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A Comprehensive Guide to Detecting and Monitoring Fluorine Contamination on Al Bond Pads in Wafer Fabrication

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ABSTRACT

Fluorine (F) contamination on aluminum (Al) bondpads is a critical yield and reliability issue in semiconductor manufacturing, leading to corrosion, defects, and non-stick on pad (NSOP) problems. The accurate detection and monitoring of this surface-level contamination are paramount. This comprehensive study addresses the critical question of how to correctly determine fluorine contamination levels on Al bondpads. We first elucidate the fundamental differences between bulk analysis techniques, like Energy Dispersive X-Ray Spectroscopy (EDS) and surface-sensitive techniques, such as Auger Electron Spectroscopy (AES). Through theoretical calculations and practical case studies, we demonstrate that EDS is fundamentally incapable of detecting the thin, surface-level fluorine contamination, as its signals are diluted by the bulk of the Al bondpad. We introduce the practical rule: "EDS clean is not clean; Auger clean is clean." To provide a robust solution, we propose a comprehensive AES monitoring scheme for wafer fabrication. This scheme includes detailed instrument parameters, quantitative data analysis, sampling methods, and the establishment of statistically-based Control and Specification Limits. We also detail Out-of-Control (OOC) and Out-of-Specification (OOS) procedures, providing a complete framework for process engineers and failure analysis teams to eliminate F-induced defects. Finally, a case study is presented demonstrating the successful use of this scheme for process improvement.

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Introduction

In the semiconductor industry, the integrity of Al bondpads is crucial for successful wire bonding and long-term device reliability. Fluorine contamination on these pads is a well-known and persistent problem. Fluorine-based gases like CF_4 and SF_6 are extensively used in plasma etching processes, particularly for passivation layer openings and pad definition. Despite subsequent rigorous cleaning steps, residual fluorine can remain on the bondpad surface.

This residual fluorine initiates a corrosive chemical reaction with the aluminum, leading to the formation of aluminum fluorides (e.g., AlF_3). These compounds can further react with moisture and oxygen from the ambient environment to form aluminum hydroxides and oxides, leading to visible defects often classified as "flower-like", "crystal-like" or "cloud-like" and "oxide-like" defects. Ultimately, this corrosion compromises the bondability of the pad, resulting in non-stick on pad (NSOP) defects during the assembly process, causing significant yield loss and reliability concerns.

The fundamental challenge lies not only in preventing contamination but also in accurately detecting and monitoring it. Process and failure analysis engineers frequently turn to common analytical tools like EDS, which is readily available on most scanning electron microscopes (SEM). However, this can lead to a critical analytical error. While EDS is excellent for bulk analysis, it is a poor choice for thin-film or surface contamination analysis.

This Paper Aims to Resolve this Analytical Ambiguity by Providing a Definitive Guide. It Accomplishes this through a Two-Pronged Approach:

- **Demonstrating the Inadequacy of EDS:** We will first explain the fundamental physics that renders EDS unsuitable for surface F detection, using simulation and calculations to show why an EDS signal, when present, represents a highly diluted and often undetectable fraction of the true surface concentration.
- **Providing a Complete Monitoring Solution:** We will then present a fully developed and validated monitoring scheme using Auger Electron Spectroscopy (AES), which is inherently surface-sensitive technique. This scheme provides engineers with the necessary tools to establish a robust quality control process for their wafer fabs.

Theory and Methodology: Understanding the Analysis Techniques

Energy Dispersive X-Ray Spectroscopy (EDS)

EDS is a powerful and widely used technique for elemental analysis. The incident electron beam penetrates the sample and generates X-rays characteristic of the elements present within the interaction volume, as shown in Figure 1. However, its critical limitation for surface analysis is the large interaction volume. The penetration depth, which can range from 0.3 to 8.5 µm depending on the beam voltage and the material's atomic number (Table

1), is significantly larger than the few-nanometer thickness of a surface contaminant layer.

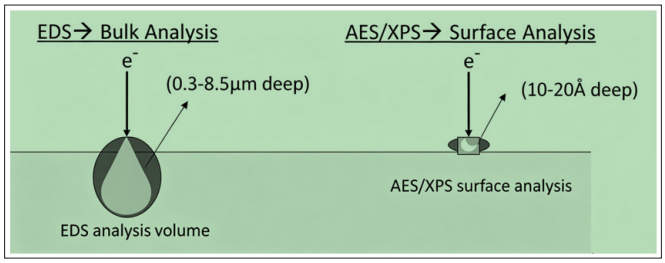


Figure 1: Schematic Comparison of EDS and AES Analysis Volumes and EDS's penetration is ~0.3-8.5 μm and the tiny surface volume for AES is only about ~10-20 Å

Table 1: EDS Penetration Depth (μm) for Various Materials

Acceleration Voltage (kV)	Al (Z=13)	Si (Z=14)	SiO_2	Si_3N_4
5	~0.38	~0.40	~0.41	~0.35
10	~1.10	~1.15	~1.20	~1.05
20	~4.10	~4.25	~4.40	~3.80

This means the X-ray signal from a surface layer of fluorine, if any, is dwarfed and diluted by the signal from the underlying aluminum and other bulk materials. As a result, EDS has a detection limit of only 0.1-1.0 at%, and it is inherently insensitive to trace amounts of low-Z elements like fluorine on a surface. Furthermore, the technique's quantitative analysis is not reliable for layers thinner than its interaction volume.

Auger Electron Spectroscopy (AES)

In contrast to EDS, AES is true surface analysis techniques. The inelastic mean free path (IMFP) of the emitted Auger electrons and photoelectrons is on the order of 1-2 nm (10-20 Å). This means that the analytical signal detected originates exclusively from the topmost atomic layers of the sample (Figure 1). The sampling depth is independent of the electron beam energy.

AES is intrinsically sensitive to low atomic number (Z) elements such as C, O, and F. Their detection limits are also in the range of 0.1-1.0 at%, but critically, this limit applies to the surface composition, not the bulk. A 0.5 at% F signal from AES is not diluted and directly represents a 0.5 at% fluorine concentration on the bondpad surface, making it detectable and quantifiable. A comparison of the key differences is shown in Table 2.

Table 2: Key Differences Between EDS and AES

Feature	EDS	AES
Technique Type	Bulk Analysis	Surface Analysis
Sampling Depth	~0.3 - 8.5 μm	~10 - 20 Å (~1-2 nm)
Sensitivity	Good for high Z elements	Excellent for low Z elements (C, O, F)
Detection Limit	~0.1 - 1.0 at% (bulk)	~0.1 - 1.0 at% (surface)
Applicability	Visible, thick contaminants	Thin films, surface monolayers

The Inadequacy of EDS for F Contamination: A Case Study

A practical case study from our previous work clearly demonstrates the pitfalls of using EDS [1]. Two Al bond pad samples were analyzed by AES:

- **Sample 1:** High F contamination at 8.5 at%.
- **Sample 2:** Low F contamination at 3.3 at%.

In our previous studies, we have studied F contamination on Al bondpads in wafer fabrication. Based on extensive sample analysis and three-sigma statistical calculations from more than 200 production samples, we established the following control limits for as-received (0nm) and after 5nm sputtering (Ar+, 3kV, calibrated against SiO2/Si reference) as shown in Table 3.

Table 3: Control Limits (Using AES analysis)

Element	As-received (0 nm)	After 5 nm sputtering
Fluorine (F)	5.0 at%	0.0 at% (or < LLD)
Carbon (C)	30.0 at%	00.0 at% (or <LLD)

Table 4: Spec Limits

Element	As-received (0 nm)	After 5 nm sputtering
Fluorine (F)	6.0 at%	0.0 at% (or < LLD)
Carbon (C)	30.0 at%	00.0 at% (or <LLD)

According to Table 3, if we use AES to determine the F contamination on Al bondpads, the control limit of F is 5.0at% for for as-received (0nm). Therefore, the above sample 1 is OOC as the concentration of F is 8.5 at%, which is large than the control limit 5.0 at%. However, the sample 2 is normal as the concentration of F is 3.3 at%, which is less than the control limit 5.0 at%. Our simulation results using SLAT (shelf-life acceleration test) showed that there were lot of the "Crystal-like" defects on Al bondpads of the sample 1 with higher F (8.5 at%) after SLAT test (refer to Figure. 2 & 3). But there was no changed on Al bondpads of the sample 2 with lower F (3.3 at%) after SLAT test (refer to Figure. 4 & 5). Therefore, we can use AES data to justify and determine quality of bondpads/wafers by using AES with the control limits in Table 3.

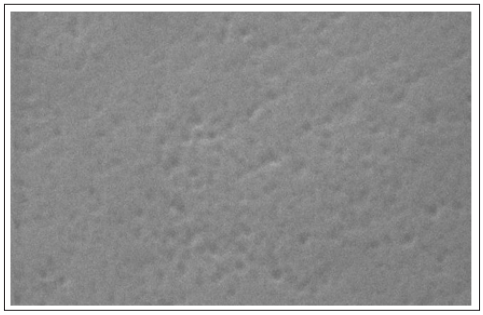


Figure 2: Sample 1: Bond pad with high F (AES result about 8.5 at%)

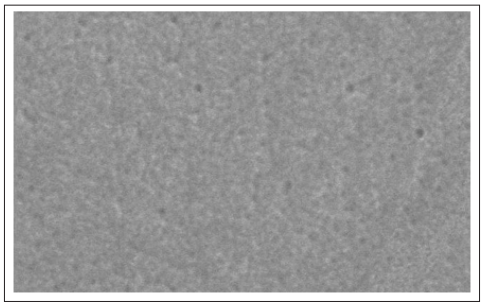


Figure 3: Sample 2: Bond pad with low F (AES result about 3.3 at%).

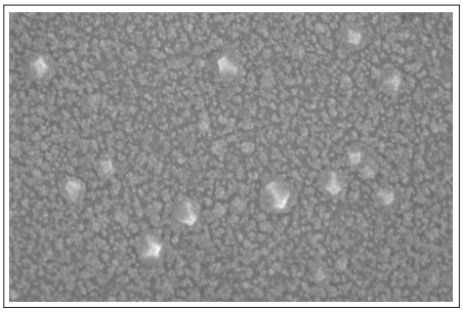


Figure 4: There were Lot of the "Crystal-Like" Defects on Al Bond Pad of the Sample 1 with Higher F (8.5 at%) after SLAT Test

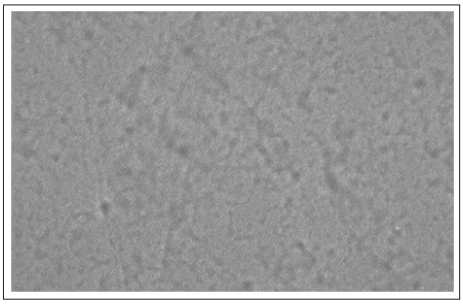


Figure 5: There was no Changed on Al Bond Pad of the Sample 2 with Lower F (3.3 at%) after SLAT Test

These values are well within the detectable range of AES. Using the known physical principles, we can calculate the equivalent signal EDS would detect. By taking the ratio of the AES sampling depth (~20 Å) to the EDS penetration depth (~10,000 Å or 1 μm), the EDS-detectable signal is diluted by a factor of 500. The predicted EDS signals would be:

- Sample 1 (Predicted EDS Signal): (8.5 at% x 20 Å) / 10000 Å = 0.017 at%
- Sample 2 (Predicted EDS Signal): (3.3 at% x 20 Å) / 10000 Å = 0.0066 at%

Both of these values are far below the typical detection limit of an EDS system (0.1 - 1.0 at%). Therefore, an EDS analysis would see no fluorine in either sample, falsely concluding that both surfaces were clean. This is the basis for the critical rule in surface contamination analysis: "EDS clean is not clean." Only when a surface-sensitive technique like AES detects no contamination can we confidently state, "Auger clean is clean." At the same time, we not recommend to use EDS to determine or monitor the F contamination level on a normal Al bondpad in wafer fabrication.

The Solution: A Complete AES Monitoring Scheme

To effectively monitor and control F contamination on Al bondpads in wafer fabrication, we propose a comprehensive monitoring scheme based on AES, which are surface analysis methods.

Instrument Parameters and Quantitative Analysis

AES Instrument (Example: PHI 710):

- Beam Voltage: 10 kV
- Beam Current: 10 nA
- Sample Tilt: 30° (to enhance signal)
- Sputter Source: Argon ion beam (2 kV, 3 mA/cm²) for depth profiling.

Data Quantification: Quantitative analysis is performed using standard sensitivity factors. The atomic percentage (at%) of element i is given by:

$$C_i = (I_i / S_i) / \Sigma (I_i / S_i) \quad (1)$$

Where I_i is the peak intensity and S_i is its relative sensitivity factor. Commercially available software performs this calculation automatically.

Establishing Control and Specification Limits

Control Limit (Process Capability): This limit is determined by analyzing a large number of samples from a standard, well-controlled production process. It is statistically defined using a 3-sigma (3σ) calculation, which has been summarised in Table 3:

- CL (As Received) = 5.0 at%
- CL (After 5 nm Sputter) = 0.0 at% (Indicates contamination is only on the very top surface)

Specification Limit (Product Quality): This limit is determined experimentally by correlating F levels with bondability and corrosion performance. It is the maximum allowable limit, which has been summarised in Table 4:

- SL (As Received) = 6.0 at%
- SL (After 5 nm Sputter) = 0.0 at%

A sample is considered acceptable only if it meets both the "As Received" and "After 5nm Sputter" limits.

Monitoring Protocol

Sampling Strategy: A wafer is considered good for monitoring only if it is representative and fresh (less than 1 week old).

Analysis Points: The number of analysis points should be proportional to wafer size to ensure adequate spatial coverage (Figure. 6):

- 6-inch: 2 points (center, edge)
- 8-inch: 3 points (center, middle, edge)
- 12-inch: 5 points (center, four edges)

Elements Monitored: The core elements to track are Al, F, O, C, N, Si, and Ti.

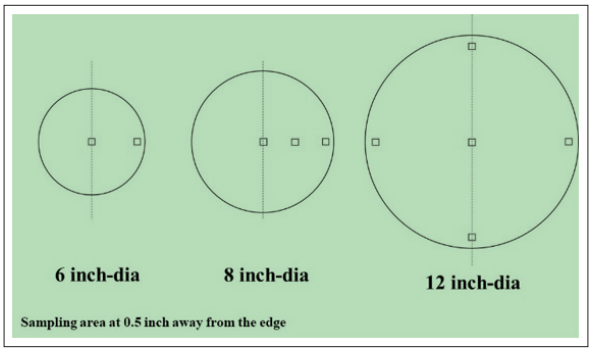


Figure 6: The Number of Analysis Points should be Proportional to Wafer Size to Ensure Adequate Spatial Coverage

Out-of-Control (OOC) and Out-of-Specification (OOS) Procedure A clear and documented OOC/OOS procedure is essential for ensuring product quality and initiating corrective actions:

- **Detection:** The AES analysis result exceeds the Control Limit (CL) or Specification Limit (SL).
- **Verification:** Re-analyze the same sample (if possible) or analyze a new sample to confirm the result.
- **Immediate Action:** If OOC is confirmed, the wafer fabrication team is alerted.
- If the result is OOS (F > 6.0 at%), the production line is halted.
- **Root Cause Investigation:** The process team investigates the source of the contamination (e.g., from etch, PRS, or

clean steps).
- **Corrective Action:** Implement process changes to eliminate the root cause.
- **Verification of Corrective Action:** Analyze wafers from the new, improved process to ensure the F level is back within the CL.

Vt Shift Concern in AES Analysis
It is important to note that exposing transistor gates to an electron beam during AES can cause a shift in the threshold voltage (Vt). Therefore, AES analysis is strictly recommended for monitor wafers that will be scrapped, or on the incomplete edge die of a wafer to avoid impacting good die intended for shipment.

Application and Case Study: A Successful Process Improvement
The developed AES monitoring scheme was applied to evaluate and improve a wafer fabrication process. As shown in Figure 7, the initial process (Old Process) had a significant number of wafers with F contamination levels exceeding the CL of 5.0 at%, with some points as high as 6.0 at% or more. This triggered the OOC procedure.

Following a root cause investigation, improvements were made to the cleaning steps after passivation etching. The new process was validated using the same AES monitoring scheme. The results (New Process) show a significant reduction in the F contamination level, with all measured points falling well below the established Control Limit. This demonstrates the practical efficacy of the monitoring scheme in guiding process improvements.

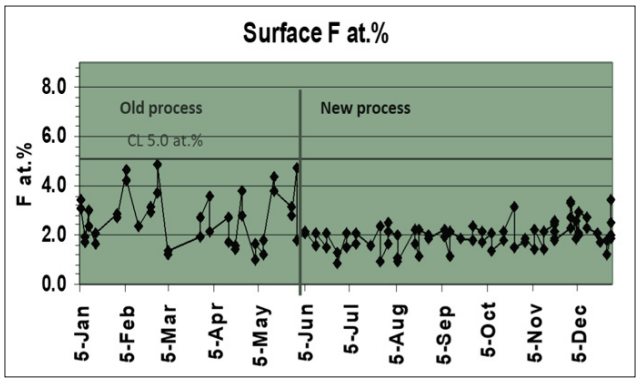


Figure 7: AES Monitoring Results Showed that for the Old Process, F Level on Al Bond Pads were Scattered about 1.0-5.0 at% and Some Points were OOC. However, after Process Improvement, the F Level had been Reduced for New Process Comparing to the Old Process and All Points were within CL

Conclusion
This study resolves the critical analytical challenge of detecting and monitoring fluorine contamination on Al bond pads. We have definitively shown that the use of EDS is inappropriate and ineffective for this task due to its deep sampling depth, leading to the dilution and non-detection of surface-level contaminants. The analytical rule "EDS clean is not clean; Auger clean is clean" serves as a crucial guide for engineers in failure analysis and process control [1-6].

To address this, we have Detailed a Robust and Comprehensive Monitoring Scheme using Surface-Sensitive AES. This Scheme, Validated by Practical Case Studies, Provides a Complete Framework, Including:
- Specific instrument parameters and quantitative data analysis.
- A clear methodology for establishing Control and Specification Limits based on process capability and product performance.
- Detailed protocols for sampling, analysis, and an Out-of-Control/Out-of-Specification procedure.
- A case study demonstrating its successful use in process improvement.

By adopting this monitoring scheme, semiconductor manufacturers can effectively control fluorine contamination, eliminating the risk of corrosion-induced NSOP defects and significantly improving product yield and reliability. This work serves as a definitive guide for the industry, replacing guesswork with a scientifically sound and practically implementable solution.

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