Development of Sputtering Module "SEGul" for Forming GaN Epitaxial Thin Films

Masanori SHIRAI[*1], **Souichirou TSUKUDA**[*1],
Hiroki KOBAYASHI[*1] **and Ryuichiro KAMIMURA**[*1]

[*1]Advanced Electronics Equipment Division, ULVAC, Inc., 2500 Hagisono, Chigasaki, Kanagawa 253-8543, Japan

We have developed the radical assist sputter epitaxy (RaSE) method to enable epitaxial growth of gallium nitride (GaN) by sputtering and the "SEGul" system for mass production. Compared to the metal organic chemical vapor deposition (MO-CVD) method, which is a common GaN film formation method, the RaSE method has the advantages of a low deposition temperature and a low material cost when forming epitaxial GaN thin films. The MO-CVD method uses organometallics and toxic gases such as NH_3 as raw materials at a formation temperature of about 1000°C. In contrast, the "RaSE" method uses common materials such as Ga, N_2, and Ar, and GaN formation can be performed at relatively low temperatures of 700°C or lower. It can also be applied to the formation of high density n-type GaN thin films with n-type carrier density in the $1x10^{20}$ cm^{-3} range by using an additional sputtering source for doping. In this report, we describe the characteristics of GaN thin films formed by the RaSE method, as well as the mass production system "SEGul" which can handle up to 8-inch wafer sizes.

1. Introduction

Gallium nitride (GaN), a compound semiconductor, is widely used as a light emitting element in LEDs for lighting. As a semiconductor, GaN offers the features of "high saturated electron velocity" and "high dielectric breakdown voltage." The former property is expected to be useful in applications such as GaN HEMT communication devices, while the latter property is expected to be useful in vertical GaN power devices. For example, GaN HEMTs (High Electron Mobility Transistors) using AlGaN/GaN heterojunctions are being developed as communication devices for 5G, a high-speed and high-capacity mobile communication standard. Development is also underway for the practical application of GaN vertical power devices as power supplies for EVs and servers. In recent years, the use of GaN devices in power supplies for PCs and mobile devices and in AC adapters for battery chargers has attracted attention for their compact size and high output power.

One of the problems shared by GaN-based LEDs and power devices is the reduction of contact resistance between semiconductor and metal electrode. As a solution to this problem, researchers have proposed a device structure that improves contact resistance by re-growing a high-density n-type GaN layer with a carrier density in the 10^{20} cm^{-3} range at the contact area between the electrode and the semiconductor[1,2)]. Meanwhile, the MO-CVD method, which is widely used as a manufacturing method for GaN, is said to be limited in terms of the concentration of n-type GaN that can be achieved[3)]. If the MO-CVD method is supplemented with a re-growth process, in addition to the extra equipment and materials, there is also the issue of increased costs associated with production, such as toxic gas abatement equipment. As a solution to these problems, we are developing epitaxial growth of GaN by the sputtering method. The sputtering method is a physical vapor deposition method in which a high voltage is applied to a target material in an argon (Ar) atmosphere and the plasma generated is used to deposit the material as a film on a substrate. In addition, nitrides can be formed by adding reactive gases such as nitrogen (N_2). In this way, GaN can be formed using materials that are easier to handle in comparison to the MO-CVD method.

In this report, we introduce the RaSE method, a GaN epitaxial thin film deposition technique that we developed, and the "SEGul" sputtering module designed specifically for RaSE.

2. Overview of the RaSE method

In this section, we briefly explain the formation of GaN by the RaSE method. Reactive sputtering is a method of forming compound thin films such as GaN by sputtering. It includes a method for sputtering a compound layer obtained by reacting a metal target surface with a process gas (for example, N_2) by using plasma, as well as a method that uses the desired

---

[*1] Advanced Electronics Equipment Division, ULVAC, Inc.
2500 Hagisono, Chigasaki, Kanagawa 253-8543, Japan

compound as the sputtering target. In both methods, the desired compound is deposited on the substrate to form a thin film. In Thornton's model[4,5], to achieve epitaxial growth through grains deposited on the substrate, it is considered effective to migrate the material on the surface to promote rearrangement and crystallization. To provide the energy required for migration, it is desirable to make the substrate temperature close to the melting point of the target material. However, while the melting point of GaN is high at about 2000°C or higher, thermal decomposition is said to occur from about 1000°C. When using the reactive sputtering method, the challenge is how to migrate the GaN grains.

The RaSE method we developed utilizes a metal Ga target and a plasma beam source for bombarding N^* (nitrogen radicals). It is characterized by the formation of GaN through the reaction of metallic Ga and N^* supplied as standalone elements on the substrate. Ga has a low melting point of less than 30°C and is easily dissolved by the heat of the sputtering plasma. Meanwhile, it can be handled stably as a liquid in the sputtering process because of its low vapor pressure. This property allows Ga to exist as liquid Ga even on the substrate, which seems to allow good migration to take place during the reaction process to GaN. Using this method, GaN epitaxial growth was achieved at substrate temperatures in the 600-700°C range, which is considered to be low for a GaN formation method. The N^* generated and supplied by the plasma source has stronger reactivity compared to the N_2 ion species generated in sputtering plasma, allowing the Ga adhered to the substrate to be sufficiently nitrified. The amount of N_2 required for this method is less than that of the reactive sputtering method, and it is possible to stably supply metallic Ga to the substrate without nitriding the Ga target surface.

2.1 Equipment configuration

Fig. 1 shows the components of the RaSE method. The basic structure of the processing chamber consists of an appropriate configuration of a sputtering cathode, a nitrogen radical source, a heater for substrate heating, and a process gas inlet. The gallium (Ga) target is placed on the sputtering cathode. Since Ga has a low melting point of approximately 30°C and is in a liquid state during the process, it is handled in a dedicated target container. The nitrogen radical source supplies N^* to the process chamber, allowing N^* to be utilized in the process in addition to the usual sputtering gases, Ar and N_2. Since the target Ga becomes a liquid, the equipment uses a "deposit-up" configuration in which the substrate is placed on top of the cathode. The heater for heating the substrate is installed on top of the equipment. When n-type GaN is grown by doping, a cathode for the dopant target, which is separate from the Ga cathode, can be used for co-sputtering with Ga. Typical additive elements are silicon (Si) or germanium (Ge), which can be swapped in by replacing the target.

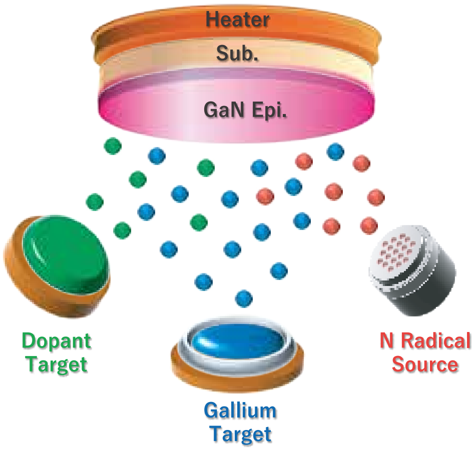


Fig. 1 Schematic diagram of RaSE method

2.2 RaSE method process flow

Fig. 2 shows the standard process flow of the RaSE method.

Substrate transfer

The substrate is transferred from the L/UL (Load/Unload) chamber to the process chamber. Using this mechanism,

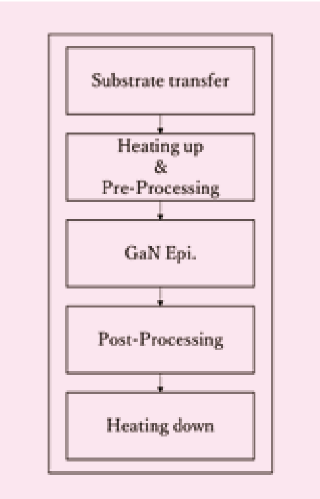


Fig. 2 RaSE method process flowchart

SEGul can load and unload the substrate while maintaining the heater temperature in the process chamber at 500℃ and the ultimate pressure at the 10^{-5} Pa range.

Heating up & Pre-Processing

After substrate transfer, the temperature is raised to the desired growth temperature. At the same time, the substrate can be bombarded with N* from the radical source.

GaN Epi.: Ga sputtering and epitaxial growth

Sputtering is performed by introducing the process gas (Ar or Ar+N$_2$) and N* from a radical source under specified conditions and applying voltage to the Ga and dopant sputter cathodes. On the substrate surface, the reaction between Ga and N* proceeds and a GaN layer grows.

Post-Processing

In the RaSE method, the GaN is formed by nitriding Ga on the substrate surface with N*. At the end of the sputtering phase, unreacted residual Ga may be present on the substrate surface. N* bombardment can promote the nitridation of this residual Ga.

Heating down

The substrate temperature is lowered to a predetermined temperature and the substrate is collected.

3. Characteristics of sputtered GaN thin films

In this section, we use the deposition results of SEGul, a sputtering module developed exclusively for RaSE, to introduce the characteristics of GaN thin films deposited by the RaSE method.

SEGul supports the direct transfer of 8 inch diameter wafers. By using a specially designed substrate holder, it is also possible to deposit films on surfaces such as chip substrates and wafers less than 8 inches in diameter. We used a 10 × 20 mm chip substrate for verification. We used two substrates: a sapphire substrate with an HVPE un-doped GaN template layer ("GaN on Sap. substrate") and a normal sapphire substrate ("Sap. substrate"). For the former, we evaluated various properties of sputtered GaN (SP-GaN) films, and for the latter, we measured film thickness from a cross-sectional image obtained by SEM to estimate the growth film thickness of the SP-GaN film.

3.1 Correlation between growth conditions and film quality in the RaSE method

Here we describe the change in film quality with respect to the amount of Ga supplied during the formation of GaN thin films. The growth flow of the SP-GaN layer is shown in Fig. 2. The substrate temperature during growth was set at about 600°C. The SP-GaN layer was grown by supplying Ga and n-type dopants to the substrate by co-sputtering and N* from the radical source. The target thickness of the SP-GaN layer was 100 nm, and an Si target was used as the n-type dopant. We prepared four conditions of SP-GaN thin films by varying the output power of the RF power supply connected to the Ga cathode. We evaluated each of the films and examined the change in film quality relative to the amount of Ga supplied.

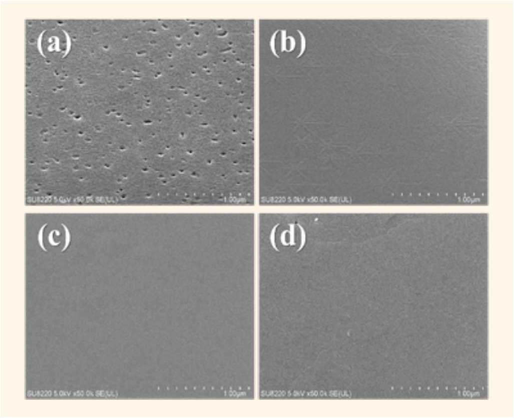


Fig. 3 SEM image of Si doped SP-GaN thin film formed by the RaSE method. (a) Ga power 77 W, (b) Ga power 80 W, (c) Ga power 85 W, (d) Ga power 90 W

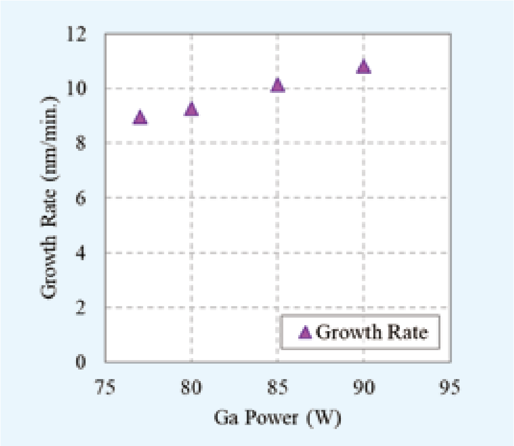


Fig. 4 Growth rate of Si doped SP-GaN layer formed on sapphire substrate

Fig. 3 shows surface SEM images of the Si-doped SP-GaN thin films on the GaN on Sap. substrate at various Ga power levels. It can be seen that the surface morphology improves as Ga power increases.

Next, we confirmed the thickness of the SP-GaN layer on the Sap. substrate by using SEM to measure the cross-sectional depth of the layer. The growth rate of the SP-GaN layer calculated from the obtained film thickness is shown in Fig. 4. Since the amount of sputtered grains (Ga) ejected from the target during sputtering depends on the RF power applied to the cathode, the amount of Ga supplied to the substrate increases with the RF power. Meanwhile, the amount of N^* supplied is constant, and when the amount of Ga supplied exceeds a certain level, the growth rate of GaN is predicted to plateau as Ga begins to accumulate on the substrate surface due to the lack of N^*. As a result, as shown in Fig. 4, the growth rate continues to increase proportionally with Ga power. Therefore, the growth in the scope of study is considered to represent growth under nitrogen-rich conditions where the supply of N^* is relatively large compared to Ga. In this study, we define Ga power dependence as the ratio of Ga and N^* on the GaN growth surface.

If the RF power applied to Ga is small and the relative abundance of N^* increases, the probability of collision between Ga and N^* at the growth surface will increase. Since the Ga that reaches the substrate reacts successively with N^* to form GaN, failure to maintain a Ga state favorable for migration inhibits epitaxial growth. As a result, the surface morphology of the GaN deteriorates as shown in Fig. 3(a). The probability of collision with N^* at the growth surface decreases when the abundance of Ga increases (increasing RF power). It is thought that the epitaxial growth progressed and the surface morphology improved because there was time to maintain a favorable Ga state for migration on the growth surface.

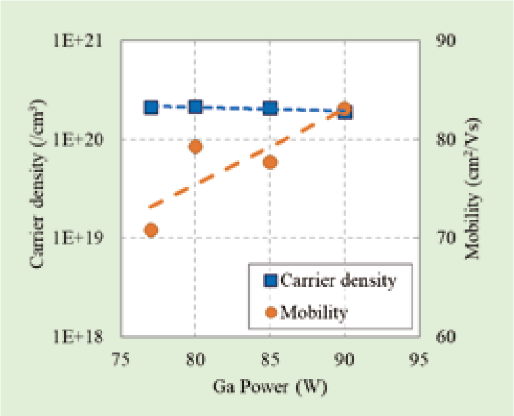


Fig. 5 Hall effect measurement results of Si doped SP-GaN layer formed on sapphire substrate with GaN template

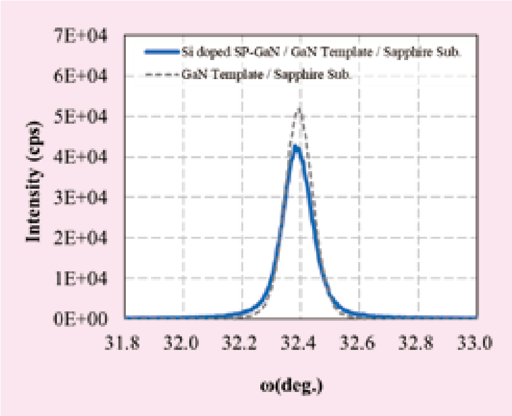


Fig. 6 XRD ω scan of GaN (10-10) plane

Fig. 5 shows the dependence of carrier density and mobility on Ga power in the SP-GaN thin film formed on the GaN on Sap. substrate. The data were obtained from Hall effect measurements. The carrier density is generally around 2.0×10^{20} cm^{-3} regardless of the Ga power. Mobility, on the other hand, which is sensitive to crystal quality, showed a tendency to increase with power. This result, which is consistent with the trend of improved surface morphology, is likely due to the improvement in crystal quality due to the increase in Ga power. For reference, Fig. 6 shows the results of a ω scan of the GaN (10-10) plane measured by

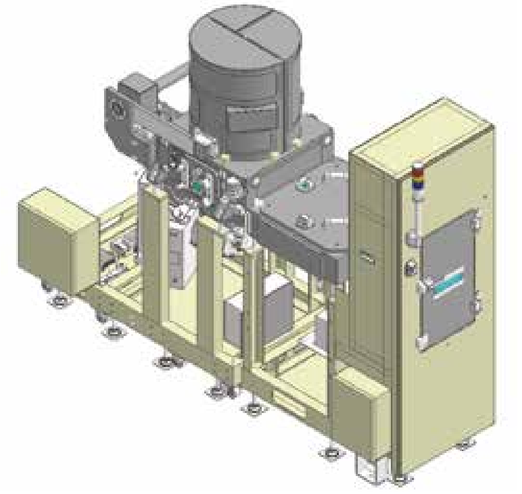
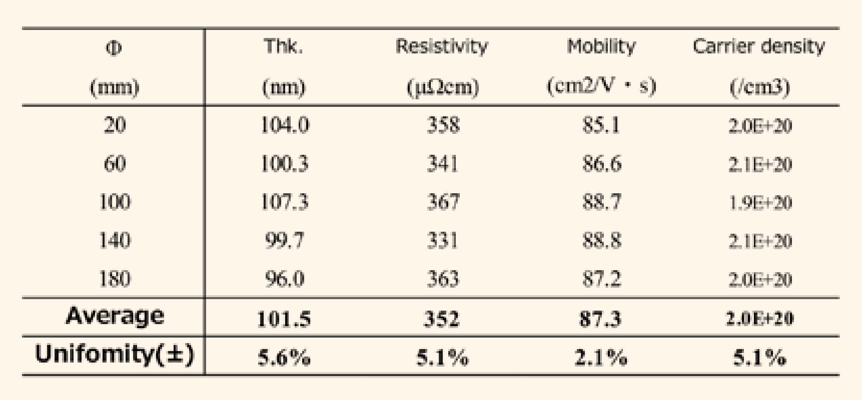


Fig. 7 External view of the GaN sputtering module "SEGuI"

Table 1 Uniformity performance of sputtered GaN films



Φ (mm)	Thk. (nm)	Resistivity (μΩcm)	Mobility (cm2/V・s)	Carrier density (/cm3)
20	104.0	358	85.1	2.0E+20
60	100.3	341	86.6	2.1E+20
100	107.3	367	88.7	1.9E+20
140	99.7	331	88.8	2.1E+20
180	96.0	363	87.2	2.0E+20
Average	**101.5**	**352**	**87.3**	**2.0E+20**
Unifomity(±)	**5.6%**	**5.1%**	**2.1%**	**5.1%**

X-ray diffraction (XRD) on the GaN on Sap. substrate. We compared the SP-GaN layer formed at Ga = 80 W with the HVPE GaN layer, which is the underlying film. The width at half maximum calculated from the obtained peak intensity was about 425 arcsec for the SP-GaN layer and about 401 arcsec for the GaN template layer.

The above results indicate that the supply ratio of Ga and N^* affects the basic film quality of GaN thin films grown by the RaSE method, including their growth rate, morphology, and electrical properties. We believe that optimization of both Ga and N^* is important in setting growth conditions.

3.2 GaN deposition performance of SEGul

Fig. 7 shows an external view of SEGul. The equipment basically consists of three chambers: a substrate cassette chamber, a transfer core chamber, and a process chamber. It is possible to increase the production volume by adding new process chambers to the transfer core chamber. When a hexagonal core is adopted, up to three process chambers can be deployed.

In this section we present the performance of SEGul in terms of the in-plane uniformity of its SP-GaN layer formation. To evaluate the uniformity, we used the same chip substrates (Sap. substrate and GaN on Sap. substrate) as in the previous section. Using a dedicated chip holder, we arranged substrates at positions corresponding to Ø20, 60, 100, 140, and 180 mm from the center of the Ø8 inch substrate to obtain the deposition performance at those positions. We set the growth conditions to the level of 80 W Ga power indicated in section 3.1, taking into account the in-plane distribution, and then evaluated the film thickness and electrical characteristics of each substrate using the same method as in the preceding section.

Table 1 summarizes the results of evaluating the film thickness and electrical properties. The average in-plane electrical properties for the obtained n-type GaN were as follows: mobility 87 cm^2/V • sec, carrier density 2.0×10^{20} cm^{-3}. The distribution of each property within the 8-inch plane was roughly ±5%. The substrate size used in GaN-based devices varies depending on the application and substrate type, but is typically 4 to 6 inches in diameter. These results indicate that in addition to the manufacturing of current devices, our method can also support the manufacturing of future larger-diameter devices.

4. Summary

In this paper, we introduced the RaSE method, a GaN epitaxial thin film deposition technique, and the SEGul sputtering module designed specifically for RaSE. While at present, this technology is specialized for the formation of high-concentration n-type GaN, it has advantages not found in existing GaN manufacturing techniques, including low temperature film formation, low cost, and ease of use. In device development, it is very important to have a choice of manufacturing methods to suit the purpose and application, and we expect that this technology will contribute to device development as a new option in GaN manufacturing.

References

1) N. Yafune, M. Nagamori, H. Chikaoka, F. Watanabe, K. Sakuno, and M. Kuzuhara: "Low-resistivity V/Al/Mo/Au ohmic contacts on AlGaN/GaN annealed at low temperature," Jpn. J. Appl. Phys., 49, (2010) 04DF10.

2) J. Zhang, X. Kang, X. Wang, S. Huang, C. Chen, K. Wei, Y. Zheng, Q. Zhou, W. Chen, B. Zhang, and X. Liu: "Ultralow-contact-resistance Au-free ohmic contacts with low annealing temperature on AlGaN/GaN hetrostructures," IEEE Electron Device Lett., 39, (2018) 847-850.

3) A. Suzuki, S. Choe, Y. Yamada, N. Otsuka, and D. Ueda: "NiO gate GaN-based enhancement-mode hetrojunction field-effect transistor with extremely low on-resistance using metal organic chemical vapor deposition regrown Ge-doped layer," Jpn. J. Appl. Phys., 55, (2016) 121001.4)

4) J.A. Thornton: J. Vac. Sci. T., 11, 666 (1974)

5) J.A. Thornton: J. Vac. Sci. T., A4 (6), 3059 (1986)