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Reflection coefficient and optical conductivity of gallium nitride GaN

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Abstract. Here we report the reflection coefficient and optical conductivity of gallium nitride (GaN). The reflection coefficient obtained in the photon energy range 2–10 eV shows five distinct peaks at photon energies 3.5, 5.0, 7.0, 8.0, and 9.0 eV. It was observed that the reflection coefficient has its highest value 0.54 at the photon energy 7.0 eV. Variation of the real part of optical conductivity with photon energy shows five distinct peaks at photon energies 3.5, 5.0, 7.0, 8.0, and 9.0 eV. It was observed that the real part of optical conductivity has the maximum value $5.75 \cdot 10^{15}$ for the photon energy 7.0 eV, and it decreases until coming to zero at 10.0 eV. The peaks indicate regions of deeper penetration of electromagnetic waves, and they also show high conductivity. The imaginary part of optical conductivity obtained for GaN in the photon energy range 2.0 to 10.0 eV shows five distinct peaks at photon energies 3.5, 5.0, 7.0, 8.0, and 9.0 eV. It was observed that it has a minimum value of $-6.46 \cdot 10^{15}$ for the photon energy 8.0 eV and a maximum value at $-1.2 \cdot 10^{15}$. This implies that there is a reduction in conductivity of GaN, and likewise, reduction in the propagation of electromagnetic waves in this region.

Keywords: reflection coefficient, optical conductivity, photon energy.

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1. Introduction

Gallium nitride (GaN) is a binary III-V direct band gap 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. [1] and the achievement of *p*-doping in GaN by Akasaki [2] 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 observed in GaN crystals [3] and the first LEDs [4] fabrication. When one of the group III elements, boron, aluminum, 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), aluminum nitride (AlN). Group III – nitride are now a widely studied class of semiconductor materials, and they have found commercial success in recent twenty years as light emitting diodes and lasers in the green to near-ultraviolet regions of the electromagnetic spectrum [5-11]. GaN is a very hard material that has a wurtzite crystal structure. Its wide band gap of 3.4 eV [12-14] affords it special properties for applications in optoelectronics, high-power and high-frequency devices [1]. 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 at much higher voltages than gallium arsenide (GaAs) transistors, they make ideal power amplifiers at microwave frequencies. Relatively wide band of GaN

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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 frequencies 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 to operate 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 [15]. GaN transistors have already been demonstrated [16] as operating at temperatures up to 600 °C.

Wide band gap compounds using GaN have important applications in communications. By creating lasing and detection devices that operate in the 240-280 nm range, the earth's atmosphere could be used as an effective communication 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 [11]. 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 [17, 18]. In this work, we have investigated reflection coefficient and optical conductivity of gallium nitride (GaN).

2. Method of calculation

The 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. The reflectance spectrum of GaN obtained by Bloom *et al.* [19] was used to obtain the reflection coefficient using Eq. (1). We carried out the Kramers–Kronig analysis of the reflectivity data to obtain the refractive index and the extinction coefficient using Eqs (2) and (3):

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

$$k(\omega) = \frac{2r(\omega)\sin\theta(\omega)}{1 + r^2(\omega) - 2r(\omega)\cos\theta(\omega)}. \tag{3}$$

The absorption coefficient (α) was calculated using the equation

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

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

The refractive index, extinction coefficient and absorption coefficient obtained are reported in another article.

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

$$\sigma = \frac{\alpha n c}{4\pi}, \tag{5}$$

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

3. Results and discussion

The reflection coefficient for GaN obtained in the photon energy range 2 to 10 eV shows five peaks at photon energies 3.5, 5.0, 7.0, 8.0, and 9.0 eV as shown in Fig. 1. It was observed that the reflection coefficient has a maximum value 0.54 at the photon energy 7.0 eV and then decreases gradually to zero at 10.0 eV. This shows that GaN reflects all the electromagnetic radiation that falls on it at 7.0 eV. Variation of the reflection coefficient with photon energy shows the reflection coefficient first increases with the photon energy and then decreases with increase in the photon energy, which agrees with that obtained by Mullhauser [21] and Seifert *et al.* [22]. The energy at which reflection occurs for GaN corresponds to its direct band gap at 3.4 eV. GaN shows low reflection below its band gap at 3.4 eV.

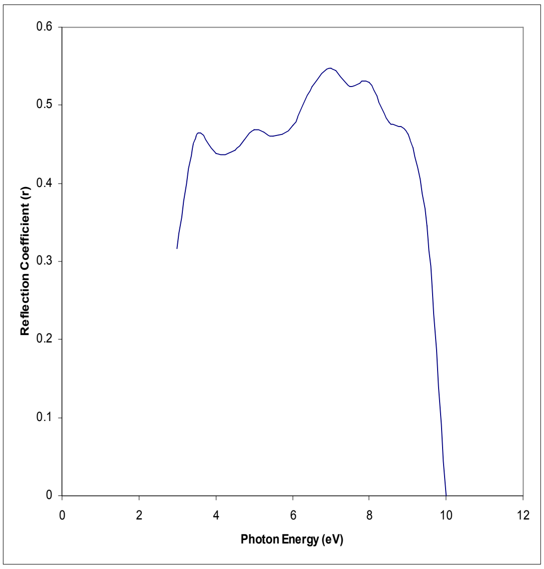

Fig. 1. Reflection coefficient of gallium nitride.

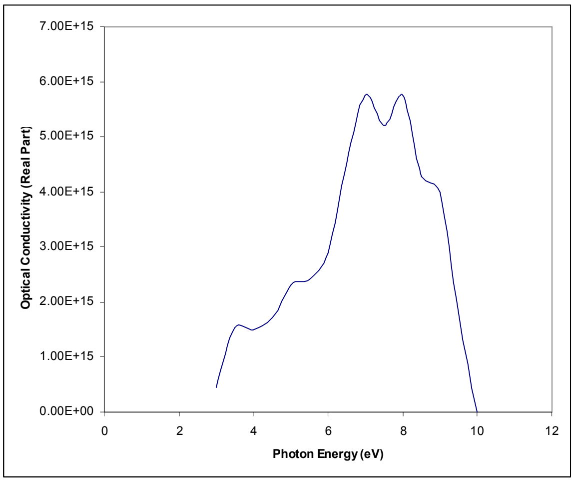

Fig. 2. Optical conductivity (real part) of gallium nitride.

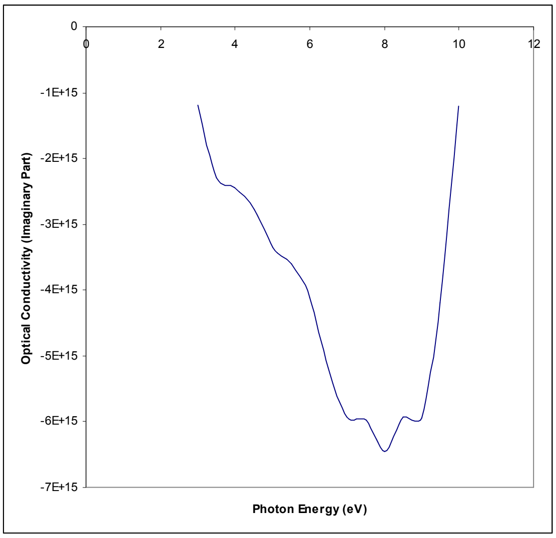

Fig. 3. Optical conductivity (imaginary part) of gallium nitride.

The real part of optical conductivity σ_{real} obtained for gallium nitride (GaN) in the photon energy range 2.0 to 10.0 eV shows five distinct peaks at photon energies 3.5, 5.0, 7.0, 8.0, and 9.0 eV as shown in Fig. 2. It was observed that the real part of optical conductivity σ_{real} increases with the photon energy up to 7.0 eV exhibiting the peak value σ_{real} equal to $5.75{\cdot}10^{15}$ for the photon energy 7.0 eV and decreases with increase in the photon energy within the range 7.0 to 10.0 eV. Increase in the real part of optical conductivity up to 7.0 eV can be attributed to increase in the absorption coefficient in this region, and decrease in the real part of optical conductivity within the energy range 7.0 to 10.0 eV can be attributed to decrease in the absorption coefficient within this energy region. These peaks indicate regions of deeper penetration for electromagnetic waves, and they also show high conductivity. Thus, GaN can be optimized for high conductivity when the photons are at these peak energy values.

The imaginary part of the optical conductivity σ_i obtained for GaN in the photon energy range 2.0 to 10.0 eV shows five distinct peaks at the photon energies 3.5, 5.0, 7.0, 8.0, and 9.0 eV as shown in Fig. 3. It was observed that the imaginary part of the optical conductivity decreases with increase within the photon energy range 3.0 to 8.0 eV with the minimum value $-6.46{\cdot}10^{15}$ at the photon energy 8.0 eV, it then increases with the photon energy within the photon energy range 8.0 to 10.0 eV with the peak value $-1.2{\cdot}10^{15}$. The negative value of imaginary part of optical conductivity is because of the increase in extinction coefficient, and it implies that there is a reduction in conductivity of the GaN, and likewise, a reduction in the propagation of electromagnetic waves within this region.

4. Conclusions

We have investigated theoretically the reflection coefficient and optical conductivity of gallium nitride (GaN). The reflection coefficient obtained for GaN within the photon energy range 2.0 to 10.0 eV shows that the reflection coefficient has its maximum value 0.54 at the photon energy 7.0 eV. This shows that GaN reflects all the electromagnetic radiation that falls on it at 7.0 eV. The energy at which reflection starts for GaN corresponds to its direct band gap at 3.4 eV. So, GaN shows low reflection below its band gap at 3.4 eV.

The real part of optical conductivity obtained for GaN in this energy range shows five peaks at 3.5, 5.0, 7.0, 8.0, and 9.0 eV. These peaks indicate regions of deeper penetration of electromagnetic waves and high conductivity. Therefore, gallium nitride can be optimized for high conductivity. It was observed that the real part of optical conductivity has its peak value $5.75{\cdot}10^{15}$ at the photon energy 7.0 eV.

The imaginary part of optical conductivity obtained within the same energy range showed that it has their maximum values $-1.2{\cdot}10^{15}$ at the photon energies 3.0 and 10.0 eV and its minimum value at $-6.46{\cdot}10^{15}$. The negative value of imaginary part is as a result of increase in the extinction coefficient, and it implies that there is a reduction in conductivity of GaN, and likewise, a reduction in the depth of penetration of electromagnetic waves in this region.

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