Optical properties of GaAs

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Abstract: We have investigated the optical properties of gallium arsenide (GaAs) in the photon energy range 0.6–6.0 eV. We obtained a refractive index which has a maximum value of 5.0 at a photon energy of 3.1 eV; an extinction coefficient which has a maximum value of 4.2 at a photon energy of 5.0 eV; the dielectric constant, the real part of the complex dielectric constant has a maximum value of 24 at a photon energy of 2.8 eV and the imaginary part of the complex dielectric constant has a maximum value of 26.0 at a photon energy of 4.8 eV; the transmittance which has a maximum value of 0.22 at a photon energy of 4.0 eV; the absorption coefficient which has a maximum value of 0.22×10^8 m^{-1} at a photon energy of 4.8 eV, the reflectance which has a maximum value of 0.68 at 5.2eV; the reflection coefficient which has a maximum value of 0.82 at a photon energy of 5.2 eV; the real part of optical conductivity has a maximum value of 14.2×10^{15} at 4.8 eV and the imaginary part of the optical conductivity has a maximum value of 6.8×10^{15} at 5.0 eV. The values obtained for the optical properties of GaAs are in good agreement with other results.

Key words: complex index of refraction; extinction coefficient; complex dielectric constant; transmittance; absorption coefficient; semiconductor and photon energy

DOI: 10.1088/1674-4926/34/3/032002 **EEACC:** 2520

1. Introduction

Gallium arsenide (GaAs) is a compound of the elements gallium and arsenic. It is grey, has cubic crystals with a melting-point of 1238 ℃, and a density of 5.3176 g/cm^3[1]. GaAs is a III–V compound semiconductor composed of the element gallium (Ga) from column III and the element arsenic (As) from column V of the periodic table of the elements. GaAs does not occur naturally. It is present in the earth's crust at 5–15 mg/kg and is recovered as a by-product of the extraction of aluminum and zinc from their ores[2, 3]. Goldschmidt[4] first created GaAs in the 1920's and found it to have a cubic zincblende lattice.

GaAs is the most technologically important and most studied compound semiconductor material. It is widely used in the semiconductor industry due to its wider direct band gap energy and higher electron mobility compared to crystalline silicon[5]. Many band structure parameters for GaAs are known with a greater precision than for any other compound semiconductor. This is especially true of the fundamental energy gap with a value of 1.519 eV[6]. Particular properties studied are its direct band gap for photonic applications[7], nanotubes[8] and its internal-carrier transport and higher mobility for generating microwaves[9]. GaAs has light-emitting properties, high electron mobility, electromagnetic properties and photovoltaic[10] properties. As a semiconductor, it has several unique material properties which can be utilized in high speed semiconductor devices, high power microwave and millimeter-wave devices, and optoelectronics devices[11–13] including fibreoptic sources and detectors. Its advantage as a material for high speed devices are its high electron mobility and saturation velocity and relatively easy growth of semi-insulating substrates. Other useful properties are its controllable band gap by alloying, desirable ionization and optical absorption properties. GaAs has certain advantages over other semiconductor materials: (1) faster operation with lower consumption, (2) better resistance to radiation and most importantly (3) it may be used to convert electrical into optical signals[14, 15]. In this work, we have investigated complex optical properties of GaAs.

2. Method of calculation

The reflection coefficient measures the fractional amplitude of the reflected electromagnetic field and is given by[16]

$$r(\omega) = \frac{n(\omega) - 1 + \mathrm{i}k(\omega)}{n(\omega) + 1 + \mathrm{i}k(\omega)}, \tag{1}$$

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

The reflectance R is given by[17]

$$R(\omega) = \frac{[n(\omega) - 1]^2 + k^2(\omega)}{[n(\omega) + 1]^2 + k^2(\omega)}. \tag{2}$$

The reflectance is the square of the reflection coefficient

$$R = r^2. \tag{3}$$

We used the refractive index and extinction coefficient data obtained by Schubert[18] to obtain the reflection coefficient and reflectance of GaAs using Eqs. (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

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Received 3 September 2012

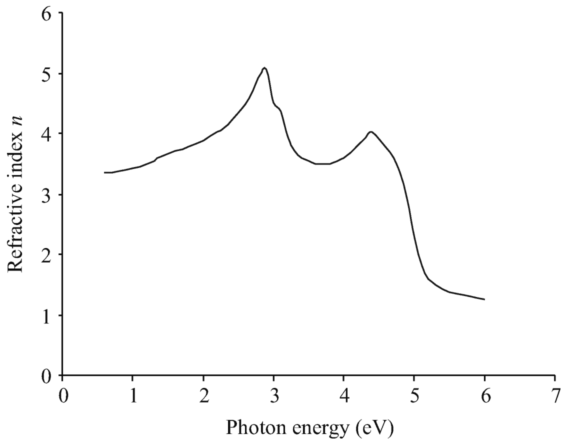

Fig. 1. Refractive index of GaAs.

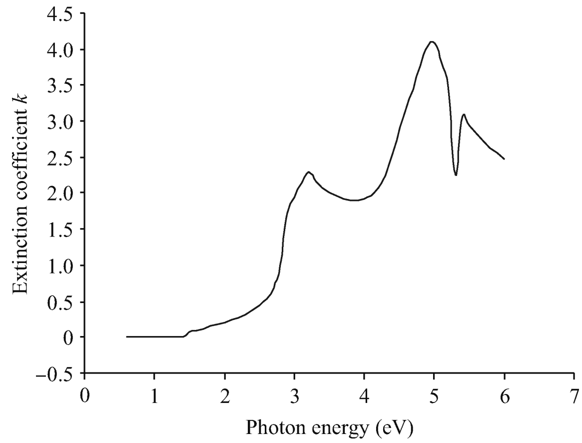

Fig. 2. Extinction coefficient of GaAs.

motion. The knowledge of the real and the imaginary parts of the dielectric constant provides information about the loss factor which is the ratio of the imaginary part to the real part of the dielectric constant. The real and the imaginary parts of the dielectric constant can be estimated using the relationship[19]

$$E_1 = n^2 - k^2, \tag{4}$$

$$E_2 = 2nk. \tag{5}$$

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

$$\alpha = \frac{4\pi k}{\lambda}, \tag{6}$$

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

The transmittance is obtained from the relationship

$$R + T + A = 1, \tag{7}$$

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 the reflected, transmitted and absorbed intensity. The absorbance A is given by

$$A = \lg \frac{1}{R}. \tag{8}$$

The optical response of a material is mainly studied in terms of the optical conductivity (σ) which is given by the relationship[20]

$$\sigma = \frac{\alpha n c}{4\pi}, \tag{9}$$

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 of GaAs increases with an increase in photon energy in the energy range 0.6 eV to 3.0 eV as shown in Fig. 1. It has a maximum value of 5.0 at 3.0 eV. The refractive index decreases afterwards in the energy range 3.0–6.01 eV. This decrease in the refractive index indicates that GaAs shows normal dispersion behaviour. Two peaks are observed at 3.0 eV and 4.5 eV. Our result for the refractive index is higher than that reported by Blakemore (3.78)[21] and Brian *et al.* (3.6)[22].

The extinction coefficient of GaAs increases with increase in energy in the energy range 1.5–5.0 eV as shown in Fig. 2. It rises to a maximum value of 4.2 at 5.0 eV and then decreases to a value of 2.8 at 6.01 eV. The increase in the extinction coefficient with an increase in photon energy in the energy range 1.5–5.0 eV 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 5.0–6.01 eV 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 0.6–1.5 eV which means that GaAs is transparent in this energy region. Three peaks are observed at 3.2, 5.0 and 5.8 eV.

The real part of the complex dielectric constant ε_1 of GaAs increases with an increase in photon energy in the energy range 0.6–2.8 eV as shown in Fig. 3. It rises to a maximum value of 24 at 2.8 eV which is in agreement with the value reported by de Boeij *et al.* (24 at 2.4 eV)[23], Lautenschlager *et al.* (28 at 3.0 eV)[24] and Alouani *et al.* (22 at 2.0 eV)[25]. The increase in dielectric constant with increase in photon energy in the photon energy range 0.6–2.8 eV shows that the loss factor increases with an 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 2.8–6.01 eV with a minimum value of –10 at 5.0 eV. This shows that the loss factor decreases with increase in photon energy in this energy range.

The imaginary part of the complex dielectric constant, ε_2, of GaAs is constant in the photon energy range 0.6–1.5 eV and increases with an increase in photon energy in the energy range 1.5–4.8 eV as shown in Fig. 4. It rises to a maximum value of 26 at 4.8 eV which is in good agreement with that reported by de Boeij *et al.* (25 at 5.0 eV)[23] and Lautenschlager *et al.* (27 at 4.8 eV)[24]. The increase in the imaginary part of the complex dielectric in the photon energy range 1.5–4.8 eV shows that the loss factor increases with increase in photon energy in this energy range. The imaginary part of the complex di-

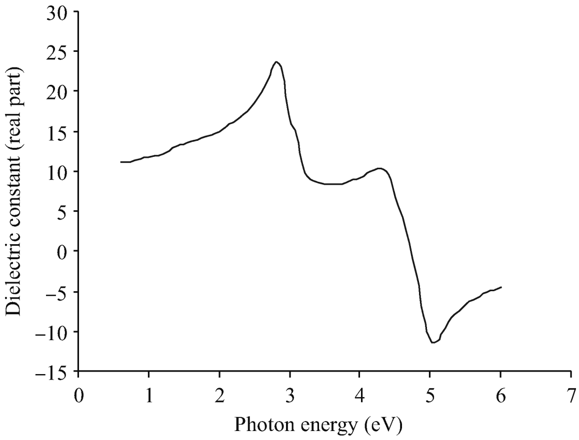

Fig. 3. Complex dielectric constant (real part) of GaAs.

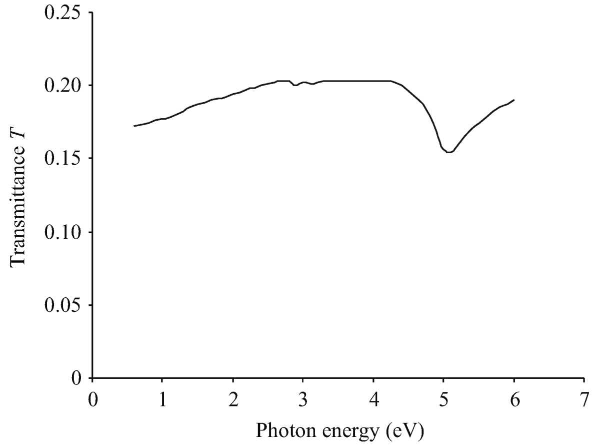

Fig. 5. Transmittance of GaAs.

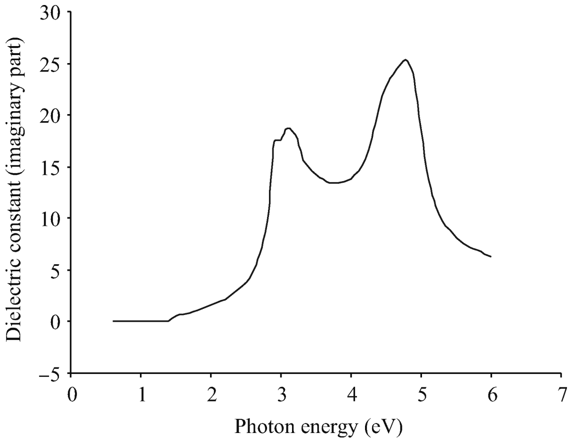

Fig. 4. Complex dielectric constant (imaginary part) of GaAs.

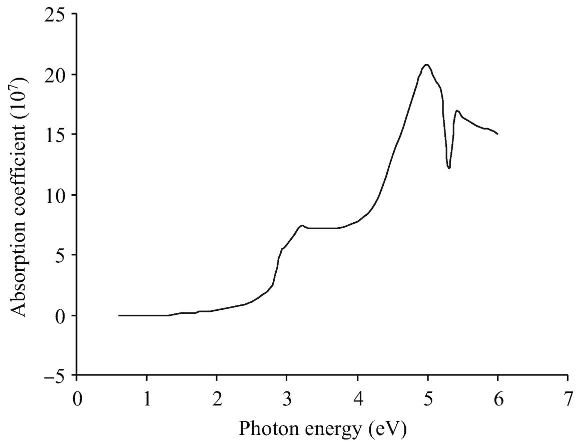

Fig. 6. Absorption coefficient of GaAs.

electric constant decreases with an increase in photon energy in the photon energy range 4.8–6.01 eV which shows that the loss factor decreases with increases in the photon energy in this energy range.

The transmittance (T) of GaAs increases with an increase in photon energy in the energy range 0.6–4.0 eV as shown in Fig. 5. It rises to a maximum value of 0.22 at 4.0 eV after which it decreases and then it rises again in the energy range 4.8–6.01 eV. With a maximum of 0.22 for transmittance, this means that GaAs is not a good transmitter of electromagnetic waves in this energy region.

The absorption coefficient, α of GaAs increases with an increase in photon energy in the energy range 0.6–4.8 eV as shown in Fig. 6. It rises to a maximum value of 0.22×10^8 m^{-1} (22×10^4 cm^{-1}) at 4.8eV which is in agreement with that reported by Sturge (14×10^4 cm^{-1})[26], Blakemore (14×10^4 cm^{-1})[21] and Aloulou *et al.* (10^5 cm^{-1})[27]. The value of the absorption coefficient then drops to a value of 0.15×10^8 m^{-1} at 6.0 eV. This high value of the absorption coefficient is typical for interband absorption in semiconductors[26]. It is important to emphasize that there is no absorption in the energy range 0.6–1.5 eV which is the energy range of the bandgap of GaAs. That is, the energy at which the absorption starts correspond to the direct band gap at 1.52 eV[6]. GaAs shows no absorption below its band gap. The absorption coefficient shows three peaks at photon energies 3.2 eV, 4.8 eV and 5.4 eV.

The reflection coefficient of GaAs increases with the increase in the photon energy in the energy range 0.6–5.1 eV as shown in Fig. 7. It rises to a maximum value of 0.82 at 5.1 eV which agreed with that obtained by Holm *et al.* (0.88)[28].

The reflectance of GaAs increases with an increase in photon energy in the energy range 0.6–5.2 eV as shown in Fig. 8. It rises to a maximum value of 0.68 at 5.2 eV and it then drops to a value of 0.56 at 6.1 eV. Two peaks are observed at 2.8 eV and 5.2 eV. The reflectance obtained by us is in good agreement with that reported by El-Nahass *et al.* (0.62)[29] and Phillipp and Ehrenreich (0.6 at 5.0 eV)[30].

The real part of the optical conductivity of GaAs is constant in the photon energy range 0.6–1.6 eV as shown in Fig. 9 which means that GaAs do not conduct in this energy range. It then increases with photon energy in the energy range 1.6–4.8 eV. It rises to a maximum value of 14.2×10^{15} at 4.8 eV. The increase in the real part of optical conductivity in the photon energy range 1.6–4.8 eV can be attributed to the increase in absorption coefficient in this energy range. The real part of the optical conductivity shows two peaks at 3.1 and 4.8 eV. The real part of optical conductivity of GaAs decreases with photon energy in the photon energy range 4.8–6.0 eV.

The imaginary part of the optical conductivity of GaAs first decreases with the increase in photon energy in the en-

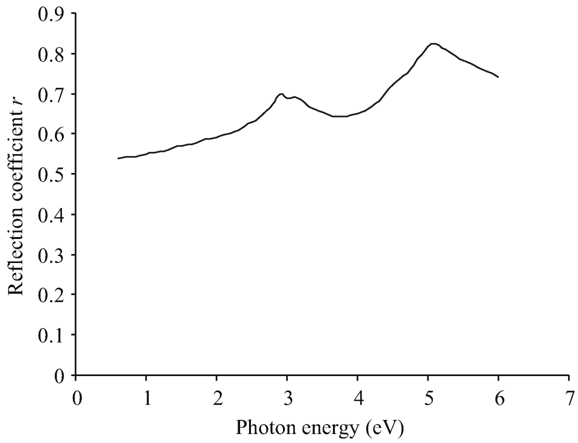

Fig. 7. Reflection coefficient of GaAs.

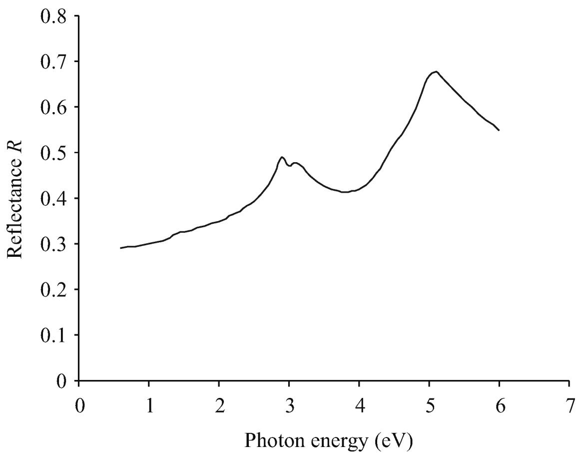

Fig. 8. Reflectance of GaAs.

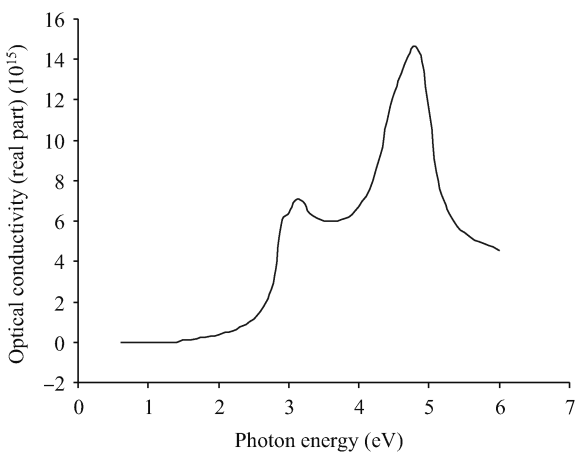

Fig. 9. Optical conductivity (real part) of GaAs.

ergy range 0.6–2.9 eV from a value of -1.0×10^{15} at 0.6 eV to a minimum value of -8.4×10^{15} at 2.9 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 a reduction in the conductivity of GaAs in this energy range. It then increases with an increase in photon energy in the photon energy range 2.9–5.0 eV with a maximum value of 6.8×10^{15} at 5.0 eV and then drops to a value of 3.0

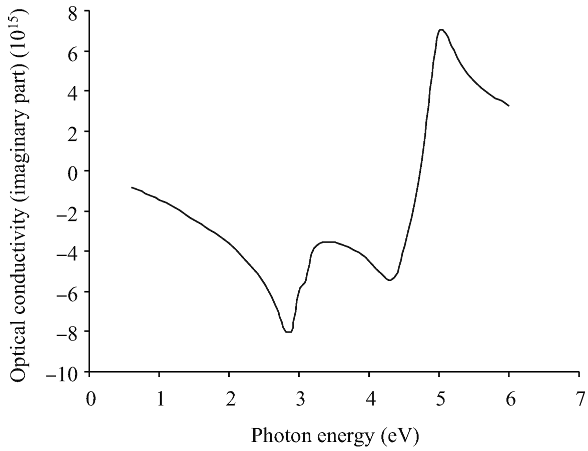

Fig. 10. Optical conductivity (imaginary part) of GaAs.

$\times 10^{15}$ at 6.0 eV.

4. Conclusions

In conclusion, we have investigated theoretically the complex index of refraction of GaAs in the energy range 0.6–6.0 eV. The refractive index has a maximum value of 5.0 at 3.0 eV. The refractive index decreases with the increase in photon energy in the energy range 3.0–6.01 eV. This decrease in the refractive index indicates that GaAs shows normal dispersion behaviour.

The increase in the extinction coefficient with the increase in photon energy in the photon energy range 1.5–5.0 eV 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 5.0–6.01 eV 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 0.6–1.5 eV which means that GaAs is transparent in this energy region.

The real part of the complex dielectric constant has a maximum value of 24 at 2.8 eV which is in good agreement with that reported by de Boeij *et al*., Lautenschlager *et al.,* and Alouani *et al*. The increase in dielectric constant with an increase in photon energy in the photon energy range 0.6–2.8 eV 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 an increase in photon energy in the photon energy range 2.8–6.0 eV shows that the loss factor decreases with an increase in photon energy in this energy range.

The imaginary part of the complex dielectric constant has a maximum value of 26 at 4.8 eV which is in good agreement with that reported by de Boeij *et al.* and Lautenschlager. The increase in the imaginary part of the complex dielectric in the photon energy range 1.5–4.8 eV shows that the loss factor increases with an increase in photon energy in this energy region. The decrease in the imaginary part of the complex dielectric constant with an increase in photon energy in the photon energy range 4.8–6.0 eV shows that the loss factor decreases with the increase in photon energy.

The transmittance has a maximum value of 0.22 at 4.0 eV which shows that GaAs is not a good transmitter of electromagnetic waves in this energy region. The absorption coefficient has a maximum value of 0.22×10^8 m^{-1} (22×10^4 cm^{-1}) which is in good agreement with that reported by Sturge and Blakemore. This high absorption coefficient value is typical for interband absorption in semiconductors. GaAs shows no absorption below its band gap.

The reflection coefficient has a maximum value of 0.82 at 5.1 eV which means GaAs is highly absorbing. The reflectance has a maximum value of 0.68 at 5.2 eV which is in good agreement with that reported by El-Nahass *et al.* and Phillip and Enhenreich.

The real part of the optical conductivity has a maximum value of 14.2×10^{15} at 4.8 eV. The increase in the real part of optical conductivity in the photon energy range 1.6–4.8 eV can be attributed to the increase in absorption coefficient in this energy range. At low energies between 0.6 eV and 1.6 eV, the conductivity is zero, which means that GaAs do not conduct in this energy range.

The imaginary part of the optical conductivity has a minimum value of -8.4×10^{15} at 2.9 eV and a maximum value of 6.8×10^{15} at 5.0 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 a reduction in the conductivity of GaAs in this energy range.

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

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