How Precision Motion Systems are Shaping the Future of Semiconductor Manufacturing

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Introduction

In the ever-evolving landscape of semiconductor manufacturing, precision motion systems have been a cornerstone of innovation and progress. As the computational demands of emerging technologies such as artificial intelligence (AI) grow exponentially, Moore's Law remains a key industry benchmark. In order to support this need for more processing power density, the semiconductor industry continues to develop innovative methods to manufacture increasingly smaller nodes, exploit advanced packaging techniques such as heterogeneous integration and 3D stacking, and broaden the use of photonic integrated circuits (PICs).

This article highlights the pivotal role precision motion systems play in supporting some of these key semiconductor manufacturing trends. Precision motion underpins every stage of the semiconductor production process, enabling nanoscale fabrication, increasingly complex packaging and highly sensitive test and inspection processes. The semiconductor industry's relentless pursuit of innovation, reliability and efficiency would not be possible without precision motion.

Continued Node Miniaturization

Constant miniaturization efforts have always driven the semiconductor industry. The most advanced commercialized microchips are manufactured using ASML's extreme ultraviolet (EUV) lithography machines, which can unlock a 3 nm node size [1]. The objective of continuing to shrink minimum feature size – still the key metric for tracking the industry's progress against Moore's Law – demands ever-increasing precision in manufacturing processes. Precision systems, including EUV lithography machines and scanning electron microscope (SEM) inspection tools, are vital in the fabrication and validation of the microscopic circuitry on modern chips.

The positioning accuracy and repeatability of the motion systems within these machines are crucial to ensuring chips are manufactured to specification and at viable yield levels. The EUV lithography process, for instance, requires extremely precise positioning and optical systems capable of guiding beams of EUV light to project patterns onto silicon wafers. EUV light is generated by vaporizing droplets of tin using pulses from a CO2 laser at up to 50,000 droplets per second and then directed through the machine with extreme precision using tightly calibrated positioners and optics manufactured to within nanometer-level tolerances. Additionally, because EUV light is absorbed by air, it must be routed in a vacuum environment, further increasing the requirements of subsystems within EUV lithography machines. Undesirable deviations during the wafer manufacturing process will result in defects that impact chip performance and yield, so every system in the process is tightly controlled.

After the wafer is manufactured, precision metrology tools such as the aforementioned scanning electron microscopes (SEMs) are crucial for measuring critical dimensions of a chip's features at nanoscale, ensuring compliance with design specifications. Much like the EUV manufacturing process, SEMs also require highly precise positioning of various components within the system, including the scanning electron beam, focusing optics, imaging sensors and the sample. High-performance positioners are critical for these nanoscale inspection tools, as the tool can only be as precise as its least precise subsystem. From fabrication to verification, tightly coordinated and controlled motion subsystems are a key technology enabling nearly every step in manufacturing modern semiconductors. An example of an ultra-high vacuum e-beam microscopy stage from Aerotech is shown below in Figure 1.

Figure 1. *Aerotech's custom-engineered, ultra-high vacuum-rated stage is designed for minimal outgassing and particle generation. These features support the semiconductor industry's advanced applications.*

Emergence of Advanced Packaging Techniques

While the continued miniaturization of feature sizes has been an ongoing trend for the industry, the shift to novel packaging techniques is a recent development. These techniques include heterogeneous integration (HI), which is aimed at enhancing chip performance and functionality by fundamentally changing the way chips are packaged. Heterogeneous integration refers to the process of integrating different semiconductor devices, components and technologies into a single package. This is accomplished in a number of ways, including the use of chiplets, system-on-chip (SoC) designs and system-in-package (SiP) integration [2].

Another emerging packaging technique, 3D stacking, can be either heterogeneous or homogeneous and involves vertically stacking multiple chips or layers to increase packing density. These 3D-stacked chips can be integrated using numerous approaches, including at the wafer level (monolithic 3D integration) and with or without the use of silicon or glass interposers between each layer.

Industry-leading semiconductor companies are using these advanced packaging methods to push the boundaries of performance in innovative ways. For example, NVIDIA has revolutionized heterogeneous integration in GPUs, introducing technologies like NVLink that combine with the benefits of advanced packaging to increase compute density and power efficiency by orders of magnitude [3]. Their emphasis on heterogeneous computing architectures has extended the role of GPUs beyond graphics, significantly impacting high-performance computing used in artificial intelligence applications.

Highly precise motion systems are crucial for executing many advanced packaging techniques and manufacturing supporting components such as the silicon and glass interposers that enable some of these packaging methods. Precision positioning systems are essential to align and bond components accurately, ensuring fully functional electrical connectivity in the final packaged product.

Particularly when feature sizes and electrical connection points are so small, it is crucial to have positioning systems capable of making these alignments to manufacture ICs that take advantage of these modern packaging methods. An example of a custom motion subsystem for advanced packaging is shown in Figure 2.

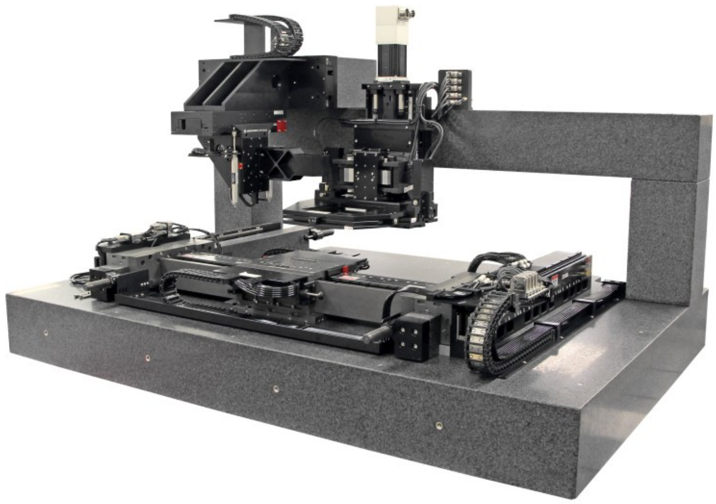


Figure 2. *An example of an Aerotech custom-engineered motion system used for the heterogeneous integration of various semiconductor devices.*

Deployment of Photonic Integrated Circuits

Another emerging technology within the semiconductor industry is the increasing deployment of photonic integrated circuits, or PICs, in various applications. A PIC is an integrated circuit that includes both electrical and photonic components, enabling signals to be sent over fiber optics. PICs are expected to be pivotal to the future of the semiconductor industry due to their capacity for high-speed, energy-efficient data transfer using light particles [4].

Leaders in this space, such as Intel and IBM, and silicon photonics-focused companies like Ciena and Ayar Labs are driving innovations in PICs. Their efforts in integrating optical components on a single chip enhance reliability, reduce costs and address the increasing demand for efficient interconnects in applications like data centers and high-performance computing.

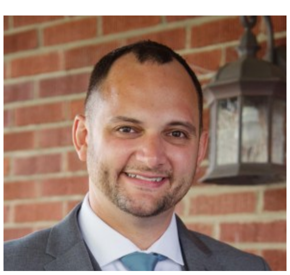
Key to both the assembly and testing of PICs is the precision alignment of the optical components, including light sources, optical fibers, waveguides, gratings and detectors. Precision stages and controls that enable these alignments are critical in the manufacturing and testing of PICs, as anything than ideal alignment results in signal and performance degradation. An example of a 6-axis photonic aligner is shown in Figure 3.

Figure 3. *A 6-axis photonic alignment system with direct-drive motion used for precision alignment of fiber optic systems and PIC probing test processes.*

As PICs continue to be used in a growing number of applications, the precision motion control needed to reliably and rapidly test these devices will be key to scaling their fabrication.

Conclusion

In conclusion, systems that deliver extreme levels of precision enable the trends shaping the future of traditional semiconductor and photonic integrated circuit manufacturing and testing. Whether helping to achieve nanoscale accuracy for advanced node scaling, enabling precise bonding and assembly in 3D stacking, or performing precision alignments of photonic test systems, precision motion is the backbone of modern semiconductor fabrication processes. The deployment of these highly precise systems not only ensures the quality and reliability of existing semiconductor products but also facilitates the industry's continuous innovation and advancement.



About the Author

Justin Bressi is Aerotech's business development manager for precision automation market segments, including semiconductor, photonics, optics, aerospace, R&D and inspection systems. He has 10+ years of experience in precision motion systems and robotics, holding roles in applications engineering, field sales and business development. Justin earned his bachelor's degree in mechanical engineering and his master's degree in business administration from the University of Pittsburgh.

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