Midterm Exam-Solutions, Spring 2009

ECSE-6962, Light-Emitting Diodes and Solid-State Lighting

1. Consider the semiconductor GaAs, at 300 K, and two types of deep-level traps that are found in this semiconductor. One of these trap levels is located directly at the midgap position; the other one is located 590 meV below the conduction band (CB).
   (a) What are impurities? What are native defects? Can deep-level traps be caused by (i) impurities, (ii) native defects, or (iii) both?
   (b) Which of the two traps (midgap or 590 meV below CB) is more deleterious for the operation of the device?
   (c) Calculate the ratio of the non-radiative recombination lifetimes associated with the two traps (feel free to assume that the Fermi level of intrinsic GaAs is located at midgap).
   (d) Assume that the midgap trap results in a non-radiative recombination lifetime of 1 ns. What is the lifetime associated with the traps located 590 meV below the conduction band?
   (e) Assume that the semiconductor contains only one type of trap, namely the one located 590 meV below the conduction band. Assume further that the radiative lifetime is 10 ns. What is the internal quantum efficiency of the material?
   (f) Assume that the semiconductor is now heated to 450 K. What is the lifetime associated with the 590-meV trap?
   (g) What is the internal quantum efficiency of the material at 450 K?
   (h) What is the internal quantum efficiency of the material at 77 K?

Solution:

(a) Impurities are foreign atoms added into semiconductors. Native defects are defects which come from a semiconductor itself. Native defects include interstitial lattice atoms, vacancies, and antisite defects. Both foreign impurities and native defects can cause deep-level traps.

(b) The trap level located at the middle of the gap is more deleterious. According to the equation:

$$\tau = \tau_{n_0}\left[1+\cosh\left(\frac{E_T - E_{Fi}}{kT}\right)\right]$$

The non-radiative life time is minimized if $E_T - E_{Fi}$ is zero. Therefore deep levels are very effective recombination centers if they are near the middle of the gap, which is deleterious to the operation of the device.

(c) The ratio of non-radiative lifetimes of the two traps is:

$$\frac{\tau_{\text{590 meV below the conduction band}}}{\tau_{\text{midgap}}} = \frac{1+\cosh\left(\frac{(E_c - 590\text{ meV}) - (E_c - 1.42\text{ eV}/2)}{8.6175\times10^{-5}\text{ eV/K}\times 300\text{ K}}\right)}{1+\cosh(0)}$$

$$= \frac{1+\cosh\left(\frac{1.42\text{ eV}/2 - 590\text{ meV}}{8.6175\times10^{-5}\text{ eV/K}\times 300\text{ K}}\right)}{1+\cosh(0)} = 26.4$$

(d) 26.4 ns

(e) Internal quantum efficiency:

$$\eta_{\text{int}} = \frac{\tau_r^{-1}}{\tau_r^{-1}+\tau_{nr}^{-1}} = \frac{\frac{1}{10\text{ ns}}}{\frac{1}{10\text{ ns}}+\frac{1}{26.4\text{ ns}}} = 73\%$$

(f) Lifetime associated with the 590-meV trap at 450 K is:

$$\tau_{450\ \mathrm{K}} = 26.4\ \mathrm{ns} \times \frac{1 + \cosh\left(\dfrac{1.42\ \mathrm{eV}/2 - 590\ \mathrm{meV}}{8.6175\ \times\ 10^{-5}\ \mathrm{eV/K}\ \times 450\ \mathrm{K}}\right)}{1 + \cosh\left(\dfrac{1.42\ \mathrm{eV}/2 - 590\ \mathrm{meV}}{8.6175\ \times\ 10^{-5}\ \mathrm{eV/K}\ \times 300\ \mathrm{K}}\right)} = 6.0\ \mathrm{ns}$$

(g) Internal quantum efficiency at 450 K:

$$\eta_{\mathrm{int}} = \frac{\tau_{\mathrm{r}}{}^{-1}}{\tau_{\mathrm{r}}{}^{-1} + \tau_{\mathrm{nr}}{}^{-1}} = \frac{\dfrac{1}{10\ \mathrm{ns}}}{\dfrac{1}{10\ \mathrm{ns}} + \dfrac{1}{6.0\ \mathrm{ns}}} = 37.5\%$$

(h) Non-radiative lifetime at 77 K:

$$\tau_{77\ \mathrm{K}} = 26.4\ \mathrm{ns} \times \frac{1 + \cosh\left(\dfrac{1.42\ \mathrm{eV}/2 - 590\ \mathrm{meV}}{8.6175\ \times\ 10^{-5}\ \mathrm{eV/K}\ \times 77\ \mathrm{K}}\right)}{1 + \cosh\left(\dfrac{1.42\ \mathrm{eV}/2 - 590\ \mathrm{meV}}{8.6175\ \times\ 10^{-5}\ \mathrm{eV/K}\ \times 300\ \mathrm{K}}\right)} = 1.8\ \times 10^{7}\ \mathrm{ns}$$

Internal quantum efficiency at 77 K:

$$\eta_{\mathrm{int}} = \frac{\tau_{\mathrm{r}}{}^{-1}}{\tau_{\mathrm{r}}{}^{-1} + \tau_{\mathrm{nr}}{}^{-1}} = \frac{\dfrac{1}{10\ \mathrm{ns}}}{\dfrac{1}{10\ \mathrm{ns}} + \dfrac{1}{1.8\ \times 10^{7}\ \mathrm{ns}}} = 100\%$$

2. A 460 nm blue LED is tested in a manufacturing environment by measuring the V_{f} = 9.0 V at 500 mA. Note that the large forward voltage indicates that there is a problem with the series resistance of the device. The device has an external quantum efficiency of 20%.
   (a) What is the total optical power emitted by the device?
   (b) What is the power consumed in the series resistance?
   (c) What the power dissipated in the active region due to non-radiative recombination?
   (d) What is the total thermal power dissipated in the device?
   (e) What is the electrical input power of the device?
   (f) Assume that the device has a package with a thermal resistance of 25 K/W and assume that the ambient temperature is 20°C. What is the junction temperature (= device temperature)?

Solution:

(a) Number of 460 nm photons emitted:

$$\frac{I}{e} \times \eta_{\mathrm{ext}} = \frac{500\ \mathrm{mA}}{1.60\ \times\ 10^{-19}\ \mathrm{C}} \times 20\% = 6.25\ \times\ 10^{17}\ \mathrm{s}^{-1}$$

Total optical power emitted:

$$P_{\mathrm{emitted\ power}} = 6.25\ \times 10^{17}\ \mathrm{s}^{-1}\ \times \frac{6.63\ \times\ 10^{-34}\ \mathrm{Js}\ \times 3.0\ \times\ 10^{8}\ \mathrm{ms}^{-1}}{460\ \mathrm{nm}} = 0.27\ \mathrm{W}$$

(b) Energy of a 460 nm photon:

$$E_{\mathrm{photon}} = hc/\lambda = 2.696\ eV$$

Power consumed in the series resistance:

$$P_{\text{series resistance}} = I\left(V_{\text{f}} - E_{\text{g}}/e\right) = 500\text{ mA} \times (9.0\text{ V} - 2.696\text{ V}) = 3.15\text{ W}$$

(c) Power dissipated in the active region due to non-radiative recombination:

$$P_{\text{non-radiative}} = 0.27\text{ W} \times \frac{1 - 20\%}{20\%} = 1.08\text{ W}$$

(d) Total thermal power dissipated in the device:

$$P_{\text{thermal}} = P_{\text{series resistance}} + P_{\text{non-radiative}} = 3.15\text{ W} + 1.08\text{ W} = 4.23\text{ W}$$

(e) Electrical input power: $P_{\text{electrical input}} = IV_{\text{f}} = 500\text{ mA} \times 9.0\text{ V} = 4.5\text{ W}$

(f) Temperature of the device: $T = 20\text{ °C} + 25\text{ K/W} \times 4.23\text{ W} = 125.8\text{ °C}$

3. A 300 nm AlGaN LED, a 360 nm GaN LED, and a 450 nm GaInN LED are tested by a photoluminescence measurement, which uses optical excitation of electron-hole pairs to investigate the optical emission properties of devices. Three laser sources are available for excitation: (i) a frequency-quadrupled Nd:YAG laser emitting at 266 nm, (ii) a He-Cd laser emitting at 325 nm, and (iii) a GaInN-based semiconductor laser emitting at 405 nm.
   (a) Which laser source(s) is/are suitable for excitation of the 300 nm AlGaN-based LED?
   (b) Which laser source(s) is/are suitable for excitation of the 360 nm GaN-based LED?
   (c) Which laser source(s) is/are suitable for excitation of the 450 nm GaInN-based LED?
   (d) The blue LED has GaInN quantum wells (QW) emitting at 450 nm and GaN quantum barriers. Which laser source(s) is/are suitable to optically excite only the active QW region of the LED? (Explain)
   (e) Assume that one uses a 405 nm laser with a power of 1 mW to pump the blue LED. What is the number of incident photons per second?
   (f) The blue LED has five QWs, each QW having a thickness of 3 nm. Assume that the absorption coefficient of the QW is $\alpha = 5 \times 10^4\text{ cm}^{-1}$ at 405 nm, how much power is absorbed?
   (g) What is the number of photons absorbed per second?
   (h) If this LED emits 1.0×10^{13} photons per second, what is its external quantum efficiency?

Solution:

(a) A photon with energy $h\nu \geq E_{\text{g}}$ can be absorbed in a semiconductor, therefore only the 266 nm laser is suitable for testing the 300 nm AlGaN-based LED.

(b) The 266 nm laser and the 325 nm laser are suitable for testing the 360 nm GaN-based LED.

(c) All of the three lasers are suitable for testing the 450 nm GaInN-based LED.

(d) The GaN barrier has a bandgap energy of about 3.4 eV (~ 360 nm), therefore the 405 nm laser can be used to test the GaInN quantum well (450 nm) without exciting the GaN barrier.

(e) The number of incident photons per second:

$$\frac{P_{\text{optical}}}{hc/\lambda} = \frac{1\ \text{mW}}{\left(\frac{6.63\ \times\ 10^{-34}\ \text{Js}\ \times 3.0\ \times\ 10^{8}\ \text{ms}^{-1}}{405\ \text{nm}}\right)} = 2.04\ \times\ 10^{15}\ \text{s}^{-1}$$

(f) $P_{\text{incident}} = P_0$,

$P_{\text{transmitted}} = P_0\ \text{e}^{-\alpha l}$

$P_{\text{absorbed}} = P_{\text{incident}} - P_{\text{transmitted}}$

$$= P_0\ (1 - \text{e}^{-\alpha l}) = 1\ \text{mW} \times \left(1 - \text{e}^{-5 \times 10^{4}\ \text{cm}^{-1} \times 5 \times 3\ \text{nm}}\right) = 0.072\ \text{mW}$$

(g) The number of absorbed photons:

$$\frac{P_{\text{absorbed}}}{hc/\lambda} = \frac{0.072\ \text{mW}}{\left(\frac{6.63\ \times\ 10^{-34}\ \text{Js}\ \times 3.0\ \times\ 10^{8}\ \text{ms}^{-1}}{405\ \text{nm}}\right)} = 1.47\ \times\ 10^{14}\ \text{s}^{-1}$$

(h) External quantum efficiency:

$$\eta_{\text{ext}} = \frac{\text{number of 450 nm photons emitted per second}}{\text{number of 405 nm photons absorbed per second}} = \frac{1.0\ \times\ 10^{13}\ \text{s}^{-1}}{1.47\ \times\ 10^{14}\ \text{s}^{-1}} = 6.8\%$$