# **Power Devices Used in Automobile Technology**

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Dramatic changes have been occurring in the automotive industry. Among the targets of technological development has been the shift to all-electric vehicle (EVs) and fuel-cell vehicles (FCVs). Batteries, motors, and power devices represent the most essential technologies for EVs and FCVs. A power device is a semiconductor element that functions as a switch for converting the electric power. Examples include metal oxide semiconductor field effect transistors (MOSFETs) and insulated gate bipolar transistors (IGBTs). Power device technology is currently based primarily on silicon (Si) wafers. Silicon carbide (SiC) and gallium nitride (GaN) are gaining attention as next-generation alternatives due to their high voltage resistant property with low electric resistance, which is well suited to power devices. ULVAC is working on productivity enhancement for thin Si wafer processing equipment, ion implantation equipment for SiC, and process development of activating annealing to form a p-type region in GaN power devices based on magnesium (Mg) ion implantation.

# . Introduction

The automotive industry has been experiencing great changes recently. Until now, the industry has been focused on the comfort and convenience of cars. However, as a result of concerns about global warming caused by  $CO_2$ and the increasing incidence of accidents caused by older drivers, the focus is shifting to reducing environmental impacts and increasing safety. For these reasons, development of plug-in hybrid electric vehicles (PHEVs), electric vehicles (EVs), and fuel cell vehicles (FCVs) is underway in countries around the world. An important consideration for the various on-board parts is power electronics, represented by such components as the power control units (PCUs) that control batteries and motors.

# 2. Application of power electronics and power devices

Power electronics is a technology that converts AC and DC into forms most suitable to various instruments, and, as shown in Figure 1, is widely used in automobiles and home appliances. As the automobile industry transitions

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from gasoline-powered vehicles to PHEVs and EVs, PCUs are needed to ensure proper mutual power conversion between batteries and motors. Insulated gate bipolar transistors (IGBTs) are being used for PCUs. Metal oxide semiconductor field effect transistors (MOSFETs) and IGBTs are being used as the mainstay power devices because they offer a high cost-performance ratio, desirable functions, and high performance, and their drive circuits are simple and do not break easily.

MOSFETs are ideal for small-capacity, high-speed applications. An IGBT has a device structure in which a p+ layer is added to the drain side of a MOSFET; this is ideal



Fig. 1 Current state of power device applications

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for large-current, high-voltage applications. To improve the characteristics of IGBTs, technologies are being developed to achieve a miniaturized gate structure and use of thinner wafers. Additionally, to reduce cost, some manufacturers have begun to increase the diameter of thin wafers (from 200 mm to 300 mm).

#### B. Materials for Power Devices

Typical substrates for power devices include Si, SiC, and GaN. Currently, the mainstream material for power devices is Si, and many Si-MOSFET and Si-IGBT products are in use. Si's greatest advantage is its low wafer cost. The cost of an Si wafer is in the range of several thousand to tens of thousands of yen per wafer, whereas the cost of an SiC wafer is higher, starting at tens of thousands of yen. A GaN wafer is even more expensive, costing hundreds of thousands of yen for the 2-inch size. However, there is high expectation for Sic, GaN, and diamond as next-generation power device materials because they possess a wide band gap, high dielectric voltage, and high electron mobility, as shown in Table 1. Taking advantage of these features, PCUs can be made smaller and more efficient, rendering them both space-efficient and energy-efficient.

## 4. ULVAC's Activities

#### 4.1 Systems for handling Si-IGBTs

Since 1997, ULVAC has been selling an ion implanter (capable of handling thin Si wafers of between 150- $\mu$ m and 100- $\mu$ m in thickness) for IGBTs made from thin wafers. In order to improve the performance of IGBTs, device makers need to make a deep implantation layer in the Field Stop (FS) layer from the back side of a thin wafer, and must reduce the drive power loss and improve the switching speed characteristics. ULVAC is selling the SOPHI-400 ion implanter (Figure 2), which supports these needs. This ion implanter can implant phosphorus (P) ions with 2.4 MeV energy. It can also form an FS layer that uses hydrogen (H), creating an approximately 4- $\mu$ m deep profile.

A reverse conducting (RC) IGBT has a single-chip structure consisting of an IGBT and a diode. An RC IGBT requires a low-acceleration and high-concentration process in order to reverse the p-type area in the collector on the backside of the thin wafer to the n-type.

Material	Band-gap (eV)	Breakdown field (MV/cm)	Saturation speed (xE7cm/s)	Mobility (cm² /Vs)
Si	1.1	0.3	1.0	1350
SiC	3.3	2.8	2.2	1000
GaN	3.4	3.0	2.4	2000
Diamond	5.5	>10	1.5	4500

Table 1 Physical property comparison of various semiconductor materials When carrying out a low-acceleration and highconcentration process, conventional ion implanters require a long processing time, resulting in low productivity. Because the SOPHI-400 has a new lens mechanism in the acceleration area, it can obtain approximately three times as much current as before, achieving improved productivity.

ULVAC is currently selling the SOPHI-400 model that can handle 200-mm wafers, but a model capable of handling thin 300-mm wafers will also be introduced.

A large number of ULVAC sputtering systems compatible with thin wafers are also being used in mass-production plants. These sputtering systems can control the stress caused by the Ni film deposition used for avoiding thinwafer breakage. ULVAC is also planning to begin selling the SME-300 capable of handling 300-mm thin wafers.

#### 4.2 Ion implanter for SiC

Because SiC has a much smaller diffusion coefficient than Si, thermal diffusion technology cannot be used to achieve implantation into a deeper region. Therefore, high-acceleration implantation is required. Also, when high-concentration ion implantation is performed using a 4H-SiC substrate, the crystals end up transitioning to the 3C crystal structure after annealing, which means that implantation must be performed at high temperature. However, it is known that the 4H crystal structure is maintained when low-concentration implantation is used. Because a photo resist cannot be used when processing is performed at high temperature, an oxide film mask or the like must be used. Although low-concentration implantation ends up increasing the number of process steps, a photo resist can be used because implantation can be performed at normal temperature. In terms of process, it is known that implantation at high temperature can improve the characteristics in the case of highconcentration implantation, and conversely that processing at low temperature can improve the characteristics in the





case of low-concentration implantation. The IH-860PSIC is equipped with two platens for high temperature and cooling, and therefore can support both high-temperature and normal-temperature processes.

The IH-860PSIC is capable of implantation with implantation energy of 400 keV using single ions, and of 1200 keV using triple ions.

Starting in 2019, improvements in the ion source area of the IH-860PSIC ion implanter for SiC (Figure 3) have enabled it to achieve an increase of around 30% in beam current compared to the conventional IH-860PSIC. Additionally, ULVAC has begun selling the IH-860PSIC II with an improved lens mechanism, which increases the current in the low-energy region of 100 kV or lower by around 200%, greatly improving productivity.

This system can also cope with problems such as warping of SiC substrates.

ULVAC also plans to make and market a version of the IH-860PSIC II capable of supporting GaN ion implantation.

	Ion implantation	Anneal
Equipment	IMX-3500 (Magnesium)	HT-RTA59HD
Maker	ULVAC,Inc.	ADVANCE RIKO,Inc.
Main condition	1E19/cm <sup>3</sup> 300nm-box-deep	$1 { m atm} \ { m N}_2  { m Flow}, 1300 {}^\circ { m C}$

Table 2 Experimental equipment and conditions

## 4.3 Fabricating vertical GaN power devices using ion implantation

ULVAC has been carrying out development work jointly with Nagoya University under the theme "Research and development of next-generation semiconductors to realize an energy-saving society." This work has been undertaken in anticipation of an expansion of the market for GaN power devices. As part of this project, we are examining dopant activation technologies in order to form a vertical GaN p-type layer using Mg ion implantation.

Annealing is performed to activate the dopant following Mg ion implantation and to repair the crystal defects caused by the implantation process. However, under normal pressure, there is a problem of the GaN becoming thermally decomposed, causing nitrogen to escape. This paper reports on the world's first successful activation of the p-type region using ultra-high-pressure, high-temperature annealing.

### 4.3.1 Activating annealing and the temperaturepressure state during GaN decomposition

Using the system shown in Table 2, ions were implanted into a GaN substrate, and activating annealing was applied under normal pressure. Following annealing, GaN was thermally decomposed, causing the surface to become





rough, showing countless numbers of Ga chunks, as shown in Figure 4.

Figure 5 shows the temperature-pressure state of the GaN<sup>1)</sup>. As can be seen from the figure, the region where activating annealing was applied under normal pressure (in the vicinity of 1,200°C) is where the GaN separated into gallium and nitrogen.

### 4.3.2 Mg+N ion implantation and ultra-highpressure annealing

An ion implanter was used to implant Mg ions into the GaN, and activating annealing was applied without a passivation film, using an ultra-high-pressure and hightemperature annealing system. The measurement results



of the low-temperature cathode luminescence (CL) of the sample following annealing showed that the donor acceptor pair (DAP) intensity, which is the Mg activation index, had increased markedly, as shown in Figure  $6^{2}$ . Additionally, the green luminescence (GL), which is the nitrogen vacancy (VN) index, was at a nearly negligible level, in contrast to how it peaked in the DAP. Furthermore, applying Mg+N ion implantation and ultra-high-pressure N<sub>2</sub> annealing in combination increased the DAP's intensity while suppressing the GL. By implanting Mg ions together with N ions, it is possible to compensate for the VN defects.





## 4.3.3 Electrical characteristics resulting from Mg+N ion implantation and ultra-highpressure N<sub>2</sub> annealing

A PN diode was fabricated by forming electrodes on a GaN substrate that had undergone Mg+N ion implantation and ultra-high-pressure  $N_2$  annealing, and its I-V characteristics were checked. As shown in Figure 7<sup>2</sup>, rectifying characteristics and EL emissions were confirmed, indicating that carriers had been formed. Hall effect measurements proved that Mg ion implantation and ultrahigh-pressure annealing had caused activation, forming acceptors.

Figure 8<sup>2</sup>) shows the temperature dependence of Hall effect measurements. Both the carrier density and mobility showed the same tendency as a p-type GaN epitaxial film.

# 5. Conclusion

The number of areas in automobiles where power devices are used is increasing. Against this background, ULVAC is selling ion implanters needed for fabricating power devices, such as Si-IGBT and SiC devices. Additionally, for GaN devices, ULVAC is validating activation processes that use ion implantation and developing systems that will contribute to society in the future.

#### References

- 1) J. Karpinski et al.: J.Cryst.Growth 66, (1984) 1.
- H. Sakurai, M. Omori, S. Yamada, Y. Furukawa, H. Suzuki, T. Narita, K. Kataoka, M. Boćkowski, J. Suda, and T. Kachi: Advanced Program, Int. Workshop on SPIE2019 PHOTONICS WEST OPTO Session 6: Doping 10918–30.