4.12 Laser diode efficiency

a There are several laser diode efficiency definitions as follows:

The **external quantum efficiency** η_{EQE}, of a laser diode is defined as

$$\eta_{EQE} = \frac{\text{Number of output photons from the diode (per unit second)}}{\text{Number of injected electrons into diode (per unit second)}}$$

The **external differential quantum efficiency**, η_{EDQE}, of a laser diode is defined as

$$\eta_{EDQE} = \frac{\text{Increase in number of output photons from diode (per unit second)}}{\text{Increase in number of injected electrons into diode (per unit second)}}$$

The **external power efficiency,** η_{EPE}, of the laser diode is defined by

$$\eta_{EPE} = \frac{\text{Optical output power}}{\text{Electical input power}}$$

If P_o is the emitted optical power, show that

$$\eta_{EQE} = \frac{eP_o}{E_g I}$$

$$\eta_{EDQE} = \left(\frac{e}{E_g}\right)\frac{dP_o}{dI}$$

$$\eta_{EPE} = \eta_{EQE}\left(\frac{E_g}{eV}\right)$$

b A commercial laser diode with an emission wavelength of 670 nm (red) has the following characteristics. The threshold current at 25°C is 76 mA. At I = 80 mA, the output optical power is 2 mW and the voltage across the diode is 2.3 V. If the diode current is increased to 82 mA, the optical output power increases to 3 mW. Calculate the external QE, external differential QE and the external power efficiency of the laser diode.

c Consider an InGaAsP laser diode operating at λ = 1310 nm for optical communications. At I = 40 mA, the output optical power is 3 mW and the voltage across the diode is 1.4 V. If the diode current is increased to 45 mA, the optical output power increases to 4 mW. Calculate external quantum efficiency (QE), external differential QE, external power efficiency of the laser diode.

Solution

a The **external quantum efficiency** η_{EQE}, of a laser diode is defined as

$$\eta_{EQE} = \frac{\text{Number of output photons from the diode (per unit second)}}{\text{Number of injected electrons into diode (per unit second)}}$$

$\therefore$ $$\eta_{EQE} = \frac{\text{Optical Power} / h\upsilon}{\text{Diode Current} / e} = \frac{P_o/E_g}{I/e} = \frac{eP_o}{IE_g}$$

The **external differential quantum efficiency**, η_{EDQE}, of a laser diode is defined as

$$\eta_{EDQE} = \frac{\text{Increase in number of output photons from diode (per unit second)}}{\text{Number of injected electrons into diode (per unit second)}}$$

$\therefore$ $$\eta_{EDQE} = \frac{\text{(Change in Optical Power)} / h\upsilon}{\text{(Change Diode Current)} / e} = \frac{\Delta P_o/E_g}{\Delta I/e} = \frac{e}{E_g}\left(\frac{dP_o}{dI}\right)$$

The **external power efficiency**, η_{EPE}, of the laser diode is defined by

$$\eta_{EPE} = \frac{\text{Optical ouput power}}{\text{Electical input power}} = \frac{P_o}{IV} = \frac{P_o}{IV}\frac{eE_g}{eE_g} = \left(\frac{eP_o}{IE_g}\right)\left(\frac{E_g}{eV}\right)$$

$\therefore$ $$\eta_{EPE} = \left(\frac{eP_o}{IE_g}\right)\left(\frac{E_g}{eV}\right) = \eta_{EQE}\left(\frac{E_g}{eV}\right)$$

b **670 nm laser diode**

$E_g \approx hc/\lambda = (6.626\times10^{-34})(3\times10^{8})/[(670\times10^{-9})(1.6\times10^{-19})] = 1.85$ eV,

so that $$\eta_{EQE} = \frac{eP_o}{E_g I}$$

$\therefore$ $$\eta_{EQE} = \frac{(1.6\times10^{-19}\ \text{C})(2\times10^{-3}\ \text{Js}^{-1})}{(80\times10^{-3}\ \text{A})(1.85\ \text{eV}\times1.6\times10^{-19}\ \text{eV/J})} = \mathbf{0.0135\ or\ 1.35\%}$$

$$\eta_{EDQE} = \frac{e}{E_g}\left(\frac{dP_o}{dI}\right) = \frac{(1.6\times10^{-19}\ \text{C})}{(1.85\ \text{eV}\times1.6\times10^{-19}\ \text{C})}\left(\frac{3\times10^{-3}-2\times10^{-3}\ \text{Js}^{-1}}{82\times10^{-3}-80\times10^{-3}\ \text{A}}\right)$$

$$= \mathbf{0.270\ or\ 27\%.}$$

$$\eta_{EPE} = \frac{P_o}{IV} = \frac{2\times10^{-3}\,\text{W}}{(80\times10^{-3}\,\text{A})(2.3\ \text{V})} = 0.009 \text{ or } \mathbf{1.09\%}$$

c **1310 nm laser diode**

$E_g \approx hc/\lambda = (6.626\times10^{-34})(3\times10^{8})/[(1310\times10^{-9})(1.6\times10^{-19})] = 0.9464$ eV,

so that $$\eta_{EQE} = \frac{(1.6\times10^{-19}\ \text{C})(3\times10^{-3}\ \text{Js}^{-1})}{(40\times10^{-3}\ \text{A})(0.9464\ \text{eV}\times1.6\times10^{-19}\ \text{J/eV})} = \mathbf{0.079\ or\ 7.9\%}$$

$\therefore$ $$\eta_{EDQE} = \frac{e}{E_g}\left(\frac{dP_o}{dI}\right) = \frac{(1.6\times10^{-19}\ \text{C})}{(0.9464\ \text{eV}\times1.6\times10^{-19}\ \text{C})}\left(\frac{4\times10^{-3}-3\times10^{-3}\ \text{Js}^{-1}}{45\times10^{-3}-40\times10^{-3}\ \text{A}}\right)$$

$$= \mathbf{0.211\ or\ 21\%.}$$

and $$\eta_{EPE} = \frac{P_o}{IV} = \frac{3\times10^{-3}\,\text{W}}{(40\times10^{-3}\,\text{A})(1.4\,\text{V})} = 0.0535 \text{ or } \mathbf{5.3\%}$$

4.14 Single frequency lasers Consider a DFB laser operating at 1550 nm. Suppose that the refractive index n = 3.4 (InGaAsP). What should be the corrugation period Λ for a first order grating q = 1. What is Λ for a second order grating, q = 2. How many corrugations are needed for a first order grating if the cavity length is 20 μm? How many corrugations are there for q = 2? Which is easier to fabricate?

Solution

Bragg wavelength λ_B is given by the condition for in-phase interference,

$$q\frac{\lambda_B}{n} = 2\Lambda$$

<u>q = 1</u> $$\Lambda = q\frac{\lambda_B}{2n} = 1\cdot\frac{1.550\ \mu\text{m}}{2(3.4)} = 0.23\ \mu\text{m}.$$

Number of corrugations is

$$N_{\text{corrugations}} = \frac{\text{Cavity length}}{\text{Corrugation period}} = \frac{L}{\Lambda} = \frac{20\ \mu\text{m}}{0.23\ \mu\text{m}} = 87$$

<u>q = 2</u> $$\Lambda = q\frac{\lambda_B}{2n} = 2\cdot\frac{1.550\ \mu\text{m}}{2(3.4)} = 0.46\ \mu\text{m}.$$

Number of corrugations is

$$N_{\text{corrugations}} = \frac{\text{Cavity length}}{\text{Corrugation period}} = \frac{L}{\Lambda} = \frac{20\ \mu\text{m}}{0.45\ \mu\text{m}} = 43$$

The corrugation dimension (Λ) is larger and number of corrugations smaller in q = 2 and would be "easier" to fabricate.

NOTE The allowed DFB modes are not exactly at Bragg wavelengths but are symmetrically placed about λ_B. If λ_m is an allowed DFB lasing mode then

$$\lambda_m = \lambda_B \pm \frac{\lambda_B^2}{2nL}(m+1)$$

Putting m = 0, λ_m = 1.55 μm, we find, λ_B = 1.5319 and 1.5681, that is 1.2% different. We can then recalculate the corrugation period Λ and the number of corrugations but the differences will be small since the wavelength change is only 1.2%.

4.15 The SQW laser Consider a SQW (single quantum well) laser which has an ultrathin active InGaAs of bandgap 0.70 eV and thickness 10 nm between two layers of InAlAs which has a bandgap of 1.45 eV. Effective mass of conduction electrons in InGaAs is about $0.04m_e$ and that of the holes in the valence band is $0.44m_e$ where m_e is the mass of the electron in vacuum. Calculate the first and second electron energy levels above E_c and the first hole energy level below E_v in the QW. What is the lasing emission wavelength for this SQW laser? What is this wavelength if the transition were to occur in bulk InGaAs with the same bandgap?

Solution

The lowest energy levels with respect to the CB edge E_c in InGaAs are determined by the energy of an electron in a one-dimensional finite potential energy well

Using $d = 10\times10^{-9}$ m= 100 Å, $m_e^* = 0.04m_e$ and $n = 1$ and 2 (for first and second energy levels), we find the following *electron energy levels*

$\Delta E_C = \frac{2}{3}\Delta E_g = \frac{2}{3}(1.45\text{-}.07 \text{ eV}) = 0.5\text{eV} = 500\text{meV}$

From the handouts (Appendix 1 of Coldren and Corzine),

$$E_1^\infty = 3.76\left(\frac{m_0}{m}\right)\left(\frac{100\text{Å}}{L}\right)^2 \text{ meV} = 3.76\left(\frac{m_0}{0.04m_0}\right)\left(\frac{100\text{Å}}{100\text{Å}}\right)^2 = 94 \text{ meV}$$

$$n_{max} = \sqrt{\frac{V_0}{E_1^\infty}} = \sqrt{\frac{\Delta E_c}{E_1^\infty}} = \sqrt{\frac{500}{94}} = 2.306$$

Looking at Fig A1.4 in handouts,

For $n_{max} = 2.306$,

$n=1$; $n_{QW} - (n-1) = 0.78$; $n_{QW} = 0.78$

$n=2$; $n_{QW} - (n-1) = 0.53$; $n_{QW} = 1.53$

$$n_{QW} = \sqrt{\frac{E_n}{E_1^\infty}} \qquad E_n = E_1^\infty\, {n_{QW}}^2$$

$$E_1 = E_1^\infty\,(0.78)^2 = 94meV(0.78)^2 = \mathbf{57.19\ meV}$$

$$E_2 = E_1^\infty\,(1.53)^2 = 94meV(1.53)^2 = \mathbf{220.045\ meV}$$

Using $d = 10\times10^{-9}$ m = 100 Å, $m_h^* = 0.44m_e$ and $n = 1$, we find the *hole energy levels* below E_v

$\Delta E_V = \frac{1}{3}\Delta E_g = \frac{1}{3}(1.45\text{-}.07 \text{ eV}) = .25 = 250 \text{ meV}$

$$E_1^\infty = 3.76\left(\frac{m_0}{m}\right)\left(\frac{100\text{Å}}{L}\right)^2 \text{ meV} = 3.76\left(\frac{m_0}{0.44m_0}\right)\left(\frac{100\text{Å}}{100\text{Å}}\right)^2 = 8.55 \text{ meV}$$

$$n_{max} = \sqrt{\frac{V_0}{E_1^\infty}} = \sqrt{\frac{\Delta E_V}{E_1^\infty}} = \sqrt{\frac{250}{8.55}} = 5.41$$

$n=1$; $n_{QW} - (n-1) = 0.89$; $n_{QW} = 0.89$

$$E_1 = E_1^\infty\,(0.89)^2 = 8.55meV(0.89)^2 = \mathbf{6.77\ meV}$$

The wavelength light emission from the QW laser with E_g = 1.45 eV is

$$\lambda_{Qw} = \frac{hc}{E_g + E_{1C} + E_{1V}} = \frac{(6.626\times10^{-34})(3\times10^{8})}{(0.7+.157+.00677)(1.6\times10^{-19})} = 1.438\mu\text{m} = \mathbf{1438nm}$$

The wavelength of emission from bulk InGaAs with E_g = 0.7 eV is

$$\lambda_g = \frac{hc}{E_g} = \frac{(6.626\times10^{-34})(3\times10^{8})}{(0.70)(1.602\times10^{-19})} = \mathbf{1771\times10^{-9}\ m\ (1771\ nm)}$$

The difference is $\lambda_g - \lambda_{QW}$ = 1771 - 1438 = **333 nm**.

4.16 A GaAs quantum well Effective mass of conduction electrons in GaAs is $0.07m_e$ where m_e is the electron mass in vacuum. Calculate the first three electron energy levels for a quantum well of thickness 8 nm. What is the hole energy below E_v if the effective mass of the hole is $0.47m_e$? What is the change in the emission wavelength with respect to bulk GaAs which has an energy bandgap of 1.42 eV.

Solution

The lowest energy levels with respect to the CB edge E_c in GaAs are determined by the energy of an electron in a one-dimensional finite potential energy well

$\Delta E_C = \frac{2}{3}\Delta E_g = \frac{2}{3}(1.67 - 1.42\text{ eV}) = 166.7$ meV

$E_1^\infty = 3.76\left(\frac{m_0}{m}\right)\left(\frac{100Å}{L}\right)^2$ meV $= 3.76\left(\frac{m_0}{.07m_0}\right)\left(\frac{100Å}{80Å}\right)^2$ meV = 83.93 meV

$n_{max} = \sqrt{\frac{V_0}{E_1^\infty}} = \sqrt{\frac{\Delta Ec}{E_1^\infty}} = \sqrt{\frac{166.7}{83.93}} = 1.41$

n=1; $n_{QW} - (n - 1) = 0.67$; $n_{QW} = 0.67$

n=2; $n_{QW} - (n - 1) = 0.27$; $n_{QW} = 1.27$

n_{QW} for n=3 does not exist; the barrier is not high enough to contain 3 energy levels.

$n_{QW} = \sqrt{\frac{E_n}{E_1^\infty}}$ $\quad E_n = E_1^\infty\, n_{QW}^2$

$E_1 = E_1^\infty\,(0.67)^2 = 83.93meV(0.67)^2 = \mathbf{37.68\ meV}$

$E_2 = E_1^\infty\,(1.27)^2 = 83.93meV(1.27)^2 = \mathbf{135.371\ meV}$

The hole energy levels below E_v is

$\Delta E_V = \frac{1}{3}\Delta E_g = \frac{1}{3}(1.67\text{-}1.42) = .0833 = 83.3$ meV

$$E_1^{\infty} = 3.76\left(\frac{m_0}{m}\right)\left(\frac{100\text{Å}}{L}\right)^2 \text{ meV} = 3.76\left(\frac{m_0}{0.47m_0}\right)\left(\frac{100\text{Å}}{80\text{Å}}\right)^2 = 12.5 \text{ meV}$$

$$n_{max} = \sqrt{\frac{V_0}{E_1^{\infty}}} = \sqrt{\frac{\Delta E_V}{E_1^{\infty}}} = \sqrt{\frac{83.3}{12.5}} = 2.58$$

$n=1$; $n_{QW} - (n-1) = 0.80$; $n_{QW} = 0.80$

$$E_1 = E_1^{\infty}(0.80)^2 = 12.5meV(0.80)^2 = \mathbf{8\ meV}$$

The wavelength of emission from bulk GaAs with $E_g = 1.42$ eV is

$$\lambda_g = \frac{hc}{E_g} = \frac{(6.626\times10^{-34})(3\times10^8)}{(1.42)(1.602\times10^{-19})} = 874\times10^{-9} \text{ m or } \mathbf{874\ nm.}$$

Whereas from the GaAs QW, the wavelength is

$$\lambda_{Qw} = \frac{hc}{E_g+E_{1C}+E_{1V}} = \frac{(6.626\times10^{-34})(3\times10^8)}{(1.42+.03768+.008)(1.6\times10^{-19})} = .846\mu\text{m} = \mathbf{846nm}$$

The difference is $\lambda_g - \lambda_{QW} = 874 - 846 =$ **28nm.**