FT28_mks.qxp 21/11/2005 14:06 Page 1

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The critical components of a production-worthy ALD system

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ABSTRACT

Fundamentally, atomic layer deposition (ALD) is a straightforward and tolerant deposition technique. Most chemical vapor deposition (CVD) reactors (i.e. batch and single wafer) can be modified to deposit materials in an ALD mode. However, the critical barriers in making ALD a production-worthy process lies in the challenge of processing films in ALD mode that is quick enough to meet the technical film requirements for uniformity, step coverage, defect density and electrical properties. The design of the liquid/gas delivery/ distribution system, the chamber and exhaust mechanism are the key differentiators between R&D tools vs. high-volume manufacturing tools.

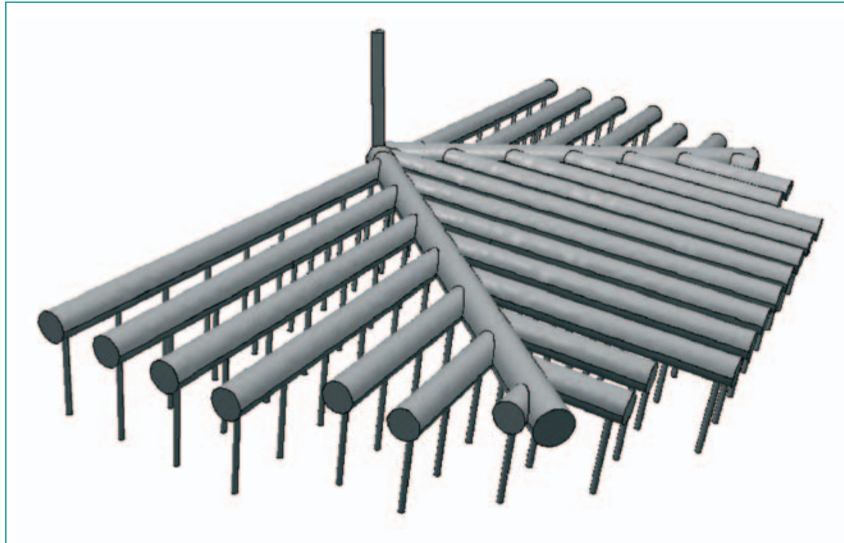

Figure 1. Computational volume for internal flow simulation of one half of showerhead gas injector. (Single gas inlet at top; multitude of gas outlets at bottom.) Flow velocity uniformity at each gas outlet is ±4%.

Introduction

ALD involves a two-step process, where the first step is exposure of a Si substrate to the first chemical under reduced pressure and at a low temperature. After a period of time, the Si substrate becomes saturated with the first chemical and no other absorption occurs. During the subsequent step, the first chemical is flushed and pumped out of the chamber and the second chemical is introduced. The second chemical reacts with the first chemical absorbed on the surface, and after a given time, the entire first chemical has reacted completely with the second such that no more film growth can occur. Then with the flushing and pumping of the second chemical, one ALD cycle is complete. The process repeats itself until the desired thickness is achieved. During the ALD process, there are certain self-limiting characteristics, such as its saturated state and the point during each process step where no more additional film growth can occur.

If the chemical delivery system cannot compensate for the longer pulse times by delivering a higher concentrated dose of the precursor, it results in longer cycle times to achieve the desired film saturation and uniformity – and ultimately slower throughput. Similarly, rapid chamber evacuation and chemical purging are critical to maximizing productivity of ALD processes. Longer precursor pulse times for certain compounds poses a difficulty in maintaining the required compositional control in the film. Thus the liquid/gas-injection mechanism attains important criteria to meet such goal.

The thickness of film deposited per ALD cycle is somewhere between 0.5 Å and 1.5 Å per cycle, which makes ALD an inherently slow process. The key to enabling ALD as a production-worthy process is to reduce the cycle time, while simultaneously achieving the film's technical requirements. Through our modeling and characterization efforts, we have established how gas-distribution systems and chamber designs of an ALD system can meet the demanding manufacturing requirements, while offering a cost-effective and production-worthy solution.

Increasing the throughput for ALD involves fast cycling of the precursors. The precursor is introduced as a short pulse then quickly purged. The pulse times range from 10ms to minutes. The limit of how fast the chemical can be pulsed depends on how quickly one can achieve a state of uniform saturation across the entire wafer surface. This is a two-part problem where the first part depends on the uniform distribution of the gases and the second part is dependent on the wafer surface topography and surface area. In the following sections we will focus on the importance of certain components in the ALD system that are essential to achieving uniform distribution.

Gas-injection design

The gases in a single-wafer system are distributed through an injector. The injector can be a single orifice introduced from the top or side of the wafer or a multipoint showerhead. For a single-point source, the chemical flight time from the source to the wafer surface will vary as function of distance from the source. Therefore in a top-down single-point injection, the center achieves saturation sooner than the edge. The precursor must continue to flow until the wafer edge has achieved saturation to obtain good uniformity. This added center-to-edge saturation time leads to longer chemical pulse times and lower throughputs.

Understandably, the injection-point distance in a showerhead is equal for all points on the wafer. The internal

dimensions within the showerhead are designed to achieve gas velocities that quickly distribute the pulsed chemical uniformly across the wafer surface. Full wafer saturation for a 300mm wafer can occur with a chemical pulse in times as short as 20ms. With saturation occurring quickly and uniformly, the precursor can be pulsed very rapidly leading to reduction of the ALD cycle time and consequent improvement in throughput. Figure 1 and Figure 2 illustrate a computational simulation of a single-point inlet showerhead gas injector optimized for the highest outlet flow uniformity.

The ability to shorten the chemical pulse times needed to saturate the wafer surface is an important added benefit of reducing the chemical consumption per wafer. We have seen close to a 20% reduction of chemical usage between systems with nonoptimized and ones with optimized injection and distribution designs. This is an important consideration in manufacturing for lowering the cost-of-ownership for processes requiring the use of expensive chemical precursors.

ALD valve considerations

Other key hardware components are the valves that control the chemical pulsing o the precursors. The valves are required to deliver a precise dose of chemistry repeatable within ±1 ms when the valves are signaled to open or close. A delay of opening or closing the valve can cause unwanted overlap or underlap of the opening and closing with the other valves. An unwanted underlap can cause pressure build-up behind the valve causing a burst in pressure the next time the valve is opened. An unwanted overlap can cause mixing of gases if the valves do not shut off before the next valve opens. This precise orchestration of the valve timing is critical in achieving process repeatability in ALD. The more precise a valve's operation, the more efficient a recipe can be written, resulting in reduced time and increased system throughput.

As simple as it may sound, the location of the ALD valve and its distance from the process chamber is actually key in achieving a fast, high-dose delivery. If the valve opening and closing occurs far away from the reaction chamber, then it causes longer pulses because the chemical packet being delivered to the chamber lengthens as a function of line length. This stretching of the chemical packet can act like a delayed

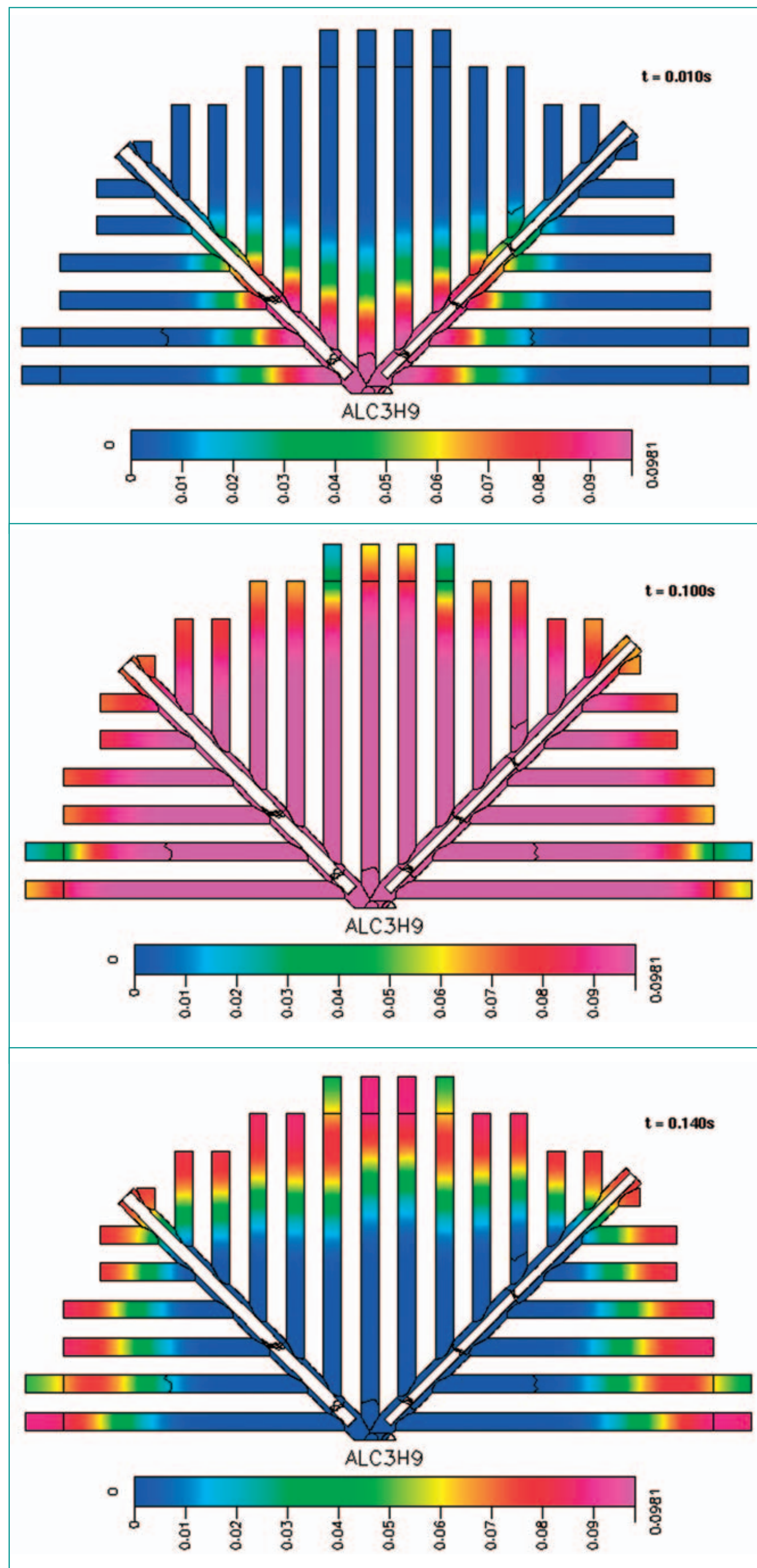

Figure 2. Time series of simulated flow through optimized showerhead gas injector, showing precursor concentration in a 100ms pulse. Top to Bottom: 10ms after pulse begins, end of pulse, 40ms after pulse ends. (Four outlet holes are blocked for this simulation, associated with the green regions in the center figure.)

FT28_swagelok.qxp 16/11/2005 14:53 Page 1

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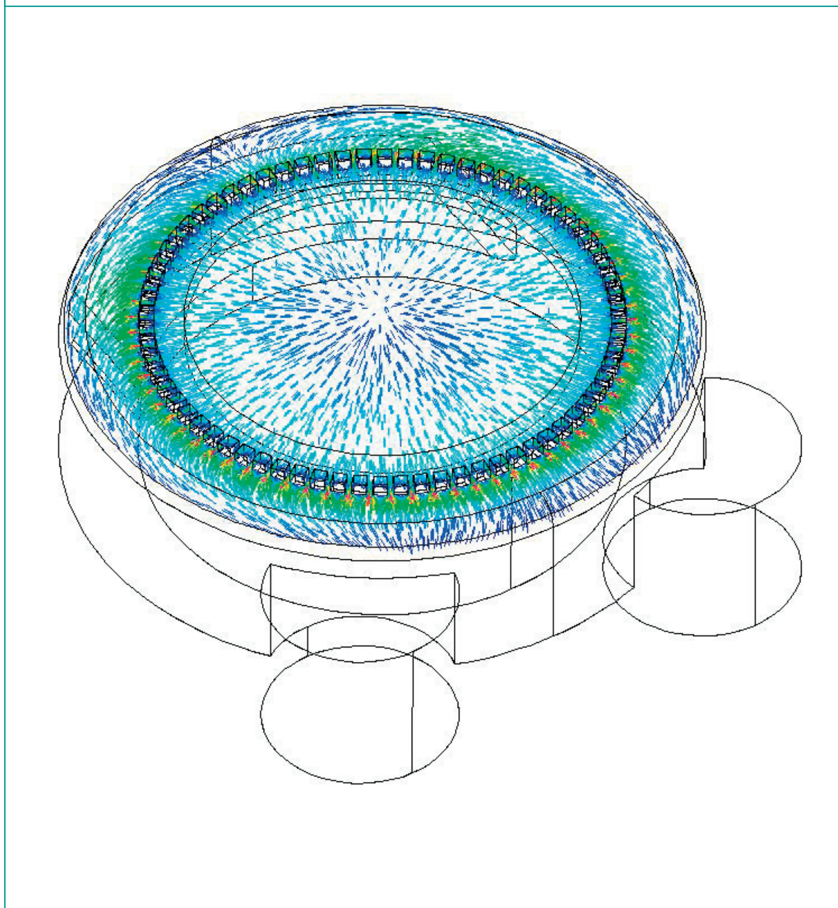

Figure 3. Computational volume (top) and flow vector plot at a plane midway between the wafer and showerhead (bottom), showing the highly radial flow distribution pattern despite the double-point exhaust.

closing of a valve, thereby affecting the overlap of chemicals into the reaction chamber. Having the shortest practical distance between the ALD valve and the reaction chamber minimizes the pulse-stretching effect.

The valve's lifetime is also critical in maintaining the overall system reliability. As a valve begins to fail, the opening and closing characteristics of the valve may begin to change and may possibly cause the opening of the valve to misfire. Such valve behavior results in underdosing and consequent issues with thickness, uniformity or film composition. A valve with a lifetime of one million cycles will reach the end of life by ~7140 wafers for a typical 140 cycle/wafer recipe. A valve must have a lifetime of at least 20 million cycles to be suited for a production system. The valve's opening and closing characteristics must also be monitored and tracked for behavioral changes to prevent process excursions or wafer scrap.

Process chamber design

The process chamber or reactor is one of the key components of the equipment configuration that will allow fast pulse and purging of the gases. The volume of the process chamber will determine the minimum recipe cycle times required to prevent mixing of the gases. The volume between the showerhead and the wafer surface is sufficiently small so the time to saturation is fast. The determining factor of when the next gas can be introduced depends on how quickly the first gas is removed from the reaction chamber. Thus, the smaller the reactor volume, the faster the removal of the gases is from the process chamber.

Also, the need for a reduced volume should be addressed both at the level of the chamber volume as well as the reactor volume. The chamber volume is defined as the interior space inside the process module. This space includes all the area around the wafer, under the wafer and the slot valve and exhaust plenum. This area is considerable because of the wafer handling and exhaust requirements of the chamber.

The small reactor volume leads to other benefits such as improved temperature control in the wafer environment and good control of byproduct condensation. There is less volume to control the pressure that allows improved uniformity and there is less surface for particulate build up in the wafer area.

The management of the gas-flow dynamics within the chamber is another design feature, which must be taken into account for production worthiness. This design feature enables the extraction of the gases out of the reaction chamber into the chamber volume and out into the vacuum pump to occur smoothly and quickly. When the gas-flow management has been optimized, not only can the cycle times be reduced, but also the mixing of residual gases is minimized, resulting in less chance of byproduct and particle formation.

Summary

The design of the gas-distribution system, reactor volume and ALD switching valves provide precise control of the ALD film thickness uniformity and composition. Efficient injection and extraction of the gases result in faster cycle times and higher wafer throughputs. Quick exhaust of gases and byproducts out of the reaction chamber leads to the reduction of the recipe cycle times and particle formation. Combination of all these design features in the ALD system culminates in achieving higher productivity and lower chemical/gas consumption and defects. Therefore, these components are the critical constituents of a production-worthy ALD system to meet the demands of high-volume, cost-effective manufacturing.

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