3.5 AlGaAs LED emitter An AlGaAs LED emitter for use in a local optical fiber network has the output spectrum shown in Figure 3.33. It is designed for peak emission at 820 nm at 25°C.

(a) What is the linewidth $\Delta\lambda$ between half power points at temperatures -40°C, 25°C, and 85°C? What is the empirical relationship between $\Delta\lambda$ and T given three temperatures and how does this compare with $\Delta(h\nu) \approx 2.5k_BT - 3k_BT$?

(b) Why does the peak emission wavelength increase with temperature?

(c) Why does the peak intensity decrease with temperature?

(d) What is the bandgap of AlGaAs in this LED?

(e) The bandgap, E_g, of the ternary alloys $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ follows the empirical expression,

$$E_g(eV) = 1.424 + 1.266x + 0.266x^2.$$

What is the composition of the AlGaAs in this LED?

(f) When the forward current is 40 mA, the voltage across the LED is 1.5 V, and the optical power that is coupled into a multimode fiber through a lens is 25 μW. What is the overall efficiency?

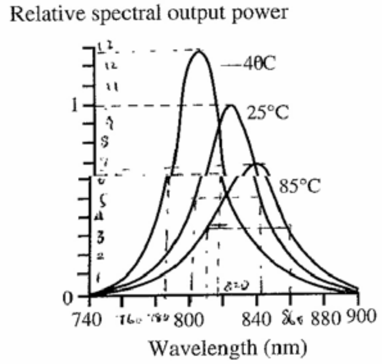

FIGURE 3.33 The output spectrum from AlGaAs LED. Values normalized to peak emission at 25°C.

3.6 III-V compound semiconductors in optoelectronics Figure 3.34 represents the bandgap E_g and the lattice parameter a in the quarternary III-V alloy system. A line joining two points represents the changes in E_g and a with composition in a ternary alloy composed of the compounds at the ends of that line. For example, starting at GaAs point, $E_g = 1.42$ eV and $a = 0.565$ nm, and E_g decreases and a increases as GaAs is alloyed with InAs and we move along the line joining GaAs to InAs. Eventually, at InAs, $E_g = 0.35$ eV and $a = 0.606$ nm. Point X in Figure 3.34 is composed of InAs and GaAs and it is the ternary alloy $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{As}$. It has $E_g = 0.7$ eV and $a = 0.587$ nm, which is the same a as that for InP. $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{As}$ at X is therefore lattice matched to InP and hence can be grown on an InP substrate without creating defects at the interface.

Further, $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{As}$ at X can be alloyed with InP to obtain a quarternary alloy, $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{As}_y\mathrm{P}_{1-y}$, whose properties lie on the line joining X and InP and therefore all have the same lattice parameter as InP but different bandgap. Layers of $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{As}_y\mathrm{P}_{1-y}$ with composition between X and InP can be grown epitaxially on an InP substrate by various techniques such as liquid phase epitaxy (LPE) or molecular beam expitaxy (MBE).

The hatched area between the solid lines represents the possible values of E_g and a for the quarternary III-V alloy system in which the bandgap is direct and hence suitable for direct electron and hole recombination.

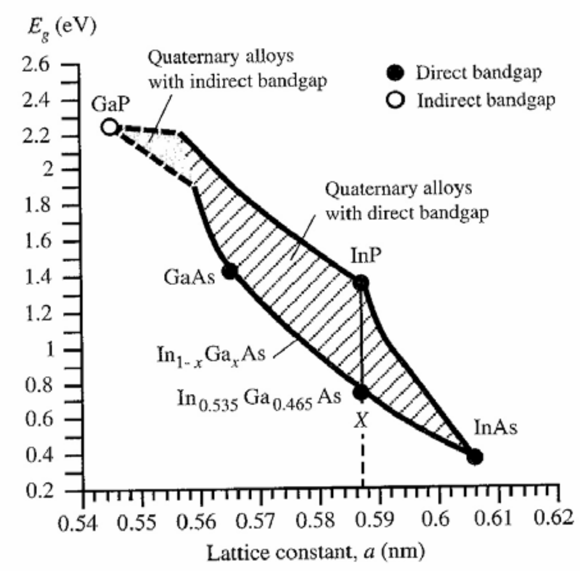

FIGURE 3.34 Bandgap energy E_g and lattice constant a for various III-V alloys of GaP, GaAs, InP and InAs. A line represents a ternary alloy formed with compounds from the end points of the line. Solid lines are for direct bandgap alloys whereas dashed lines for indirect bandgap alloys. Regions between lines represent quaternary alloys. The line from X to InP represents quaternary alloys $In_{1-x}Ga_xAs_{1-y}P_y$ made from $In_{0.535}Ga_{0.465}As$ and InP which are lattice matched to InP.

The compositions of the quarternary alloy lattice matched to InP follow the line from X to InP.

(a) Given that the $In_xGa_{1-x}As$ at X is $In_{0.535}Ga_{0.465}As$, show that quarternary alloys $In_xGa_{1-x}As_yP_{1-y}$ are lattice matched to InP when $y = 2.15x$.

(b) The bandgap energy E_g, in eV for $In_xGa_{1-x}As_yP_{1-y}$ lattice matched to InP is given by the empirical relation,

$$E_g(\text{eV}) = 1.35 - 0.72y + 0.12y^2$$

Find the composition of the quarternary alloy suitable for an emitter operating at 1.55 μm.

3.7 External conversion efficiency The *external power or conversion efficiency* η_{ext} is defined as

$$\eta_{\text{ext}} = \frac{\text{Optical power output}}{\text{Electrical power input}} = \frac{P_o}{IV}$$

One of the major factors reducing the external power efficiency is the loss of photons in extracting the emitted photons that suffer reabsorption in the *pn* junction materials, absorption outside the semiconductors, and various reflections at interfaces.

The total light output power from a particular AlGaAs red LED is 2.5 mW when the current is 50 mA and the voltage is 1.6 V. Calculate its external conversion efficiency.

3.8 Linewidth of LEDs Experiments carried out on various direct bandgap semiconductor LEDs give the output spectral linewidth (between half intensity points as in Figure 3.33) listed in Table 3.3. From Example 3.8.1, we know that a spread in the wavelength is related to a spread in the photon energy,

$$\Delta\lambda \approx \frac{hc}{E_{ph}^2}\Delta E_{ph} \qquad \textbf{(1)}$$

Suppose that we write $E_{ph} = hc/\lambda$ and $\Delta E_{ph} = \Delta(h\upsilon) \approx mk_BT$ in which m is a numerical constant. Show that,

$$\Delta\lambda \approx \lambda^2 \frac{mk_BT}{hc} \tag{2}$$

and by appropriately plotting the data in Table 3.3, and assuming $T = 300$ K, find m.

TABLE 3.3 Linewidth $\Delta\lambda_{1/2}$ between half points in the output spectrum (Intensity vs. wavelength) of various LEDs.

Peak wavelength of emission (λ) nm	650	810	820	890	950	1150	1270	1500
$\Delta\lambda_{1/2}$ nm	22	36	40	50	55	90	110	150
Material (Direct E_g)	AlGaAs	AlGaAs	AlGaAs	GaAs	GaAs	InGaAsP	InGaAsP	InGaAsP

Table 3.4 shows the linewidth $\Delta\lambda_{1/2}$ for various visible LEDs. Radiative recombination is obtained by appropriately doping the material. Using $m \approx 3$, $T = 300$ K, in Eq. (2), calculate the expected spectral width for each and compare with the experimental value. What is your conclusion? Do you think E_N in Figure 3.24 (b) is a discrete level?

TABLE 3.4 Linewidth $\Delta\lambda_{1/2}$ between half points in the output spectrum (intensity vs. wavelength) of various visible LEDs using SiC and GaAsP materials.

Peak wavelength of emission (λ) nm	468	565	583	600	635
$\Delta\lambda_{1/2}$ nm	66	28	36	40	40
Color	Blue	Green	Yellow	Orange	Red
Material	SiC (Al)	GaP (N)	GaAsP (N)	GaAsP (N)	GaAsP