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Investigation of AlInN HEMT structures with different AlGaN buffer layers grown on sapphire substrates by MOCVD

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We investigate the structural and electrical properties of $Al_xIn_{1-x}N$/AlN/GaN heterostructures with AlGaN buffers grown by MOCVD, which can be used as an alternative to AlInN HEMT structures with GaN buffer. The effects of the GaN channel thickness and the addition of a content graded AlGaN layer to the structural and electrical characteristics were studied through variable temperature Hall effect measurements, high resolution XRD, and AFM measurements. Enhancement in electron mobility was observed in two of the suggested $Al_xIn_{1-x}N$/AlN/GaN/$Al_{0.04}Ga_{0.96}N$ heterostructures when compared to the standard $Al_xIn_{1-x}N$/AlN/GaN heterostructure. This improvement was attributed to better electron confinement in the channel due to electric field arising from piezoelectric polarization charge at the $Al_{0.04}Ga_{0.96}N$/GaN heterointerface and by the conduction band discontinuity formed at the same interface. If the growth conditions and design parameters of the $Al_xIn_{1-x}N$ HEMT structures with AlGaN buffers can be modified further, the electron spillover from the GaN channel can be significantly limited and even higher electron mobilities, which result in lower two-dimensional sheet resistances, would be possible.

1. Introduction

Al(In)GaN/(In)GaN-based high-electron mobility transistors (HEMTs) have been studied extensively as ideal candidates for high frequency and high power applications [1,2]. In order to improve the performance of devices, various barrier and channel alternatives have been used in nitride based HEMTs [3–9]. Several achievements have been made in AlGaN/GaN HEMT performance by optimizing the material quality, device fabrication, and the epitaxial layer designs [10]. An AlN interlayer has been inserted between the AlGaN barrier and GaN layer, which makes polarization effects stronger and this causes a higher sheet carrier density. In addition, due to less alloy disorder scattering, a higher mobility has been achieved [3–6]. Moreover, achieving higher 2DEG densities in either undoped or modulation-doped AlGaN HEMT structures requires the growth of ternary alloys with higher Al composition in which the polarization-induced electric field is much larger. However, growing AlGaN layers with a high (>%30) Al mole fraction contains problems due to the large tensile strain that these layers experience. This tensile strain degrades the quality of the layer above a critical thickness and then causes a significant reduction in electron mobility [6,11]. To overcome this problem, Kuzmík proposed using a nearly lattice-matched AlInN/GaN structure to improve the performance of HEMTs with high sheet carrier densities provided by spontaneous polarization only [12,13]. Following the original proposal of Kuzmik, AlInN barriers have become increasingly attractive due to their much higher spontaneous polarization, which leads to higher 2DEG densities even with zero piezoelectric polarization and allows thinner barrier thicknesses compared to AlGaN [14,15]. In addition, as AlInN barriers can be grown lattice-matched to GaN, they have the potential to reduce the density of strain-related defects.

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Table 1
Summary of the main structural parameters of the samples and characterization results, such as AFM rms, Hall mobility, sheet carrier density, and sheet resistance at room temperature.

Sample	Buffer	GaN channel thickness (nm)	rms roughness (nm)	Mobility @300 K (cm^2/V.s)	2DEG density @300 K (x10^{13} cm^{-2})	Sheet resistance @300 K (Ω/sq)
A (control)	GaN	–	0.54	841	2.54	292
B	$Al_{0.04}Ga_{0.96}N$	20	0.58	918	2.02	337
C	$Al_{0.04}Ga_{0.96}N$	40	0.51	1013	1.97	313
D	$Al_{0.04}Ga_{0.96}N$ + Graded $Al_xGa_{1-x}N$	20	0.70	723	1.91	453

Table 2
The material parameters used for the energy band profile and sheet carrier density calculations. [31]

Parameter	AlN	GaN	InN
a (Å)	3.112	3.189	3.545
e_{31} (C/m^2)	−0.50	−0.35	−0.57
e_{33} (C/m^2)	1.79	1.27	0.97
C_{13} (GPa)	108	106	92
C_{33} (GPa)	373	398	224
P_{SP} (C/m^2)	−0.081	−0.029	−0.032

Recent advances in the growth of AlInN have resulted in respectable HFET performance in devices employing this lattice matched barrier [16–23]. Gonschorek et al. improved the mobility to 1170 cm^2/V for an undoped nearly lattice-matched AlInN/GaN heterostructure, but the low temperature mobility was still low when compared to the AlGaN/GaN HEMT structures [24]. They inserted an AlN interlayer between the AlInN and GaN layers to suppress alloy-disorder scattering, which has also been demonstrated in AlGaN/GaN heterostructures. Hiroki et al. employed AlInN/AlGaN double barriers in order to make the surface flatter and they obtained a mobility of 1960 cm^2/V but with the cost of a significant reduction in sheet carrier density (9×10^{12} cm^{-2}) [22]. In addition to these efforts, Wu et al. have grown nearly lattice-matched AlInN HEMT structures on Fe-doped semi-insulating GaN substrates in order to obtain high power levels owing to the good thermal conductivity of GaN substrates [18]. Despite these works reported in the literature, alternative buffers for AlInN HEMT structures have not been studied systematically, which is very important for obtaining high-electron mobilities and low leakage currents.

In this study, we aim to investigate the potential use of AlGaN buffers in AlInN HEMT structures, which were also used in AlGaN/GaN heterostructures in order to improve electron confinement in the channel [25–29]. Electrical and structural characteristics of AlInN HEMT structures with different AlGaN buffers and with

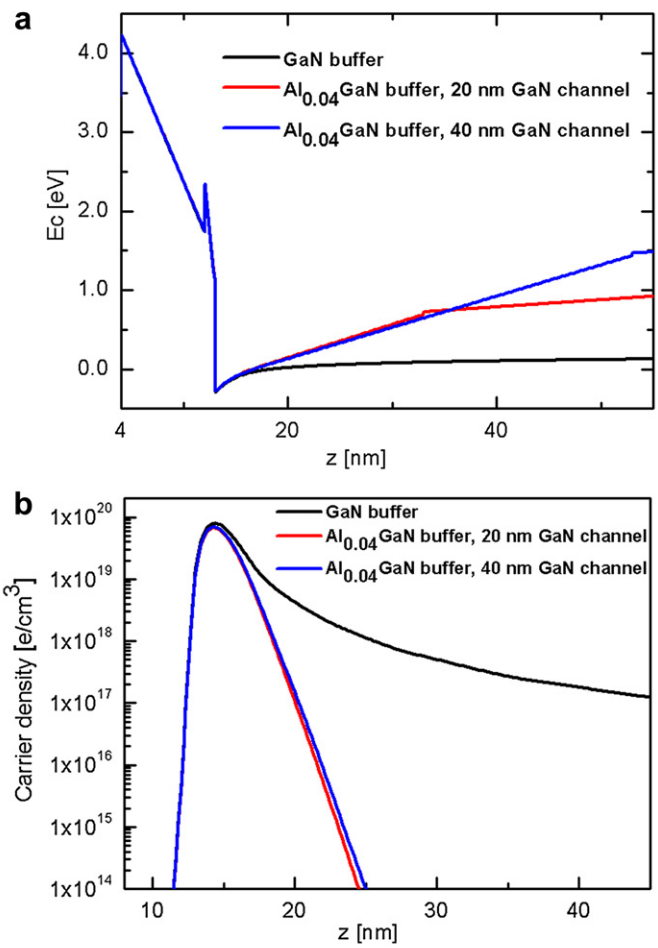

Fig. 2. (a) Calculated conduction band profiles and (b) The carrier distributions along the z axis for the AlInN heterostructure with standard GaN buffer and the structure with AlGaN buffers.

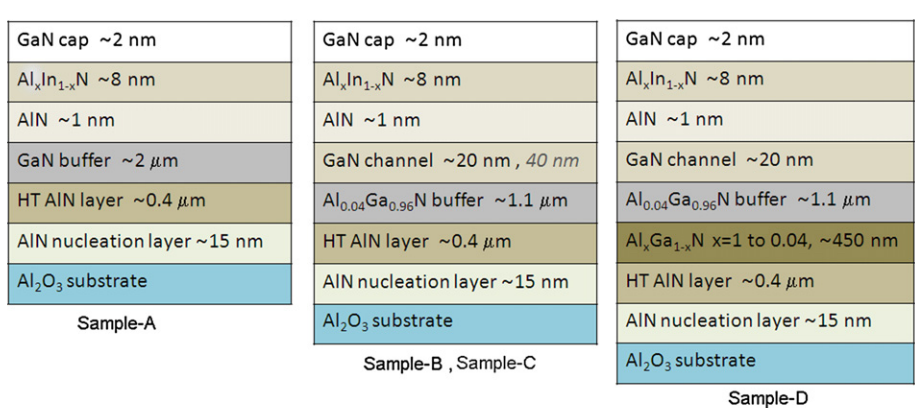

Fig. 1. Schematic cross-sectional view of the investigated AlInN HEMT structures.