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SPRAY SYSTEMS FOR CLEANING DURING SEMICONDUCTOR MANUFACTURING

Kurt Wostyn*, Masayuki Wada°, Ken-Ichi Sano°, Michael Andreas+, Tom Janssens*, Twan Bearda*,
Leonardus Leunissen* and Paul Mertens*

* IMEC vzw, Kapeldreef 75, 3001 Leuven, Belgium
° Dainippon Screen Mfg Co Ltd, 2426-1, Mikami, Yasu, Shiga 520-2323, Japan
+ Micron Technology Inc, 8000 S. Federal Way, Boise, Idaho, 83707, USA

ABSTRACT
Contamination, e.g. metallic residues or particles, can have a detrimental impact on transistor performance and needs to be removed during semiconductor manufacturing in order to obtain high yields. As a result cleaning is one of the most frequently applied steps during chip manufacturing. As transistor dimensions shrink they also become more vulnerable to forces applied onto them during cleaning, possibly leading to damage formation. The goal is then also to develop a cleaning technique that shows a high particle removal efficiency without adding damage. Here we show that spray cleaning is a very promising cleaning technique to remove particles with minimal damage addition. In order to optimize spray cleaning for future technology nodes a better understanding of the cleaning and damage addition mechanisms is needed. Here, based on available literature and approximate extensions, we describe the spray cleaning process from spray formation to spray impact leading to particle removal and damage addition. Droplets impacting onto a surface give rise to the formation of a shock wave, followed by lateral jetting. Droplet impact in a shallow pool gives rise to the formation of a crown. Using an approximate description, we link these processes with the spray characteristics, indicating a combination of the droplet size and speed could be important for particle removal and damage formation.

INTRODUCTION

Transistor performance and manufacturing yield is, among others, influenced by three types of contamination: organic, metallic and particulate contamination. Chemical routes have been developed for the removal of all three types of contamination. In order to remove all particles approximately 3 nm of substrate needs to be etched [1]. With every new technology node the transistors have become smaller and smaller and the process window for the chemical removal of contamination gets smaller and smaller. The current chip fabrication schemes no longer allow for the removal of 3 nm of substrate and alternative particle removal techniques need to be considered.

Particulate contamination is removed by a combination of the right chemical mixture and the application of physical forces [2]. Several methods are available to develop the required physical forces to remove particulate contamination from the substrates. Megasonic cleaning generates cavities that, under the influence of a high-frequency sound field, can generate shock waves and liquid jets that can remove these particles [3]. These forces can also be generated by the impact of droplets. Spray cleaning for semiconductor manufacturing was introduced in 1997 [4].

The application of a force during semiconductor manufacturing also stresses the patterns present on the substrate. As IC manufacturing moved into sub-100 nm dimensions theses structure became sensitive to forces acting upon them, possibly leading to the addition of damage [5]. Spray cleaning shows promising results for efficient particle removal without damage addition [2, 6, 7]. In order to extend spray cleaning to future technology generations a better understanding of the cleaning mechanism should enhance the performance of spray cleaning.

In the experimental section of the paper some experimental results obtained using spray cleaning are shown and linked to the spray characteristics. In the following section an approximate description of droplet impact during spray cleaning is derived in order to relate the spray characteristics to its cleaning performance. These results are discussed and limitations are indicated.

EXPERIMENTAL

Materials and methods

Cleaning tests were performed on a single-wafer cleaning tool (DNS SU3000) equipped with a high-velocity-aerosol nozzle (Nanospray^{TM}). The nozzle is an air-assist nozzle where de-ionized water (DIW) is mixed with pressurized N_2 to obtain optimal atomization. A DIW flow of 100 ml/min is used and the N_2 flow was varied.

The test vehicles consisted of 300 mm wafers patterned with 20 nm to 65 nm wide gate stack lines, 160 nm high (2.4 nm SiON – 100 nm polycrystalline Si – 60 nm SiO_2). Defect sites were detected using a bright-field inspection tool (KLA-Tencor 2351). Map-to-map analysis has been used to determine the added defect sites (KLA-Tencor Klarity software).

The spray characteristics (droplet size and velocity) were measured using a LaVision PIV system.

Results

Figure 1 shows the particle removal efficiency for the Nanospray^{TM} nozzle as a function of the peak droplet velocity. Here we see that the particle removal efficiency increases with increasing peak droplet velocity. Starting from a peak droplet velocity of approximately 35 m/s damage is added to the patterns present on the substrate.

It has been observed that upon increasing the N_2 flow, i.e. an increase in the peak droplet velocity, a wider damage-length distribution is found, a shift to larger defects is seen, and more damage is added [7]. These changes are explained by an increase in the physical force due to droplet impact upon increasing the N_2 flow. Figure 2 shows a pictorial description of (spray) cleaning [8]. Spray cleaning gives rise to a certain force distribution (middle distribution, full line). In order to remove particles spray cleaning needs to apply forces exceeding the force with which the particles are attached to the substrate (left distribution, dotted line). In order to avoid the detrimental damage addition the cleaning distribution needs to apply forces lower that the yielding force for the fragile structures present on the wafer (right distribution, dashed line). The overlap between the different distributions corresponds, as indicated in Fig. 2, to either no or bad particle removal, and damage addition. Consequently, for optimal cleaning performance, the cleaning force distribution should be adjusted to fit the process window between particle removal and damage addition.

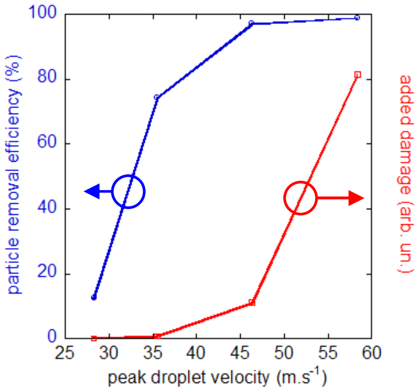

Figure 1: Particle removal efficiency and damage addition due to spray cleaning.

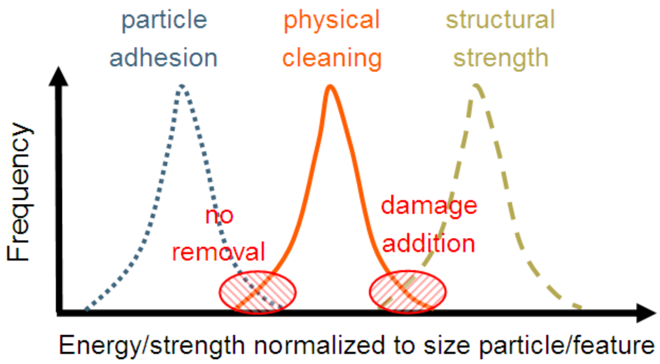

Figure 2: Cleaning strength distribution versus structural strength and particle adhesion.

In order to understand and improve spray cleaning the size, shape and position of the particle adhesion, cleaning force, and yielding force distributions need to be known. The particle adhesion and structural strength distributions are being measured using lateral-force AFM [9]. In order to determine the cleaning force distributions we need to know the relation between the spray characteristics, which can be measured, and the resulting impact on the substrate.

RELATION BETWEEN CLEANING PERFORMANCE AND SPRAY CHARACTERISTICS

Particle removal, but also damage formation, is caused by applying a force onto either the particles or fragile features present on the substrate. In order to understand spray cleaning we need to find a relation between the spray characteristics (droplet size and speed, angle of impact on the substrate ...) and their impact onto the substrate. Although no longer explicitly mentioned below, the mechanism for particle removal and damage addition are not necessarily the same.

Impact on a dry surface

In a first order approximation [4], spray cleaning can be explained based on the impact of droplets on a solid substrate. During the first phase of the impact liquid adjacent to the substrate is highly compressed, leaving the rest of the droplet undisturbed. These two regions are separated by a shock front which can approximately be described by the water-hammer pressure [10]:

$$p_{wh} = \rho s v \qquad (1)$$

ρ, v and s are respectively the liquid density, velocity of the droplet and the velocity of the shock wave. The shock velocity can be approximated by:

$$s = s_0 + kv \qquad (2)$$

s_0 for water is 1647 m/s and the proportionality factor k is approximately equal to 2. According to Eqs. 1 and 2, initially the impact of a water droplet on a dry surface only depends on the velocity of the droplet.

In a later stage of droplet impact on a dry surface the shock front detaches from the surface of the substrate resulting in sideways jetting [10]. The lateral jetting, which occurs when the shock front inside the droplet detaches from the solid substrate, has a speed approximately an order of magnitude larger than the impact speed [11, 12]. The impact of sideways jetting also only depends on the velocity of the droplet.

Although this is only a rude description, the model may indicate that droplet velocity is the most important parameter for spray cleaning.

Compressible flow: formation of shock wave

Spray cleaning consists of the impact of millions of droplets per second on the surface of the substrate. This is expected to lead to a thin liquid film on the substrate, softening the impact of the droplets. A liquid film thickness from 10 to 100 µm was measured during spray impact [13]. The preceding description of spray cleaning needs to be adapted to accommodate for the thin liquid layer present during spray cleaning. To describe droplet impact during spray cleaning droplet impact on a thin liquid film has been divided into two parts: 1. shock wave formation during droplet impact, dubbed compressible flow, and 2. crown formation after droplet impact, dubbed incompressible flow. The latter parts neglects this initial compressible stage and describes the dynamic pressure at the surface of the substrate as caused by crown formation. In the following two section we present how (using an approximate description) the droplet size and velocity can be linked to cleaning impact.

The impact of a spherical droplet onto a liquid surface will give rise to the formation of a shock wave [14, 15]. The initial shock wave is approximately equal to the water hammer pressure. As the impact proceeds, the shock wave is pinned at the droplet – surface contact line and reaches a maximum pressure of approximately two [16] to three times [14] the water hammer pressure (Eq. 1). At this stage, the shock wave detaches from the substrate allowing the compressed liquid to 'escape' and sideways jetting starts. All of this happens in a very short period in the order of 10^{-9}s [15]. The radius of the shock wave at which it detaches from the substrate is usually referred to as the critical radius and is approximately given by [15]:

$$r_c = \frac{d\,v}{2c} \qquad (3)$$

where c is the speed of sound in the water. After the impact, the shock wave has to travel across the liquid layer (thickness d_{pool}) to the liquid – substrate interface (see Fig. 3).

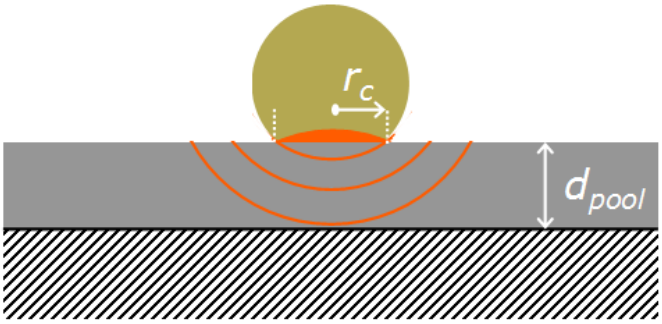

Figure 3: Expansion of the shock wave formed during droplet impact to the surface of the substrate.

In order to calculate the pressure at the surface due to the shock wave the following assumptions are taken into account:

1. Conservation of energy: This means that the shock wave does not lose strength due to viscosity or heat generation. The initial energy of the shock ($E=p\cdot V$) remains constant.
2. The size r_c of the contact area between the droplet and the liquid surface is small compared to the liquid layer thickness d_{pool}. The contact area between the droplet and the fluid surface can be assumed to be a point source and the shock wave spreads hemi-spherically
3. The shock wave thickness remains constant as the shock wave expands.
4. The liquid layer thickness d_{pool} remains constant during the formation of the shock wave.

This leads to the following expression for the pressure generated at the surface:

$$p_{surface} = \frac{3\,p_{wh}\,\pi r_c^2}{2\pi d_{pool}^2} = \frac{3\rho s v^3 d^2}{4c^2 d_{pool}^2} \qquad (4)$$

Equation 4 shows that the pressure of the shock wave at the surface of the substrate depends not only on the droplet velocity, but also on the droplet size, and on the liquid layer thickness. Figure 4a is a plot of the shock wave pressure developed as a function of the droplet size and velocity for a liquid layer thickness of 10µm.

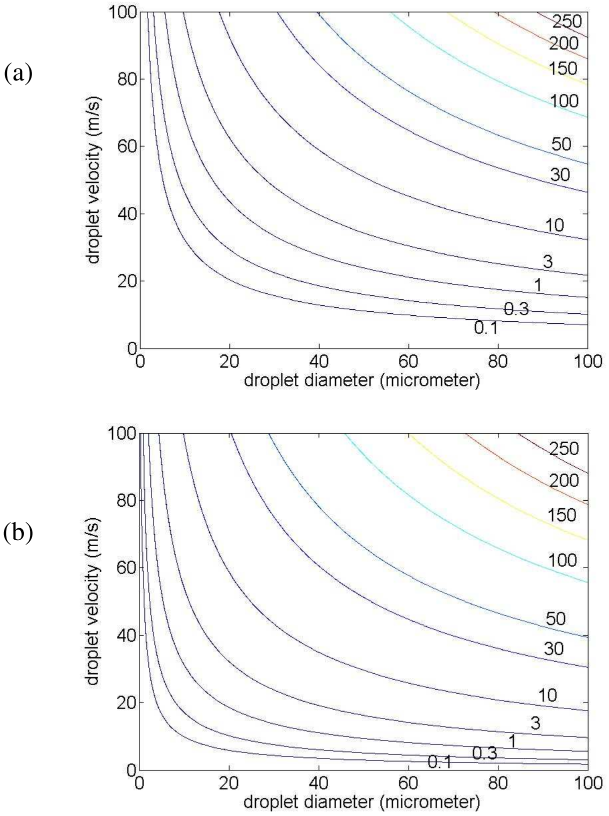

Figure 4: a. Pressure at the surface (in bar) due to the expansion of the shock wave as a function of droplet size and velocity for a liquid film thickness of 10 µm; and b. dynamic pressure (in bar) at the surface of the substrate during crown formation.

Some approximations can now be checked using values reported in literature. Droplet size and velocities up to 0-150 µm and 0-200 $m.s^{-1}$ were reported, the largest velocities mainly occurring for the smallest droplets and vice versa [17, 18]. The largest critical radii should typically be in the order of 1 µm. Liquid film thicknesses for spray nozzles have been reported to be in the range of 10-100µm [13, 15]. The critical radius is approx. or more than an order of magnitude smaller than the liquid layer thickness, supporting the approximation of considering the initial shock wave to be a point source and subsequently expanding hemi-spherically.

Incompressible flow: dynamic pressure at the surface during crown formation

The impact of a droplet into a liquid film can lead to the beautiful phenomenon of crown formation. A crater is formed with a water rim around it. The droplet impact does (almost) not disturb the water just outside this rim [19]. The evolution of the crater depth and width has been studied and described both theoretically and experimentally in literature [13, 15, 19]. For the theoretical descriptions the initial compressible stage, as described in the previous section, is neglected. The compressible and incompressible flow take place on different time scales and are not expected to influence each other [15]. An (approximate) analytical expression for the evolution of the crown radius r_{crown} (i.e. the position of the rim) as a function of time t is given by [15]:

$$r_{crown} = \left(\frac{2}{3}\right)^{\frac{1}{4}} \frac{v^{\frac{1}{2}} d^{\frac{3}{4}}}{d_{pool}^{\frac{1}{4}}} t^{\frac{1}{2}} \qquad (5)$$

As only the water adjacent to the water-air interface is disturbed during the crater formation process, the crown velocity v_{crown} may provide an estimate of the fluid velocity at the substrate surface when the crater depth is equal to the liquid pool thickness. The time at which the crater depth is equal to the liquid pool thickness is estimated by the time it would take for a droplet to travel a distance equal to the liquid pool thickness. Using Eq. 5, the dynamic pressure is then given by:

$$p_{dynamic} = \left[\rho\left(\frac{d\,r_{crown}}{dt}\right)^2 \Big/ 2\right]_{t=\frac{d_{pool}}{v}} = \frac{\rho v^2 d^{1.5}}{9.8\, d_{pool}^{1.5}} \qquad (6)$$

Figure 4b is a plot of the dynamic pressure developed as a function of the droplet size and velocity for a liquid layer thickness of 10μm.

Discussion

Although the pressure at the surface of the substrate still shows a higher dependency on the droplet velocity, Eqs. 4 and 6 indicate that in addition to droplet velocity, also droplet size and the thickness of the liquid layer are important parameters that determine the impact strength. It was already found before that the presence of even a very small liquid layer has a significant effect on droplet impact [19].

Figure 4 shows that for droplet impact on a 10 μm liquid film the dynamic pressure as predicted by Eq. 6 is higher than the pressure caused by the expansion of the shock wave (Eq. 4). The pressures at the substrate surface as predicted by Eqs. 4 and 6 can now be compared to the predicted pressures needed to remove particles or damage structures. In order to remove a particle by the drag forces acting on it, the surrounding liquid needs to have a minimum velocity of 52 $m.s^{-1}$ [20]. This corresponds to a minimum dynamic pressure of 13 bar for particle removal. Comparing Fig. 4 with the droplet size and velocity distributions available in literature [17, 18], the tail of the spray distribution would contribute to particle removal. Figure 4 is calculated for a film thickness of 10 μm. A more precise estimate for the liquid film thickness is needed to improve the comparison between the spray characteristics and the particle removal criterion. At least the comparison indicates that the surface pressures predicted by these approximate description is in the right order of magnitude.

Here we only considered droplet impact on an undisturbed liquid film. However, during spray cleaning the surface will be far from undisturbed [13]. This may indicate that locally the liquid layer thickness varies substantially from the 10-100 μm range. Especially for either big and/or fast droplets this may make a large difference.

Other possible links between cleaning performance and spray characteristics

An additional source of damage formation may be air bubbles in droplets. Several processes can entrain air bubbles. Air bubbles can be formed inside an impacting droplet [21] or air can be trapped between the impacting droplet and the thin liquid film when a droplet impacts an agitated liquid film [22]. Subsequent implosion of these air bubbles could lead to particle removal and/or damage formation. Cavitation, i.e. the formation, pulsation and implosion of air bubbles, has been linked to the removal of small particles and damage formation during megasonic (high-frequency ultrasound) cleaning [3].

Here we assumed both cleaning and damage addition during spray cleaning is due to the physical processes related to droplet impact in a shallow pool. As already briefly mentioned before particle removal and damage formation are not necessarily linked to the same phenomena. The impact of particles during spray cleaning could also induce damage. These particles can have two different sources: 1. particles present in the ultra pure water or chemicals used during cleaning [23] or 2. the particles present on the wafer that the cleaning step is supposed to remove.

CONCLUSION AND OUTLOOK

In this paper we determined the cleaning performance of an air-assisted nozzle. There is a process window for the removal of 78 nm large particles with minimal addition of damage to 20-65nm wide features, showing that spray cleaning is a promising technique for particle removal without the addition of damage. To link the cleaning performance of the nozzle to its spray characteristics, an approximate description is provided for droplet impact on thin liquid layer. The description shows that the cleaning performance depends on the droplet size and velocity; and on the thickness of the liquid layer on which the spray impacts. However we have also indicated that the cleaning efficiency, i.e. the particle removal efficiency and/or damage addition, may also be due to cavitation during droplet impact.

In order to further improve our understanding of the relation between the spray characteristics and its cleaning efficiency, it is important to be able to measure the liquid layer thickness during spray impact and understand how the thickness varies with varying spray conditions. Also the 'roughness' of the liquid layer thickness will be important as this will have a big impact on the strength of droplet impact.

Furthermore, in order to optimize spray cleaning it is not only important to know the relation between the spray characteristics and its impact on a surface, but also to understand the relation between nozzle designs and settings and their spray characteristics.

NOMENCLATURE

Symbol	Quantity	SI Unit
c	Speed of sound in water	m/s
d	Droplet size	m
d_{pool}	Liquid film thickness	m
E	Energy	J
k	Proportionality factor	-

p	Pressure	Pa
r_c	Critical radius	m
r_{crown}	Crown radius	m
s	Shock wave velocity	m/s
v	Droplet velocity	m/s
V	Volume	m^3
ρ	Density	kg/m^3

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