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LdI/dt, though it can be seen that treating it as an EMF equal to $-LdI/dt$ is equally valid. No problem arises, of course, if the nature of both PD and EMF are fully understood.

To summarise; EMF is produced by an *electro-pump*, a device which uses non-electrical energy to maintain a potential difference between its terminals. The EMF is produced whether or not the 'pump' is delivering current. If this concept of an electropump is firmly understood, there should be no difficulty in understanding the nature of EMF and its relationship to PD.

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Computers in physics teaching

The Computational Physics and Education Groups of The Institute of Physics are planning a series of joint meetings on topics of common interest to both Groups. The first meeting, on 'The use of computers in mainstream physics teaching', will be held at the University of Essex on Thursday 9 January 1986 and will be a full day meeting (10.30–17.00) organised jointly by Dr D Tilley (Education Group) and Dr H Liddell (Computational Physics Group). The meeting will consist of a mixture of invited and contributed talks, poster presentations and demonstrations by manufacturers, publishers and individuals who have developed interesting software in this area.

The provisional programme includes the following speakers and topics:
'The Computer Board initiative on facilities for teaching' by R J Elliott (Oxford) or J Forty (Warwick); 'Computer assisted texts' by R A Harding (Cambridge); 'Physics students and computers' by G Toombs (Nottingham); 'Microcomputer perturbation theory' by J Killingbeck (Hull); and 'Software for undergraduate physics' by A D Boardman (Salford).

Further details can be obtained from the Meetings Officer, The Institute of Physics, 47 Belgrave Square, London SW1X 8QX (tel. 01-235 6111).

The refractive index of thin solid films

S K J Al-Ani and J Beynon

A fundamental optics experiment in the school/undergraduate physics laboratory is the investigation of the dispersion of visible light using a prism spectrometer. The refractive index, n, of the prism material can be calculated for various wavelengths with the help of the familiar relation

$$n = \sin[(A + D_{min})/2]/\sin(A/2), \qquad (1)$$

where A is the refracting angle of the prism and D_{min} is the angle of minimum deviation. Figure 1 shows the variation of n with wavelength obtained with an ordinary 'student' optical spectrometer and a sodium discharge lamp as source.

With reasonable care it is possible to verify that n and λ satisfy a simplified Cauchy relation of the form

$$n = L + M\lambda^{-2}, \qquad (2)$$

where L and M are constants characteristic of the prism material. Equation (2) is also plotted in

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John Beynon *is a lecturer in physics and co-director of the physics and electronics joint honours course at Brunel University. He gained a doctorate from the University of Wales, was a CEGB Research Fellow at University College, Swansea and has worked with The Signals Research and Development Establishment. His main research interests are thin films and vacuum technology and his publications include* Conduction of Electricity in Gases *(1971 London: Harrap) and* Physics and Chance *(1974 London: Hutchinson Educational).*

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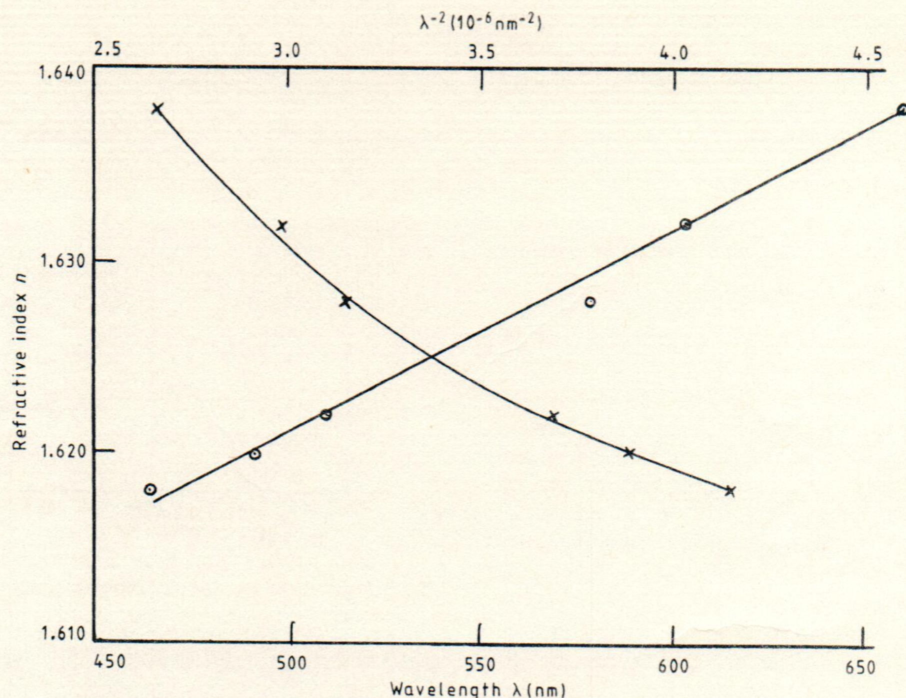

Figure 1 Variation of refractive index with wavelength (and the Cauchy relation)

figure 1; in this case, L is 1.570 and M is $1.0 \times 10^4\,\text{nm}^2$.

An experiment of this kind is an invaluable aid for understanding the meaning of refractive index and its variation with wavelength in the visible spectrum. However, it is our experience that many students have the impression that refractive index is a parameter peculiar to the visible region. Thus it is essential to extend any discussion of figure 1 to other regions of the electromagnetic spectrum. The main objective of this article, therefore, is to widen the student's appreciation of refractive index beyond the visible into the infrared: a thin solid film is used as a vehicle for achieving this purpose. A secondary objective is to introduce the student to absorption in solids and the concept of the optical absorption edge; absorption can be used for characterising the composition and structure of a material and the absorption edge for determining its electronic properties.

The wavelength range investigated in figure 1 lies in the *normal* dispersion region. On increasing λ into the infrared, equation (2) is no longer applicable. This is the *anomalous* dispersion region. Here it will be found that n decreases fairly sharply at first and then increases again as the medium absorbs the incident radiation. The range of wavelengths covering this absorption band, as well as the number of bands observed, depends on the material being studied.

The refractive index n and the absorption index k are the only parameters needed to characterise the optical behaviour of an isotropic material. They are both real and positive, and describe the amplitude and phase of a plane wave inside the material. Normally two separate experiments are required for their determination but later we shall see how they may be obtained from the same set of optical transmission measurements.

Thin solid films

A thin film generally possesses physical properties, such as optical transmittance and electronic conductivity, very different from those of the material in bulk. For example, a material which is opaque to radiation in bulk form may well transmit in thin film form. Some materials, like germanium, silicon and silicon monoxide, are unable to form solid glasses when cooled (even very rapidly) from the melt but can form amorphous thin films when condensed on to a substrate maintained at, or below, ambient temperature. Hence their properties can be studied if they are conveniently made as thin films. The term *amorphous* implies the lack of any long range order. Thin films have been an extremely active research area for many years but

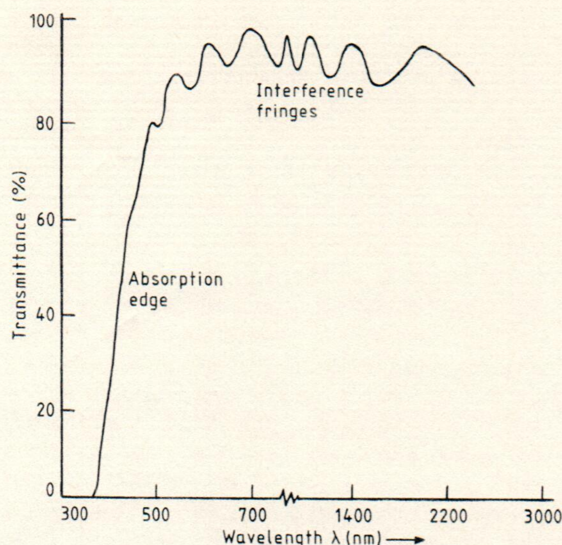

Figure 2 Transmission spectrum of a silicon oxide thin film showing the absorption edge and interference fringes

recently the importance of information technology has seen a resurgence of interest in their properties.

Determination of refractive index

The refractive index of a thin solid film can be found using multiple beam interferometry (Tolansky 1973). For a given film thickness, constructive interference of either the transmitted or reflected system of waves will occur for particular wavelengths present in the incident radiation. The transmission spectrum of the solid film is first obtained from the visible to the near infrared using a spectrophotometer. Figure 2 shows the result for a silicon oxide film, 850 nm thick, prepared by evaporating silicon oxide powder *in vacuo* $\sim 10^{-4}$ Pa at a deposition rate $>5\ \mathrm{nm\,s^{-1}}$ on to a Corning 7059 alkali-free substrate held at a temperature of 20 °C.

It is important to make sure that the temperature does not rise much above this value (due to radiant heating by the evaporation source) if an amorphous thin film is required. The set of interference fringes are clearly evident. In this instance the first order interference fringe occurs at a wavelength of 2000 nm, which means that the order of interference m of any other maximum beyond 800 nm can be unambiguously established. The position of the first order maximum, however, does not always occur at 2000 nm even for the same film material. In general, it is a function of the film and substrate material and the film thickness. The refractive index may now be calculated using the relation

$$2nd = m\lambda \tag{3}$$

where d is the film thickness. Figure 3 was obtained in this way. It can be seen that n gradually decreases in value to 700 nm wavelength followed by a flat response to 2000 nm.

In general, however, it is not essential for m to be known because we may write, for adjacent maxima in figure 2,

$$2nd = m\lambda_m = (m+1)\lambda_{m+1}$$

allowing m to be eliminated to give

$$(2nd)^{-1} = \lambda_{m+1}^{-1} - \lambda_m^{-1}. \tag{4}$$

As λ_{m+1} and λ_m can be read directly from figure 2, n can be calculated. In both equations (3) and (4) it is essential that the film thickness, d, be known accurately. The principle of multiple beam interference in an air wedge is almost universally applied for this purpose. Table 1 gives mean values of n for a BaO/SiO co-evaporated thin film obtained by us using equation (4). Table 2 gives values of n for three different oxides of silicon (Pliskin 1968). These results are presented because they indicate the way in which the refractive index of an oxide film depends on the degree of oxidation.

The various silicon oxide compositions quoted in table 2 may be obtained by evaporating silicon monoxide powder at various deposition rates and vacuum conditions. As mentioned previously, SiO thin films can be prepared at high deposition rates ($\geqslant 5\ \mathrm{nm\,s^{-1}}$) and residual gas pressures $\sim 10^{-4}$ Pa. At lower deposition rates there is an increasing probability that oxidation will occur and an intermediate oxide SiO_x, will be formed, where $1 < x < 2$. Usually low deposition rates of about $0.5\ \mathrm{nm\,s^{-1}}$ and high residual gas pressures ($\geqslant 10^{-2}$ Pa) are required for complete oxidation to occur.

Absorption

Figure 2 indicates that the incident radiation is strongly absorbed between wavelengths of 350 nm and 500 nm. This region is called the *fundamental*

Table 1 Variation of refractive index of BaO/SiO thin films with thickness

Film thickness (nm)	n
390	2.16
500	2.17
750	2.22

Table 2 Refractive index and main IR absorption band of various silicon oxides (Pliskin 1968)

Film composition	n	IR centre wavelength (nm)
SiO	1.95	10.0
Si_2O_3	1.54	9.6
SiO_2	1.46	9.2

optical absorption edge and is very important because it allows the energy gap E_g between the valence and conduction bands of the solid film to be estimated.

Using Planck's law, the energy gap E_g can be expressed in terms of the frequency f_g of the absorbed radiation as

$$E_g = hf_g \qquad (5)$$

In a highly crystalline material the absorption edge is normal to the frequency (or wavelength) axis, and indicates that there is a well-defined energy gap. This means that only radiation of energy $>hf_g$ will be absorbed, and release an electron into the conduction band. Figure 2, on the other hand, depicts an absorption edge of varying slope. This suggests that silicon oxide is essentially non-crystalline, as can be confirmed by electron diffraction, and, therefore, possesses no well-defined energy gap.

Besides allowing n to be estimated, figure 2 also enables the absorption index k to be determined at given wavelengths. k is related to the absorption coefficient α and the transmittance T by

$$k = \alpha\lambda/4\pi$$
$$= -2.303\lambda \log (T/4\pi d). \qquad (6)$$

Table 3 shows how k varies along the optical absorption edge in figure 2.

Table 2 lists the central wavelengths of the main absorption bands of the silicon oxides (Ritter 1962). Together with n, the position of these absorption bands helps to characterise the composition of the oxides. The infrared spectrum is conveniently divided into three regions: near IR (12000–4000 cm^{-1}); mid IR (4000–200 cm^{-1}); and far IR (200–10 cm^{-1}). A study of the IR spectra of molecules leads to precise information about their rotational, vibrational and electronic energy levels. From these energy levels the inter-nuclear distances, the vibrational frequencies and force constants, the dissociation energy and other data concerning the structure of the molecules may be obtained. However, because of experimental difficulties in generating and detecting radiation in the far IR, the latter is rarely used in chemical spectroscopy.

Figure 3 Variation of refractive index of a silicon oxide thin film with wavelength in the normal dispersion region

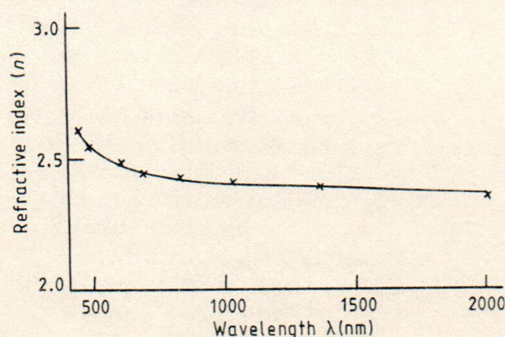

Table 3 Variation of absorption index with wavelength (calculated from figure 2)

λ(nm)	T	$\alpha(cm^{-1})$	k
395	0.2	18910	0.060
405	0.3	14170	0.046
415	0.4	10785	0.035
440	0.6	8810	0.030

The absorption bands of the three silicon oxides given in table 2 agree well with the known values for Si–Si and Si–O bond stretching. Besides these main absorption bands, subsidiary bands may also be present, such as that at $\lambda = 2.8$ μm (due to the Si–OH group) and at $\lambda = 2.9$ μm (due to absorbed water). These subsidiary absorption bands are undesirable as they indicate that the films are highly porous; atmospheric water vapour has diffused into the specimens. Devices made from such materials have limited usefulness unless they are encapsulated.

In conclusion, it may be stated that refractive index/wavelength measurements give essential information about: (i) the way in which the speed of light varies in a material other than air; (ii) the performance of various optical components; (iii) the values of certain physical constants of a material, and (iv) information about the electronic band structure of a material. In addition, the combination of refractive index with band gap E_g and infrared studies enables composition and structure to be determined and the stability of the material to be assessed.

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