

# Improved Yields for the Nano-Technology Era Using Cryogenic Aerosols

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## ABSTRACT

*In this paper, cryogenic aerosol processing for enhancing final device yield in state-of-art 180 and 130nm devices is demonstrated. Significant advantages of this particle removal technology is demonstrated and discussed: excellent particle removal efficiency on both hydrophilic and hydrophobic surfaces, no watermarks, no feature damage, no charge induced damage and no film modification or loss.*

## KEYWORDS

Yield Enhancement, Defect Reduction, Particle Removal, Cryogenic Aerosols, Argon Aerosols, Nitrogen Aerosols, Low-K Dielectrics, Polysilicon Lines

## INTRODUCTION

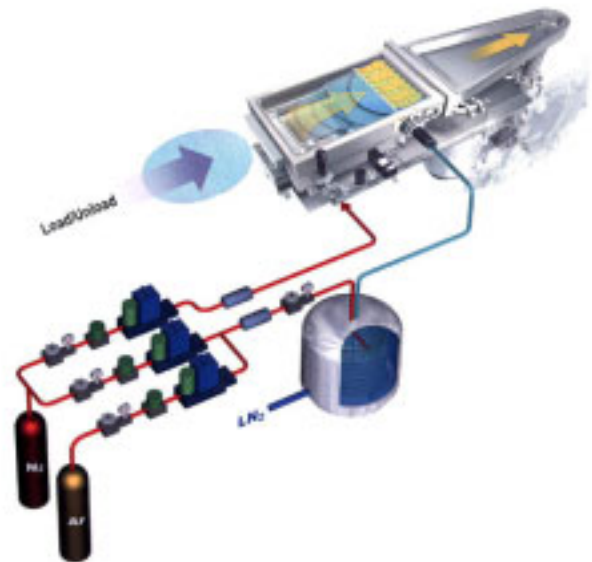
Yield teams today are challenged by smaller device geometries and the incorporation of new materials. Smaller device geometries mean more fragile features and smaller killer defect sizes. A significant yield detractor is particle defects. Whether the particle defects are random or due to process excursions, their removal is becoming more difficult without damaging the surrounding structures or altering material properties.

Cryogenic aerosol has been successfully used for nearly a decade to control device defectivity and enhance overall final yield [1-4]. The inert properties of this aerosol, along with the ability to control the aerosol aggressiveness, makes it a viable technique to remove particles from most surfaces. In addition, insertion of cryogenic aerosol treatment within the process flow is simplified by the inertness of the process; no chemical reactivity, no particles added (particle neutral process), and no electrical charging [5].

In this paper, three primary aspects of the cryogenic aerosol process are discussed. First it is demonstrated that cryogenic aerosol does not alter the properties of exposed materials, e.g., porous low-k materials. Secondly, it is shown that cryogenic aerosol is capable of cleaning substrates with fragile structures, e.g., sub-100 nm polysilicon line structures and low-k damascene structures. Finally, decreased defectivity and increased final yields are demonstrated when inserting cryogenic aerosols to control defectivities in 180 and 130nm process flows.

## CRYOGENIC AEROSOL TECHNOLOGY

Figure 1 shows a general layout of a commercially available toolset capable of removing particles with cryogenic aerosols. The schematic identifies three main components; the gas manifold, cryogenic chiller and process chamber. The aerosol cleaning process starts with a blend of argon and/or nitrogen gases. The volume of each gas is controlled individually by mass-flow controllers and mixed prior to entering the cryogenic chiller. The cryogenic chiller is a pressure controlled liquid nitrogen heat exchanger that partially liquefies the gas mixture at cryogenic temperatures. This gas/liquid mixture flows to an injection nozzle and is injected into the process chamber through an array of nozzle holes. Expansion of the gas/liquid mixture into the process chamber is controlled at a partial vacuum of approximately 50 Torr and results in breakup of the liquid phase and evaporative cooling to generate the solid aerosol species.



**Figure 1. General layout of FSI's ANTARES<sup>®</sup> cryogenic aerosol system showing its three main sub-systems; gas manifold, cryogenic chiller and process chamber.**

The wafer passes under the injection nozzle and is sprayed with the aerosol. The nozzle consists of 129 uniformly machined and spaced holes resulting in a continuous line of aerosol up to 300mm in length [6]. Tests on wafers with saturated particle counts confirm no streaking with respect to particle removal. In addition, full wafer maps testing for damage confirm no local areas of damage. The angle of

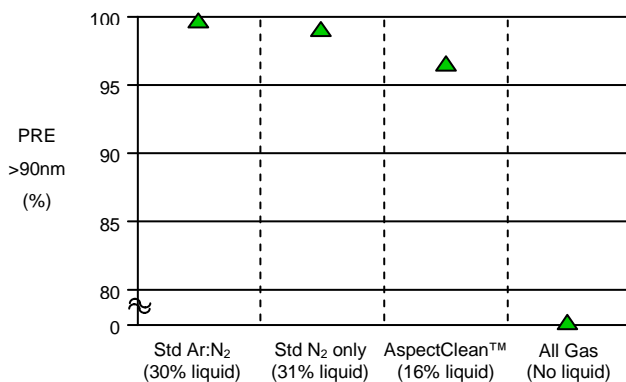
incidence and distance to the wafer of the injection nozzle has been optimized for maximum particle removal efficiency and to avoid recirculating flow patterns in the chamber.

The intensity of the aerosol's energy and size can be controlled most effectively by varying the argon to nitrogen ratio, process chamber pressure, and the pressure (temperature) of the liquid nitrogen bath. The argon to nitrogen ratio is particularly useful in tuning the process aggressiveness; such that increasing the argon concentration yields a more aggressive process.

The aerosol cleaning mechanism has been described in detail elsewhere [7]. Briefly, the aerosol crystals collide with the particles on the surface and the resultant transfer of kinetic energy facilitates the particle in overcoming the adhesion energy between the particle and substrate. The suspended particles are entrained in the gas flow and removed from the process chamber via a vacuum pump.

### CRYOGENIC AEROSOL PROCESS RECIPES

The cryogenic aerosol process recipes can be divided into three main types as shown in Figure 2. A fourth process, an all gas process, is shown simply for comparison purposes. To obtain the particle removal efficiency (PRE) information, Si<sub>3</sub>N<sub>4</sub> particles were dry-deposited onto bare silicon wafers.



**Figure 2.**

**PRE is shown for four cryogenic aerosol processes. From left to right the cryogenic aerosol process becomes less aggressive, with no damage observed (60nm polysilicon lines) for either the AspectClean™ or the All Gas processes. Only nominal reduction in PRE is observed for the AspectClean™ process. This data was taken with a nozzle angle of 60 degrees relative to normal incidence.**

The Std Ar:N<sub>2</sub> and Std N<sub>2</sub> Only recipes deliver a substantial amount of liquid (~30% by weight) to the nozzle, resulting in an aggressive cleaning process with excellent particle removal efficiency, however some damage to sensitive structures was observed (e.g. <100nm polysilicon line structures). These processes are best for planar surfaces or surfaces with more robust structures.

The AspectClean™ recipe is also an N<sub>2</sub> Only recipe but delivers substantially less liquid (16% by weight) to the nozzle, resulting in a less aggressive process that does not damage sensitive structures. The amount of liquid delivered to the nozzle is controlled by the chiller pressure (temperature) setting. For comparison purposes, a N<sub>2</sub> Gas process is shown. The N<sub>2</sub> Gas process has no liquid content, but the N<sub>2</sub> is cooled to approximately 100K prior to being delivered to the nozzle. The N<sub>2</sub> Gas process shows no damage, but also has no particle removal efficiency for challenge particles down to 65 nm.

While the AspectClean™ recipe results in no damage to sensitive structures, it does show a nominal reduction in particle removal efficiency. While one may take note that the remaining particle levels increase, this is often insignificant since the cryogenic aerosol process is normally inserted at levels where the defect density is <100/wafer. Couple the fact that the cryogenic process can be inserted at levels where other cleaning processes are not feasible (due to damage or film sensitivities), and in the end, one must view the process for the >95% particles removed and not so much the <5% particles left behind.

Particle removal efficiency and damage threshold may also be controlled via nozzle incident angle and/or overall aerosol travel distance. Higher removal efficiency and more damage are observed for steeper incident angles (45 degrees) and shorter travel distances. The opposite is true for shallower incident angles and longer travel distances. The data in Figure 6 was taken at an aerosol incident angle of 60 degrees relative to normal and an overall travel distance of 10.6 mm.

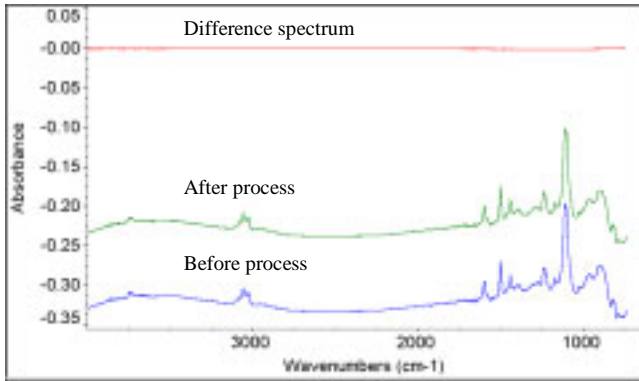
### CLEANING OF MOISTURE SENSITIVE SUBSTRATES

Low-k materials provide perhaps the best example of the inertness and versatility of the cryogenic aerosol clean. These materials tend to be mechanically fragile, hydrophobic and hygroscopic.

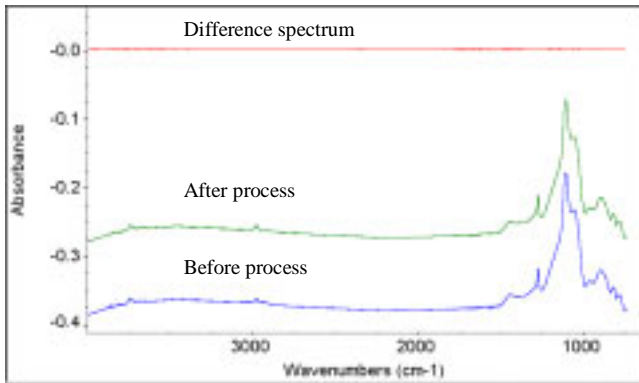
It has been previously reported that cryogenic aerosols do not change the thickness or refractive index of either as-deposited SiLK® or porous MSQ [8]. In that study, it was shown via ellipsometry that to within measurement error there was no change in film thickness or refractive index after exposure to cryogenic aerosols.

FTIR analysis using a Nicolet ECO-RS spectrometer with a MCT-A detector also showed no significant changes in peak intensity or peak values of either the as-deposited SiLK® or porous MSQ films. These results are detailed in Figures 3 and 4 below. All spectra share a common scale, with difference spectra highlighting the null result. The difference spectra were obtained by subtracting the “before

process” from the “after process”. The Std Ar:N2 recipe was used since blanket films were used in this study.

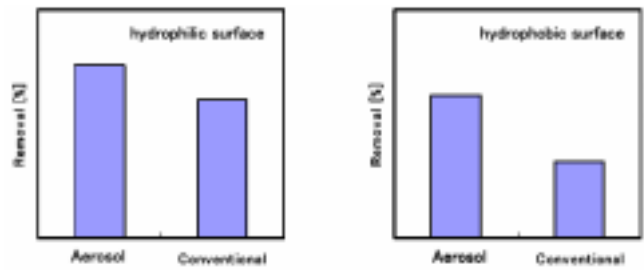


**Figure 3 FTIR Spectra of Dow SiLK® before and after processing with cryogenic aerosols.**



**Figure 4 FTIR Spectra of JSR LKD-5109 (porous MSQ) before and after processing with cryogenic aerosols.**

In Figure 5 particle removal efficiency from hydrophilic and hydrophobic surfaces is shown [5]. In both cases, the cryogenic aerosol process is compared to the conventional aqueous processes. The particle challenge was PSL spheres. Conventional cleans comprise both a high-velocity aqueous jet and a variable-velocity atomized aqueous spray. SiO<sub>2</sub> was the hydrophilic surface tested, with SiN and SiOC being the hydrophobic surfaces tested. In both the hydrophilic and hydrophobic cases, the cryogenic aerosol process was superior. However, most noteworthy is the larger advantage seen on hydrophobic surfaces. All three recipes described above (Std Ar:N<sub>2</sub>, Std N<sub>2</sub> Only and AspectClean™) were used in this study, with very comparable results.



**Figure 5 Particle removal efficiency comparison of cryogenic aerosol vs. conventional aqueous-based cleans for both hydrophilic and hydrophobic surfaces. Cryogenic aerosol was found to be superior in both cases, but more-so for the hydrophobic surface [5].**

Further advantages of the cryogenic aerosol process on hydrophobic surfaces were observed when comparing watermark performance [5]. As one would expect, the cryogenic aerosol process did not leave any watermarks on either the hydrophilic or hydrophobic surfaces. However, the aqueous-based conventional cleans left watermarks on the hydrophobic surfaces.

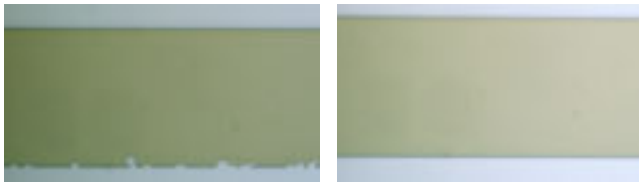
### CLEANING OF PHYSICALLY SENSITIVE STRUCTURES

The physical aggressiveness of the cryogenic aerosol process requires that the appropriate recipe is chosen depending upon the robustness of the structures being cleaned. Damascene structures, typically more robust than thin 60nm polysilicon lines, have been shown to withstand the Std N<sub>2</sub> Only process. In particular, SiLK® test structures with geometries ranging from 0.20µm to 0.30µm, were found to have no damage from the Std N<sub>2</sub> Only process [8].

The primary particle removal mechanism for the cryogenic aerosol process is the transfer of momentum from the incoming aerosol to particles and other features on the wafer surface. As a result, features that run perpendicular to the direction of aerosol travel are most exposed to the aerosol forces and thus must be susceptible to physical damage and/or delamination. Therefore, all damage assessment experiments are run with the incident aerosol velocity vector perpendicular to the linear features on the wafer surface.

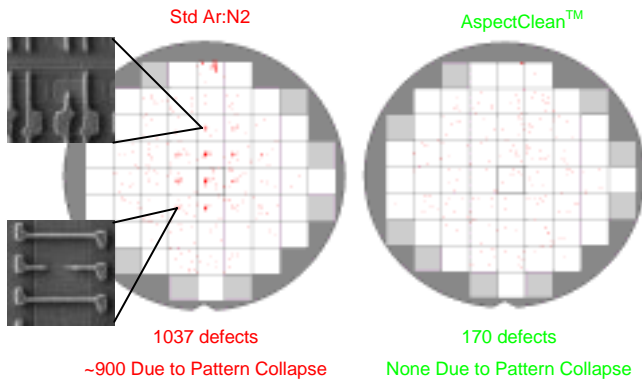
Figure 6 shows 60nm polysilicon lines processed with the standard Ar:N<sub>2</sub> recipe (left) and AspectClean™ recipe (right). In both cases, the aerosol treatment was perpendicular to the polysilicon lines. Polysilicon line height is 225nm and line spacing is 240nm. The high aspect ratio (3.75:1) polysilicon lines are used to provide a more difficult challenge. As shown on the left, numerous damage sites were observed with the standard Ar:N<sub>2</sub> process, especially on the leading edge of aerosol impact (bottom of picture). The photo on the right shows *no* damage from our specially designed AspectClean™ process. Since maximum line stress remains constant for constant aspect ratio [9], one would expect the AspectClean™ process to clean thin-

ner lines without damage as long as the aspect ratio remains constant.



**Figure 6. Left panel shows damaged 60nm polysilicon lines processed using Std Ar:N2 process. Right panel shows same lines, without damage, processed with the new AspectClean™ process.**

Figure 7 shows the AspectClean™ process successfully applied to device wafers. The device wafers tested had 110nm wide polysilicon lines with no spacers. The lines were 180nm thick, with minimum separation distance of 250nm. The wafer on the left was processed with the Std Ar:N2 recipe while the wafer on the right was processed with the AspectClean™ recipe. A KLA scan showed that the wafer processed with the Std Ar:N2 recipe had 1037 defects, of which ~900 were due to pattern collapse. A similar scan of the wafer processed using the AspectClean™ recipe had only 170 defects, of which none were caused by pattern collapse. In both cases, the ~150 remaining defects were non-cleanable defects from the exposed under layer. It should be noted that polysilicon lines with sidewall spacers are much more robust, and no pattern collapse was observed even with the Std Ar:N2 recipe.



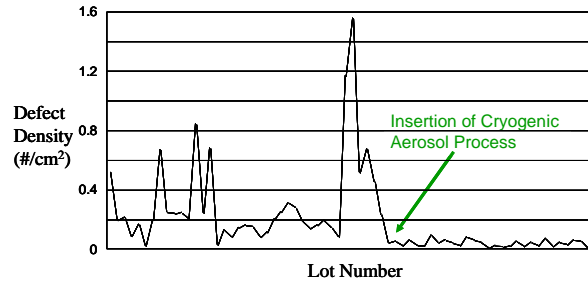
**Figure 7. Left panel shows damaged 110nm polysilicon lines processed using Std Ar:N2 process, along with SEM images of typical pattern collapse defects. Right panel shows same lines but processed with new AspectClean™ process.**

### IMPROVED YIELD WITH CRYOGENIC AEROSOL PROCESSING

The individual advantages of the cryogenic aerosol cleaning process described thus far all add up to the most compelling advantage of all; increased final device yield. Though many fabs would prefer to eliminate defects at their source, often this time consuming task leads to much device waste. In addition, this waste typically occurs early in a products

ramp, a time when one commands the greatest average selling price (ASP).

Often defectivity results from process excursions. A great example of how process excursions can be controlled by the cryogenic aerosol process is shown below in Figure 8. In this Figure, defect density is plotted as a function of lot number. The defect density was measured by an in-line pattern defect metrology tool. To the left of the arrow, no cryogenic aerosol treatment was performed. To the right of the arrow, a cryogenic aerosol treatment was performed prior to the TiN barrier deposition step. Prior to insertion, baseline defect densities were achieved, however frequent process excursions periodically impacted product yield. Insertion of the cryogenic aerosol process flat-lined the defect density and subsequently stabilized lot-to-lot yield numbers. Overall electrical yield increased by as much as 4% [3].



**Figure 8. Defect Density as a function of Lot Number prior to and after a cryogenic aerosol tool is inserted prior to TiN barrier deposition [3].**

A more comprehensive study of how cryogenic aerosols control defectivity and improve final device yield was performed and is summarized in Table 1 below. Cryogenic aerosol splits were conducted on both 180nm and 130nm Logic devices. KLA defectivity analysis was performed, including measurements for pattern damage. With the appropriate application of the AspectClean™ process for sensitive structures, no pattern damage was observed in any of the splits. In addition, for all levels measured, the splits having cryogenic aerosol applied had lower overall defectivity than the reference split.

**Table 1. Table summarizing the improvement in final device yield by incorporating cryogenic aerosol processing into the specified process flow.**

Device	Trial Layer	Recipe	# of Wafers	Percent Yield Improvement
180nm Logic	4 Cleans - Post Spacer Dep, Post Spacer Etch, M1 Post Nitride Dep, M1 Post SiO Dep	Aspect-Clean™	12	+1.51
	1 Clean - M4 Post Line Etch	Aspect-Clean™	5	+0.65
	6 Cleans - M1 through M6 Post Line Etch	Aspect-Clean™	5	+4.74

130nm Logic	1 Clean – Post Salicide Formation	Std Ar:N2	5	+3.11
	Multiple FEOL Cleans – Post Spacer Etch, Post Salicide Formation, Post Film Dep	Std Ar:N2	6	+12.9
	Multiple BEOL Cleans – Post Film Dep, Post CMP	Aspect-Clean™		

The first column in Table 1 specifies device node, while the second column shows the number of cleans for each row as well as insertion point(s) in the process flow. The third column shows the recipe used, with the fourth column specifying the number of wafers in the split. The final column shows the device yield improvement when compared to the reference lots.

Table 1 shows various FEOL and BEOL process splits. Perhaps the split most representative of the versatility of the cryogenic aerosol process is that which is summarized in the last two rows. This particular split consisted of multiple cleans in both the FEOL and BEOL. In total, these wafers were exposed to cryogenic aerosol over 30 different times during the process sequence. Together, they combined for a net increase in yield of 12.9%. While it is quite likely that the cryogenic aerosols did not boost yield at each and every step, it is interesting to note that it did not negatively impact yield. This observation is an excellent testimony of the inert and non-damaging aspect of this process.

Another representative example is shown in the fifth row of Table 1. In this case, a single cryogenic aerosol clean is inserted just after salicide formation. This single clean at this particularly high defectivity step results in a >3% yield increase.

## CONCLUSIONS

Cryogenic aerosol processing is inert and non-etching and can be controlled to be non-damaging. It has excellent particle removal efficiency, and has been shown to be particularly advantageous for hydrophobic surfaces. By properly

selecting the cryogenic aerosol recipe and thus the overall process aggressiveness, it has been demonstrated that substantial yield benefits can be obtained without concern for pattern collapse or film damage. With cost-of-ownerships below one US dollar per wafer pass, it is reasonable to expect breakeven within one or two months of system startup.

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