Finding Planck's constant with LEDs

A value for Planck's constant can be found by plotting the forward voltage across a series of LEDs versus the frequency of radiation. Though simple in execution, the method is flawed.

Theory and method

Let *V* be the forward voltage across a LED that is emitting radiation and *e* be the electronic charge. The method presumes that if work *eV* is put into an atom causing an electron to jump from its valence to conduction band then when the electron returns to the valence band energy is emitted in the form of a photon whose energy is *hf* where *h* is Planck's constant and *f* is the frequency of radiation emitted. The experimenter measures the forward voltage across a set of different coloured LEDs. By plotting a graph of forward voltage against frequency it should turn out if this simple model is correct that the relationship is linear. The gradient then should be *h*/*e*. If the value of *e* is known, the value of *h* can be derived.

The method can be tried out with apparatus supplied from Lascells (*Photon Energy Array*) or Philip Harris (*Planck Experiment*), or home-made circuits. The applied voltage is controlled by a pot across a 5 V supply. There should be a resistor and possibly also an ammeter in series with the LED. Forward voltage should be measured with a multimeter directly across the LED.

The size of the forward voltage is dependent on the forward current. At its threshold, when a LED is only just emitting light, *V* might be around 1.5 V at 0.1 mA. Then when the current is increased to 20 mA, *V* might have risen to 1.8 V. Which value should you take? Or should you use a sub-threshold voltage at 1 µA, or 1 nA? One common method is to measure *V* for 2 or 3 high current values, lets say 10 mA and 15 mA, fit a straight line through an *I*-*V* plot and extrapolate back to the voltage axis. The value of *V* to use is the point on the axis cut by this line, which is effectively a tangent to the *I*-*V* plot.

Results

The experiment has been tried out with apparatus from Lascells and Harris, and with home-made arrays of LEDs. Three ways of getting forward voltage have been tried:

- Tangent method whereby a tangent fitted to the *V*-*I* curve at high current values is extrapolated to cut the voltage axis as already described.
- Switch-on voltage method where the LED just starts emitting light.
- Constant current method where all the LEDs are driven at the same current and the resulting forward voltage is used in the analysis.

None of the ways gives good results. Two graphs are shown for illustration: the tangent method with the Lascells kit (Fig. 1) and the constant current way with home-made circuits (Fig. 2). The following patterns emerged:

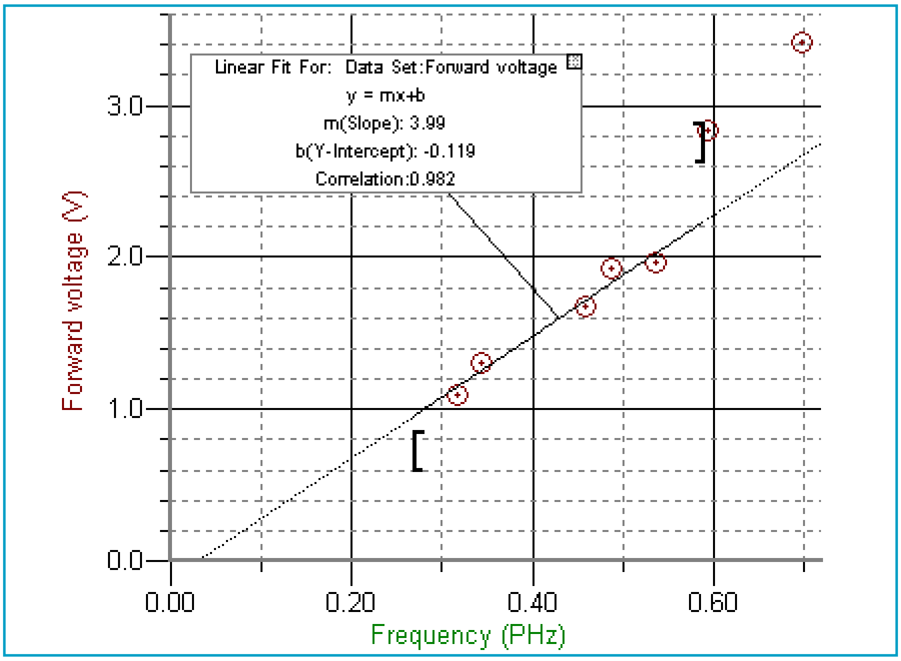

Figure 1 *V-f graphed data from a Lascells Photon Energy Array. Forward voltages obtained by the tangent method. Note discontinuity at 550 nm.*

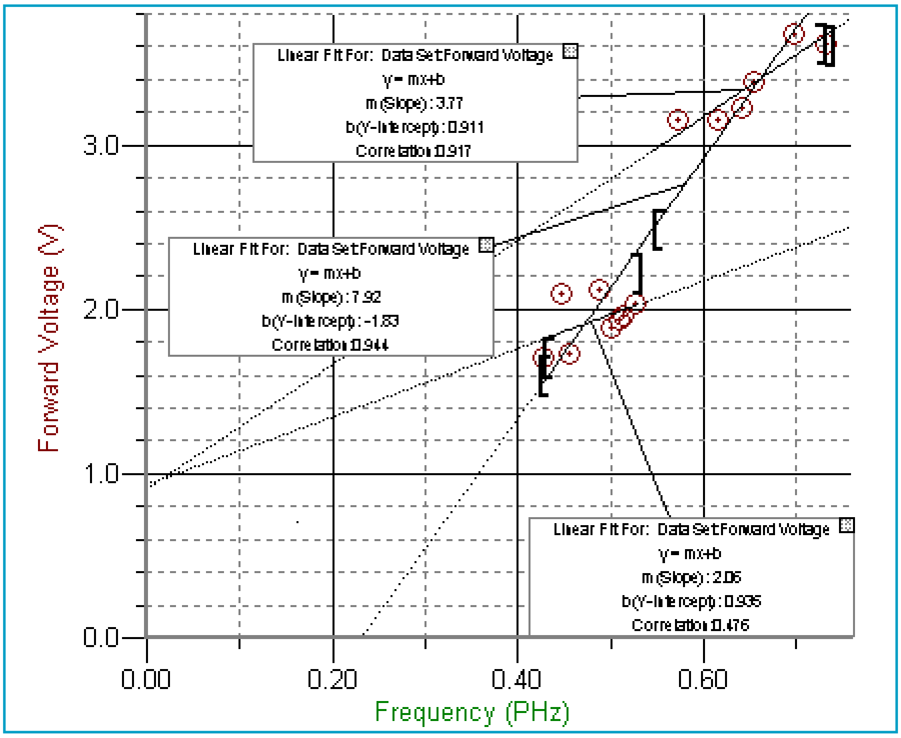

Figure 2 *V-f graphed data from a home-made LED array. Forward voltages obtained by the constant current (10 mA) method. Note discontinuity at 550 nm.*

Apparatus	Method	LED set	Value of *h* derived from gradient (x 10^{-34} J s)
Lascells Photon Energy Array (Fig. 1)	Tangent	All LEDs Infrared to yellow-green	9.5 6.4
Home-made array (Fig. 2)	Constant current	All LEDs Red to yellow-green Green to violet	12 3.3 6.0

Table 1 *Values of Planck's constant from different methods and sets of LEDs.*

Method used to measure forward voltage	Advantages	Disadvantages
Minimum voltage needed to cause emission	Simple procedure	Inefficiency of eye at detecting optical radiation at the extremes of the spectrum
Tangent to an *I-V* curve method	Method seems to give the correct result for *h* for GaAs or GaN LEDs, but not both together	Lengthy procedure, which makes no physical sense
Constant current method	Simple procedure	Claimed to make physical sense, but theory lies outwith school science

Table 2 *Comments on different methods for measuring the forward voltage of a LED.*

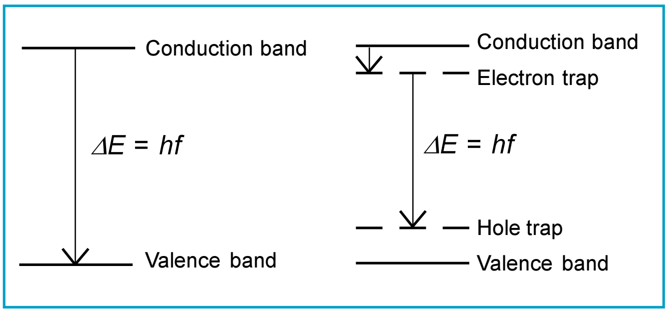

Figure 3 *Photon emission from a LED tends to be from electron trap to hole trap rather than from conduction band to valence band.*

- There is a discontinuity between yellow-green and mid green colours (i.e. between GaAs and GaN LEDs).
- On either side of the discontinuity, the results are scattered about linear lines from whose gradients a value of Planck's constant to within the right order of magnitude can be derived (Table 1).
- There is less scattering if the tangent method is used.

Discussion

Both pedagogically and physically, as a method for investigating the relationship between photon energy and frequency, there is disagreement. We have one correspondent[1] who believes that the method is "simple" and "easily understood". However we know of another physics teacher[2] who is concerned that the method is in the "realm" of "cookbook" physics. The reader is left to form his or her own opinion on the aptness of the method. Those who tried the experiment at last year's Physics Summer School did seem favourably impressed.

In our opinion the method is flawed. The underlying physics is more complicated than the simple model presents – namely that electrons are pumped directly from the valence to conduction band, then jumping cleanly back, with resulting photon emission. In practice there are lots of electron traps lurking under the conduction band. Similarly there are lots of hole traps lurking just above the valence band. Photon emission tends to be associated with electrons jumping from trap to trap rather than band to band. Therefore the photon energy is a little less in practice than it might be had there been a clean transition (Fig. 3). We understand also that there is disagreement amongst GaN scientists as to how GaN LEDs work.

Another pedagogical difficulty is the method[1] used to measure forward voltage. LEDs conduct current for all values of forward voltage. Simply, since the emission of light is part of the phenomenon being investigated, voltage values below that needed to cause emission should be discounted. This then leaves three methods at least (Table 2).

Although the method is flawed, lying as it does on unsound foundations, only partially understood, it will be appealing to many teachers because it is simple to carry out, uses inexpensive components and can yield a result fairly close to Planck's constant. So for those of you who want to use this experiment, we suggest that you treat the theory as follows.

Let E_{input} = Electrical energy given to atom = eV

Let E_{output} = Radiant energy released by atom = hf

E_{output} should not be equated with E_{input}; the underlying physics would not seem to support that identity. Thus $hf \neq eV$.

E_{output} is generally a little lower than E_{input}, so we can write:

$$E_{input} \geq E_{output}$$
$$\Rightarrow \quad eV \geq hf$$
$$\Rightarrow \quad V \geq (h/e)f$$

Although the relationship between V and f is an inequality, it turns out that a graph of a set of ordered pairs of V versus f obtained from different coloured LEDs has a linear dependence, albeit with a lot of scatter (Figs. 1 and 2). The gradient tends to lie within 50% of the accepted value of h/e, from which a rough value for Planck's constant can be derived.

Wavelength measurement

The mean wavelength of LED radiation can be determined quite easily with a diffraction grating – see 'LED arrays' and 'UV LED experiments' in Bulletin 206

Because the radiation has a bandwidth of 20 nm typically, there is uncertainty as to what wavelength value to take.

Acknowledgement

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[1] John Whitehead, Lascells, private correspondence.

[2] D F Holcombe, letter to 'The Physics Teacher', Vol. 35, April 1997.

[1] R Morehouse, Answer to Question #53, *Measuring Planck's constant by means of an LED*, Am. J. Phys., Vol. 66, No. 1, January 1998.