CFB® Solutions for Co-Creating Technological Innovation - Open Innovation Case Studies -

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Recently, with the realization of an energy-saving society, including carbon neutrality, and the accelerating digitalization/automation in production sites and living environments, social demands on semiconductor technology have become more diverse and sophisticated than ever before. The continuing spread of smart grids that support a decarbonized society, real-time control and data analysis using advanced AI and IoT devices, and the construction of a global, high-capacity, high-speed information and communications infrastructure are expanding the role of the semiconductor industry.

Meanwhile, miniaturization technologies, which have driven the semiconductor industry's evolution for many years, are approaching their physical and economic limits. Moving away from traditional integration using a single material and a single process, heterogeneous material integration technologies, which combine diverse materials and device types to realize high-density, high-performance, high-reliable, and high-value-added integrated systems, are now becoming increasingly important.

OKI's proprietary Crystal Film Bonding (CFB®[*1]) technology enables heterogeneous materials to be firmly bonded at room temperature. The process is shown in **Figure 1**. CFB technology was first put into practical use in 2006 to manufacture light sources for LED printers. OKI was first in the world to successfully bond GaAs (gallium arsenide) LEDs with Si (silicon) ICs, despite their vastly different physical properties. In close to 20 years of mass production, OKI has supplied over 100 billion dots into the market[1]. Furthermore, during this period, there has not been a single incident of delamination of the thin-film LEDs bonded using CFB, demonstrating the high stability and reliability of CFB.

OKI is currently leveraging the features of this CFB technology and its proven mass production track record to promote open innovation with a wide range of partners. The technology is being expanded into a variety of application fields, including power devices, analog ICs, and optical devices, with the aim of building photonics-electronics convergence ecosystems and GaN power device ecosystems.

This article introduces specific examples of co-creation with partners using CFB technology in the fields of power devices, analog ICs, and optical devices, and discusses the evolution of OKI's technology, which contributes to solving social issues and creating innovation, as well as the technology's outlook for the future.

CFB Solutions for Power Devices

Demand for power devices is expanding with the spread of electric vehicles and renewable energy. There are issues with conventional silicon-based power devices, such as limitations in voltage resistance and high-speed switching, creating a need for new materials to overcome these issues. For this, gallium nitride (GaN) is attracting considerable attention as a next-generation material capable of providing high-voltage power, high-speed

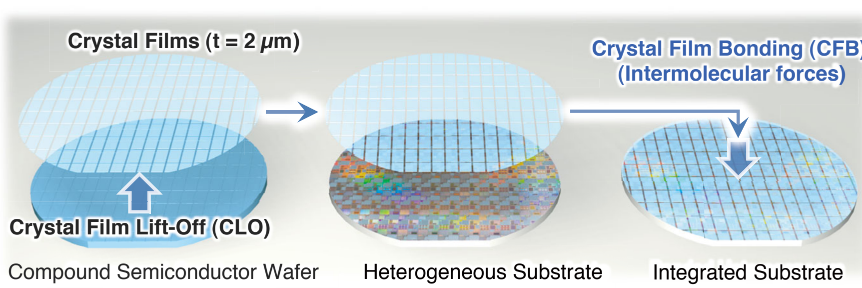


Figure 1. CFB Process

*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 US trademark of Qromis, Inc. It is a composite material substrate technology developed by Qromis specifically for GaN growth. Shin-Etsu Chemical acquired the license in 2019.

switching, and high-temperature operation.

However, achieving a high-current vertical conduction structure using a GaN functional layer grown on a conventional silicon substrate poses technical barriers, including the difficulty of achieving high voltage resistance through thick film growth and high crystal quality. Furthermore, the existence of an insulating buffer layer between the substrate and the GaN functional layer required during crystal growth impedes vertical conduction.

In contrast, Shin-Etsu Chemical Co., Ltd.'s QST®*2) substrate, developed with a unique structure that closely resembles the thermal expansion coefficient of the GaN functional layer, significantly reduces crystal distortion and defects that occur during GaN functional layer growth, enabling the growth of high-quality thick-film GaN functional layers[2]. Furthermore, since substrate distortion is minimized, the process can be applied to Si device manufacturing lines. This raises expectations as a new material technology for the mass production of high-voltage power devices. However, an insulating buffer layer is still required between the QST substrate and the GaN functional layer to ensure crystalline quality, and achieving vertical conduction for large currents remained an issue.

To address this issue, OKI developed a new process using CFB technology shown in **Figure 2**. The process only lifts off the GaN functional layer grown on the QST substrate, and after the insulating buffer layer is removed, the GaN functional layer is directly bonded to the metal layer on the Si substrate. Cross-sectional scanning electron microscope (SEM) observations and heat treatment tests at 600°C confirmed high-quality bonding with no voids between the GaN functional layer and the metal layer. Furthermore, evaluation of the electrical properties through the bonded interface revealed excellent vertical conduction characteristics, successfully demonstrating the feasibility of vertical conduction in GaN power devices.

This result is expected to significantly contribute to improving device performance in the power electronics field and accelerating industrial applications.

CFB Solutions for Analog ICs

Analog ICs are becoming increasingly important as IoT and industrial equipment become more functional and energy-efficient. Compact, high-performance analog ICs are a key technology for supporting the future smart society infrastructure, and low noise, high sensitivity, space-saving design, and high reliability are strongly demanded. In response to this challenge, Nisshinbo Micro Devices Inc. has refined its proprietary analog semiconductor design technology to develop analog semiconductors with high-precision signal processing and excellent low-noise characteristics. However, there are limitations in the degree of integration and product miniaturization that can be achieved with conventional chip mounting.

OKI applied CFB technology to Nisshinbo Micro Devices' analog ICs to develop a thin-film process for analog ICs and their integration onto separate substrates. Analog ICs are advanced devices integrating numerous transistors. CFB technology enabled functional layers to be lifted off from silicon substrates without impairing their operating characteristics and then be reliably bonded to other substrates[3]. **Figure 3** shows a cross-section of the stacked chips.

Furthermore, since analog ICs perform continuous analog signal processing under high operating voltages, it is important to design the ICs to suppress inter-layer interference noise when stacking layers. By combining CFB technology with Nisshinbo Micro Devices' proprietary local shielding technology, OKI succeeded in protecting the functional layer while lifting off the layer

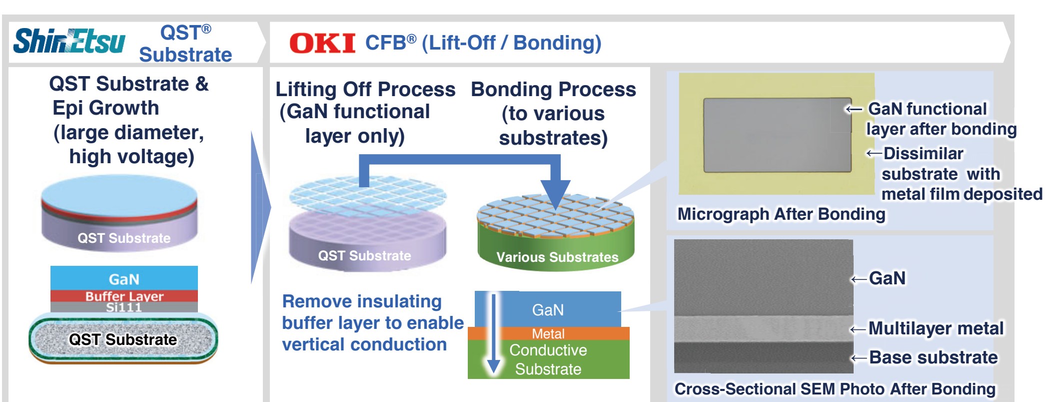


Figure 2. New QST and CFB Technology for Vertical GaN Devices

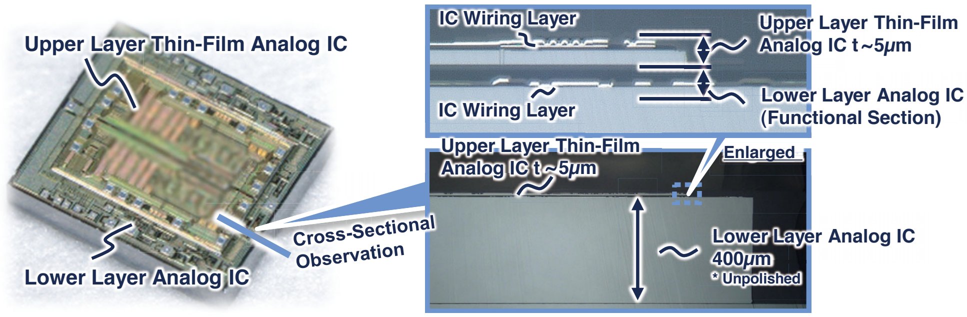


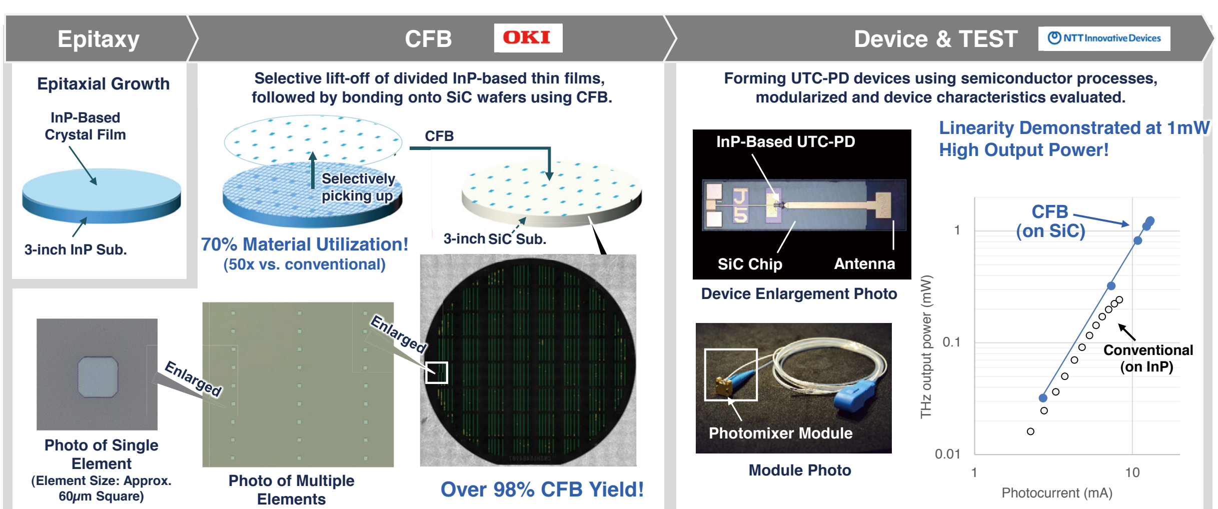
Figure 3. Analog IC Stacking using CFB

and stacking it on top of another IC substrate. This method has been demonstrated to effectively prevent noise caused by interference between ICs even when stacked, maintaining high-precision, high-sensitivity signal processing performance. As a result, the prototype device possessed input/output characteristics equivalent to mass-produced devices, and implementation experiments in an audio system confirmed that the sound quality was comparable to existing products.

These results demonstrate that analog IC integration using CFB technology opens new possibilities, enabling high-performance integration of a variety of elements, including analog and digital ICs. This is expected to make a significant contribution to the future development in the analog IC field.

CFB Solutions for Optical Devices

Increasing communication speeds and reducing power consumption at data centers are major challenges in the information and communications field, and the shift from electrical communications to optical communications is accelerating. To meet these needs, it is imperative that the cost structure be reviewed and the performance of optical devices used in optical communications be improved. Optical devices are typically fabricated using expensive indium phosphide based (InP-based) epitaxial materials grown on InP substrates, However, only a small portion is actually functional, leaving most of the material unused. Furthermore, InP substrates have inferior thermal conductivity compared to Si and SiC substrates, making them susceptible to heat during high-power operation.



Device enlargement photo, module photo, and characterization graph provided by NTT Innovative Devices Corporation

Figure 4. UTC-PD and CFB Combined Terahertz Device

*3) The SiC substrate-bonded UTC-PD photomixer technology is based on part of research conducted by The University of Osaka, Kyushu University, and the University of Tokyo under the general project (JPJ012368C-00901) of the Beyond 5G R&D Promotion Project's Beyond 5G Function Realization Program, commissioned by the National Institute of Information and Communications Technology (NICT).

*4) The technology was partially developed as part of the New Energy and Industrial Technology Development Organization (NEDO)'s "Research and Development Project of the Enhanced Infrastructures for Post-5G Information and Communication Systems / Development of Manufacturing Technologies for Advanced Semiconductors / R&D of Optical Chiplet Packaging Technology" to investigate heterogeneous material bonding.

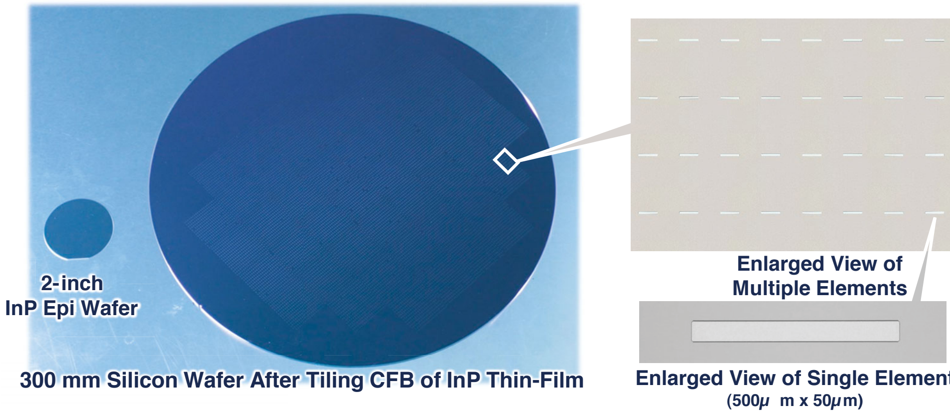


Figure 5. Tiling CFB Technology

OKI is working to address these issues by utilizing CFB technology. One example is its co-creation effort with NTT Innovative Devices Corporation. NTT Innovative Devices has collaborated with The University of Osaka, Kyushu University, and the University of Tokyo, in an aim to increase the output power of Uni-Traveling Carrier Photodiode (UTC-PD) terahertz devices, which are expected to be used in next-generation communications. By bonding heterogeneous materials onto a SiC substrate, which has thermal conductivity approximately seven times higher than that of an InP substrate, the collaboration team succeeded in developing a high-power UTC-PD that significantly improves heat dissipation characteristics and achieves an output saturation power of over 1mW[*3]. However, with conventional bonding technology, the utilization efficiency of the InP-based epitaxial material was low at approximately 1%, and the bonding yield was also limited to approximately 50% or less, posing issues for mass production.

As shown in **Figure 4,** when CFB technology was implemented, the utilization efficiency of the epitaxial layer was improved to approximately 70%, more than 50 times that of the conventional technology, and the bonding yield was improved to nearly 100%[*4]. Furthermore, it was confirmed that the device characteristics were good, maintaining the same performance as the existing technology. This established the fundamental technology that will enable the mass production of high-power terahertz devices[4].

The advancement of the information society also raises concerns about power supply shortages at data centers. There is a strong demand for photonics-electronics convergence, which integrates and combines optical devices made from compound semiconductors and other materials with silicon devices. In particular, the integration of optical devices with silicon photonics fabricated on silicon substrates is an important factor for future technological development. However, the significant differences between Si and InP, such as physical properties, substrate size, and manufacturing infrastructure, were big barriers for practical implementation. To solve this issue, OKI developed the tiling CFB technology, establishing a technique for precisely and seamlessly bonding multiple InP-based functional layers onto large-area substrates such as 300mm Si wafers[5]. **Figure 5** shows tiling CFB on a 300mm Si wafer. The solution is a major step toward realizing the integration of silicon photonics with the large-scale, multi-function optical devices, which is necessary for photonics-electronics convergence.

Future Outlook

CFB technology has made it possible to bond heterogeneous materials with high adhesion and high quality at room temperature in a wide range of fields such as power devices, analog ICs, and optical devices, achieving functional integration that was not possible with conventional technology. OKI will further promote open innovation to advance the creation of photonics-electronics convergence ecosystems and GaN power device ecosystems centered around CFB technology, and contribute to the realization of a sustainable society through improved semiconductor performance and reduced power consumption.

Acknowledgments

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TIPS

【Glossary】

Power Devices
Semiconductor elements used for the purposes of power conversion, control, and switching.

Analog ICs
Integrated circuits that process, amplify, and convert continuous analog signals such as voltage and current.

Optical Devices
Semiconductor elements with functions of generating, modulating, transmitting, receiving, and converting light.

Photonics-Electronics Convergence
Technology that combines optical and electronic technologies to improve the performance of information processing, signal transmission, etc.