TECHNOLOGY TRENDS

Meeting the metrology and inspection needs of next-generation advanced packaging processes

By Timothy Kryman [Rudolph Technologies, Inc.]

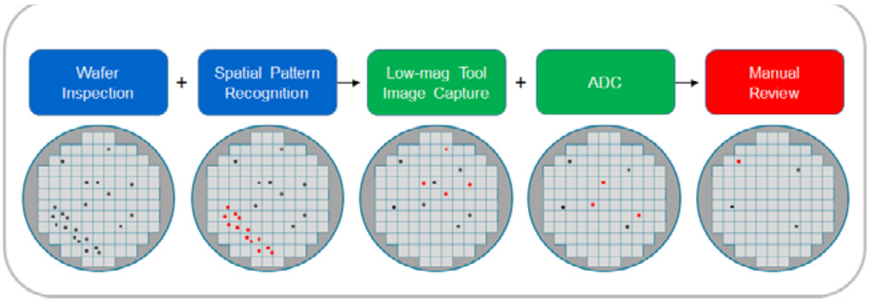
Advanced packaging (AP) technologies have imported many processes from front-end wafer fabrication to the back end of the manufacturing process. Controlling these processes in the back end requires similar approaches to inspection and measurement. Like the front end, shrinking feature sizes are driving requirements for improvements in accuracy, precision, sensitivity and throughput. But AP processes also present measurement and inspection challenges that are unique to back-end applications, such as bump metrology and nonvisual defects. These unique needs, coupled with the greater diversity and rapid evolution of AP processes, are creating demand for flexible measurement and inspection systems that can be used to control a variety of parameters, such as both two-dimensional (2D) and three-dimensional (3D) geometries, and can be adapted to new requirements as they arise. Combining these capabilities in a single platform permits the most efficient and effective use of capital. Keeping pace with the industry roadmap will require innovative solutions from equipment suppliers that are focused on the specific needs of AP processes.

Manufacturers are also facing increasing market pressure to improve quality and reliability. This is especially true of market segments like automotive, where consumer safety is a significant consideration. Current-generation automobiles already contain thousands of semiconductor components, and with the prospect of fully autonomous vehicles, that number may grow by orders of magnitude. A component failure rate of one in a million equates to a vehicle failure rate of 1 in 100 for a vehicle with 10,000 components—a rate that is not acceptable. Meeting this challenge in current and next-generation packages requires defect sensitivity down to the micrometer level and the ability to distinguish killer defects quickly and reliably within enormous streams of raw data. Statistical tools like gauge repeatability and reproducibility (R&R) studies and sophisticated software capabilities like spatial pattern recognition will become increasingly important. More data alone is not enough—engineers need systems that can turn raw data into actionable process information.

Improving throughput, sensitivity, accuracy and precision

Throughput, sensitivity, accuracy and precision are fundamental performance characteristics for any inspection and measurement system. Throughput ultimately determines the cost of ownership. Sensitivity determines the smallest defect that can be reliably detected. Accuracy and precision determine how tightly the process can be controlled. All are becoming more challenging to improve as package feature sizes continue to shrink.

Conventional imaging systems that use 2D area-scan sensors impose unavoidable trade-offs among resolution, sensitivity and speed. Rudolph's latest-generation system (Dragonfly™ G2) incorporates an advanced imaging sensor and optical design that circumvent these limitations to provide both significantly faster imaging and sensitivity to defects as small as 1µm. The optical system is specifically designed to accommodate larger package sizes. Streamlined image processing routines provide the analytical speed required to keep pace with the accelerated data flow. Stage speed and accuracy have also been increased to meet the requirements of the



- Multiple mags, passes and ROIs
- Rules-based binning

- Classification of defects via pattern recognition, including nuisance defects
- 30% reduced image capture typical for population

- Removal of defects via low-mag defect attributes, including nuisance defects
- 20-30% reduced image capture typical for remaining population

- Classification of defects via high-mag defect attributes, including nuisance defects
- 60-90% classification typical for remaining population

- Unknown defects only require manual disposition
- Very few nuisance defects remain
- 90% defect reduction typical before review

Customer	Process Area	Nuisance Classification Rate
Taiwan #1	Post Dicing	>80% Nuisance
Taiwan #2	Post Dicing	>50% Nuisance
China #1	Post Dicing	80% Nuisance
Malaysia #1	Post Dicing	>50% Nuisance
Taiwan #3	Post Dicing	80% Nuisance
Taiwan #4	Post Dicing	50% Nuisance

Figure 1: The table on the right shows a representative sampling of the percentage of nuisance defects detected in various applications at user facilities. All are greater than 50%, one is greater than 80%. The graphic on the right illustrates the data analysis process that automatically classifies 90% or more of defects, including most nuisance defects, before any manual operator review.

new imaging scheme. Initial customer evaluations have reported throughput increases of 50% and more.

Nonvisual and nuisance defects

Advanced packaging processes face unique inspection challenges, including nuisance defects and nonvisual defects. Nuisance defects are false positives that can occur in large numbers, overwhelming detection systems and consuming significant resources to review and reject. They are caused by the variable grain patterns of metal conductors that appear to the inspection algorithm as deviations from the standard. These same grain patterns can hide true defects. Another class of defects, known as nonvisual, are caused by residues of the organic materials used to insulate conductors and planarize the surface. These materials tend to be transparent under conventional illumination and yield little signal in bright field and dark field inspection. They can be especially troublesome when they occur on contacts, such as bumps and pillars.

The impact of nuisance defects can be greatly reduced through an effective application of optical principles and sophisticated defect review software. Clearfind™ Technology suppresses the variable contrast patterns generated by metal grains, thereby reducing the nuisance defects these patterns can cause and providing improved sensitivity to structural defects in conductive lines and pads. Reducing the number of nuisance defects in the initial data stream also reduces the load on subsequent review software. This automated process proceeds stepwise through classification with spatial pattern recognition, removal based on low-magnification attributes, and automatic defect classification (ADC) using high magnification attributes (**Figure 1**). Typically, the automated review software can classify 90% or more of the defect population, including nuisance defects, without manual review.

The technology also addresses the issue of nonvisual defects by generating a strong, high color-contrast signal from organic materials. This distinctive signal makes residues of organic materials on metals and other inorganic materials, or traces of metals on organic surfaces, easy to detect (**Figure 2**). In some AP processes, such as post-lithography inspection, the technique can be used exclusively, with no need for conventional bright field and dark field passes.

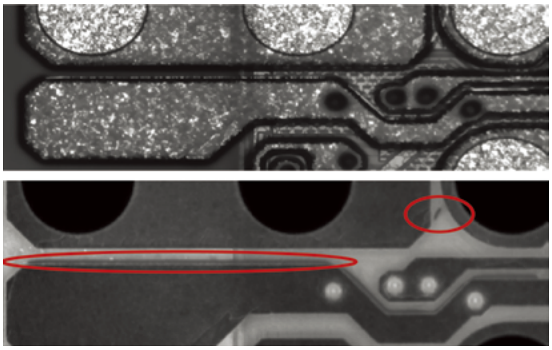


Figure 2: Nonvisual defects: a) Bright field image of RDL, the metal surface with rough grain structure looks noisy, but it cannot show the under-etch metal residue because the white light reflected from the metal residue and the organic underlayer look the same; b) Image using Clearfind Technology clearly shows the under-etched metal.

2D/3D bump metrology

Many AP processes use vertical integration schemes that require interlayer connections as small and reliable as the multilayer interconnect technologies used within the chip. Most of these vertical connections involve the creation of a conductive "bump" protruding through an insulating layer to carry the signal to the next layer above or below. Controlling the bumping process requires a combination of 2D and 3D inspection and measurement techniques that is unique to AP applications. Total bump process control requires 2D defect detection of voids and shorts, foreign material, and misprocessing; 2D measurement of bump diameter, bump position, bump presence; and 3D measurement of bump height and coplanarity. Bumps are already trending to smaller dimensions as low as 10µm diameters and 5µm heights. As a result, repeatability and resolution requirements are going beyond the capability of conventional white light techniques and now require laser-based technologies. Inspection systems are also challenged by the increasing number of bumps, with total bump counts already exceeding 80 million per wafer.

Achieving consistent bump height and coplanarity is critical to ensuring reliable connections. A bump that is not high enough will not connect, while one that is too tall may prevent connection by neighboring bumps. Even the slightest bump height variations can cause weak connections and lead to costly failures in the field. Bump height measurement has become more challenging with the introduction of processes that eliminate the under-bump metallization (UBM) layer used to improve bond strength between the solder ball and the copper redirect pad. The intermetallic compounds (IMC) formed there are mechanically weak and subject to fracture under the thermally-induced mechanical stress generated by the different expansion coefficients of the silicon die and the package substrate. UBM-free integration (UFI) eliminates the UBM and uses a thick polymer protection layer (PL) to secure the solder in place and provide stress relief between the chip and the substrate. In addition to eliminating the IMC as a source of failure, UFI reduces package cost and cycle time by eliminating layers and allows a significant reduction in final package thickness. Unfortunately, the PL, which is semitransparent and varies in thickness, causes errors in bump height measurements.

A new hybrid approach to bump height measurement (Truebump™ Technology) uses a high-accuracy sensor that combines interferometry and reflectometry to measure the top of the bump, the top and bottom of the PL and step heights at the edges of opaque materials underlying the PL with nanometer-scale accuracy and precision. The system then calculates corrections and applies them to bump height measurements made with a high-speed sensor in a subsequent 100% inspection.

Summary

Advanced packaging processes are becoming more complex and package feature sizes are shrinking, leading to process control requirements similar to the front-end applications where many AP processes originated. As feature sizes continue to decrease, performance requirements for inspection and measurement tools are becoming more difficult to meet. In addition to improvements in basic performance characteristics, like speed and sensitivity, these tools must also incorporate innovative solutions to problems that are specific to AP applications, including accurate bump height measurements and sensitivity to nonvisual defects. Ultimately, the process control needs of AP processes are best met by a flexible system that can deliver the full range of required capabilities in a single, high-throughput, capital-efficient platform.

Biography

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