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Cleaning Technique Using High-Speed Steam-Water Mixed Spray

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Introduction

A novel cleaning technique using steam-water mixed spray is proposed. Relatively low-pressure super-purified steam (0.1 MPa - 0.2 MPa) is mixed with super-purified water in a nozzle, and then sprayed on a silicon wafer surface, which is located at approximately 10 mm from the nozzle. The most striking result of this proposed technique is that we are able to clean a wafer surface, i.e., to eliminate fine particles, *without using any chemicals*.

We investigated the cleaning performance of the proposed technique, and confirm the validity and usefulness. We arrived at the idea that water droplet impact in steam is enormously larger than that in air since the droplet kinetic energy reduction in steam is much less than that in air, mainly due to condensation. For this reason, we numerically studied the dynamics of a water droplet impact on a water thin film on a solid surface. We discuss both generation and propagation of the shock wave, which plays a significant role in cleaning, inside both water droplet and water thin film upon the impact.

Experimental study

Apparatus and procedure Super-purified steam and super-purified water are mixed in a nozzle. This mixture is accelerated in a converging-diverging nozzle and sprayed on a silicon wafer surface. The steam is generated by an electrical heating of super-purified water and stored in a pressure tank. The steam pressure and water flow rate range from 0.05 MPa to 0.2 MPa and from 100 mL/min to 500 mL/min, respectively. The distance between the nozzle and the silicon wafer surface is set as 10 mm. A schematic diagram of the experimental apparatus is shown in Figure1.

The basic cleaning performance of this proposed cleaning technique was evaluated by measuring the degree of particle contamination of both before and after this cleaning technique application, using particle counter (KLA-Tencor SP1). We used particle removal efficiency (PRE) as the index of cleaning performance.

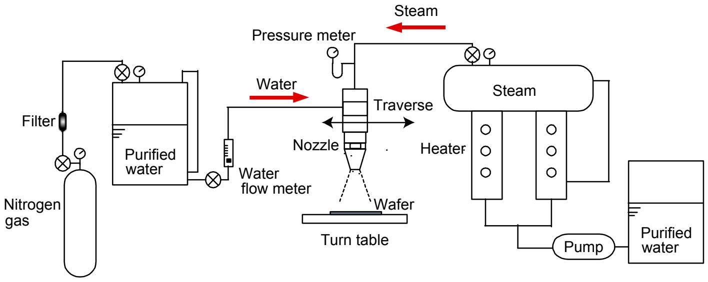

Figure 1: Schematic of experimental setup.

Experimental results. We applied the proposed cleaning technique on wafers coated with various diameters of latex particles in order to evaluate the cleaning performance. We found that particle removal efficiency (PRE) of this technique depends on the particle diameter, and results are shown in Figure 2 (a).More than 95 % of particles with diameter of more than 130 nm were successfully removed, while only 60 % of particles were removed when their diameters were approximately 100 nm, as shown in Figure 2(a).

We further examined the effect of the process time on the cleaning particles with diameters of approximately 100 nm. Results are shown in Figure 2(b). We found that PRE increased with the increase in process time, and that the proposed cleaning technique proved the excellent performance in removal of 100 nm particles

We also found that the proposed technique shows great performance in cleaning some other objects, such as post CMP cleaning. Microscopic photos of the post CPM cleaning surface both before and after the proposed cleaning technique was applied are shown in Figure 2(c). It is understood that the proposed technique successfully removes particles of very fine scale without any chemicals.

We also confirmed that the present cleaning technique causes harsh erosion on the metal surface [1]. This experimental results lead us to strongly believe that physical/ mechanical processes are more likely dominant in this cleaning technique; hence we investigate the pressure generation due to the water droplet impact and pressure wave propagation thereafter in the next section by using numerical analysis. It should be added that the application of the present cleaning technique on the photo-resist stripping process results in the extraordinary success, as explained in detail [2].

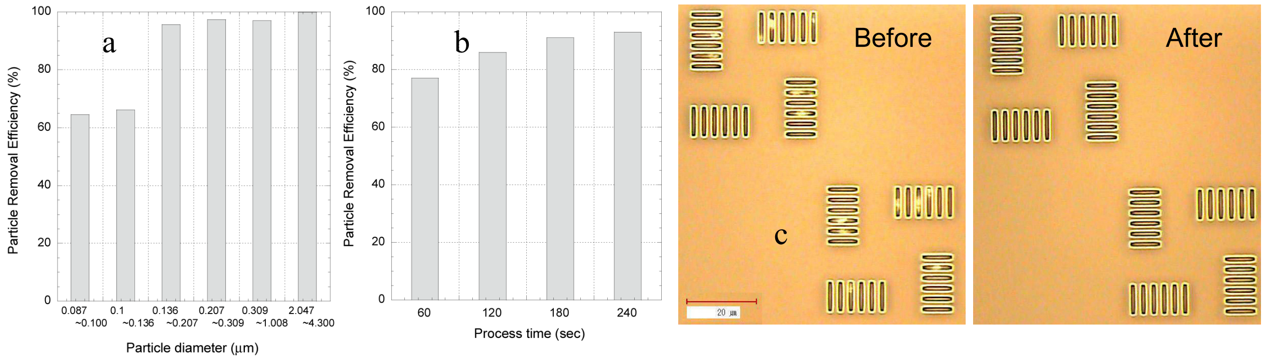

Figure 2: Cleaning performance: a) Particle removal efficiency, b) Effects of process time on PRE, c) Examples of post CMP cleaning

Numerical study

Model and assumption. The most characteristic feature of the present technique is that water droplets are sprayed in steam atmosphere, not in air. This difference in the surrounding gas atmosphere causes the huge difference in the cleaning performance. As we have already reported [3], there are no significant difference in both droplet velocities and droplet diameter distribution between steam-water mixture spray and air-water mixture spray, measured at the downstream of the nozzle outlet, i.e., in the macroscopic scale; hence the most important phenomena dominating this cleaning technique should occure in the microscopic scale either on or in the close vicinity of the solid surface, i.e., wafer.

Although the detailed physical/chemical mechanisms are not yet fully understood, we assume that condensation is the most important key factor, especially both *condensation on the droplet* and *condensation on the solid surface*. The viscous energy dissipation in air, in general, causes tremendously huge velocity decrease of high speed droplet in the case of air-water spray. Especially air trapped between impacting droplet and the solid surface acts as if it were cushion: hence the droplet impact velocity should be drastically decreased. On the other hand, in the case of steam-water spray remarkable decrease in the vapor volume due to the condensation is assumed to reduce the velocity decrease: hence water droplet impacts on the surface with maintaining the relatively high velocity. Furthermore, more uniform and thiner water film is expected to exist in steam-water spray than in air-water spray: hence water droplet impacts more likely on the thin water film rather than the solid surface. With these assumption stated above, we numerically study the high speed droplet impact on the thin water film.

We assume that the kinetic energy dissipation in steam is so small that we use the characteristic water droplet velocity, i.e., 200 m/s, which was obtained by experiment [3] as the droplet impact velocity in the calculation. We also used the experimentally obtained characteristic droplet diameter, i.e., 20 µm as the droplet diameter. We simply assumed the water film thickness is 2.5 µm. The impact of water droplet with this magnitude of velocity, i.e., sufficiently large kinetic energy, causes significantly large compression pressure wave, i.e., shock wave, inside both water layer on the solid surface and droplet.. It is well known that the shock wave propagation inside water extremely contributes to the cleaning process, as shown in laser cleaning process [4, 5]. We study the pressure wave generation and propagation inside liquid phase. We study the flow field of a water droplet impacting on a solid surface by solving the Euler equation [6, 7] for a two-phase compressible fluid in the plane using a Cartesian two-dimensional coordinates system. The level-set method combined with the ghost-fluid method [8] with 3rd-order ENO-LLF is used; the 3rd-order TVD Runge-Kutta scheme [7] is also used for time integration.

Numerical results We calculated the flow field with droplet diameter of 20 µm and velocity of 200 m/s impacting on water film of 2.5 µm on the solid surface. Time evolution of the pressure field distribution inside both water film and droplet is shown in Figure 3. Although the maximum and minimum pressure observed in this calculation are -50 MPa and 250 MPa, respectively, the pressure range between -20 MPa and 100 MPa are plotted for the enhancement of pressure wave propagation. As a water droplet impacts on water film, the strong shock wave, which is shown by dark gray in Figure 3, is generated at the impact point and propagates inside both film and droplet. The shock wave propagating downward inside film reaches the solid surface, and then reflects as the shock wave with much enhanced magnitude. This reflected shock wave propagates upward and reaches film free surface and then is reflected to become the rarefaction wave.

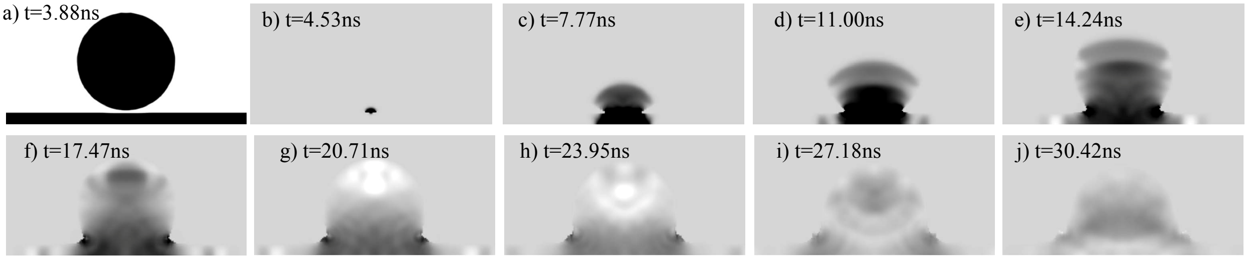

Figure 1: Numerical results: a) Shape of droplet and water film just before impact, b)-j) Time evolution of pressure distribution inside both water droplet and thin film on a solid surface.

As easily explained in terms of the acoustic impedance [9], a compression pressure wave reflected at the free surface turns over to be an expansion pressure wave and the magnitude of a reflection pressure wave of a compression pressure wave is enhanced at the solid surface. On the other hand, the shock wave propagating upward inside droplet is also reflected on to the free surface to become the rarefaction wave; this qualitatively agrees with results of Haller, et.al. [6]

It is observed that both shock and rarefaction waves propagate inside both water thin film and water droplet alternatively. The time evolution of pressure on the solid surface at the point just below the impact point is plotted in Figure 4, with those measured apart from this point with *h*=5.1 µm, 10.1 µm, 15.2 µm. The most striking characteristic nature of this calculation result is the both the strong shock and strong rarefaction waves propagate on the solid surface away from the point just below the impact. We strongly believe this alternating generation of shock and rarefaction waves affect severely on the particle, and play a significant role in the proposed cleaning technique.

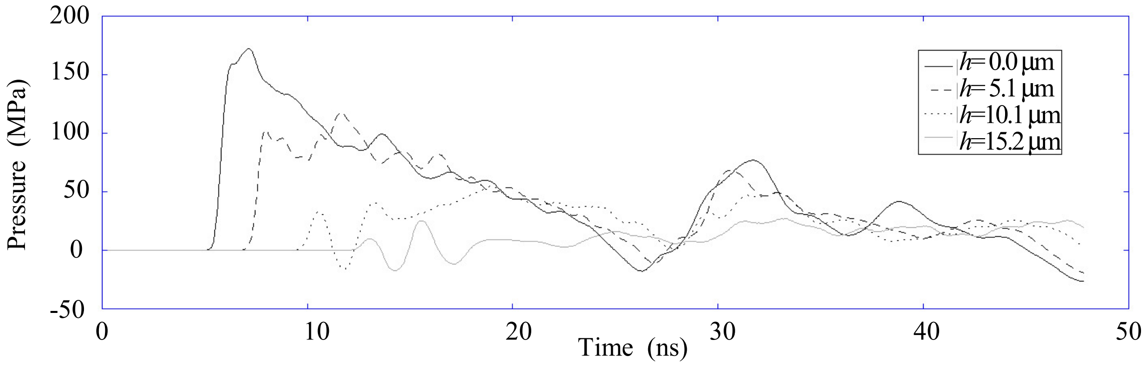

Figure 4: Time evolution of pressure at various points on the solid surface: just below the impact point (on the water droplet line (h=0.0 μm)), and *h*=5.1 μm, 10.1 μm and 15.2 μm from this point.

Summary

We have developed a novel cleaning technique using a high-speed mixture of steam and purified water droplets. It is experimentally demonstrated this proposed technique remove fine particles, without any chemicals.

We also numerically studied the alternating generation of shock and rarefaction pressure waves propagating inside both water droplet and water thin film on the solid surface, during water droplet impact, which plays a significant role in the proposed cleaning technique in particle removal.

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References

[1] T. Sanada, M.Watanabe, M. Shirota, Masao Yamaser and T.Saito: Fluid. Dyn. Res. **40** (2008), p. 627-636.

[2] T. Sanada, M.Watanabe, A. Hayashida and Y. Isago: Proc. 9th Int. Symp. UCPSS (2008).

[3] T. Sanada, M. Shirota, M. Watanabe, Y. Morita and M. Yamase, M.: FEDSM2007-37129, (2007),.

[4] A.C. Tam, W.P. Leung, W. Zapka and W. Ziemlich: J. Appl. Phys. **71**(7) (1992) 3515-3523.

[5] J.M.Lee and K.G. Watkins: J. Appl. Phys., **89**(11) (2001), 6496-6500.

[6] K.K. Haller, Y. Ventikos and D. Poulikakos: J. Appl. Phys., **93**(5) (2003), 3090-3097.

[7] A. Harten: J. Comput. Phys., **71** (1987), 231-303.

[8] R. Fedkiw, T. Aslam, B. Merriman and S. Osher: J. Comput. Phys., **152**, (1999), 457-4-92.

[9] J. Lighthill: *Waves in Fluids* (Cambridge, Great Britain, 1978).

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