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No-splatter spray makes better wafers

Pressureless sprays that never clog are the basis for new and more productive semiconductor manufacturing techniques.

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Ultrasonic nozzles break up liquid into a fine mist. Compared with conventional pressure spray nozzles, ultrasonic nozzles deliver a low-velocity spray. They can dispense extremely small amounts of spray onto a substrate precisely and repeatedly. Operation is pressureless and they never clog. The spray velocity is approximately one-one hundredth that produced by a pressure nozzle, so there is no overspray. This minimizes the amount of material released into the environment. The controlled, low flow rate (rates as small as a few microliters per second are possible) ensures the amount deposited is exactly what is needed.

The technique is proving to be especially valuable in photolithographic processing. Semiconductor makers since the mid-1980s have deployed ultrasonic spray nozzles in spin-coating silicon and gallium-arsenide wafer substrates. Here they typically deposit photoresist developer, the chemical that develops circuitry imaged by an optical stepper.

The technique itself is surprisingly simple. Spin-coating starts with a substrate that usually is rotating slowly or not at all. A nozzle with a capacity of 60 ml/min or more sits over a rotating wafer such that it can spray the entire surface. The substrate then quickly spins up to a high speed, perhaps several thousand revolutions per minute, to uniformly distribute the coating.

Uniformity of deposition is not important when depositing photoresist developer. The objective is to apply enough spray without much bounceback, where particles bounce off the surface and become dust. Ultrasonic nozzle systems have proven successful because of their soft spray and ability to continuously replenish the entire

Low-flow, focused spray systems can produce patterns as narrow as 0.070 in., and deliver single-shot sizes of only a few hundred nanoliters or continuous flow rates as low as a few microliters/min. The nozzle assembly can mount on a robotic arm, as in this application, or on an *X-Y* table to execute continuous patterns. Alternatively, it can also mount in a fixed position to dispense a precise amount of spray at a selected site.

surface with fresh material.

The gentle, yet continuous deposition over the wafer surface boosts chemical activity (providing better development efficiency). This and minuscule bounceback help cut material consumption. Semiconductor makers adopting this technique have reported material savings of up to 70%. Control of critical dimensions improves as well.

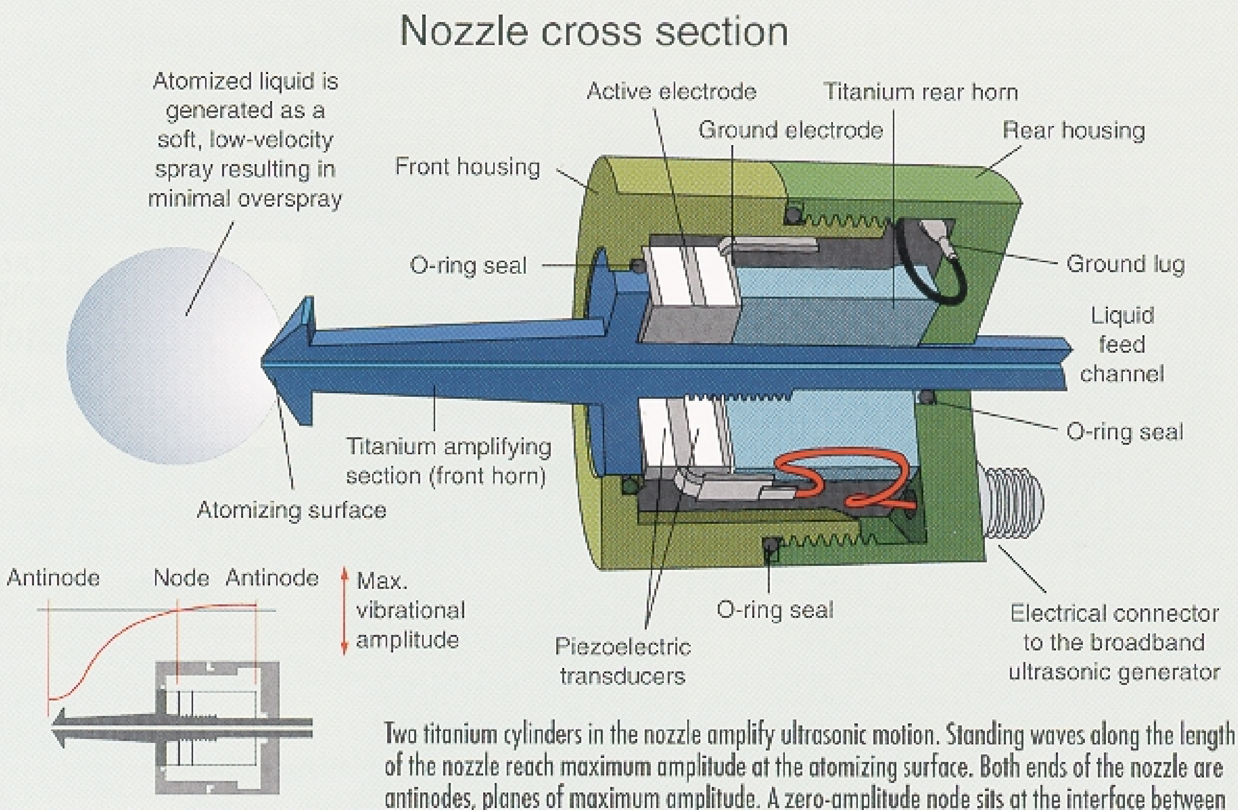
Another exciting application has emerged over the past year or so. Ultrasonic nozzles are now practical not only for depositing photoresist developer, but also for the more critical spin-coating of photoresist. Under a grant from Sematech, a consortium of U.S. companies involved in semiconductor manufacturing, Sono-Tek Corp. developed a way of ultrasonically spraying photoresist on 200-mm silicon wafers. This dramatically reduces the required coating material to about 1.3 ml. Moreover, the method maintains the same

A TRIP THROUGH AN ULTRASONIC NOZZLE

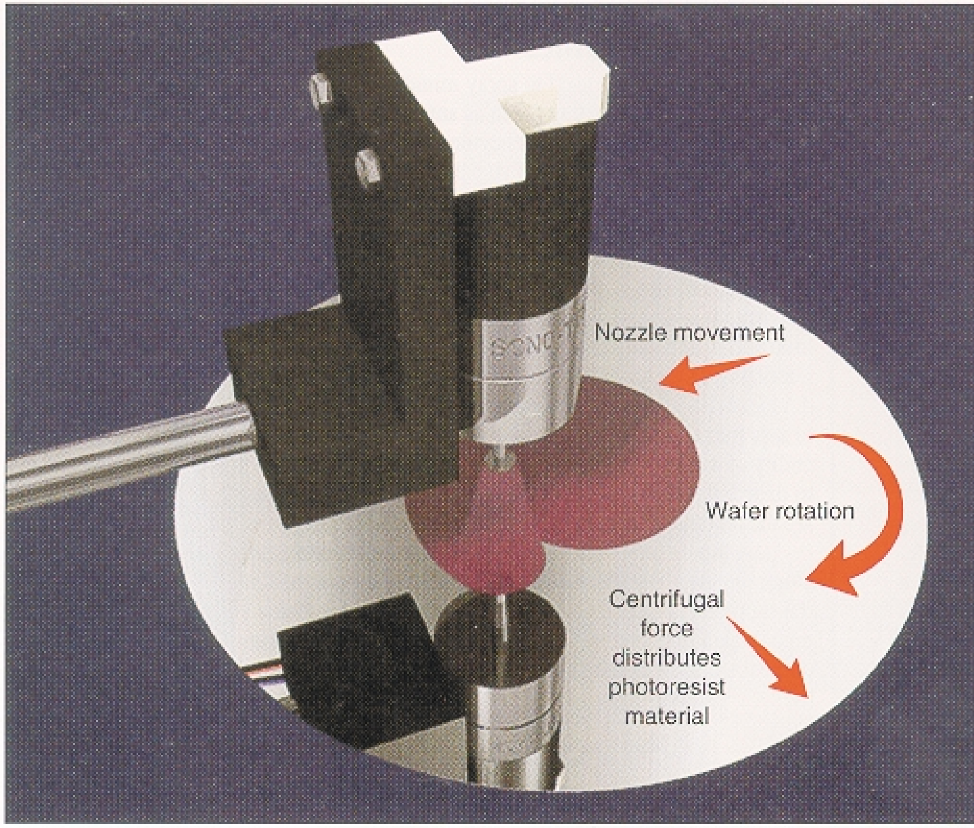
Ultrasonic nozzles are basically tuned devices that resonate at a certain frequency consistent with their size. Their maximum length and diameter are inversely proportional to the resonant frequency, in the range of 25 to 120 kHz; that is, the higher the operating frequency, the smaller the nozzle. Another consequence of the atomization process is that the median drop size produced also decreases as the resonant frequency increases.

A nozzle has several parts. The driving element consists of a pair of piezoelectric transducers which convert electrical energy into mechanical motion. High-frequency power comes from a separate generator capable of locking onto the nozzle resonant frequency. The transducers sit between two titanium cylinders which magnify the vibrating motion of the transducers, maximizing it at the atomizing surface. Titanium is the choice because of its high tensile strength, positive acoustical properties, and excellent corrosion resistance.

Liquid feeds to the atomizing surface through a large-diameter channel running the length of the nozzle. Once emerging onto the atomizing surface, the liquid sees high-amplitude vibrations that break it into a mist of fine drops, which move away at low velocity (under 3 in./sec). To accomplish this effect, applied power must stay within a fairly narrow window. Too little will stall the nozzle, meaning atomization will not occur. Too much will rip off the liquid in large chunks, which is unsuitable for an atomized spray. Typically, nozzles operate at power levels around 2 to 10 W, depending on the specific design and the nature of the liquid sprayed.



Two titanium cylinders in the nozzle amplify ultrasonic motion. Standing waves along the length of the nozzle reach maximum amplitude at the atomizing surface. Both ends of the nozzle are antinodes, planes of maximum amplitude. A zero-amplitude node sits at the interface between the transducers. A step transition from the large to the small diameter of the front horn provides the amplification at the atomizing surface. Because both ends are antinodes, the nozzle must be a half wavelength long for the ultrasonic frequency used. Thus nozzle dimensions are governed by frequency. High-frequency nozzles are smaller and create smaller drops.



CONVENTIONAL SPIN COATING

One typical photoresist coating strategy uses a spiral pattern created as the dispense nozzle moves from the rotating wafer's center to its edge (or vice versa). This technique distributes the material over most of the wafer prior to spin coating. But the technique requires twice as much material as does the ultrasonic spray method, because the initial distribution of material over the wafer is much more uniform. Application with ultrasonic nozzles cuts photoresist use by more than half because most of the material stays on the wafer.

across-the-wafer uniformity seen with conventional dispense methods that consume a lot more material.

For comparison, one major commercial supplier of photoresist says conventional dispense techniques consume 3 to 3.5 ml per dispense on average when coating 200-mm wafers with I-line photoresist. Such methods of applying photoresist usually deposit material as a continuous stream. They may also apply material as a puddle in the center of a wafer, or in a spiral pattern executed as the dispense nozzle moves across the wafer (from center to edge or vice versa) while the wafer spins slowly. In either case, centrifugal force during spin coating spreads the initial deposit out over the surface. Most of the material (over 99%) flies off. The residual film is the final coating. These chemicals cost as much as $850/gallon. Thus a 60% cut in consumption brings an obvious and dramatic cost savings.

One major reason equipment makers have stayed away from spray processes is air-borne contamination. Specifically, spray opens the door to possible redeposition of dried, airborne photoresist particles on the wafer surface.

UNCONVENTIONAL WISDOM

However, ultrasonic nozzles negate the conventional wisdom about air-borne contamination. Their extremely soft spray tends to eliminate bounceback, allowing successful management of redeposition.

There are two principal reasons why ultrasonic spray deposition enhances the photoresist coating process and saves material. First, the technique distributes material more uniformly than is possible with a non-atomizing method. To see why, consider conventional spin coating: material starts out as a puddle or stream over one part of the wafer, and depends on centrifugal force for distribution. The process deposits enough photoresist to completely coat the surface as the puddle migrates outward.

However, there are process complexities associated with ensuring that the wafer gets a complete coating (especially toward the edges). For example, temperature control must be precise. Ditto for calculations of solvent evaporation rate (affecting photoresist viscosity). Otherwise the coating action may not be enough to lay a 1 or 2-μ film thickness with the required coating uniformity of below 0.003 μ.

By comparison, spray deposition distributes material over the entire surface of the wafer at the outset. Moreover, the pattern is more or less contiguous; that is, the drops have coalesced into large areas of continuous film. There are bare spots, but the distance between them is small. Solvent evaporation is less of an issue, and coating uniformity and quality doesn't depend as much on material viscosity.

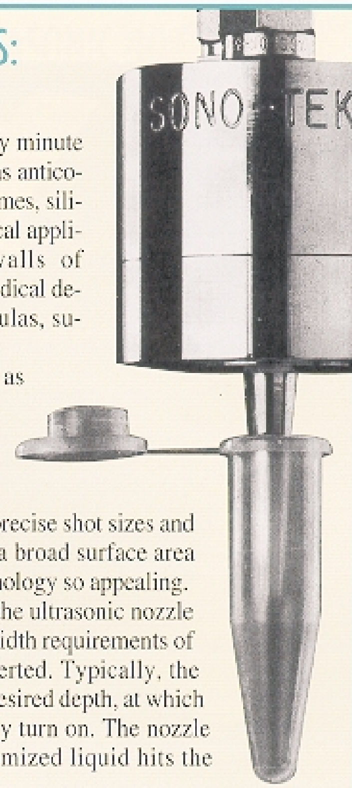
A second related reason that ultrasonic spraying provides benefits is that it significantly reduces the dependence of liquid distribution on surface tension. Processes using unatomized material rely on spinning action to overcome surface forces between the advancing front of bulk liquid and the uncoated surface beyond it. Surface forces are less of a problem in processes depositing atomized material. Here the work of distributing the liquid is largely complete before spin-coating.

In operation, the ultrasonic spray nozzle sits above the wafer on an arm that moves from center-to-edge or vice versa. It produces spray envelope diameters of up to 0.5 in. Because the spray envelope extends over a broad area, the entire surface can be covered.

The flow rate varies during dispensing so more material hits the outer part of the rotating wafer where the surface travels fastest, less on the more slowly traveling inner portion.

An important by-product of a spray technique is the elimination of a back-side rinse step. It is unnecessary first because there is less excess liquid. Second, distribution of the material over the entire wafer during deposition prevents splashing, the cause of back-side deposition. Splashing results when large chunks of excess photoresist fly off as a single mass.

MEDICAL APPLICATIONS: SPRAY-ON ENZYMES



Ultrasonic nozzles are used to spray minute quantities of special coatings such as anticoagulants, coagulants, proteins, enzymes, silicone lubricants, and antigens. Typical applications are on the interior walls of blood-collection tubes and other medical devices such as syringe barrels, canulas, sutures, and catheters.

Ultrasonic nozzles can deposit as little as 5 μliters uniformly over the interior walls of blood-collection devices with a volume accuracy of less than 5%. The exceptional ability of such systems to atomize precise shot sizes and to distribute the dose evenly over a broad surface area are the features that make this technology so appealing.

Developers select the shape of the ultrasonic nozzle atomizing head for the depth and width requirements of the tube into which it is being inserted. Typically, the nozzle head first penetrates to the desired depth, at which point the nozzle and liquid delivery turn on. The nozzle then slowly withdraws as the atomized liquid hits the sidewalls.

PCB SPOTS

Wafer processing isn't the only manufacturing process to benefit from the use of ultrasonic nozzles. They are increasingly applied in selective soldering. The term covers a wide variety of processes, all with the requirement that liquid solder flux hit the circuit board only where desired. Candidates for selective soldering include advanced "chip-scale" packaging and attachment methods for semiconductors — ball-grid array devices, flip-chips, and various types of multichip modules. These compact packaging methods require the application of flux only within specific areas and at precisely controlled flow rates.

Ball-grid arrays, for example, require flux only on the tiny spots of the circuit board where the balls touch (ball-grid array connections are not leads, but rather small spherical balls composed of solder or of a hard, heat-resistant substance coated with solder). Ultrasonic nozzles can be used to produce a low-flow, focused spray ideal for this application.

Similarly, board preparation for components on a continuous tape or reel also involves precise deposition of flux. The component lead is the only region that needs fluxing, and none is allowed on the component body. The focused spray mechanism can direct flux onto this small area without overspray.

Although wave-soldering is a mature technique, it is still prospering. Ultrasonic spray systems used in spray-fluxing printed-circuit assemblies have helped advance wave-soldering technology. The industry now recognizes that spray techniques are far better than flux application methods such as foam or wave fluxing. They can save up to 80% in flux material costs, significantly cut solder defect rates, reduce emissions, and eliminate disposal costs. Such advantages have helped ultrasonic systems become widely used for applying solder flux to printed circuit assemblies varying in width from 2 to over 20 in.

Ultrasonic spray technology has demonstrated its value in other areas such as thin-film chemical vapor deposition processes and the fabrication of high-temperature superconductors. Its benefits are becoming evident to manufacturers in a diversity of industries. This has led to exploitation of the technique in medical devices, float-glass manufacturing, nonwoven fabrics, spray drying of pharmaceuticals and ceramic slurries, chemical reactors, and combustion. ■