2001

Electrostatic removal of particles

Chunzhi Yan
San Jose State University

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ELECTROSTATIC REMOVAL OF PARTICLES

A Thesis

Presented to

The Faculty of the Department of Chemical and Material Engineering

San Jose State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

By

Chunzhi Yan

May 2001

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ABSTRACT

ELECTROSTATIC REMOVAL OF PARTICLES

By Chunzhi Yan

Electrostatic removal of particles was studied using bipolar electrostatic particle getters (ESPGs). The particle removal effectiveness was investigated with a fixed ESPG in an air environment and mobile ESPGs in a vacuum environment. Three process parameters were varied: process cycle, applied voltage, and cleaning method. It was found that the ESPGs were not effective at removing particles due to its bipolar nature. Mono-polar ESPG with external flow was recommended for further research.

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CHAPTER 1

INTRODUCTION

1.1 Background on CMOS devices

The electronics industry has grown rapidly in the last three decades. The first integrated circuit was created in 1960. P-MOSFETs (P-type Metal Oxide Semiconductor Field Effect Transistors) were the original structure of early computer chips. By the early 1970s, NMOS replaced PMOS because of the higher mobility of the electron. It was widely used through the 1970s and into the early 1980s. The idea of complimentary MOSFETs (CMOS) was first proposed by Wanlass and Sah in 1963 (Campbell, 1996). The technologies used were not dense and were quite slow. CMOS was used initially in toys, watches, and calculators where slow speeds could be tolerated. The invention of LOCOS (local oxidation of Si) together with many other improvements has dramatically improved the acceptance of CMOS. Its inverter structure, reduction in packaging cost, and increase in density make CMOS the dominant semiconductor technology of today. It is also expected to continue to dominate the IC market for the foreseeable future.

Fig 1-1 shows the cross section of a CMOS device. A variety of successive thin films have to be formed to build integrated circuits (IC) devices. These films can be metals, semiconductors, or insulators (Table 1-1).

Fig.1-1 Cross section of completed devices in a basic CMOS process (Wolf and Tauber, 2000)

Table 1-1 Thin film materials

Substrate	Si
Well/Source/Drain	Phosphor/Boron doped Si
Gate oxide	Thermally grown SiO ₂
Interconnect/Metal "plug"	Al
Dielectric	SiO ₂ , Si ₃ N ₄

Thin films must meet rigorous chemical structural, and electrical requirements. Each layer is carefully designed and patterned to perform a specific function. It usually links with surrounding areas and subsequent layers. The fabrication process is similar no matter how many transistors are on the chip. Fig1-2 is a simple example of the fabrication steps used to form an integrated circuit MOS capacitor. A relatively thick

SiO₂ layer is grown on a bare n-type Si substrate by thermal oxidation. The oxide layer isolates the metallization-interconnect film deposited at the end of the process from the Si substrate. An opening in the SiO₂ layer is then formed by a photolithographic process and an etch process. At the opening place in the SiO₂ layer, the boron atoms are implanted into the Si substrate. A sufficient implant dose is used to ensure this region becomes p-type. The energy of the implant and the SiO₂ thickness are also selected so that the boron atoms will not penetrate to the Si where the SiO₂ layer exists. In this manner, p-regions are selectively formed in the Si.

Another new thin SiO₂ film is grown over the exposed p-type Si region, and a contact hole is etched in the film to allow an Al film to make contact to the lower plate of the capacitor. The Al film, deposited next, is the top plate of the capacitor (Wolf, 1990). The formation of the contact holes and Al patterns requires alignment. The capacitor will function properly only if the two plates of the capacitors are isolated from each other. If the Al pattern is misaligned, it will result in an accidental contact between the Al and the p-type Si region, the two plates of the capacitor will therefore be shorted.

Fig.1-2 Process sequences for fabrication a MOS capacitor. (Wolf, 1990)

1.2 Thin film deposition

The formation of these films is accomplished by two major techniques: film growth by interaction of a vapor-deposited species with the substrate and film formation by deposition without causing changes to the substrate material. Examples of thermal growth are the oxidation of single crystal silicon and the formation of silicides by direct

reaction of a deposited metal and the substrate. These films are grown by reacting oxygen or nitrogen gas with the Si wafer. On the other hand, film formation by deposition does not cause changes to the substrate materials. Deposition can be further divided into three sub-groups. 1) In chemical vapor deposition (CVD), solid films are formed on a substrate by the chemical reaction of vapor phase chemicals that contain the required constituents. For example, LOCOS is formed by low pressure CVD (LPCVD). 2) In physical vapor deposition (PVD), species of the film eject from a source to form the thin film. Al sputtering is an example of this. 3) In coating processes, substrate is coated with a liquid, which is then dried to form the solid thin film. Photolithography process is an example of this.

1.3 Particle contamination

Semiconductor devices are known for their sensitivity to particles. Particles on the wafer can cause a short circuit between lines, a boulder that the upper layers cannot cover, or they may locally interfere a photolithography step (Fig. 1-3). In summary, they affect device performance and reliability and are very much responsible for the yield lost in semiconductor device production.

All the fabrication process steps and equipment have particle contamination problems. In a typical deposition chamber, such as reactive ion etching (RIE) chamber and plasma enhanced CVD (PECVD) chamber, there are many potential sources of particle contamination such as cracked or flaking materials, accumulated polymers on the

walls of the chamber, small metal spheres created by arcing between metal surfaces, and incidental contact or rubbing inside the chamber during wafer handling (Bouchoule, 991). Once particles are released into the chamber during processing, they enter the gas plasma and ultimately contaminate the wafer surface. In an implanter, if the particles fall on the wafer before implantation, they will screen the wafer from the implant. A later clean may remove the particle, but its unseen shadow would remain behind as a virtually undetectable killer defect.

Fig.1-3 Bridging particles on IC devices (Applied Materials, 2001)

Total elimination of contamination sources during IC processing is presently not achievable. Therefore, surface cleaning is frequently applied after each step. The most widespread cleaning techniques in the industry are wet cleaning processes, which are usually based on dilute mixtures of acids. H_2SO_4 - H_2O_2 is used to remove photoresist

from non-metallized wafers. H_2O -HF is used to remove misaligned resist imaging. Organic contaminants are removed with H_2O - NH_4OH - H_2O_2 . H_2O -HCl- H_2O_2 is used to desorb remaining atomic and ionic contaminants (Campbell, 1996). These liquids are themselves potential sources of contamination, thus one stage of a cleaning process may in fact reduce the effectiveness of other cleaning processes. Ultrasonic scrubbing is the most commonly used method for the removal of insoluble particle contamination. Wafers are immersed in a suitable liquid medium with applied sonic energy at 20,000-50,000 Hz or higher frequency (~850KHz). Problems associated with this technique are: 1) particles must be removed from the liquid through overflow or filtration after being initially detached and 2) the substrate films may be removed in certain regions as a result of the high sonic energy.

Wet chemical cleaning has been the dominant technology for removing contaminants from the wafer surface for the past 50 years. However, at current levels of device integration, cleaning technologies must remove submicron particles from trenches and other surface features with high aspect ratios. Very low densities of both particle defects and film imperfections, such as pinholes, become critical for the small linewidths, high densities, and large areas necessary for ultra large scale integration (ULSI). Table 1-2 below shows the particle reduction requirements set forth by the 1994 National Technology Roadmap for Semiconductors (Campbell, 1996).

Table 1-2: Requirements for contamination-free semiconductor manufacturing (Campbell, 1996)

Year	1998	2001	2004	2007	2010
Minimum feature size (um)	0.25	0.18	0.13	0.10	0.08
Minimum particle size (um)	0.08	0.06	0.04	0.04	0.03
Wafer diameter (mm)	200	300	300	400	400
Maximum particles per wafer					
DRAM chip	23	35	23	28	19
Microprocessor	22	42	35	50	43
ASIC chip	10	20	17	25	19

As a wafer diameter extends from 8 to 12 inches and a device's critical dimensions shrink from micron to submicron, the disadvantages of wet chemical cleaning become significant. It is not effective enough on sub micron particulate contaminants. It could be a source of sub micron particulate contaminants itself. Moreover, it is not easily integrated in present cluster tools, chambers combining several gas phase processes for multiple film deposition.

From conservation and environmental points of view, continuing use of wet chemistry techniques is also not a wise choice. The chemicals used in wet cleans are a major source of pollution. With some wafer fabs using 1 billion gallons of water per

year. the worldwide cost of ultra pure water for semiconductor production is nearly \$3 billion for year 2000 (Mahoney et al, 1998).

Limitations in the capabilities of wet chemical cleaning are pushing the industry to seek replacements. As more and more processing is integrated within single, vacuum-isolated systems, a dry cleaning technique would be preferred. The industry needs a fully automated “dry” apparatus or process capable of being integrated into on-line fab device-processing steps. The clean must remove all conductive and dielectric particles and particles generated within semiconductor processing chambers and not re-contaminate the surface.

Over the past several years, several dry technologies such as laser-assisted particle removal and cryogenic aerosol cleaning have been developed for the removal of particles. They offer the promise to improve contamination control in the sub micron area. The purpose of this paper is to explore one of these technologies, electrostatic particle removal, and to estimate its potential to be integrated into the next generation of semiconductor manufacturing equipment.

CHAPTER 2

ELECTROSTATIC FORCE PARTICLE REMOVAL

2.1 Adhesion forces

A basic understanding of particle adhesion is critical to insure particle free semiconductor processing. The adhesion strength at and around the interface of a particle and a surface is a mixture of physical and chemical forces and mechanical strains and stresses.

There are mainly three kinds of adhesion forces: van der Waals force from interacting dipole moments of the molecules, capillary force from the surface tension of any adsorbed liquids, and electrostatic forces from either bulk excess charges present on the surface and/or particle or the differences in the local energy states and electron work functions of two different materials in contact (Cooper et al., 1990 a). The magnitude of adhesive forces relative to the particle mass increases significantly for micron and submicron sized particles, thus their removal is very difficult (Bowling, 1985). The variation of gravitational, van der Waals, and capillary forces as a function of particle sizes is shown in Fig. 2-1 (Kumar, et al., 1998). As the particle size reduces to the submicron range, the gravity force becomes less significant compared to adhesive forces. For instance, adhesion forces easily exceeds gravity force by a factor greater than 10^4 for a 1 μm diameter particle (Lu et al., 1999).

Fig. 2-1 Variation of gravitational, van der Waals and capillary forces between particles and smooth solid surfaces as function of particle size (Kumar et al., 1998)

2.1.1 Van der Waals forces

Total forces of adhesion of small particles to surfaces can range from 10^{-10} to 10^{-3} N, which corresponds to pressure of 10^8 N/m² or more (Bowling, 1985). Van der Waals and electrostatic are the primary forces that bring particles to a surface and then hold them there. Fig. 2-1 shows that for a dry surface (absence of capillary forces), van der Waals forces dominate for smaller particles. The van der Waals adhesion force between a spherical and a flat surface is

$$F(\text{vdW}) = \frac{hr}{8\pi z^2} = 2hd \text{ mdyn} \quad (2.1)$$

Where h is the Lifshitz-van der Waals constant, which ranges from about 0.6 eV for polymers to about 9.0 eV for metal, z is the adhesion distance, d is the particle diameter

in microns, and r is the particle radius. They can increase as a function of time due to particle and/or surface deformation, which increases the contact area.

Table2-1: Lifshitz-van der Waals constants

Particle	Surface	h (eV)
Polymer	Polymer	0.6-0.9
Al ₂ O ₃	Al ₂ O ₃	2.0
Si	Si	6.8-7.2
Ge	Si	7.5
Graphite	Si	6.8

The additional van der Waals force due to deformation is given by

$$F (\text{vdW deform.}) = h\rho^2/8\pi z^3 \quad (2.2)$$

where ρ is the radius of the adhesive surface area. The total van der Waals force is then

$$F (\text{vdW total}) = F (\text{vdW}) + F (\text{vdW deform.}) \quad (2.3)$$

The van der Waals adhesion force strength varies with the materials. Softer materials yield to greater deformations and thus result in greater forces of adhesion. Metals give the combination of a greater h and deformation from the soft material. A hard oxide layer on a metal surface, on the other hand, tends to reduce adhesion of hard particles to that surface (Lu et al., 1999).

2.1.2 Electrostatic forces

Electrostatic forces are comprised of two types of forces, excess charge image forces and electrostatic contact potentials, also known as electrical double layer forces.

Electrostatic image force is the Coulombic force from excess charges present on the surface and particle. This attractive force is given by equation

$$F(i) = q^2 / (4\pi\epsilon_0\kappa l^2) \quad (2.4)$$

where i means electrostatic force, ϵ_0 is the permittivity of free space, κ is the dielectric constant of the medium between the particle and surface, l is the distance between charge centers, and q is the charge.

Electrical double layer force is induced by the contact potential of two different materials. The differences in local energy states and electron work functions of the two materials in contact cause electrons to transfer from one solid to another until equilibrium is reached, the current flow in both directions is equal. Fig. 2-2 is a simple example. The work function, denoted as Φ , is the energy difference between the vacuum level and the Fermi level (Kasap, 2000).

The contact potential, ΔV , sets up a double layer charge region. In the case of two metals in contact, only the surface layer carries contact charges. For semiconductors and insulators, these regions may extend to the bulk up to 1 μm or deeper. For a particle on a surface, the double layer force can be calculated as

$$F(\text{el}) = \pi\epsilon_0 d V^2 / 2z \text{ dyn} = 4dV^2 \text{ mdyn.} \quad (2.5)$$

where d is the particle diameter, z is the adhesion distance.

- (a) Electrons are more energetic in Mo. So they tunnel to the surface of Pt.
- (b) Equilibrium is reached when the Fermi levels are lined up.

Fig.2-2 Metal contact potential (Kasap, 2000)

Fig. 2-3 (Bowling, 1985) is a comparison of the van der Waals forces and electrostatic forces of particle adhesion vs. particle diameter. The figure shows that: 1) Van der Waals forces for particles with h equal to 4eV and 8eV dominate over electrostatic forces when the particles are very small; 2) Double layer forces dominate

over electrostatic image forces for small particles when a maximum of contact potential difference of 0.5V is assumed. For conductors, the electrostatic potential is small. For nonconductors, the electrostatic attraction is significant. Materials that can carry charges high enough to allow electrostatic forces to contribute significantly to the total force of adhesion are generally polymers of poor conductivity or other insulators.

Fig. 2-3 Van der Waals forces in comparison to electrostatic forces of adhesion as a function of particle diameter (4eV and 8eV are the Lifshitz-van der Waals constants h of Al_2O_3 and Cu) (Bowling, 1985)

Real particles are rarely smooth and spherical. In fact, most natural particles are bumpy and rough. Electrostatic forces can sometimes dominate over van der Waals forces when real particles have asperities large enough to remove the bulk of the particle

from the contact point. This is due to the rapid decrease in van der Waals force with increasing distance between the adherents. In the presence of surface asperities, calculation of the van der Waals force should not be based on the full radius of the particle but rather on the radius of curvature of the surface elevation at which the adherents are in contact. Electrostatic forces do not change much with asperities; at small deviations from spherical, the effective radius for electrostatic forces is approximately equal to the true radius. However, deformation of particles and/or surfaces after a period may change these asperities at the contact point so that van der Waals force again dominates.

2.1.3 Capillary forces

Due to high humidity or to an adhered particle/surface system having been immersed and then withdrawn from a liquid, a liquid film can be formed by capillary condensation or capillary action between the particle and surface. The resulting capillary force can make a large contribution to the total force of adhesion (see in Fig. 2-1). The capillary force is a function of the particle radius and liquid surface tension as shown by the formula

$$F(\text{cap.}) = 2\pi d\gamma \text{ dyn} = 0.63d\gamma \text{ mdyn} \quad (2.6)$$

where d is the particle diameter, γ is the liquid surface tension.

By immersion of adherent particles in a liquid, the van der Waals force can be reduced by, in most cases, about a factor of two, since the liquid partially shields the

attraction (Bowling, 1985). Electrostatic image forces are more or less eliminated by immersion. Electrostatic contact potential forces are greatly reduced. The electrostatic forces become negligible because the liquid's dielectric constant is much larger comparing to that of a gaseous or vacuum environment and the sorption phenomena also tends to shield the charges.

Liquid molecules adsorbed at the solid surfaces are polarized and oriented in a certain direction so that an electrical double layer is formed at each solid-liquid interface (Kolomenskii et al., 1998). Whether the force is attractive or repulsive is completely system dependent. If particles are the same material as the surface, charges generally form double layers the same on both surfaces so that the double layer interactions are repulsive. If particles are the different materials, the double layer interactions are attractive (Fig. 2-4). If the liquid itself is dissociable into ions and/or if the liquid contains dissolved species that are present as ions, the forces can be approximated by the formula

$$F = \pm 64\pi r N k T \delta \quad (2.7)$$

where r is the particle radius, N is the charge density in charges per cubic centimeter, k is Boltzman constant, T is the temperature in degrees Kelvin, and δ is the double layer thickness, which is typically 50 Å (R. Allen Bowling, 1985). Different ions may collect differently at unlike surfaces so that either attractive or repulsive forces are possible depending on their alignment. In principle it would be possible to charge the particle

and/or surface, unimmersed, so that repulsion would cause particle removal, so-called electrostatic removal (Bowling, 1985).

(a) The particle and the surface are of different material

(b) The particle and the surface are of the same material

Fig.2-4 Interaction electrostatic forces of solid-liquid interfaces

Theoretical calculations by Bowling showed that, for particles smaller than about 50 microns, van der Waals force generally dominates over electrostatic forces in dry conditions and that capillary forces can dominate over other forces in humid conditions. We must diminish the forces of adhesion of particles, overcome these forces, or both, to remove particles from a surface. In dry cleaning techniques, people primarily or exclusively apply forces to overcome the adhesion force. Two new dry cleaning technologies: laser-assisted (induced) removal and electrostatic removal are under intensive investigation.

2.2 Laser-assisted (induced) removal of particles on silicon wafers

Laser-assisted particle removal uses high-amplitude surface acoustic waves (SAWs) or pulsed-laser irradiation. It has been used to generate enough force to eject particles. The mechanisms proposed in the literature are generally based on a rapid thermal energy transfer between the incident laser beam and the different sample components, which leads to rapid thermal expansion and provides forces to eject particles. The lifted particles are then removed from the surface by an inert gas flow (Vereecke et al., 1999). Several variations of radiant cleaning processes have been proposed depending on whether the laser light wavelength was mainly absorbed at the sample surface or in the contaminant particles.

G. Vereecke et al have studied pulsed-laser irradiation used to generate enough force to eject particles. They tested a dry laser-cleaning tool equipped with an excimer laser (LPX210ICC, lambda Physik) delivering about 30 ns pulses of nonpolarized deep ultraviolet (DUV) light at 248 nm wavelength (KrF) using Si wafers contaminated with Si_3N_4 and SiO_2 particles of different sizes. The light was strongly absorbed by the silicon substrate, giving rise to surface melting and ablation at fluence higher than 300 mJ/cm^2 . A model was developed to simulate the cleaning process and analyze the influence of experimental parameters on laser cleaning efficiency. In this model, the jet gas flow was assumed laminar and parallel to the wafer surface with a boundary layer of constant thickness. The velocity profile was assumed linear. The particles experienced an adhesion force which was predominately van der Waals force according to Bowling's

theory. There were also external forces which include the drag force, $F_{\text{gas drag}}$, exerted by the surrounding gas which is used to take particles away, the laser beam radiation pressure force directed vertically towards the surface, and the force resulting from air thermal agitation which was random in direction, and gravity mg .

G. Vereecke et al theoretically calculated the distance D that particles could be lifted-off from substrates by equaling the corresponding forces with van der Waals force in the differential vertical motion equation (Vereecke et al., 1999)

$$m d^2 D / dt^2 = -F_{\text{vdW}} - F_{\text{gas drag}} - mg \quad (2.8)$$

where m is the mass of the particle, d is particle diameter, D is the distance separating the particle and substrate and t is the laser pulse duration.

In the experiments, the process parameters were varied in the following indicated range shown in Table 2-2. Cleaning efficiency was monitored as a function of laser fluence, repetition rate, and number of pulses. It was found that the highest laser fluence without hazing wafer surfaces was 300 mJ/cm^2 . The best cleaning efficiencies obtained with $1.0 \text{ }\mu\text{m SiO}_2$, $\sim 0.3 \text{ }\mu\text{m Si}_3\text{N}_4$, and $0.3 \text{ }\mu\text{m SiO}_2$ particles deposited on Si wafers were $84 \pm 8\%$, $33 \pm 4\%$, and $12 \pm 7\%$ respectively at 40%RH, which is a normal cleaning condition. Improved cleaning efficiencies were obtained with wafers pre-equilibrated with 100% RH air.

Fluence showed the highest influence on removal efficiency, before the number of laser pluses and the laser repetition rate. The use of fluence to improve the cleaning efficiency was limited by the damaging of the wafer surface by laser pluses at high fluence. The experiment result is in qualitative agreement with theoretical calculations showing that there is a size threshold for particle removal by dry laser cleaning. The cleaning was more effective for bigger particles. This means that even if the highest fluence possible without damaging wafer surfaces is used, smaller particles, which may cause killer defects, will remain on the wafer surface. The experiments were only carried out for SiO₂ and Si₃N₄ particles on Si substrates. The capability of laser-assisted technology to remove metallic ion impurities or plastic particles was not investigated.

Table 2-2. Laser-assisted particle removal experiment parameters

Beam fluence	150-300 mJ/cm ²
Laser repetition rate (RR)	5-100 Hz
Overlap (OL)	1-20
Relatively humidity of wafer (RH)	40% and 100%

There are also studies conducted on liquid assisted laser cleaning, additional forces are provided by the explosive evaporation of a thin liquid film deposited just before the pulsed laser irradiation. It has been reported to give the highest efficiency for

the removal of submicron particles but very little quantitative data has been presented (Al.A.Kolomenskii et al., 1998).

2.3 Electrostatic removal of particles

Electrostatic removal of particles is another very promising dry method consistent with processing in a vacuum environment. Some prior work done at IBM tried particle removal by charging the particles and exposing them to an electric field. DeGeest patented a technique that particles are precharged with a corona in 1970. Shang made use of a needle-like electrostatically chargeable probe for detaching particles from the surface (Cooper, 1988). However, both of these systems are limited to removing relatively large particles greater than 5 μm because the dielectric field breaks down at the field strengths required for the smaller particles. Cooper, who has done extensive work on electrostatic removal of particles, patented an electrostatic film cleaner capable of removing 0.5 μm particles (Cooper et al., 1990 a).

Particles on a surface are charged by conduction through the bulk material or along the surface. A high electric field is created by the closeness of an insulated counter electrode that may or may not touch the particles. The particles experience a force that may exceed the adhesive force. If so, they move to the insulated counter electrode, but they charge more slowly there and generally do not return to the product. By selecting time, insulator conductivity and adhesiveness, and the geometry, one can design the

collecting insulated electrode to prevent redeposition of particles onto the product surface. If there is no gap, then the collecting electrode should be deformable.

Fig. 2-5 (Cooper et al., 1990 a) shows a general schematic of a capacitor, the basis of an electrostatic removal technique. A DC power maintains a voltage difference V (in unit of E) across parallel metal plates that have an air or vacuum gap of thickness g and an additional insulator material of thickness b between the plates. The electrostatic field in the gap is given by the formula:

$$E=(V/300)/(g+b/\kappa) \quad (2.9)$$

where κ is the relative dielectric constant of the insulation material. The factor 300 is used to convert the voltage in volts to stat-volts. The electrostatic charge, esu, is measured in stat-volts per centimeter. A spherical particle of diameter d (cm) in contact with the metal plate can acquire a charge q :

$$q=0.42 E d^2 \text{ esu} \quad (2.10)$$

because of the electrostatic field (Cooper et al 1990 b). The characteristic time for the particle to reach charge equilibrium is equal to the product of the permittivity of the medium and the bulk receptivity of the particle material. The particle will experience a force (dynes) of

$$F=0.42 E^2 d^2 \quad (2.11)$$

in the gap. On the surface, the particle experiences less repulsive force because of the offsetting effects of image attraction, etc. The net force for a fully charged particle will

then be (Cooper et al., 1990 b)

$$F = 0.34 E^2 d^2 \quad (2.12)$$

Fig. 2-5 Capacitor geometry (Cooper et al., 1990a)

Fields of hundreds of kV/cm should be sufficient to remove micron particles; fields of 1MV or greater are needed to remove submicron particles (Cooper et al., 1990 b). The resistivity of the substrate influences the rate at which the particles charge. Eventually, even very resistive substrates allow complete charging, as the substrate surface touching the particles reaches the same potential as its other surfaces. The resistivity of the particle also influences the rate at which the particles charge (Cooper et al., 1990 b). Hendricks found that the characteristic time for the particle to reach charge equilibrium on the surface would be independent of particle size but approximately equal to the product of the permittivity of the medium and the bulk resistivity of the particle material. For metals and carbon, the characteristic time is less than 1 μ s; for SiO₂ it is on

the order of a minute; for some organic polymer plastics it is on the order of days (Cooper et al., 1990 a).

In a study of surface cleaning by electrostatic removal of particles, Copper tested an electrostatic cleaner, which is schematically showed in Fig.2-6 (Cooper et al., 1990 b).

Fig. 2-6 Schematic diagram of the electrostatic film cleaner (Cooper et al. 1990)

The DC power supply keeps the roller at a few thousand volts. A thin polymer film passes between the roller and the product surface. The roller's speed is adjusted for the product and the degree of difficulty of cleaning. The product is kept at or near ground potential by its contact with the grounded plate. The migration of charge to the product surface also charges the particles, which are then attracted toward the roller, onto the film. Once deposited on the film, the particles are pulled with the film to a take-up roller, from which the film can be discarded later.

In practice, it appears that the electric field only needs a few seconds rather than a few minutes to transfer enough charge across an insulating product to charge up the particles. Given enough time, an insulator becomes grounded throughout. It was found that 0.5 μm dry SiO_2 particles can be totally removed from metal surfaces in a few seconds; the same removal result was found on glass plates, but in 15 minutes (Cooper et al., 1990 b). The electrostatic cleaning works best on particles that deposit as solids on dry solid surfaces. If the particles are wet or the surface is wet, then the capillary forces make the particles adhere stronger. The same is true for particles that melt and resolidify. The removal efficiencies are listed in Table 2-3 (Cooper et al., 1990 a).

Table 2-3. Summary of measured removal efficiencies, Electrostatic Film Cleaner (Cooper et al., 1990 a).

Particle diameter (μm)	Particle type	Film used	Removal efficiency (%)	Field (MV/cm)	Voltage (kV)
Conductive surfaces—smooth (specular)					
Metal film					
1.1	Latex	Polyimide	> 46–98	2.8	—
0.5	Latex	Polyimide	> 95	7.0	—
0.5	SiO_2	Polyimide	> 95	8.4	—
Silicon wafer					
6	Ni	Laminate	80–100	—	4
2	SiO_2	Laminate	> 95	—	6
0.5	SiO_2	Laminate	> 80	—	6
Insulator surfaces—smooth (specular)					
SiO_2 (5000Å) on silicon wafer					
2–5	Ni	Laminate	98	—	4
2	SiO_2	Laminate	97	—	3
1	Latex	Laminate	~ 60	—	3
Ceramic substrate					
12	SiO_2	Laminate	96–100	—	10
6	Ni	Laminate	93–100	—	10
Glass plate, 1.5 mm thick					
6	Ni	Laminate	93	—	8
2	SiO_2	Laminate	—	—	8
0.5	SiO_2	Laminate	—	—	8
Insulator surfaces—patterned or rough					
Multilayer ceramic with metal pads					
12	SiO_2	Laminate	97	—	3–4
6	Ni	Laminate	95–99	—	3–4

Table 2-3 shows that the electrostatic film cleaner removed 0.5 μm particles from metal surfaces, 0.5 μm particles from Si wafers, 0.5 μm particles from 1.5 mm thick glass plates, and 1 μm particles from Si wafers with 5000Å SiO_2 coating. It confirms the trend expected: smaller particles require larger fields for successful removal. We can expect that submicron size particles require mega volt per centimeter magnitudes (Cooper et al., 1990 b). Most importantly, the removal of submicron particles can be achieved in various ways without damaging the surfaces, including the use of higher voltages, smaller spacings etc. However, there still remains some practical difficulties for its use in IC manufacturing, such as difficulties associated with prevention of the transfer of minute amounts of material from the contacting insulating film used in the electrostatic film cleaner and difficulties from preventing dielectric breakdown, which produces high-current arcing.

Compared to laser beam technology, electrostatic removal offers several advantages: 1) it can provide relatively larger removal forces; 2) it does not need a jet of high-velocity gas; 3) it is economically more applicable; 4) no liquid or hazardous chemicals are introduced onto the surface. Considering the advantages of electrostatic particle removal, the micro- contamination control group in Applied Materials designed a novel electrostatic particle getter (ESPG1) to clean semiconductor processing equipment and the backside of wafers processed through such equipment.

CHAPTER 3

EXPERIMENTAL DEVICES

3.1 Fixed and mobile electrostatic particle getter (ESPG)

The fixed electrostatic particle getter (ESPG1) and the mobile electrostatic particle getter (ESPG2) used in the experiment are the invention of the microcontamination control group in Applied Materials. The configuration of the fixed ESPG1 and mobile ESPG2 are shown in Fig. 3-1 and 3-2 respectively.

Fig. 3-1 Fixed ESPG1 configuration

Both ESPG1 and ESPG2's functional parts are the same. Each of them is a thin disc comprised of several layers (Fig. 3-3). The outermost surfaces are polyimide on top and silicon on the back. Particles can be attached to the polyimide surface by mechanical

Fig.3-2. Mobile ESPG2 configuration

contact and electrostatic force via locally induced dipoles. The device is edged by an insulating ring, which allows handling without the risk of electrical discharge. The electrostatic force is generated by charging of the embedded copper electrodes. The electrodes are bipolar. Under the electrodes is a metal plate. Once charged, the plate serves as one side of a capacitor. The test wafer is the other side. Discharging will take place prior to cleaning to eliminate the electrostatic force and loosen particles.

Discharging can be accomplished via multiple paths such as grounding, application of equal and opposite charge, and wet cleaning.

Fig.3-3 ESPG's electrode configuration (Applied Materials, 2000)

The application of fixed ESPG1 is to clean the backside of wafers processed through semiconductor equipment (Fig. 3-4). In between two processing steps, wafers will be treated on the ESPG1 outside the processing equipment to reduce backside particles.

The application of mobile ESPG2 is to clean semiconductor equipment (Fig.3-5). ESPG2 will go into the equipment after a certain number of wafers are processed in it to reduce the particles left on the electrostatic chucking (ESC), part of the equipment.

Fig. 3-4 Schematic for fixed ESPG1's application

Fig.3-5 Schematic of ESPG2's application

3.2 KLA Tencor surfscan

All the wafers will be pre-scanned and post-scanned by KLA-Tencor Surfscan SP1, a widely used light-scattering-based wafer surface scanner in the semiconductor industry (Fig. 3-6). It illuminates the wafer surface with a laser beam normal to the wafer, Fig. 3-7. To scan the entire wafer, SP1 rotates and translates the wafer. Any object that scatters light can be detected if an appreciable amount of the scattered light (photons) is collected by a detector: Photo Multiplier Tube (PMT). Through amplifier and signal processing, these signals are converted to the light scattering cross-section that is related to the properties of the particle, the substrate, and the beam (Huang et al. 1999). This cross-section is then converted to a size according to a given calibration curve. Each light-scattering event is counted as a light point defect (LPD). An XY location is assigned to this LPD with respect to a defined coordinate system (Huang et al. 1999). The built-in software in the Tencor Surfscan SP1 analyzes the results of measurements for each wafer automatically and plots a histogram of the number of particles in various scattering cross-section ranges.

Two recipes were developed to detect particles at different ranges of interest; one for particles less than 1 micron, the other for particles less than 10 microns. Map to map comparison of the pre-scan and post-scan of wafers enables us to compare particle removal uniformity and to calculate overall particle removal efficiency or removal efficiency of a specific size range.

Fig.3-6 Schematic diagram of Tencor Surfscan wafer surface scanner (Chae et al. 1992)

Normal Incidence on Smooth Surface

Fig. 3-7 Light scattering of a particle (Chae et al. 1992)

3.3 Scanning electron microscope

A scanning Electron Microscope (SEM) is a microscope that uses electrons rather than light to form an image. Its combination of higher magnification, larger depth of focus, greater resolution, and ease of sample observation makes the SEM one of the most widely used instruments in microscopy. Fig.3-8 shows the heart of the SEM: the electron optics column. The electron beam comes from a filament, made of a tungsten hairpin gun. This filament is a loop of tungsten, which functions as the cathode. A voltage is applied to the loop, causing it to heat up. The anode, which is positive with respect to the filament, forms powerful attractive forces for electrons. This causes electrons to accelerate toward the anode. Some accelerate right by the anode and on down the column, to the sample.

Fig. 3-8 Schematic representation of the Electron Optics Column

When a SEM is used, the column must always be under a vacuum. If the sample is in a gas filled environment, an electron beam cannot be generated or maintained because of a high instability in the beam. Gases could react with the electron source, causing it to burn out, or cause atoms in the gas to ionize, which produces random discharges and leads to instability in the beam. The transmission of the beam through the electron optic column would also be disturbed by the presence of other molecules. Those other molecules, which could come from the sample or the microscope itself, could form compounds and condense on the sample. This would lower the contrast and obscure detail in the image.

The regular SEM used here requires a conductive sample. Non-metallic samples, such as bugs, plants, fingernails, and ceramics need to be coated by gold so that they are electrically conductive. The interaction of electron and specimen is shown in Fig. 3-9. In this research, the Auger electrons were detected to gain compositional information of particles added on to clean wafers by mobile ESPG2.

Fig. 3-9 Electron and specimen interaction (<http://www.mse.iastate.edu/microscopy/>)

CHAPTER 4

EXPERIMENTAL PROCEDURES

4.1 Overview of experimental design

Experiments have been designed to verify the bipolar ESPG's particle removal capability in semiconductor manufacturing. Fig. 4-1 is an overview of the experimental plan. Preliminary experiments were carried out on the charged fixed ESPG1 to find a baseline of particle removal efficiency in an air environment. Preliminary experiments were also carried out on uncharged mobile ESPG2 in a vacuum environment to ensure the ESPG2 would not add particles to chamber's electrostatic chuck (ESC). Cleaning experiments were carried out on mobile ESPG2 in a vacuum environment after the ESPG was megasonic-cleaned, vacuum de-moisturized and charged up. Experiments in which wafers were not in contact with ESPG were also carried out on mobile ESPG2 in an air environment to compare with the experiments in which wafers were in contact with ESPG.

4.2 Preliminary experiments on charged, uncleaned, fixed ESPG1 in an air environment (Exp.A)

The main purpose of the preliminary experiment was to determine if the electrostatic particle removal method is applicable in an air environment. Experiments were first carried out to evaluate the fixed ESPG1's ability of picking up particles small than 5 μm from wafers. A good baseline particle amount was defined as less than 50

adders at 0.300 μm and 10 adders at 1.000 μm . Adders, particles added to the wafer from the EPSG, were calculated from the particle count on the KLA tencor wafer maps.

200mm clean bare Si wafers were used.

Fig.4-1 Experimental design flow chart

The experimental procedures are:

1. Pre-scan clean wafers KLA SP1 tencor
2. Power on ESPG1 to desired voltage
3. Load wafer onto ESPG1
4. Let the wafer and the ESPG1 be in contact for 1 min
5. Turn off power & wait for 10 sec
6. Remove wafer
7. Post-scan processed wafers by KLA SP1 tencor

The variables in the experiment were voltage of ESPG1 and number of times the ESPG1 and wafer were contacted (process cycle), see Table 4-1. Set A was conducted at 500V for a single process cycle. Set B was carried out at 850V to see the effect of a moderate voltage. Set C was aimed to find a baseline at a practically high voltage, 1200V. Set D and E were designed to simulate processing n different wafers repeatedly by processing one wafer n times. Set D was conducted after half of both the D parts of the ESPG1 were cleaned with IPA to see the cleaning effect of IPA.

Table 4-1: Contacting experiments on fixed ESPG1 in an air environment for small particles

Set No.	Wafer No.	Voltage	Process cycle	IPA clean	Polarity switch
A	4 clean	500V	1	N	N
B	4 clean	850V	1	N	Y
C	4 clean	1200V	1	N	Y
D	1 clean	850V	1,5,10	Y	Y
E	1 clean	1200V	1,5,10,30	N	Y

As will be discussed in Chapter 5, the fixed ESPG1 was proved not effective at picking up particles smaller than 5 μm . Therefore, two-factor, two-level, one center-point screen experiments were designed by JMP software to determine its ability to pick up large particles ranging from 1 μm to 20 μm . The design selection dialog is shown in Fig. 4-2. Voltage and process cycles were varied from 500V to 1200V and 1 to 10 respectively. The center point was chosen at 850V and 5 process cycles (Table 4-2).

Fig. 4-2 Screen experiment design selection dialog for large particles

Table 4-2: Contacting experiment on fixed ESPG1 in an air environment for large particles

Pattern	Voltage	Process Cycle	Center Pt
--	500	1	0
+-	500	10	0
+-	1200	1	0
++	1200	10	0
00	850	5	1

4.3 Preliminary experiments on uncharged mobile ESPG2 in vacuum environment (Exp.B & Exp.C)

As will be discussed in chapter 5, ESPG1 could not effectively clean wafers in an air environment. Therefore, mobile ESPG2 was tested under vacuum using a PVD chamber. The removal of particles from an electrostatic chuck (ESC) in the chamber to the ESPG2 was tested. The ESC is a standard chuck for holding wafers in many process tools made by Applied Materials, such as plasma etch systems, high density plasma chemical vapor deposition systems, and ion implanters. They pull the wafer completely flat to achieve a very good cooling efficiency and uniformity and can also reduce particle generation compared to ring-clamps and clips previous used in those systems. The experiments were done with an uncharged mobile ESPG2 before and after megasonic cleaning.

4.3.1 Preliminary experiments before megasonic cleaning (Exp.B)

For the first experiment, the uncharged ESPG2 was not megasonic-cleaned. The experiments were comprised of 2 sets. Set 1 was a baseline experiment, only clean wafers were processed on an ESC in a ceramic PVD chamber. The ESPG2 was not used; this data was to serve as a control. Set 2 was a cleaning experiment; the ESPG2 was processed in between every two clean wafers to see if it could remove particles from the ESC. Process conditions of the clean wafers used in both sets and the ESPG2 are shown in Table 4-3.

The experimental procedures for set 1 are:

1. Pre-scan clean wafers KLA SP1 Tencor
2. Load wafer onto ESC in a PVD chamber
3. Let the wafer and the ESC be in contact for 1 min
4. Remove wafer
5. Post-scan processed wafers by KLA SP1 Tencor

The experimental procedures for set 2 are:

1. ~~Pre-scan clean wafers~~ KLA SP1 Tencor
2. Load wafer onto ESC in a PVD chamber
3. Let the wafer and the ESC be in contact for 1 min
4. Remove wafer
5. Load ESPG2 onto ESC in a PVD chamber

6. Let the ESPG2 and the ESC be in contact for 1 min
7. Remove ESPG2
8. Repeat step 2 to step 7
9. Post-scan processed wafers by KLA SP1 Tencor

Table 4-3: Preliminary experiment condition before megasonic cleaning

	Chuckling Voltage	Chamber Pressure	Backside Pressure	Temp.	Process Time	Process Cycle
Exp. condition for wafer	505V/- 498V	1.00mtorr	14mtorr	142C	1min	6
Exp. condition for ESPG2	1V/-1V	1.00mtorr	14mtorr	142C	1min	5

4.3.2 Megasonic cleaning and de-moisture of mobile ESPG2 (Exp.C)

ESPG2s were cleaned by megasonic method at Prosys company and then de-moisturized in a laminar hood environment to drive out the water that might be absorbed by the polyimide. The treatment conditions are listed in Table 4-4. The treated uncharged ESPG2 was used in the preliminary experiment. The conditions of both clean wafers and the ESPG2 are listed in Table 4-5.

Table 4-4. Megasonic cleaning and de-moisture of ESPG2s

Megasonic cleaning		De-moisturizing chamber	
Cleaning Solution	2% H ₂ O ₂	Pressure	10 ⁻³ to 10 ⁻⁴ torr
	98% DI water		
Cleaning Time	5 minutes	Time	24 hours
Power	1000W		
Rinse Solution	DI water	Temperature	26 C
Rinse Time	5 minutes		
Dry method	Spinning		
Dry time	10 minutes		

Table 4-5: Preliminary experiment condition after megasonic cleaning and etch chamber de-moisture

	ESC Voltage	Chamber Pressure	Backside Pressure	Temp.	Process Time	Process Cycle
Exp. condition for wafer	503V/- 496V	1.00mtorr	14mtorr	147C	1min	7
Exp. condition for ESPG2	1V/-1V	1.00mtorr	14mtorr	147C	1min	5

4.4 Cleaning experiment on charged mobile ESPG2 in vacuum environment (Exp.D & Exp.E)

ESPG2s were megasonic cleaned, de-moisturized in different ways, and charged to different voltages (Table 4-6). Their particle removal efficiency from the ESC was tested under vacuum to confirm the results from Exp.C.

Table 4-6. Treatment of mobile ESPG2

Treatment #	Step 1	Step 2	Step 3
1	Megasonic-cleaning	Etch chamber de-moisturizing	Charging up
2	Megasonic-cleaning	CVD chamber de-moisturizing	Charging up

4.4.1 Cleaning experiments of megasonic-cleaned, etch chamber de-moisturized, and charged ESPG2 (Exp.D)

The cleaning experiments were designed similarly to the preliminary experiments in 4.3.1 and 4.3.3 (Exp.B&C). The ESPG2 was first treated at the conditions listed in Table 4-4 except the de-moisturizing time is 168 hours and then charged up to 900V. The process conditions are shown in Table 4-7.

Table 4-7: Cleaning experiments on megasonic-cleaned and etch chamber de-moisturized ESPG2

	ESC Voltage	Chamber Pressure	Temp.	Process Time	Process Cycle
Exp. condition for wafer	557/-551V	1.80×10^{-4} mtorr	42C	1min	7
Exp. condition for ESPG2	1V/-1V	1.80×10^{-4} mtorr	42C	1min	5

4.4.2 Cleaning experiment of megasonic-cleaned, CVD chamber de-moisturized, and charged ESPG2s (Exp.E)

The ESPG2 used was cleaned at the conditions listed in Table 4-8, charged up to 900V, and then test in a PVD chamber with a low temperature ESC at conditions listed in Table 4-9.

4.4.3 Multi-cycle experiment of megasonic-cleaned and CVD chamber de-moisturized ESPG2 (Exp.F)

The ESPG2 used was cleaned at conditions listed in Table 4-10, and then charged up to 1200V. The wafers processed in the baseline experiment were increased to 25; the ESPG2 was processed 10 times in between every two clean wafers instead of 1 time as in the cleaning experiment in 4.4.2 to verify the result of previous sections. The experiment conditions are shown in Table 4-11.

Table 4-8: Megasonic-cleaning and CVD chamber de-moisturizing conditions for ESPG2

Megasonic cleaning (step 1)		De-moisturizing chamber (step 2)	
Cleaning Solution	2% H ₂ O ₂ 98% DI water	Pressure	1.30×10 ⁻⁷ torr
Cleaning Time	5 minutes	Time	16 hours
Power	1000W		
Rinse Solution	DI water	Temperature	150 C
Rinse Time	5 minutes		
Dry method	Spinning		
Dry time	10 minutes		

Table 4-9: Cleaning experiment on megasonic-cleaned and CVD chamber de-moisturized ESPG2

	Chuckling Voltage	Chamber Pressure	Temp.	Process Time	Process Cycle
Exp. condition for wafer	557/-551V	7.0×10 ⁻⁶ mtorr	36C	1min	6
Exp. condition for ESPG2	1V/-1V	7.0×10 ⁻⁶ mtorr	36C	1min	5

Table 4-10: Megasonic-cleaning and CVD chamber de-moisturizing conditions for ESPG2

Megasonic cleaning (step 1)		De-moisturizing chamber (step 2)	
Cleaning Solution	2% H ₂ O ₂ 98% DI water	Pressure	6.50×10 ⁻⁷ torr
Cleaning Time	5 minutes	Time	21 hours
Power	1000W		
Rinse Solution	DI water	Temperature	155 C
Rinse Time	5 minutes		
Dry method	Spinning		
Dry time	10 minutes		

Table 4-11: Multi ESPG-cycle experiments on megasonic-cleaned and CVD chamber de-moisturized ESPG2

	Chuckling Voltage	Chamber Pressure	Temp.	Process Time	Process Cycle
Exp. condition for wafer	557/-551V	3.10×10 ⁻⁵ mtorr	40C	1min	25
Exp. condition for ESPG2	1V/-1V	3.10×10 ⁻⁵ mtorr	40C	1min	6×10

4.5 Non-contacting experiments on charged mobile ESPG2 (Exp.G)

As will be discussed in chapter 5, the fixed ESPG1 was not effective at picking up particles from wafers and the mobile ESPG2 was not effective at picking up particles from the ESC when they were in contact with wafer or ESC. Therefore, non-contacting experiments were carried out on mobile ESPG2s charged at 900V, 1200V, and 1500V. The ESPG2s were brought as close to wafers contaminated with ESC particles as possible to exclude the mechanical abrasion interference. The experiment conditions are listed in Table 4-12.

Table 4-12: Non-contacting experiment on mobile ESPG2

ESPG2 #	Contaminated Wafer #	Charges of ESPG2s (volts)	Distance between ESPG2 & wafer (mm)
1	1	900	5
2	2	1200	5
3	3	1500	5

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Preliminary experiments on charged uncleaned ESPG1 in an air environment (Exp.A)

The main purpose was to determine the applicability of ESPG1 in an air environment and to find a baseline of particle removal efficiency when the ESPG1 was charged and uncleaned.

5.1.1 Small particle removal experiments

Single and multi process cycle experiments were conducted to test ESPG1's ability of picking up particles less than 5um. The same fixed ESPG1 underwent set A, set B, set C and set E experiments in a chronological order. It then underwent set D experiment with half of each polarity of the polyimide film of the ESPG1 cleaned with IPA. The KLA SP1 Tencor results are shown in Table 5-1 and 5-2. The pre-scan and the post-scan numbers are the particles on clean wafers before and after they were processed on the ESPG1. The adders are the particles added to the clean wafers from the ESPG1 divided by the process cycles. The mean number is the average amount of adders at a certain voltage. Standard Deviation is the square root of the variance. It is calculated as:

$$\text{Std. Deviation} = \sqrt{\frac{\sum (x - M)^2}{N - 1}} \quad (5.1)$$

where M is the mean of the sample, N is the number of measurement.

Table 5-1: SP1 Tencor scan result for 5 um size particles and less in single process cycle experiments

Set	Voltage	Process	IPA	Polarity	Pre-scan	Post-scan	Adders/n	Mean	Std.
No.	Volt	cycle	clean	switch	No.	No.	No.	No.	deviation
A	500	1	N	N	1	361	360	473	96.78
A	500	1	N	N	2	539	537		
A	500	1	N	N	4	572	568		
A	500	1	N	N	3	429	426		
B	850	1	N	Y	5	642	637	633	24.89
B	850	1	N	Y	13	610	597		
B	850	1	N	Y	46	687	641		
B	850	1	N	Y	1	656	655		
C	1200	1	N	Y	4	4170	4166	2856	1243.35
C	1200	1	N	Y	2	2960	2958		
C	1200	1	N	Y	2	2312	2310		
C	1200	1	N	Y	5	1996	1991		

As shown in Table 5-1 and Fig. 5-1, from set A to set C, the higher the applied voltage, the more adders onto the clean wafer. However, within set C adders per process cycle decreased from 4166 to 1991. Particles with adhesion forces that could be overcome by the external electrostatic force were decreasing on the ESPG1 as experiments went on. However, particles with adhesion forces that were too high to overcome would still remain. Even though the ESPG1 was getting cleaner, the 1991 adders were too many to be the baseline for small particle removal. As shown in Table 5-2, in the multi cycle experiment set E, adders per cycle dropped from 2310 to 93 as process cycles increased from 1 to 30 at 1200V. 93 adders could be an acceptable baseline. However, using 30 clean wafers and processing 1 minute on each of them to reach a baseline is too wafer and time consuming thus not economic (Fig. 5-2).

Fig.5-1 Adders per process cycle vs. applied voltage in single process cycle experiments

Table5-2: SP1 Tencor scan result for 5 um size particles and less in multi process cycle experiments

Set No.	Voltage Volt	Chuckling cycle	IPA clean	Polarity switch	Pre-scan No.	Post-scan No.	Adders/n No.
D	850	1	Y	Y	5	793	788
D	850	5	Y	Y	793	992	40
D	850	10	Y	Y	992	2304	131
E	1200	1	N	Y	2	2312	2310
E	1200	5	N	Y	2312	4189	375
E	1200	10	N	Y	4189	5294	110
E	1200	30	N	Y	5294	8080	93

The baseline in an air environment was yet not satisfying. Therefore, in set D, half of each polarity of polyimide film on ESPG1 was cleaned with IPA to see its cleaning efficiency. Adders in set D were still not desirable. As shown in Table 5-2 and Fig. 5-3, in multi cycle experiment set D, adders per process cycle dropped from 788 for 1 process cycle to 40 for 5 process cycles, but it then increased to 131 for 10 process

cycles. Increasing from 40 to 131 could be a mixture result of increasing mechanical abrasion and decreasing capillary force at the surface-water-particle interface as time went on.

Fig. 5-2 Adders per process cycle vs. process cycles at 1200V in multi cycle experiment set E

The overall mean adders per process cycle in multi-process cycle experiment set D was:

$$2304 - 5/(1 + 5 + 10) \cong 144 \quad (5.2)$$

Comparing 144 with 633 (Table 5-3), the overall mean adders per process cycle in single process cycle experiment set B at the same applied voltage (850V), it was concluded that IPA cleaning of the ESPG1 did improve the process. However, the amount of particles added after 10 cycles was still too high for a baseline ESPG1 cleaning process.

Fig. 5-3 Adders per process cycle vs. process cycle at 850V with IPA cleaning in multi cycle experiment set D

Table 5-3: Adder comparison for ESPG1 with and without IPA wiping

	With IPA wiping at 850V	Without IPA wiping at 850V
Adders	144	633

5.1.2 Large particle removal experiment

The ESPG1 was proved not effective at picking up particles less than 5 μm . Therefore, experiments were carried out to evaluate its effectiveness at picking up particles ranging from 1 μm to 20 μm . Experiment results are shown in Table 5-4, the single variable effect and interaction effect are shown in Fig. 5-4. The desirability of this experiment was defined to remove as many particles from the ESPG1 as possible.

As shown in Fig. 5-4, in prediction profile, the slope of process (chucking) cycle was steeper than that of voltage when both were increasing. This indicated that the chucking cycle had more affect on adders to clean wafers. In interaction profiles, when the voltage increased from 500V to 1200V, the slopes for 1, 3.25, 5.5, 7.75, and 10 chucking cycles were almost the same and not intercrossed. When chucking cycle increased from 1 to 10, the slopes for 500V, 675V, 850V, 1025V, and 1200V were getting steeper and steeper, but they were not intercrossed either. In other words, both voltage and process (chucking) cycle had positive effects on adders to clean wafers and they didn't have strong interaction to each other. The process (chucking) cycle's effect was more obvious.

Fig.5-4 Single variable effect and interaction effect on adders

Even though more particles could be removed from the ESPG1 by increasing voltage and process cycles, it was not practical and economic to do so infinitely. Higher voltage would cause arcing and more process cycles would become too time-consuming. As shown in Table 5-4, even at the highest applied voltage 1200V, larger particles added to wafers were not very many. Adders per process cycle decreased from 95 to 40 when the process cycles increased from 1 to 10.

In summary, the fixed ESPG1 was not efficient at picking up larger particles in air either. The focus was then switched to test mobile ESPG2's particle removal efficiency in vacuum environment.

Table 5-4: SP1 Tencor scan result for particles ranging from 1 μm to 20 μm

Voltage	Process Cycle	Pre-scan	Post-scan	Overall Adders	Adders/n
500	1	19	19	0	0
500	10	11	221	210	21
1200	1	4	99	95	95
1200	10	1	404	403	40
850	5	17	179	162	16

5.1.3 Particle removal mechanism

5.1.3.1 Particle removal mechanism in a dry condition

ESPG with a Si wafer on it can be considered as two capacitors in series (Fig 5-5). In a dry condition, the positive electrode and the right side of the Si wafer composes the first capacitor and the negative electrode and the left side of the Si wafer composes the second capacitor. The gap between the Si wafer surface and the electrode is polyimide and air. It is at the millimeter level or even lower. Therefore, when power is supplied, the electrical field in between will be very strong. Since electrostatic force is proportional to the square of the electrical field, it can reach Mega volts level as demonstrated in Table 5-5 and will provide enough force to overcome particle adhesion forces which is only composite of van der Waals force and electrostatic forces in a dry condition.

The electrostatic force between the wafer and the ESPG1 is a pure Coulombic force. It can be calculated as:

$$F_c = \frac{1}{2} A \epsilon_0 \kappa \left(\frac{V}{d} \right)^2 \quad (5.3)$$

A is the contacting area between the wafer surface and the ESPG surface, ϵ_0 is the dielectric constant of the gas gap, κ is the dielectric constant of polyimide film, V is the

Fig 5-5: Fixed ESPG1's working mechanism in a dry condition

applied voltage, and d is the distance between two surfaces. Since the ESPG is bipolar and the diameter of ESPG 200mm; therefore, A is:

$$A = \frac{1}{2}\pi R^2 = \frac{1}{2}\pi(0.01)^2 = 0.000007m^2 \quad (5.4)$$

Assuming the air gap is 50um, then the Coulomb forces of different applied voltages are shown in Table 5-5.

Table 5-5. Coulomb forces of different applied voltages between wafer and ESPG's surfaces

Applied voltages (V)	500	850	1200
Coulomb force (Fc)	1.24×10^9	3.58×10^9	7.14×10^9

The Coulomb force works differently on particles carrying a net charge and neutral dielectric particles as shown in Fig 5-6. For particles carrying a net charge, each polar attracts particles charged oppositely and repels particles charged with the same polarity. For neutral dielectric particles, dipoles are formed when they are exposed to the applied external electric field, which means a positive and a negative charge of the same numerical value at a fixed distance are formed within the particles. The field from the dipoles will be superimposed on the external field resulting in a lowered field strength and an alignment of the particles with the external field.

A) For particles carrying a net charge

B) For neutral dielectric particles

Fig.5-6. Coulomb force between wafer and ESPG

As the applied voltage increases, the particles carrying opposite net charge to the polarity they face are subjected to an increasing repulsive force. Particles are repelled from uncleaned ESPG1's surface even though particles carrying the same net charge are held on to the ESPG1 surface. More and more particles are accumulated on the clean wafers as experiments are carried out. Meanwhile, the polarity of the ESPG1 is switched

for every process cycle in multi-process cycle experiment to improve particle removal uniformity. The particles are therefore forced to bounce between the ESPG1 and the clean wafers' surfaces instead of moving toward either surface. This resulted in much lower particle adding in the multi process cycle experiments shown in Table 5-2. For example, 93 particles per cycle were added to clean wafers in the 30 multi-cycle process, while 2310 particles per cycle were added to clean wafers in the single cycle process.

5.1.3.2 Particle removal mechanism in a wet condition

After the ESPG1's polyimide was wiped with isopropyl alcohol (IPA), the mechanism for particle removal may have changed due to residual liquid on the surface. Where there was no water film, the electrical field and force would be identical to that in a dry condition. Where there was a liquid film over the substrate, the liquid film, together with the polyimide surface could be considered as one plate of the capacitors, see Fig. 5-7. Voltage drop within liquid films would be very small or near zero. Thus, the electrostatic force would be very weak or near zero. Particles carrying a net charge would then experience a smaller force; neutral particles would develop a weaker dipole. Meanwhile, the water left over by isopropyl alcohol wiping gave rise to capillary force to the polyimide-water-particle interface making it harder to remove particles on a wet-cleaned ESPG1. With the decreasing electrostatic force and the additional capillary force, adders on clean wafers processed on IPA wiped ESPG1 were less than on non-IPA wiped ESPG1 (Table 5-3).

Fig.5-7 Fixed ESPG1's working mechanism in a wet condition

5.2 Preliminary experiment on uncharged mobile ESPG2 in vacuum

5.2.1 Experiments on uncharged mobile ESPG2 before megasonic cleaning

The experiments were comprised of 2 sets. Set 1 was a baseline experiment with only clean wafers processed in a PVD chamber. It is shown in the first part of Table 5-6. Set 2 was a cleaning experiment with ESPG2 processed in between every two clean wafers. It is shown in the second part of Table 5-6. Both the clean wafers and the ESPG2 were processed at 142C and 1.00 mtorr for 1 minute. However, the ESC voltage for the clean wafers was 505/-498V and the one for the ESPG was 1/-1V. Pre-scan and post-scan counted particles on the clean wafers before and after processing. Adders were the particles added to the clean wafers. They decreased from 863 to 515 in the baseline

experiment (set 1), but increased from 515 to 1393 in the cleaning experiment (set 2) as shown in both Table 5-6 and Fig. 5-8. This could be a sign that ESPG2 without charging didn't work at all, or could be that the ESPG2 was saturated with particles before we processed.

Wafer # 6 in the set 1 experiment and wafer # 2 in the set 2 experiment were analyzed with SEM/EDS to check whether ESPG2 added abnormal particles onto the chamber's ESC. The ESC's surface is an AlN ceramic thin film. Wafer # 6 and 2 went into chamber before and after ESPG2. The particle analysis data is summarized below in Table 5-7. The scanning pictures are shown in Fig 5-9. Each light-scattering event is counted as a light point defect (LPD).

Wafer # 2 has 2 times more particles than wafer # 6. As shown in Fig. 5-9, TiN₂, C, SiO₂, P, and Si particles were found on wafer # 6. Al, Al₂O₃, and SiO₂, Si, F and K were found on wafer # 2. Al, Al₂O₃, TiN₂ and SiO₂ are commonly founded particles in this type of process chamber and K might come from human contact. P and F probably come from the slit valve and O ring. All in all, the ESPG2 before megasonic cleaning did not add uncommon particles to chamber.

Table 5-6: SP1 Tencor scan result of preliminary experiment on uncharged mobile ESPG2 before megasonic cleaning

Wafer	Temp.	Time	Voltage	Chamber Press.	Pre-scan	Post-scan	Adders
(ESPG)	(C)	(Min)	(Volt)	(mtorr)			
1	142	1	505/-498	1.00	5	868	863
2	142	1	505/-498	1.00	10	552	542
3	142	1	505/-498	1.00	9	668	659
4	142	1	505/-498	1.00	5	528	523
5	142	1	505/-498	1.00	5	565	560
6(1)	142	1	505/-498	1.00	9	524	515
E2	142	1	1/-1	1.00			
2	142	1	505/-498	1.00	7	930	923
E2	142	1	1/-1	1.00			
3	142	1	505/-498	1.00	10	997	987
E2	142	1	1/-1	1.00			
4	142	1	505/-498	1.00	11	1196	1185
E2	142	1	1/-1	1.00			
5	142	1	505/-498	1.00	7	1092	1085
E2	142	1	1/-1	1.00			
6	142	1	505/-498	1.00	5	1398	1393

5.2.2 Experiments on uncharged ESPG2 after megasonic cleaning and etch chamber de-moisture (Exp.C)

The experiments were designed similar to the one in 5.2.1. Set 1 was a baseline experiment with only clean wafers processed in a PVD chamber. It is shown in the first part of Table 5-8. Set 2 was a cleaning experiment with megasonic-cleaned and etch chamber de-moisturized ESPG2 processed in between every two clean wafers. It is shown in the second part of Table 5-8. Both the clean wafers and the ESPG2 were

Fig.5-8 Preliminary experiment of uncharged mobile ESPG2 before megasonic cleaning

Fig. 5-9: Particle composition comparison of wafer # 2 & 6.

Table 5-7: SEM/ analysis results of adders on wafer # 2 & 6.

Particle/Defect No.	Wafer # 6 before ESPG2		Wafer #1 after ESPG2	
	Particle/Defect Composition	LPD size	Particle/Defect Composition	LPD size
1	C, N, O, Ti	0.3	(O), Al	61.2
2	C, N, O, Ti	1.3	O, Al	0.8
3	C, N, O, Ti	1	O, Al	0.5
4	C, N, O, Ti	0.6	O, Al, K	1.1
5	C, N, O, Ti	1.8	O, Al, K	1.5
6	C, O	1.9	O, F, Al	1.2
7	C, O	0.6	O, Si	889
8	C, O	1.5	O, Si	0.8
9	C, O	1.4	O, Si	0.4
10	C, O, P, Ni	0.7	O, Si	0.7
11	C, O, P, Ni	13.1	O, Si	0.9
12	C, O, P, Ni	0.6	O, Si	0.3
13	O, Al	3.6	O, Si	0.6
14	O, Si	0.9	Si	414
15	Si	2.3	Si	1.6
16	Si	0.3	Si	7
17	Si	0.3	Si	7.5
18	Si	2.5	Si	78.8
19	Si	0.6	Si	20.2
20	Si	0.4	Si	0.3

processed at 147C and 1.00 mtorr for 1 minute. However, the ESC voltage for the clean wafers was 503/-496V and the one for ESPG was 1/-1V. Comparing Table 5-8 and Table 5-6, we can see that adders on clean wafers decreased from 952 to 761 when a cleaned ESPG2 was inserted while adders increased from 515 to 1393 when a non-cleaned ESPG2 was inserted. As shown in Fig. 5-11, when a cleaned ESPG2 was inserted, the constants of the exponential fitting curves' equation (1567.1 and 1028.4) are very close. However; they are very different (-194.79 and 435.25) when a non-cleaned ESPG2 was

inserted (Fig 5-8). All these confirm the result in 5.2.1 and show that the megasonic cleaned and etch chamber de-moisturized ESPG2 did not add particles to the chamber's ESC and did not necessary move particles from the ESC either.

Sample ID: wafer # 6

Sample ID: wafer # 2

Fig.5-10 Scanning pictures of adders on wafer # 2 & 6

Table 5-8: SP1 Tencor result of the experiment on uncharged ESPG2 after megasonic cleaning and etch chamber de-moisture

Wafer (ESPG)	Temp. C	Time Min	Press. mtorr	Voltage Volt	Pre-scan	Post-scan	Added
1	147	1	1.00	503/-498	7	1509	1502
2	147	1	1.00	503/-498	4	1322	1318
3	147	1	1.00	503/-498	12	1006	994
4	147	1	1.00	503/-498	10	938	928
5	147	1	1.00	503/-498	9	841	832
6	147	1	1.00	503/-498	4	983	979
7	147	1	1.00	503/-498	7	771	764
1	147	1	1.00	503/-498	10	962	952
E2	147	1	1.00	1/-1			
2	147	1	1.00	503/-498	15	933	918
E2	147	1	1.00	1/-1			
3	147	1	1.00	503/-498	18	904	886
E2	147	1	1.00	1/-1			
4	147	1	1.00	503/-498	23	852	829
E2	147	1	1.00	1/-1			
5	147	1	1.00	503/-498	6	780	774
E2	147	1	1.00	1/-1			
6	147	1	1.00	503/-498	2	763	761

5.3 Cleaning experiments on charged ESPG2 in vacuum

5.3.1 Experiments on megasonic-cleaned, etch chamber de-moisturized, and 900V charged ESPG2 (Exp.D)

The cleaning experiments were designed similarly to the preliminary experiments in 5.2.1 and 5.2.2 (Exp.B & Exp.C) to find out whether cleaned and charged ESPG2 could remove particles from an ESC. Set 1 was a baseline experiment with only

Fig. 5-11 Megasonic-cleaned, etch chamber de-moisturized uncharged ESPG2 particle removal result

clean wafers processed in a PVD chamber. It is shown in the first part of Table 5-9. Set 2 was a cleaning experiment with megasonic-cleaned, etch chamber de-moisturized, and 900V charged ESPG2 processed in between every two clean wafers. It is shown in the second part of Table 5-9. Both the clean wafers and the ESPG2 were processed at 42C and 1.80×10^{-4} mtorr for 1 minute. However, the ESC voltage for clean wafers was 557/-551V and the one for ESPG was 1/-1V. Table 5-9 shows that adders onto clean wafers in both sets decreased. However, as shown in Fig. 5-12, the trend line equation constant's absolute value (363.19) in set 1 when the ESPG2 was not inserted was just slightly smaller than 530.5, the absolute value when the ESPG2 was inserted. We concluded that the treated ESPG2 was not effective at picking up particles from chamber's ESC.

Table 5-9. SP1 Tencor result of the cleaning experiment on megasonic-cleaned, etch chamber de-moisturized, and charged mobile ESPG2

Wafer (ESPG)	Temp. C	Time Min	Voltage Volt			
				Pre-scan	Post-scan	Added
1	42	1	557/-551	0	3795	3795
2	42	1	557/-551	10	3683	3673
3	42	1	557/-551	1	3284	3283
4	42	1	557/-551	9	3362	3353
5	42	1	557/-551	12	3230	3218
6	42	1	557/-551	7	3301	3294
7	42	1	557/-551	4	3081	3077
1	42	1	557/-551	5	3761	3756
E2	42	1	1/-1			
2	42	1	557/-551	3	3303	3300
E2	42	1	1/-1			
3	42	1	557/-551	9	3138	3129
E2	42	1	1/-1			
4	42	1	557/-551	3	2964	2961
E2	42	1	1/-1			
5	42	1	557/-551	13	2932	2919
E2	42	1	1/-1			
6	42	1	557/-551	4	2785	2781

5.3.2 Experiment on megasonic-cleaned, CVD chamber de-moisturized, and 900V charged ESPG2 (Exp.E)

The experiment set up was the same as that of 5.3.1 (Exp. D) except that the ESPG2 was CVD chamber de-moisturized. Set 1 was a baseline experiment with only clean wafers processed in a PVD chamber. It is shown in the first part of Table 5-10. Set 2 was a cleaning experiment with megasonic-cleaned, CVD chamber de-moisturized, and 900V charged ESPG2 processed in between every two clean wafers. It is shown in the

second part of Table 5-10. Both the clean wafers and the ESPG2 were processed at 36C and 7.0×10^{-6} mtorr for 1 minute. However, the ESC voltage for clean wafers was 557/-551V and the one for ESPG was 1/-1V. The same decreasing trend of adders onto clean wafers was found in this experiment (Table 5-10) like the one found in Exp. D (Table 5-9). As shown in Fig 5-15, the absolute value of the trend line constant for set 1 when the ESPG2 was not inserted, 555.68, was also just slightly smaller than 817.68, the absolute value when the ESPG2 was inserted. This confirmed that the cleaned and charged ESPG2 was not effective at picking up particles from ESC.

Fig. 5-12 Megasonic-cleaned, etch chamber de-moisturized, and 900V charged ESPG2

Table 5-10. Experiment result of megasonic-cleaned, CVD chamber de-moisturized and 900V charged ESPG2

Wafer (ESPG)	Temp. C	Time Min	Voltage Volt	Pre-scan	Post-scan	Added
1	36	1	557/-551	1886	3795	1909
2	36	1	557/-551	2295	3683	1388
3	36	1	557/-551	2270	3284	1198
4	36	1	557/-551	2227	3362	1135
5	36	1	557/-551	2244	3230	1014
6	36	1	557/-551	2350	3301	986
1	36	1	557/-551	2025	3761	1736
E2	36	1	1/-1			
2	36	1	557/-551	1837	3138	1301
E2	36	1	1/-1			
3	36	1	557/-551	2145	3303	1158
E2	36	1	1/-1			
4	36	1	557/-551	2431	2964	533
E2	36	1	1/-1			
5	36	1	557/-551	2271	2785	514
E2	36	1	1/-1			
6	36	1	557/-551	2626	2932	306

5.3.3 Multi-experiment with megasonic-cleaned, CVD chamber de-moisturized, and 1200V charged ESPG2 (Exp.F)

The cleaning experiments were carried out on a large scale to further confirm the results in 5.3.1 and 5.3.2 (Exp. D & Exp. E). Set 1 was a baseline experiment with 25 clean wafers processed in a PVD chamber. It is shown in the first part of Table 5-11. Set 2 was a cleaning experiment with a megasonic-cleaned, CVD chamber de-moisturized, and 1200V charged ESPG2 processed in between every two clean wafers. It is shown in the second part of Table 5-11. Both the clean wafers and the ESPG2 were processed at

40C and 3.10×10^{-5} mtorr for 1 minute. However, the ESC voltage for clean wafers was 557/-551V and the one for ESPG was 1/-1V. The result is shown in Table 5-11 and Fig. 5-14. The decreasing trend of adders onto the clean wafers was confirmed in Table 5-11. The closeness of the absolute values of both sets' trendline equation constants (380.09 for set 1, 445.33 for set 2) further confirmed that the varied-way treated ESPG2 was not effective at removing particles from chamber's ESC. Particles bounced between ESC's surface and the ESPG2's surface rather than be removed from the ESC's surface because of the ESPG2's bipolar nature, as discussed in 5.1.3.

Fig. 5-13 Megasonic cleaned, CVD chamber de-moisturized, and 900V charged ESPG2

Table 5-11. SPI Tencor result of the multi-experiment on megasonic-cleaned, CVD chamber de-moisturized, and 1200V charged ESPG2

Final	Temp.	Time	Voltage	Pre-scan	Post-scan	Adders
position	C	Min	Volt			
1	42	1	503/-496	40	3004	2964
2	42	1	503/-496	6	2660	2654
3	42	1	503/-496	7	2664	2657
4	42	1	503/-496	22	2613	2591
5	42	1	503/-496	17	2561	2544
6	42	1	503/-496	3	2363	2360
7	42	1	503/-496	4	2350	2346
8	42	1	503/-496	10	2221	2211
9	42	1	503/-496	8	2309	2301
10	42	1	503/-496	5	2303	2298
11	42	1	503/-496	6	2270	2264
12	42	1	503/-496	5	2186	2181
13	42	1	503/-496	9	2131	2122
14	42	1	503/-496	18	2069	2051
15	42	1	503/-496	5	2113	2108
16	42	1	503/-496	9	1959	1950
17	42	1	503/-496	14	1968	1954
18	42	1	503/-496	5	1851	1846
19	42	1	503/-496	6	1819	1813
20	42	1	503/-496	6	1976	1970
21	42	1	503/-496	11	1820	1809
22	42	1	503/-496	33	2037	2004
23	42	1	503/-496	24	1878	1854
24	42	1	503/-496	4	1735	1731
25	42	1	503/-496	8	1700	1692
1	42	1	503/-496	9	2758	2749
E2	42	1	503/-496			
2	42	1	503/-496	4	2304	2300
E2	42	1	503/-496			
3	42	1	503/-496	9	2053	2044
	42	1	503/-496			
4	42	1	503/-496	19	1990	1971

E2	42	1	503/-496			
5	42	1	503/-496	12	1966	1954
E2	42	1	503/-496			
6	42	1	503/-496	14	1926	1912
E2	42	1	503/-496			
7	42	1	503/-496	5	1861	1856

Fig.5-14. Multi-experiment with megasonic-cleaned, CVD chamber de-moisturized, and 1200V charged ESPG2

5.4 Non-contacting experiments on charged mobile ESPG2s

When wafers were not in contact with ESPG2, the mechanical abrasion effect was eliminated. However, the charged mobile ESPG2 was not effective either (Table 5-12). This could be resulting from the experiment limitation: 5-mm big gap between

wafer and ESPG2's surface. The coulomb forces (Table 5-13) were four orders of magnitude less than the ones in the contacting experiment.

Table 5-12: Non-contacting experiment result

Wafer No.	voltage(V)	Pre-scan	Post-scan	removed
1	900	1509	1469	40
2	1200	1322	1331	-9
3	1500	1006	1040	-34

Table 5-13: The external electrostatic forces in non-contacting experiments

Applied voltage (V)	900	1200	1500
Coulomb force (Fc)	1.57×10^5	2.80×10^5	4.37×10^5

5.5 Conclusion and recommendation

Both dry and wet ESPG were not effective at removing particles in an air or a vacuum environment. Its bipolar nature was the main reason that it failed. The residual liquid in the ESPG could be the other reason. The capillary force's effect can be eliminated by baking the ESPG at higher temperature and longer time and monitoring the process with residual gas analyzer. As discussed theoretically in 5.1.3, the added external electrostatic force was strong enough to overcome particles' adhesion forces. Therefore, the particle-bouncing problem should be able to be prevented by changing the ESPG to mono-polar design. The particles dislodged by the electrostatic force can be dragged

away by adding an external inert gas flow between wafer and ESPG. Further research could be done in the three aspects mentioned above.

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