

This homework is dedicated to III-V semiconductors (You will know the reason soon). Almost all the problems can be solved by theories given in the textbook and lectures. (50+10pts)

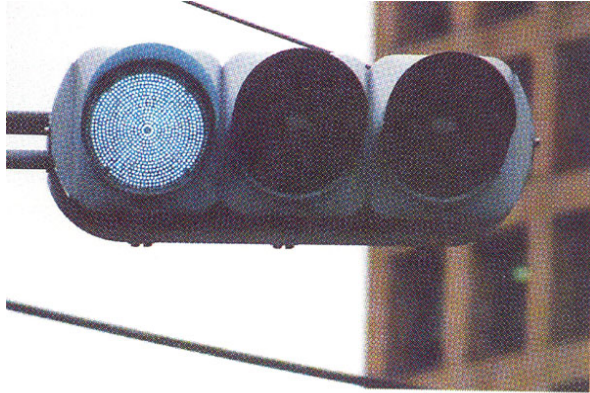


Fig.HW 6-1 The traffic light which uses the InGaN/AlGaIn blue-green, AlInGaP yellow and AlGaAs red LEDs instead of conventional light bulbs

As you might know or not, there are recently many promising achievement on the research and applications of III-V compound semiconductor. Digital versatile disks (DVDs), which came onto the market in 1996, rely on red AlInGaP semiconductor lasers and have a data capacity about 4.7 gigabytes (GB)*, compared to 0.650 GB for compact disks^[12]. Figure HW6-1 shows the first actual LED traffic light placed in Japan in 1994, which uses InGaN / AlGaIn blue-green, AlInGaP yellow and GaAlAs red LEDs^[1,2].

1) Band Gap

It has been shown experimentally that the lowest direct band gap E_0 ($\Gamma_{15}^v - \Gamma_1^c$) in many semiconducting alloys $(AB)_x(CD)_{1-x}$ of compounds AB and CD has an approximately quadratic dependence on the mole fraction of one compound x , i.e.

$$E_0(x) = xE_{g,AB} + (1-x)E_{g,CD} - bx(1-x), \quad (\text{Eqn. 1})$$

where constant b is the nonlinear or bowing parameter^[3-5]. For instance, there are similar relationships between energy gaps and compositions for $\text{Al}_x\text{Ga}_{1-x}\text{N}$ and $\text{In}_x\text{Ga}_{1-x}\text{N}$ alloys with almost the same bowing parameter of 1.0 eV^[1, 2, 6-11].

1. Show that the bowing parameter is given by (3 pts)

$$b = 4\left[\frac{E_{g,AB} + E_{g,CD}}{2} - E_0(x=0.5)\right] \quad (\text{Eqn. 2})$$

2. Show that the energy gap of $\text{Al}_x\text{Ga}_{1-x}\text{N}$ can be expressed as (3 pts)

$$E_g(x) = xE_{g,\text{AlN}} + (1-x)E_{g,\text{GaN}} - bx(1-x), \quad (\text{Eqn. 3})$$

3. Explain the reason why the energy gaps of these ternary alloys are dependent on their compositions. (6 pts)
4. Why don't they show linear relations, i.e. $b \neq 0$? (+5 pts)

*Actually, a typical DVD holds 4, 700, 000, 000 Bytes, i.e. about 4.38GB, not 4.7GB! Moreover, the capacity of today's CD can reach 0.700 GB.

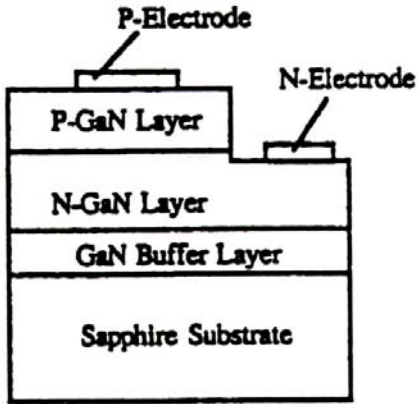


Figure HW6-2 The structure of the GaN pn junction LEDs.

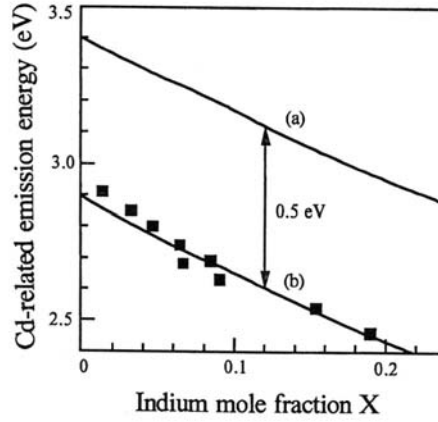


Figure HW6-4 The emission energy as a function of the indium mole fraction of Cd-doped $\text{In}_x\text{Ga}_{1-x}\text{N}$.^[2]

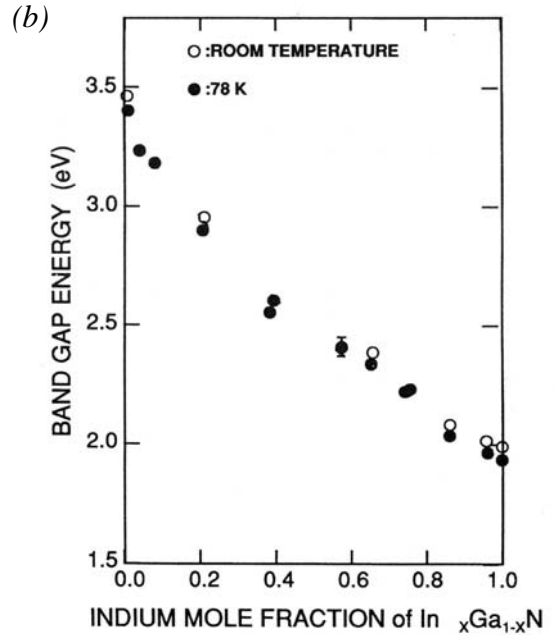
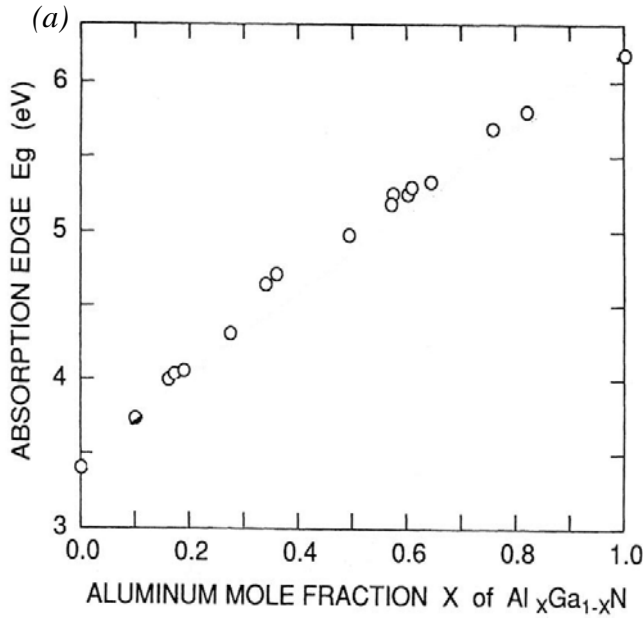


Figure HW6-3 Composition dependence of the direct energy gap E_g of (a) $\text{Al}_x\text{Ga}_{1-x}\text{N}$ alloys^[9], and (b) $\text{In}_x\text{Ga}_{1-x}\text{N}$ alloys^[10].

II) The *pn* Junction LED

Although Pankove^[13] demonstrated the first metal-insulator-semiconductor LED based on GaN in 1971, it takes a very long way to get GaN blue *pn* junction LEDs. The major problem is that people couldn't obtain *p*-type GaN even though they tried doping with Zn, Be, Mg, Cd and similar metals. It was clarified by S. Nakamura, who proposed the acceptor compensation mechanism^[12,14]. A hydrogenation process formed acceptor-H neutral complex, which hinder people get *p*-type GaN for about two decades. N₂- (or NH₃-) ambient thermal annealing at temperature above 700°C can remove hydrogen from acceptor-H complex, and *p*-type can be formed.

Another big breakthrough was that high-quality InGaN films become available since an InGaN active layer is used for all III-V nitride-based LEDs and LDs (laser diodes) emitting red to UV light.

5. Explain light emission mechanism of a GaN *pn* junction LED, as shown in Figure HW6-2. (6 pts) (A sketch might help.)
6. Explain why direct bandgap semiconductors are preferred instead of indirect bandgap semiconductors. (6 pts)
7. Suppose you are an engineer and assigned to build (i) blue and (ii) green LEDs, using Al_xGa_{1-x}N or In_xGa_{1-x}N alloys, calculate possible compositions for each material. Assume that $h\nu = E_g$ and use the data given in Figures HW6-3. (20 pts) (Please don't use band gap data from other references!).
8. Figure HW6-4 shows the emission energy as a function of the indium mole fraction of Cd-doped In_xGa_{1-x}N, which tells that $h\nu = E_g$ is not valid anymore. (i) Why is it *p*-type? (ii) Indicate and argue which curve is the calculated band gap using Eqn. 3, while the other one is the emission energy level of this material. (6 pts)

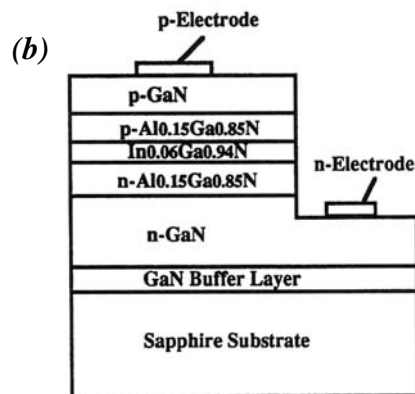
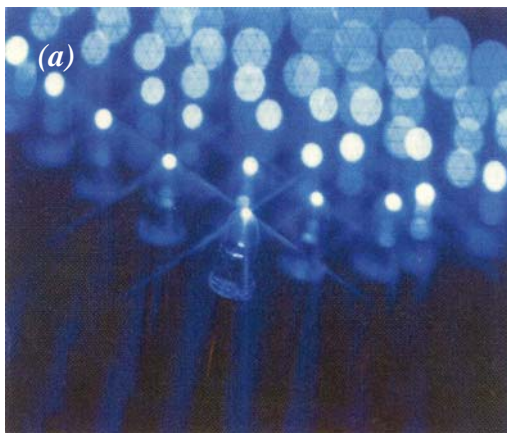


Figure HW6-5 (a) A blue InGaN / AlGaN DH-LED and (b) its structure.^[2]

III) The DH Device

However, the external efficiencies are usually quite low for the above *pn* junction diodes. People are smart enough to make LEDs using double heterostructures (DH)^[1,2,15].

9. Why are DH devices more efficient? (+5 pts)

IV) Quantum Well (Quantum Dots...)

Do you still remember the important results we got through solving the Schrödinger equation for a particle in a potential well? I hope you do. Quantum well devices are based on a very similar theory. However, the details are beyond the scope of this assignment. The structure of a typical InGaN Multi-Quantum Well (MQW) is given in Figure HW6-6.

(Note: There are no problems for this part.)

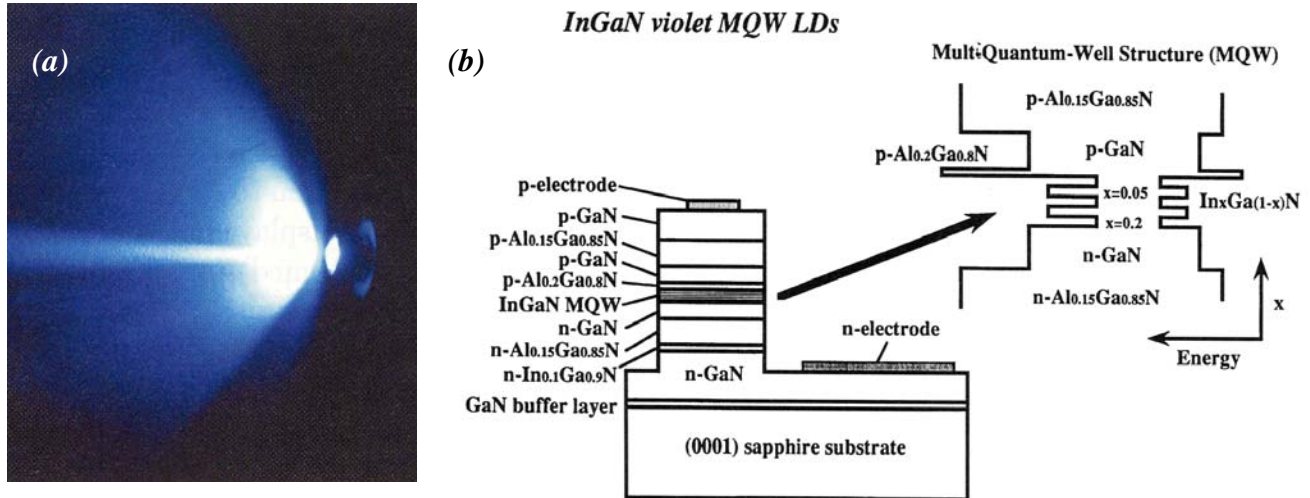


Figure HW6-6 (a) A violet InGaN MQW LD and (b) its structure. ^[2]

References

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