EECS 2077
Semiconductor
Devices

17 - LEDs

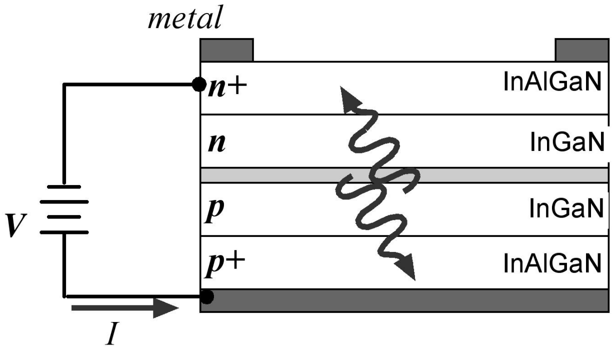
Name:____________________________

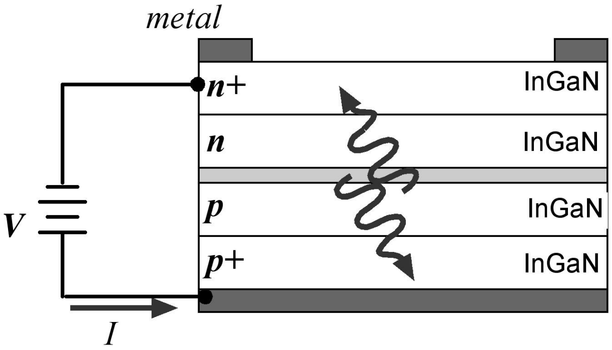
In-Class Problems

(1) Advantages of a double heterojunction for a light emitting device include:

(a) improved carrier confinement (confine electrons and holes to the same region where they can recombine)
(b) wider-bandgap around the emitting region so that most light gets out of the device without being re-absorbed
(c) both
(d) neither
(e) arguably higher nutritional value than Kellogg's Fruit Loops

(2) Consider two LEDs. The LEDs are made from semiconductors with a bandgap of 2.6 eV for the InGaN material and a bandgap of 3.0 eV for the InAlGaN material.





(a) What wavelengths of light will each LED emit?

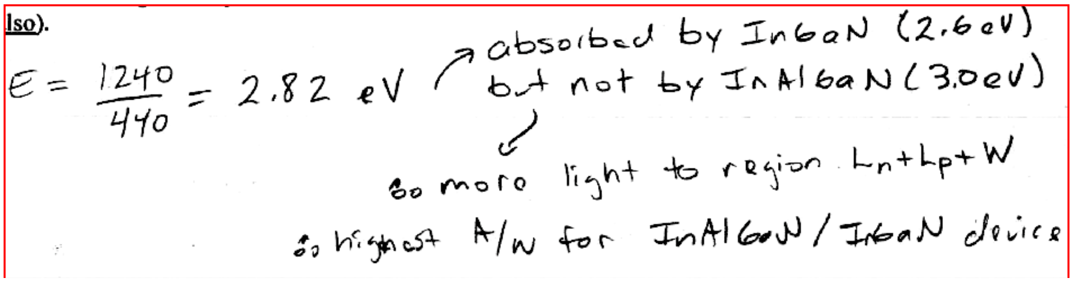
$E = \frac{hc}{\lambda} \approx \frac{1240}{\lambda} = 2.6\ \text{eV}$ so $\lambda = 477\ \text{nm}$ (blue!)

FOR BOTH!

(b) Which LED would be more efficient and why?

The one on the left, which has wider bandgap regions outside the emitting region which allows light to escape without being absorbed.

(c) For the two LED structures shown above, you decide to use the structures as a photodetectors. Which structure would have the highest responsivity (A/W) for light detection at a wavelength of 440 nm (please explain why also).



lso).

$E = \frac{1240}{440} = 2.82$ eV ↗ absorbed by InGaN (2.6eV) but not by InAlGaN (3.0eV)

so more light to region L_n+L_p+W

so highest A/W for InAlGaN / InGaN device

(d) back to LEDs. Assume you use the layers for the device on left to create a quantum well LED. The quantum well region (the InGaN) is narrow enough that the energy gap between the resulting quantum well levels decreases the emission wavelength (increases the emission energy for each photon) to 477 nm. Assume the semiconductors have a resistance of 10 ohms. For a driving current of 10 mA calculate the total voltage required to operate the quantum well LED.

$$V = \frac{E_{photon}}{q} + I \times R_S + \frac{\Delta E_C}{q} + \frac{\Delta E_V}{q}$$

Ephoton = 2.6 eV
Vr = 10E-3 x 10 = 0.1 V
Delta' E's are = 3.0 eV - 2.6 eV = 0.4 eV (0.2 eV for conduction band, and 0.2 eV for valance band, or you could split them anyway you want and it would not matter, the total would still be 0.4 eV).

Total Voltage required = 2.6+ 0.1 + 0.4 = 3.1 V

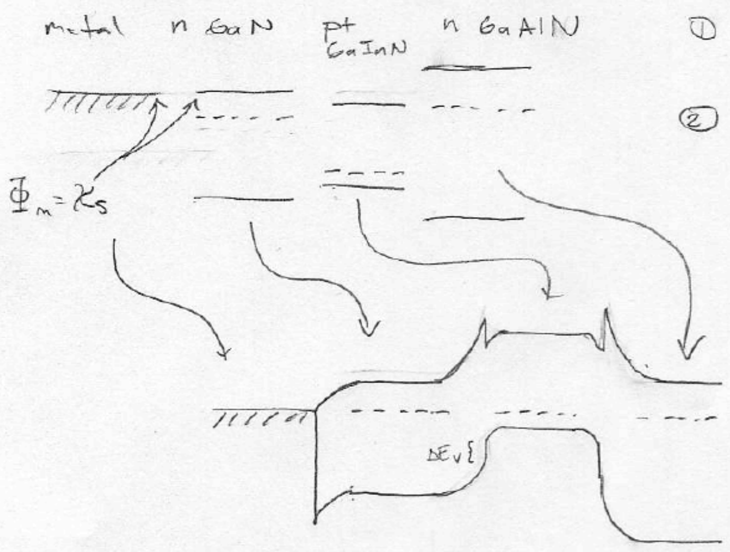
(3) This question is related to heterojunctions. The goal is to convince you that you know enough to create the band diagram for ANY set of semiconductors and metals, even modern LEDs which have numerous layers and are highly band-gap engineered. These are GaN semiconductors where the column III element (Ga) is partially replaced with other column III elements (such as In, and Al) to change the bandgap.

For this problem, see lecture 11, slide 24. Another hint, start with a Schottky diode example too as a warmup, e.g. from the Schottkey diode lecture 5.

GaN has a bandgap of 3.4. Assume the GaAIN has a bandgap of 3.8 (only a little bit of Al added). Assume the GaInN has a bandgap of 3.1 (only a little bit of In added). The additional parameters you need can be found at the end of this document (see the appendix). Electron affinities for these are not given, but notice in the appendix how the electron affinity for GaN is ~2.2 eV greater than AlN and the bandgap difference is ~2.6 eV. So for simplicity, just assume the semiconductor workfunctions for all three of these are equal for the UNDOPED cases.

Draw a band-diagram for a metal / n GaN / p+ GaInN / n GaAIN. Assume the metal workfunction is the same as the <u>electron affinity for the GaN</u> (which is the vacuum level to conduction band). The diagram need not be exact, but should be representative.

Helpful tip. Starting from the left, do ONE material at a time. And for each, do 'dots – lines – bending'. Draw dots for the offsets and connect them with a vertical line (that has to stay the same), then move all the flat lines for the Fermi level aligment (Ec, Ef, Ev) leaving a bit of space next to the dots for the last part, which is to add bending to connect the flat lines to the dots!

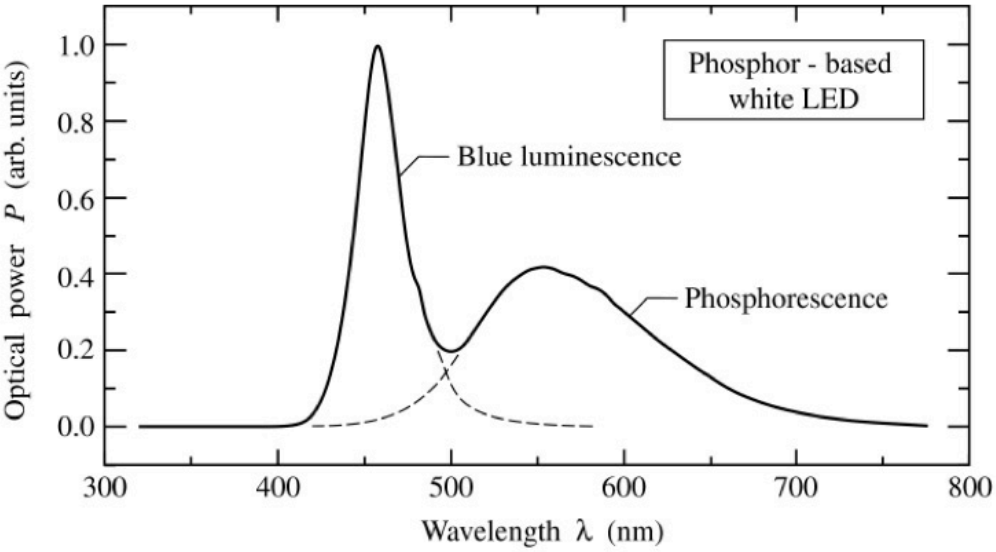


① line-up Fermi levels why keeping ΔE_c & ΔE_v

② band bending, & account for doping concentrations

← your answer just needs to look close to this.... not exact.

(4) Below is a simple white LED. Question… what percent of the optical power is automatically lost in using a blue LED to create the yellow light? Do a rough calculation based on peak wavelengths and energy….



delta = 2.75 eV – 2.25 eV = 0.5 eV
0.5/2.75 = 18% lost

(5) A more challenging diode question. Remember, for the real diode, up in the exponential you need to subtract contact potential from the applied voltage. Lets calculate the REAL diode characteristics (including contact potential) for a pure p+n+ GaN LED doped to 10^{18}/cc on both sides, and 100 μm x 100 μm diode area.

For simplicity, assume the contact potential is 90% of bandgap energy (because is heavily doped).

For simplicity, use the parameters shown below which are for lightly doped material (mobility, diffusion length, etc. all decrease with increased doping, but lets keep it simple).

Also, be careful, the n_i for GaN is x10^{-10} (hard to read in the table).

Note, some key equations are shown below the table too.

Lastly, just remember that typically blue LEDs are made of InGaN, pure GaN would be a UV LED.

(a) What is the drift current across the junction at an applied reverse bias of -4V?

The first solution below is for 10^{10} for n_i (a mistake) the correct version is below that for 10^{-10} for n_i. In reality, there are defects in GaN that will give rise to a greater n_i and which will increase the currents.

$$I = qA\overbrace{\left(\frac{L_p}{\tau_p}p_n + \frac{L_n}{\tau_n}n_p\right)} e^{q(V-V_0)/kT}$$

$$= 1.6\times10^{-19}(0.01)^2\left(\frac{8.7\times10^{-5}}{10^{-8}}361 + \frac{6.2\times10^{-4}}{10^{-8}}361\right)$$

$$= 4.08\times10^{-16}\,A$$

$$= 0.41\,fA$$

$$L_p = \sqrt{D_p\tau_p} = \sqrt{0.75\cdot10^{-8}}$$

$$= 8.7\times10^{-5}\,cm$$

$$= 0.87\,\mu m$$

$$L_n = \sqrt{D_n\tau_n} = \sqrt{39\cdot10^{-8}}$$

$$= 6.2\times10^{-4}\,cm$$

$$= 6.2\,\mu m$$

$$p_n = n_p = \frac{n_i^2}{10^{18}} = \frac{(1.9\times10^{10})^2}{10^{18}} = 361/cc$$

$n_i = 1.9\times10^{-10}$ version $\Rightarrow$

answer will be 10^{40}, $(10^{20})^2$ lower

$$I_o = 4.08\times10^{-56}\,A$$

(b) How much voltage would be needed to obtain 20 mA of forward bias current through the diode (which is a common spec for small individual LEDs). Remember, assume the REAL case.

The first solution below is for 10^{10} for n_i (a mistake) the correct version is below that for 10^{-10} for n_i. In reality, there are defects in GaN that will give rise to a greater n_i and which will increase the currents.

$$20\times10^{-3} = 4.08\times10^{-16}\,e^{(V-3.08/0.0259}$$

$$V_0 = 0.9\cdot3.425$$

$$= 3.08\,V$$

↳ $\therefore V = 3.9\,V$ ☺

$n_i = 1.9 \times 10^{-10}$ Vo, 500m

$V = 6.28\ V$ ☺

Quantity	***Symbol***	***AlN***	***GaN***	***InN***	***(Unit)***
Crystal structure		W	W	W	–
Gap: Direct (*D*) / Indirect (*I*)		*D*	*D*	*D*	–
Lattice constant	$a_0 =$	3.112	3.191	3.545	Å
	$c_0 =$	4.982	5.185	5.703	Å
Bandgap energy	$E_g =$	6.28	3.425	0.77	eV
Intrinsic carrier concentration	$n_i =$	9.4×10^{-34}	1.9×10^{-10}	920	cm^{-3}
Effective DOS at CB edge	$N_c =$	6.2×10^{18}	2.3×10^{18}	$9{:}0\times10^{17}$	cm^{-3}
Effective DOS at VB edge	$N_v =$	4.9×10^{20}	1.8×10^{19}	5.3×10^{19}	cm^{-3}
Electron mobility	$\mu_n =$	300	1800	3200	cm^2/Vs
Hole mobility	$\mu_p =$	14	30	–	cm^2/Vs
Electron diffusion constant	$D_n =$	7	39	80	cm^2 / s
Hole diffusion constant	$D_p =$	0.3	0.75	–	cm^2 / s
Electron affinity	$\chi =$	1.9	4.1	–	V
Minority carrier lifetime	$\tau =$	–	10^{-8}	–	s
Electron effective mass	$m_e^* =$	0.40 m_e	0.20 m_e	0.11 m_e	–
Heavy hole effective mass	$m_{hh}^* =$	3.53 m_e	0.80 m_e	1.63 m_e	–
Relative dielectric constant	$\varepsilon_r =$	8.5	8.9	15.3	–
Refractive index near E_g	$\overline{n} =$	2.15	2.5	2.9	–
Absorption coefficient near E_g	$\alpha =$	3×10^5	10^5	6×10^4	cm^{-1}

- D = Diamond. Z = Zincblende. W = Wurtzite. DOS = Density of states. VB = Valence band. CB = Conduction band
- The Einstein relation relates the diffusion constant and mobility in a non-degenerately doped semiconductor: $D = \mu\,(k\,T / e)$
- Minority carrier diffusion lengths are given by $L_n = (D_n\tau_n)^{1/2}$ and $L_p = (D_p\tau_p)^{1/2}$
- The mobilities and diffusion constants apply to low doping concentrations ($\approx 10^{15}$ cm^{-3}). As the doping concentration increases, mobilities and diffusion constants decrease.
- The minority carrier lifetime τ applies to doping concentrations of 10^{18} cm^{-3}. For other doping concentrations, the lifetime is given by $\tau = B^{-1}\,(n + p)^{-1}$, where $B_{GaN} \approx 10^{-10}$ cm^3/s.

(6) See the two white LED product spec sheets on blackboard. In terms of how they are made, what is the MAIN difference between the two and why?

The artists version has more or better phosphor to fill in the emission gap between blue and green, so that artwork and other colorful items will appear their true color (similar to how they would with incandescent or sunlight).

(7) If you modulated LEDs fast enough, could you potentially use them to send data optically? Next question, could a reverse biased LED could also be used as a photodetector? So could you just use two LEDs and some electronics to create a complete communication system?

Hint, see this article: http://spectrum.ieee.org/telecom/internet/lifi-gets-ready-to-compete-with-wifi

Appendix: III-V Nitride Semiconductor Parameters (courtesy of Prof. Fred Schubert at RPI).

Room temperature properties of semiconductors: III–V nitrides

Quantity	***Symbol***	***AlN***	***GaN***	***InN***	***(Unit)***
Crystal structure		W	W	W	–
Gap: Direct (*D*) / Indirect (*I*)		*D*	*D*	*D*	–
Lattice constant	a_0 =	3.112	3.191	3.545	Å
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Effective DOS at VB edge	N_v =	4.9×10^{20}	1.8×10^{19}	5.3×10^{19}	cm^{-3}
Electron mobility	μ_n =	300	1800	3200	cm^2/Vs
Hole mobility	μ_p =	14	30	–	cm^2/Vs
Electron diffusion constant	D_n =	7	39	80	cm^2 / s
Hole diffusion constant	D_p =	0.3	0.75	–	cm^2 / s
Electron affinity	χ =	1.9	4.1	–	V
Minority carrier lifetime	τ =	–	10^{-8}	–	s
Electron effective mass	m_e^* =	0.40 m_e	0.20 m_e	0.11 m_e	–
Heavy hole effective mass	m_{hh}^* =	3.53 m_e	0.80 m_e	1.63 m_e	–
Relative dielectric constant	ε_r =	8.5	8.9	15.3	–
Refractive index near E_g	$\bar{n}$ =	2.15	2.5	2.9	–
Absorption coefficient near E_g	α =	3×10^5	10^5	6×10^4	cm^{-1}

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