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Investigation of The Temperature Dependent Electrical Properties of LT-GaN Layer Grown on A Sapphire Substrate

Didem Altun[1,a,*], Sezai Elagöz[2,b]

[1]Sivas Technical Sciences Vocational School Department of Electricity and Energy, Sivas Cumhuriyet University, Sivas, Turkey
[2]Sivas Cumhuriyet University, Sivas, Turkey
**Corresponding author*

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ABSTRACT

In this study, the electrical characterization of a low-temperature GaN (LT-GaN) layer within an InGaN/GaN blue light-emitting LED structure grown on a sapphire substrate using the Metal Organic Chemical Vapor Deposition (MOCVD) method was examined. For high-quality growth of the GaN layer on a sapphire substrate, a two-stage GaN growth process is employed, consisting of a low-temperature GaN (LT-GaN) layer and a high-temperature GaN (HT-GaN) layer. This study specifically investigates the structural and electrical properties of the LT-GaN layer, which is the first stage of the GaN growth process. Structural characterization was performed using high-resolution X-ray diffraction (HRXRD), while electrical characterization involved Hall effect measurements and current-voltage (I-V) measurements. Based on the results from structural and electrical measurements, the optimal growth temperature for the LT-GaN layer was determined, and the effect of growth temperature on the electrical properties was demonstrated.

Keywords: Gallium Nitride (GaN), Electrical Characterization, I-V, Hall Effect Measurement

Safir Alttaş Üzerine Büyütülen LT-GaN Tabakasının Sıcaklığa Bağlı Elektriksel Özelliklerinin Araştırılması

Araştırma Makalesi

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ÖZ

Bu çalışmada, Metal Organik Kimyasal Buhar Biriktirme (MOCVD) yöntemi kullanılarak safir alttaş üzerine büyütülen InGaN/GaN mavi ışık yayan LED yapısında düşük sıcaklık GaN (LT-GaN) tabakasının elektriksel karakterizasyonu incelenmiştir. Safir alttaş üzerine GaN tabakasının kaliteli büyütülebilmesi için düşük sıcaklık GaN (LT-GaN) tabakası ve yüksek sıcaklık GaN (HT-GaN) tabakası şeklinde iki aşamalı GaN büyütmesi yapılır. Bu çalışmada GaN tabakasının büyütme aşamalarından ilki olan düşük sıcaklıkta GaN (LT-GaN) tabakasının yapısal ve elektriksel özellikleri incelenmiştir. Yapısal karakterizasyon yüksek çözünürlüklü X ışını kırınımı (HRXRD) ile, elektriksel karakterizasyon ise Hall etkisi ölçümü ve akım gerilim ölçümleri ile yapılmıştır. Yapısal ve elektriksel ölçümlerden elde edilen sonuçların değerlendirilmesi ile düşük sıcaklık LT-GaN tabakası için ideal büyütme sıcaklığı belirlenmiş, büyütme sıcaklığının elektriksel özellikler üzerindeki etkisi gösterilmiştir.

Anahtar Kelimeler: Galyum nitrat (GaN), Elektriksel Karakterizasyon, I-V, Hall Etkisi Ölçümü.

[a] *didemaltun@cumhuriyet.edu.tr* *0000-0002-1964-3538* | [b] *elagoz@cumhuriyet.edu.tr* *0000-0002-3600-8640*

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Introduction

III-N structures and alloys are increasingly used in significant applications in electronics and optoelectronics, and this field is rapidly expanding with each new study. In particular, GaN-based semiconductors attract considerable attention for producing optoelectronic devices, such as high-efficiency light-emitting diodes (LEDs) (Nakamura et al., 1995), laser diodes (LDs) (Nakamura et al., 1996a), and electronic devices requiring high power and temperature tolerance (Eastman, 2002), due to their broad range of applications.

The frequency of light emitted by LEDs can correspond to different regions of the electromagnetic spectrum, including the visible light region, the infrared (IR) region, or the ultraviolet (UV) region. The spectrum of light emitted by LEDs is determined by the semiconductor materials used in the LED structure. Examples of semiconductor materials used in LED structures and the colors of light they emit include GaN – Blue, SiC – Blue, GaP – Green, $GaAs_{0.14}P_{0.86}$ – Yellow, $GaAs_{0.35}P_{0.65}$ – Orange, $GaAs_{0.6}P_{0.4}$ – Red, and GaAs – Infrared (Colinge and Colinge, 2005; Kruangam, D., 1987; Yamaguchi, T., 1981; Salii, R. A., 2024). With advances in nitride-based semiconductors, such as InN, GaN, and AlN, as well as improvements in epitaxial thin-film technologies, light sources have emerged in the blue, green, and UV regions of the electromagnetic spectrum, enabling the production of white light. With the spread of white light production, LED technologies are quickly replacing traditional lighting methods in modern lighting applications (Pimputkar et al., 2008).

There are two techniques for producing white light. The first involves combining three different LEDs that emit red, blue, and green light, resulting in white light (Muthu, S.). However, this method is costly, and its light efficiency does not reach the desired levels, making it less commonly preferred today. The second technique, which is widely used for white-light-emitting LEDs, is to coat a blue LED chip with phosphor to produce white light. This approach is both cost-effective and has high light efficiency. These high-brightness nitride-based blue LEDs and other optoelectronic LEDs are now used in many fields. The invention of blue light-emitting LEDs can be considered the basis for the widespread use of white-light-emitting LEDs today.

Blue light-emitting nitride semiconductor LEDs are predominantly based on GaN and InGaN thin films. Such LEDs consist of p-n junctions containing a thin InGaN quantum well. A typical LED structure is shown in Figure 1 (Mukai, 2003). This structure includes epitaxial layers containing InGaN multiple quantum wells that produce light between p-type and n-type GaN layers grown on a sapphire substrate.

The first step in producing devices from epitaxially grown semiconductor structures is the precise definition of these epitaxial layers. Achieving this requires a thorough characterization of the structural, optical, electrical, and magnetic properties of the semiconductor structures. Additionally, for the development and production of electronic and optoelectronic devices, it is crucial to accurately determine numerous parameters that provide insights into the quality of the epitaxial layers. Key parameters include the crystal quality of the epitaxial layers, chemical alloy ratios, carrier densities, energy band structures, critical energy points, and band gap.

Today, sapphire is generally used as the substrate for GaN growth due to its cost-effectiveness, large size, and advancements in high-quality production techniques. However, due to the high lattice mismatch (16%) and thermal expansion coefficient mismatch between sapphire and the GaN layer, achieving high-quality GaN crystal growth is challenging. Nevertheless, high-efficiency blue light-emitting diodes have been produced (S. Nakamura et al., 1996b). Moreover, compared to other semiconductor devices, nitride-based devices are less sensitive to defects (Lester et al., 1995). However, defects that lead to non-radiative recombination or act as leakage pathways for vertical transmission (Li et al., 2009) can reduce device performance and shorten lifespan (Mukai and Nakamura, 1999; Nakamura et al., 2000). Thus, while LEDs emitting light can still be produced despite high lattice mismatch between sapphire and GaN, growth-related problems also arise. A common issue in GaN growth is the high defect density due to lattice mismatch, which degrades the quality of the GaN crystal. For this reason, to improve the crystal quality of GaN, a two-stage GaN growth was performed using the MOCVD growth technique, involving both a low-temperature GaN (LT-GaN) layer and a high-temperature GaN (HT-GaN) layer, and various parameter studies were conducted.

In two-stage GaN growth studies, a four-stage growth process was carried out to determine the optimal growth parameters. These stages are presented in Table 1. In this study, the electrical characterization of the temperature-dependent growth, the first of these growth studies, was examined.

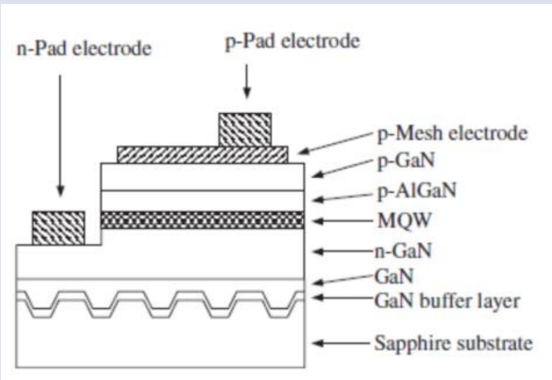

Figure 1: General structure of GaN/InGaN LEDs (Mukai, 2003).

Table 1: GaN single-layer study groups.

GaN Single Layer Studies			
Temperature study for LT-GaN nucleation layer*	Growth duration (thickness) study for LT-GaN nucleation layer	Nitridation time study	V/III ratio study for HT-GaN layer
* In this study, only this group of studies on GaN growth were conducted.			

Materials and Methods

In this study, the temperature-dependent growth of the LT-GaN layer on a sapphire substrate for blue light-emitting diode (LED) structures was examined, and electrical characterization was performed. Optimal growth recipes were developed by considering carrier density values to preserve the crystal quality in the growth parameters.

Imaging the atomic structure of a material is possible using various high-resolution electron microscopes (Aygün and Zengin, 1998). However, diffraction techniques are required to identify unknown structures or determine structural parameters. Diffraction experiments are techniques used to evaluate the structural quality of crystallized materials (Singh, 2003). X-ray diffraction is the most widely used diffraction technique for analyzing the crystal structures of solids. This technique is particularly suitable for thin-film analysis for two main reasons: first, the wavelengths of X-rays are on the scale of atomic distances in condensed matter, making them effective for structural investigations. Second, X-ray scattering techniques are non-destructive and do not damage the sample being analyzed.

The purpose of this study was to investigate the effect of temperature on the electrical properties of the LT-GaN layer. However, since maintaining crystal quality was prioritized, structural analysis was conducted prior to electrical analyses. For this, High Resolution X-Ray Diffraction (HRXRD) scans (symmetric omega (0002), asymmetric omega (10-12), and 2Theta/Omega) were performed on GaN layers grown at temperatures of 455, 475, 495, 525, and 550°C.

Electrical measurements and some electrical characteristics of the GaN samples studied for crystal quality through structural characterization were obtained using the Hall effect. Hall effect measurement is one of the most common and effective techniques in semiconductor studies, providing information on the resistivity, carrier density, mobility, and carrier type of the grown layer. The Van der Pauw technique with four-point geometry was used for Hall effect measurements in this study. This technique was preferred because it requires only four contacts and does not require measuring the spacing between contacts or the dimensions of the sample. According to this technique, ohmic contacts were made with indium on the four corners of the square-cut sample. Before Hall effect and Van der Pauw measurements, contact resistances were measured by applying current to the contacts and measuring the voltage. Then, current-voltage measurements were conducted for each contact pair on the sample surface to verify the ohmicity of the contacts. The linearity of the resulting current-voltage (I-V) curves confirmed that the contacts were ohmic (Mott and Twose, 1961). Ohmic contacts indicate that all measured data pertain to the sample itself, with no influence from the contacts. Next, desired magnetic fields were applied to the sample using a computer, constant current source, gaussmeter, electrometer, and electromagnet power supply, and measurements of the Hall coefficient, resistivity, Hall mobility, and Hall carrier densities were obtained.

To understand the characteristic parameters of semiconductor crystals, it is essential to examine their conductivity properties thoroughly. For this purpose, I-V measurements were repeated using the I-V measurement system. To conduct this examination, Schottky diodes were formed by creating suitable contacts on the crystal. In this study, the contacts were made using the evaporation method. First, ohmic contacts were created on the samples by evaporating aluminum onto the samples placed in a vacuum system once the vacuum pressure reached 4x10^-6 torr. Schottky contacts were then made by evaporating silver under the same vacuum conditions. I-V measurements were carried out on these contacts.

Among the samples that underwent structural and electrical analyses, the most suitable sample for the next stage was selected.

Findings and Discussion

First, structural characterization studies were conducted to evaluate the crystal quality of LT-GaN layers grown at the temperatures listed in Table 2. HRXRD measurements were taken for this purpose. XRD is a technique used in the analysis of crystal structures, providing information on atomic arrangement and crystal perfection. For GaN samples, 10-12 asymmetric omega, 0002 symmetric omega, and 2Theta/Omega measurements were taken. These measurements are shown in Figure 2.

To assess crystal quality, the FWHM values obtained from our HRXRD measurements are presented in Table 3. Considering these values, sample LED.031 is observed to have the best crystal structure. Additionally, Figure 3 illustrates the FWHM values obtained from symmetric (0002), asymmetric (10-12), and theta/2 theta measurements plotted against growth temperatures, further confirming that LED.031 is the optimal sample.

To perform electrical optimization for the structurally characterized samples, I-V measurements were conducted. The results of these measurements are presented in Figure 4. The threshold voltages of the samples in this study group are consistent with each other, with the expected threshold voltage being around 1.1–1.2V. For a sample with high electrical quality, we expect a rapid increase in current after the breakdown voltage. This behavior is observed in samples LED.031 and LED.033. In contrast, sample LED.032 does not reach high current values, which is attributed to lower crystal quality, as also indicated by HRXRD measurements. The crystal quality observed in HRXRD and reflection measurements for samples LED.031 and LED.033 is consistent with their electrical quality. In these samples, both crystal quality was maintained, and electrical improvement was achieved.

For the samples grown in this study group, Hall effect measurements were conducted under magnetic fields of 1000 and 5000 Gauss. The values obtained from these measurements are presented in the table below. The carrier densities for all samples are of the same order of magnitude. The Hall mobility for sample LED.031 is approximately 195 cm²/V·s, while for sample LED.033 it is around 230 cm²/V·s. These values align with the previously conducted current-voltage measurements. Considering the obtained values, sample LED.033 exhibits the best electrical properties.

Table 2: Growth temperatures of each sample used in LT-GaZ layer growths.

Sample No	Growth Temperature (°C)
LED.031	475
LED.032	455
LED.033	495
LED.034	525
LED.035	550

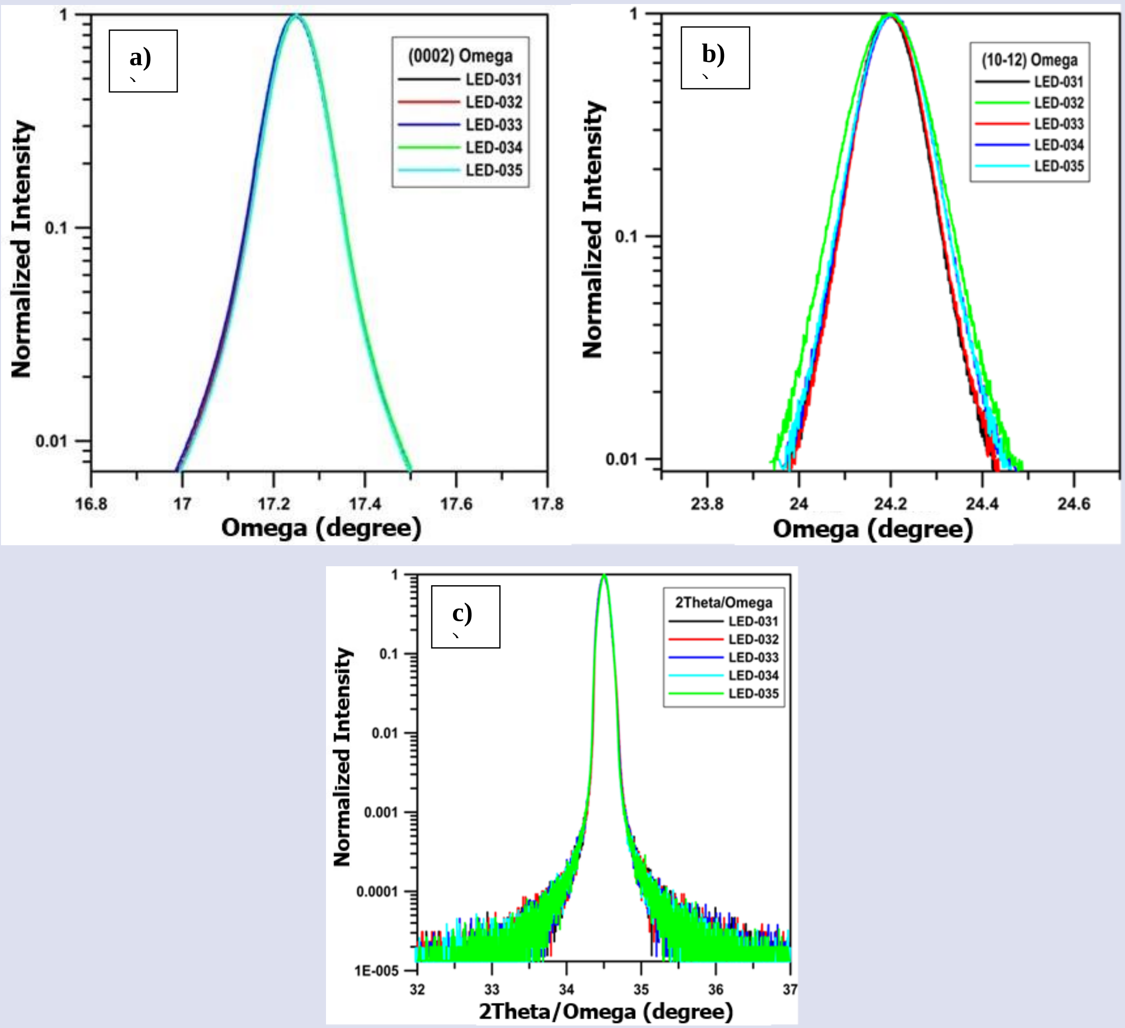

Figure 2: (0002) symmetric omega (a), (10-12) asymmetric omega (b) and 2Theta/Omega (c) scans for samples with different LT-GaN growth temperatures.

Table 3: FWHM values from symmetric omega, asymmetric omega, and 2Theta/Omega scans for samples with different LT-GaN growth temperatures.

Sample No	(0002) Symmetric Omega FWHM (arcsec)	(10-12) Asymmetric Omega FWHM (arcsec)	2Theta/Omega FWHM (arcsec)
LED.031	384	420	500
LED.032	393	430	502
LED.033	390	416	501
LED.034	381	455	500
LED.035	390	457	498

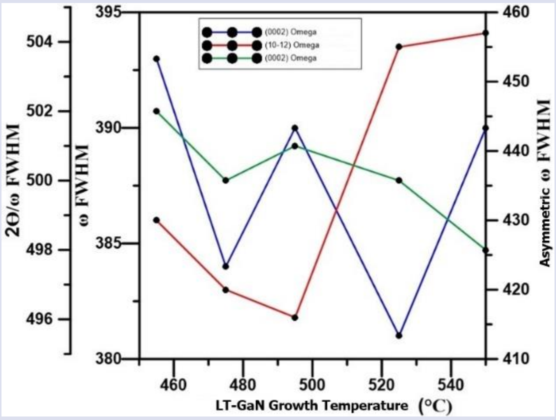

Figure 3: Changes in the FWHM values obtained from the symmetric omega, the asymmetric omega and 2Theta/Omega scans with respect to the changing growth temperatures of the LT-GaN layer.

Table 4: Hall effect measurements for samples LED.031, LED.032, LED.033, LED.034, and LED.035.

Numune No	Magnetic Field (Gauss)	Hall Coefficient (cm^3/C)	Layer Carrier Density ($1/cm^2$)	Hall Mobility ($cm^2/(V.s)$)	Bulk Carrier Density ($1/cm^3$)	Resistivity (Ohm.cm)
LED.031	1000	34,3	2,94 e+13	196,3	1,81 e+17	0,17
	5000	34,1	2,96 e+13	195,1	1,83 e+17	0,17
LED.032	1000	25,52	3,67 e+13	174,2	2,14 e+17	0,14
	5000	28,23	3,32 e+13	222,4	2,21 e+17	0,12
LED.033	1000	59,08	1,58 e+13	230,9	1,05 e+17	0,25
	5000	58,07	1,61 e+13	226,7	1,07 e+17	0,25
LED.034	1000	63,26	1,48 e+13	220,4	0,98 e+17	0,28
	5000	62,38	1,50 e+13	217,0	1,00 e+17	0,28
LED.035	1000	84,65	1,33 e+13	183,1	0,73 e+17	0,46
	5000	85,20	1,32 e+13	183,6	0,73 e+17	0,46

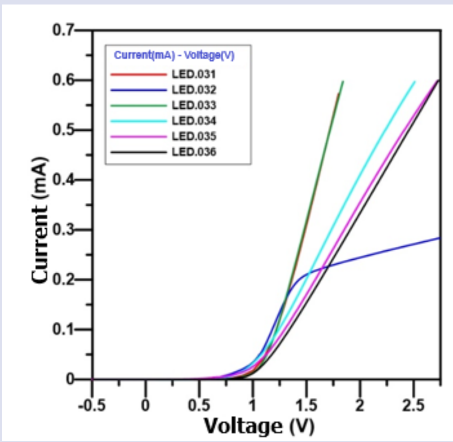

Figure 4: Current-Voltage curves of samples LED.031, LED.032, LED.033, LED.034, LED.035 and LED.036.

Conclusion

In this study, structural and electrical characterizations of LED samples with LT-GaN layers grown at different temperatures were conducted. Structural characterization using HRXRD indicated that the lowest FWHM values were obtained from sample LED.031. For electrical characterization, I-V and Hall effect measurements were performed on the same samples. Based on the breakdown voltage and current variation in the I-V measurements, samples LED.031 and LED.033 exhibited the best electrical properties. The Hall effect measurements further indicated that sample LED.033 had the best electrical characteristics. This study represents only one phase of the development process for blue LED structures grown on sapphire substrates. For further improvement of subsequent phases, crystal quality should also be prioritized, even before electrical properties. Therefore, sample LED.031 exhibited the best overall characteristics, both structurally and electrically.

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