Multivariable Process Monitoring to Enhance CMP Yield

White paper

INTRODUCTION

Successful fabrication of high-performance, complex semiconductor devices relies on chemical mechanical planarization (CMP) to planarize the wafer surface before depositing the next layer of metal or dielectric. Trends in lithography are putting more pressure on CMP process steps. Decreases in line width and spacing of metal features push the limits of 193 nm immersion lithography. One way around this challenge is to adopt self-aligned double patterning (SADP) and even quadruple patterning to achieve the necessary dimensions. As a result, wafers are undergoing multiple CMP steps for each layer.

While CMP is necessary, it can also contribute to yield loss if the process is not tightly controlled and monitored. As the number of CMP steps increases and the thickness of material being removed decreases, CMP defect reduction becomes a greater challenge. The more complex the chip architectures and the smaller the critical feature size, the greater the risk. With less room for error, process optimization of CMP slurries is necessary to achieve desired yields.

CMP slurries consist of alumina, silica, or ceria nanoparticles suspended in an aqueous solution. The material removal rate (MRR) of CMP slurries depends on the type of oxide or metal being removed, slurry properties, and process parameters such as the speed of the polisher and applied pressure. Tight control over slurry properties including chemistry, working particle size, and particle size distribution helps achieve the desired removal rate and also minimize CMP-induced defects. Lower concentrations of polishing particles and oxidizing agents in a slurry will slow the rate of material removal, resulting in more precise control when working with nanoscale layers.

For leading-edge devices, the working particle size in a CMP slurry typically ranges from 30 to 200 nm, which means that even sub-micron particles are considered large from the defect risk viewpoint. Because CMP removes extremely thin layers of material, slurry stability is crucial for maintaining an appropriate removal rate.

The balance of process speed, performance, and cost tilts toward performance when particles around 100 nm in diameter can cause killer defects. Precise control of slurry chemistry and working particle size is the key to enhancing yield. Slurries must have a narrow, uniform particle size distribution and a reliable, consistent balance of chemical components.

This white paper discusses three types of process data analytics that can help ensure high CMP yields: electrochemical analysis during blending, in-line process chemistry monitoring, and particle sizing determination, Figure 1.

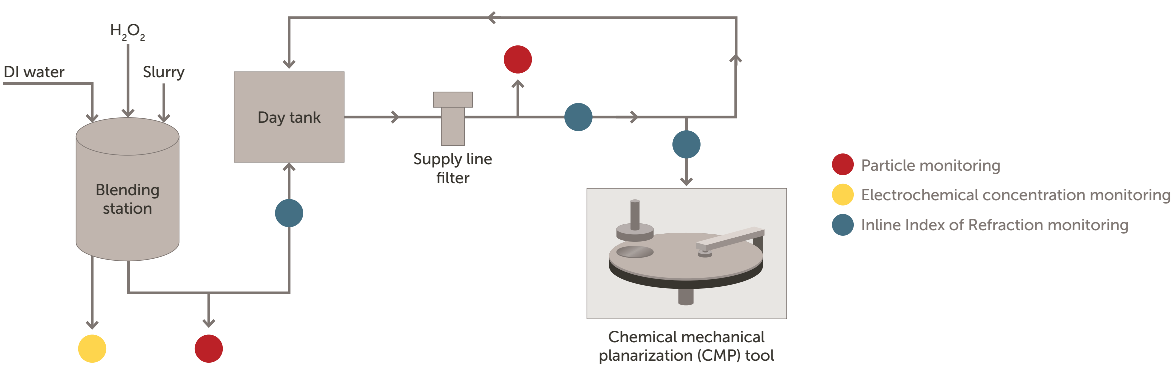

Figure 1. CMP process overview showing where chemical concentration monitoring and particle size analysis fit into the process flow.

EVALUATING PROCESS CHEMISTRY COMPOSITION

Proper chemical composition of the slurry makes a difference for any CMP process, but composition is especially critical for the CMP slurries used to remove aluminum, tungsten, and other metals. Oxide-removing slurries can handle a wider process tolerance since the blending process in the fab simply dilutes the slurry with deionized water. Managing metal CMP slurries, however, also involves adding hydrogen peroxide (H_2O_2) to the slurry to oxidize the metal. Doing so accelerates material removal, allowing for lower polishing particle concentration or smaller particles for the same removal rate, which reduces the risk of mechanically induced defects. Ultraprecise control of the hydrogen peroxide added during blending in the fab ensures the exact concentration required for optimal performance.

Targets for chemical concentrations have little room for error. A target peroxide concentration of 1%, for example must be maintained within ±0.005%. Peroxide levels that are too high can cause metal lift and dishing. If the level drops too low, metal removal rates will not be adequate.

Sensitivity is critical since the results of process monitoring are only as good as the accuracy and precision of the measurements. Process control for slurry blending can only be as good as the data coming from the instrument.

Titration is considered the gold standard for accurate measurements of H_2O_2 concentration in CMP slurries. The technique can precisely measure composition even in solutions with a low concentration of a particular component. Conventional bench titration, however, requires sending samples to a lab for analysis, which is not workable in a production setting. Labs may take several hours to process the samples and report results.

Real-time chemical monitoring allows for corrections in composition during slurry blending to ensure consistency from batch to batch. Analytical instruments integrated into the process flow make this possible. These instruments automatically take samples at regular intervals, titrate the samples, and report concentrations within minutes rather than hours.

Sampling intervals can be adjusted so they provide rapid feedback before the slurry drifts too far out of specifications but are not so frequent that they slow down the blending process and add unnecessary expense. It is important to take more frequent measurements whenever H_2O_2 is added to the system to avoid overshoot. While the excess H_2O_2 will eventually decompose, waiting for it to do so wastes valuable time.

While in-line auto-titration for metal CMP slurries is standard in almost every fab today, it is not the only monitoring process available. Complementary techniques give fabs additional data that help optimize slurry stability.

IN-LINE PROCESS MONITORING

Even if a metal CMP slurry passes all quality checks after blending, that is no guarantee that the chemistry will still be in balance when the slurry enters the CMP polisher. Hydrogen peroxide naturally decomposes into oxygen and water. When blended slurries are stored in a central tank before being distributed to individual lines, peroxide decomposition can occur during the lag time between blending and slurry application. Regular checks with an auto-titration instrument help, but it is also helpful to re-evaluate the process chemistry immediately before the slurry is delivered to the wafer.

It is not practical or economical to install a complex analytical instrument at every polishing station in the fab. The alternative is compact tools that can take rapid measurements with minimal disruption to the process flow. Such in-situ process monitoring can be achieved with simple refractometers that are cost effective and easy to install. Their role is to serve as a pre-check or early warning system to verify whether the slurry still meets specifications. If the composition has drifted too far, an alarm will trigger and the process can be stopped, averting a potential wafer scrap or yield problem.

Refractometers for in-situ chemical concentration measurement do not sample slurries directly. Instead, they rely on index of refraction (IoR) measurements, which they compare to expected values for a specific slurry chemistry and convert to concentrations. The IoR technique functions in any type of fluid, including turbid media such as a CMP slurry. Shifts in percent solids or peroxide concentration will alter the refractive index of the fluid according to predictable metrics. The refractometer automatically adjusts for changes in IoR due to temperature, Figure 2.

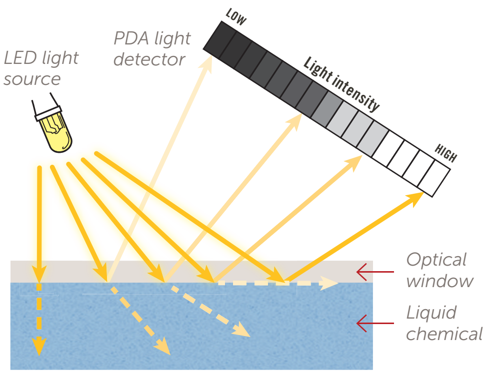

Figure 2. Index of refraction measurement technique for in-situ chemical composition monitoring. The angle of reflection is based on the refractive index ratio between the liquid and the window.

The IoR approach offers a robust way to obtain continual in-process data and reduce cost of ownership.[1] The small size and low cost of the monitors means that they can be installed at every polishing station in the fab. They can also be used to monitor incoming slurry chemicals and newly blended slurries.

Fabs can calibrate the monitors based on reference values for the IoR of any fluid. The technique, therefore, is equally applicable to all types of CMP slurries. Studies show that IoR data correlate well with results from titration measurements.[2]

Chemical monitoring, while important, is not sufficient to guarantee slurry health. Particle size and distribution are equally, if not more, critical. Drifts in IoR measurements usually indicate that the peroxide concentration has dipped, so that is the most reasonable assumption. Particle clumping is another possible cause, but IoR does not provide a direct measure of particle distribution.

PARTICLE SIZE MEASUREMENT

CMP slurry manufacturers provide data on the nominal particle size of each batch of slurry concentrate. Manufacturer data on particle size and distribution alone, however, is not reliable for precise quality control. The existence of large particles, typically defined as those with diameters twice that of the nominal particle size or above approximately 1 µm, is a serious problem. Although the large particle tail is a small fraction of the total particle count, a large particle count (LPC) of even 0.1% can cause yield loss.[3]

The nanoparticles of alumina, silica, or ceria in a CMP slurry can create micro-scratches on a wafer, and the larger the particles, the larger the scratches. These micro-scratches attract metal particles, leaving residue which, if it occurs in a critical location, will cause bridging defects and device failure. The finer the features on a wafer, the tighter particle distribution the CMP slurry must maintain.

The particle distribution of the slurry as received is not the only concern. During mechanical handling, including mixing and pumping, particle agglomeration can occur, resulting in clumping and an increase in LPC. These large particles tend to gather in the corners of valve fittings or at bends in tubing. If they remain in those locations, they are relatively harmless, but once they are dislodged, they continue downstream to the wafer. The severity of the agglomeration problem varies depending on the type of equipment used.

Ideally, slurry filters installed at the point of use will remove all large particles before they reach the wafer, but filters are not perfect. The filtration system cannot be trusted to capture all the large particles that might cause device failure. Also, filters degrade over time, and particle agglomeration reduces filter lifetime by clogging filters prematurely. A filter replacement schedule based on time in service or even on flow rate measurements is not optimal.

By monitoring LPC in real time, it is possible to mitigate the problem. Single particle optical sizing (SPOS) measures light obscured and scattered from individual particles to determine LPC values. LPC data is helpful for directing decisions about components like pumps and filters. Studies show that, for example, magnetically levitated pumps cause less agglomeration than diaphragm or bellows pumps. A fab that is facing poor yields may be able to solve the problem by swapping out equipment.

LPC data is useful in the lab when developing CMP processes. The system can be designed to limit the incidence of large particles and enhance the CMP yield.

But LPC measurements are even more important during production. Online monitoring serves as an “insurance policy” to keep large particles from reaching the polishing tools. Figure 3 shows LPC count versus time at several particle size ranges in a CMP delivery system. Rather than relying on standard replacement intervals for filters, LPC monitoring can inform the replacement schedule for each filter based on real-time, in-line data. Monitoring can also signal when a supply tank is nearly depleted, as LPC increases near the bottom of the tank. A continual stream of LPC data ensures slurry quality.

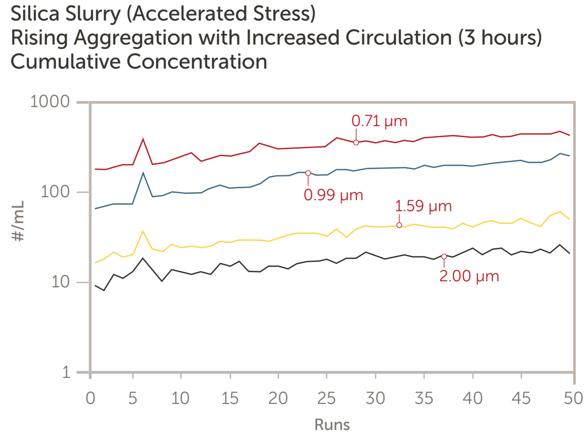

Figure 3. LPC counts versus time.

SUMMARY

Because of the precise nature of CMP, process monitoring is more important than ever. Automated tools installed in the fab make such monitoring seamless. Accurate, reliable, real-time data on chemical composition and particle size distribution ensures that slurries remain within stringent specifications. Process monitoring reduces the risk of CMP-induced defects and improves overall process yield.

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