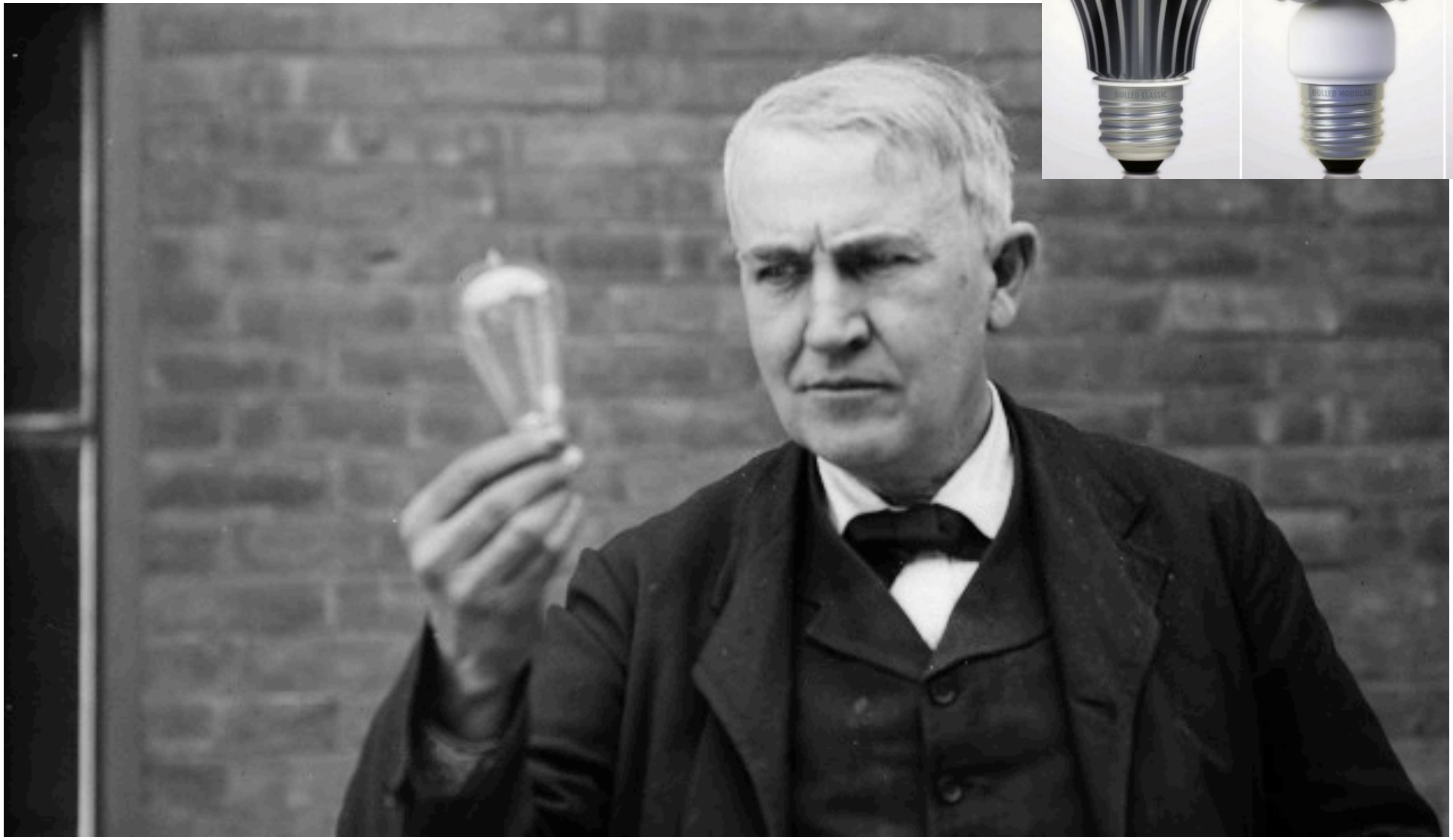
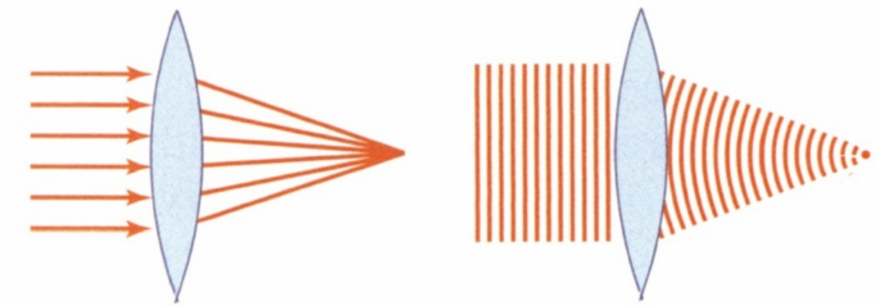
10 – Emitters/Detectors

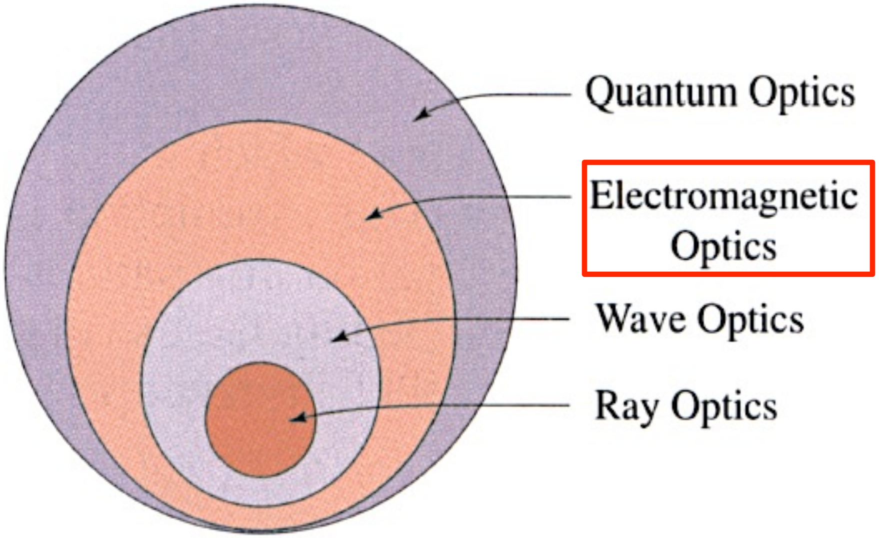


Today…

- Today's lecture is not really optics, but on devices used in optical system to emit or detect light…



Credit: Fund. Photonics – Fig. 2.3-1

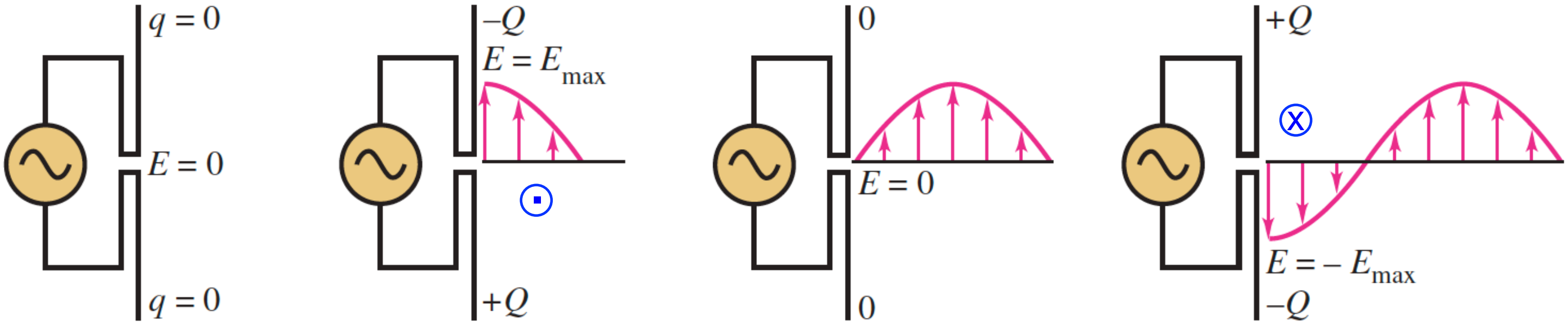


Credit: Fund. Photonics – Fig. 1.0-1

- Topics related to Emitters
  - mechanisms for light emission
  - absorbance leading to fluorescence (related to the lab)
  - devices for light emission (focus on those most used in optics)
  - optics of LEDS
- Topics related to Detectors
  - common types of detectors
  - performance comparison (how to select the right detector for your project)

How A Photon is Created

Credit: Young - Physics



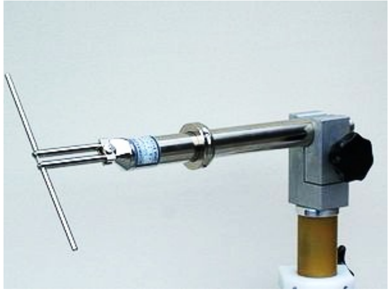
(b) $t = 0$ (c) $t = T/4$ (d) $t = T/2$ (e) $t = 3T/4$

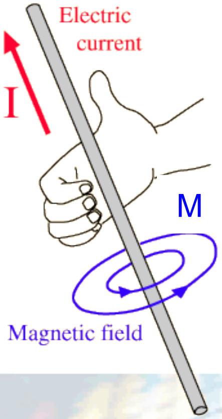
- Consider a simple dipole antenna with two wires each about λ/4 long attached to a 10 GHz sinusoidal voltage(microwave)…

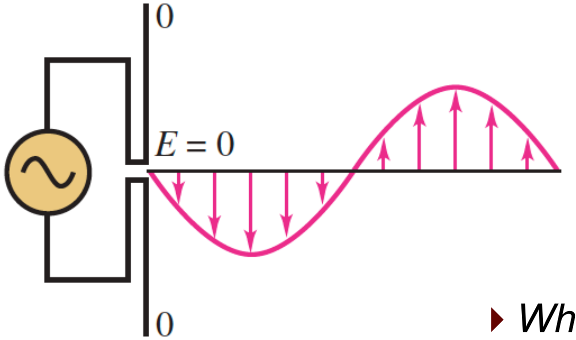
- The voltage hits its 1st positive maximum in ¼ the period, notice the E-field from + to – direction. As current flows 'down' to create the +/-Q, 'M' field is out of the plane.

- In ½ the period V and E = 0 again.

- The voltage hits its first negative max in ¾ the period, E-field from + to – direction. As current flows 'up' to create the +/-Q, 'M' field is into the plane.







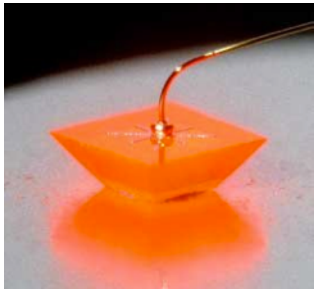
(f) $t = T$

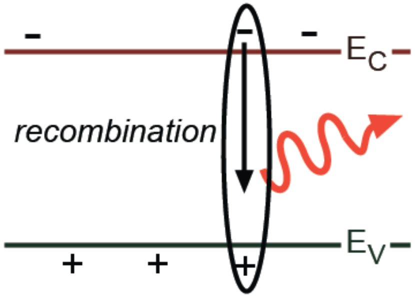
- Cycle complete! These time varying E and M fields sustain each other through freespace!

- *Why were the first mass-broadcasts 'AM radio' @ f~200 kHz?*

How A Photon is Created

- So how are visible and infra-red photons created? Any guesses? What do we need fundamentally to occur?

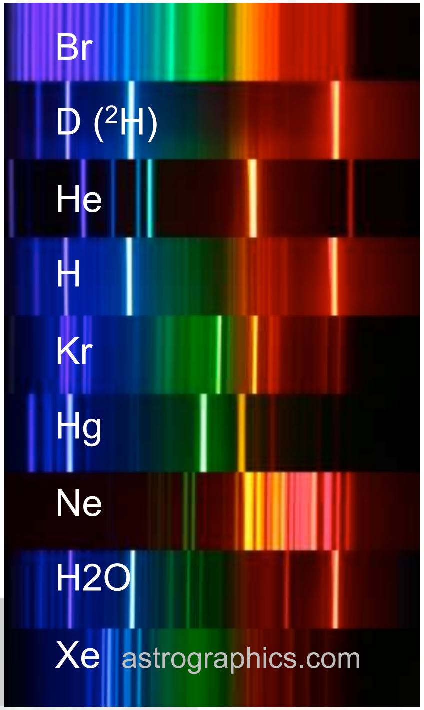




- For semiconductors, also have electric charge that moves and creates E&M fields as it does so!

  …but, works only if the bandgap is "direct" (same momentum for electrons and holes). If is indirect, then they have to 'change direction' somehow, requiring momentum transfer to the crystal lattice (phonons = vibrations = heat).

- Other common sources are 'atomic' or 'molecular' transitions… What are they?



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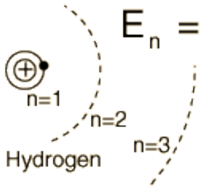
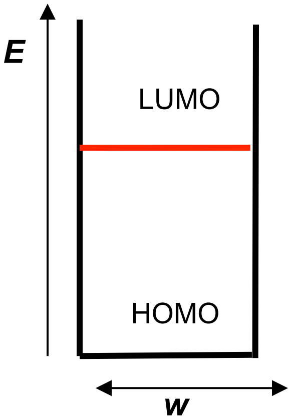


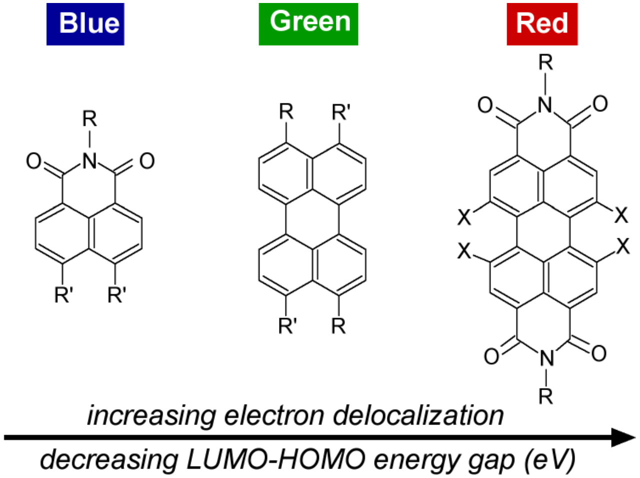
$$E_n = \frac{-13.6\ \text{eV}}{n^2}$$

- Ne is our laser source in the lab!

- How excite the atoms?

- In a molecule, you have a highest occupied 'MO' (molecular orbital for electrons) and a lowest *unoccupied* MO. Why larger molecules emit longer λ?





increasing electron delocalization

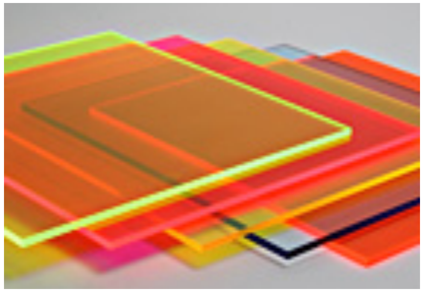
decreasing LUMO-HOMO energy gap (eV)

$$E(eV) = hc/\lambda$$
$$\approx 1240/\lambda(nm)$$

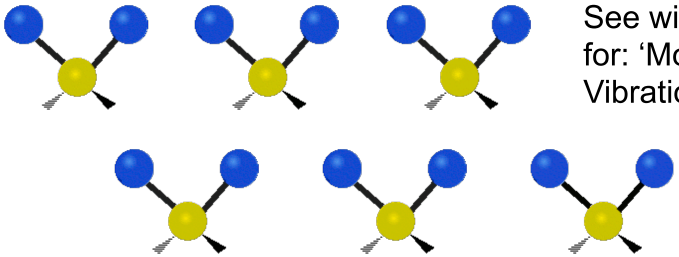
Molecules That Emit Light

- Lets look at molecular light emission in detail, because:

- it is used frequently in medical imaging, chemistry, etc...
- we will be performing fluorescence experiments in the lab this week!



Vibrations of a Methylene group ($-CH_2-$)

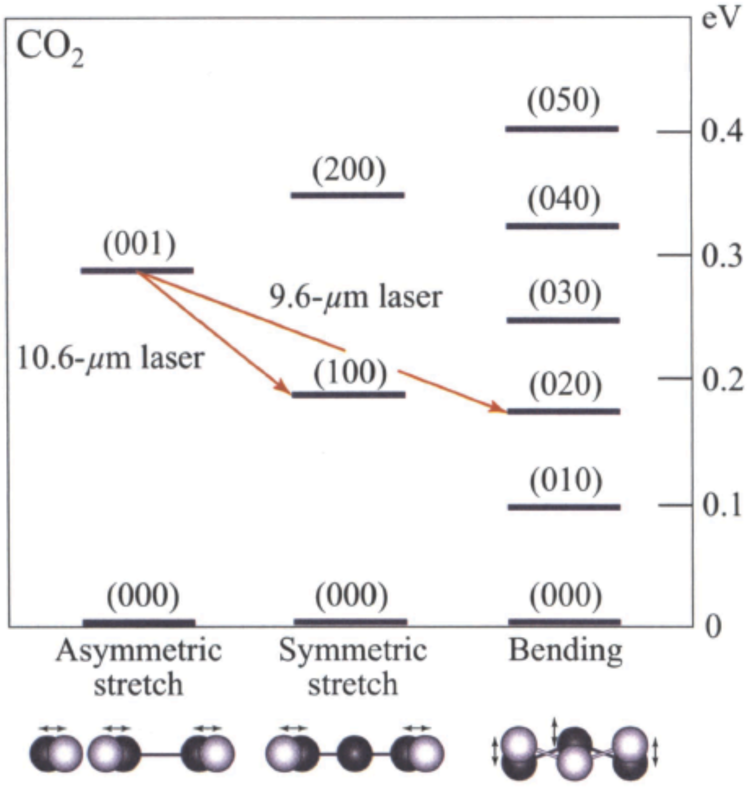


See wiki animation for: 'Molecular Vibrations'

- We know that with light emission, energy is lost ALWAYS and therefore we are transitioning between two energy states…

- For a molecule, the energy states can have different vibrational modes (and even within that mode, there are different energy levels):

- CO_2 laser uses high voltage plasma excitation (like a neon tube)



Molecules That Emit Light

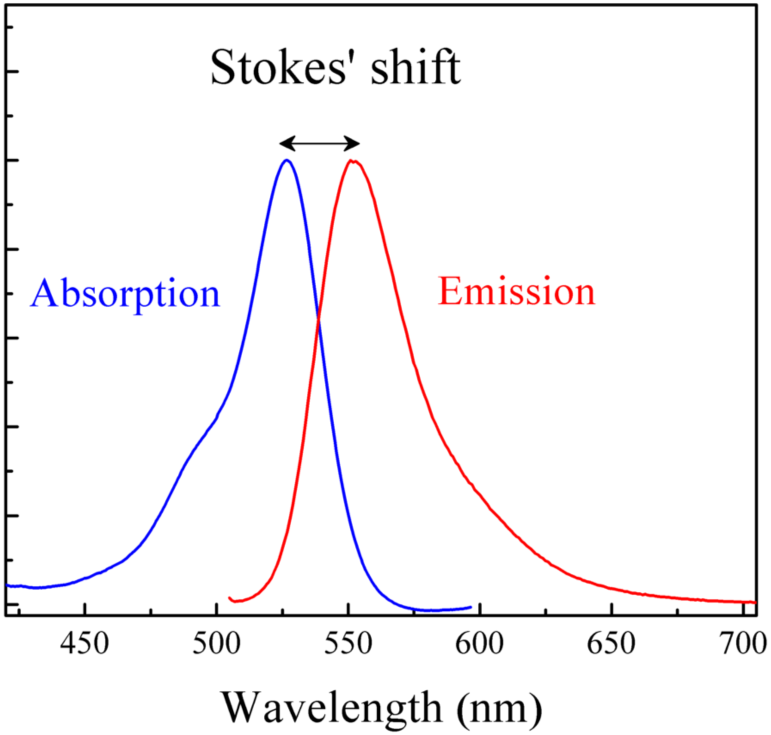
- Some organic dyes are VERY large (like orange Rhodamine, image/photo below) and they have a vast array of energy states (makes sense, more ways to twist/turn/increase-decrease energy).

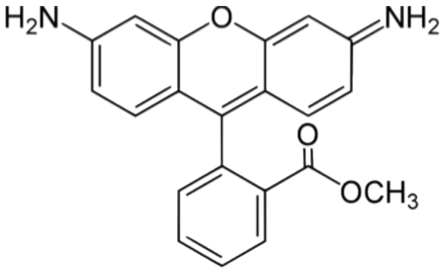
- AND the molecule is subject to its surrounding environment (other molecules charges etc.) which can broaden the emission spectrum!

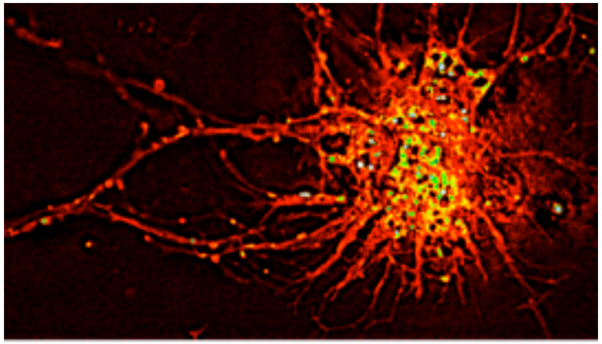
- Notice how absorption peak is shifted from emission peak!

- Some other peaks show up (can you find the other two)?

- Also, often a big UV peak (off the scale in this plot).







Mitochondria of neuron revealed by staining with a rhodamine 123 derivative

Expert Reviews in Molecular Medicine
©2002 Cambridge University Press

More on Light and Molecules

- In this course we deal mainly with visible and UV absorptions…
  - Electronic transitions

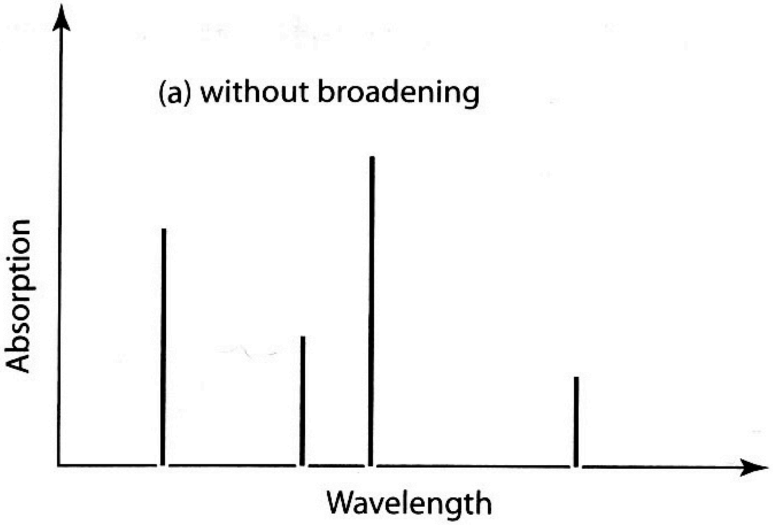
- Thermal infrared wavelengths are absorbed due to…
  - Molecular vibrations

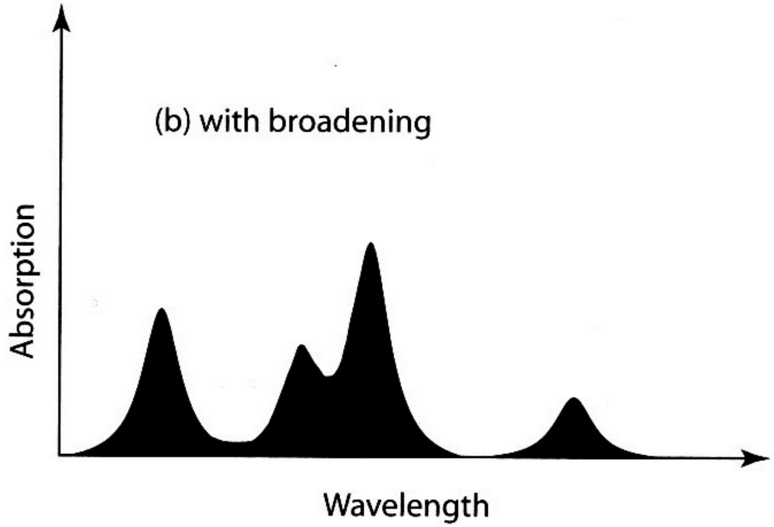
- Microwave and far-IR wavelengths…
  - Molecular rotations

Why is a microwave oven 2.45 GHz (10.2 cm)? This is also why submarines cannot radio communicate when fully submerged, and why they use SONAR instead of RADAR!

- Again, if it were not for molecules interacting with each other (colliding, vibrating next to each other, E-field interactions, etc.) the emission/absorption would be very narrow.

Top plot: for a single molecule (like humidity in air).
Bottom plot: for an ensemble of molecules (like a droplet)





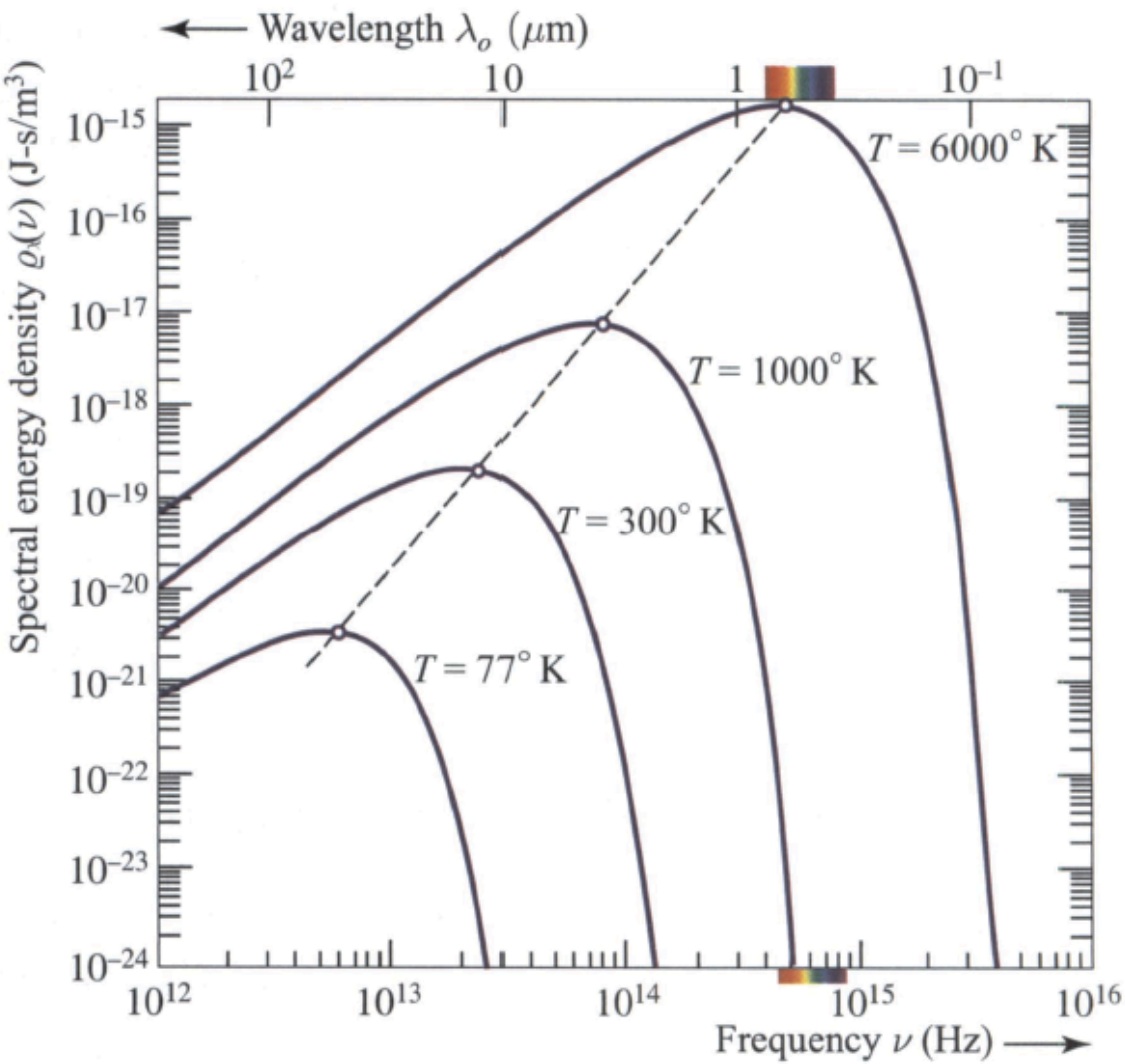
Devices: Blackbody Light Sources

- Blackbody radiation.

When you heat up a solid material you create more phonons (lattice vibration). Eventually many phonons locally can add up to a photon energy.

- Is extremely smooth in spectral output. How is that useful?

Credit: Fund. Photonics



Review! Take a break!

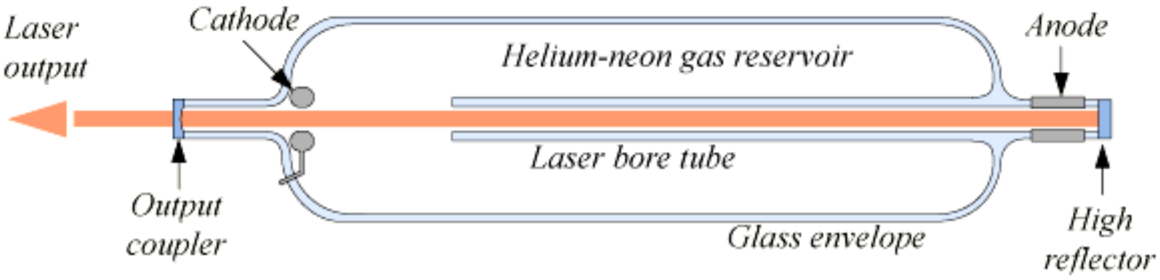
- Do materials such as fluorescent dyes and phosphors absorb light most strongly at the same wavelength that they emit? Or not? What is this called?

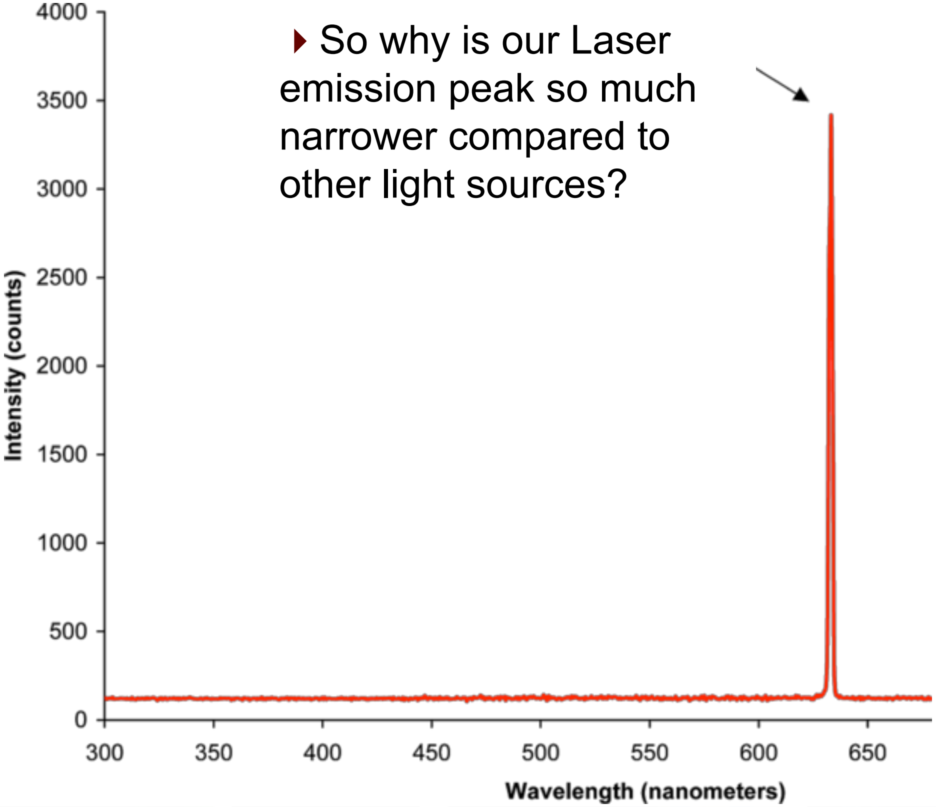
(a) Yes / fluorescence.
(b) No / fluorescence.
(c) Yes / Stokes shift.
(d) No / Stokes shift.

- Whew! Lets take a quick break!

Devices: The HeNe Laser

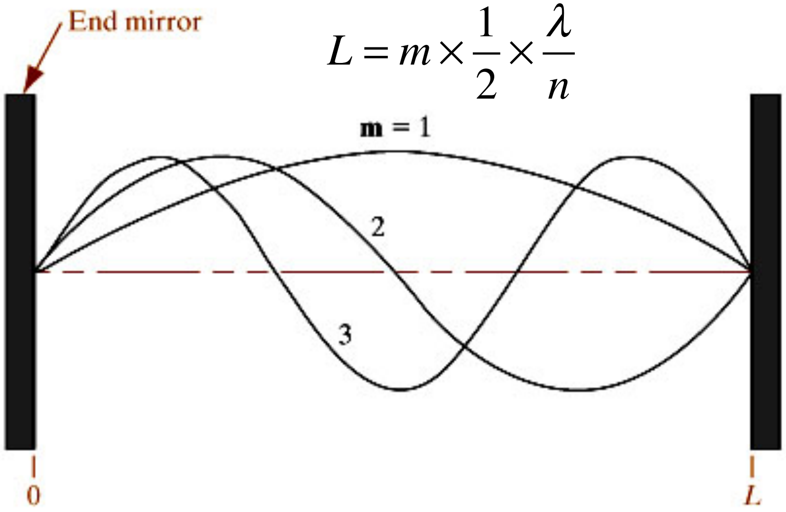
- **L**ight **A**mplification via **S**timulated **E**mission and **R**esonance





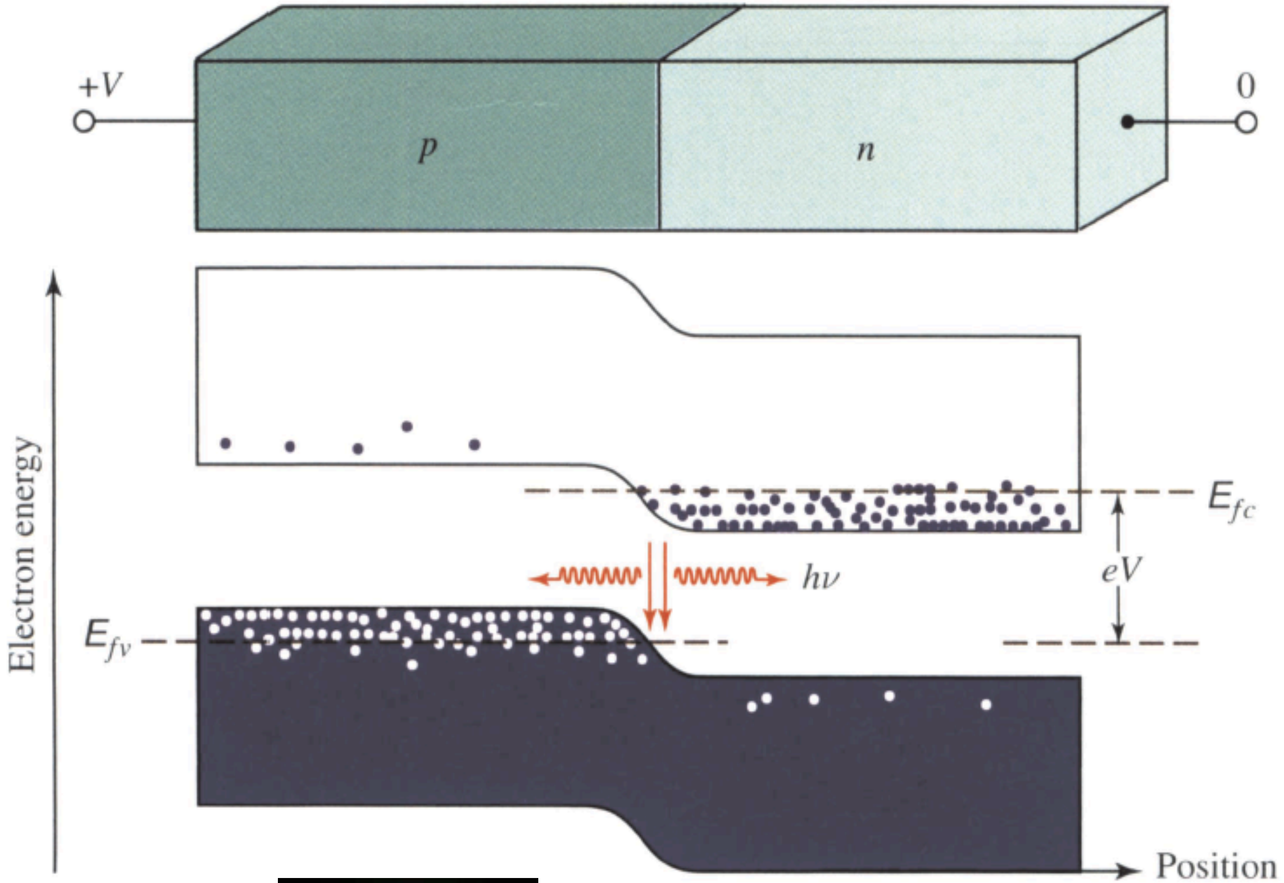
- So why is our Laser emission peak so much narrower compared to other light sources?

- One of the requirements for a laser is that the cavity length between the mirrors must be an integer number (m) of half-wavelengths… (why?).



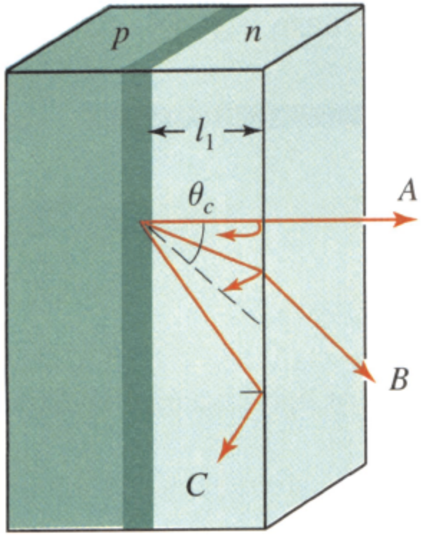
$$L = m \times \frac{1}{2} \times \frac{\lambda}{n}$$

Devices: Light Emitting Diodes



Credit: Fund. Photonics

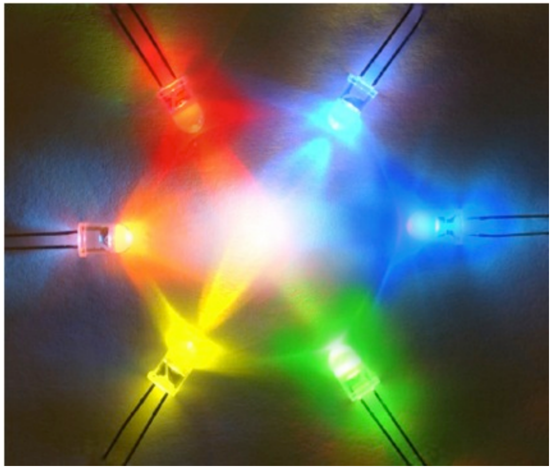
- Looks like some light is totally internally reflected (lets' talk more about this in a moment).



Devices: White LEDs

- So, how do they make white LEDs?

Prof. Fred Schubert (RPI)
http://www.rpi.edu/~schubert/



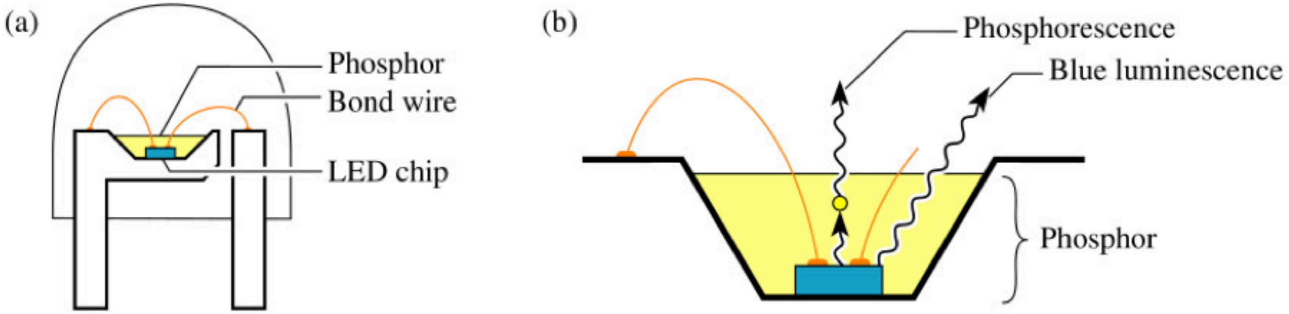
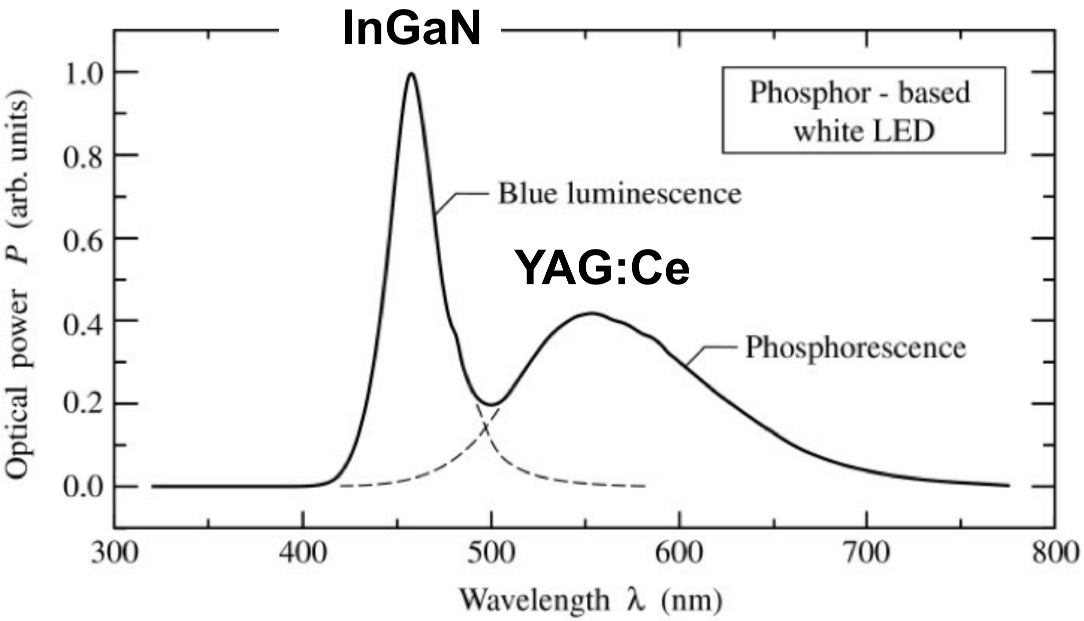


Fig. 12.5. (a) Structure of white LED consisting of a GaInN blue LED chip and a phosphor-containing epoxy encapsulating the semiconductor die. (b) Wavelength-converting phosphorescence and blue luminescence (after Nakamura and Fasol, 1997).

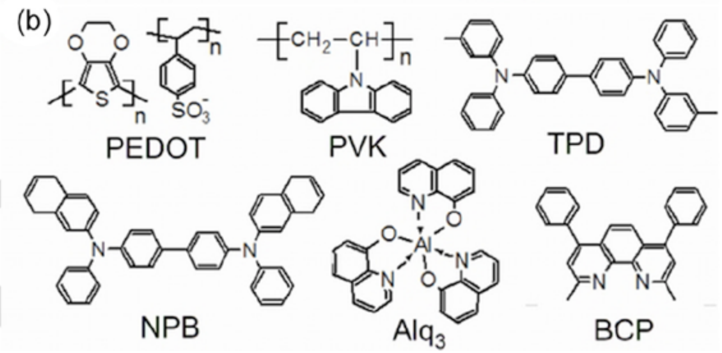
Cree XR-E

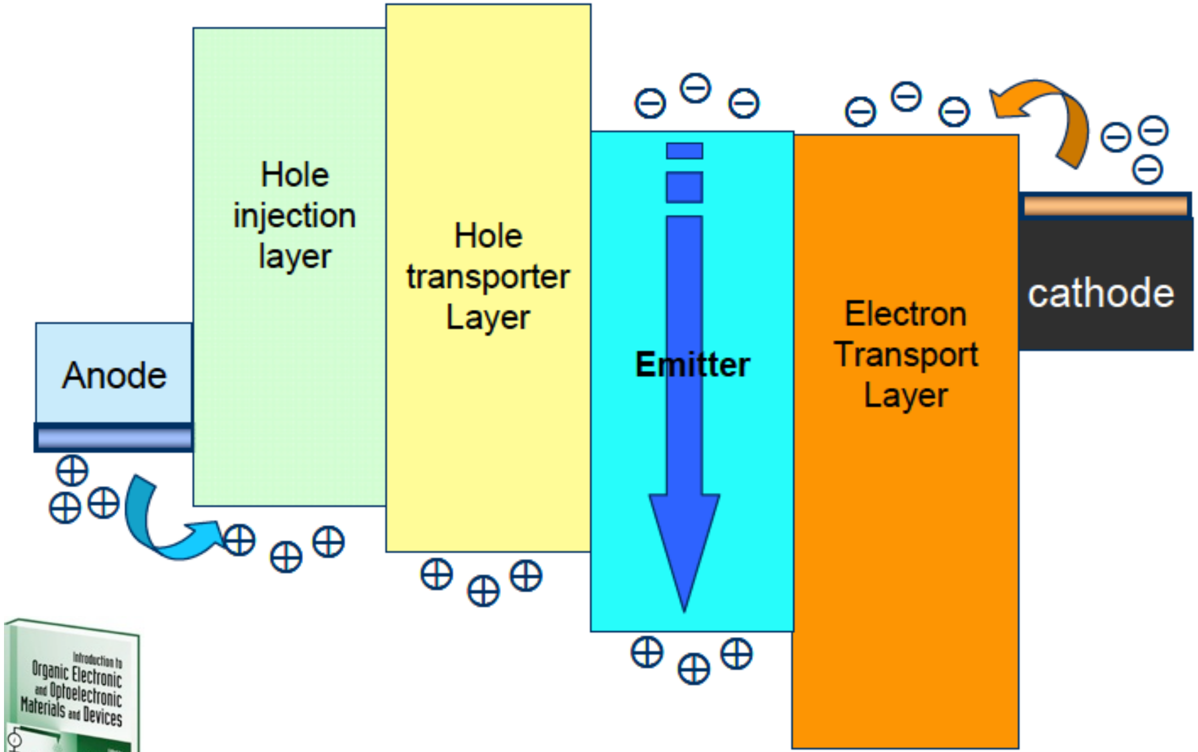


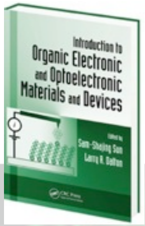
- So, your local art museum switches to these type of white LEDs and the patrons say all the art looks terrible (colors are off a bit). Why? How fix?

Devices: Organic LEDs (OLEDs)

- OLEDs act like LEDs but are made from organic semiconductors (great! but they degrade more quickly…)







Review! Take a break!

- A typical white LED is made of:

(a) A blue LED and a yellow phosphor.
(b) At least a mix of red, green, and blue LEDs.
(c) A black LED with white paint over it.
(d) Magic.

- The output of a LASER is:

(a) Coherent, all photons are in phase.
(b) Very narrow in spectral width compared to an LED.
(c) Highly directional.
(d) All the above.

- Whew! Lets take a quick break!

''Brightness' of Lighting & Displays

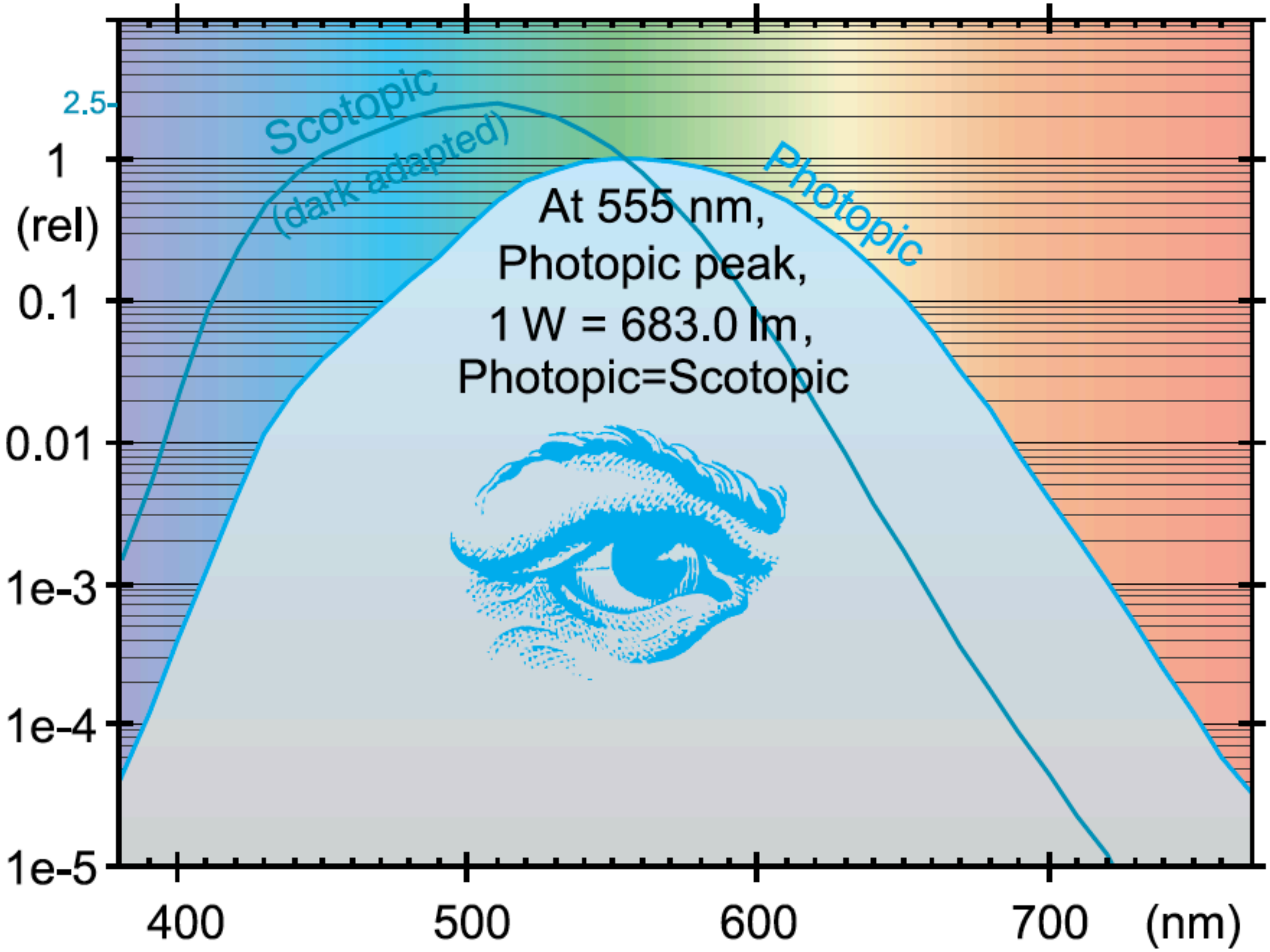
- 1 W of 555 nm light (green) = 683 Lumens to the human eye.

* Blue: ~50 lm/W
* Green: ~>600 lm/W
* Red~250 lm/W

- Questions:

Why is the human eye adapted to green light?

For a white light source, is the theoretical maximum 683 lm/W also?



Credit: Alex Ryer – Light Meas. Handbook

Comparing Lighting Devices

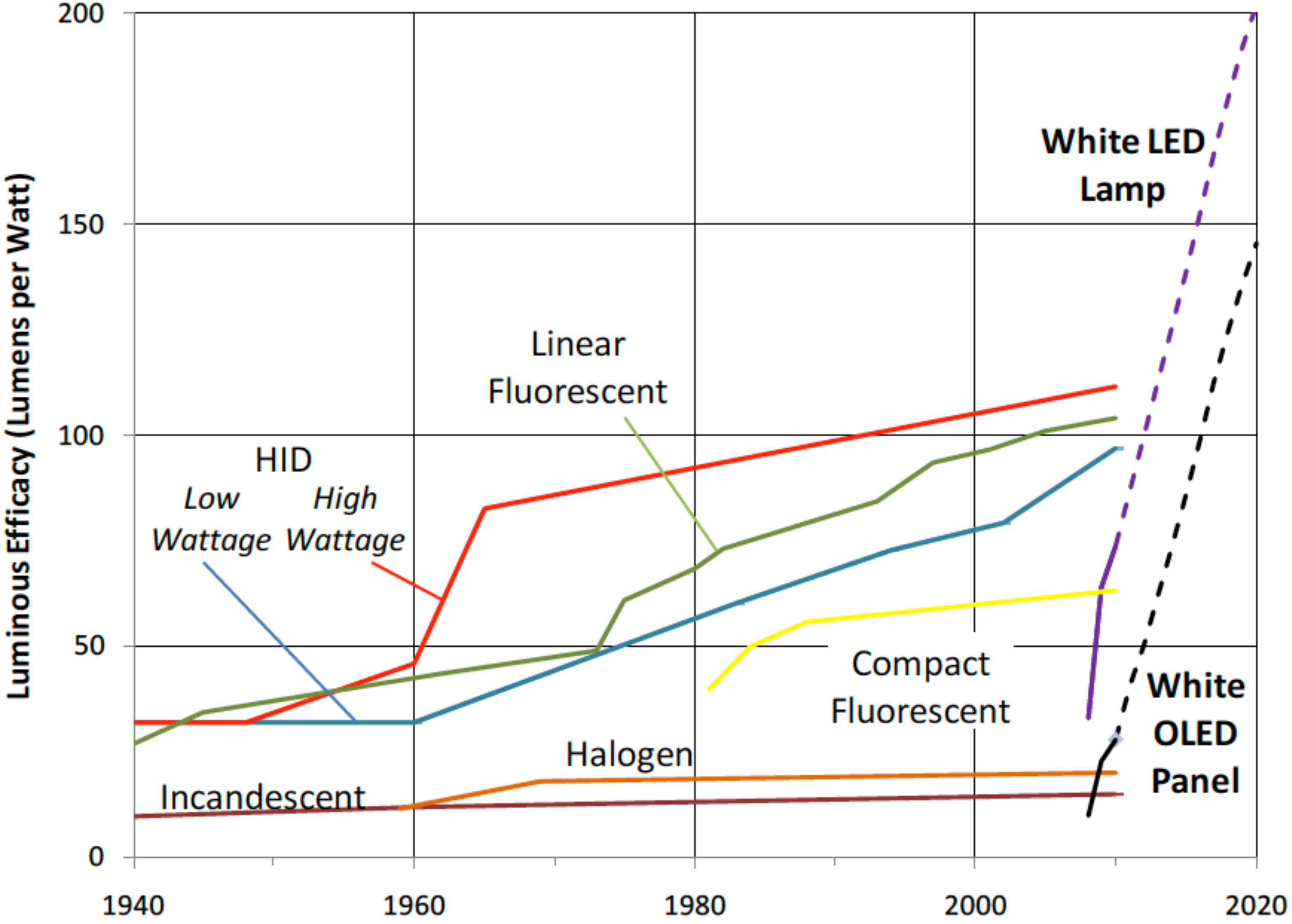
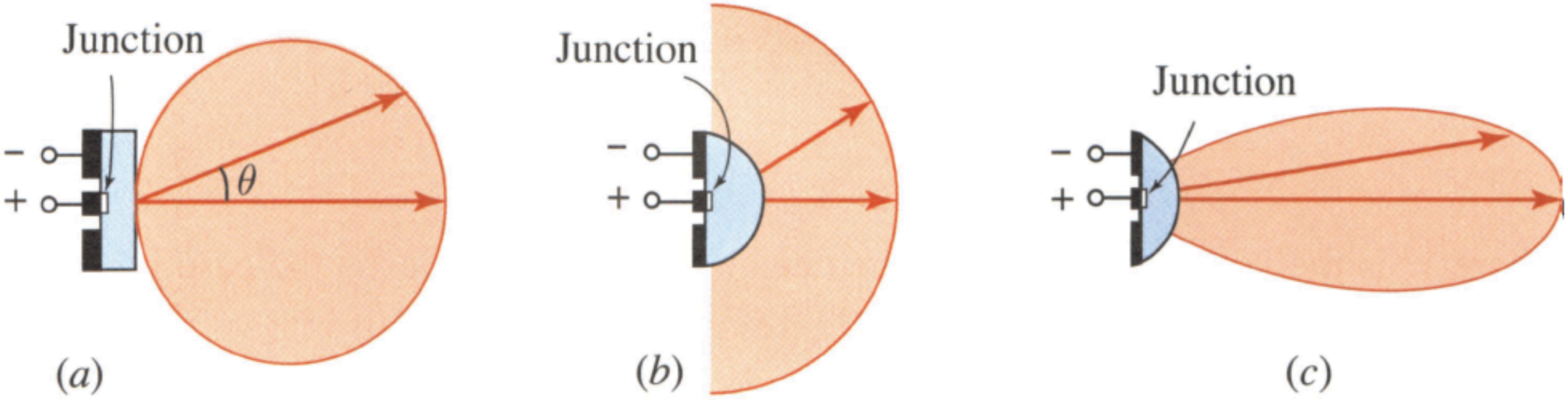


Figure 3.4: Historical and Predicted Efficacy of Light Sources[34]

Source: Navigant Consulting, Inc - Updated Lumileds' chart with data from product catalogues and press releases

Note: Efficacies for HID, fluorescent, and LED sources include driver or ballast losses.

- LEDs are isotropic emitters (photons are generated in ALL directions equally). However, refraction and total-internal reflection can change the radiation pattern as it exits a packaged LED!
- Notice the flat LED at left (Lambertian profile, intensity (arrow length) decreases as cosine of angle).
- Notice the hemispherical LED at center (it is isotropic, light undergoes no refraction at all).
- The LED at right uses a parabolic shape (more light in the forward direction).



Credit: Fund. Photonics

Optics of LEDs

- So for example, how much light escapes from a GaP LED?

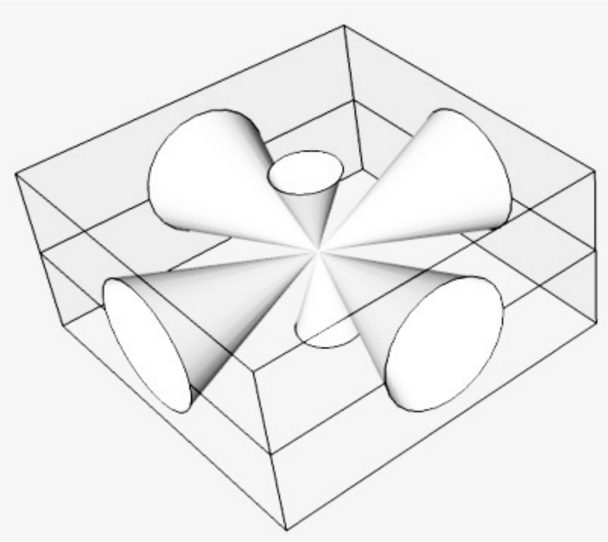
(1) Fresnel reflection.

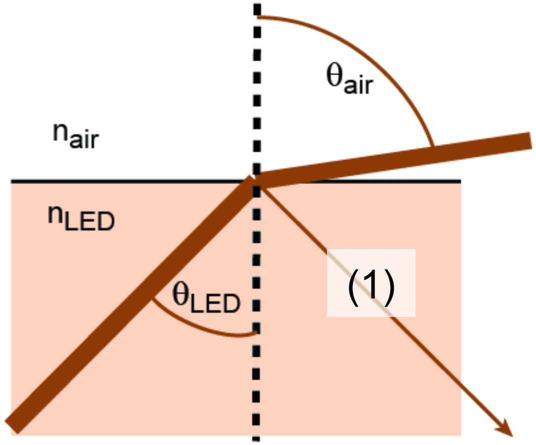
$$\% = \frac{(n_{LED}-n_{air})^2}{(n_{LED}+n_{air})^2}$$

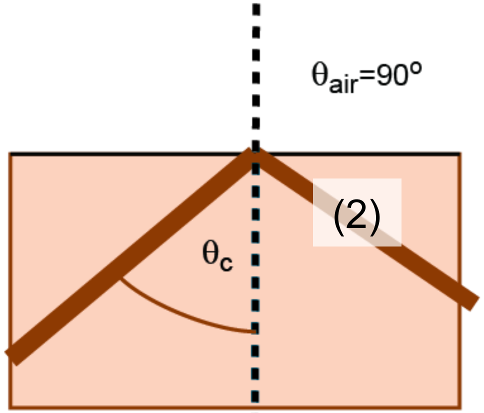
(2) Total internal reflection (TIR)

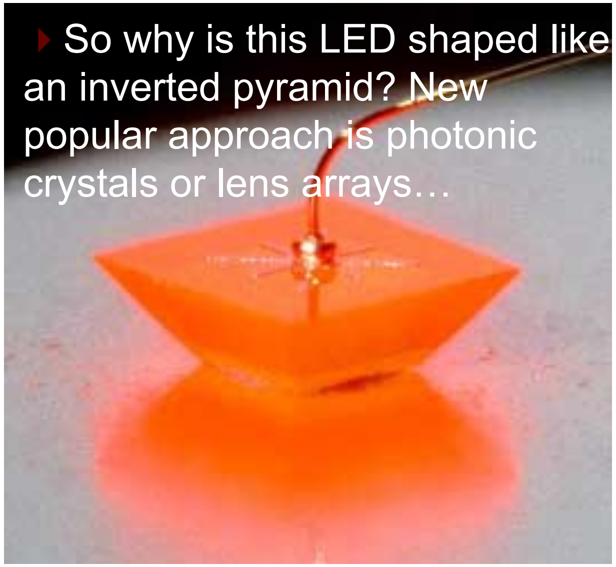
$$\theta_C = \sin^{-1}\frac{n_{air}}{n_{LED}}$$

$$isotropic\ emit : each\ cone\ \% \approx 1/4n_{LED}^2$$









- So why is this LED shaped like an inverted pyramid? New popular approach is photonic crystals or lens arrays…

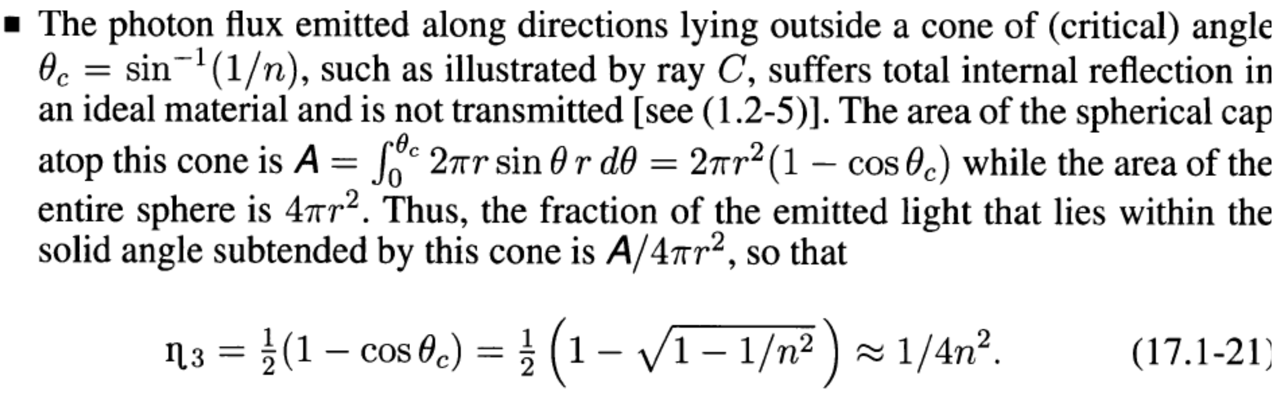
Example for GaP (n~3.4): Fresnel % = (1-0.3) or 70% out …

θ_C=17° so 2% escapes at each of 6 sides …

70% x 2% x 6 sides = 8.4% (at best!)

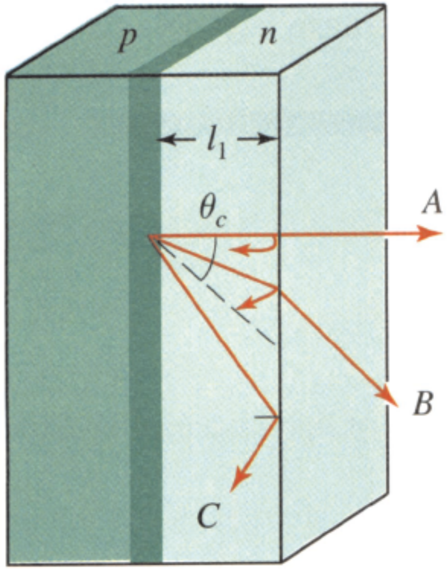
Optics of LEDs

- Here is a derivation for out-coupling for LEDs and OLEDs, which are isotropic in radiation pattern *(credit Fund. Photonics).*

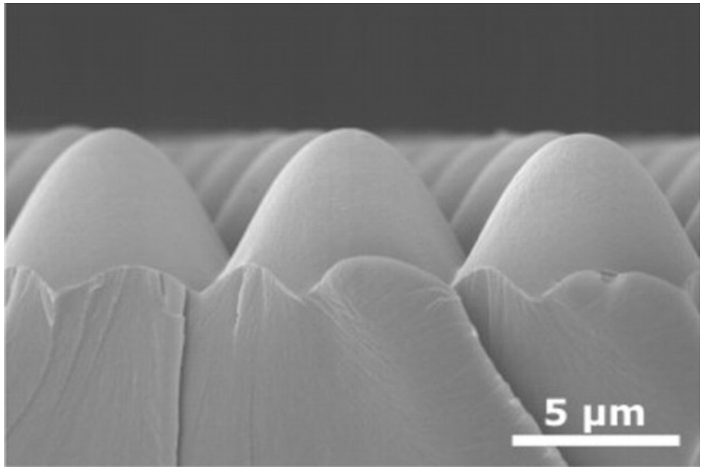


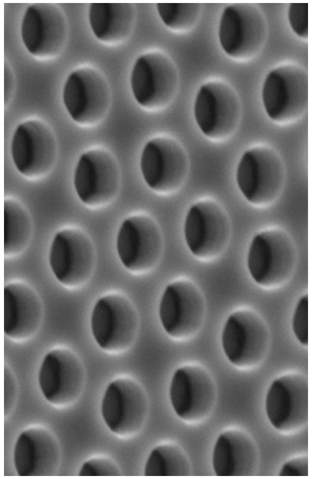
- The photon flux emitted along directions lying outside a cone of (critical) angle $\theta_c = \sin^{-1}(1/n)$, such as illustrated by ray C, suffers total internal reflection in an ideal material and is not transmitted [see (1.2-5)]. The area of the spherical cap atop this cone is $A = \int_0^{\theta_c} 2\pi r \sin\theta \, r \, d\theta = 2\pi r^2(1 - \cos\theta_c)$ while the area of the entire sphere is $4\pi r^2$. Thus, the fraction of the emitted light that lies within the solid angle subtended by this cone is $A/4\pi r^2$, so that

$$\eta_3 = \tfrac{1}{2}(1 - \cos\theta_c) = \tfrac{1}{2}\left(1 - \sqrt{1 - 1/n^2}\right) \approx 1/4n^2. \qquad (17.1\text{-}21)$$



- At right are two techniques that are applied at the surface to improve outcoupling, one refractive, on diffractive, which is which?





Optical Absorption (Beer-Lambert)

- So what does the absorption look like?

- Are all the photons absorbed instantly at the surface? Do they penetrate a bit of distance before being absorbed? What does this look like?

- *Some disciplines/books use log base 10 (not ln base 2.303). Remember, you can go back and forth*

e x log(X) = ln(X)

- *Remember, if someone reports attenuation in dB it is 10 log (I/Io)… you only use "20 log" in cases such as circuits where you measure current and voltage because power is I^2R or V^2/R*

$$I(z) - I(z+dz) = \alpha\, I(z)\, dz$$

$$\alpha = amount\ absorbed\ over\ dz$$

$$\frac{dI(z)}{dz} = -\alpha I(z)$$

simple first order linear diff. eq. , the derivative is proportional to α so you can maybe guess the solution?

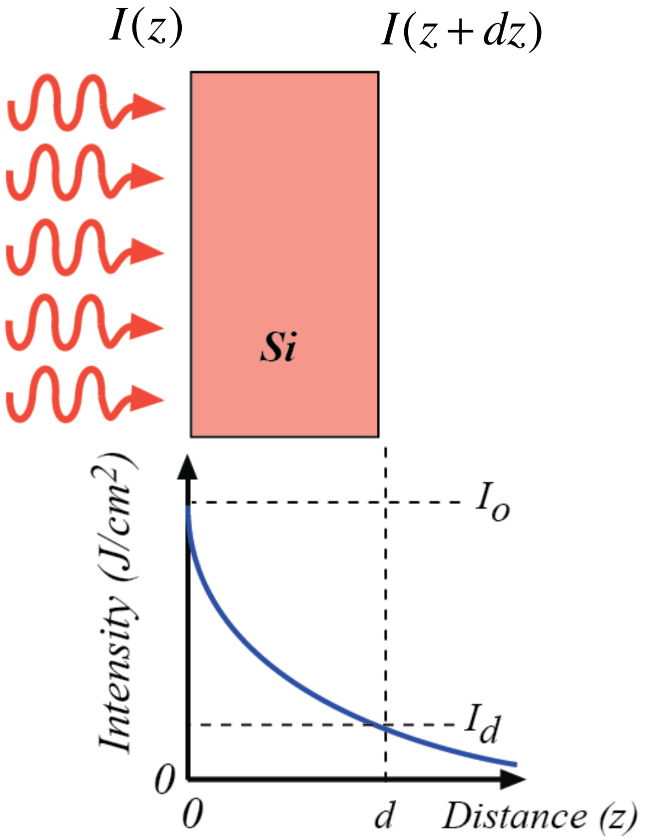
$$\frac{d\,I(z)}{dz} + \alpha\, I(z) = f(z) = 0$$

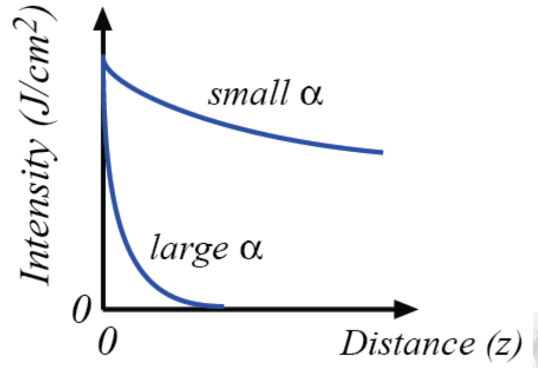
$$gen.\ sol. = e^{-h}\left[\int e^{-h} f(z)\,dz + c\right]$$

$$where\ h = \int \alpha\ dz = \alpha z$$

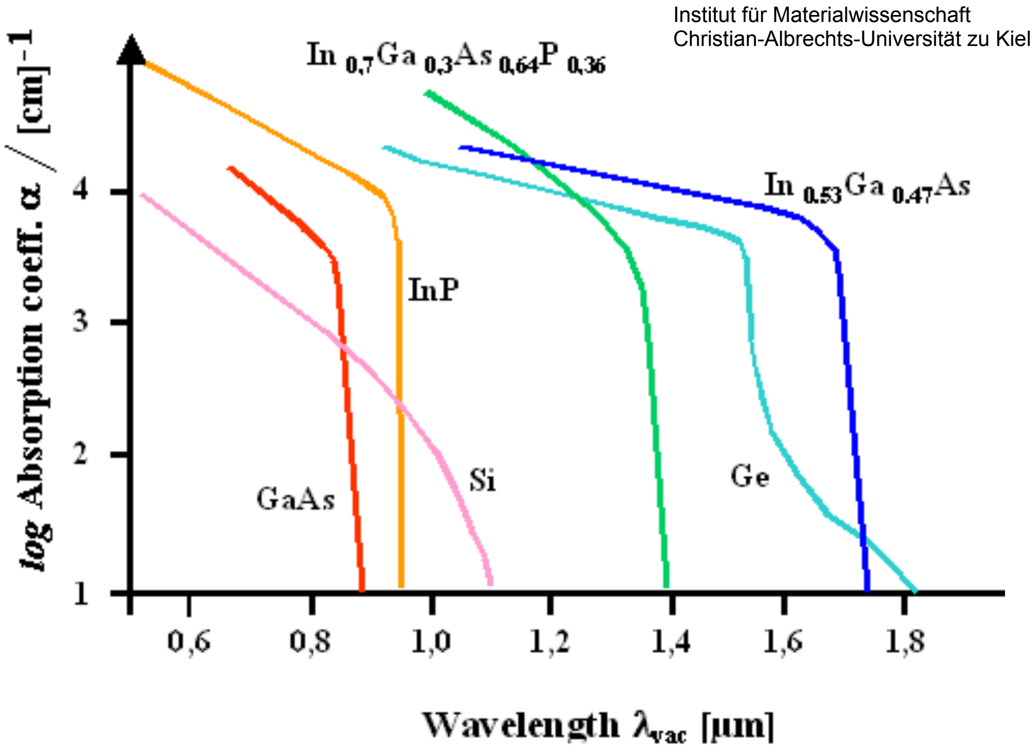
$$\therefore I(z) = I(0)e^{-\alpha Z}$$

$$\alpha = absorbtion\ coef. = (1/cm)$$





Optical Absorption (Beer-Lambert)



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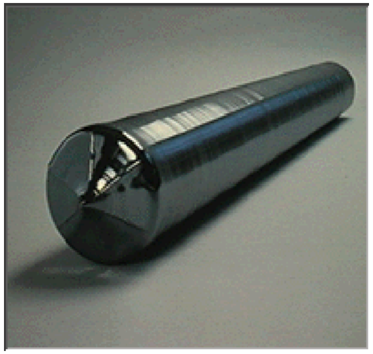
Christian-Albrechts-Universität zu Kiel



- Example, how thick does a Si wafer need to be to absorb 90% of 1.0 μm light? Assume α~100 cm^{-1} (is a bit less)

$$I(z) = I(0)e^{-\alpha Z}$$

$$\frac{I(z)}{I(0)} = 0.1 = e^{-100\times Z} \qquad \therefore z = \frac{\ln(0.1)}{-100}\, cm = 230\,\mu m$$

- Same 90% calculation for green light (peak of sunlight spectrum), and z only ~2 μm!

Review! Take a break!

- Light traveling into an absorbing medium decreases in intensity:

(a) Quadratically.
(b) Linearly.
(c) Asymptotically.
(d) Exponentially.

- lm/W is a unit of:

(a) Optical power for 1W of light.
(b) Brightness of 1 W of light as perceived by the human eye.
(c) Brightness of a light regardless of wattage.
(d) Outcoupling efficiency of an LED.

- lm/W in order of most efficient to least efficient (bright).

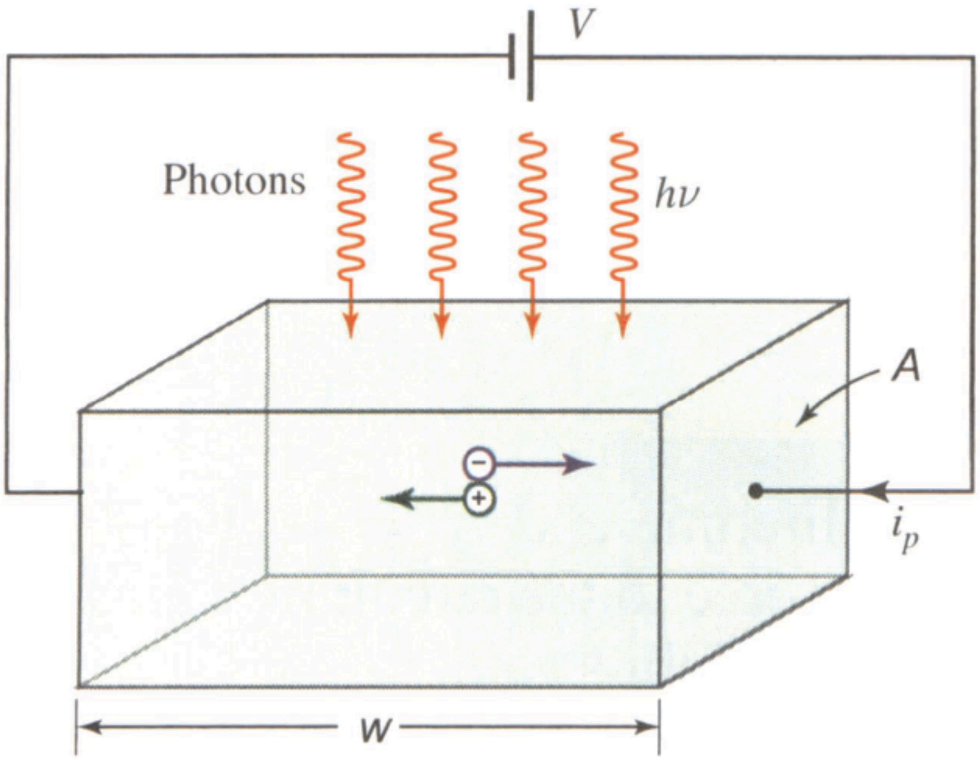
(a) Blue / red / green.
(b) Green / blue / red.
(c) Green / red / blue.
(d) Red / green / blue.

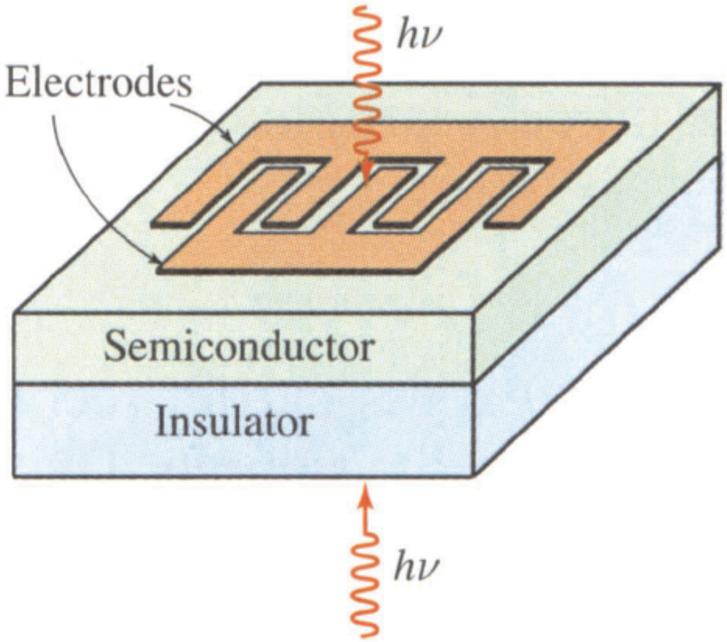
- Whew! Lets take a quick break!

Switch Topics… Detectors!

- Lets switch topics now… Detectors!

- One of simplest detectors is a photoconductive detector (main drawback is that background current is high in a semiconductor, so that limits the minimum sensitivity).



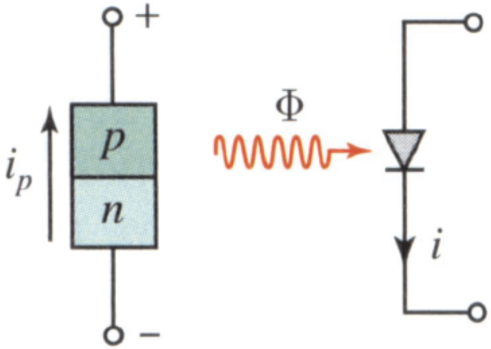


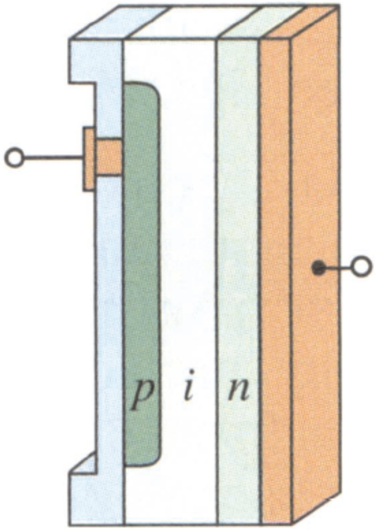
Credit: Fund. Photonics

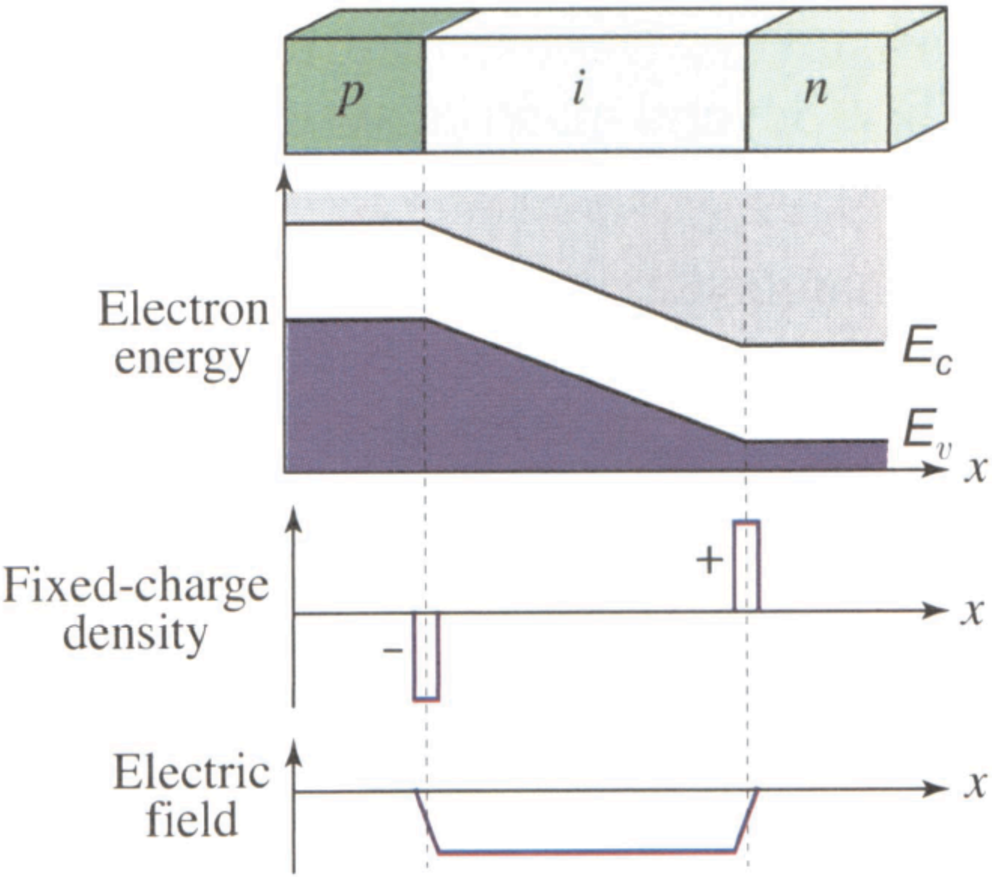
A Better Detector - Photodiode

- Photodiode, typically is reverse biased (as seen in diagram at right).
- Background current is very low (is reverse saturation current).

Credit: Fund. Photonics





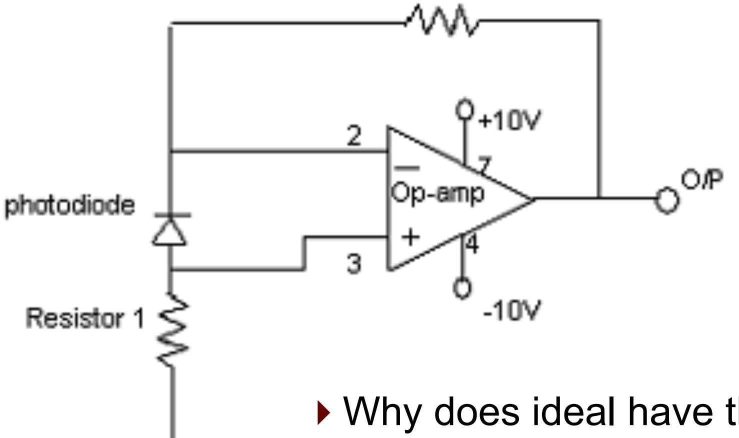


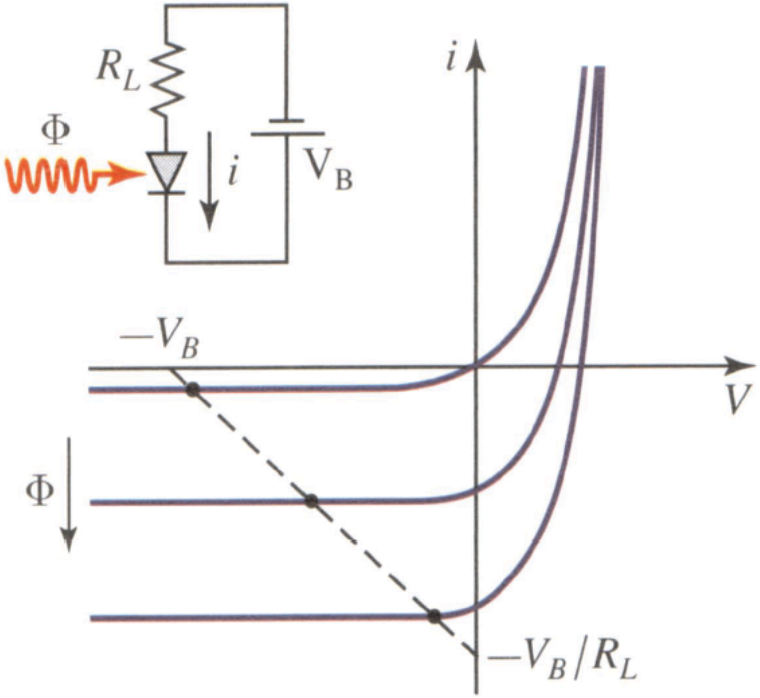
Ways To Use Photodiodes

- Typically add a DC voltage to reverse bias the diode, and then allows the most linear response to incoming light…

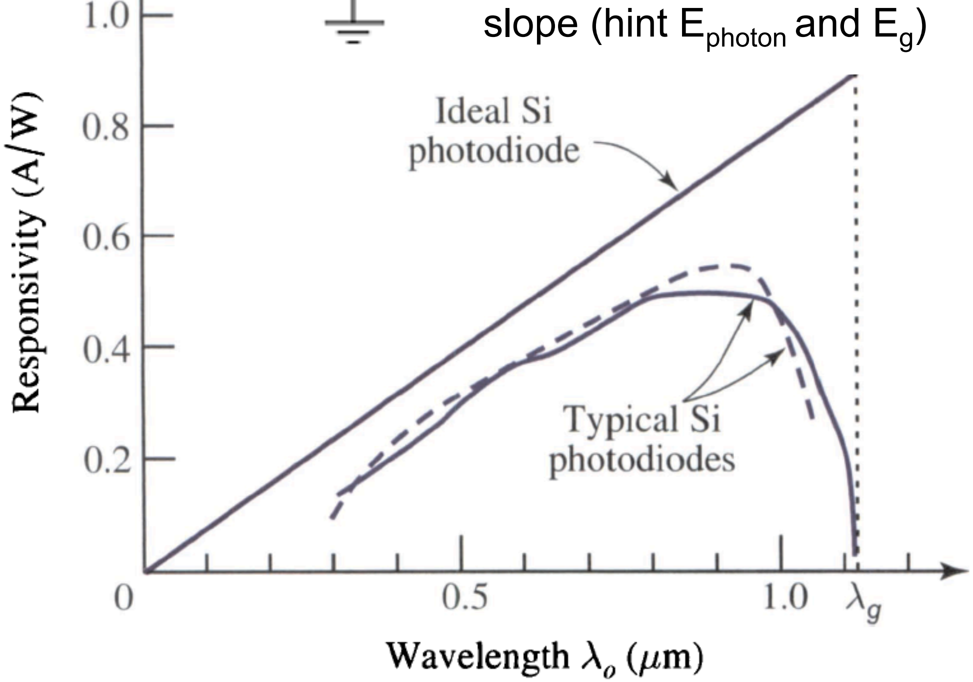
- Also, typically feed right into an amplifier…

Look familiar?



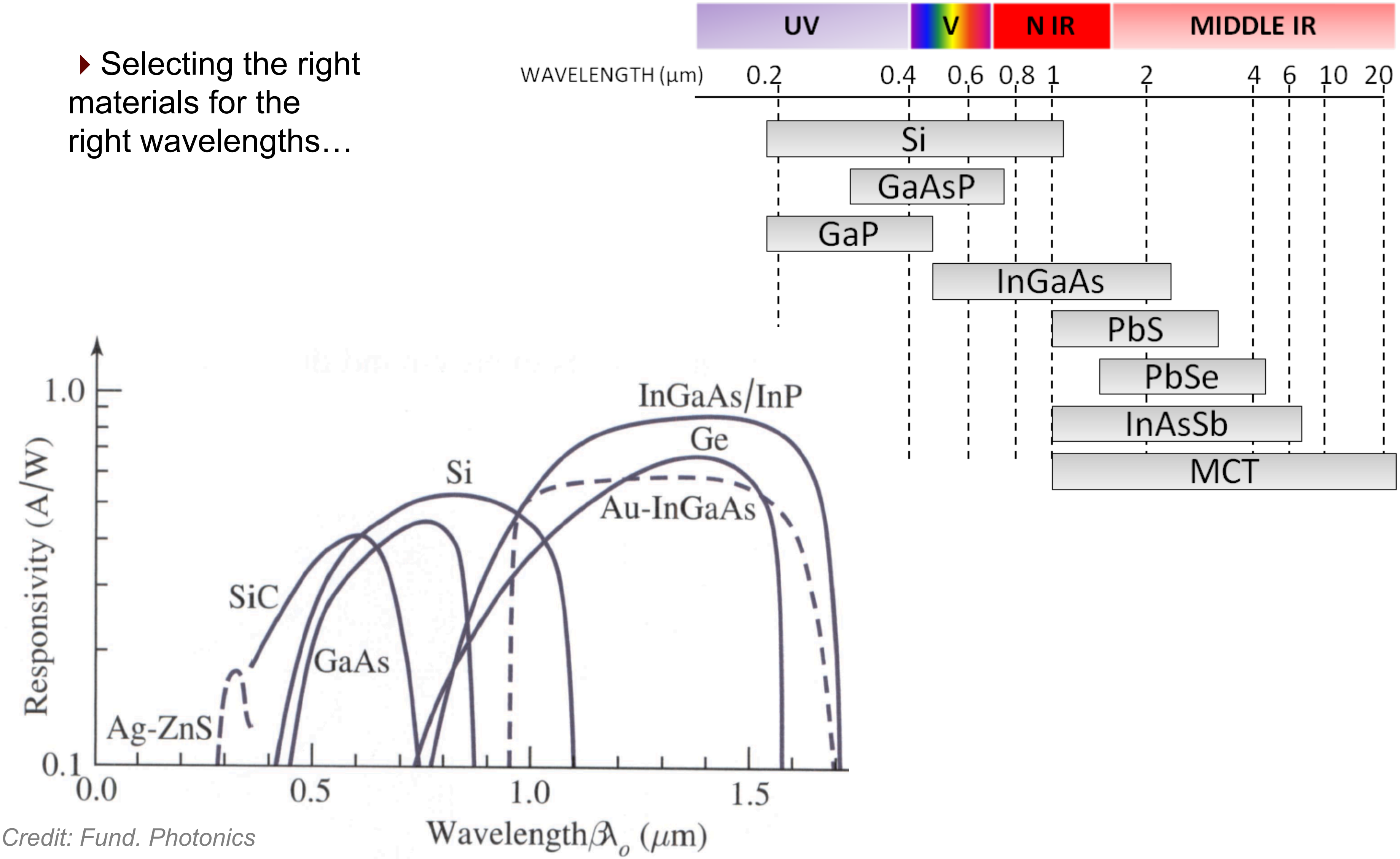


- Why does ideal have this slope (hint E_{photon} and E_g)



Credit: Fund. Photonics

- Selecting the right materials for the right wavelengths…

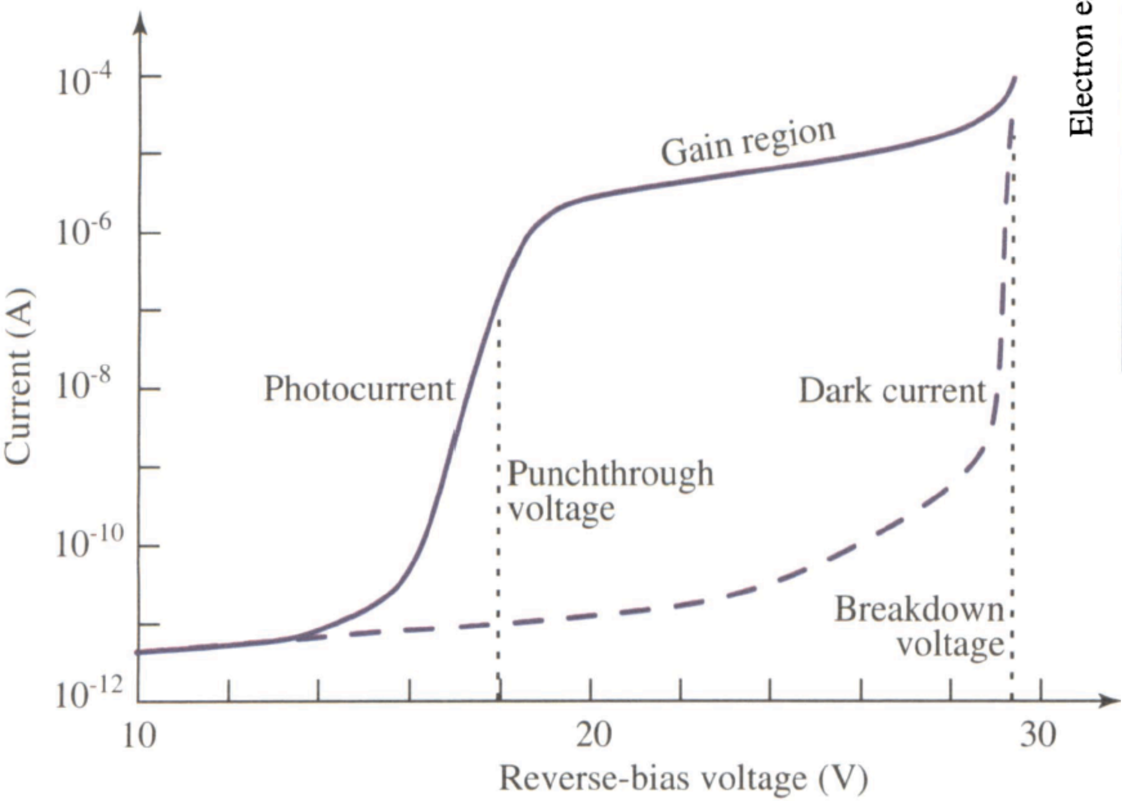


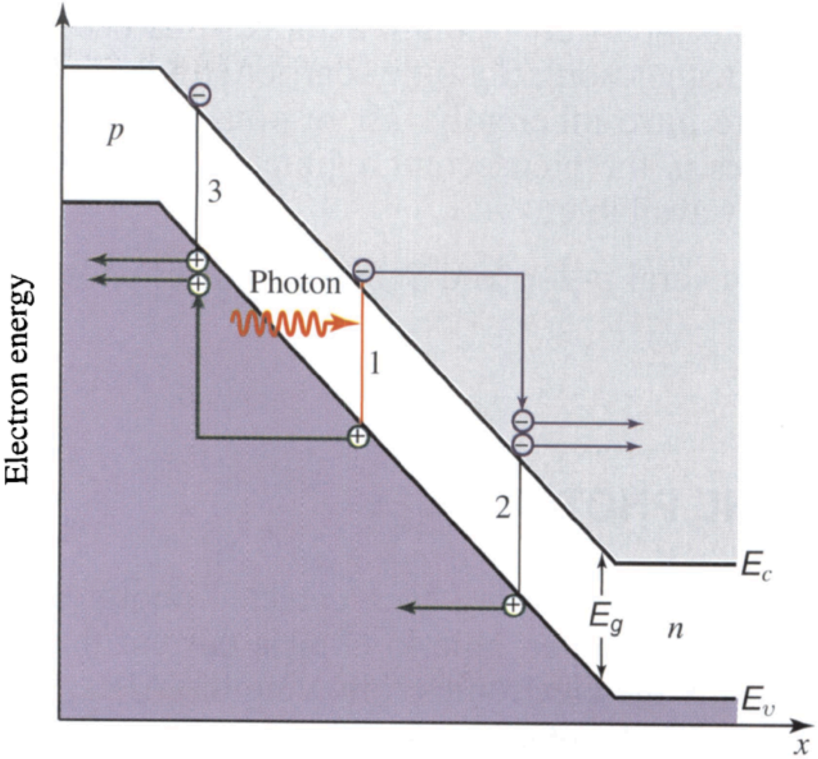
Credit: Fund. Photonics

Avalanche Photodiode (APD)

- APD's are specially designed diodes that can handle a large reverse bias to create carrier multiplication (internal amplification!)

- Gain region (requisite operating voltage range) for an InGaAs APD is show below.



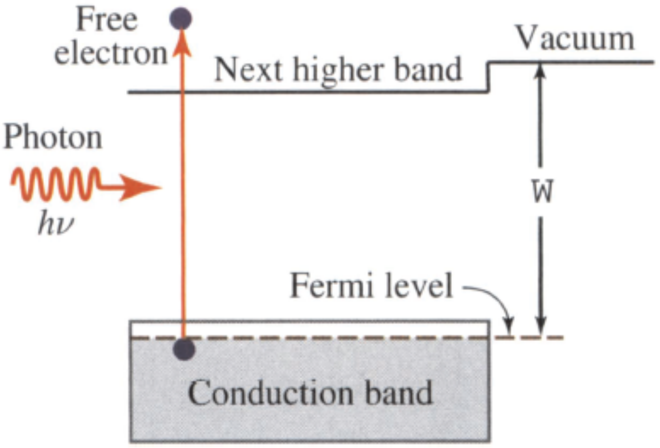


Credit: Fund. Photonics

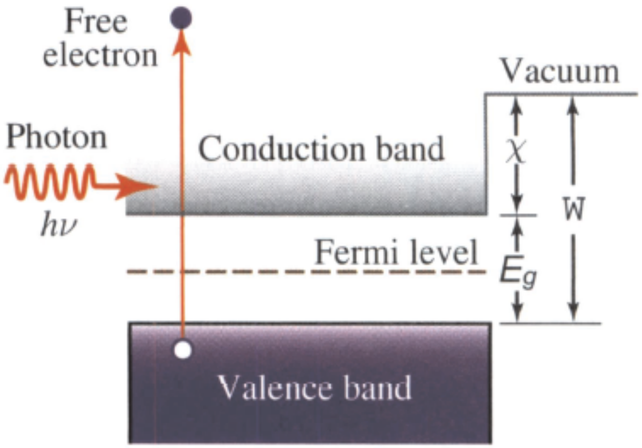
Photomultiplier Tube (PMT)

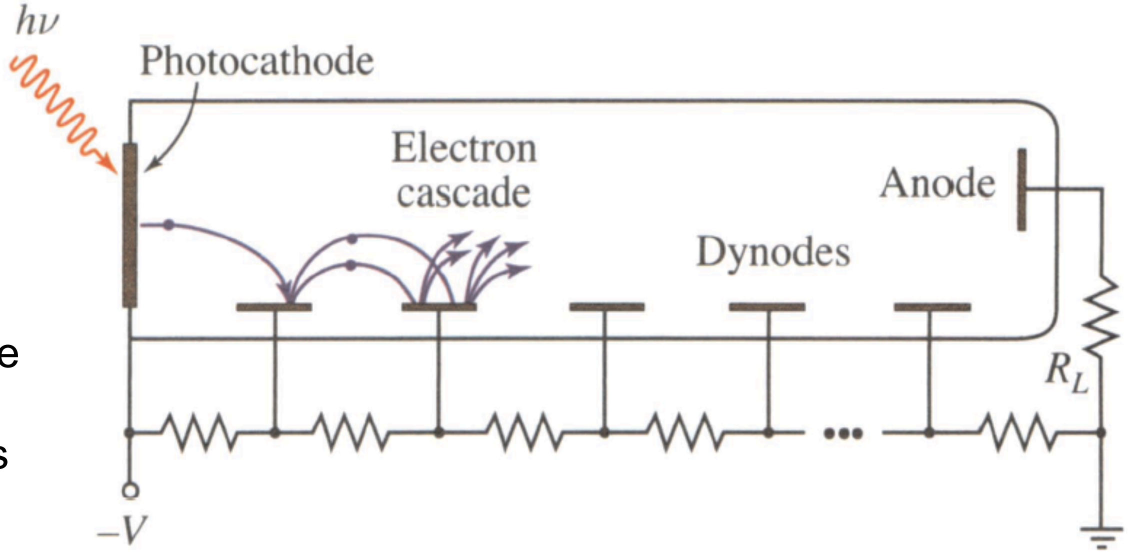
- Photomultiplier Tubes (PMT) have even higher amplification than APDs…

- Using a photon to kick an electron free from a metal (W = workfunction)



- Using a photon to kick an electron free from a semiconductor (W= electron affinity + bandgap)





- Add high voltage inside a vacuum (~1000 V) and lots of amplification!

Credit: Fund. Photonics

Key Photodetector Metrics

Dark Current: The DC current that flows through a detector when there is no light present. Usually measured in the nanoamp range.

NEP: The amount of optical input power that produces the same output level as the inherent noise level of the detector/receiver, i.e. a signal-to-noise ratio of one. Usually given in picowatts per root bandwidth. Total noise level is calculated by multiplying the NEP by the square root of the full bandwidth.

Power Bandwidth, -3 dB: The frequency at which the electrical output power of the detector falls to 50% of its value at DC. Same as “electrical” bandwidth. Typically used for specifying analog microwave detector bandwidths.

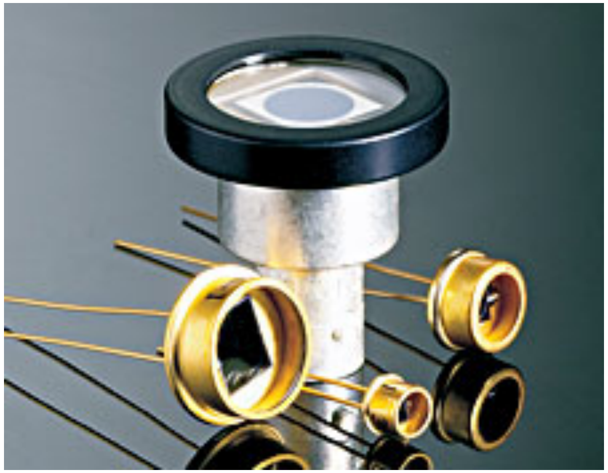
Responsivity, R: The sensitivity of a detector element to light given in amps/watt, independent of load resistance.

$$R = \eta \frac{q}{h\upsilon} = \frac{\#e's}{\#\,photons} \frac{1.6x10^{-19}C}{6.63x10^{-34}(J\cdot s)f(1/s)} \approx \eta \frac{\lambda(nm)}{1240} \quad A/W \qquad R_{\max} = 2\ A/W\ \ for\ 2eV$$

Rise Time: The 10–90% rise time of the output voltage step when the detector is illuminated by a negligibly short optical step function. This is difficult to do in practice, so the measurement is simulated mathematically by integrating the pulse width (see above).

Sensitivity: The optical input power (in dBm) required to achieve a particular Bit Error Rate, BER (or signal to noise ratio) at the output of the detector/receiver. Usually specified for BERs of 10^{-9} (or a S/N of 6). BERs of 10^{-12} require a S/N=7.

Si Photodiodes ($22)



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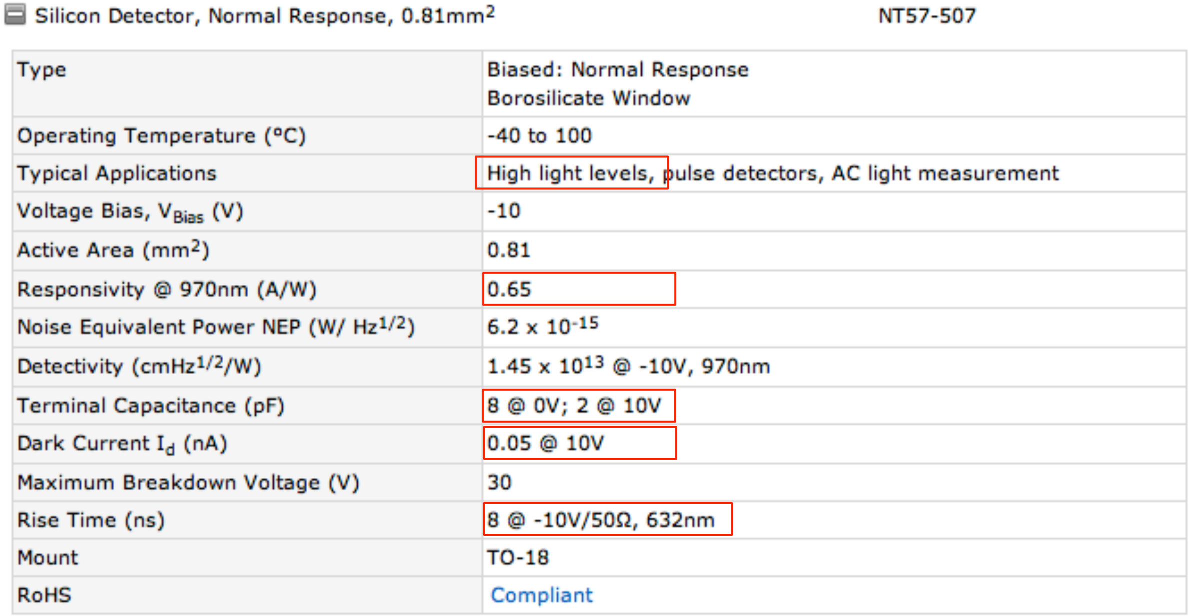
No gain…

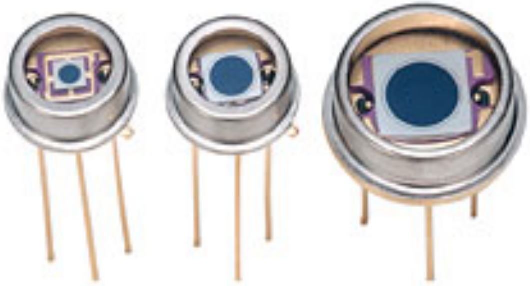


Silicon Detector, Normal Response, 0.81mm^2 NT57-507

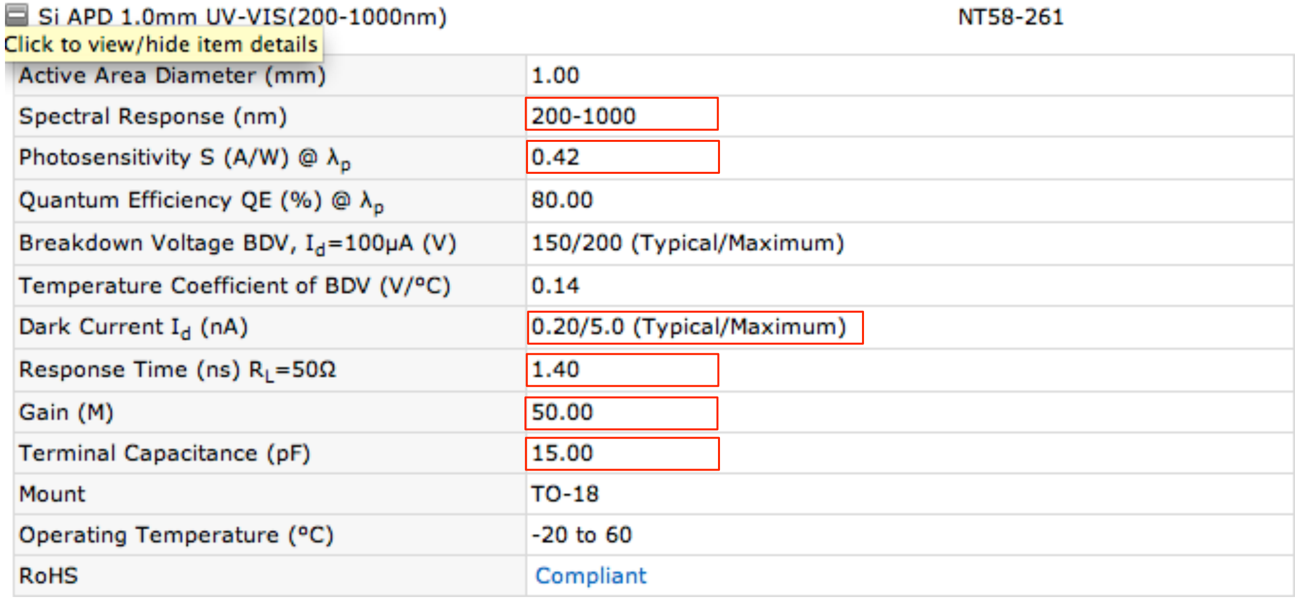
Type	Biased: Normal Response Borosilicate Window
Operating Temperature (°C)	-40 to 100
Typical Applications	High light levels, pulse detectors, AC light measurement
Voltage Bias, V_{Bias} (V)	-10
Active Area (mm^2)	0.81
Responsivity @ 970nm (A/W)	0.65
Noise Equivalent Power NEP (W/ Hz$^{1/2}$)	6.2×10^{-15}
Detectivity (cmHz$^{1/2}$/W)	1.45×10^{13} @ -10V, 970nm
Terminal Capacitance (pF)	8 @ 0V; 2 @ 10V
Dark Current I_d (nA)	0.05 @ 10V
Maximum Breakdown Voltage (V)	30
Rise Time (ns)	8 @ -10V/50Ω, 632nm
Mount	TO-18
RoHS	Compliant

When light, with enough energy to excite an electron from the valence to the conduction band, is incident upon the detector, the resulting accumulation of charge leads to a flow of current in an external circuit. Since light is not the only source of energy that can excite an electron, detectors will have some amount of current that is not representative of incident light. For example, fluctuations in thermal energy can easily be mistaken for light intensity changes. A variety of these "non-light" contributions are present and, when summed up, make up the total noise within the detector.

Avalanche Photodiodes ($169)



Gain up to 100…



Si APD 1.0mm UV-VIS(200-1000nm) NT58-261

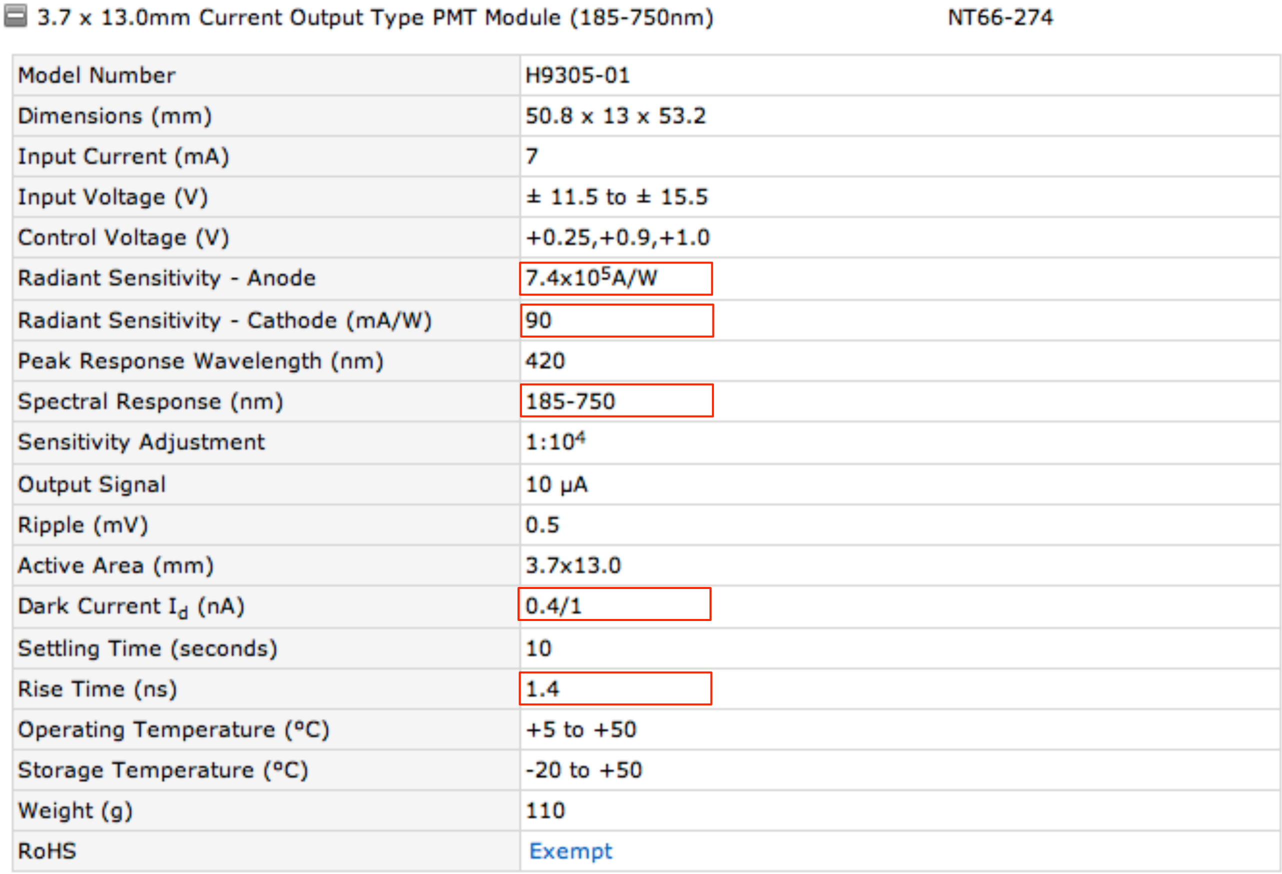
Click to view/hide item details

Active Area Diameter (mm)	1.00
Spectral Response (nm)	200-1000
Photosensitivity S (A/W) @ λ_p	0.42
Quantum Efficiency QE (%) @ λ_p	80.00
Breakdown Voltage BDV, I_d=100μA (V)	150/200 (Typical/Maximum)
Temperature Coefficient of BDV (V/°C)	0.14
Dark Current I_d (nA)	0.20/5.0 (Typical/Maximum)
Response Time (ns) R_L=50Ω	1.40
Gain (M)	50.00
Terminal Capacitance (pF)	15.00
Mount	TO-18
Operating Temperature (°C)	-20 to 60
RoHS	Compliant

As with a conventional photodiode, absorption of incident photons creates electron-hole pairs. A high reverse bias voltage creates a strong internal electric field, which accelerates the electrons through the silicon crystal lattice and produces secondary electrons by impact ionization. The resulting electron avalanche can produce gain factors up to several hundred.

Si APDs are used when light signals are too high for photomultiplier tubes and too low for conventional photodiodes. Si APDs are often used in high-speed applications since the excess noise from the avalanche process is still lower than the noise that would be generated in connecting an external amplifier to a conventional photodiode operated at high frequencies.

Photomultiplier Tube ($895)



3.7 x 13.0mm Current Output Type PMT Module (185-750nm) NT66-274

Model Number	H9305-01
Dimensions (mm)	50.8 x 13 x 53.2
Input Current (mA)	7
Input Voltage (V)	± 11.5 to ± 15.5
Control Voltage (V)	+0.25,+0.9,+1.0
Radiant Sensitivity - Anode	7.4×10^5 A/W
Radiant Sensitivity - Cathode (mA/W)	90
Peak Response Wavelength (nm)	420
Spectral Response (nm)	185-750
Sensitivity Adjustment	$1:10^4$
Output Signal	10 μA
Ripple (mV)	0.5
Active Area (mm)	3.7x13.0
Dark Current I_d (nA)	0.4/1
Settling Time (seconds)	10
Rise Time (ns)	1.4
Operating Temperature (°C)	+5 to +50
Storage Temperature (°C)	-20 to +50
Weight (g)	110
RoHS	Exempt

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Gain up to 10^6…

Why is cathode responsivity 10X worse than a photodiode but anode 10^5X higher than a photodiode responsivity?

When light enters the photocathode of a photomultiplier tube, photoelectrons are emitted from the photocathode. These photoelectrons are multiplied by secondary electron emission through the dynodes and then collected by the anode as an output pulse. PMTs generally operate 500V to about 1200V DC or higher. Warning: This product is extremely light sensitive. Exposing aperture to room light will permanently damage product. Should only be used with sources less than 1 nano-watt.

Review! Complete!

- Which ordering is correct from least to most sensitive for light:

(a) APD / photodiode / PMT / photoconductor.
(b) photodiode / APD / PMT / photoconductor.
(c) photodiode / APD / photoconductor / PMT.
(d) photoconductor / photodiode / APD / PMT.

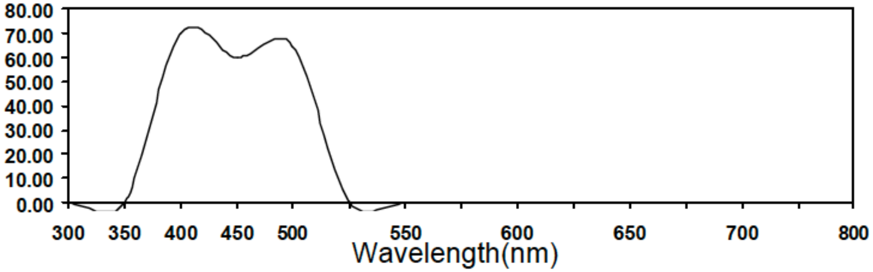
- The detectors we use in this lab are:

(a) Photoconductors.
(b) Photodiodes.
(c) APDs.
(d) PMTs.

- Complete!

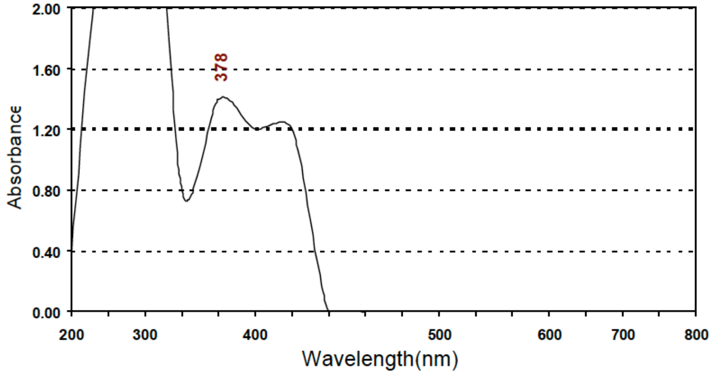
Examples – Lumogen Dyes

LUMOGEN® F Violet 570
Fluorescence curve run in Acetone

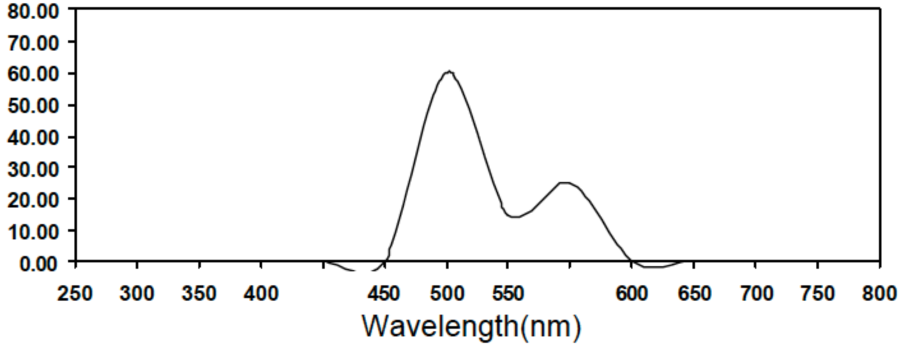


Max (nm) Absorption in ethylene dichloride	Max (nm) Absorption in PMMA	Fluorescence (nm) in ethylene dichloride	Max Quantum Yield
378	378	413	0.94

LUMOGEN® F Violet 570
Spectral curve run in Acetone

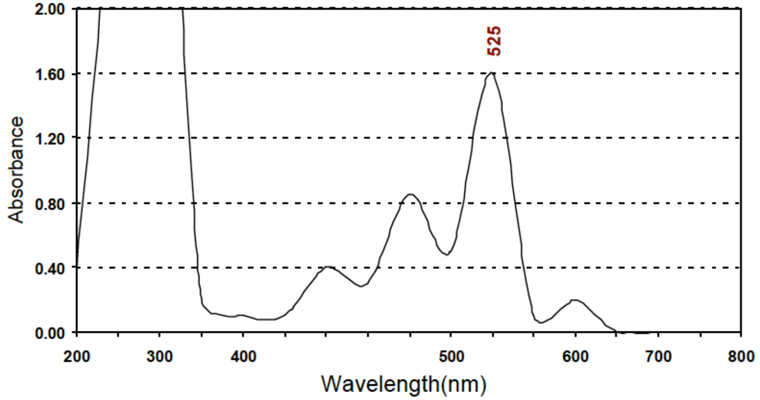


LUMOGEN® F Orange 240
Fluorescence curve run in Acetone



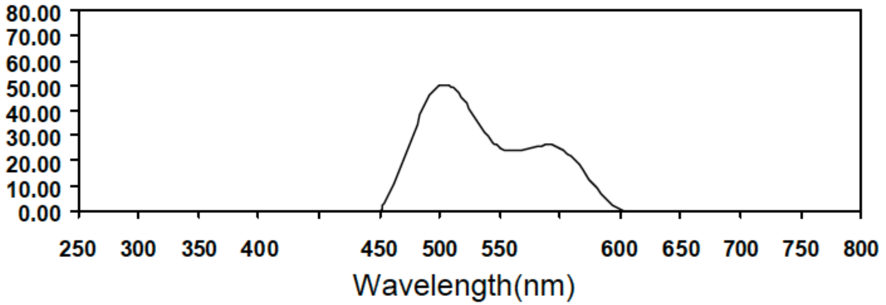
Max (nm) Absorption in ethylene dichloride	Max (nm) Absorption in PMMA	Fluorescence (nm) in ethylene dichloride	Max Quantum Yield
524	525	539	0.99

LUMOGEN® F Orange 240
Spectral curve run in Acetone



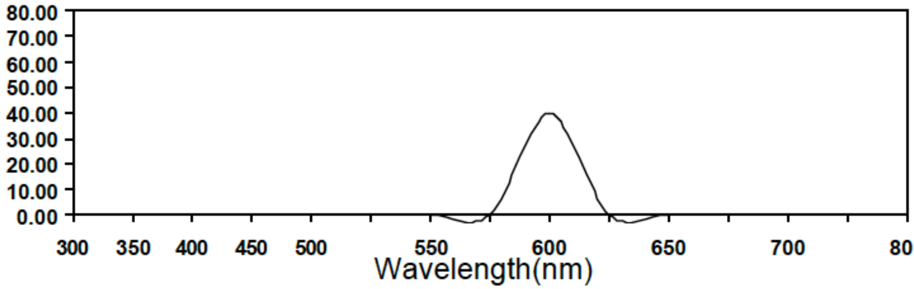
Examples – Lumogen Dyes

LUMOGEN® F Yellow 083
Fluorescence curve run in Acetone



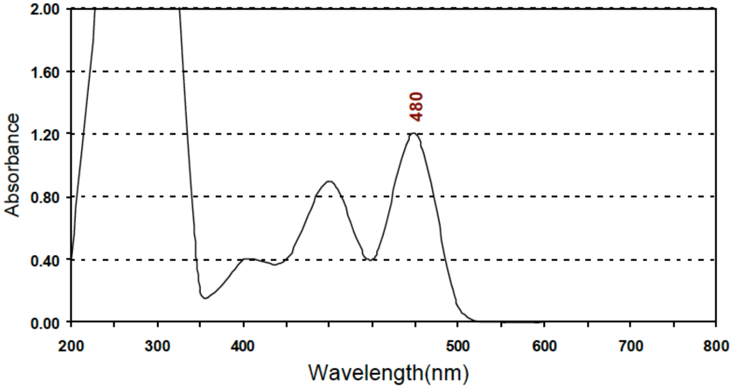
Max (nm) Absorption in ethylene dichloride	Max (nm) Absorption in PMMA	Fluorescence in ethylene dichloride	Max(nm Quantum Yield
476	473	490	0.91

LUMOGEN® F Red 300
Fluorescence curve run in Acetone



Max (nm) Absorption in ethylene dichloride dichloride	Max (nm) Absorption in PMMA	Fluorescence (nm) in ethylene dichloride	Max Quantum Yield
578	578	613	0.98

LUMOGEN® F Yellow 083
Spectral curve run in Acetone



LUMOGEN® F RED 300
Spectral curve run in Acetone