Improvement of Electrical Properties of p-type GaN and Au Contact Interface*

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In order to improve electrical conductivity of Mg-doped p-GaN, the enhancement of H release from Mg-doped p-GaN were attempted by applying current flow and electrical field through the p-GaN substrates during low temperature annealing. The microstructure and electrical properties after annealing were then investigated by transmission electron microscopy observation, direct current conduction test and Hall effect measurement. The results reveal that no reaction occurs between deposited Au film and GaN substrate during annealing at 573 K for 3600 s. The electrical conductivity does not show any improvement only by applying electrical field or by annealing at 573 K for 3600 s without current flow. It is likely due to the limited mobility of H within p-GaN. However, by applying current flow under the constant voltage of 30 V during annealing at 573 K for 3600 s, a significant improvement of the electrical conductivity has been observed. By applying electrical field and current flow during annealing at 573 K for 3600 s, the H release from p-GaN was enhanced and Mg was activated, resulting in increasing carrier concentration of acceptor and improving the electrical conductivity.

Key Words: p-type Gallium Nitride, Au Film, Hydrogen Release, Annealing, Current Flow, Electrical Field, Microstructures, Electrical Properties

1. Introduction

Silicon (Si) is still now used mainly as power electronic devices. But, it is important to seek for better alternative materials for use in the next-generation power electronic devices due to the physical limitation of silicon. Gallium nitride (GaN) is one of the most promising candidates. Also, GaN has an advantage as a high frequency communication element. GaN-based power electronic devices promise higher energy efficiency devices, with capability of handling higher power and longer service life^{1, 2)}, compared with silicon devices. However, in spite of having a significant development in the crystal growth^{3, 4)} and device processing technology of light emitting diodes (LED) and laser diodes (LDs)⁵⁾, the application of GaN semiconductor to power electronic devices is still far from real.

One of the main problems in realizing GaN-based power electronic devices is related to the fact that the only effective p-type dopant known for GaN is magnesium (Mg). Although some decent annealing methods were developed^{6, 7)} after the breakthrough discovery of Mg-activation by electron-beam irradiation⁸⁾, new developments of improvement methods for

p-type GaN conductivity has not been accomplished. It is reported that only approximately one percent of doped magnesium atoms are activated during Mg-activation^{9, 10)}. This is due to the presence of hydrogen (H) within the Mg-doped GaN, incorporated during growth¹¹⁾. H is known to electrically passivate the acceptors¹²⁾. This passivation is attributed to the formations of neutral Mg-H complexes where H is bonded interstitially to a neighboring nitrogen atom¹³⁻¹⁵⁾. Furthermore, in order to more improve p-type conductivity, postgrowth activation of Mg by thermal annealing, which releases H from GaN, is necessary⁶⁾. The thermal annealing is believed to releases H from GaN but not so effective. The high annealing temperature (973 K)⁶⁾, required to activate p-type conductivity, damages GaN device because GaN is decomposed and N vacancy concentration increases in GaN, *i.e.*, p-GaN properties can be failed. Thus, it is important to understand and improve the processes of H release from GaN.

In the present study, in order to improve the conductivity of Mg-doped p-GaN, the enhancement of H release from Mg-doped p-GaN under temperatures much lower than 973 K is attempted by applying electrical field and current flow through the p-GaN substrates during low temperature annealing (573 K). In that stage, pure Au is used as an electric pad (contact) film because Au does not react with nitrogen in GaN and has a work function of 5.1 eV. The microstructure and electrical properties after annealing used in the present study were then analyzed by transmission electron microscopy (TEM), direct current (DC) conduction tests and Hall effect measurement.

*Received: 2014.12.28

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2. Experimental procedure

Substrates used in the present study were 2.0- μm -thick p-type GaN epitaxially grown on a 330- μm -thick sapphire (0001) wafer with undoped GaN buffer layer. The thickness of undoped GaN was 2.3 μm . The surface orientation and carrier concentration of the substrate were (0001) Ga-face and $3 \times 10^{17} \text{ cm}^{-3}$, respectively. The sizes of all substrates were 4.0-mm-square. The electric pad (contact) areas were obtained by using 1.0-mm-wide Al masking ribbons. Before the sputter depositing process, the substrates were cleaned with acetone applying ultrasonic vibration. After that, the substrates were fixed on the depositing plate designed in a radio-frequency magnetron sputtering deposition apparatus. High-purity Au (99.95 mass %) plates was used as a target material, *i.e.*, Au atoms was sputter-deposited as a contact thin film on p-GaN.

Before sputter depositing Au thin film on the electric pad area, the surfaces of Au target and substrates (p-GaN with pad areas) were sputter-cleaned to remove native oxide layer. The sputter cleaning of Au target and substrates were carried out under 0.8 Pa of high-purity Ar (99.9999 volume %) under a radio-frequency power of 100 W and 200 W, respectively. The sputter cleaning time was 300 s. The sputter deposition of Au thin film was performed under 0.8 Pa high-purity Ar (99.9999 volume %) under a radio-frequency power of 100 W for 36 s.

Some of the deposited samples were then subjected to annealing at 573 K under 0.1 MPa of nitrogen ambient for 3600 s. In the present study, two methods of applying voltage through the sample during annealing were used. These methods are to be referred to as Method (a) for applying electrical field under the condition of DC 100 V without current flow and Method (b) for applying current flow under the condition of DC 30 V. The schematic illustrations of these methods are shown in Figure 1. The annealing conditions of the samples are shown in Table 1.

The microstructure and electrical properties of the samples were then analyzed by TEM observation and conduction tests at room temperature and Hall effect measurement using the van der Pauw method at room temperature.

3. Results and discussion

Figure 2 shows the TEM microstructure of the p-GaN/Au contact (sample 3) after annealing at 573 K for 3600 s. As seen in the bright-field image shown in Figure 2 (a), a layer of Au film with approximately 400-nm-thickness is observed adjacent to GaN substrate. The electron diffraction pattern of the whole area shown in Figure 2 (a) was taken. The result is shown in Figure 2 (b). The diffraction pattern consists of only net pattern

Sample No.	Annealing Temperatures	Methods of Applying Voltages
1 (as-deposited)	-	-
2	-	(a)
3	573 K	-
4	573 K	(a)
5	573 K	(b)

Table 1 The annealing conditions of the samples.

Figure 1 Schematic illustrations of the methods of applying voltages during annealing at 573 K: (a) applying electrical field under the condition of DC 100 V without current flow, (b) applying current flow under the condition of DC 30 V.

Figure 2 Microstructure of the p-GaN/Au contact (sample 3) after annealing. (a) bright-field image, (b) selected area electron diffraction pattern of the area shown in (a).

of GaN. This result indicates that after the annealing at 573 K for 3600 s, the crystallization of Au film still does not occur or the Au film is in a very early stage of crystallization. Thus, no diffraction pattern consisting of Au net pattern is observed.

The fact that any net pattern except for GaN is not observed indicates that no reactions occur between deposited Au film and GaN substrate during the annealing at 573 K. If the reaction occurs at the interface between GaN and Au film, Au-Ga intermetallic compounds will be produced at the interface.

Compared with Au, these intermetallic compounds have lower values of work functions. Thus, the formation of these compounds at the interface will increase the Schottky barrier height and deteriorate the electrical properties of the contact. This reaction will also introduce unstable N atoms within p-GaN substrates, which consequently diffuse to the interface of p-GaN and Au film and form voids. The formation of voids at the interface decreases the area of contact interface and deteriorates the electrical properties of the p-GaN/Au contact. As seen in Figure 2 (a), no reaction layers exist at the interface. So, the reaction of Au-Ga under the annealing condition of 573 K for 3600 s can be negligible, *i.e.*, the deterioration of electrical properties of the contact have been avoided by annealing at low temperature.

Figure 3 shows the electrical conduction profile (I - V curves) of the samples, where I is the current and V is the voltage between electric pads. Numbers inset in Figure 3 correspond to sample numbers shown in Table 1. The electrical conduction profiles of sample 2 and sample 3 shows no clear differences from that of sample 1. As seen in Figure 3, marks of $\diamond$, $\square$, and $\triangle$ are overlapped. That is, no improvement of conductivity has been achieved. This implies that H release from p-GaN cannot be enhanced by only applying electrical field or annealing at 573 K. H within p-GaN has a very limited mobility at low temperatures because H combines with Mg. Thus, only the electric field applying or low temperature annealing of 573 K is not effective to release H from p-GaN.

However, by applying electrical field during the annealing at 573 K (sample 4; marks of $\blacktriangle$), some improvement of electrical conductivity has been achieved, as can be seen in Figure 3. This result reveals that a significant amount of H within p-GaN has been released by applying the electrical field at 573 K, resulting in improving I - V properties. It is likely that during annealing at 573 K, H within p-GaN formed H ions and H ions have enough mobility to be effected by the applied electrical field. H ions are moved near the interface between contact film and p-GaN by the applied electrical field, thus increasing the concentration of H at the interface. H diffuses along the interface to the surface of GaN and can be released to the outside. The higher concentration of H at the interface enhances the H release from the surface of p-GaN. The I - V properties improvement of sample 4 shown in Figure 3 indicate the increase of carrier (acceptor) concentration and decrease of Schottky barrier width at the contact interface have been achieved. These improvements can be attributed to the enhancement of H release from p-GaN.

As can be seen in Figure 3 (sample 5; marks of $\blacksquare$), further improvement is observed by applying current flow under the condition of DC 30 V during the annealing at 573 K. This

Figure 3 Electrical conduction profiles of the samples.

suggests that the amount of H released from p-GaN of sample 5 are much higher compared to other samples 2 ~ 4. If using Method (b), the interface and surface area necessary for releasing H from GaN is much smaller, compared with using the Method (a). In Method (a), the effective surface for releasing H from GaN is equal to the exposed p-GaN surface. The surface of the deposited Au film must not be an effective surface for H release, because Au film cannot contain H. On the other hand, in Method (b), the effective area for H release is only the interface (contact area) between Au film and p-GaN and the surface of GaN adjacent to the contact area.

With a smaller effective surface and interface area for H-release, the H concentration is much higher in Method (b), compared with Method (a). The increase of H concentration can enhance the H release. As a result, Method (b) gave the best I - V curve in the present study although Ohmic properties could not be obtained.

Finally, in order to investigate the dominant carrier-type of the sample, sample 3 (annealed at 573 K for 3600 s) was subjected to the Hall effect measurement at the room temperature. The result revealed that the dominant carrier-type for the sample was p-type; the dominant carrier-type of the samples could be retained after the annealing at 573 K for 3600 s. The annealing at 573 K for 3600 s is suitable for improving the electrical conductivity of p-GaN, while maintaining the p-type carrier.

In the present study, as shown in electrical conduction profiles in Figure 3, the I - V properties of the samples are not ohmic. Ohmic contact is necessary to achieve accurate measurement of carrier concentration. Therefore, the measured carrier concentration of the samples were considered not accurate and have been omitted. In the present study, the carrier concentration values obtained by Hall effect measurement were only be used qualitatively to determine the dominant carrier-type of the samples.

4. Conclusions

In the present study, in order to improve the conductivity and electric contact properties of Mg-doped p-GaN, the enhancement of H release from Mg-doped p-GaN are attempted by applying current flow and electrical field through the substrates during low temperature annealing at 573 K. The microstructure and electrical properties after annealing were then analyzed by transmission electron microscopy (TEM) observation, direct current (DC) conduction tests and Hall effect measurement. The result reveals that no reaction occur between deposited Au film and GaN substrate during annealing at 573 K for 3600 s. The electrical conductivity of p-GaN does not show any improvement only by applying electrical field or only by annealing at 573 K for 3600 s. This is likely due to the limited mobility of H within p-GaN. However, by applying electrical field or current flow during annealing at 573 K for 3600 s, significant improvement of electrical conductivity of p-GaN has been achieved. By applying electrical field or current flow during annealing at 573 K for 3600 s, the concentration of H near the surface and interface was increased, thus it was suggested that this high concentration of H enhanced the H release from p-GaN and improved the electrical conductivity of p-GaN.

Acknowledgements

The authors express their gratitude to Prof. H. Yasuda and Mr. E. Taguchi for their kind permission and assistance to use facilities in the Research Center for Ultra-High Voltage Electron Microscopy, Osaka University, Japan.

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