Influence of AlN spacer on the properties
of AlGaN/AlN/GaN heterostructures

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AlGaN/GaN heterostructures attract attention of many research groups over the last decade because of their superior properties (high mobility and saturation velocity of 2DEG) and strong capability in high frequency/power electronics and sensors applications. One of the factors which reduces the mobility of two-dimensional electron gas (2DEG) is the alloy and interface roughness scattering mechanism occurring at the heterointerface. Mathematical calculations of a wave-function of 2DEG in the channel show that theses two phenomena play an important role, due to the fact that some electrons in 2DEG can migrate into AlGaN barrier and be strongly dissipated. One of the proposed solutions against alloy scattering in the buffer layer is the use of thin AlN spacer at the heterointerface between AlGaN and GaN layers. AlN layer enhances the conduction band offset due to a polarization-induced dipole in the AlN layer, and therefore increases carrier confinement. Several $Al_{0.18}GaN_{0.82}$/AlN/GaN heterostructures with different AlN spacer layer thickness were grown by MOVPE method for studies of the Hall mobility and sheet carrier concentration of 2DEG. Hall measurements performed using Van der Pauw shown mobility maximum at nominally 1.3 nm AlN spacer thickness and almost linear dependence of sheet carrier concentration with AlN spacer thickness in the range from 0.7 to 2 nm.

Keywords: AlGaN/GaN, heterostructure, AlN spacer, MOVPE.

1. Introduction

III-nitride based material has shown promise in high power and high frequency applications due to its superior properties compared to other material systems. Johnson's figure of merit (JM) [1], which is the product of dielectric breakdown field and carrier saturated drift velocity, describes the power-frequency limit of specific material system. JM for GaN is almost 30 times greater than for Si and 10 times greater than for GaAs and comparable to SiC, but difficulty in the production of heterojunctions in SiC, makes nitrides the most promising material in high power and high frequency applications.

The performance of heterojunction field effect transistors is strictly related to the carrier transport properties of the transistor channel. III-nitride based high electron

mobility transistors made in AlGaN/GaN heterostructures have shown their potential on the field of high power and high frequency applications [2–4] because of the high mobility ($\sim$1500 cm^{2}V^{-1}s^{-1}) and high carrier sheet concentration ($\sim$1$\times$10^{12} cm^2) of the two-dimensional electron gas (2DEG) formed at the heterointerface. The product of these two values is the sheet conductivity of 2DEG, therefore a way to reduce the channel resistance is the increase in carrier density and mobility. The main source of the electrons in 2DEG are the donor-type surface states and ionized donors in the barrier layer [5, 6]. Because III-nitrides are strongly piezoelectric, polarization--induced charges additionally enhance the confinement of the electrons in a transistor channel. From this point of view, the 2DEG concentration can be controlled by the doping and Al mole fraction of the AlGaN barrier layer. Electron mobility of 2DEG is limited by several scattering mechanisms occurring in AlGaN/GaN hetero-structures [7, 8]. The most significant scattering mechanism at room temperature is the optical phonon scattering, whereas at low temperatures alloy disorder and interface roughness scattering are the dominating factors reducing mobility. Alloy disorder scattering becomes significant at room temperatures for relatively high carrier concentration [9].

Figure 1 shows calculated by BandEng Poisson–Schrödinger solver [10] band diagrams and wave-function of 2DEG in Al$_{0.18}$Ga$_{0.82}$N/GaN heterostructure without and with 1 nm thick AlN spacer.

The penetration of the wave-function into barrier depends on the height of a potential barrier. AlN spacer significantly increases the barrier height and therefore suppresses this effect. Because AlGaN is a ternary material, the electrons are strongly dissipated due to alloy disorder scattering. This can lead to a decrease in the 2DEG's mobility. The integrated probability of electron presence in the barrier reaches 3.9% and 0.33% for Al$_{0.18}$Ga$_{0.82}$N/GaN and Al$_{0.18}$Ga$_{0.82}$N/AlN/GaN, respectively. It means that AlN bar-
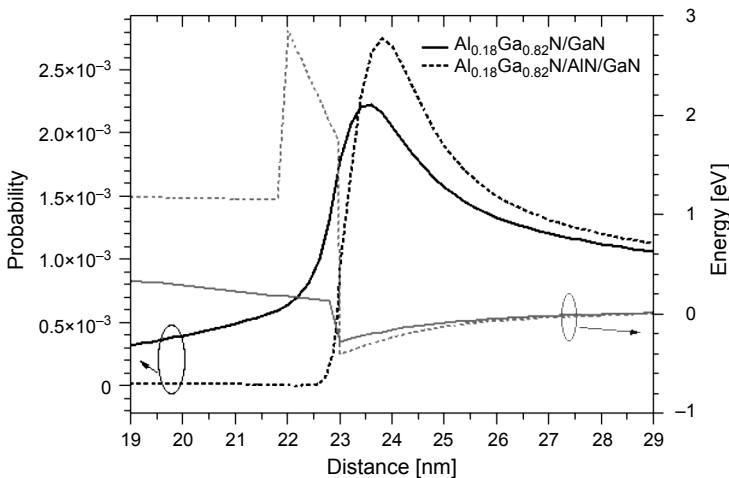
Fig. 1. Wave-function and conduction band traces on the Al$_{0.18}$Ga$_{0.82}$N/GaN and Al$_{0.18}$Ga$_{0.82}$N/AlN/GaN interfaces calculated in BandEng.

rier strongly decreased the electron penetration into AlGaN barrier. Moreover, electrons which can be found in AlN spacer experience lower dissipation because AlN is a binary material with no alloy disorder effects. The influence of the AlN spacer thickness on the carrier transport properties (2DEG mobility and concentration) has been the subject of experimental research.

2. Experiment

AlGaN/AlN/GaN heterostructures were grown on a *c*-plane sapphire substrate with 0.2° miscut in AIXTRON CCS reactor. Trimethylgallium and trimethylalluminium were used as alkyl sources, ammonia as a source of nitrogen and hydrogen as a carrier gas. Prior to the deposition, the substrate temperature was calibrated in the range of 500 to 1080 °C using an optical probe pyrometer. The maximal deviation of the susceptor temperature measured between each of the three zones was 2.5 °C at 1040 °C. *In-situ* reflectometry at 635 nm was used to investigate the initial growth stages of GaN nucleation layer, migration of the NL and coalescence of NL during high temperature deposition and to determine the growth rate. Conditions of the nitridation of the surface and low temperature GaN layer deposition and annealing were chosen experimentally to obtain the sheet resistance of the buffer higher than 10×10^8 Ω/sq [11]. The previous work has shown that parameters of nucleation layer deposition play an important role in resistivity control of GaN buffer what is essential for high performance HEMT's [12–14]. Prior to nitridation and NL deposition, substrates were annealed for 10 min at 1100 °C in H_2 atmosphere, then nitrided in the mixture of H_2 and NH_3 at 530 °C for 5 minutes. Pressure during all stages of the growth was kept at 100 mbar. Low temperature nucleation layers were grown by 240 sec with the TMGa and NH_3 flow of 39 µmol/min and 54 mmol/min, respectively (V/III ~ 1400). NL was subsequently annealed during the temperature ramp to 1040 °C and high temperature GaN was grown by 50 min with the TMGa and NH_3 flow of 106 µmol and 1.3 mol/min

$Al_xGa_{1-x}N$, 23 nm, x = 0.185
Spacer AlN, d = 0.7–2 nm
Channel HT-GaN, 250 nm
- - - - - - - - - - - - - - - - - - -
Buffer HT-GaN, 2550 nm
LT-GaN, 40 nm, NL
Sapphire

Fig. 2. The schematic cross-section of AlGaN/AlN/GaN heterostructure.
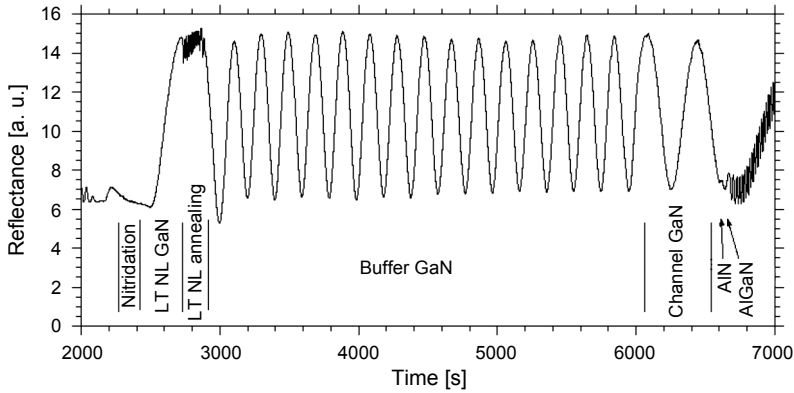
Fig. 3. Reflectance trace of AlGaN/AlN/GaN heterostructure growth.

(V/III ~ 1300), which leads to the growth rate of 42.5 nm/min. Next, temperature was ramped to 1060 °C and 250 nm of high quality GaN channel layer was deposited which was followed by AlN spacer and 23 nm undoped AlGaN barrier layer. Thickness of the AlN spacer was controlled by the shut-off time of the TMGa run valve after GaN and before AlGaN layer deposition. Four samples with different AlN deposition times: 8, 12, 16 and 24 sec were investigated. These times were chosen based on earlier calibration experiments and they correspond to the nominal thicknesses of 0.7, 1, 1.3 and 2 nm. The composition of AlGaN barrier layer was determined by the PL method and for all samples amounted to 18.5%. The schematic cross-section of AlGaN/AlN/ GaN heterostructures and *in situ* reflectance trace of their growth are presented in Figs. 2 and 3. For better understanding, some characteristic points and growth stages were marked on the trace.

3. Results

Hall measurements using Van der Pauw geometry structures with indium dots were performed at 300 K. Measured Hall electron mobility and calculated sheet carrier concentrations are presented in Fig. 4. The highest Hall mobility (1770 cm^2Vs) was observed for the sample with the 1.6 nm thick AlN spacer. For this sample, the sheet carrier concentration reached 6.5×10^{12} cm^{-2}. The sheet carrier concentration of 2DEG is almost linearly dependent on the thickness of AlN spacer in the range from 0.7 to 2 nm.

The increase in the sheet carrier concentration of 2DEG with the increase in AlN spacer thickness is the result of enhancement of polarization-induced sheet charge at the AlN/GaN interface. This effect gives the same result as increasing of Al-mole fraction in AlGaN barrier. However, after exceeding a critical thickness of about 1.3 nm, the AlN spacer may cause an increase in dipole scattering due to strong polarization effect [15] and therefore deteriorate 2DEG's mobility. Below this critical
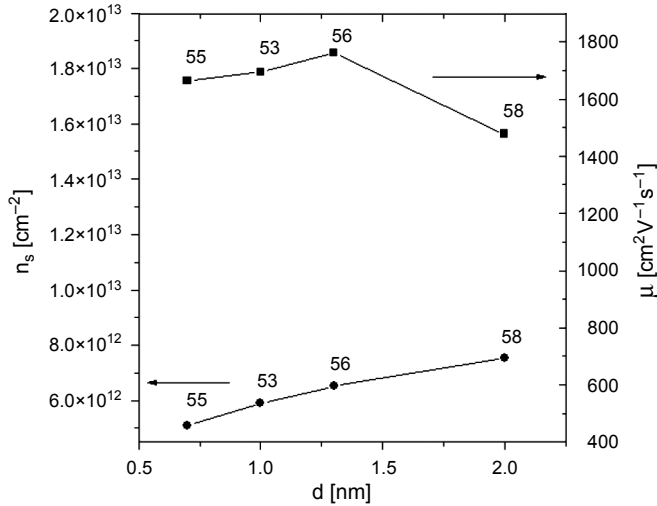
Fig. 4. Carrier sheet resistance and mobility of 2DEG as a function of AlN spacer thickness in $Al_{0.18}Ga_{0.82}N$/AlN/GaN heterostructure.

thickness, the AlN spacer enhances the conduction band offset what effectively reduces the penetration of the wave-function into AlGaN barrier and thus reduces the effect of alloy disorder scattering. This is consistent with theoretical calculations.

4. Conclusions

Based on theoretical calculations, the influence of AlN spacer layer thickness on the properties of $Al_{0.18}Ga_{0.82}N$/AlN/GaN heterostructure has been experimentally investigated. Hall effect measurements have shown the optimum thickness of the spacer (1.3 nm) at which the maximum value of mobility of 1770 cm^2Vs was obtained. The linear dependence of AlN layer thickness on carrier sheet concentration was observed. The increase in 2DEG Hall mobility in the samples with AlN spacer can be associated with alloy disorder scattering suppression due to a decrease in the penetration of electron wave-function into AlGaN barrier. The mobility drop for AlN spacer thicknesses greater than 1.3 nm is probably caused by an increase in the polarization induced dipole scattering mechanism. Because alloy disorder scattering suppression by the AlN spacer layer is strongly dependent on the sharpness of AlN/GaN interfaces, future work will focus on the optimization of MOVPE process to achieve mono-layer resolution and on the investigation how different process flows influenced the AlN/GaN interface and properties of 2DEG.

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