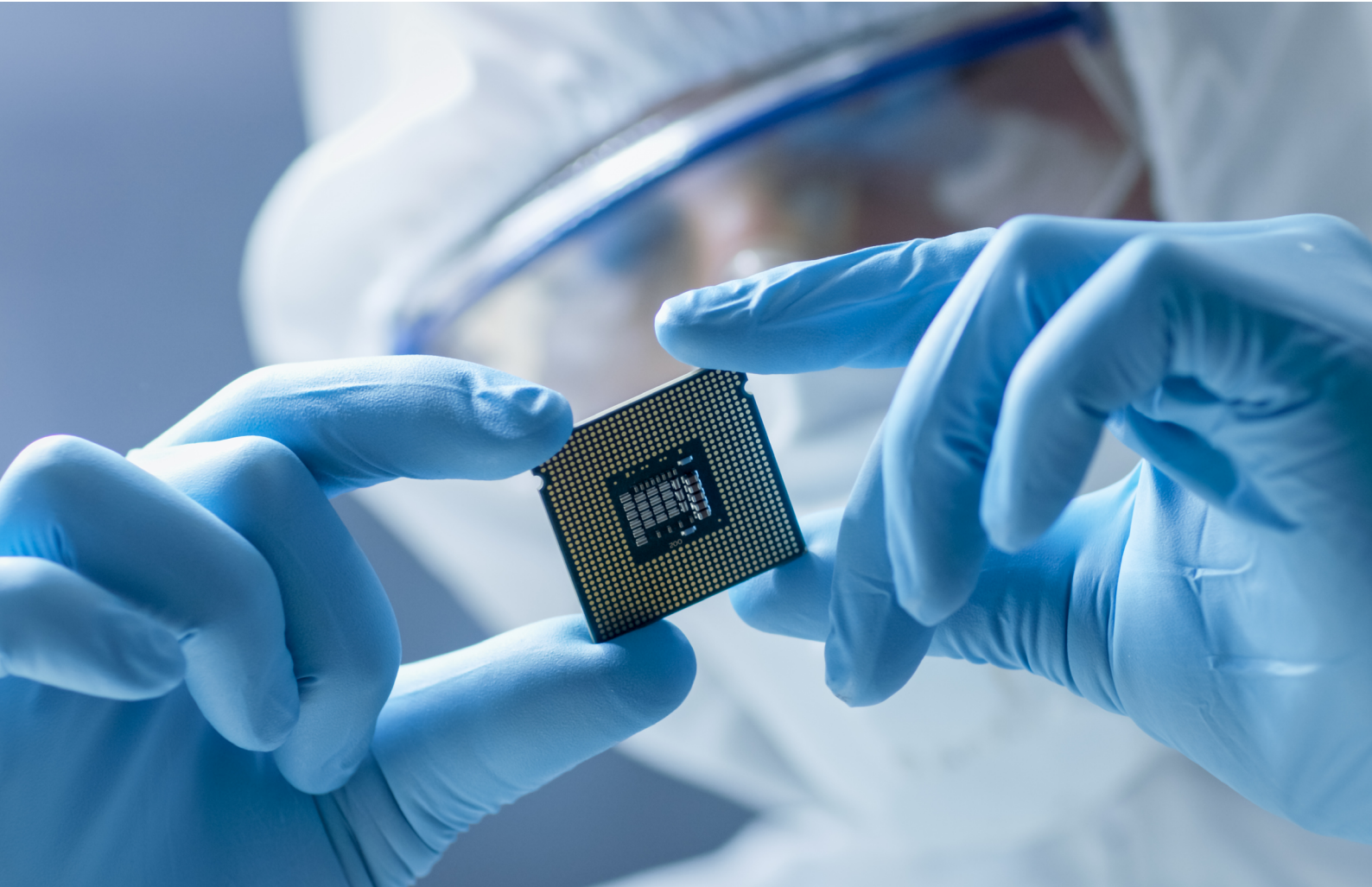




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Metrology for Sustainable Semiconductor Manufacturing: Enabling Quality, Precision, and Efficiency

The enhanced yield of high-quality microchip production has been enabled through the use of advanced metrology and SI-traceable standards

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The Challenge

Microchips are ubiquitous and used in electronic devices that underpin our daily life, from communications and mobile phones to medical devices and automotive technology. Driven by surging demand for AI-related chips, the global semiconductor industry is rapidly advancing beyond the 2 nm technology node and progressing toward a 3D package of multiple chips to achieve higher performance, lower power consumption, and reduced costs.

To meet the semiconductor industry's demands for sustainability and innovation, this advancement requires extremely precise control over nanoscale device geometry and material composition, posing significant challenges for manufacturing metrology. These challenges include measuring complex nanoscale critical dimensions (CDs) and film thickness, detecting particle contamination below 10 nm with densities $< 10^2 \text{ cm}^{-2}$, and characterizing »100 nm warpage with micrometre accuracy. Furthermore, with the transition to sub-nanometre components, the tolerance for impurities in the raw materials used to make chips is becoming more stringent. Reliable and SI-traceable measurement capabilities help reduce process deviations, thereby minimizing wafer scrap, rework, material losses, and energy-intensive reprocessing, making the advanced metrology essential for both manufacturing efficiency and sustainable production.

Addressing these challenges requires both innovative metrology solutions for characterizing buried 3D structures and reliable reference standards to ensure measurement accuracy and precision, thereby improving tool-to-tool measurement consistency. These efforts are essential for improving semiconductor manufacturing precision and yield, thereby enabling the stable production of advanced chips that underpin next-generation digital applications such as AI, cloud computing, high-performance computing, and 5G/6G communication technology.

The Solution

To address the aforementioned metrology requirements, a national metrology framework at the Center for Measurement Standards in the Industrial Technology Research Institute (CMS/ITRI) has been established to ensure accuracy, consistency, and metrological traceability across the semiconductor manufacturing ecosystem. The framework is built on the following two key metrological pillars: 1) development of advanced metrological techniques to characterize microchips and 2) the development of reference materials to ensure that important instruments and sensors used throughout the semiconductor production are adequately calibrated.

X-ray-based techniques (CD-SAXS, 2.5D/3D XCT) are used to provide non-destructive, high-resolution measurements of buried structures (< 0.5 μm resolution) in 3D packaging, complex geometries (CD with precision < 0.1 nm) in front-end processes, and material compositions ($\text{Si}_{1-x}\text{Ge}_x$) for Gate-All-Around (GAA) nanosheets.

Reference materials (RMs) for iron oxide nanoparticles (15 nm and 30 nm) are developed to calibrate and validate measurements of particle size and particle number concentration in solution (shown on the left of **Figure 1**). In addition, gas RMs (shown on the right of **Figure 1**) consisting of impurity gas mixtures covering concentration ranges from sub-ppm to percent levels are developed to calibrate analytical instruments used for impurity analysis and incoming quality checks of semiconductor process gases. All RMs are prepared from high-concentration source materials and diluted with ultra-clean gases or matrix-matched solvents to achieve the target concentration. These RMs also provide metrologically traceable calibrations for particle and contamination measurements in microchip manufacturing processes and throughout the supply chain.

A Quantifiable Impact

Implementing this metrological framework has enabled high-precision, metrologically traceable measurements that improve process control, resulting in higher yields, reduced variability, and enhanced microchip manufacturing productivity. Advanced 3D XCT imaging enables the non-destructive detection of dimensional defects in buried structures of 3D packaging at a spatial resolution of less than 0.5 μm . **Figure 2** shows a typical image of defects in micro-bumps measured using 3D XCT. By integrating this metrology into statistical process control, process quality can be improved at an early stage, helping manufacturers maintain product yields above 90 %. Together with a precision of < 0.1 nm in CD metrology for front-end GAA and CFET fabrication, the metrological framework supports reliable manufacturing of advanced integrated circuits while reducing rework rate by approximately 0.1 %.

The 15 nm and 30 nm nanoparticle RMs have been used as validation standards for particle inspection and new analytical instruments in semiconductor manufacturing. Applications included wafer surface scanners, scanning mobility particle sizers, and single-particle Inductively Coupled Plasma Mass Spectrometry (ICP-MS) to detect nanoscale contaminants < 10 nm. These nanoparticle RMs help ensure traceable measurements and support the ultra-clean environments required for reliable production at 2 nm nodes and beyond.

The use of SI-traceable gas and nanoparticle standards has directly improved measurement consistency, minimized variation across measurement tools, and accelerated process optimization and efficiency. In a practical industrial case, the developed nanoparticle RMs were used to validate a new DMA-CPC system for contamination analysis in semiconductor raw materials, thereby improving the semiconductor materials supplier's production yield from approximately 75 % to 99 %.



Figure 1. Reference Materials for iron oxide nanoparticles (left) and a Certified Reference Gas Mixture containing carbon monoxide, carbon dioxide, and propane in nitrogen (right).

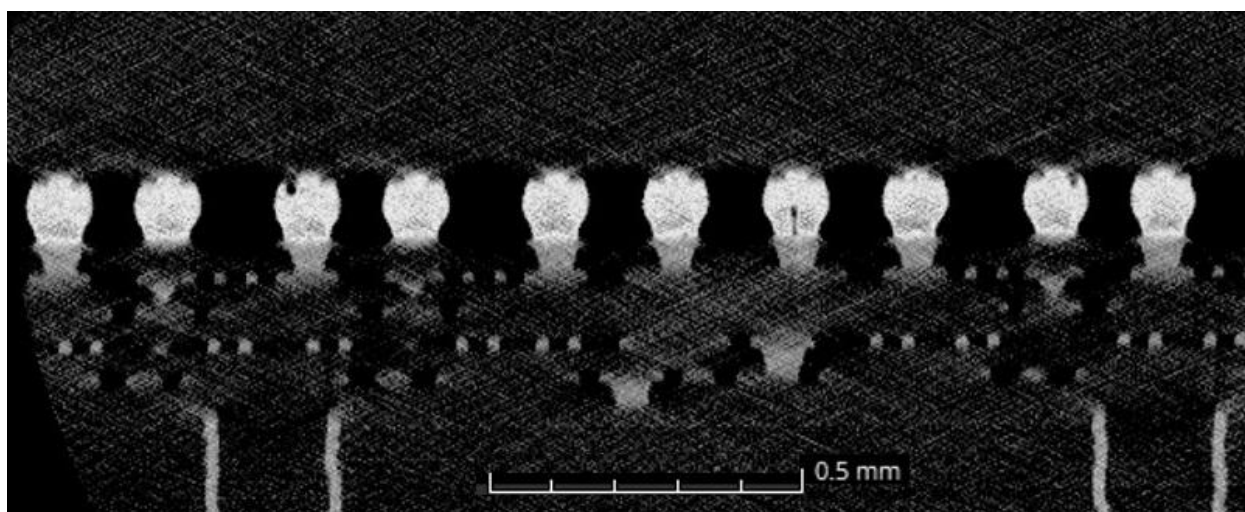


Figure 2. A typical 3D XCT image of defects and micro-bumps on silicon substrate.

The high-quality chips produced by the semiconductor industry in Chinese Taipei have resulted in a global market share of 70 %.¹ The metrological intervention described herein has also been developed in alignment with international metrology frameworks (e.g. CIPM MRA) to ensure that measurement results of the underlying metrological capabilities used in production are globally recognized and products are globally accepted. This has eliminated redundant testing and accelerated time-to-market for next-generation semiconductor products.

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¹ Taipei Times. TSMC nets nearly 70% of 2025 foundry market. 14 March 2026.
<https://www.taipeitimes.com/News/biz/archives/2026/03/14/2003853777>