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Araştırma Makalesi / Research Article

Application of QMSA Method for $Al_{0.3}Ga_{0.7}N$/GaN HEMT Structure

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Abstract

In this study, $Al_{0.3}Ga_{0.7}N$/GaN high electron mobility transistor (HEMT) structure is grown on a sapphire (Al_2O_3) substrate by using metal-organic vapor phase epitaxy (MOVPE), and its electron transport and magnetic transport properties are investigated. Resistivity is measured in the 20-350 K temperature range. Hall mobility and Hall carrier concentration are measured in the 0-1.5 T magnetic field range and the same temperature range. Magnetic transport properties are analyzed using quantitative mobility spectrum analysis (QMSA). 2DEG and 3DEG transport mechanisms are separated by using QMSA results.

Keywords: GaN, HEMT, AlGaN, QMSA, Hall, Mobility.

$Al_{0.3}Ga_{0.7}N$/GaN HEMT Yapısı için QMSA Metodu Uygulanması

Öz

Bu çalışmada, $Al_{0.3}Ga_{0.7}N$/GaN yüksek elektron mobiliteli transistör (HEMT) yapısı, metal-organik buhar fazlı epitaksi (MOVPE) kullanılarak safir (Al_2O_3) bir alttaş üzerinde büyütülmüş, elektron taşıma ve manyetik taşıma özellikleri incelenmiştir. Özdirenç 20-350 K sıcaklık aralığında ölçülmüştür. Hall hareketliliği ve Hall taşıyıcı konsantrasyonu, 0-1,5 T manyetik alan aralığında ve aynı sıcaklık aralığında ölçülmüştür. Manyetik taşıma özellikleri, kantitatif hareketlilik spektrum analizi (QMSA) kullanılarak analiz edilmiştir. 2DEG ve 3DEG taşıma mekanizmaları QMSA sonuçları ile birbirinden ayrılmıştır.

Anahtar Kelimeler: GaN, HEMT, AlGaN, QMSA, Hall, Mobilite.

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1. Introduction

GaN is a compound semiconductor material that has been investigated for the last 15 years. Today GaN is used commonly but its importance is noticed late according to other III-V group semiconductor materials (Bulbul and et al., 2000; Erol, 2000; Bulutay and et al., 2000). The importance of GaN material stems from its physical properties. GaN has a wide band gap, high thermal conductivity, high melting point, and low dielectric coefficient. These properties make GaN available in the construction of high-frequency power transistors. The ability to operate at high power and high temperature also makes it convenient for military applications (Bulutay and et al., 2000; Gokden, 2007; Yu and, 2006).

In this study, AlGaN/GaN HEMT structure is grown by using the MOVPE method. In the 15-350 K temperature range and the 0-1.5 T magnetic field range, resistivity and Hall effect measurements are made. Gained data are used in the QMSA method and mobility and carrier concentration for electrons and holes are calculated. Some parameters for sapphire wafer and $Al_{0.3}$ $Ga_{0.7}N$/GaN are presented. QMSA method is used to decide which scattering mechanism is dominant and if the transport mechanism is 2DEG or 3DEG. Comments are made in accordance with the results of the QMSA analysis.

2. Experimental

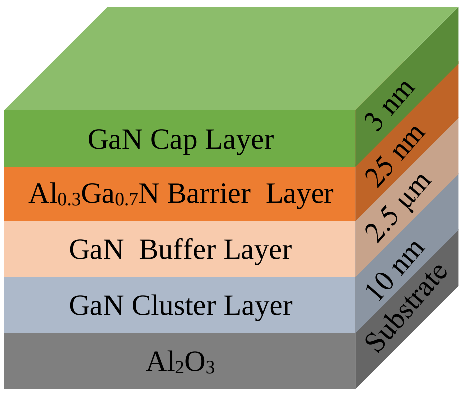

Figure 1. Schematic diagram for AlGaN/GaN HEMT

Semiconductor layers are grown on a c-(0001) oriented sapphire (Al_2O_3) wafer under low pressure in the MOVPE reactor. Before the growth of these semiconductor layers, the sapphire wafer is cleaned at 1100 ^oC in an H_2 atmosphere. First, a 25 nm thick GaN cluster layer is grown at 500 ^oC. Reactor pressure is kept constant at 50 mbar during the cleaning procedure and growth of the cluster layer. After the growth of the cluster layer at a low temperature, the sample temperature is increased and the sample is annealed for crystallization. The resistivity of GaN buffer layer and surface roughness are dependent on increasing speed of temperature in two-step growth method, annealing temperature, and thickness of the cluster layer (Ozbay and et al., 2004; Zanato and et al., 2004; Balkan and et al., 2002). Two-step growth method is applied as 2.5 and 5 minutes annealing duration for 1100 ^{o}C and 1050 ^{o}C temperatures. Later, over annealed cluster layer, a 2.5 μm thick GaN buffer layer, which decreases dislocations, is grown in constant growth conditions. As the last step, at the same conditions, a 25 nm thick $Al_{0.3}Ga_{0.7}N$ barrier layer and 3 nm thick GaN cap layer, which reduce incontuinity of the conduction band and help construct ohmic contact, are grown. All of the epitaxial layers are grown as undoped layers.

3. Results and Discussion

In this study, electrical and magnetic transport properties of $Al_{0.3}Ga_{0.7}N$ HEMT structure, which is grown by using the MOVPE method, are investigated. For this aim, resistivity and Hall effect measurements are made in the 20-350 K temperature range and in the 0-1.5T magnetic field range.

For $Al_{0.3}Ga_{0.7}N$ HEMT structure, resistivity measurements are made by using the Van der Pauw method in 20-350 K temperature and 0-1.5T magnetic field ranges. When there is no magnetic field applied, resistivity versus inverse of temperature plot is given in Figure 2. For $Al_{0.3}Ga_{0.7}N$/GaN HEMT structure, resistivity dependent on temperature presents metallic behavior. At low temperatures, resistivity is almost constant. Behavior of resistivity at high temperatures is in accordance with the literature (H. M. Milchberg et al., 1988). A decrease in resistivity at low temperatures will be explained in mobility examinations.

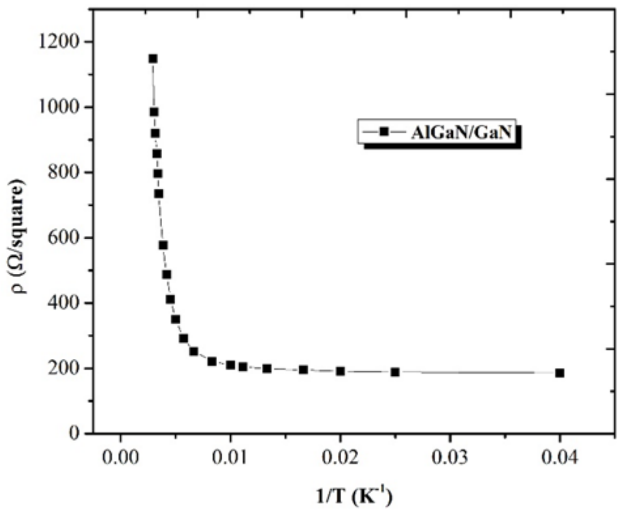

Figure 2. Resistivity vs. temperature graph

Along the temperature range applied to the sample, Hall coefficient presents negative behavior. This situation implies that free carriers are electrons. Hall mobility and Hall carrier concentration dependent on temperature and measured at 0.5 T magnetic field are given in Figure 3. As can be seen in Figure 3, Hall mobility becomes independent of temperature at temperatures lower than 100 K. At temperatures higher than 100 K, Hall mobility decrease in accordance with $T^{-3/2}$ dependency which belongs to optical phonon scattering (Lee and et al., 2001; Feng and et al., 2004; Xing and et al., 2001). For this reason, in this sample, optical phonon scattering is dominant at high temperatures. It can be concluded that Hall carrier density is independent of temperature in general. At high temperatures, impurities are excited in a thermal way and a few carriers contributed to increasing in Hall carrier density.

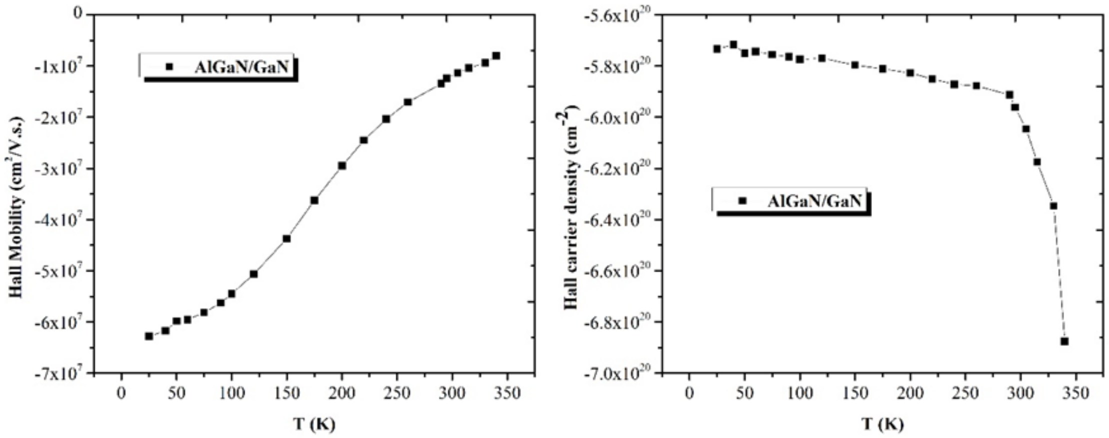

Figure 3. a) Hall mobility vs temperature for AlGaN/GaN b) Hall carrier density vs temperature for AlGaN/GaN.

Electron mobility does not decrease at low temperatures and it is independent of temperature, the reason for this may be, electrons are not exposed to impurity scattering. Impurity scattering is the most effective scattering mechanism in 3D electron transport at low temperatures. The sample is not affected by this scattering mechanism, this situation implies transport is not in 3D. Transport comes out at the interface of $Al_{0.3}Ga_{0.7}N$/GaN structure around a few nanometers well in 2D. Electrons moving in such a small area interacts with randomized impurities only which are near the well. This behavior of Hall mobility and the independency of Hall carrier density from temperature are typical properties of 2D electron gas. For this sample Hall mobility and Hall carrier density in the room are -1.23x 10^7 cm^2/V.s,-6.01x10^{20} 1/cm^2, respectively. At 20 K, Hall mobility is measured as -6.18x10^7 cm^2/V.s. This great difference may be because of three different mechanisms. These three mechanisms are accepted as dominant scattering mechanisms at low temperatures in 2D transport systems (Shen and et al., 2001; Balmer and et al., 2003; Smorchkova and et al., 2000). These are impurity scattering, alloy scattering, and interface roughness scattering.

In addition to the examination of mobility qualitatively, quantitative examination may help gain some important parameters. Matching Hall mobility and Hall carrier density values gained from different scattering mechanisms is called scattering analysis.

In this section, it is assumed that scattering mechanisms limit electron mobility independently of each other. Scattering analysis is made by using, polar optical phonon, acoustic phonon, alloy, impurity, and interface roughness scattering mechanisms. During calculations, the amount of impurity (Nd) is taken as 10^{23} m^{-3}. Lateral values of interface roughness (Δ) are taken as $5.2x10^{-10}$ m [124]. Other parameters such as well width (Z_0), deformation potential (Ξ), and correlation length (Λ) are accepted as adjustable parameters.

By using Mattheisen rule approximation, all scattering mechanisms are summed up with software, and limited mobility values are found. In the first step, scattering mechanisms are matched with measured values by using Hall mobility and Hall carrier concentration versus temperature plot given in Figure 3. Matching results are shown in Figure 4.

Interface roughness scattering, alloy scattering, acoustic phonon scattering and impurity scattering are directly related with variation of well width. Optical phonon scattering is indirectly related with well width. Electrons in a wider quantum well interacts with impurities more. For this reason, difference in Hall mobility at low temperatures is not determined by only interface roughness. High carrier density shows itself as high deformation potential in acoustic phonon scattering.

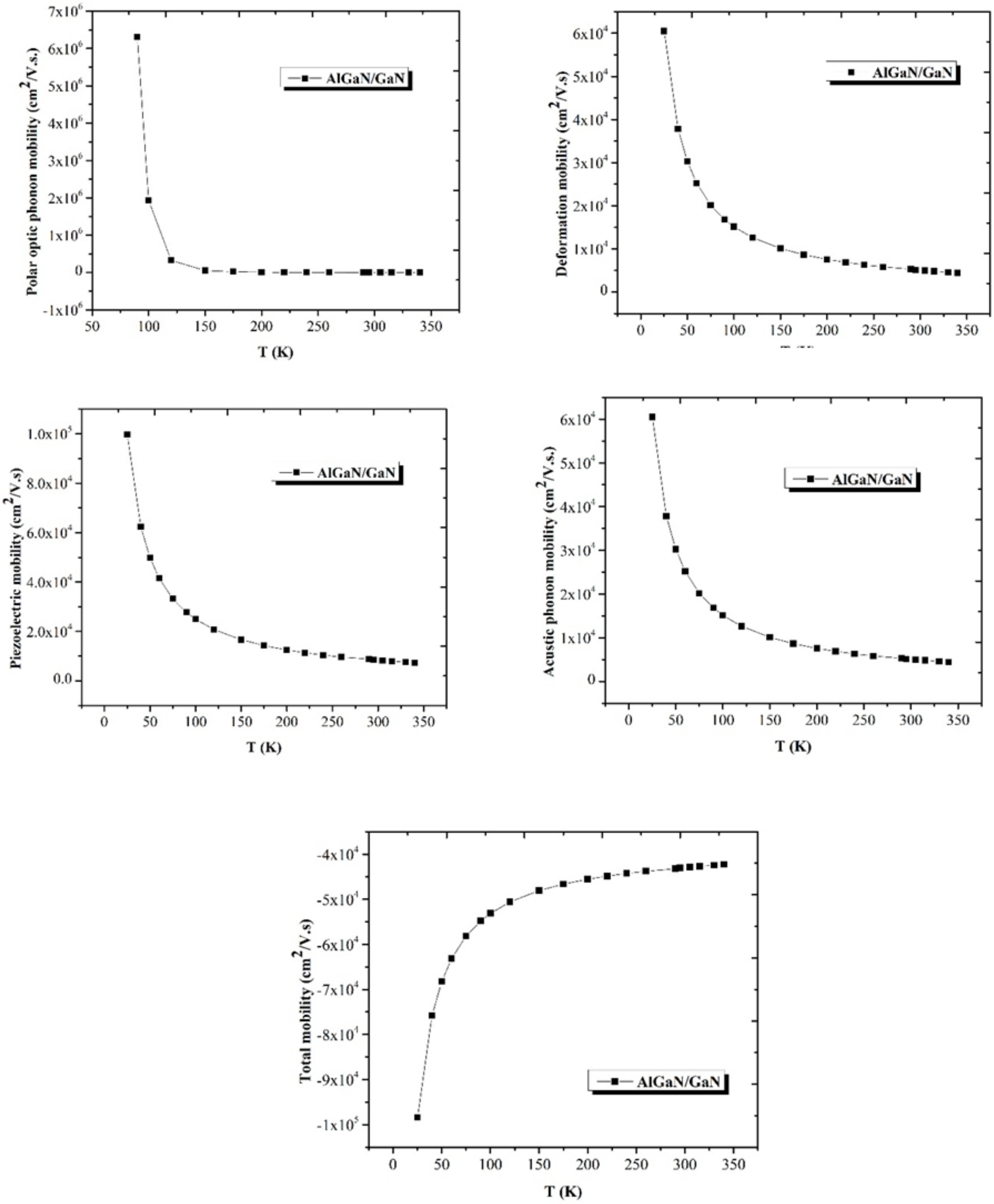

Figure 4. Mobility vs temperature plots for different scattering mechanisms.

As the result of QMSA, indivisual carrier parameters are calculated. Hall coefficient (R_H), dependent on magnetic field is measured experimentally. Resistivity (ρ), is also measured experimentally. By using these values, Hall mobility and Hall carrier density can be determined and by using these values, transport tensor σ_{xy} can be found. Mobility plots are gained by iterative examination of dependency of transport tensor on magnetic field.

In Figure 5, dependency of transport tensor and their match as the result of QMSA analysis are shown for three different temperatures. As can be seen in Figure 5, matching results are in perfect accordance. Planary transport values are not too high but AlGaN/GaN structure does not obey this finding. At high temperatures, there is only one electron carrier. Carriers with low mobility at high temperatures are 3D impurity carriers excited by thermal way.

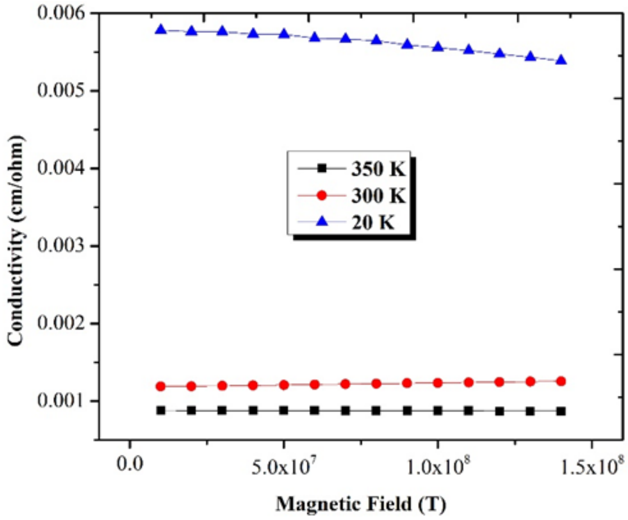

Figure 5. Conductivity vs magnetic field for three different temperatures.

4. Conclusion

In this study, $Al_{0.3}Ga_{0.7}N$/GaN high electron mobility transistor (HEMT) structure is grown on a sapphire (Al2O3) substrate by using metal-organic vapor phase epitaxy (MOVPE), and its electron transport and magnetic transport properties are investigated. At high temperatures, polar optic phonon scattering is dominant. At low temperatures, impurity and alloy scatterings are dominant. Interface roughness scattering may be strongly dominant at low temperatures and it is a very important scattering mechanism. In this sample, because there is no AlN interlayer, the obscenity of finding electrons in the AlGaN barrier has a finite value. This situation is stable by dominant alloy scattering. Also, this situation implies that the probability of finding electrons at the interface is high, resulting in effective interface roughness.

Ethics Approval

I approve that all ethic rules are obeyed during this study. *There is no conflict of interest for this study.

Consent to Participate

I consent to participate in this study.

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References

H. M. Milchberg, R. R. Freeman, S. C. Davey, and R. M. More. (1988). Resistivity of a Simple Metal from Room Temperature to 106 K. Phys. Rev. Lett. **61**, 2364

Bulbul, M. M., Smith, S. R. P., Obradovic, B., Cheng, T. S. And Foxon, C. T., (2000). Raman spectroscopy of optical phonons as a probe of GaN epitaxial layer structural quality. *Eur. Phys. J. B*, 14(3), 423-429.

Erol, M., (2000). Temperature dependence of transport characteristics of wurtzite GaN epilayers. *Czech. J. Phys.*, 50(5), 665-670.

Bulutay, C., Ridley, B. K. And Zakhleniuk, N. A., (2000). Comparative analysis of zinc-blende and wurtzite GaN for full-band polar optical phonon scattering and negative differential conductivity. *Appl. Phys. Lett.*, 77(17), 2707-2709.

Bulutay, C., Ridley, B. K. And Zakhleniuk, N. A., (2000). Full-band polar optical phonon scattering analysis and negative differential conductivity in wurtzite GaN. *Phys. Rev. B*, 62(23), 15754-15763.

Gokden, S., (2007). The analysis of scattering mechanisms in GaN by relaxation time approximation and the comparison by the transport to quantum scattering time ratios. *Eur. Phys. J. -Appl. Phys.*, 38(2), 141-145.

Yu, H., Ozturk, M. K., Ozcelik, S. And Ozbay, E., (2006). A study of semi-insulating GaN grown on AlN buffer/sapphire substrate by metalorganic chemical vapor deposition. *J. Cryst. Growth*, 293(2), 273-277.

Ozbay, E., Biyikli, N., Kimukin, I., Kartaloglu, T., Tut, T. And Aytur, O., (2004). High-performance solar-blind photodetectors based on AlxGa1-xN heterostructures. *IEEE J. Selected Topics Quant. Electron.*, 10(4), 742-751.

Zanato, D., Gokden, S., Balkan, N., Ridley, B. K. And Schaff, W. J., (2004). The effect of interface-roughness and dislocation scattering on low temperature mobility of 2D electron gas in GaN/AlGaN. *Semicond. Sci. Technol.*, 19(3), 427-432.

Balkan, N., Arikan, M. C., Gokden, S., Tilak, V., Schaff, B. And Shealy, R. J., (2002). Energy and momentum relaxation of hot electrons in GaN/AlGaN. *J. Phys – Condens. Matter*, 14(13), 3457-3468.

Lee, S. Y., Cetiner, B. A., Torpi, H., Cai, S. J., Li, J., Alt, K., Chen, Y. L., Wen, C. P., Wang, K. L. And Itoh, T., (2001). An X-band GaN HEMT power amplifier design using an artificial neural network modeling technique. *IEEE Trans. Electron. Dev.*, 48(3), 495-501.

Feng, Z. H., Zhou, Y. G., Cai, S. J. And Lau, K. M., (2004). Enhanced thermal stability of the two-dimensional electron gas in GaN/AlGaN/GaN heterostructures by Si3N4 surface-passivation-induced strain solidification. *Appl. Phys. Lett.*, 85(22), 5248-5250.

Xing, H., Keller, S., Wu, Y. –F., McCarthy, L., Smorchkova, I. P., Buttari, D., Coffie, R., Green, D. S., Parish, G., Heikman, S., Shen, L., Zhang, N., Xu, J. J., Keller, B. P., DenBaars, S. P. And Mishra, U. K., (2001). Gallium nitride based transistors. *J. Phys. -Condens. Matter*, 13(32), 7139-7158.

Shen, L., Heikman, S., Moran, B., Coffie, R., Zhang, N. –Q., Buttari, D., Smorchkova, I. P., Keller, S., DenBaars, S. P. And Mishra, U. K., (2001). AlGaN/AlN/GaN high-power microwave HEMT. *IEEE Electr. Device Lett.*, 22(10), 457-459.

Balmer, R. S., Hilton, K. P., Nash, K. J., Uren, M. J., Wallis, D. J., Wells, A., Missous, M. And Martin, T., (2003). AlGaN/GaN microwave HFET including a thin AlN carrier exclusion layer. *Phys. Stat. Sol. (c)*, 0(7): 2331-2334.

Smorchkova, I. P., Keller, S., Heikman, S., Elsass, C. R., Heying, B., Fini, P.,Speck, J. S. And Mishra, U. K., (2000). Two-dimensional electron-gas AlN/GaN heterostructures with extremely thin AlN barriers. *Appl. Phys. Lett.*, 77(24), 3998-4000.