LEDs

Laboratory investigation

This problem provides an introduction to semiconductors.

Intended Learning Outcomes

By the end of this activity students should be able to recall:

- The purpose, use and properties of an LED
- Band gaps in semiconductors
- The definitions of 'intrinsic' and 'extrinsic' semiconductors
- p-n and n-p junctions, and how they relate to LEDs
- The relation of the band gap to the wavelength of emitted light for LEDs
- The significance of direct and indirect band gaps
- The Kronig-Penney model

KEYWORDS:

Band gap, emitted light, experimental, Kronig-Penney model, LED, mathematical modelling, p-n & n-p junctions, programming, semiconductors.

Contents

Reading List

The following textbooks are suggestions, other equivalent textbooks are available:

- Tipler, P.A. ***Physics for Scientists and Engineers***. Freeman.
- Tipler, P.A. & Llewellyn, R.A. ***Modern Physics***. W. H. Freeman
- Ayars, E. ***Bandgap in a Semiconductor Diode***, Paper presented at AAPT Summer meeting, Edmonton Alberta, Advanced and Intermediate Instructional Labs Workshop, July 20, 2008.
- Sze, S.M. ***The Physics of Semiconductor Devices***. Wiley, 1969.

Preamble

LEDs is a Core Group Research Project, undertaken by students organised into small groups working as teams, on the Physics degree programme at the University of Leicester. This project has been run in various forms; the version given here has been run but has not yet been evaluated.

This project is divided into several sections.

1. Perform experiments on the LEDs provided in order to ascertain information about their band gap. Share this information at the final conference to ascertain the accuracy of your results (or to improve them) and to answer the questions raised in the problem statements below.
2. Compare the estimates of wavelength of the LEDs from the band gap determination with diffraction measurements. Is there a simple relationship?
3. Implement a computer programme to calculate the Kronig-Penney model and use it to calculate the effect of high pressures on the band gap (and hence the colour of an LED).
4. Use your program for the Kronig-Penney model to determine the temperature dependence of the band gap. Compare this with an empirical model. (Your equipment is probably too insensitive to test the empirical model.)

Only two students from each team should be conducting the experiment at any one time. The other members of the team should be engaged in the computing task and in writing up results. The teams MUST swap roles in each experiment and for each program.

Module pacing

For each group four experimental sessions in the laboratory have been timetabled, together with two afternoons in the dark room. Each experimental session is followed by a short formal meeting with your facilitator. This should allow time to swap roles and repeat or extend the experimental tasks, to check the computer code and produce results, and to write up the report as you go along. Nevertheless, you are not required to use all of these sessions if you feel you have completed the project.

Each group has a different pair of LEDs. There is a final conference presentation to exchange information.

Problem Statement

Problem 1

Find the band gap E_g of two LEDs from the T-dependence of current or the voltage dependence on T.

Compare this with the gap E_I from extrapolation of the I-V curve. Compare the results. Can E_g be obtained by calibration of E_I?

Problem 2

Find the wavelengths of the LED light by a diffraction experiment.

Can the wavelengths be obtained from the band gaps? Use the data from other groups to support your conclusion.

Problem 3

The diamond anvil pressure cell can used to generate pressures of up to 30GPa on small samples. This pressure is measured by the shift in the optical fluorescence line of a ruby crystal (or for more accuracy a quartz crystal) due to the change in lattice spacing. This gives an accurate reading but is complicated to set up. Is the change in colour of a GaAs LED at high enough pressure sufficient to enable it to be used as a warning device to indicate high pressures if the ruby fluorescence fails for some reason? If not would an LED of a different composition be viable? Detailed quantitative calculations based on a theoretical model will be required to settle the issue.

Problem 4

Although your experiments in Problem 1 are probably too insensitive to show it, the band gap depends on temperature. The band gap variation with temperature can be fitted empirically as

$$E = E_g(0) - \alpha_0 T$$

where $E_g(0)$ is the value of the band gap at T =0 K and α_0 is a constant (depending on the material, typically of order 10^{-4} eV K^{-1}).

A more accurate empirical fit is $E_g(T) = E_g(0) - \frac{\alpha T^2}{T+\beta}$ where $E_g(0)$ is the value of the band gap at T =0 K and α is a constant of order 10^{-4} eV K^{-1} and β is of order 100 K .

Use the Kronig-Penney model to find out if it is likely that this change in band gap can be attributed to changes in the lattice spacing alone.

Can you predict how the LED colour should change at low temperatures?

Can you suggest an experiment to test this?

Suggested Deliverables

Project Plans (or Group Action Plan i.e. the documentation of your group meetings according to the LEIC model).
This could be kept on a Virtual Learning Environment (VLE, e.g. Blackboard) wiki or submitted as a Word/pdf document along with the formal reports.

Group laboratory report in standard formal laboratory report format

The report should be in a uniform style (fonts, layout etc.) and an agreed submission from the group as a whole. The individual contributions to each section should be clear from the group action plan, but may be summarized in the 'front matter' (i.e. the contents pages). Remember that the experimental, computing and writing tasks should each be shared amongst the group.

Please do **not** include:

- copies of material from other groups (e.g. conference handouts): the information should be integrated into your report;
- material from lab notebooks: your lab notebooks must be available for inspection by facilitators and will be assessed during the sessions.

Conference presentation
Present your results and any features of your experimental design that may affect accuracy. Do not spend time telling the audience what they already know about the experiments. Your results must be available electronically to other groups.

Laboratory Equipment

Problem 1

- A power pack
- An insulated LED
- 3 x multi-meters
- Thermocouples and signal booster or thermometer
- Flask
- Flask heater
- Ice
- Dry ice (solid CO_2)
- Liquid N_2
- An accurate resistance meter (one between groups)

Problem 2

- Optical bench
- Mount for LED (Blu-tac and lens holder)
- Slit
- Lenses for collimating and holder
- Mounted diffraction gratings – various sizes, transmission +/- reflection
- Screen for viewing diffraction pattern

You may have access to: Prisms, sodium lamps, lasers for calibrating

Laboratory Sessions

Problem 1: Band Gap

Session Aims

- It is possible to measure the band gap of the LED by examining its response to varying temperatures.

Relevant Theory: Band Gap in a Semiconductor Diode[1]

The current through an ideal diode is given by[2]

$$I = I_0 \left(\exp(eV/kT) - 1 \right)$$

with I_0 the reverse bias current (at $V_b = -\infty$), V the applied voltage, T the temperature in Kelvin and k Boltzmann's constant. If $e^{eV/kT} >> 1$ (i.e. $eV/kT > 4$ or so) then

$$I = I_0 \exp(eV/kT)\ . \tag{1}$$

The reverse bias current I_0 is dependent on temperature also, and the dependence is somewhat more complicated[3]:

$$I_0 = AT^{3+\gamma/2} \exp(-E_g/kT) \tag{2}$$

where E_g is the band gap energy and γ a constant. For the relatively small temperatures and temperature differences the power dependence term $T^{3+\gamma/2}$ changes relatively little compared to the exponential term $\exp(-E_g/kT)$. This allows us to approximate the temperature dependence of I_0 as

$$I_0 = B \exp\left(-\frac{E_g}{kT} \right) \tag{3}$$

with B = constant. If we combine equations (1) and (3), we obtain

$$I = B \exp\left(\frac{-E_g + eV}{kT} \right). \tag{4}$$

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[1] From: Ayars, E., ***Bandgap in a Semiconductor Diode***, Paper presented at AAPT Summer meeting, Edmonton Alberta, Advanced and Intermediate Instructional Labs Workshop, July 20, 2008

[2] Paul Allan Tipler and Ralph A. Llewellyn. Modern Physics. W. H. Freeman

[3] Sze, S.M.. ***The Physics of Semiconductor Devices***. Wiley, 1969

Real LEDs do behave differently from the 'ideal' case above, because of second order effects (such as electron-phonon interactions) or more complex doping schemes. A simple way to modify the relationship is to include an 'ideality factor', or 'slope parameter', η. This term is introduced in a manner that alters the 'effective temperature' of the electrons, as described in the Boltzmann distribution. Thus, for an LED:

$$I = B\exp\left(\frac{-E_g + eV}{\eta kT}\right). \qquad (5)$$

Thus the current that flows through an LED will vary with the temperature of the LED, as well as with the forward bias voltage. If we keep one of these constant, we can investigate the other.

You will also need to consider the measurement of temperatures. You are provided with a pair of 'k-type' thermocouple junctions. You will need to know how to relate their output to the temperature difference between the junctions (calibration).

Laboratory Equipment Provided

- A power pack
- An insulated LED
- 3 x multi-meters
- Thermocouples and signal booster or thermometer
- Flask
- Flask heater
- Ice
- Dry ice (solid CO_2)
- Liquid N_2
- An accurate resistance meter (one between groups)

Suggested Experimental Method

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NOTE CAREFULLY: A resistor is attached to the LED to protect it.

The power pack MUST be connected through the resistor and NOT directly across the LED.

The LEDs have been specially adapted for the experiment and cannot be replaced.

Connecting the power directly across the LED will destroy it and you will not be able to continue with the experiment.

The multi-meter **can** be attached across the LED if required.

You will need to consider measurements not only of the current through the LED and constant voltage applied across it, but also the temperature. The temperature is given by the potential of the thermocouple, as this can be related to the temperature difference between the thermocouple junctions.

You will initially have to measure the ideality factor for your particular LED, by measuring the current which flows through the LED at given temperatures and external voltages.

Once this has been done, it is possible to measure the current flowing through the LED at a range of temperatures, for a set voltage. Using the ideality factor previously calculated, this can be related to the band gap of the material.

Note: Remember that the equation governing the current flow of a p-n junction is not valid at voltages in the region at and beyond the band gap, where saturation occurs. Yet too low a voltage will cause only a very small current to flow (given the exponential nature of the current to voltage relationship), in which region errors and inaccuracies from the multi-meters will become significant.

Problem 2: Wavelength of the Emitted Light

Session Aims

- One way to measure the properties of the materials used in an LED is to measure the wavelength of light which it emits.

In this problem you are to design and perform an experiment which can measure the wavelength of the emitted light using a diffraction grating, and then relate your answer to the band gap of the semiconductor in the LED.

Laboratory Equipment Provided

- Optical bench
- Mount for LED (Blu-tac and lens holder)
- Slit
- Lenses for collimating and holder
- Mounted diffraction gratings – various sizes, transmission +/- reflection
- Screen for viewing diffraction pattern

You may have access to: Prisms, sodium lamps, lasers for calibrating

Problem 3: LEDs as Pressure Sensors

Session Aims

- You are to assess the possibility of an LED as a pressure sensor, by considering how the band gap changes with applied pressure. GaAs has been suggested, although it may be beneficial in some way to use a different material.

GaAs	
Lattice constant (at standard conditions)	5.65 Å
Band gap (at standard conditions)	1.43 eV
Bulk modulus	75.5 GPa

Suggested Experimental Method

Your understanding of the theory which you will use will affect how you approach the problem. In this case, it is worth considering how simple it is to solve any equations you wish to use. For example, if you only wish to solve a simple equation but for many values of pressure, a spreadsheet may be useful (such as Microsoft Excel). If, however, the equation is more complicated (and difficult to find an analytical solution for) you may require something more complex. A good example would be finding approximate solutions to complex equations. If they cannot be found analytically, then a computer can be used to run an iterative function or repeat the same process many times using differing values in each, in order to find the best estimate for the solution. A programming language such as C can be used in this case.

Problem 4: Temperature Variation of Band Gap

Use your computer programme and a value for the thermal expansion coefficient to derive a theoretical prediction for the temperature variation of a semiconductor band gap. Compare this with the empirical curves. Can you make any predictions of the colour change with temperature?