Lecture 18 - Light Emitting Diodes - Outline

- **Recombination Processes** (continued from Lecture 17)
  - Radiative vs. non-radiative
  - Relative carrier lifetimes
- **Light emitting diode basics**
  - Concepts, operation; the eye and color
  - Device design challenges; performance metrics
- **LED practice** (history; LED evolution and revolution)
  - Early devices
    - materials
    - device structures
  - Fiber coupled devices
  - Resonant cavity devices
  - Modern devices
    - high efficiency, high intensity advances (getting heat and light out)
    - new material advances (nitrides)
    - white light sources

Recombination models: radiative and non-radiative

- **Radiative recombination rate:**

$$R_{rad} = r_{rad}(T)\, n\, p \quad = B\, n\, p$$

where we have followed the convention of writing the proportionality factor, $r_{rad}(T)$, as B.

If we assume we have a p-type sample, we define a radiative lifetime for the minority carriers as:

$$R_{rad} = \frac{n}{\tau_{rad}}, \quad \text{where we define} \quad \tau_{rad} \equiv \frac{1}{Bp} \cong \frac{1}{Bp_o}$$

- **Non-radiative recombination rate: Non-radiative recombination also depends on the np product, but since it occurs via mid-gap levels it is much less sensitive to the majority population, p in this case. Thus we define a non-radiative lifetime as**

$$R_{non-rad} = r_{non-rad}(T)\, n\, p = A\, n = \frac{n}{\tau_{non-rad}}, \quad \text{with} \quad \tau_{non-rad} \equiv \frac{1}{A}$$

Recombination models: net recombination

- Net generation/recombination: In thermal equilibrium generation and recombination balance:

$$G_o = R_o = \left(r_{rad} + r_{non-rad}\right)n_o p_o = Bp_o n_o + An_o$$

When we disturb thermal equilibrium by injecting excess carriers and/or having current, we can have net generation or recombination, and a population change:

$$\frac{\partial n}{\partial t} = \frac{1}{q}\frac{\partial J_e}{\partial x} + G_o + g_{ext}\left(x,t\right) - Bnp - An$$

Using our equilibrium relation, we can write this as:

$$\frac{\partial n}{\partial t} - \frac{1}{q}\frac{\partial J_e}{\partial x} = g_{ext}\left(x,t\right) - B\left(np - n_o p_o\right) - A\left(n - n_o\right)$$

It is convenient to define excess carrier populations:

$$n' \equiv \left(n - n_o\right), \quad p' \equiv \left(p - p_o\right)$$

Recombination models: net recombination, cont.

With these definitions, we have

$$\frac{\partial n'}{\partial t} - \frac{1}{q}\frac{\partial J_e}{\partial x} \approx g_{ext}(x,t) - \left[B(p_o + p') + A\right]n'$$

To obtain this we assumed quasineutrality, n' ≈ p', and extrinsic p-type, $p_o >> n_o$.

If we assume low-level injection, defined as $p' << p_o$, then we can neglect p' relative to p_o and write:

$$\frac{\partial n'}{\partial t} - \frac{1}{q}\frac{\partial J_e}{\partial x} \approx g_{ext}(x,t) - \left[Bp_o + A\right]n' = g_{ext}(x,t) - \frac{n'}{\tau_{\min}}$$

where the minority carrier lifetime is defined as:

$$\tau_{\min} \equiv \frac{1}{(Bp_o + A)}$$

Recombination models: net recombination, cont.

It is important to relate the total minority carrier lifetime to the radiative and non-radiative lifetimes we introduced earlier:

$$\frac{1}{\tau_{\min}} \equiv Bp_o + A = \frac{1}{\tau_{rad}} + \frac{1}{\tau_{non-rad}}$$

Finally, note that if we have <u>high-level injection</u>, we find that the lifetime decreases with injection level:

$$\tau_{\min} = \frac{1}{B(p_o + p') + A}$$

Note also that the it is the radiative lifetime that is decreasing and thus that the fraction of carriers recombining radiatively is increasing.

Light emitting diodes: current-output relationships

Assume we have an LED where the efficient radiative emission occurs on the p-side of the device (a typical situation). The optical power out of this LED is:

$$P_{out} = \eta_{ext} P_{\substack{generated \\ internally}} = \eta_{ext}\, h\nu\, A \int_{dev} \frac{n'}{\tau_{rad}} dx$$

where:

- $h\nu$: energy per photon
- η_{ext}: extraction or external efficiency (the fraction ot of photons generated that get out)
- A: device cross-section area normal to current

and the integral is the total number of photons generated per unit time in the device.

This integral can be related to the total diode current and the minority carrier current on the p-side.

Light emitting diodes: current-output relationships, cont

We return to:

$$\frac{\partial n'}{\partial t} - \frac{1}{q}\frac{\partial J_e}{\partial x} = g_{ext}(x,t) - \frac{n'}{\tau_{\min}}$$

In the steady state, with no external generation term this becomes:

$$\frac{1}{q}\frac{\partial J_e}{\partial x} = \frac{n'}{\tau_{\min}}$$

And the integral in the output power equation becomes:

$$\int_o^{w_p} \frac{n'}{\tau_{rad}} dx = \frac{1}{q}\frac{\tau_{\min}}{\tau_{rad}} \int_o^{w_p} \frac{\partial J_e}{\partial x} dx = \frac{1}{q}\frac{\tau_{\min}}{\tau_{rad}} \left[J_e(0^+) - J_e(w_p) \right]$$

Inserting this, we arrive at:

$$P_{out} = \frac{h\nu}{q} \eta_{ext} A \frac{\tau_{\min}}{\tau_{rad}} \left[J_e(0^+) - J_e(w_p) \right]$$

Light emitting diodes: current-output relationships, cont

Finally, we recognize that it is useful conceptually to identify several of the terms in this result as efficiencies. Doing so we write:

$$P_{out} = h\nu \frac{i_D}{q} \eta_{ext} \frac{A\left[J_e\left(0^+\right) - J_e\left(w_p\right)\right]}{i_D} \frac{\tau_{\min}}{\tau_{rad}} = h\nu \frac{i_D}{q} \eta_{ext} \eta_i \eta_{rad}$$

where:

- $h\nu$: energy per photon
- η_{ext}: extraction or external efficiency (the fraction of of photons generated that get out)
- η_i: current efficiency (the fraction of the total diode current that is current into the p-side of the device and that recombines there before getting to the contact)
- η_{rad}: radiative efficiency (the fraction of electron current that recombines radiatively)

Identifying these efficiencies is useful because doing so helps us understand how to make the device better. We will next look at them each in turn, …bottom to top…

Light emitting diodes: radiative efficiency

The radiative efficiency is defined as:

$$\eta_{rad} \equiv \frac{\tau_{\min}}{\tau_{rad}} = \frac{1/\tau_{rad}}{1/\tau_{rad} + 1/\tau_{non-rad}} = \frac{1}{1+\tau_{rad}/\tau_{non-rad}}$$

From this we confirm our intuition that a short radiative lifetime and long non-radiative lifetime are best. This is largely a question of using the right materials, and making sure they are high quality.

We can also write η_{rad} in terms of A and B:

$$\eta_{rad} \equiv \frac{\tau_{\min}}{\tau_{rad}} = \frac{B(p_o + p')}{B(p_o + p') + A} = \frac{1}{1 + A/[B(p_o + p')]}$$

from this we see that driving the device to high level injection may help. (We say "may" because this may also lead to heating which will reduce the non-radiative lifetime.)

Light emitting diodes: radiative efficiency, cont

Material choices:

- **Direct band gap** - the radiative lifetime is much shorter for direct band gap materials:

  B: 10^{-11} to 10^{-9} cm^3s^{-1} for direct gap

  10^{-15} to 10^{-13} cm^3s^{-1} for indirect gap

  Sample values:

  GaAs: 7.2×10^{-10}

  Si: 1.8×10^{-15}

  Ge: 5.25×10^{-14}

  Common materials:

  IR: GaAs, InGaAsP, GaInNAs

  Visible: GaAsP, InGaP, InGaAsP, GaN, GaAlInN

- **Gap level transitions** - there are a few examples of useful radiative transitions via levels in the energy gap

  GaP: Zn-O pairs (red)

  N-valence band (green)

  GaAs: Si-donor to Si-acceptor (980 nm)

Light emitting diodes: current efficiency

The current efficiency is the fraction of the total diode current that is due to the desired minority carriers (electrons injected into the p-side in the present example) that recombine before reaching the ohmic contact:

$$\eta_i \equiv \frac{A}{i_D}\left[J_e\left(0^+\right) - J_e\left(w_p\right)\right]$$

We can make the current efficiency approach 100% by taking the following precautions:

- **Use asymmetric doping:** this insures injection into the appropriate side of the device $N_{Dn} >> N_{Ap}$
- **Make the diodes wide:** this insures that the carriers recombine before reaching the contacts $w_p << L_e$
- **Use heterojunctions:** to increase injection efficiency and to shield carriers for ohmic contacts

Light emitting diodes: extraction efficiency

The extraction efficiency, how much of the radiation actually leaves the device, is the most difficult issue for many LEDs. There are several contributions:

1. Total internal reflection
2. Internal (re)absorption
3. Blocking by contacts

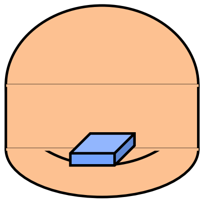
Because of the refractive index of most semiconductors is high, 3.5 being a typical value, Item 1 is a major issue. The critical angle for total internal reflection is only 16˚ at a semiconductor-to-air boundary. Spontaneous radiation (which is what we are dealing with) is directed uniformly in all directions, and the fraction hitting a flat surface within the critical angle, Θ_{crit}, is:

$$\eta_{ex} = \left(\sin^2 \Theta_{crit}\right)/4$$

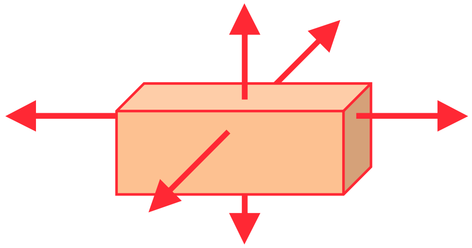
Evaluating this for n = 3.5, we find that only 2% of the light can escape the solid!

Light emitting diodes: fighting total internal reflection

Total internal reflection can be alleviated if the device is packaged in a domed shaped, high index plastic package:



If the device is fabricated with a substrate that is transparent to the emitted radiation, then light can be extracted from the 4 sides and bottom of the device as well as from the top. This increases the extraction efficiency by a factor of 6!



Light emitting diodes: fighting total internal reflection, cont.

Other solutions to the total internal reflection that are not as widely used as these are:

Thin devices with roughened surfaces: The idea is that if there is very little internal (re)absorption of the emitted light, the light will bounce around inside the device until it hits the surface at an angle within the critical angle. If the surface is rough, the chance of this happening is increased.

Resonant cavity LEDs: If a one-dimensional photonic crystal (a distributed Bragg reflector) is placed on the bottom of the device, the light emitted downward will be redirected up.

Superluminescent emitting LEDs: If a device is driven strongly enough, there can be some stimulated emission, and this will be highly directed, as we shall see when we talk about laser diodes. This can be used to increase an LEDs emission.

None of these ideas work as well as using a transparent substrate, collecting the light from all sides of a device, and putting the device in a high-index package positioned in a suitable reflector.

Light emitting diodes: historical perspective

LEDs are a very old device, and were the first commercial compound semiconductor devices in the marketplace. Red, amber, and green LEDs (but not blue) were sold in the 1960's, but main research focus was on laser diodes, and little LED research was done after the 1970's.

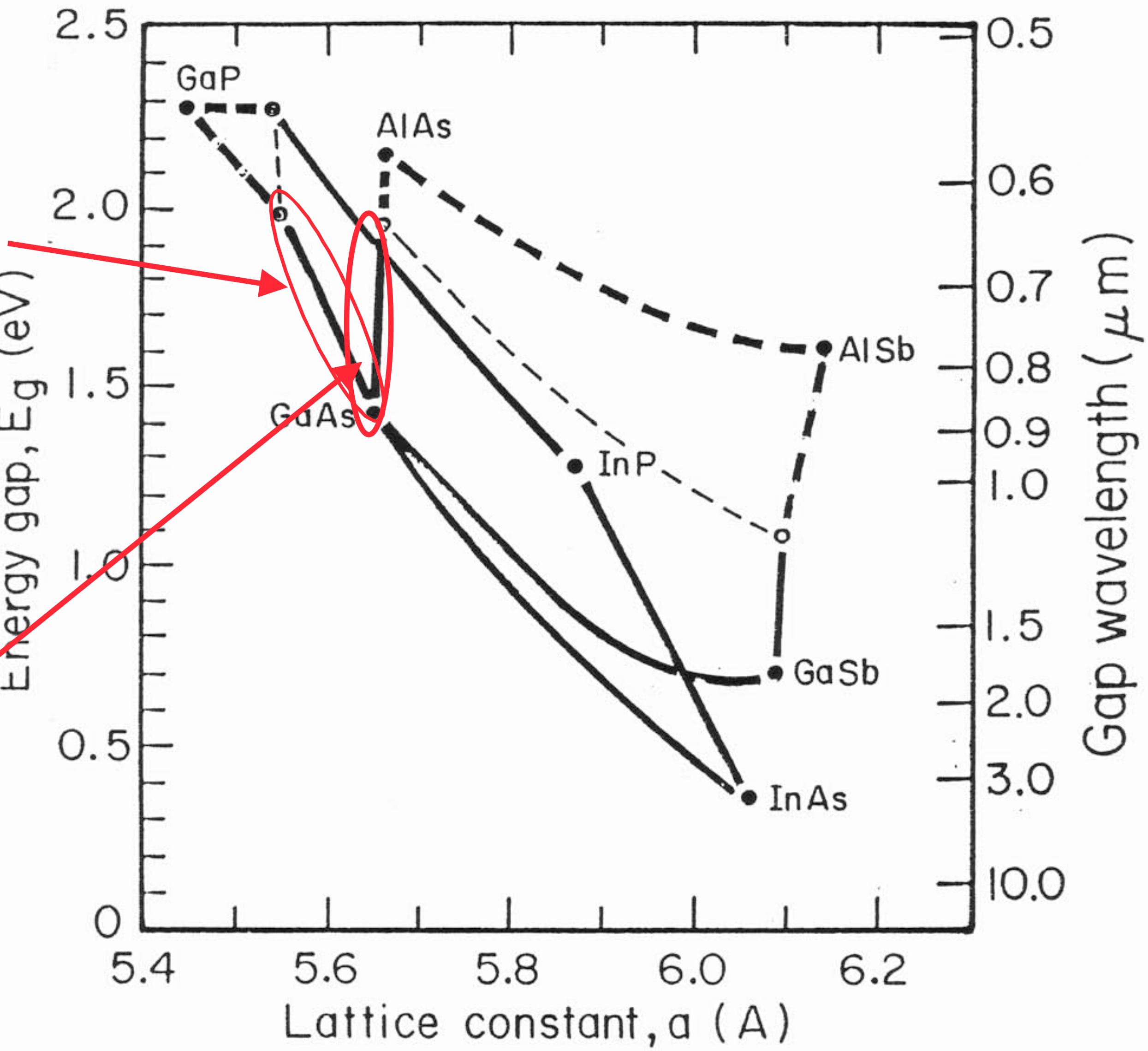
Things changed dramatically in the 1990's,

- in part because of new materials developed in the search for red and blue lasers, InGaP/GaAs, GaInAlN/GaN
- in part because of packaging innovations,
  - improved heat sinking and advanced reflector designs
- in part due to advances in wafer bonding, and
  - transparent substrates for improved light extraction
- in part due to the diligence of LED researchers.
  - taking advantage of advances in other fields

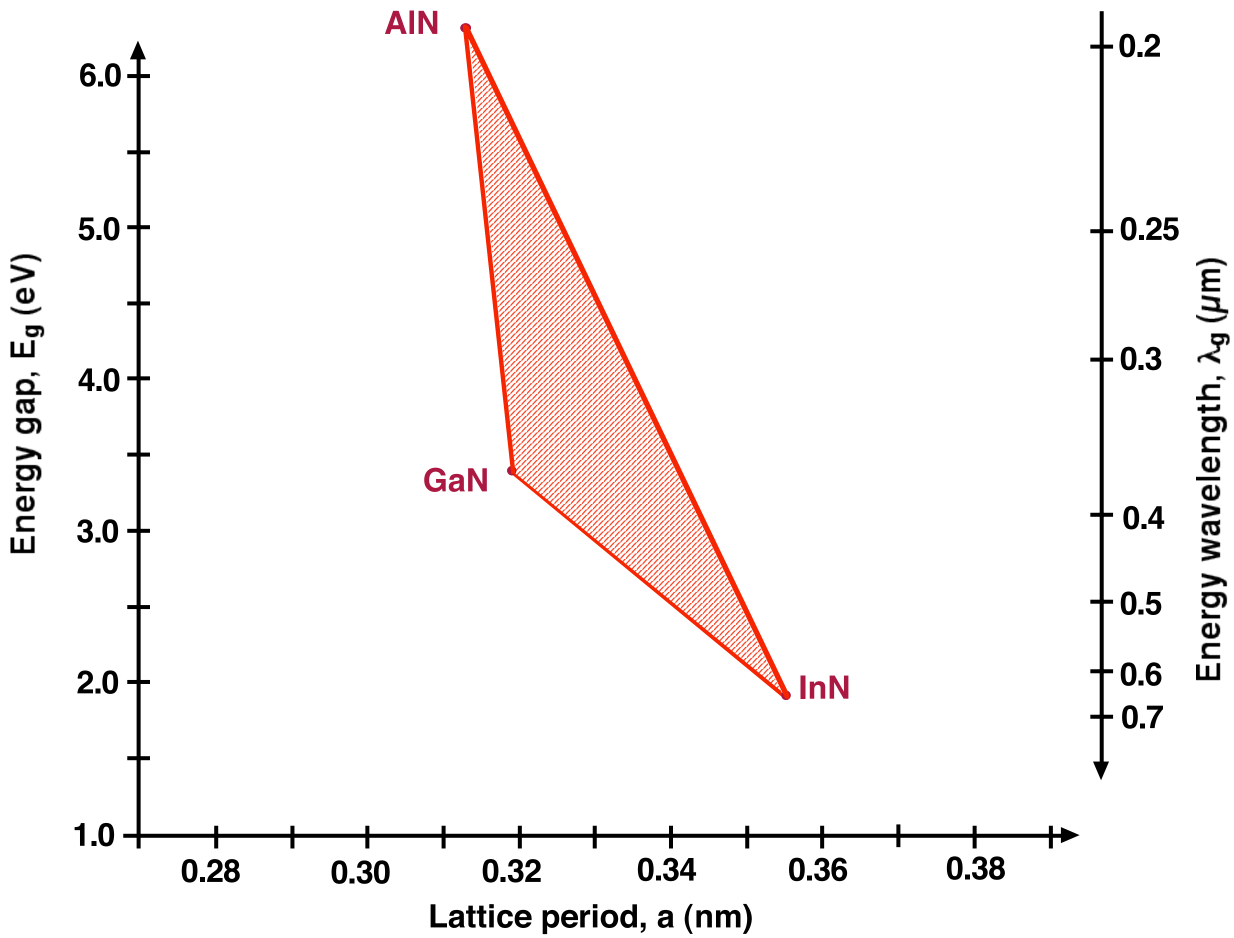
III-V quarternaries: InGaAsP

Early GaAsP red LEDs grown on linearly graded buffer on GaAs

Modern InGaAlP red LEDs grown lattice-matched on GaAs, and transferred to GaP substrates



The III-V wurtzite quarternary:
GaInAlN

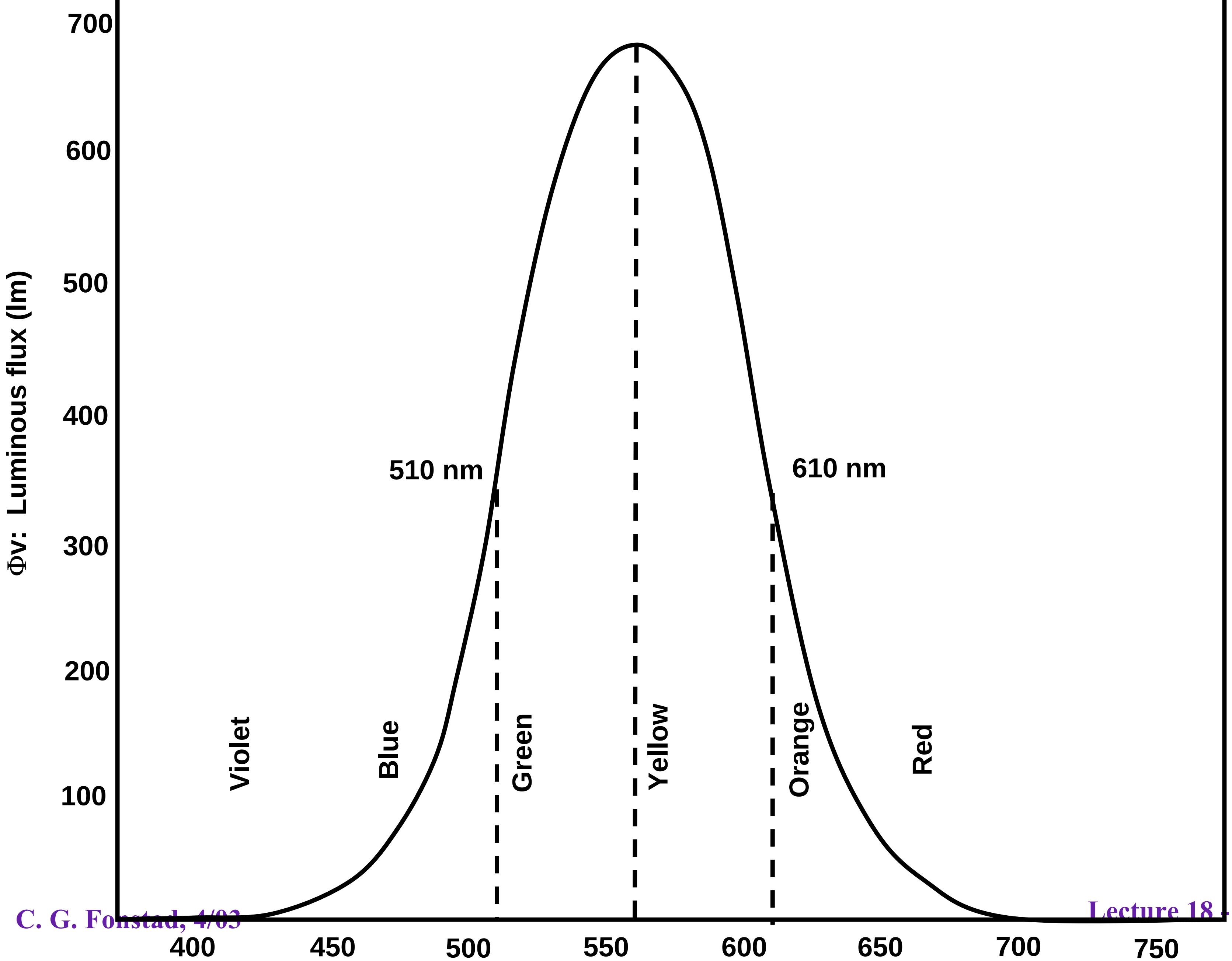


Light emitting diodes - typical specta

- LED emission - typ. 20 nm wide

- Important spectra for comparison with LED spectrum

Light emitting diodes - human eye response



Light emitting diodes - Red and Amber LEDs

- **Red LEDs**

- **Yellow/Amber LEDs**

Light emitting diodes - Conventional green LEDs; Burrus-type

- **Green LEDs**

- **LED designed to couple efficiently to a fiber (Burrus geometry)**

Light emitting diodes - illustrating recent advances

(Images Deleted)