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Araştırma Makalesi / Research Article

Optical Properties of AlInN/AlN HEMTs in Detail

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Abstract

In this study, the optical properties of AlInN/AlN high electron mobility transistor (HEMT) structure, grown on c-oriented sapphire with Metal-Organic Chemical Vapor Deposition (MOCVD) technique, being investigated. Optical characterization is made Kubelka- Munk method. Transmittance, absorbance, and reflectance are investigated in detail. Also, the Kubelka-Munk theory is employed to determine the forbidden energy band gap of InN by using special functions. The energy band gap obtained by this method was compared.

Keywords: MOCVD, HEMT, AlInN/InN, Transmittance, Kubelka-Munk Method, Mobility.

AlInN/AlN HEMT'in Detaylı Optik Özellikleri

Öz

Bu çalışmada, Metal Organik Kimyasal Buhar Biriktirme (MOCVD) tekniği ile c-yönelimli safir üzerinde büyütülen AlInN/AlN yüksek elektron hareketli transistör (HEMT) yapısının optik özellikleri incelenmiştir. Optik karakterizasyon Kubelka-Munk yöntemiyle yapılmıştır. Geçirgenlik, absorbans, yansıma detaylı olarak incelenmiştir. Ayrıca özel fonksiyonlar kullanarak InN'nin yasak enerji bant aralığını belirlemek için Kubelka-Munk teorisinden yararlanılmıştır. Bu yöntemle elde edilen enerji bant aralığının karşılaştırılması yapılmıştır.

Anahtar Kelimeler: MOCVD, HEMT, AlInN/AlN, Geçirgenlik, Kubelka-Munk Metod, Mobilite.

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1. Introduction

There are many fields in which we can not use conventional III-V group semiconductors. Short wavelength electromagnetic wave emitters are needed for color screens, laser writers, high-density data storage, and underwater communication. High power and high-temperature transistors are needed for automobile motors and developed power multipliers. Silicon and conventional III-V group semiconductors are not suitable for designing and producing optoelectronic devices operating in blue and ultra-violet regions of spectra. Gallium arsenide (GaAs) based optoelectronic devices can not be used at high temperatures. Group-III nitrites are suitable for applications in this field. The band gap of group III nitrites has a direct band structure. Band gap values are 0.7 eV for InN, 3.4 eV for InN and 6.2 eV for AlN (Vurgaftman, 2003; Meyer, 2003). These structures can be used for high temperature transistors and blue-green-violet light emitting devices because of their strong bonds and wide band gaps. Group III nitrites such as InN, InN, and AlN have wide band gaps, significant polarization effects, and hexagonal structure (Aleksan et al, 1991). InN and AlInN play the head role among group III nitrites in terms of technological developments. They have proved themselves in Field-Effect Transistor (FET) applications in the condition of modifying technological problems caused by a big difference between In and N on the ionic scale (Li et al, 2006).

The use of InN in electronic devices started by Pankove and co-workers in 1960, they made an InN-based blue light emitting diode (LED). Manufacturing problems prevented the production of p-doped InN. Studies on InN stopped because high-quality substrates were not present. To overcome this problem InN epitaxial layers are grown on substrates with big lattice mismatch. This procedure resulted in high dislocation density in the structure of device and life of devices was shortened. Through the end of the 20th century, Shuji Nakamura succeeds growth of high-quality InN epitaxial layer on sapphire substrate by using MOCVD (Nakamura, 1991). InN-based structures prepared a good ground for new developments in optoelectronics. At the same time InN has a perfect electron carrying property with its high electron mobility (Xing et al, 2001; Hajlaoui et al, 2016).

In this study Kubelka- Munk theory is employed to determine the forbidden energy band gap of the AlInN/InN structure. In earlier studies by the authors, the band gap was determined by PL and Tau methods. The results of this study are compared with them (Akpinar et al, 2020).

The aim of this study is to calculate the optical band gap using the Kubelka-Munk method and to compare it with its theoretical value.

2. Experimental

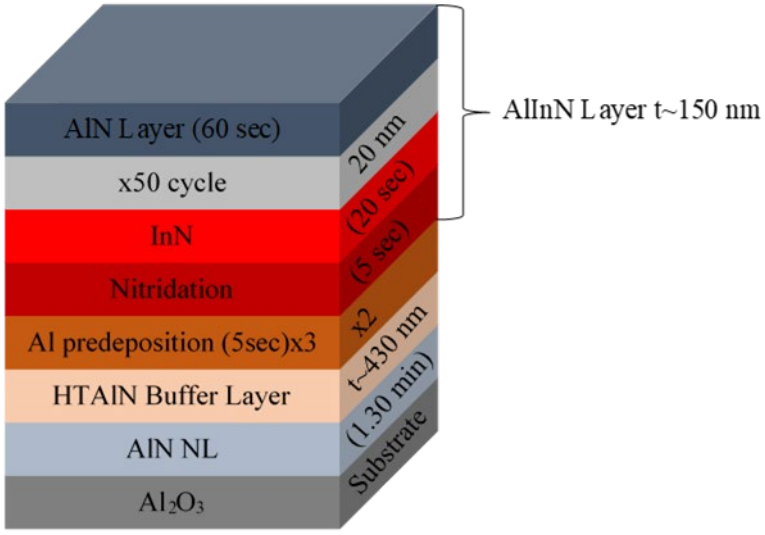

Figure 1. Schematic diagram of AlInN/InN HEMT

A schematic diagram of AlInN/InN HEMT is given in Figure 1. Before the growth of structure, sapphire substrate is kept under hydrogen flow at 1100ºC for 10 minutes. After 60 seconds nitration step temperature is decreased to 550ºC. Here, LT-AlN and HT-AlN layers are grown between substrate and InN Buffer layers. To perform this period the first temperature is increased to 750ºC and pressure is increased to 50 mbars. Later nitration operation is made under 300 sccm NH_3 flow. By adding 15 sccm TMAl flow, LT-AlN nucleation layer is grown for 3 minutes. This layer is a preparation step for the next HT-AlN layer. Also, this layer is responsible for low dislocation density in HT-AlN layer. After growth of LT-AlN nucleation layer temperature is increased to 1130ºC in 4 minutes. Increasing temperature to 1130ºC in 4 minutes caused the annealing of LT-AlN layer. This step aims to shift of LT-AlN layer to a mono-crystal structure. After annealing, 520 nm thick HT-AlN layer is grown under 25 sccm TMAl flow and 150 sccm NH3 flow at 25 mbar pressure. The flow of NH_3 is decreased to 40 sccm and growth of the remaining HT-AlN layer is maintained.

Because mobility of Al atoms on the surface of the substrate is low, for gaining high crystal quality high-temperature growth is needed. In addition, during HT-AlN growth period, 50 sccm TMIn flow is given. The presence of In atoms increases the mobility of Al atoms but In atoms can not diffuse in AlN crystal structure at this temperature. HT-AlN layer also plays a barrier role towards oxygen atoms in sapphire substrate. Oxygen atoms pass through the InN buffer layer and change its electronic properties by decreasing its resistance. HT-AlN layer prevents diffuse of oxygen atoms into InN buffer layer and helps the formation of high resistant InN. After HT-AlN layer, the first InN layer with a thickness of 90 nm at 200 mbar pressure and 1000ºC under 1300 sccm NH3 and 10 sccm

TMGa flows. Later in 5 minutes temperature and NH3 flow increased to 1050ºC and 1500 sccm respectively. Under these conditions, 800 nm thick second InN layer is grown. The rapid growth step is InN by changing the temperature to 1060ºC and flows of NH3 and TMGa to 1800 sccm and 17 sccm respectively for the third InN layer with a thickness of 110 nm. After this layer, the temperature parameter is changed to 1075ºC and a 300 nm thick InN layer is grown. Later at 1050ºC and 750ºC two additional InN layers are grown with a thickness of 150 nm and 5 nm respectively. Reactor conditions are changed for the growth of 1-2 nm thick AlN interlayer. Reactor pressure and NH3 flow rate decreased to 50 mbar and 210 sccm. Temperature is kept constant and 10 sccm TMAl flow is given. For the growth of 25 nm, thick AlInN barrier layer 5 sccm TMGa and 500 sccm NH_3 flow is given. As the last step by keeping other parameters constant TMAl flow is stopped and a 3 nm thick InN cap layer is grown.

3. Results & Discussion

Transmittance is a physical property that makes light transmit from a material without scattering possible. On a macroscopic scale, it can be said that photons act by obeying the Snell law. Semi-transmittance is an up-group in transmittance. It permishes light to be transmitted but it does not have to obey Snell's law. Photons may present a dispersion behavior in both interfaces if there is a variation in diffraction. The opposite term for semi-transmittance is opaque. Semi-transparent materials may have any combination to form a perfect spectrum. In figure 2 transmittance versus wavelength plot can be seen. According to this plot, the transmittance is dominant at higher wavelengths of incident light. Approximately after 700 nm wavelength value transmittance reaches saturation according to the plot. Transmittance starts at a 200 nm wavelength value. Saturation of transmittance may be related to decreasing photon energy.

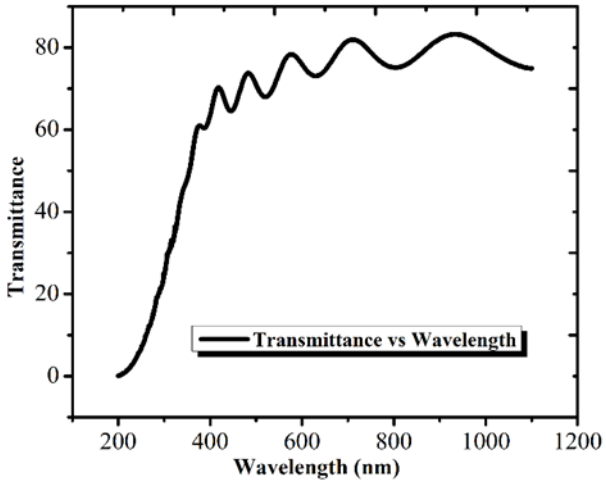

Figure 2. Transmittance vs wavelength for AlInN

Absorption is the suction of light by a material. Every material can only absorb light at its color frequency. Electrons in orbitals jump higher energy levels by absorption. Light is an electromagnetic wave with a specific energy. The energy of a photon can be calculated by E=h*υ. The energy of light is inversely proportional to wavelength. If an atom is excited by a photon with an energy equal to the difference in energy levels electrons jump upper energy level and the incident photon is absorbed. This physical event is called absorbance. In figure 3 absorbance versus wavelength plot can be seen. Absorbance starts at 200 nm wavelength, it decreases with decreasing incident photon energy and reaches a saturation value at approximately 400 nm wavelength value. This behavior may be attributed to decreasing photon energy.

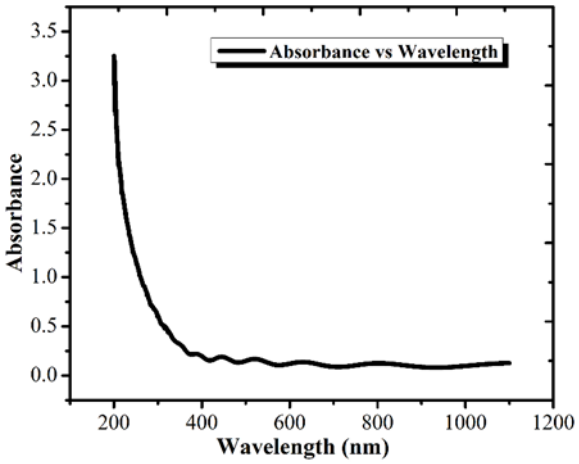

Figure 3. Absorbance vs wavelength for AlInN

Reflectance may be described as returning of an incident photon to the medium it came from after hitting a surface. In classical electrodynamics, as described in Maxwell's equations light is accepted as an electromagnetic wave. Light waves reaching the surface of material causes small polarized oscillations. All these waves make reflection according to the Huygens-Fresnel principle. The electric field of light interacts with electrons of the target material, moving electrons cause new fields noticed as reflected light. In figure 4 reflectance versus wavelength plot can be seen. According to this plot, reflectance starts at 200 nm, increases until 400 nm wavelength value, and stays approximately constant after 400 nm. This situation implies that increasing wavelength that is decreasing photon energy makes reflectance constant. This result may be attributed to the penetration obscenity of photons increasing as the wavelength of incident light decreases.

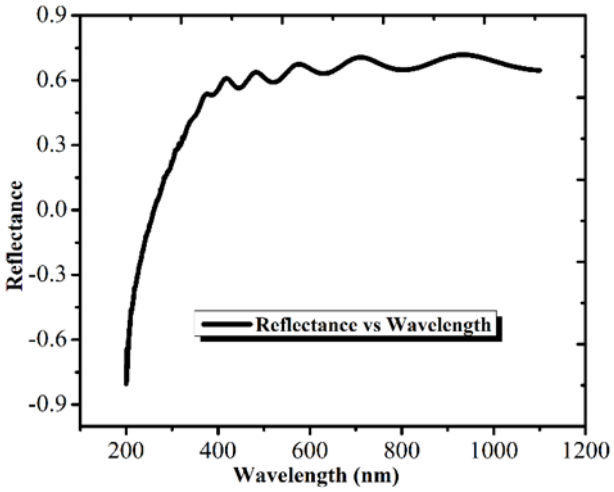

Figure 4. Reflectance vs wavelength for AlInN

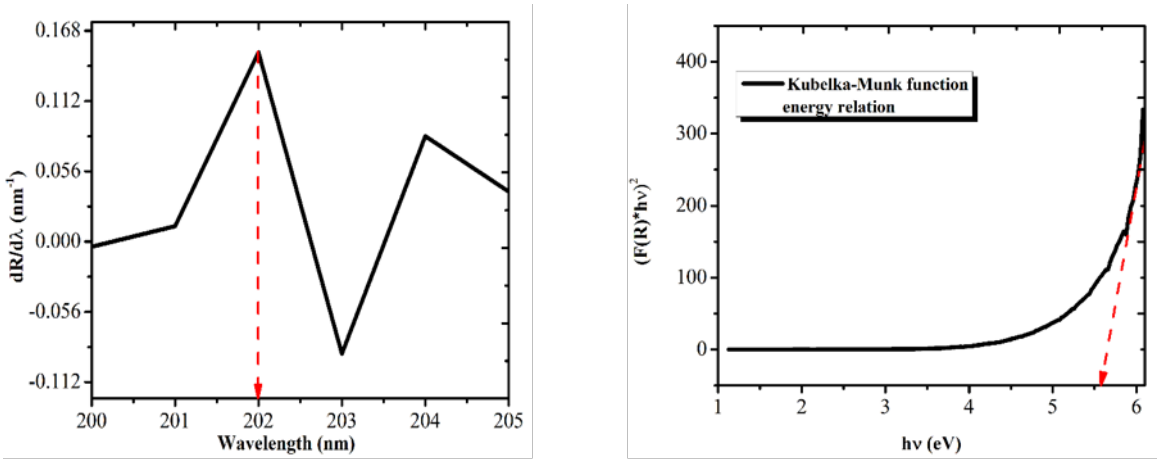

Figure 5. dR/dλ vs wavelength and Kubelka-Munk function- photon energy relation

For determining the forbidden energy band gap of InN, the Kubelka-Munk theory is employed. Kubelka-Munk's theory is a mathematical model including the transfer and reflection of two radiation currents over homogeneous opaque support dependent on some assumptions. These assume are:

1- The object must have a constant thickness

2- Lumination must be homogeneous

3- Optical interactions at edges may be neglected

4- Optical dispersion has homogeneous dispersion in a smaller region than sample thickness.

This theory is recommended by Schuster (Groh, 1992; Osa, 2020). It explains the analysis of the interaction of incident light with matter. According to this theory, matter, assumed as homogeneous, isotropic, and opaque, is illuminated with monochromatic light. In this model scattered reflection data are used.

Kubelka-Munk Function can be seen in equation (1),

$$F(R) = \frac{(1-R)^2}{2R} \tag{1}$$

Here R is the reflectance. To calculate the forbidden energy band gap of InN, reflection values should be converted to absorbance to do this equation (2) is employed,

$$\frac{K}{S} = F(R) \tag{2}$$

In this equation, S is the scattering factor and K is absorbance. To calculate the optical band gap of materials, one of the best methods is the differential reflectance method. In this method firstly, the first derivative of reflectance data versus wavelength is taken and the dr/dλ versus wavelength plot is drawn. The optical band gap can be calculated by using the wavelength value corresponding to the center of the maximum peak in this plot. As can be seen in figure 5 center of maximum peak value is 202 nm. The band gap value corresponding to this value is approximately 6 eV.

To calculate the optical band gap by using the Kubelka-Munk theory, first reflectance data should be converted to absorbance data. To determine the optical band gap equation (3) can be used (Murphy, 2007),

$$(\frac{F(R)h\nu}{t})^2 = B(h\nu - E_g) \tag{3}$$

In this equation F(R) is the Kubelka-Munk function, t is thickness, B is a coefficient independent of energy and Eg is the optical band gap. ((F(R)hυ)/t)The 2-hυ plot can be seen in figure 5. This plot is used to determine the optical band gap of film. The curve in the plot is extrapolated and the x-axis intercept of it gives an optical band gap. As expected optical band gap value calculated by this method is smaller than the one calculated by the derivative method (Inbaraj, 2018). The reason for this small difference may be defects and variation in carrier density.

4. Conclusions

In this study, the optical properties of the AlInN/AlN HEMT structure are investigated in detail. Transmittance, absorbance, and reflectance spectra are shown and comments are made on them in the text. Kubelka-Munk method and derivative of reflectance methods are employed to determine the optical band gap. The optical band gap is calculated at around 6 eV. The latter method gave a bit

smaller value of the optical band gap than the first method. The reason for this situation is attributed to defects and variation in carrier density.

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Authors' Contributions

All authors contributed equally to the study.

Statement of Conflicts of Interest

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

This study complies with Research and Publication Ethics.

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