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Research Article

Growth and Device Performance of AlGaN/GaN Heterostructure with AlSiC Precoverage on Silicon Substrate

Jae-Hoon Lee[1] and Jung-Hee Lee[2]

[1] *Discrete Development Team, System LSI, Samsung Electronics Co., Ltd., Giheung 446-711, Republic of Korea*
[2] *The School of Electronic Engineering & Computer Science, Kyungpook National University, Daegu 702-701, Republic of Korea*

Correspondence should be addressed to Jae-Hoon Lee; jaehoon03.lee@samsung.com

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A crack-free AlGaN/GaN heterostructure was grown on 4-inch Si (111) substrate with initial dot-like AlSiC precoverage layer. It is believed that introducing the AlSiC layer between AlN wetting layer and Si substrate is more effective in obtaining a compressively stressed film growth than conventional Al precoverage on Si surface. The metal semiconductor field effect transistor (MESFET), fabricated on the AlGaN/GaN heterostructure grown with the AlSiC layer, exhibited normally on characteristics, such as threshold voltage of −2.3 V, maximum drain current of 370 mA/mm, and transconductance of 124 mS/mm.

1. Introduction

Group III-nitride semiconductors and their ternary solid solutions are very promising materials for both short wavelength optoelectronics and power electronic devices [1–4]. The AlGaN/GaN heterostructure field effect transistors (HFETs) have a great potential for future high-frequency and high-power applications because of the intrinsic advantages of materials such as wide band gap, high breakdown voltage, and high electron peak velocity [5, 6]. Si substrate is considered as a promising candidate, which may replace expensive and small-sized wafers such as sapphire and SiC, even though the GaN layer grown on Si substrate has a large strain and dislocation due to a large lattice mismatch and thermal expansion coefficient difference between the grown GaN layer and the Si substrate [7, 8]. The mismatch between thermal expansion coefficients is about 56%, which induces a large tensile stress and may cause a severe crack generation in the grown GaN films during the cooling process after growth.

A GaN film grown directly on Si using conventional two-step method usually exhibits poor surface morphology and low crystal quality. In general, the GaN film grown on Si is very sensitive to growth conditions such as MOCVD chamber condition, substrate, III/V ratio, temperature, pressure, source, and layer materials. Therefore, various types of intermediate layer between the GaN epilayer and the Si substrate, such as 3C-SiC, AlN, GaAs, AlAs, Si_3N_4, and r-Al_2O_3, have been studied to improve the crystalline quality of the GaN layer grown on Si substrate [9–12]. Steckl et al. [12] reported that (111) Si-on-insulator (SOI) structures can be converted to single crystalline SiC by carbonization of the thin (<100 nm) Si layer using rapid thermal chemical vapor deposition with mixtures of propane and H_2 at atmospheric pressure. The structure of GaN films grown on (111) SiC SOI structure is comparable to GaN grown on sapphire substrates. This is because the single crystalline SiC interlayer decreases lattice mismatch between the grown GaN layer and the substrate. However, this method requires additional *ex situ* processes which cannot be always easily controlled. Since AlN has good wetting properties on Si substrate compared with other intermediate layers, the recent experimental results have concluded that an AlN buffer layer can alleviate the difficulties in growing the GaN layer on Si substrate. In addition, the Al precoverage on the surface of Si substrate is performed prior to the growth of the AlN layer to prevent

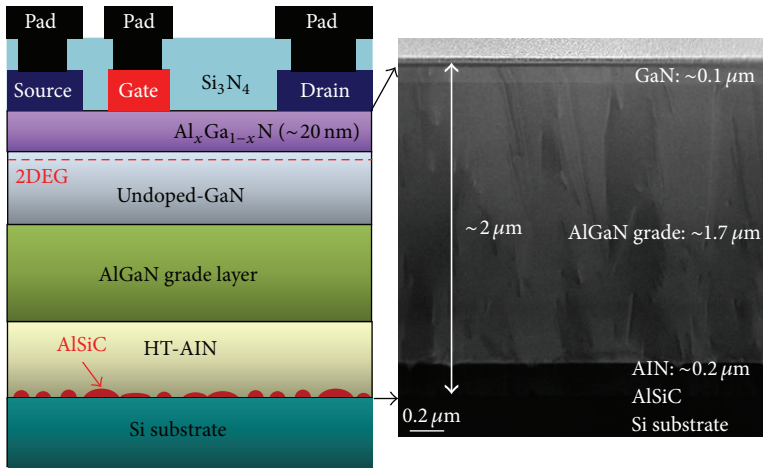

Figure 1: A schematic cross-sectional view and TEM image of the fabricated MESFET layer structure.

the formation of the amorphous SiN_x layer and hence to obtain high crystal quality [13, 14], because the formation of amorphous SiN_x in the initial stage of the growth passivates the surface and suppresses the GaN growth.

In this work, for the purpose of reducing the crack density in the AlGaN/GaN heterostructure grown on Si substrate, we have covered dot-like AlSiC layer on the surface of the Si substrate prior to the growth of the AlN wetting layer. The device performances of the normally on AlGaN/GaN HFETs fabricated on the Si substrate grown with AlSiC precoverage were also demonstrated.

2. Experiments

The AlGaN/GaN heterostructure investigated in this work was grown on 4-inch (111) p-type Si substrates by metal organic chemical vapor deposition (MOCVD). Trimethylgallium (TMGa), trimethylaluminum (TMAl), carbon tetrabromide (CBr_4), ditertiarybutylsilane (DTBSi), and ammonia (NH_3) were used for the precursors of Ga, Al, C, Si, and N, respectively [15]. Prior to the growth of AlN wetting layer, the Si substrate was baked in an H_2 ambient at 1100°C for 10 min to remove the native oxide and then presurface coverage on the Si substrate with AlSiC was performed for 60 seconds in order to prevent formation of amorphous SiN_x layer. For comparison, the heterostructure with conventional Al presurface coverage was also grown. The layer structure with total thickness of about 2 μm consists of 200 nm thick high temperature- (HT-) AlN layer, 1.7 μm thick AlGaN graded layer, 100 nm thick GaN layer, and 20 nm thick AlGaN barrier in growth sequence [16]. The Al content in the AlGaN barrier is 20%, determined by high-resolution X-ray diffraction (XRD). The mobility and the density of the two-dimensional electron gas (2DEG) formed at the AlGaN/GaN heterointerface were 1100 $cm^2/V{\cdot}s$ and $8 \times 10^{12}/cm^2$, respectively. For the device fabrication, the active region of the device was defined by inductively coupled plasma (ICP) reactive ion etching using a BCl_3/Cl_2 gas mixture. After opening contact holes, Ti/Al/Ni/Au metal layer for Ohmic contact was deposited and followed by rapid thermal annealing at 850°C for 30 s in N_2 ambient. The specific contact resistance of $2 \times 10^{-5}\ \Omega{\cdot}cm^{-2}$ was obtained for the annealed sample using transmission line measurements (TLM). After depositing Ni/Au for the gate metal, Si_3N_4 interdielectric layer with thickness of 800 nm was deposited to cover the entire surface of the device. Ti/Al pad metals were finally deposited to connect the gate and the source/drain region. The current-voltage (I-V) characteristics were measured by using Agilent 4155 parameter analyzer and STI curve tracer 5000E. A schematic cross-section and the transmission electron microscope (TEM) image of the fabricated metal semiconductor field effect transistor (MESFET) are shown in Figure 1.

3. Results and Discussion

The existence of AlSiC precoverage layer on Si surface was confirmed by the secondary ion mass spectroscope (SIMS) analysis as shown in Figure 2(a). For the purpose of finding the atomic composition of the AlSiC layer, a reference AlSiC layer with thickness of 20 nm was grown on Si substrate under the same growth condition as the AlSiC precoverage layer in real epitaxial structure. X-Ray photoelectron spectroscopy (XPS) analysis for this AlSiC layer reveals that Al, Si, C, and O atoms exist in the AlSiC layer with atomic composition of 37, 31, 23, and 9%, respectively, as shown in Figure 2(b). High concentrations of carbon and Si atoms were observed at interface between AlN buffer layer and Si substrate. The slight C, Ga, and Al peaks also appear to be within the silicon bulk, which is due to diffusion at high temperature growth condition. Figures 2(c) and 2(d) show atomic force microscopy (AFM) images for the surface of the Si substrate after deposition of Al and AlSiC precoverage layer with corresponding rms roughness of 0.5 and 3.9 nm, respectively. It is noticed that the grain size of the randomly distributed AlSiC precoverage layer is larger than that of the Al precoverage.

The growth with AlSiC precoverage resulted in crack-free surface while the layer with Al precoverage showed many cracks on the surface, as shown in Figure 3. This probably

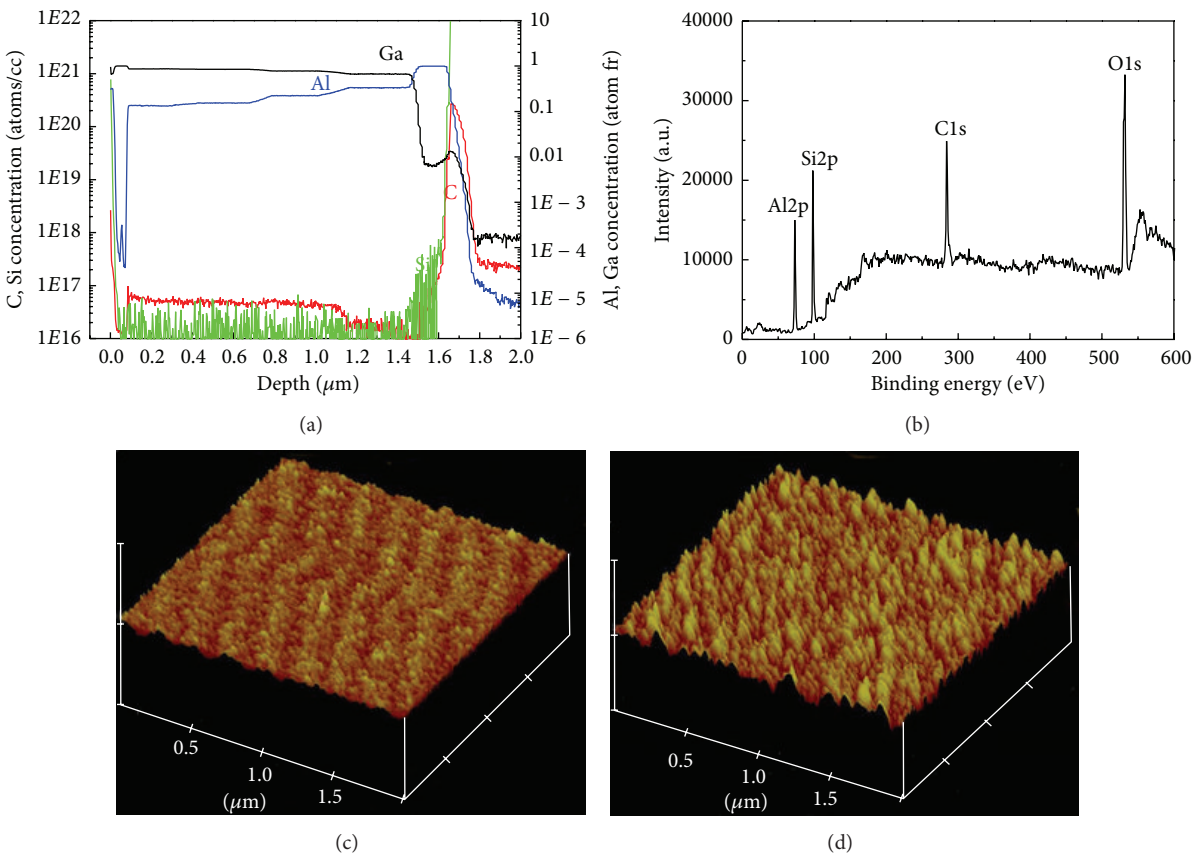

Figure 2: (a) SIMS profile of film grown on Si substrate with AlSiC precoverage layer in real epitaxial layer. (b) XPS measurement of 20 nm thick reference AlSiC film. (c) AFM images of Si surface covered with Al precoverage layer. (d) AFM images of Si surface covered with AlSiC precoverage layer.

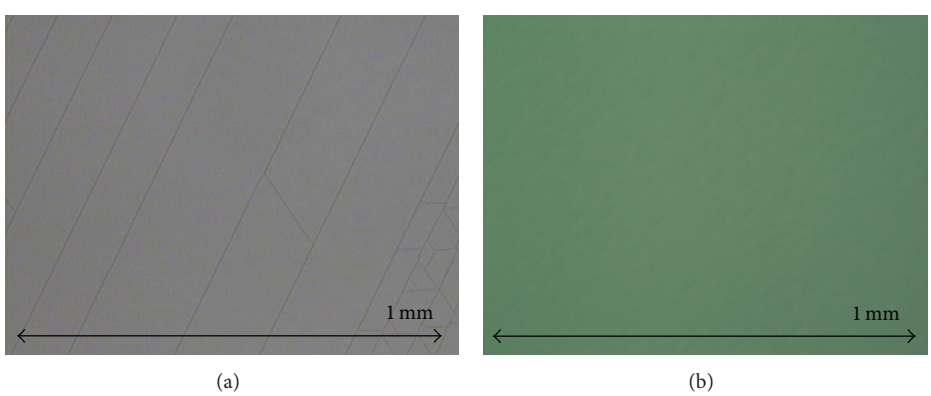

Figure 3: Optical photography of AlGaN/GaN surface grown on Si substrate with Al (a) and AlSiC precoverage interlayer (b).

explains that AlSiC precoverage is effective in compensating the tensile stress in the GaN layer grown on Si substrate. The Raman scattering spectra shown in Figure 4(a) exhibit peak shift at frequencies of 567.08 and 568.53 cm^{-1} for the grown film with Al and AlSiC precoverage, corresponding to the calculated biaxial stresses of 0.099 and −0.240 GPa, respectively [17]. This indicates that the biaxial stress in the AlGaN/GaN heterostructure grown on Si substrate with AlSiC precoverage is compressive while that with Al precoverage still remains tensile, considering the reference value of 567.5 cm^{-1} for the freestanding GaN. It is believed that the insertion of AlSiC precoverage layer gives rise to strong compressive stress in the GaN film grown on Si substrate during the high temperature growth, which sufficiently overcomes the tensile stress caused by cooling down and remains compressive even after completing the growth. Photoluminescence mapping in inset of Figure 4(a) showed the average peek wavelength at 361.5 nm, which belongs to the shifted wavelength for

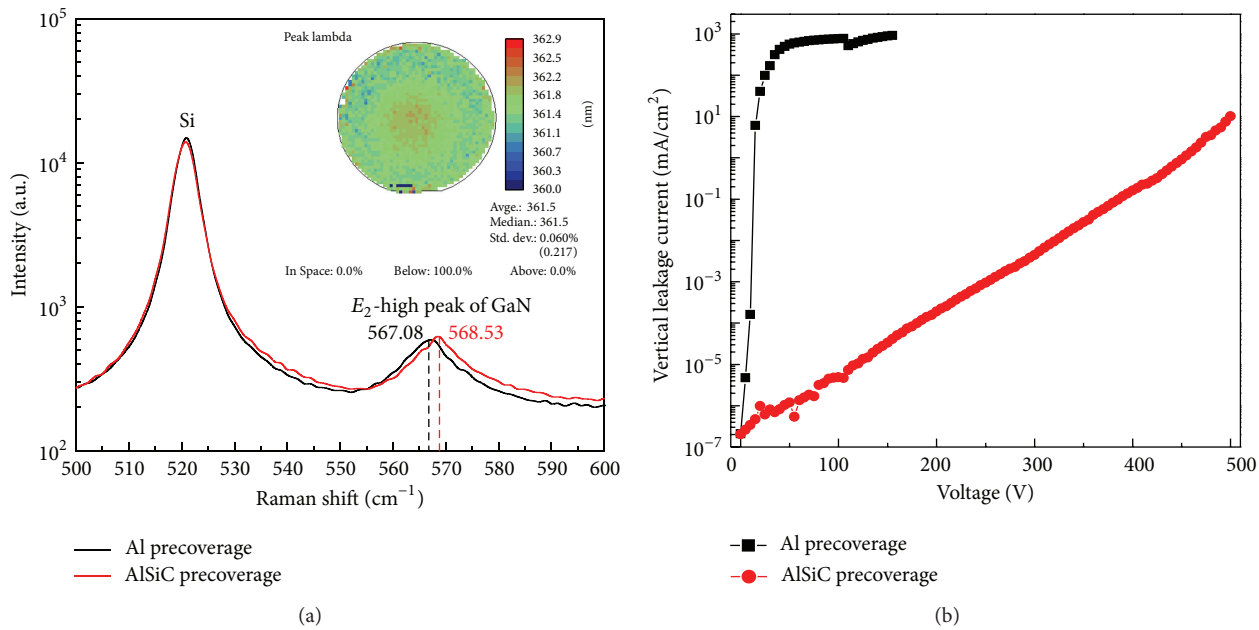

Figure 4: (a) Raman scattering spectra of AlGaN/GaN layers grown on Si substrate with Al and AlSiC precoverage layer. The inset shows the map image of wavelength for grown films with AlSiC precoverage layer. (b) Vertical leakage current of AlGaN/GaN layers grown on Si substrate with Al and AlSiC precoverage layer.

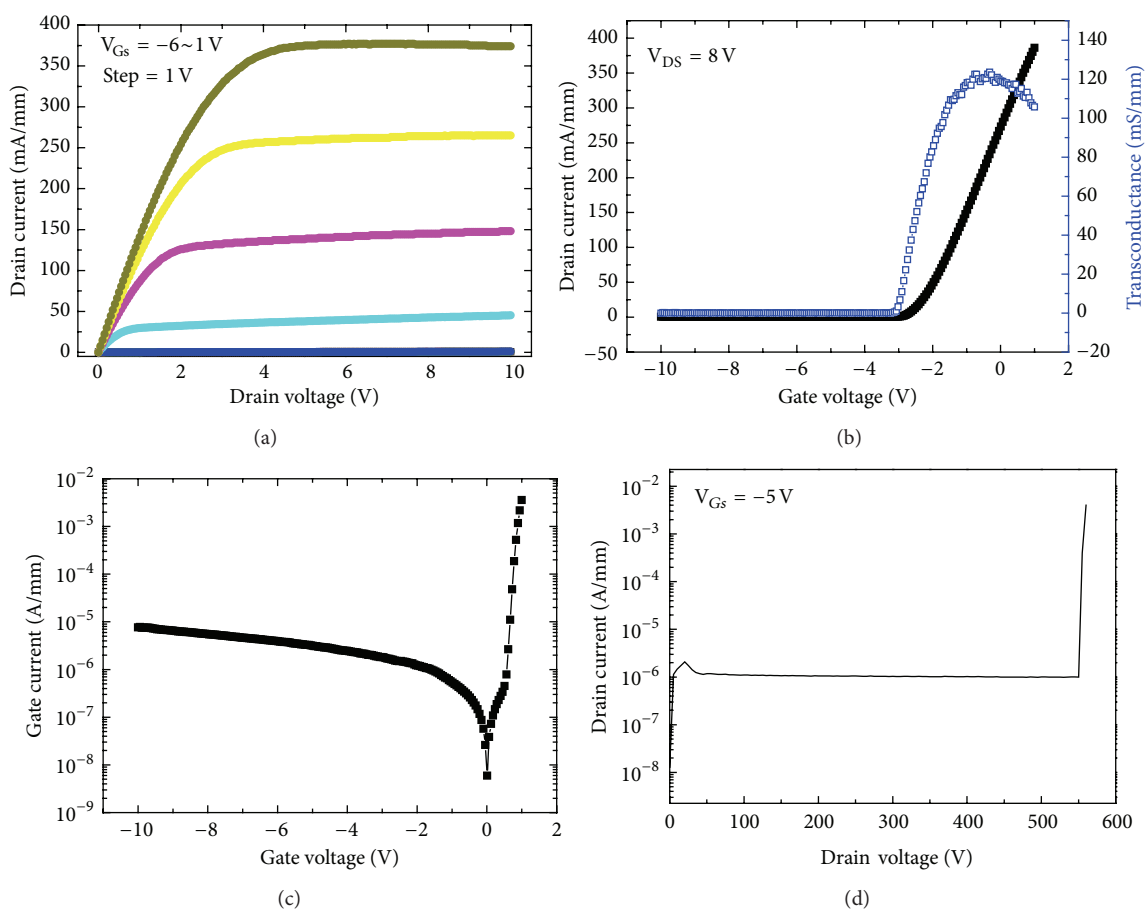

Figure 5: I-V characteristics of the fabricated device with AlSiC precoverage layer. (a) Drain current, (b) transfer characteristics, (c) gate leakage current, and (d) breakdown voltage.

the compressively stressed GaN layer. On the other hand, the films with Al precoverage were not able to sufficiently overcome the tensile stress which resulted in generation of crack on GaN surface due to different thermal expansion coefficient after cooling down. Figure 4(b) showed the vertical leakage current-voltage (I-V) characteristics for both AlGaN/GaN heterostructure grown on Si substrate with Al and AlSiC precoverage layer. The leakage current was measured by using a circular type pattern with diameter of 100 μm between Ohmic contact pads and Si substrate. As shown in Fig ure 4(b), the film with Al precoverage layer exhibits the short characteristics due to the crack path. On the other hand, the film with AlSiC precoverage layer exhibits relatively higher semi-insulating characteristics of $3 \times 10^8\ \Omega$ (1 μA at 300 V), which make it attractive for high-power application.

Figure 5 shows the I-V characteristics for the normally on AlGaN/GaN HFET fabricated on the grown AlGaN/GaN heterostructure with the AlSiC precoverage on the Si substrate. The gate length, the gate width, and the gate-to-drain distance of both devices were 2, 140, and 20 μm, respectively. The total area of the device was $500 \times 500\ \mu\text{m}^2$. The maximum drain current (I_{dmax}) and the specific on state-resistance (R_{ON}) of the normally on HFET are 370 mA/mm and 5 m$\Omega\cdot$cm^2, respectively, as shown in Figure 5(a). The threshold voltage and the maximum transconductance (Gm) of device at a fixed V_{DS} of 8 V are −2.3 V and 124 mS/mm (I_{DS}-V_{GS}), respectively, as shown in Figure 5(b). The gate leakage current is −5 μA at gate voltage of −10 V (Figure 5(c)), which is comparable to that of AlGaN/GaN HFET grown on the sapphire substrate [18]. In addition, the offstate breakdown voltage of the device is as high as 550 V (Figure 5(d)), even though no additional processes are applied to increase the breakdown voltage, which demonstrates that the AlGaN/GaN HFET with the AlSiC precoverage on the Si substrate has a great potential application to the high-power device.

4. Conclusion

To obtain a crack-free AlGaN/GaN heterostructure grown on Si substrate, we proposed the insertion of the AlSiC precoverage layer between AlN and Si substrate. The AlSiC precoverage layer generates the compressive stress in the film grown on Si substrate during the high temperature growth, which resulted in crack-free films due to compensation of tensile stress after finishing epitaxial growth. The fabricated normally on HFET exhibits a threshold voltage of −2.3 V, I_{dmax} of 370 mA/mm, R_{ON} of 5 m$\Omega\cdot$cm^2, and Gm of 124 mS/mm.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

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