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ECE 531 Project

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LED Design Emitting 1.3 μm-wavelengths Light

1 Design Outline:

Seven design considerations are outlined for a general LED design procedures. It can be a referred as a basis for further optimization of an LED design. Material choosing, junction type, emission type, geometry, dimension, doping and packaging scheme will be discussed in the subsequence sections.

2.1 Choice of Material

The material for the LED is strictly related to the wavelength of the LED. As we know from the basic semiconductor physics, light or photon emitted from the semiconductor is the energy released from the recombination of electron-hole pairs (EHP). If we assume a direct band-gap material, we can have the following result.

$$E_g = h\nu$$

The above formula can be simplified for a given light wavelength.

$$E_g\,(\text{eV}) = \frac{1.24}{\lambda(\mu\text{m})} = \frac{1.24}{1.3(\mu\text{m})} \cong 0.96\ \text{eV}$$

Fig 1 [1] shows the relationship between band gap, wavelength and lattice for InGaAsP and AlGaAsSb compound systems. We will choose our material and mole fraction based on this graph. If we neglect the nonlinear relationship and assume a linear mole fraction relationship for $In_xGa_{1-x}As$ ternary compound semiconductor, we can estimate mole faction from Fig 2 as below.

$$x \cong 0.29$$

So, we have the semiconductor material as $In_{0.29}Ga_{0.71}As$.

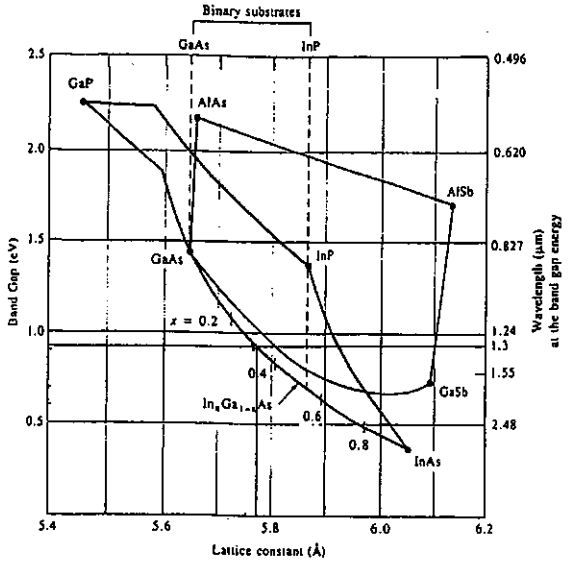

Fig. 1 Relationship between band gap, wavelength and lattice for InGaAsP and AlGaAsSb systems

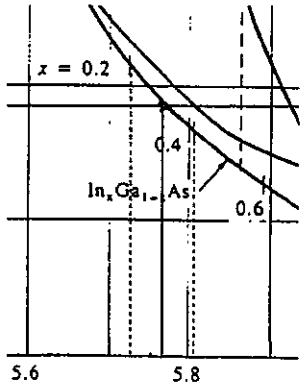

Fig. 2 Mole fraction for $In_xGa_{1-x}As$ ternary compound semiconductor

There are other reasons to choose InGaAs as the LED material. First, the lattice constant changing from pure GaAs to InAs is only about 0.4 Å. This is similar to the lattice mismatch for heterojunction which results in the lattice stretch or compress between different material atoms. The second reason is more important for LED design. The direct band-gap quaternary system, InAlGaAs, covers the wavelength from 1.3 -1.6 μm [2]. $In_xGa_{1-x}As$ is a direct band-gap material for the 1.3 μm wavelength [3][4], which means the energy released from recombination will mostly goes to photons. The ratio of photon generated to the recombination happens is called quantum efficiency η_q. For direct band-gap material this ratio is around 90% to 95%. Indirect band-gap material will also produce lattice vibration, or phonons, which ended with heat and lower efficiency.

2.2. Junction Type

We choose homo-junction for this LED design, which means both p-side and n-side of the pn junction will be $In_{0.29}Ga_{0.71}As$ material with different doping types and levels. For LED design, junction type is not an important factor. So, the main consideration here is the lower cost comparing with hetero-junction.

2.3. LED Emission type

There are two emission types for LED, surface emission and edge emission. Surface emitting type is easy for construction and also the photon output is high. For simplicity, we choose traditional surface emitting LED.

2.4. Device Geometry

It is reasonable to choose flat diode since we chose surface emitting scheme. Flat diode is also the most economical way of constructing LED based on the current semiconductor process. It will be very costly to build a non-Manhattan geometry on our current IC manufacturing facilities.

2.5. Doping Consideration

We should avoid making a degenerated semiconductor since its property could be hard to predict and control. For non-degenerated material, the maximum doping level should be less than the theoretical values of effective density of state function from Fermi-Dirac distribution. On the other hand, we also want to make the high doped side as large as possible which means more carriers can be injected into the less doped side. We can choose either p^+n junction or n^+p junction. Conventional one-sided pn junction will make the doping level of either side differ from 100 times to 1000 times. If we choose the heavily doped p-side to be

$$N_a \cong 10^{17}\ \mathrm{cm}^{-3}$$

Then, the lightly doped side could be

$$N_p \cong 10^{14}\ \mathrm{cm}^{-3}$$

2.6. Device Dimension [5]

The three dimensions for LED diode active part are the cross-section area and the depth for p-side and n-side of the junction.

To maximize the chance of photon emission, we must make the recombination happens as close as possible to the surface of the diode. We can chose a one-sided junction and make the less doped side as thin as possible such that most of the minority recombination happens when the electrons reach the p-side of the junction and the generated photon can easily emitted from the p-side. If we choose p^+n junction, the p-side junction depth can be

$$x_p \cong 100\ \mu\text{m}$$

The n-side junction, which is on the top of the p-side, should be wide enough such that there is enough space for electrons to be recombined. Normally we can choose this length to be the minority carrier diffusion length which is related to the minority carrier diffusion coefficient and life time. For InGaAsP compound material, based on the doping concentration we have chosen, we can set

$$x_n \cong L_p = \sqrt{D_p \tau_p} \cong 0.7\ \mu\text{m}$$

The cross section of a photo diode usually is around $10^{-3}\ \text{cm}^2$ to $10^{-4}\ \text{cm}^2$ [4]. The limiting factors for a bigger size of the pn junction usually come from the effective manufacturing control and heat dissipation requirements. Here we can choose $10^{-4}\ \text{cm}^2$ for the cross section.

$$A = 10^{-4}\ \text{cm}^2$$

Based on the choices 2.2 to 2.6, a simplified LED diode is shown in Fig. 3.

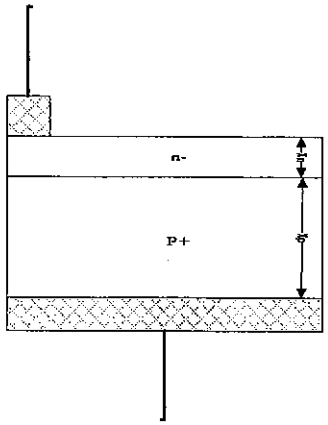

Fig. 3 A simplified p^+n LED diode

2.7. Packaging Scheme

Based on the structure improvement, the final cross section of LED on a TO 5 type header can be shown as in Fig 8.

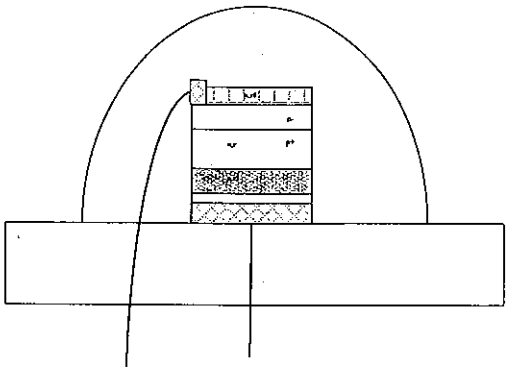

Fig. 8 An LED mounted on top of a TO 5 header

3. Estimation of LED Efficiency [5]

The total efficiency, which is also called external efficiency of an LED, is the combination of internal efficiency and extraction efficiency.

$$\eta_{\text{external}} = \eta_{\text{internal}} \cdot \eta_{\text{extraction}}$$

Internal efficiency is the multiplication of internal quantum efficiency and injection efficiency.

$$\eta_{\text{internal}} = \eta_{\text{quantum}} \cdot \eta_{\text{injection}}$$

Internal quantum efficiency η_{quantum} is determined by the probability of a radiative or non-radiative transition once an EHP recombines. It is calculated as the ratio of photon generated to the recombination happens. Quantum efficiency depends on the material we choose. For a direct band-gap material, this value is normally 90% to 95%. Injection efficiency is the fraction of diode current that will produce luminescence. Injection efficiency is the ratio of electron, or hole recombination current to the total current. If we neglect the space region recombination current, we can have the following formula for $\eta_{\text{injection}}$.

$$\eta_{\text{injection}} \cong \frac{I_p(x_n)}{I_p(x_n)+I_n(-x_p)} = \frac{\dfrac{D_p p_{no}}{L_p}}{\dfrac{D_p p_{no}}{L_p}+\dfrac{D_n n_{po}}{L_n}}$$

Since we have a one-sided junction, we can estimate the above value to be higher than 99% by assuming all other parameters of p or n side are in the same order.

$$p_{no} \cong \frac{n_i^2}{N_d} \quad n_{po} \cong \frac{n_i^2}{N_a}$$

So, we can have estimate for internal efficiency.

$$\eta_{\text{internal}} \cong 0.9 \times 0.99 \cong 90\%$$

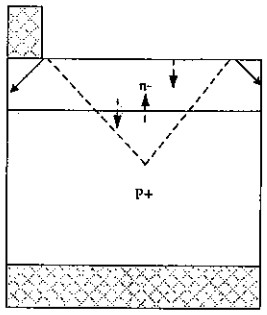

Fig. 4 Photon loss due to the direction of traveling and refection on the front surface

Extraction efficiency, $\eta_{\text{extraction}}$, is the fraction of a photon density or light intensity received from the surface of an LED. There are at least three mechanisms contributed to the low extraction efficiency. The first is simply the loss due to photon traveled to the back contact. Theoretically, half of the photons will travel toward the surface and the other half will travel backward to the bulk. For pessimistic estimate we normally set it to be one half. The second reason for the photon to travel backward is due to the finite the reflectivity of on the front surface. Under normal incidence, the transmitted faction is given as following.

$$T = \frac{4n_r}{(1+n_r)^2}$$

n_r is the index of refraction of the LED material relative to air. For $In_xGa_{1-x}As_yP_{1-y}$ we have the refractive index given as below.

$$n(x,y) = 3.52xy + 3.39x(1-y) + 3.60y(1-x) + 3.56(1-x)(1-y)$$

Based on the result from 2.1, for $In_{0.29}Ga_{0.71}As$, the refractive index can be calculated.

$$n_r\big|_{\substack{x=0.29 \\ y=1}} = 3.577$$

Then we can calculate the transmission factor T.

$$T\big|_{n_r=3.577} = 0.683$$

The third contribution of loss comes from the critical angel in optical theory when light is transmitted from denser material to a lighter material. The portion of photons traveling toward surface greater than the critical angle will be completely reflected back. Based on hte Snell's law, the fraction of light transmitted is given by

$$T = 1 - \cos\theta_c = 1 - \left(1 - \sin^2\theta_c\right)^{1/2} = 1 - \left(1 - \frac{1}{n_r^2}\right)^{1/2} \qquad T\big|_{n_r=3.577} = 0.040$$

Based on the above results, the total extraction efficiency can be calculated below.

$$\eta_{\text{extraction}} = \frac{1}{2}\frac{4n_r}{(1+n_r)^2}\left[1 - \left(1 - \frac{1}{n_r^2}\right)^{1/2}\right] = 1.4\%$$

The total external efficiency of the designed LED can be estimated as

$$\eta_{\text{extemal}} = \eta_{\text{internal}} \cdot \eta_{\text{extraction}} = 0.9 \times 1.4\% = 1.3\%$$

The final efficiency we may also include is the energy conversion efficiency $\eta_{\text{conv.}}$.

$$\eta_{\text{conv.}} = \frac{\text{Luminous light flux per unit junction area}}{\text{Input dc power per unit junction area}}$$

The loss here is mainly due to the resistance related to the outside circuit. Normally we should neglect this loss since it may not belong to the efficiency of an LED itself. But if we assume it to be 90%, then the total efficiency should be around 1.2%. The input dc power per unit junction area can be estimated from the voltage drop across the pn junction and current flow through the junction.

$$P'_{dc} = J_F \cdot V_F$$

Based on the values we chose for the pn junction, we can estimate it as typical values as following.

$$J_F \approx 10^{-10} \text{ A/cm}^2$$

$$V_F \cong 0.65 \text{ V}$$

For these values, we can estimate dc input power.

$$P_{dc} = A \cdot J_F \cdot V_F$$
$$\approx 10^{-4} \cdot 10^{-10} \cdot 0.65 = 6.5 \times 10^{-15} \text{ W}$$

The light power for the designed LED will be 1.3 % of the dc input power.

$$P_{light} \approx 6 \times 10^{-17} \text{ W}$$

4. Structural Improvement

As we can see, the total efficiency of the LED is only around 1% to2%. It is very clear than most of the photon loss is due to the traveling of photons and reflection from the front surface. There are several methods we can do to improve the LED efficiency.

4.1 Bottom Reflection Layer

Photons once generated, they can travel in any direction. At least one half of the photons travel to the bottom and finally get lost in the form of heat. A realistic way is to add another lighter density material which can result in more than half of photons to be reflected again.

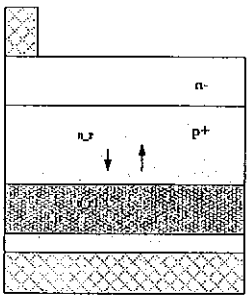

Fig. 5 Reflection layer added in the p^+ layer to introduce reflection

4.2 Dome Shape to Increase Critical Angle

As we mentioned earlier any incident wave which has incident angle greater than the critical angle will be totally reflected at the surface. A dome shape surface will significantly increase the critical angle by makes most of incident wave normal to the dome shape surface. Fig 6 can gives us a clue on this principle.

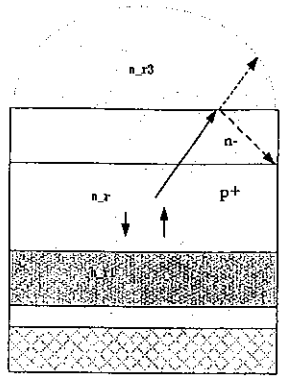

Fig. 6 Dome shape surface to reduce the reflection due to critical angle

4.3 Upper Anti-refection Coating Layer

Just like we add a lower density reflection layer to increase the reflection for the photon travels backward, we can insert another layer with higher density than air between the semiconductor and air to reduce the reflection for the photon travels toward the surface. This will gives the photon a smoother transition from higher density semiconductor to low density air. Reflection will be greatly reduced at the surface.

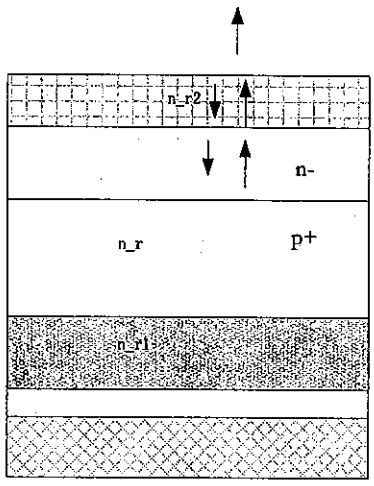

Fig. 7 Anti-Reflection coating to reduce the reflection at the surface

4.4 N^- Layer with Increased Band-gap Energy

The final improvement we can make is to increase slightly the band-gap energy on the n-side of the diode. When photons are created by the recombination of EHP at the n-side, there is also another trend that the generated photons can also be absorbed by the electrons in the valence band. If the band-gap energy on the n-side can be slightly wider as in hetero-junction case, more photons can be released from n-side junction. One method could slightly adjust the mole factor of $In_xGa_{1-x}As$ ternary compound such that it could reach a different band-gap for a homo-junction material.

5. Reference

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