New Technology using QST x CFB for Social Implementation of Vertical GaN Devices

Kenichi Tanigawa Takahito Suzuki Hironori Furuta
Takuma Ishikawa Ryohei Hanawa

As efforts accelerate to achieve carbon neutrality, there is growing need for higher performance semiconductor devices to improve society's energy efficiency.

In 2006, OKI became first in the world to successfully mass produce devices that integrated LEDs and ICs of dissimilar materials using a unique CFB (Crystal Film Bonding)[*1] technology[1]. Since then, the number of integrated LED elements shipped has exceeded 100 billion dots, establishing it as a core technology with high mass production reliability.

The case above integrated an LED onto an IC with a reflective structure, which increased luminous efficiency and also improved the energy efficiency of the device. New structures developed using CFB will further contribute to creating added value for semiconductor devices.

"CFB Solution" (**Figure 1**) is an initiative that not only applies CFB technology to LEDs but also extends application to various other crystalline materials and devices to create new semiconductor devices with additional value. CFB substrates are created by lifting off high-performance materials and devices with dissimilar functions (crystal layer films) from a seed substrate and bonding them onto a different substrate.

Here, two business models for the CFB solution will be introduced. The first model, referred to as the "bonded-type CFB business," will sell CFB substrates in which crystalline films are bonded onto substrates made from a dissimilar material. The second is the "supply-type CFB business," in which OKI supplies crystalline films that are temporarily bonded onto carrier substrates and provides licenses to enable transfer of the crystalline film in the customer's development process. Supply-type CFB can overcome differences in substrate size and equipment constraints when providing CFBs.

Currently, OKI's development is proceeding with the aim of contributing to four fields: micro LED displays, MEMS devices, optical devices, and power devices introduced in this article.

This article will clarify the issues associated with GaN (gallium nitride) devices from trends in next-generation power devices that are expected to help realize a carbon-neutral society. Then the article will introduce a new technology aimed at the development of vertical GaN devices through co-creation with Shin-Etsu Chemical Co., Ltd. using their QST[*2] substrate and OKI's CFB technology.

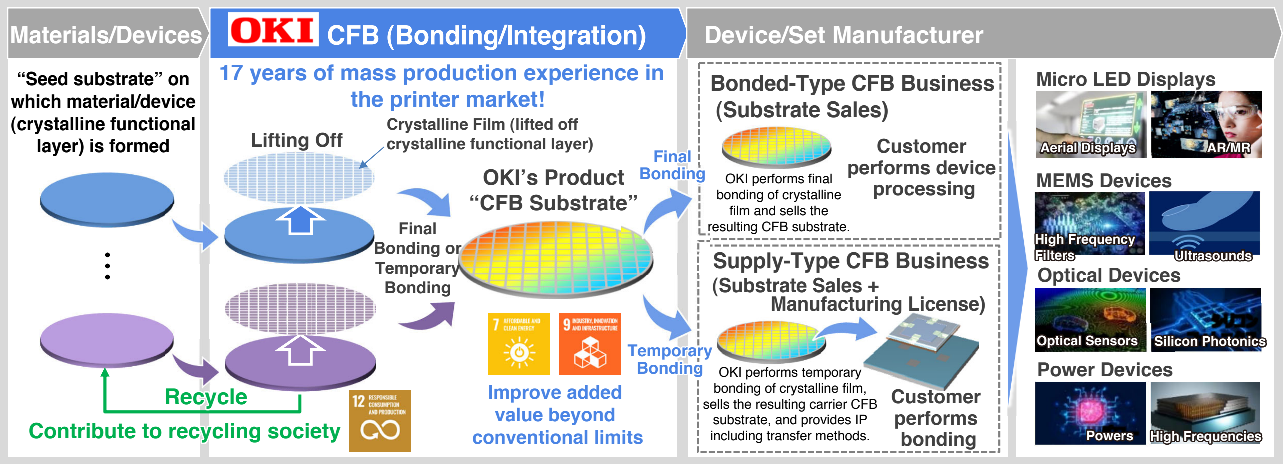


Figure 1. CFB Solution Business Models

[*1] CFB is a registered trademark of Oki Electric Industry Co., Ltd. in Japan.

[*2] QST is an abbreviation for Qromis Substrate Technology and is a registered trademark of Qromis, Inc. in the U.S. QST is a composite material substrate technology developed by Qromis specifically for GaN growth. Shin-Etsu Chemical acquired its license in 2019.

Market and Technology Trends for Next-Generation Power Devices

The market for next-generation power devices is expected to grow explosively and predicted to reach 5.4 trillion yen by 2035, more than 30 times the current market size2). Power devices are extremely vital devices installed in a wide range of equipment that uses electricity, such as those used in power, transportation, industry, EV (electric vehicles), small home appliances, and communications.

The reason behind the high expectations for next-generation power devices is the performance limits of the materials used in conventional Si power devices. For example, in the electrification of engines and turbines, it is necessary to achieve both high voltage for increased power and low resistance for reduced power consumption. Although higher voltage can be achieved by increasing the thickness of the element, increasing the thickness also increases electrical resistance. Thus, there is a trade-off between high voltage and low resistance, and further performance improvements to overcome current technical issues are difficult with Si power devices.

Hence, next-generation power devices using new materials that exceed the physical property limits of Si power semiconductors are attracting attention. Typical examples are SiC (silicon carbide), GaN, Ga_2O_3 (gallium oxide), and diamond. Among these candidates, SiC and GaN are the most promising materials in terms of their properties and feasibility.

High Material Properties of GaN

Figure 2 is an index that shows the characteristic limits inherent to the materials of power devices. It is expressed as the relationship between breakdown voltage, which shows how much high voltage the device can withstand, and on-resistance, which is related to device efficiency3). Closer the material is to the lower right, the higher its performance. Compared to SiC, the breakdown voltage of GaN is twice as high and the on-resistance is just one-fourth, showing that the material properties of GaN is much more superior than that of SiC.

Furthermore, AlN (aluminum nitride), which is similar in crystalline structure and lattice constant to GaN, has a breakdown voltage that is 35 times higher and an extremely low on-resistance that is 1/50 compared to SiC, demonstrating amazing high performance. Since GaN can be used in mixed crystal compound semiconductors such as AlGaN and AlInGaN, which have performances that fall between GaN and AlN, the pursuit of GaN-based technology will also contribute to the practical application of AlN, AlGaN, and AlInGaN.

As shown above, the material properties of GaN and GaN-based mixed crystal compound semiconductors greatly exceed those of SiC. Therefore, when power semiconductors using GaN becomes wide spread and next-generation rapid charging of EVs such as 900kWh (1500V) becomes possible, charging time could be reduced to just a few minutes. GaN is expected to make a significant contribution to improving society's energy efficiency.

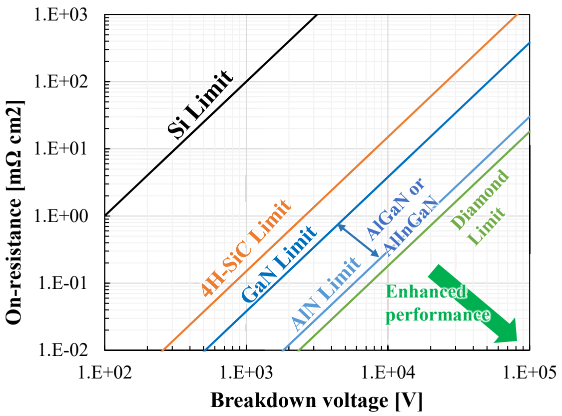


Figure 2. Theoretical Characteristic Limits of Power Device Materials

Issues Hindering Widespread Use of Vertical GaN Devices

Although the potentials of GaN are high, there are major issues with spreading the use of vertical GaN devices that can control relatively large currents. Therefore, in the EV market, which is predicted to be the largest market among next-generation power devices, there is presently a strong view that SiC will prevail over GaN.

Figure 3 summarizes the issues with the current vertical GaN devices. GaNon Si is a technology that grows GaN crystals on low-cost Si (111) substrates. There is a large 17% mismatch in the lattice constant between GaN and Si, which prevents growing crystals directly on the Si. Furthermore, the difference in CTE (Coefficient of Thermal Expansion) is extremely large at approximately 20% near the crystal growth temperature of 1,000K. This difference results in a tremendously large residual stress at room temperature that leads to a large number of cracks and defects. Therefore, a buffer layer is introduced to alleviate the crystal defects caused by lattice constant mismatch and residual stress, thereby making crystal growth possible. However, since the buffer layer is insulating, vertical conduction cannot be achieved.

On the other hand, GaN on GaN is an ideal technology for growing GaN on a GaN substrate. Since the lattice constants match and no buffer layer is required, vertical conduction is possible. However, the extremely high cost of the substrate limits the substrate diameter to 2 to 4 inches, and the inability to create large diameter substrates is preventing widespread adoption.

From the above, the challenge for the popularizing vertical GaN devices lies in balancing Issue (1): large diameter and Issue (2): vertical conductivity.

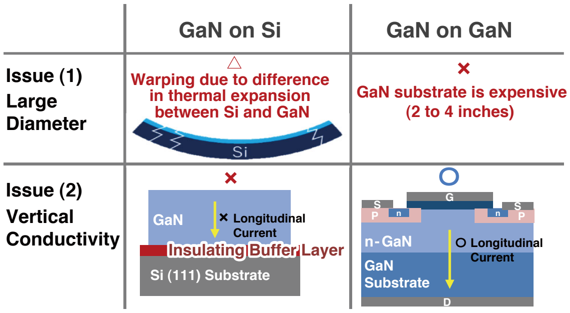


Figure 3. Issues for Vertical GaN with Conventional GaN Technology

Features of Shin-Etsu Chemical's QST Substrate

Figure 4 shows the structure of the QST substrate that addresses Issue (1): large diameter. The QST substrate has a CTE matched Core containing polycrystalline AlN, which has a CTE close to that of GaN. The area surrounding the core is coated with engineered layers that are made up of multiple layers of inorganic film. On the top surface, Si (111) is formed over a BOX (buried oxide) layer, making it possible to grow GaN crystals on the QST substrate.

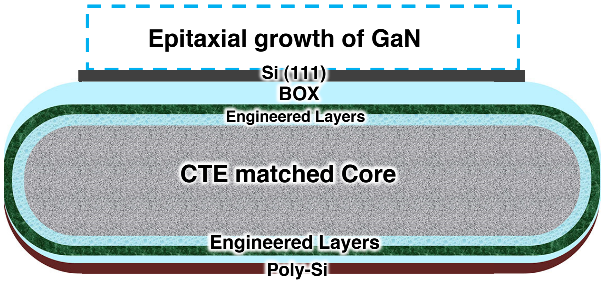


Figure 4. QST Substrate Structure (Source: Shin-Etsu Chemical)

As shown in **Figure 5**, the biggest feature of the QST substrate is its close CTE with that of GaN over a wide range of temperatures, and it also possesses many advantages, including:

1) Capable of high-quality and high-voltage thick-film GaN
2) Capable of high throughput with simplified buffer layer
3) Capable of standard board thickness
4) Capable of large 8-inch diameter
5) Proven with various GaN devices

In addition to its advantages in high material performance, it also has extremely excellent productivity and cost, thus it can solve Issue (1): large diameter. On the other hand, Issue (2): vertical conductivity is difficult to achieve on an insulated QST substrate. The next section will report the results of OKI's effort to achieve vertical conductivity through co-creation with Shin-Etsu Chemical.

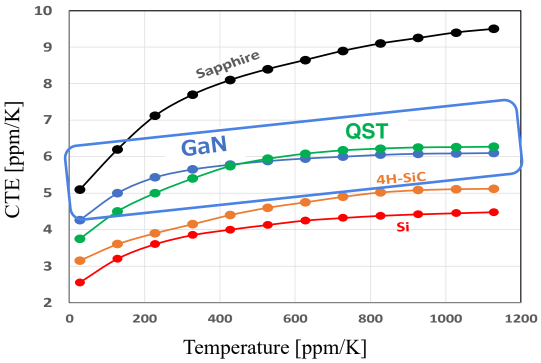


Figure 5. CTE Temperature Dependence of Various Substrates (Source: Shin-Etsu Chemical)

Co-Creation Results with Shin-Etsu Chemical's QST and OKI's CFB

Figure 6 shows the evaluation sample achieved through co-creation that demonstrates the structural solution to Issue (2): vertical conductivity. In this evaluation sample, only the GaN functional layer lifted off from the QST substrate was subjected to CFB on a metal layer formed on a conductive Si substrate with the insulating layer removed. The upper image on the rightmost side of **Figure 6** shows the top view photo, and the lower image shows a scanning electron microscope (SEM) photo of the cross section. Although heat treatment was performed at 600°C after CFB, it can be seen that the bond remained firmly in place without lifting off. Note that in addition to Si, CFB evaluations were conducted using SiC substrates, which have high thermal conductivity, and glass substrates, which have high insulation properties, and similar results were confirmed.

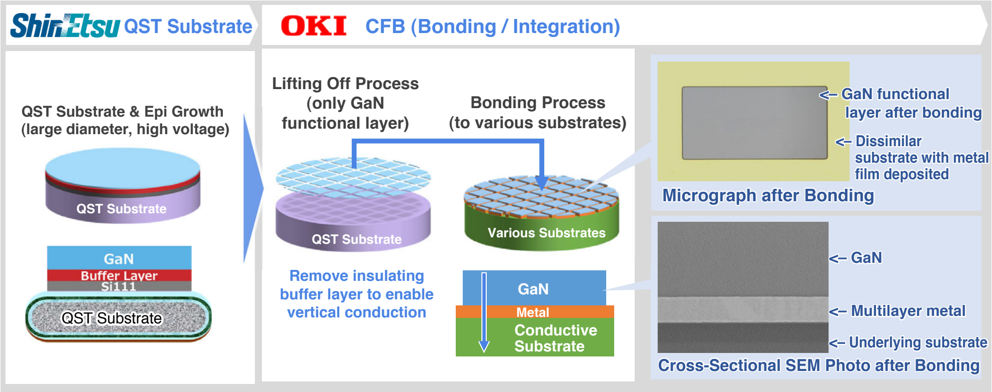


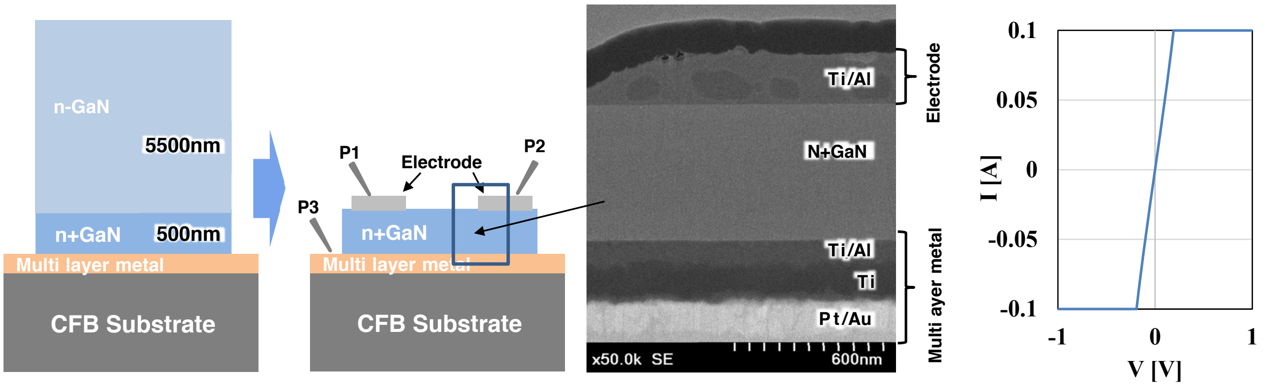
Figure 6. New QST x CFB Technology for Vertical GaN Devices

In evaluating the prototype devices' electrical characteristics, the contact resistance values at the CFB interface were measured (**Figure 7**). The structure and contact resistance measurement method of the n+GaN (Si doping concentration of 5x10^{18}) samples subjected to CFB are shown. **Figure 7(a)** shows the state after CFB with n-GaN having a thickness of 5500 nm and n+GaN having a thickness of 500 nm. N-type Si (100) substrate was used for the CFB substrate. The n-GaN of the sample in **Figure 7(a)** was dry-etched to expose the n+GaN and a Ti/Al electrode was formed at two locations on the surface. Then, heat treatment was performed at 600°C. **Figure 7(b)** shows the cross-sectional structure of the completed measurement sample. **Figure 7(c)** is a cross-sectional SEM photo in which a Ti/Al contact electrode was formed on the n+GaN.

As shown in **Figure 7(b)**, the method for measuring contact resistance is to first calculate the top contact resistance by measuring the resistance between P1 and P2. Then, the resistance of the CFB interface was calculated by subtracting the top contact resistance and the theoretical resistance of n+GaN from the measured resistance between P1 and P3. **Figure 7(d)** shows that a good ohmic contact is formed between P1 and P3. Furthermore, when the resistance was converted into current path area and the resistivity calculated, it was found to be 6.33x10$^{-7}\Omega$cm^2. The resistivity of Ti/Al and n+GaN is reported to be 10^{-6} to 10$^{-8}\Omega$cm^2 4) indicating that contact characteristics at the CFB interface are also good, and there is no deterioration due to CFB.

Conclusion

This article introduced a new technology for vertical GaN devices born from a new idea and co-created with Shin-Etsu Chemical. To improve society's energy efficiency and contribute to carbon neutrality, future plans call for operational demonstration of vertical GaN devices to promote the social implementation of this co-created technology.



(a) State after CFB

(b) Measurement Sample Structure

(c) Sample Cross-Sectional SEM Photo

(d) Linear IV Characteristic between P2 and P3

Figure 7. n+GaN Contact Resistance Measurement Sample and Measurement after CFB

Acknowledgment

The development of this technology was a co-creation effort with Shin-Etsu Chemical Co., Ltd. OKI expresses its utmost gratitude and appreciation. ◆◆

References

1) Norio Nakajima: Small LED Heads realizing High-speed and High-quality Gradation Printing, OKI Technical Review Issue 227 Vol. 83 No. 1, May 2016 (in Japanese)
2) Current Status and Future Prospects of Next-Generation Power Devices and Power Electronics Related Equipment Markets 2023 Edition, P12, Fuji Keizai, March 3, 2023 (in Japanese)
3) J. Y. Tsao, et al.: Ultrawide-Bandgap Semiconductors: Research Opportunities and Challenges, Advanced Electronic Materials, vol.4,Issue1, 1600501, 04 Dec.2017
4) B. P. Luther, et al.: Investigation of the mechanism for Ohmic contact formation in Al and Ti/Al contacts to n-type GaN, Appl. Phys. Lett. 70, 57–59, 06 Jan. 1997

Authors

Kenichi Tanigawa, CFB Development Department, Innovation Business Development Center

Takahito Suzuki, CFB Development Department, Innovation Business Development Center

Hironori Furuta, CFB Development Department, Innovation Business Development Center

Takuma Ishikawa, CFB Development Department, Innovation Business Development Center

Ryohei Hanawa, CFB Development Department, Innovation Business Development Center

【Glossary】

dry etching

A method of etching materials using reactive gases, ions, or radicals.

ohmic contact

A state in which there is no electrical barrier between semiconductor and metal, and the contact resistance is sufficiently small. Therefore, the current-voltage characteristics are linear in both positive and negative directions.