Midterm Exam – Solutions, Spring 2005

ECSE-6961, Light-Emitting Diodes and Solid-State Lighting

1. Consider a light-emitting diode, biased at 3.5 V, emitting 10^{16} photons per second having a wavelength of 650nm when injected with 10^{17} electrons per second.

   $h\nu = 1.9$ eV. The forward voltage drop for an ideal diode would be: $V_{\mathrm{F,\,ideal}} = h\nu/e = 1.9$ V

   a) External quantum efficiency,

   $$\mathrm{EQE} = \frac{\#\text{ of photons emitted per second}}{\#\text{ of electrons injected per second}} = \frac{10^{16}}{10^{17}} = 0.1 = 10\%$$

   b) Injection current,
   I_{inj} = Injected charge per unit time = # of electrons injected per second × charge of electron = $10^{17}\ \mathrm{s}^{-1} \times 1.602 \times 10^{-19}$ C = 16 mA

   c) Electrical input power,
   $P_{\mathrm{in}} = I_{\mathrm{inj}} \times V_{\mathrm{A}} = 16\ \mathrm{mA} \times 3.5\ \mathrm{V} = 56\ \mathrm{mW}$

   d) Optical output power,

   $$P_{\mathrm{out}} = \#\text{ of photons emitted per sec.} \times \left(\frac{hc}{\lambda}\right) = 10^{16} \times \left(\frac{6.63 \times 10^{-34} \times 3 \times 10^{8}}{650 \times 10^{-9}}\right) = 3\ \mathrm{mW}$$

   e) Power efficiency, $\eta = \dfrac{P_{\mathrm{out}}}{P_{\mathrm{in}}} = \dfrac{3\ \mathrm{mW}}{56\ \mathrm{mW}} = 5.4\%$

   f) Series resistance, $R_{\mathrm{S}} = \dfrac{V_{\mathrm{A}} - V_{\mathrm{D}}}{I_{\mathrm{inj}}} = \dfrac{3.5 - 1.9}{16 \times 10^{-3}} = 100\ \Omega$

   g) Power consumed in series resistor, $P_{\mathrm{res}} = I_{\mathrm{inj}}^{2} \times R_{\mathrm{S}} = (16\ \mathrm{mA})^{2} \times 100\ \Omega = 25.6\ \mathrm{mW}$

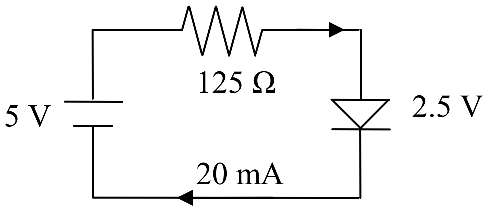
   h) Power converted to heat in the device, $P_{\mathrm{dev}} = P_{\mathrm{in}} - P_{\mathrm{out}} = 56\ \mathrm{mW} - 3\ \mathrm{mW} = 53\ \mathrm{mW}$

   i) Heat generated in the resistor is from Joule heating of the resistor. Heat generated in the device is caused by both, non-radiative recombination plus Joule heating of the series resistor.

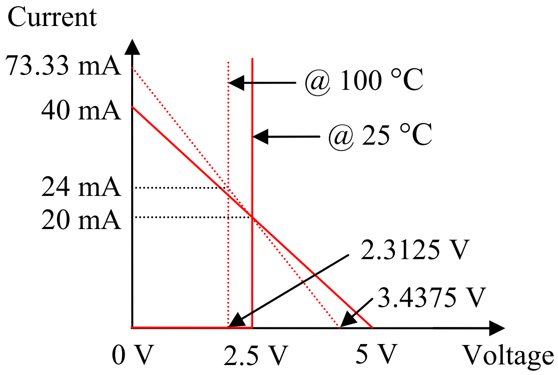
2. Assume a constant voltage power supply of 5 V driving a diode with a threshold voltage of $V_{\mathrm{th}} = 2.5$ V, a forward voltage of $V_{\mathrm{f}} = V_{\mathrm{th}} = 2.5$ V at 25 C (see sketch below), and a temperature coefficient of the forward voltage of – 2.5 mV/K.

   a) Design a circuit for $I_{\mathrm{inj}} = 20$ mA.

   $$R_{\mathrm{S}} = \frac{V_{\mathrm{p/s}} - V_{\mathrm{f}}}{I_{\mathrm{inj}}} = \frac{5 - 2.5}{20 \times 10^{-3}} = 125\ \Omega$$



b) Load line of above circuit



c) Forward current at 100 °C

$$I_{F,100} = \frac{V_{p/s} - (V_f - \alpha(T_1 - T_2))}{R_S} = \frac{5 - (2.5 - 2.5\times10^{-3}(100-25))}{125} = 21.5\text{ mA}$$

d) For 20% increase from 25 °C to 100 °C

$$R_{S,20\%} = \frac{\alpha(T_1 - T_2)}{I_{F,100,20\%} - I_{F,25}} = \frac{2.5\times10^{-3}(100-25)}{24\times10^{-3} - 20\times10^{-3}} = 46.875\ \Omega$$

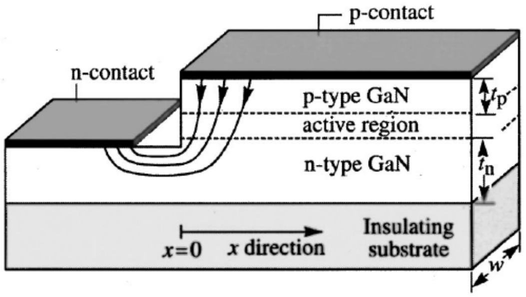
$$V_{p/s,20\%} = V_f + (R_{S,20\%} \times I_{F,25}) = 3.437\text{ V}$$

e) Why increase drive current with temperature?
As temperature increases, the efficiency decreases. Hence, to maintain the output optical power, it is desirable to increase the drive current.

3. Discuss the advantages of double heterostructure design over homojunction design.

a) Better carrier confinement
b) Better optical transparency
c) Better injection efficiency
d) Index guiding

4. Choose one LED structure where current spreading/current crowding is an issue. Discuss how the materials parameters (doping and mobilities) and structural parameters (e.g. thickness of layers) affect current spreading.



Resistance of the n-type layer should be as small as possible. Therefore, the n-type doping concentration and the electron mobility in the n-type layer should be as high as possible. Narrow p-type finger contacts will result in more uniform current distribution.

5. Choose and discuss two schemes that afford high light-extraction efficiency.

Light extraction in light-emitting diodes can be improved by minimizing losses occurring mainly due to two factors, i) Absorption of emitted photons and ii) Total internal reflection of light at the boundary of media with different refractive indices.

These losses can be minimized by employing the following techniques.

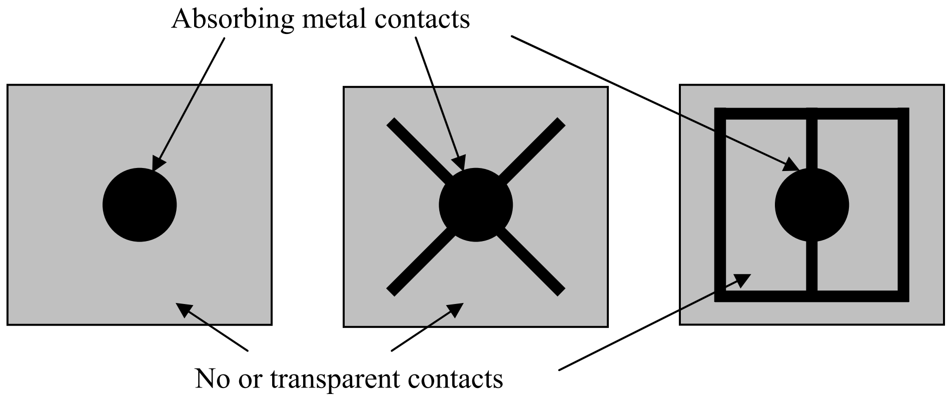
1. Absorption

Substrate technology:

- Removal of non-transparent substrate
- Use of transparent substrate

Contacts:

- Use of transparent contacts
- Micro-contacts
- Cross shaped contacts etc.



2. Total internal reflection

Refractive index matching:

- Use of high refractive index encapsulation material to increase the critical angle and hence enlarge the escape cone.

Surface:

- Surface roughening will increase the probability of the light extraction by randomizing the angle of incidence.

Device geometry:

- Tapered, hemispherical, cylindrical geometries to minimize or eliminate surface area where light can be incident at angle greater than the critical.