Epitaxial Layers of AlGaN Channel HEMTs on AlN Substrates

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Epitaxial structures of aluminum gallium nitride (AlGaN) channel high electron mobility transistors (HEMTs) were grown on sapphire and aluminum nitride (AlN) substrates. Reduction in the full width at half maximum of X-ray rocking curve for ($10\bar{1}2$) peak of the AlGaN channel layer, owing to the reduction of threading dislocation density, resulted in a sharp decrease in the sheet resistance of 2-dimensional electron gas (2DEG). For AlGaN channel HEMTs, it was found that improvement of the crystalline quality of the AlGaN channel layers was essential to reduce the sheet resistance of 2DEG. The use of AlN substrates improved the crystalline quality of the AlGaN layer and lowered the 2DEG resistance. These results suggested the high potential of AlN substrates for AlGaN channel HEMTs.

Keywords: HEMT, AlN, AlGaN, dislocation, AlGaN channel HEMTs

1. Introduction

For energy saving purposes and prevention of global warming, the performance of power devices needs to be improved. The performance of Si power devices, however, is limited by the material property of Si and/or device structures. Therefore, to increase the performance of power devices drastically, wide bandgap semiconductors, such as gallium nitride (GaN) and silicon carbide (SiC), are being explored actively.

Table 1 shows the physical constant of various semiconductors for power applications. GaN has some attractive physical properties. Compared to Si, the bandgap energy (3.4 eV) is 3 times larger, the electric breakdown field (3.3 MV/cm) is about 10 times larger, and the electron saturation velocity (2.7×10^7 cm/s) is about 3 times higher.

Therefore GaN is promising for high frequency and electrical power device applications. GaN power devices, which have attractive properties for high frequency power device applications, have been investigated for wireless communications, such as base stations for cell phones(1), and have already been put to practical use. In addition, they are also expected to play a key role in electric power device applications(2),(3). Sumitomo Electric had developed free-standing GaN substrates with low-dislocation-density(4), and has investigated GaN power devices grown on these substrates. By using the GaN substrates with low-dislocation-density for electrical power device applications, crystalline quality of active layers are improved drastically and high performance GaN power devices are realized(5)-(7).

On the other hand, aluminum nitride (AlN) has excellent physical properties. Compared to GaN, the band gap energy (6.2 eV) is about 2 times larger, the electric breakdown field (12 MV/cm) is about 4 times larger and the thermal conductance (2.9 W/cmK) is about 1.5 times higher. Therefore AlN and AlGaN, which is a ternary alloy composed of GaN and AlN, have high potential as next generation semiconductors for power devices. For instance, high electron mobility transistors (HEMTs) which use AlGaN for channel layers, or the so-called "AlGaN channel HEMTs" showed remarkably higher breakdown voltages than those which use GaN for channel layers, or the so-called "GaN channel HEMTs"(8). Therefore, Sumitomo Electric has been developing AlN substrates as one of the candidates for next generation semiconductors and has reported that the crystalline quality of the AlN substrates grown by sublimation method, which was suitable for large diameter crystal growth, were excellent(9),(10).

Table 1. Physical constant of various semiconductors for power applications.

	Semiconductors			
	Si	4H-SiC	GaN	AlN
Bandgap energy, E_g [eV]	1.1	3.3	3.4	6.2
Electron mobility, μ_e [cm^2/Vs]	1,400	1,020	2,000	1,090
Electric breakdown field, E_c [MV/cm]	0.3	3.0	3.3	12
Thermal conductance, λ [W/cmK]	1.5	4.9	2.0	2.9
Electron saturation velocity, v_{sat} [10^7cm/s]	1.0	2.0	2.7	2.2
Baliga's figure of merit (high frequency), $\mu_e E_c^2$	1	73	180	1,250
Baliga's figure of merit (low frequency), $\varepsilon \mu_e E_c^3$	1	600	1,450	36,000

We have explored for the applications of AlN substrates, because it is expected that high crystalline quality AlN and AlGaN epitaxial layers and high performance devices are obtained by using the AlN substrates. In this study, the use of AlN substrates resulted in excellent crystalline quality of the AlGaN layers and better 2DEG characteristics, suggesting the advantage of AlN substrates for AlGaN channel HEMTs.

2. Experiment

AlN and AlGaN epitaxial layers were grown on sapphire and AlN substrates by metal-organic vapor phase epitaxy (MOVPE), using ammonia (NH_3), trimethylaluminum (TMA) and trimethylgallium (TMG) as precursors. The threading dislocation densities (TDDs) of the AlN substrate were less than 1×10^6cm^{-2}. **Figure 1** shows the schematic structure of an AlGaN channel HEMT. An AlN layer was grown directly on the substrate, followed by an $Al_{0.29}Ga_{0.71}N$ channel layer and an undoped $Al_{0.49}Ga_{0.51}N$ barrier layer. The AlN layers on sapphire substrates were grown with several thicknesses and growth conditions to control the crystalline quality. The structures and growth conditions of AlGaN channel and AlGaN barrier layers were the same on both substrates.

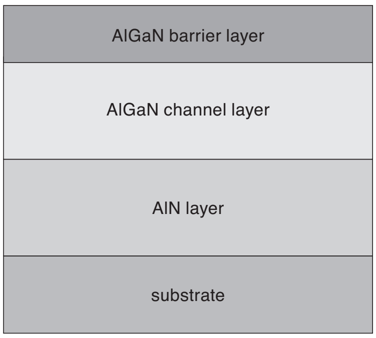

Fig. 1. Schematic structure of an AlGaN channel HEMT.

X-ray rocking curve (XRC) was measured with high resolution X-ray diffraction equipment to characterize the crystalline quality of the HEMT structure. Sheet resistance of the epitaxial layers was measured by eddy current measurement equipment. Depth profiles of carrier concentrations were obtained from capacitance-voltage (C-V) measurements with Au schottky electrodes. The surface morphology and the roughness of the epitaxial layers were measured with atomic force microscope (AFM).

3. Results and Discussion

To fabricate HEMT devices, it is necessary to form the two-dimensional electron gas (2DEG) at the interface between barrier and channel layers and suppress the residual carrier concentration in channel layers. We obtained depth profiles of carrier concentrations from C-V measurements to evaluate the epitaxial layers of AlGaN channel HEMTs.

Figure 2 shows a depth profile of the carrier concentration in an AlGaN channel HEMT grown on a sapphire substrate and the inset shows the enlarged figure near the surface of the depth profile. The structure of the sample is $Al_{0.49}Ga_{0.51}N$ (25 nm)/$Al_{0.29}Ga_{0.71}N$ (600 nm)/AlN (800 nm)/sapphire substrate. From the depth profile of the carrier concentration in the inset, the carrier concentration has the maximum value at a depth of around 25 nm, corresponding to the interface between barrier and channel layers. The carrier concentration in the AlGaN channel layer distant from the AlGaN/AlGaN interface was less than 1×10^{16}cm^{-3}, and at AlGaN/AlN interface and AlN/sapphire substrate interface the carrier concentration was less than 1×10^{15}cm^{-3}. These results indicate that 2DEG is formed only at the $Al_{0.49}Ga_{0.51}N$/$Al_{0.29}Ga_{0.71}N$ interface and that only the 2DEG at the interface contributes to the sheet resistance. The sheet carrier concentration calculated from the integration of the depth profile was 8.6×10^{12}cm^{-2}. All samples in this study were confirmed to form 2DEG only at the interface between barrier and channel layers by C-V measurements.

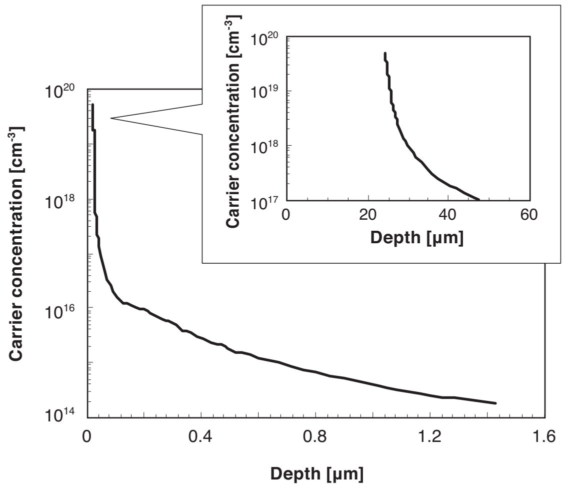

Fig. 2. A depth profile of a carrier concentration from a C-V measurement. Inset: the enlarged figure near the surface of the depth profile.

Next, we examined the dependence of the 2DEG characteristics on crystalline quality of AlGaN channel layers. To evaluate crystalline quality, we measured XRCs for (0002) and ($10\bar{1}2$) diffractions of AlN and AlGaN channel layers of the HEMTs. **Figure 3** shows the dependence of sheet resistance on the full widths at half maximum (FWHMs) of XRCs for ($10\bar{1}2$) peaks of AlGaN channel layers. As clearly shown in **Fig. 3**, a sharp decrease in the sheet resistance is observed with decreasing FWHMs of XRCs for ($10\bar{1}2$) peaks of the AlGaN channel layer on sapphire substrates. In addition, by using low-dislocation-density AlN substrate, a lower sheet resistance was obtained. The FWHMs of XRCs for $(10\bar{1}2)$ peaks, rather than those for (0002) peaks, are related clearly to the sheet resistance. Since screw dislocations affect the FWHMs of XRCs for (0002) peaks and edge dislocations affect those for $(10\bar{1}2)$ peak[11], it is suggested that sheet resistance of 2DEG in AlGaN channel HEMTs is notably affected by edge dislocations.

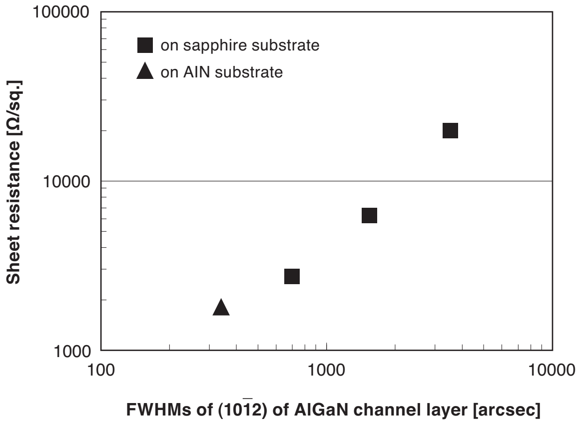

Fig. 3. Dependence of sheet resistance on FWHMs of XRC for $(10\bar{1}2)$ peak of AlGaN channel layer in AlGaN channel HEMTs.

Table 2 shows the FWHMs of XRCs for AlN layers and AlGaN channel layers and sheet resistance on a sapphire substrate and on an AlN substrate. On the AlN substrate, the FWHM of XRC for the AlN layer is smaller than that on the sapphire substrate, and the FWHM of XRC for the AlGaN channel layer is also smaller than that on the sapphire substrate. This indicates that a higher quality AlN layer is obtained on the AlN substrate, and that a higher quality AlGaN channel layer is also obtained on the AlN substrate. As a result, the sheet resistance on the AlN substrate is lower than that on the sapphire substrate. Thus the advantage of the AlN substrate for AlGaN channel HEMT was confirmed in this experiment. For conventional GaN channel HEMTs, SiC, sapphire and Si substrates are usually used in spite of high TDDs between 10^8 and 10^{10}cm^{-2}. In particular, with respect to GaN channel HEMTs on Si substrates, although the FWHM of XRC for GaN channel layer was very broad[12], i.e. the crystalline quality of GaN channel layer was not good, 2DEG characteristics, such as mobility, sheet carrier concentration and sheet resistance, were excellent. It was also clarified by theoretical calculation[13],[14] that the influence of dislocations on mobility of 2DEG in GaN channel HEMTs was small enough. In contrast, in AlGaN channel HEMTs, it was found that the growth of a high quality AlGaN channel layer is essential for the reduction of sheet resistance of 2DEG.

For further discussion of the sheet resistance of 2DEG at AlGaN/AlGaN interface, we calculated the mobility from the sheet carrier concentration from C-V measurements and sheet resistance. **Figure 4** shows the dependence of the mobility and the sheet carrier concentration on the FWHMs of XRCs for $(10\bar{1}2)$ peaks of AlGaN channel layers on sapphire substrates. The mobility and the sheet carrier concentrations decrease with increasing the FWHMs of XRC for $(10\bar{1}2)$ peaks. This result indicates that the mobility and the sheet carrier concentration are affected by the crystalline quality, that is to say, dislocation density of the AlGaN channel layer in the case of AlGaN channel HEMTs.

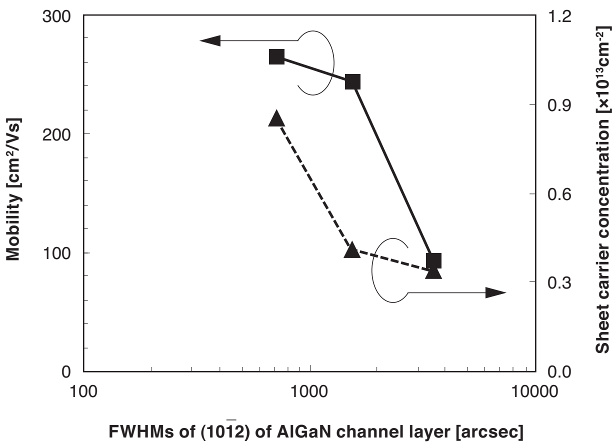

Fig. 4. Dependence of the mobility and the sheet carrier concentrations on the FWHMs of XRCs for $(10\bar{1}2)$ peaks of AlGaN channel layer in AlGaN channel HEMTs.

It is speculated that the reason of these results is as follows. In general, obtaining the flat surface of AlGaN epitaxial layers is more difficult than that of GaN layers. In the case of AlGaN epitaxial layers, the flatness of the surface of AlGaN epitaxial layers deteriorates with increasing FMHMs of XRC for AlGaN channel layers due to increase of dislocations. The flatness of the surface depresses V-pits generated by dislocations. Hence, it is

Table 2. FWHMs of XRCs for AlN layers and AlGaN channel layers and sheet resistance as a typical value.

	Unit	On AlN substrate		On sapphire substrate	
		(0002)	$(10\bar{1}2)$	(0002)	$(10\bar{1}2)$
FWHM of AlN layer	[arcsec]	37	92	449	742
FWHM of AlGaN channel layer	[arcsec]	160	341	513	771
Sheet resistance	[Ω/sq.]	1737		2754	

considered that in the case of growing AlGaN barrier layers on the AlGaN channel layers which have some roughness of the layers,

1. The sheet carrier concentration decreases with decreasing piezoelectric polarization because of the relaxation of the AlGaN barrier layer.
2. The mobility decreases with increasing carrier scattering due to degradation of interface between AlGaN barrier and channel layers.

So the dependence of the sheet carrier concentration and the mobility on the dislocation density was considered to be significant for AlGaN channel HEMT epitaxial layers.

Figure 5 shows the AFM images of the surface of the epitaxial layers for AlGaN channel HEMTs on AlN and sapphire substrates. Fine step-flow growth was observed on both substrates. However, in the epitaxial layer on the sapphire substrate, a lot of V-pits generated by dislocations and roll of steps deteriorate the flatness of the surface. The root mean square (RMS) value was as rough as 0.50 nm which is not well. In contrast, on the AlN substrate, the steps were extremely smooth, and the RMS value was 0.12 nm, which was a very small value. These results from AFM measurements are consistent with the above speculation and show one of the advantages of AlN substrates for AlGaN channel HEMT epitaxial layers.

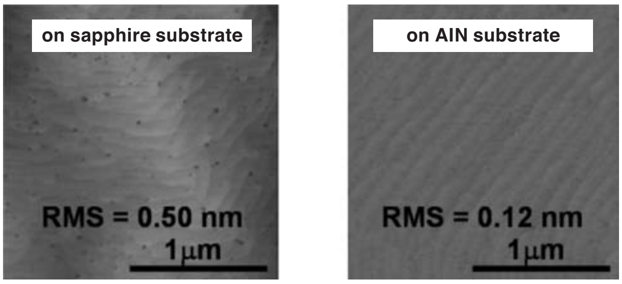

Fig. 5. The AFM images of the surface of AlGaN channel HEMT epitaxial layers on sapphire and AlN substrates.

These results indicate that it is essential for AlGaN channel HEMTs to obtain high crystalline quality of AlGaN channel layers to reduce sheet resistance of 2DEG, and using low-dislocation-density AlN substrates are one of the most effective methods to grow AlGaN epitaxial layers with high crystalline quality.

5. Conclusion

We have grown epitaxial structures of AlGaN channel HEMTs on sapphire and on AlN substrates. The sheet resistance of 2DEG remarkably decreased with decreasing FWHMs of XRCs for $(10\bar{1}2)$ peaks of AlGaN channel layers owing to the reduction of the TDDs of the AlGaN channel layers. On the AlN substrate, crystalline quality of AlGaN channel layers has become higher than that on sapphire substrates and the sheet resistance has been reduced, which suggests the advantage of AlN substrates for AlGaN channel HEMTs. Consequently, for AlGaN channel HEMTs, it was concluded that improvement of crystalline quality of AlGaN channel layers is essential to reduce the sheet resistance of 2DEG.

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