Optical Properties of Indium Antimonide InSb

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An understanding of the optical properties of Indium Antimonide (InSb) is important because of the increasing application of InSb in many optical and electronics devices. Optical properties of Indium Antimonide (InSb) have been investigated by means of the Kramers and Kronig method in photon energy range 1.0 – 6.01eV. The properties investigated includes: refractive index which has a maximum value of 4.91 at photon energy 1.82eV; the extinction coefficient which has a maximum value of 3.72 at photon energy 4.05eV; the dielectric constant, the real part of the complex dielectric constant, which has a maximum value of 22.3 at photon energy 1.77eV; the imaginary part of the complex dielectric constant having a maximum value of 21.3 at photon energy 3.85eV; the transmittance which has a maximum value of 0.20 at photon energy 3.61eV; the absorption coefficient which has a maximum value of 1.53 x 10^8 m^{-1} at photon energy 4.09eV; the reflectance which has a maximum value of 0.64 at 4.17eV; the reflection coefficient which has a maximum value of 0.80 at photon energy 4.17eV; the real part of optical conductivity which has a maximum value of 9.99 x 10^{15} at 3.89eV; and the imaginary part of the optical conductivity has a maximum value of 4.49 x 10^{15} at 4.13eV. The values obtained for optical properties of InSb are essentially important for emerging InSb applications such as fabrication of antenna-coupled infrared detectors, photo-electric, magnet-electric conversion devices and optoelectronic devices.

1. Introduction

Indium Antimonide (InSb) is a crystalline compound made from the elements Indium (In) and Antimony (Sb). It is a narrow-gap semiconductor with an energy band gap of 0.17 eV at 300K and 0.23 eV at 80K. The crystal structure is Zincblende with a 0.648 nm lattice constant [1]. Un-doped InSb possess the largest ambient-temperature electron mobility 7800 cm^2/V_s [2], electron drift velocity and ballistic length up to 0.7 μm at 300K [1] of any known semiconductor, except possibly for carbon nanotubes.

InSb is an important III-V semiconductor material in the field of infrared detectors [3-4] in the 3-5 μm wavelength range due to its high electron and hole mobility and low energy gap [5] at room temperature [6,7]. It is also used for the fabrication of devices such as antenna-coupled infrared detectors [8], high speed, Hall and optoelectronic devices [9-13]. InSb photodiode detectors are photovoltaic, generating electric current when subjected to infrared radiation [14].

A detailed knowledge of the optical properties is important for the realization of optoelectronic devices. However, experimental and theoretical data on the optical properties of InSb are few. In this work, we have investigated optical properties of Indium Antimonide (InSb) in the photon energy range 1.0 – 6.01eV because of the increasing application of InSb in many optical, electronics and photonic devices. The rest of the paper is organized as follows: Sec. 2, describes the method of calculation of optical properties, Sec. 3 presents the results and discussion, while conclusions are given in Sec. 4.

2. Method of Calculation

Kramers-Kronig analysis of measured refractive index and extinction coefficient data obtained by Schubert [15] was carried out to obtain reflection coefficient and reflectance of InSb using Eqn. (1) and Eqn. (2). Reflection coefficient measures the fractional amplitude of the reflected electromagnetic field [16] and it is given by

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

Where, n is the refractive index and k is called the extinction coefficient.

The measured values of n and k at different wavelengths were used as input in Eqn. (1) to obtain reflection coefficient of InSb and in Eqn. (2) to obtain reflectance of InSb.

The reflectance R is given by [17] as

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

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 imaginary and real parts of the dielectric constant [18,19]. The real and the imaginary parts of the dielectric constant can be estimated using the relations [20]

$$E_1 = n^2 - k^2 \quad (3)$$

$$E_2 = 2nk \quad (4)$$

The measured values of n and k at different wavelengths were used as input in Eqn. (3) and Eqn. (4) to obtain the real and imaginary parts of the dielectric constant of InSb, respectively.

The absorption coefficient (α) can be calculated using the equation [21,22]

$$\alpha = \frac{4\pi k}{\lambda} \quad (5)$$

Where, k is the extinction coefficient and λ is the wavelength.

The transmittance is obtained from the relation

$$R + T + A = 1 \quad (6)$$

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

$$A = LOG\left(\frac{1}{R}\right) \quad (7)$$

The optical response of a material is mainly studied in terms of the optical conductivity (σ), which is given by the relation [23]

$$\sigma = \frac{\alpha n c}{4\pi} \quad (8)$$

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 [18,19].

3. Results and Discussion

The refractive index spectrum of InSb in the energy range 1.0eV to 6.01eV is shown in Fig. 1. There is an increase in the refractive index in the energy range 1.0eV to 1.82eV, with a peak value of 4.91 at 1.82eV as shown in Fig. 1. The refractive index decreases afterwards in the energy range 1.82 – 6.01eV. This decrease in refractive index indicates that InSb shows normal dispersion behavior and also that InSb is a semiconductor because the refractive index of a semiconductor typically decreases with increasing energy. Two peaks are observed at 1.82 eV and 3.56 eV, they are mainly due to the transitions from the last valence band to the first conduction band. The result for refractive index is in good agreement with a value of 5.0 reported by Adachi [24]. With a refractive index of 4.91, InSb can be used as a reflector. The variation of refractive index values in investigated energy range shows that some interactions take place between photons and electrons. The refractive index changes with the variation of the photon energy due to these interactions.

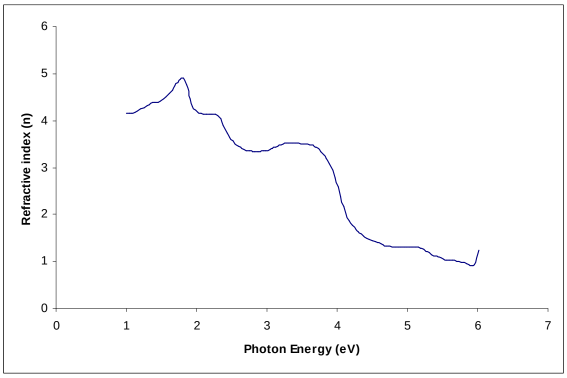

Fig.1: Refractive Index of Indium Antimonide (InSb).

The extinction coefficient spectrum in the energy range 1.0eV – 6.01eV is as shown in Fig. 2. There is an increase in extinction coefficient in the energy range 1.0 – 4.05eV as shown in Fig. 2. It has a peak value of 3.72 at 4.05eV and then decreases to a value of 1.9 at 6.01eV. The increase in extinction coefficient with increase in photon energy in the energy range 1.0 – 4.05eV 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 4.05 – 6.01eV shows that the fraction of light lost due to scattering and absorbance decreases in this energy region. The peak value of extinction coefficient indicates a good absorption in the energy range. Three peaks are observed at 1.9, 2.43 and 4.05 eV, which are mainly due to the transitions from the last valence band to the first conduction band. Also the peaks indicate regions of deep penetration of the electromagnetic wave. This penetration of the electromagnetic wave decreases as the extinction coefficient values approaches the peaks and consequently, the absorption loss also increases with these peaks.

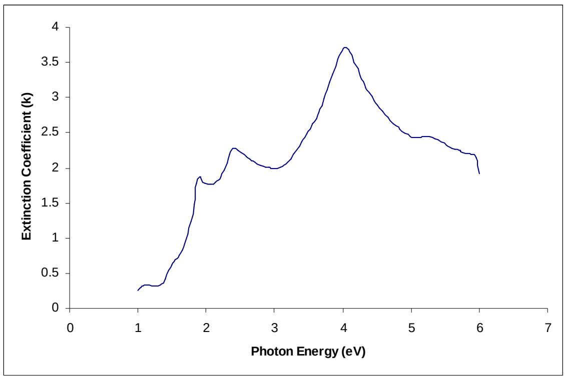

Fig.2: Extinction Coefficient of Indium Antimonide (InSb).

The real part of the dielectric constant spectrum in the energy range 1.0eV – 6.01eV is shown in Fig. 3. There is an increase in the real part of the dielectric constant in the energy range 1.0 – 1.77eV as shown in Fig. 3. It peaks at a value of 22.3 at 1.77eV, which is in good agreement with a value of 23.0 reported by Alouani et al. [25]. The increase in real part of the dielectric constant with an increase in photon energy in the photon energy range 1.0 – 1.77eV shows that the loss factor increases with the increase in photon energy in this energy range. The real part of the dielectric constant then decreases with an increase in photon energy in the photon energy range 1.77 – 6.01eV with a minimum value of -8.98 at 4.13eV. This shows that the loss factor decreases with an increase in photon energy in this energy range. The maxima correspond to higher propagation of electromagnetic waves. At higher photon energy, the propagation of the electromagnetic wave drops drastically, thus InSb tends to become an insulator at this energy range.

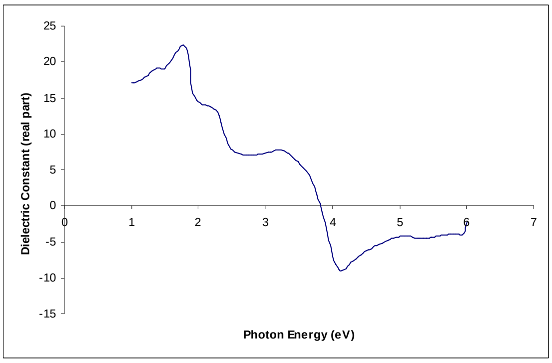

Fig.3: Complex Dielectric Constant (Real part) of Indium Antimonide (InSb).

The imaginary part of the dielectric constant spectrum in the energy range 1.0eV – 6.01eV is shown in Fig. 4. There is an increase in the imaginary part of the dielectric constant with increase in photon energy in the energy range 1.0 – 3.85eV as shown in Fig. 4. It has a peak value of 21.3 at 3.85 eV, which is in good agreement with a value of 21.0 reported by Alouani *et al* [25]. The increase in imaginary part of the dielectric in the photon energy range 1.0 – 3.85eV shows that the loss factor increases with increase in photon energy in this energy range. The imaginary part of the dielectric constant decreases with an increase in photon energy in the photon energy range 3.85 – 6.01eV, which shows that the loss factor decreases with increases in photon energy in this energy range. The propagation of electromagnetic waves is faster at the peak energy values and reduces for higher photon energies, which show that the imaginary part of the complex dielectric constant has a dependence on the photon energy.

Fig. 5 shows the transmittance spectrum for InSb in the photon energy range 1.0 – 6.01eV. The transmittance of InSb is 20% (0.20), which is constant in the energy range 1.0 – 3.61eV, it then decreases with the increase in photon energy in the energy range 3.61 – 4.13eV and afterwards increases with the increase in photon energy in the energy range 4.13 – 6.01eV as shown in Fig. 5. With a peak value of 20% (0.20) for transmittance it means that InSb is a material for optoelectronic devices.

InSb have good absorption in the energy range 1.0eV – 4.09eV as shown in Fig. 6. The absorption coefficient of InSb increases with increase in photon energy in the energy range 1.0 – 4.09eV as shown in Fig. 6, this shows that absorption coefficient is photon energy dependent. It rises to a maximum value of 1.53 x 10^6 cm^{-1} at 4.09 eV, which is in agreement with a value of 1.4 x 10^6 cm^{-1} reported by Aspnes and Studna [26], and a value of 1.6 x 10^4 cm^{-1} reported by Moss et al. [27]. The value of absorption coefficient then drops to a value of 1.16 x 10^8 m^{-1} at 6.01 eV. This high value of the absorption coefficient is typical for inter-band absorption in semiconductors [28]. InSb shows no absorption below its band gap 0.17 eV [5, 29]. The peaks and valley in the absorption coefficient spectrum are of course related to possible transitions between states in the energy bands. The degree of absorption depends among other things, for example, on the number of free electron capable of receiving the photon energy. At the maximum absorption coefficient, the electromagnetic wave is observed more. Thus, InSb absorbs more at these energy values.

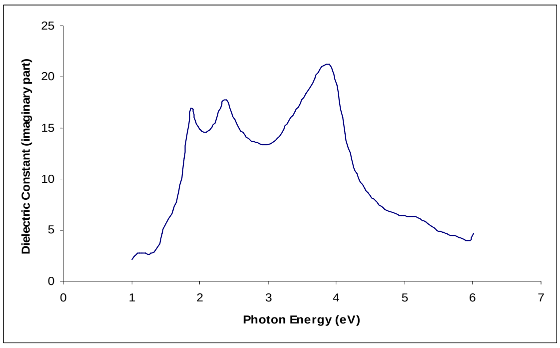

Fig.4: Complex Dielectric Constant (Imaginary Part) of Indium Antimonide (InSb).

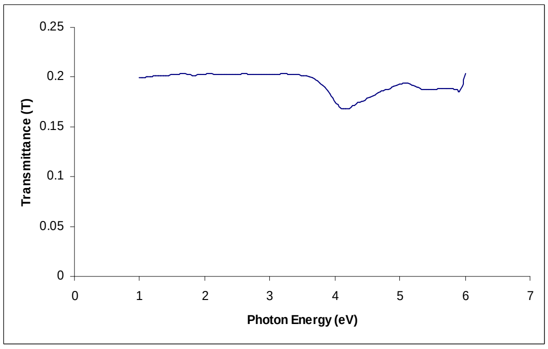

Fig.5: Transmittance of Indium Antimonide (InSb).

Fig. 7 shows the reflection coefficient for InSb. The reflection coefficient of InSb increases with an increase in photon energy in the energy range 1.0 – 4.17eV as shown in Fig. 7. It has a peak value of 0.80 at 4.17eV. The high value of the reflection coefficient means that InSb is highly absorbing because high reflectivity occurred when the electromagnetic wave is appreciably absorbed as well slowed down.

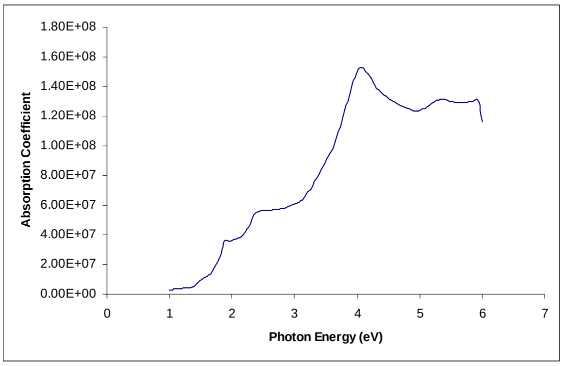

Fig.6: Absorption Coefficient of Indium Antimonide (InSb).

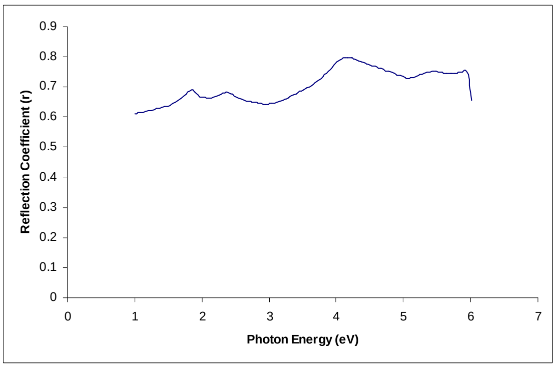

Fig.7: Reflection Coefficient of Indium Antimonide (InSb).

Fig. 8 shows the reflectance for InSb. The reflectance of InSb increases with an increase in photon energy in the energy range 1.0 – 4.17eV as shown in Fig. 8. This is the characteristics of inter-band transitions spread over the spectrum region. It has a peak value of 0.64 at 4.17eV, which is in agreement with a value of 0.64 reported by Aspnes and Studna [26] and it then drops to a value of 0.43 at 6.01 eV. Four peaks are observed at 1.86, 2.38, 4.17 and 5.48 eV, these are mainly due to transitions from the last valence band to the first conduction band.

Fig. 9 shows the real part of the optical conductivity for InSb. The real part of the optical conductivity of InSb increases with an increase in photon energy in the energy range 1.0 – 3.89eV as shown in Fig. 9. It has a peak value of 9.99 x 10^{15} at 3.89 eV. The increase in the real part of optical conductivity in the photon energy range 1.0 –

3.89eV can be attributed to the increase in absorption coefficient in this energy range. The real part of optical conductivity of InSb decreases with photon energy in the photon energy range 3.89 – 6.01eV.The real part of the optical conductivity shows three peaks at 1.9, 2.38 and 3.89 eV, these are mainly due to the transitions from the last valence band to the first conduction band. These peaks indicate regions of deeper penetration for electromagnetic waves, and they also show high conductivity. Thus, InSb can be optimized for high conductivity when the photons are at these peak energy values.

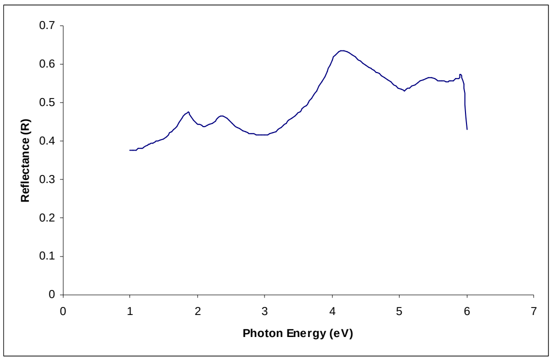

Fig.8: Reflectance of Indium Antimonide (InSb).

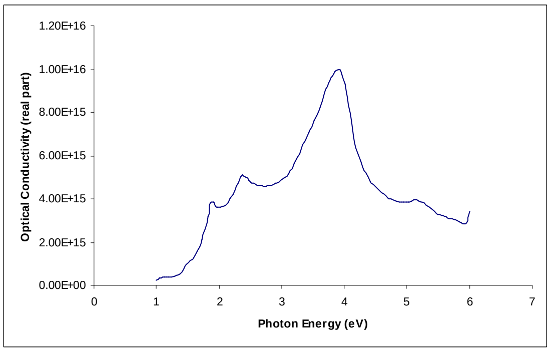

Fig.9: Optical Conductivity (Real part) of Indium Antimonide (InSb).

Fig. 10 shows the imaginary part of the optical conductivity for InSb. The imaginary part of the optical conductivity of InSb first decreases with the increase in photon energy in the energy range 1.0 – 1.82 eV from a value of -2.08 x 10^{15} at 1.0 eV to a minimum value of -4.80 x 10^{15} at 1.82 eV as shown in Fig. 10. 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 InSb in this energy range. It then increases with increase in photon energy in the photon energy range 1.82 – 4.13 eV with a maximum value of 4.49 x 10^{15} at 4.13 eV and then drops to a value of 1.55 x 10^{15} at 6.01 eV.

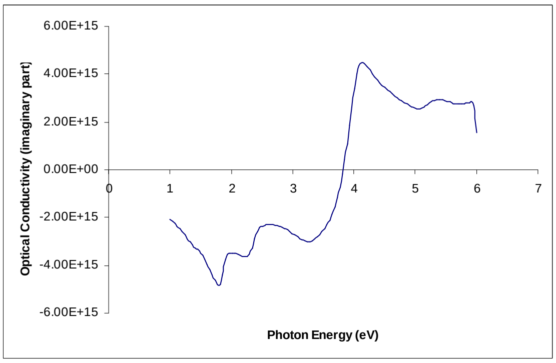

Fig.10: Optical Conductivity (Imaginary Part) of Indium Antimonide (InSb).

4. Conclusions

In conclusion, the optical properties of Indium Antimonide (InSb) have been investigated theoretically in the energy range 1.0eV – 6.01eV. The refractive index has a peak value of 4.91 at 1.82 eV and it shows normal dispersion behavior. With a refractive index of 4.91, InSb can be used as a reflector. The extinction coefficient has a peak value of 3.72 at 4.05eV, which indicates a good absorption in the energy range. The real part of the dielectric constant has a peak value of 22.3 at 1.77eV. The imaginary part of the dielectric constant has a peak value of 21.3 at 3.85eV. The transmittance has a peak value of 0.20 at 3.61eV, which shows that InSb is a material for optoelectronic device. The absorption coefficient has a peak value of 1.53 × 10^8 m^{-1}. This high value of the absorption coefficient is typical for inter-band absorption in semiconductors and it shows no absorption below its band gap. The reflection coefficient has a peak value 0.80 at 4.17eV which shows that InSb is highly absorbing. The reflectance has a peak value of 0.64 at 4.17eV. The real part of the optical conductivity has a peak value of 9.99 × 10^{15} at 3.89 eV. The imaginary part of the optical conductivity has a minimum value of -4.80 × 10^{15} at 1.82 eV and a peak value of 4.49 x 10^{15} at 4.13 eV. 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 InSb in this energy range. The values obtained for the optical properties of InSb over the energy range 1.0 – 6.01 eV are essentially important for emerging InSb applications such as the fabrication of antenna-coupled infrared detectors, photo-electric, magnet-electric conversion devices and optoelectronic devices.

References

[1] C. L. Littler and D. G. Seller, Appl. Phys. Lett. **46**(10), 986 (1985).

[2] D. L. Rode, Phys. Rev. **B3**(10), 3287 (1971).

[3] K. I. Wei, E. A. Wang, J. J. Taft, M. Sawab, M. D. Gibbons, W. Davern and D. M. Brown, IEEE Trans Electron Devices **27**, 170 (1980).

[4] R. D. Thom, T. L. Koch, J. D. Langan and W. J. Parrish, IEEE Trans Electron Devices **27**, 160 (1980).

[5] V. Raghavan, *Material Science and Engineering*, fifth edition, (Prentice-Hall of India Private Limited, New Delhi 110001, 2004)) p.368.

[6] A. H. Z. Welker, Naturforsch. **7a**, 744 (1952).

[7] L. P. Chen, J. J. Luo, R. H. Liu, S. P. Yang and Y. M. Pang, J. Appl. Phys. Lett. **31**, L817 (1992).

[8] Y. Yasuoka, T. Okuda and N. Inoue, Jpn. J. Appl. Phys. **27**, 2886 (1998).

[9] G. C. Osborn, J. Vac. Sci. Technol. **B2**, 176 (1984).

[10] T. Oi, N. Kotera, J. Shigeta, N. Yamamoto and N. Nakashima, Jpn. J. Appl. Phys. **17**, 407 (1978).

[11] A. G. Milnes, *Deep Impurities in Semiconductors* (New York, Wiley, 1973) p.45.

[12] R. Asauskas, V. Dobo and A. Krotkus, Sov. Phys. Semiconductor **14**, 1377 (1980).

[13] P. L. Baranski, O. P. Gorodrichi and V. V. Shevchenko, Infrared Phys. **30**, 59 (1990).

[14] D. G. Avery, D. W. Goodwin and A. E. Rennie Miss, J. Scientific Instruments, **34**(10), 394 (1957).

[15] E. F. Schubert, "Refractive index and extinction coefficient of materials" (2004).

[16] M. Fox, *Optical Properties of Solids* (Oxford University Press, 2001) p.3.

[17] P. Y. Yu and M. Cardona, *Fundamentals of Semiconductors* (Springer-Verlag, Berlin, 1996).

[18] N. A. Bakr, A. M. Funde, V. S. Waman, M. M. Kamble, R. R. Hawaldar, D. P. Amalnerkar, S. W. Gosavi and S. R. Jadkar, Pramana J. Physics, **76**(3), 527 (2011).

[19] J. O. Akinlami and A. O. Ashamu, J. Semicond. **34** (3), 032002-1 (2013).

[20] A. Goswami, *Thin Film Fundamentals* (New Age International, New Delhi, 2005).

[21] J. I. Pankove, *Optical Processes in Semiconductors* (New Jersey: Prentice-Hall, 1971) p.88.

[22] R. Swanepoel, J. Phys. E: Sci. Instrum. **16**, 1214 (1983).

[23] P. Sharma and S. C. Katyal, J. Phys. D: Appl. Phys. **40**, 2115 (2007).

[24] S. Adachi, J. Appl. Phys. **66**(12), 6030 (1989).

[25] M. Alouani, L. Brey and N. E. Christensen, Phys. Rev. **B37**(3), 1167 (1988).

[26] D. E. Aspnes and A. A. Studna, Phys. Rev. **B27**(2), 985 (1983).

[27] T. S. Moss, S. D. Smith and T. D. F. Hawkins, Proceedings of the Physical Society **B70**(8), 776 (2002).

[28] M. D. Sturge, Phys. Rev. **127**, 768 (1962).

[29] K.–H. Hellwege and O. Madelung, Semiconductors, Physics of Group IV Elements and III-V Compounds, Landolt-Bornstein, New Series, Group III, Vol.17, Pt. A (Springer-Verlag, Berlin, 1982).

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