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Abstract
The impact of an InGaN/GaN superlattice (SL) on AlGaN/GaN high electron mobility transistor characteristics was investigated, and two effects were discovered: one is a substantial improvement in the conduction characteristics as a result of the InGaN/GaN channel layer, while the other is the effect of diffusion suppression relating to impurities or point defects from the carbon-doped layer. The InGaN/GaN SL was used as a channel layer to improve the mobility and concentration of the two-dimensional channel electron gas. It was found that by inserting the InGaN/GaN SL just above a C-doped semi-insulating GaN layer as the InGaN underlayer, the conduction current of the SL with five periods (5SL) was observed to be much higher than that of the conventional material with a GaN channel layer of over 2 μm in thickness. The results demonstrated that this SL layer is effective in suppressing the diffusion of impurities or point defects originating from the carbon-doped layer, resulting in device performance improvement.

I. INTRODUCTION

Recently, the AlGaN/GaN high electron mobility transistor (HEMT) was found to hold great promise for high-power, high-frequency electronics applications, owing to its high breakdown voltage and high saturation current. This HEMT is operated using a high density two-dimensional electron gas (2DEG) at the AlGaN/GaN interface without the need for any doping due to the spontaneous polarization and piezoelectric properties of this group III nitride heterojunction.

This HEMT requires a highly resistive (semi-insulating, or SI) buffer layer or substrate for isolation to attain a high-frequency and high-power operation. To fabricate highly resistive GaN, Fe or C are often used as acceptor impurities to form deep acceptor levels. When Fe or C are used for such a highly resistive buffer layer, the use of a thicker, unintentionally doped (UID) GaN layer is necessary for recovery against any deterioration in the device characteristics brought about by the influence of the impurities. Moreover, these impurities or defects cause on-state drain current collapse. To obtain sufficient drain current, for the C-doped layer, it is necessary to grow the GaN layer to over 200 nm and over 2 μm for the Fe-doped layer. Previously, it was confirmed with secondary ion mass spectrometry that carbon does not diffuse into the UID GaN layer; therefore, point defects originating from carbon are generated by carbon doping and it is presumed that these defects may cause a reduction in the on-state drain current.

On the other hand, heterostructures with an InGaN channel have been reported as promising candidates in the HEMT fabrication, owing to their superior density with respect to their traditional GaN channel structures. InN has been found to have a higher electron mobility than that of 2DEG with an AlGaN/GaN structure and high 2DEG is expected due to a larger band offset using the InGaN/GaN heterojunction. We have previously reported that InGaN has the effect of inducing the trapping of impurities and point defects and can be used to confirm the recovery of the performance of the light-emitting diodes (LEDs). In fact, such an
InGaN underlayer (UL) or InGaN/GaN superlattice (SL) is commonly used in high efficiency commercial blue LEDs. Its role is to trap surface defects and avoid their further incorporation into the InGaN/GaN active region. This phenomenon using InGaN may be useful as a diffusion suppression layer from the C- or Fe-doped layers.

In this study, the influence of an InGaN/GaN SL when used as a channel layer and InGaN UL on AlGaN/GaN HEMT characteristics was investigated.

II. EXPERIMENTAL

In this study, a HEMT containing an InGaN/GaN SL was grown on a (0001) plane sapphire substrate using metal-organic vapor phase epitaxy (MOVPE). Figure 1(a) shows a conventional AlGaN/GaN HEMT structure consisting of a 25 nm thick low-temperature (LT) GaN buffer layer, 2 μm thick UID GaN layer, 2 μm C-doped SI GaN layer, 2 μm channel GaN layer, and 25 nm Al0.25Ga0.75N layer. Here, the UID channel GaN layer was optimized by thicker growth of the GaN channel layer to saturate the drain current and the thickness was over 2 μm. To confirm the recovery of the HEMT performance, we investigated the thickness dependence of the channel GaN layer, as shown in Fig. 2. As a result, \( I_{DS} \) was significantly improved with an increase in the channel GaN layer, which means that the C-doped SI GaN layer definitely deteriorates the HEMT performance. In this study, the UID channel GaN thickness was set to 2 μm. The growth temperatures of the LT GaN buffer, UID GaN, C-doped SI GaN, UID channel GaN, and AlGaN layers were 460 °C, 1150 °C, 1000 °C, 1050 °C, and 1050 °C, respectively. The C-doped SI GaN layer was grown under a low pressure (20 kPa). A metal with a gate-length of \( L = 3 \mu \text{m} \) and gate-width of \( W = 120 \mu \text{m} \) was deposited on the HEMT structure. The length from the gate to source and the gate to drain was both 3.5 μm. The contacts for the source/drain and gate electrodes were fabricated using electron-beam evaporated Ti/Al/Ti/Au (30/100/20/50 nm) and Ni/Au (30/50 nm), respectively. Ti/Al/Ti/Au were annealed at 850 °C for 30 s.

A. Improvement of device characteristics using the InGaN channel layer

First, the InGaN/GaN SL was used as a channel layer, as shown in Fig. 1(b). However, InGaN is easily desorbed, and thus, a capping layer is required. Therefore, the device characteristics were investigated by changing the capping GaN thickness from 0 nm to 50 nm on the InGaN/GaN SL. Here, this value is only the as-grown set value. The final thickness could be lower due to subsequent desorption of GaN.

B. Effect as InGaN UL to impurities or point defects from the carbon-doped layer

The effect of the diffusion suppression layer with respect to the impurities or point defects from the carbon-doped layer was investigated using the structure shown in Fig. 1(c). The InGaN/GaN SL was inserted just above the C-doped SI GaN layer. The device performance was investigated by changing the number of periods of the SL to 1, 3, or 5. The capping GaN thickness was 20 nm, and the InGaN/GaN SL layer consisted of In0.1Ga0.9N 2.5 nm/GaN 2.5 nm grown at 800 °C.

C. Combination of the effect of the InGaN UL and the InGaN channel layer

The improvement ratio of the drain current density by the InGaN UL and the InGaN channel layer shown in Fig. 1(d) was...
FIG. 3. Plots of mobility and sheet carrier concentration as a function of the capping GaN layer thickness.

compared with the conventional structure. When used as an InGaN UL, the InGaN SL is inserted just above the C-doped SI GaN layer and the UID GaN thickness on SI GaN was 0 nm. The UID GaN thickness on SI GaN was 2 μm, and the InGaN SL was inserted on UID GaN. The capping GaN thickness was 20 nm, and the InGaN/GaN SL layer consisted of five periods of In$_{0.1}$Ga$_{0.9}$N 2.5 nm/GaN 2.5 nm grown at 800°C.

III. RESULTS

A. Improvement of device characteristics using the InGaN channel layer

In this section, the improvement in the HEMT characteristics using the InGaN/GaN SL as a channel layer was investigated, as schematically shown in Fig. 1(b). Figure 3 shows the channel electron mobility and sheet carrier concentration as a function of the capping GaN layer thickness. The mobility of the 20 nm-thick-capping GaN layer showed the highest value, whereas GaN capping layers that were thinner and thicker than this showed lower mobility. The trend shown by the sheet carrier concentration is the complete opposite of that of the mobility trend. The trend of the mobility may be due to the (i) alloy scattering effect of the InGaN and AlGaN layers by the thinner capping layer and (ii) deterioration of the GaN quality because of the lower growth temperature of the GaN capping layer compared to the optimized growth temperature of GaN. Figure 4 shows the temperature dependence of the electron mobility, indicating that the electron mobility increases with a decrease in temperature due to reduced alloy scattering and lower impurity scattering. At 20 K, the mobility of the 20 nm structure is higher than that of the conventional structure without InGaN. The improvement in the mobility of the 20-nm-capping layer sample at 20 K shows that the InGaN channel works well and that it is possible for InGaN to improve the mobility of the HEMT through the optimization of growth conditions such as thickness, temperature, and In content. In this study, although optimization of the InGaN SL is not sufficient yet, we use the InGaN/GaN SL with the 20-nm-capping layer as the InGaN channel layer, which has comparative or slightly higher performance to the conventional HEMT according to the higher mobility at low temperatures.

B. Effect as InGaN UL to impurities or point defects from the carbon-doped layer

As shown in previous reports, the role of the InGaN UL in an LED structure is to bury surface defects and ensure a high efficiency active region. So, when the SL is inserted just above the carbon-doped layer, the SL suppresses the diffusion of the defects, such as impurities or point defects arising from the C-doped layer. Therefore, the effect of the InGaN/GaN SL on the recovery of the deterioration of the device characteristics by the C-doped SI GaN layer in Fig. 1(c) was explored and the results are shown. Here, the SL structures with 20-nm-capping GaN layers were used based on the results in Sec. III A. Figure 5 shows a plot of the $I_{DS}$ values as a function of the total thickness from the C-doped layer to AlGaN layer, where the red triangles and black circles represent the InGaN suppression and conventional channel GaN layers, respectively. The $I_{DS}$ values show the maximum saturated drain current density in saturation when the drain voltage was varied from 0 V to 10 V and the gate voltage was 3 V. As can be clearly seen in Fig. 5, showing the drain current value accompanying the increase in the SL number, the drain current density increases upon an increase in the SL number, and a drain current density of around 630 mA/mm was obtained for the 5 period SL structure. This is an improvement in the current value of about 200 mA/mm compared to that of the conventional structure with the same film thickness of 50 nm. This is a significant improvement compared to the result in Sec. III A, which indicates that this is an InGaN channel layer effect and also other factors contribute to the improvement.

FIG. 4. (a) The temperature dependence of mobility. (b) A plot of the mobility at 20 K as a function of the capping GaN layer thickness.
Here, we attribute this improvement as a result of suppression of the defects. When the SL is inserted just above the carbon-doped layer, the SL suppresses the diffusion of the defects, such as impurities or point defects arising from the C-doped layer. Considering this way, these results were due to the tendency of vacancies to diffuse toward the surface, as observed in other materials. As the nitrogen vacancies from the C-doped layer diffuse to the surface, it is speculated that the AlGaN surface and the near-surface area provide a sink of point defects that segregate on the surface until they react with the indium atoms. Consequently, it has been demonstrated that the InGaN/GaN SL is effective in enhancing the electrical characteristics as a diffusion suppression layer relating to the device performance deterioration, for instance, such as impurities or point defects originating from the C-doped Si GaN layer. The reservoir effect of C impurity has been reported in GaAs based heterostructures, and the same effect could happen in the InGaN/GaN SL structure.

C. Combination of the effect of the InGaN UL and the InGaN channel layer

The improvement ratio of the drain current density by the InGaN UL and the InGaN channel layer was compared with the conventional structure. Figure 6 shows a plot of the improvement ratio of $I_{DS}$ values as a function of the total thickness from the C-doped layer to AlGaN layer, where the black squares represent the conventional structure without the InGaN layer, the red square represents the structure as InGaN channel layers, and the blue square represents the suppression structure by the InGaN SL. When the UID GaN thickness was 2 $\mu$m from GaN:C to AlGaN in the conventional structure, the drain current density was set to 1.0 times.

As can be clearly seen in the figure showing the improvement ratio of $I_{DS}$ along with the increase in total film thickness from the C-doped layer to AlGaN layer, $I_{DS}$ was improved by inserting the InGaN layer, and the improvement ratio of $I_{DS}$ became about 1.2 times. When the total thickness (InGaN/GaN 5SL + Capping GaN) from GaN:C to AlGaN is about 50 nm, the structure using the InGaN SL as the channel layer has a 1.26 times improvement in $I_{DS}$ compared to the conventional structure with the same film thickness. Therefore, using InGaN as a diffusion suppression layer for impurities and point defects indicates that it may be more useful to improve the ratio of $I_{DS}$ than using InGaN as a channel layer.

IV. CONCLUSION

By using an InGaN/GaN SL as a channel layer, it was demonstrated that InGaN has the ability to improve the mobility of a HEMT through the optimization of growth conditions such as thickness, temperature, and In content. However, when the InGaN/GaN SL was inserted just above a C-doped Si GaN layer as the InGaN UL, the drain current density increased upon an increase in the SL number, and the on-state drain current density of around 630 mA/mm was obtained for an SL structure with five periods. This presents an improvement over the current value of around 200 mA/mm achieved by the conventional structure with the same film thickness of 50 nm. In addition, the improvement ratio of the drain current density by the InGaN UL and the InGaN channel layer was compared with that of the conventional structure. Using the InGaN UL as a diffusion suppression layer for impurities and point defects indicates that it may be more useful to improve the ratio of $I_{DS}$ than using InGaN as a channel layer. From these results, it was demonstrated that the InGaN/GaN SL is effective as a diffusion suppression layer with respect to impurities or point defects originating from C in addition to the effect of the InGaN channel layer for improving 2DEG and electron mobility.

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