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**PHYSICS**

**9792/02**

Paper 2 Part A Written Paper

**October/November 2013**

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The question in Section B of this paper will relate to the subject matter in this Insert. You will have received a copy of this booklet in advance of the examination.

The extracts on the following pages are taken from a variety of sources. University of Cambridge International Examinations does not necessarily endorse the reasoning expressed by the original authors, some of whom may use unconventional Physics terminology and non-SI units.

You should draw on all your knowledge of Physics when answering the questions.

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This document consists of **8** printed pages.



**Extract 1: What are LEDs?**

**Light emitting diodes**, commonly called LEDs, are real unsung heroes in the electronics world. They do dozens of different jobs and are found in all kinds of devices. Among other things, they form numbers on digital clocks, transmit information from remote controls, light up watches and tell you when your appliances are turned on. Collected together, they can form images on a jumbo television screen or illuminate a traffic light.

Basically, LEDs are just tiny light bulbs that fit easily into an electrical circuit. But unlike ordinary incandescent bulbs, they don't have a filament that will burn out, and they don't get especially hot. They are illuminated solely by the movement of electrons in a semiconductor material, and they last just as long as a standard transistor. The lifespan of an LED surpasses the short life of an incandescent bulb by thousands of hours. Tiny LEDs are already replacing the tubes that light up LCD HDTVs to make dramatically thinner televisions.



**Fig. E1.1**

**From:** <http://www.howstuffworks.com/led.htm>

### Extract 2: How Can a Diode Produce Light?

Light is a form of energy that can be released by an atom. It is made up of many small particle-like packets that have energy and momentum, but no mass. These particles, called photons, are the most basic units of light.

Photons are released as a result of moving electrons. In an atom, electrons move in orbitals around the nucleus. Electrons in different orbitals have different amounts of energy. Generally speaking, electrons with greater energy move in orbitals further away from the nucleus.

For an electron to jump from a lower orbital to a higher orbital, something has to boost its energy level and this can be done by an applied voltage. The greater the energy jump, the greater the applied voltage needs to be.

Conversely, an electron releases energy when it drops from a higher orbital to a lower one. This energy is released in the form of a photon. A greater energy drop releases a higher-energy photon, which is characterized by a higher frequency.

Free electrons moving across a diode can fall into empty 'holes' from the P-type layer. This involves a drop from the conduction band to a lower orbital, so the electrons release energy in the form of photons. This happens in any diode, but you can only see the photons when the diode is composed of a certain material. The atoms in a standard silicon diode, for example, are arranged in such a way that the electron drops a relatively short distance. As a result, the photon's frequency is so low that it is invisible to the human eye – it is in the infra-red portion of the electromagnetic spectrum. This isn't necessarily a bad thing, of course: infra-red LEDs are ideal for remote controls, among other things.

Visible light-emitting diodes (VLEDs), such as the ones that light up numbers in a digital clock, are made of materials characterized by a wider gap between the conduction band and the lower orbitals. The size of the gap determines the frequency of the photon – in other words, it determines the colour of the light emitted and the size of the forward operating voltage that needs to be applied. While LEDs are used in everything from remote controls to the digital displays on electronics, VLEDs are growing in popularity and use, thanks to their long lifetimes and their miniature size. 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.

**Adapted from:** <http://electronics.howstuffworks.com/led2.htm>

### Extract 3: The Advantages of LEDs

While all diodes release light, most don't do it very effectively. In an ordinary diode, the semiconductor material itself ends up absorbing a lot of the light energy. LEDs are specially constructed to release a large number of photons outward. Additionally, they are housed in a plastic bulb that concentrates the light in a particular direction. As shown in Fig. E3.1, most of the light from the diode bounces off the sides of the bulb, travelling on through the rounded end.

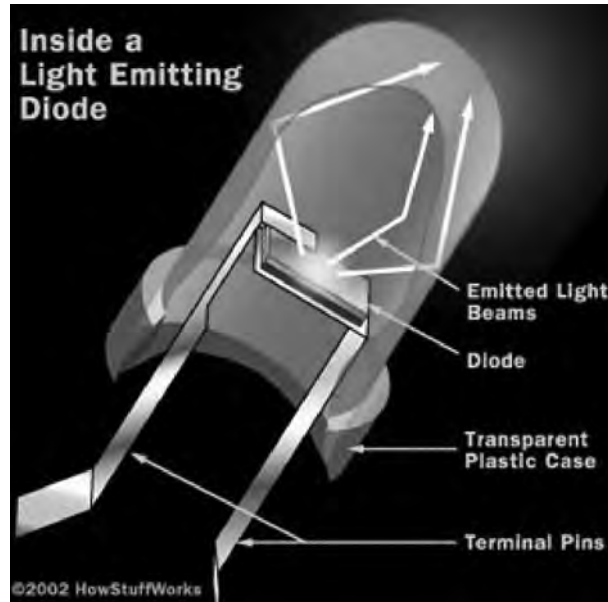


Fig. E3.1

LEDs have several advantages over conventional incandescent lamps. For one thing, they don't have a filament that will burn out, so they last much longer. Additionally, their small plastic bulb makes them a lot more durable. They also fit more easily into modern electronic circuits.

But the main advantage is their **efficiency**. In conventional incandescent bulbs, the light-production process involves generating a lot of heat (the filament must be warmed). This is completely wasted energy, unless you're using the lamp as a heater, because a huge portion of the available electricity isn't going toward producing visible light. LEDs generate very little heat, relatively speaking. A much higher percentage of the electrical power is going directly to generating light, which cuts down on the electricity demands considerably.

LEDs output more lumens of light, per watt, than regular incandescent bulbs. Light emitting diodes have a higher **luminous efficacy** (how efficiently electricity is converted to visible light) than incandescents – for example, Sewell's EvoLux LED bulb produces 76.9 lumens per Watt compared to an incandescent bulb's 17lm/W [source: Sewell]. And they last: LEDs can have lifetimes of **50 000 hours or more**.

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. Several companies have begun selling LED light bulbs designed to compete with incandescent and compact fluorescents that promise to deliver long lives of bright light and amazing energy efficiency.

One day, LEDs may be plugged into our light bulb sockets, lighting up our digital readouts and illuminating the millions of pixels that make up our high-definition televisions.

From: <http://electronics.howstuffworks.com/led2.htm>

**Extract 4: Coloured LEDs**

How does a light emitting diode get its colour?

Unlike normal signal diodes which are made for detection or power rectification, and which are made from either Germanium or Silicon semiconductor materials, light emitting diodes are made from exotic semiconductor compounds such as Gallium Arsenide (GaAs), Gallium Phosphide (GaP), Gallium Arsenide Phosphide (GaAsP), Silicon Carbide (SiC) or Gallium Indium Nitride (GaInN), all mixed together at different ratios to produce a distinct wavelength of colour. Different LED compounds emit light in specific regions of the visible light spectrum and therefore produce different intensity levels. The exact choice of the semiconductor material used will determine the overall wavelength of the photon light emissions and therefore the resulting colour of the light emitted.

<b>typical LED characteristics</b>			
<b>semiconductor material</b>	<b>wavelength /nm</b>	<b>perceived colour</b>	<b>forward operating voltage <math>V_F</math> at 20 mA/V</b>
GaAs	850 to 940	Infra-red	1.2
GaAsP	630 to 660	Red	1.8
GaAsP	605 to 620	Amber	2.0
GaAsP:N	585 to 595	Yellow	2.2
AlGaP	550 to 570	Green	3.5
SiC	430 to 505	Blue	3.6
GaInN	450 to 780	White	4.0

**Fig. E4.1**

The colour of a light emitting diode is not determined by the colour of the plastic bulb of the LED. Rather, the colour of an LED is determined by the wavelength of the light emitted, which in turn is determined by the actual semiconductor compound used in forming the PN junction during manufacture. Light emitting diodes are available in a wide range of colours with the most common being red, amber, yellow and green and thus, they are widely used as visual indicators and as moving light displays.

Recently, blue and white coloured LEDs have been developed, but these tend to be much more expensive than the normal standard colours due to the production costs of mixing together two or more complementary colours at an exact ratio within the semiconductor compound and also by injecting nitrogen atoms into the crystal structure during the doping process.

From Fig. E4.1, we can see that the main P-type dopant used in the manufacture of light emitting diodes is Gallium (Ga, atomic number 31) and that the main N-type dopant used is Arsenic (As, atomic number 33) giving the resulting compound of Gallium Arsenide (GaAs) crystal structure. The problem with using Gallium Arsenide on its own as the semiconductor compound is that it radiates large amounts of low brightness infra-red radiation (850 nm–940 nm approx.) from its junction when a forward current is flowing through it. This infra-red light is okay for television remote controls, but not very useful if we want to use the LED as an indicating light. However, by adding Phosphorus (P, atomic number 15), as a third dopant, the overall wavelength of the emitted radiation is reduced to below 680 nm, giving red light visible to the human eye. Further refinements in the doping process of the PN junction have resulted in a range of colours spanning the spectrum of visible light as we have seen above, as well as infra-red and ultraviolet wavelengths.

Like conventional PN junction diodes, LEDs are current-dependent devices with their forward operating voltage  $V_F$  depending on the semiconductor compound (its light colour) and on the forward biased LED current. The point where conduction begins and light is produced is about 1.2V for a standard red LED to about 3.6V for a blue LED. The exact voltage drop will of course depend on the manufacturer because of the different dopant materials and wavelengths used. The voltage drop across the LED at a particular current value, for example 20 mA, will also depend on the initial conduction  $V_F$  point.

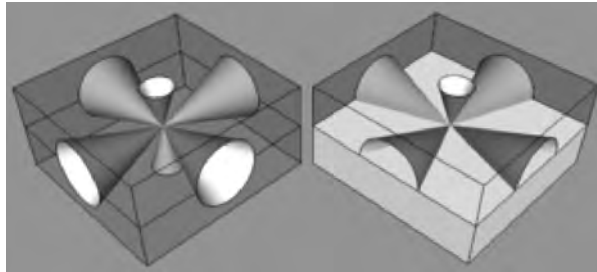
**From:** [http://www.electronics-tutorials.ws/diode/diode\\_8.html](http://www.electronics-tutorials.ws/diode/diode_8.html)

### Extract 5: Light in One Direction

Bare, uncoated semiconductors such as silicon, exhibit a very high refractive index relative to open air, which prevents the passage of photons at sharp angles relative to the air-contacting surface of the semiconductor. The refractive index of silicon is 4.24, while air is 1.00.

This property affects the light-emission efficiency of LEDs. It also severely reduces the efficiency of light transmission in directions away from the perpendicular. In general, a flat-surface, 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 referred to as the *light cone*, *cone of light*, or the *escape cone*. The maximum angle of incidence is referred to as the *critical angle*. When this angle is exceeded, photons no longer penetrate the semiconductor, but are instead, reflected both internally inside the semiconductor crystal and externally off the surface of the crystal as if it were a mirror.

Encapsulating the semiconductor chip in a dome-shaped transparent medium that has a higher refractive index than air reduces the total internal reflection and improves the efficiency of the LED.



**Fig. E5.1**

In a semiconductor LED, light is emitted equally in all directions from the point-source, but a large amount of light energy is trapped and wasted as heat.

Fig. E5.1 gives an idealized example of light emission cones in a semiconductor, for a single point-source emission zone. The left illustration is for a fully translucent wafer, while the right illustration shows the half-cones formed when the bottom layer is fully opaque.

The light emission cones of a real LED wafer are far more complex than a single point-source light emission. The light emission zone is typically a two-dimensional plane between the wafers. Every atom across this plane has an individual set of emission cones.

**Adapted from:** [http://en.wikipedia.org/wiki/Light-emitting\\_diode](http://en.wikipedia.org/wiki/Light-emitting_diode)

### Extract 6: Efficiency and efficacy

Typical indicator LEDs are designed to operate with no more than 30–60 milliwatts of electrical power. Around 1999, Philips Lumileds introduced power LEDs capable of continuous use at one watt. These LEDs used much larger semiconductor die sizes to handle the large power inputs. Also, the semiconductor dies were mounted onto metal slugs to allow for heat removal from the LED die.

The luminous flux of an LED is effectively the total amount of light produced per second. The SI unit of luminous flux is the lumen (symbol: lm). The efficacy of an LED is the ratio of its luminous flux to the electrical power supplied and this is measured in lumens/watt (lm/W). The luminous efficacy of a device is a measurement related to its efficiency.

One of the key advantages of LED-based lighting sources is high luminous efficacy.

White LEDs have quickly matched and overtaken the efficacy of standard incandescent lighting systems. In 2002, Lumileds made five-watt LEDs available with a luminous efficacy of 18–22 lumens per watt (lm/W). For comparison, a conventional incandescent light bulb of 60–100 watts emits around 15lm/W, and standard fluorescent lights emit up to 100lm/W. A recurring problem is that efficacy falls sharply with rising current. This effect is known as *droop* and effectively limits the light output of a given LED, raising heating more than light output for higher current.

In September 2003, a new type of blue LED was demonstrated by the company Cree Inc. to provide 24mW at 20 milliamperes. This produced a commercially packaged white light giving 65lm/W at 20 mA, becoming the brightest white LED commercially available at the time, and more than four times as efficient as standard incandescents. In 2006, they demonstrated a prototype with a record white LED luminous efficacy of 131 lm/W at 20 mA. Nichia Corporation has developed a white LED with luminous efficacy of 150lm/W at a forward current of 20 mA. Cree's XLamp XM-L LEDs, commercially available in 2011, produce 100 lumens per watt at their full power of 10 watts, and up to 160 lumens/watt at around 2 watts input power.

Practical, general lighting needs high-power LEDs, of one watt or more. Typical operating currents for such devices begin at 350 mA.

Note that these efficiencies are for the LED chip only, held at low temperature in a lab. Lighting works at higher temperature and with drive circuit losses, so efficiencies are much lower. United States Department of Energy (DOE) testing of commercial LED lamps designed to replace incandescent lamps or CFLs showed that average efficacy was still about 46lm/W in 2009 (tested performance ranged from 17lm/W to 79 lm/W).

**From:** [http://en.wikipedia.org/wiki/Light-emitting\\_diode](http://en.wikipedia.org/wiki/Light-emitting_diode)

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