

Advanced Cryogenic Aerosol Cleaning: Application to Damage-Free Cleaning of Sensitive Structured Wafers

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Abstract

Cryogenic aerosols formed from either argon and nitrogen or nitrogen gas only have proven successful for high particulate removal without material loss or modification and damage free cleaning of poly silicon line structures. Particle removal efficiency is reported on particulate contamination down to 65nm. Results on 60nm poly silicon structures have shown no damage and particle removal efficiency greater than 92%. Further reducing the poly line critical dimension to 40nm resulted in particle removal efficiency greater than 71% and no damage.

Keywords

Cryogenic Aerosol, Damage Free Cleaning, ArgonClean™ Process, N2Clean™ Process, AspectClean™ Process.

INTRODUCTION

The removal of particulate defects from a semiconductor wafer surface by physical or chemical means has long been a requirement to maintain product integrity throughout the device manufacturing process. This cleaning requirement is becoming increasingly difficult not only as the size of the particulate defect decreases but also as the underlying material performance becomes increasingly sensitive to the physical or chemical forces applied during defect removal. The ITRS mentions several potential technologies applicable to particle removal without etching or structural damage [1]. The approaches vary widely but the one commonality seems to be a single wafer approach. The single wafer approach to be detailed in this discussion relies on a cryogenic aerosol for particle removal. One immediate advantage of the cryogenic aerosol is the removal of particles without etching, satisfying that ITRS requirement. The ability to remove small particles without structural damage will also be addressed and discussed in detail. Both process and hardware modifications were made to achieve high particle removal efficiency (PRE) down to 65nm and no damage to 40nm poly silicon lines.

CRYOGENIC AEROSOL GENERATION

The term cryogenic, by definition, can be applied to processing where temperatures are below -150°C (123 K). In the current toolset, the process gas for cleaning (either N_2 or a mixture of N_2/Ar) is passed through a liquid N_2 dewar. The process gas is cooled by the liquid N_2 , and a portion of

the gas is turned to liquid. This liquid is cryogenic for both argon and nitrogen (freezing points of -189°C and -196°C respectively). For comparison, CO_2 freezes at -78.5°C and has very different aerosol properties (e.g. size distribution, charge, and impurities). This gas/liquid mixture is then delivered to the process chamber through a nozzle mounted above the substrate to be cleaned. The primary nozzle design, referred to as the standard nozzle, consists of a number of evenly spaced holes capable of processing up to and including 300mm substrates. The process chamber is maintained at a lower pressure than the pressure inside the nozzle resulting in the generation of a cryogenic aerosol as the gas/liquid mixture exits the nozzle (see Figure 1).

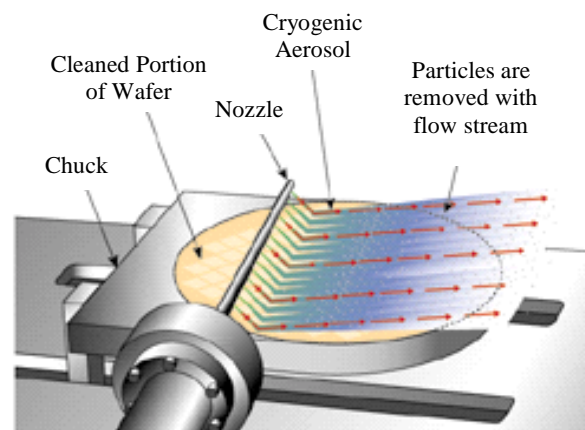


Figure 1. A diagram of the cryogenic aerosol chamber in the FSI Antares® Advanced Cleaning System.

The cryogenic aerosol in the process chamber consists of gas and solid aerosol clusters generated as the liquid phase is broken up and cooled when exiting the nozzle [2, 3]. With the proper processing conditions, the solid aerosol clusters impact the substrate providing the necessary removal force to dislodge the particulate defects without structural damage. The solid aerosol clusters either sublime or are swept away along with the dislodged contamination by a laminar flow of N_2 gas.

The end result is processing without material modification (e.g. k-value), material loss (etching), or charging [4-7]. Physical damage is also eliminated when cleaning sensitive structures with the correct hardware and process modifica-

tions. The details of these hardware and process modifications are discussed below.

PROVEN PROCESS APPLICATION

Defect density (DD) reduction and yield improvements have been confirmed in production environments [6 - 8]. Fujitsu has increased yields in both FEOL and BEOL logic device flows in their 180nm and 130nm aluminum technology nodes. Two cryogenic aerosol processes implemented with the standard nozzle, the ArgonClean™ and AspectClean™ processes, resulted in the yield increases [7]. The details of the cryogenic processes will be discussed in detail below, but the main difference is the AspectClean™ process was developed specifically for cleaning sensitive structures without damage. For instance, the AspectClean™ process increased yield by 4.74% when used to clean after each aluminum line etch (layers one through six) on the 180nm logic technology. Significant yield increases were also seen on the 130nm logic technology with the use of the ArgonClean™ and AspectClean™ processes in multiple FEOL and BEOL cleaning steps. These yield increases were a result of the cryogenic cleaning processes reducing the defect density after the process of record cleans already in place.

This yield enhancing performance of the AspectClean™ process was verified at another production facility with a FEOL clean of the 130nm node gate structure before the Si₃N₄ spacer depositions [8]. The clean of the sensitive structure before the Si₃N₄ spacer depositions can not damage the structure, etch the oxide, or charge the structure. The AspectClean™ process resulted in a DD reduction of 12% and yield increases of 2% compared to the previously used wet cleaning sequence. At this facility, the wet clean has now been replaced with the dry, cryogenic AspectClean™ process.

CRYOGENIC PROCESS DEVELOPMENT

Significant process advantage with respect to damage elimination has been seen by switching the process gas from a mixture of N₂ and Ar (ArgonClean™ process) to only using N₂ (N2Clean™ and AspectClean™ processes) [7 - 11]. The argon and nitrogen gas mixture, when cooled in the dewar, forms a gas and liquid mixture containing 30% liquid (by weight). The N2Clean™ process forms a similar amount of liquid (31% by weight) while the AspectClean™ process generates 16% liquid N₂ (by weight) in the dewar. The aerosols generated with only N₂ contain a smaller average aerosol size (aerosol size refers to solid clusters in the aerosol) compared to an Ar and N₂ aerosol (see Figure 2).

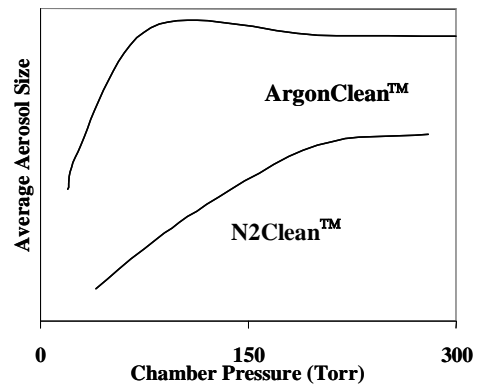


Figure 2. Average aerosol size versus chamber pressure determined by phase Doppler particle analysis for the standard nozzle. The aerosol containing nitrogen has a smaller average aerosol size than an aerosol containing argon and nitrogen.

The intended outcome with the cryogenic aerosols development is to generate aerosols with smaller average sizes which are lower in momentum and therefore less damaging. Reducing damage is not the only goal. PRE must be maintained as well. The conditions under investigation in this report that have an effect on PRE and damage are the process recipe, nozzle design, and angle of aerosol impact relative to the wafer. In general, the ArgonClean™ process will maintain a higher PRE than the nitrogen only recipes. This trend with PRE does correspond to the amount of damage observed with the standard nozzle (higher PRE, higher damage). The goal with any process or hardware modification is to maintain the aerosol impact force on the wafer above the particle removal threshold but below the damage threshold. As will be demonstrated with the standard nozzle, all three processes are above the particle removal threshold, not all were under the damage threshold.

Experimental

The wafers used in this work for PRE and damage evaluation are described below. Wafers were prepared for PRE with a wet dip contamination procedure to deposit Si₃N₄ (at ≥ 90 nm or ≥ 65 nm) particles. A low pH bath was prepared containing the Si₃N₄ particulate contamination. After the wafers were pre-cleaned to reduce starting particle counts, the wafers were placed in the low pH bath for two minutes, rinsed and then dried. The contamination on the wafers was further allowed to age for approximately one day before use. The damage evaluations were performed on wafers containing poly line structures with a critical dimension (CD) of 70nm, 60nm or 40nm. Aspect ratios (AR) were greater than 2:1 for the 70nm polysilicon lines, and approximately 3.8:1 for the 60nm and 40nm structures. The spacing of the polysilicon lines ranged from isolated structures down to a pitch of 300nm. The wafer source of the 60nm and 40nm polysilicon line structures was the same.

The source wafer contained the polysilicon structures at a CD greater than 60nm which was not sensitive enough for damage process definition. An isotropic wet chemical etching procedure was used to thin the polysilicon to the desired dimension [11 - 13]. The final dimension of the polysilicon structures was confirmed with SEM or TEM. Images of the 60nm poly line structure are shown in Figure 3.

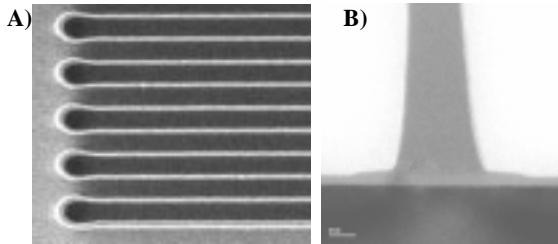


Figure 3. A) SEM image of 60nm polysilicon lines with an AR of 3.8:1. B) TEM cross section of polysilicon line with the base dimension equal to 60nm.

Regardless of the process recipe, all wafers contaminated with Si₃N₄ for PRE were processed with two passes under the aerosol. The poly line wafers were run under more demanding conditions maximized for the potential of creating damage. Each damage wafer was processed with four passes under the aerosol. Additionally, the poly lines were orientated perpendicular to the aerosol to insure the aerosol impact force was as large as possible for the damage evaluations [13].

DAMAGE FREE PROCESSING

The ArgonClean™ process has proven to dramatically reduce defect density and increase yields on robust wafer surfaces [6, 7, 9, 10]. On polysilicon patterned wafers, damage prohibited the use of the ArgonClean™ process with the standard nozzle. A dramatic decrease in damage to 70nm polysilicon lines (AR > 2:1) was observed with the N2Clean™ and AspectClean™ processes without sacrificing particle removal efficiency (see Figure 4).

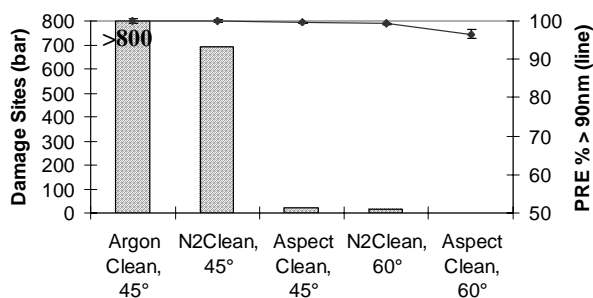


Figure 4. Damage (wafer pieces containing 70nm polysilicon, AR > 2:1) and PRE for aerosols produced with the standard nozzle at 45° and 60° nozzle angles.

The trend for reducing damage is clear with the three processes at a 45° nozzle angle, an angle that is optimized for PRE (cryogenic aerosol perpendicular to wafer surface = 0°). The lower liquid fraction of the AspectClean™ process dramatically reduces damage while maintaining a PRE > 99%. The standard nozzle orientated with an angle of 45°, regardless of process recipe, is still above the damage threshold for the 70nm poly silicon lines.

To reach a damage free condition with the standard nozzle, the nozzle angle was increased to 60°. By increasing the angle of cryogenic aerosol impact, damage is greatly reduced for the N2Clean™ process with little reduction in PRE. The damage is eliminated with the AspectClean™ process and a standard nozzle angle at 60°. The increase in nozzle angle combined with the AspectClean™ process reduces the average aerosol impact force delivered to the wafer to a level below the damage threshold but still above the particle removal threshold.

Investigating damage free cleaning further, the polysilicon line CD was decreased to 60nm and the AR increased to 3.8:1. This structure required further process advancement. The AspectClean™ with the standard nozzle at 60°, while damage free for the 70nm polysilicon lines, resulted in 7 damage sites on the 60nm polysilicon lines with a greater AR (see Figure 5). Modifications to the nozzle were required to achieve damage free cleaning and maintain a high PRE. A new nozzle was designed containing more holes with smaller diameters. The net effect is the generation of a cryogenic aerosol with a smaller average aerosol size compared to the aerosols generated with the standard nozzle (see Figure 2). Direct measurement of the cryogenic aerosol generated with the new nozzle has not been done, but based on theoretical work the trend to smaller average aerosol size is well substantiated [2, 3].

The benefit of a smaller average aerosol size generated with the new nozzle is confirmed by investigation of figure 5. The aerosols containing only nitrogen and processed with a 45° nozzle angle show damage. The damage is less than the standard nozzle, AspectClean™ process at 60° but PRE is similar for the three conditions.

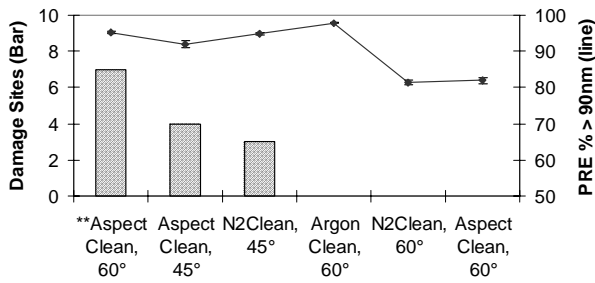


Figure 5. Damage (full wafer, 60nm polysilicon lines, AR 3.8:1) and PRE for aerosols with the standard and new nozzle at 45° and 60° nozzle angles. **The standard nozzle was used for this AspectClean™ process at 60°. All other processing was with the new nozzle.

Following the same procedure as the standard nozzle investigation in Figure 4, the nozzle angle was increased to 60°. Damage free cleaning was achieved not only with the N2Clean™ and AspectClean™ processes but also with the ArgonClean™ process. Based on the results with the standard nozzle, the performance of the ArgonClean™ process was unexpected. The level of PRE associated with the three damage free results is high considering the CD of the poly line structure. Especially interesting is the level of PRE obtained with the ArgonClean™ process.

Moving the damage evaluation one step further, a smaller CD poly line structure was evaluated. The CD of the polysilicon line structures, after the wet isotropic etch was 40nm. Additionally, PRE ≥ 65nm was measured with wet dipped Si₃N₄ contaminated wafers as described earlier (see Figure 6).

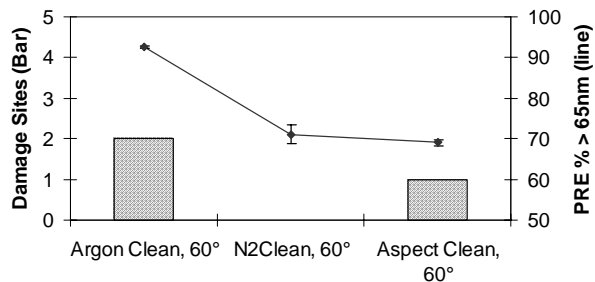


Figure 6. Damage (wafer pieces containing 40nm polysilicon, AR ~ 3.8:1) and PRE ≥ 65nm for cryogenic aerosols produced with the new nozzle at a 60° nozzle angle.

For the three process recipes, damage was either low or non-existent. The PRE trend is as expected with the ArgonClean™ process maintaining the highest level of PRE. Although there were a few damage events with the ArgonClean™ process there were none with the N2Clean™ proc-

ess. The AspectClean™ process had one damage event and a PRE ≥ 65nm similar to the N2Clean™ process. This one damage event is likely in the noise of the measurement with wafer pieces as the test vehicle. Full wafer analysis of the same polysilicon line structures is under way as a confirmation of the wafer piece data set.

Again, the number of wafer passes under the aerosol and the orientation of the poly line structure on the wafer relative to the aerosol were set to maximize the possibility of generating damage on the poly line structures. The low damage results indicate that under normal processing conditions (two pass and sensitive structures orientated parallel or at a glancing angle to the aerosol) damage will be less. This is verified by the inspection of the polysilicon line structures which contain polysilicon lines both perpendicular and parallel to the aerosol. Damage, in all cases, was located in structures perpendicular to the aerosol. No damage was observed with structures parallel to the aerosol. It is clear that not all wafers will have this same sensitive structure orientation as the wafers in this study but the angle of the structures relative to the aerosol can be optimized to eliminate damage without sacrificing PRE. Processing with two passes under the aerosol as opposed to four passes does not significantly affect PRE also. For example, at ≥ 65nm, the two pass recipe with the ArgonClean™ process and new nozzle at 60° has a PRE of 93.0% (Figure 6) while the four pass recipe has a PRE of 94.1%.

A summary of all the damage free process results is shown in Table 1 for each polysilicon line structure investigated. Additional data points for PRE ≥ 65nm are included in the table. Keep in mind the cryogenic aerosol processes remove particles without material etching or modification. For comparison, on the same 70nm polysilicon structures, a wet chemical SC1 dispense followed by an accelerated chemical mist resulted in ~0.05nm of oxide etching to achieve a PRE of ~80% at 60nm and no damage [14]. Without the SC1 chemical etching, the PRE drops by at least 10%. Combining a similar wet chemical, SC1 dispense (0.03nm oxide loss) followed by the AspectClean™ process increases PRE to 98% at ≥ 65nm [11].

Table 1. Damage free conditions for a four pass, poly line structures orientated perpendicular to the aerosol.

Poly CD	Nozzle, angle	Cryogenic Process	PRE% (2 pass)	
			≥90nm	≥65nm
70nm	Standard nozzle, 60°	AspectClean™	96 ± 1	88.8 ± 0.7
60nm	new nozzle, 60°	ArgonClean™	97.8 ± 0.1	92.6 ± 0.4
		N2Clean™	84 ± 1	71 ± 2
		AspectClean™	81.9 ± 0.9	69.1 ± 0.8
40nm	new nozzle, 60°	N2Clean™	84 ± 1	71 ± 2
		*AspectClean™	81.9 ± 0.9	69.1 ± 0.8

*1 damage site on wafer piece. Full wafer analysis is underway.

SUMMARY

Three cryogenic aerosol process recipes are available for high PRE and damage free cleaning. The performance of the cryogenic aerosols can be maximized with the correct nozzle choice and angle. With the standard nozzle, damage free processing is possible with the AspectClean™ process and a 60° nozzle angle for polysilicon lines with a CD of 70nm. Processing with the new nozzle results in an aerosol with a smaller average size and lower momentum than an aerosol generated with the standard nozzle. Experimental results confirm damage free cleaning on the 60nm polysilicon structures with the ArgonClean™, N2Clean™ and AspectClean™ processes. PRE is maintained at a high level for all aerosol recipes with the new nozzle. Damage free cleaning was also observed on polysilicon lines with a CD of 40nm. Work continues on process optimization to maximize PRE and damage performance with the cryogenic aerosols.

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