Optical properties of indium phosphide inp

J. O. AKINLAMI*, U. G. IKPEOHA
Department of Physics, Federal University of Agriculture, P.M.B 2240, Abeokuta, Ogun State, Nigeria

Knowledge of the optical properties of Indium Phosphide is important because of the increasing application of InP in many electronics and photonic devices. We have investigated the optical properties of Indium Phosphide (InP) in the photon energy range 0.6 – 6.0eV. We obtained refractive index which has a maximum value of 4.42 at photon energy 3.1eV, the extinction coefficient which has a maximum value of 3.5 at photon energy 4.80eV, the dielectric constant, the real part of the complex dielectric constant has a maximum value of 17.0 at photon energy 3.0eV and the imaginary part of the complex dielectric constant has a maximum value of 23.0 at photon energy 4.8eV, the transmittance which has a maximum value of 0.22 at photon energy 3.0eV, the absorption coefficient which has a maximum value of 17 x 10^7 m^{-1} at photon energy 5.0eV, reflectance which has a maximum value of 0.62 at 5.1eV, reflection coefficient which has a maximum value of 0.79 at photon energy 5.0eV, the real part of optical conductivity has a maximum value of 13 x 10^{15} at 4.8eV and the imaginary part of the optical conductivity has a maximum value of 4.8 x 10^{15} at 5.1eV. The values obtained for the optical properties of InP is in good agreement with other results by Adachi, Kim *et al*, Maloney and Aspnes and Studna.

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1. Introduction

The developments of compound semiconductor materials technology, invention and demonstration of semiconductor lasers together with low loss optical fibers have spurred the progress of optoelectronics industry. Optoelectronics combines the properties of light with the capabilities of microelectronics [1].

Atoms from group III of the periodic table combine with atoms from group V to form crystalline semi conducting compounds. These are called semiconductors III – V compound. The first of the III – V compounds to be reported was Indium Phosphide InP by Thiel and Keelsch [2] and prepared over fifty years ago by Hilsum and Rose-Innes [3].

InP is a direct-gap semiconductor of great technological significance [4-6], since it serves as the substrate for most optoelectronic devices operating at the communication wavelength of 1.55μm [7]. In recent years there has been considerable interest in Indium Phosphide (InP) and related alloys because of their applications in many electronic and photonic devices. Specifically, as an example, the heterojunction bipolar transistor (HBT) is an improvement of the bipolar junction transistor (BJT) and can handle signals of very high frequencies up to several hundred GHz. InP is also used for InP/GaInAs-based HBTs, which have demonstrated improved microwave characteristics [8].

According to Talazac [9] a number of InP Schottk devices are recently developed for radiation and gas detection like ozone O_3 and Nitrogen Oxide NO_3 and other components/pollutants in the environment. Because of these applications, InP-related materials have become an important class of III-V semiconductors [10].

In this work, we have investigated complex optical properties of Indium Phosphide (InP) because of the increasing application of InP in many electronics and photonic devices.

2. Method of calculation

Reflection coefficient measures the fractional amplitude of the reflected electromagnetic field and it is given by [11]

$$r(\omega)=\frac{n(\omega)-1+ik(\omega)}{n(\omega)+1+ik(\omega)} \quad (1)$$

where n is the refractive index and k is called the extinction coefficient.

The reflectance R is given by

$$R(\omega)=\frac{(n(\omega)-1)^2+k^2(\omega)}{(n(\omega)+1)^2+k^2(\omega)} \quad (2)$$

The reflectance is the square of the reflection coefficient

$$R=r^2 \quad (3)$$

We used the refractive index and extinction coefficient data obtained by Schubert [12] to obtain reflection coefficient and reflectance of InP using equations 1 and 2.

The complex dielectric constant is a fundamental intrinsic property of the material. The real part of the dielectric constant shows how much it will slow down the speed of light in the material, whereas the imaginary part shows how a dielectric material absorbs energy from an electric field due to dipole motion. The knowledge of the real and the imaginary parts of dielectric constant provides information about the loss factor which is the ratio of the imaginary part to the real part of the dielectric constant [13]. The real and the imaginary parts of the dielectric constant can be estimated using the relations [14]

$$E_1 = n^2 - k^2 \quad (4)$$

$$E_2 = 2nk \quad (5)$$

The absorption coefficient (α) can be calculated using the equation

$$\alpha = \frac{4\pi k}{\lambda} \quad (6)$$

where k is the extinction coefficient and λ is the wavelength.

The transmittance is obtained from the relation

$$R + T + A = 1 \quad (7)$$

where R, T and A represent the reflectance, transmittance and absorbance respectively. The sum of these macroscopic quantities which are usually known as the optical properties of the material must equal unity since the incident radiant flux at one wavelength is distributed totally between reflected, transmitted and absorbed intensity. The absorbance A is given by

$$A = LOG\left(\frac{1}{R}\right) \quad (8)$$

The optical response of a material is mainly studied in terms of the optical conductivity (σ) which is given by the relation [15]

$$\sigma = \frac{\alpha nc}{4\pi} \quad (9)$$

where c is the velocity of light, α is the absorption coefficient and n is the refractive index. It can be seen clearly that the optical conductivity directly depends on the absorption coefficient and the refractive index of the material.

3. Results and discussion

The refractive index obtained for InP in the photon energy range 0.6eV to 6.0eV is shown in Fig. 1. As can be seen from Fig. 1, the refractive index first increases with increase in photon energy in the photon energy range 0.6 – 3.0eV with a maximum value of 4.42 at 3.1eV. The refractive index drops and then rises and decreases afterwards in the energy range 4.7 – 6.0eV. This decrease in refractive index indicates that InP shows normal dispersion behaviour. The refractive index shows two peaks at 3.0eV and 4.7eV. Our result for refractive index is in good agreement with that reported by Adachi [16] which also shows two peaks at 3.2eV and 4.7eV with a maximum value of 4.6. With a refractive index of 4.42, InP can be used as a reflector.

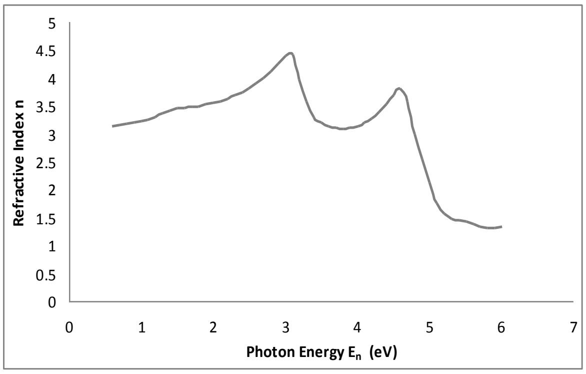

Fig. 1. Refractive index and extinction coefficient of indium phosphide.

The extinction coefficient obtained for InP in the photon energy range 0.6 – 6.0eV is shown in Fig. 2. As can be seen from Fig. 2, the extinction coefficient first increases with increase in photon energy in the photon energy range 1.3 – 3.2eV. It then drops and rises to a maximum value of 3.5 at 4.8eV and afterwards decreases with increase in photon energy. The increase in extinction coefficient with increase in photon energy in the photon energy range 1.3 – 3.2eV shows that the fraction of light lost due to scattering and absorbance increases in this energy range and the decrease in the extinction coefficient in the photon energy range 4.8 – 6.0eV shows that the fraction of light lost due to scattering and absorbance decreases in this energy region. The extinction coefficient is zero in the photon energy range 0.6 – 1.3eV which means that InP is transparent in this energy region. The extinction coefficient also shows two peaks at 3.2 and 4.8eV.

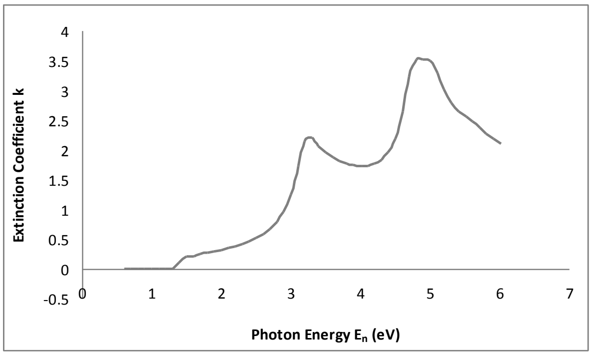

Fig. 2. Extinction coefficient of indium nitride.

The real part of the complex dielectric constant ε_1 obtained for InP in the photon energy range 0.6 – 6.0eV is shown in fig. 3. As can be seen from fig. 3, the real part of complex dielectric constant, ε_1, first increases with increase in photon energy in the photon energy range 0.6 – 3.0eV with a maximum value of 17 at 3.0eV which is in good agreement with that reported by Kim *et al* (17 at 3.2) [17]. The increase in dielectric constant with increase in photon energy in the photon energy range 0 – 3.0eV shows that the loss factor increases with increase in photon energy in this energy range. The real part of the complex dielectric then decreases with increase in photon energy in the photon energy range 3.0 – 5.2eV. This shows that the loss factor decreases with increase in photon energy in this energy range.

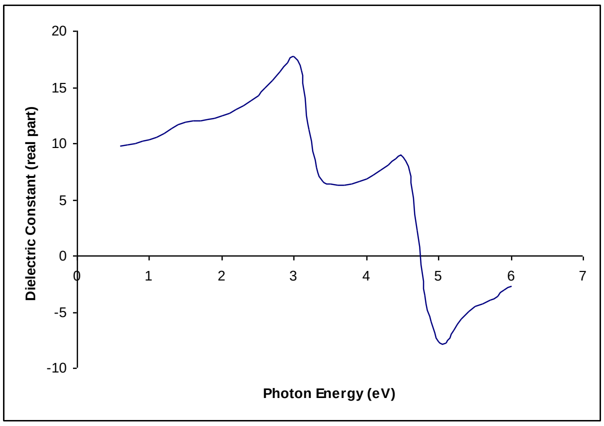

Fig. 3. Complex dielectric constant (real part) of indium phosphide.

The imaginary part of the complex dielectric constant, ε_2, obtained for InP in the energy range 0 – 6.0eV is shown in fig. 4. The imaginary part of the complex dielectric constant is constant in the photon energy range 0.8 – 1.3eV and then increases with increase in photon energy in the photon energy range 1.3 – 4.7eV with a maximum value of 23 at 4.8eV which is in good agreement with that reported by Kim *et al* (24 at 4.8eV) [17]. The increase in imaginary part of the complex dielectric in the photon energy range 1.3 – 4.8eV shows that the loss factor increases with increase in photon energy in this energy region. The imaginary part of the complex dielectric constant decreases with increase in photon energy in the photon energy range 4.8 – 6.0eV which shows that the loss factor decreases with increases in photon energy.

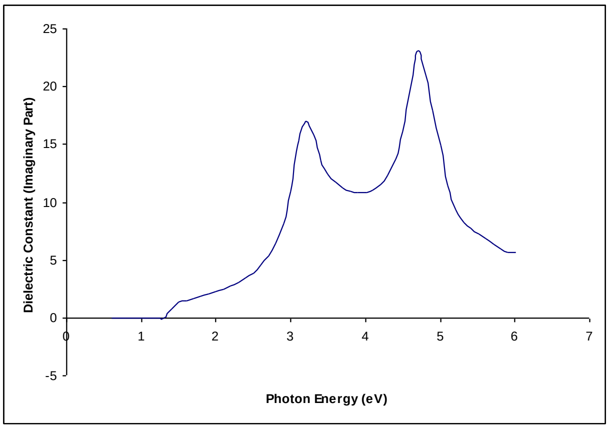

Fig. 4. Complex dielectric constant (imaginary part) of indium phosphide.

The transmittance (T) obtained for InP in the energy range 0eV – 6.0eV is shown in fig. 5. It can be seen from Fig. 5, the transmittance increases with increase in photon energy with a maximum value of 0.22 at 3.0eV. With a maximum of 0.22 for transmittance it means that InP is not a good transmitter of electromagnetic wave in this energy region. With a peak value of 0.22 for transmittance, it means that InP is a material for optoelectronic devices.

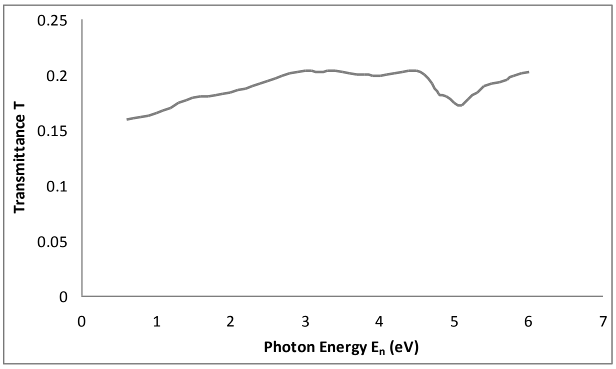

Fig. 5. Transmittance of indium phosphide.

The absorption coefficient, α obtained for InP in the photon energy range 0eV – 6.0eV is shown in fig. 6. As can be seen from Fig. 6, the absorption coefficient increases with increase photon energy in the energy range 1.3 – 5.0eV with a maximum value of 17 x 10^7 m^{-1} (17 x 10^5 cm^{-1}) at 5.0eV which is in good agreement with that reported by Maloney [18] which shows two peaks at 3.3eV and 5.0eV with a maximum value of 17.8 x 10^5 cm^{-1} and that reported by Aspnes and Studna [19] which also shows two peaks at 3.2eV and 5.2eV with a maximum value of 1.78 x 10^6 cm^{-1}. The value of absorption coefficient then drops to a value of 13 x 10^7 m^{-1} at 6.0eV. This high value of the absorption coefficient is typical for interband absorption in semiconductors [20]. It is important to emphasize that there is no absorption in the energy range 0.6 – 1.3eV which is the energy range of bandgap of InP. That is, the energy at which the absorption starts corresponds to the direct band gap at 1.42eV [21]. InP shows no absorption below its band gap. The absorption coefficient shows two peaks at photon energies 3.2eV and 5.0eV.

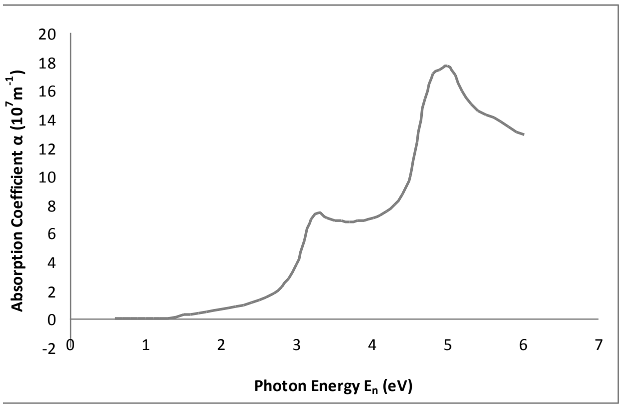

Fig. 6. Absorption coefficient of indium phosphide.

The reflection coefficient for InP obtained in the photon energy range 0 – 6.0eV is shown in Fig. 7. As can be seen from Fig. 7, the reflection coefficient increases with increase in photon energy in the energy range 0.6 –

5.0eV with a maximum value 0.79 at 5.0eV. Hence, InP is highly absorbing.

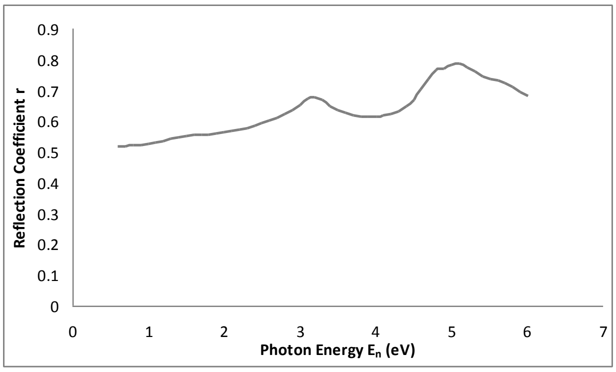

Fig. 7. Reflection coefficient of indium phosphide.

The reflectance for InP obtained in the photon energy range 0 – 6.0eV is shown in Fig. 8. As can be seen from the figure, the reflectance increases with increase in photon energy in the photon energy range 0.6 – 5.1eV with a maximum value of 0.62 at 5.1eV. The reflectance then drops to a value of 0.45 at 6.0eV. The reflectance shows two peaks at 3.2 and 5.1eV. The reflectance obtained by us is in good agreement with that reported by Aspnes and Studna [19] which shows two peaks at photon energies 3.2 and 5.3eV with a maximum value of 0.63 and that reported [22] which also shows two peaks at 3.2 and 5.2eV with a maximum value of 0.62.

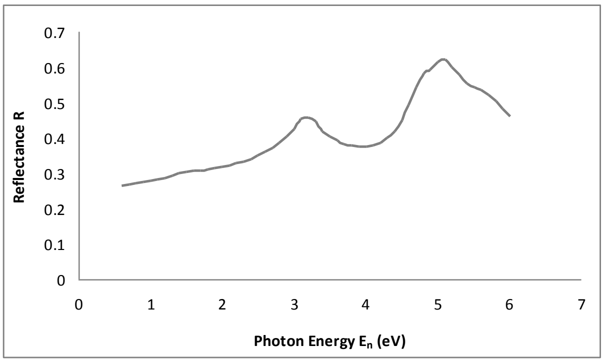

Fig. 8. Reflectance of indium phosphide.

The real part of the optical conductivity for InP in the photon energy 0.6 – 6.0eV is shown in Fig. 9. As can be seen from the figure, the real part of the optical conductivity increases with increase in photon energy in the energy range 1.4 – 4.8eV and it then decreases with increase in photon energy in the photon energy range 4.8 – 6.0eV. It has a maximum value of 13 x 10^{15} at 4.8eV. The increase in the real part of optical conductivity in the photon energy range 1.4 – 4.8eV can be attributed to the increase in absorption coefficient in this energy range. The real part of the optical conductivity shows two peaks at 3.2 and 4.8eV. However, at low energies between 0.6eV and 1.2eV, the conductivity is zero, which means that InP do not conduct in this energy range. With a peak value of 13 x 10^{15} for real part of optical conductivity it means that InP can be used for electronic devices.

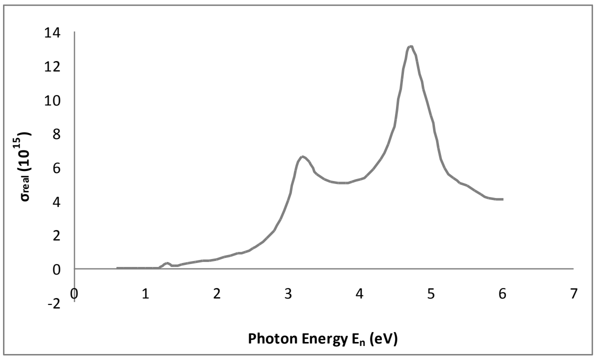

Fig. 9. Optical conductivity (real part) of indium phosphide.

The imaginary part of the optical conductivity for InP in the photon energy 0 – 6.0eV is shown in figure 10. As can be seen from figure 10, the imaginary part of the optical conductivity first decreases with increase in photon energy in the energy range 0.6 – 3.0eV with a minimum value of -6.8 x 10^{15} at 3.0eV and it then increases with increase in photon energy in the photon energy range 3.0 – 5.1eV with a maximum value of 4.8 x 10^{15} at 5.1eV. The negative value of the imaginary part of the optical conductivity is due to the increase in extinction coefficient and it implies that there is reduction in the conductivity of InP in this energy range.

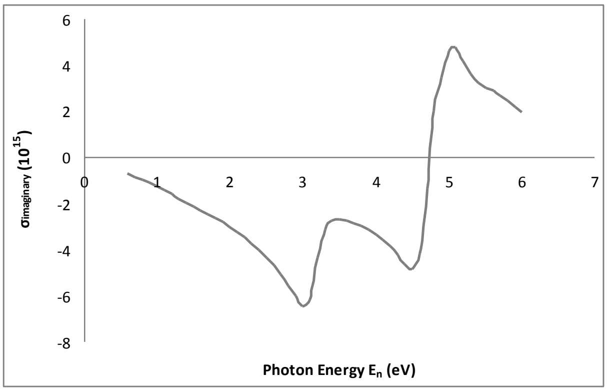

Fig. 10. Optical conductivity (imaginary part) of indium phosphide.

4. Conclusions

In conclusion, we have investigated theoretically the complex index of refraction of Indiun Phosphide (InP) in the energy range 0.6eV – 6.0eV. The refractive index has a maximum value of 4.42 at 3.1eV. The refractive index decreases with increase in photon energy in the energy range 4.7 – 6.0eV. This decrease in refractive index indicates that InP shows normal dispersion behaviour. Our result for refractive index is in good agreement with that reported by Adachi. With a refractive index of 4.42, InP can be used as a reflector.

The increase in extinction coefficient with increase in photon energy in the photon energy range 1.3 – 3.2eV shows that the fraction of light lost due to scattering and absorbance increases in this energy range and the decrease in the extinction coefficient in the photon energy range 4.8 – 6.0eV shows that the fraction of light lost due to scattering and absorbance decreases in this energy region. The extinction coefficient is zero in the photon energy range 0.5 – 1.3eV which means that InP is transparent in this energy region.

The real part of the complex dielectric constant has a maximum value of 17 at 3.0eV which is in good agreement with that reported by Kim et al. The increase in dielectric constant with increase in photon energy in the photon energy range 0.6 – 3.0eV shows that the loss factor increases with increase in photon energy in this energy range. The decrease in the real part of the complex dielectric with increase in photon energy in the photon energy range 3.0 – 5.2eV shows that the loss factor decreases with increase in photon energy in this energy range.

The imaginary part of the complex dielectric constant has a maximum value of 23 at 4.8eV which is in good agreement with that reported by Kim et al. The increase in imaginary part of the complex dielectric in the photon energy range 1.3 – 4.8eV shows that the loss factor increases with increase in photon energy in this energy region. The decrease in the imaginary part of the complex dielectric constant with increase in photon energy in the photon energy range 4.8 – 6.0eV shows that the loss factor decreases with increase in photon energy.

The transmittance has a maximum value of 0.22 at 3.0eV which shows that InP is not a good transmitter of electromagnetic wave in this energy region. With a peak value of 0.22 for transmittance, it means that InP is a material for optoelectronic devices. The absorption coefficient has a maximum value of $17 \times 10^7\ m^{-1}$ ($17 \times 10^5\ cm^{-1}$) which is in good agreement with that reported by Maloney, Aspnes and Studna This high value of the absorption coefficient is typical for interband absorption in semiconductors. InP shows no absorption below its band gap.

The reflection coefficient has a maximum value 0.79 at 5.0eV which means InP is highly absorbing. The reflectance increases has a maximum value of 0.62 at 5.1eV which is in good agreement with that reported by Aspnes and Studna.

The real part of the optical conductivity has a maximum value of 13×10^{15} at 4.8eV. The increase in the real part of optical conductivity in the photon energy range 1.4 – 4.8eV can be attributed to the increase in absorption coefficient in this energy range. At low energies between 0.6eV and 1.2eV, the conductivity is zero, which means that InP do not conduct in this energy range. With a peak value of 13×10^{15} for real part of optical conductivity it means that InP can be used for electronic devices.

The imaginary part of the optical conductivity has a minimum value of -6.8×10^{15} at 3.0eV and a maximum value of 4.8×10^{15} at 5.1eV. The negative value of the imaginary part of the optical conductivity is due to the increase in extinction coefficient and it implies that there is reduction in the conductivity of InP in this energy range.

The values obtained for the optical properties of InP over the energy range 0.6 – 6.0eV are essentially important for emerging InP applications such as the design of optoelectronic devices, electronic and photonic devices.

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*Corresponding author: johnsonak2000@yahoo.co.uk