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Effect of Discharge Power on the Properties of GaN Thin Films on AlN-(002) Prepared by Magnetron Sputtering Deposition

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ABSTRACT

Aluminum nitride (AlN) and gallium nitride (GaN) thin films were grown on silicon (Si) substrates using the conventional RF magnetron sputtering plasma deposition system. The growth rate of GaN increased as the deposition power of GaN increased. There was no crystalline peak of GaN observed, since there was no additional substrate heating. However, a highly crystalline AlN was observed and its peak orientations of (001) and (002) changed with the growth of GaN films at various RF discharge powers. The film's composition analysis using energy-dispersive X-ray spectroscopy (EDS) confirmed the existence of Ga and N in the thin films. AFM results showed that the surface roughness (Ra) of the GaN/AlN thin films increased with increased RF discharge power. FESEM images showed a good agreement with the AFM results, since the grain size increased as the surface roughness increased. The electrical properties studied using Hall effect showed that a low discharge power of GaN led to low resistance, high carrier concentration and low Hall mobility, which are good for devices in optoelectronic applications.

Keywords: Magnetron Sputtering Plasma, GaN thin film, AlN Thin Film, Blue LED.

1. INTRODUCTION

Aluminum gallium nitride (AlGaN)-based optoelectronic devices for light-emitting diodes (LEDs) operating in the ultraviolet (UV) wavelength are usually grown on sapphire substrates by using the metal-organic chemical vapor deposition (MOCVD) technique [1]–[3]. Compared to sapphire substrates, silicon substrates have several advantages, such as lower cost, availability in various sizes and good thermal and electrical conductivity [4]. There have been reports on the successful growth of GaN on silicon [5], [6]. However, there are some issues in developing GaN thick films on Si substrates, such as cracking, high-density threading dislocations and a cloudy surface morphology [7]. These issues are said to be the cause of decreasing quality, performance and emission in AlGaN-based devices.

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The reactive frequency (RF) magnetron sputtering plasma deposition technique could produce good structural, electrical and optical properties of AlN and GaN thin films [8]–[11] The advantages of the RF magnetron sputtering method are it produces thin films at high growth rates, with a uniform and large coating area and strong adhesion, at low temperature and low production cost [12], [13]. Due to these reasons, the RF magnetron sputtering method is very promising for industrial applications.

The deposition technique using RF magnetron sputtering on GaN directly on Si substrates gives several challenges, such as the formation of the SiN amorphous layer at the interface due to the strong reaction of nitrogen atoms with the Si substrate [14]. Other than that, there are also thermal expansion coefficient mismatch (57%) and the large lattice mismatch (16.9%) in the lattice constant between GaN and Si [4], [7], [15]. To overcome these issues, an AlN buffer layer was introduced between the substrate and the nitride film [16]. According to previous reports, the AlN buffer layer helps to improve the structure, crystal quality, electrical properties and optical properties of GaN thin films, as well as in reducing cracks [17]–[19].

In this study, a GaN thin film was deposited on an AlN buffer layer on a Si substrate. Both layers were deposited using the RF magnetron sputtering plasma deposition system. The GaN/AlN thin films were characterized using Filmetrics, X-ray diffraction (XRD), atomic force microscope (AFM), field-emission scanning electron microscope (FESEM), energy-dispersive X-ray spectroscopy (EDS) and Hall effect to study the films' morphological, topographical, elemental and electrical properties. These thin films may have the potential to be used as a key material for the production of high-quality III-nitrate semiconductors in power electronic and optoelectronic devices.

2. MATERIAL AND EXPERIMENTAL SETUP

The GaN/AlN thin films were grown on Silicon (100) (Si) substrate using a magnetron sputtering system from SNTEK PSP 5004 (09SN70) and RF power supply from Advance Energy. Figure 1 shows the schematic of AlN and GaN depositions on Si substrate. First, the AlN buffer layer was deposited on silicon (Si) (100) substrate for 2 hours. The sputtering conditions for the growth of AlN layer were 5 mTorr working pressure, and 200 W RF discharge power. Then, GaN layer was grown on top of the AlN thin films, for 2 hours using 10 mTorr working pressure. The GaN discharge power was varied at 40 W, 60 W and 80 W. The argon (Ar) gas and nitrogen ($N_{2)}$ gas flow rates for both ALN and GaN films sputtering were fixed at 100 sccm and 50 sccm, respectively. Prior to the deposition, pre-sputtering using Ar gas was performed on AlN target with 99.999% purity, and GaN target with 99.99% purity, to remove the natural oxide layer on the target surface for 10 minutes. The size for each AlN and GaN sputter targets was 3 inches in diameter. The chamber background pressure was maintained below than 1×10^{-6} Torr.

The thicknesses of GaN/AlN thin films were measured using Filmetrics (FILM Measure). The structural of GaN/AlN thin films were characterized using XRD (Panalytical Xpert3 Powder). Surface morphology was studied using AFM (Hitachi, XE- Series SPM Controller). Topographical and elemental information of AlN thin films were studied using FESEM (Jeol JSM-1763) and EDS (X-Max, Oxford Instrument). The electrical properties were investigated using Hall effect measurement.

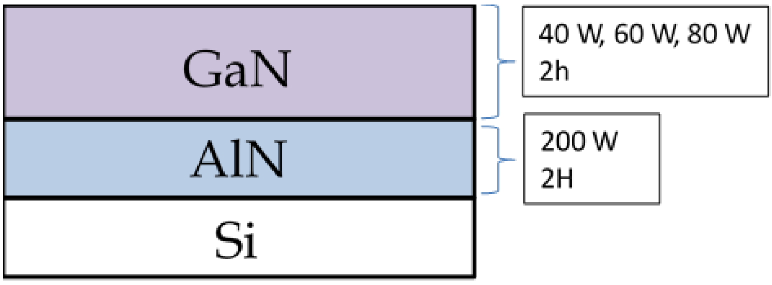


Figure 1. Schematic of GaN/AlN films grown on Si (100) substrate.

3. RESULTS AND DISCUSSION

3.1 Thin Film Thickness and Composition

Power (W)	GaN (nm)	GaN growth rate (nm/min)
40	115.00	0.96
60	158.57	1.32
80	279.79	2.33

Since the condition for AlN layer deposition were fixed at 200 W, 5mTorr and had the same background pressure, the thickness of AlN layer should be consistent, and it is reasonable to assume that the sputtering process rates for all AlN growth for all samples were same. The growth rate of AlN that was 1.68 nm/min, which yielded AlN thickness of 200 nm at 120 min. Then, the GaN thin film was deposited on AlN film. Table 1 shows the thickness of GaN thin films evaluated from the ellipsometry technique using Filmetrics. Figure 2 shows a graph thickness of GaN/AlN thin film on the Si substrate. From the graph, the GaN/AlN thin films thickness increased with the increasing of GaN deposition power. The growth rates of GaN thin film were 0.96, 1.32, 2.33 nm/min for 40, 60 and 80 W, respectively. This happened due to the increase in the kinetic energy of the ions accelerating towards the target.

Table 1 Result of thickness by using Filmeasure

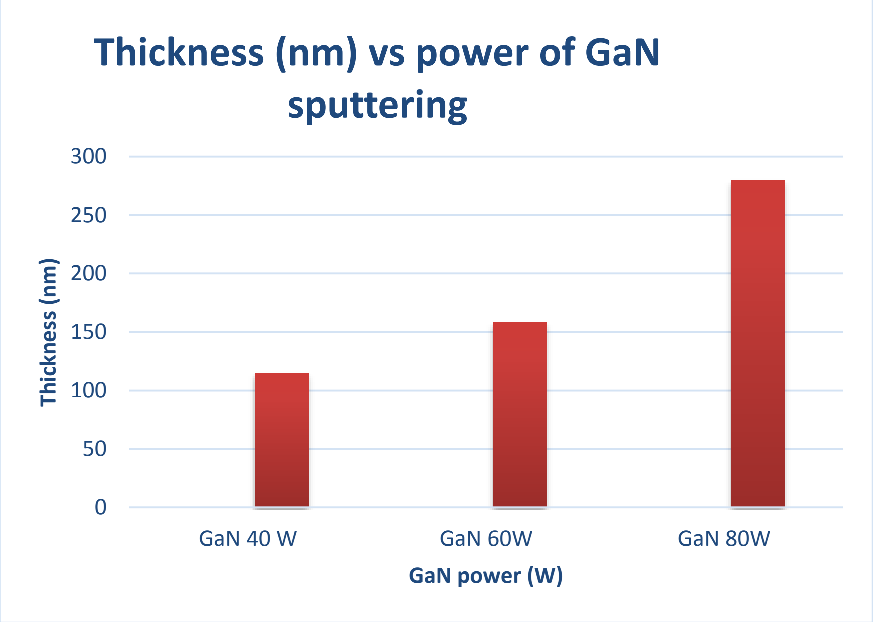


Figure 2. Thickness of GaN thin film at different GaN deposition powers.

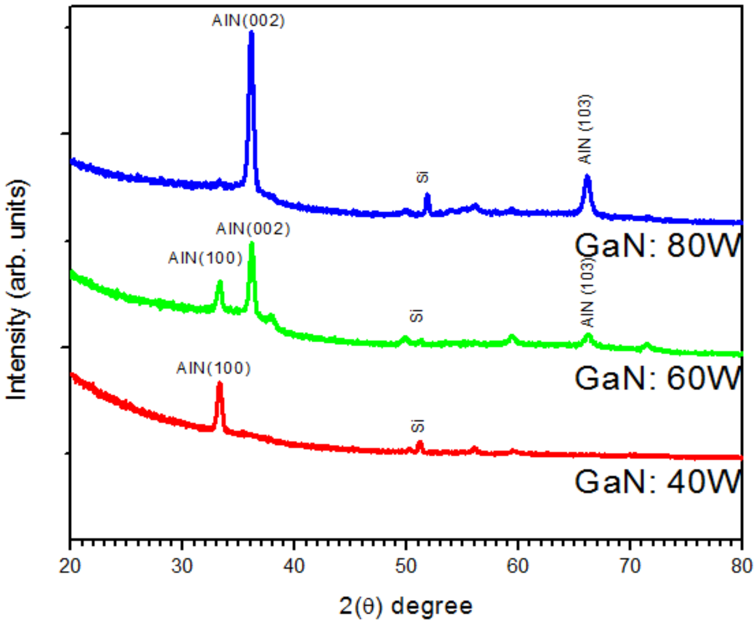


Figure 3. XRD peaks of deposited AlN and GaN on silicon (100) substrate.

Figure 3 shows the XRD patterns obtained from the deposition of GaN/AlN on Si substrates. In order to determine the influence of GaN discharged power on the GaN/AlN crystal formation, the sputtering power during deposition of GaN layer was varied, while the deposition of AlN layer was fixed for all samples. From the XRD analysis, at 40 W of GaN input power, the AlN peak orientation tended towards a-axis (100) . As the power of GaN increase, the AlN peak orientation slowly shifted to c-axis 002. The peak intensity of (100) decreased as the discharged power of GaN increase. At the same time, the peak intensity at (002) was increasing. The reason behind this phenomena is that during the bombardment of the surface of the growing film on the substrate with increasing discharge power, the energised electrons provided thermal energy to the existing AlN thin film. This energy acted as additional energy to promote the growth of AlN towards the c-axis crystal structure. Therefore, it can be concluded that a high discharge power of GaN gave additional energy in the form of thermal energy which helped the AlN crystal structure to be organised towards the preferred orientation. However, no peak of GaN was detected on the GaN/AlN thin films. This indicated that the GaN films depositeded was in an amorphous structure. Based on [1], GaN crystal quality was greatly affected by the growth methods and conditions. Conventionally, a high crystalinity of GaN can be easily obtained using the MOCVD method, as the flow rate of gases and high temperature condition can be controlled easily [20]. Thus, the sputtering method and temperature condition in this study were not suitable and must be improved to produce high-quality crystallinity of GaN.

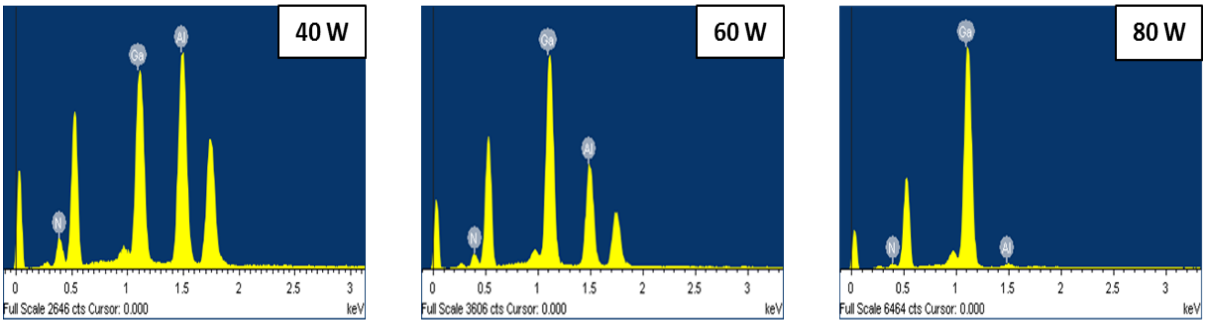


Figure 4. EDX spectrum traces of the GaN films grown on AlN layer using Si substrates.

Table 2. Atomic percentages of GaN/AlN thin films.

Element/ Power	**40 W**	**60 W**	**80 W**
Nitrogen	47.41%	40.95%	34.61%
Aluminium	36.57%	31.55%	2.76%
Gallium	16.02%	27.50%	62.64%

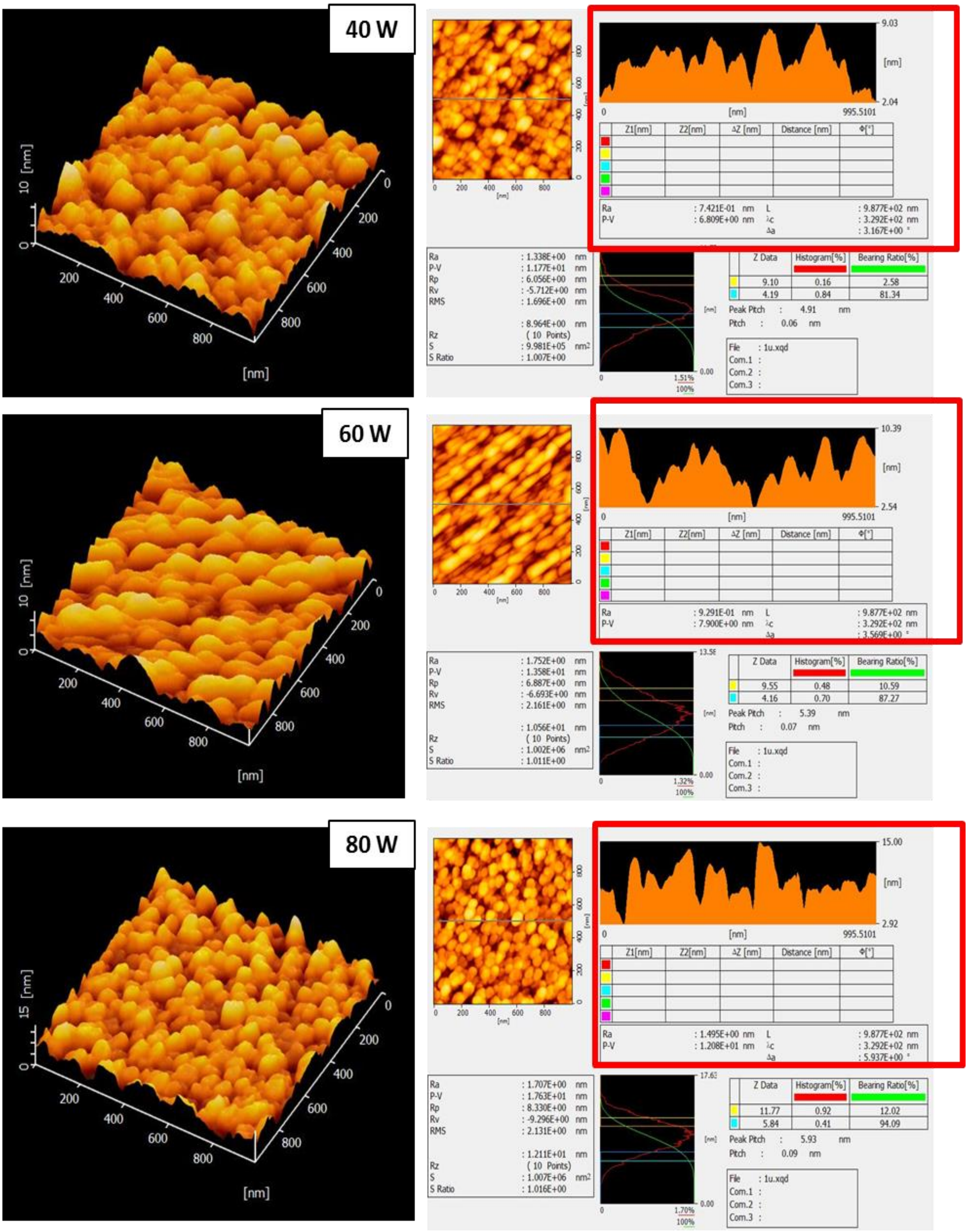
To evaluate the elemental composition of the thin film, a quantitative analysis of the energy dispersive X-ray spectroscopy (EDS) spectra was performed using an accelerating voltages 15 kV. The EDS spectrum in Figure 4 obviously showed the presence of Ga, Al and N elements. These indicated that the Ga compound was actually deposited on the top of AlN layer but do not form a crystalline structure. Table 2 shows the atomic percentages of GaN/AlN thin films on Si substrates. It was found that atomic percentages of Ga elements increased as the power increase. At the same time, the results show that Al atomic percentages are decreased. The reason that caused the atomic percentages of Al and Ga to change is because of the increased thickness of GaN layer on the top of AlN layer. These EDS results proved that the deposition of GaN/AlN thin films on the Si substrates was successful.

3.1 Morphology Properties of GaN Thin Films

The AFM images of GaN/AlN on Si (100) substrates are shown in Figure 5 to study the morphological properties of the thin films. Based on the line profiler results retrieved from the AFM results, the highest peak-to-valley (P-V) obtained was 1.208 x 10^1 nm corresponding to 80 W and follow by 7.900 nm corresponding to 60 W. The lowest (P-V) is 6.809E+00 corresponding to 40W GaN power from the AFM. The highest average absolute slope (Δa) obtained was 5.937° corresponding to 80 W GaN power, follow by 3.569° corresponding to 60 W. The lowest average absolute slope was 3.167° corresponding to 40 W. Normally, for optoelectronic devices application, GaN thin films must have low roughness value, which is not more than 20 nm [21][22]. This is to prevent the GaN materials to be heavily dislocated which will cause a crack and cloudy surface morphology, which can reduce performance quality emission in AlGaN based devices [7][23].

Hyoun Woo Kim and Nam Ho Kim in their study analyzed that the average roughness of GaN thin films ranged from 0.7 to 20 nm [22] which is within this experiment's results. The surface roughness (Ra) of GaN/AlN thin films during 40 W was 0.7421 nm, 60 W was 0.9291 and 80W are 1.495 nm, respectively. Since all the samples were homogeneous and had low roughness, it is concluded that using the GaN with deposition power ranging between 40 W- 60 W gave a homogenous and smooth surface morphology for GaN/AlN thin films.

Figure 6 shows the morphology of different thicknesses of GaN film grown on AlN layer and silicon substrate as analyzed by FESEM using a magnification of 50, 000. It can be seen that the particle size of GaN grains had homogenous grain boundaries and have a granular structure. The granular size of GaN was approximately 20-40 nm. In addition, no film crack is found, which exhibited an excellence deposition of AlN and GaN using a conventional RF magnetron sputtering system. Based on rough observation, the granular particles of GaN is increasing homogeneously as the power of GaN increase. According to [21], [24], these may be attributed to the Van der Waals forces between particles. The FESEM analysis also revealed that the grain boundaries sizes of the thin films increased with various GaN deposition power. Since the larger grain boundary size may cause the rougher surface, the AFM measurements agree with FESEM images.



40 W

	Z1[nm]	Z2[nm]	ΔZ [nm]	Distance [nm]	Φ[°]
🟥					
🟨					
🟦					
🟩					
🟪					

Ra : 7.421E-01 nm
P-V : 6.809E+00 nm
L : 9.877E+02 nm
λc : 3.292E+02 nm
Δa : 3.167E+00 °

Ra : 1.338E+00 nm
P-V : 1.177E+01 nm
Rp : 6.056E+00 nm
Rv : -5.712E+00 nm
RMS : 1.696E+00 nm
Rz : 8.964E+00 nm (10 Points)
S : 9.981E+05 nm²
S Ratio : 1.007E+00

	Z Data	Histogram[%]	Bearing Ratio[%]
🟨	9.10	0.16	2.58
🟦	4.19	0.84	81.34

Peak Pitch : 4.91 nm
Pitch : 0.06 nm

File : 1u.xqd
Com.1 :
Com.2 :
Com.3 :

60 W

	Z1[nm]	Z2[nm]	ΔZ [nm]	Distance [nm]	Φ[°]
🟥					
🟨					
🟦					
🟩					
🟪					

Ra : 9.291E-01 nm
P-V : 7.900E+00 nm
L : 9.877E+02 nm
λc : 3.292E+02 nm
Δa : 3.569E+00 °

Ra : 1.752E+00 nm
P-V : 1.358E+01 nm
Rp : 6.887E+00 nm
Rv : -6.693E+00 nm
RMS : 2.161E+00 nm
Rz : 1.056E+01 nm (10 Points)
S : 1.002E+06 nm²
S Ratio : 1.011E+00

	Z Data	Histogram[%]	Bearing Ratio[%]
🟨	9.55	0.48	10.59
🟦	4.16	0.70	87.27

Peak Pitch : 5.39 nm
Pitch : 0.07 nm

File : 1u.xqd
Com.1 :
Com.2 :
Com.3 :

80 W

	Z1[nm]	Z2[nm]	ΔZ [nm]	Distance [nm]	Φ[°]
🟥					
🟨					
🟦					
🟩					
🟪					

Ra : 1.495E+00 nm
P-V : 1.208E+01 nm
L : 9.877E+02 nm
λc : 3.292E+02 nm
Δa : 5.937E+00 °

Ra : 1.707E+00 nm
P-V : 1.763E+01 nm
Rp : 8.330E+00 nm
Rv : -9.296E+00 nm
RMS : 2.131E+00 nm
Rz : 1.211E+01 nm (10 Points)
S : 1.007E+06 nm²
S Ratio : 1.016E+00

	Z Data	Histogram[%]	Bearing Ratio[%]
🟨	11.77	0.92	12.02
🟦	5.84	0.41	94.09

Peak Pitch : 5.93 nm
Pitch : 0.09 nm

File : 1u.xqd
Com.1 :
Com.2 :
Com.3 :

Figure 5. AFM images of GaN/AlN on Si (100) substrates using same parameter of AlN but different power of GaN.

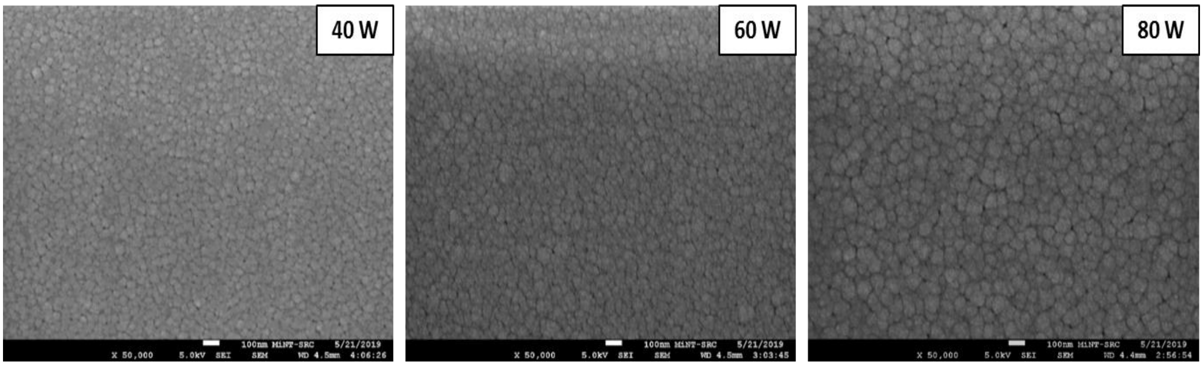


Figure 6. FESEM image of GaN/AlN film grown on silicon substrate.

3.3 Electrical properties of GaN / AlN thin films

Table 3 Hall effect measurements for GaN/AlN thin films grown on silicon substrate at different GaN sputtering power

Power	**40 W**	**60 W**	**80 W**
Carrier type	N	N	N
n, Carrier concentration [1/m^3]	2.330 x10^{24}	1.068 x10^{25}	1.244x10^{24}
ρ, Resistivity [Ω·m]	1.025 x10^{-5}	1.574 x10^{-5}	6.168 x10^{-5}
μH, Hall mobility [m^2/V·s]	2.613 x10^{-1}	3.713 x10^{-2}	8.133 x10^{-2}

The electrical properties of GaN/AlN thin films using different deposition powers of GaN were measured using Hall effect measurement system at room temperature. GaN/AlN thin films on Si substrate are usually implemented in optoelectronic devices such as LED. For such applications, the most important things is to have is low resistivity so that the electrical current easily flow through this material [25]. In addition, for the diode current in LED, there is substantial carrier concentration gradient across p-n junction, hence, the GaN/AlN thin films must have an n-type carrier behavior, low resistivity, high carrier concentration and low Hall mobility [14] [26] [14], [27]. The carrier type, resistivity ρ, carrier concentration n, and Hall mobility μH, are shown in Table 4.10. It can be seen that the deposition of GaN layers exhibited a larger charge carrier concentration and a lower electrical resistivity and this agree with previous report for GaN [14] [28].

All sample shows N- type material behavior which is the correct type for building n-GaN, a part of the materials for the n-juction of LED devices. Based on the results, the lowest resistivity ρ, which is 1.025x10^{-5} Ω·m corresponding to 40W of GaN deposition power, followed by 1.574x10^{-5} Ω·m corresponding to 60W and the highest was 6.168x10^{-5} Ω·m corresponding to 80W. The value from the other literature usually around (~10^{-4} Ω ·m) for GaN resistivity for development of LED [26] [14]. Recent report by M. Veneges (~ x10^{24} m-^{3}) on deposition of GaN by using MBE [14]. The highest carrier concentration n, was 1.068x10^{25} m-^{3} corresponding to GaN power of 60 W, follow by 2.330x10^{24} m-^{3} corresponding to 40 W and the lowest is 1.244x10^{24} m-^{3} corresponding to 80 W. This shows that all the samples exhibited a large carrier concentration which is normally around (~ 10^{21} m^{-3} to ~10^{24} m^{-3}) [26], [30]. Meanwhile, for the Hall mobility, μH, the lowest was 2.613x10^{-1} m^2/V·s corresponding to GaN power of 40W, followed by 3.713x10^{-2} m^2/V·s corresponding to GaN power of 60W and 8.133x10^{-2} m^2/V·s corresponding to GaN power of 80W. Therefore, it was found that using low deposition power of GaN led to low resistance, high carrier concentration and low Hall mobility, which are good for optoelectronic devices.

4. CONCLUSION

In summary, GaN/AlN thin films were successfully prepared using the conventional RF magnetron sputtering plasma deposition technique on a Si substrate. The structural and electrical properties of GaN/AlN thin films were analyzed using ellipsometry, XRD, EDS, AFM, FESEM and Hall effect measurement. The XRD data demonstrated that high-quality crystals of AlN (002) can be achieved. However, the structure of GaN did not form a crystalline structure; in other words, it was in amorphous form. Therefore, an EDS analysis was performed by analyzing the composition and elemental analyses of the GaN/AlN thin films in order to check whether GaN was successfully deposited. Based on the EDS spectrum, there was a presence of the Ga element, and the spectrum's intensity increased as the deposition power of GaN was increased. This revealed that a GaN layer was actually deposited on the AlN thin film, but due to the very low temperature, the GaN thin film did not form a crystalline structure, which was the main cause that no GaN peak was detected on the XRD analysis. AFM surface morphology showed that the GaN/AlN thin films had a smooth surface, with Ra of 0.7421 nm, 0.9291 and 1.495 nm at 40 W, 60 W and 80 W of deposition power, respectively. FESEM analysis also agreed with the AFM results, as smaller grain sizes were obtained when the surface roughness was low. A change in the GaN deposition power slightly changed the electrical properties of the thin films. It was found that using a lower deposition power of GaN, the resistivity of the GaN/AlN thin films decreased, their carrier concentration increased, and their Hall mobility decreased, which are good for devices in optoelectronic applications. The conventional RF-magnetron sputtering technique has been proven to be easy to control and is a convenient and low-cost manufacturing technique to deposit GaN/AlN thin films on Si substrates. Therefore, these thin films have the potential to be used as a key material for the production of high-quality III-nitrate semiconductors in power electronic and optoelectronic devices.

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REFERENCES

[1] I. Akasaki, "Key inventions in the history of nitride-based blue LED and LD," J. Cryst. Growth **300**, 1 (2007) 2–10.

[2] S. Nakamura, "Background story of the invention of efficient blue InGaN light emitting diodes (Nobel Lecture)," Ann. Phys. **527**, 5–6 (2015) 335–349.

[3] K. D. Jandt & R. W. Mills, "A brief history of LED photopolymerization," Dent. Mater. **29**, 6, (2013) 605–617.

[4] R. Horng, B. Wu, C. Tien, S. Ou, & M. Yang, "Performance of GaN-based light-emitting diodes fabricated using GaN epilayers grown on silicon substrates Performance of GaN-based light-emitting diodes fabricated using GaN epilayers grown on silicon substrates," Opt. Express **22**, 1 (2014) 180–187.

[5] W. Y. Pang et al., "Growth of wurtzite and zinc-blende phased GaN on silicon (100) substrate with sputtered AlN buffer layer," J. Cryst. Growth **382** (2013) 1–6.

[6] M. Wosko, B. Paszkiewicz, T. Szymanski, & R. Paskiewicz, "Optimization of AlGaN/GaN/Si(111) buffer growth conditions for nitride based HEMTs on silicon substrates," J. Cryst. Growth **414** (2015) 248–253.

[7] T. Egawa, B. Zhang, & H. Ishikawa, "High performance of InGaN LEDs on (111) silicon substrates grown by MOCVD," IEEE Electron Device Lett. **26**, 3 (2005) 169–171.

[8] T. Watanabe et al., "AlGaN/GaN heterostructure prepared on a Si (110) substrate via pulsed sputtering," Appl. Phys. Lett. **104**, 18 (2014).

[9] T. Miyazaki et al., "Properties of GaN films deposited on Si (111) by radio-frequency-magnetron sputtering," J. Appl. Phys. **8316**, 111 (2008) 18–23.

[10] Z. Chen, J. Zhang, S. Xu, J. Xue, T. Jiang, & Y. Hao, "Influence of stacking faults on the quality of GaN films grown on sapphire substrate using a sputtered AlN nucleation layer," Mater. Res. Bull. **89**, 2 (2017) 193–196.

[11] P. Panda et al., "Reduction of residual stress in AlN thin films synthesized by magnetron sputtering technique," Mater. Chem. Phys. **200** (2017) 78–84.

[12] E. Valcheva, J. Birch, P. O. Å. Persson, S. Tungasmita, and L. Hultman, "Epitaxial growth and orientation of AlN thin films on Si(001) substrates deposited by reactive magnetron sputtering," J. Appl. Phys. **100**, 12 (2006) 0–6.

[13] S. Xiao, R. Suzuki, H. Miyake, S. Harada, & T. Ujihara, "Improvement mechanism of sputtered AlN films by high-temperature annealing," J. Cryst. Growth **502**, May (2018) 41–44.

[14] M. A. Venegas, "Electrical characterization of GaN / ALN heterostructures grown by molecular beam epitaxy on silicon substrates," Rev. Mex. F´ısica **62**, February (2016) 68–72.

[15] S. A. Kukushkin, A. M. Mizerov, A. V. Osipov, A. V. Redkov, & S. N. Timoshnev, "Plasma assisted molecular beam epitaxy of thin GaN films on Si(111) and SiC/Si(111) substrates: Effect of SiC and polarity issues," Thin Solid Films **646**, October 2017 (2018) 158–162.

[16] J. W. Shon, J. Ohta, K. Ueno, A. Kobayashi, & H. Fujioka, "Fabrication of full-color InGaN-based light-emitting diodes on amorphous substrates by pulsed sputtering.," Sci. Rep. **4** (2014) 5325.

[17] P. Drechsel et al., "Impact of buffer growth on crystalline applications and materials science quality," Phisica Status Solidi A **430**, 3 (2012) 427–430.

[18] S. Khan, M. Shahid, A. Mahmood, A. Shah, I. Ahmed, & M. Mehmood, "Texture of the nano-crystalline AlN thin films and the growth conditions in DC magnetron sputtering," Prog. Nat. Sci. Mater. Int., (2015)1–9.

[19] O. Properties & A. Algan, "Structural and Optical Properties of AlN/GaN and AlN/AlGaN/GaN thin films on Silicon Substrate prepared by Plasma Assisted Molecular Beam Epitaxy (MBE)," Results Phys., (2018).

[20] I. Akasaki & H. Amano, "Breakthroughs in improving crystal quality of GaN and invention of the p-n junction blue-light-emitting diode," Japanese J. Appl. Physics, Part 1 Regul. Pap. Short Notes Rev. Pap. **45**, 12 (2006) 9001–9010.

[21] A. Mantarc, "Production of GaN / n – Si thin films using RF magnetron sputtering and determination of some physical properties : argon flow impacts," (2019).

[22] H. W. Kim & N. H. Kim, "Preparation of GaN films on ZnO buffer layers by rf magnetron sputtering," **236** (2004) 192–197.

[23] J. Li, Y. Tang, Z. Li, X. Ding, & Z. Li, "Applied Surface Science Study on the optical performance of thin-film light-emitting diodes using fractal micro-roughness surface model," Appl. Surf. Sci. **410** (2017) 60–69.

[24] R. Kudrawiec, M. Syperek, A. Podhorodecki, & J. Misiewicz, "Photoluminescence from GaN nanopowder : The size effect associated with the surface-to-volume ratio Photoluminescence from GaN nanopowder : The size effect associated with the surface-to-volume ratio," no. May, (2006) 1–5.

[25] F. Akyol, S. Krishnamoorthy, Y. Zhang, J. Johnson, & J. Hwang, "Low-resistance GaN tunnel homojunctions with 150 kA / cm 2 current and repeatable negative differential resistance," Appl. Phys. Lett. **08**, 131103 (2016) 1–4.

[26] J. O. Song, J. S. Ha, & T. Y. Seong, "Ohmic-contact technology for GaN-based light-emitting diodes: Role of p-type contact," IEEE Trans. Electron Devices **57**, 1 (2010) 42–59.

[27] M. E. Lin, Z. Ma, F. Y. Huang, Z. F. Fan, L. H. Allen, & H. Morkoç, "Low resistance ohmic contacts on wide band-gap GaN," Appl. Phys. Lett. **64**, 8 (1994) 1003–1005.

[28] D. L. Rode & D. K. Gaskill, "Electron Hall mobility of nGaN," Appl. Phys. Express **1972**, 1995 (2011) 15–17.

[29] X. Wang & A. Yoshikawa, "Molecular beam epitaxy growth of GaN, AlN and InN," Prog. Cryst. Growth Charact. Mater. **48–49**, 1-3 SPEC. ISS. (2004) 42–103.

[30] H. Amano, "Development of GaN-based blue LEDs and metalorganic vapor phase epitaxy of GaN and related materials," Progress in Crystal Growth and Characterization of Materials **62**, 2. Elsevier Ltd (2016)126–135.