ASML Is Building a Hybrid Bonding Tool!

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ASML has not announced anything yet, but its patent filings, a news report and its own roadmap all suggest so. We believe it will start with a die-to-wafer (D2W) hybrid bonding (HB) tool. This is harder to build than wafer-to-wafer but is where ASML could gain an edge. We see the move as a natural extension of ASML's vertical integration, and one that should strengthen its customer ties.

In this article we unpack the tool's design end to end, starting with patent filings. What makes it unique is that it **runs on a track**. That changes how the tool and the dies move: each die rides its own holder past the process stations, and the tools get closer at each station to process the dies. The track's independent shuttles also lift station utilization, save on duplicate tooling, and enable heterogeneous integration.

We believe ASML could **gain an edge in alignment accuracy and particle control** for Hybrid Bonding. These are the two factors that set bonding yield. And ASML has expertise in solving the same problems in lithography.

Despite the advantages, ASML **still needs to solve challenges** around feed-forward metrology, the die-to-wafer contact, the modification of the non-bonding tools so they can process dies on the track, and keeping the whole loop clean.

We expect advanced logic, where D2W already runs in volume, to adopt ASML's D2W HB tool first. This is **bad news for Besi**. Logic accounts for most of Besi's HB business today concentrated at TSMC and Intel. ASML has been working with both for more than two decades and just announced a joint photomask initiative in September. We won't be surprised to see a similar move in the back end process. Besi's HBM prospects are also weakening. Korean challengers are catching up, in addition to an HBM adoption that we expect to slip to 2029 or beyond.

ASML is Building a Hybrid Bonder

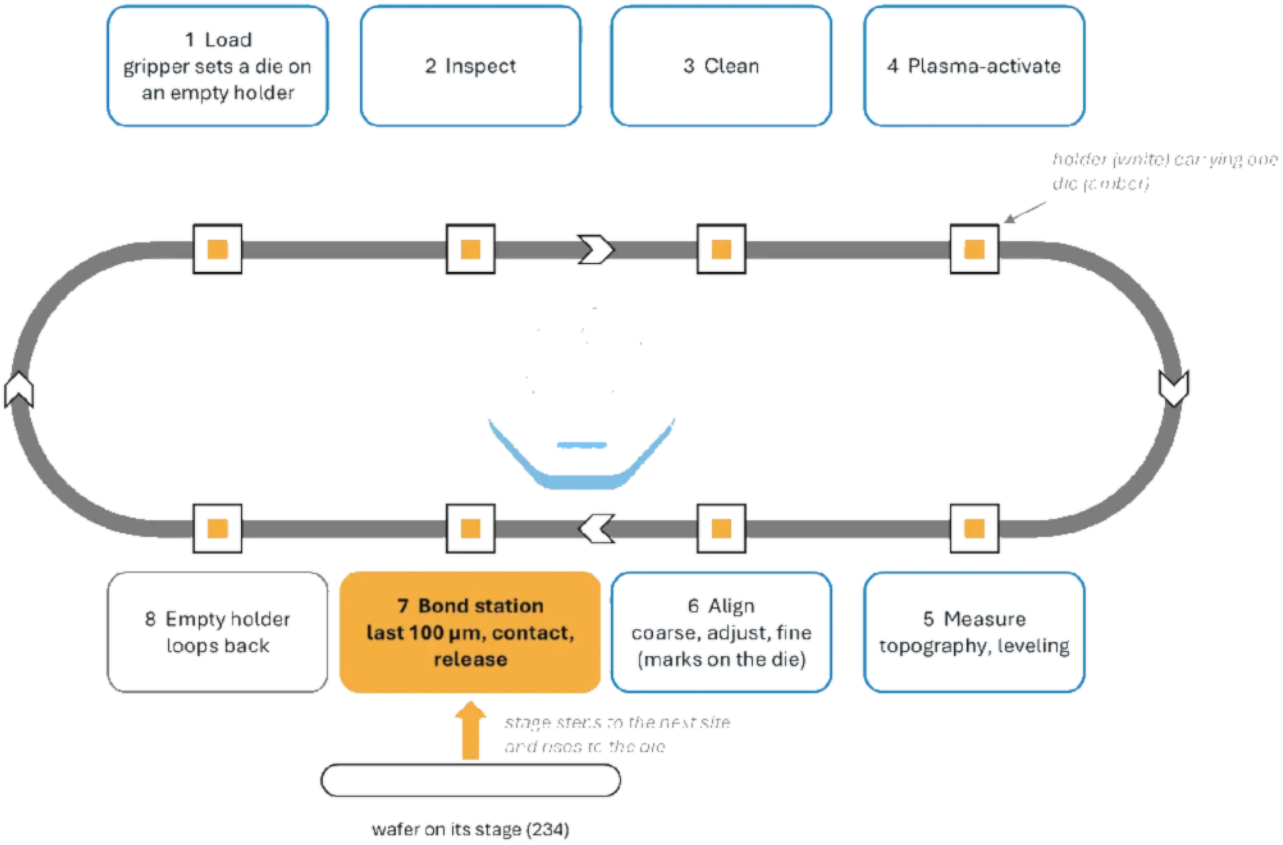
We did a deep dive on hybrid bonding in 2024, and we still see it as the most transformative innovation in semiconductor manufacturing since EUV. Wafer-to-

wafer (W2W) hybrid bonding (HB) is already in volume in image sensors and 3D NAND, and DRAM makers will be next. **Die-to-wafer (D2W) HB is moving slower**, because the industry still lacks mature tools that combine satisfying alignment accuracy and throughput (our check indicates upper bound in current applications is only one wafer per hour), which keeps cost per die high. Today D2W runs in volume only in logic: AMD has shipped hybrid-bonded V-Cache since 2022, and TSMC's SoIC bonds at about 6um pitch today and targets 4.5um around 2029. The market expected HBM to become the big D2W volume driver from 2028. However, our view is different: we believe HBM will not adopt D2W HB before 2029, if at all.

Besi has led D2W and is the only supplier with tools in volume production. Everyone else is still trying to get a first tool qualified. But we believe **the situation will soon change, because ASML is building a D2W hybrid bonding tool.** Management hasn't announced anything yet. But the company filed 27 bonding patent families between December 2022 and November 2024, most of them D2W, and the true count is likely higher because filings made after November 2024 are not yet public. The Elec also reported in March that ASML had started the architecture design of a hybrid bonder with Prodrive Technologies and VDL ETG.

In the anchor filing (WO2025201788A1), ASML drew how its bonding flow works. Interestingly, the system looks nothing like a traditional D2W bonder (see Advanced Packaging Part 5 for how those work). Instead of a bond head picking each die off a diced wafer and placing it, ASML **moves single dies on independent holders around a track** (Fig 1). Each die passes inspection, cleaning, plasma activation and metrology (topography, leveling and alignment) stations before it reaches the bonding station where the chuck lifts the bottom wafer up to meet the die. We unpack the design in the sections below.

Fig 1: ASML's track-based D2W bonder, SA annotated and simplified



The die stays face-down on its own holder for the whole loop and stations work on it where it stops. The track only gets the die close (~10 µm); the holder's short-stroke actuators and the wafer stage do the nanometres at the bond.

Source: ASML;

ASML could be building a W2W hybrid bonding tool as well. According to a patent analysis by Inha University, ASML is likely building W2W HB equipment on its TWINSCAN platform, leaning on its wafer overlay accuracy. We focus on the D2W machine in this note, because it is the harder tool to build and the one where ASML could gain a real edge.

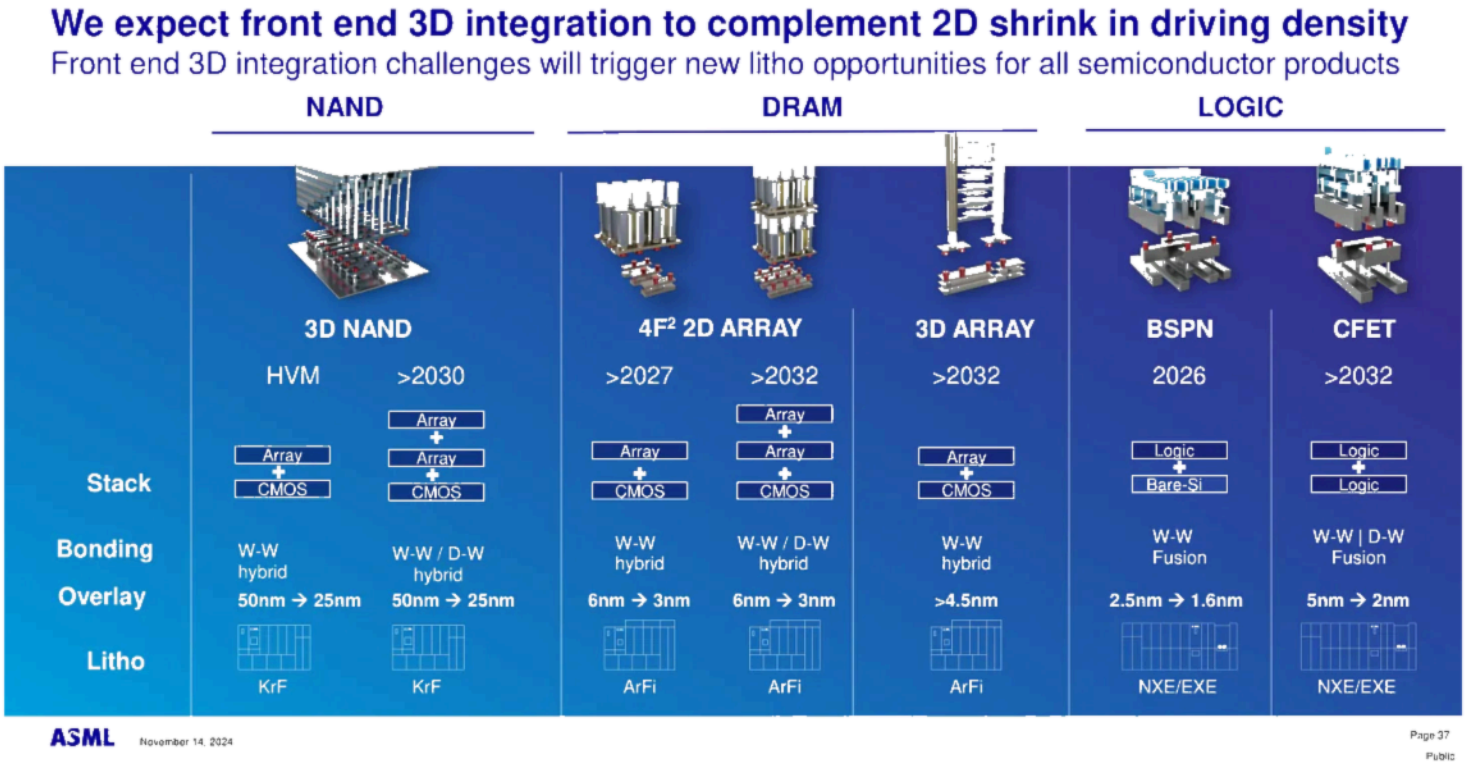
...as Part of its Vertical Integration Initiative

We believe this is a continuation of ASML's effort to integrate vertically and tighten customer relationships. ASML bought Cymer for its light source in 2013, HMI for e-beam inspection in 2016 and Berliner Glas for optics modules in 2020. It shipped its first back-end product, the XT:260 i-line packaging scanner, in 3Q25. And most recently, ASML announced joint initiatives with TSMC, Intel Foundry and Samsung to move the industry from 6-inch to 12-inch photomasks for High NA EUV.

Building a bonder would be a natural next step. In fact, ASML's own roadmap already puts bonding inside the front-end flow. Its 2024 Investor Day listed W2W and D2W hybrid bonding for NAND, DRAM and logic (Fig 2). And a July 2024 filing shows how the bonder and the scanner would work together by sharing die position data. Today a scanner printing on a bonded wafer must pre-align and coarse-align every die before it

can expose. In ASML's design the bonder already knows where it put each die and hands that map (a "coordinate system" in the filing) to the scanner, which checks a few marks and exposes. Customers get faster lithography on bonded wafers, and ASML gets to sell the bonder and the scanner as a pair.

Fig 2: ASML's map of front-end 3D integration



Source: ASML Investor Day, 14-Nov-2024

We expect advanced logic to be the first adopter. Logic is where D2W HB already runs in volume, and where the alignment requirement keeps tightening. TSMC calls overlay "always the biggest challenge" for SoIC. As its HB pitch moves from 6um to 4.5um by 2029, the placement accuracy requirement will tighten further. ASML is strong in alignment, as we will elaborate below, so an edge here should help it win logic customers first. Advanced logic dies are also among the most expensive chips, so logic customers can afford a premium tool. We expect ASML to price its tools at a premium to peers.

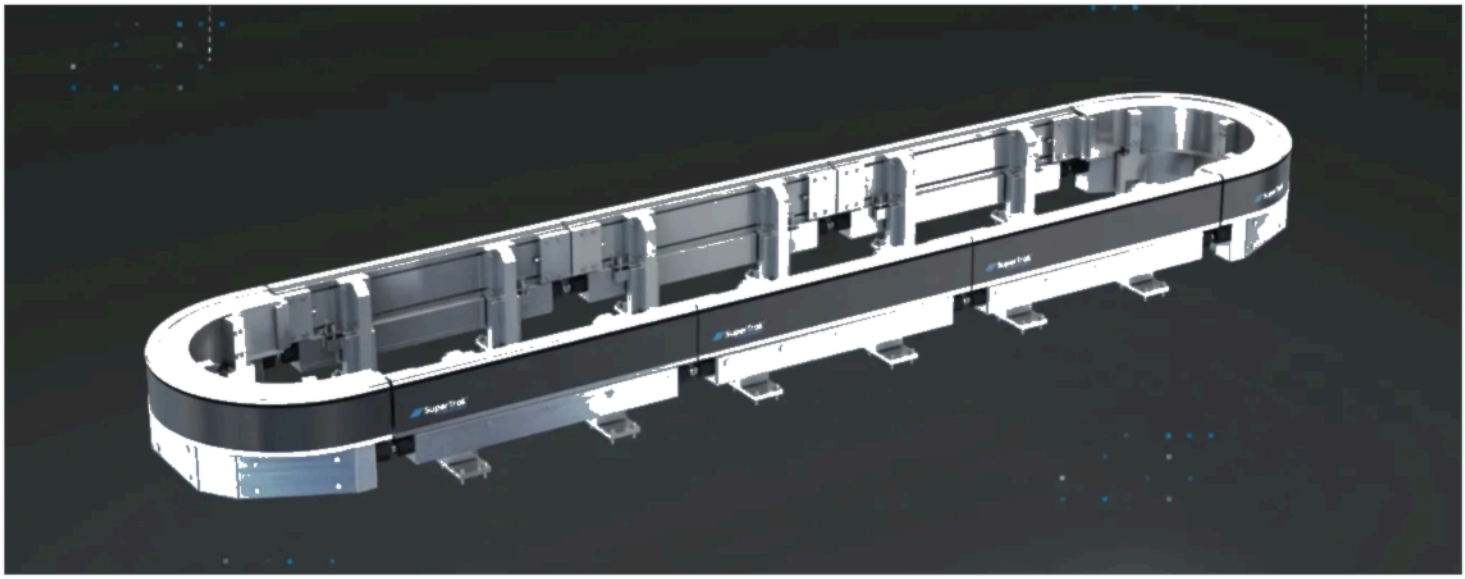
In the next three sections, we discuss (1) the tool's track system - the most unusual thing about it compared with what is on the market; (2) how ASML's strengths in alignment, particle control and motion could make its HB tool superior; and (3) the challenges ASML or its supply chain partners still need to resolve to build a working tool. Let's dive in.

What's Unique About the Tool

One of the most interesting things about the tool is that it **runs on a track**. ASML names SuperTrak CONVEYANCE (Fig 3) as an example in its patent filing, so we assume it uses that track and we base our analysis on the track's published design.

The fundamental difference from a traditional bonder is where the die lives. In a Besi-type tool, the die is prepared elsewhere, and a bond head picks it up only for the final placement. **In ASML's design, each die sits on its own holder from the moment it leaves the carrier and stays there until the bonding step.** The process stations are built around the track: the die stops in front of a station, the station cleans, activates or measures it in place, and the die moves on.

Fig 3: SuperTrak CONVEYANCE track (HORIZON10 platform)

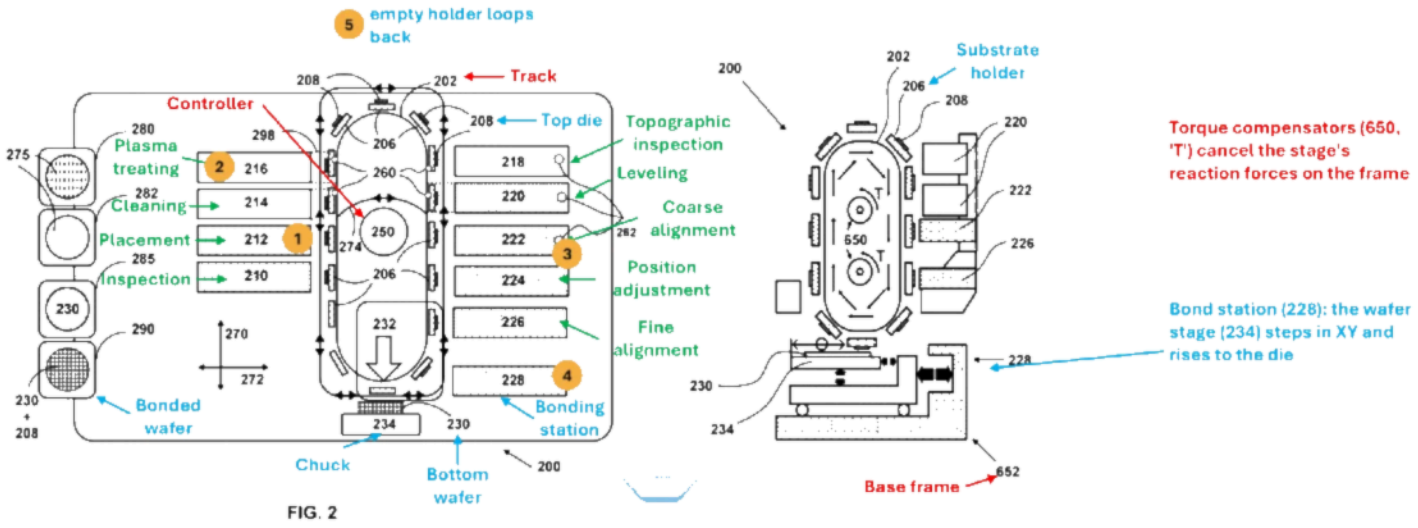


Source: Company website

Now let's go through the process step by step. For illustration, we took the patent drawing and labelled every station in Fig 4. A gripper takes the die off its carrier and sets it on an empty substrate holder (206), which carries it along the track (202). The die stops in turn at the inspection, cleaning, plasma activation, topographic inspection, leveling, coarse alignment, position adjustment and fine alignment stations (210 to 226). At each stop the die stays on its holder, and the station does its work. Note the reversal here: in the patent it is the station's sensor or head that moves in to reach the die, not the die that is carried into the tool as in today's flow. After these steps the die arrives at the bonding station (228).

This bonding station deserves a closer look. The first thing to note is that the final placement is done by the holder (206) and the chuck (234), not the track: SuperTrak's spec sheet puts the shuttles' repeatability at about 10um, nowhere near the 50nm placement accuracy the bond needs. Next, zoom in on the right-hand part of Fig 4 for the bonding work. The chuck lifts the bottom wafer to within tens of microns of the die, the holder's actuators adjust the die's position, the die is pressed onto the wafer to form the bond, and the holder releases it. The empty holder then starts another loop.

Fig 4: Patent WO2025201788A1 Fig. 2 (left) and Fig. 6 side view (right), SA annotated



Source: ASML;

This design has three major benefits:

First, **independent shuttles lift the utilization of every station.** The number of stations per step can be set from that step's cycle time: a three-second cleaning step gets three stations, and a 1.2-second bond step gets one, so every station stays busy. The patent asks for exactly this, to "occupy all process stations simultaneously".

Second, capacity is added by adding a station rather than a second tool, as long as the equipment chamber has room for it. That **saves duplicate tooling and budget.**

Last but not least, the design suits **heterogeneous integration**: a new die type is a new software recipe, so mixed chiplets could share one line.

That said, the track brings its own challenges around the non-bonding stations and the cleanliness of the whole loop. We come back to them later.

How ASML May Gain an Edge

Before that, let's look at how ASML could bring its existing strengths to the HB tool.

First, a reminder of why **alignment accuracy and cleanliness matter so much in hybrid bonding.** As we elaborated before, a single 1um particle between two full-thickness wafers can unbond an area around 10mm across, resulting in a defective bond (Fig 5). So particle control is extremely important for HB. Alignment matters for two reasons: **placement accuracy** sets bond yield directly, and **alignment time** weighs far more on D2W throughput than on W2W because it compounds with the die count. These two hurdles are what make hybrid bonding almost a front-end process.

Fig 5: A small particle opens a void and an open contact in hybrid bonding

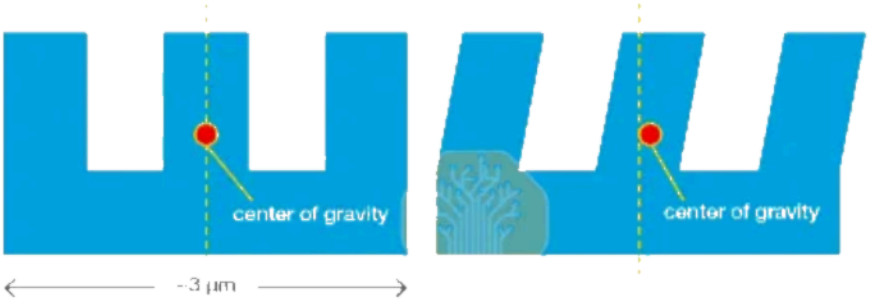


Source: SemiAnalysis

We believe ASML can tackle both with decades of experience solving the same two problems in lithography.

For alignment, we believe ASML can reuse its wafer-alignment sensor technology. Based on its patent filings, the bonding system puts a tiny diffraction grating on each die and reads the die's position from the light the grating scatters. The principle is the same as ORION, the wafer-alignment sensor on every new TWINSCAN since 2017. ORION was built to read marks that CMP and etch have tilted or deformed (Fig 6), and a mark on a bonding die goes through the same CMP and plasma activation as the copper pads next to it, so it carries the same asymmetry. We believe the same sensor family can serve the D2W bonder.

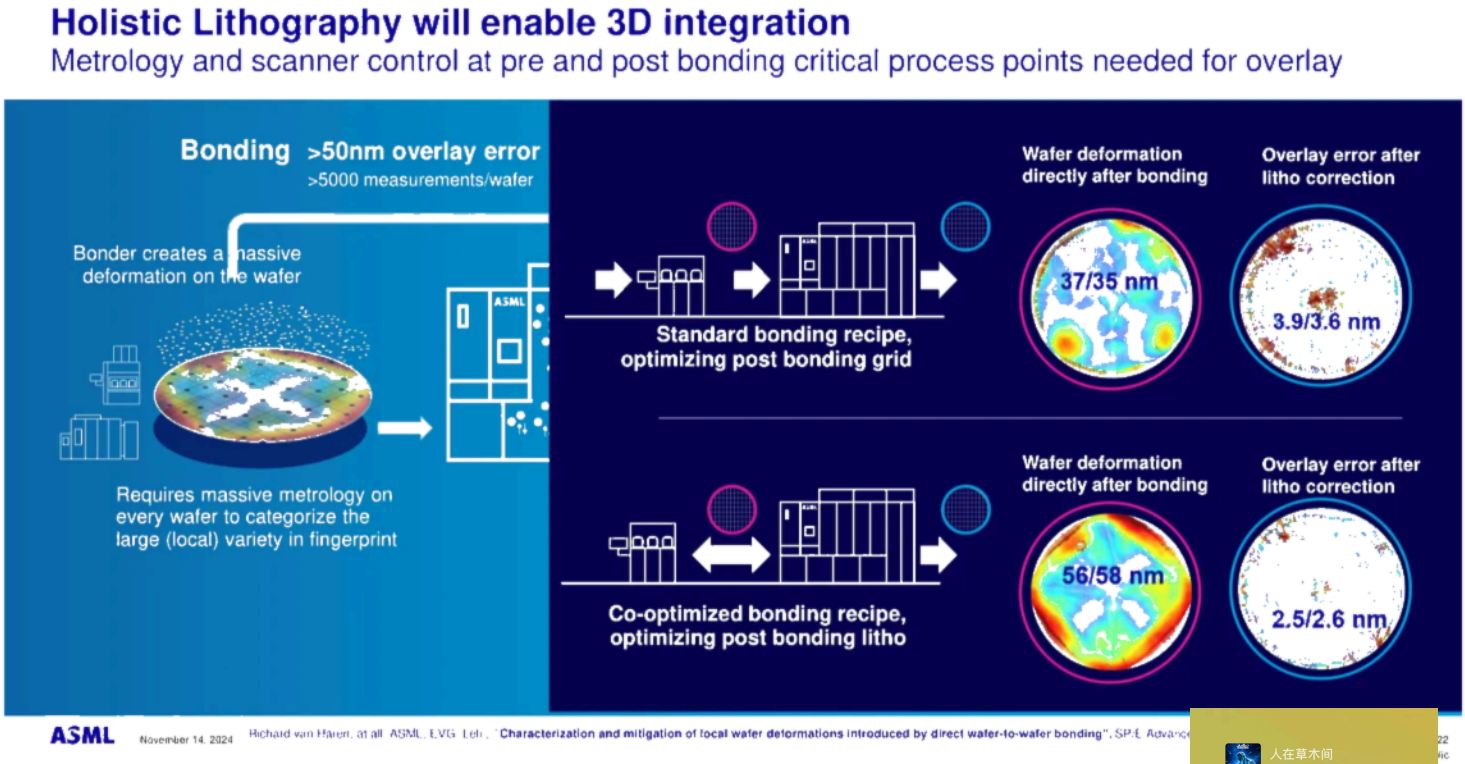
Fig 6: A symmetric and a tilted alignment mark. Process steps shift the apparent center; ORION's multi-color readout was built to see through that



Source: ASML, Aligning lithography to the nanometer, Dec-2021

Its sensing and motion capabilities also provide it with more room in total alignment error budget. Its NXT:2100i holds 0.9nm overlay on a single machine. And ASML can already measure the distortion of a W2W bonded wafer and correct the next lithography layer for it, bringing post-bond overlay from 40-60nm down to below 4nm (Fig 7). These are litho numbers, not bond results. But they mean ASML's sensor and stage errors sit more than an order of magnitude below the 50nm a bonder needs. Higher stage precision leaves more room in a bonder's error budget for the other factors: die shift on the holder, thermal drift and movement during contact.

Fig 7: ASML metrology plus scanner correction brings post-bond overlay to 2.5-3.9nm

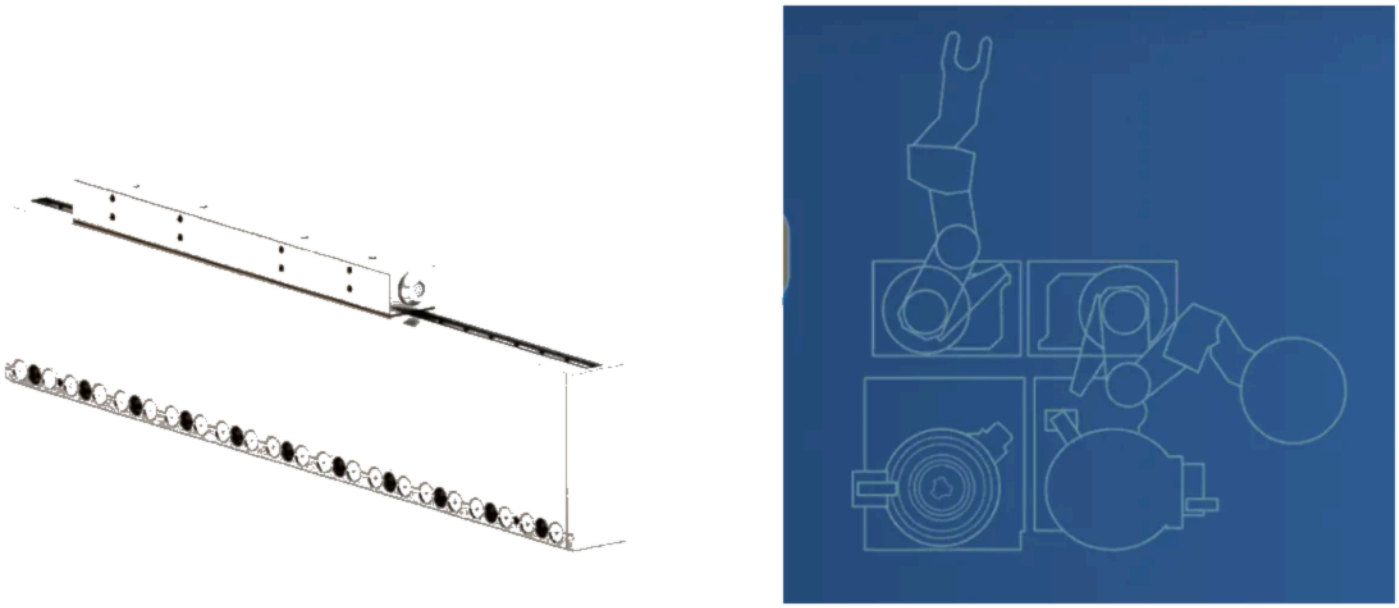


Source: ASML Investor Day, 14-Nov-2024

Prodrive Technologies and VDL ETG are the likely component supplie
ASML's bonder move fast on motion. Prodrive makes the linear motors

ASML's EUV maglev stages and has also built Hanwha Semitech's SHB2 Nano bonder. VDL ETG builds ASML's frames and modules (Fig 8).

Fig 8: Prodrive's linear motor (left) and VDL ETG's wafer handler module (right)



Source: Company websites

On cleanliness, the requirements for ASML's EUV systems are more strict as a bonder's. Few tool makers have fought particles at the nanometer scale for as long as ASML. EUV scanners move reticles and wafers in vacuum and keep reticle particle adders at a level "compatible with HVM requirements for sub-10nm node lithography". We believe ASML has thought about the bonding surfaces too: its bonding apparatus filing adds a tool that cleans the substrate supports and a sensor that watches their flatness, particle load and distortion.

That said, contaminants in a bonder differ from those in a scanner. Most are dicing debris on die edges and particles landing on freshly activated, hydrophilic surfaces. We look for more detail on how ASML handles these bonder-specific contaminants in future filings.

After the paywall we discuss the challenges ASML needs to tackle to build a working tool, and how its tool will impact on Besi's business prospects.

Open Questions ASML Needs to Solve

Despite these advantages, ASML still needs to solve several technical challenges before it has a working tool with high yield. We believe the first two are engineering

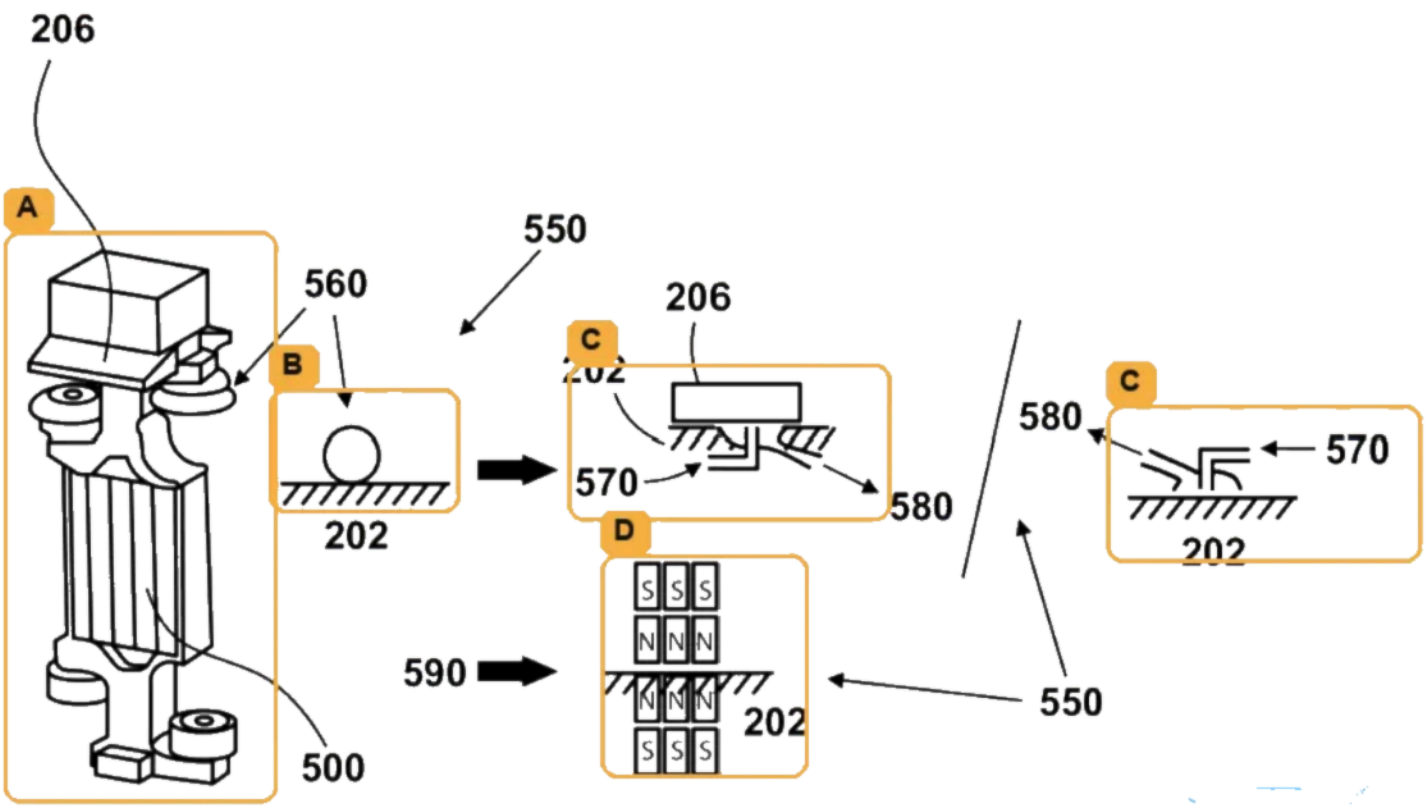
problems ASML needs to solve itself, while the last two are supply-chain questions to work out with partners.

Feed-forward metrology is critical to the track system's throughput. ASML measures each die against its holder at one station and trusts that reference at the bond station, where silicon is opaque to its sensors and nothing can look through the die. The scheme only works if the die does not move on its holder in between, on a shuttle that SuperTrak rates for up to 4G of acceleration. And the error budget stacks: the die-to-holder measurement, any shift in transit and the holder-to-wafer reference at the bond each must stay within 10-20nm for the total to land near 50nm. Nothing published shows a repeated measure-transport-measure loop on real holders. ASML would need to prove this with measured data.

Contact is the second challenge. Holding the die, releasing it and steering the bond wave take years of process know-how, and ASML is new to the field. A conventional hybrid bond forms like this: the bond head presses the die so that its center touches the wafer first. The two surfaces grab each other, and a bond wave runs from the center to the edges, pushing trapped air and voids out ahead of it. If the die is warped or the wave starts off-center, voids stay trapped and the bond fails.

ASML's filings describe its own version of this flow (Fig 9). A shaped clamp holds the die from above and bows it slightly, so the center meets the wafer first when the wafer chuck rises. Segmented heaters and addressable burls in the holder stretch or shrink the die to match the pads below. An infrared sensor watches the bond wave spread. Once the wave has run, the clamp releases the die and the holder moves on. This is theoretically possible, but none of it has been shown in practice. An industry expert we spoke to also doubts the warpage control of this design. We would need more evidence from ASML to better assess its feasibility.

Fig 9: ASML bonder's substrate holder per patent descriptions, SA annotated. The holder is a small shuttle with its own chuck and fine actuators. It could ride the track via wheels (B), air and vacuum bearings (C), or magnetic levitation (D)



Reading ASML's substrate holder (patent Fig. 5)

A Holder (206): a shuttle for ONE die. Its chuck (500) grips the die; actuators (550) add a short-stroke fine move in X, Y, Z and rotation on top of the track's coarse motion.

B Wheels (560) on the track (202): how SuperTrak's standard shuttles ride.

C Air bearing (570) with vacuum pull-down (580): the holder floats, no rolling contact.

D Magnetic bearing (590): maglev, like the wafer stages in ASML's EUV scanners.

Take-away: the track only gets the die close. The holder's own stage and the wafer stage under it do the last nanometres at the bond station.

Source: ASML, WO2025201788A1; SemiAnalysis

The other tools must change too, and this will take a collaborative supply chain effort. As we described above, ASML's track needs stations that work on a die where it stops. The tools on the market today are chamber tools: a wafer, or a diced wafer on a frame, is carried into the chamber and sits there while the tool works. Nobody sells a track-side module that cleans, activates or measures one die in a few seconds. But incumbents such as AMAT, EVG and Lam should have enough process know-how to adapt their existing tools. We believe ASML will need to work with them to build these station modules, which in turn need support from subsystem and component suppliers.

Lastly, **how clean the whole loop needs to be and how to keep the cost reasonable.** A hybrid bond needs an ISO 3 or Class 1 environment at the interface, and customers

evaluate bonders in Class 1 rooms. SuperTrak's standard platform is rated ISO 6, three classes below what HB needs, and the die rides the track face-down with its freshly activated surface exposed. The patent filings suggest ASML will put isolators (a gasket, a plate, suction or a gas flow) between the track and each station so that every station can keep its own environment. But particle control between stations and the cost of maintaining these clean mini environments could affect the tool's yield and price performance by a lot.

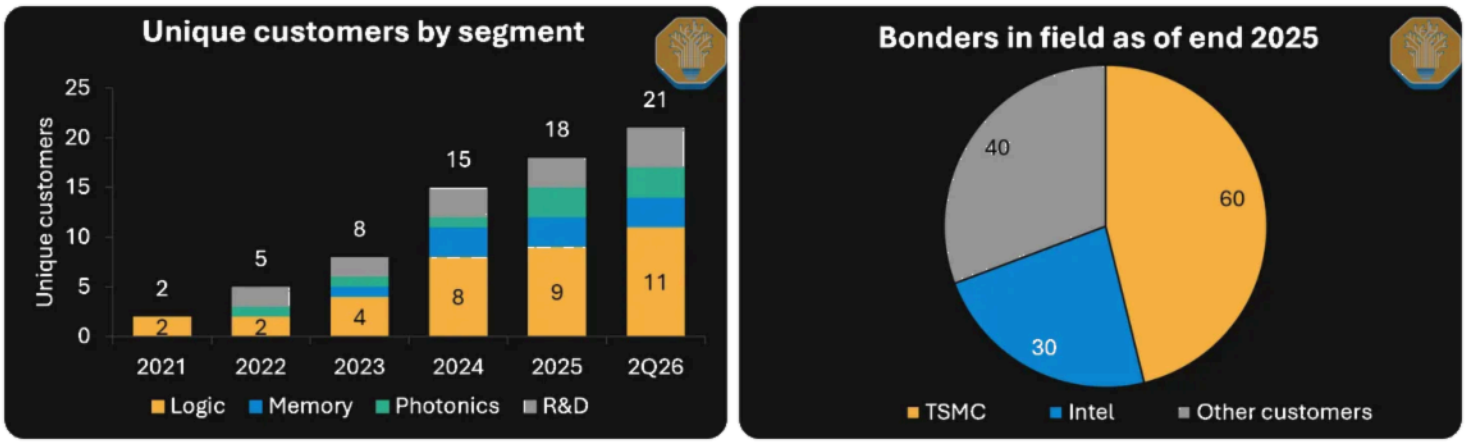
It is hard to put a date on the tool given how little information is available. Management puts revenue "well beyond 2030", and our channel checks found no ASML bonder at any Taiwanese foundry or OSAT. So, we expect volume production no earlier than 2030, which keeps ASML out of the first D2W wave, a wave we expect to slip to 2029 or beyond anyway. Even so, **its entry adds meaningful pressure to Besi**, whose TAM is already getting a haircut due to the HBM de-spec.

More Pressure on Besi

The D2W HB market has changed meaningfully from what we wrote in early 2024. Besi remains the leader and the only supplier with tools in volume production at customer lines. But its growth prospects are less attractive, both in logic and in HBM.

Logic is half of Besi's hybrid bonding customers and **about 70% of its installed bonders** on our estimate. And it is concentrated on two major customers: Intel and TSMC (Fig 10). Management describes the mix as "skewed to logic" via two leading customers.

Fig 10: Besi's hybrid bonding exposure: customers by segment (left) and bonders in the field by customer, SA estimate (right)

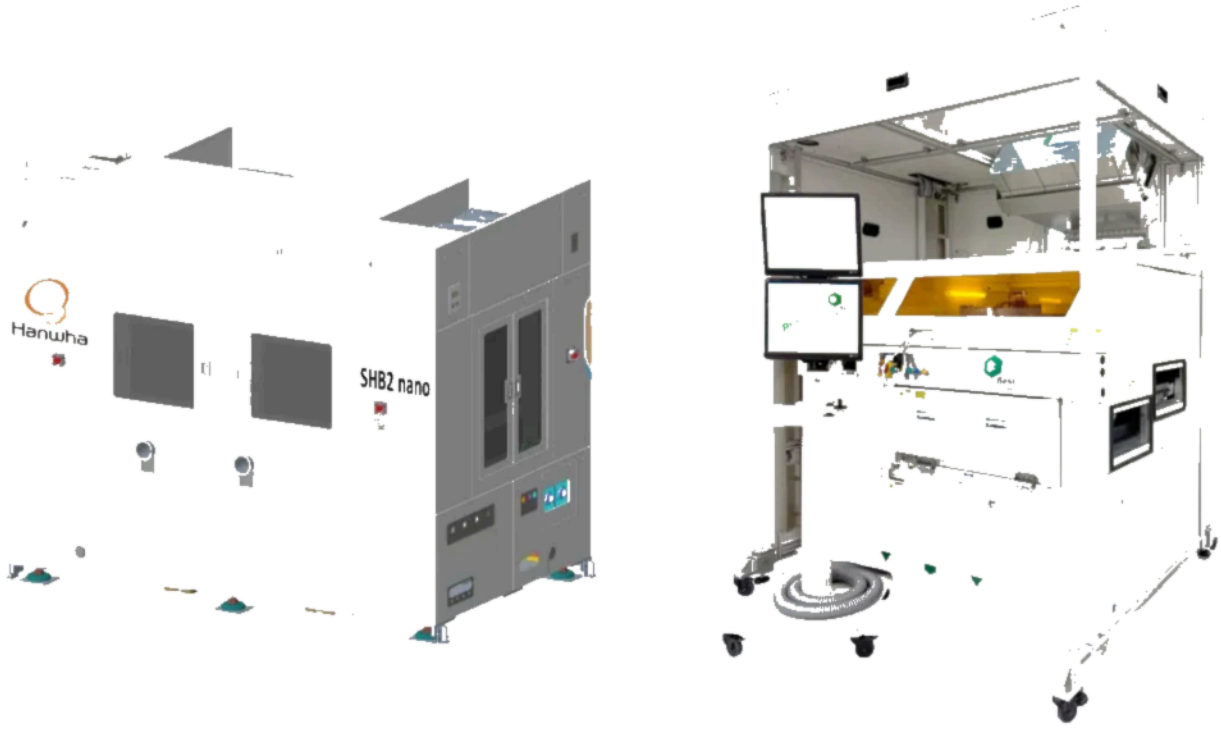


Source: Company filings, SemiAnalysis estimates

ASML has worked with TSMC for almost 40 years and with Intel for more than two decades. Besi has worked with the two on hybrid bonding for less than 10 years. The 12-inch photomask initiative ASML announced with TSMC and Intel Foundry also signals deepening co-development in the front end process. We would not be surprised to see a similar move in the back end, especially if ASML can match the incumbents' placement accuracy. One caveat: we expect ASML's D2W HB tool to come to market only after 2030, so its impact on Besi's 2026-29 logic order book should be muted.

HBM was the next growth market Besi was betting on, but Korean players are catching up. Hanwha Semitech co-developed the SHB2 Nano with ASML's reported motion supplier Prodrive Technologies, per The Elec. The tool claims placement accuracy of 0.1 um, in line with Besi's CHAMEO 8800, and has been in evaluation at SK hynix since April (Fig 11). Samsung is also considering Hanwha as a potential supplier and has asked its equipment-subsidiary SEMES for D2W hybrid bonders. It is reported in July that the evaluation units at Samsung had passed internal testing. While volumes should be small in the near term, the domestic tools could add pricing pressure on Besi at about half of its price.

Fig 11: The challengers: Hanwha Semitech SHB2 Nano (left) vs. Incumbent: Besi CHAMEO 8800 (right)



Source: Company websites

And Besi's D2W prospects are already worse from the HBM de-spec. The 4-hi and 8-hi de-spec we flagged in August removed the height problem hybrid bonding was meant to solve. SK hynix has pushed hybrid bonding to HBM5, Samsung talks about partial commercialization at HBM4E, and Micron is evaluating liquid cooling instead. Besi management also acknowledged in July a potential delay to HBM adoption beyond its 2027 timeline. We estimate HBM hybrid bonding accounts for up to 20% of Besi's 2028 consensus revenue, so a delay weighs heavily on the company's growth prospects.

Besi still has advantages as the first mover and through partners such as AMAT. Packaging houses such as NHanced also sell D2W hybrid bonding as a service on Besi CHAMEO tools. These integrations raise the bar for competitors, because customers would need to requalify the entire process, not just a tool.



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