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INVESTIGATION OF COMPLEX INDEX OF REFRACTION OF GALLIUM NITRIDE GaN

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ABSTRACT

An understanding of the complex index of refraction of Gallium Nitride (GaN) is important because of the increasing application of GaN in many high frequency, optical and electronics devices. Complex index of refraction of Gallium Nitride (GaN)have been investigated theoretically by means of Kramers and Kronig method in the photon energy range 2.0 – 10.0eV. We obtained refractive index which has a maximum value of 2.89 at photon energy 7.0eV, the extinction coefficient which has a maximum value of 1.17 at photon energy 7.0eV, the dielectric constant, the real part of the complex dielectric constant has a maximum value of 7.0 at photon energy 7.0eV and the imaginary part of the complex dielectric constant has a maximum value of 6.79 at photon energy 7.0eV, the transmittance which has a maximum value of 0.18 at photon energy 7.0eV, the absorption coefficient which has a maximum value of 86.18 at photon energy 7.0eV. The values obtained for complex index of refraction ofGaN are essentially important for emerging GaN applications such ashigh-power and high-frequency devices, solar cell arrays for satellites, communications and optoelectronics devices.

Key words: Complex Index of Refraction, Extinction Coefficient, Complex Dielectric Constant, Transmittance, Photon Energy,

INTRODUCTION

Gallium Nitride (GaN) is a binary III-V direct bandgap semiconductor commonly used in bright light-emitting diodes since the 1990s.Recently, group III nitride-based semiconductors have emerged as the leading material for the production of blue LEDs, blue laser diodes and high-power, high-temperature electronics. The achievement of high brightness blue InGaN LEDs has basically caused a revolution in LED technology. The use of InGan/Gan double heterostructures in LEDs in 1994 by Nakamura *et al* and the achievement of p-doping in GaN by Akasaki *et al* (1990) are widely credited with re-igniting the III-V nitride system. The recent realization of blue lasers has taken over 20 years from the first optical pumped stimulated emission was observed in GaN crystals (Dingle *et al,* 1971, 1994) and the first LEDs (Pankove *et al,* 1971) were fabricated. Whenone of the group IIIelements, Boron, Aluminium, Gallium or Indium is bonded to the group V element Nitrogen, a III-Nitride compound semiconductor is formed. Different combinations of group III-V elements have produced more than twenty-five (25) III-V compound semiconductors, examples of which are Indium Nitride (InN), Gallium Arsenide (GaAs), Gallium Nitride (GaN), Aluminium Nitride (AlN). Group III –Nitride are now a widely studied class of semiconductor materials and they have found commercial success in the last twenty years as light emitting diodes and lasers in the green to near –ultraviolet regions of the electromagnetic spectrum (Nakamura *et al*, 1996; Lei *et al*, 1992; Hwang *et al*, 1994; Rubio *et al*, 1993; Albanesi *et al*, 1993; Wright and Nelson, 1994; Strite and Morkoc, 1992). GaN is a very hard material that has a wurtzite crystal structure. Its wide band gap of 3.4eV (Marques *et al*, 2003; Munoz and Kunc, 1993; Belouifa *et al,* 2009) affords it special properties for applications in optoelectronics, high-power and high-frequency devices (Nakamura *et al, 1994*). Its sensitivity to ionizing radiation is low (like other group III nitrides), making it a suitable material for solar cell arrays for satellites. Because GaN transistors can operate at much hotter temperatures and work at much higher voltages than Gallium Arsenide (GaAs) transistors, they make ideal power amplifiers at microwave frequencies. Relative wide band of GaN permits highly energetic electronic transitions to occur. Such electronic transitions can result in Gallium Nitride materials having a number of attractive properties including the ability to efficiently emit blue light, the ability to transmit signals at high frequency and others. Due to promising properties such as excellent conductivity, large breakdown field, and resistance to chemical attack, GaN represents an ideal candidate for electronic devices capable of operation at high power levels, high temperatures and in caustic environments. The need to tolerate high temperature and hostile environments required by industry application including aerospace, automotive, petroleum and others has stimulated many researchers to turn their attention to GaN as a material candidate to meet these requirements (Morkoc *et al*, 1994). GaN transistors have already been demonstrated (Yoshida and Suzuki, 1998) that work at temperatures up to 600^{o}C.

Wide band gap compounds using GaN have important applications in communications. By creating lasing and detection devices that operate in the 240-280nm range, the earth's atmosphere could e used as an effective communications screen. This is due to the large degree of absorption of the ozone layer in this wavelength range that renders the atmosphere nearly opaque to these devices.This would allow space to space communications to be secure from the earth and also allow imaging array detectors to provide sensitive surveillance of objects coming up through the atmosphere (Strite and Morkoc, 1992). Also of great importance are GaN photoconductive devices that are highly suited as solar-blind UV photodetectors for applications such as missile detection, flame sensing and solar UV monitoring. GaN based materials are ideal for these applications due to their wide and direct band gaps, making detectors transparent to visible and infrared radiation (Smith *et al*, 1999; Carrano *et al*, 1998).

Complex refractive index is the combination of both the absorption and the refraction. It is knowledge enables us to calculate the reflectivity (R) and hence the transmissivity (T). A detailed knowledge of complex index of refraction is important for the realization-of optoelectronic devices. In this work, we will investigatecomplex index of refractionof Gallium Nitride (GaN) in the energy range 2.0-10.0eV because of the increasing application of GaN in many electronic and optoelectronics devices.

METHOD OF CALCULATION

Kramers-Kronig analysis of the reflectance data of GaN obtained by Bloom *et al* (1974) was carried out to obtain reflection coefficient, refractive index and the extinction coefficient of GaN using equation 1, 2 and 3 respectively. Reflection coefficient measures the fractional amplitude of the reflected electromagnetic field and it is the square root of reflectance.

$$r = \sqrt{R} \tag{1}$$

where r is the reflection coefficient and R is the reflectance.

$$n(\omega) = \frac{1 - r^2(\omega)}{1 + r^2(\omega) - 2r(\omega)Cos\theta(\omega)} \tag{2}$$

$$k(\omega) = \frac{2r(\omega)Sin\theta(\omega)}{1 + r^2(\omega) - 2r(\omega)Cos\theta(\omega)} \tag{3}$$

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 (Bakr *et al*, 2011; Akinlami and Ashamu, 2013; Akinlami and Bolaji, 2012; Akinlami and Olateju, 2012). The real and the imaginary parts of the dielectric constant can be estimated using the relations (Goswami, 2005)

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

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

The absorption coefficient (α) can be calculated using the equation (Pankove, 1971; Swanepoel, 1983)

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

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

The transmittance is obtained from the relation

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

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

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

RESULTS AND DISCUSSION

The refractive index spectrum of GaN in the energy range 2.0eV - 10.0eV is shown in Figure 1. There is an increase in the refractive index in the energy range 2.0eV to 7.0eV, with a peak value of 2.89 at 7.0eV as shown in Figure 1. The refractive index decreases afterwards in the energy range 7.0 – 10.0eV. This decrease in refractive index indicates that GaN shows normal dispersion behaviour and also that GaN is a semiconductor because the refractive index of a semiconductor typically decreases with increasing energy. Five peaks were observed at 2.50eV, 4.00eV, 6.00eV, 7.00eV, and 8.00eV, they were mainly due to the transition from the last valence band to the first conduction band. The result for refractive index is higher than that of Ejder (2.33)(1971) using transmission and absorption measurements. With a refractive index of 2.89, GaN can be used as a material in the making of lenses. The variation of refractive index values in the 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.

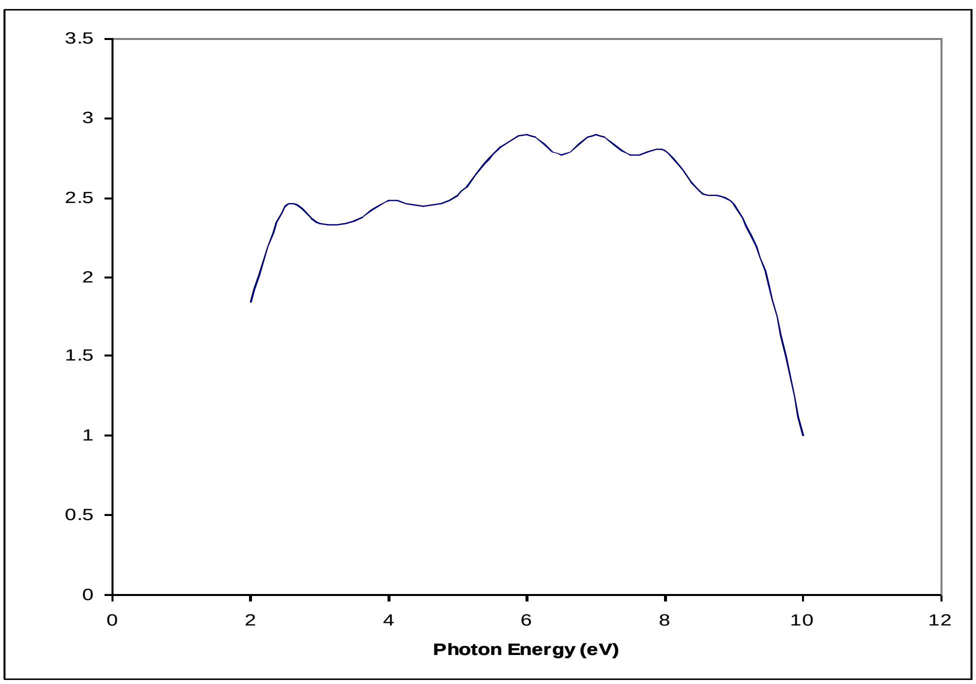

Figure 1:Refractive Index of Gallium Nitride

The extinction coefficient spectrum in the energy range 2.0 – 10.0eV is as shown in Figure 2. There is an increase in extinction coefficient in the energy range 2.0eV – 7.0eV as shown in figure 2. It has a peak value of 1.17 at 7.0eV and then decreases to zero at 10.0eV. The increase in extinction coefficient with increase in photon energy in the energy range 2.0 – 7.0eV shows that the fraction of light due to scattering and absorbance increases in this energy range and the decrease in extinction coefficient in the energy range 7.0eV – 10.0eV shows that the fraction of light lost due to scattering and absorbance decreases in this energy range. The peak value of extinction coefficient indicates a good absorption in this energy range. Five peaks were also observed at 2.5eV, 4.0eV, 6.0eV, 7.0eV and 8.0eV, they were 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.

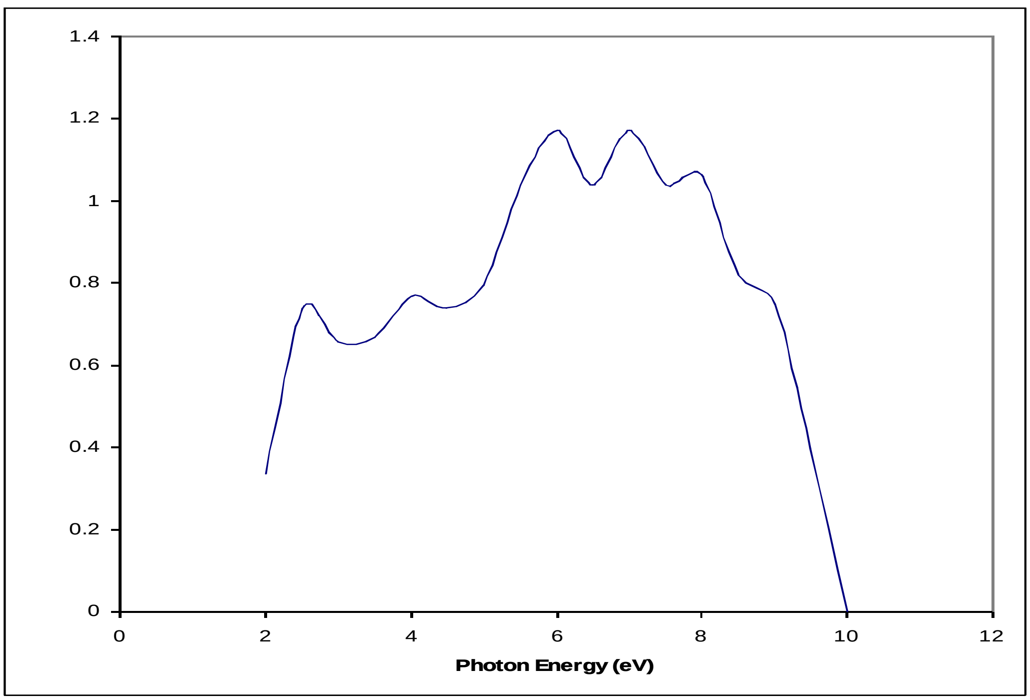

Figure 2: Extinction Coefficient of Gallium Nitride

The real part of the dielectric constant in the energy range 2.0eV – 10.0eV is shown in Figure 3. There is an increase in the real part of the dielectric constant in the energy range 2.0 – 7.0eV as shown in Figure 3.

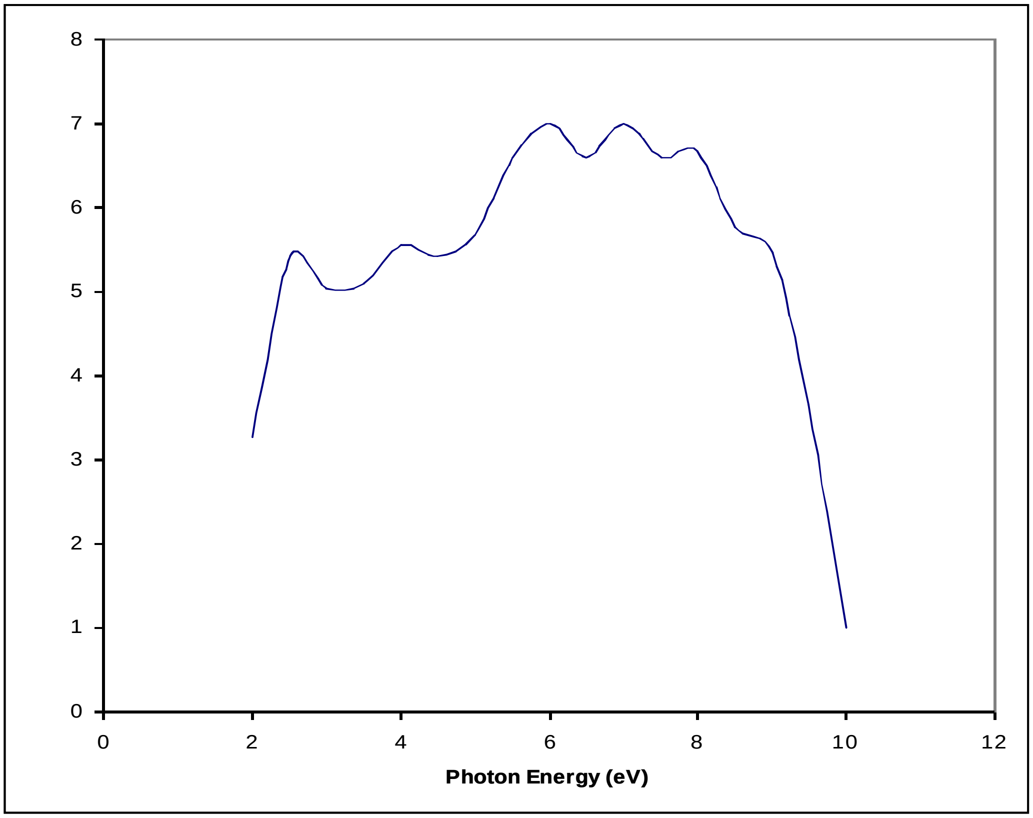

Figure 3:Complex Dielectric Constant (Real part) of Gallium Nitride

It peaks at a value of 7.0 at 7.0eV which is less than the values 8.9 and 9.5 reported by Matsubara and Takagi (1982) using optical reflectivity measurement and Barker and Ilegems (1973) using infrared reflectivity measurements. This difference is suspected to have come from the experimental procedures taken in the other works. The increase in real part of the dielectric constant with an increase in photon energy in the energy range 2.0 – 7.0eV shows that the loss factor increases with the increase in photon energy in this energy range. The real part of dielectric constant then decreases with an increase in photon energy in the energy range 7.0 – 10.0eV. 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 GaN tends to become an insulator at this energy range.

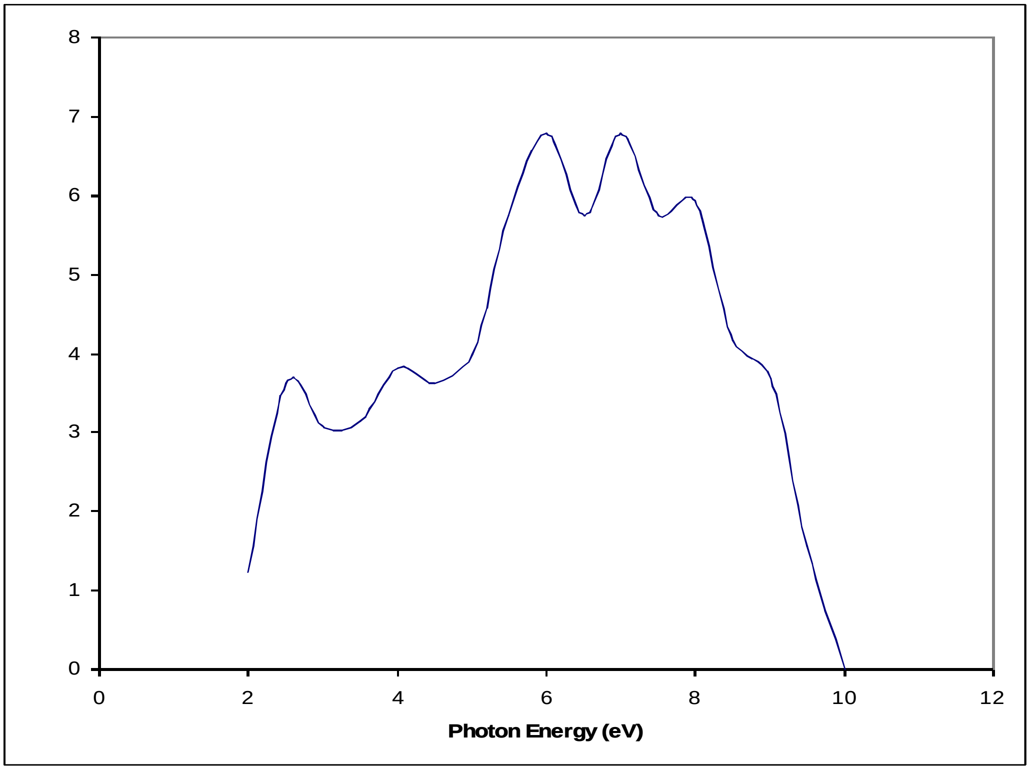

Figure 4: Complex Dielectric Constant (Imaginary Part) of Gallium Nitride

The imaginary part of the dielectric constant spectrum in the energy range 2.0eV – 10.0eV is shown in Figure 4. There is an increase in the imaginary part of the dielectric constant with increase in photon energy in the energy range 2.0 – 7.0eV as shown in Figure 4. It has a peak value of 6.8 at 7.0eV. The increase in imaginary part of the dielectric in the energy range 2.0 – 7.0eV 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 7.0 – 10.0eV, which shows that the loss factor decreases with increase 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.

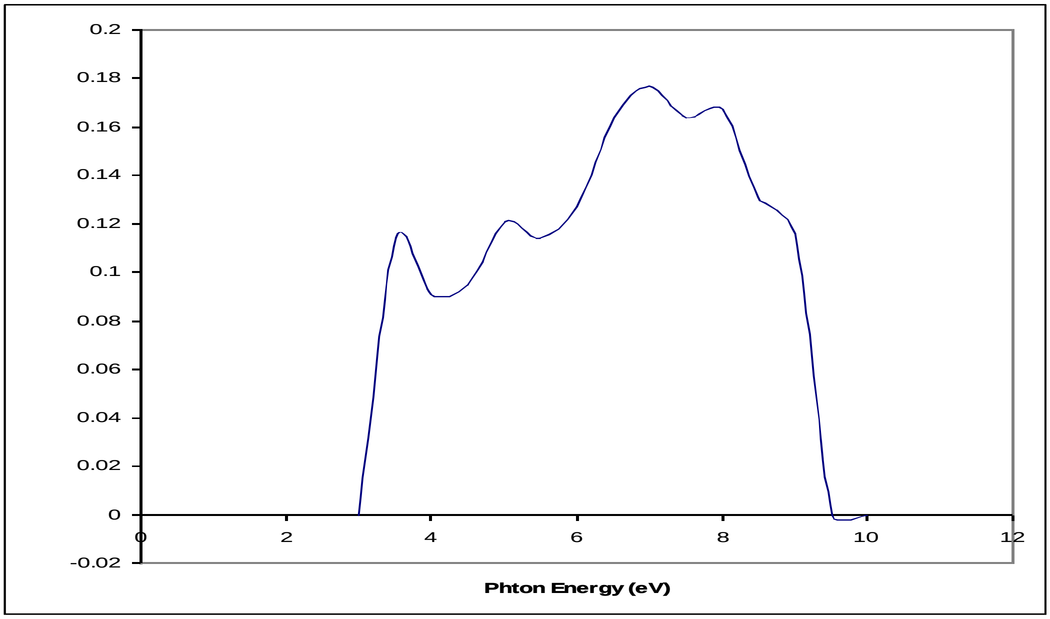

Figure 5: Transmittance of Gallium Nitride

Figure 5 shows the transmittance spectrum for GaN in the photon energy range 2.0 – 10.0eV. The transmittance peaks at a value of 0.18 (18%) at 7.0eV which means that GaN is a material for optoelectronic devices.

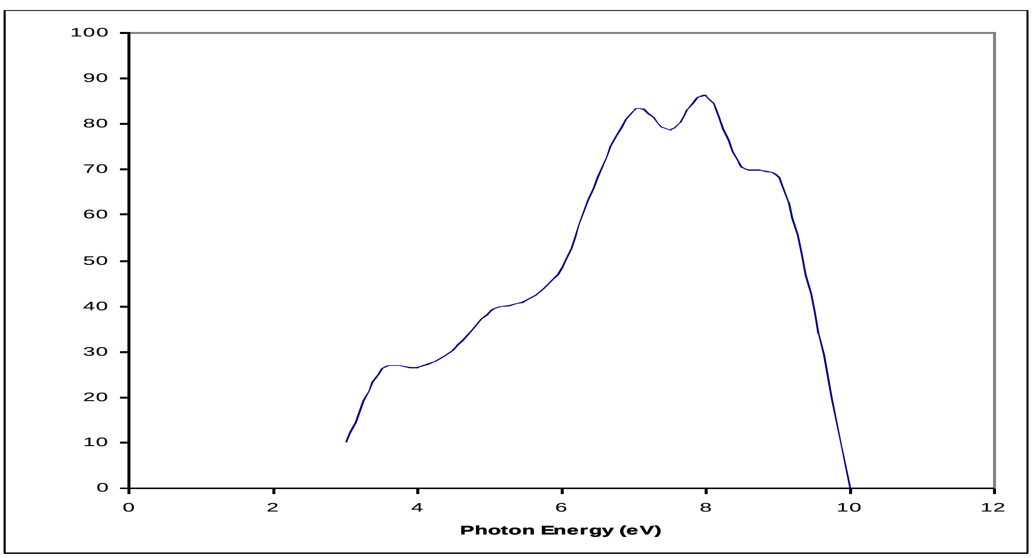

Figure 6: Absorption Coefficient of Gallium Nitride

GaN have good absorption in the energy range 2.0 – 8.0eV as shown in Figure 6. The absorption coefficient of GaN increases with increase in photon energy in the energy range 2.0eV – 8.0eV as shown in Figure 6, this shows that absorption coefficient is photon energy dependent. It rises to a maximum value of 86.2 at 8.0eV. The value of absorption coefficient then drops to zero at 10.0eV. This high value of the absorption coefficient is typical for interband absorption in semiconductors (Sturge, 1962). The energy at which the absorption starts corresponds to its direct band gap at 3.4eV. GaN shows no absorption below its band gap. The degree of absorption depends among other things on the number of free electron capable of receiving the photon energy. At the maximum absorption coefficient, the electromagnetic wave is observed more. Thus, Gallium Nitride absorbs more at these energy values.

CONCLUSION

In conclusion,complex index of refraction of Gallium Nitride (GaN)have been investigatedin the energy range 2.0eV – 10.0eV.The refractive index has a peak value of 2.89 at 7.0eV and it shows normal dispersion behaviour. With a refractive index of 2.89, GaN can be used as a material in the making of lenses. The extinction coefficient has a peak value of 1.17 at 7.0eV which indicates a good absorption in the energy range. The real part of the dielectric constant has a peak value of 7.0 at 7.oeV. The imaginary part of the dielectric constant has a peak value of 26.8 at 7.0eV. The transmittance has a peak value of 0.18 at 7.0eV, which shows that GaN is a material for optoelectronic device. The absorption coefficient has a peak value of 86.2 at 7.0eV. 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 value obtained for the complex index of refraction of GaN over the energy range 2.0-10.0eV are essentially important for emerging GaN applications such as high-power and high-frequency devices, solar cell arrays for satellites, communications and optoelectronics devices.

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