can "see" why it was "hurting" them.

We hope that our project will start your students on the road to realizing that they are going to damage, or possibly lose their hearing, if they continue to expose themselves to such high levels of sound pressure.

References

1. Realistic Music/Sound Level Meter Operating Instruction, and Service Data (Radio Shack Cat. No. 33-1028)
2. P. Sarnoff, *Dictionary of the Environment* (Quadrangle Books, New York, 1971)

# Measuring Planck's constant using a light emitting diode

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To determine Planck's constant experimentally, it is necessary to measure the energy of a photon of known frequency. There are two ways to make this measurement. One can either look at the energy gained by a material when it is struck by a photon or one can look at the energy lost when the photon is produced.

The photoelectric effect experiment falls into the first category. When light strikes a metal, electrons are emitted from the surface. For instance, a 2.4 eV photon striking the surface of a cesium cathode (having a work function of 1.9 eV) will cause it to emit a 0.5 eV electron. Theoretically, a student need only measure the voltage developed across the photo-electric tube to find the energy of the photo-electron. But the photocurrent developed is too small to drive the meters generally available. A second method requires the student to measure the stopping voltage, which poses two more problems. First, it complicates the concept by making it harder for the student to understand exactly what he is measuring, and second, the student must be able to recognize the exact voltage at which the current has been stopped. Finally, the student must be able to repeat the experiment at least twice to eliminate the work function from his data.

The emission of a photon by an electron falling from a higher energy-state to a lower energy-state fits into the second category. Although the energies in the atomic orbitals are not measurable, they could be calculated on the basis of the equations of circular motion and electrostatic attraction. To the beginning student, who seldom encounters algebra problems of more than four or five lines, this is a very complicated and abstract procedure.

Even if he is not expected to understand the derivation, the final equation is not a simple one to use. How much more convincing would it be if we could place a voltmeter from one orbital to another and calculate the energy in electron-volts? Solid state physics now enables us to do something almost as good.

## The Light Emitting Diode (L.E.D.)

Biasing any semiconductor diode in the forward direction will generate photons at the junction. This is caused by electrons from the "n" region giving up light as they fall into holes in the "p" region. The photons are not always evident because most types of semiconductor materials are not transparent to the photons produced; in addition, many semiconductors have too small an energy-gap to produce visible light.

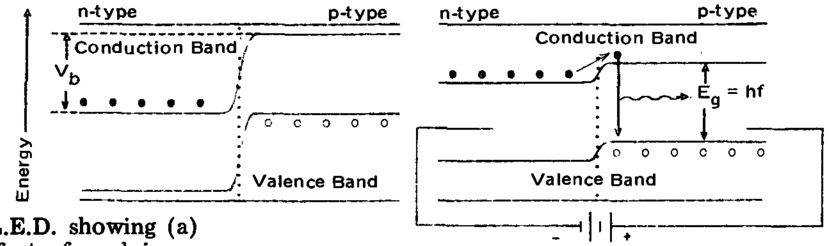
Try to visualize the diode as an assembly of atoms with the valence orbitals merged to form one big "monster" orbital out of all the individual ones. If the "monster orbital" is "filled", it corresponds to a single, filled valence orbital of an atom. Any additional electrons must occupy an excited state which is separated from the lower level by an "energy-gap", Eg.

In semiconductor jargon, the "monster orbital" is called the "valence band", and the electrons in the excited state are called "free" electrons. These electrons are not part of the bonding structure of the crystal, and hence are not confined to a specific location within the crystal. The energy-level they occupy is termed a "conduction band", since it is populated by mobile electrons. The thing to remember about this system is that it still behaves like a single atom in many respects. If a vacant space — a "hole" — appears in the valence band, an electron from the conduction band may fall into it and release a photon, exactly as in a single atom.

By this process, a semiconductor may produce light in a transition that is not taking place inside an atom. While this result is interesting because of its novelty, its value lies in the way voltage affects the diode in making it conduct.

In a light emitting diode, one of the materials (the n-type or negative type) has been doped with impurity atoms providing more electrons than are needed for bonding. The extra electrons occupy the bottom of the conduction band in this particular material. The p-type (positive type) has been doped with impurity atoms that need extra electrons for bonding; thus "holes" are produced in the valence band and no electrons at all are in the conduction band. When the two materials are placed in contact, electrons from the conduction band of the n-type material move into the conduction band of the p-type. They can go to lower energy by dropping into the valence band in the p-region and taking part in the bonding arrangements there, thus cancelling a hole. Note, however, that both materials are electrically neutral to begin with; the positive "hole" was simply an extra bonding position for an electron. Hence the extra electrons filling those positions in the p-type build up a negative electrostatic charge in the region, while over in the n-type a positive region develops because electrons have left. This charge separation immediately builds up a barrier potential preventing any further electron flow.

One way to view the result is in terms of the band levels shown in Fig. 1. The bottom of the *conduction* band in n type has been lowered d to the level of the top of the *valence* band in p-type. (Remember that lower negative charge density lowers the potential level for negative electrons. Similarly, the extra electrons in the p-type raise the potential levels there.) The effects of a bias voltage can be viewed as providing the necessary energy to lift an electron from the n-type conduction band to the p-type conduction band, or simply shifting the relative potentials of both bands in the two materials, as shown in Fig. 1. From either view, electrons can now move from one conduction band to the other. Once again, any electrons in the conduction band of the p-type can drop into the valence band, emitting a photon, and filling a bonding vacancy. As long as the bias voltage is maintained, any extra electrons in the p-type can move around through the circuit and get back to the n-type region.



1. Band levels in the gallium-arsenide L.E.D. showing (a) the barrier potential and (b) the effect of applying a forward bias voltage.

A. No Bias Voltage

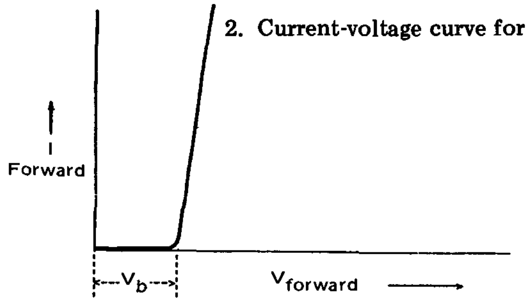
B. Bias Voltage

In Fig. 1, $V_b$ is the barrier potential, which is about the same as the energy lost by an electron between the conduction band of the n and valence band of the p region. Therefore, all that is needed to measure the voltage drop through which an electron has fallen is a measurement of the forward voltage on a conducting diode. ($V_b$ is actually about 90% of $E_g$ when measured by projecting a tangent to the linear portion of the curve back to the V axis. This figure is about the same for all the diodes described.)

## The Experiment

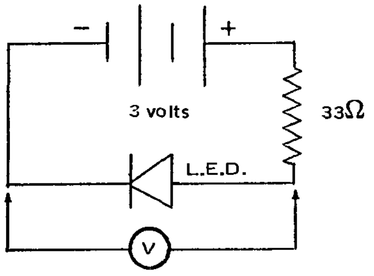
Light is produced by the light-emitting diode when it is connected in the circuit of Fig. 3. Finding the point at which the light "goes on" will be highly subjective, as it depends on the dark adaptation of the eye. Also, this level will not be of suitable brightness for use with a grating or prism spectrometer in determining the wavelength. For this reason, a current level near the maximum value given by the manufacturer is desirable.

The slight IR drop on the diodes brings the forward voltage-drop, V up to $E_g$, compensating for the thermal energy previously mentioned (which is why the bands in the diagram for forward-bias didn't have to be *completely* straightened out before conduction could take place).



2. Current-voltage curve for L.E.D.

Light-emitting diodes, like most diodes, require a series load resistor (the 33-Ω resistor shown in Fig. 3) to prevent thermal runaway — unlimited forward current — from destroying them. Selection of the load resistor is not too critical; 20% variation may be tolerated without adverse effect on either the diode or the experimental value for h. Too high a load resistor, though, will result in low voltage measurements and difficult measurement of wavelength.



3 Schematic of experimental circuit.

Too low a value, and excessive current may burn out the diodes.

Gallium-arsenide-phosphide L.E.D.'s are heavily doped with impurity atoms, and have a rather low reverse-bias breakdown voltage as a consequence. A three-volt battery is the largest that can be safely attached to an L.E.D. if it is accidentally placed into the circuit backwards. This is quite easy to do, since students (and others!) have a hard time telling the cathode from the anode on these devices (and sometimes just forget to look).

The wavelength of the emitted photons is measured using a spectrometer. Alternatively, to keep apparatus requirements simple, without losing the pedagogical effectiveness of the experiment, wavelengths can be taken from the manufacturer's specifications.

The energy of each photon, $hf$ or $hc/\lambda$, is assumed equal to that lost by each electron, $qV$. Therefore:

$$h = qV\lambda/c.$$

Clearly, the only procedure needed is to measure the voltage, V, and the wavelength λ, for several different types (colors) of light-emitting diodes. The four types presently available[1] are red, amber, green and infra-red (which is not visible, but might make a nice "unknown" for the experiment). Results obtained with sample diodes using catalog values of wavelength are shown in Table I. The results of $6.5x10^{-34}$ joule seconds agree rather well with the accepted value of $6.625x10^{-34}$ joule seconds. Compare this with the results obtained by R.A. Millikan, a meticulous experimenter, when he first announced verification of Einstein's prediction. Millikan's results, as announced in Phys. Rev. 7, 18, 355 (1916) gave a final value of $h$ of $(6.57=0.03)x10^{-34}$ joule sec.

TABLE I

| | Monsanto catalog number | λ from catalog | V measured | h calculated (joule-seconds) |
|---|---|---|---|---|
| (infrared) | ME-4 | 9100 A | 1.35 v. | $6.57x10^{-34}$ |
| (red) | MV-10B | 6700 A | 1.7 v. | $6.07x10^{-34}$ |
| (amber) | MV-1 | 6100 A | 2.0 v. | $6.5x10^{-34}$ |
| (green) | MV-2 | 5600 A | 2.3 v. | $6.87x10^{-34}$ |
| Average h = $6.51x10^{-34}$ | | | | |

Table I. Results, calculated from measured voltages and wavelengths supplied by the manufacturer.

With the L.E.D., photons can now be produced by an energy-drop which does not take place inside an atom, and which can be accurately measured with generally available equipment. The experiment could be done by high school students with no more theory than the analogy to the Bohr atom.

Because the apparatus puts out light for a given voltage instead of vice versa, the attractive feature of a tangible, concrete output by which the student measures a relationship makes sensory involvement with the experiment more certain. $E=hf$ becomes a perceivable fact, instead of a theoretical abstraction.

**Reference**

1. "1972 Directory of GaAsLite Products", Monsanto Electronic Special Products

**Further Reading**

1. "Advances in Optical Masers", Arthur L. Schawlow, Scientific American, July 1963
2. "Light-emitting Semiconductors", Frederick F. Morehead, Jr. Scientific American, May, 1967
3. "A New Class of Diode Lasers", Morton B. Panish and Izou Hayashi, Scientific American, July 1971
4. "Junction Lasers", L.A.D'Asaro and Jose E. Ripper, Physics Today, March 1971
5. "The family of Lasers: a survey", Marce Eleccion, IEEE Spectrum, March 1972
6. "The future for LEDs", C.J. Nuese, H. Kressel, I. Ladany, IEEE Spectrum, May 1972
7. "Advances in Light-emitting Diodes", C.B. Duke and N. Holonyak, Jr. Physics Today, December 1973

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# An electronics laboratory for physics students

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Of prime concern for an experimental physicist is a thorough knowledge of electronic fundamentals and technique. In most physics departments a part of this skill in electronics is acquired from a laboratory prepared by a single professor who may have neither the time nor the experience to put together state of the art experiments.

This problem has been solved at Sir George Williams University. The National Radio Institute (a division of the McGraw-Hill Continuing Education Center) has generously permitted the physics department to use the electronics course "Complete Computer Electronics" for the training of student physicists[1].

The experimental procedure in the Kit experiments has been modified to permit many students to use the same