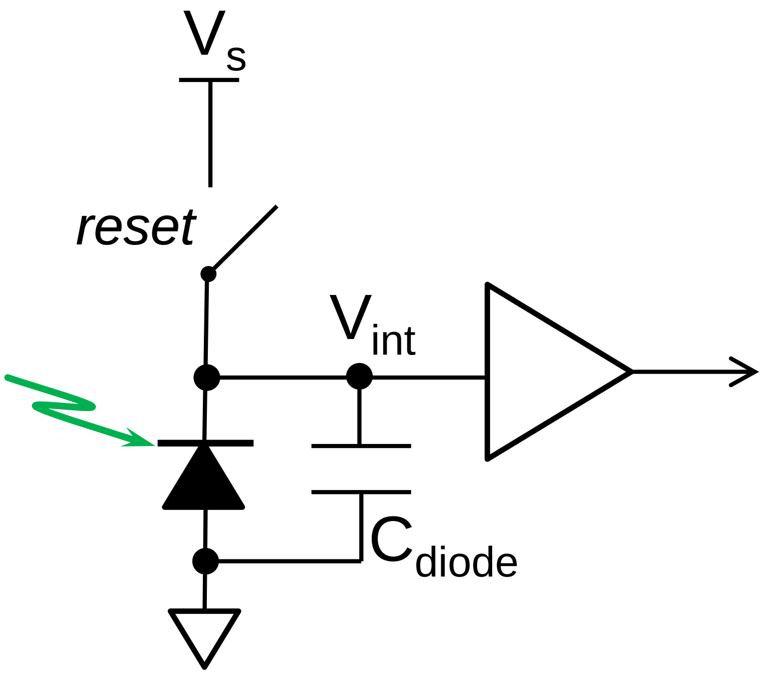
CMOS Imager

- CMOS imager consists of large number of pixels arranged in a rectangular array:
  - Each pixel consists of a photodiode and small read-out amplifier
  - Accessed by row and column (much like memory array)



- I_{opt} is very small
  - pixel size (5 μm)
  - low light (~ 1 lux)
  - not possible to measure this small current directly
- Optical current is integrated into a small capacitor for a specified exposure period to produce an optical charge
  - can use parasitic capacitance of photodiode

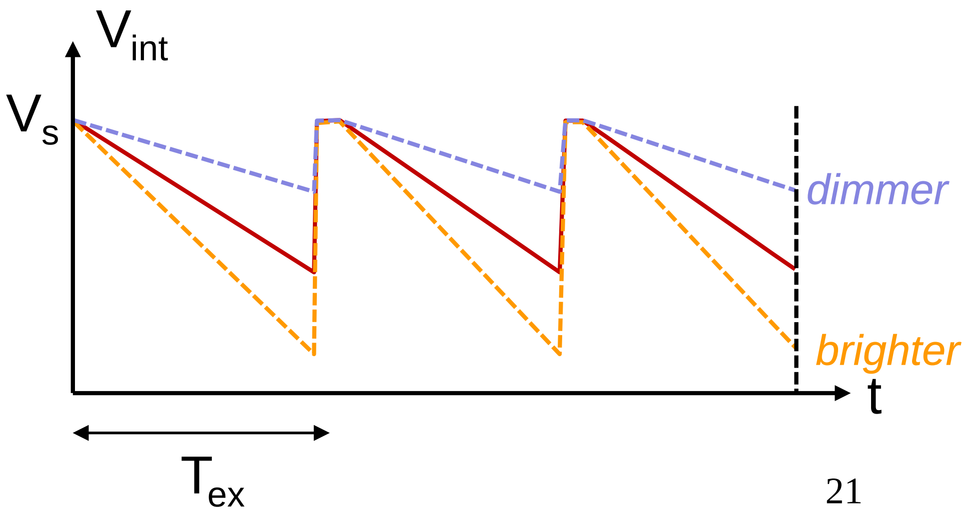
CMOS Imager Pixel



- Pixel is reset at beginning of exposure period T_{ex}

$$V_{int} = V_s + \frac{1}{C_{diode}} \int_0^{T_{ex}} I_{diode} \, . dt$$

$$= V_s - \frac{(I_{dark} + I_{opt}). T_{ex}}{C_{diode}}$$

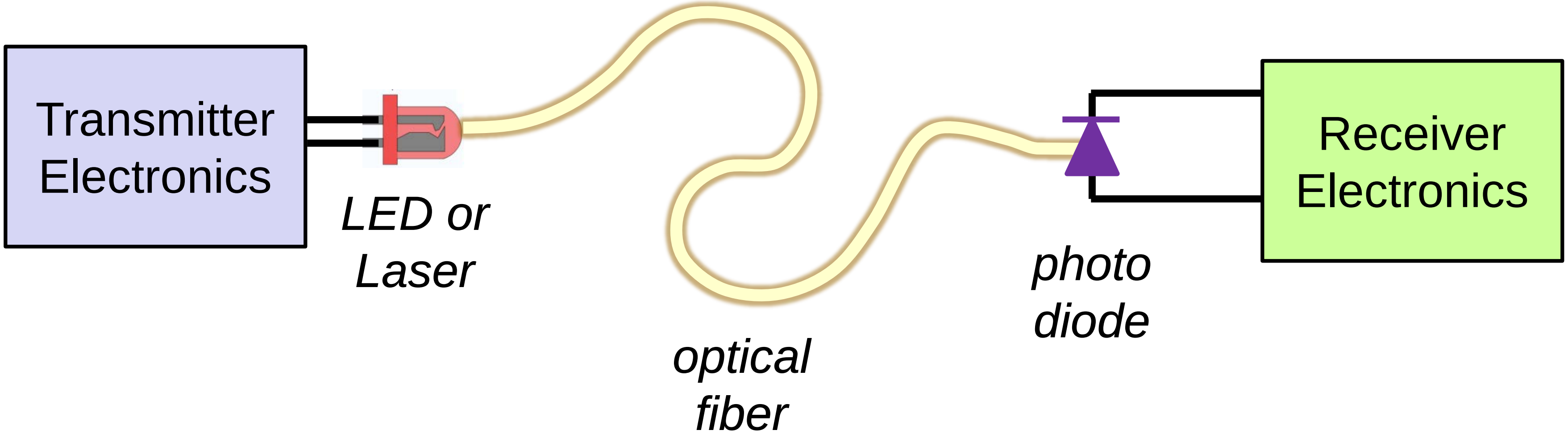


Example:

If $I_{opt} = 10\ fA$
$C_{diode} = 50\ fF$
$T_{ex} = 30\ ms$

then $(V_s - V_{int}) = 6\ mV$

Optical Communications



- Most broadband communication links are optical:
  - high-speed 1-0 (on-off) light pulses sent down optical fiber
  - fiber is high bandwidth, low dispersion and immune to electrical interference
  - speeds range from 6 Mb/s (audio) to 100Gb/s (per wavelength)
  - requires high-speed photodetector – ability to turn-on and turn-off very quickly

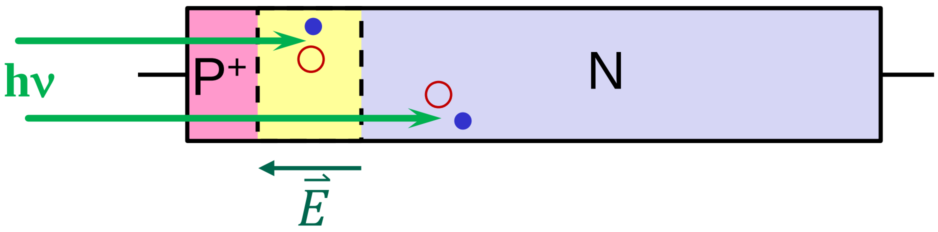
Speed Limitations of PN Photodiodes

- Photodiode speed limited by:
  - reverse bias diode capacitance
  - time for excess carriers to diffuse once illumination is turned off
- Diode capacitance limits speed of receiver electronics

$$C_{dep} = \frac{\varepsilon_s . A}{W_{dep}} = A . \sqrt{\frac{q . N . \varepsilon_s}{2(\emptyset_{bi} + V_r)}}$$

- Hole generated in depletion region accelerated by E field

$$\tau = \tau_{tr} = \frac{{W_{dep}}^2}{\mu_p . V_{dep}}$$



- Hole generated in neutral N region diffuses toward junction

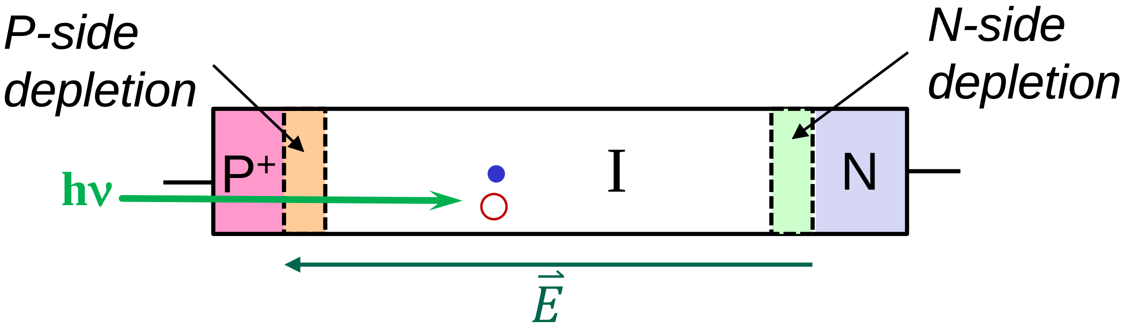
$$\tau \approx \tau_p$$

Example: Speed Limitations

- Consider a P^+N silicon photodiode with a shallow (1μm) P^+ diffusion with $N_a=10^{17}$ cm^{-3} and a deep N diffusion with $N_d=10^{15}$cm $^{-3}$.
- Assume T = 300°K and $\tau_p = 10^{-7}$ s.
- Calculate and compare the transit time τ_{tr} of holes optically generated in the depletion region to the diffusion time of holes optically generated in the neutral N region when the diode is reverse biased with V_r = 5V.
- If the diode has an area of 1 mm^2, what is the capacitance of the diode under this reverse bias?
- If the load resistance is 470 Ω, what is the electrical time constant of the detection circuit?

PIN Photodiode

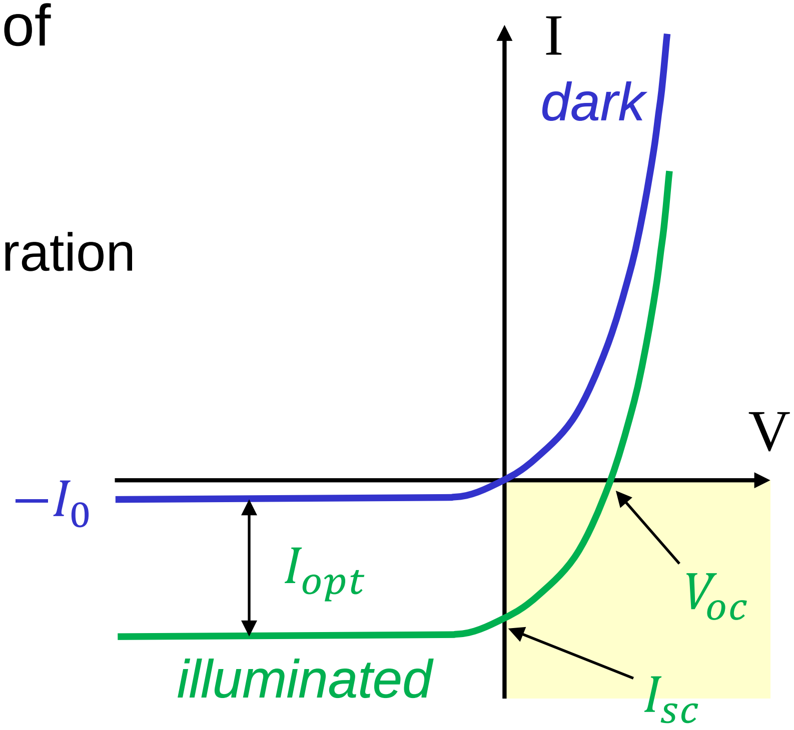
- Both speed limitations of PN photodiode can be reduced by extending width of depletion region
  - Increasing reverse bias – eventually reach breakdown
- PIN *(P-type: Intrinsic: N-type)* photodiode achieves this by adding an intrinsic (undoped) region between N & P



- If a reverse bias is applied, the space-charge region extends completely through the intrinsic region
  - Electrons & holes, most of which will now be generated in intrinsic region will be accelerated out of junction by E field
  - Diode capacitance reduced dramatically
- Ex: Recalculate τ_{tr}, C_{diode} and τ_{elec} for previous example if a 20μm intrinsic layer is inserted between N and P regions

Solar Cell

- Solar cell operates in 4^{th} quadrant of photodiode I-V curve
  - V is positive, I is negative
  - P = V.I is negative ⇨ power generation



- Short circuit current:

$$I_{sc} = I_{opt}$$ *(remember I_{opt} is negative)*

- Open circuit voltage:

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

solving for $I(V_{oc}) = 0$ gives: $$V_{oc} = \frac{kT}{q} ln\left(\frac{-I_{opt}}{I_0}\right)$$

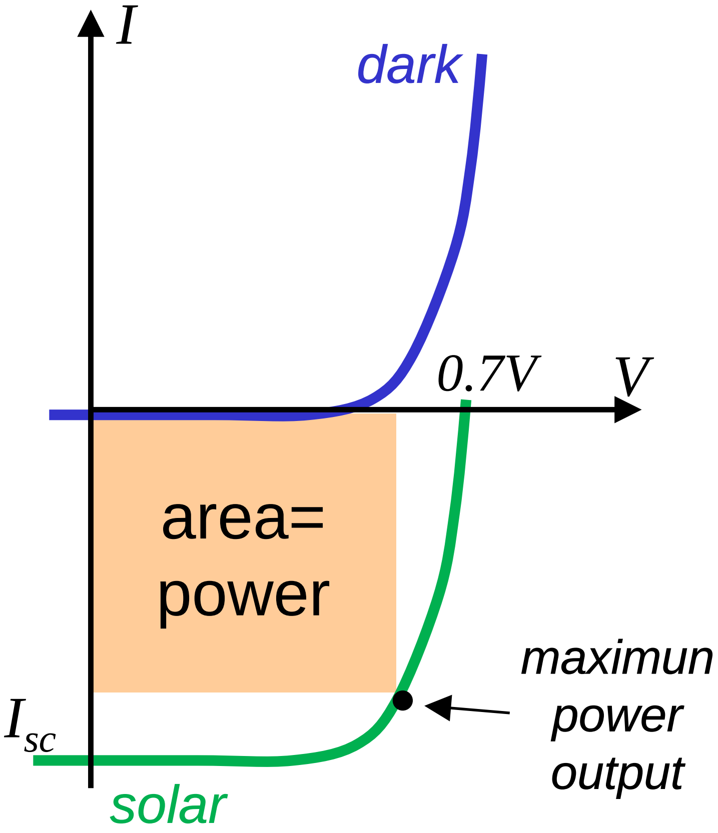
- How can we improve V_{oc} ?

Solar Cell Output Power

- Output Power = $V \times I$
- Need to pick correct operating point to maximize power output
- Max. Output Power = $I_{sc} \times V_{oc} \times FF$
  where FF (fill-factor) typically 75%
- Conversion efficiency η

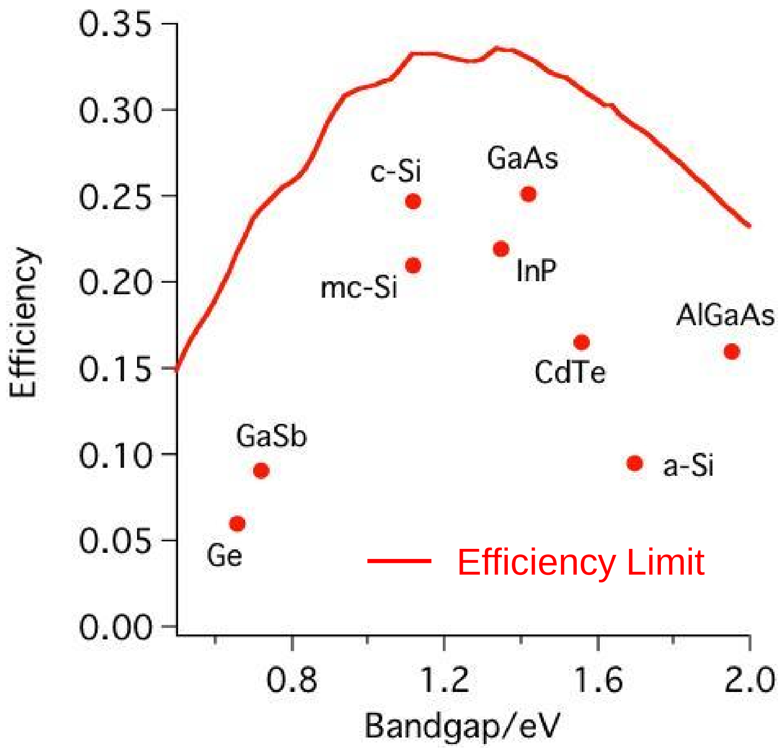
$$\eta = \frac{electrical\ power\ out}{optical\ (solar) power\ in}$$

- To compete against other forms of energy, need to
  - maximize efficiency
  - reduce capital cost of manufacture & installation



Solar Cell Efficiency

- Maximum achievable η depends on how well bandgap is matched to photon energy
  - E_g too large, no absorption
  - E_g too small, excess energy wasted as heat
- Crystalline silicon too expensive to use in commercial solar cells
- Amorphous silicon has lower η but is much cheaper to manufacture
- Exploring organic semiconductors

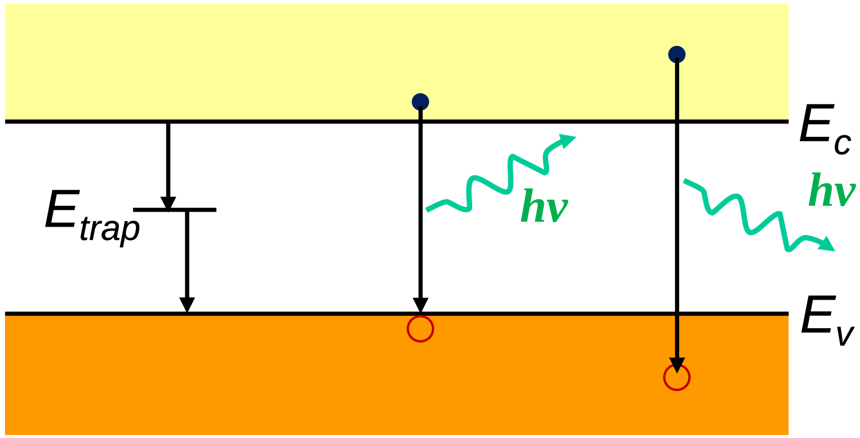


- Commercial (roof-top) solar panels have η ≈ 15-20%
- Output power typically 200 W/m^2 (peak), 25 W/m^2 averaged over day/night/cloudy days etc.

Electroluminescence

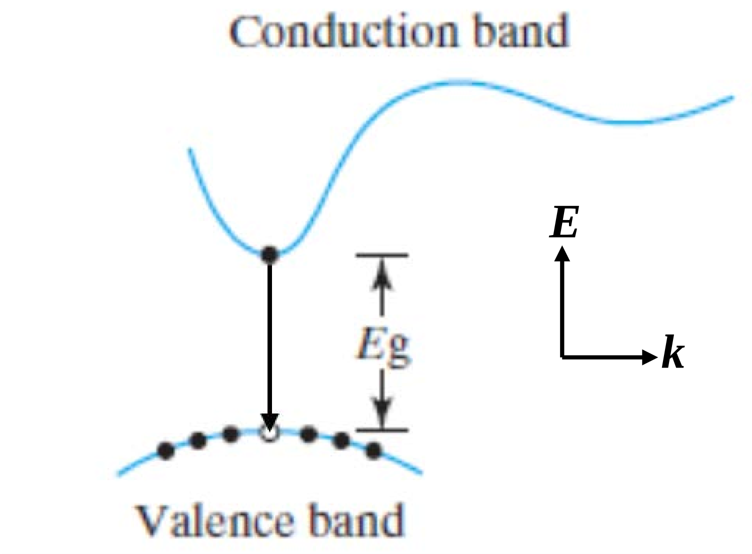
- Electron-hole pairs are generated by application of energy
  - e.g. thermally or by incoming photon
- When recombination occurs, energy is released
  - as a photon (radiative recombination)
  - or as heat (non-radiative recombination)

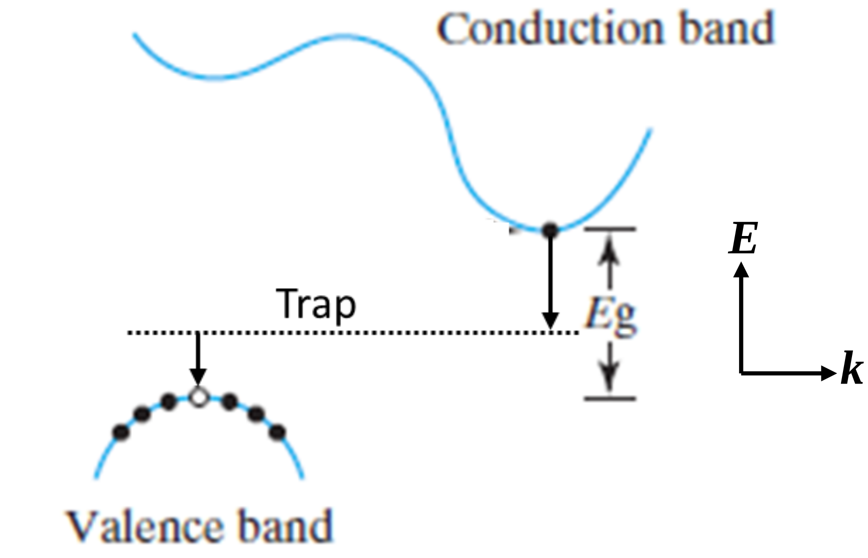
- *Direct bandgap transition <u>may</u> result in photon emission (electroluminescence)*
- *Indirect transitions (e.g. via traps) never result in photon emission (energy released as heat)*



- When photon is emitted, $\lambda(\mu m) \approx \dfrac{1.24}{E_g(eV)}$

Direct & Indirect Band Gaps

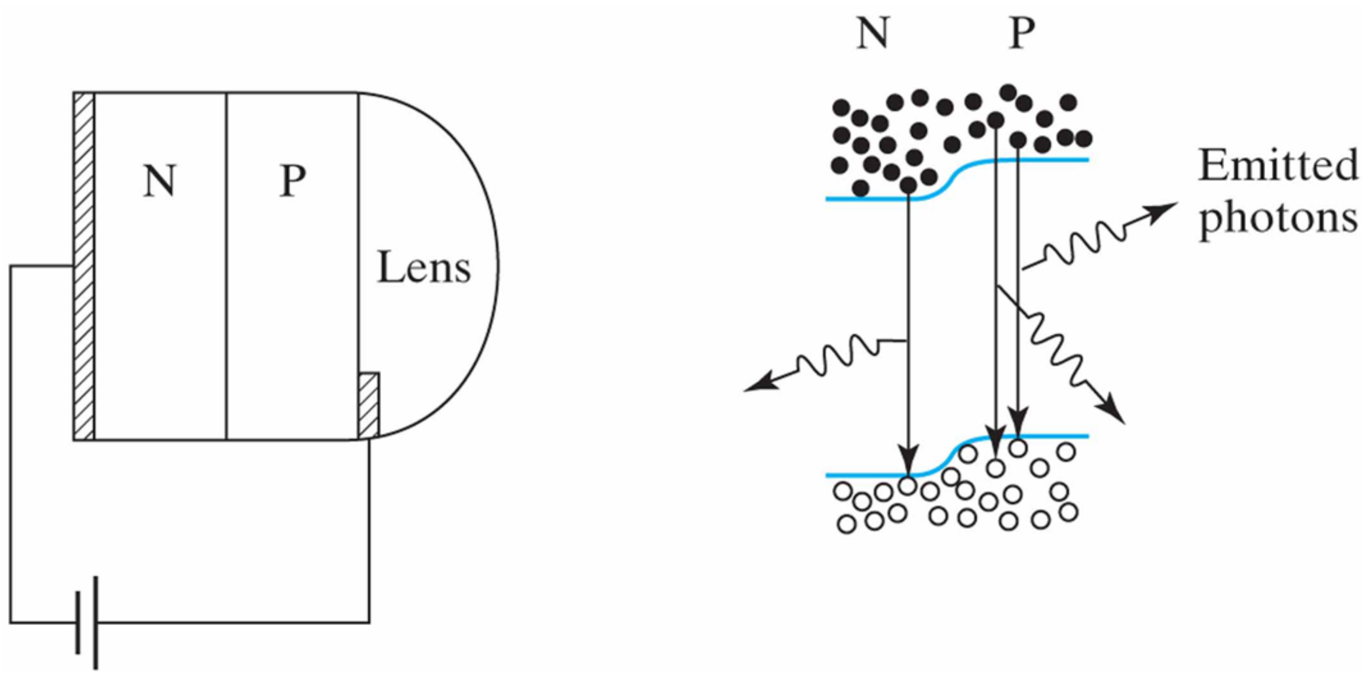




- **Direct Band Gap**
- *Example: GaAs, GaP*
- Direct recombination is possible since momentum is conserved
- Light emitting devices are built using variety of direct bandgap (typically III-V) semiconductors

- **Indirect Band Gap**
- *Example: Si, Ge*
- Direct recombination is rare since momentum is not conserved
- Silicon and other indirect bandgap semiconductors are not used to build light emitting devices

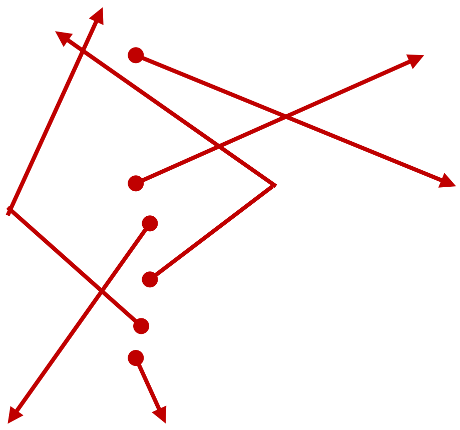
Light Emitting Diode (LED)



- Direct bandgap diode is forward biased.
  - Minority electrons injected into P region,
  - Minority holes injected into N region
  - Excess minority carriers recombine with majority carriers
  - Some fraction of these recombinations generate a photon

LED Efficiency

- Quantum efficiency η of LED is limited by:
- Percentage of recombinations that generate a photon
  - Depends on ratio of radiative and non-radiative carrier lifetimes
  - Often referred to an internal quantum efficiency
  - Can be as high as 90%



- Emitted photons reabsorbed by semiconductor
  - If $E_{photon} \approx E_g$, photon can be absorbed, recreating elec-hole pair
  - Need to have radiative junction close to surface
- Photons are emitted in all directions
- Internal reflection at semiconductor-air interface
  - Typically add a dome-shaped plastic lens
- Typically overall η < 10%

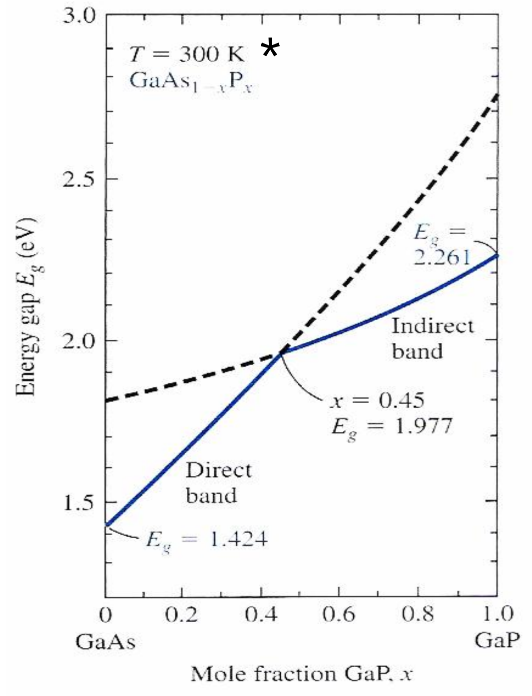
Binary Compound Semiconductor LED's

- Binary compound semiconductors output light at fixed wavelength $\lambda(\mu m) \approx 1.24/E_g(ev)$
- Spectral bandwidth typically 20-50 nm
  - due to small variation in electron and hole energies

	Eg (eV)	Wavelength (μm)	Color	Lattice constant (Å)
InAs	**0.36**	**3.44**	**infrared**	**6.05**
InN	**0.65**	**1.91**		**3.45**
InP	**1.36**	**0.92**		**5.87**
GaAs	**1.42**	**0.87**		**5.66**
GaP	**2.26**	**0.55**	**green**	**5.46**
AlP	**2.45**	**0.51**	**aqua**	**5.45**
GaN	**3.39**	**0.37**	**UV**	**3.19**
AlN	**6.20**	**0.20**		**3.11**

Higher Order Semiconductor LED's

- Tertiary semiconductor allows wavelength tuning by varying relative composition of constituent elements
- For example $GaAs_{1-x}P_x$
  - direct bandgap for 0<x<0.45
  - gives 870nm < λ < 630nm (NIR to red-orange)
  - highest efficiency at 640nm (red)



- Quaternary semiconductors allow simultaneous tuning of bandgap and lattice constant
  - e.g. *AlInGaP*
  - high quality epitaxial films on low-cost substrates
- Heterojunction LEDs
  - Inject electrons from wide bandgap $N\text{-}GaAl_{0.7}As_{0.3}$ into narrow bandgap $P\text{-}GaAl_{0.6}As_{0.4}$
  - High bandgap material is transparent to photons generated in narrow bandgap material

* *D. Neaman, Semiconductor Physics & Devices*

Common LED's

Spectral range	Material System	Substrate	Example Applications
Infrared	InGaAsP	InP	Optical communication
Infrared-Red	GaAsP	GaAs	Indicator lamps. Remote control
Red-Yellow	AlInGaP	GaA or GaP	Optical communication. High-brightness traffic signal lights
Green-Blue	InGaN	GaN or sapphire	High brightness signal lights. Video billboards
Blue-UV	AlInGaN	GaN or sapphire	Solid-state lighting
Red-Blue	Organic semicon-ductors	glass	Displays

Solid State Lighting

Incandescent lamp	Compact fluorescent lamp	Tube fluorescent lamp	White LED	Theoretical limit at peak of eye sensitivity (λ = 555 nm)	Theoretical limit (white light)
17	60	50-100	90-?	683	~340

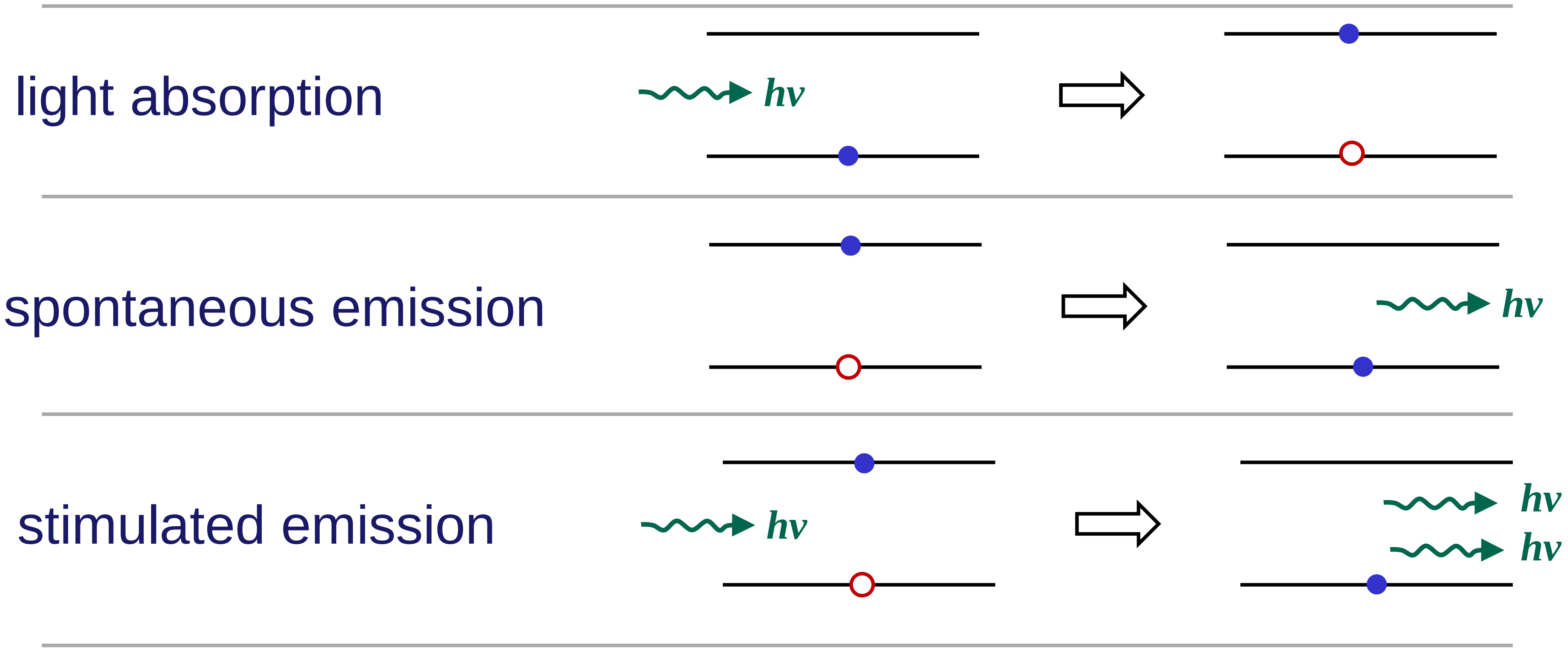
- Luminous efficacy measured in lumens/watt
  - Lumen is measure of light power normalized to response of human eye at different wavelengths
- Lighting consumes ~25% of world electricity usage
- White light achieved by:
  - combination of different color LEDs (e.g. red/blue/green)
  - UV LED with phosphor
- Organic LEDs cheaper to produce but as yet have lower efficiency

Semiconductor Laser

- Light from LED is diffuse, incoherent with a spectral bandwidth of 20-50nm.
  - Good for illumination but difficult to form into narrow, non-divergent beam
- Semiconductor laser produces coherent, monochromatic beam
  - spectral bandwidth < 0.1 nm
  - easily focused to narrow spot
  - high efficiency
  - cheapest and most compact of laser technologies
- Application in
  - fiber optic communications (monochromatic ⇨ low dispersion)
  - DVD/CD-ROM readers
  - laser pointers, surveying, bar-code readers, surgery etc.

Stimulated Emission

- Three types of photon-electron interaction:



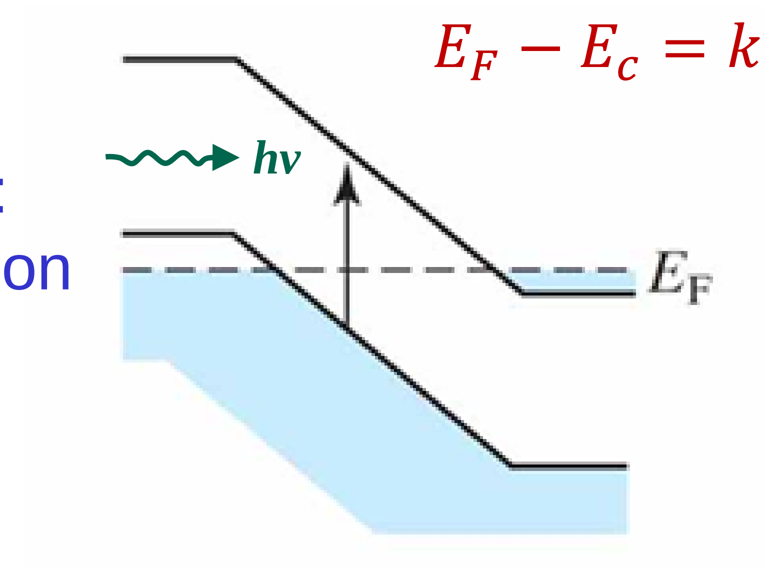
- Unlike electrons (fermions), photons (bosons) like to "hang around together" in same state
- stimulated photon will have frequency, phase and direction very similar to incident photon - coherent

Population Inversion

- Stimulated emission provides optical amplification
  - Offset by light absorption
  - In a regular forward biased PN LED, rate of absorption greater than rate of stimulated emission
  - net optical gain < 1
- In a heavily doped (degenerate) PN diode, possible to move Fermi level into conduction & valence bands

$$E_F - E_c = kT.\ln(N_c/n) < 0 \; if \; n > N_c$$

zero bias:
net absorption



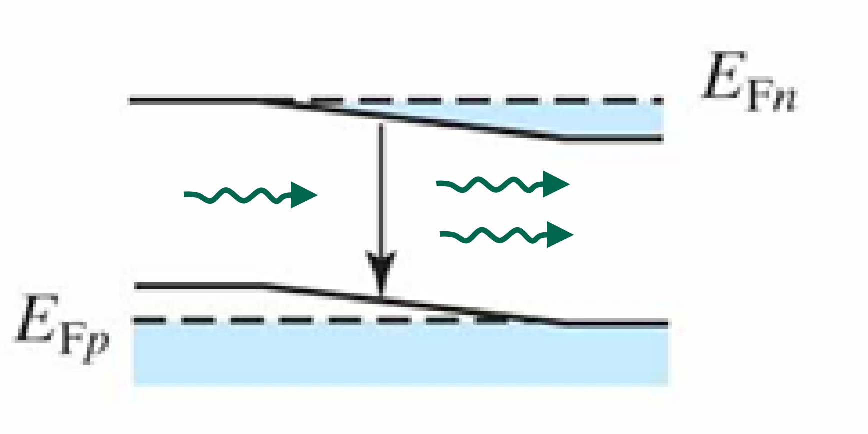
Optical Amplification

- Under forward bias, in depletion region, there are energy states in conduction band that have higher occupancy than some states in valence band
- When there is incident illumination, rate of stimulated emission > rate of absorption ⇨ optical gain

forward bias:

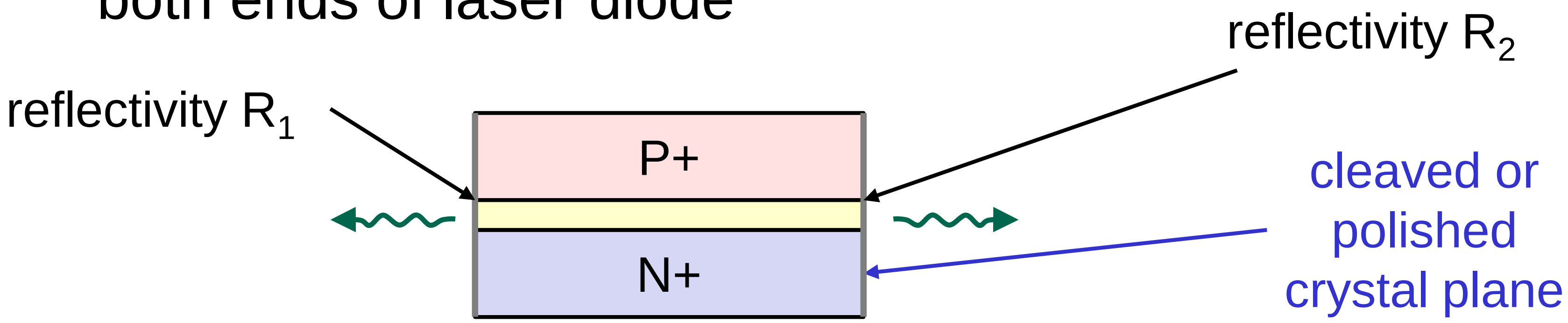
$qV = E_{Fn} - E_{Fp} > E_g$

net stimulated emission



Optical Feedback

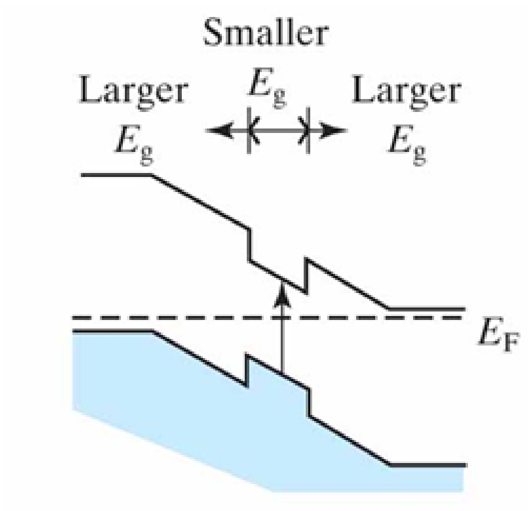
- Laser is an optical oscillator
  - oscillation requires gain and feedback
- Feedback provided by creating reflective surfaces at both ends of laser diode



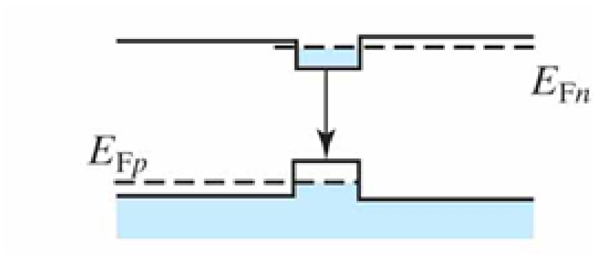
- Fraction of light is allowed to pass through the reflective surface to provide optical output
- Laser threshold is reached when forward current high enough to ensure $Gain_{opt} \times R_1 \times R_2 > 1$
  - Light intensity grows until it is just large enough to stimulate carrier recombinations at the same rate as carriers are injected by the diode forward current.

Quantum Well Laser

- Population inversion achieved more easily if thin layer of narrow-gap semiconductor is inserted between two wider gap semiconductors



zero bias

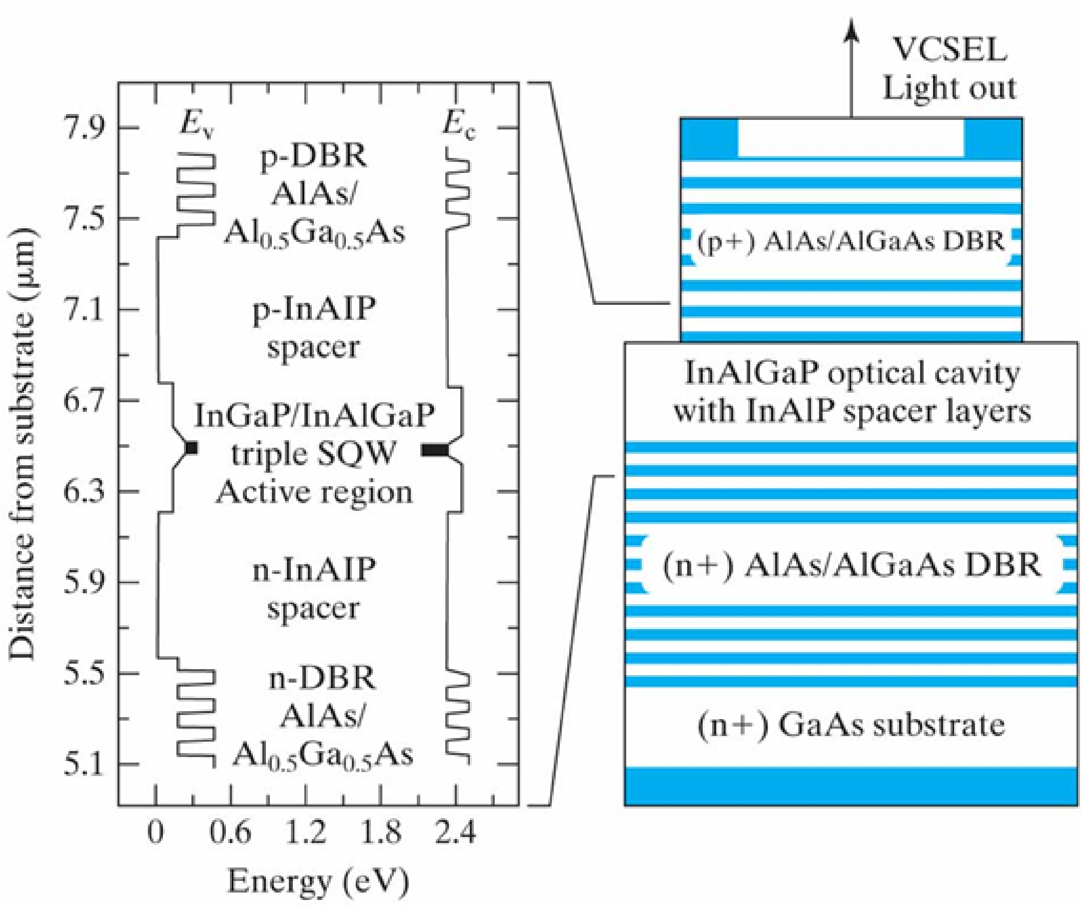


forward bias

- Quantum well confines population inversion to narrow region
- Reduces threshold current required for lasing

VCSEL

- Vertical cavity surface emitting laser (VCSEL) uses Distributed Bragg Reflector (DBR)
  - alternating layers of two different semiconductors provide constructive interference reflector



- Compatible with planar processing
  - unlike cleaving & polishing
- Thousands of diode lasers per wafer
- Vertical output permits in-wafer testing