Journal of Electrostatics 86 (2017) 50–58

Contents lists available at ScienceDirect

Journal of Electrostatics

journal homepage: www.elsevier.com/locate/elstat

A finite element analysis of multiple ion receiving plates for ionizer balance monitoring

S. Plong-ngooluam [a,*], N. Jindapetch [b], P. Wounchoum [b], D. Sompongse [a]

[a] Western Digital (Thailand) Company Limited, 140 Moo 2, BangPa-in Industrial Estate, Klongjig, Bangpa-in, Ayuthaya, 13160, Thailand
[b] Department of Electrical Engineering, Faculty of Engineering, Prince of Songkla University, Hat Yai, Songkhla, 90112, Thailand

ARTICLE INFO

Article history:
Received 11 July 2016
Received in revised form
8 January 2017
Accepted 18 January 2017

Keywords:
Electrostatic potential
Finite element analysis
Ion balance
Multiple ion receiving plates

ABSTRACT

This paper reports a finite element analysis of multiple ion receiving plates to investigate the optimum number of plates for achieving fine-grained resolution in ionizer balance measurement. Both square and circular plates, also subdivided into 4, 9, 16, 25, and 36 segment plates, were modeled in an electrostatic field. The potential distribution of each model was further analyzed by simple linear regression to assess the measurement resolution. The results indicate that the segmented plates provide improved measurement resolution.

1. Introduction

Ionizers are necessary to eliminate undesirable charges in the production lines of electrostatic discharge (ESD) sensitive devices [1]. The charge separation and accumulation models [2] were extended by Robinson et al. to identify electric charges present in manufacturing processes, and to provide methods to eliminate the undesirable charges [3]. Grounding is a general method to dissipate electrostatic charges to the ground and to achieve equipotential conditions. However, it is not effective against static charges on insulating surfaces or in isolated conductive particles [3–5]. Instead, air ionization is used to remove these static charges by providing the opposite polarity ions to attract the static charges on the object surfaces until the static charges are neutralized.

For measuring such ionizing performance, ANSI/ESD STM3.1 [6] provides the standard test method (STM) for ionizer evaluation and selection. This STM requires a charged plate monitor (CPM) for ion balance measurement to identify the equilibrium of positive and negative ions. This characteristic is defined by the voltage induced on a standard charged plate, which is a floated 15 cm × 15 cm square shaped conductive surface. The size of this plate agreed with a typical silicon wafer at the time of drafting the standard, in the late 1980s [7]. However, the current electronics manufacturers are comparatively tiny devices, such as integrated circuits or magnetoresistive heads. These devices are sensitive to ESD damage at low voltage levels, so the ionizer balance must be less than ±1 V or even better [8]. The sub-1V ion balance environment requires sufficient resolution and accuracy in determining the ion balance of an ionizer [9]. The standard charged plate has insufficient resolution in ion balance measurement, because the measurement plate is larger than the devices to be treated. Therefore miniaturized ion balance analyzers were launched to serve the sub-1V measurements, such as the ionizer controller in US patents US 6,985,346 B2 [10], US 7,522,402 B2 [11], and the biased-plate monitor [12]. However, these analyzers do not characterize the ion balance over a 15 cm × 15 cm area as the conventional plate does. Their results only represent a single point at a time. Such point measurements are insufficient because the ion distribution in the transport region depends on drift and airflow velocities, as in the Ohsawa's ionizer models [13–15] that are based on electrohydrodynamics. The ions are distributed according to their spatial motility, which depends on air velocity, ion mobility, diffusion, and ion-ion recombination factors. The wafer surface charge monitor (CHARM) [16] offered the ability to measure the charging characteristics on the wafer surface by using multiple charge collection plates. Then, simulations in Ref. [17] were used to investigate smooth changes in the electrostatic potential distribution as measured by multiple plates. The results indicated that measurement errors could be reduced by

* Corresponding author. Tel.: +6635 35 278 772; fax: +6635 278 050.
E-mail address: Sayan.Plong-ngoolaum@wdc.com (S. Plong-ngooluam).

http://dx.doi.org/10.1016/j.elstat.2017.01.011
0304-3886/

using multiple plates. However, those simulations did not resolve fully the subdivision to multiple plates. Shape and number of segments should be investigated to determine a reasonable number of segments based on measurement performance and practicality. The experimental results in Ref. [18] validated the hypothesis that ion balance measurement resolution could be improved by using multiple plates. The multiple plate measurement results could resolve the ion balance distribution at a fine-grained level not possible with the standard CPM. Moreover, the experiment also revealed good correlation between the average over multiple plates and the standard CPM results. Furthermore, a feasibility study [19] evaluated measurements of ionized air with multiple ion-receiving plates. The eventual voltage on each plate was measured by a commercial electrostatic voltmeter. The results proved that multiple ion receiving plates offered fine-grained spatial resolution and the average voltage correlated well with the results from standard CPM.

In this work, the electrostatic behavior of multiple plates was analyzed by the finite element method and statistical analysis, to determine the changes of the electrostatic potential in the quantitative results. Simple linear regression (SLR) was used to estimate the gain and offset errors, while the goodness of fit indicates the confidence level of the linear regression models. Furthermore, circular and square shaped plates were modeled and compared, to investigate shape effects. The results help to select suitable plates for improving the resolution of ionizer balance measurements.

2. Ion receiving plate and its curvature effect

This section describes the relationship of electrostatic field and electrostatic potential, the characteristics of conductive surfaces when they are used as ion receiving plates in ion balance measurements, and curvature effects on the accuracy of the ion balance measurement.

2.1. Electrostatic field, flux, potential and their relationship

The Gauss's law [20] explains that the electrostatic field flux through any closed surface of free space is equal to the total charge enclosed by that surface. By the divergence theorem, this requires locally that

$$\nabla \cdot \mathbf{E} = \frac{\rho_v}{\varepsilon_0}, \tag{1}$$

where $\mathbf{E}$ is electrostatic field, ρ_v is volume charge density, and ε_0 is permittivity of free space.

The electrostatic field $\mathbf{E}$ is related to the electrostatic potential V by

$$\mathbf{E} = -\nabla V. \tag{2}$$

Since, the electrostatic field $\mathbf{E}$ in (2) depends on the permittivity of free space, the vector field $\mathbf{D}$ is electrostatic displacement or electrostatic flux density defined by

$$\mathbf{D} = \varepsilon_0 \mathbf{E}. \tag{3}$$

This electrostatic flux $\mathbf{D}$ is properly scaled for the flow of electrostatic field through a given area. It is proportional to the number of electrostatic field lines through a surface element, as shown in Fig. 1.

2.2. Ion receiving plate

The conductive surface S which is orthogonally exposed to an electrostatic field $\mathbf{E}$ is able to collect the charge Q. This collected charge is directly proportional to the electrostatic field tangential to such surface E_s as

$$Q = \varepsilon_0 \varepsilon_r E_s S, \tag{4}$$

where ε_r is the relative permittivity of the environment around the surface S.

The electrostatic potential V on this surface is directly proportional to the charge quantity Q, but inversely proportional to the capacitance C as

$$V = \frac{Q}{C}. \tag{5}$$

The measurement of this electrostatic potential has been used as the charge induced meter for observing the electrostatic field [8,27–30]. In the ion balance measurement, the charge Q is accumulated from positive and negative ions, when this surface is exposed to ionized air. It is then called an ion receiving plate. In this situation, the charge Q on the ion receiving plate is the integral of the neutralizing current $i_n(t)$ and proportional to the voltage V across the plate as

$$V = \frac{1}{C} \int_{t_0}^{t} i_n(t)\, dt + V_0, \tag{6}$$

where V_0 is the initial voltage of the ion receiving plate.

The neutralizing current $i_n(t)$ is the flow rate of the charge Q as is contributed by the positive and the negative ions. Their motions in the transport region [15] are given by

$$i_n(t) = -e \int_{v} \left(n_p \mathbf{v}_p - n_n \mathbf{v}_n - D_p \nabla n_p + D_n \nabla n_n \right) \cdot \mathbf{e}_L \, dv, \tag{7}$$

where e is the elementary charge, v is the system volume, n_p and n_n are the positive and negative ion densities, respectively. Here, $\mathbf{v}_p$ and $\mathbf{v}_n$ are positive and negative ion velocities composed of the air and the drift velocities. D_p and D_n are the positive and the negative ion diffusion coefficients, respectively. $\mathbf{e}_L$ is the Laplace field when unit voltage is applied to the plate.

2.3. Curvature effect

The charge Q on the conductor surface, which is not necessary to be closed, is obtained by integrating the surface density ρ_s over all differential surface elements dS as

$$Q = \int_S \rho_s \, dS. \tag{8}$$

The surface charge density in (8) is non-uniform because the surface charges are distributed to create an equipotential surface or equivalently to eliminate the electric field tangential to the surface E_s by their distribution. Thus the surface charge density ρ_s is described by

$$\rho_s = \varepsilon_0 E_s. \tag{9}$$

The surface charges near a convex edge of the conductor are denser than elsewhere on the surface. Then, the electrostatic field density and the electric flux are maximal, as in region A of Fig. 1. On the other hand, the electrostatic field and the electric flux are minimal at concave edges as in region B of Fig. 1. This phenomenon has been applied to corner detection as described in Ref. [22]. Thus