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Controlling Electrostatic Attraction of Particles in Production Equipment

Douglas W. Cooper, *Texwipe*

Robert P. Donovan, *Sandia National Laboratories*

Arnold Steinman, *Ion Systems*

Among users and manufacturers of semiconductor production equipment, the effects of electrostatic surface charge are well known. Electrostatic discharge (ESD) damages both products and reticles. ESD events also result in unwanted electromagnetic interference (EMI), causing equipment to malfunction. These problems are widely discussed in the literature of the semiconductor, disk drive and flat panel display industries.^{1,2,3}

Also important are the effects of static charge that impact contamination control. Charged wafer and reticle surfaces attract particles (electrostatic attraction or ESA) and increase the defect rate. In this article, we review the issues involved in particle deposition enhanced by static charge. The calculations contained here form the basis for recommendations contained in Semiconductor Equipment and Materials International (SEMI) Document E78-0998, "Electrostatic Compatibility — Guide to Assess and Control Electrostatic Discharge (ESD) and Electrostatic Attraction (ESA) for Equipment," recently balloted by SEMI Standards.

The charged wafer

The presence of a net electrical charge on a wafer can create an electrostatic field that accelerates the deposition of particles onto the wafer. Particle deposition velocity (which is equal to the surface particle flux divided by the aerosol particle concentration) increases with growing wafer charge. It has been shown that particle deposition rates onto wafers in a manufacturing environment closely follow theoretical predictions.^{4,5} A clear increase in particle deposition on charged wafers in this kind of environment, exposed in an area of controlled particle concentrations, has been observed and documented.⁶

The ESA of particles is contingent upon the electrostatic field created by the charge on an object's surface. Electrostatic particle deposition velocity is also subject to particle size, shape and charge. The concentration of particles deposited on a surface depends on the aerosol particle concentration in the area and the exposure time during which particle deposition occurs.

Mechanisms other than electrostatic deposition — gravitational settling and diffusion — can also contribute to particle deposition. The concentration of particles deposited by these non-electrostatic mechanisms also varies with aerosol particle concentration in the ambient and exposure time. Comparing the electrostatic particle deposition velocity with that of these other mechanisms is the key to determining threshold values of allowed electrostatic field from the view-point of particle deposition.

Threshold values for electrostatically enhanced particle deposition can then be combined with assumptions regarding ambient aerosol particle concentrations and product exposure times. These calculations yield allowed values of electrostatic field — the levels that will not significantly increase the deposition of particles onto critical surfaces.⁷

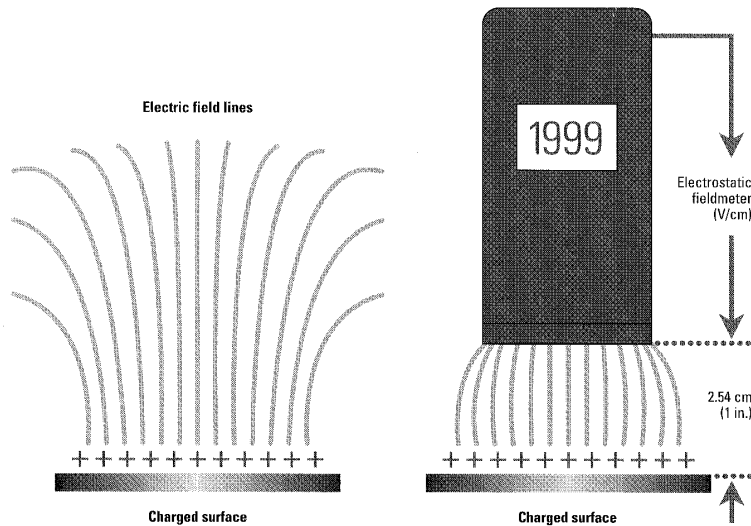


Figure 1. *The nature of an object — whether it is an insulator or a conductor — and its geometry, surroundings and often the presence of the measuring equipment itself, can affect the accuracy of electric field measurements. (Source: Ion Systems)*

Theoretical background

Diffusion is the dominant nonelectrostatic mechanism of particle deposition, at standard temperatures and pressures, for particle sizes ranging from 0.01 to 0.3 μm . Thus, electrostatic field values that do not produce particle deposition velocities (v_{elect}) greater than those attributable to particle diffusion (v_{diff}) are deemed tolerable.

Although there are various electrostatic interactions between particles and surfaces, the dominant one is almost always the “Coulombic” interaction: the attraction (or repulsion) of a charged particle by a charged surface. The attractive Coulomb interaction, in which net surface charge is of opposite polarity to net charge on adjacent aerosol particles, is the only electrostatic effect considered here.

For particles of charge, q , the particle deposition flux, j (the number of particles deposited per unit area per unit time), is the product of aerosol particle concentration, c ; the electric field created by the charged wafer, E ; and particle mechanical mobility, B :

$$j = cqEB \quad (1)$$

The group qEB is the “electrostatic deposition velocity,” v_{elect}

$$v_{\text{elect}} = qEB = j/c \quad (2)$$

where v_{elect} values are calculated for comparison with those of v_{diff} , the particle deposition velocity attributable to particle diffusion and values of E for which $v_{\text{elect}} < v_{\text{diff}}$ are those considered tolerable in wafer manufacturing.

Note that the total number of particles, N , deposited on a wafer, obtained by integrating equation (1) over the wafer area, A , and the time of exposure, t , depends on c as well as the deposition velocity:

$$N = cqEBA t \text{ or}$$

$$N/A = ctv_{\text{elect}} \text{ (3)}$$

Typical values of particle charge

There are many charging and discharging mechanisms for particles, so q is difficult to predict and highly variable. In a normal atmosphere, positive and negative air ions tend to have roughly equal effectiveness in charging particles, so the number of positively charged particles is roughly equal to that of negatively charged particles. Thus, approximately half the particles are attracted and half repelled by a net charge on the wafer. Special circumstances, such as unbalanced corona discharge ionizers, could alter this result. Without ionizers, cleanrooms tend to have few ions compared to the outdoors or other indoor atmospheres, because HEPA/ULPA filters efficiently remove them from the recirculating air.

A Boltzmann charge equilibrium, the charge distribution approximated by aerosol particles exiting a radioactive neutralizer, is a plausible *lower limit* for particle charge. An improved version of this distribution, derived by Fuchs, is assumed in the calculations of v_{elect}^8 ; assuming higher values of particle charge usually means that $v_{\text{elect}} > v_{\text{diff}}$ for virtually any value of $E > 0$ and that the only method for avoiding electrostatically enhanced particle deposition is to reduce wafer charge to zero.

Surface electrostatic field

The electrostatic field, E , in equations (1)-(3) is the electric field in the wafer surface’s vicinity, created by charges on the wafer. This electrostatic field depends on the charge on the wafer divided by a quantity with the units of length squared; either a distance squared (far from the wafer) or an area (close to the wafer) or some combination at intermediate distances. The criterion of interest is not the allowable charge on the wafer; it is the resulting electrostatic field near the wafer surface, E_0 , evaluated at a distance of less than or equal to one radius perpendicular to the wafer surface above its center. A tolerable value of E_0 , $E_0 \text{ (tol)}$, is estimated by calculating the maximum E_0 values for which $v_{\text{elect}} < v_0$, assuming a Fuchs distribution for the particle charge.

Table 1. Tolerable Levels of Electrostatic Field at a Distance of Less Than or Equal to One Radius from the Center of a Wafer	
Minimum Particle Diameter, d μm	Tolerable Field, E_0 Volts/cm
0.01	15
0.02	21
0.03	26
0.05	34
0.10	47
0.20	67
0.30	82

Table 2. Calculation of Tolerable Electrostatic Field $E_0(\text{tol})$
<p>V_{diff}</p> <p>For a wafer perpendicular to the laminar airflow in a cleanroom, references I-m support the following approximation:</p> <p>The diffusional deposition velocity is about 0.006 cm/sec at particle diameter of 0.25 μm and about 0.03 cm/sec at particle diameter of 0.01 μm or:</p> $V_{\text{diff}} = (0.03 \text{ cm/sec})(d/0.01 \mu\text{m})^{1/2} \quad (4)$ <p>For 0.01 $\mu\text{m} < d < 0.3 \mu\text{m}$ in cleanroom air.</p>
<p>V_{elect}</p> <p>From reference d, using the Fuchs particle charge distribution, the electrical mobility, qB is approximated by:</p> $qB = (0.002 \text{ cm/sec})/(d/0.01 \mu\text{m})(1 \text{ V/cm}) \quad (5)$ <p>Substituting in Equation (2):</p> $V_{\text{elect}} = (0.002 \text{ cm/sec})[E_0/(\text{V/cm})]/(d/0.01 \mu\text{m}) \quad (6)$
<p>$E_0(\text{tol})$</p> <p>Setting $v_{\text{elect}}/v_{\text{diff}} = 1$, the maximum value of E_0 for which $v_{\text{elect}} \square v_{\text{diff}}$ (the tolerable value of E_0):</p> $[E_0(\text{tol})/(\text{V/cm})] = 15 [d/(0.01 \mu\text{m})]^{1/2} \quad (7)$ <p>Values of $E_0(\text{tol})$ for various particle sizes are shown in Table 1.</p>

Table 1 lists the calculated values (see also Table 2) of a tolerable electrostatic field adjacent to a wafer surface. Note that electrostatic fields are calculated at a distance of one wafer radius from the center of the wafer. $E_0(\text{tol})$ is the value of the field at that distance for which electrostatically enhanced particle deposition is estimated to match the particle deposition velocity attributable to diffusion, assuming a Fuchs charge distribution on the particles. This charge distribution represents a minimal particle charge. Balanced ionization to achieve the Fuchs charge distribution on the aerosol particles in the wafer environment is the first step in controlling particle deposition on wafers. Using ionization to neutralize charge in a manufacturing area also reduces wafer charge and the resulting electrostatic field.

As indicated in Table 1, the calculated value of tolerable electrostatic field is just 47 V/cm for particles of 0.1 μm diameter, assuming the minimal Fuchs particle charge distribution. This minimum value of particle charge is normally exceeded in most environments, hence the conclusion that electrical forces are the dominant mechanism of particle deposition on wafers.

In a Federal Standard 209E Class 1 environment (maximum $c = 0.00124$ particles/cm³ for particle size 0.1 μm and greater), with $v_{\text{elect}} \approx 0.01$ cm/s (the value predicted by equation (6) for a 0.1 μm particle in an electric field of 47 Volts/cm), the target areal particle density ($N/A = 0.016$ particles/cm² for the 0.25 μm technology of 1998), specified in the 1994 National Technology Roadmap for Semiconductors, is reached after an exposure time of about 1300 seconds.⁹ This calculation is made using equation (3).

With less favorable electrical conditions or higher ambient particle levels, the maximum allowed exposure time becomes shorter. Target values for N/A continue to decrease with each technology generation, shortening allowed exposure time. Fortunately, one or more of the following variables can be controlled: particle concentration in the ambient, time a charged surface is exposed to a given particle ambient and charge level on a surface.

Measurement methods and instrumentation

SEMI Document E78-0998, "Electrostatic Compatibility — Guide to Assess and Control Electrostatic Discharge (ESD) and Electrostatic Attraction (ESA) for Equipment," was recently approved by the SEMI standards membership.⁷ The recommended electrostatic field levels in this guide for minimizing electrostatically enhanced particle deposition are based on the analyses reviewed here.

There is no single method of testing for static charge to determine a "safe" level. The amount of static charge, the distribution of static charge on an object and the nature of the static discharge all interact to determine if the charge level is safe. It is difficult to determine levels at which *guaranteed* static-related problems are totally eliminated. The broader scope of the SEMI guide is to help the user identify static charge levels that cause problems of any type (ESD and ESD-caused EMI, in addition to particle deposition) in process equipment, and recommend methods to control static charge below these problem levels.

Electrostatic attraction of particles depends on the electrostatic field created by the charge on the surface of an object, and the particle size, shape and electrical charge. Unfortunately, even under controlled laboratory conditions, accurate measurements of electric field strength, particle size and shape distribution, and particle charge, are difficult. Of these parameters, electric field measurements, made with a commonly available electrostatic fieldmeter, are the most likely to be available. The accuracy of electric field measurements is affected by the nature of the object (insulator or a conductor), its geometry, its surroundings and the presence of the measuring equipment itself. This is shown in Figure 1. SEMI Method E43 is a test method describing measurement techniques using an electrostatic fieldmeter.¹⁰

Electrostatic deposition velocity depends on the electric field, while the number of actual particles deposited also depends on the aerosol particle concentration in the equipment/area and the length of the exposure time during which particle deposition occurs. For the purposes of the SEMI Guide, some basic assumptions are made about aerosol particle concentrations and exposure times to make it possible to specify the allowable field measurements.

Tolerable electrostatic field levels

Starting from equation (3), $N/A = cv_{\text{elect}}t$, where N/A is the areal density of particles added to a wafer during exposure time t , exposed to an aerosol particle concentration c , in an environment characterized by an electrostatic particle deposition velocity v_{elect} . The only variable in equation (3) that depends on electrical forces is v_{elect} . Both particle charge and the electric field in the vicinity of the wafer affect the magnitude of v_{elect} .

Having a target value of N/A and estimating the value of v_{elect} , as outlined previously, allows calculation of the tolerable value of ct and, by assuming the aerosol particle concentration, t:

$$ct = [N/A]/v_{\text{elect}} \quad (8)$$

Equation (8) calculates target values of ct by setting N/A = 0.016 particles/cm² (as specified for 0.25 μm technology) and using Equation (6) to calculate v_{elect} for 0.1 μm particles, with a Fuchs charge distribution at various values of electric field. The allowed exposure times in a Federal Standard 209E Class 1 environment (c ≤ 0.00124 particles/cm³, size 0.1 μm and greater) can be deduced (Table 3). Using higher values of N/A in equation (8) increases the acceptable values of ct and max t; alternatively, higher values of c reduce max t.

Table 3. Electrostatic Field Limits Proposed in the SEMI Guide				
E V/cm at 2.5 cm	N/A defects per cm²	V_{elect} cm/sec	ct sec/cm³	max t in 209E Class 1 sec
4000	0.016	0.21	0.0762	61
400	0.016	0.021	0.762	610
200	0.016	0.0105	1.524	1220

The value of the electrostatic field calculated in Table 1 is at a distance of less than or equal to one wafer radius away from the wafer. Assuming a uniform charge distribution, the electrostatic field should not change rapidly as the distance decreases (e.g., from 10 cm to 2.5 cm). While electrostatic field measurements can be made at one wafer radius, they are typically made at 2.5 cm with common instrumentation. Measurements made with a fieldmeter at this smaller distance will be higher, but it is difficult to determine a precise relationship between electric field and measurement distance.

To provide the values contained in the SEMI guide, a linear relationship is assumed, since the fieldmeter makes measurements in volts/cm. For example, with a 200 mm wafer, 4000 Volts/cm at 2.5 cm would correspond to 1000 Volts/cm at 10 cm.

The limits contained in Table 3's first column are chosen to limit the number of particles that deposit on a product surface for a given set of conditions. Table 3 may be used to determine the tolerable electric field measured on objects, given the ambient particle level (assumed for a cleanroom class) and exposure time (based on a knowledge of a particular cleanroom process). The end user and manufacturer of the equipment involved need to collaboratively determine the appropriate conditions for using this table.

At the upper extreme, higher fields are tolerated because there are few particles present or product is exposed in the ambient for short periods of time. At the lower extreme, lower values of field are required due to relatively high concentrations of particles (possibly due to process), long exposure times (e.g., for cooling), or the high relative cost of even a single defect (e.g., a flat panel display screen).

Conclusion

Deposition of submicron particles on wafers is very sensitive to electrical charges on the particles and wafers. Coulomb attraction dominates the electrical interaction when the wafer and particle charges are of opposite polarities. The values of electric field adjacent to the wafer surface, below which electrostatic forces do not dominate particle deposition velocity, are calculated and shown to be less than 100 V/cm even for “neutralized” particles. Charge neutralization of particles and wafers is essential in minimizing the electrostatic contribution in virtually all practical manufacturing scenarios.

SEMI Document E78-0998 describes the elements of a static control program: these include grounding, static dissipative materials and air ionization. These elements are supported by personnel training and regular program audits. SEMI’s guide relies on the calculations and conclusions presented here to recommend maximum values of electric field adjacent to wafer surfaces during entry and exit from processing equipment and while in transport between equipment.

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Arnold Steinman is CTO for Ion Systems in Berkeley, Calif., where he has been responsible for the design of the company's static control products. He holds four patents covering air ionizer technology and is a member of the Board of Directors of the ESD Association. Steinman graduated from Polytechnic Institute of Brooklyn, receiving both IEEE and MSEE degrees.

Dr. Douglas W. Cooper is the director of contamination control at The Texwipe Co. He is involved in R&D relating to advanced cleaning materials including reduction of chemical, particulate and biological contaminants. He is the author or co-author of over 100 articles. Cooper received his doctorate from Harvard in applied physics in 1974.

Robert P. Donovan is a process engineer assigned to the Sandia National Laboratories as a contract employee by L & M Technologies Inc. His project work is developing technology for recycling spent rinse waters from wet benches.