Removal of 10-nm contaminant particles from a wafer surface with supersonic CO_2 particle beam

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ABSTRACT

Contaminant control is becoming a major issue of nano-scale device. Cryogenic aerosol beam using micron-sized aerosol particles has long been successfully used to remove contaminant particles (CPs) down to 50nm, and supersonic particle beam using particles smaller than 100nm lowered the limit of cleaning down to 20nm size.

In this study, the supersonic particle beam technique that uses nanometer-sized bullet particles moving at supersonic velocity was improved and successfully used to remove 10-nm CPs. Nanometer-sized bullet particles were generated by gas phase nucleation and growth using CO_2/He. Cleaning performance for 10nm contaminant particle was sensitive to the combined condition of the beam particle size and velocity. The velocity of the nano-bullets was the most important factor for the removal efficiency of CPs, and the use of light carrier gas was very effective in increasing particle velocity. Also, the cleaning performance is closely related with chamber pressure, improving at a lower chamber pressure. The best cleaning efficiency was about 95% for 10nm Al_2O_3 particle, which was the best performance reported to date.

Keywords: nano-bullet, CO_2, supersonic nozzle, gas-phase nucleation, cleaning efficiency

1 INTRODUCTION

Particle contamination seriously affects the manufacturing yield of submicron scale devices. Device feature for DRAM/flash memory is expected to decrease continuously, reaching 25nm by 2015, and together with it the critical defect size to decrease to 12.5nm by 2015 [1]. Various nanotechnology based devices with feature dimensions in the nanometer size range will also be marketed in due time, which may accelerate the decrease of the required killer defect size. Since the use of drag force becomes less efficient as the contaminant size decreases, it is generally agreed that conventional techniques should work poorly for submicron particles, and state-of-the art of various cleaning technique stays around 50-90nm.[2, 3]

One promising technique applicable in the nanometer range is the cryogenic aerosol technique, where contaminated surface is bombarded by fine particles of volatile material at high velocity. Contaminant particles adhered on a surface can be removed when the energy transferred from the bullet particles is sufficient to overcome the adhesion energy between the contaminant and substrate. Lee et al.[4] showed that Argon bullet particles could remove contaminant particles effectively, and other studies reported the applicability of Argon aerosol technique to nano contaminant cleaning. Argon, nitrogen, carbon dioxide and water are the most common cleaning agents used, and each offers advantages and disadvantages over the others. In current technology gas is expanded through a simple nozzle like a cylindrical hole. During the cooling process part of the gas becomes liquid, and the nozzle expansion atomizes the liquid into fine droplets. Solidification follows through further expansion. Typical particle size generated in this way is a few microns and the velocity about 100m/s, which is effective for cleaning down to 50nm but cleaning efficiency drops very rapidly for smaller particles thereof.[5,6]

Recently, Yi et al.[7] showed by MD simulation that far smaller bullet particles have to be used for removing nano-sized contaminants. Removal efficiency for nano-sized contaminants depended more on the velocity of the bullet particle, and concluded that even at the same kinetic energy level a smaller particle moving at a higher velocity should give a better removal. It was also shown that when the bullet particle was too big compared to the target contaminant, by a factor of 10 or more, the fragmented atoms/molecules of the bullet particle after collision may even surround the contaminant particle, preventing it from leaving the surface. Thus the use of smaller bullets moving at high velocities is expected to have extra advantages in cleaning narrow trenches and in reducing the damage potential. Lee et al.[4, 8] succeeded in removing 20nm ceramic and metal particles using bullet particles of 100nm or smaller diameter.

This study aims to explore the possibility of using the same bullet particles smaller than 100nm for removing nano-sized contaminants down to 10nm. CO_2 particles were generated by homogeneous nucleation and growth during supersonic expansion through a Laval nozzle. Particle size and velocity were varied by varying the nozzle contour, gas composition, and stagnation pressure. Cleaning experiments were done for a flat surface contaminated with a variety of particles of size down to 10nm.

2 EXPERIMENT

The experimental system is schematically shown in Fig.1. At room temperature and atmospheric pressure, gas phase CO_2 was used. A condensable gas mixture expanded through a supersonic Laval nozzle and sublimates directly to solid in a vacuum. During supersonic expansion through the nozzle, tiny condensation nuclei form and grow; their final size can be controlled by adjusting the stagnation pressure, the back pressure of the vacuum chamber, and the nozzle geometry. The nano-bullets formed entirely by homogeneous nucleation and growth downstream of the nozzle throat. Nucleation onset point and growth rate were controlled by adjusting the nozzle contour and stagnation conditions.

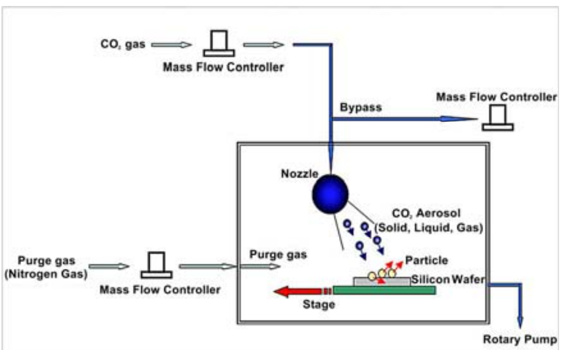

Figure 1: Schematic of the experimental setup.

To generate nano-bullets travelling at supersonic velocity, CO_2/He mixture gas was used. Stagnation pressure was varied in the range 1~50 bar; stagnation temperature was kept at room temperature. The shape and size of the nozzle were adjusted to make Mach number at the nozzle exit > 5.0 over the whole range of experimental conditions. The nozzle is nearly conical at the throat but rapidly expands near the exit to compensate for boundary layer growth and to prevent shock-wave formation.

Silicon wafers coated with Al_2O_3 particles were exposed to the bullet particle beam for variable period of time up to 2-3minutes. Size of the contaminant particles was in the range of 5~80nm. Particles were dispersed in alcohol using an ultrasonic stirrer, and then dripped and spin-coated on a Si wafer. Coated wafers were dried with dry N_2 gas flowing for 1-7 days. SEM pictures of the wafer surfaces were taken before and after cleaning. Distance between the nozzle and the wafer and the angle of the particle beam were variable. Chamber pressure was also varied to guarantee a supersonic flow in the range of 1~200torr.

2.1 Cleaning with CO_2/He

First, the size of the generated CO_2 nano-bullets was determined by using atomic force microscopy (AFM) to measure dents formed in a photo resist (PR) film on a wafer when bombarded by the nano-bullets. The hardness of the PR film was controlled so the nano-bullets could make dents of size comparable to the bullet size. The nano-bullets generated by homogeneous nucleation and growth of pure CO_2 gas at moderate pressures formed dents of only 10~50 nm (Fig. 2). Compared to previous studied based on atomization technique, nano-bullets generated in this study were smaller and had a narrow size distribution. Size of the nano-bullets used in this study is on the same order of magnitude as that of the CPs.

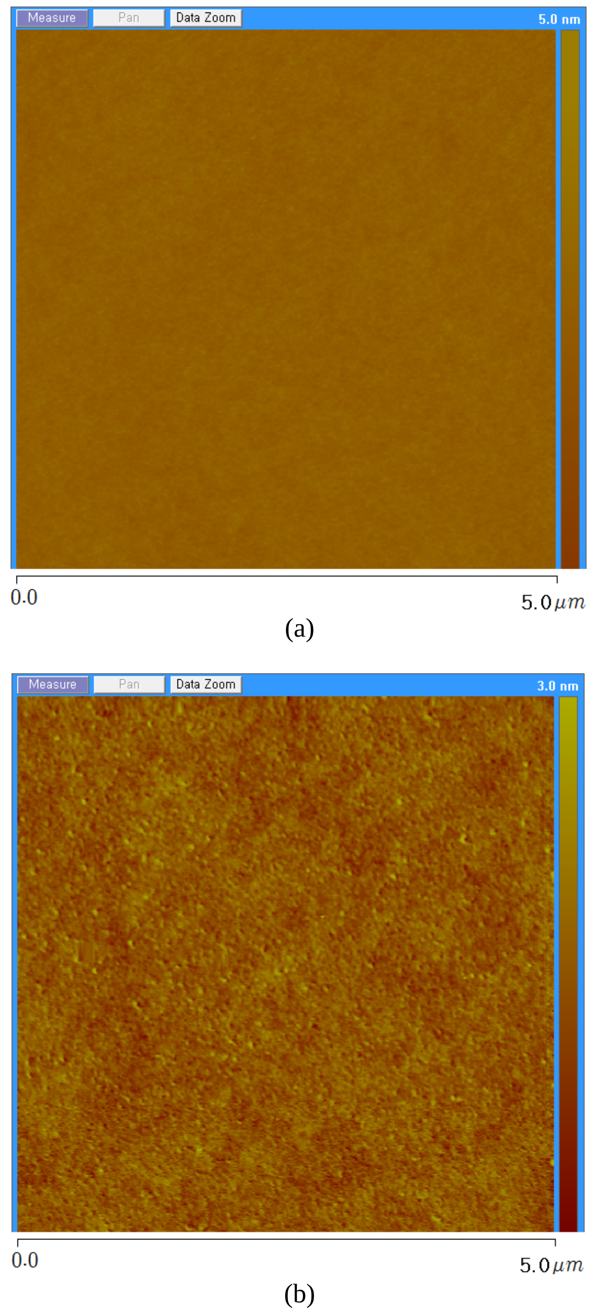

Figure 2: AFM images before (a) and after (b) image of dents on a photo resist film made by nano-particles generated by nucleation and growth with pure CO_2.

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Removal was tried with 10-nm Al_2O_3 contaminant particle on a flat silicon wafer (Fig. 3a), where nano-bullets were generated with CO_2/He mixture gas at different pressure of 1 ~ 50 bar. No CPs were removed at 10 bar (Fig. 3b), but removal was partially observed at 20bar (Fig. 3c), and substantial removal was attained at 30~40 bar (Fig. 3d-e). But, 10-nm Al_2O_3 particle were not perfectly cleaned. When pressure was increased to 50bar, almost all 10-nm CPs were perfectly removed (Fig. 3f). These results imply that the size and velocity of the nano-bullets are the most important factor contributing to removal of nanometer-sized CPs from a substrate by collision with volatile nano-bullet. Also, damage to the substrate is much less than by micron-bullets, because damage is proportional to the total kinetic energy of each bullet particle.

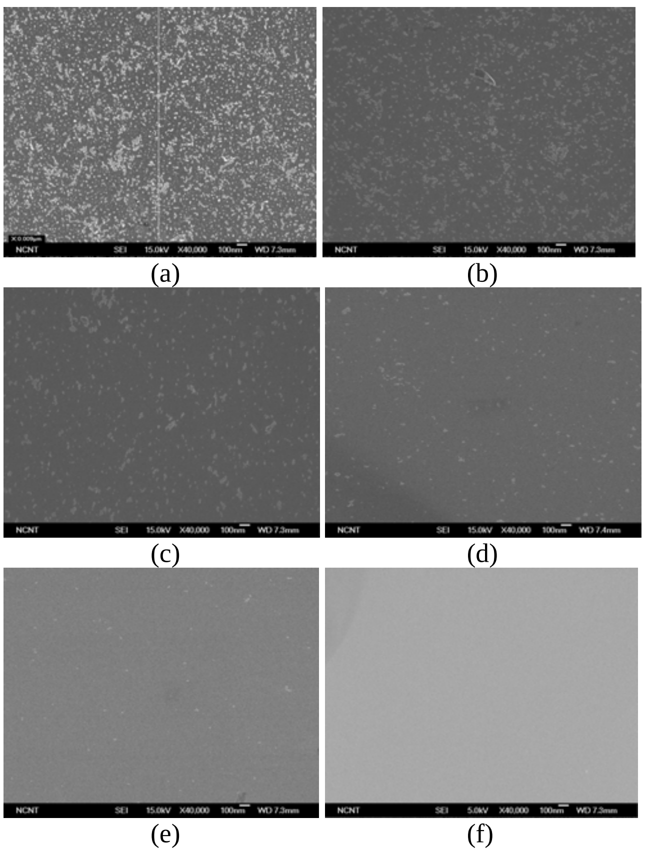

Figure 3: SEM images before (a) and after at (b) 10bar, (c) 20bar, (d) 30bar, (e) 40bar, and (f) 50bar cleaning of 10nm Al_2O_3 particle using 1:9 CO_2/He nano-particles.

2.2 Effect of Chamber Pressure

The cleaning performance is closely related with chamber pressure (back pressure). To confirm the interrelation between cleaning performance and chamber pressure, cleaning was done at different background pressure. The cleaning performance was degraded with increase in chamber pressure (Fig. 4), which can be attributed to the insufficient expansion or acceleration at high chamber pressure conditions.

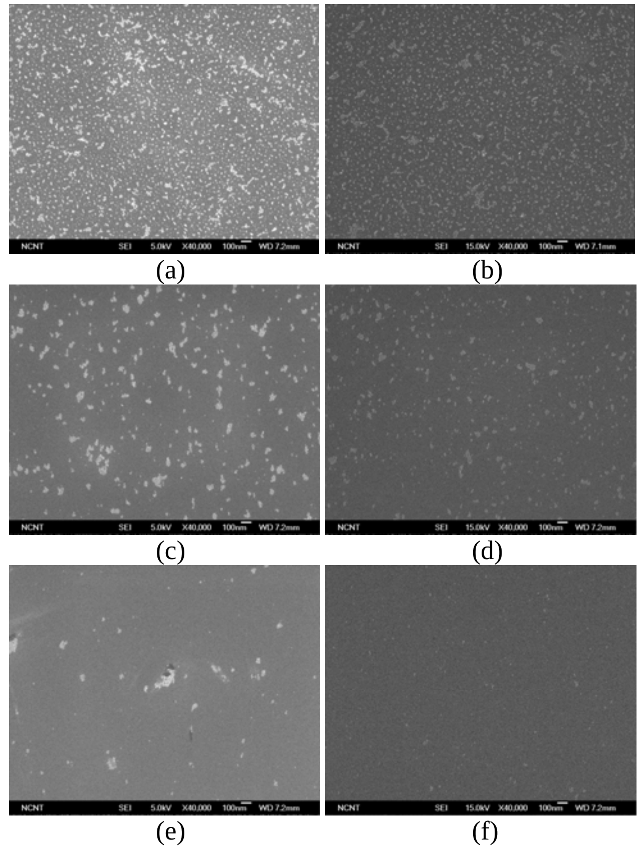

Figure 4: SEM images after cleaning of 10nm Al_2O_3 particles on Si surface using pure CO_2 at different chamber pressure(P_c): (a) P_c=3.7torr at 10bar, (b) P_c=0.37torr at 10bar, (c) P_c=8.4torr at 30bar, (d) P_c=0.84torr at 30bar, and (e) P_c=11torr at 50bar, (f) P_c=1.1torr at 50bar.

3 CONCLUSIONS

Nano-particles on a flat surface were cleaned by bombardment with supersonic CO_2 particle beam. Particle beams were generated by supersonic expansion through contoured Laval nozzles, such that the final particle velocity was in the supersonic range. By controlling the nozzle contour and expansion pressure, CO_2 bullets of 1 ~ 100nm size were generated by gas-phase nucleation and growth. The cleaning efficiency was almost perfect for various ceramic particles down to 10nm, which was attributed mostly to the small size and increased velocity of the bullet particles. Cleaning performance increased with decreased chamber pressure.

4 ACKNOWLEDGMENT

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