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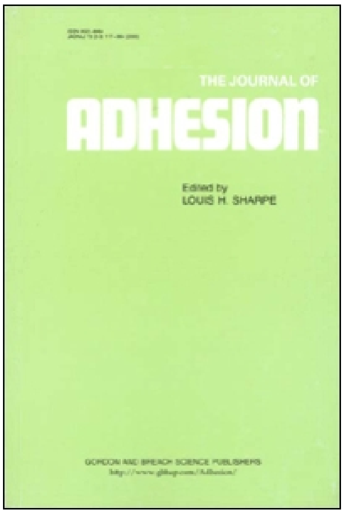

The Journal of Adhesion

Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453635

The Effect of Time and Humidity on Particle Adhesion and Removal

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To cite this Article Tang, Jing and Busnaina, Ahmed A.(2000) 'The Effect of Time and Humidity on Particle Adhesion and Removal', The Journal of Adhesion, 74: 1, 411 — 419

To link to this Article: DOI: 10.1080/00218460008034539

URL: http://dx.doi.org/10.1080/00218460008034539

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J. Adhesion, 2000, Vol. 74, pp. 411–419
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Note

The Effect of Time and Humidity on Particle Adhesion and Removal

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(Received 30 September 1999; In final form 3 January 2000)

Time and humidity greatly influence particle adhesion and removal in many particle-substrate systems. The effect of time (aging) and humidity on the adhesion and removal of 22 μm PSL (Polystyrene Latex) particles on polished silicon wafers is investigated. The results show that the effect of time on the adhesion and removal of the 22 μm PSL particles on silicon substrates in high humidity environment is very significant. The removal efficiency of PSL particles significantly decreased after the samples were aged for more than one day in high humidity environment. The combined effect of the van der Waals force and the capillary force tend to accelerate the adhesion-induced deformation process. When capillary force occurs at the particle substrate interface, the removal efficiency decreases quickly by more than 50% within 24 hours. Without the capillary force, the adhesion-induced deformation is negligible within the first 24 hours.

Keywords: Particle adhesion; Time effect; Humidity; van der Waals force; Capillary force; Particle removal

1. INTRODUCTION

Particle adhesion and removal is of scientific and technological interest in many industries such as semiconductor manufacturing, xerography and pharmacology. The mitigation of defects caused by particulate

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*Corresponding author. Tel.: 315-268-6574, Fax: 315-268-6438, e-mail: aab@clarkson.edu contamination depends on the understanding of the mechanisms and factors that influence particle adhesion and removal. Many models have been introduced to predict particle adhesion and deformation [1–3]. The effect of time and humidity on adhesion and removal on different particle/substrate systems has also been studied [4–8]. Krishnan, Busnaina *et al.*, used scanning electron microscopy to observe adhesion-induced deformation of sub-micrometer PSL (Polystyrene Latex) particles on silicon substrates as a function of time only. The contact area between the particle and the substrate was found to increase with time for a period of approximately 72 hours before reaching a constant value. They also related this result to the study of particle removal conducted using hydrodynamic and centrifugal removal forces for different time periods. The removal efficiency correlates well with the increase of particle adhesion force with time as observed from the SEM measurement [4]. Busnaina and Elsawy [5, 7, 8] measured the removal and adhesion force as a function of humidity. The trend of high adhesion at high and low humidity was observed. At high humidity, the capillary force constitutes a large adhesion force in addition to the van der Waals force and as a result the removal efficiency significantly drops. At low humidity, the low removal efficiency is attributable to the electrostatic force because of the higher charge that can build up during airflow over the silicon substrate (an insulator) [5].

2. THEORETICAL

For small, uncharged particles on uncharged surfaces, the primary force is usually attributed to van der Waals (vdW) interaction. For the ideal case in which both the spherical particle and the surface are not deformed, the vdW force is proportional to the radius of the sphere. When deformation occurs, the magnitude of the adhesion force will also depend on the contact area between the particle and the surface. According to Bowling [9], when a sphere and a flat substrate come into contact with one another, the attractive force, $F_{(\mathrm{vdW})}$, deforms the interface and a circular adhesion area is formed. The total adhesion force consists of two additive components, the force acting between the adherents before deformation, $F_{(\mathrm{vdW})}$, and the force acting on the contact area due to the deformation, $F_{(\mathrm{vdW\_deform})}$:

$$F_{(\mathrm{vdW\_total})} = F_{(\mathrm{vdW})} + F_{(\mathrm{vdW\_deform})} \tag{1}$$

Bowling gave the total van der Waals force including the component due to the deformation as:

$$F_a = F_0\left(1 + \frac{a^2}{Rz_0}\right) \tag{2}$$

where $F_0 = (\mathrm{A}R/6z_0^2)$ is the van der Waals force for the spherical particle, A is the Hamaker–van der Waals constant, R is the radius of the spherical particle, z_0 is the separation distance between the particle and the substrate (For smooth surfaces, it is taken as 4 Å) and a is the contact radius between the deformed particle and surface.

When moisture is present in the air medium, condensation can take place between the particle and substrate as shown in Figure 1. This capillary condensation gives rise to a very large capillary force, which increases the total force of adhesion. The capillary force is made up of two components: surface tension at the perimeter of the meniscus and the difference in pressure between the liquid and vapor phases. Zimon [10] concluded that when the relative humidity is above 70%, the capillary force dominates and should be the only adhesion force considered. Bowden and Throssel [11] found that the force required for removing 98% of 50-micron glass particles from a glass substrate increases with increasing relative humidity. At relative humidity near 100%, the capillary force can be predicted by [12]:

$$F_c = 4\pi R\gamma_{LV} \tag{3}$$

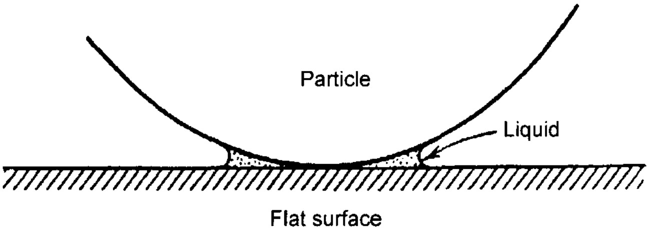


FIGURE 1 Condensed film between particle and substrate.

3. EXPERIMENTAL

The objective of this study is to determine the combined effect of time and relative humidity on the removal efficiency of PSL particles from silicon substrates.

3.1. Experimental Facilities

Polished silicon wafers, 5 inches (125 mm) in diameter, were used as the deposition substrates in the experiments. A dry powder of PSL spheres (22 μm) manufactured by Duke Scientific Inc. was used to simulate particulate contaminants. A humidity chamber system that consists of a humidifier with a controller that allows settings at different humidity was used to provide the environment in which particles were deposited. A dessicator was used to keep the samples during the aging period. A Headway research photo-resist spinner was used to generate the removal force required to detach particles. The spinner has a maximum rotational speed of 10,000 rpm. An Olympus BH-2 UMA optical microscope equipped with a CCD camera and a computer-controlled auto-focus micro-stage was used to count the particles on the substrate.

3.2. Experimental Procedure

The substrate was placed on the platform in the humidity chamber with the desired relative humidity for two minutes. Dry powder of 22 μm PSL particles was deposited very gently on the substrate in a 0.5 × 0.5 cm square, which is about 2 cm from the center of the wafer. Usually, there were about 100 to 200 particles in the square. The sample was kept in the dessicator with the desired relative humidity for the desired time. The microscope was used to obtain the exact number (n_{before}) of the PSL particles deposited on the substrate before the sample was cleaned. Using air as the medium, the spin coater generated the removal force that consists of drag, lift and centrifugal forces. The silicon substrate was rotated at 3000 rpm or 6000 rpm, successively, each for 120 seconds. The microscope was used again to determine the number (n_{after}) of the particles still present on the silicon substrate. The above procedure was repeated for different values of relative humidity.

4. RESULTS AND DISCUSSION

Figure 2 illustrates the theoretical calculation results that show the contact area between particle and substrate with and without the capillary force. The MP (Maugis–Pollock) model [3] is used to calculate the contact area:

$$P = \pi a^2 H \tag{4}$$

where P is the total force causing the deformation, a is the radius of contact and H is the hardness of particle material. Figure 2a depicts that the contact area between the particle and the substrate due to adhesion-induced deformation with the capillary force is more than eight-fold that without the capillary force. When the capillary force occurs (at high humidity), calculations in Figure 2b show that before deformation commences, the capillary force is the dominant force of adhesion while after deformation occurs the van der Waals force

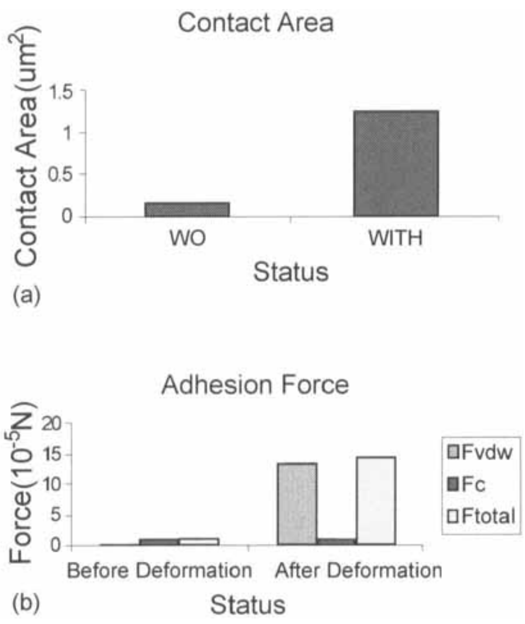


FIGURE 2 a: Comparison of Contact Areas with and without Capillary Force. b: Comparison of Adhesion Forces Before and After Deformation (with capillary force).

becomes the dominant force because of the adhesion-induced deformation. The increase in the contact area due to the adhesion-induced deformation caused by the combined van der Waals and capillary forces significantly increases the final van der Waals force between the particle and the substrate.

Figures 3 and 4 show the particle removal efficiency results ($1 - (n_{\text{after}}/n_{\text{before}})$) corresponding to intermediate and high humidity environments with low and high rotational speeds at 3000 rpm and 6000 rpm. Figure 3 illustrates particle removal efficiency results at 45% relative humidity using low and high rotational speeds (corresponding

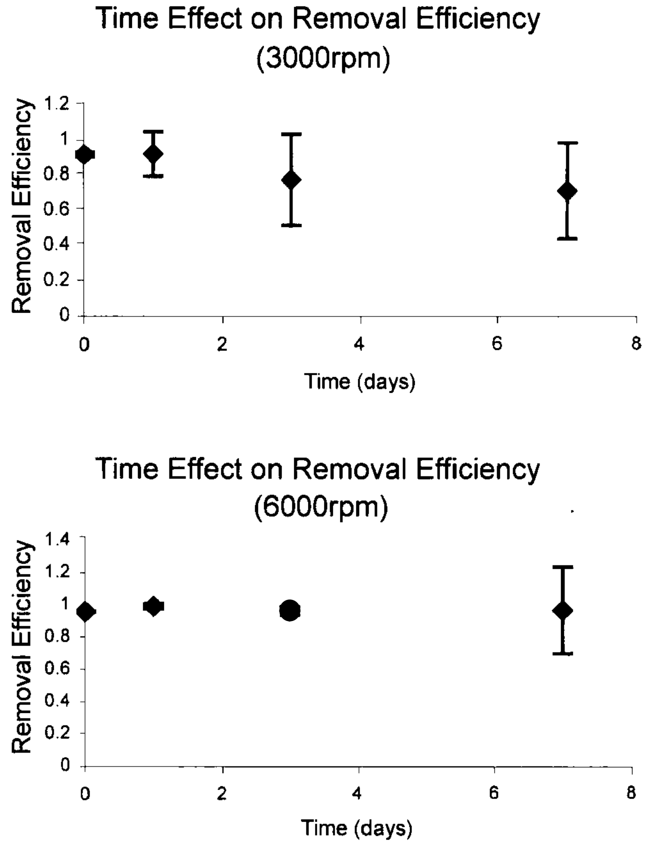
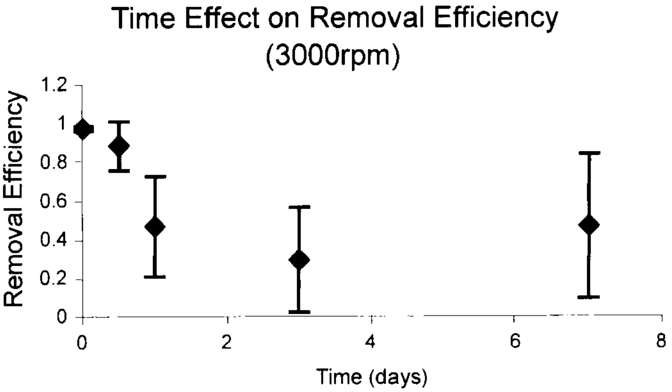


FIGURE 3 Time Effect on Removal Efficiency ($1 - (n_{\text{after}}/n_{\text{before}})$) at 45% Relative Humidity.



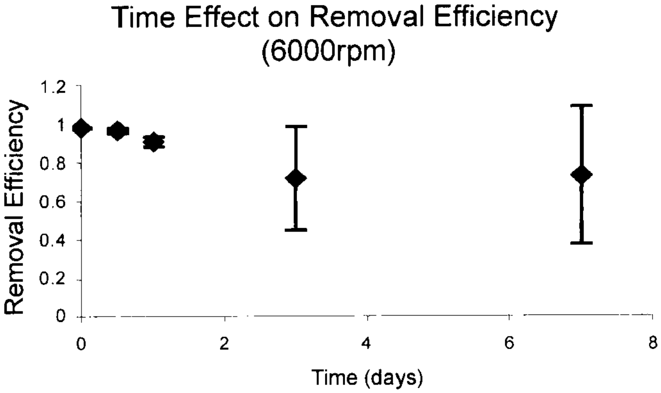


FIGURE 4 Time Effect on Removal Efficiency $(1-(n_{\mathrm{after}}/n_{\mathrm{before}}))$ at 100% Relative Humidity.

to low and high removal forces). The figure shows that the removal efficiency of PSL particles on silicon substrates decreases with time. The decrease of removal efficiency is caused by the increase of the adhesion force due to the adhesion-induced deformation of the PSL particles due to the van der Waals force only and without the capillary force effect. When capillary condensation occurs the adhesion-induced deformation also increases due to the additional capillary force. Figure 4 shows the combined effect of the van der Waals force and the capillary force on the removal efficiency. The combined effect of the van der Waals force and the capillary force tends to accelerate the deformation process. In Figure 4, the removal efficiency decreases by 50% after one day at 3000 rpm and 10% at 6000 rpm at 100% relative humidity. By comparison, at 45% relative humidity the decrease in the removal efficiency after one day is negligible at 3000 rpm and 6000 rpm. The decrease in removal efficiency over a week is 50% at high humidity (100%) and low rotational speed (3000 rpm) where at 45% relative humidity and the same speed the decrease is about 20%. At higher speed (6000 rpm) the decrease in the removal efficiency at high humidity (100%) and long aging time of one week is 25–30%. However, at lower humidity (45%) the decrease in the removal efficiency over a week was negligible.

5. CONCLUSIONS

The effect of time on the adhesion and removal of 22 μm PSL particles on silicon substrates in high humidity environment is very significant. The removal efficiency of PSL particles significantly decreased after the samples were aged for more than one day in high humidity environment. The combined effect of the van der Waals force and the capillary force tends to accelerate the adhesion-induced deformation process. Both time and humidity have a remarkable effect on the adhesion force. When the capillary force occurs, the removal efficiency decreases quickly by more than 50% within 24 hours. Without the capillary force, the adhesion-induced deformation is negligible within the first 24 hours.

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