
# White Paper
## Semiconductor Etch Applications

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# Background

## Increasing Challenges in Semiconductor Etch

Etch is one of the most frequently used processes in semiconductor manufacturing. While *dielectric etch* is employed to form insulating structures, contacts, and via holes, *polysilicon etch* is used to create the gate in a transistor, and *metal etch* removes material to reveal circuit connectivity patterning and drills through hard masks.

Continuous etching of process metals such as Aluminum (Al), Tungsten (W), Copper (Cu), Titanium (Ti), and Titanium Nitride (TiN) are often challenging, because many form non-volatile metal halide byproducts (e.g., tungsten hexachloride $WCl_6$) that re-deposit on etched sidewalls resulting in lowered yield (through particulate contamination or deposited material causing electrical shorts).

A variety of new etch challenges have emerged as the semiconductor industry continues to shrink critical feature sizes and adopt vertical scaling e.g., in 3D-NAND memory and gate-all-around advanced technology nodes. These include etching smaller features, high aspect ratio (HAR) trench etch (with small open area percentage - OA%) on the wafer and etching new materials such as metal-gates, rare earth metals in emerging non-volatile memories and high-k dielectrics. For advanced process nanoscale features e.g. etch into silicon dielectrics and metal films, selective processing such as atomic layer etching (ALE) removes a few atomic layers of material at a time. ALE offers more control than conventional etch techniques. For both 3D-NAND and advanced DRAM, significant challenges in transitioning into volume production include addressing difficult conductor etch requirements, meeting aggressive production ramps and achieving the needed throughput to drive cost benefits.

High performance, embedded, and reliable *in-situ* quantitative molecular gas metrology have emerged as a crucial tool to qualify process chambers and continuously monitor process chemistries, all to ensure high yields and maximize throughput in production environments.

# Introduction

## Aston: A Total Chamber Solution

This paper describes critical challenges associated with emerging etch process techniques and how to address them using Atonarp's Aston™ *in-situ, real-time,* quantitative and accurate molecular sensor.

Atonarp's **Aston**™ upgrades conventional gas analysis metrology by addressing challenges revolving around sensor durability, sensitivity, matching, system integration and ease-of-use. Aston is a total chamber solution for real time *in-situ* monitoring of precursors, reactants, and byproducts during various process steps.

These include baseline chamber and process fingerprinting, chamber clean, process monitoring (including in the presence of corrosive gases), particle deposition, and gaseous contaminant condensation. The small footprint and flexible communication interface allow for on-chamber installation and total integration into the process equipment control system. Intended for full integration into the process tool, Aston's high performance and dependability are designed for high volume run-to-run process control of production wafers.

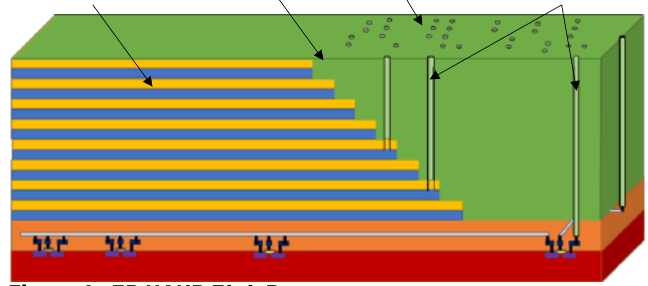


**Figure 1 - 3D NAND Etch Process**

Table 1. Key Aston Specifications

| Parameter | Typical | Units |
|---|---|---|
| **Mass resolution** | 0.8 | u |
| **Mass number stability** | 0.1 | u |
| **Sensitivity (FC/SEM)** | $5x10^{-6}/5x10^{-4}$ | A/Torr |
| **Minimum detectable partial pressure (FC/SEM)** | $10^{-9}/10^{-11}$ | Torr |
| **Limit of Detection** | 10 | ppb |
| **Maximum operating pressure** | $1 \times 10^{-3}$ | Torr |
| **Dwell time per u** | 40 | ms |
| **Scan update rate per u** | 37 | ms |
| **Emission current** | 0.4 | mA |
| **Emission current accuracy** | 0.05 | % |
| **Start-up time** | 5 | mins |
| **Ion Current Stability** | < ±1 | % |
| **Concentration Accuracy** | < 1 | % |
| **Concentration Stability** | ±0.5 | % |
| **Power consumption** | 350 | W |
| **Weight** | 13.7 | Kg |
| **Size** | 400 x 297 x 341 | mm |

Refer to Aston datasheet for full list of specifications

## Measurement-Based Control

The semiconductor industry is shifting from scaling of 2D-structures to the challenging requirement of complex 3D structures. Conventional offline wafer metrology is no longer sufficient to achieve performance and yield goals and in-situ etch measurement has traditionally lacked the robustness and repeatability needed for production. Embedded into the architecture of Aston™ are patented technologies enabling superior analytical and operational performance. To meet the stringent requirements for process control and matching on production tools across fab locations, Aston is designed from the ground up for high up-time and throughput with low maintenance, long-term signal stability, and repeatability.

To withstand the harsh environment of etch and deposition processes, Aston™ introduces two revolutionary features: Plasma Ionization and self-cleaning (ReGen™ mode). Plasma ionization eliminates filament degradation due to reactivity with aggressive gases (e.g., $NF_3$, $CF_4$, $Cl_2$). Additionally, the removal of particles such as (Tetraethyl Orthosilicate) TEOS and vapor contaminant deposits concurrently with regularly scheduled chamber clean cycles, give the Aston™ an extended lifetime. The ReGen™ mode enables the instrument to clean itself using energetic plasma ions, by removing deposits on the sensor and chamber walls that may occur during film deposition processes. Combined, these two features maintain sensor sensitivity over hundreds of RF (Radio Frequency) hours of operation. The measurement-based control enabled by Aston offers the potential to extend the mean time between cleans (MTBC). An increase in MTBC translates into an increase in tool availability and long-term throughput. In addition to the Plasma ionizer (for process), the sensor is outfitted with conventional electron impact (EI) filament ionizer, which is used for baselining and calibration.

The analytical stage of the molecular sensor is a quadrupole using micro-metre-level machined accurate hyperbolic electrodes. Driven by a highly linear Radio Frequency (RF) circuitry, Aston's HyperQuad sensor produces superior analytical performance (Table 1.) over a mass range of 2 to 300 amu.

## High Aspect Ratio (HAR) 3D-Etch

With the advent of multi-patterning technologies and 3D device structures, metrology requirements are driven by highly intensive etch and deposition processes. 3D multi-layer film stacks, such as NAND memory architectures, represent complex, challenging etch processes with critical etch angle, uniform channel diameter and shape required, despite high etch aspect ratio channels >100:1 being common. For 3D-NAND, critical conductor etch processes include staircase etch (figure 1) and HAR mask open for vertical channels and slit. Etching through alternate layers of silicon nitrate and silicon oxide requires high speed quantitative end point detection. For DRAM, etch processes include HAR gates, HAR trenches and metal recess. For staircase etch, it is critical that equal-width "steps" are created at the edge of each dielectric-film pair throughout the 3D stack to form a staircase-shaped structure. Extensive repetition of these steps during device processing requires etching at high throughput with stringent process control.
Versatile *in-situ* gas metrology is needed to perform multiple monitoring functions in a single tool:

- Detect and quantify contamination, cross-contamination, gas impurities and process chemistry inside the process chamber
- Assess performance of developed etch recipes on complex features on production tools/runs,
- Measure post-etch clean (including advanced wafer-less auto clean; WAC) as chamber condition is critical to eliminating process drifts and ensuring repeatable performance
- Rapid and accurate etch endpoint detection (EPD), through plasma or gas monitoring, as it is a critical control function. Examples include carbon monoxide (CO) byproducts decline in dielectric etching or Chlorine (Cl) reactants rise in polysilicon and metal etching at endpoint
- Comprehensive real-time metrology data to allow for *dynamic* etch control of process plasma and reactants to manage the demanding etch profiles

## End Point Detection without Plasma

While optical emission spectroscopy (OES) has been widely adopted for etch EPD, the trend for low open area (OA) and HAR designs make it ineffective for many etch tasks. OES techniques require plasma 'on' and light emitting species. More sensitive data and analysis techniques are required to achieve prompt and deterministic EPD as dim and remote plasmas are increasingly used in 3D devices and atomic level etch (ALE) processes. Further, pulsed plasma is often used to manage the etch profile in HAR and low OA% processes making OES an impractical solution for EPD. In 3D structures, multi-layer film and multiple contact depths hinder the ability to get a sharp step change in optical emission signal for endpoint as each row of contacts reaches the bottom (figure 2). Other OES Limitations include:

- In *dielectric etch* EPD on patterns with <5% OA has always been challenging as OES has low signal to noise at low concentrations. In high pressure Si deep etch (i.e. Bosch process), where EPD for OA% under 0.3% is required, the large background noise level in OES inhibits detecting any changes in the amount of emitting species.

- In *metal etches* the OA% may be under 10% depending on the size of the inter-connects involved. For contact and via etches the OA can be between 0.1-0.5% or less depending on the size of the features involved. In the case of *tungsten (W) etch*, the consumption of chlorine (Cl) reactants decreases with smaller OA, and due to material transport into the HAR etch feature, the etch tends to slowdown. Both factors decrease the rate of consumption of reactant gas. Therefore, it is difficult to see a significant change in OES signal at endpoint due to depletion of reactants from the plasma.

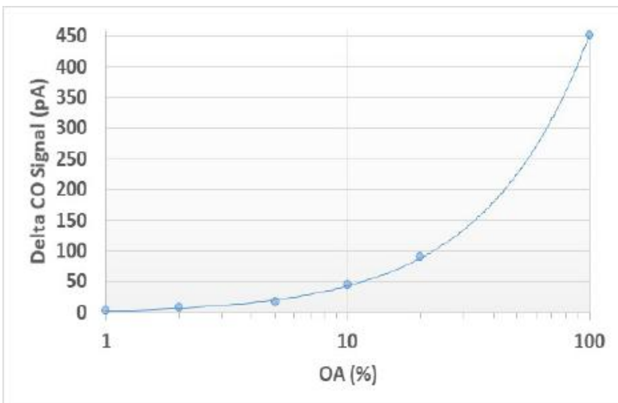


**Figure 3a – Linear EPD Results: 100 to low% OA**

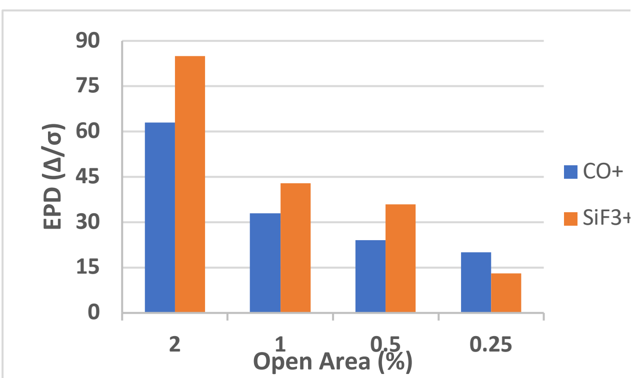


**Figure 3b - EPD Data Tracking with OA down to 0.25% with Δ/σ (Signal/Noise) > 10:1**

Aston™ can utilize both etch reactants and byproducts for EPD. Furthermore, Aston is able to run a periodic clean on the small, confined volume of the sensor to maintain its performance (sensitivity) over extended number of wafer runs for maximum uptime. OES however, require an access window on the chamber that must remain clean to obtain stable signals of sufficient intensity. Typically, a heated quartz window is used to slow down buildup of process products. With Aston™, detection at low concentrations is not affected by either background light spectrum being emitted by plasma nor fluctuations in plasma intensity during RF power pulsing.

Figures 3a/3b show dielectric etch EPD data as a function of OA% down to 0.25% for both $CO^+$ and $SiF_3^+$ byproducts. The data clearly shows a linear behavior and a detection at low concentrations not affected by background light spectrum being emitted by plasma. Sub 0.1% OA performance is targeted with Aston's ppb sensitivity

## Atomic Level Etch (ALE)

In 3D structures, layer-by-layer removal in ALE processes require pulsed RF power sources to control radical densities and lower ion energy to minimize surface damage and maintain directionality. In such sources, the plasma's overall light intensity is lower and exhibits a fluctuating magnitude. Often the plasma is far away (> 25 cm separation from the wafer region) and so few byproducts are excited by the plasma making optical metrology impractical.

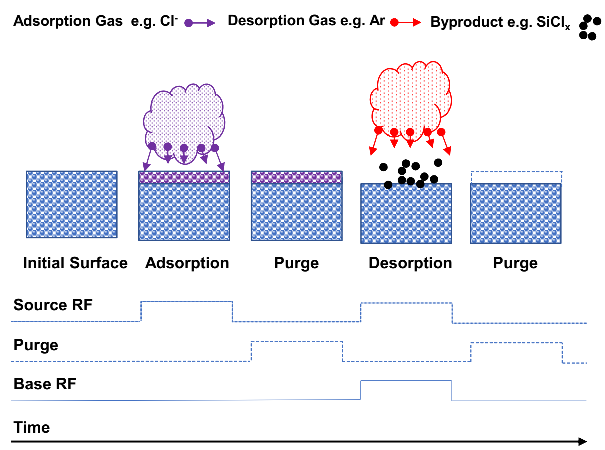


**Figure 4 – Typical ALE Cycle**

In ALE, since each cycle is self-limiting, endpoint detection may not be as critical. However, in the absence of gas analysis, process engineers are "blind" to monitoring chamber and process health as there is no visibility to chemical state, especially the dynamic state when transitioning between process steps (adsorb / purge / react / purge) as shown on Figure 4. The self-limiting nature of ALE does not make it immune to process drifts. Furthermore, since ALE is not plasma-based, chemical changes in the process are not necessarily detected via plasma monitoring.

There is a misconception that ALE techniques are truly one atomic layer at a time; rather, they have a characteristic removal/deposition amount per cycle which can be a little bit more than a monolayer (or a little less). Process shifts (change in Å/cycle) can occur due to changes in surface saturation and surface reactivity caused by changes in pumping performance, wafer temperature or ion bombardment energy (voltage) respectively.

In ALE (figure 5), since a plasma is not used consistently, the gaps in chemical monitoring are not as obvious. In such scenarios, Aston™ offers the following benefits:

- Develop a fingerprint of the chemical state of a chamber during each process step. This can be in-reference to its own normal behavior, or to a reference golden chamber
- Characterize and monitor the dynamics associated with chemical changes during the steps and when transitioning from one step to the next
- Monitor time for adsorbing species to be purged from the system after the first step of the ALE cycle (figure 5). The plasma is typically used to create adsorbing species (radicals), but it is created far from the wafer
- Monitor change in reaction product formed during the 2nd step of ALE cycle. The plasma optical intensity is typically low since it uses a low duty cycle pulsed RF

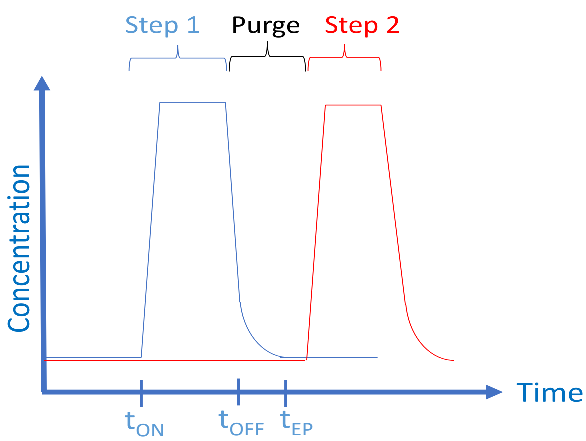


**Figure 5 – ALE Timing Diagram**

- Monitor time for reaction product and reactant to be purged after 2nd step of ALE cycle

## Conclusion

Atomic level etch can only be truly measured and monitored using a molecular sensor device such as Aston™. Its high sensitivity, speed, and lower susceptibility to plasma intensity variations produce reliable quantitative measurements even with low concentrations of reactants and byproducts. With high accuracy at sub-1% levels, it can monitor subtle process drifts and process variation effects providing insights that can be used for machine learning models.

Using its high scan speed, step-time optimization is achieved via monitoring of the time for reaction product to decrease as it is an indication of a change in surface reactivity, increasing overall throughput.

ALE is the most advanced etch technique and it lies at the frontier of the ability to cost effectively manufacture advance semiconductor processes. Aston enables ALE advanced chemistry metrology, to measure and control reactions and their duration, providing a robust solution for high volume production.