Stacked Integration of Analog ICs using "Thin Film Chiplets" by CFB

Takuma Ishikawa **Kenichi Tanigawa** **Hironori Furuta**
Hideharu Kuwabara **Kouhei Kuwahara**

Semiconductors have become an important element in supporting the foundations of society and the economy. High-performance semiconductors are indispensable, especially in advanced technology fields such as smartphones, automobiles, social infrastructure, and defense. The advancement of semiconductors is one of the driving forces behind the sustainable growth of modern society.

Until now, the advancement of semiconductors has been supported by miniaturization. However, due to physical limitations and rising costs, there is a shift toward a new trend that incorporates not only miniaturization but also compounding. One compounding technique is the chiplet technology. Chiplet technology enables the building of large-scale systems by combining multiple small-scale functional semiconductor chips (chiplets) on an interposer (intermediate substrate) in a planar connection (2.5D integration) or a 3D stack (stacked integration), allowing physical limitations and cost issues to be avoided. Furthermore, the ability to combine heterogeneous chips makes "heterogeneous integration" possible, and this is attracting attention as a new added value. Heterogeneous chips are chips made of different process nodes (generations of microfabrication technology), different manufacturing processes (logic, memory, analog IC, RF/ power semiconductors, etc.), or semiconductor materials other than silicon (compound semiconductors, etc.). If the various homogeneous chips can be integrated into one chip, large-scale and highly functional composite systems that were previously unrealizable can be built.

OKI was able to achieve "heterogeneous integration" using its proprietary crystal film bonding (CFB) technology, which bonds thin-film LEDs and IC chips for stacked integration, and in 2006 became the world's first to successfully mass-produce LED elements utilizing this technology[1]. Since then, OKI's shipment of LED elements has surpassed 100 billion dots, and the technology has established itself as a core technology with high mass production reliability.

OKI's "CFB Solutions" is an initiative that extends CFB technology beyond LEDs to various crystal materials and devices, contributing to the added value of semiconductor devices. Currently, development is underway in the fields of micro LEDs, photonics devices, and power devices, as well as analog ICs, which are introduced in this article.

This article explains the issues with integrating analog ICs using conventional chiplet technology, and introduces the "thin film chiplet" technology that utilizes Nisshinbo Micro Devices Inc.'s analog ICs and OKI's CFB.

Issues with Analog IC Chiplet Technology

Analog ICs play an important role in converting sensed physical phenomena (temperature, sound, light, pressure, etc.) into electrical signals and amplifying/arranging them into a form that can be easily handled by digital ICs. Among chiplet technologies, stacked package integration, which stacks different chips, is expected to bring many benefits to analog ICs other than simple miniaturization. For example, individually selecting the process nodes of the ICs to be integrated will enable optimization of costs and characteristics, or use of short wirings to reduce electrical resistance will lead to higher speeds and less heat generation. However, at present, stacked integration of analog ICs has not progressed as much as digital semiconductors mainly due to the following two issues.

Issue 1

The most common stacked integration method is TSV (Through Silicon Via)[2]. TSV places large-aspect ratio vias, which are about several μm to 30μm in diameter and 100μm in depth, on a silicon substrate in an extremely dense formation. This necessitates highly advanced manufacturing technology and precision equipment. Formation of the vias requires high temperature processing, special etching, and filling technology such as for the conductive materials, and these processes are optimized for 12-inch large-diameter wafer processes. On the other hand, analog ICs are generally manufactured using legacy processes with substrate diameters of 8 inches or less. Due to the simple equipment used, it is difficult to apply precise processing technology, which is conducted at relatively low temperatures. It is necessary to introduce non-generic advanced manufacturing equipment, which incurs huge costs in building the manufacturing line. Therefore, there is a demand for the development of stacked integration utilizing legacy processes.

Issue 2

Compared to digital ICs, analog ICs use continuous high-voltage signals, and therefore noise (crosstalk) is more likely to occur due to interference of electrical signals between stacked circuits. The voltage range of digital ICs is generally 1V to 5V, but the voltage of analog signals applied to an audio amplifier, for example, can reach several tens of volts. In such a high-voltage environment, suppressing crosstalk becomes an issue.

The purpose of this article is to propose a new chiplet technology for achieving a large-scale composite integrated system that includes analog ICs, and solves issues 1 and 2 of the legacy process.

CFB enables stacked integration of analog ICs, and it is a promising means to solve issue 1. However, the thinner ICs would bring the circuits closer to each other, and it was expected that the problem of crosstalk in issue 2 would become more pronounced. This issue was resolved through the collaboration with OKI's co-creation partner, Nisshinbo Micro Devices Inc.

OKI's Co-Creation Partner

Nisshinbo Micro Devices Inc. provides analog IC products for a variety of applications, including high-quality audio and automobiles. As the smart society develops, the number of communication devices such as IoT devices is increasing, and the impact of noise from surrounding devices is also growing. Nisshinbo is also working to address this noise issue[3]. Using analog technology that it has developed over the years, Nisshinbo has designed a technology for "localized shielding," which places noise shielding in necessary areas, to provide high-precision, low-noise analog ICs.

An analog IC with this localized shielding was used to solve the crosstalk issue encountered in the development of the stacked integration of thin film ICs by CFB that is presented in the article.

Outcome of Co-Creation

This section describes the development outcome of stacked integration of analog ICs using "thin film chiplets" by CFB.

(1) CFB effectiveness on glass substrate bonding

In this demonstration experiment, a transparent glass substrate was used for IC on Glass bonding. The appearance of the bond from the back side and the operation of the thin film IC were confirmed.

The thin film analog IC fabricated was an audio op-amp where elements, including many transistors, are formed on silicon (Si) substrate through a semiconductor process. The chip size was approximately 2mm x 1.5mm, and the thickness including the Si substrate was several hundred μm. However, the part that actually functions as an analog IC (functional layer) is only a few μm thick. A newly developed CFB process (**Figure 1**) for this analog IC is explained below.

In the trench process, grooves were formed around the analog IC functional layer all the way down to the Si substrate using photolithography and dry etching.

In the isolation process, the IC functional layer and its surroundings separated in the trench process were covered with a protective film.

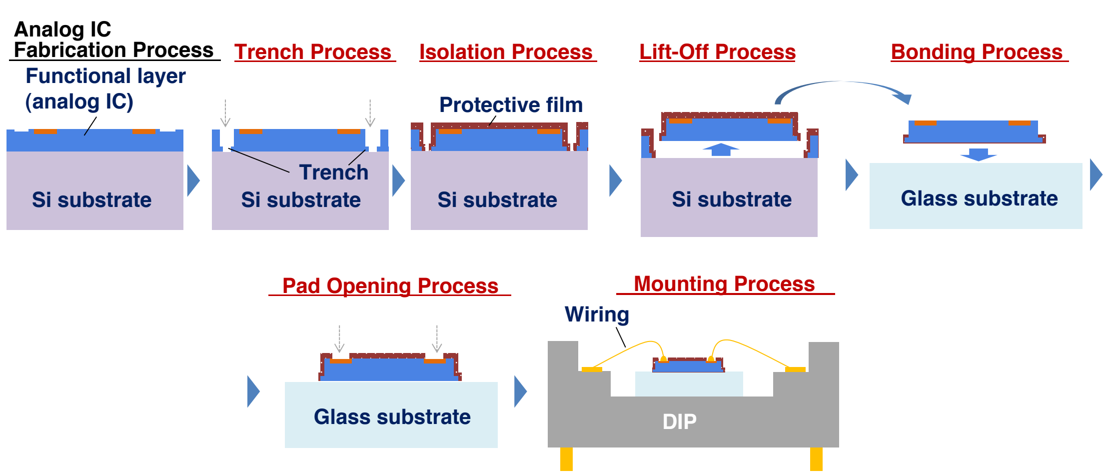


Figure 1. Newly Developed CFB Process for Analog ICs

In the lift-off process, the analog IC functional layer was lifted off from the Si substrate. The protective film prevented erosion damage during lift-off, and the IC was completely lifted off as a thin film analog IC while maintaining its structure.

In the bonding process, the lifted-off thin film analog IC was bonded onto a glass substrate with intermolecular forces. No damages were detected on either the top (front surface) or bottom (back surface) of the glass substrate, and no air bubbles were observed in the bounded area, confirming that the bond was good (**Figure 2**).

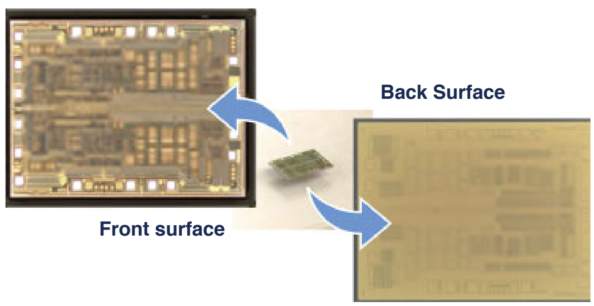


Figure 2. External View of IC on Glass by CFB

In the pad opening process, part of the protective film was removed using photolithography and dry etching to expose the electrodes for inputting operating signals to the IC. Then, the CFB glass substrate was diced into small 5 mm square pieces for easier mounting.

From the mounting process onwards, the work was performed by Nisshinbo. The IC and CFB glass substrate combination was mounted on a ceramic DIP (Dual In-line Package) and wired to the drive circuit.

When an electrical signal was input to the IC for performance testing, input/output characteristics equivalent to those of mass-produced products were obtained (**Figure 3**). Furthermore, when it was actually connected to an audio system and the signal was amplified, it was possible to reproduce clear sound without any sense of incongruity. As a result, even for analog ICs with complex circuits containing many transistors, the CFB technology, which does not use adhesives, was able to bond the ICs while suppressing changes in resistance and capacitance. The experiment confirmed that stacked integration is possible with legacy processes without compromising functionality.

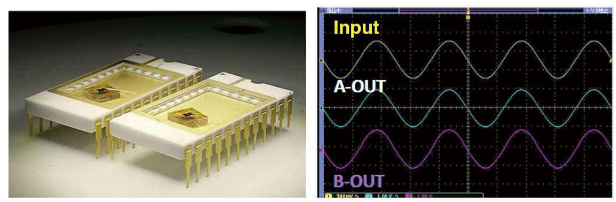


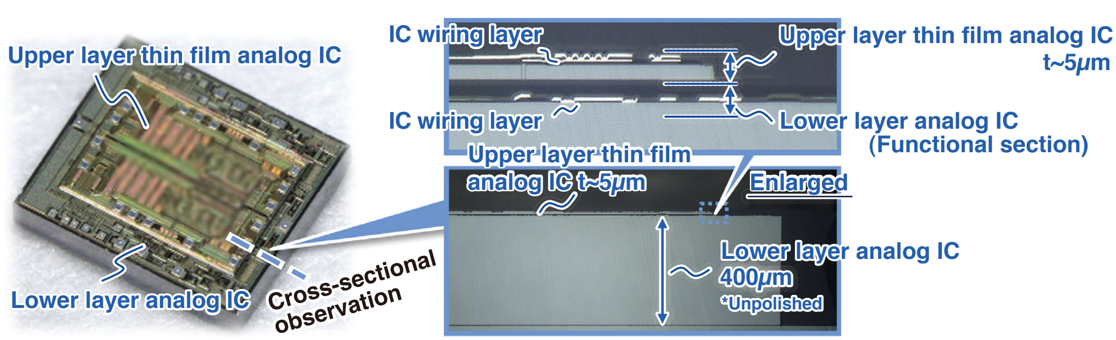
Figure 3. View of Mounted IC on Glass and Measurement Results

(2) Operation with IC-on-IC bonding

In this demonstration experiment, an IC-on-IC sample was created to verify crosstalk occurrence between stacked chips. The IC (lower layer), to which the thin film analog IC was bonded, was a high-precision op-amp with a slightly larger area (approximately 2.6mm x 2.3mm) and was different in design from the thin film analog IC. This IC had localized shielding that was previously mentioned.

First, similar to the processes of experiment (1), the trench process to the lift-off process were carried out to prepare the thin film analog IC.

Next, the bonding process to the lower layer analog IC was carried out. **Figure 4(a)** shows an external view after bonding and **Figure 4(b)** shows an electron microscope image of the cross-section. Unlike the glass substrate in experiment (1), the surface of the IC is uneven on the order of several μm due to the circuit formation. Therefore,



Cross-section photo taken by Oki Engineering Co., Ltd.

(a) External View **(b) Electron Microscope Photo of Cross-Section**

Figure 4. External and Cross-Sectional Views of IC-on-IC

a planarization film was formed enabling intermolecular force bonding without the use of adhesive. As a result, the thin film analog IC was successfully bonded in the same way as experiment (1).

The pad opening process and mounting process were carried out similar to experiment (1), and the characteristics were evaluated. Figure 5 shows the output characteristics measured with a test signal. First, a square wave was input to the lower analog IC and a sine wave to the thin film analog IC, simultaneously. Both ICs exhibited a two times voltage amplification as specified (**Figure 5(a)**). Next, a square wave with a relatively large peak voltage (10V) was input to the lower analog IC and the thin film analog IC was set to 0V (off state). The lower analog IC again exhibited a two times voltage amplification as specified while the output of the thin film analog IC was 0v and unaffected (**Figure 5(b)**). Other major characteristics such as current consumption and input offset voltage were measured, and no significant differences were found compared with operating the two types of chips independently. This demonstrated the feasibility of stacked integration that solves issue 2.

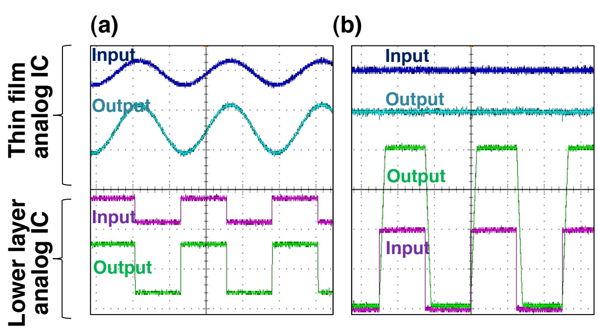


Figure 5. Characteristic Evaluation of IC-on-IC by CFB

Future Development of Thin Film Chiplets

Experiments (1) and (2) demonstrated that thin film chiplets can be achieved by CFB, dramatically expanding the possibility of advancing analog IC integration technology. Since the film is less than 10μm thick, typical photolithography can be used on the substrate after CFB. For example, ICs can be interconnected by wiring over the edge of the thin film, making integration possible regardless of the process nodes. The overall chip thickness is almost the same as the thickness of the lower analog IC alone. Therefore, it can be mounted in existing packages and will be easy to introduce into the market. The possibilities are not limited to stacked integration of analog semiconductors. Thin film chiplets that integrate miniaturized digital semiconductor ICs, sensor elements, and electronic components such as resistors and capacitors in 2.5D or 3D can be combined on top of a large-area low-noise analog IC to develop small, multifunctional, and highly value-added semiconductor devices such as analog-digital mixed circuits (**Figure 6**).

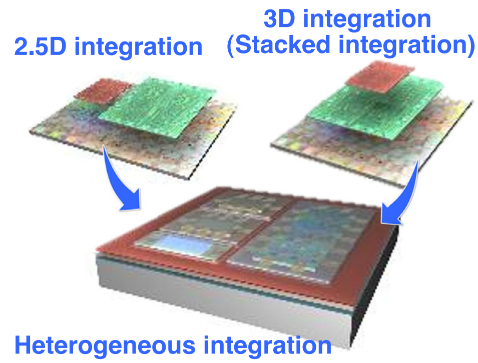


Figure 6. Heterogeneous Integration of Thin Film Chiplets

Conclusion

As one CFB solution, this article introduced the “Thin Film Chiplet,” a new technology that uses analog ICs and OKI’s CFB.

OKI will continue its collaboration with Nisshinbo Micro Devices, which has advanced analog IC design technology, and expand applications.

Acknowledgement

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Authors

Takuma Ishikawa, CFB Development Department, Global Marketing Center

Kenichi Tanigawa, CFB Development Department, Global Marketing Center

Hironori Furuta, CFB Development Department, Global Marketing Center

Hideharu Kuwabara, CFB Development Department, Global Marketing Center

Kouhei Kuwahara, CFB Development Department, Global Marketing Center

TIPS

【Glossary】

Heterogeneous integration
A semiconductor integration technology that combines different technologies and materials to build a single system.

Op-amp (Operational amplifier)
An electronic component widely used to amplify and process analog signals.

Legacy process
A semiconductor manufacturing method that uses existing manufacturing techniques and equipment. The method is old compared to the latest technology, but it is still used in many analog ICs today since it is stable, reliable, and cost-effective.