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Non-Damaging Particle Removal Using Cryogenic Aerosols

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Introduction

Removing particles in both the FEOL and BEOL is becoming more challenging. For FEOL cleans, the 2003 ITRS roadmap [1] calls for less than 0.5 Angstrom material loss for the 65nm technology node and beyond. To achieve this material loss goal, more dilute and reduced temperature chemistries are being implemented. To minimize the drop in particle removal efficiency (PRE), energetic particle removal techniques such as megasonics and/or atomized spray may be utilized. However, care must be taken to prevent structure damage. Shrinking features in the BEOL, along with the incorporation of low-k materials, provide additional challenges. One is not only concerned with structure damage, but also moisture absorption, chemical reactions, and the removal of particles from phobic surfaces.

Cryogenic aerosols have been used to increase manufacturing yield of integrated circuits for nearly a decade [2-6]. The benign characteristics of this all-dry process makes for straightforward insertion into any process flow requiring the removal of particle defects. These characteristics include no charging [7], no water marks, no scratching, no chemicals and no material loss [8], addressing many of the challenges addressed above. In addition, recent studies show that cryogenic aerosols have superior PRE from phobic surfaces when compared to conventional wet cleans [7]. In this paper we show that cryogenic aerosols can be tuned to prevent damage to sensitive patterns.

Cryogenic Aerosols

The cryogenic aerosol process [2, 9] is summarized in Figure 1. Argon and/or Nitrogen gases are pre-cooled to form a liquid/gas mixture, delivered to the nozzle, and expanded into the vacuum chamber. The liquid droplets freeze, through evaporative cooling, prior to impact with the wafer surface. The solid cryogenic aerosols dislodge surface contaminates before sublimating. Particles entrained in the gas flow are removed from the chamber via a vacuum pump.

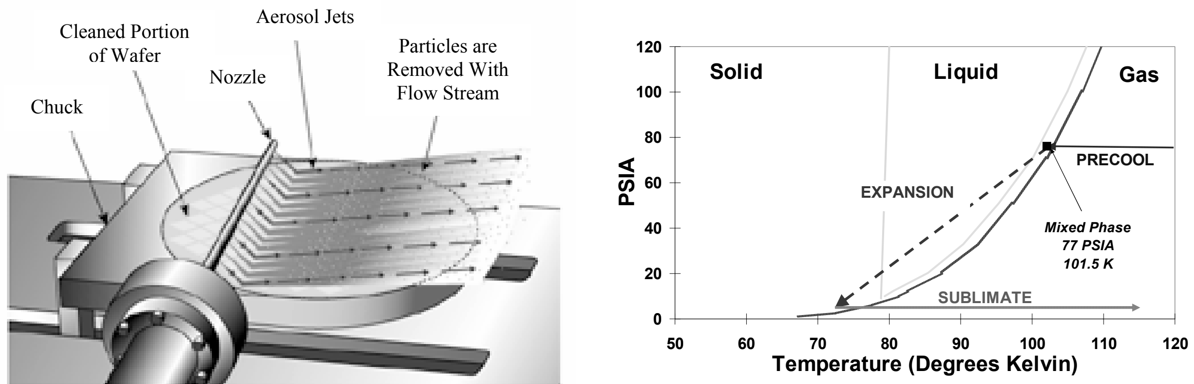

Figure 1: Sketch of cryogenic chamber layout (left panel) and phase diagram for a 3:1 ratio of $Ar:N_2$ cryogenic aerosol process (right panel).

The properties of the cryogenic aerosols are best controlled via the $Ar:N_2$ gas ratio, the vacuum chamber pressure, and the gas to liquid ratio delivered to the nozzle. Lower chamber pressures result in smaller cryogenic aerosols, as shown for an all nitrogen process at 300 Torr (Figure 2a)

and 50 Torr (Figure 2b). Data obtained by Phased Doppler Particle Analysis (PDPA), shown in Figure 2c, also show this trend of decreasing aerosol size with a decrease in chamber pressure. Note that a 3:1 Ar:N_2 ratio aerosol has a larger size than does an all nitrogen aerosol given the same process chamber pressure. Corresponding to this decrease in aerosol size is an increase in aerosol velocity as shown in Figure 2d. These smaller, faster cryogenic aerosols have been shown to increase particle removal efficiency, especially for smaller particles down to 65nm in size. Based on this knowledge, all processes discussed in this paper have a chamber pressure of 50 Torr.

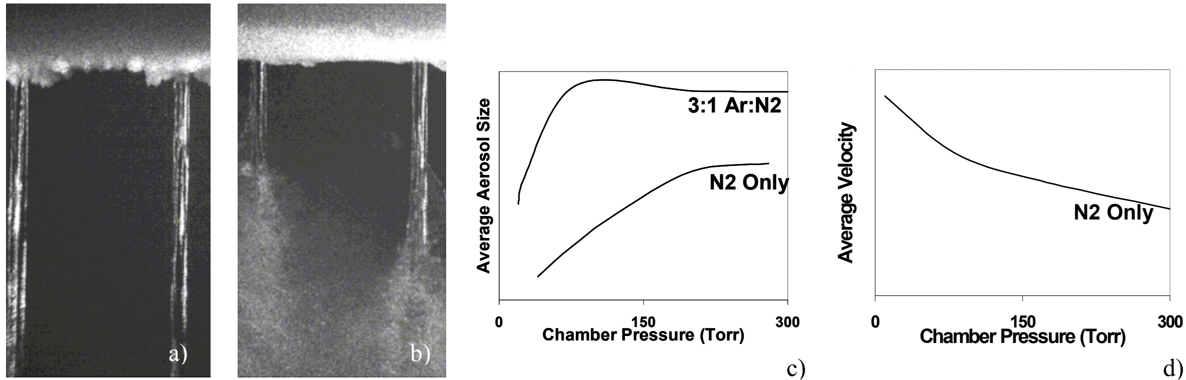

Figure 2: Photo of cryogenic aerosol formation for an all nitrogen process with a chamber pressure of 300 Torr (a) and 50 Torr (b). Summary of Phased Doppler Particle Analysis (PDPA) of cryogenic aerosol size (c) and velocity (d) as a function of chamber pressure.

In Figure 3, particle removal efficiency and aerosol aggressiveness is compared for four different aerosol processes. The ArgonClean™ process, with a 3:1 Ar:N_2 ratio, is the most aggressive process and recommended for planar surfaces. The ArgonClean process has a liquid fraction of 30% by weight. An all nitrogen process, called the NitrogenClean™ process, has a liquid fraction of 31%. The NitrogenClean process has a nominal drop in removal efficiency, but is able to clean less robust structures such as 200nm SiLK® trenches without damage. A more significant drop in aerosol aggressiveness is found by dropping the liquid fraction in the NitrogenClean process to 16%. This less aggressive process, called the AspectClean™ process, has successfully cleaned many sensitive structures without damage, including 160nm p-MSQ trench structures and 60nm polysilicon lines. For comparison purposes, a no liquid process is also shown in Figure 3. This process results in zero (0) PRE, demonstrating the importance of liquid in the generation of cryogenic aerosols that contribute to the removal of particles >65nm in size.

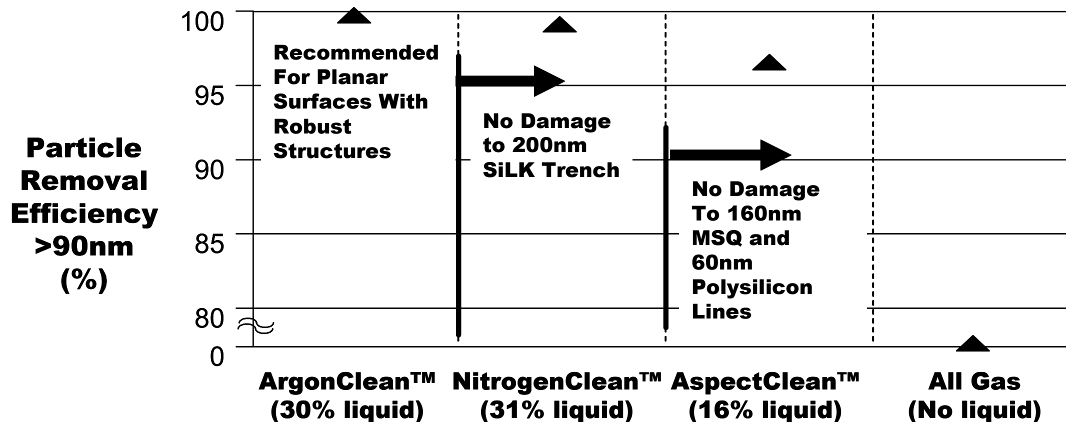

Figure 3: Comparison of particle removal efficiency and aerosol aggressiveness measured for four different cryogenic aerosol processes. Particle challenge is 1-day aged dry-deposited Si_3N_4 particles on bare silicon.

Comparison of Non-Damaging Particle Removal

The non-damaging AspectClean process is compared to a number of non-damaging wet-clean processes in the left panel of Figure 4. Non-damaging is characterized by no physical damage defects on 60nm wide by 230nm tall polysilicon test structures as summarized in the right panel of Figure 4. PRE is plotted as a function of oxide loss (A). The particle challenge is one day-old Si_3N_4 wet-deposited particles. The AspectClean process removes nearly 80% of the particles without etching any material. Interestingly, pretreating the challenge wafer with a spray APM process (including dry) increases the PRE to 98%.

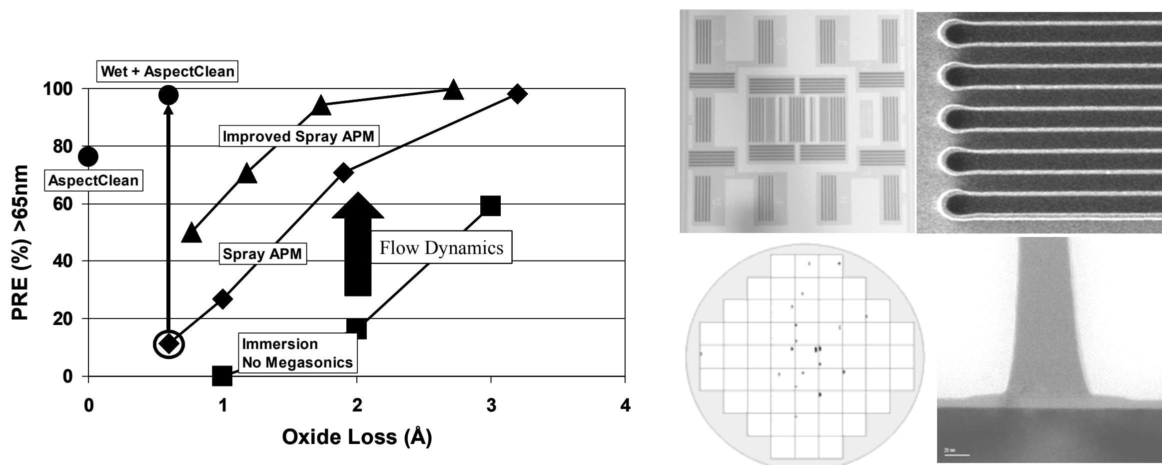

Figure 4: Left Panel - Comparison of multiple non-damaging clean processes; AspectClean process, spray APM + AspectClean process, improved spray APM, spray APM, and immersion without megasonics. Right Panel – Summary of damage assessment methodology; Clockwise, starting in upper left corner. Photo of 20x20mm die, SEM of 60x230nm polysilicon lines, TEM of 60nm polysilicon line, and characteristic automated full wafer defect scan.

Device Yield Results

Figure 5 shows the AspectClean process successfully applied to device wafers. The device wafers shown in Figure 6 have 110nm wide polysilicon lines with no spacers. The lines are 180nm thick, with a minimum separation distance of 250nm. A patterned wafer defect scan shows that the wafer processed with the ArgonClean process has 1037 defects, with ~900 due to pattern collapse. With the AspectClean process, only 170 defects are observed, with none due to pattern collapse. In both cases, the ~150 remaining defects are 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 is observed with the ArgonClean process.

Cryogenic aerosol splits were conducted on both 180 and 130nm node logic devices at an IC manufacturing site. Patterned wafer defectivity analysis was performed, including measurements for pattern damage. By appropriately applying the AspectClean process for sensitive structures, no pattern damage was observed in any of the splits. Six different splits were performed, resulting in final yield increases as high as 12.9% [6]. Representative FEOL cleans included post-deposition or post-etch process steps. Representative BEOL cleans included post-etch, post-CMP, and post-deposition.

Summary

Cryogenic aerosol processing is inert and non-etching and can be controlled to be non-damaging. It has excellent PRE, and has been shown to be particularly advantageous for hydrophobic surfaces. Processes with varying aggressiveness have been developed to successfully clean, without damage, substrates ranging from planar to those with fine gate or damascene structures.

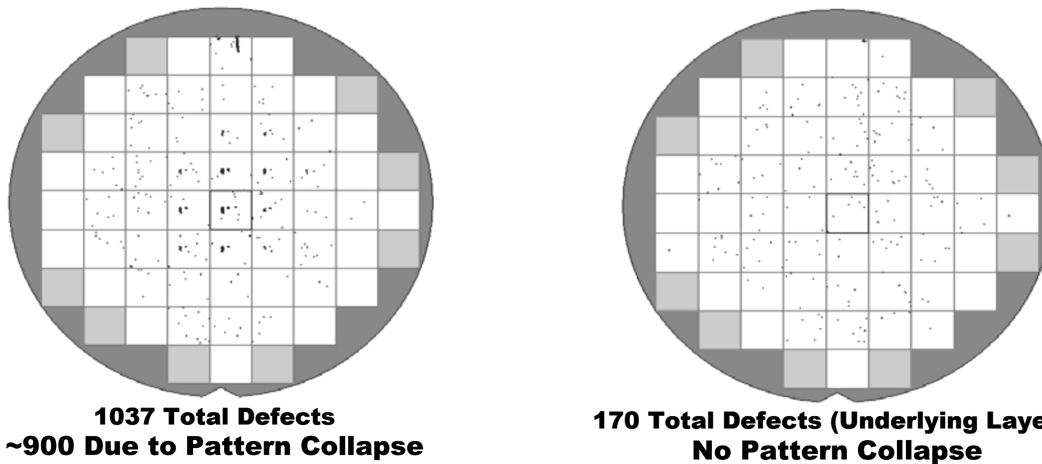

Figure 5: Defect maps for wafers with exposed 110nm width poly gate structures (without spacers). The wafer in the left panel was processed with the ArgonClean process, while the wafer in the right panel was processed with the AspectClean process. Wafers processed with the AspectClean process showed no pattern collapse defects.

References

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