

SEMI AUX021-0611 ELECTROSTATICS GUIDE

The information in this document has been furnished by the SEMI International ESD/ESC Task Force, operating under the auspices of the SEMI Standards Metrics Committee, for informational use only and is subject to change without notice. The Semiconductor Equipment and Materials International (SEMI) Standards Program is publishing this information as furnished by the task force in the form of Auxiliary Information so that it may be referenced by the industry, as desired. **No material in this document is to be construed as an official or adopted standard.** SEMI assumes no liability for the content of this document, which is the sole responsibility of the authors, nor for any errors or inaccuracies that may appear in this document. SEMI grants permission to reproduce and distribute this document provided that:

- (1) the document is maintained in its original form, and
- (2) this disclaimer and the notice below accompany the document at all times.

NOTICE: By publication of this document, SEMI takes no position respecting the validity of any patent rights or copyrights asserted in connection with any item mentioned herein. Users of this document are expressly advised that determination of any such patent rights or copyrights, and the risk of infringement of such rights, are entirely their own responsibility.

Copyright 2011 by SEMI (Semiconductor Equipment and Materials International, 3081 Zanker Road, San Jose, CA 95134). See above for information on limited rights for reproduction and distribution; all other rights reserved.

Foreword

This auxiliary information document was written to provide basic electrostatics knowledge that relates to SEMI Standards for electrostatic charge, discharge, and attraction (i.e., SEMI E78 and SEMI E129). It was written by Thomas Sebald (Estion) and Maciej Noras (University of North Carolina – Charlotte), with editing assistance from the members of the ESD Task Force in the North America Metrics Committee of the SEMI Standards Program. Development of this document started in 2007 and was completed in 2010.

1 Correlation between Electric Charge, Electric Field, and Electric Potential

By Thomas Sebal, Estion GmbH & Co. KG

Physical interrelations between the electric charge (measured in Coulombs), the electric field (measured in volt/meter, or volts/cm or volts/inch), and the electric potential (measured in Volts), especially regarding the measurement techniques in the area of electrostatics, are not always clear. Therefore, we will here try to clarify these correlations by showing their interrelations rather than the mathematic explanations.

There are several different approaches to these interrelations. Since we are discussing basic principles of electrostatics, our starting point should be the primary electrical property, the electric charge (Q).

1.1 Electric Charge

The electric charge is a property of the electrons (negative) and the protons (positive) which compose all matter¹. Charge is measured in units of Coulombs [C]. One electron holds a charge of approximately 1.602×10^{-19} Coulombs. This means that an accumulation of approx. 6.242×10^{18} ($=1/1.602 \times 10^{-19}$) electrons makes up a charge of -1 Coulomb.

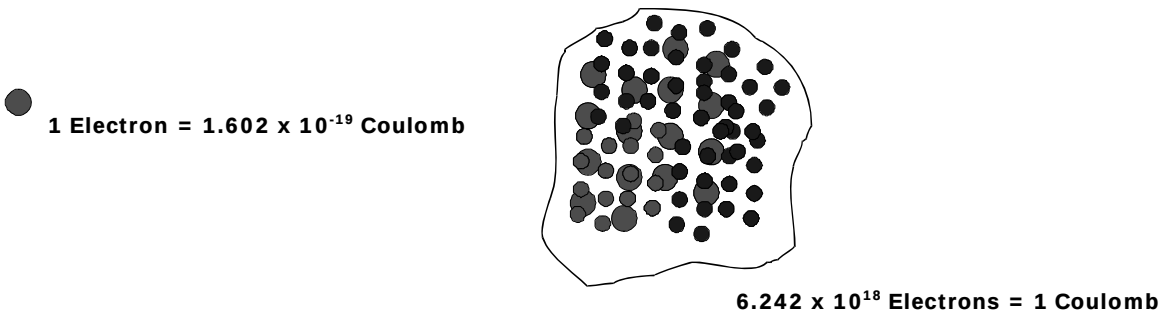


Figure 1
Electric Charge

We can superimpose these electrons on, for example, an electrically neutral² solid metal ball. A metal is, as generally known, as an electrical conductor. Electroconductivity means that electrons can more or less freely move within a material. So if we deposit the electrons on the metal ball, they will evenly spread across the entire surface of the ball. They will blend in with the equally free-moving valence electrons³ of the metal atoms. The reason for this equal distribution is an interaction between charged particles. This interaction is called the Coulomb interaction. Particles which are charged with the same polarity repel each other. Thus, the electrons on the metal ball will repel each other and spread evenly across the entire surface without moving inside of the metal body.

¹ The smaller elements („Quarks“) forming the basis of it will not be regarded any further, here. We will also, as far as possible, refrain from a quantum-physical view and use classical physics as the basis of all measuring technique.

² In electrically neutral matter the amount of protons and electrons is equal. In the macroscopic scale it appears neutral.

³ Valence electrons” means the more or less free electrons of the outmost orbit of an atom.

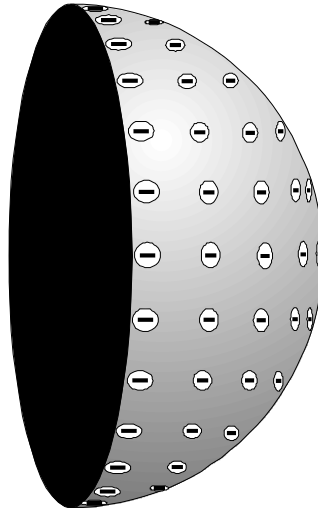


Figure 2
On A Conducting Body the Charges are Evenly Spread Across the Surface

If 6.242×10^{18} electrons are removed from an electrically neutral metal ball, its metal lattice will carry more protons than electrons giving it a positive charge. As a result of the electrons being removed, this ball now holds a charge of +1 Coulomb. Since the atoms, containing the protons in their nuclei are not free-moving, the reduced population of electrons left will spread evenly across the surface of the electrical conductor. Notes that this applies only to a smooth spherical surface. If there are edges or sharp points, the charge will concentrate in these locations.

Example:

A metal ball with a diameter of 20 cm (about the size of a volley ball) has approximately 2×10^{18} surface atoms. To positively charge this ball with 1 Coulomb, three valence electrons would have to be removed from each surface atom. In reality it is impossible to produce a charge that large owing to the enormous self repulsive force that would result. Under normal air conditions, one electron can be removed from (or applied to) every 10^{10} th surface atom maximum! Thus, such a volley-ball-sized metal ball can carry a maximum charge of approx. 32×10^{-12} Coulomb = 32 pC.

In non-conductors (or insulators) the electrons are fixed, and do not move freely. Thus, a surplus of electrons (negative charge) and a shortage of electrons (positive charge) can exist at different places on the surface of insulators at the same time.

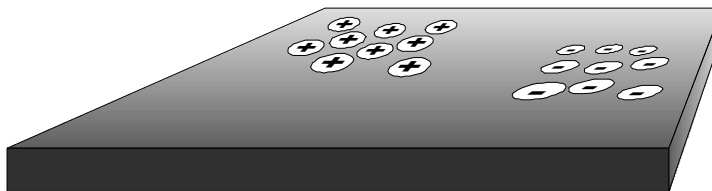


Figure 3
On A Non-Conductor Different Charges And Polarities Can Exist Simultaneously

In this case, closer examination of the surface will show islands of positive and negative charges on the object. It may appear neutral from far away if the total amount of positive and negative charges are equal.

Before we can talk about the measurement of charges we should take a closer look at the interactions between charges mentioned earlier – the Coulomb force. For this purpose the term “electric field” lends itself.

1.2 Electric Field

One should notice that the term “field” is a conceptual quantity helping to describe interactions between the charges (the electrostatic forces of repulsion and attraction).

The interaction between two charged bodies, called the Coulomb force and is described in ¶ 1.1. It is the repulsive force between like charged bodies, and the attractive force for oppositely charged bodies. This force is a remote action, meaning that it is effective over any distance—but weaker over greater distances.

This force is described by the Coulomb’s law:

$$F = \frac{1}{4\pi\epsilon_0} \frac{q_1 q_2}{R^2} \quad (\text{Equation 1-1})$$

Here ϵ_0 is the permittivity of free space with ($\epsilon_0 = 8.8542 \times 10^{-12} [\text{C}^2 / \text{N m}^2]$), q_1 and q_2 are the two interacting amounts of charge, and R is the distance between the two centers of both charges. This center of charge is an abstract concept as well. This single charge replaces the charge distributed over the surface of a real body by a point charge concentrated inside in the center of that body producing the same force at a distance much greater than the dimensions of the original object.

In order to illustrate the term “electric field” we will use the example of two metal balls and apply a certain quantity of electrons to one of them to make it negatively charged, and remove the same quantity of electrons from the other ball, making it positively charged. Let us assume that the diameter of each ball is 10 mm and that they are fixed in a big room at a distance of 1 m from each other. Placing a single electron close to the surface of the negatively charged ball, at the position on the ball’s surface that is closest to the positive ball, causes a repulsive force on the electron, by the negative ball and an attractive force by the positive ball. (Note that this is a theoretical exercise, since one single electron could never exist in the air. We will therefore ignore the influence of the air environment). It is important to note that although the electron would travel from negative to positive, the convention for the corresponding field lines is that they are shown from positive to negative.

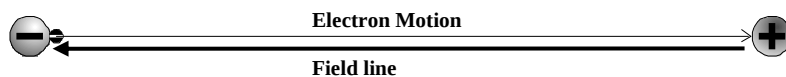


Figure 4

The Trajectory of a Free Electron Starting at the Point Closest to the Ball with Opposite Polarity

If we place the electron at a different point on the surface of the negative ball we will observe a different force magnitude and direction toward the positive ball. If we represent all of the magnitudes and directions of the force per unit charge acting on such a free electron, we will get the image of the “field lines” of a system of charges (in this case: of two commensurate but oppositely charged balls).

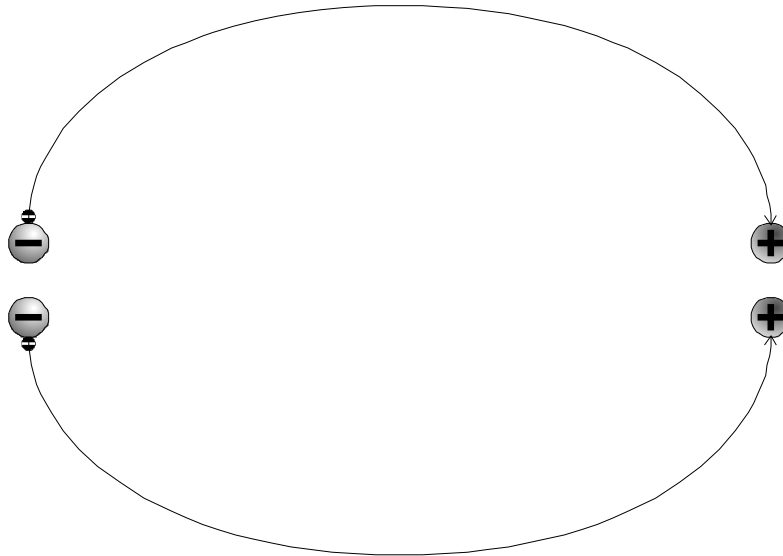


Figure 5
Electric Force Lines

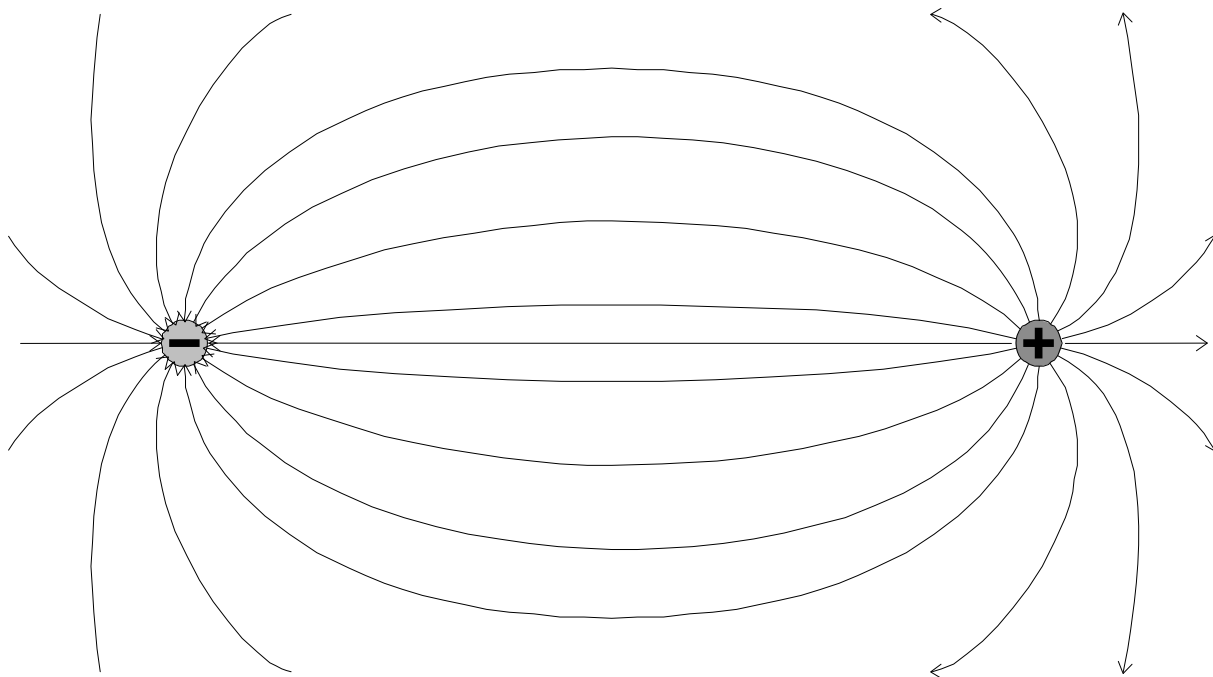


Figure 6
Electric Force Lines

Thus, the electric field is defined as the electric force affecting a charge. More precisely, it is the force per amount of charge at one particular point in space.

The above illustrations show that this force has a direction—and, of course, a certain intensity.

Therefore, the electrical field E at the point P is defined as:

$$E = \frac{F_e}{q} \quad \text{(Equation 1-2)}$$

This equation shows that the unit of the electric field can be measured in “Newtons per Coulomb”[N/C]. Another form of unit will be explained in ¶ 1.6.

It is essential to know that the electric field created by the two charged balls in space becomes greater as the difference of charge between the two balls increases. If 1000 electrons (1.602×10^{-16} Coulombs) were removed or deposited on the ball the resulting field would be less strong compared to the case that 100,000 electrons (1.602×10^{-14} Coulombs) were added or subtracted. The form of the field stays the same but the intensity increases proportionally to the difference of charge at each point—this means that the free electron takes the same route but moves faster at a greater difference of charge between the two balls.

Before giving an example, we should take a look at the influence the electric field has on an electric conductor. We have already learned that in an electric conductor the valence electrons are free to move. One could visualize the electrons whirling around the fixed lattice atoms like gas particles. Now, consider only one of the aforementioned balls, negatively charged and placed at a set distance in front of a metal plate. It is obvious that a remote action (Coulomb force) from the charged metal ball will affect the free-moving electrons on the metal plate. The electrons will be repelled by the negative charge of the ball and pushed to the rear side of the plate. This charge movement within the conductor is called electrostatic induction. If now the electric field is determined by means of a free electron and its trajectory, one will observe that this electric field is formed in the same way as if there was a positively charged ball, with the same amount of charge as the field-creating negative ball, behind the metal plate. This is referred to as „mirror charge“, which is just an illustrative term.

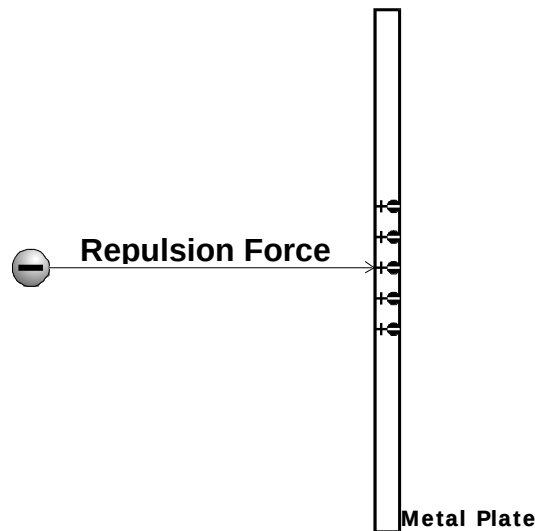


Figure 7
An Electrically Charged Body Induces a Shift of Electrons Within a Metal Plate
due to the Remote Action of the Coulomb Power

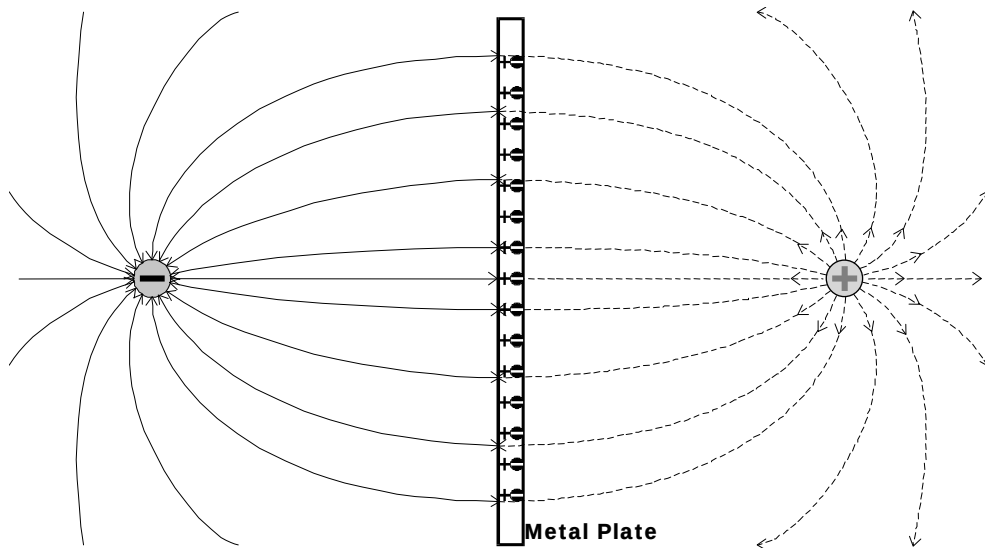


Figure 8
The Resulting Electric Field is of the Same Geometry and Intensity as if There was an Equally Strong but opposite Polar Charge Behind the Metal Plate (Imaginary Mirror Charge)

It is essential to understand that such shift of the charge is induced in any conductor near a field producing charge and that this shift of charge in turn considerably affects the geometry of the field.

Example:

The previous example of the two balls reveals that the electric field depends strongly on the geometric structure of the charges which create the field. Consider the following example:

Imagine a plastic window which is positively charged by friction. More precisely, during the friction process electrons were removed from the plastic surface (while the friction-partner—for example a dry wipe—now gains these electrons). Assume that 5×10^4 electrons were evenly removed from the square area of $10 \text{ cm} \times 10 \text{ cm}$ at the center of this $1 \text{ m} \times 1 \text{ m}$ plastic window. Thus, this area carries a charge of $+0.8 \times 10^{-14} \text{ C} = +0.008 \text{ pC}$.

Suppose that at a distance of 1 m , there is a grounded metal wall. After what has been explained so far we can conclude that the field lines (opposite to the force on a free negative charge) would appear as shown in Figure 9.

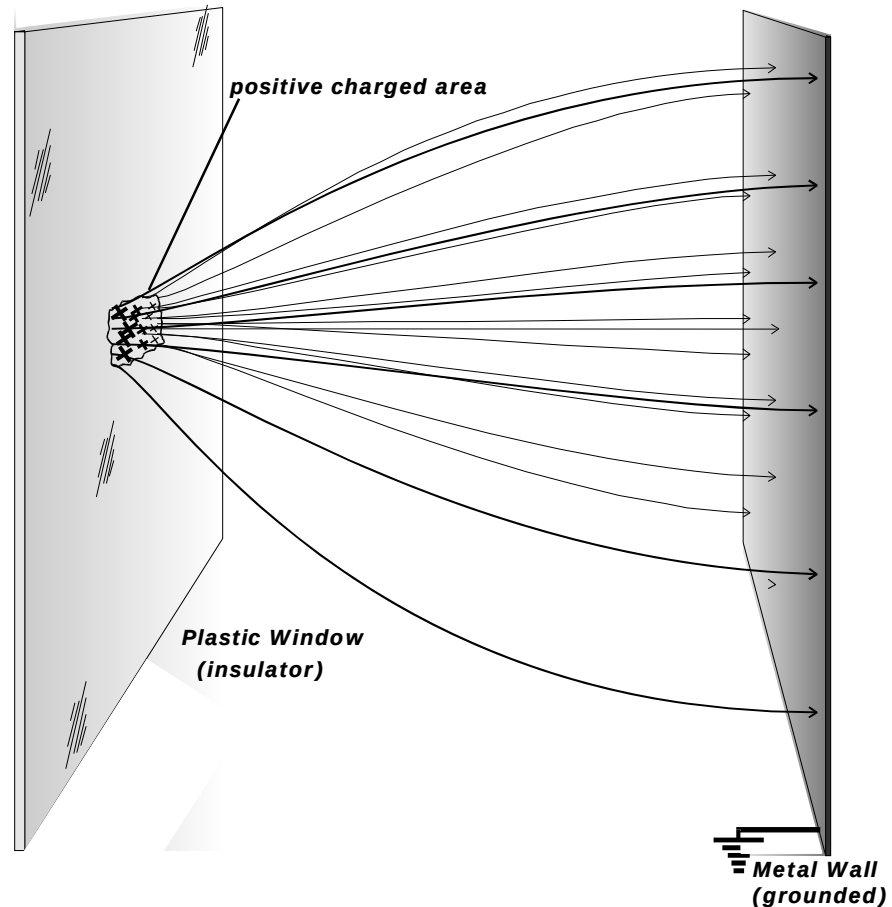


Figure 9
Electric Field Between a Charged Dielectric and a Ground Plane

This picture shows that the intensity of the electric field, or the force acting on an electric charge, increases towards the charged area on the plastic plate (field-generating charge) and decreases close to the grounded metal wall. The direction of the field lines describes the direction of the force and that their density describes the relative intensity of the electric force.

1.3 Correlation between Electric Charge and Electric Field

Based on the correlation between the Coulomb force on a charge q (as mathematically described above) and the definition of the field, the following mathematical descriptions of an ideal situation of a charge (Q) in an infinitely large volume and the resulting field (E) is given by:

$$\text{Coulomb force: } F = \frac{1}{4\pi\epsilon_0} \frac{qQ}{R^2} \quad (\text{Equation 1-3})$$

$$\text{Definition of the field: } E = \frac{F}{q} \quad (\text{Equation 1-4})$$

The electrical field E of the point charge Q_1 and at a distance R_1 is:

$$E = \frac{1}{4\pi\epsilon_0} \frac{Q}{R^2} \quad (\text{Equation 1-5})$$