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Effect of Different Deposition Mediums on the Adhesion and Removal of Particles

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The purpose of this study is to investigate the effect of the different deposition mediums on the adhesion and removal of particles. Polystyrene latex (PSL) particles (50 μm) are deposited on thermal oxide and silicon nitride coated silicon wafers using different suspension mediums: air, isopropyl alcohol (IPA), and deionized water and then removed in a dry environment. The results show that PSL particles deposited on oxide are easier to remove than those on nitride due to a higher van der Waals force in all deposition mediums. In addition, dry particles deposited in air are much easier to remove than those deposited in a liquid medium. When particles are deposited from a liquid suspension, a liquid meniscus is formed between the particle and the substrate, resulting in a capillary force. The capillary force induces a plastic deformation for soft particles such as PSL, which increases the contact area between the particle and the substrate, making them more difficult to remove. The liquid meniscus evaporates shortly after it is exposed to either a dry air environment or vacuum; however, the plastic deformation of particles would take place mainly due to the initial adhesion force in addition to the short time exposure of the capillary force.
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Particle adhesion is one of the main causes of yield loss in the semiconductor industry¹ because particles can cause short-circuit or open circuit;² however, particle adhesion has other useful applications. For example, the adhesion of drug particles to specific sites is important to the pharmaceutical industry.³ In xerography, the ability to transfer toner particles successfully from the photoconductor to the receiver requires an understanding of the mechanisms of particle adhesion.^{4,5} In nanomanufacturing,⁶ researchers have made nanowires out of nanoparticles using directed assembly.⁶⁻⁸

Although there are many published studies on the adhesion and removal of particles, there has been a dearth of studies addressing the effect of the different deposition mediums on particle adhesion and removal. In this paper, three different deposition mediums, air, isopropyl alcohol (IPA), and deionized (DI) water, were used to deposit polystyrene latex (PSL) particles on thermal oxide and silicon nitride wafers. These particles were removed using a spinner in air to observe the effect of deposition mediums on particle removal efficiency (PRE).

Theoretical Background

Adhesion force and adhesion moment.—The first major adhesion force is the omnipresent van der Waals force. Without any external load applied on the particle, the attractive van der Waals force brings the particle into contact with the surface when a particle is within the force's range. A liquid meniscus can form between the particle and the substrate when either a liquid film or a high humidity is present. The resulting capillary force makes a large contribution to the total adhesion force. In this paper, we focus on these van der Waals and capillary adhesion forces.

The van der Waals attractive force between an undeformed sphere and a flat substrate can be written as⁹

$$F_{\text{vdW}} = \frac{A_{12}R}{6z_0^2} \quad [1]$$

where A_{12} is the Hamaker constant between the sphere and the substrate, R is the radius of the particle, and z_0 is the separation distance between the particle and the surface. The van der Waals force between a deformed sphere and a flat substrate is given by⁹

$$F_{\text{vdW}}^{\text{deform}} = \frac{A_{12}R}{6z_0^2} \left(1 + \frac{a^2}{Rz_0} \right) \approx \frac{A_{12}a^2}{6z_0^3} \quad \text{when } \frac{a^2}{Rz_0} \gg 1 \quad [2]$$

where a is the contact radius of the sphere after its deformation.

Assuming a plastic deformation, the adhesion moment around point O, as shown in Fig. 1, is simply the product of adhesion force and contact radius

$$M_A = F_{\text{vdW}}^{\text{deform}} a = \frac{A_{12}a^3}{6z_0^3} \quad [3]$$

When a liquid meniscus forms between a sphere and a flat substrate, as shown in Fig. 2, it results in a capillary force because of the negative pressure inside the meniscus. In humid environments, liquid can condense between a particle and a substrate, giving rise to a large capillary force. It was shown by Busnaina¹⁰ that the capillary force is significant at a relative humidity above 50% and dominates above 70%. For a small filling angle ϕ , the capillary force is given by¹¹

$$F_{\text{cap}} = 2\pi R\gamma_1(\cos \theta_1 + \cos \theta_2) \quad [4]$$

where γ_1 is the surface tension of the liquid and θ_1 and θ_2 are the contact angles of the sphere and the substrate, respectively. In the present study, both PSL particles and substrates used are hydrophilic, and hence their contact angles are relatively small.

Particle removal by hydrodynamic flow.—Hydrodynamic removal of particles¹²⁻¹⁵ is one of the practical ways to remove particles from surfaces. Hydrodynamic flow parameters such as velocity distribution, wall shear stress, and drag and lift forces applied on a stationary sphere are well established for a fluid flow over a flat surface. The knowledge of the hydrodynamic forces on a sphere enables us to study the adhesion and removal mechanism of particles down to a submicrometer size.

Schlichting¹⁶ used the Reynolds number ($Re = r^2\omega/\nu$) criterion to determine the turbulent and laminar regimes generated by a rotating disk, where r , ω , and ν are the radial distance from the disk center, the rotational speed, and the fluid kinematic viscosity, respectively. In this study, the wafer where the particles were deposited was rotated using a photoresist spinner at a maximum rotational speed of 7500 rpm in air, which generated a laminar flow regime.

The flow velocity profile within the laminar boundary layer is assumed to be linear, as shown in Fig. 1. O'Neil¹⁷ derived an exact solution of the linearized Navier–Stokes equations for a viscous flow past a stationary sphere in contact with a surface when the Reynolds number is small. The drag force is given by

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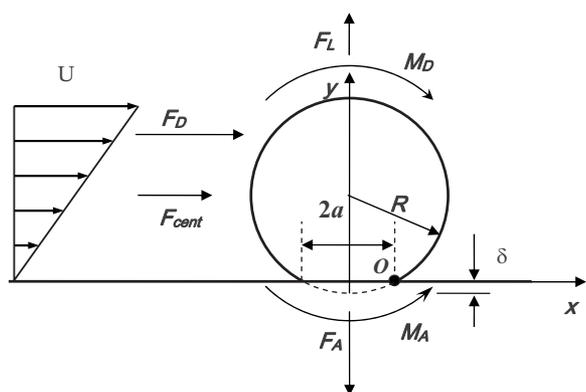


Figure 1. Forces applied on a deformed spherical particle on a flat surface in a linear shear flow during substrate spinning.

$$F_d = 1.7 \cdot 6\pi\mu R U_r \approx 32R^2\tau_0 \quad [5]$$

where U_r is the fluid velocity at the center of the sphere, μ is viscosity of the fluid, and τ_0 is the wall shear stress. The resulting moment applied on the sphere about its center is given by

$$M_d = 0.944 \cdot 8\pi\mu R^2 U_r \approx 23.7R^3\tau_0 \quad [6]$$

Therefore, the total moment about the contact point O is given by

$$M_d + F_d R = 55.7R^3\tau_0 = 1.74F_d R \quad [7]$$

This shows that the drag force F_d acts at the point, which is 1.74R above the surface. In O'Neill's analysis, the lift force is negligible because the lift force F_l is proportional to R^4 and the drag force F_d is proportional to R^2 . Leighton and Acrivos¹⁸ determined the lift force on a stationary sphere in contact with a surface in a linear shear flow under condition of the small Reynolds number, as shown in Eq. 8

$$F_l = 9.22\rho \frac{\tau_0^2 R^4}{\mu^2} \quad [8]$$

Particle removal mechanism.—As shown in Fig. 1, a particle adhered to a spinning disk (wafer) in air is subjected to the following forces: the attractive adhesion force F_a , the lift force F_l , the drag force F_d , and the centrifugal force F_{cent} , which is given by

$$F_{cent} = m r \omega^2 \quad [9]$$

where m is the mass of the particle, ω is the rotational speed, and r is the distance between the particle and the center of the disk.

The particle could be removed from a substrate by lifting, sliding, or rolling. When the total detachment force in the y -direction (perpendicular to the surface) is larger than the total adhesion force, i.e., $F_l > F_a$, the particle would be lifted up from the substrate. The

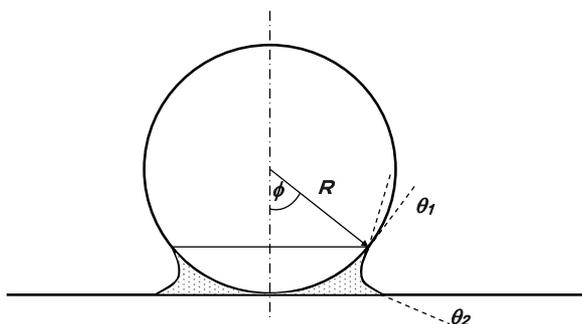


Figure 2. A schematic diagram of liquid meniscus formed between a sphere and a flat surface.

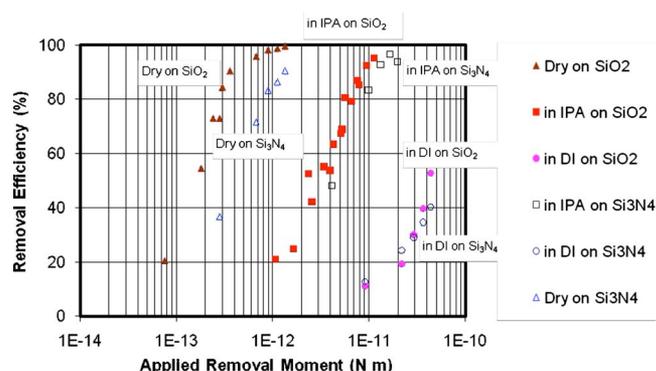


Figure 3. (Color online) A comparison of PRE of 50 μm PSL particles deposited using three different deposition mediums and removed by spin cleaning from thermal oxide wafer and silicon nitride wafer, respectively.

particle can also be removed by sliding, when the total applied forces in the x -direction (parallel to the surface) is larger than the friction force

$$F_d + F_{cent} > \mu_f (F_a - F_l) \quad [10]$$

where μ_f is the friction coefficient.

The particle would be removed by rolling when the total removal moment is larger than the adhesion resisting moment

$$(1.74F_d + F_{cent})(R - \delta) + F_l a > M_a \quad [11]$$

where a is the particle contact radius and δ is the relative approach between the particle and the substrate due to the deformation. In the present study, the rolling mechanism is used as a criterion for the particle removal. The force required to remove a particle by rolling is less than that required by sliding and lifting.

Experimental

All the experiments were conducted in a class 10 clean room (45% humidity). Thermal oxide (600 nm) and plasma-enhanced chemical vapor deposition silicon nitride (300 nm) films used in the experiments were deposited on 150 mm silicon wafers. The wafers were cleaned using a Piranha solution (mixture of H_2SO_4 and H_2O_2) before the start of every experiment. PSL spherical particles with a diameter of 50 μm (dry powder) were deposited onto the wafer using three different mediums: air, IPA, and DI water. Following the deposition, the wafer was then spun at relatively low revolutions per minute using a photoresist spinner (Headway Research, PWM 32 Series) to spread the particles and achieve a uniform deposition of particles. The wafers with the particles were then spun in an air environment at higher revolutions per minute. After the wafer spinning, the wafer was scanned again and the removal efficiency at different wafer radii was obtained by

$$\text{PRE}(r) = \frac{n(r)_{\text{before}} - n(r)_{\text{after}}}{n(r)_{\text{before}}} \quad [12]$$

where $n(r)_{\text{before}}$ and $n(r)_{\text{after}}$ are the number of particles at radius r before and after the cleaning experiment, respectively. The wafers were scanned using a laser surface particle scanner (KLA-Tencor, SurfScan 5500) for different rings of radii from 25 to 65 mm to obtain the particle count and distribution for each ring.

To investigate and measure the contact regions between the 50 μm PSL particle and the substrate, a field-emission-scanning electron microscope (FESEM, Carl Zeiss Supra 25) was also used.

Results and Discussion

Figure 3 shows a comparison of the PRE of PSL particles on the oxide and nitride wafers as a function of the applied removal moment when particles are deposited in air, IPA, and DI water mediums. The results show that a higher removal moment is required to

Table I. A comparison of capillary and van der Waals forces for a PSL particle of radius R on SiO_2 and Si_3N_4 substrates (wafers).

Separation distance (Å)	van der Waals force (N)		Capillary force (N)	
	PSL/ SiO_2	PSL/ Si_3N_4	DI water	IPA
	4	$0.068R$	$0.11R$	
9	$0.013R$	$0.022R$	$0.91R$	$0.28R$
14	$0.0055R$	$0.0089R$		

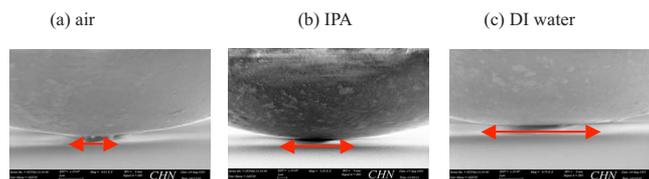
remove particles from the nitride wafers than the oxide wafers for all the deposition mediums considered. This is because silicon nitride has a higher Hamaker constant ($A_{\text{Si}_3\text{N}_4} = 17 \times 10^{-20}$ J) than silicon dioxide ($A_{\text{SiO}_2} = 6.5 \times 10^{-20}$ J). A higher removal moment is required to remove particles from the DI water suspension than those from the IPA suspension. This shows that when the particles are deposited from the liquid suspension, the removal moment becomes dependent on the surface tension of liquid mediums. Much higher removal moments are necessary to remove the particles deposited in a liquid medium compared to air. The removal of particles in a DI water medium requires more than 2 orders of magnitude higher removal moment compared with removal in an air medium.

Particles deposited in a DI water medium are the most difficult to remove, followed by IPA and air deposition. These results indicate that the capillary force, which is proportional to the surface tension of the liquid, plays an important role here.

Table I lists the capillary force for water and IPA ($\gamma_{\text{H}_2\text{O}} = 72.8$ dyn/cm for water and 22.3 dyn/cm for IPA, respectively) and van der Waals force for the PSL particle on the SiO_2 and Si_3N_4 wafers ($A_{\text{PSL}} = 6.5 \times 10^{-20}$ J, $A_{\text{SiO}_2} = 6.5 \times 10^{-20}$ J, and $A_{\text{Si}_3\text{N}_4} = 17 \times 10^{-20}$ J) for comparison. The separation distance is assumed to be 4 Å for an atomically smooth surface. However, the FESEM observation of the PSL particles shows that the particle surface is relatively rough, and therefore the equivalent separation distance between the rough PSL particle and the atomically smooth wafer could be assumed to be larger than 4 Å. Table I also shows the calculated van der Waals forces at different separation distances of 4, 9, and 14 Å. The capillary force is much higher than the van der Waals force, and it dominates the total adhesion force, as shown in Table I.

To understand how the capillary force affects the particle adhesion and removal, the contact region between the PSL particles and a substrate using three different deposition mediums is observed using FESEM by tilting the sample at an angle of almost 90° , as shown in Fig. 4. Table II shows the measured contact radius after the PSL particles are aged for 2 h on the wafer. The contact radius increases from 2.5 μm for an air deposition medium to 3.8 and 5 μm for the IPA and DI water deposition mediums, respectively. The resulting capillary force applied on the particles from a liquid suspension causes more deformation than dry particles in the air deposition medium. The increase in the surface tension of the liquid increases the capillary force and, consequently, the contact radius.

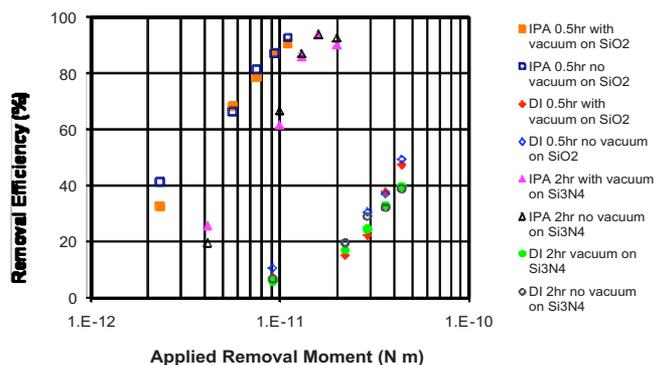
Figure 4 shows the SEM images of the interface between the particle and the substrate. The figure also shows that no meniscus is

**Figure 4.** (Color online) Change in contact areas of a 50 μm PSL particle on silicon nitride wafer after an aging time of 2 h deposited in (a) air, (b) IPA, and (c) DI water mediums.**Table II.** The measured contact radius of a 50 μm PSL particle using different deposition mediums after an aging time of 2 h.

Deposition medium	Air	IPA	DI water
Contact radius (μm)	2.5	3.8	5.0
Standard deviation (μm)	0.4	0.3	0.5

observed at the interface on all samples, indicating that the liquid has evaporated. To verify whether the liquid meniscus remains on the wafer after the deposition of particles from a liquid suspension, the following experiments were conducted. Wafers with the particles deposited from the IPA and DI water suspensions are put into a vacuum chamber to evaporate the meniscus. Then, wafers are taken out of the vacuum chamber, and the particle removal is conducted at atmospheric conditions. The PRE of these wafers is compared with particles that were not dried in vacuum for the same time interval. Figure 5 shows a comparison of the PRE of 50 μm PSL particles deposited from an IPA and DI water suspensions on the thermal oxide wafer with and without vacuum for an aging time of 0.5 h (the time needed to reach 2×10^{-5} Torr). The figure also shows the PRE for particles on the silicon nitride wafer with and without vacuum for an aging time of 2 h (the time needed to reach 5×10^{-6} Torr). The results show that the PRE is almost the same with and without vacuum, indicating that even when the liquid meniscus is evaporated for wafers in vacuum, the capillary force effect is the same for wafers in an atmospheric environment. The reason for the low PRE for particles deposited from IPA and DI water suspension compared to dry particles deposited in air is that the capillary force deforms the particle before the liquid meniscus evaporates. As Table II shows, the resulting capillary force deforms the PSL particle much more than the initial van der Waals force does. Liquids with a higher surface tension give rise to a higher capillary force and therefore cause more deformation, as shown in Fig. 4. The observed deformation is plastic, and therefore the deformation does not change after the capillary force is no longer in effect. Therefore, the adhesion force increases because of the plastic deformation caused by the initial capillary force and not the presence of the capillary force itself during particle removal.

As discussed in Fig. 3, the required removal moment to obtain the same PRE for particles deposited in the IPA medium is about 1 order higher than that for the dry particles. Also, the removal moment for the particles deposited in DI water is about 2 orders higher than those deposited in air. Equation 3 shows that the adhesion moment is proportional to a^3/z_0^3 . A higher removal moment is attributed to the increased contact radius caused by the capillary force. The capillary force deforms the PSL particle and also flattens the

**Figure 5.** (Color online) PRE comparisons of 50 μm PSL particles on thermal oxide wafer aged for 0.5 h and on silicon nitride wafer aged for 2 h when they are deposited from IPA and DI water suspension (with and without vacuum).

soft rough PSL particle surface within the contact area to decrease the equivalent separation distance, which would increase the total adhesion force.

Conclusion

This paper investigates the effect of the different deposition mediums on the adhesion and removal of particles to gain a better understanding of particle adhesion and removal mechanisms. PSL particles are deposited in air, IPA, and DI water mediums on oxide and nitride wafers. The PRE of these particles is measured as a function of removal moment. When the particles are deposited in an air medium, the van der Waals force dominates. However, when particles are deposited onto a substrate from a liquid suspension, a meniscus forms between the particle and the substrate, resulting in a capillary force, which dominates the van der Waals force and causes the particles to deform much more than the dry particles. Liquids with higher surface tension give rise to a larger capillary force and consequently cause more deformation. Even though the liquid meniscus evaporates when it is exposed to either a dry air environment or vacuum, the initial effect of the capillary force leaves a larger plastic deformation than dry particles. Even after liquid meniscus vanishes, the particles from the liquid suspension remain more difficult to remove than those dry particles because of larger plastic deformation caused by the capillary force.

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