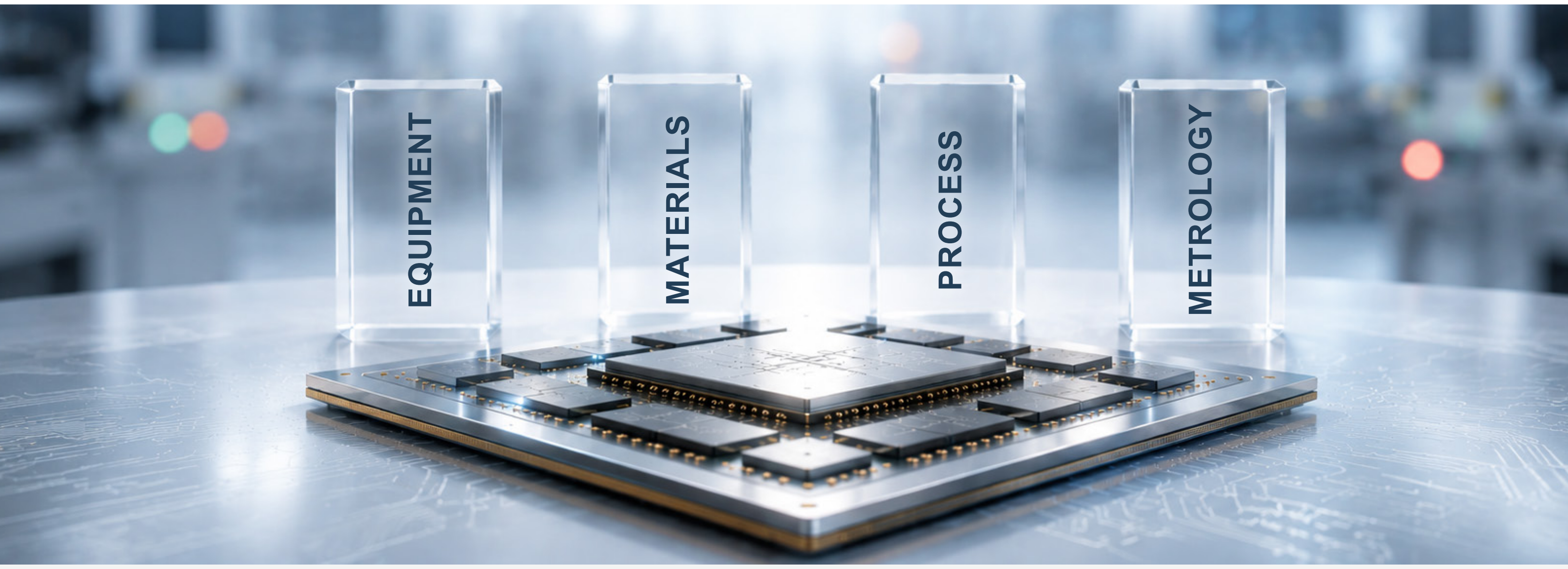


White Paper

Driving Next-Generation Bonding Technologies Through Four Fundamental Pillars

Why advanced packaging requires the co-development of materials, process, equipment and metrology.

Dr. Ami Eitan, SVP, Chief Scientific Officer, ASMPT

Bonding Becomes an Integration Constraint

Advanced packaging is allowing the semiconductor industry to combine specialised devices rather than relying only on increasingly complex monolithic designs. Logic, memory, analogue, radio-frequency and other functions can be integrated through two-dimensional, 2.5D and three-dimensional package architectures.

This creates four important bonding layers:

- memory die stacking
- chiplet integration stacking on an active Interposer
- bonding of HBM, system-on-integrated-chip structures or other devices to a passive interposer
- bonding of the populated interposer on an organic substrate

Each layer serves a different purpose and places different demands on the bonding process. Memory stacking requires stack-height control and thermal management. Fine-pitch chiplet integration increases the need for highly accurate alignment and controlled surfaces. Larger passive interposers introduce warpage and handling challenges. Final attachment to an organic substrate may create additional requirements for residue control, coplanarity and fluxless processing.

The difficulty is not simply that every requirement is becoming more stringent. Several requirements must now be achieved simultaneously.

A process may need to accommodate a thin or warped die, create thousands of reliable interconnects, maintain a tightly controlled gap, limit thermal exposure, prevent contamination and operate at a viable production rate. Optimising only one of these measures can move another outside its acceptable range.

Bonding therefore becomes a system-level integration problem.

Where the traditional approach falls short

Bonding technologies have often been developed through sequential hand-offs. Materials and equipment are supplied, process engineers establish a working recipe, and metrology is subsequently applied in-line or off-line to confirm the result.

The sequence appears logical, but it can delay the discovery of interaction effects.

If surface roughness, oxide state or contamination is not measured before bonding, an interface problem may appear only after voids or electrical opens are found. If a process recipe is developed without accounting for normal equipment drift, it may not transfer reliably to production. If inspection detects a defect but cannot connect it to the state of the surface, material or tool, root-cause isolation remains difficult.

The consequences include:

- late detection of interface problems
- extended trial-and-error qualification
- difficulty isolating the origin of fine-pitch defects
- loss of valuable dies and substrates during ramp-up
- process windows that do not scale reliably from laboratory to factory
- slower progress towards stable yield

At fine interconnect pitch, seemingly small excursions can have large effects. A particle, local topography deviation, alignment error or variation in polymer flow may affect many neighbouring interconnects. Inspection after bonding is necessary, but it cannot by itself recover the value already added to the package.

The alternative is to design the materials, process, equipment and measurement strategy together.

The four-pillar control loop

Materials establish the bonding interface
The materials pillar includes the bonding surfaces and all materials that enable or surround the connection. Depending on the technology, these may include copper pads, dielectric surfaces, solder bumps, non-conductive film, underfill, substrate materials and surface treatments.

Materials establish the boundary conditions for bonding. Surface chemistry affects bond initiation. Roughness and topography influence contact. Oxide condition affects solder-joint formation. Polymer flow affects gap filling and void formation. Thermal and mechanical properties influence warpage and reliability.

The relevant question is not only whether a material possesses the desired nominal properties. It is whether its condition can be measured, prepared and maintained within a repeatable manufacturing window.

Process forms the bonded structure
The process pillar covers the sequence through which the prepared materials become an integrated package. It may include cleaning, activation, alignment, contact, force, temperature, dwell time, annealing, underfill and post-bond treatment.

A process recipe must reflect actual material behaviour and demonstrated equipment capability. The objective is not a single successful bond under controlled development conditions. It is a window that tolerates realistic variation while maintaining bond integrity, alignment, gap control and yield.

The process must therefore be developed together with the measurements that define its inputs and verify its outputs.

Equipment holds the process window
The equipment pillar provides alignment accuracy, force control, thermal control, cleanliness, atmosphere, coplanarity, handling and automation.

These capabilities are interdependent. Alignment performance, for example, must be maintained with the relevant die size, thickness, substrate condition, handling sequence and production environment. Temperature and force must be sufficiently controlled for the material system without causing excessive deformation.

ASMPT's LITHOBOLT G2

The LITHOBOLT G2 represents the new standard in die-to-wafer hybrid bonding technology, designed to meet the demands of next-generation semiconductor packaging. This fully automatic system operates in a class 1 (ISO 3) clean environment, delivering unparalleled precision for advanced packaging. It enables direct copper-to-copper connections without solder or flux, revolutionising the way chiplets are integrated. Operating in a highly clean environment, it supports both die face-up and face-down applications, making it versatile for various advanced packaging requirements. LITHOBOLT G2 is essential for the redesign of system-on-chip (SoC) devices into 3D stacked chips via chiplet technology. It offers alignment accuracy of less than 100 nm (3σ), enabling, for example, AI/HPC chiplets with more than 10,000 interconnects per mm².

Figure 1: LITHOBOLT G2 hybrid bonding solution
SOURCE: ASMPT

Equipment should consequently be evaluated as part of the complete bonding system, rather than through isolated headline specifications.

Metrology closes the loop
Metrology includes pre-bond, in-situ and post-bond measurement. Relevant parameters may include surface roughness, copper recess, contamination, oxide condition, warpage, alignment, chip gap, voids and electrical continuity.

Its role is not limited to accepting or rejecting the final bond. Metrology establishes whether the interface is ready, whether the equipment and process remain inside the required window, and whether the bonded result corresponds with upstream measurements.

This creates a closed loop. Measurements inform material preparation, process settings and equipment conditions. Those adjustments produce new measurements, enabling the system to learn and stabilise.

Example 1: Hybrid bonding - controlling the interface

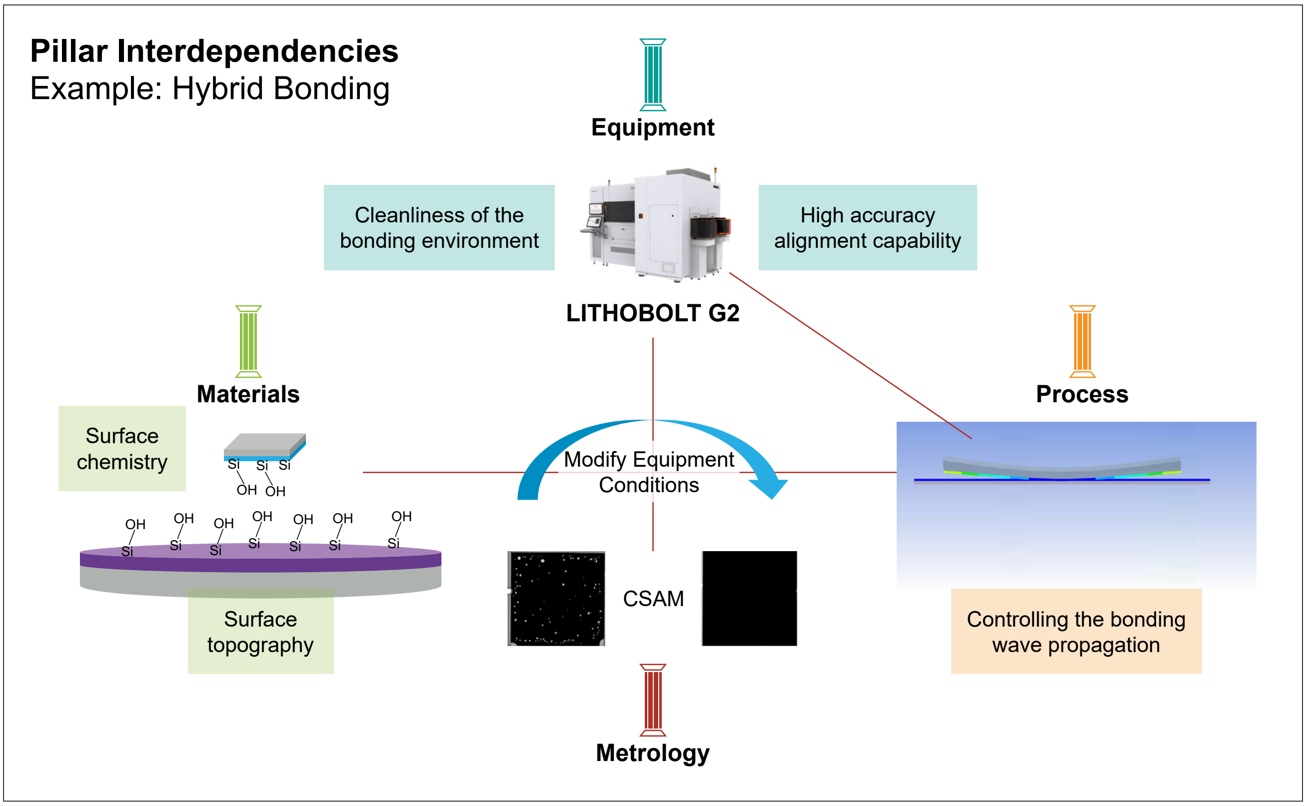
Hybrid bonding joins surfaces that contain dielectric and metal regions. Initial contact is followed by thermal processing to establish the metal interconnections. The absence of conventional solder bumps supports much tighter interconnect density, but also increases sensitivity to the condition of the bonding surfaces.

The four pillars interact throughout the flow.

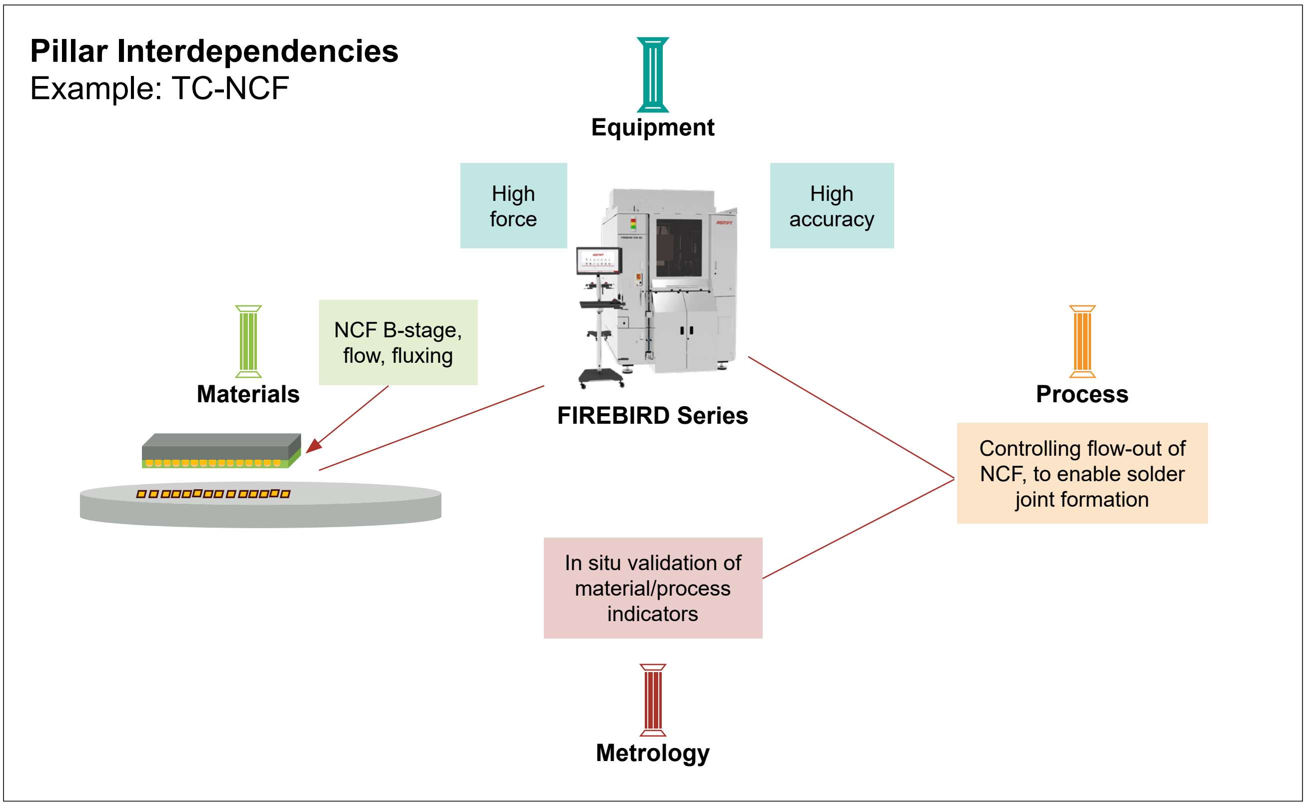
Materials: Dielectric chemistry, copper pad condition, roughness, recess and particle levels must support uniform contact.

Process: Surface preparation, cleaning, activation, alignment, initial contact, bond-wave propagation and annealing must be considered as one sequence.

Equipment: The bonder must combine precise alignment with clean, controlled handling and stable bonding mechanics.



Example 1: Successful HB outcome requires intimate interaction between materials/equipment, state/process conditions and metrology capabilities



Example 2: Successful TC-NCF outcome requires close design and interaction between materials/equipment/process conditions and in situ metrology capabilities

ASMPT’s FIREBIRD Series

With the FIREBIRD series, ASMPT sets the standard for bonding modern three-dimensional chips. FIREBIRD combines the latest technologies in thermal compression bonding (TCB). With ASMPT’s patented AOR TCB™ technology, Active Oxide Removal (AOR) ensures clean, residue-free surfaces and reliable bonding, improving package integrity and overall performance. For cases where lower pressure is required, the option of the Liquid Phase Contact (LPC) process in an inert environment is available.

The FIREBIRD TCB achieves an angular accuracy of ±0.01° for larger dies and ±0.05° for smaller dies, with a coplanarity of 3 µm over 33 mm. This exceptional precision makes it ideal for CPUs, GPUs and hybrid memory with through-silicon vias. The dual-range bonding force system (0.1–30 N / 30–300 N) offers flexibility for different configurations. Equipped with pulse heating nozzle technology that enables temperatures of up to 400 °C, the FIREBIRD TCB ensures precise temperature control during the bonding process. This feature is crucial for maintaining bonding quality and preventing substrate deformation.

Figure 2: FIREBIRD Series thermocompression solution
SOURCE: ASMPT

Metrology: Surface topography and defectivity must be assessed before bonding, while overlay, voids and electrical continuity must be evaluated afterwards.

These functions cannot compensate fully for one another. Greater placement accuracy cannot correct an unsuitable surface. Improved surface preparation cannot overcome contamination introduced during handling. Post-bond inspection can reveal a void, but useful yield learning requires the result to be correlated with pre-bond surface and equipment data.

Hybrid bonding therefore demonstrates why metrology must form part of process development rather than remain a final quality gate.

Example 2: TC-NFC - controlling material flow and joint formation

TC-NCF uses a thermocompression process to form interconnects while a pre-applied non-conductive film fills the gap around them. The technology supports die-by-die control and fine-pitch applications, but requires a careful balance among film behaviour, heat, force, time and alignment.

The NCF material is supplied in a partially cured state and must perform several functions during bonding. It must flow away from the interconnect regions, support oxide removal and solder-joint formation, fill the remaining gap and avoid excessive voiding or thermal resistance.

This creates another four-pillar interaction.

Materials: Polymer flow, fluxing behaviour, cure characteristics and compatibility with the interconnect structure define the available process conditions.

Process: Force, temperature and timing must control flow-out while allowing consistent joint formation and chip gap.

Equipment: Accurate placement, controlled force, thermal response and coplanarity must be delivered for each die.

Metrology: Material and process indicators must validate flow behaviour, gap height, void formation and joint quality.

Thermocompression bonding can also be considered alongside mass-reflow approaches. Mass reflow can process many joints together and may offer advantages in throughput and thermal performance, while die-by-die thermocompression can provide greater control of alignment, warpage and chip gap. The appropriate technology depends on the package architecture and manufacturing priorities.

The four-pillar model makes these trade-offs explicit. It places the decision within a complete manufacturing context rather than treating it as a comparison of bonding tools alone.

From successful bonding to stable manufacturing

For manufacturing organisations, the value of the four-pillar model lies in the transition from technical possibility to repeatable production.

Earlier risk identification
Interface, equipment and measurement requirements can be addressed before the process architecture is fixed. This reduces the likelihood that a material or inspection limitation will be discovered late in qualification.

Faster yield learning
When material state, equipment condition, process parameters and inspection results can be correlated, teams have a stronger basis for identifying the source of defects.

More robust technology transfer
A defined process window, supported by measurable control variables, is more transferable than a recipe demonstrated at a single operating point.

Better capital and technology decisions
Manufacturers can evaluate technologies against system-level measures such as yield, throughput, thermal performance, cleanliness, inspection capability, scalability and cost.

Stronger ecosystem alignment
Advanced bonding depends on technical exchange among device manufacturers, material providers, equipment suppliers and metrology specialists. The four-pillar model gives these participants a common framework for defining requirements and reviewing results.

Priorities for industry leaders

Manufacturing and technology leaders should consider five actions:

1. **Organise bonding programmes around cross-functional teams.** Materials, process, equipment, metrology, quality and manufacturing expertise should be represented from the beginning.

2. **Define the required interface state before selecting the process.** Surface, material and dimensional conditions should be expressed through measurable parameters.

3. **Design metrology into the development flow.** Teams should identify what will be measured before, during and after bonding, and how that information will affect decisions.

4. **Qualify a process window rather than a single recipe.** Development should account for material variation, equipment drift and production conditions.

5. **Evaluate the complete manufacturing system.** Technology choices should reflect package performance, yield, throughput, reliability, scalability and cost rather than one equipment metric.

ASMPT Perspective

ASMPT's bonding portfolio includes LITHOBOLT G2 for hybrid bonding and the FIREBIRD series for thermocompression bonding applications. These platforms address different bonding mechanisms and application requirements, but both sit within the same wider engineering challenge: converting demanding material interfaces into repeatable, measurable production processes.

ASMPT's perspective is that future bonding progress will require close interaction among equipment suppliers, material providers, metrology specialists and device manufacturers. Equipment capability remains essential, but its value is realised only when it is developed around the relevant materials, integrated into a viable process window and connected to effective measurement and feedback.

The four-pillar model provides a practical basis for this collaboration.

Outlook: bonding as a connected manufacturing system

The next stages of advanced packaging will bring smaller interconnect pitches, taller stacks, larger package formats and more diverse material combinations. Panel-level manufacturing may further increase the importance of warpage, process uniformity, die shift and large-area measurement.

These developments will make sequential optimisation increasingly difficult. Bonding technologies will need to be developed as connected manufacturing systems in which interface state, equipment condition, process behaviour and measurement results are considered together.

The industry should therefore move beyond asking whether an individual material, process or machine can meet a target. The more useful question is whether all four pillars can hold the complete bonding system inside a stable production window.

Conclusion

Advanced packaging is changing the role of bonding. What was once treated primarily as an assembly step now has a direct influence on interconnect density, thermal performance, package integrity, yield and time to market.

No single technological improvement can address the complete challenge.

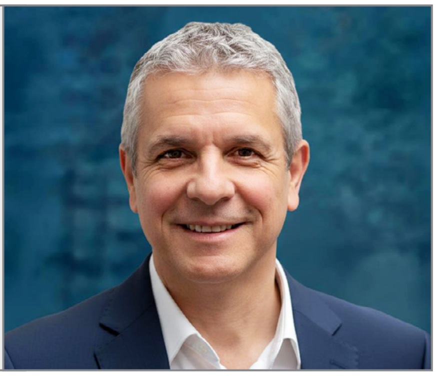
Materials establish the bonding interface, and the process converts that interface into a completed bond. The equipment provides the controlled, repeatable conditions necessary for reliable operation. Measurement technology verifies that the system remains within its intended operating window and provides the necessary feedback to drive continuous improvement.

The four pillars must therefore be developed as one connected control loop, from early research through high-volume manufacturing.

Organisations that adopt this approach can identify integration risks earlier, improve the efficiency of yield learning and make more informed bonding technology decisions. More broadly, the framework can help align the semiconductor ecosystem around a shared objective: scalable bonding processes capable of supporting the next generation of AI, high-performance computing and heterogeneous integration.

Dr. Ami Eitan

Dr. Ami Eithan is the Senior VP and Chief Scientific Officer in ASMPT. With over 20 years of experience in the semiconductor industry, he has been positioned in advanced packaging leadership role in Intel's back-end organization, followed by TSMC's back-end organization, driving bonding technology innovations, development, and implementation. Dr. Ami holds more than 20 US patents in semiconductor packaging technologies.



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