CFB Solutions for High Performance Semiconductor Devices using Novel Bonding Technology

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As companies accelerate their efforts to achieve SDGs (Sustainable Development Goals), the need for semiconductor devices that support the evolution of DX (Digital Transformation) have been increasing in recent years.

However, based on Moore's law, silicon ICs (Integrated Circuits) are approaching their limit of miniaturization, and the trend is shifting toward adding higher value in semiconductor devices through the integration of different functions (More than Moore). Technology that integrates different devices such as optical, power, and sensors/actuators through compositing increases added value by providing functions that silicon ICs do not possess on its own. The technology is attracting attention as a key to sustainable growth of the semiconductor industry.

OKI was first in the world to successfully mass produce "CFB (Crystal Film Bonding) technology" that integrated LEDs and ICs, contributing to the miniaturization of printers[1]. Since then, OKI has shipped more than 100 billion integrated LED elements, establishing the technology as a highly reliable core technology for mass production.

"CFB Solutions" (**Figure 1**) introduced in this article utilize the aforementioned CFB*[1] technology cultivated within OKI to increase the added value of compositing semiconductor devices thereby contributing to "Delivering OK! to your life." Simply stated, it is the "externalization" initiative of OKI's DX strategy.

Figure 1. Values Provided by CFB Solutions

The article will first introduce the CFB technology cultivated in OKI's printer business. This will be followed by the explanation of the CFB solution business model including the introduction of the microLED display application and MEMS application (co-creation with KRYSTAL, Inc.) that are underway with external collaboration.

CFB Technology Cultivated in Printer Business

OKI's LED printers feature the use of an LED head as the writing light source, which in 1979, became the world's first to be put into practical use. For example, in a 1200dpi (dot per inch) A3-sized LED head, approximately 15,000 LED dots are arranged linearly at a pitch of 21μm, and the driver IC is driven according to print data to control the lighting of individual LED dots.

Conventionally, two separate chips needed to be utilized for the LED array and driver IC due to the large difference in their manufacturing processes. Consequently, these chips were electrically connected through wire bonding (**Figure 2A**).

However, as the resolution of the LED head increased, the mounting density of the gold bonding wires increased as well making further size reduction difficult. Therefore, the LED array chip was integrated on the driver IC using CFB technology (**Figure 2B**). This reduced the width of the printed circuit board, and the volume of the LED head was reduced to half[1].

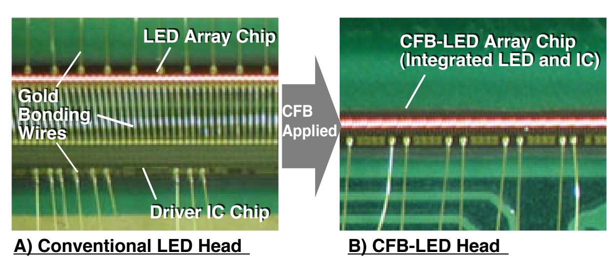

Figure 2. Application of CFB Technology to LED Head

*1) CFB is a registered trademark of Oki Electric Industry Co., Ltd.

Figure 3 shows an overview of the CFB technology applied to the LED head. The LED film grown on the gallium arsenide semiconductor wafer is peeled and directly bonded without an adhesive onto the driver IC wafer, which is a silicon semiconductor. Afterwards, LED element processing and wiring formation are performed using semiconductor processing, and a CFB LED array chip in which the LED and the IC are integrated is completed.

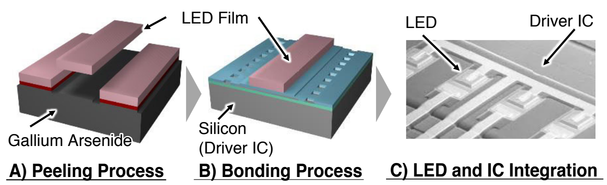

Figure 3. CFB Technology for LED Printer

CFB Solution Business Model

The CFB solution business model is shown **Figure 4**. Upstream partners manufacture high-performance functional thin film wafers for MEMS, optical, power and other devices. OKI manufactures “CFB wafers” obtained by peeling and bonding the functional thin film layers from wafers and provides them to device manufacturers. Semiconductor processing is performed on “CFB wafers,” and device manufacturers are able to manufacture devices with higher functionality than before.

There is a wide variety of peelable functional thin film materials, including silicon semiconductors, compound semiconductors, piezoelectric, inorganics, organics, and metals.

Wafer/substrate materials that can be bonded include compound semiconductors, silicon semiconductors, glass, ceramics, and plastics, and can also be bonded to wafers/ substrates with circuits such as ICs and TFTs (Thin Film Transistors).

As a bonding method, OKI has succeeded in developing a “batch CFB” that bonds multiple elements at once and has achieved high productivity. Additionally, there are three features that increase added value. The first is “parallel CFB” that allows multiple different functional elements to be integrated in parallel on the same plane, the second is “stacked CFB” that stacks multiple different functional elements, and the third is “on-structure CFB” that enables bonding onto a three-dimensional structure such as a cavity, which is often used in MEMS devices.

CFB solutions have great potential to increase added value in various application markets. OKI especially believes there is high affinity with microLED displays, MEMS, optical devices, and power devices, and is proceeding with research and development in these areas.

Example of CFB Solutions: LED Display Application

In this section, the microLED display application is introduced as a leading case of CFB solutions.

(1) Needs and Challenges of Application Market

In recent years, AR (Augmented Reality) / MR (Mixed

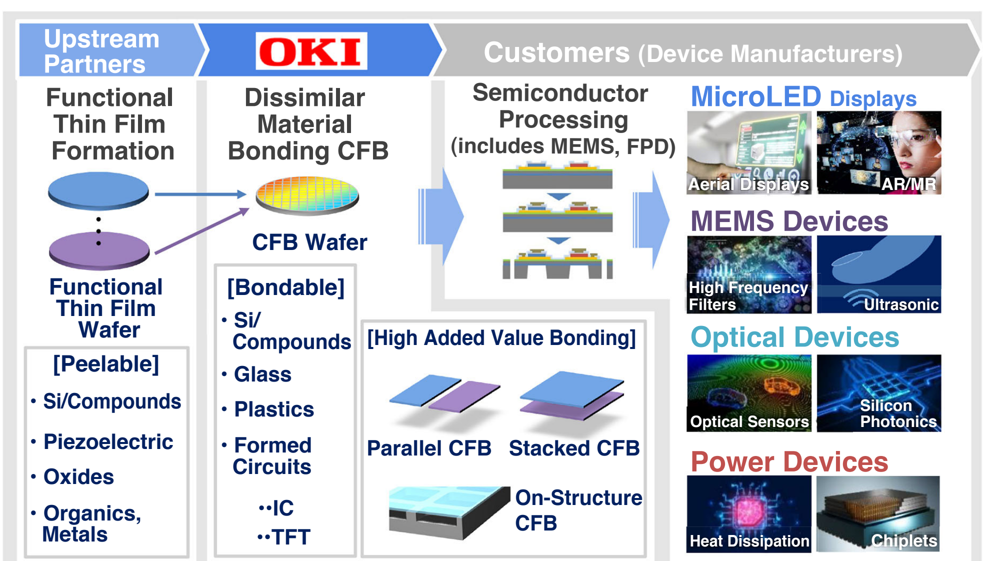

Figure 4. CFB Solutions / CFB Business Model

Reality) have increased the need for smart glasses and head-up displays that enable visual recognition of new business atmosphere that fuses the real and the virtual. The challenges for widespread use are higher luminescence for better visibility outdoors during daytime and lower power consumption for battery miniaturization. MicroLED displays are attracting attention as a means to solve these problems. In a microLED display, all pixels are configured using microLEDs, which are self-luminous elements. Therefore, high luminescence and low power consumption are expected.

However, in order to achieve full color, a large number of microLEDs using different materials to emit the red, green, and blue (R, G, B) colors must be bonded together, which poses a challenge in manufacturing technology. Hence, OKI has been addressing this manufacturing challenge with CFB solutions.

(2) Demonstration of MicroLED Display's Added Value

Figure 5 demonstrates the full-color microLED display using CFB solutions. Over 140 thousand microLEDs comprised of 176 individual RGB LEDs lined vertically and 272 RGB groups lined horizontally are bonded in "parallel CFB" formation atop a silicon substrate on which wiring is formed. Since the R, G, and B microLEDs are formed from different materials, "batch CFB" is repeated three times. The achieved bonding speed is approximately 10,000 elements/second, which is about 200 times faster than the conventional method[2]. The size of the LED elements is 10μm×20μm, and full color has been achieved with extremely small microLEDs expected for AR.

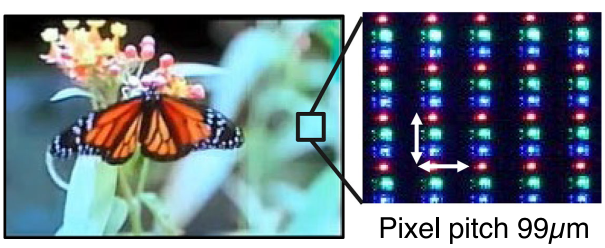

Figure 5. 1.5Inch Full-Color MicroLED Display using CFB Solutions

As demonstrated above, CFB solutions solve the problem of production technology for full-color microLED displays. Development will be continued for even higher luminescence and density to further contribute to the creation of microLED displays with increased added value.

Example of CFB Solutions: MEMS Device Application

The example presented in this section is a co-creation effort between KRYSTAL, Inc. and OKI to increase the added value of ultrasonic sensors by applying CFB solutions to MEMS devices.

(1) Co-Creation Business Model

KRYSTAL, Inc. is an upstream partner in the CFB business model shown in **Figure 4** and manufactures "piezoelectric single crystal thin film wafers" that determine the performance of MEMS devices. OKI peels off the piezoelectric single crystal thin films and bonds it to the requested wafers to manufacture "CFB wafers" then supplies the wafers to semiconductor/MEMS device manufacturers.

Conventional piezoelectric thin films are polycrystalline, and the arrangement of the crystals is inconsistent, therefore the true performance of the material could not be exhibited. If the crystals of the single crystal film are correctly arranged, the true physical properties can be exhibited, but obtaining single crystallization on a practical sized area has been difficult. However, KRYSTAL, Inc. has succeeded in single crystallizing a practical 8-inch size area using a proprietary buffer layer, and extremely higher performance was achieved compared to polycrystals[3]. The ability of OKI's CFB solutions to peel and bond KRYSTAL, Inc.'s thin films without compromising performance raised expectation for increasing added value in way that could not be imagined in the past, and led to this co-creation effort.

(2) Needs and Challenges of Application Market

Due to the increasing need to handle highly confidential information, recent smartphones have adopted fingerprint authentication that achieves both usability and security.

Electrostatic, optical, and ultrasonic are the three methods used for fingerprint authentication. Electrostatic and optical methods recognize only the two-dimensional information on the surface of the fingerprint, and therefore they are less resistant to falsification.

On the other hand, the ultrasonic method uses an ultrasonic sensor to penetrate the object and obtains cross-sectional information. Therefore, in addition to the surface of the fingerprint, the internal veins can be detected to improve anti-spoofing. As technology advances, three-dimensional recognition of the vein shape will lead to the possibility of vein authentication to further improve security.

Unfortunately, the detection depth of conventional ultrasonic sensors is about 0.5 mm. In order to detect veins that typically exist 2mm below the skin, it is necessary to improve the detection depth by 4 times, or 16 times in terms of sensitivity.

Conventional fingerprint authentication was realized by stacking an ultrasonic sensor array chip on top of a driving silicon IC chip (**Figure 6A**). However, the thickness of the sensor must be reduced so that it can be embedded in a smartphone. Therefore, KRYSTAL, Inc. and OKI began work on improving the sensitivity and reducing the chip thickness in an aim to develop an IC-integrated ultrasonic sensor vein authentication chip (**Figure 6B**).

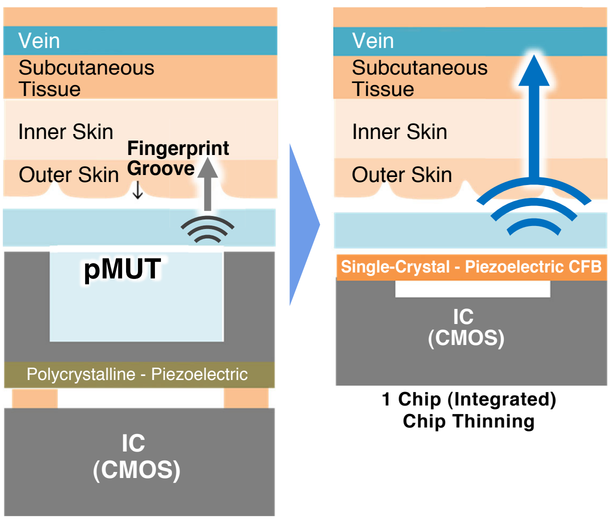

Figure 6. Conventional Fingerprint Authentication and Vein Authentication Chips

(3) Demonstration of Ultrasonic Sensor's Added Value

The purpose of the demonstration was to prove the principle and feasibility of an IC integrated ultrasonic sensor vein authentication chip, and establish the CFB technology to peel and bond KRYSTAL, Inc.'s piezoelectric single crystal thin film without compromising performance.

In order to demonstrate the principle, a prototype ultrasonic sensor was manufactured by bonding a piezoelectric single crystal thin film onto an SOI (Silicon on Insulator) wafer. PZT (lead zirconate titanate) was used as the piezoelectric single crystal material, and hereinafter referred to as single crystal PZT. Additionally, a prototype ultrasonic sensor produced through peeling/bonding single crystal PZT with CFB then using a semiconductor and MEMS processes is referred to as a CFB single crystal PZT ultrasonic sensor.

Figure 7A shows the structure of the CFB single crystal PZT ultrasonic sensor, and **Figure 7B** is a cross-sectional image of the sensor taken with an electron microscope. Single crystal PZT was bonded using CFB to the lower electrode (platinum: Pt) formed on the SOI wafer, and then subjected to semiconductor and MEMS processes. Good bonding was confirmed with no air bubbles found on the bonding interface.

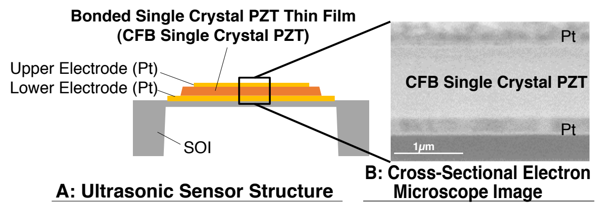

Figure 7. Demonstration of CFB Single Crystal PZT

Figure 8 shows a comparison of sensitivities between a conventional ultrasonic sensor using polycrystalline PZT and a CFB single crystal PZT ultrasonic sensor that were prototyped at the same time. With the CFB single crystal PZT, the transmission efficiency of the ultrasonic waves was improved four times and the reception sensitivity of the reflected ultrasonic waves converted into voltage was improved six times for a dramatic 24-fold improvement in total sensitivity. This exceeds the targeted 16-fold sensitivity improvement.

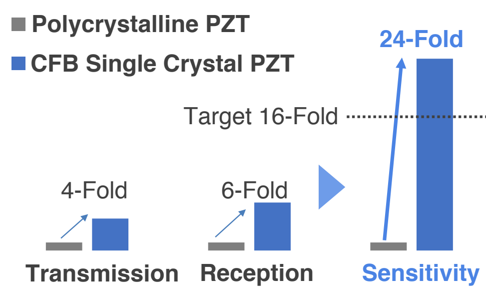

Figure 8. pMUT Operation Demonstration of Single-Crystal PZT

As demonstrated above, CFB solution enables peeling and bonding without compromising the high performance of the single crystal PZT. Furthermore, the 24-fold increase in sensitivity indicates the possibility of realizing vein authentication, which provides higher security than fingerprint authentication.

OKI will be working with device manufacturers on integration with actual ultrasonic sensor ICs. Furthermore, OKI will perform similar developments using various other piezoelectric single crystal thin film materials and explore the applicability to new MEMS devices.

Conclusion

This article introduced an overview of the CFB solution, micro LED display application, and “MEMS application” co-created with KRYSTAL, Inc. OKI will continue to contribute to improving the added value of various semiconductor devices. ◆◆

References

1) Norio Nakajima: Small LED Heads realizing High-speed and High-quality Gradation Printing, OKI Technical Review, Issue 227, Vol.83 No.1, pp62-65, May 2016 (in Japanese)
2) Overview of Electronic Display Manufacturers’ Plan 2021, p239, March 29, 2021, Sangyo Times, Inc. (in Japanese)
3) KRYSTAL, Inc. homepage: https://www.i-pex.com/ips/info/articles/single-crystal-technology

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TIPS 【Glossary】

Moore’s law
An empirical law that “semiconductor density will double every 18 months” advocated in 1965 by Gordon Moore, one of the founders of Intel.

MEMS (Micro Electro Mechanical Systems)
A micron-level electromechanical system that integrates piezoelectric elements such as sensors, actuators, and electronic circuits on a semiconductor substrate.