High Precision Photoresist Dispense Monitoring

Overview

This white paper discusses the need to reduce photoresist usage in wafer patterning and considers ways to monitor and improve resist dispense that enable statistical process control and faulty product segregation. Fab-wide integration is discussed and a novel track monitoring system based on MEMS sensors is introduced.

Introduction

Lithography has been a critical step in semiconductor manufacturing for several decades. Improvements in linewidth and resolution have been fundamental to increases in transistor density and chip complexity.

Each lithographic exposure requires a photosensitive film, deposited in a track system. Light sensitive resin is pumped through a metered liquid delivery system to a nozzle mounted on top of a rotating chuck. As the wafer spins, resist is ejected from the edges and dries to form a light-sensitive film. Typically, more than 90% of the photoresist is wasted.

The cost of resist increases as exposure wavelength decreased. Moreover, the number of exposures per finished wafer scales with die complexity. As a result, photoresist is a major cost center for semiconductor fabs. Multi-exposure techniques and EUV will continue to drive up resist costs in the future.

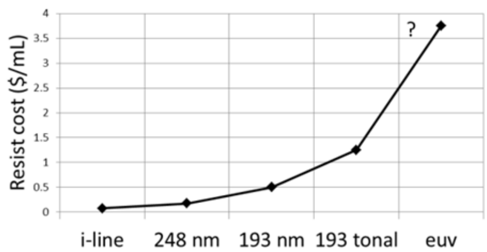

Figure 1 - Resist cost per mL as a function of light source linewidth

Over the years, various techniques have been proposed to reduce the quantity of resist used per dispense. Pre-wet, pump upgrades, and sensors are some of the most important changes implemented.

As the quantity of resist per dispense is reduced from 10 mL per film to as little as 0.3 mL per film, detecting imperfect films before further processing becomes increasingly critical. Smaller dispense volumes are more sensitive to equipment and process variations. Finally, improperly coated wafers can result in costly yield problems, undetectable by metrology.

In summary, the industry’s goal is to use the smallest amount of resist possible to achieve perfect coverage on every wafer. Track OEMs are taking great strides to address these problems in a forward way but there remains a general need for optimization for the thousands of resist dispense systems already deployed.

Resist delivery, dispense problems and statistical control

Statistical process control can be applied to any process where the "conforming product" output can be measured. A process is said to be in statistical control when all sources of variations are common to the process. Monitoring the process outcome is necessary to calculate its standard deviation and differentiate between intrinsic and external sources of variations. This is especially critical in track systems with their multi-component delivery systems. However, most track systems only infer resist volume but do not measure it directly.

Resists are usually supplied pre-mixed with an appropriate solvent that controls viscosity and film formation. The resist is delivered to each wafer through a liquid delivery system consisting of a pump, a filter to remove impurities, a suck back valve and a nozzle, usually mounted on a moveable lance. All these components are connected using high precision PFA tubing.

Gas-based delivery systems use mass flow controllers to control the amount of reagents delivered. In liquid delivery systems, the dispense process is time-based, not mass or volume based. The process will seemingly work, even if there is no liquid in the line. In other words, the “recipe” turns on the pump for a fixed number of seconds and it is assumed that this will result in an actual dispense of a proper volume of resist on the wafer. In practice, many factors can alter the actual dispense volume.

External sources of flow variations

In general, anything that displaces liquid within lines or causes flow restrictions will lead to volumetric variations.

Bubbles can appear within the liquid delivery lines for various reasons. In particular, filtering can introduce air in the lines. A bubble displaces resist within a dispense event and will lower the final dispense volume.

There are many meters of tubing within a track system. For maintenance access, chucks and pumps are mounted on large drawers that can be pulled out. This pulling back and forth can cause lines to get pinched or kinked. This creates flow obstructions that reduce line capacity. The total flow per dispense is thus reduced for a given event duration.

Clogged in-line filters can create flow restrictions that lead to under-dispense events.

There can be timing errors within the system that cause the flow to the wafer to be delayed, uneven or pulsed. These types of flow errors can prevent film formation at the edges because there is not enough time to draw the resist to the wafer edges or because the higher initial flow rate causes splashes.

Resist bottles are changed frequently. New systems monitor liquid levels and change-outs but it is possible for older tracks to run dry. In this scenario, the dispense takes place as normal but no resist is delivered to the wafer. Such wafers cannot be patterned.

Similarly, a pump malfunction can cause an under-dispense or no-dispense event.

Finally, it is possible to switch bottles (wrong resist) and this can result in an under-dispense or over-dispense depending on the new resist viscosity.

Table 1 – Issues within liquid delivery systems and their consequences

Defect	Root cause	Effect
Bubble	Filtration, problem with inlet, leak	Under-dispense, splashing
Kinked bent line	Line bent during maintenance process	Under-dispense
No photoresist	Empty bottle, valve off.	No dispense
Wrong resist	Incorrect bottle used	Change in viscosity, under- or over-dispense
Valve error	Calibration	Under dispense
Timing error	Calibration, machine malfunction	Under dispense
Pump malfunction	Maintenance	No dispense
Dried nozzle, other flow restrictions	Suck valve problem	Flow restriction, under-dispense or splashing
Fluid contamination		Splashing, particles
Degradation of the fluid	Time in bottle or temperature control	Viscosity change, over or under-dispense
Clogging of filters (upstream or downstream)	Dirty filter	Flow restriction, under-dispense
Changes in pressure and temperature		Changes in flow, over- or under-dispense

Preventing and detecting dispense errors

It is possible to monitor and minimize dispense errors and variations by implementing changes within the liquid delivery system. This can be accomplished by recording the pump pressure dispense profile or the actual liquid flow, by thermal or ultrasonic means. Finally, some tools can be retrofitted with camera-based inspection systems.

Direct flow monitoring

Pressure profile monitoring

During a dispense event, pressure builds up within the delivery line. It is possible to monitor that pressure change[1] over time and compare the resulting profile to a known good event[2]. The pressure gauge is installed within the pump. An algorithm, built into the pump controller or tool operating software, compares each dispense to a standard and generates an alarm signal when the deviation is more than a user-set percentage. Each profile is discarded once conformance has been calculated.

Pressure gauges are relatively fast but only provide an inferred volumetric measurement. The sensor is coupled to the metered liquid through a viscous hydraulic fluid that can be unresponsive to sudden flow changes. Pressure gauges integrated in pumps provide limited feedback on suck-back valve operation and volume. Finally, pressure gauges do not detect backward flow.

Ultrasonic liquid flow measurements

Ultrasonic sensors can directly measure liquid flows. These sensors are widely used in industrial environments such as oil refineries, breweries, and other large chemical facilities.

Flow detection is based on the timing difference between sound waves traveling in the direction of the flow and against the flow.

Within a delivery event, the dispense volume is simply the integration of the liquid speed multiplied by the tube cross-section over the dispense duration:

$$\int_t \mathbf{speed}\left(\frac{\mathbf{mm}}{\mathbf{s}}\right) \times \mathbf{Xsection}(\mathbf{mm^2}) \cdot d\mathbf{t} = \text{volume (mm}^3\text{)}$$

(where t is the dispense time)

Ultrasonic sensors need to be placed in series to the metered flow. The speed of sound within the measured liquid must be known or calculated to get an absolute flow and volume measurement.

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[1] A pressure profile is a chart representing fluid pressure over time within a dispense event. The pressure is typically measured within the pump.

[2] A known good profile or reference is created via gravimetric analysis.

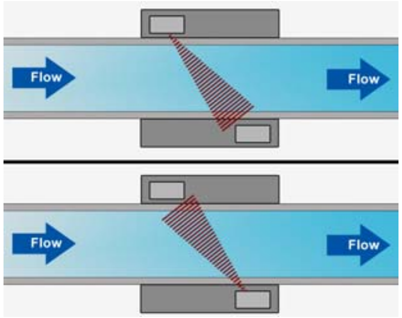

Figure 2 - Ultrasonic flow meter. Speed is inferred from the delay between the 2 signals.

Ultrasonic sensors are large and cannot be used for all retrofit applications because of space limitations and poor resolution at low flows.[3]

Thermal Mass Flow Meters

Thermal mass flow meters use combinations of heated elements and temperature sensors to measure the difference between static and flowing heat transfer to the measured fluid and infer its flow with information about the fluid's specific heat and density. Originally developed for gaseous applications, this technology has been miniaturized and adapted for use in semiconductor liquid delivery applications.

Sensirion developed and released fast ultra-sensitive liquid flow sensors suitable for resist delivery applications. The liquid to be measured passes through a small quartz tube. A small MEMS heated element is placed on the outside of the tube, with 2 thermocouples on either side. The element is powered so that a 0.3 °C difference is detected between the 2 thermocouples. The current needed to maintain the temperature difference is proportional to the liquid flow, its heat capacity and density.

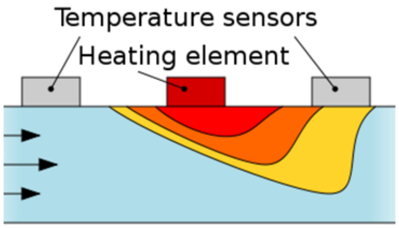

Figure 3 - Thermal Mass Flow Sensor

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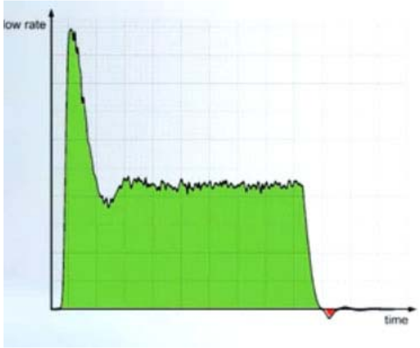
[3] The type of ultrasonic flow meter described here is called time of flight meter. There is another kind of flow meter called Doppler flow meter that relies on particles or bubbles to measure the speed. This technology is not suitable for photoresist delivery analysis.

MEMS sensors are fast and sensitive (see Table 2) and they are widely used for resist dispense monitoring and many other delicate applications [medicine delivery, pharmaceutical manufacturing,etc.]. Because of their symmetry, MEMS sensors can detect flow in both directions.



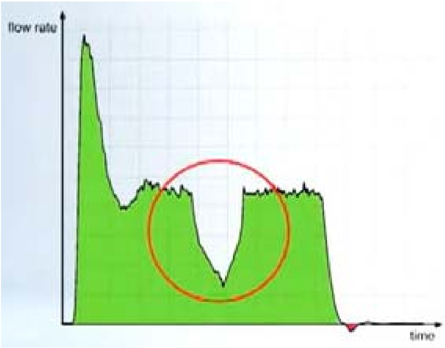


Figure 4 - Dispense profiles as measured by a MEMS sensor. The profile on right shows an air bubble. MEMS sensors are able to measure reverse flow (suck back) (red area in both profiles).

Table 2 - Sensors compared

	Minimum flow	Response time	Size (mm)	Comments
Ultrasonic sensor	N/A	50-200 ms	31 x 45 x 117	Slow
MEMS heat sensor	50 µL/min	~ 20 ms	20 x 33 x 55	Real volume, can measure reverse flow
Pressure gauge	N/A[4]	1-5 ms	Built-into pump	Inferred volume

Sensor integration

Track coating systems work intermittently because the metered resist flow is periodically stopped so that film formation can be completed and wafers can be transferred in and out. Any monitoring system must be able to distinguish between idle (normal no-flow condition) and air bubbles (abnormal no-flow within a dispense event) or other similar errors. Regardless of the sensor technology used, sensor integration is critical to error detection. In practice, sensors must be gated by one or 2 triggers and have end-point detection systems built into the controller or data acquisition system. This is important to distinguish between false dispenses (for flush or maintenance for example) and idle vs. no-resist event. In most fabs, there are thousands of dispense events per day and full automation back to fab-wide systems is often the only way to cost-effectively monitor dispense errors and implement statistical process control.

[4] Pressure gauge does not measure flow or volume

In practice, a well-integrated monitoring system will keep track of tool ID, bowl ID, line ID, wafer serial number (or time stamp) and volumetric dispense information.

Camera inspection

It has been proposed to perform camera-based inspections between resist dispense and wafer exposure, after exposure or after resist development. Such "machine vision" system compares each coated die or wafer to a reference and segregates bad wafers for rework.

When retrofitting a track system with camera inspection, external shutter triggers are required, adding to the system complexity. Moreover, the wafer or die identity must be merged into the picture file. Camera inspection is not readily compatible with moving wafers, limiting integration opportunities. Finally, camera, brackets and lights can create particle contaminants by disrupting laminar flow.

Machine vision systems are available in new track systems but they are not easily retrofitted to existing tracks, especially in 200 mm. Moreover, camera inspection is expensive and requires complex integration to fab-wide control systems.

Data Integration and Tool Control

Modern semiconductor manufacturing is data intensive. Recipes flow one way while process parameters and measurement results flow the other way. FDC or SPC servers are used to regulate the work flow and take proactive measures such as tool maintenance or product rework.

Using MEMS thermal sensors such as Sensirion, it is relatively easy to detect dispense errors. However, proper care must be taken in routing the information and automating the fault response.

At its simplest, a properly configured sensor[5] can be programmed to generate a 24V alarm signal. This signal can sound a local alarm but there needs to be someone to hear or see the alarm. This cost effective solution does not enable the use of statistical control technique.

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[5] Sensor and data acquisition system must be triggered by soft or hard triggers. Time is usually used to detect the end of a dispense event.

A more practical approach couples the error signal to a time stamp and a bowl serial number and sends a SMS or e-mail to the appropriate engineer. The suspect wafers can be segregated and reworked in a relatively timely manner, typically within 15 minutes. This technique is not compatible with statistical process control because it only reports erroneous dispense events and not volumetric information.

It is also possible to interlock the pump[6] so that no additional wafers are processed until the lines are flushed and the system reset. Since each liquid delivery line contains a few dispenses between the flow sensor and the nozzle, such integration can effectively stop a bad dispense before it occurs[7]. On the other hand, interlocked bowls can be down for significant time periods if no one is around to clear the error.

Alternately, flow profile information can be downloaded to fab-wide servers using the SECS/GEM protocol. The data can be formatted in 2 ways.

In the most common method, dispense volumes are integrated by the local host and sent to the SPC server as serialized and time-stamped volumetric information. This approach is ideal for detecting long term trends and implementing fab-wide SPC control.

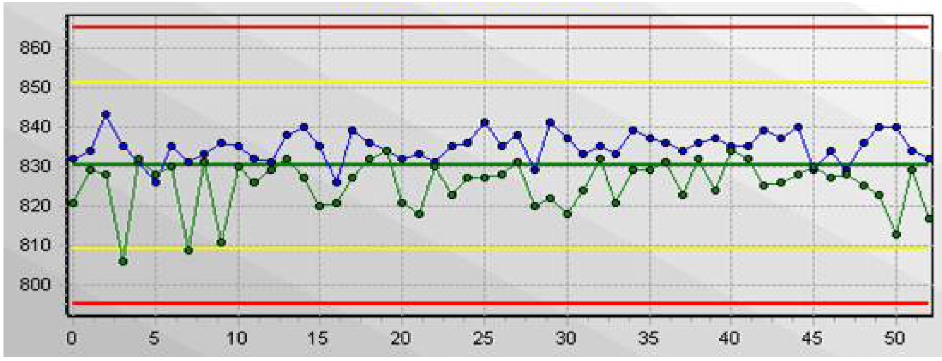

Figure 5 – SPC charts for 2 bowls, in µL per dispense (300 mm fab). The green line contains suspect dispense events with external variations that call for maintenance.

Alternately, full flow profiles can be downloaded from the local host to the FDC server. In turn, the FDC can be programmed to make decisions based on the

[6] This can be done through existing interlocks at doors, pumps, valves, motors…

[7] The # of dispenses in the line will depend on the sensor position, the length of the line and the dispense volume.

profile shape, slope, area... This technique is the most flexible but it requires extensive software integration.

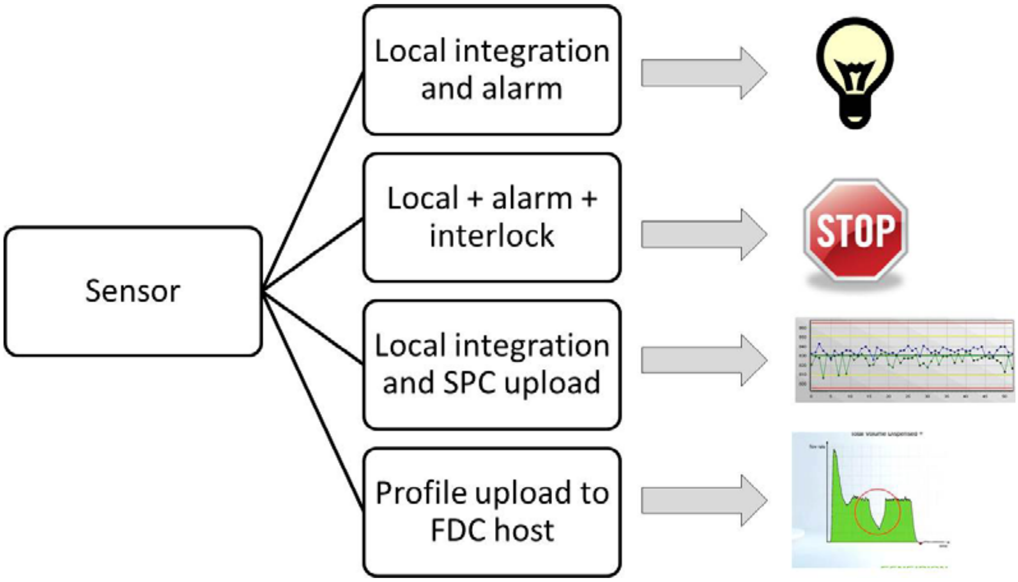

Figure 6 - Four data integration schemes

In general, costs increase with the level of integration required.

Table 3 – Integration schemes compared

Integration technique	Description	Comments
Local + alarm	Gated sensor output is integrated using local controller. Alarm generates a buzz or SMS or e-mail	Simplest, controller needs to be set manually. Data not stored. Tool keeps running. Acceptable for low frequency issues.
Local + alarm + interlock	Gated sensor output is integrated using local controller, alarm condition triggers interlock	Simple, requires each controller to be set manually, can idle tool for long time periods. Bad wafers can be reworked.
Local + upload (SPC)	Gated sensor output is integrated and dispense volume is uploaded to fab-side server	Most widely used. Tagging and alarms generated by SPC server. Long term trends observable. Intrinsic and external sources of variations easily identified.
Profile upload (FDC)	Raw sensor output is uploaded to fab-wide server	Most sophisticated, able to alarm off volume variations AND profile variations. Data intensive, requires extensive integration.

Conclusion

Modern semiconductor fabrication facilities must continue to lower resist dispense volumes while segregating improperly coated wafers. Newer track systems have built-in volumetric detection capabilities but existing tracks must be retrofitted to detect liquid flows and volumes. MEMS heat flow sensors have the speed, resolution and size needed to work with nearly all existing resist delivery systems. Volumetric monitoring is necessary to implement SPC and successfully reduce resist volume.