Transducers Kit - Detection of Light

TK2942-3

Feedback

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TRANSDUCERS KIT
TK2942

Part 3 – Detection of Light

Feedback

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CAUTION -
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CAUTION -
ELECTROSTATIC
SENSITIVE DEVICE

Refer to accompanying documents

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We maintain a policy of continuous product improvement by incorporating the latest developments and components into our equipment, even up to the time of dispatch.

All major changes are incorporated into up-dated editions of our manuals and this manual was believed to be correct at the time of printing. However, some product changes which do not affect the instructional capability of the equipment, may not be included until it is necessary to incorporate other significant changes.

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Where components are of a 'Safety Critical' nature, i.e. all components involved with the supply or carrying of voltages at supply potential or higher, these must be replaced with components of equal international safety approval in order to maintain full equipment safety.

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NOTES

ASSIGNMENTS

The following assignments can be carried out using the TK2941M Measurements Package and the TK2941L Light Transducers Kit:

24 The Nature of Light

25 The Photoconductive Cell

26 The Semiconductor Photodiode

27 This assignment is no longer present.

28 The Phototransistor

29 Spectral Response

THE NATURE OF LIGHT — ASSIGNMENT 24

CONTENT

The terms and definitions used in the study of light are introduced. The Optical Detector Assembly is described and its method of use investigated.

EQUIPMENT REQUIRED

Qty	Designation	Description
1	TK294	Linear Transducer Test Rig
1	–	Lampholder
1	–	Light Transducer Box
1	–	Pack of nine optical filters

PRACTICALS

24.1 Relative Illumination

24.2 Lambert's Cosine Law

THE NATURE OF LIGHT — ASSIGNMENT 24

OBJECTIVES

When you have completed this assignment you will:

- Recognise the terms Candela (cd), Lumen (lm) and Lux (lux).
- Know how to use the Inverse Square Law of illumination and Lambert's Cosine Law.
- Be familiar with the use of the Optical Detector Assembly and have produced a relative illumination table for it.

KNOWLEDGE LEVEL

No previous knowledge of the subject is assumed.

The Nature of Light — Assignment 24

INTRODUCTION

When light falls onto certain materials it gives up its energy, which appears in the form of an electric current. This is the principle of a PHOTO-ELECTRIC TRANSDUCER.

The output from a particular transducer will depend upon the intensity of the incident light and its colour. These factors are examined in relation to the physical action of the transducer itself.

The facts of light

Light is a form of electromagnetic radiation having a velocity of 3×10^8m/s or about 186,000 miles/second, or about 670 million miles/hour. Its wavelength is in the range to which our eyes respond; thus we are able to see. Our eyes in fact are acting as a type of transducer, converting light energy into signals which are sent to the brain. This is the phenomenon we call vision.

Alternatively, light can be considered as consisting of little packets of energy, called photons, and the energy of each photon is directly proportional to the frequency of the light. The colour of light is determined by its frequency, which in turn is proportional to the reciprocal of its wavelength. Blue light has a wavelength of about 450nm, whilst at the other end of the spectrum red light has a wavelength of about 700nm (1nm = 10^{-9} metres). Thus a photon of blue light carries more energy than a photon of red light. The full explanation of this quantum theory of light and its duality with the wave theory are beyond the scope of this manual.

We are going to study the operation of transducers which convert light falling on them into electrical signals. From the above discussion you will see that there will be two factors that will vary the output — the intensity of the incident light (number of photons hitting the transducer) and the colour of the wavelength of the light (energy of the photons). We will discuss colour later, but first let us look at light intensity.

In our practical work we are going to use an ordinary tungsten filament lamp, fed from a stabilised 15V d.c power supply. This will not give pure white light, but as the power supply is stabilised its colour and light output will be constant. You will see later how we can take the colour of the source into account when required.

Units of Light

The original standard used in photometry was a wax candle but this was very unreliable and a lamp soon took its place. Standard lamps, as they were called, were difficult and expensive to manufacture so it was decided to define luminous intensity in terms of the radiation from a black body at the temperature of melting platinum. Although this system is complex it gives a very accurate standard. This unit of luminous intensity, is called the CANDELA (cd). One candela is 1/60 of the luminous intensity, measured normal to the surface of 1cm^2 of a black body held at the temperature of melting platinum (2046°K). This standard can very nearly be reproduced by a gas-filled tungsten filament projector lamp operating at a colour temperature of 2854°K. This is the absolute temperature at which a black body emits radiation that gives the same colour impression to the human eye as the lamp in question; this is known as CIE illuminant A.

In order to obtain further definitions we can imagine a point source of intensity one candela, emitting uniformly in all directions, to be placed at the centre of a transparent sphere of radius 1 metre. Imagine an area of 1m^2 on the surface of this sphere. The solid angle subtended by this area is called a STERADIAN (Sr) - see fig 6.24.1. This would also be true if the radius and area are measured in feet, cm, or any other unit, provided they are both unity.

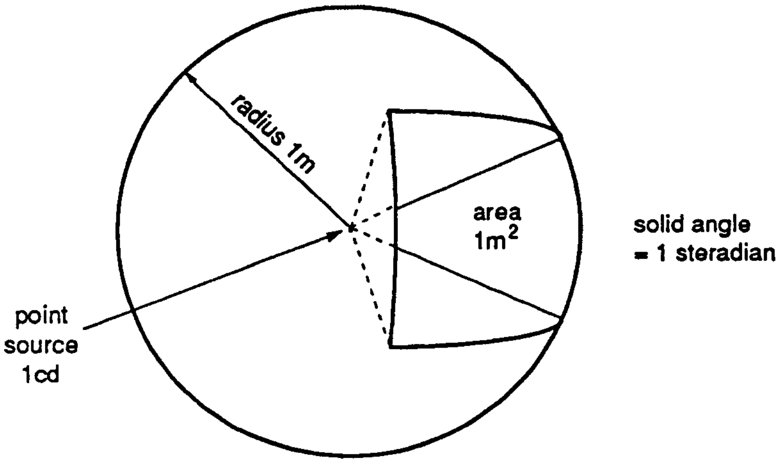


Fig 6.24.1

The unit of *luminous flux* is called the LUMEN (lm). This is the luminous flux from a point source of 1 candela within a solid angle of 1 steradian. The complete sphere comprises 4π, steradians, that is 12.57. Therefore the *total* luminous flux from a point source of 1cd is 12.57 lm. Luminous flux can be thought of as light power, or the energy (number of photons) emitted per second.

The *illumination* at any point on this surface is defined as the luminous flux per unit area falling perpendicular to the surface. When a luminous flux of 1 lumen falls onto our surface of area 1m^2 we say we have an *illumination* of 1 LUX (lx) or to put it another way, an illuminance of 1 lx is produced on an area of 1m^2 at a distance of 1m from a point source of 1cd. Much work is concerned with light falling on flat surfaces rather than spheres, but the error introduced by ignoring the difference is often negligible.

The Inverse Square Law

If the radius of our imaginary sphere is increased from 1m to 2m, the area subtended on the surface by the solid angle of 1 Sr is increased from 1m^2 to 4m^2 i,e in proportion to the square of the radius. The luminous flux over this area is still 1 lm but the illumination has now fallen to a quarter of its previous value as the luminous flux is spread over four times the area. We can say then that the illumination on a surface is inversely proportional to the square of its distance from the source.

If the luminous flux is Φ lumens, the illuminance E lux at a distance d metres from the source is given by:

$$E = \frac{\Phi}{d^2}$$

This is called the INVERSE SQUARE LAW of illumination.

Question 24.1 ***How can we vary the illumination of the various transducers using the bulb attached to the linear motion rig?***

Question 24.2 ***How can we use the inverse square law to calculate the relative intensities of illumination?***

You should have been able to see that by setting the Linear Transducer Test Rig to a known position and taking this to represent 100% Relative Illumination, you can obtain various other intensities of illumination by moving the bulb backwards and calculating the required distance by the Inverse Square Law.

Let us work out a table which will be of help in subsequent assignments. We wish to obtain Relative Illuminations of 100%: 90%: 80%: 70%: etc.

Exercise 24.1

Fill in your own copy of the table, fig 6.24.2, with the help of the formulae above. The first line has been done for you.

Note particularly the inclusion of the set of values corresponding to the Relative Illumination of 25%. This is a quarter of the first figure and corresponds to double the first distance. This figure can be used as a quick check. This table will be used in all future Assignments to enable us to see how a transducer output varies with the illumination upon it.

PRACTICAL 24.2

Lambert's Cosine Law

We have assumed up to now that the light falls perpendicularly on the surface to be illuminated; in this case that the transducer is at right angles to the oncoming light. Suppose the surface is placed so that there is an angle θ between it and the oncoming light, as in fig 6.24.4.

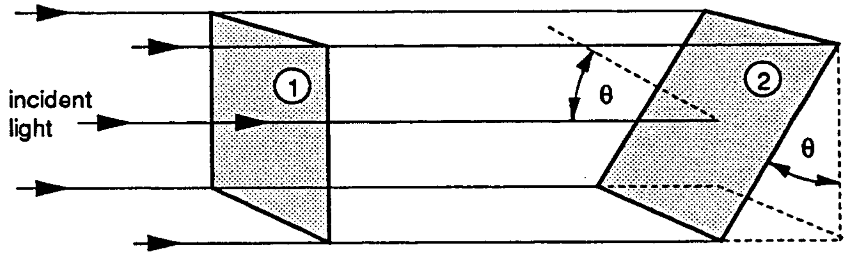


Fig 6.24.4 Lambert's Cosine Law

The luminous flux falling on surface (2) is exactly the same as that which would fall on surface (1) normal to the rays.

But,

$$\frac{\text{area of surface (1)}}{\text{area of surface (2)}} = \cos\theta = \frac{\text{illumination on surface (1)}}{\text{illumination on surface (2)}}$$

Thus as we rotate the surface, in this case the transducer, the illumination is proportional to cos θ. This is known as LAMBERT'S COSINE LAW.

The inverse square law becomes modified to read:

$$E = \frac{\Phi}{d^2}\cos\theta$$

Look at the top of the box containing the light transducers. You will see there is an angular scale enabling us to rotate the transducers, to simulate this effect, and also to bring the different transducers into line. Turn the centre pillar and see how this can be used.

In future assignments we must remember to adjust this angle for maximum response before taking each set of readings. You will be told how to do this in each assignment. Unfortunately the geometry of the transducer box and the necessity for the narrow opening in the box will not allow us to verify the cosine law accurately, but we can show that the output will vary with angle.

Colour

If white light, such as is given by the sun, is passed through a glass prism, it is split up into colours in the well-known spectrum sequence:

red / orange / yellow / green / blue / indigo / violet.

These colours have different wavelengths, from about 450nm at the blue end of the spectrum to about 700nm at the red end of the spectrum. Radiations that are immediately below the red and above the violet ends of the spectrum are called INFRA RED and ULTRA VIOLET respectively. The human eye is sensitive by different amounts to different colours, as shown in fig 6.24.5 It is most sensitive to green/yellow light of wavelength about 550nm.

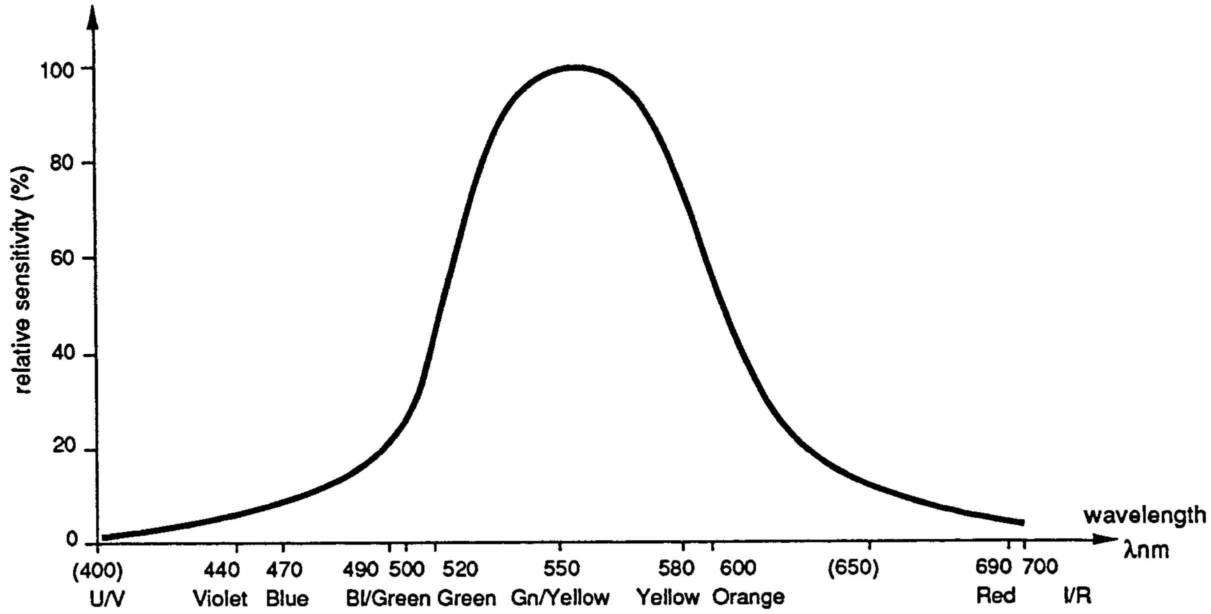


Fig 6.24.5

PRACTICAL 24.1

Relative Illumination

Remove the micrometer assembly from the linear rig by loosening the locking screw and sliding it out of the dovetail track at the end nearest the transducer mount position. Replace it by the lamp holder, sliding it into the track. Ensure that the engraved index mark on the lamp holder is on the same side as the 90mm scale.

Take the Optical Detector Assembly box and locate it in the set of holes nearest to the lamp, with the aperture facing the lamp. You should note that the dimensions have been chosen to bring the filament of the bulb into line with the hole in the box behind which are the various light transducers we are going to study. Ensure that the infra-red absorbent glass filter in its carrier is removed from inside the box.

Move the bulb near to the Optical Detector Assembly Box until the scale reads 90mm. Record this value in your own copy of the table given in fig 6.24.2 opposite 100% relative illumination.

Relative Illumination Y%	$\frac{100}{Y}$	$\sqrt{\frac{100}{Y}}$	$d\sqrt{\frac{100}{Y}}$	Scale Setting Required	Hole Position *
100	1.0	1.0	50.0	90.0	0
90	1.11	1.05	52.5	87.5	0
80					
70					
60					
50					
40					
30					
25					
20					
10					

* 0 = nearest position, then 1, then 2.

Fig 6.24.2

The dimensions of the assembly are such that the bulb is now exactly 50mm from the transducer. Let us call this distance d. Assume the luminous flux is Φ lumens.

By the Inverse Square Law, Illumination $E = \frac{\Phi}{d^2}$ lux.

Let us call this 100%, i.e when E = 100, then $\Phi = 100d^2$.

If we move the light source back by a distance x, it is now d + x from the transducer, as shown in fig 6.24.3. If we call the Relative Illumination at this position Y% by the Inverse Square Law:

$$Y = \frac{\Phi}{(d+x)^2}$$

Substituting for Φ $\quad Y = \frac{100d^2}{(d+x)^2}$

$$\text{or } (d+x)^2 = \frac{100d^2}{Y}$$

Taking Roots $d + x = d\sqrt{\frac{100}{Y}}$

Thus we can calculate how much to move the bulb backwards to obtain different light intensities. By knowing the starting position d of the rig on the scale, we can then calculate the required setting on the scale of the linear transducer test rig.

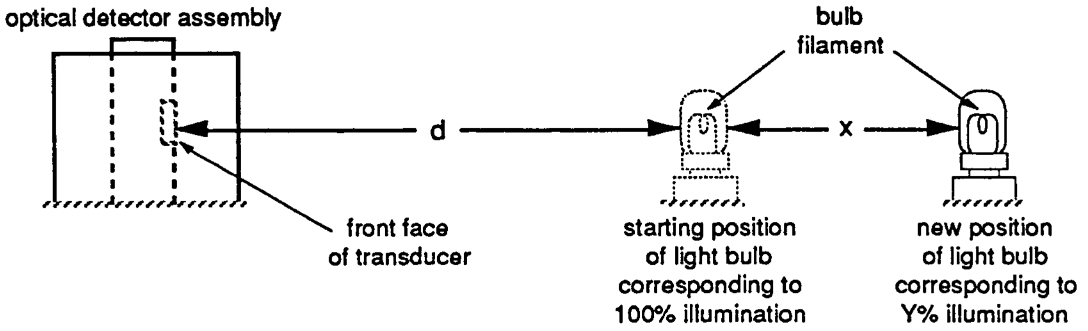


Fig 6.24.3

As we increase the distances, additional sets of holes are provided to increase the source-transducer distance by 50mm for each set. Try moving the box to another set of holes to see how it affects the separation. The last column in the table acts as a reminder which set of location holes to use.

As mentioned before, white light is composed of all colours in approximately equal proportions. Light from other sources may have different proportions of different colours. Our tungsten filament lamp does not give white light. It produces more red than blue light, including much infra-red. The characteristics of this lamp for its colour temperature of about 2540°K with 15 volts applied are as shown in fig 6.24.6. The spectral distribution of sunlight is also shown, for comparison.

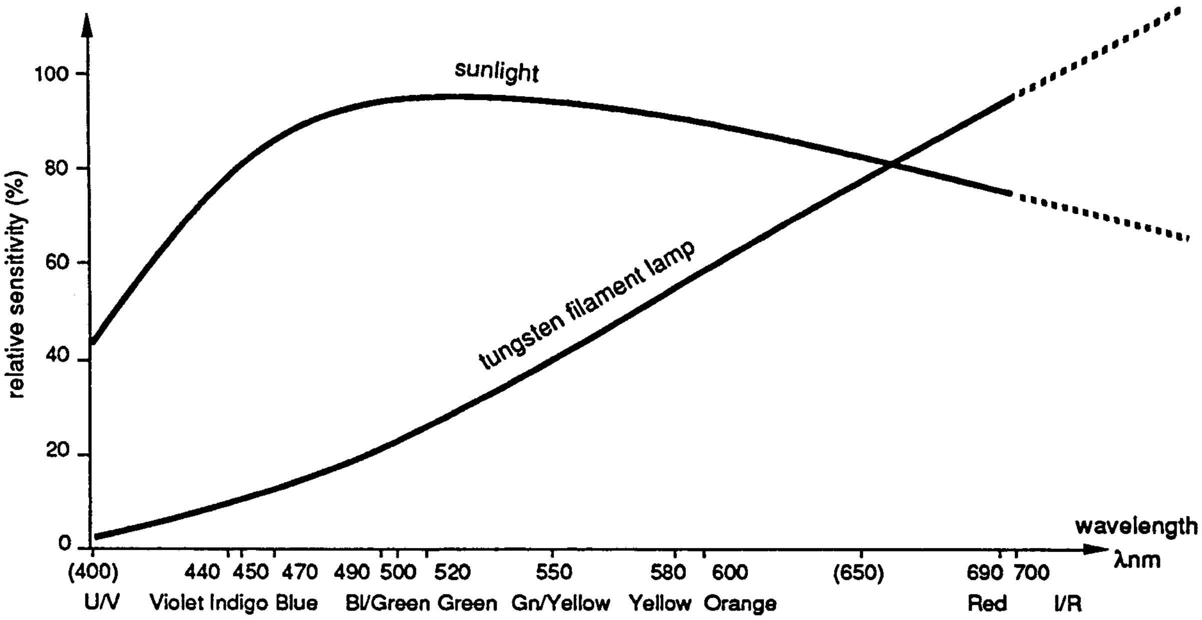


Fig 6.24.6 Light output of filament lamp and sunlight

When light photons strike a material, several things may happen.

- Some may be reflected from the surface. It is these photons reflected into our eyes which allow us to see objects. If the surface is highly polished, it reflects nearly all the photons and we have a mirror.
- They may pass straight through. The material is then said to be transparent.
- They may give up some or all of their energy to the material.

Photo-electric transducers are designed so that the last of these things happens and the light (photon) energy is transduced into electrical energy. However we have noted that the energy of a photon is dependent on the colour of the light, so we would expect some variation of output with colour.

In fact the quantum theory of light, mentioned earlier states that the energy quantum of each photon is given by:

$$\varepsilon = hf \text{ Joules}$$

where f is the frequency of the light (Hz or cycles/sec) h is Planck's constant: 6.626×10^{-34} joule-sec and the frequency f is related to the wavelength λ by the formula:

$$v = f\lambda$$

When λ is the wavelength in metres
v is the velocity of light (3×10^{8} metres/sec)

The measurement of the spectral response of a given transducer requires a means of applying light of different colours at equal illuminations to the transducer, and noting the corresponding outputs. This may be done by various means; for example a diffraction grating can be used to split white light into its various components, much as a glass prism does. A diffraction grating is a piece of optical glass with lines ruled on it at very close intervals and it has certain advantages over the prism as a light-splitter. Alternatively, spectral colour filters known as 'interference filters' can be used; these have very narrow 'bandwidths' that is to say they produce very pure coloured light.

Unfortunately both these techniques involve very expensive items of equipment and could not be applied in this kit; instead some gelatine filters are supplied. These have quite broad bandwidths and so do not produce pure colours. Also they have different degrees of peak light transmission. The table in fig 6.24.7 shows the wave lengths of peak transmission of the nine filters and the percentage of light transmitted at the peaks.

Colour	nm	% Peak Transmission of filter only
Violet	440	13
Blue	470	11
Blue-Green	490	12
Green	520	9
Yellow-Green	550	6
Yellow	580	6.5
Orange	600	17
Red	690	83
Deep Red	700	76

Fig 6.24.7

Examine these filters by holding them up to the light. Note the colours corresponding to the marked wavelengths. You should also note that the amount of light passed through each filter is not the same.

A severe disadvantage of these filters is that they transmit not only the designed colour band but also the infra-red band; since the tungsten lamp emits large amounts of infra-red and since three of the four transducers are very sensitive to infra-red, this makes spectral measurements on those types so difficult as to be virtually impracticable. For this reason only the Photoconductive Transducer will be examined for quantitative spectral response, in Assignment 29, where the necessary precautions will be explained in detail. In addition, some qualitative tests will be made on the phototransistor.

In Assignments 25 to 28 the spectral characteristics of the transducers will be explained in terms of their physical construction and the consequent applications will also be discussed, but no measurements will be made.

PRACTICAL ASPECTS

Light Measurement

This assignment has been largely qualitative and is intended to provide an introduction to the light rig and to light units and colour. Its relevance may be seen in future assignments on the transducers themselves.

We have only been considering the relative intensity of the light, that is relative to that when the bulb is as close as it will go to the transducers. In terms of practical units the illumination on the transducers at this point has been calculated to be just over 450lx. By increasing the distance between bulb and transducer we can vary this down to 10% or about 45 lx. For comparison the following table, fig 6.24.8, shows the levels of illumination recommended by the British Illumination Engineering Society for various work situations.

Class	Examples	Illumination (lx)
Casual seeing	Locker rooms	150
Rough tasks with large detail	Heavy machinery, Stores assembly	300
Ordinary tasks with medium detail	Wood machinery, general office, general assembly	500
Fairly severe tasks with small detail	Clothing cutting and sewing, business machines, drawing offices	750
Severe prolonged tasks with small detail	Fine assembly and machining, handtailoring	1000
Very severe prolonged tasks with very small detail	Hosiery mending, inspecting small parts, gem cutting	1500
Exceptionally severe tasks with minute detail	Watchmaking, inspecting very small parts	3000
School Assembly Hall or Classroom		300
University or Technical College Lecture Room		500
Shop or Supermarket		500
Hypermarket		1000

Fig 6.24.8 Recommended levels of illumination for various work stations

Daylight

The level of daylight in a typical laboratory has been measured as between 80 and 100 lx on a good day. Photoelectric transducers can be used to measure these figures, remembering that room lighting systems are often designed for maximum illumination on a horizontal working surface.

Ambient Light

You may be wondering how the level of daylight or ambient lighting in your own laboratory will affect your readings. Now because our transducers are mounted vertically and behind a small aperture inside a box, unless the light is directed into the aperture only a small proportion of the ambient lighting will reach the transducer. This should not have a great effect. Any effect will appear as a constant factor added to your results, which will shift all your graphs by a constant amount without altering their shape. It is, therefore, not essential to carry out your experiments in a darkroom but excessive ambient lighting should be avoided and the unit should not be pointed directly at a window or other light source.

It is a good idea to take your results as quickly as possible in case the daylight varies, e.g cloud passes over the sun. However, extra care should be taken when measuring the spectral response using the colour filters, for as well as working with low light intensities we are also varying the colour, and external lighting could influence the results. It is also a good idea to keep your hands away from the rig while taking readings as they may cause unwanted light reflections.

Use of Units

Take care not to confuse the units of luminous flux (light output) measured in *lumens*, and illuminance measured in *lux*. Luminous flux can be likened to power output and it has been found experimentally that 621 lumens of green light (λ=554nm) is equivalent to 1 watt. By comparison, our light bulb burns 1.65 electrical watts, and operating at an efficiency of 8.6 lumens/watt has therefore a total output of about 14 lumens. There have also been other units used in the past, mainly in the English system. The units given in this manual are S I (metric) units and conversion factors can be found elsewhere.

Colour Filters

The application of the filters to the measurement of spectral response involves some detailed preparatory calculations, explained in Assignment 29, which will give you a good appreciation of the practical difficulties of obtaining reliable spectral data.

Application

As well as being used to measure light intensity directly, photo-electric transducers are used in many other ways. The following list is by no means exhaustive. The selection of a particular transducer for a particular purpose may be discussed in subsequent assignments.

Photometry — light measurement, exposure meters.

Switching circuits — counting objects, computer tape and punched card readers.

Communications — cine film sound-track readers, modulated light detectors.

Photocopying machines.

Industrial Electronics — counters, conveyor stop/start systems, proximity and level controls, pinhole detection, thickness measurement, food processing and sorting.

Automatic street lighting systems.

Character recognition.

Intruder and Fire detection.

Positioning and alignment of servo systems.

Solar energy conversion.

Infra-red heat-seeking missiles and night vision devices.

TYPICAL RESULTS AND ANSWERS — ASSIGNMENT 24

Question 24.1 and Question 24.2

These questions are answered immediately in the text following the questions.

Exercise 24.1

The completed table is given in fig E6.24.2

This gives how far back (x mm) to move the bulb from the base distance d = 50mm to obtain a relative illumination of Y% by application of the formula:

$$d + x = d\sqrt{\frac{100}{Y}}$$

There is no point in working to more significant figures than those given for no increase in accuracy will result.

The last column in the table shows in which set of holes in the baseplate to locate the optical detector assembly box. These provide a means of increasing the separation. The distance between each set of holes is 50mm.

Relative Illumination Y%	$\frac{100}{Y}$	$\sqrt{\frac{100}{Y}}$	$d\sqrt{\frac{100}{Y}}$	Scale Setting Required	Hole Position *
100	1.0	1.0	50.0	90.0	0
90	1.11	1.05	52.5	87.5	0
80	1.25	1.12	56.0	84.0	0
70	1.43	1.19	59.5	80.5	0
60	1.67	1.29	64.5	75.5	0
50	2.00	1.41	70.5	69.5	0
40	2.50	1.58	79.0	61.0	0
30	3.33	1.83	91.5	48.5	0
25	4.00	2.00	100.0	40.0	0
20	5.00	2.24	112.0	28.0	0
10	10.00	3.16	158.0	32.0	1

* 0 = nearest position, then 1

Fig E6.24.2

THE PHOTO-CONDUCTIVE CELL **ASSIGNMENT 25**

CONTENT

The illumination and polar response of a cadmium sulphide photo-conductive cell are measured. The use of the device is investigated

EQUIPMENT REQUIRED

Qty	Designation	Description
1	TK2941A	Instrumentation Module
1	TK294	Linear Transducer Test Rig
1	–	Lampholder
1	TK294	Light Transducer Box
1	–	Power Supply +15V dc *(eg Feedback PS446)*
1	–	DC Milliammeter *
1	–	Voltmeter 10V dc *

* Alternatively multimeters may be used.

PRACTICALS

25.1 Illumination Response

25.2 Lambert's Cosine Law

THE PHOTO-CONDUCTIVE CELL — ASSIGNMENT 25

OBJECTIVES

When you have completed this assignment you will:

- Understand the photo-conductive effect.
- Recognise the terms 'photo-resistor', 'photo-conductor' and 'light dependent resistor'.
- Have measured the illumination and polar response of a photo-conductive cell.

KNOWLEDGE LEVEL

Before starting this assignment you should:

- Understand the basic theory and operation of semi-conductor devices.
- Understand the basic theories concerning the nature of light.
- Be familiar with the use of the Optical Detector Assembly and the Linear Transducer Test Rig; and preferably have completed Assignment 24, The Nature of Light.

INTRODUCTION

A semiconductor, as its name implies, is a material with an electrical conductivity in between that of an insulator and a conductor. Typical materials of interest are Germanium and Silicon, but other materials and combinations of materials behave in a similar fashion. They are extensively used in semiconductor devices, e.g diodes and transistors.

Electrical conduction in such a material occurs when free charge carriers, e.g electrons, are available in the material to move when an electric field is applied. It happens that in certain semiconductors, light energy falling on them is of the correct order of magnitude to release charge carriers which will increase the flow of current produced by an applied voltage. This is known as the PHOTO-CONDUCTIVE effect, and such a device is called a PHOTO-RESISTOR or a PHOTO-CONDUCTOR, or sometimes a LIGHT DEPENDENT RESISTOR, as incident light will effectively vary its resistance.

We would expect the current, or the number of charge carriers, to be related to the number of photons, or the intensity of the incident light, and we will investigate this. The colour of the light will affect the response, due to the different energies of the photons, but this may be investigated fully in Assignment 29. A small number of charge carriers are also produced at room temperature by thermal effects, and this will also contribute to the current.

The physical effects which cause this phenomenon are rather involved, but are given here to make the study complete.

It is assumed that you have already a basic knowledge of semi-conductor physics. You will remember that in an intrinsic (pure) semi-conductor crystal all the valence electrons have formed covalent bonds together with their neighbours. Their energies may be represented on a diagram of energy bands. It is found that there is a forbidden energy gap of the order of an electron-volt (1eV) between the valence band (where the electrons are bound to their parent atoms) and the conduction band (where the electrons are now free charge carriers). This corresponds to the minimum energy necessary to break a covalent bond and form a hole/electron pair. The electron is raised into the conduction band and contributes to conduction as well as the hole left in the valence band. This theory is fully described in most standard textbooks. It is of interest to us now if this energy can be supplied by light photons.

Consider first the effect of impurities in the semiconductor. Very small amounts of the correct impurities can introduce either extra holes (P type) or extra electrons (N type) because of their atomic structure. These will appear on our energy diagram as energy levels just below the conduction band (doNor level for N type) or just above the valence band (accePtor level for P type). If photons of the correct energy illuminate such a specimen, several things may happen, as shown in fig 6.25.1.

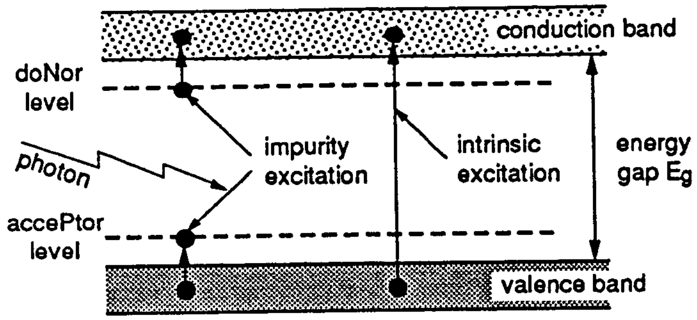


Fig 6.25.1 Effect of photons in energy bands of a semiconductor with both P & N type impurities

- An electron/hole pair may be generated by a high energy photon as described above. The electron 'jumps' the energy gap into the conduction band. This is called *intrinsic excitation.*
- An electron in the doNor level (for N type) may be excited into the conduction band.
- A valence electron may fill a hole in the accePtor level (for P type).

These last two transitions are known as *impurity excitations* and require less energy than intrinsic excitations. However, since the impurity concentration is very low, the density of states in the conduction and valence bands greatly exceeds the density of impurity states. At room temperature, most of the impurity atoms are ionised in any case.

Thus photoconductivity is due principally to intrinsic excitation. Impurities however do have advantages as discussed later. Our transducer is actually an N-type semi-conductor.

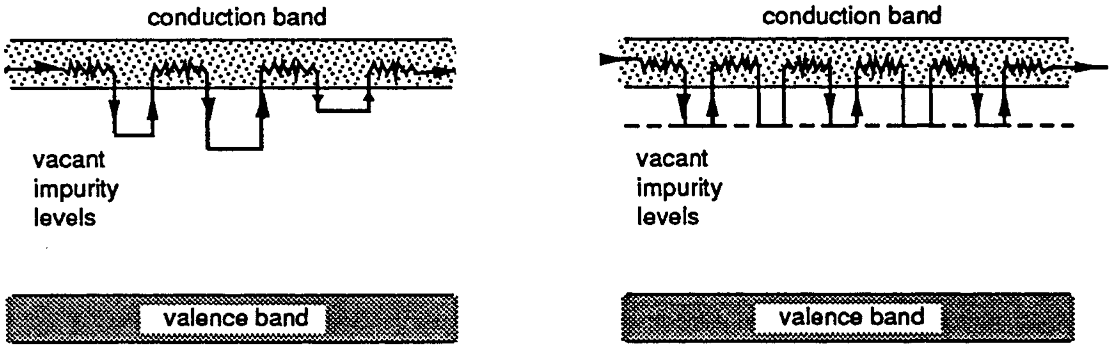
The carriers generated by the photo-excitation will move if an external voltage is applied to the device. This superimposes a regular drift on their random diffusion motion colliding with others. They may however, recombine with an available hole or electron before they reach the edges of the material. This may affect the response time of the device, cut down the available current (loss of sensitivity) or introduce non-linearities. Those carriers remaining will constitute the device current which thus depends initially on the number of photons.

The actual process is extremely complicated and depends on several factors, including the density of the states in the energy

The actual process is extremely complicated and depends on several factors, including the density of the states in the energy bands, the probability that a photon will excite an electron, and other factors, including carrier lifetime and mobility which depends upon recombinations and trappings. Thermal effects also play a part.

Advanced mathematics is available to predict the form of the characteristics, but this is beyond the scope of this manual. A qualitative discussion of carrier lifetime will help you to appreciate some of the effects.

Recombination may occur directly at the surface or deep into the volume of the semi-conductor. Surface recombinations are dealt with in Assignment 29 where it is seen how they affect the spectral response of the photoconductor. Direct recombination of holes and electrons is rare. Volume recombination occurs at vacant impurity levels in the energy gap. Such levels will trap an electron for a certain time before being excited back into the conduction band for further travel, as in fig 6.25.2(a). A material with a low impurity concentration would produce a device with low sensitivity. If more impurity, N-type in our discussion, is added, this raises a donor level just below the conduction band. At room temperature, most donor electrons have been raised into the conduction band so there are many free states just below the conduction band into which electrons, travelling under the direction of an applied voltage, may fall or be trapped. It requires then only a small energy to raise them back into the conduction band and consequently they spend less time trapped as in fig 6.25.2(b).



(a)
Trapping in a lightly doped semiconductor

(b)
Trapping in a more highly doped semiconductor

Fig 6.25.2

The lifetime of the carriers and hence the sensitivity therefore increases. However, this happens more frequently and since the response time of the effect is proportional to the time required for recombination of the excess carriers, there must be a trade-off between sensitivity and response time. The more sensitive the device, the slower acting it is and has a poorer frequency response. This is shown in fig 6.25.3. Fall time is longer than rise time because it takes longer for the electrons to 'drain back' after being trapped. This sensitisation process also increases the dark current of the device, as discussed later.

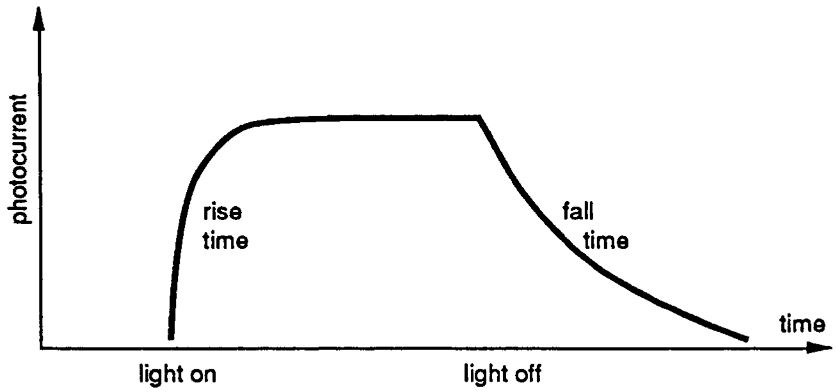


Fig 6.25.3

The same effect can cause non-linearities in that the previous history of the device can be important. Suppose a very strong light is shone onto the device. It will produce an excess of charge carriers. These will saturate all the available energy levels. Thus sensitivity decreases at high light levels. It takes time for these excess carriers to recombine, thus the operation of a photoconductor may be temporarily impaired by exposure to strong light. The same applies if the device is suddenly put into darkness. Even in normal operation, as described above, a sudden change in light is not accompanied by an immediate change in current. To avoid history effects, it is best to pre-condition the device by illuminating it with light of the order of intensity to be used, for a period of time before taking readings. Times of the order of hours are often quoted, but it has been found that five minutes, in our rig, is sufficient for any further changes to be well below the limit of experimental error.

It has already been mentioned that at room temperature, thermal energy is sufficient to ensure that most of the impurity atoms have been ionised, i.e most of the donor electrons have been excited into the conduction band. This thermal energy is also sufficient to break some of the covalent bonds and create hole/electron pairs which also contribute to conduction. Thus as in a normal semi-conductor, even with no light falling on the device, a small current will flow if a voltage is applied. This is known as the DARK CURRENT and in a photoconductor may correspond to a *dark resistance* of over 100Ω. This effect will become greater if more impurity is added to sensitize the device as explained earlier.

PRACTICAL 25.1

Illumination Response

We have seen, either intuitively, or by examining the physics of the device, that the current which flows through a photoresistor when a voltage is applied, depends upon the illumination of the device. Let us investigate this practically. We are simply going to measure the current flowing with a milliammeter as we vary the illumination of the device by moving the bulb.

Mount the lamp holder on the Linear Transducer Test Rig.

Position the Optical Detector Assembly box on the Linear Transducer Test Rig in the set of holes nearest the lamp, with the aperture in front of the transducers facing the lamp. Ensure that the infra-red absorbent glass, in its carrier, is removed from inside the box.

Connect up the circuit as shown in fig 6.25.4 with the photoresistive transducer (R1) behind the aperture in the box. Ensure that the photoresistive transducer is set so that its position on the angular scale is 0. Check that the potentiometer control knob on the Operational Amplifier is set to 0 and switch on the power supply. The lamp should light. Position the lamp holder at the position corresponding to 100% Relative Illumination by reference to the table given in Assignment 24.

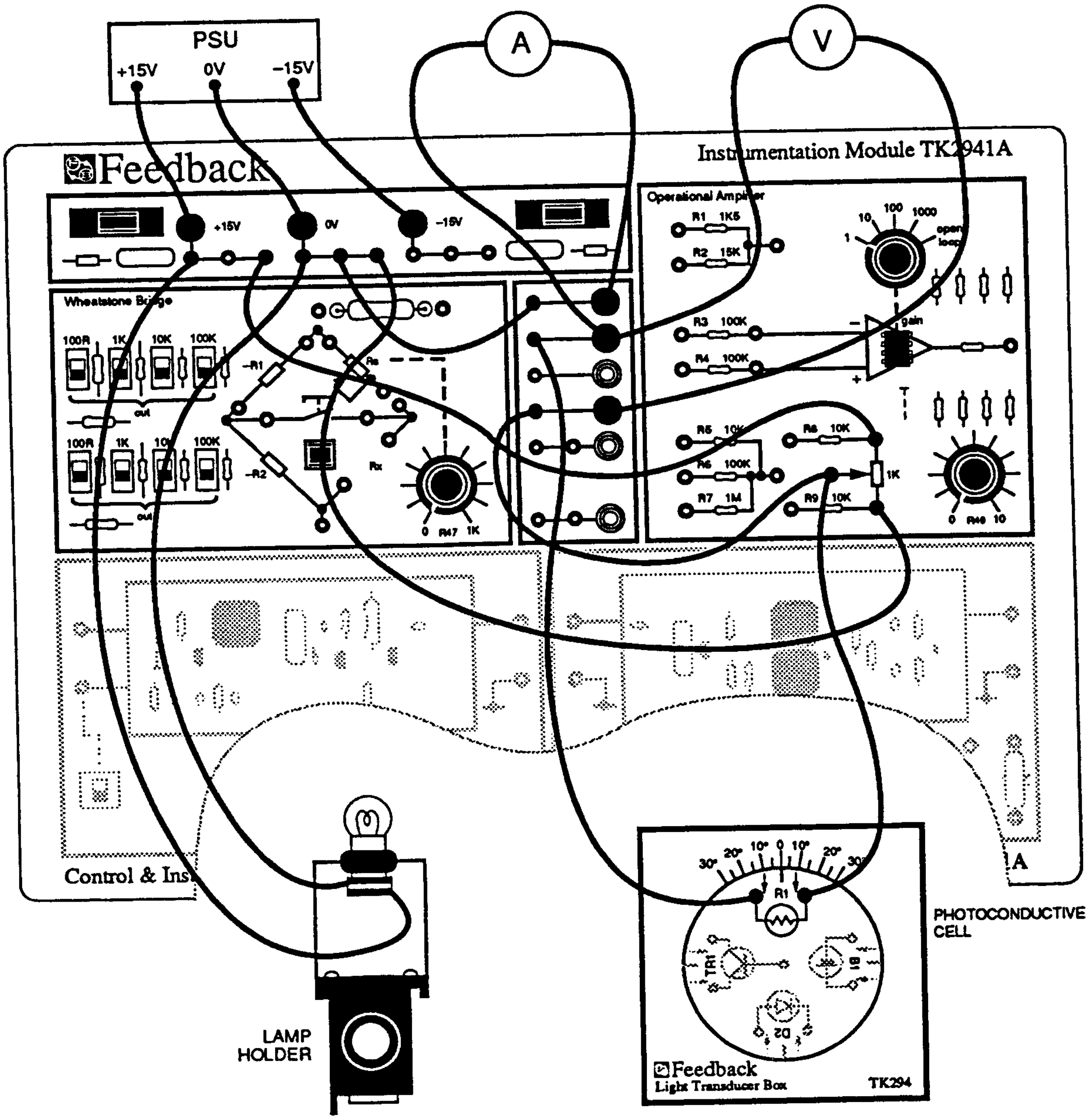


Fig 6.25.4

Although as explained in Assignment 24 and as you will see, ambient lighting does not have any great effect, ensure that the transducer is not facing directly into a window or other light source, as excessive lighting could swamp your readings and possibly damage the transducer.

Slowly increase the variable d.c control. The meter should indicate a current. When the reading gets to about 8mA, stop.

Now rotate the Optical Detector Assembly against the scale on top of the transducer box, so that your milliammeter reading is a maximum. You may need to adjust the variable d.c output control if you were a long way out initially. This ensures that the light is falling perpendicularly on the transducer and we have maximum sensitivity. Do not move this scale during your experiment.

Leave the equipment like this for at least five minutes, so that the light is continually falling on the transducer. This ensures that the necessary pre-conditioning of the device is carried out.

Now adjust the variable d.c voltage so that approximately 10mA flows. Measure and record the value of the applied voltage and keep it constant throughout the test. This current has been chosen so that at this position of highest illumination (100% relative) the power rating of the device is not exceeded. Higher currents should not be used as they may damage the transducer.

Move the bulb backwards to vary the illumination on the transducer according to the table of distances given in Assignment 24. At each step record the current in your own copy of the table given in fig 6.25.5.

Applied Voltage =

Relative Illumination (%)	Scale Setting	Current (mA)	Device Resistance (Ω)
100			
90			
80			
70			
60			
50			
40			
30			
25			
20			
10			
0			

Fig 6.25.5

If you are doing the experiment in daylight, take your readings as quickly as possible in case the daylight varies. Also keep your hands away from the rig when taking readings in case they cause unwanted reflections of light onto the transducer.

Disconnect the bulb and take a reading corresponding to ambient light illumination. Finally rotate the Optical Detector Assembly so that the transducer faces away from the aperture in the box and take a reading corresponding to zero illumination.

Exercise 25.1 ***For each illumination, calculate the resistance of the transducer by applying Ohm's law and dividing the applied voltage by the current flowing, $R = {}^{Vdc}/_{I}$***

Exercise 25.2 ***Plot a graph, on linear graph paper, of current flowing against relative illumination. Label your graph with the value of applied voltage.***

Question 25.1 ***What shape is the graph? Does it pass through the origin?***

Exercise 25.3

Draw in the best straight line through the points you plotted. Calculate the linearity over the range by measuring the worst deviation from this straight line and express it as a percentage of the total change, stating the range of currents over which this linearity holds.

Question 25.2

When you removed all lighting by turning the transducer to face into the box, did the current fall exactly to zero?

Question 25.3

Although the device may be called a photoresistor, and we have calculated its resistance for each illumination, why do you think we have plotted current flowing and not resistance?

Before we discuss your results, let us see how the angle at which light falls on our transducer affects its response.

PRACTICAL 25.2

Lambert's Cosine Law

With the circuit of fig 6.25.4 still connected, return the box and bulb to their starting positions corresponding to 100% relative illumination. Reconnect the bulb and slowly increase the variable d.c control until the meter reads about 8mA. Rotate the transducer until this reading is a maximum and then adjust the variable d.c control until this reading is approximately 10mA. Do not touch the voltage control again during your experiment. Note the value of voltage you have set.

Now set the angular scale to 30° anti-clockwise and record the current flowing. Repeat these readings for angle of 25°, 20° and so on at 5° intervals up to 30° clockwise. Record your results in your own copy of the table given in fig 6.25.6.

When you are setting the angles, take care to look directly on top of the transducer box when aligning the marks, to avoid parallax. Again, perform the experiment as quickly as possible and keep your hands away from the rig when taking readings.

Angle (degrees)	Current (mA)
30 ACW	
25	
20	
15	
10	
5	
0	
5 CW	
10	
15	
20	
25	
30	

Fig 6.25.6

Exercise 25.4

Plot a graph, on linear graph paper, of current flowing against angle. You may alternatively plot this graph on polar (circular) paper if available.

Question 25.4 ***Between what angles do you consider the device to be useful?***

Question 25.5 ***Why does this graph not follow accurately the cosine law as described in Assignment 24?***

The spectral response of this device can be investigated more fully in Assignment 29. You will see that the peak response of the photoconductive cell is at about 630nm, i.e in the orange-red portion of the spectrum and the shape corresponds roughly to the response of the human eye.

Question 25.6 ***Can you suggest the principal advantages and disadvantages of the Photoconductive Cell?***

Question 25.7 ***Taking what we have just said into consideration with your results, can you suggest some uses for such a transducer?***

PRACTICAL ASPECTS

You should have found that your graph of current against relative illumination was of the form shown in fig 6.25.7.

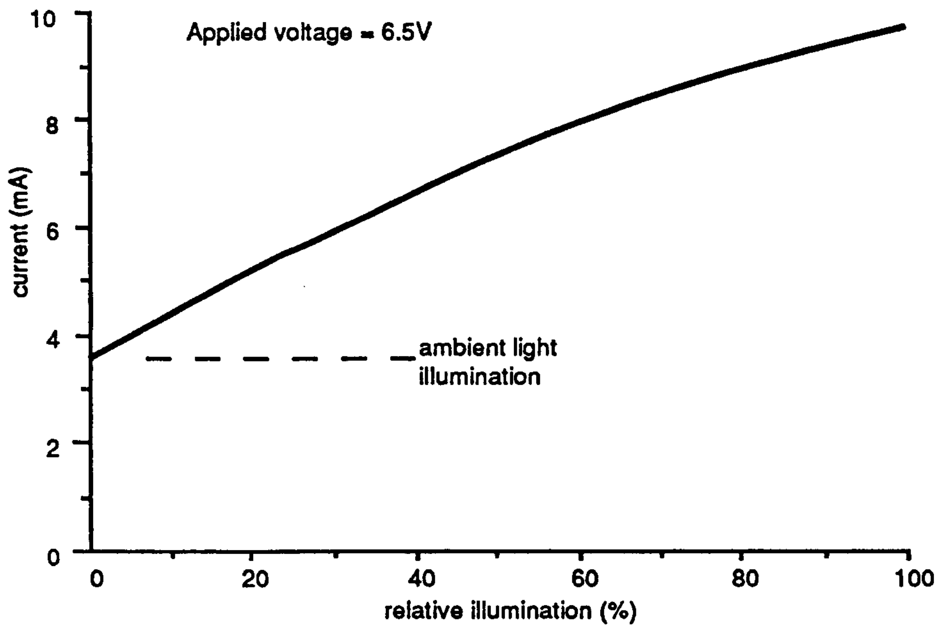


Fig 6.25.7

You would have found that at low values of illumination the current increased with increasing illumination, then the increase became less rapid as you move towards 100% relative illumination. This, of course, is not the maximum illumination that the device may be subjected to, but only the maximum we can obtain with our rig. Brighter bulbs and shorter distances would produce larger currents, but the shape of the curve would follow the same form, provided the current was not so excessive as to damage the transducer.

In order to account for the shape of this curve, many physical factors must be taken into account which, as mentioned in the theory, are beyond the scope of this manual.

The graph you plotted under normal lighting conditions should show that the ambient lighting provides a 'bias'. The value of this can be estimated from the intercept of the curve on the current axis, the reading you took when you turned the bulb off. This 'bias' of the ambient lighting reduces the overall range of illumination for our tests, but lifts the curve away from the very non-linear region at low light levels. Drawing in the best straight line over this portion of the curve, should show a linearity of better than 5% over the range we have used. Use of the transducer over greater ranges or at other light levels would mean a different figure for linearity.

The current you obtained with the transducer facing away from all light is called the DARK CURRENT, and should be typically less than 100μA, corresponding to a dark resistance of greater than 100kΩ. This residual current is caused by thermal energy at room temperature providing a few charge carriers. A good transducer should have as high a dark resistance as possible and this is dependent on the manufacture of the device.

Since resistance is proportional to the inverse of the current (by Ohm's law) for a fixed applied voltage, there is little point in plotting resistance as this would only produce another non-linear curve, as the current curve is non-linear. As said, the actual form of the curve is complex, and varies slightly with the device manufacture. For some devices it may be almost exponential, for others a form of logarithmic function. Some manufacturers plot log resistance against log illumination and this produces a straight line in some cases. They then can define a factor called *gamma*, relating resistance to illumination.

$$\text{gamma } (\gamma) = \frac{\log R1/R2}{\log E2/E1}$$

where R1 = resistance of illumination E1
R2 = resistance of illumination E2

If such a graph is not linear, values of γ would only be true at a single point. This method has not been adopted in this assignment since we are only working over small ranges.

When comparing specifications, all conditions must be equal. All your readings have been taken using an ordinary tungsten filament lamp bulb operating at a colour temperature of about

2540°K. This has a tendency to being 'red'. Commercial specifications are normally produced at a slightly higher colour temperature of 2700°K or 2850°K for example. Such small differences can sometimes produce marked differences in results.

You have calculated the resistance of the transducer for each value of illumination used, and these should be in the range of about 500Ω to 1800Ω, again varying slightly with each individual transducer. Compare this range with the dark resistance of over 100kΩ, and you will see that there is a very large change from darkness to even moderate values of light. This type of transducer is very sensitive at low values of illumination, but the response is very non-linear.

If you have plotted your polar response graph on linear graph paper, it will be of the form of fig 6.25.8.

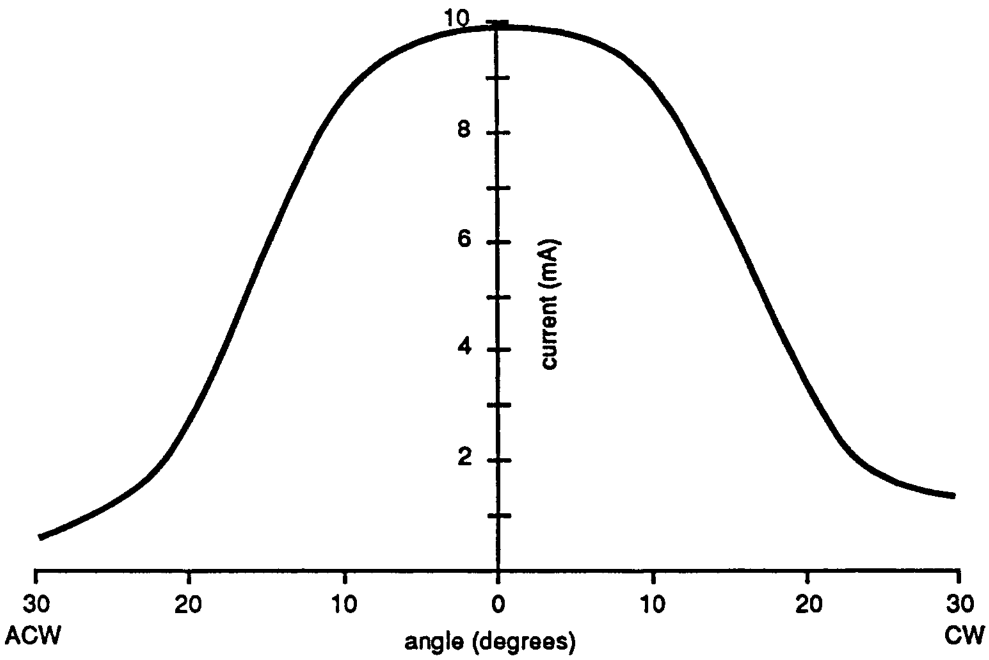


Fig 6.25.8

This does not follow the cosine law accurately as explained in Assignment 24 because of the geometry of the transducer box, and the necessity for the aperture in front of the box. However it does show that there is an optimum 'window' of best response for the device of about ±15° or less and over this range the resistance is relatively constant. If you did your experiment with ambient lighting, you should have found that this provides a form of 'light bias'. There may also be a peak on one side of the centre if the ambient lighting is coming in at an angle, e.g from a side window.

The spectral response of this device can be more fully investigated in Assignment 29, but let us say for the moment that different photoconductive materials can have different spectral responses. The material in our device is Cadmium sulpho-selenide, an N type semi-conductor which has a response in the visible spectrum, close to the human eye. Consequently they are used in photometers to measure the sensation as would be experienced by the human eye. Such an example occurs in photograph exposure meters. Here linearity is an advantage, but this is not so at low illuminations. If intended for low light measurement, such meters often have two or more light ranges, the lowest range having a non-linear scale. Alternatively, compensating linearising circuits may be employed.

The principle disadvantage of the photoconductive transducer is that it requires a source of potential to drive the current through it. This means that the exposure meter suggested above needs to have a battery. The power consumption is moderate, and for this application is not disadvantage; a pushbutton is usually incorporated to connect the battery only when actually taking readings.

Their low resistance when exposed to light means that they can, and are, designed to carry moderate currents, such as are capable of operating a relay direct, without intermediate amplification. They can be designed to operate on low voltages, and are thus used in industrial control equipments, for example counting packages moving along a conveyor belt, or in burglar alarms, where the interception of a beam of light triggers an alarm. Actually, in the latter application a device would be used which is sensitive in the infra-red region, so that the burglar would not see the beam of 'light'. The low cost of photoconductive transducers makes them particularly useful in these applications.

Another application makes use of their property as a resistor. If inserted as a component in another circuit, light can be made to control a parameter of that circuit, e.g the bias on a transistor or the gain of an amplifier. Such circuits are used in automatic brightness compensation of TV receivers, so that when the room light is switched on, the brightness is automatically adjusted. The volume of an audio amplifier can be controlled by light — this is particularly useful if several channels have to be controlled together. Or the device may simply be used as a light-activated switch.

Fig 6.25.9 shows a more sophisticated light measuring circuit consisting of a balanced bridge for measuring the attenuation of light at resistor R2. This is a form of differential circuit, and such circuits have already been examined in relation to measuring linear motion in earlier assignments in this manual. Since the two photoresistors are similar, they will track up and down together, tending to keep the bridge balanced under varying environmental conditions. This reduces the effect of power supply shifts, light history and temperature drifts of the photoresistors, and lamp output variations, as both halves of the bridge will experience the same change and the output will tend to remain constant. The equation for balance has already been derived in Assignment 2,

$$R2 \times R3 = R4 \times R1$$

If a translucent object is inserted in the path of light to R2 only, the bridge will become unbalanced and the change can be amplified and used to measure the light attenuation.

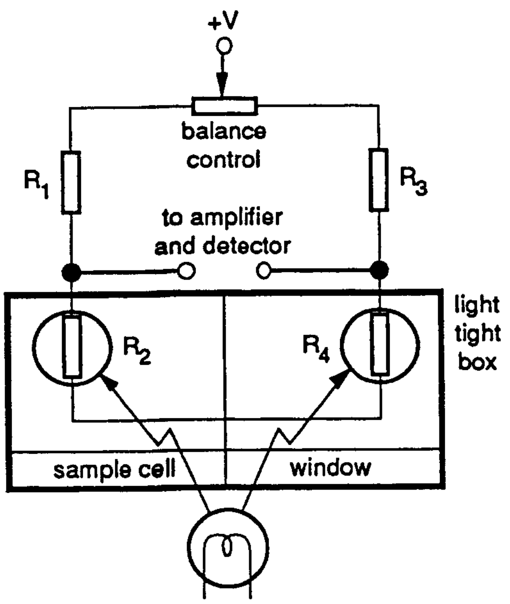


Fig 6.25.9

Photoconductive cells have a relatively long response time, which means that they cannot be used for fast moving processes. Other devices with this capability are examined in future assignments. In contrast CdS cells are inexpensive and have a long life, typically up to 10,000 hours. Their response is temporarily impaired by exposure to strong light, but they recover by themselves and are not damaged. Damage may be caused by electrical overload, and thus the applied voltage and current for the required illumination must be known. If in doubt, a series resistor can be incorporated to limit the current. Overheating can cause damage, but the device is usually vibration resistant.

Finally, a brief description of how these transducers are manufactured. More details can be found in the manufacturer's literature.

Photoconductive Cells are made by chemically sintering the required powder (e.g Cadmium Sulphide) into tablets of the required shape, and enclosing them in a protective envelope of glass or plastic. Electrodes are deposited on the tablet surface and are made of materials which give an ohmic contact, but with low resistance compared with that of the photoconductor. Gold is typically used. The electrodes are usually inter-digital, ie the form of interlocked fingers or combs, as shown in fig 6.25.10.

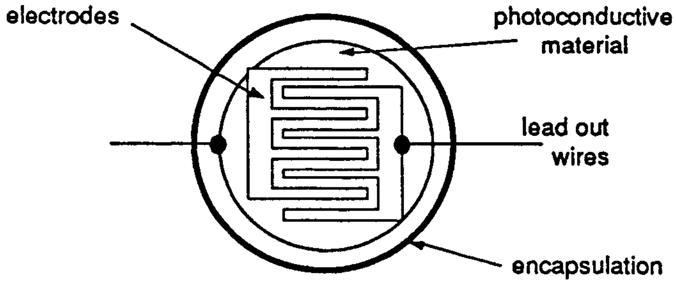


Fig 6.25.10

The design of the electrode system affects the resistance and voltage ratings of the cell, so that different resistances and voltage ratings can be achieved on a table of a given size. A device with a small number of widely spaced electrodes will have a higher resistance and voltage rating than a device using the same tablet with a large number of closely spaced electrodes. Devices can be made for end on or side illumination, and the encapsulation is hermetically sealed so that it is tropic proof, shock and vibration resistant.

Exercise 25.1 Typical resistance figures are shown in fig E6.25.5.

Applied Voltage = 6.5V

Relative Illumination (%)	Scale Setting	Current (mA)	Device Resistance (Ω)
100	90.0	9.70	670
90	87.5	9.29	700
80	84.0	8.86	734
70	80.5	8.42	772
60	75.5	7.89	824
50	69.5	7.33	887
40	61.0	6.62	982
30	48.5	5.86	1109
25	40.0	5.49	1184
20	28.0	5.23	1243
10	32.0	4.29	1515
0	lamp off	3.36	1935
transducer facing into box (at hole position 1)		0.011	591K

Fig E6.25.5

Exercise 25.2 The shape of the graph is shown in fig E6.25.5.

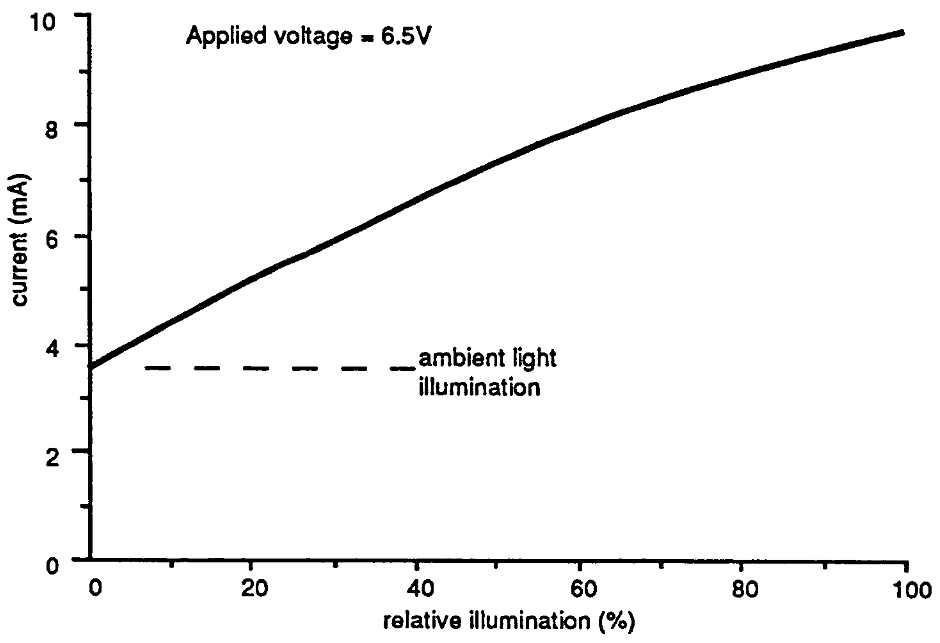


Fig E6.25.5 graph

TYPICAL RESULTS AND ANSWERS — Assignment 25

Question 25.1

It does not pass through the origin due to ambient lighting and the device dark current.

Exercise 25.3

A linearity of 5% over a current range between 4.4 and 8.4mA should be expected.

The effect of ambient lighting is to reduce the range of illuminations over which this holds.

Question 25.2 and Question 25.3

These questions, about dark current and resistance, are answered in the Practical Aspects section.

Exercise 25.4

Typical response figures are shown in fig E6.25.6

Angle (degrees)	Current (mA)
30 ACW	0.45
25	0.97
20	2.41
15	5.69
10	8.43
5	9.44
0	9.67
5 CW	9.61
10	8.91
15	6.38
20	3.45
25	1.56
30	1.22

Fig E6.25.6 (table)

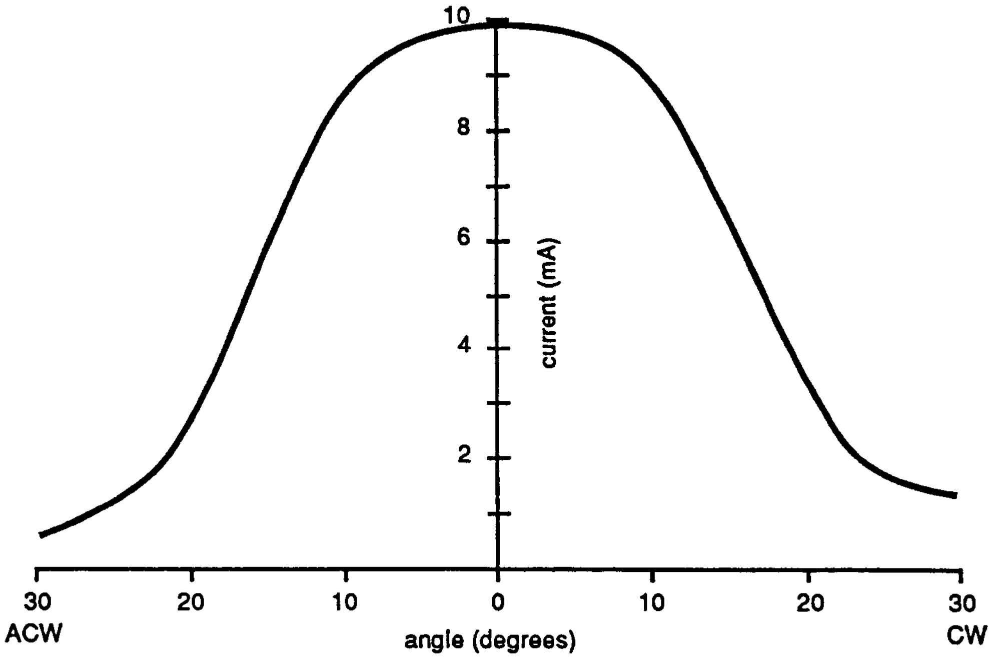


Fig E6.25.6 (graph)

Question 25.4 The useful range of the device is between ±14°.

Question 25.5 The cosine law is not followed due to the geometry of the box.

Question 25.6 and Question 25.7 The advantages and disadvantages of the transducer, and some of its uses are discussed in the Practical Aspects section of the manual.

NOTES

THE SEMICONDUCTOR PHOTODIODE **ASSIGNMENT 26**

CONTENT

The illumination and polar response of a silicon semiconductor photodiode are measured. The use of the device is investigated.

EQUIPMENT REQUIRED

Qty	Designation	Description
1	TK2941A	Instrumentation Module
1	TK294	Linear Transducer Test Rig
1	–	Lampholder
1	TK294	Light Transducer Box
1	–	Power Supply +15V dc *(e.g Feedback PS446)*
2	–	Voltmeter 15V dc *

* Alternatively multimeters may be used.

PRACTICALS

26.1 Photodiode Reverse Characteristic

26.2 Photodiode Load Line

26.3 Polar Characteristic

THE SEMICONDUCTOR PHOTODIODE — ASSIGNMENT 26

OBJECTIVES

When you have completed this assignment you will:

- Have observed the effect of incident light on the behaviour of a semiconductor photodiode.
- Recognise the term 'reverse leakage current'.
- Have measured the illumination and polar response of a semiconductor photodiode.

KNOWLEDGE LEVEL

Before starting this assignment you should:

- Understand the basic theory and operation of semiconductor devices.
- Understand the basic theories concerning the nature of light.
- Understand the operation of an operational amplifier.
- Be familiar with the use of the Optical Detector Assembly and the Linear Transducer Test Rig; and preferably have completed Assignment 24, The Nature of Light.

INTRODUCTION

In a block of doped semi-conductor material exposed to light, light photons liberate charge carriers within the material which are then free to constitute a current. Let us now see what happens if a PN junction is illuminated.

Firstly, we must recall the principle of an ordinary semi-conductor diode. If P-type and N-type semi-conductor materials are chemically joined together to form a junction, some of the holes and electrons recombine near the junction and form a *depletion layer* with no charge carriers. The P-type material loses holes and thus becomes negatively charged; the N-type material loses electrons and thus becomes positively charged near the junction. An electric field therefore exists across the junction. If a battery is connected across the junction, positive terminal to the P-type, this weakens the electric field and if the voltage is increased beyond a certain value, a current will flow. This is the *forward bias* condition.

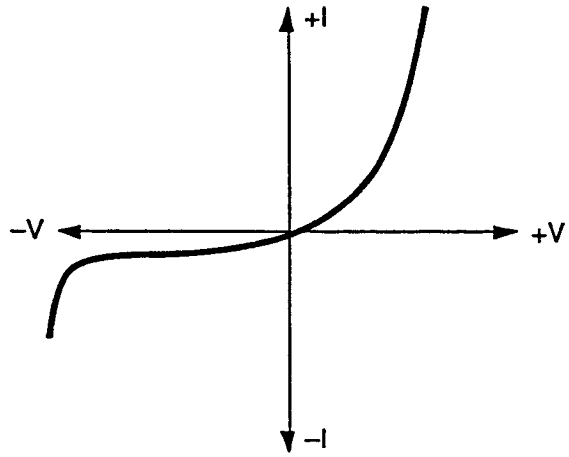
If the battery is connected the other way round, positive terminal to N-type, this reinforces the electric field and no current flows. This is the *reverse bias* condition.

We thus have a *rectifier.*

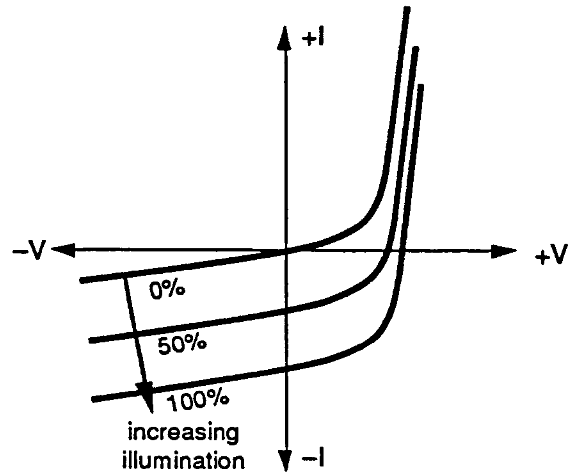
Actually with reverse bias, a small current does flow. This is because thermal effects generate hole/electron pairs in the material. If these minority carriers are generated in, or diffuse into the depletion layer, the holes travel into the P-type and the electrons travel into the N-type due to the electric field. They return to the regions in which they are majority carriers and thus form a small current. This is known as the *reverse leakage current.* It is temperature dependent, and increases slightly with reverse bias, until the reverse bias is too great and the junction breaks down. These characteristics are indicated in fig 6.26.1(a).

If light is allowed to fall on the semi-conductors, the photons liberate extra hole/electron pairs. The effect is much greater on the minority carriers, since there are fewer of them in the first place, than majority carriers. These injected minority carriers diffuse to the junction, cross it, and contribute to the current.

Thus you can see that this extra current is of the same form as leakage current. The characteristic is therefore progressively shifted downwards from the origin by an amount equal to the photon current, as shown in fig 6.26.1(b).



(a) in darkness



(b) when illuminated

Fig 6.26.1 PN junction diode characteristics

First we are going to plot these characteristics, then investigate how to utilise this phenomenon. We can reverse bias the photodiode and measure the current flowing. Alternatively, if the diode is left open-circuit, the extra charge carriers will produce a voltage across it, as indicated on the righthand side of the graph of fig 6.26.1(b).

This *photovoltaic effect* can be more fully examined in Assignment 27. Meanwhile a more theoretical explanation of the effect follows, in order to complete the study. If you like you may omit this without disadvantage and proceed directly to the practical section.

The treatment here can only be brief, and you are referred to any of the standard textbooks for a fuller explanation.

When p and n materials are chemically brought together, electrons and holes recombine near the junction to form a depletion layer as indicated in the previous paragraphs. This continues until the probability that a given energy level is occupied, is the same on each side of the junction. This means that the Fermi levels must be the same, and the energy band diagram is as shown in fig 6.26.2, if no bias is applied.

The donor and acceptor levels are now shown for clarity.

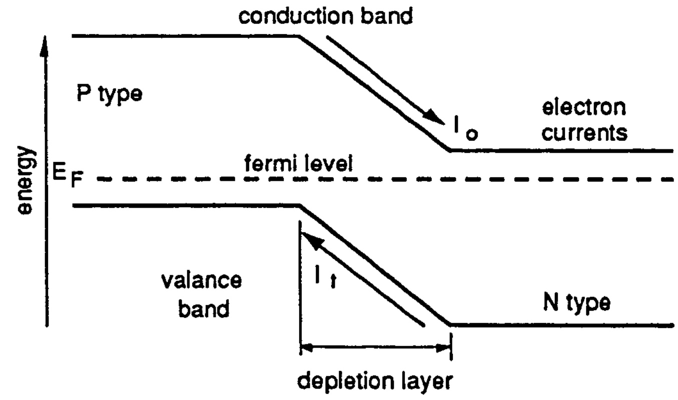


Fig 6.26.2

Thus an electric field exists across the junction whose magnitude depends upon the energy gap of the material. It is represented on the diagram by the sloping lines in the depletion layer. In such a diagram, electrons tend to run downhill, and holes tend to float uphill. Such minority carriers are generated thermally and diffuse across the junction. Under zero bias conditions, an equal and opposite drift current must flow. This is composed of some majority carriers having sufficient energy to overcome the small barrier and cross the junction.

If the junction is now forward biased, the height of the potential barrier across the depletion layer is effectively decreased and this makes it easier for the majority carriers to cross the junction. Sizeable currents may flow.

If the junction is now reverse biased, the height of the barrier is effectively increased. Only the very highest energy majority carriers can now cross the junction, but there will still be a small reverse current flowing.

This is the reverse leakage current, I_o, caused by thermally generated minority carriers being swept across the junction by the depletion layer field. This diffusion current is thus almost independent of the reverse bias.

If the junction is now exposed to light, the photons generate extra hole/electron pairs and these contribute to the reverse current which therefore becomes pI_o where p is a constant depending upon the level of illumination (number of photons).

The trapping effects mentioned in Assignment 25 for bulk photoconductors are not relevant here if the light is allowed to fall on the junction, as the depletion layer is very thin.

It can be shown that the magnitude of the forward current depends on the number of majority carriers with energy greater than the energy required to surmount the barrier; this is given by the equation:

$I_f = I_o \exp(-eV/kT)$

where:
I_o is the reverse leakage current
k is Boltzmann's Constant (1.3806×10^{-23} joule/°K)
T is the absolute temperature (°K)
$-e$ is the electron charge (1.6021×10^{-19} coulomb)
V is the potential difference across the junction, positive for forward bias and negative for reverse.

But there will always be the leakage current I_o present.

Thus the total current flowing is $I_f - I_o$ or $I_d = I_o(\exp(-eV/kT) - 1)$

This is the standard diode equation. Note that it gives the following results:

With zero bias ($V = 0$), as $I = 0$ as I_f and I_o cancel.

With reverse bias (V negative), the exponential quantity is very small and

$I \approx -I_o$

Thus the reverse leakage current is almost independent of the applied reverse voltage but more dependent upon temperature.

This equation holds good for low reverse voltages until reverse breakdown, and for low forward currents until the resistance of the diode or the contacts begin to have an effect.

We can consider now the equivalent circuit of the photodiode. If we ignore the series resistance we can represent the photon current by a constant current generator of magnitude I_p ($=pI_o$) in parallel with an ideal diode. Also across the junction is a capacitor. The depletion layer is effectively a capacitor as it consists of two opposite charges separated by a layer of material. The capacitance depends upon the applied voltage, but in many applications it can be neglected. This arrangement is shown in fig 6.26.3. R_L is a load resistor which may be connected.

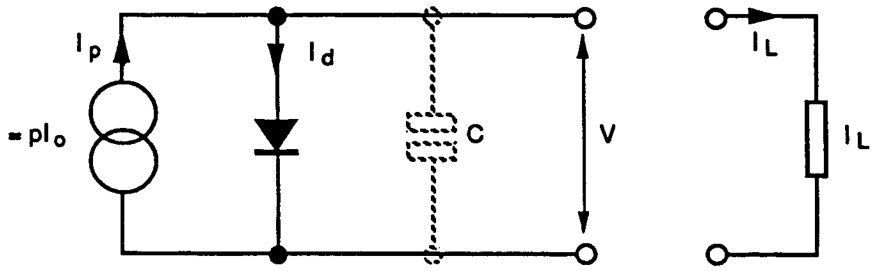


Fig 6.26.3

The load current $I_L = I_p - I_d$

substituting $I_L = pI_o - I_o\,[\exp(-eV/kT) - 1]$

$I_L = I_o\,[p+1 - \exp(-eV/kT)]$

With the load short circuit, this is the photodiode mode we will investigate,

V = O and the load current I_L is the short circuit current I_{sc}

Thus, putting V = O in the equation:

$$I_{sc} = I_o\,[p+1 - \exp(0)]$$

$$\therefore \quad I_{sc} = pI_o$$

Thus I_{sc} is directly proportional to p; i.e the short-circuit current is directly proportional to the level of illumination. This assumes that I_o is constant thus the photodiode is likely to be temperature sensitive.

With the load open-circuit. This is the photovoltaic mode which can be investigated more fully in Assignment 27. Here no current flows and $I_L = 0$ and we can thus obtain an expression for the open-circuit voltage V_{oc} by equating the equation to zero.

i.e $\quad 0 = I_o\,[p+1 - \exp(-eV_{oc}/kT]$

or $\quad \exp(-eV_{oc}/kT) = p+1$

Taking natural logarithms of both sides:

$$-eV_{oc}/kT = \log_e(p + 1)$$

or $$V_{oc} = \frac{kT}{-e} \cdot \log_e(p + 1)$$

Thus the open-circuit voltage is a logarithmic function of the level of illumination. As the expression does not include I_0 and T appears in the numerator, the photovoltaic cell is likely not to be as temperature sensitive as the photodiode.

For load resistors in between these two extremes the situation is more complex. Here we aim for maximum power output. The choice of load resistor depends upon the reverse bias (if operated as a photodiode) and inversely upon the level of illumination i.e more light needs a lower resistance for maximum output. Complex mathematics are required to demonstrate this which is beyond the scope of this manual. Empirical formulae can be derived to give satisfactory results, and one is

$$R_{optimum} = 0.86 \frac{V_{oc}}{I_{sc}}$$

where V_{oc} is the open-circuit voltage

I_{sc} is the short-circuit current for the maximum level of illumination at which the device is to be operated.

This result will be referred to again in Assignment 27.

PRACTICAL 26.1

Photodiode Reverse Characteristic

We want to measure the current flowing through the photodiode for different light intensities as we control the bias voltage. The normal way to do this is to have a resistor in series to measure the current, as in fig 6.26.4. A much better method, which avoids much calculation, is to use an operational amplifier. Referring to the theory in Appendix D, the inverting input of the amplifier is virtual earth, and if we connect the photodiode as in fig 6.26.5, it is effectively working under short-circuit conditions and driving current into the amplifier.

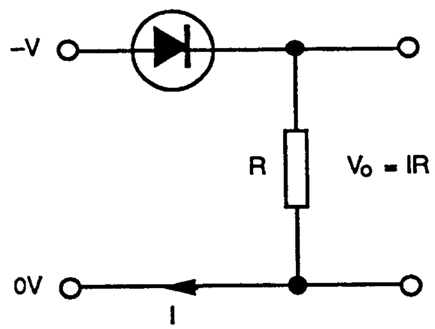


Fig 6.26.4

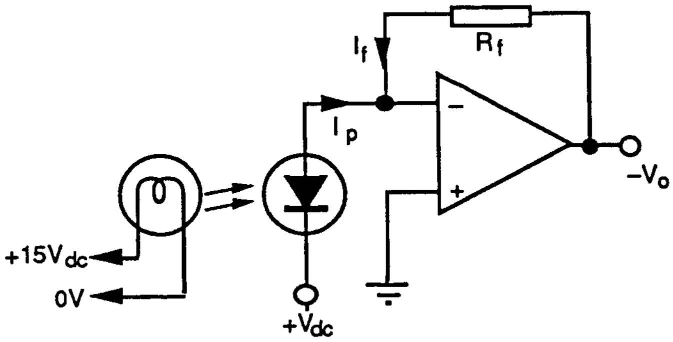


Fig 6.26.5

By Kirchoff's laws,

$$I_p = I_f = \frac{-V_o}{I_{sc}}$$

Thus by knowing R_f and measuring V_o we can calculate the current supplied by the photodiode. The cathode is connected to a positive variable d.c supply to ensure that the photodiode is under reverse bias.

The switch which controls the gain of the Operational Amplifier in TK2941A changes R_f as follows:

gain setting	R_f
1	100K
10	1M
100	10M

Thus if we set the gain to 10 and we measure V_o as –1 volt, we have 1µA flowing. V_o will be negative due to the polarity reversal of the amplifier.

Mount the lamp holder on the Linear Transducer Test Rig and connect the two leads from it to the 0V and +15V sockets on the module.

Position the Light Transducer Box on the Linear Transducer Test Rig in the set of holes nearest to the lamp, with the aperture in front of the transducers facing the lamp. Ensure that the infra-red absorbent glass, in its carrier, is removed from inside the box.

Set the gain of the Operational Amplifier to 10, connect your voltmeter to the output of the amplifier.

Although ambient lighting does not have any great effect, ensure that the transducer is not facing directly into a window or other light source, as excessive lighting could swamp your readings.

Connect up the circuit of fig 6.26.5 as shown in fig 6.26.6. Position the lamp holder at the position corresponding to 100% Relative Illumination by reference to the table given in Assignment 24.

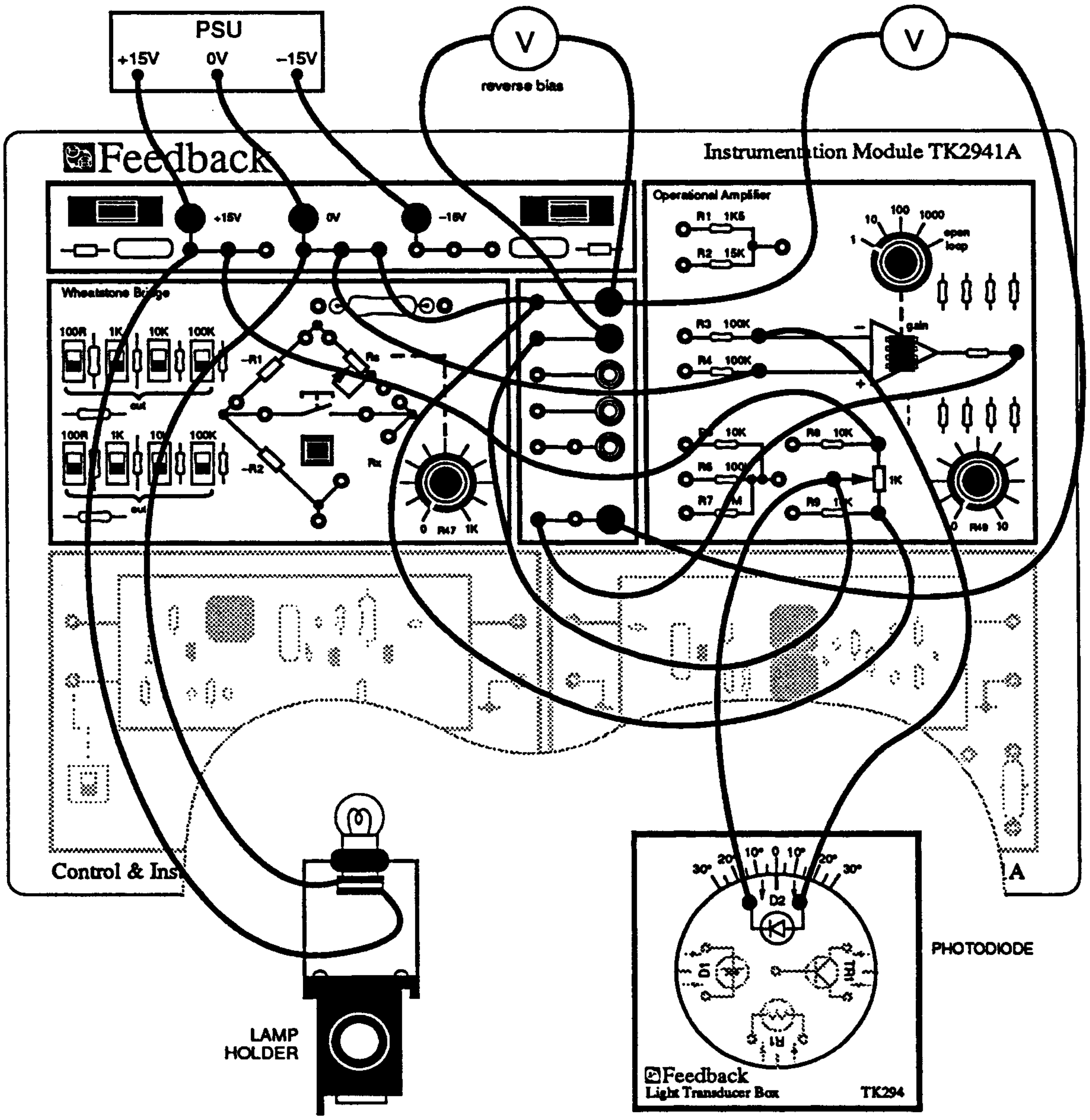


Fig 6.26.6

Switch on the power supply and check that the lamp is lit. Rotate the Optical Detector Assembly until the voltmeter on the output of the amplifier shows a maximum. This ensures that light is falling perpendicularly on the transducer and we have maximum sensitivity. Do not move this scale during your experiment.

Now use the potentiometer control on the Operational Amplifier section of TK2941A to set the variable d.c voltage in steps to 0, −1, −2, −5, −10 and −15V and read the amplifier output voltage at each step. Record your readings in your own copy of the table shown in fig 6.26.7. Since the feedback resistor of the amplifier is 1MΩ the input current in μA is numerically the same as the output voltage in volts and you may record the value directly in the current column.

Reverse Bias (V)	Reverse current (μA) for values of Relative Illumination (%)					
	100	80	60	40	25	10
0						
−1						
−2						
−5						
−10						
−15						

Fig 6.26.7

Move the bulb backwards to vary the illumination on the transducer according to the table of distances given in Assignment 24. At each value of illumination, 80%, 60%, 40%, 25% and 10%, repeat the measurements above and record the values in the remaining columns of your table.

If you are doing the experiment in daylight, take your readings as quickly as possible in case the daylight varies. Also keep your hands away from the rig when taking readings in case they cause unwanted reflections of light onto the transducer.

Disconnect the light bulb and see if you can obtain any current at any value of variable d.c voltage. Rotate the transducer so that it faces into the box and see if you can obtain any readings in total darkness.

Exercise 26.1

On the same sheet of linear graph paper, plot graphs of reverse current against reverse voltage, for each value of illumination. Use axes as shown in fig 6.26.8. (Remember you are in fact plotting the reverse characteristics of a diode). Label your curves with the value of relative illumination used.

Question 26.1

Do the graphs support the theory that the light photons produce extra current of the same form as leakage current?

Question 26.2

What can you say about the variation in reverse current if the illumination stayed constant but the bias voltage varied?

What parameter of the diode is used to define this?

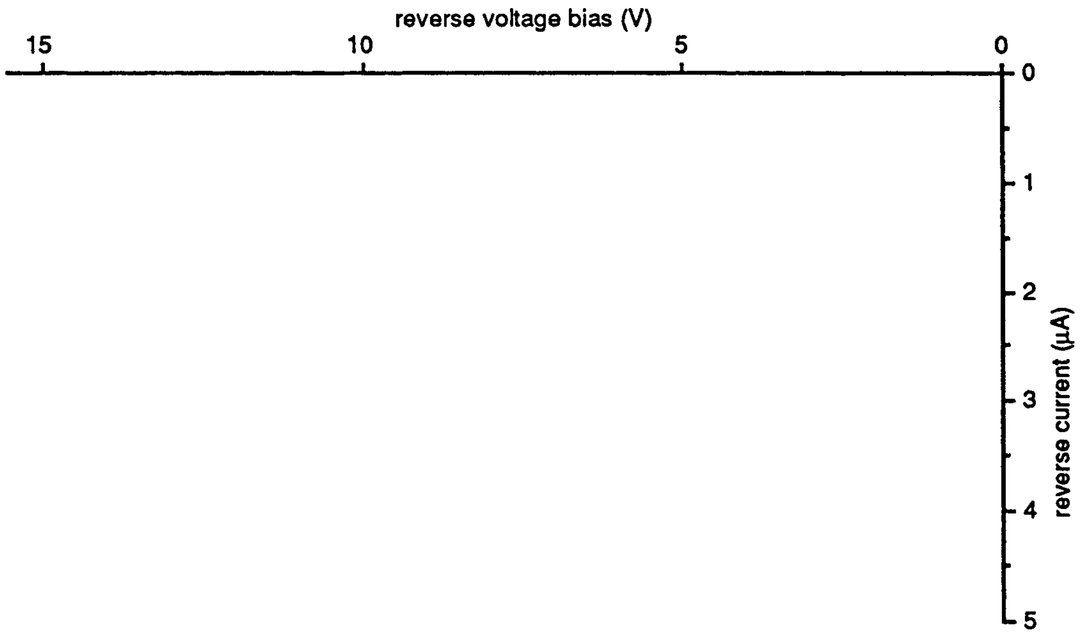


Fig 6.26.8 Photodiode reverse characteristics

Let us now see if we can find the exact form of the variation of current with illumination for a fixed bias voltage. We are going to use exactly the same circuit and first set the bias to a fixed value. Let us use –15V.

PRACTICAL 26.2

Photodiode Load Line

With the circuit of fig 6.26.6 still connected, reset the bulb-transducer distance to that corresponding to 100% relative illumination. Adjust the variable d.c voltage to 15V and rotate the transducer for maximum output from the amplifier. You should find that this is the same as you obtained before, if the ambient light has not changed. Do not adjust the variable d.c control during this experiment. Observing the same precautions as before, vary the values of relative illumination by increasing the bulb-transducer distance according to the table given in Assignment 24. At each step read the amplifier output voltage and record your readings in your own copy of the table shown in fig 6.26.9. Disconnect the lamp and see if any current is indicated.

Relative Illumination (%)	Scale Setting (mm)	Current (μA)
100		
90		
80		
70		
60		
50		
40		
30		
25		
20		
10		

Illumination Characteristics with –15V bias

Fig 6.26.9 Photodiode Illumination Characteristics

Exercise 26.2

Plot a graph on linear graph paper of current in μA against relative illumination %. Extrapolate your graph in dotted line to zero illumination. Label your graph with the value of bias voltage used.

Question 26.3

What shape is the graph? Does the extrapolation pass through the origin, if not can you think why not?

Question 26.4

Why do you think it was difficult to take a reading corresponding to zero illumination?

Before going on to the polar characteristics we must discuss load lines as applied to the photodiode.

As explained earlier, all our practical work has been measuring the current a photodiode can produce into a zero resistance. If we have an open circuit and therefore no bias, a voltage is produced. This is more fully investigated in Assignment 27. However if we have a finite load resistance in our reverse bias condition, things are a little different. You have verified the curves of fig 6.26.8, repeated below. When you plotted the illumination characteristics for –15V current, this voltage remained constant as the current was driven into a short circuit, and did not affect the reverse bias on the photodiode. We can draw on this graph a *load line* for zero resistance as shown in fig 6.26.10 which is applicable when the photodiode is used as we have used it in this Assignment, that is in the input of an operational amplifier.

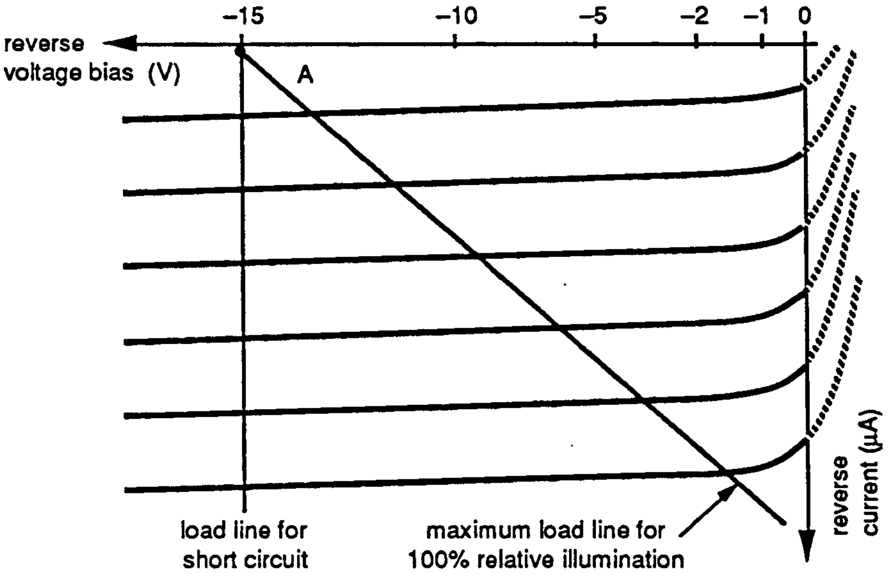


Fig 6.26.10

However, if we wished to use a circuit like that of fig 6.26.4, the load resistor could not be zero or very low as no voltage output would be achieved. How high could the load resistor safely be made?

To answer this, consider a load line for some non-zero resistance R; for a fixed bias this would also start from point A and have a slope determined by the resistance, intersecting the current axis at a value:

$$I = \frac{15}{R} \quad \text{eg for } R = 1M\Omega, \quad I = \frac{15}{10^6} = 15\mu A$$

If we wish the voltage developed across R to increase steadily with the illumination we must arrange that this load line intersects the characteristic corresponding to the maximum desired illumination at a point just above its 'knee' (the point where the current just starts to fall sharply with reducing bias). A typical load line meeting this requirement has been drawn in fig 6.26.10.

Exercise 26.3

On your graph of the photodiode reverse characteristics, draw what you consider to be the maximum load line for the levels of illumination we have used. Calculate the resistance corresponding to this load line.

Before we discuss your results, let us see how the angle at which light falls on our transducer affects its response.

PRACTICAL 26.3

Polar Characteristic

With the circuit of fig 6.26.6 still connected, reset the bulb-transducer distance to that corresponding to 100% relative illumination. Set the variable d.c to 15V and do not adjust it further during the test.

Now set the angular scale to 30° anti-clockwise and record the current flowing. Repeat these readings for angles of 25°, 20° and so on at 5° intervals up to 30° clockwise. Record your results in your own copy of the table shown in fig 6.26.11.

Angle (degrees)	Current (μA)
30 ACW	
25	
20	
15	
10	
5	
0	
5 CW	
10	
15	
20	
25	
30	

bias = −15V

Fig 6.26.11 Polar Characteristics of Photodiode

When you are setting the angles, take care to look directly on top of the transducer box when aligning the marks, to avoid parallax. Again, perform the experiment as quickly as possible and take your hands away from the rig when taking readings.

Exercise 26.4 ***Plot a graph on linear graph paper of current against angle. You may alternatively plot this graph on polar (circular) paper if available.***

Exercise 26.5 ***Finally look into the transducer itself. Note the size of the active area compared with the device size.***

Question 26.6 ***Why do you think ambient lighting has only a very small effect in this experiment?***

The spectral response of this transducer when plotted with advanced equipment, shows that the peak response of such a silicon transducer is at about 800nm — well into the infra-red region of the spectrum.

Question 26.7 ***Taking what we have just said into consideration, with your results, can you suggest some uses for such a transducer?***

Question 26.8 ***Can you suggest the principal advantages and disadvantages of the semiconductor photodiode?***

PRACTICAL ASPECTS

It is important to realise that the photodiode and the photovoltaic cell are similar devices operating on the same principle, that of a single pn junction. Then we can discuss the relative merits of one method of operation over the other, and the differences in construction of the two devices. The photodiode may be examined fully in Assignment 27, but if things are not clear at this stage, re-read the introduction to this Assignment or ask you instructor.

The reverse characteristic curves you produced show that the photon current is of the same form as reverse leakage current. This photocurrent is only slightly dependent on reverse voltage and this indicates a high dynamic source resistance, typical of a constant current source. Also, at a constant reverse bias, the output photocurrent is linear with illumination. It is found that this holds good for several decades of illumination.

This advantage of excellent linearity may offset the disadvantage of having to provide a bias source. However this source does not have to be precisely stabilised because of the high dynamic resistance of the device. We will call this the *current* mode of operation. The leakage current with no illumination is very low — typically a few nano-amperes.

The physical construction of the device is shown diagramatically in fig 6.26.12.

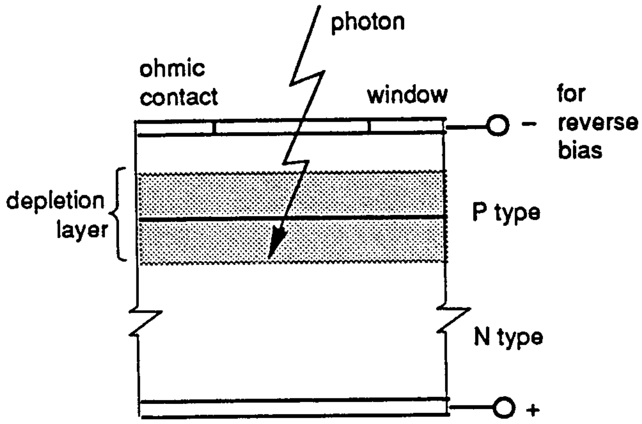


Fig 6.26.12 Cross section of typical pn junction photodiode

The generation of hole/electron pairs by the incident photons occurs at various depths depending on the energy of the photons and the nature and thickness of the material. In order to ensure that the maximum number of these reach the depletion layer, where they are swept across by the electric field and contribute to the current, it is necessary to make the top (p) layer as thin as possible, and the depletion layer as wide as possible for good efficiency. The depletion layer can be widened by increasing the reverse bias. In practice, efficiencies of the order of 10% are obtained. The sensitivity depends upon the distance from the junction at which the charge carriers are liberated.

Widening of the depletion layer also reduces the capacitance of the device, which reduces the response time. Thus a photodiode with reverse bias has a faster response time than a photovoltaic cell with zero bias, because of the wider depletion layer.

A special device, called a PIN photodiode may be used, if capacitance is a problem. An I or intrinsic layer is introduced between the p and n ends. This effectively increases the width of the depletion layer thus reducing the capacitance. Thus a faster response and low noise are obtained.

Typical values for a photodiode are:

Junction capacitance	10pF
Reverse resistance	50MΩ
Forward resistance	100Ω

The forward resistance depends upon the thickness of the layers.

The photodiodes are often manufactured by the well-known planar process. This gives a lower leakage current and therefore a high signal-to-noise ratio. This technique however can only be used for small area photodiodes of standard shapes. Ohmic contacts, often of gold, are bonded to the surfaces. These contacts have to be made to both top and bottom of the cell. Sometimes a 'wrap around' junction can be made by carrying the top surface round to the bottom.

This facilitates plug-in contacts being made to the bottom surface. Unencapsulated cells are coated with a protective varnish to maintain low leakage and the whole is then encapsulated in resin or any moulding required by the customer.

Because of their small area, their polar response is very narrow as you should have found, and thus ambient light has less effect. This small area may also be a advantage in precise measurements but is often a disadvantage, as a concentrated illumination is required. They are sometimes used with lenses to focus the light onto the active area.

If only a small portion of the active area is illuminated, the photon current reduces but the effective capacitance increases. The lowest light level of operation is determined by the signal-to-noise ratio (light-dark current ratio). Photocells are low current output devices, typically a few micro-amp, and amplification is often required. There is a maximum value of load resistor for each value of illumination and bias voltage that can be used if linearity is to be maintained, but this value is usually quite high, as you should have found from your results.

Care needs to be taken to ensure that the power rating of the transducer is not exceeded. As noted in the theory, the photodiode is rather temperature sensitive. Dark current doubles about every 10°C for Silicon and this increases the signal-noise ratio. Comparing junction photodiodes with the photoconductors of Assignment 25, the photodiode possesses considerably better frequency response, linearity, spectral response (see Assignment 29) and lower noise. The photodiode's disadvantages include small active area (although this may be an advantage as discussed), rapid increase in dark current with temperature, bias voltage requirement, and the necessity of amplification at low illuminations.

The circuit used in this assignment has become increasingly popular as integrated circuit operational amplifiers come down in price. It has the disadvantage of requiring a dual power supply but it has a linear voltage output capable of driving a meter direct. Thus it is used in high quality light meters for photometry and studio photographic use.

Some the applications in the next Assignment on the photovoltaic cell can also be applied to the photodiode. With some it is a matter of convenience; with others, the advantage of one or other of these two devices is apparent.

Because of their fast response time, photodiodes are used as cine film sound-track readers. The sound-track is printed on the film as a variable area. As it moves through the projector, it is examined through a fine (<0.1mm) slit, and the light falling on the photodiode is varied. The highest note that can be reproduced is thus dependent upon the response time of the photodiode as well as the film speed, the width of the slit and the definition of the photographic emulsion. This is shown diagramatically in fig 6.26.13.

Similarly, they can be used a detectors of modulated light in optical communication systems.

Fast response times are also necessary in switching circuits.

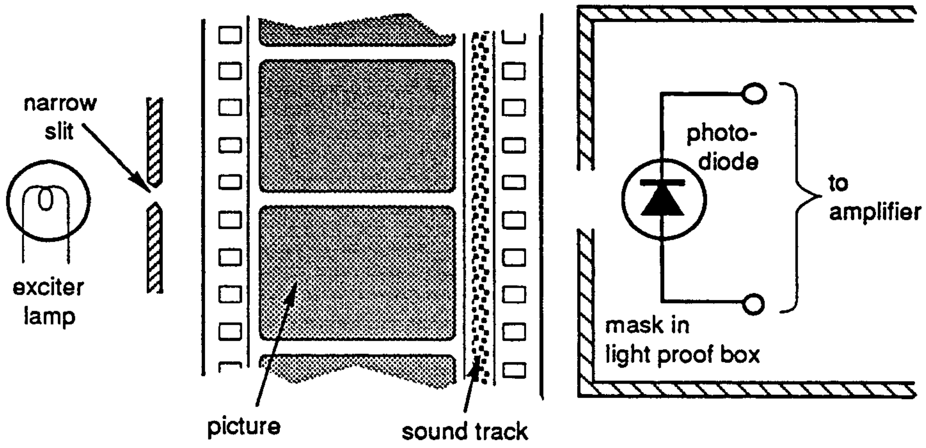


Fig 6.26.13

A switching circuit is shown in fig 6.26.14.

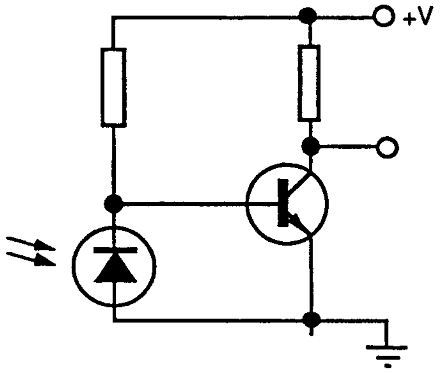


Fig 6.26.14

The transistor is normally 'on' due to current supplied by the base bias resistor. When the photodiode is illuminated the base current is reduced turning the transistor 'off'. The reverse bias is limited to V_{be} of the transistor.

Exercise 26.1

Typical results and graph for Practical 26.1 are shown in figs E6.26.7 and E6.26.8

Reverse Bias (V)	Reverse current (μA) for values of Relative Illumination (%)					
	100	80	60	40	25	10
0	–3.45	–2.73	–2.11	–1.42	–0.91	–0.73
–1	–3.62	–2.93	–2.26	–1.53	–0.97	–0.78
–2	–3.72	–3.02	–2.33	–1.58	–1.00	–0.81
–5	–3.89	–3.15	–2.44	–1.64	–1.05	–0.84
–10	–4.06	–3.28	–2.54	–1.73	–1.10	–0.88
–15	–4.17	–3.36	–2.62	–1.76	–1.15	–0.91

Fig E6.26.7

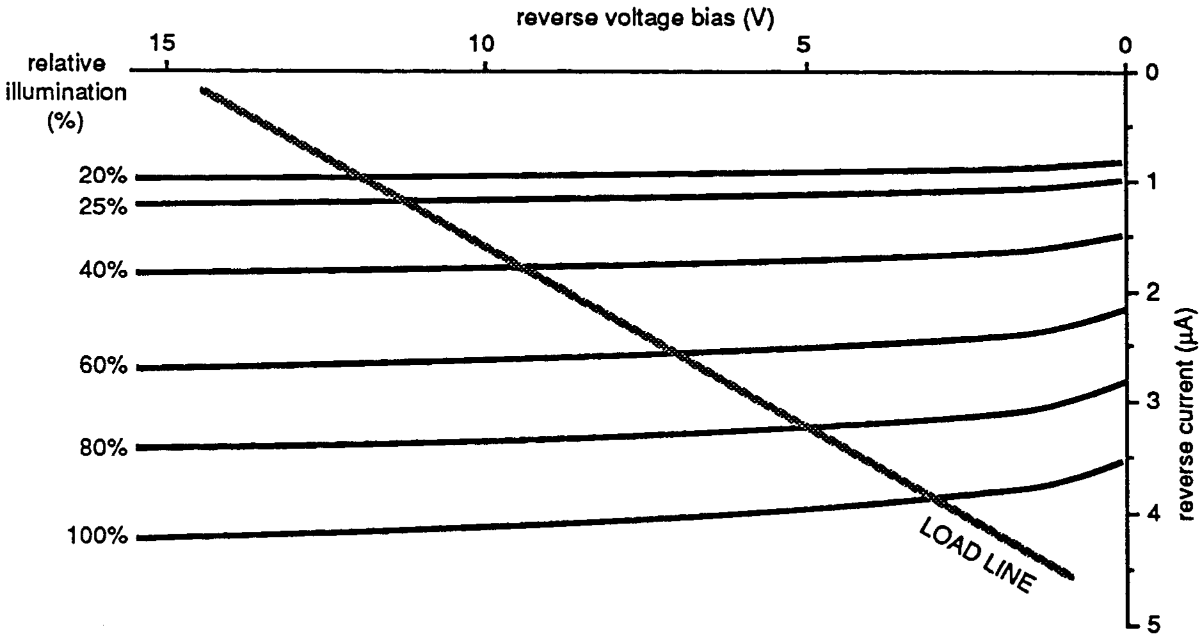


Fig E6.26.8

Question 26.1

The shape of the graph is as suggested in the theory and supports the idea that light photons produce extra current of the same form as leakage current and shift the curves.

Question 26.2

The lines are almost horizontal, so if the illumination stayed constant and the bias voltage varied, the current would not vary all that much. This is equivalent to a high diode reverse resistance.

Exercise 26.2

Typical results and graphs for Practical 26.2 are shown in fig E6.26.9.

Relative Illumination (%)	Scale Setting (mm)	Current (μA)
100	90.0	–4.15
90	87.5	–3.82
80	84.0	–3.37
70	80.5	–3.01
60	75.5	–2.60
50	69.5	–2.19
40	61.0	–1.77
30	48.5	–1.34
25	40.0	–1.15
20	28.0	–0.91
10	32.0 (Hole position 1)	–0.47

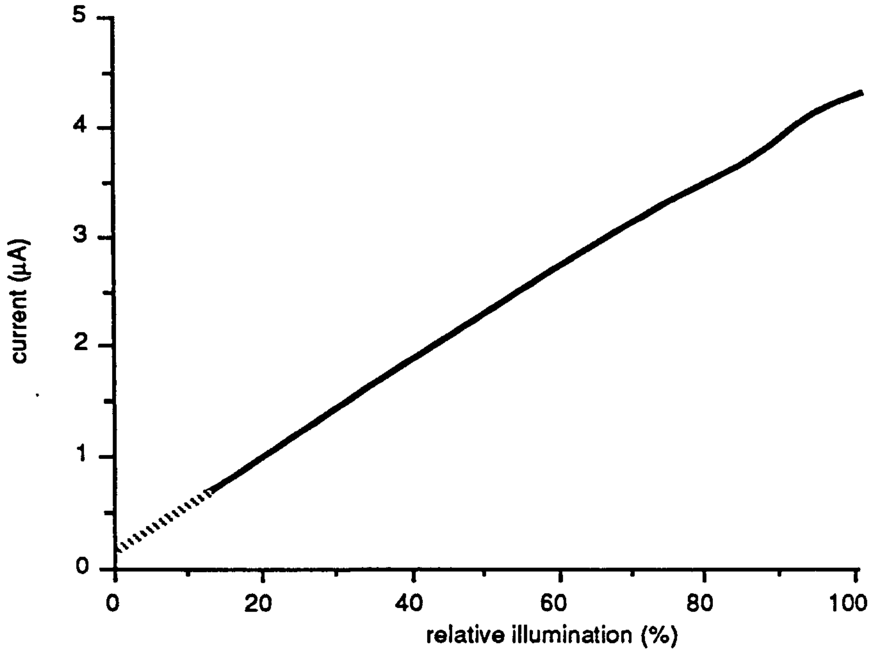


Fig E6.26.9

Question 26.3

The graph is a very good straight line. If you wanted to calculate linearity it would be less than 1% typically. The extrapolation does not pass through the origin due to the dark current of the device.

Question 26.4

The extrapolation may not give a true result, but indicates the dark current, as it is difficult to measure this due to noise.

Exercise 26.3

The maximum load resistance for the illumination levels we have used is about 3MΩ. This is because we are using comparatively low light levels. No resistor of this size is included in our kit, so it was not used in the experiments.

TYPICAL RESULTS AND ANSWERS

ASSIGNMENT 26

Exercise 26.2

Typical results and graphs for Practical 26.3 are shown in fig E6.26.11.

Angle (degrees)	Current (mA)
30 ACW	0.03
25	0.03
20	–1.07
15	–3.68
10	–4.04
5	–4.08
0	–4.21
5 CW	–4.12
10	–3.92
15	–0.08
20	–0.01
25	–0.03
30	–0.03

bias = –15V

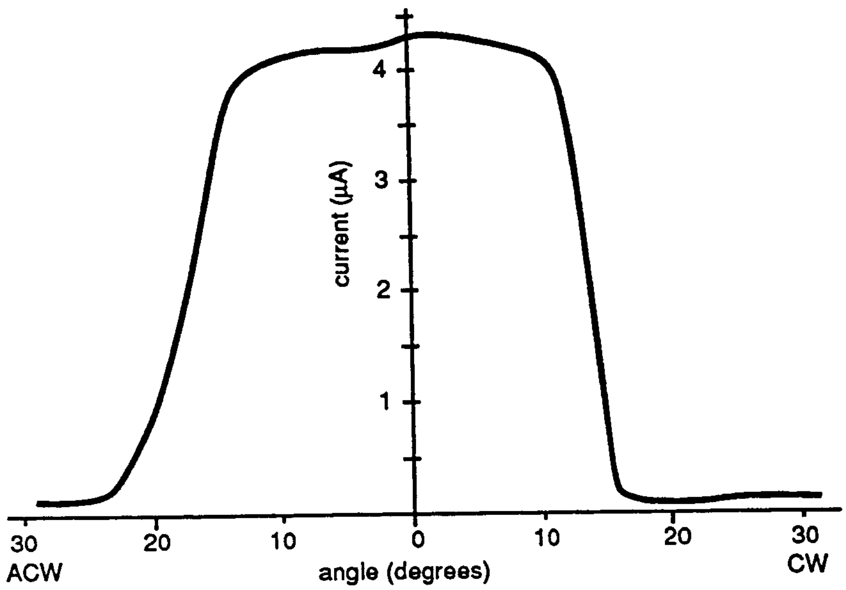


Fig E6.26.11

Question 26.5

The useful 'window' of the device is narrow, between +12° ACW and +9° CW.

Exercise 26.5 and Question 26.6

The active area of the transducer is small; therefore it has only a small operating angle and ambient lighting has only a small effect.

Question 26.7 and Question 26.8

The advantages and disadvantages of the transducer and some of its uses are discussed in the Practical Aspects section.

Assignment 27 has been removed from the curriculum.

Therefore, pages 435 to 459 have been removed.

THE PHOTOTRANSISTOR — ASSIGNMENT 28

CONTENT

The illumination and polar response of a silicon phototransistor are measured. The use of the device is investigated.

EQUIPMENT REQUIRED

Qty	Designation	Description
1	TK2941A	Instrumentation Module
1	TK294	Linear Transducer Test Rig
1	–	Lamp holder
1	TK294	Light Transducer Box
1	–	Power Supply ±15V dc *(eg Feedback PS446)*
1	–	Milliammeter 20mA dc *
1	–	Voltmeter 10V dc *

* Alternatively multimeters may be used.

PRACTICALS

28.1 Phototransistor Characteristics

28.2 Phototransistor Load

28.3 Polar Characteristics

THE PHOTOTRANSISTOR

ASSIGNMENT 28

OBJECTIVES

When you have completed this assignment you will:

- Have observed the effect of incident light on the behaviour of a phototransistor.
- Have measured the illumination and polar response of a phototransistor.
- Be able to compare the behaviour of a phototransistor with that of a bipolar transistor.

KNOWLEDGE LEVEL

Before starting this assignment you should:

- Understand the basic theory and operation of semiconductor devices.
- Understand the basic theories concerning the nature of light.
- Be familiar with the use of the Optical Detector Assembly and the Linear Transducer Test Rig; and preferably have completed Assignment 26, The Semiconductor Diode.

INTRODUCTION

Phototransistors combine the ability to detect light and amplify within a single device. They are similar to conventional bipolar transistors, except that part of the device is exposed to the light via a window or lens. Such an arrangement is equivalent to an ordinary transistor with a photodiode connected between the collector and the base, as shown in fig 6.28.1 together with the usual circuit symbol.

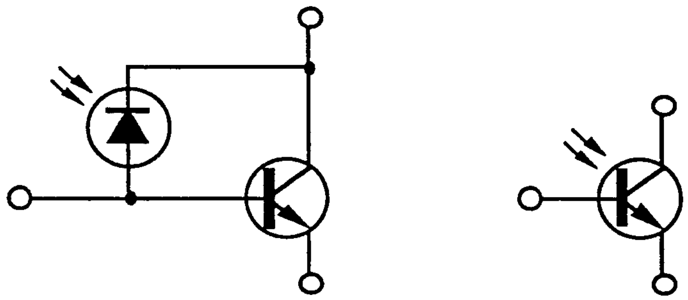


Fig 6.28.1

When a reverse-biased photodiode is illuminated, the light photons generate extra reverse current which is linear with the illumination. In normal operation the collector-base junction of a phototransistor is reverse-biased and this provides the photon current. This travels into the base region as a normal transistor receives base current from its bias network for example. This current is then amplified by normal transistor action.

We would thus expect to be able to plot the normal transistor characteristics, using illumination as a parameter instead of base current. This will then lead us to plot the illumination characteristics.

In the common emitter connection, the output circuit current is given by:

$I_C = h_{FE} I_B + h_{OE} V_{CE}$

Where the symbols have their usual meanings.

Now as $h_{OE} V_{CE}$ is very small

$I_C \approx h_{FE} I_B$

and h_{FE} is the current gain of the transistor.

In a phototransistor, the collector-base junction is reverse-biased and provides a base current linear with illumination.

Thus we would expect I_C to vary linearly with p (illumination) and be greater than the diode current by the factor h_{FE}

$$I_C = h_{FE}\, p\, I_O$$

This assumes that the transistor is always conducting and we will investigate graphically the effect of different load resistances.

First we are going to plot the standard transistor output characteristics for different values of illumination.

Although as explained in Assignment 24 and, as you will see, ambient lighting does not have any great effect, ensure that your transducer is not facing directly into a window or other light source, as excessive lighting could swamp your readings. The lens on the phototransistor helps to lessen the effect of stray lighting.

PRACTICAL 28.1

Phototransistor Characteristics

Mount the lamp holder on the Linear Transducer Test Rig and connect the two leads from it to the 0V and +15V sockets on the module.

Position the Light Transducer Box on the Linear Transducer Test Rig to the set of holes nearest to the lamp, with the aperture in front of the transducers facing the lamp. Ensure that the infra-red absorbent glass, in its carrier, is removed from inside the box.

Connect up the circuit of fig 6.28.2 with the phototransistor behind the aperture in the light box. Do not connect the base terminal of the phototransistor. Position the lamp holder at the position corresponding to 100% relative illumination by reference to the table given in Assignment 24.

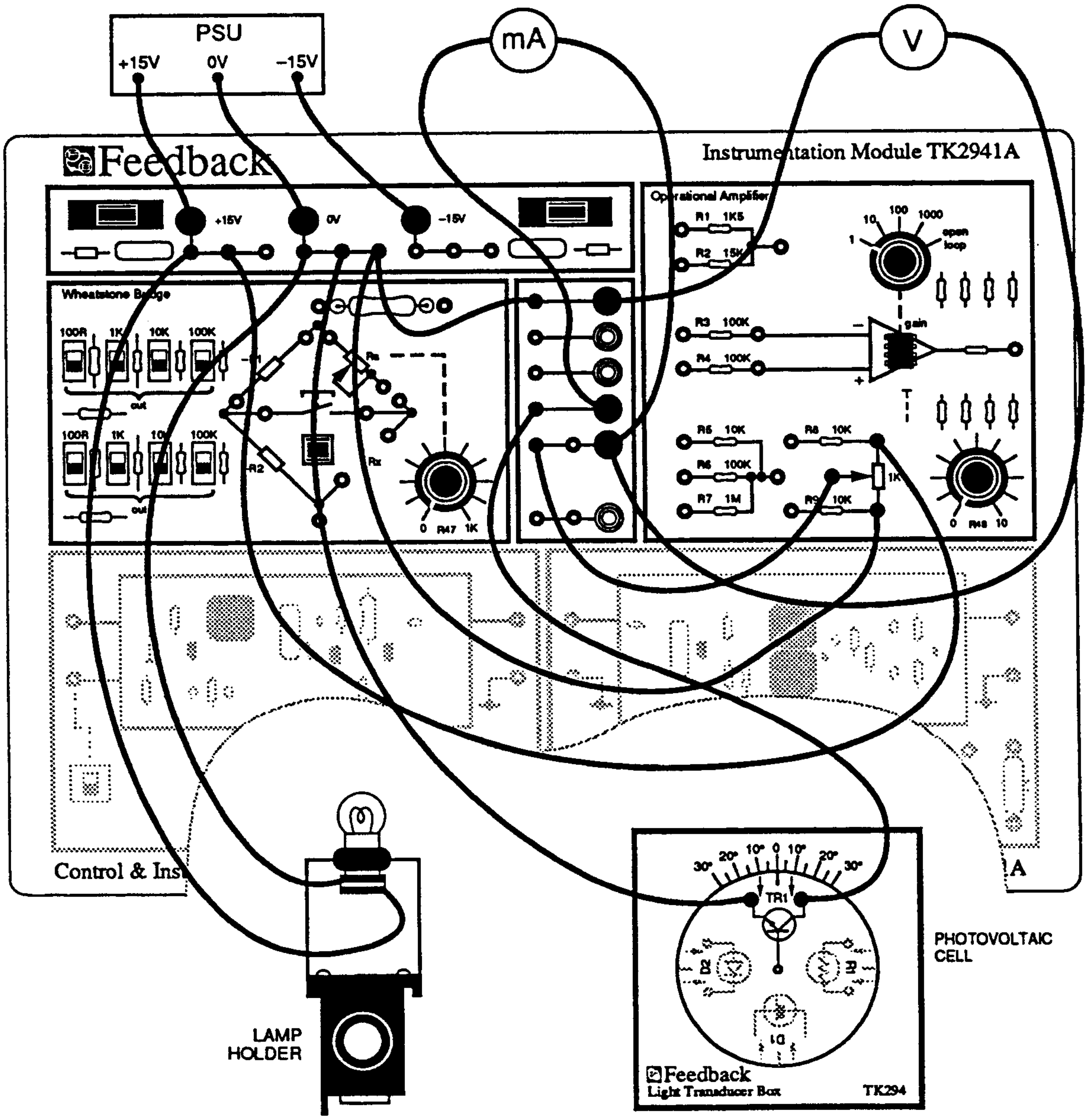


Fig 6.28.2

Check that the variable d.c is at minimum, with the potentiometer control on the Operational Amplifier set to 0, and switch on the power supply. The lamp should light.

Slowly increase the variable d.c. The meter should indicate a current. When the reading gets to between 8 and 10mA, stop. Now rotate the Optical Transducer Assembly against the scale on top of the transducer box, so that your milliameter reading is a maximum. You may need to adjust the variable d.c output control if you were a long way out initially. This ensures that the light is falling perpendicularly on the transducer and we have maximum sensitivity. Do not adjust this scale during your experiment.

Return the variable d.c to zero and draw up a table for your results as in fig 6.28.3. Adjust the variable d.c voltage in steps as indicated in the table and at each step record the current flowing. Move the bulb backwards to vary the illumination on the transducer according to the table of distances given in Assignment 24. At each value of illumination, 80%, 60%, 40%, 25% and 10%, repeat the measurements above and record the values in the remaining columns of your table.

If you are doing the experiment in daylight, take your readings as quickly as possible in case the daylight varies. Also keep your hands away from the rig when taking readings in case they cause unwanted reflections of light onto the transducers.

Bias voltage (V)	Current (mA) for values of Relative Illumination						
	Relative illumination (%)	100	80	60	40	25	10
	Scale setting (mm)	90.0	84.0	75.5	61.0	40.0	32.0 (Hole position 1)
0							
0.1							
0.2							
0.3							
0.4							
0.5							
1.0							
2.0							
5.0							
10.0							
12.0							
14.0							

Fig 6.28.3 Phototransistor Characteristics

Exercise 28.1

Plot graphs of current flowing against the supply voltage which, in this case, is also the collector-emitter voltage V_{ce} across the transistor. Label each curve with the value of relative illumination to which it corresponds.

Question 28.1

Are the graphs similar to the output characteristics of a normal transistor? Do they support the theory that the light photons produce an effect equivalent to base current?

Question 28.2

What can you say about the variation in collector current if the light intensity is held constant and the collector-emitter voltage is varied? What parameter of the phototransistor is used to define this? Is it the same for all values of illumination?

Before we look into the exact variation of collector current with illumination, we need to consider load resistance.

For the output curves you have just plotted, the phototransistor was effectively working into a short circuit, or zero resistance. This means that if our supply voltage was 10 volts, the whole of this voltage appeared between the collector and the emitter of our transducer for all values of illumination. This allowed current to flow in the collector circuit and this current did not reduce the voltage. This can be represented on our graph by a vertical load line as shown in fig 6.28.4.

The other limiting condition is with the collector open circuit. No current can flow at all.

In between these two limiting conditions, if we have a finite resistance in the collector circuit, as the collector current increases, the voltage drop across the load resistor will increase and this will lower the value of V_{ce} of the phototransistor. In the limiting case where the phototransistor is in the dark, we have all the voltage across our load resistor and no current flowing. (This is not strictly true, as a small leakage current does flow in the dark, but this can often be ignored). This state of affairs can be represented on your output graphs as a straight line whose slope is determined by the load resistance. This is also shown in fig 6.28.4.

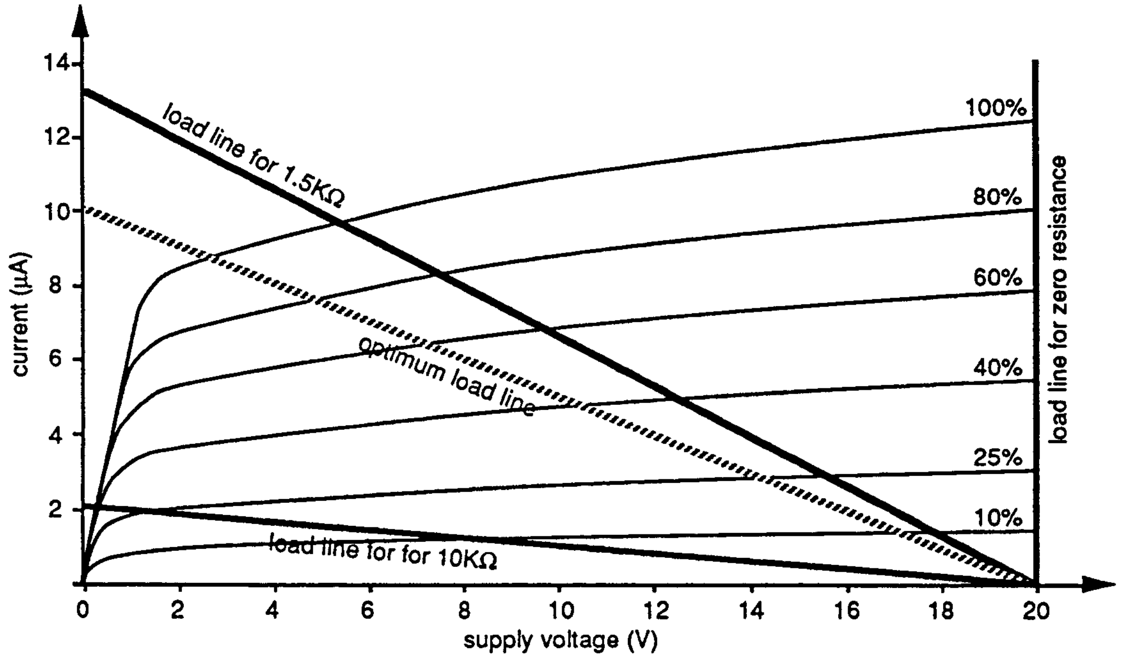


Fig 6.28.4 Load lines for a phototransistor

You should be able to see that if we wish to use the variation of voltage with illumination as the output of the transducer, then in order to avoid distortion, we must keep the load line above the knee of the curve so that the phototransistor is never limited.

To obtain maximum power output from the transducer there will thus be an optimum value of load resistance giving us maximum voltage swing with maximum current swing.

Question 28.3

Will this optimum value vary with the level of illumination and for the supply voltage?

Exercise 28.2

Mark on your graph what you consider to be the optimum load line for a 14V supply voltage and for the range of relative illuminations up to 100% that we have used. Calculate the optimum load resistance. Draw the load lines for 750Ω on your graph.

Question 28.4

If we vary the illumination from 10% to 100% with a supply voltage of 14V, for which value(s) of load resistance will the output be very distorted?

Let us see if you are right.

PRACTICAL 28.2

Phototransistor Load

First, leave the circuit of fig 6.28.2 connected up. With only the milliammeter in the collector circuit, this corresponds to zero load resistance.

Return the bulb-transducer distance to that corresponding with 100% relative illumination. Adjust the variable d.c voltage to 14V and rotate the transducer for maximum reading on the collector circuit milliammeter. You should find that this is the same reading that you obtained before, provided the ambient lighting hasn't changed. Do not adjust the variable d.c control during this experiment.

Observing the same precautions as before, vary the values of relative illumination by increasing the bulb-transducer distance. At each step read the collector current and record your readings in your own copy of the table shown in fig 6.28.7.

Switch off the power supply and reconnect the circuit to include a resistor in the collector as shown in fig 6.28.5. Select first the 1.5kΩ resistor. This corresponds to a module set up as shown in fig 6.28.6. Switch on the power supply and repeat the experiment with the variable d.c control set to 14V. Record your readings in the appropriate column of your table.

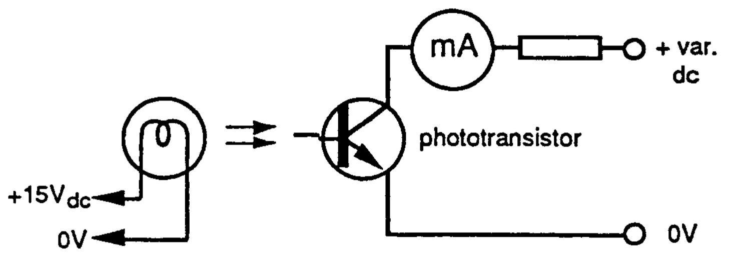


Fig 6.28.5

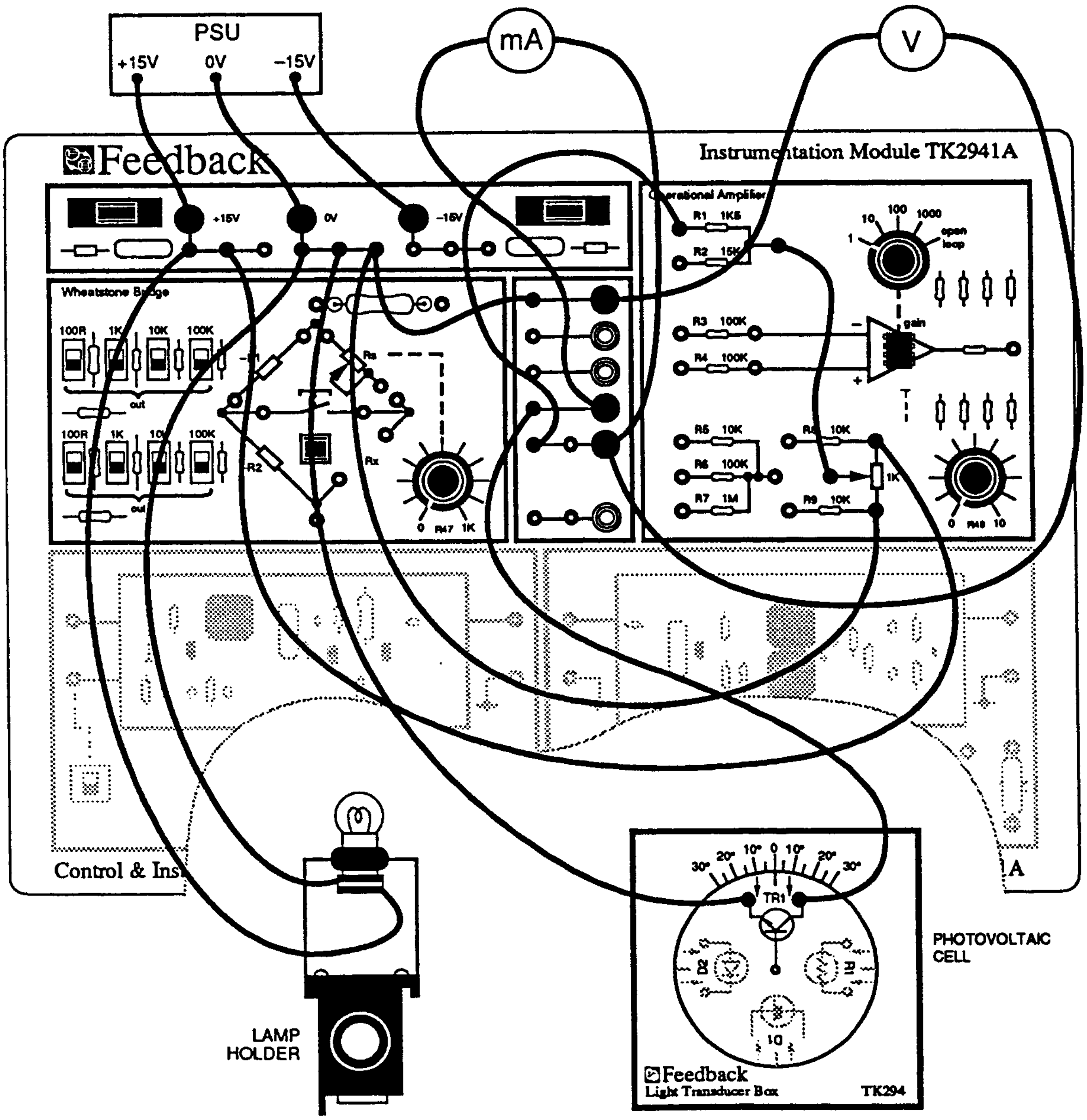

PSU
+15V
0V
−15V
mA
V
Feedback
Instrumentation Module TK2941A
Wheatstone Bridge
Operational Amplifier
Control & Ins
LAMP HOLDER
PHOTOVOLTAIC CELL
Feedback
Light Transducer Box
TK294
TR1

Fig 6.28.6

Replace the 1.5kΩ resistor with the 10kΩ resistor on the module and repeat the experiment again with a supply voltage of 14V. Record your readings in the appropriate column of your table.

Relative Illumination	Scale Setting	Current (mA) for values of load resistance with 14V applied		
(%)	(mm)	Zero	1.5kΩ	10kΩ
100				
80				
60				
40				
30				
25				
20				
10				
0				

Fig 6.28.7 Illumination characteristics of phototransistor

Exercise 28.3

Plot graphs of current against relative illumination for the three conditions. Label each curve with the load resistance to which it corresponds, and the supply voltage.

Question 28.5

Why does the graph for the load resistance of 10kΩ flatten out at high levels of illumination? What limits the load current?

Exercise 28.4

For the graphs for zero load and 1.5kΩ load draw the best straight line through the points. Calculate the linearity by expressing the maximum deviation of your graph from this straight line as a percentage of the total range.

Exercise 28.5

Calculate the power dissipated in the load resistance of 100% relative illumination for all three cases. Use the formula Power = I^2 R where I is the current in amperes, and R is the load resistance in ohms.

Question 28.6

Which is the most efficient load?

Before we discuss your results, let us see how the angle at which light falls on the transducer affects its response.

PRACTICAL 28.3

Polar Characteristic

Return to the circuit of fig 6.28.2, i.e with zero load resistance. Reset the bulb-transducer distance to that corresponding to 100% relative illumination. Slowly increase the variable d.c control until the meter reads about 8mA. Rotate the transducer until this reading is a maximum then adjust the variable d.c control until this reading is exactly 10mA. Do not touch the control again during your experiment. Note the value of voltage you have set.

Now set the angular scale to 30° anti-clockwise and record the current flowing. Repeat these readings for angle of 25°, 20° and so on at 5° intervals up to 30° clockwise. You may have to interpolate between two values to find the absolute maximum. Record your results in your own copy of a table as in fig 6.28.8.

When you are setting the angles, take care to look directly down on top of the transducer box when aligning the marks, to avoid parallax. Again, perform the experiment as quickly as possible and keep your hands away from the rig when taking readings.

Angle (degrees)	Transducer Output (mV)
30 ACW	
25	
20	
15	
10	
5	
0	
5 CW	
10	
15	
20	
25	
30	

Fig 6.28.8 Polar response of phototransistor

Exercise 28.6

Plot a graph, on linear graph paper, of current flowing against angle. Label it with the value of applied voltage.

Question 28.7 ***Between what angles do you consider this device to be useful?***

Question 28.8 ***What effect does the lens in the casing have?***

Question 28.9 ***Why does the ambient lighting not have a significant effect with this phototransistor?***

The spectral response of this transducer when plotted with advanced equipment shows that the peak response of such a silicon transducer is about 800nm — well into the infra-red region of the spectrum.

Question 28.10 ***Taking what we have just said into consideration with your results, can you suggest some uses for such a transducer?***

Question 28.11 ***Can you suggest the principal advantages and disadvantages of the phototransistor?***

PRACTICAL ASPECTS

Your family of curves of I_C against V_{CE} for different levels of light intensity should be the same as you would expect to find for a conventional transistor with base current as a parameter. These are shown later in this section as fig 6.28.11. Under dark conditions the collector is approximately at the supply voltage and little dark current flows. This is one disadvantage of the phototransistor, that the dark current is multiplied by the h_{FE} of the transistor, as well as the photo-generated current. These curves support the theory that the photon current is of the same form as base current. If the illumination is held constant and V_{CE} is varied, I_C does not change much because the graph is almost horizontal. This represents a high output resistance of the phototransistor but the actual value depends slightly on the illumination. The load lines you drew on these graphs and the calculations you made on power output should indicate that there is an optimum load resistance for maximum power output. It varies both with level of illumination and supply voltage. High illumination and low supply voltages require a lower optimum load resistance.

You should see that the optimum load resistance for any particular case falls just above the 'knee' in the characteristic. The graphs you plotted of output against illumination should indicate that the linearity gets worse as the load resistance is increased and, at 10kΩ, distortion should be apparent. In practice there is a compromise between maximum power output and linearity. For analogue applications, linearity is important and the transducer should always be operated in full conduction at or below the optimum load resistance. The linearity is not so good as the photodiode as h_{FE} varies with current level.

In order to increase the efficiency, a large area device is required. This increases the junction capacitance and as always reduces the speed of response. The sensitivity can be further increased by the use of a lens to increase the effective area of illumination. The lens also narrows the angle of acceptance as you should have found when plotting the polar response. High discrimination can be achieved by careful alignment.

Ideally the transducer and light source should have matched spectral responses. This depends upon the material of manufacture and is further discussed in Assignment 29. Our phototransistor has a peak response at about 800nm — in the infra-red region. It is thus a good match for our tungsten lamp which emits much infra-red.

As in normal use the effective base current is supplied by the incoming illumination, no connection is usually made to the base terminal. In some applications it is necessary to forward bias the transducer to the centre of its operating characteristic by a d.c voltage applied to the base terminal. Thermal stabilisation techniques may be employed, or an electrical threshold control is possible.

Another use of the base terminal is at extremely low light levels. Here the dark current is important and can be reduced by connecting a high resistance between base and emitter. The resistance acts as a by-pass and greatly reduces the dark current through the phototransistor.

Although a meter in the collector circuit will indicate illumination, the circuit is sensitive to variations. If another transistor is used to amplify the transducer current, feedback is available across the emitter resistor for stabilising the gain of the phototransistor. This produces a good quality linear light meter which may be calibrated against a standard source or by comparison with a lux meter. The circuit is shown in fig 6.28.9.

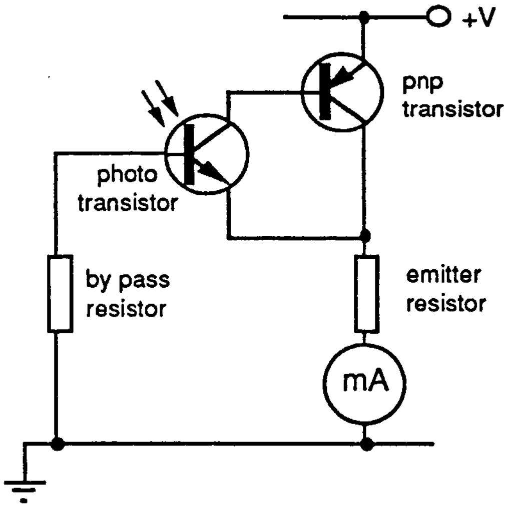


Fig 6.28.9 Linear light meter

A device for further increasing the sensitivity is the photo Darlington transistor, shown diagramatically in fig 6.28.10. Here the phototransistor has a second transistor connected as a Darlington pair in the same case. The two transistors can be matched and the photocurrent is multiplied by the combined h_{FE} of both transistors. This gives enough current to operate a large relay directly as shown in the diagram.

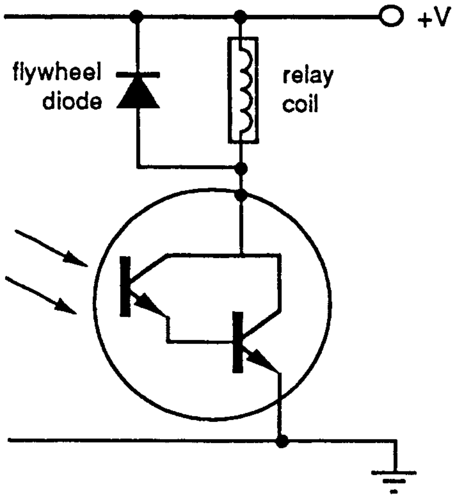


Fig 6.28.10

It should be evident that although it has disadvantages for analogue work, the phototransistor will make an excellent switching device for digital applications. Here load resistance is not so much a consideration as we are only concerned whether the transistor is 'on' or 'off'. They can be used in a wide range of applications such as punched tape and punched card readers for computers, machine control, process control, counting objects, burglar alarms, pattern recognition, optical isolators and so on. The list is very long.

No connection to the base terminal is necessary and very simple circuits result. If the photo-Darlington of fig 6.28.10 above is replaced by a single phototransistor, it is capable of switching a smaller relay directly. The flywheel diode is used to limit the collector voltage when the photon current ceases.

An important consideration in such simple circuit is the maximum power dissipation in the transistor. If there is not an abrupt change from dark to light and the phototransistor is only part illuminated, it is possible to damage it. The maximum dissipation occurs when the transistor has a collector voltage of half the supply voltage whilst passing half of its required maximum collector current. This is shown in fig 6.28.11.

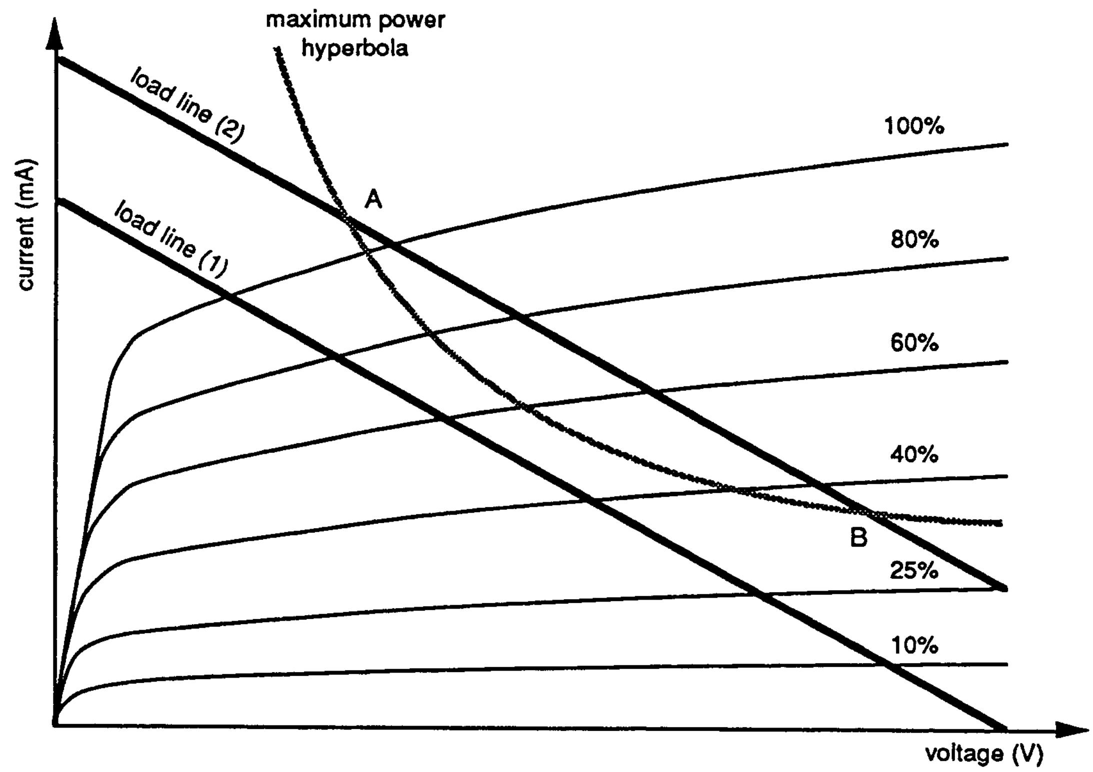


Fig 6.28.11

For the normal load line (1) the circuit has been well designed and the load line does not cut the maximum power curve. Nowhere will the transducer be damaged. If the supply voltage is increased, the new load line (2) intersects the power curve at A and B. Operation between these two light levels will damage the transducer. Such circuits must be designed so that the maximum dissipation is not exceeded. Alternatively the phototransistor must receive all the available illumination, or none at all.

Such simple circuits are often used in industrial safety systems. A forbidden zone such as a corridor, doorway or part of a machine, is crossed by a beam of light directed onto a phototransistor. If the beam is interrupted, an alarm is given or the machine stopped to prevent injury to the operator.

Other applications require an amplifier if the dissipation of the transistor is too low. Alternatively they can be arranged to trigger a thyristor or triac to control power circuits directly.

In some applications, the fitting of a light-operated safety device is complicated by excessive stray light. For example light-operated devices in a well-lighted workshop might need screening if they are to be effective; the adjustment of a bench lamp by one workman must not jeopardize the safety of another.

If the light directed on the phototransistor is coded, and the following circuit responds only to that code, stray light can be ignored. In practice an oscillator operating at a few kilohertz drives a light-emitting diode. The phototransistor is followed by a tuned amplifier such that it responds only to the frequency of operation. Stray light thus produces no output. If the beam is interrupted all output ceases and the appropriate safety device can be operated. Such a system is shown diagramatically in fig 6.28.12.

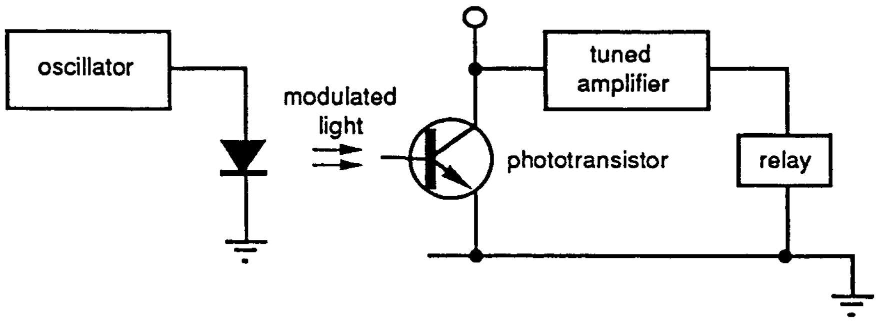


Fig 6.28.12

Modulated light is also used in communication systems, for example to transmit speech down a light beam. Such a system has the advantages of secrecy and freedom from interference but the transmitter and receiver must be in line of sight and the range is limited to a few hundred metres.

Phototransistors can also be used with logic circuits, either via an amplifier or trigger circuit, or directly with TTL logic gates as shown in fig 6.28.13. These are used in tape readers for computers. Another application is to sense an object between the doors of an automatic lift and this information is entered into the logic circuits controlling the lift together with information about the position of the lift and which button is pressed.

With the circuit shown, a controlled amount of hysteresis in the trigger circuit is provided by the resistor R. Two gates are necessary to achieve the correct phase relationship.

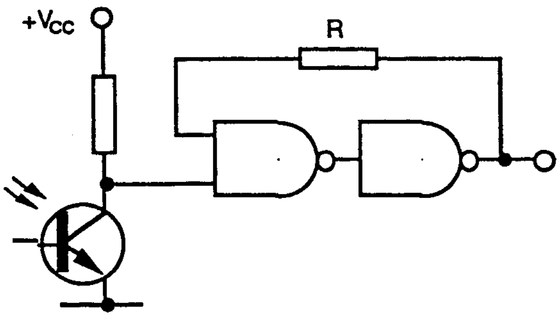


Fig 6.28.13

Finally, a circuit for an automatic car parking lamp is shown in fig 6.28.14. The circuit is regenerative, that is a higher light level is required to turn the lamp off than to turn it on. This avoids excessive dissipation in the power transistor driving the lamp and also helps to prevent spurious operation of the circuit by small changes of illumination. It is important that the transducer should be shielded from the light produced by the lamp or the resulting optical feedback would cause oscillation. The transducer should also be protected against contamination by dirt and moisture. A similar circuit could be used to operate a relay or thyristor to control domestic lights.

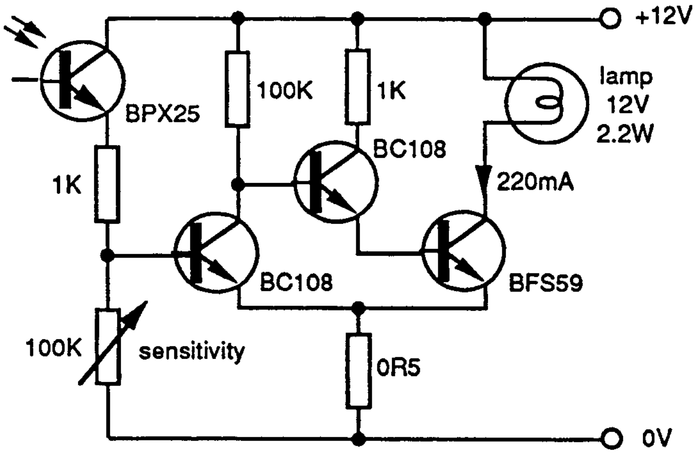


Fig 6.28.14

Phototransistors are also used in Shaft Encoders. These devices which translate angular position into a digital code (negative or positive logic respectively). This is done by shining lamps through a coded perspex disc onto the phototransistors. The code used is a *Gray* code which may then be translated into binary code by a logic network and used as the input to a control system.

The applications given here are only a selection. Much more information can be found in manufacturer's literature.

Other photoelectric transducers manufactured include photo field effect transistors (pfet's) and photothyristors. Again, you are referred to manufacturer's literature for details of these devices.

Exercise 28.1 Typical results and graph for Practical 28.1 are shown in fig E6.28.3.

Bias voltage (V)	Current (mA) for values of Relative Illumination						
	Relative illumination (%)	100	80	60	40	25	10
	Scale setting (mm)	90.0	84.0	75.5	61.0	40.0	32.0 (Hole position 1)
0		0	0	0	0	0	0
0.1		0.49	0.28	0.28	0.21	0.11	0.05
0.2		3.25	2.82	2.37	2.07	1.58	0.83
0.3		4.91	4.41	3.83	3.11	2.42	1.40
0.4		5.31	4.78	4.24	3.47	2.69	1.59
0.5		5.62	5.14	4.51	3.71	2.94	1.72
1.0		6.98	6.33	5.73	4.83	3.89	1.95
2.0		8.92	8.37	7.71	6.56	4.81	2.01
5.0		13.45	12.43	11.23	8.33	5.15	2.12
10.0		17.52	16.16	12.77	9.17	5.56	2.24
12.0		18.56	17.02	13.35	9.50	5.73	2.29
14.0		19.47	17.37	14.01	9.97	5.91	2.32

Fig E6.28.3 (table)

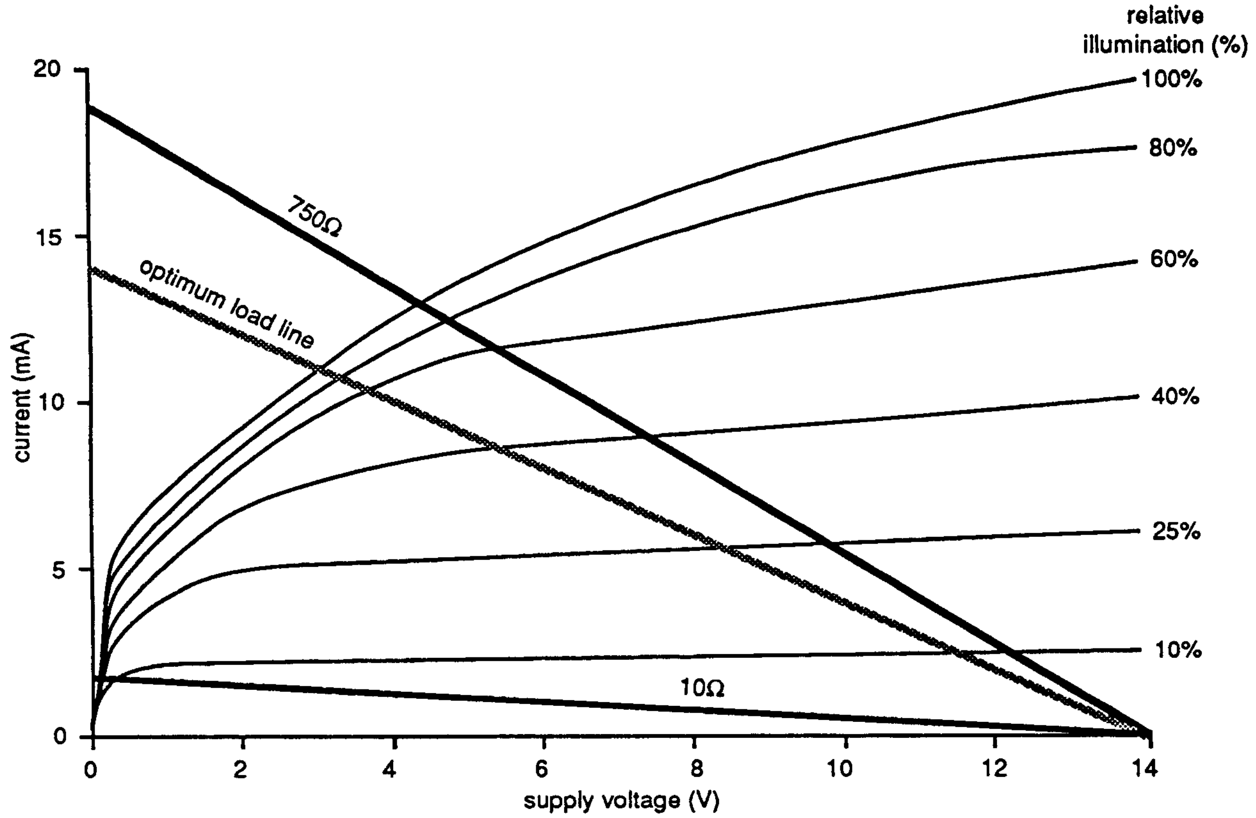


Fig E6.28.3 (graph)

Question 28.1

The graphs are similar to the output characteristics of a normal transistor but with illumination level as a parameter instead of base current.

Question 28.2

If the light intensity is held constant and the collector-emitter voltage is varied, the collector current does not change much because the curves are almost horizontal. This represents a high output resistance of the phototransistor, but the actual value (slope) depends slightly upon the level of illumination.

Question 28.3

The optimum load varies both with level of illumination and supply voltage. High values of illumination and low supply voltages require a much lower optimum load resistance.

Exercise 28.2

The load lines are marked on fig E6.28.3 (graph). The optimum load is about 1kΩ.

Question 28.4

The output will be very distorted with the 10kΩ load resistance, as the current limits with only about 25% relative illumination.

Exercise 28.3

Typical results and graph for Practical 28.2 are shown in fig E6.28.7.

Relative Illumination (%)	Scale Setting (mm)	Current (mA) for values of load resistance with 14V applied		
		Zero	1.5kΩ	10kΩ
100	90.0	19.24	8.57	0.97
80	84.0	17.22	8.42	0.97
60	75.5	13.98	8.21	0.97
40	61.0	9.68	7.69	0.97
30	48.5	7.21	6.24	0.97
25	40.0	6.05	5.41	0.97
20	28.0	4.82	4.40	0.97
10	32 (Hole position 1)	2.44	2.28	0.97
0	—	0.03	0.03	0.03

Fig E6.28.7 (table)

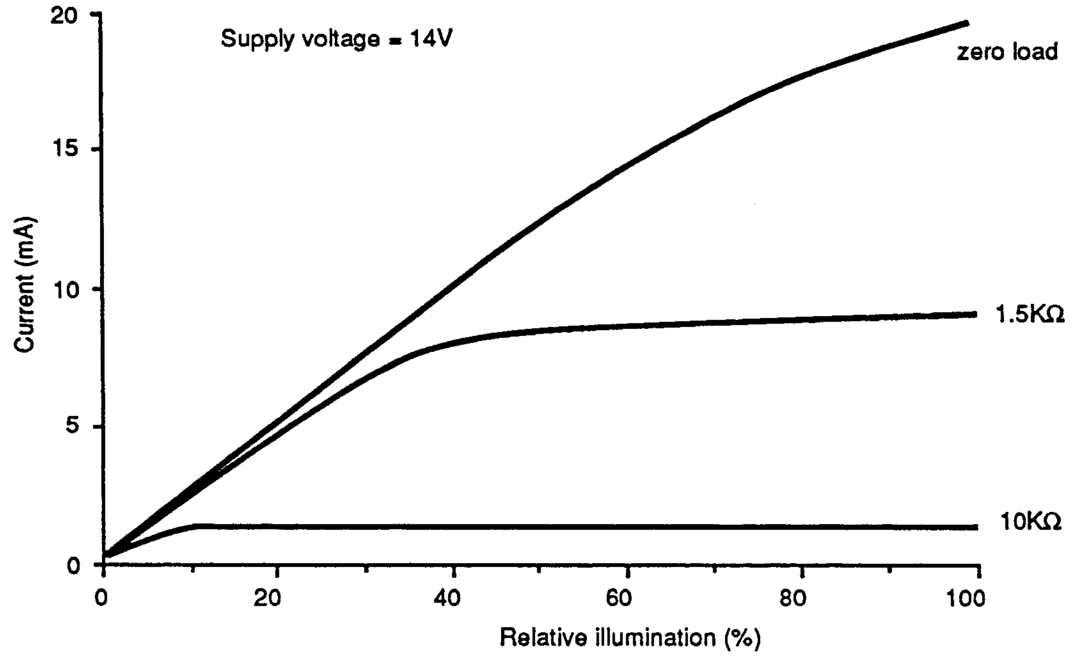


Fig E6.28.7 (graph)

Question 28.5

As already explained, the graph for the load resistance of 10kΩ flattens out for high levels of illumination as the current is limited by the load resistor for levels of illumination over 25%. Excessive voltage is dropped in the load resistor and the remainder is not sufficient to bring the phototransistor into full conduction.

Exercise 28.4

The linearities should be of the order of less than 2% for short-circuit load, and about 7% for 1.5kΩ load over its useful range.

Exercise 28.5

Load Resistance (kΩ)	Power at 100% relative illumination (mW)
Zero	0
1.5	110
10	9.4

Question 28.6

At the values of relative illumination and supply voltage used a 1kΩ load, as discussed earlier, is the most efficient.

Exercise 28.6

Typical results and graph for Practical 28.3 are shown in fig E6.28.8.

Angle (degrees)	Transducer Output (mV)
30 ACW	0
25	0
20	0
15	0.03
10	0.66
5	9.43
2	10.03
0	9.51
5 CW	0.55
10	0.06
15	0.01
20	0
25	0
30	0

Fig E6.28.8 (table)

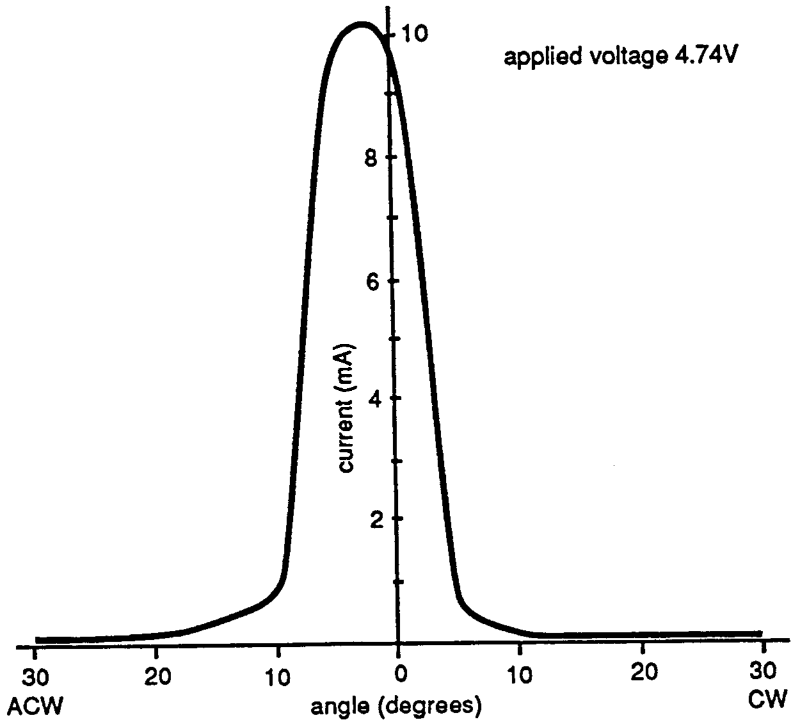


Fig E6.28.8 (graph)

Question 28.7

The useful 'window' should be very narrow, approximately 5°.

Question 28.8 and Question 28.9

The lens in the casing increases the effective sensitive area but narrows the angle of acceptance. Ambient lighting thus has only a small effect.

Question 28.10 and Question 28.11

The advantages and disadvantages of the transducer and some of its uses are discussed in the Practical Aspects section of the manual. These should be read in conjunction with the corresponding section of Assignment 26.

SPECTRAL RESPONSE — ASSIGNMENT 29

CONTENT

The response of photoelectric transducers to incident light of varying wavelengths is investigated. This spectral response of a photoconductive cell is measured.

EQUIPMENT REQUIRED

Qty	Designation	Description
1	TK2941A	Instrumentation Module
1	TK294	Linear Transducer Test Rig
1	–	Lampholder
1	TK294	Light Transducer Box
1	–	Pack of nine optical filters
1	–	Power Supply ±15V dc *(e.g Feedback PS446)*
1	–	Milliammeter 10mA dc *

*Alternatively a multimeter may be used.

PRACTICALS

29.1 Phototransistor Spectral Response

29.2 Photoconductive Cell Infra-Red Response

29.3 Photoconductive Cell Spectral Response

SPECTRAL RESPONSE

ASSIGNMENT 29

OBJECTIVES

When you have completed this assignment you will:

- Understand the effect that light of differing wavelengths, and therefore colours, has on the response of a phototransistor and photoconductive cell.
- Have measured the spectral response of a photoconductive cell.

KNOWLEDGE LEVEL

Before starting this assignment you should:

- Understand the basic theory and operation of semiconductor devices.
- Understand the basic theories concerning the nature of light.
- Be familiar with the use of the Optical Detector Assembly and Linear Transducer Test Rig; and preferably have completed Assignment 25, The Photoconductive Cell.

INTRODUCTION

Colour is mentioned in Assignment 24 where it is stated that the energy of a light photon determines the colour of the light. Thus we would expect some variation of the output of a photoelectric transducer with colour. Exact measurement of the spectral response of the transducers requires a means of applying light of different colours at equal illuminations and noting the outputs. The method employed with this kit is to use gelatine filters. These each have a different degree of light transmission and also pass infra-red. This last effect will be used to advantage to demonstrate the infra-red sensitivity of the transducers. For quantitative measurements we need to remove this infra-red or it would upset the results. We also need to take account of the different transmission factor of each filter and the colour output of our lamp in order to keep the illumination on the transducer constant as we vary the colour of the incident light.

We will explain how these difficulties are overcome and the appropriate precautions as you progress through the assignment. Firstly, the physical reasons for this effect are explained in detail.

Consider light of constant intensity and variable wavelength incident on a crystal of semi-conductor material. In order for any of the photoelectric effects mentioned previously to happen, the light photons must give up their energy to the material to liberate charge carriers.

The minimum energy of a photon required for intrinsic excitation (no impurities present) is the forbidden gap energy E_g (usually measured in electron-volts) of the material.

The energy of each photon is given by:

$$\varepsilon = hf$$

where f is the frequency of the light (Hz or cycles/sec)

h is Planck's constant: 6.626×10^{-34} joule-sec

and the frequency f is related to the wavelength λ by the

formula $v = f\lambda$ where λ is the wavelength in metres and v is the velocity of light 3×10^8 m/s

therefore, substituting, $\varepsilon = \frac{hv}{\lambda}$.

Photons having lower energies than that required to overcome the energy gap can have no effect — they pass straight through the material. For normal semiconductors this happens at long wavelengths well into or even past the infra-red region, so we cannot see it. This is why glass is transparent; the energy gap is so large that visible light passes straight through.

As the wavelength decreases, the photon energy increases to a point where it is equal to the energy gap of the material. The photons then begin to be absorbed and conduction begins. This wavelength λ_c is known as the *long wavelength threshold* of the material. It can be calculated by re-arranging the above equation:

$$\lambda_c = \frac{hv}{Eg} = \frac{3 \times 10^{8} \times 16.625 \times 10^{-34}}{E_g(eV) \times 1.6 \times 10^{-1.9}}$$

$$= \frac{1240}{E_g}$$

This gives a numerical value of 1240 to give λ_c in nm if E_g is expressed in electron volts (1eV = 1.6 x 10^{-19} joules) Thus for pure Silicon for example, where E_g = 1.1eV:

$$\lambda_c = \frac{1240}{1.1} = 1130\text{nm}$$

and for pure Cadmium Sulphide, E_g = 1.85eV:

$$\lambda_c = \frac{1240}{1.85} = 670\text{nm}$$

Further figures are given in a table later in the assignment.

Thus you can see that the spectral characteristics of a photoelectric transducer depend mainly on the choice of material.

The exact value of the threshold wavelength depends on the doping level, i.e the amount of impurities present. More doping needs less energy for extrinsic excitation, as discussed in Assignment 25, and λ_c increases. It also depends on the thickness of the material, as the photons must have time to give up their energy.

If the wavelength is further decreased, more photons will release charge carriers as the range of photon energy encompasses the range of the energy bands. Thus the response increases to a maximum. The position of the actual peak again depends on the thickness and doping level of the material.

Practically, however, the effect does not remain constant but drops off at shorter wavelengths after the peak. This is because at short wavelengths the high energy photons do not travel as far into the material before they give up their energy, which they do fairly near the surface. Here recombination occurs more easily and the charge carriers have less chance of contributing to conduction. Surface recombinations depend upon the physical and chemical state of the surface. Cleaning methods have been used to reduce this and obtain better short wavelength sensitivity.

As λ is further decreased and the energy increases, the photoelectric process becomes less efficient, reflections occur and the response tails off to zero.

You have seen that the output from a photoelectric transducer depends on the colour of the light, and the exact form of this variation depends on the physics of the transducer action within the material. By suitable choice of material transducers can be made to respond better to light of different colours.

In our rig we have transducers of two different materials. The phototransistor, photovolatic cell and photodiode are all silicon devices and the photoconductive cell is made from a combination of *Cadmium Sulphide* and *Selenium*. From the theory we would expect our silicon transducers to be more sensitive in the infra-red region than the Cadmium Sulpho-selenide transducer.

Tungsten filament lamps give out much infra-red light, as shown in fig 6.29.5(a). Let us first see how this affects the transducers.

PRACTICAL 29.1

Phototransistor Spectral Response

Mount the lamp holder on the Linear Transducer Test Rig and connect the two leads from it to the 0V and +15V sockets on the module.

Position the Light Transducer Box on the Linear Transducer Test Rig in the set of holes nearest the lamp, with the aperture in front of the transducers facing the lamp. Ensure that the infra-red absorbent glass, in its carrier, is removed from inside the box.

Connect up the silicon Phototransistor as shown in fig 6.29.1.

Position the lamp holder at the position corresponding to 100% relative illumination by reference to the table given in Assignment 24. Switch on the power supply and the lamp should light. Slowly increase the variable d.c voltage using the potentiometer control on the Operational Amplifier and the meter should indicate a current. Rotate the transducer for maximum response then set the variable voltage so that the meter reads exactly 10mA. Do not adjust the voltage again during this practical.

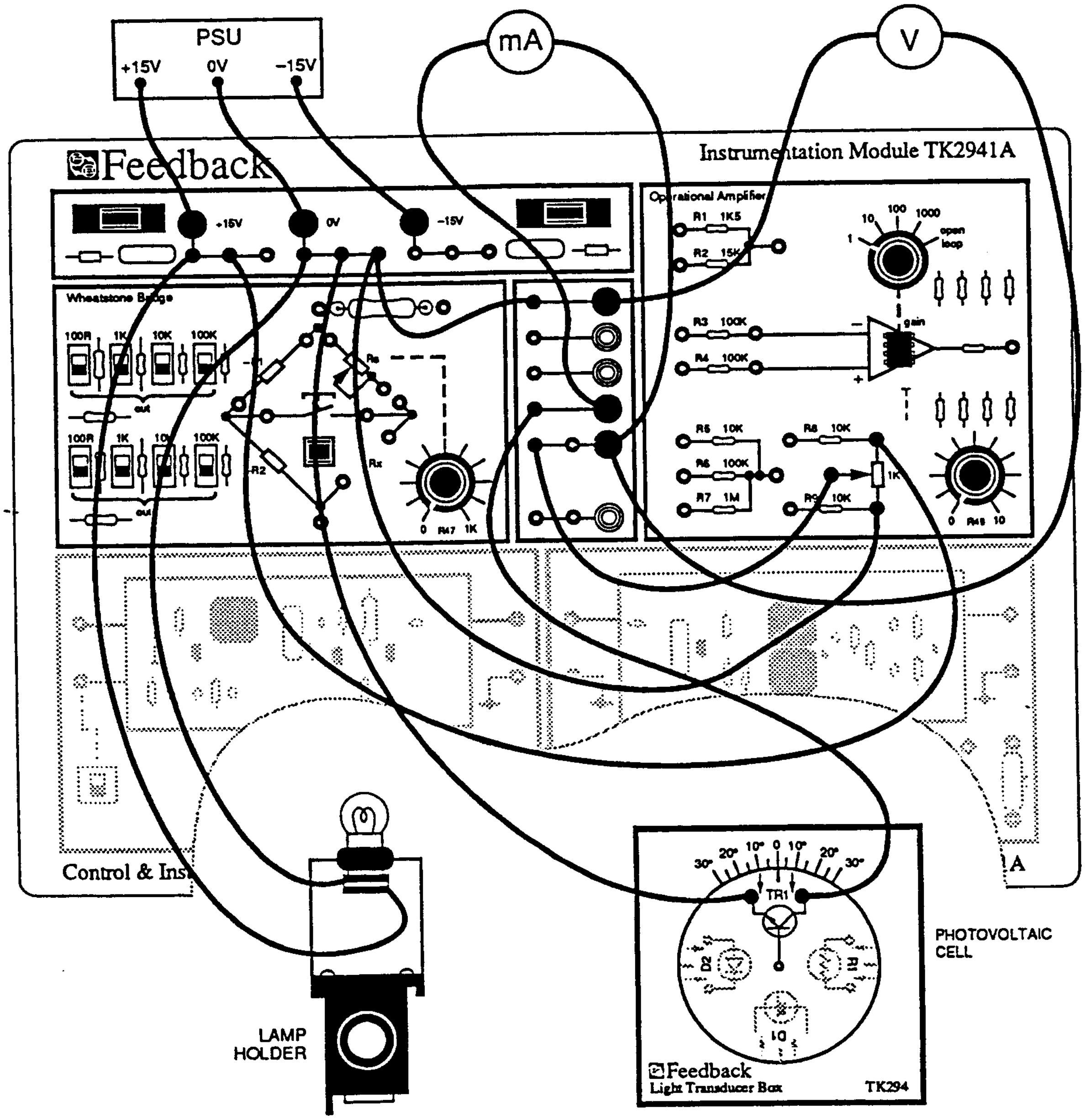


Fig 6.29.1

Although this part of the assignment is qualitative in nature, you should still take care with your results and pay attention to the precautions we discussed in previous assignments.

Take the pack of colour filters and insert them into the clips in front of the transducer in order of increasing wavelength. For each filter note the reading on the meter and put your results in your own copy of the table given in fig 6.29.2. Take care not to disturb the angle of the transducer when inserting the filters.

Peak Wavelength λp (nm)	Colour	Current (mA)	
		Phototransistor	Photoconductive Cell
—	no filter	10	10
440	violet		
470	blue		
490	blue/green		
520	green		
550	green/yellow		
580	yellow		
600	orange		
620	red		
700	deep red		
—	infra-red		

Fig 6.29.2

Question 29.1

Ignoring for the moment the different transmission factors of the filters, what can you say about the relative response of the transducer at the red and blue ends of the spectrum?

Question 29.2

Remembering that the bulb output is more red light than blue light, does this support your answer to Question 29.1?

Now select pairs of filters and hold them up to a strong light, for example the sun, overlapping each other. Take care not to hurt your eyes. You should be able to find several pairs of filters that are complementary, i.e together they appear black and pass no light. These pairs are shown in the table of fig 6.29.3.

Wavelengths of filters pairs appearing 'black'
440 + 520
440 + 550
440 + 580
470 + 550
470 + 580
490 + 590
490 + 600
490 + 700
520 + 600
520 + 700
550 + 700

Fig 6.29.3

Question 29.3

Why would a meter not go to zero if the pairs of filters appear to pass no light?

The answer is of course that the phototransistor is very sensitive in the red region of the spectrum, particularly to infra-red, and although they appear black to our eyes, the transducer responds to this. Let us see if this is correct.

Our infra-red filter is in fact a piece of heat-absorbing glass in a mount designed to fit the clips inside the transducer box.

Look at the bulb through the infra-red filter. Note how the colour of the light appears more 'bluish'. Look at a red object through the filter and note that the colour is hardly affected. This is because the filter gradually cuts off light above a certain wavelength. Its characteristics are shown later in fig 6.29.5(b). Note that in the visible spectrum its transmission factor is about 85%. Place this filter in its clips inside the transducer box and note the meter reading in the last line of your table of fig 6.29.2.

Question 29.4

Does this support the theory that the transducer responds to infra-red?

Now insert any one of the 'black' combinations of filters of table 6.29.3 in the front clips. Note which combination you use.

Question 29.5

What does the meter read now? Does this reading support the theory that the infra-red has an effect?

Question 29.6

What do you conclude about the spectral response of the silicon phototransistor?

It should be evident from your results that this silicon transducer has its peak response in the infra-red region of the spectrum. Its response to blue light is much less than its response to red light as indicated by your results in table 6.29.2. The low output of the bulb at this end also precludes the making of exact measurements, as the dark current of the transducer is of similar magnitude to the transducer's response at this point. The peak occurs in fact at about 800nm, and the long wavelength threshold, above which no photoelectric effect is possible, is about 1130nm. Our colour filters do not encompass this range and therefore we are unable to show it exactly. Also the infra-red filter is not sharp. You would have got similar results if you had performed these tests on the photodiode or the photovoltaic cell.

Now let us examine the Cadmium Sulpho-selenide photo-conductive cell.

PRACTICAL 29.2

Photoconductive Cell Spectral Response

Switch off the power supply. Return the variable d.c control to zero. Connect up the photoconductive cell as shown in fig 6.29.4.

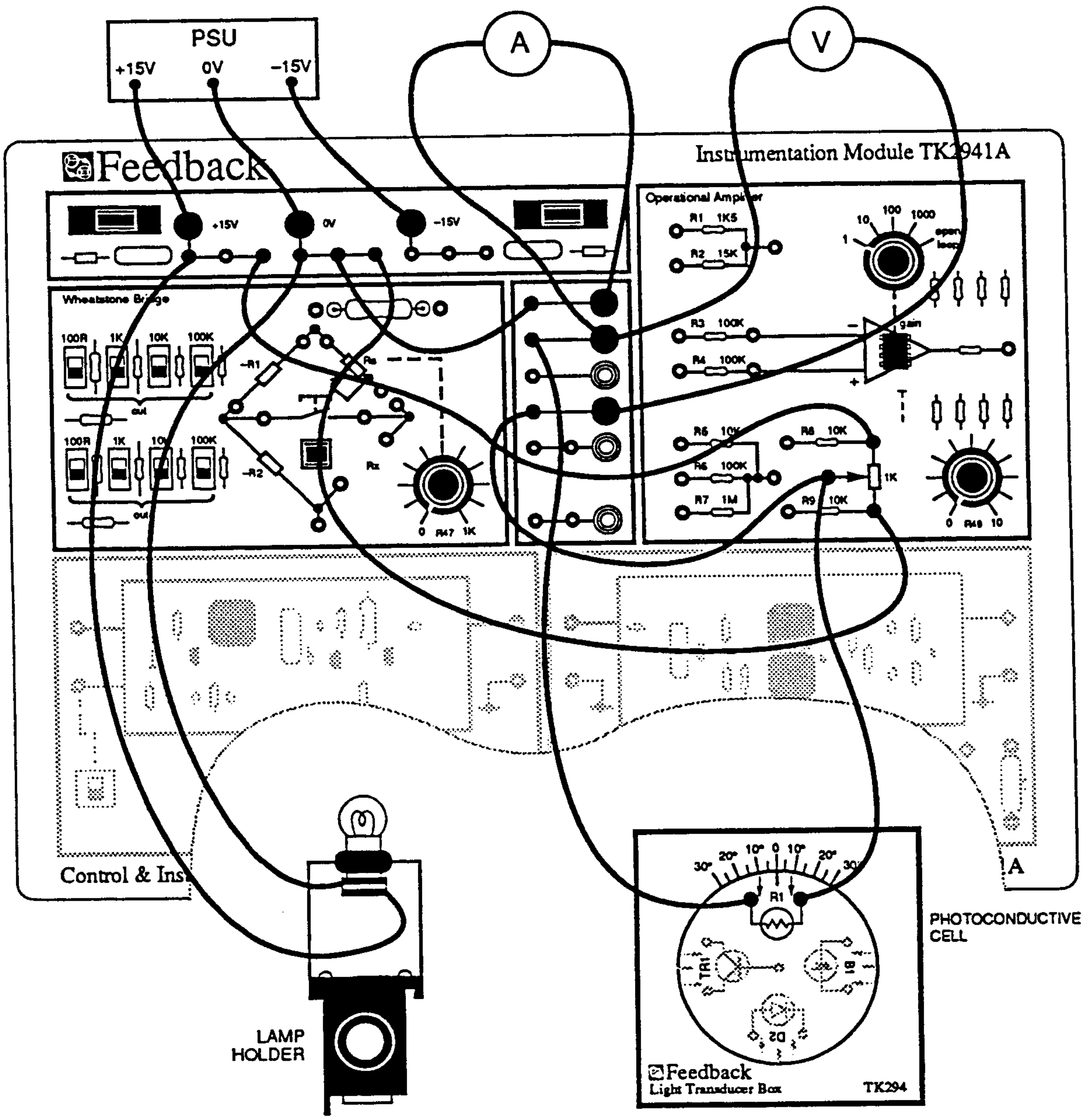


Fig 6.29.4

Remove the infra-red filter and keep the lamp holder at the position corresponding to 100% relative illumination. Switch on the power supply and check that the lamp lights. Slowly increase the variable d.c voltage and the meter should indicate a current. Rotate the transducer for maximum response and set the variable d.c control so that the meter reads 10mA. Leave the transducer like this for five minutes for the necessary pre-conditioning.

We are now going to repeat the procedure of Practical 29.1.

Insert each colour filter in order in front of the transducer and note the meter readings in the second column of your table as in fig 6.29.2.

Question 29.7 ***Ignoring for the moment the different transmission factors of the filter, what can you say about the relative response of the transducer to each filter?***

Question 29.8 ***Remembering that the bulb output is more red light than blue light, does this support your answer to Question 29.7?***

Now fit the same 'black' pair of filters as you used in Practical 29.1 in the path of the light and note the meter reading.

Question 29.9 ***Is this meter reading greater, the same or less than the one for the Silicon phototransistor?***

Question 29.10 ***What does this indicate?***

Now remove the colour filter pair and insert the infra-red filter in its clip inside the mount. Note the meter reading in your table.

Question 29.11 ***Is this greater, the same or less than that for the infra-red filter in front of the Silicon phototransistor?***

Question 29.12 ***What does this indicate? Is the photoconductive cell more or less sensitive to infra-red than the phototransistor?***

However since your answer to Question 29.9 was not zero, the infra-red does have a small effect. If we wish to make some measurements we must eliminate it. Although the cut-off of our infra-red filter is not very sharp, it is sufficient to carry out the practical.

Place one of the 'black' pairs of filters of table 6.29.3 in front of the infra-red filter which you have just put in front of the photoconductive cell.

It may be necessary to cover the top of the Light Transducer Box with your hand to prevent any stray light reflecting from the aluminium IR carrier body.

Question 29.13

Does the meter now read zero? Does it confirm that any remaining infra-red has a negligible effect?

We are going to assume that this small IR residue is negligible. Let us see if it is possible to measure the spectral response more accurately. We have mentioned some of the difficulties; let us see if they can be overcome.

PRACTICAL 29.3

Photoconductive Cell Spectral Response

Firstly the colour filters themselves are quite broad band. When you were searching for the 'black' pairs you should have noticed that one or two pairs that you would have thought to be complementary, still passed some visible light. Two filters of adjacent wavelength do not block out all the light. For example, pick up the two filters of wavelength 440nm and 690nm and look through the pair at a strong light.

Question 29.14

What do you see?

This small amount of red light confirms that the 440nm filter has transmission in the red end of the spectrum.

Since all the filters are similar it is sufficient to consider only the peak wavelength of transmission of each filter. This will produce quite a good graph. This is the wavelength which is marked on each filter. The peak transmission factor at this wavelength is shown in fig 6.29.6. You will note that each one passes a different amount of light. For this practical we need to ensure that, as we vary the colour, the illumination of the transducer is kept constant.

Question 29.15

How can we ensure this?

The answer should be obvious; vary the source transducer distance by applying the inverse square law. We must also take the characteristics of the source and the infra-red filter into account. These are shown in fig 6.29.5 (a) and (b). The necessary calculations are quite involved and the following is a summary.

We can firstly draw up a curve showing the combined characteristic of the lamp and IR filters, as these are constant. This is shown in fig 6.29.5 (c), i.e it combines 6.29.5 (a) and (b) and was derived by multiplying together the graphs. This curve gives the effective output of our bulb/IR filter combination and can thus be considered as the characteristic of the light source.

For each colour, we know the transmission factor of the filter from the manufacturer's data as shown in table 6.29.6. We know the characteristic of the lamp-IR filter combination from our graph fig 6.29.5 (c). We can thus calculate the total response of the combination by multiplying the figures together and normalising.

A special case arises with the red and deep-red filters at $\lambda = 690$ and 700 respectively. Their transmission factors of 83% and 76% respectively are far greater than the rest. However, it has been found that if we put the orange filter ($\lambda = 600$nm) in as well as these two filters, it cuts the transmission factors down to manageable proportions without affecting the colour too much.

Now that we have found the relative amounts of light transmitted by the different combinations, we can calculate how far back we must move the lamp to ensure that the light intensity reaching the transducer is the same in all cases, although its colour will now be different.

If we take the combination with the least transmission factor (this happens to be the violet filter at $\lambda = 440$nm) and with this filter put the lamp as close to the transducers as we can (50m distance, or 90mm on the scale) as we substitute other filters where the total transmission factor is greater, we can use the Inverse Square Law to calculate the lamp positions so that the illumination of the transducer remains constant. We can then determine the spectral response of the transducer.

Fig 6.29.6 is the table you must refer to in order to check out the practical. If you like you can check the distances using the inverse square law (see Assignment 24).

Switch off the power supply and make sure that the bulb is in the 100% relative illumination position and that the IR filter is in its clips inside the light box, allowing the glass area to come behind the aperture in the box. Insert the first filter (violet $\lambda = 440$nm) into the clips in front of the light box.

The effect of ambient lighting will not be great as we are operating the bulb close to the transducer and the filters will also attenuate the ambient light. Remember also to keep your hands away from the rig when taking readings in case they cause unwanted reflections of light onto the transducer. Do not disturb the angle of the transducer when changing filters.

Switch on the power supply and increase the variable d.c voltage to its maximum. Rotate the transducer for maximum response and note the current on the meter. Because of the low light levels, maximum available d.c voltage has to be used to obtain a reasonable meter reading and the power dissipated in the transducer is still quite low. However to avoid increased illumination passing excess current and damaging the transducers, always switch off when changing filters.

Replace the filter with the next and set the lamp holder to the position shown in fig 6.29.6. Switch on the power supply and note the current. Record your results in your own copy of fig 6.29.6. Switch off again, change to the next filter and reset the distance. Do this for all the filters in the table. Remember that the last two filters (λ = 690 and 700nm respectively) must have the orange filter (λ = 600nm) in as well, as explained earlier.

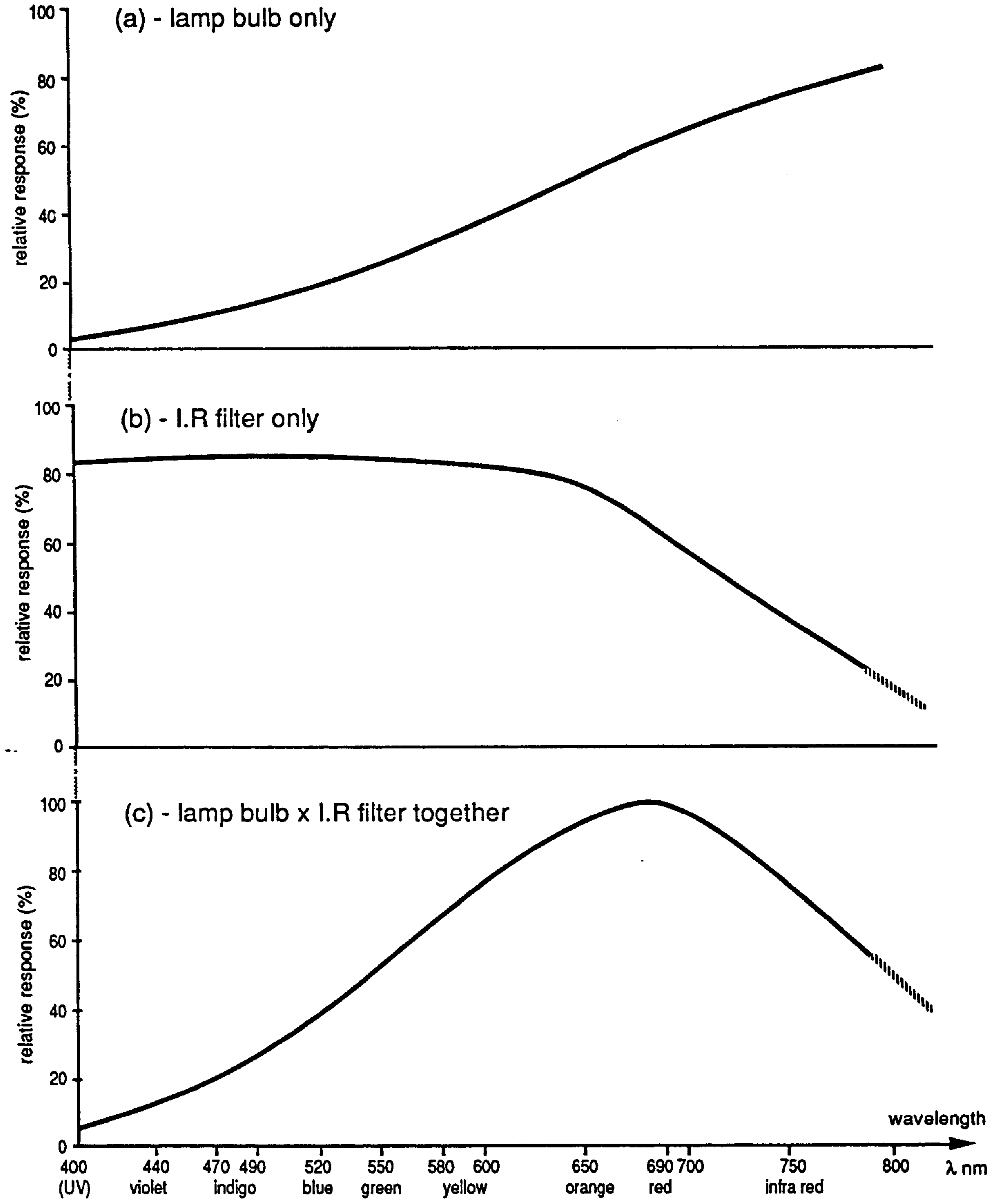


Fig 6.29.5 Lamp, I.R filter and combined responses

Spectral Response

Assignment 29

Colour	Filter wavelength (nm)	Peak transmission factor of filter only (%)	Relative transmission factor of lamp + filter	Relative illumination required (%)	Scale setting required	Your results (current mA)
Violet	440	13.0	10.8	100.0	90	
Blue	470	11.0	15.2	71.0	80.0	
Blue/green	490	12.0	21.8	49.5	69.0	
Green	520	8.9	22.6	47.8	67.7	
Green/yellow	550	6.0	23.0	47.0	67.1	
Yellow	580	6.4	33.0	32.7	52.5	
Orange	600	17.0	100.0	10.8	38.0	
* Red	690	83.0	39.6	27.3	44.2	
* Deep red	700	76.0	28.2	38.3	59.0	

* Use in conjunction with Orange (600 nm)

Fig 6.29.6

Exercise 29.1

Plot a graph on linear graph paper of current against wavelength of the light as indicated on the filter. The exception is the red filter. Inclusion of the orange filter shifts the peak slightly from 690 to 680nm so plot 680nm. Draw as smooth a curve as you can through the points. There will be some differences due to the broad bandwidth of the filters. Since we have no filter between 600 and 690nm you will have to estimate where the peak response occurs.

Question 29.16

What do you estimate to be the peak wavelength of response of the Cadmium Sulpho-selenide photoconductive cell?

Question 29.17

Has the output reduced completely to zero at wavelength of 700nm? At what wavelength above this do you estimate the output will be zero? This is the long wavelength threshold of the material.

Question 29.18

Why does infra-red not produce much output from this transducer?

Question 29.19

Is the threshold wavelength of silicon higher or lower than that of Cadmium Sulpho-selenide? Why?

Question 29.20

Which of these two materials would make the best transducer for detecting:

(a) Daylight?

(b) Fluorescent light?

(c) Tungsten filament bulb?

(d) A fire?

PRACTICAL ASPECTS

The main conclusion to be drawn from this assignment is that the spectral response of a photoelectric transducer depends upon the material from which it is manufactured. For each material there is a long wavelength threshold, above which no light can possibly excite a transducer. The response then peaks and tails off for the reasons explained in the assignment. The general form of the curve is shown in fig 6.29.7. The actual values of λ_c and λ_p are given in the table of fig 6.29.8 for some typical photoelectric materials.

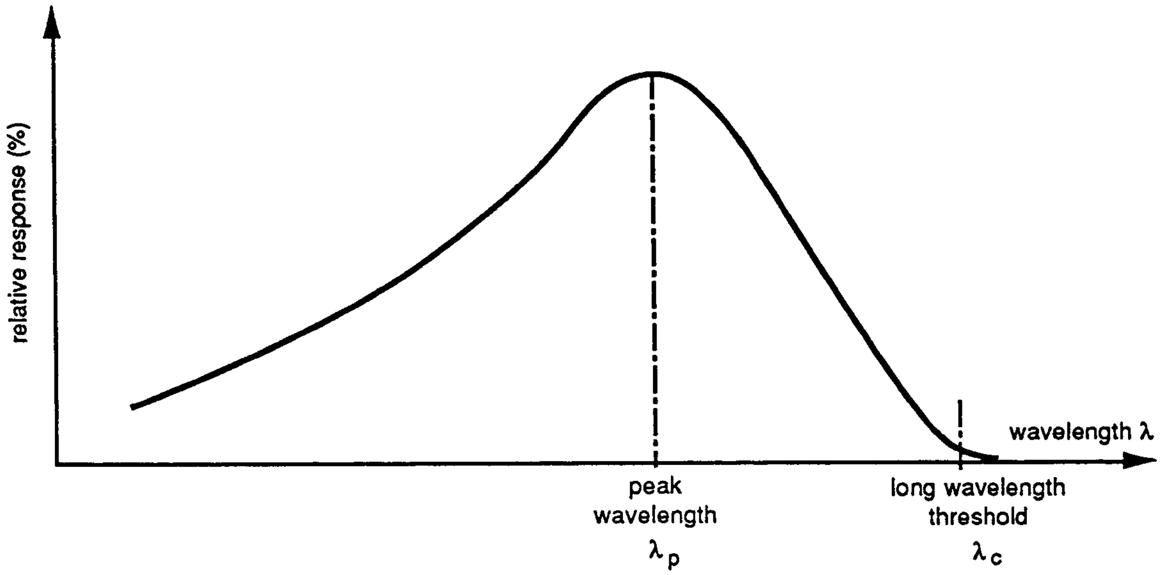


Fig 6.29.7 General spectral response curve of photoelectric effect

Material	Chemical symbol	λ_p (nm)	λ_c (nm)	Energy Gap E_g (eV)
Pure Silicon	Si	800	1130	1.1
Pure Germanium	Ge	1440	1770	0.7
Cadmium Sulphide	CdS	520	620	2.0
Cadmium Selenide	CdSe	720	830	1.5
Zinc Sulphide	ZnS	338	400	3.1
Zinc Sulphide (copper doped)	ZnS + Cu	540	650	1.9
Lead Sulphide	PbS	2900	3400	0.37
Lead Selenide	PbSe	4200	5500	0.23
Gallium Arsenic	GaAs	760	880	1.4

Fig 6.29.8

The relationship between the energy gap E_g of the material and the threshold wavelength.

$$\lambda_c = \frac{1240}{E_g}$$

When λ is measured in nm and E_g is electron-volts.

Conversely, if we can measure λ_c by experiment, we have a means of determining E_g. This requires complex equipment, as mentioned in the introduction, but is a good method of accurately determining the energy gap of a semiconductor material.

Even without complex equipment, you should have been able to obtain reasonable results from this assignment. In the first two practicals you compared the silicon and cadmium sulpho-selenide devices on a qualitative basis and found that the former was better with red light, especially infra-red, than the latter. You then went on to plot the spectral response of the photoconductive cell and your graph should have been of the general form of fig 6.29.7 with peak and threshold wavelengths of about 610 and 750nm respectively. These figures fall midway between the values quoted in table 29.8 for CdS and Cd Se. Infra-red had little effect as it is above the threshold wavelength of the material. The imperfections in the filters may have caused a greater than usual uncertainty in plotting the points for this graph but you should have been able to appreciate the basic shape. We were unable to do a similar measurement on the phototransistor as its peak response is outside the range of our colour filters. The difficulties associated with these measurements were outlined in the practical.

Matching the source to the detector is an important consideration. You should have seen that daylight and fluorescent light contain more blue than red and thus a CdS-Se device would be more suitable for detecting these. A tungsten filament bulb and a fire give out much infra-red and a silicon device responds better to this.

Fire detection is another important use of photoelectric devices; usually a different material that has its peak response well into the infra-red region such as the various lead compounds. Many infra-red applications are military in nature. Examples include:

- Infra-red heat-seeking missiles
- Night vision and photography
- Weather observation
- Vehicle exhaust detection
- Submarine observation
- Detection and analysis of impurities in liquids and gases.

Because of the heat associated with infra-red the detectors often have to be cooled. Photoelectric transducers are quite temperature sensitive. For example, as already quoted for the photodiode, the reverse current may double for every 10°C rise in temperature.

Transducers can also be made sensitive to ultra-violet. However in this range conventional glass windows cut off below about 300nm and special glass has to be used.

It should be clear by now that the required spectral response can be determined firstly by choosing the material then by adjusting the amount of impurity present. As discussed in Assignment 25, impurities are often added to photoconductors to increase the sensitivity. This lowers the response time but also shifts the spectral response. Because of the lower energy required for impurity excitation, the long wavelength threshold value is increased. The peak value may also be shifted.

Thus we can choose our transducer to match our source. Often this is best done by experiment. A light-emitting diode is a good source for a photodiode made of the same or similar material. The LED process is similar to a photodiode operated 'backwards', i.e current in - light out, instead of the other way round. The colour of the light output is determined by the energy gap of the material.

TYPICAL RESULTS AND ANSWERS — ASSIGNMENT 29

Question 29.1 Ignoring the different transmission factors of the filter, the photo-transistor responds better at the red end than the blue end of the spectrum.

Question 29.2 Since the bulb gives more red than blue light this bears out the above answer.

Peak Wavelength λp (nm)	Colour	Current (mA)	
		Phototransistor	Photoconductive Cell
—	no filter	10.00	10.00
440	violet	0.39	0.32
470	blue	5.79	0.47
490	blue/green	6.07	0.68
520	green	4.78	0.55
550	green/yellow	3.67	0.56
580	yellow	2.62	0.82
600	orange	6.77	2.82
620	red	9.26	3.80
700	deep red	8.78	2.51
—	infra-red	2.89	9.29

Fig E6.29.2

Question 29.3 The 'black' pairs of filters also pass a lot of infra-red. The photo-transistor must respond to this because the meter does not indicate zero.

Question 29.4 With the infra-red filter in place the phototransistor output drops sharply, confirming that it has a good IR response.

Question 29.5 With a 'black' pair of filters and the infra-red filter in place the current drops to typically 100µA.

Question 29.6 The qualitative conclusion about the spectral response of the silicon phototransistor is that its response is poor to blue light, better to red light and that it peaks in the infra-red region. The actual peak is about 800nm.

Question 29.7 Repeating the above practical for the photoconductive cell shows firstly that it responds better to orange/red light and tails off again in the deep red, compared with the phototransistor.

Question 29.8 Again the rising characteristic of the lamp bulb supports the above conclusions.

TYPICAL RESULTS AND ANSWERS **ASSIGNMENT 29**

Question 29.9

The meter reading for the photoconductive cell is very small, typically less than 0.2mA with 'black' pairs of filter in place.

Question 29.10

This indicates that the transducer has very little infra-red response.

Question 29.11

The reading with the infra-red filter in place is typically 9mA, much greater than that for the phototransistor.

Question 29.12

This indicates that the loss of infra-red has little effect on the output of the photoconductive cell. What reduction in output appears is mainly due to the 85% transmission factor of the IR filter in the visible region. The device is therefore less sensitive to infra-red than the phototransistor.

Question 29.13

With both the IR filter and a 'black' combination in place, the meter reads zero and confirms that any remaining infra-red has negligible effect.

Question 29.14

Looking through the combination of 440nm and 690nm you should see a faint red light. This demonstrates that our filters are not perfect and introduces some of the difficulties in measuring spectral response by this means. Two filters of adjacent wavelengths do not block out all the light due to the broad bandwidth.

Question 29.15

Vary the source-transducer distance to compensate the relative illumination.

TYPICAL RESULTS AND ANSWERS ASSIGNMENT 29

Exercise 29.1 Typical results for the compensated spectral response of the photoconductive cell are show in fig E6.29.6.

Colour	Filter wavelength (nm)	Peak transmission factor of filter only (%)	Relative transmission factor of lamp + filter	Relative illumination required (%)	Scale setting required	Your results (current mA)
Violet	440	13.0	10.8	100.0	90	0.72
Blue	470	11.0	15.2	71.0	80.0	0.66
Blue/green	490	12.0	21.8	49.5	69.0	0.81
Green	520	8.9	22.6	47.8	67.7	0.72
Green/yellow	550	6.0	23.0	47.0	67.1	0.78
Yellow	580	6.4	33.0	32.7	52.5	0.90
Orange	600	17.0	100.0	10.8	38.0	1.41 (Hole position 1)
* Red	690	83.0	39.6	27.3	44.2	0.64
* Deep red	700	76.0	28.2	38.3	59.0	0.53

* Use in conjunction with Orange (600 nm)

Fig E6.29.6 (table)

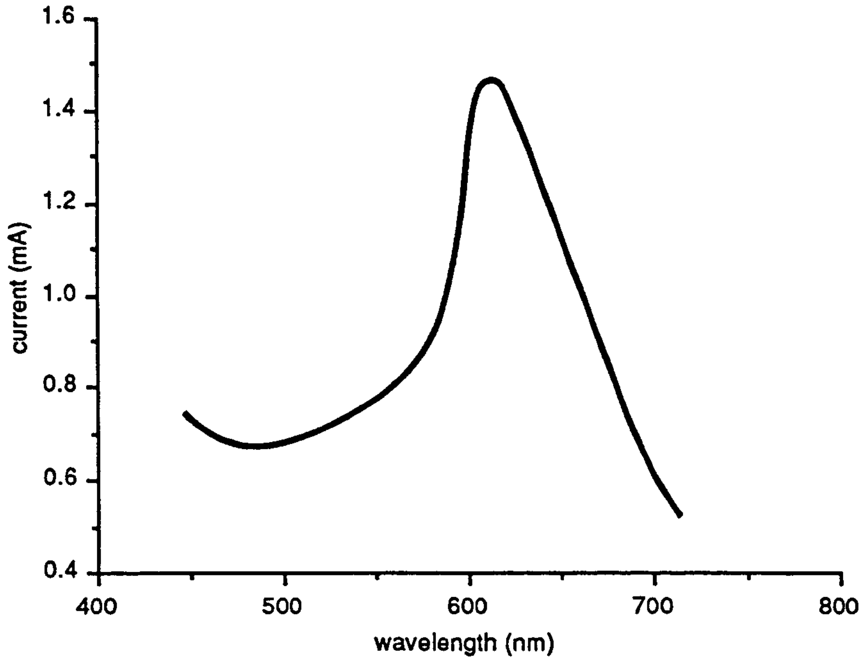


Fig E6.29.6 (graph)

Question 29.16

The peak wavelength of response is approximately 610nm. Because of the factors mentioned in the practicals the uncertainty in plotting points is higher than usual but the shape of the graph is correct.

Question 29.17

The output is not zero at 700nm, the long wavelength threshold of the material where the output is zero can be estimated from the graph to be between 700 and 800nm. This figure depends on the chemical state of the material and may vary between samples.

Question 29.18

Infra-red produces little output as it consists of light wavelength above the threshold of the material.

Question 29.19

The threshold of silicon is higher than that of Cadmium Sulpho-selenide as it responds to infra-red.

Question 29.20

The best of the two materials for detecting:

(a)	Daylight	is Cadmium Sulpho-selenide
(b)	Fluorescent light	is Cadmium Sulpho-selenide
(c)	Tungsten filament	is Silicon
(d)	A fire	is Silicon

The reasons are discussed in the Practical Aspects section of the manual.