Photodiode Quantum Efficiency

Counting photons

After several calls for help from teachers of AH students who had been trying to measure the power of a laser by irradiating a thermistor and looking for a change in resistance we thought surely there must be a better way with equipment that's readily available or components that are inexpensive. So we thought of photodiodes and came to see that this is a good way of consolidating quantum theory with classical effects.

Here is a method for counting the photons in visible radiation. When a PIN (or p-i-n) photodiode is irradiated with light, photons absorbed in the depletion or intrinsic region produce electron-hole pairs, most of which result in a photocurrent I of n_e electrons/second. If the radiant power[1] P and wavelength λ of the radiant source are known and if the area of the photodiode is large enough to intercept all of the emissions, then the rate of flux of photons n_{ph} hitting the photodiode can be found. The ratio of these two values η is the quantum efficiency.

$$\eta = (n_e/n_{ph}) \times 100\%$$

The quantum efficiency of a photodiode can be very high indeed (95%) and depends on wavelength. Photodiodes made of silicon have a good spectral response between 400 and 1000 nm, and work best around 800 to 900 nm.

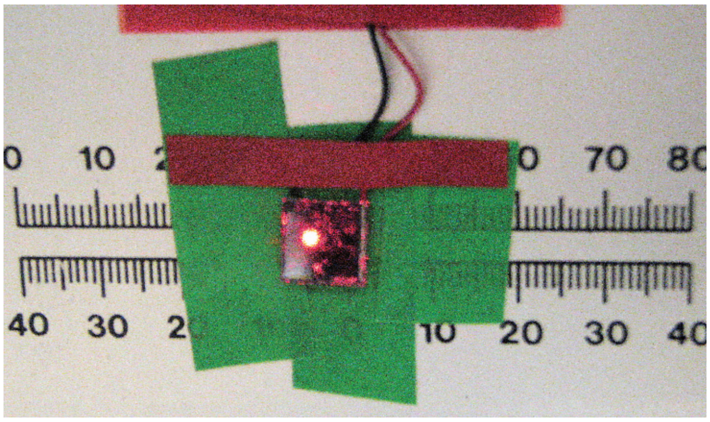

Figure 1 - *Closeup of large-area planar photodiode*

To find the quantum efficiency, your radiation source should be monochromatic, or nearly so, and produce a narrow beam of diameter under 7 mm. Either a laser or narrow-beam LED is suitable. If using a LED, the LED should touch the centre of the photodiode, ensuring that none of its emissions miss.

In our method, radiant power was measured with a photometer (Edmund, J54-038, £139.30). Unless you have such an instrument you will need to look at the technical specification of the source to find what its radiant power is. If you do not know what it is for your laser, then, since the laser ought to be a Class 2 product, its power will be less than 1.0 mW.

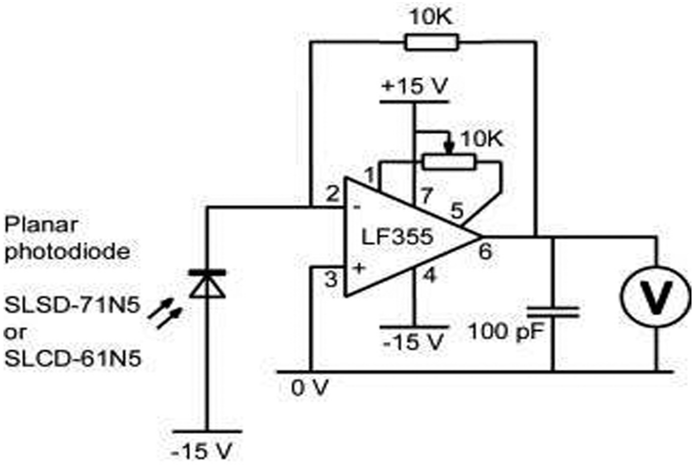

Figure 2 - *Circuit to convert a photocurrent to a voltage [1].*

If using LEDs the brightness of visible LEDs is normally specified in luminous intensity in units of millicandela (mcd). This is the radiating power of a source of light in a particular direction. This quantity is used because LED radiation is highly directional and is weighted with the spectral sensitivity of the eye. The conversion to radiant power is explained on our website. For infrared LEDs, the output is specified differently in either radiant power (mW), irradiance (mW/cm^2), or radiance (mW/sr).

The photodiode should have a large area (Fig. 1). We recommend the Silonex planar photodiode SLCD-61N5 (Farnell, order code 121-8990, £11.26) [1].

This has a slab of p-type silicon sitting on a similar-sized slab of n-type, 10 mm square, with intrinsic silicon sandwiched between. It is wired to a current-to-voltage converter, with an LF355N JFET op-amp (Fig. 2). The conversion rate ($I = V/10{,}000$) is set by the 10 k feedback resistor. If this has the usual 5% tolerance, the uncertainty is 5% also unless you measure it.

If e is the electron charge, the number of photocurrent electrons/second n_e is given by

$$n_e = I/e$$
$$= V/10{,}000e$$

The energy of a photon is hc/λ where λ is the radiation wavelength, h is Planck's constant and c is the speed of light. Therefore the number of photons per second n_{ph} from a source of radiant power P and wavelength irradiating the photodiode

is $n_{ph} = P\lambda/hc$

The quantum efficiency η is

$$\eta = (Vhc/10{,}000eP\lambda) \times 100\%$$

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[1] The proper symbol for radiant power is ϕ rather than P.

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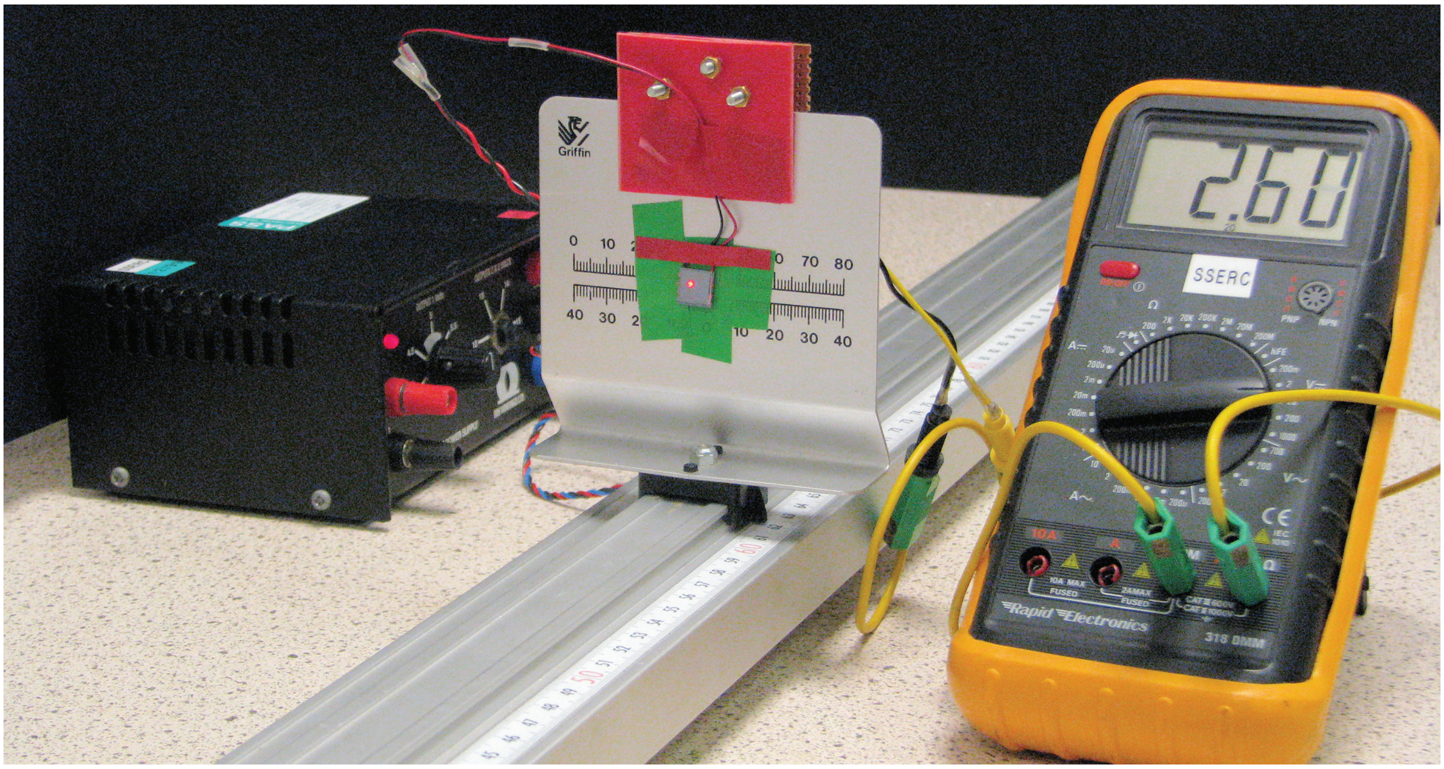

Figure 3 *- Large-area planar photodiode irradiated with laser radiation.*

The quantum efficiency of the photodiode has been found with several light sources (Table 1) and lies between 60 and 70% (±13%). It is less than 100% for several reasons – reflection at the surface, absorption within the doped silicon before the depletion region can be reached and the recombination of electrons and holes. Tabulated values of radiant power from laser sources (marked with an asterisk) have been corrected for reflection. Reflections with LED sources were impossible to correct for, but as the LED's lens was hard against the photodiode, there would have been multiple reflections to and fro between the surfaces such that perhaps not too much light was lost.

Discussion

Although we have written up this report as one of finding the quantum efficiency of a photodiode, this concept is of little interest in itself. The main purpose is to show agreement between an irradiation of photons and the generation of current that this gives rise to. Thereby two theoretical strands, photon energy (hf) and electric charge ($n_e e$), and two measurable quantities, radiant power and electric current, are both shown to be bound up together, cause and effect. The agreement is one of an inequality – there are always more photons than electrons. Knowing the rate of production of current, you have a means of counting photons.

The method lends itself to an Advanced Higher Physics investigation, perhaps being turned round to that of finding the radiant power of a laser or an LED.

Source	**HeNe laser**	**Green laser diode module**	**Green LED**	**Blue LED**
Product details	Griffin XFV-540-010V	Roithner CW531-001	Rapid 55-1668	Rapid 55-1490
Wavelength λ (nm)	633	532	525	470
Radiant power P (mW)	0.71*	0.51*	0.506	0.385
Voltage output V (V)	2.40	1.44	1.40	1.00
Photocurrent I (mA)	0.24	0.14	0.140	0.100
Quantum efficiency η (%)	66%	66%	66%	69%

Table 1 *- Values of wavelength, radiant power & photocurrent used to derive quantum efficiency of a photodiode*

Reference

[1] Laser radiation sensor, SSERC, Bulletin 201, 2001.