HIGH-TEMPERATURE RELIABILITY OF GaN ELECTRONIC DEVICES

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ABSTRACT

High-quality GaN was grown using gas-source molecular-beam epitaxy (GSMBE). The mobility of undoped GaN was 350 cm^2/Vsec and the carrier concentration was $6x10^{16}$ cm^{-3} at room temperature. A GaN metal semiconductor field-effect transistor (MESFET) and an n-p-n GaN bipolar junction transistor (BJT) were fabricated for high-temperature operation. The high-temperature reliability of the GaN MESFET was also investigated. That is, the lifetime of the FET at 673 K was examined by continuous current injection at 673 K. We confirmed that the FET performance did not change at 673 K for over 1010 h. The aging performance of the BJT at 573 K was examined during continuous current injection at 573 K for over 850 h. The BJT performance did not change at 573 K. The current gain was about 10. No degradation of the metal-semiconductor interface was observed by secondary ion-mass spectrometry (SIMS) and transmission electron microscopy (TEM). It was also confirmed by using Si-ion implantation that the contact resistivity of the GaN surface and electrode materials could be lowered to $7x10^{-6}$ $ohmcm^2$.

INTRODUCTION

III-V nitrides, SiC and diamond, are very promising materials for electronic devices that can operate under high-temperature, high-power, and high-frequency conditions [1], since these materials have a high melting point, a wide bandgap, a high breakdown electric field, and a high saturation velocity [2]. Furthermore, they have very low on-resistance during operation compared with Si devices. Several groups have reported on GaN electronic devices [3-5]. Regarding high-temperature operation devices, there have only been a few reports concerning transistors that can operate at temperatures of 673 K [3-7], and the reliability of the GaN metal semiconductor field effect transistor (MESFET) at high-temperature. We have recently investigated the GaN MESFET using gas-source molecular beam epitaxy (GSMBE) [8-11]. However, until now, no life test of the FET by continuous current-injection at 673 K for over 1010 h has been reported.

Furthermore, there have been few reports concerning the bipolar junction transistor [12-15]. Pankov fabricated a hetero-bipolar junction transistor using n-type GaN and p-type SiC, since p-type GaN with a high carrier concentration was very difficult to grow. They obtained a high current gain and high-temperature operation at 533 K. We have also recently reported that a GaN n-p-n bipolar junction transistor can be operated at high temperature [15]. However, life test at 573 K for over 800 h has not been reported.

This paper reports on the high-temperature reliability concerning a life test of a GaN MESFET at 673 K for over 1010 h, a life test of over 850 h at 623 K of an n-p-n bipolar junction transistor and Si-ion implantation technique for obtaing a low-contact resistivity.

EXPERIMENT PROCEDURE

A GSMBE apparatus was described elsewhere [8]. Dimethylhydrazine (DMHy, $((CH_3)_2NNH_2)$) as a nitrogen source gas, and ammonia (NH_3) as a nitrogen source gas, as well as Knudsen effusion cells for a solid Ga source, Si as an n-type dopant, and Mg as a p-type dopant were also placed in this chamber. The buffer layers of GaN were grown using DMHy at substrate temperatures of 973 K, since DMHy was easily decomposed at lower temperatures (below 873 K) compared to that of ammonia. The Ga beam-equivalent pressure (BEP) was $5\text{x}10^{-7}$ Torr and the BEP of DMHy was $4\text{x}10^{-5}$ Torr. A thick film of undoped GaN was grown using Ga ($6\text{x}10^{-7}$ Torr) and ammonia gas ($5\text{x}10^{-6}$ Torr) on the GaN buffer layer at 1123 K. The BEP of Si was $5\text{x}10^{-9}$ Torr and that of Mg was $8\text{x}10^{-9}$ Torr. The growth rate was 500 nm/h. The carrier concentration of undoped GaN grown at 1123 K was $6\text{x}10^{16}$ cm^{-3} and the mobility was 350 cm^2/Vsec. The carrier concentration of Mg-doped GaN was $2\sim3\text{x}10^{17}$ cm^{-3} (p-type) and the mobility was about 20~30 cm^2/Vsec at room temperature. The activation ratio of Mg was smaller than 10^{-2} compared with the results of a secondary-ion mass-spectrometry (SIMS) analysis. In the case of Si doping, the n-type carrier concentration was controlled in the range from $1\text{x}10^{17}$ cm^{-3} to $5\text{x}10^{18}$ cm^{-3}. An etching technique using an electron cyclotron resonance (ECR) plasma was used for GaN device fabrications. Si ion implantation into GaN was carried out to obtain a lower contact resistivity. The structures of the MESFET and the bipolar junction transistor were made using GaNs grown by GSMBE.

RESULTS AND DISCUSSION

Si-ion implantation

The GaN surface layer with a Si concentration of over 10^{19} cm^{-3} is very important to obtain a very lower n-type contact resistivity. When we doped the Si with a carrier concentration of over 10^{19} cm^{-3} into the GaN layer using GSMBE, the surface morphology of GaN was very rough, and sometimes Si precipitates were observed on the grown GaN surface. Furthermore, when we formed an n-type ohmic electrode, the contact resistivity between the electrode materials and the GaN was very high. In our growth system, a high Si doping of over 10^{19} cm^{-3} into the GaN layer was very difficult. In order to reduce the contact resistivity, we investigated Si ion implantation instead of high Si doping based on growth. The Si-ion implantation acceleration voltage was 30 keV. The amount of Si dose was $1\text{x}10^{19}$ cm^{-3}. The depth of Si ion implantation was 10~30 nm. The substrate was heated at 873 K during Si-ion implantation. After ion implantation, GaN was annealed at 1123 K for 30 min an the ambient of nitrogen gas. Undoped GaN was used for implantation.

The sheet resistivity of undoped GaN without was 350 ohm/cm^2. After implantation, the sheet resistivity was reduced to 25 ohm/cm^2. Furthermore, the contact resistivity between the electrode materials and the GaN surface was measured. The n-

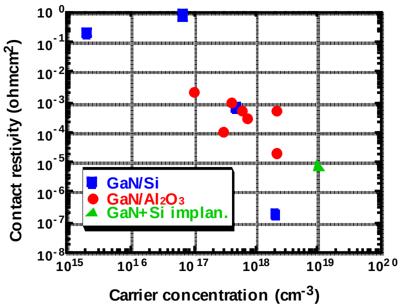

Figure 1. Contact resistivities versus GaN carrier concentrations.

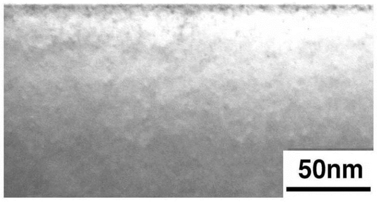

Figure 2. Cross-sectional TEM image of GaN after Si-ion implantation and annealing at 1123 K.

type ohmic electrode material was Al/Ti/Au (30nm/100nm/50nm). Before ion implantation, the contact resistivity of the undoped GaN was 3x10^{-3} ohmcm^2. After Si-ion implantation, the contact was 7x10^{-6} ohmcm^2 as shown in Figure 1. That is, it was confirmed that Si-ion implantation into the GaN layer was very effective for reducing the contact resistivity. Furthermore the cross-seat ion of Si-implanted GaN was observed by transmission electron microscopy (TEM). Figure 2 shows a TEM image of Si-implanted GaN after annealing at 1123 K. No damage based on Si-ion implantation was observed. Therefore, it was thus confirmed that Si-ion implantation is very effective for the contact resistivity.

GaN MESFET

The GaN MESFET structure is as follows [14]. A 50 nm-thick GaN buffer layer was grown on a sapphire substrate. An undoped 1000 nm-thick GaN layer was grown on an GaN buffer layer and an AlN layer was grown on the undoped GaN layer to isolate the active layer. Lastly, a 350 nm-thick Si-doped GaN active layer was grown on the AlN layer. The surface morphology of the grown GaN was smooth. The active layer had a carrier concentration of 3x10^{17} cm^{-3} and a mobility of 250 cm^2/Vsec at room temperature. Etching of the GaN was carried out by a dry-etching technique using an ECR plasma to form the FET. The etching gas was a mixture of CH_4 (5 sccm), Ar (7 sccm), and H_2 (15 sccm) [10]. The etching rate of the Si-doped and undoped GaN layers was 14 nm/min. We formed a source and drain using Au/Ti/Al, and a Schottky-gate as Au/Pt on a patterned GaN sample using an ECR sputter-evaporation method, respectively. The gate length of the GaN MESFET was 2.5 µm and the gate width was 100 µm.

The FET property was obtained at room temperature. The breakdown voltage between gate-source was also about 80 V. The pinch-off voltage was about -8 V. The transconductance (g_m) was about 25 mS/mm. Furthermore, to investigate the high-temperature reliability of a GaN MESFET, we carried out a life test of a FET by continuous current-injection at 673 K. The FET property at 673 K was measured by continuously injecting a current of I_{ds} at V_{ds}=20 V and V_{gs}=0 V. Figure 3 shows the aging time versus I_{ds} of GaN MESFET at 673 K. It should be noted that no change of I_{ds} was observed for over 1010 h. The g_m was also constant at 25 mS/mm. Figure 4 shows the characteristics of I_{ds} as a function of V_{ds} for increasing values of the gate-source voltage (V_{gs}) at 673 K. The pinch-off voltage was also about -8 V. The FET

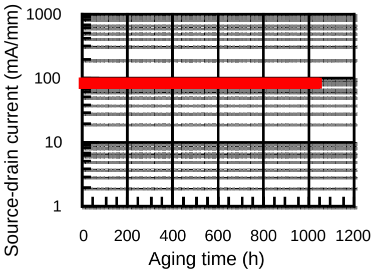

Figure 3. Aging property of I_{ds} of a GaN MESFET during continuous-current injection at 673 K.

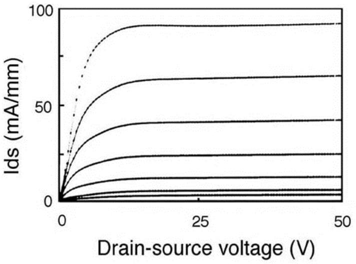

Figure 4. Current-voltage characteristics (I_{ds}-V_{ds}) of a GaN MESFET at 673 K. The gate voltages (V_{gs}) was changed from 0 V to -5 V in steps of -1 V.

property was almost the same as that at room temperature, and good performance of the FET was maintained at 673 K. Using transmission electron microscopy (TEM), we also observed that the interfaces of the electrode materials and the GaN layer were not degraded.

Based on these results, the high-temperature reliability of a GaN MESFET was confirmed, since the electrode materials did not diffuse into the GaN, and the GaN layer was not deformed at 673 K.

GaN bipolar junction transistor

We investigated the reliability of a GaN bipolar junction transistor (BJT) at high temperature. The structure of the bipolar junction transistor using GaN is shown in Figure 5 The thicknesses of the emitter, base, and collector layers were 450 nm, 350 nm, and 500 nm, respectively. The carrier concentration of the emitter and collector was $5x10^{17}$ cm^{-3} and the base carrier concentration was $1.5x10^{17}$ cm^{-3}. The structure was also formed by ECR plasma etching using $CH_3/Ar/H_2$. The emitter size was 350x400 μm^2. The sizes of the base and collector were 200x150 μm^2 and 450x600 μm^2, respectively. The electrode materials of the emitter and collector were formed using Au/Ti/Al. The base contact was also formed using Au/Ti/Ni.

In order to investigate the operation of the bipolar junction transistor at 573 K, the current-voltage characteristics, as measured in the common emitter mode at 573 K, were measured. It was found that the bipolar junction transistor performance at 573 K remained unchanged, as shown in Figure 6, although I_c was slightly changed compared with that produced at room temperature. The current gain (dI_c/dI_b) was about 10. Figure 7 shows the p-n junction property between the base and the emitter electrodes during heating at 573 K. The breakdown voltage was over 10 V. Furthermore, a life test of a bipolar junction transistor was carried out. Figure 8 shows the result of an aging test at 573 K. Here, V_c was 4 V and I_b was 120 µA. Ic did not change for over 850 h. That is, it was confirmed that the bipolar junction transistor was operated for over 850 h. It was also found by SIMS that interfaces between the electrode materials and the GaN layer after heating at 573 K was abrupt and that the GaN was not affected by heating at 573 K. We thus confirmed the reliability of the GaN bipolar junction transistor at 573 K.

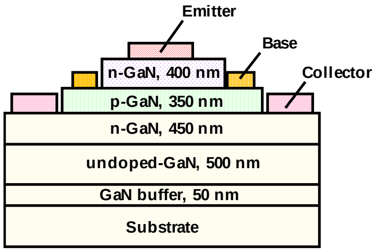

Figure 5. Schematic drawing of the structure of an n-p-n bipolar junction transistor using a GaN.

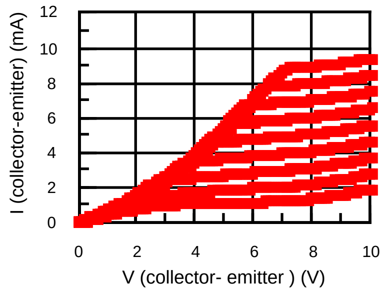

Figure 6. Current (I_c) - voltage (V_c) characteristics as measured in the common-emitter mode at 573 K.
The base current (I_b) was changed from 20 μA in steps of 50 μA.

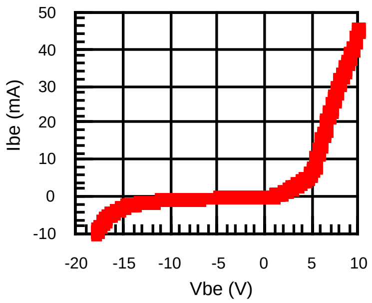

Figure 7. p-n junction property between of the base and emitter electrodes at 573 K.

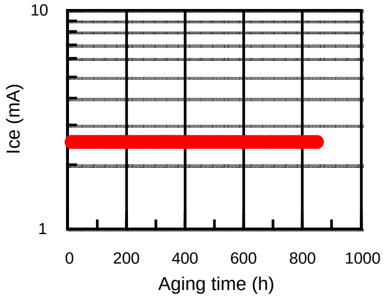

Figure 8. Aging property of GaN BJT at 573 K.

CONCLUSION

A high-quality GaN was grown using GSMBE. A GaN MESFET and an n-p-n bipolar junction transistor were fabricated. The life test of a GaN MESFET at 673 K was examined by continuous current-injection at 673 K. We confirmed that the FET performance did not change at 673 K for over 1010 h. No degradation of the metal-semiconductor interface was observed by SIMS or TEM. Furthermore, the fabrication of a GaN bipolar junction transistor was carried out. The life performance of the bipolar transistor at 573 K was examined during continuous current-injection at 573 K. We confirmed that the performance of the bipolar transistor did not change at 573 K for over 850 h. No degradation of the metal-semiconductor interface was observed by SIMS or TEM. The reliability of a GaN BJT at high temperature was thus confirmed.

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