MITIGATION OF OXYGEN PRESENCE IN AlN (100) & (002) GROWTH USING RF MAGNETRON SPUTTERING

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“In the Name of Allah, the Most Beneficent, the Most Merciful”.

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ABSTRACT

Aluminium nitride (AlN) nucleation layer (NL) is a useful nitride semiconductor for the growth of Gallium Nitride (GaN) on silicon. Major issues related to the fabrication of AlN films are on its crystallographic orientations and high processing temperatures. In order to fabricate AlN NL at low temperatures, radio frequency (RF) magnetron sputtering is used in this study. The aims are to deposit homogeneous and highly crystalline AlN NL with (100) and (002) preferential orientations at low processing temperatures. In this study, the homogeneous deposited AlN with highly crystalline along the (100) and (002) preferential orientations were successfully controlled using sputtering base pressure without any external heating. This will mitigate the presence of oxygen that presents during the deposition process. Moreover, the sputtering parameters such as target-to-substrate distance, working pressure, deposition times, and RF power were optimized. Thus, these highly crystalline AlN along the (100) and (002) preferential orientations were used in the Metal-Insulator-Semiconductor (MIS) structure to investigate their leakage currents. For the (002) preferential orientations of AlN, X-ray diffraction (XRD) showed that the full width at half maximum (FWHM) was smaller with low dislocation density and microstrain. Cross-sectional images from the field-emission scanning electron microscope (FESEM) showed that its exhibited grass-like columnar structures, showing it had a well-aligned structure. Meanwhile, its electrical properties showed that the (002)-oriented AlN NL had high electrical resistivity due to low dielectric permittivity, high capacitance, and low dielectric relaxation. The (100) and (002) preferential orientations leakage currents values in the MIS structure were 4.1 x 10^{-7} A and 2.0 x 10^{-8} A, respectively, indicating that (002) preferential orientations AlN NL displayed the lowest leakage current significantly. The effects of oxygen impurity in the layers played a crucial role in the growth of the (002) preferential orientations and acted as defects in the MIS structure, which increased the leakage current.

ABSTRAK

Lapisan penukleusan Aluminium Nitrida (AlN) merupakan semikonduktor nitrida yang digunakan untuk pertumbuhan Galium Nitrida di atas silikon. Salah satu isu utama yang berkait dengan AlN adalah keutamaan orientasi dan suhu proses yang tinggi. Untuk mengendap lapisan penukleusan AlN pada suhu yang rendah, percikan magnetron reaktif (RF) digunakan dalam kajian ini. Kajian ini bertujuan untuk mengendap lapisan penukleusan yang homogen dan tersangat berhablur berkeutamaan kepada orientasi (100) dan (002) pada suhu proses yang rendah. Dalam kajian ini, lapisan penukleusan yang homogen dan tersangat berhablur berkeutamaan kepada orientasi (100) dan (002) telah berjaya dikawal menggunakan tekanan dasar percikan tanpa pemanasan luar. Hal ini akan mengurangkan kehadiran oksigen yang hadir ketika proses pengendapan. Tambahan pula, parameter percikan seperti jarak sasaran ke substrat, tekanan kerja, masa pengendapan and kuasa RF telah dioptimumkan. Oleh itu, AlN yang tersangat berhablur berkeutamaan kepada orientasi (100) dan (002) digunakan di struktur logam-penebat-semikonduktor (MIS) untuk menyiasat nilai arus bocor. Untuk lapisan penukleusan yang berkeutamaan kepada orientasi (002), belauan sinar-X (XRD) menunjukkan nilai lebar lengkap separa maksimum yang kecil dengan perkehelan ketumpatan dan mikroterikan yang rendah. Sementara itu, pemerhatian bayangan keratan rentas daripada mikroskopi electron imbasan pancaran medan (FESEM) mendapati ia mempamerkan garis tegak turus yang mengandungi struktur seakan rumput menunujukkan ia mempunyai penjajaran yang lurus. Sementara itu, sifat elektrik AlN yang berkeutamaan kepada orientasi (002) menunjukkan kerintangan elektrik yang tinggi. Nilai arus bocor pada keutamaan orientasi (100) and (002) di dalam struktur MIS adalah masing masing menjadi 4.1×10^{-7} A and 2.0×10^{-8} A. Lapisan penukleusan AlN yang sangat berhablur pada keutamaan orientasi (002) menunjukkan arus bocor yang terendah. Kesan bendasing oksigen di dalam lapisan penukluesan memainkan peranan penting dalam pertumbuhan keutamaan orientasi (002).

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

π	-	22/7
Al	-	Aluminium
AlN	-	Aluminium nitride
Al_2O_3	-	Aluminium oxide
NH3	-	Ammonia
Ar	-	Argon
Ra	-	Average roughness
Eg	-	Band-gap energy
k	-	Boltzmann’s constant
CVD	-	Chemical vapour deposition
CTE	-	Coefficient thermal expansion
CMOS	-	Complementary metal-oxide semiconductor
$\boldsymbol{\sigma}$	-	Conductivity
D	-	Crystallite size
I	-	Current
A	-	device area.
DC	-	Direct current
A*	-	effective Richardson constant
q	-	electron charge
EDAX	-	Energy dispersive analysis of x-rays
FESEM	-	Field emission scanning electron microscope
F	-	Force
FWHM	-	Full width at half maximum
GaN	-	Gallium nitride
HBP	-	High base pressure
HIPIMS	-	high power impulse magnetron sputtering
HVPE	-	Hydride vapour phase epitaxy

HF - Hydrofluoric acid
H_2 - Hydrogen
IR - Infrared
ICSD - Inorganic crystal structure database
K - Kelvin
LED - Light-emitting diode
$LiNbO_3$ - Lithium niobate
LBP - Low base pressure
MBP - Medium base pressure
M - Mega
MOCVD - Metal organic chemical vapour deposition
CH_3 - Methane
SiH_3CH_3 - methylsilane
MEMS - Micro-electro-mechanical systems
MBE - Molecular beam epitaxy
nm - nanometer
UV - Ultra-violet
N2 - Nitrogen
NO2 - Nitrogen dioxide
$\boldsymbol{\Omega}$ - Ohm
O_2 - Oxygen
Pa - Pascal
PVD - Physical vapour deposition
KOH - Potassium hydroxide
RF - Radio frequency
RF - Radio-frequency
$\boldsymbol{\rho}$ - Resistivity
Rrms - Root mean square roughness
Is - saturation current
Si - Silicon
SiC - Silicon carbide
k - Spring constant
Sccm - Standard cubic centimeters per minute
T - Temperature

TMGa	-	Trimethylgallium
UHV	-	Ultrahigh-vacuum
V	-	Voltage
XRD	-	X-ray diffraction
ZnO	-	Zinc oxide

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background and motivation

Aluminium nitride (AlN) is a semiconductor compound from group III and group V elements of the periodic table [1]. It is commonly known as group III-nitrides. It has two crystal structures, namely wurtzite (hexagonal) and zincblende (cubic) [2][3]. AlN is commonly utilised in hexagonal wurtzite structures because it exhibits direct band-gap energy for all conventional nitrides in the wurtzite phase [4]. The zincblende (cubic) form of AlN is rarely found due to its metastable state [5], [6]. AlN has the largest direct band-gap (~6.2 eV) among materials in the III-nitride semiconductor family [7]–[10]. Due to having the largest band-gap in the nitride semiconductor family, AlN is one of the favourable materials to be used in solid-state ultraviolet light sources in the form of light-emitting diode (LED) and laser diodes [11]–[15]. AlN has been highlighted as a sensing material due to its piezoelectric and piezoresistive properties [16]–[19]. In addition, AlN has good dielectric properties, high thermal conductivity, and good chemical stability [5], [20]–[24]. AlN is also used in power electronics applications, such as high electron mobility transistor (HEMT) [25]–[27]. In addition, AlN deposition and processing are fully compatible with complementary metal-oxide-semiconductor (CMOS) and micro-electro-mechanical system (MEMS) processes [28]–[30][31].

Crystallographic orientation plays an important role in determining the properties of AlN nucleation layers [32]–[34]. The ideal AlN nucleation layers for specific applications should be single crystals. However, properly oriented polycrystalline layers are usually employed since these can offer high performance and are easier to manufacture. Therefore, the control of crystallographic orientation is key to optimise the performance of AlN nucleation layers. Commonly, the preferred orientations of (100) and (002) AlN are the most reported planes in applications [35], [36]. AlN with different crystallographic orientations have been reported in various applications, such as surface acoustic wave (SAW) devices, bulk acoustic wave (BAW) devices, light-emitting diodes, and nucleation layer for the growth of gallium nitride (GaN) [37]–[39]. AlN uses are becoming more widely attractive, as there is great interest in GaN-on-silicon technology [40], [41]. This technology has attracted much attention as an alternative to reduce cost. Si substrates are widely used in the semiconductor industry. The use of Si substrates offers many advantages, including high fabrication flexibility [42]. One of the problems that arise with silicon substrates is the lattice constant and thermal expansion coefficient mismatch between GaN and Si [43], [44]. This mismatch typically leads to deteriorating the GaN layers properties and the formation of cracks. Hence, low-temperature AlN, which act as nucleation centres, has been employed [45]. A comparative study by Chen *et al.* showed that sputtered AlN produced lower threading dislocations in GaN than the AlN grown by the conventional metal-organic chemical vapour deposition (MOCVD) [46]. Yen *et al.* also showed that GaN-based LED with sputtered AlN improved the output power of the LED [47]. A similar trend was also observed by Bessolov *et al.* when employing sputtered AlN as the nucleation layer [48].

With the strong interest in AlN, AlN nucleation layers have been deposited using several techniques, such as pulsed laser deposition (PLD) [49], molecular beam epitaxy (MBE) [50], metal-organic chemical vapour deposition (MOCVD) [51], and also sputtering plasma [52]. AlN nucleation layer also can be deposited on various substrates, such as sapphire, silicon, and silicon carbide substrates [53], [54]. Conventionally, MOCVD and MBE are the most frequently utilised techniques for III-nitrides growth as they can readily produce multilayer structures [55]–[57]. However, these techniques require a high processing temperature. A high deposition temperature has the disadvantage of a large amount of thermal strain in the layers [58]. Therefore, the deposition of AlN nucleation layer at low processing temperatures has become increasingly important and valuable. In addition, a lower deposition temperature is compatible with the back-end-of-line (BEOL) processing. Recently, the use of sputtering on the growth of III-nitrides layers has been explored by many researchers because of its relatively lower deposition temperature and versatility in terms of

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APPENDIX A

LIST OF PUBLICATIONS

As first author:

1. **Bakri, A. S.,** Nayan, N., Ahmad, M. K., Fhong, S. C., Sahdan, M. Z., Abu Bakar, A. S., Abdul Majid, W. H., Tahan, M., & Raship, N. A.” A review on the different techniques of GaN heteroepitaxial growth: current scenario and future outlook,” International Journal of Nanoelectronics and Materials, vol. 13, no. 1, pp. 199- 220, 2020. [SCOPUS indexed]
2. **Bakri, A. S.,** Nayan, N., Ahmad, M. K., Fhong, S. C., Sahdan, M. Z., Abu Bakar, A. S., Abdul Majid, W. H., Tahan, M., & Raship, N. A. “Fabrication of w-AlN Thin Films using Tilted Sputter Target and Unrotated Substrate Holder. International Journal of Integrated Engineering,″ vol. 12, no. 4, pp. 50- 56, 2020. [SCOPUS indexed]
3. **Bakri, A.S.,** Nayan, N., Soon, C.F., Ahmad, M.K., Abu Bakar, A.S., Abd Majid, W.H. and Raship, N.A. (2021), "Structural and mechanical properties of a-axis AlN thin films growth using reactive RF magnetron sputtering plasma", Microelectronics International, Vol. 38 No. 3, pp. 99-104. https://doi.org/10.1108/MI-02-2021-0015. [SCOPUS&WoS indexed, IF 0.758]
4. **Bakri, A.S.,** Nafarizal, N., Abu Bakar, A.S. *et al.* Electrical and structural comparison of (100) and (002) oriented AlN thin films deposited by RF magnetron sputtering. *J Mater Sci: Mater Electron* **33,** 12271–12280 (2022). https://doi.org/10.1007/s10854-022-08186-w. [SCOPUS&WoS indexed, IF 2.478]

As co-author:

1. Tahan, M., Nafarizal, N., Sahdan, M. Z., **Bakri, A. S.,** Raship, N. A., Ahmad, M. K., Soon, C. F., & Ahmad, M. Y. "Growth of Aluminium Nitride Thin Film using Pulse-Modulated Rf Magnetron Sputtering Plasma," International Journal of Integrated Engineering, vol. 12, no. 2, pp. 132- 138, 2020.
2. Tahan, M., Nafarizal, N., Razak, S. N. A., **Bakri, A. S.,** Azman, Z., N., Sahdan, M. Z., Raship, N. A., Abu Bakar, A. S., & Ahmad, M. Y. "Effect of Discharge Power on the Properties of GaN Thin Films on AlN-(002) Prepared by Magnetron Sputtering Deposition. International Journal of Nanoelectronics and Materials, vol. 13, no. 3, pp. 483-492, 2020.
3. Isiyaku, A. K., Ali, A. H., Abdu, S. G., Tahan, M., Raship, N. A., **Bakri, A. S.,** & Nayan, N. "Characterization and Optimization of Transparent and Conductive ITO Films Deposited on n and p-types Silicon Substrates" Physics Memoir - Journal of Theoretical & Applied Physics, vol. 2, no. 1. Pp. 15-24, 2020.
4. Raship, N. A., Mohd Tawil, S. N., Nayan, N., Ismail, K., **Bakri, A. S.,** & Azman, Z. "Influence of Substrate Rotational Speed on the Structural and Optical Properties of Sputtered Gd-Doped ZnO Thin Films," Materials Science Forum, 1023, pp. 3-8, 2021.
5. Aliyu Kabiru Isiyaku, Ahmad Hadi Ali, Sadiq G. Abdu, Muliana Tahan, Nur Amaliyana Raship, **Anis Suhaili Bakri**, Nafarizal Nayan. "Preparation of Sn doped In2O3 multilayer films on n-type Si with optoelectronics properties improved by using thin Al–Cu metals interlayer films," Materials Science in Semiconductor Processing, 131, 2021.
6. Raship, N. A., Tawil, S. N. M., Nayan, N., Ismail, K., Tahan, M., & **Bakri, A. S.** **"**Influence of Various Target to Substrate Distances on the Structural and Optical Properties of Sputtered Gd-Doped ZnO Thin Films," Solid State Phenomena, pp. 471–476, 2021.

APPENDIX G

VITA

The author was born on February 9, 1992, in Batu Pahat, Johor. She received her BSc in Physics with Electronics from the Universiti Malaysia Sabah in 2014 and Master of Electrical Engineering in 2017 from Universiti Tun Hussein Onn Malaysia. Currently, she is a PhD candidate at the Microelectronic and Nanotechnology-Shamsuddin Research Centre at Universiti Tun Hussein Onn Malaysia. Her research project related to the aluminium nitride thin films deposited by conventional magnetron sputtering plasma technique. She has been an active member of IEEE and holds a vice-chair position for IEEE UTHM Student Branch in 2021. She has been involved in IEEE activities since 2018. She has experience organizing CSR projects for school children around Batu Pahat, Johor, which encouraged STEM awareness among the school students. In addition, she was the program director for the first E-waste recycling program in UTHM. This year, she has been successfully organized an E-waste awareness campaign collaborating with the Hazardous Substance Division, Department of Environment Malaysia. She is deeply passionate about research and innovative work. Currently, she has 32 publications (as main and co-author) and H-index of 6 with 153 citations under her belt. She also has won for Bronze Medal for a postgraduate symposium in the university competition and also awarded the best presenter award during one of the conferences that she joined.