Applications of Picosecond Laser Acoustics for Advanced Packaging

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Biography

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ABSTRACT

Picosecond laser acoustic (PULSE™) Technology is an industry benchmark for metal film metrology[1]. The non-contact, non-destructive technique is well-suited for providing simultaneous multi-layer measurements in-line on product wafers. The technology has found widespread adoption across multiple device segments supporting both leading edge and specialty process monitoring and control.

Thin film thickness control in advanced packaging is vital for ensuring the electrical, thermal, mechanical, and process-related performance of semiconductor devices. Inaccurate film thickness can lead to performance degradation, higher defect rates, and increased production costs, which makes precision metrology essential in the modern semiconductor manufacturing process. This paper highlights the advantages of the application of PULSE Technology in advanced packaging process monitoring.

By presenting specific examples, we showcase PULSE Technology's capability to measure multiple-layer stacks, with excellent repeatability, easy to match between tools, and long-term stability. The small spot size makes it possible for direct measurement on BUMPs for advanced packing. Recent upgrades to the system include extending the measurement range to cover very thick, rough films and improvements to signal to noise ratios making it more suitable for advanced packaging to use a single metrology tool to cover a wide range of applications. Additionally, we present examples of the non-destructive Young's modulus measurement capability that provides critical information about the mechanical strength of the packaging material and residue detection.

INTRODUCTION

The semiconductor packaging industry is undergoing rapid evolution, driven by the increasing demand for miniaturized, high-performance electronic devices. Advanced packaging technologies, such as 3D integration, fan-out wafer-level packaging (FOWLP), and chiplet architectures, have emerged as key enablers of continued progress in semiconductor performance, addressing the limitations of traditional scaling under Moore's Law. As industries such as consumer electronics, automotive, telecommunications, and artificial intelligence (AI) demand more powerful and energy-efficient systems, the market for advanced packaging is expected to experience robust growth over the next 10 to 20 years. According to the recent report published by Allied Market Research in Aug 2024, the advanced packaging market was valued at $48.5 billion in 2023, and is estimated to reach $119.4 billion by 2032, growing at a CAGR of 10.6% from 2024 to 2032[2]. The demand is driven primarily by the growing adoption of 5G, the Internet of Things (IoT), AI, and machine learning (ML) applications, all of which require highly integrated systems with enhanced performance, reduced power consumption, and improved thermal management. The automotive industry, with its increasing reliance on electronics for autonomous driving systems, advanced driver-assistance systems (ADAS), and electric vehicle (EV) technology, is also expected to contribute significantly to market growth.

The continued investment in research and development, along with advancements in fabrication techniques and metrology, will further drive innovation in the advanced packaging space. As semiconductor companies strive to maintain competitiveness in an increasingly demanding market, packaging will become a critical differentiator, offering new solutions for performance scaling beyond traditional transistor miniaturization. Given these trends, the advanced packaging market is poised for significant expansion over the next two decades, positioning it as a cornerstone of the semiconductor industry's future.

The picosecond laser acoustic technique is well understood and described extensively in literature [2]. This is a first principles technique that relies on a pump beam for generating acoustic sound waves that reflect off various interfaces and a time-delayed probe beam that monitors the change in surface reflectivity of the returning echo. Thickness is extracted from this acoustic signature using the arrival time of the echo and the longitudinal speed of sound in the material.

Echo™ metrology system is the fifth generation of picosecond laser acoustic technology offering a first-principles approach to metal film measurements. Thickness ranging from 50Å to 35µm can be measured on a single platform. The small spot size enables direct measurements on devices (15µmx15µm sites). Fully automated wafer maps can be generated in a few minutes. The metallization films used in advanced packaging are generally rougher, either as deposited or post-etch. In some niche applications, they also tend to be ultra-thick (30µm of Cu). In this paper, we highlight the advantages of the technology in the advanced packaging, emphasizing its suitability and benefits for AP.

ADVANTAGES OF PULSE TECHNOLOGY TO PROCESS CONTROL OF ADVANCED PACKAGING

1. Dielectric Layer, Metal Interconnect, Barrier and Seed Layer

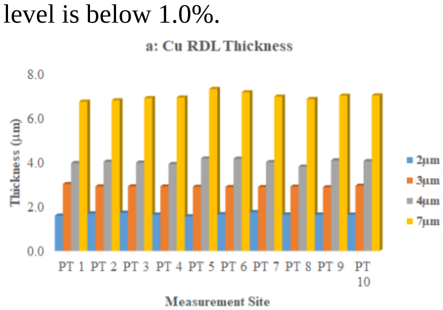
Precise control over the thickness of various films is critical for advanced packaging. These films include dielectric layers such as silicon dioxide (SiO_2), silicon nitride (Si_3N_4), and other low-k or high-k dielectrics; metal interconnects like copper (Cu), aluminum (Al), and gold (Au), as well as other conductive metals; and barrier and seed layers such as tantalum (Ta), titanium (Ti), and titanium nitride (TiN). PULSE technology enables the measurement of these film thicknesses with high accuracy, repeatability and fast throughput. Table 1 demonstrates the performance of PULSE technology for the measurement of typical films. 3 sigma for most of the films are well below 0.30% except ultra-thin 50 Å TaN.

FilmStack	Thickness (A)	Repeatability (3δ)
Ta100A	95.8	0.13%
Cu 400	370.1	0.24%
TaN 50A	46.7	0.70%
TiNLD 250A	247.5	0.03%
TiNHD 300A	363.1	0.11%
Cu 900	964.0	0.03%
Cu 1um	11228.7	0.22%
Pattern Cu Line	1098.7	0.26%
Pattern Cu Pad	818.6	0.06%

Table 1. Typical dynamic repeatability performance for PULSE measurement for commonly used films in advanced packaging

2. Redistribution Layers (RDL) Thickness Measurement

In fan-out packaging, RDLs provide the wiring required to connect the chips to external connections. Thickness control for RDL is essential to ensure proper routing and connection density. Because of its rough surface and a few microns thickness range make PULSE technology the best fit for the measurement of RDL thickness. Figure 1a and 1b show the thickness and repeatability (3 sigma) for 10 sites across each wafer measured by PULSE technology. The RDL films are 2, 3, 4, and 7 µm thick Cu films. 3 Sigma for all the films at site level is below 1.0%.



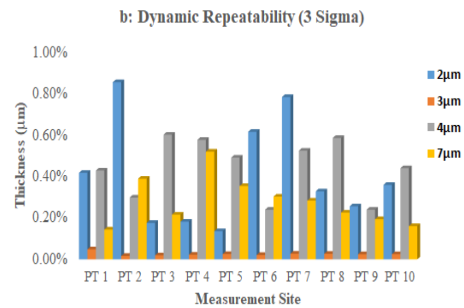


Figure 1a). PULSE measurement for RDL with thickness of 2, 3, 4, and 7µm, and b) dynamic repeatability (3 sigma) for 10 sites for the measurements

3. Multilayer measurement for backside metallization by PULSE Technology

Several metal layers are used for backside metallization (BSM) and offer good adhesion, electrical properties, and long-term reliability. Commonly used stacks for packaging are Ti/NiV/Ag or Al/Ti/NiV/Ag. Quite often, the backside metal surfaces feature rough grain structures compared to the front side. These measurements can be prohibitively slow for high-volume manufacturing and, in some extreme cases, are not able to be measured. With recent improvements to the optics design to handle the rejection of the scattered pump beam from reaching the main detector we can significantly improve SNR. Table 2 summarizes both static and dynamic repeatability when measuring Ti/NiV/Ag films. The corresponding 49-point thickness profiles are shown in Figure 2.

Layer	Ti 1000Å	NiV 3000Å	Ag 1500Å
Static Repeatability(3σ)	0.73%	0.42%	0.46%
Dynamic Repeatability(3σ)	0.57%	0.09%	0.21%

Table 2. Static and dynamic repeatability performance for PULSE measurement for commonly used multilayer metal film stack Ti/NiV/Ag in power devices.

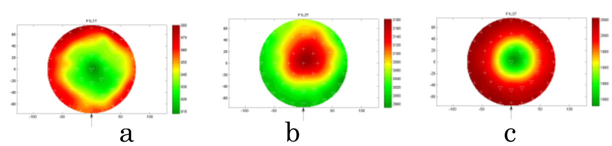


Figure 2. 49 - point maps of (a). Ti 1,000Å, (b). NiV 3,000Å, and (c). Ag 1,500Å.

4. Simultaneous measurement of thickness and Young's Modulus of dielectric films

Dielectric films are used to insulate metal interconnects in multi-layer devices and between through-silicon vias (TSVs) in 3D packages. Precise control over their thickness ensures proper insulation, which is critical for preventing electrical shorts and maintaining signal integrity in high-speed, high-density interconnect systems. Oxide films play a critical role by providing electrical isolation, threshold voltage control, reliability, and leakage current reduction. Young's Modulus serves as an important indicator for the mechanical strength of the film and ensures that the material can withstand stress and temperature fluctuations, safeguarding the long-term performance. When measuring dielectric films using picosecond laser acoustics, the films need to be either on opaque substrate or have a thin metal film on top as an opto-acoustic transducer [3,4]. Figure 3a and 3b provide results from measurement for thickness and Young's modulus measurements on oxide films. It is evident that the 3σ repeatability at the site level for both thickness and Young's modulus measurements is well below 0.10%.

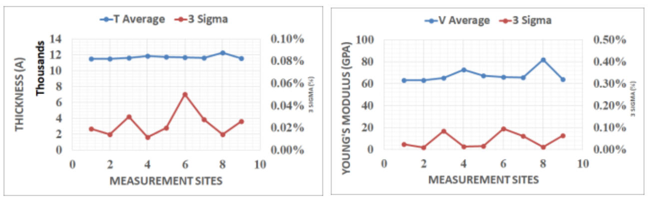


Figure 3a). Example of SiO_2 *thickness and repeatability by Picosecond Acoustics. 3b). Example of* SiO_2 *Young's modulus and repeatability by Picosecond Acoustics*

5. PULSE Technology measurement on ~ 15 µm Pad for advanced packaging

One of the most significant advantages of PULSE Technology for advanced packaging lies in its small spot size which enables the direct measurement of product wafers at tens microns of pads or arrays. Figure 2a and 2b are typical thickness and repeatability performance for simultaneously measuring the thickness of Ni layer and top Au layer. Repeatability performance of both layers are below 1.0% for 3 sigma.

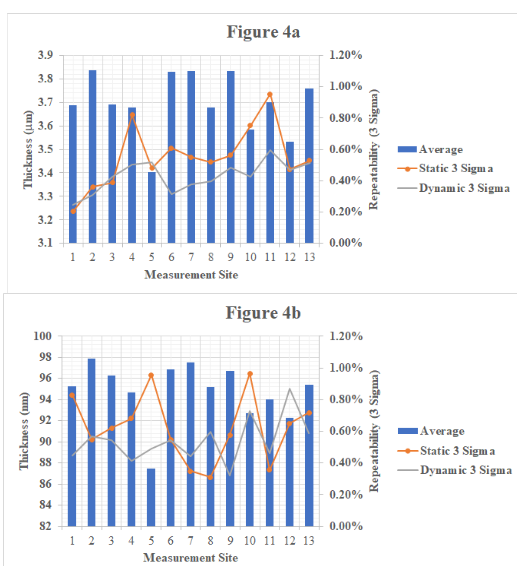


Figure 4. PULSE measurements for a HBM BS pad with the diameter of 13 µm with the metal film stack of Ni/Au for advanced packaging

6. Residue detection on TSV Cu Pillar

Residue detection on TSV (Through-Silicon Via) Cu pillars is essential, especially in advanced packaging and semiconductor manufacturing. Residues like SF6, left on the Cu pillar surface after the dry etching process, can disrupt bonding between the Cu pillars and other layers or materials. Additionally, these residues can negatively impact the electrical properties of the TSV, leading to increased resistance, signal degradation, or even complete electrical failure. Traditional inspection tools, such as AOI (Automated Optical Inspection), often lack the resolution or sensitivity to detect SF6 residues on Cu surfaces, making detection challenging and allowing contaminants to compromise the integrity of the final product. Therefore, advanced metrology techniques that can identify such residues are crucial. Figure 5 shows the standard deviation of five repeated measurements on Cu pillars with and without SF6 residues, as measured by PULSE technology. The results clearly demonstrate that Cu pillars without SF6 residue exhibit significantly more stable measurements.

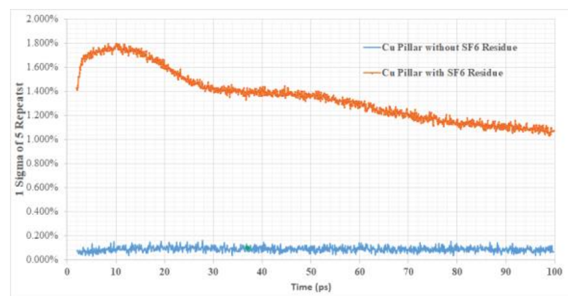


Figure 5. Standard deviation for Five PULSE measurements for Cu pillar surface with and without SF6 residues.

SUMMARY

The non-contact, non-destructive nature of PULSE technology makes it ideal for measuring metal films across multiple layers on product wafers with high accuracy, repeatability, and fast throughput. We discussed various use cases, including precise thickness control of dielectric layers, metal interconnects, and redistribution layers (RDLs), as well as backside metallization measurements. We also highlight the technology's capability in measuring site with tens of microns directly on product wafers, detecting residues, such as SF6 on TSV Cu pillars, which is crucial for ensuring bonding integrity and electrical performance. With recent improvements in signal-to-noise ratio and measurement range, PULSE technology has become indispensable for in-line metrology in high-volume semiconductor manufacturing, contributing to the ongoing evolution of advanced packaging processes.

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