September 15, 2026

Bonding Mechanism Discovered Between "Self-Activated" Thin Films That Enable Wafer Bonding Without Surface Pre-treatment

—Next-Generation 3D Semiconductor Bonding Technology That Eliminates the Need for Pre-Bonding Plasma Treatment—

Research Highlights

- Discovered that aluminum oxide (Al_2O_3) thin films formed by atomic layer deposition (ALD) are self-activating, enabling strong, void-free wafer bonding without the plasma treatment conventionally considered necessary.
- Revealed that the origin of this self-activating property lies in the high polarity of Al–O bonds, the Lewis acidity of exposed or undercoordinated Al^{3+} sites, and the amorphous low-temperature ALD-AlO_x structure, its abundant hydroxyl (OH) network, and the heat-induced rearrangement of the amorphous AlO_x structure, through surface and interface analyses.
- Succeeded in bonding 300 mm wafers and confirmed that bonding performance remained essentially unchanged for approximately 60 days, based on previously reported queue-time data. This discovery is expected to streamline manufacturing processes, minimize damage, and enhance process flexibility for next-generation 3D semiconductors.

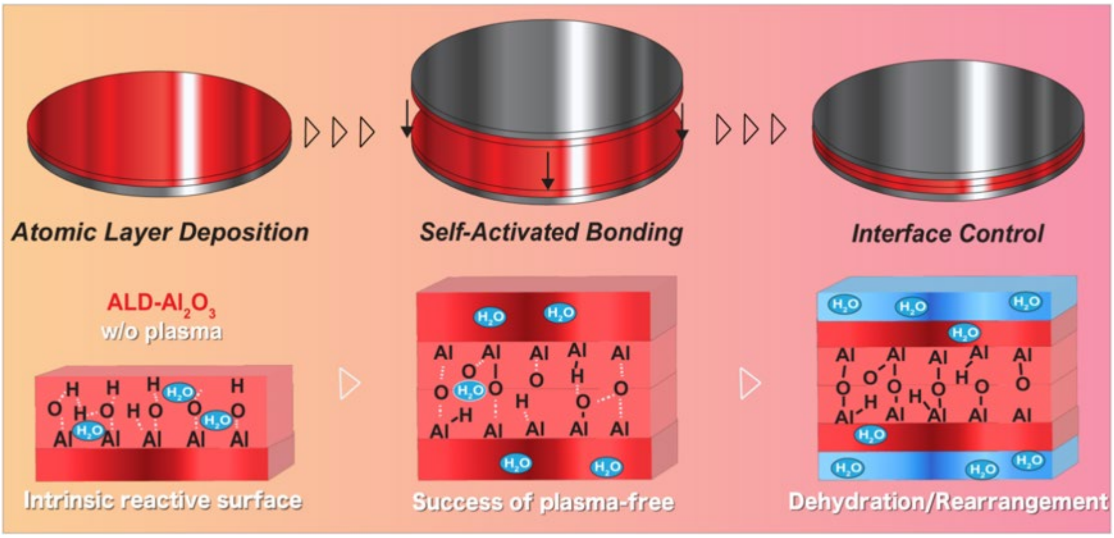

Figure 1. Self-activated bonding using ALD-Al_2O_3 and its mechanism

Research Overview

A research group (Professor Fumihiro Inoue of the Institute of Multidisciplinary Sciences (IMS) at Yokohama National University; IMS Visiting Assistant Professor Anton Myalitsin; Hayato Kitagawa, a doctoral student, and Taisuke Yamamoto, a master's student, in the university's Graduate School of Engineering Science; and Jenyu Lee, Shuntaro Machida, Kazuhiro Yuasa, and colleagues at KOKUSAI ELECTRIC CORPORATION) has discovered that thin films formed by atomic layer deposition (ALD) [Term 1] of aluminum oxide (Al_2O_3) [Term 2] can undergo direct bonding [Term 3] without plasma treatment or chemical mechanical polishing (CMP), a property termed "self-activation" [Term 4] (Figure 1).

These results were published on September 3, 2026 (local time) in *ACS Applied Materials & Interfaces*, an international journal in the materials science field published by the American Chemical Society.

Figure 2. Self-activated bonding scheme omitting the pre-treatment steps (CMP/Plasma/Rinse)

Social Background

In three-dimensional (3D) integration [Term 5] technology, in which semiconductor devices are stacked vertically, direct bonding and hybrid bonding, which join different wafers and chips at the atomic level, are essential. Conventionally, bonding oxide films together with sufficient strength was believed to require an additional step: irradiating the surfaces with plasma immediately before bonding to activate them. However, plasma treatment can cause plasma-induced damage (PID) beneath the surface and introduce excess moisture, and the waiting time from plasma treatment to bonding (queue time [Term 6]) has to be strictly controlled (Figure 2).

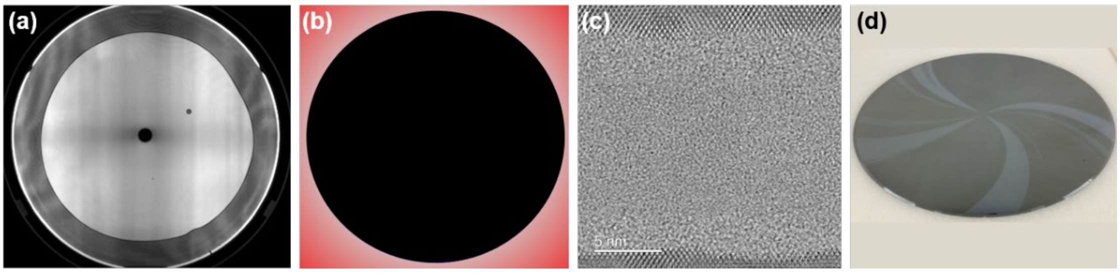

Figure 3. Wafer-scale quality and processing robustness of ALD-Al_2O_3 self-activated bonding: (a) bond wave propagating without plasma, (b) void-free bonding, (c) continuous interface without observable voids or delamination; the original bonding plane was not resolved, and (d) strong, highly-uniform bonding that withstands thinning to 10 μm

Research Findings

The research group formed ALD-Al_2O_3 thin films approximately 5 nm thick on 300 mm silicon wafers and bonded the wafers without plasma treatment. As a result, bonding free of voids [Term 7] was achieved across the entire bonding interface, and after post-bond annealing (PBA) at 300 °C for 2 h, sufficient bonding strength was achieved for subsequent processes, such as wafer grinding and CMP (Figure 3). The group also showed that bonding strength can be enhanced even further by controlling interfacial moisture through post-deposition annealing (PDA) to degas residual water from the ALD-Al_2O_3 film before bonding or an underlying thermally grown SiO_2 buffer layer that facilitates the redistribution and diffusion of interfacial water.

In addition, the surfaces and bonding interfaces were analyzed in detail using a combination of techniques including sum-frequency generation (SFG) spectroscopy [Term 8], X-ray photoelectron spectroscopy (XPS), thermal desorption spectroscopy (TDS), transmission electron microscopy (TEM), and electron energy-loss spectroscopy (EELS). The combined analyses support a mechanism in which hydrogen-bonded OH/water-related species associated with the surface or near-surface region promote initial adhesion at room temperature. During PBA, interfacial dehydration/condensation and local rearrangement of the amorphous ALD-AlO_x network toward more highly coordinated Al–O environments are considered to contribute to strong bonding.

Based on previously reported queue-time data, the bonding performance remained nearly constant for approximately 60 days even when the queue time between film deposition and bonding is extended. Unlike the active surfaces formed only temporarily by plasma, self-activation arises from the intrinsic polarity and structure of Al_2O_3, and the bondable state is therefore thought to be maintained over long periods.

This distinctive phenomenon exhibited by ALD-Al_2O_3 provides a new materials design guideline for semiconductor bonding technology, which has traditionally depended on plasma treatment. In particular, it can offer significant advantages over conventional plasma-based bonding for bonding to the carrier wafers used to form backside power delivery networks in 3D-integrated logic semiconductors. In the future, the approach is expected to lead to simplified, lower-temperature, and less damaging manufacturing processes and to multifunctional bonding materials in 3D integration technologies that stack logic, memory, image sensors, chiplets, and other devices.

Future Outlook

This research has demonstrated that ALD-Al_2O_3 is a self-activating material capable of direct bonding without plasma treatment and has clarified key factors underlying this property.

If the plasma process can be omitted, expected benefits include simpler bonding equipment configurations, lower manufacturing costs, avoidance of plasma-induced material damage, relaxed constraints on queue times between processes, and reduced variability. Applications in miniaturized chiplets, backside power delivery networks, logic-memory stacking, image sensors, and other semiconductor technologies are also anticipated.

Going forward, the group will optimize the deposition conditions, thickness, heat treatment, and underlying materials of the Al_2O_3 films, and will also pursue applications to hybrid bonding involving copper interconnects and evaluate the electrical and thermal reliability of the bonding interfaces.

Furthermore, based on the materials design guidelines identified in this study, namely high polarity, Lewis acidity [Term 11], and an amorphous structure deposited at low temperatures, the group will search for self-activated bonding materials other than Al_2O_3. In this way, the group aims to expand the range of bonding materials available for 3D integration and to build a new bonding platform suited to multilayer stacking and heterogeneous material integration.

Acknowledgments

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Glossary

[Term 1] Atomic layer deposition (ALD)
A thin-film deposition technique in which source gases are supplied alternately. It can control film thickness at the atomic-layer level and can form uniform films even on surfaces with steps and fine structures.
[Term 2] Aluminum oxide (Al_2O_3)
An insulating material composed of aluminum and oxygen. In semiconductor manufacturing, it is used as a thin-film material that offers high insulation, heat resistance, and chemical stability. In this study, amorphous Al_2O_3 thin films formed by low-temperature ALD were used as the bonding material.
[Term 3] Direct bonding
A technique for bonding planarized material surfaces to each other at the atomic or molecular level without using adhesives. It includes fusion bonding, in which insulating films are bonded together, and hybrid bonding, in which insulating films and metal interconnects are bonded at the same time.
[Term 4] Self-activation
In this study, “self-activation” refers to the ability of a material to be directly bonded through its intrinsic surface chemical state, without being externally activated using plasma or other means.
[Term 5] 3D integration
A technology for stacking multiple semiconductor chips or wafers vertically and connecting them with short interconnects. In addition to horizontal miniaturization of semiconductor devices, it combines logic, memory, sensors, and other components with different functions to form a three-dimensional structure, thereby enhancing performance and reducing power consumption.
[Term 6] Queue time
The waiting time between a process step, such as film deposition, cleaning, or plasma treatment, and the subsequent bonding step. When the surface activity decreases over time, strict time management is required.
[Term 7] Void
A gap or unbonded region remaining at the bonding interface. Because voids degrade bonding strength, reliability, and thermal and electrical properties, void-free bonding is required in semiconductor manufacturing.
[Term 8] Sum-frequency generation (SFG) spectroscopy
A nonlinear spectroscopy technique in which light of different frequencies is directed onto a material surface and light at the sum frequency is detected. It can probe the bonding states of molecules present on surfaces and interfaces with high sensitivity.
[Term 9] Hydroxyl (OH) network
A structure in which hydroxyl groups and water molecules on a material surface interact with one another through hydrogen bonding. In this study, this network is believed to enable initial adhesion at room temperature.
[Term 10] Dehydration condensation reaction
A reaction in which two hydroxyl groups or similar species react to release a water molecule and form a new covalent bond. In this study, Al–OH groups and other species are believed to react to form strong Al–O–Al and Al–O–Si bonds.
[Term 11] Lewis acidity
The ability to accept an electron pair. Because Al3+ ions in Al_2O_3 have high Lewis acidity, they are believed to promote interactions with water molecules and hydroxyl groups.

Publication Details

Title: "Self-Activated Direct Bonding with a Highly Polar Atomic-Layer-Deposited Film for 3D Integration"
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