8 Read the passage below and answer the questions that follow.

Light emitting diodes, commonly called LEDs, are real unsung heroes in the electronics world. They are found in all kinds of devices such as transmitting information from remote controls, digital display on your appliances and form images on television screen.

In LEDs, electrons in the higher energy conduction band fall into empty orbitals of lower energy to release energy in the form of photons. For a standard silicon diode, the photon's is in the infra-red portion of the electromagnetic spectrum and is invisible to the human eye. Depending on the materials used in LEDs, they can be built to shine in infra-red, ultraviolet, and all the colours of the visible spectrum in between. Fig. 8.1 shows different types of LEDs producing distinct wavelengths of colour made of exotic semiconductor compounds mixed together at different ratios such as Gallium Phosphide (GaP), Gallium Arsenide Phosphide (GaAsP), Silicon Carbide (SiC) or Gallium Indium Nitride (GaInN).

typical LED characteristics			
semiconductor material	wavelength / nm	perceived colour	forward operating voltage V_F at 20 mA / V
GaAs	850 to 940	Infra-red	1.1
GaAsP	630 to 660	Red	1.8
GaAsP	605 to 620	Amber	2.0
GaAsP:N	585 to 595	Yellow	2.2
SiC	430 to 505	Blue	3.4

Fig. 8.1

When operating in a circuit there is a minimum voltage that must be connected across an LED to make it emit light known as the forward operating voltage V_F. V_F is related to the average wavelength $\langle\lambda\rangle$ of emitted light by the following equation:

$$V_F = k\,\langle\lambda\rangle^n$$

where *k* and *n* are constants.

An LED is damaged when the p.d. across it is too high. A protective resistor is connected in series with the LED to prevent this. The normal operating current through an LED is 20 mA.

Bare, uncoated semiconductors has a very high refractive index relative to air, which prevents the passage of photons at sharp angles relative to the air-contacting surface of the semiconductor. Uncoated LED semiconductor chip will emit light only perpendicular to the semiconductor's surface, and a few degrees to the side, in a cone shape illustrated in Fig. 8.2. The angle of the cone is determined by the maximum angle of incidence known as the *critical angle*. When this angle is exceeded, photons no longer penetrate the semiconductor, but are instead, reflected internally inside the semiconductor crystal as if it were a mirror.

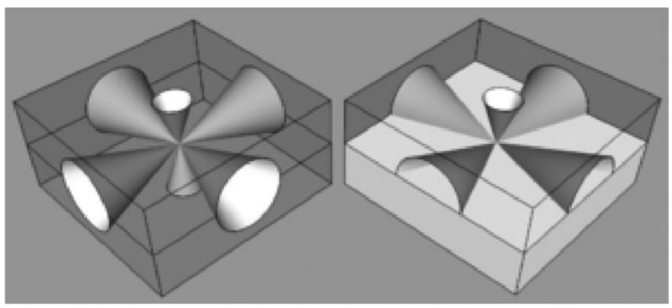

Fig. 8.2

LEDs are specially constructed to release a large number of photons outwards. Additionally, they are housed in a plastic bulb that concentrates the light in a particular direction. As shown in Fig. 8.3, most of the light from the diode bounces off the sides of the bulb, travelling on through the rounded end.

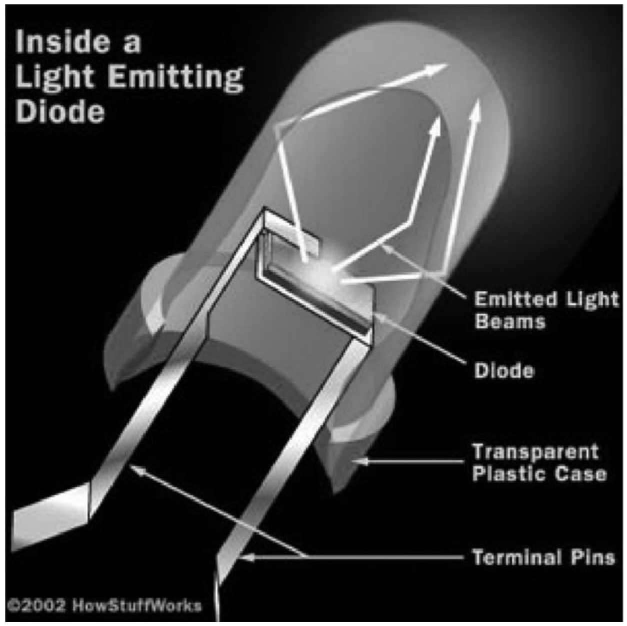

Fig. 8.3

LEDs have several advantages over conventional incandescent lamps. They don't have a filament that will burn out and their small plastic bulb makes them a lot more durable, so LEDs can have lifetimes of 50 000 hours or more. They also fit easily into modern electronic circuits. The main advantage is their efficiency. In conventional incandescent bulbs, the light-production process involves generating a lot of heat so a huge portion of the electrical energy isn't going toward producing visible light. LEDs generate very little heat, relatively speaking, so a much higher percentage of the electrical power goes directly to generating light.

The luminous flux of a device is the total amount of light produced per second and the SI unit of luminous flux is the lumen (symbol: lm). The efficacy of the device is the ratio of its luminous flux to the electrical power supplied and this is measured in lumens per watt (lm W^{-1}). The luminous efficacy of a device is a measurement related to its efficiency. The key advantages of LED-based lighting sources is high luminous efficacy.

Until quite recently, LEDs were too expensive to use for most lighting applications because they're built around advanced semiconductor material. However, the price of semiconductor devices has plummeted since the year 2000, making LEDs a more cost-effective lighting option for a wide range of situations. While they may be more expensive than incandescent lights up front, their lower cost in the long run can make them a better buy.

(a) The photons from a standard silicon diode are invisible to the human eye.

Suggest how other LEDs are able to emit light in the visible light spectrum.

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……… [2]

(b) Use information in Fig. 8.1.

(i) Determine the lowest energy of the photons emitted by a nitrogen doped Gallium Arsenide Phosphide (GaAsP:N) LED, energy = …………………………………… eV [3]

(ii) The minimum voltage that must be connected across an LED to make it emit light is called the forward operating voltage V_F.

Explain

1. why no light is emitted by an LED when the voltage supplied is less than V_F,

………………………………………………………………………………………………

…………………………………………………………………………………………….. [1]

2. why the value of V_F for an LED that emits blue light is greater than that for a LED that emits red light.

………………………………………………………………………………………………

…………………………………………………………………………………………….. [1]

(c) Data relating average wavelength $\langle\lambda\rangle$ of the light photons emitted by an LED and the forward operating voltage V_F of the five semiconductor materials in Fig. 8.1 are listed in Fig. 8.4.

semiconductor material	$\langle\lambda\rangle$ / nm	V_F / V	lg ($\langle\lambda\rangle$ / nm)	lg (V_F / V)
GaAs	895	1.1	2.952	0.041
GaAsP	645	1.8	2.810	0.255
GaAsP	613	2.0	2.787	0.301
GaAsP:N	590	2.2	2.771	0.342
SiC	468	3.4	2.670	0.531

Fig. 8.4

The variation of lg (V_F / V) with lg ($\langle\lambda\rangle$ / nm) is shown in Fig. 8.5.

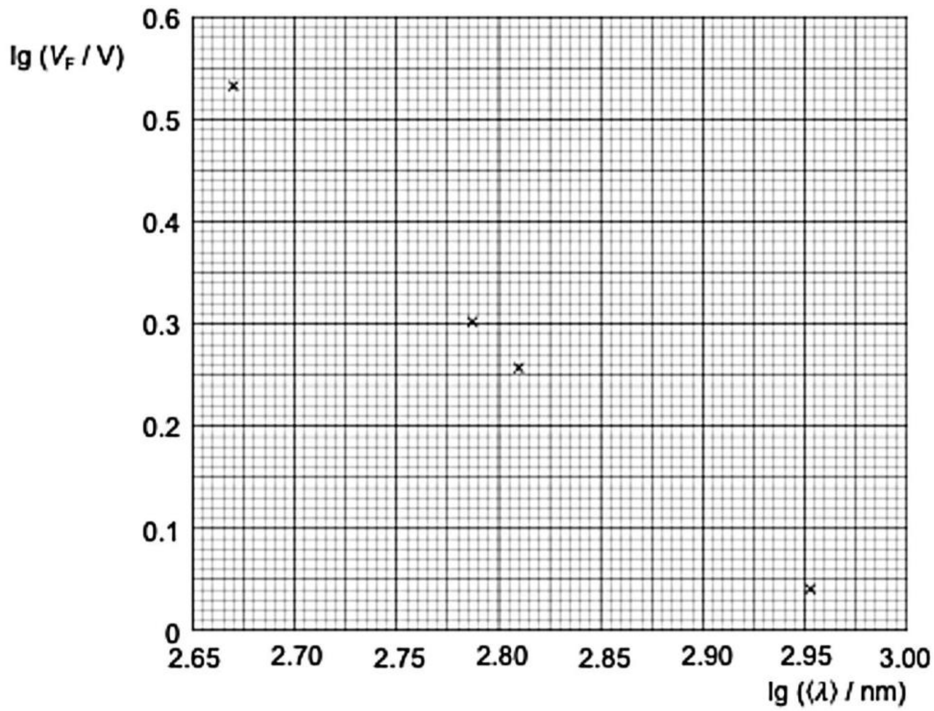

Fig. 8.5

(i) Plot the point for GaAsP:N on Fig. 8.5. [1]

(ii) Complete Fig. 8.5 by drawing the line of best fit. [1]

(iii) Determine the value of *n* from your line.

n = ……………………………………….. [2]

(d) An unknown LED emits photons of average wavelength 520 nm.

(i) Determine V_F across this LED.

V_F = …………………………………….. V [2]

(ii) The LED is connected to a power supply of e.m.f. 4.5 V with negligible internal resistance and operates under normal conditions.

Calculate the resistance of the series resistor required for safe operation of the LED.

resistance = ……………………………………….. Ω [2]

(e) The light produced by an uncoated LED is produced in the silicon layer. The refractive index of silicon is 4.24 and air is 1.00.

(i) Show that the speed of light in silicon is 7.08×10^{7} m s^{-1}.

[1]

(ii) Determine the critical angle for light passing from silicon into air.

critical angle = ... ° [2]

(iii) Explain why encapsulating a semiconductor chip in a suitable material increases the efficiency of the LED.

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…………………………………………………………………………………………………
[2]

(f) A incandescent lamp produces an illumination of 840 lumens for a 60 W power consumption.

An LED lamp produces an illumination of 900 lumens for a 9 W power consumption.

Determine the ratio

$$\frac{efficiency\ of\ LED}{efficiency\ of\ incandescent\ lamp}.$$

ratio = ……………………………………….. [2]

[Total: 22]