



## SEMI AUX021-0611 ELECTROSTATICS GUIDE

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### 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

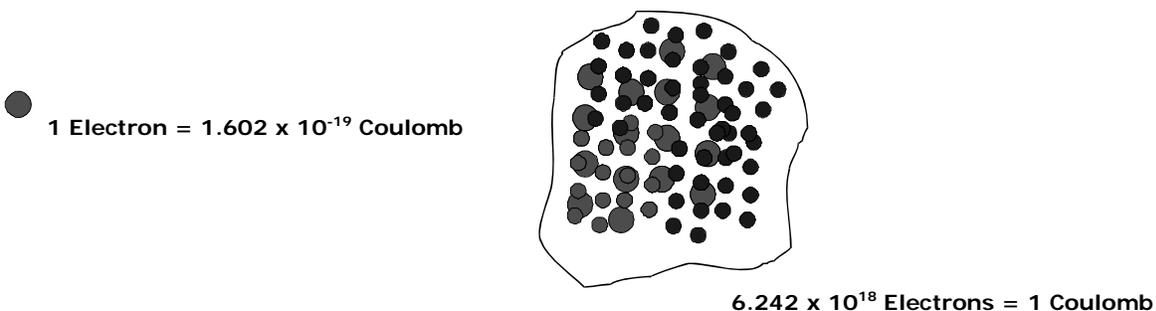
By Thomas Sebald, Estion GmbH & Co. KG

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 matter<sup>1</sup>. Charge is measured in units of Coulombs [C]. One electron holds a charge of approximately  $1.602 \times 10^{-19}$  Coulombs. This means that an accumulation of approx.  $6.242 \times 10^{18}$  ( $=1/1.602 \times 10^{-19}$ ) electrons makes up a charge of  $-1$  Coulomb.



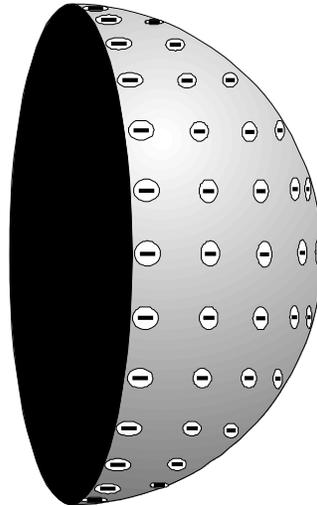
**Figure 1**  
**Electric Charge**

We can superimpose these electrons on, for example, an electrically neutral<sup>2</sup> 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 electrons<sup>3</sup> 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.

<sup>1</sup> 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.

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

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



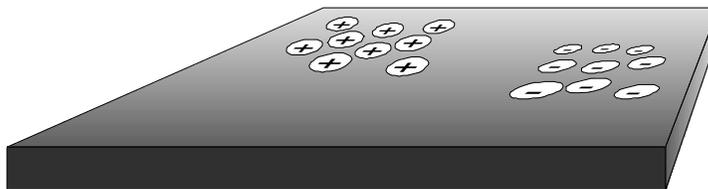
**Figure 2**  
**On A Conducting Body the Charges are Evenly Spread Across the Surface**

If  $6.242 \times 10^{18}$  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  $2 \times 10^{18}$  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.  $32 \times 10^{-12}$  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).

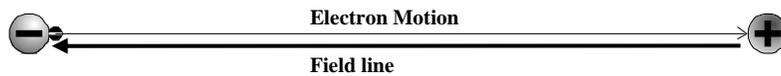
The interaction between two charged bodies, called the Coulomb force and is described in ¶ 1.1. It is the repulsive force between like charged bodies, and the attractive force for oppositely charged bodies. This force is a remote action, meaning that it is effective over any distance—but weaker over 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  $\epsilon_0$  is the permittivity of free space with ( $\epsilon_0 = 8.8542 \times 10^{-12} \text{ [C}^2 / \text{N m}^2\text{]}$ ),  $q_1$  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.

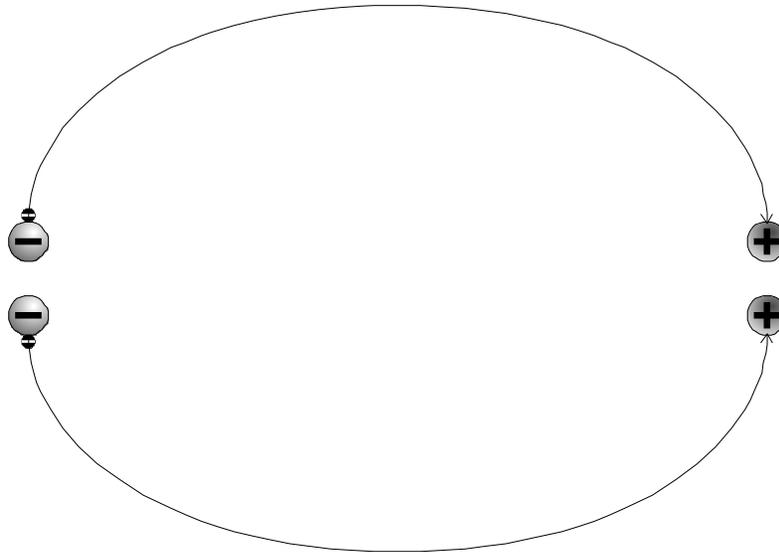
In order to illustrate the term “electric field” we will use the example of two metal balls and apply a certain quantity of electrons to one of them to make it negatively charged, and remove the same quantity of electrons from the other ball, making it positively charged. Let us assume that the diameter 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.



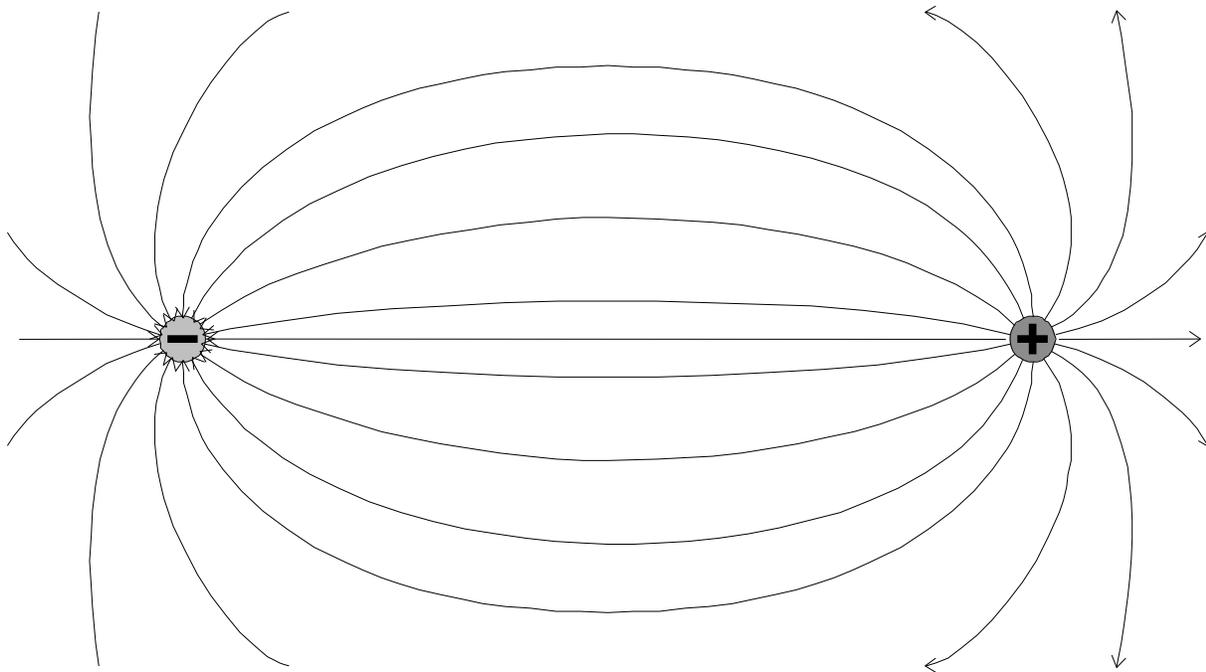
**Figure 4**

#### **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.

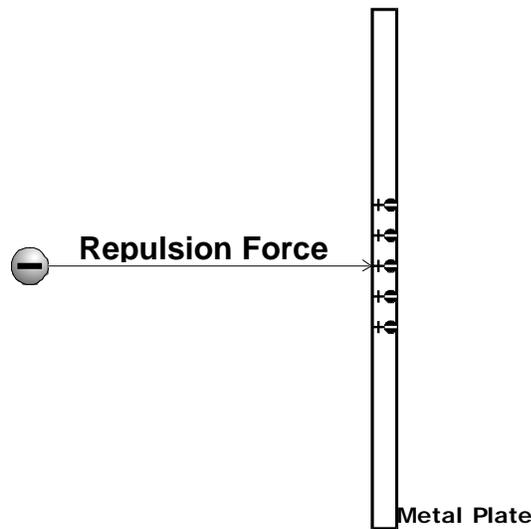
Therefore, the electrical field  $E$  at the point  $P$  is defined as:

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

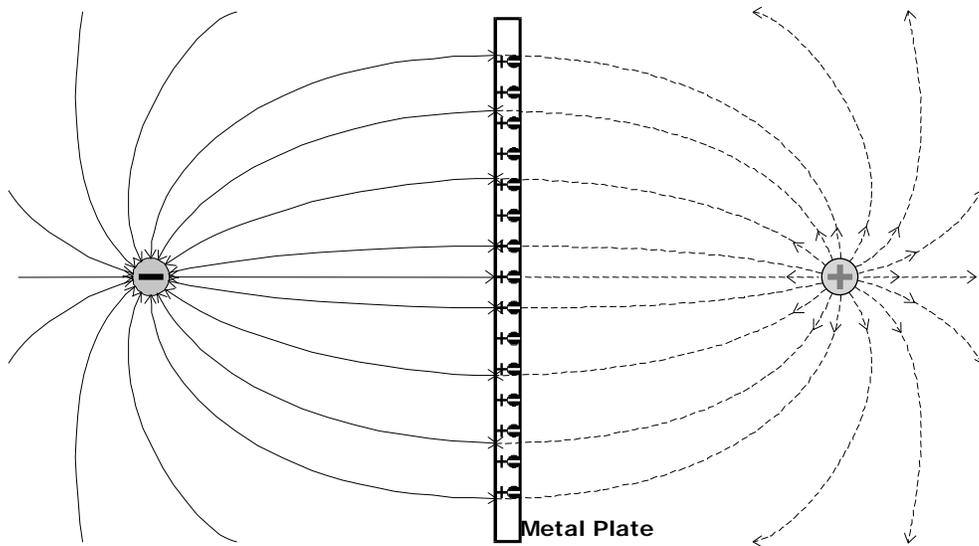
This equation shows that the unit of the electric field can be measured in “Newtons per Coulomb”[N/C]. Another form of unit will be explained in ¶ 1.6.

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 ( $1.602 \times 10^{-16}$  Coulombs) were removed or deposited on the ball the resulting field would be less strong compared to the case that 100,000 electrons ( $1.602 \times 10^{-14}$  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)**

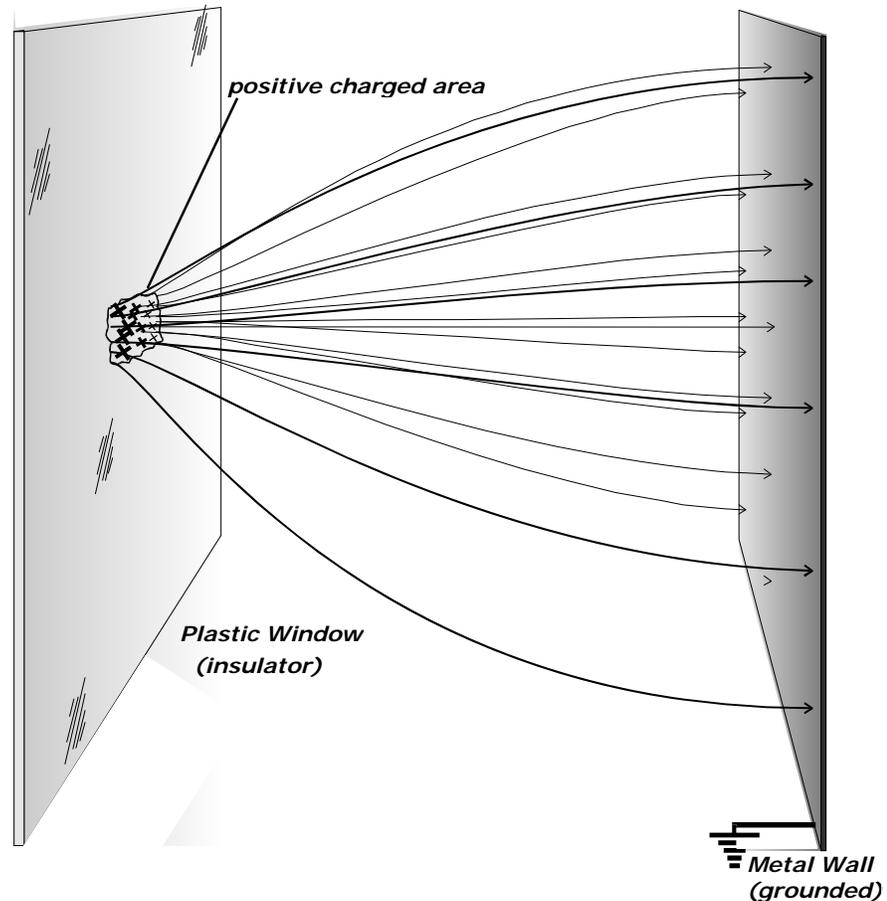
It is essential to understand that such shift of the charge is induced in any conductor near a field producing charge and that this shift of charge in turn considerably affects the geometry of the field.

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  $5 \times 10^4$  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:

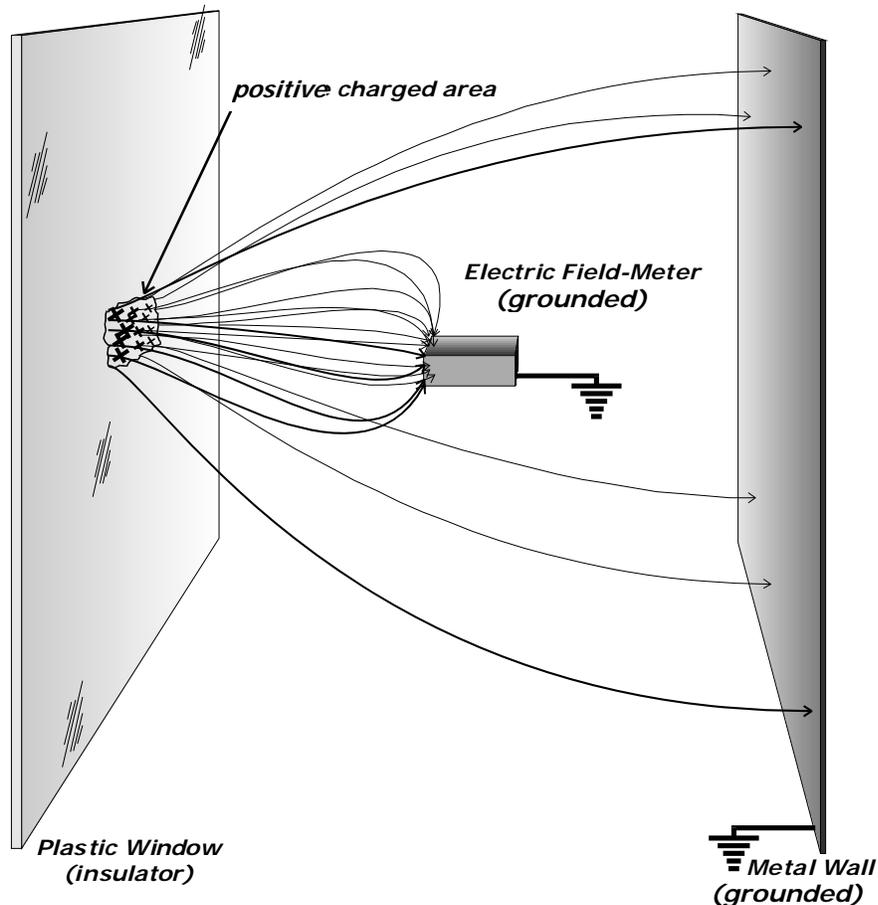
$$E = \frac{1}{4\pi\epsilon_0} \frac{Q}{R^2} \quad (\text{Equation 1-5})$$

where  $R$  is the separation between the charges  $q$  and  $Q$ .

For a real situation, as in the above described example, in which charges are distributed over a region with grounded objects closeby, the calculation is complex. In this case we can only simulate the field intensity with computer-based software, or measure it.

#### 1.4 Measurement of the Electric Field and Coulomb Force

According to the definition of the electric field (or the Coulomb force), a test charge would have to be taken to the place that is to be investigated, and the force and direction of the field affecting the test charge at that point would have to be measured by some means. It is more practical to use electrostatic induction on a conductor as an electric field or Coulomb force measuring device. This means that the intensity of the shift of charge in a small metal probe caused by the field is measured. Generally, high sensitivity ammeters are used to measure the shift of charge. These field or force measuring devices are grounded. We should note here that introducing such a grounded measuring device intensifies the original field, and under real conditions the recorded value will not correspond to the value that is true at the same location without the measuring device being present! This is understood and an acceptable measurement practice allowing estimation of field magnitudes. The following picture illustrates the situation:



**Figure 10**  
**Electric Field Distorted by the Meter**

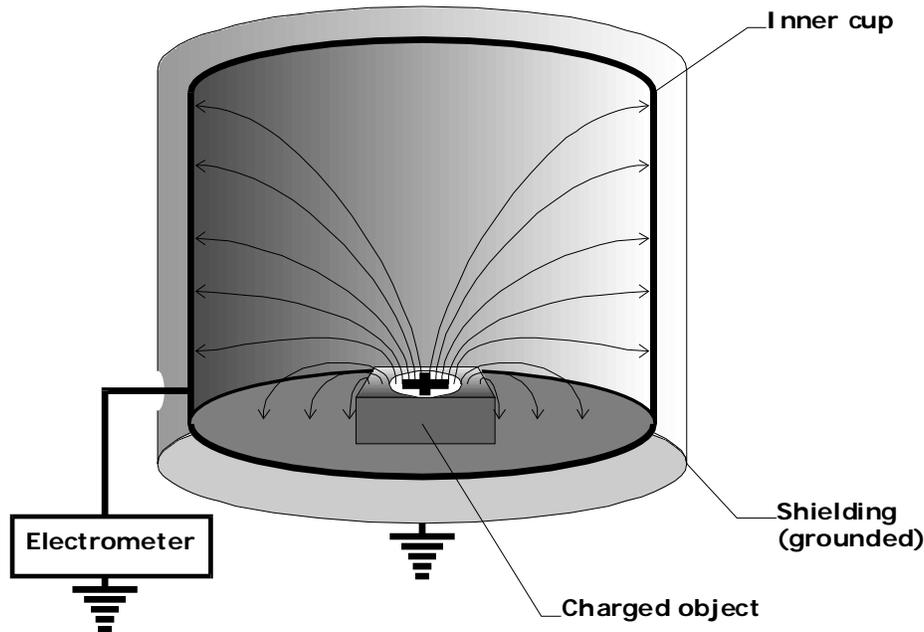
##### 1.4.1 Measurement of Electric Charges

After clarifying these correlations we will now get to the measurement of charges.

Charges on a body are generally measured using a Faraday cup. This Faraday cup is made of metal—it is therefore conductive. Let's recall the following properties of electrons in metal:

1. Electrons are free-moving.
2. Fields within an electric conductor cause a shift of charge.

If a charged body is moved into an enclosed metal cup, the charge inside it will cause a shift of charge over the entire surface area of the cup by means of the Coulomb forces. This shift of charge will flow to ground through the electrometer and corresponds to the charge on the inserted body.



**Figure 11**  
**Faraday Cup**

### 1.5 Electrical Potential

The electrical potential—or the voltage (potential difference) depends on the force between the charges, and therefore depends on the amount of charge, the field, and the geometric conditions. Just as the electric field is the electrostatic force per unit charge, the voltage is the electrostatic potential energy per unit charge.

$$V = \frac{1}{4\pi\epsilon_0} \frac{Q}{R} \quad \text{(Equation 1-6)}$$

The electric potential has the unit of **volt** [V].

Let us once again get back to the example of the partially charged plastic window of Figure 9, which in this case is now charged negatively (field lines would be in the opposite direction):

If we remove one electron from the plastic window it will be move towards the grounded metal wall by the electric field (Coulomb force). The force is effective throughout the electron's entire path, acting more strongly at in the beginning and becoming weaker as the electron gets closer to the grounded wall. Along its way the work is done on the electron (force × distance).

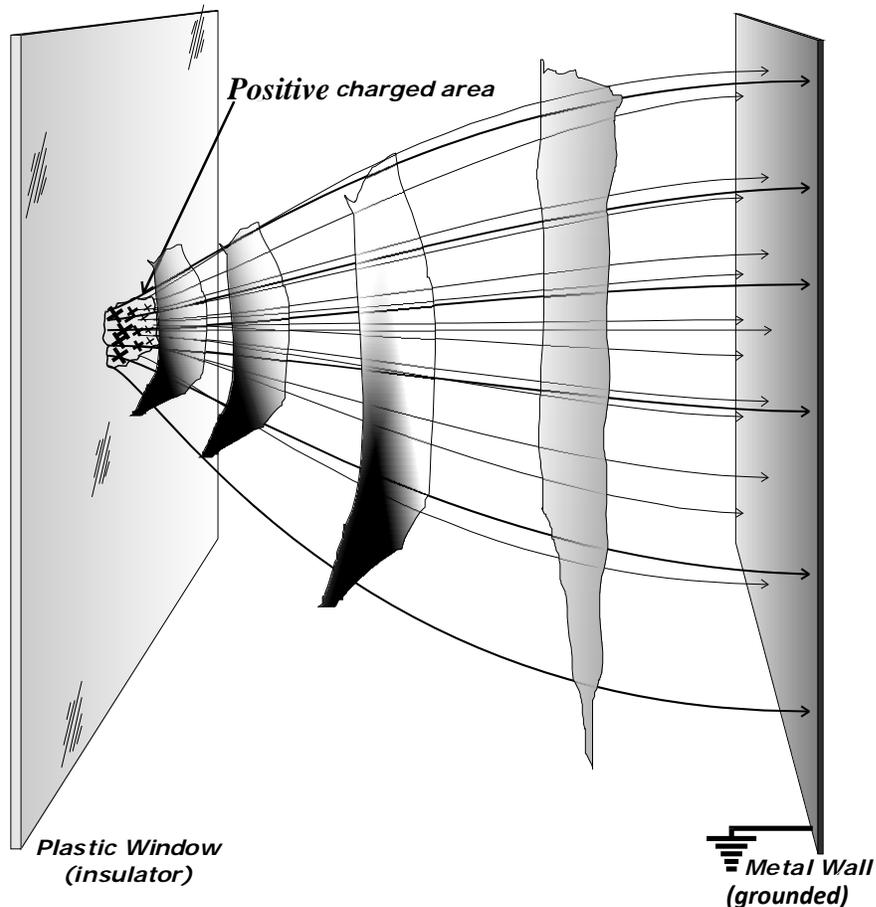
When the electron is freely moving through the space it is being accelerated—acquiring kinetic energy. This means that at its starting point—at the charged window—it does not possess any kinetic energy, but it has a high potential energy. When it reaches the grounded wall the electron has a high kinetic energy—it is at its highest speed—but its potential energy is exhausted.

Accordingly, there is a certain amount of potential energy associated with the electrons contained in the negatively charged area of the plastic window. We could remove each electron and allow it to fall onto the grounded metal plate where all of its potential energy would be exhausted. The more electrons there are, the higher the electric charge, and the higher the potential, because the Coulomb force increases accordingly.

This means that because of this accumulation of charge there is an electric potential in relation to the earth. This difference between potential “zero” of the earth and this accumulation of charges at a particular distance is called electrical voltage (potential difference). Any object connected to earth will be at a potential of zero volts and is referred to as being grounded.

### 1.6 Correlation between the Electric Potential and the Electric Field

Assuming that the electrons on the charged part of the window (of Figure 12) are uniformly deposited, we can say that the potential (measured in **volts [V]**) in this whole area is the same and that its value is  $U_1$ . The potential of the grounded wall is zero ( $U_0$ ) at any point. We can visualize “equipotential surfaces” within the space between the surface of the window with the potential  $U_1$  and the metal wall with the potential  $U_0$ , which possess the same potential  $U_x$  with a value between  $U_1$  and  $U_0$ .



**Figure 12**  
**Equipotential Surfaces with Equal Potential Differences**

The field lines (the direction of the electric field) are always perpendicular to those equipotential surfaces, and the intensity of the field is proportional to the change in potential with distance.



One can observe that in a strong field with a large Coulomb force the change of energy (change of potential) along the way is greater than in a weaker field with a low Coulomb force.

This means that there is a linear relationship between the electric field **E** (**force per charge** measured in *newtons per Coulomb* [N/C]) at a particular place and the "infinitesimal" **change of potential  $dU$  along the infinitesimal path length  $ds$**  with the dimension *volts per Meter* [V/m].

Mathematically this is:

$$E = \frac{F_e}{q} \left[ \frac{N}{C} \right] = \frac{dU}{ds} \left[ \frac{V}{m} \right] \quad (\text{Equation 1-7})$$

The electric field—and this must be emphasized—is not equal to the potential (U) but to the change of potential along the direction of the field lines ( $dU/ds$ ).

### 1.6.1 Making Practical Measurements

The measuring devices for field force are known as **electrostatic fieldmeters**. The correct units for their measurements are volts/distance, for example, volts/m, volts/cm, or volts/inch. These measuring instruments are calibrated for a very specific measuring situation. Generally the measuring instrument is placed at a particular distance (e.g., 2.54 cm or 1 inch) in front of a very big, planar metal plate to which a specified electrical potential is applied (compared to the surrounding ground) via a fixed voltage source. The instrument indicates the electric field (e.g., volts/m at a distance of 2.54 cm). It also indicates the electrical potential on this surface in volts, but only for this particular measuring situation (with a defined distance and a big conductive plane surface)! **The indication in volts is NOT true for any other distance or other surface shape**. Fieldmeters are useful for measuring the electric field from large surfaces, both insulative and conductive. One should remember that the presence of the meter alters the field that it is measuring.

**Electrostatic Voltmeters** are instruments utilizing the principle of electrostatic induction of the Coulomb forces. Unlike the electrostatic fieldmeters, they feature a sensor which adopts the potential of the measuring point. Such an instrument does not perturb the field itself and is therefore able to indicate the actual potential at this point. As the potential between the sensor and the point it is measuring is zero, the sensor is able to be placed very close to the measurement point. In this way it can be used to determine the potential of small objects. **The electrostatic voltmeter reading relates to the particular measurement point and has the units of volts. It does NOT describe an electric field strength in volts/m!**

### 1.6.2 Special case "parallel plate capacitor". Electrical capacitance, and mathematical relationship between charge, field, potential, and capacitance

The example of the ideal parallel plate capacitor is often used, since it promotes the understanding of many electrostatic phenomena. The capacitor consists of two parallel metal plates with a surface area that is large compared to the distance between the plates. As in the above example of the two metal balls, a difference of charge can be applied to those two plates by removing a certain amount of electrons from one plate and applying them to the other. An electric field will develop between the two plates, as it did between the two balls. The action force (or electric field) for this parallel plate capacitor arrangement is the same at each point between the two plates. This is called a homogeneous field. The field lines are parallel and equispaced at any point.

The applied difference in charge Q at this capacitor leads to a particular potential difference U. At a distance D between the two plates the field between them is U/D volt per Meter [V/m] at any point:

$$E = \frac{U}{D} \quad (\text{Equation 1-8})$$

The potential difference for a specified applied charge depends on the geometry, i.e. the surface area and the distance between the plates. For greater surface areas, the density of electrons, and consequently the potential difference between the plates, decreases. Roughly speaking, more electrons fit onto bigger plates. The **electric capacitance C** is greater than that of smaller plates. In other words, at a constant amount of charge the potential difference (i.e. electrical voltage) between the plates decreases as the capacity increases—and the other way round. This can be described as:



$$U = \frac{Q}{C} \quad \text{(Equation 1-9)}$$

The distance between the plates also affects the capacity. The closer the plates are to each other (i.e., the smaller the distance) the greater the capacity, that is, the ability to carry electrons. This could be explained by saying that the interaction (i.e. Coulomb forces) affecting the electrons gets constantly stronger as the distance gets smaller (this has already been described in connection with the metal balls).

The capacitance C grows proportionally to the area A and inversely proportionally to the distance:

$$C \propto \frac{A}{D} \quad \text{(Equation 1-10)}$$

From the definition of potential, the potential of a particular amount of charge is related to the distance it moves along the field lines. If we increase the distance of the two plates of the capacitor carrying a certain amount of charge we are moving the charges along the field lines against the attracting Coulomb force. So, we apply work to the system and enhance the electric potential.

$$U \propto \frac{Q \times D}{A} \quad \text{(Equation 1-11)}$$

### 1.7 Summary

The above discussion of electrostatic parameters is meant as an aid for those who are engaged in the measurement of electrostatic quantities. These examples are intended to help with proper use of instruments in order to determine the real conditions rather than calculating faulty results because of the very complex correlations and interactions. The pictures and illustrations are shown in an attempt to explain those correlations.

## 2 Electric Field, Voltage and Charge — Beyond Basics

By Maciej A. Noras, University of North Carolina.

### 2.1 Relationships Between Electric Field, Voltage and Charge

2.1.1 *Electric field*  $\vec{E}$  — usually defined as the electric force acting upon a unit charge (recall Chapter 1). It is important to remember that electric field is a vector function of position, involving both the magnitude and the direction of that vector in the three dimensional space. Electric field measurements can be affected by the measurement equipment and the presence of the equipment operator and of other surrounding objects. Electric field is typically measured in Volts/meter (V/m) or Volts/inch.

2.1.2 *Voltage*  $V$  — in electrostatics it is defined as the work needed to move a unit charge from one point “a” to another point “b” in the presence of an external electric field  $E$ . Therefore it can also be defined as the potential difference between points “a” and “b”. The advantage of introducing the potential is that it is a scalar from which the electric field can be easily calculated,

$$V = -\int_a^b \vec{E} \cdot d\vec{l} \quad \text{(Equation 2-1)}$$

where  $l$  is the vector displacement between points “a” and “b”. Electric voltage is measured in volts (V).

2.1.3 *Electric charge*  $Q$  — A basic physical quantity that is a source of electromagnetic fields. The units of electric charge are Coulombs (C).

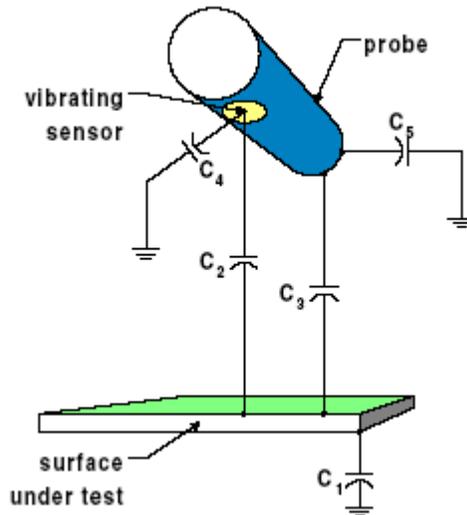
2.1.4 Basic relationship between the electric field and the electric charge is described by the Gauss law:

$$\oint_S \vec{E} \cdot d\vec{s} = \sum_S \frac{Q}{\epsilon_0} \quad \text{(Equation 2-2)}$$

It states that the net flux of the field  $E$  through a closed surface  $S$  is equal to the sum of all charges  $Q$  enclosed by that surface,  $\epsilon_0$  is the dielectric permittivity of the medium. In the vacuum  $\epsilon_0 = 8.85 \times 10^{-12}$  F/m.

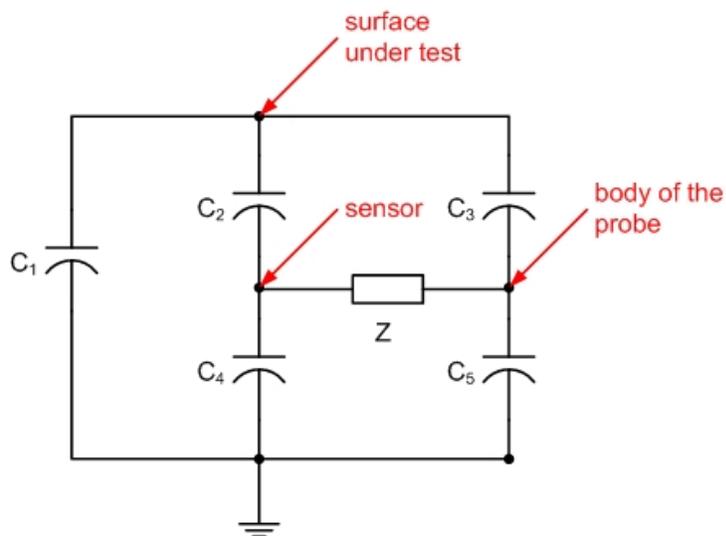
Let's examine how this law can be used by the person trying to measure the charge on a surface with a fieldmeter and then with an electrostatic voltmeter. It is extremely important to remember that electric field and voltage have different physical meanings and are measured in different units, even though they are related.

## 2.2 Role of Capacitive Couplings in Non-contacting Measurements



**Figure 13**  
**Non-Contacting Probe and Capacitive Couplings**

The basic geometry of the non-contacting surface charge measurement can be represented as in Figure 13. The sensor vibrating in the field of the surface under test produces an AC signal on the sensor that can be amplified and detected by the measurement circuitry. This diagram, transformed to a more convenient form as shown in Figure 14, will serve as a base for the analysis of each of the instruments. It will be modified in the following sections to explain the differences in the operation of fieldmeters and voltmeters.



**Figure 14**  
**Proposed Electrical Diagram of Capacitive Couplings**

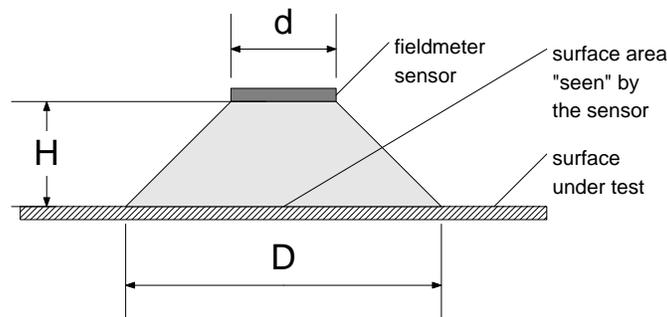
- $C_1$  is a capacitance between the surface under test and earth ground;
- $C_2$  is a capacitance between the probe sensor and the surface under test;
- $C_3$  is a capacitance between the probe body (enclosure of the probe) and the surface under test;
- $C_4$  is a capacitance between the probe's sensing element and the earth ground;
- $C_5$  is a capacitance between the probe body and the earth ground;
- **Z is an internal impedance of the instrument across which the input signal is detected.**

### 2.3 Measurement of the Charge on a Flat Surface with a Fieldmeter

2.3.1 *Example 1* — This example, although it is purely theoretical, introduces concepts that will help with understanding of the realistic scenarios that are frequently encountered during electrostatic measurements with non-contacting instruments. Let's assume that the surface that is being measured is of infinite extent and has uniform surface charge density  $\sigma$ , defined as:

$$\sigma = \frac{Q}{A} \quad \text{(Equation 2-3)}$$

where  $A$  is the surface area of the plane under the fieldmeter. That surface area will depend on the distance  $H$  between the fieldmeter sense head and on the size  $d$  (diameter) of the fieldmeter sensor. Uniform surface charge distribution can be found on conducting (metal) surfaces, except for the surface edges.



**Figure 15**  
Surface Area Detected By The Fieldmeter

The surface area  $A$  can be approximated by the equation:

$$A = \pi \left( \frac{d + 4H}{2} \right)^2 \quad \text{(Equation 2-4)}$$

It is a rough approximation, confirmed experimentally, that  $D = d + 4H$ .

From the Gauss law it can be easily calculated that the dependence between the field  $E$  and surface charge density  $\sigma$  is in the form:

$$E = \frac{\sigma}{2\epsilon_0} \quad \text{(Equation 2-5)}$$

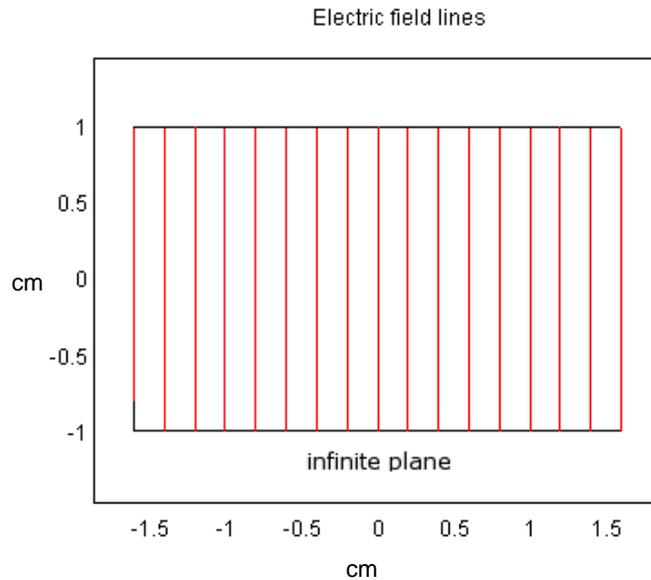
Therefore the charge on the surface that can be calculated from the fieldmeter reading is:

$$Q = 2E\epsilon_0 A \quad \text{(Equation 2-6)}$$

or, if the surface charge density is sought (keeping in mind that we assumed uniform density distribution),

$$\sigma = 2E\epsilon_0 \quad \text{(Equation 2-7)}$$

Notice that in this particular case, with all the assumptions in place, the field  $E$  does not depend on the distance from the plane. In practice we deal with finite surfaces, and in addition, the field  $E$  is affected by the surrounding objects, the fieldmeter and the operator who holds the fieldmeter.

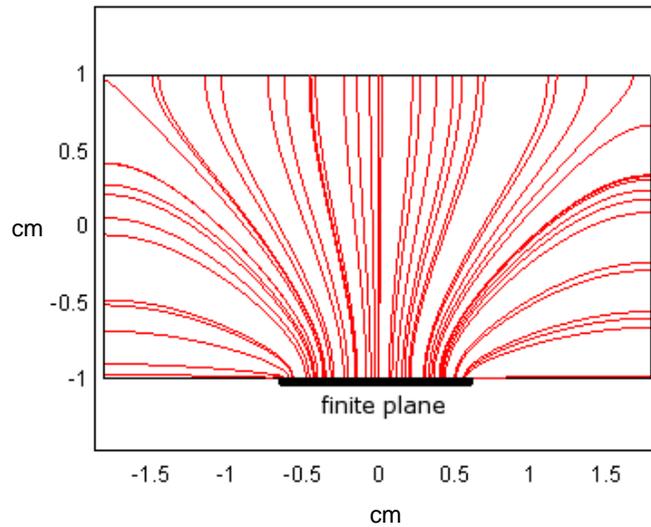


**Figure 16**  
Electric Field Lines for the Infinite Plane with a Uniform Surface Charge Distribution

2.3.2 *Example 2* — Suppose that the surface being measured is of finite extent, in the form of a disc of radius  $R$ , and has uniform surface charge density,  $\sigma$ . Such uniform surface charge distribution can be found on conducting (metal) surfaces, except at the edges. If  $R$  is greater than  $2H$ , the measurement will approximate that of an infinite plane as described above. If the  $R$  is less than  $2H$ , the meter will underestimate the field, and therefore the charge, because it will see an area outside the disk as well. This does not include the additional influence of the meter itself, the person holding the meter, and any surrounding objects.

The surface charge distribution on dielectric materials is usually non-uniform and the meter will represent the net surface charge  $Q$ , without indication of how that charge is distributed over the surface. The electric field above the center of the disk at the distance  $H$  from the surface of the disk is shown in the computer field simulation of Figure 17. Note that the further from the surface that the measurement is made, the more the effect of the fields from the edges.

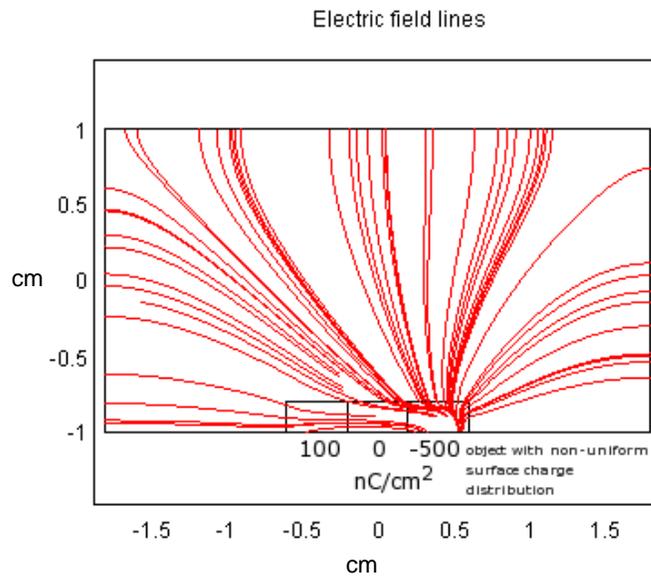
Electric field lines



**Figure 17**

**Electric Field Lines for the Finite Plane with a Uniform Surface Charge Distribution**

2.3.3 *Example 3* — Suppose that the surface that is being measured is of finite extent, in a form of a disc of radius  $R$ , and has non-uniform, random surface charge density  $\sigma$ . Non-uniform surface charge distribution can be found on most of dielectrics and semiconductor surfaces, including surfaces that incorporate separated metal (conducting) structures. An example of the electric field from such a surface is shown in Figure 18.

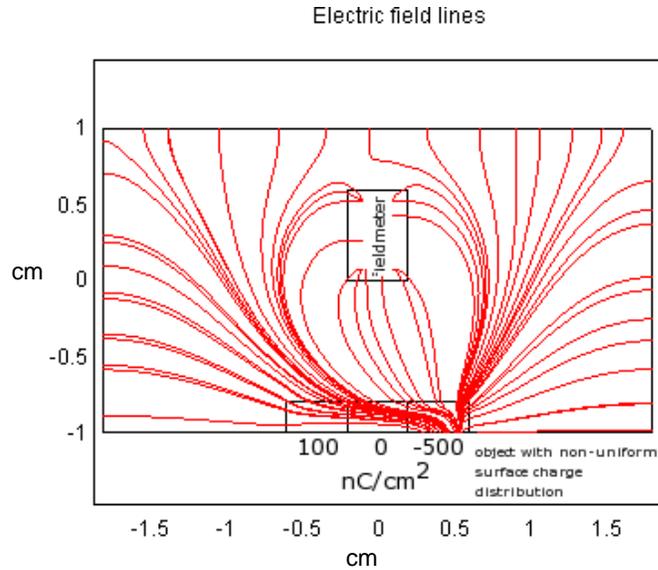


**Figure 18**

**Electric Field Lines for the Finite Plane with a Non-Uniform Surface Charge Distribution**

The electric field can be calculated only if the surface charge distribution is known. Measurements with a fieldmeter give an idea of the superposition of the fields resulting from the surface charges, but it is impossible to do the

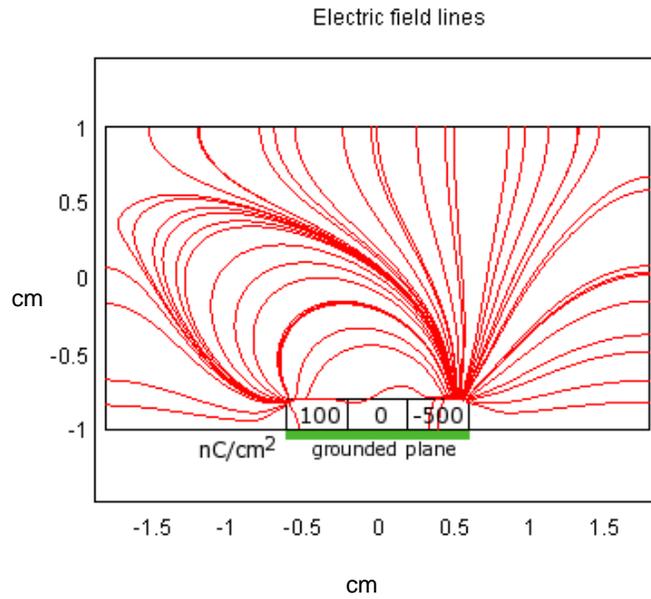
surface charge mapping due to limited spatial resolution of the fieldmeter. Additionally, the instrument itself will influence the electric field distribution. The fieldmeter's sensor is referenced to the earth ground electrode which is located in very close proximity of the sensor. Such construction assures proper operation of the fieldmeter, however the presence of the grounded electrode affects the external electric field distribution (as shown in Figure 19).



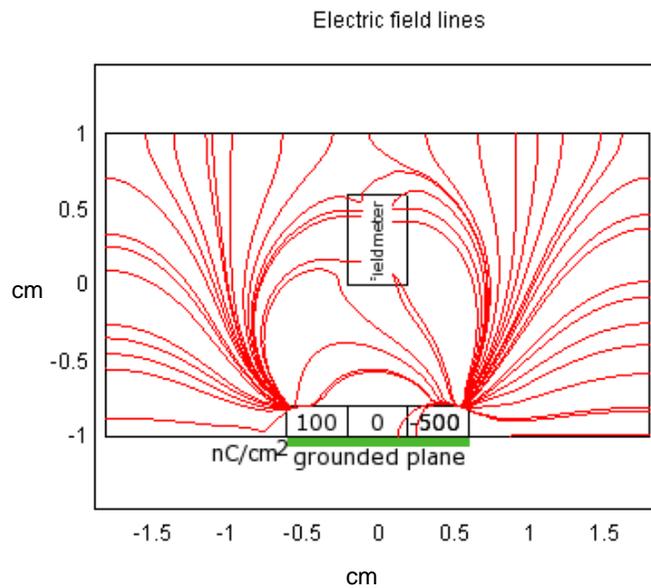
**Figure 19**  
**Influence of the Fieldmeter on the Surface Charge Measurement**

2.3.4 *Example 4* — If the planar material with a non-uniform surface charge is backed by a grounded plane (as it often happens in semiconductor manufacturing environment) the surface charge becomes coupled to the ground plane. If the capacitance between the charged surface and the ground can be defined, the calculation of the surface charge becomes very simple, as shown in Equation 2-8. Looking at the field distribution shown in Figure 20, the influence of the ground plane is to diminish the field over the surface of the material.

$$Q = C \times E \times d \quad \text{(Equation 2-8)}$$



**Figure 19**  
**Object With Non-Uniform Surface Charge Distribution with a Backing Ground Plane**

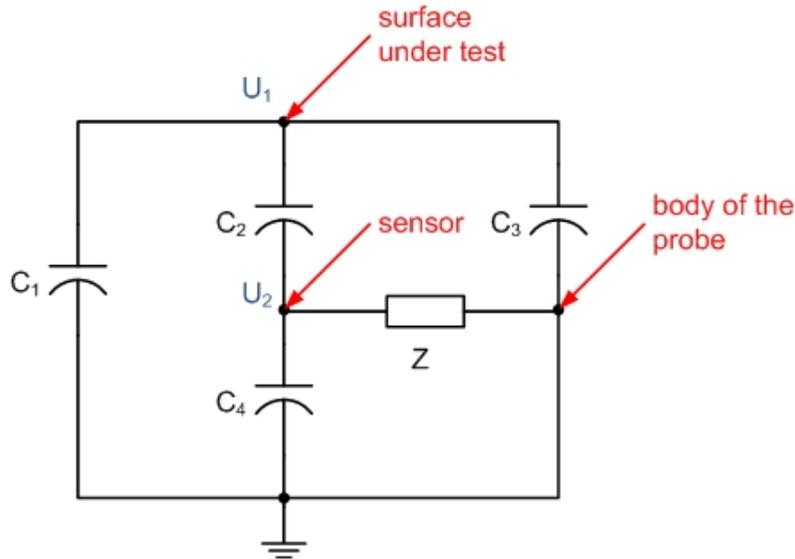


**Figure 20**  
**Influence of the Fieldmeter on the Electric Field Distribution – Object with Non-Uniform Surface Charge Distribution with a Backing Ground Plane**

Again, the fieldmeter spatial resolution is limited, and the instrument will read the resulting averaged electric field at a given location. As shown in Figure 21 the presence of the fieldmeter will continue to perturb the field.

### 2.3.5 Influence of Capacitive Couplings

Another element of the measurement setup that requires careful consideration is the capacitive coupling of the fieldmeter. The sensor of the fieldmeter is directly referenced to the earth ground. Typical constructions of the field meters assure that the body of the probe is at the ground potential level.



**Figure 21**  
**Capacitive Couplings of a Fieldmeter**

Solving the circuit for the voltage  $U_2$  that is induced on the sensor:

$$U_2 = \frac{i(t) \times Z \times (C_1 + C_3)}{C_1 + C_2 + C_3 + j\omega R(C_1C_2 + C_2C_3 + C_4C_1 + C_4C_2 + C_4C_3)} \quad (\text{Equation 2-9})$$

where impedance  $Z$  was replaced with the resistance  $R$  and  $i(t)$  is the current induced at the sensor due to the motion of the sensor:

$$i(t) = (U_1 - U_2) \times \frac{dC_2}{dt} \quad (\text{Equation 2-10})$$

Equation 2-10 presents strong evidence that the capacitive coupling of the fieldmeter to the surface under test ( $C_3$ ) distorts the electric potential induced at the sensor, introducing the measurement error. Another element of importance is the surface under test to ground capacitance  $C_2$ . That coupling should be much greater than  $C_3$  to assure results accuracy.

### 2.3.6 Conclusions

- Electric field measurements are affected by the geometry of the measurement setup.
- It is important to consider the size of the surface that is being measured and the distance between the sensor and the surface.
- Most of fieldmeters are designed for measurements at 1 inch (2.54 cm) distance from the surface under test. However, it is possible to calibrate a fieldmeter to measure at the distance other than the specified 1 inch in order to improve its spatial resolution.
- Fieldmeter cannot be brought too close to the measured surface due to an arc-over hazard.

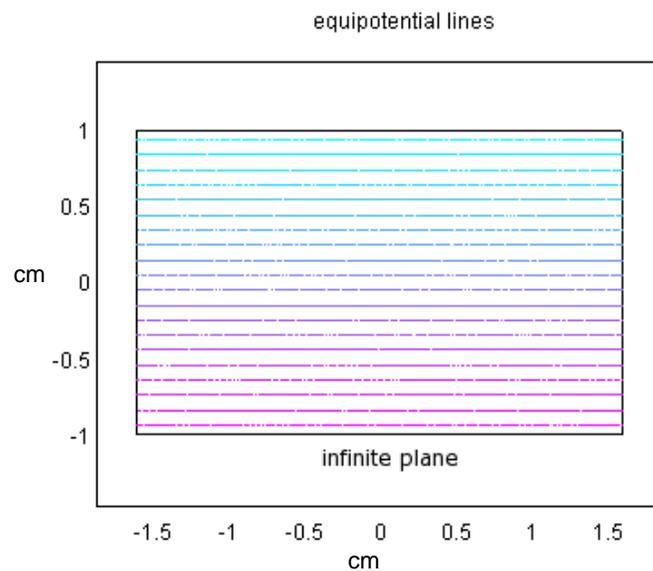
- Capacitive couplings of the fieldmeter strongly influence electric field measurement results. It is important to assure that capacitance of the surface under test to ground is larger than the capacitance between the fieldmeter and that surface.

#### 2.4 Measurement of the Charge on a Flat Surface with an Electrostatic Voltmeter

2.4.1 An electrostatic voltmeter measures the potential difference between earth ground and an object under test. Unlike in fieldmeters, that ground reference point is not present in close proximity of the voltmeter's sensor. An electrostatic voltmeter measures the voltage that is applied to the voltmeter sensor. That voltage produces the electric field equal in magnitude but of opposite direction to the field created by the measured object. Thus it nulls the electric field in the space between the probe and the surface under test.

2.4.2 Consider Example 1 from § 2.3.1. Theoretically, due to infinite size of the plane, the potential difference (voltage) between the surface of the plane and the ground reference is to be expected, infinite, as demonstrated in Equation 2-11.

$$V = - \int_{a=0}^{b=\infty} E dl = - \int_{a=0}^{b=\infty} \frac{\sigma}{2\epsilon_0} dl = - \frac{\sigma}{2\epsilon_0} \times \infty \quad (\text{Equation 2-11})$$



**Figure 22**  
**Electric Potential Distribution over the Infinite Plane with a Uniform Surface Charge Distribution**

2.4.3 When the uniformly charged plane is of the finite size, a disk of radius R as in Example 2 (§ 2.3.2), theoretical evaluation of Equation 2-8 yields [1]:

$$V = - \int_0^H \left( \frac{\sigma}{2\epsilon_0} - \frac{\sigma \times l}{2\epsilon_0 \sqrt{R^2 + l^2}} \right) dl = \frac{\sigma}{2\epsilon_0} \left( \sqrt{R^2 + H^2} - H - R \right) \quad (\text{Equation 2-12})$$

which, for the finite value of  $R \gg H$  gives

$$V = \frac{\sigma \times H}{2\epsilon_0} \quad (\text{Equation 2-13})$$

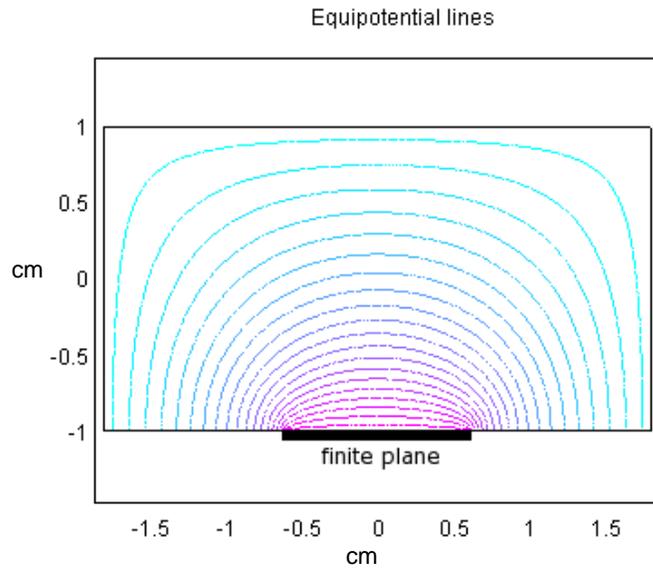
In this case, voltmeter measurement is an equivalent of the fieldmeter measurement, and the surface charge distribution  $\sigma$  or the total charge Q can be calculated from equations (Equation 2-3) through (Equation 2-7).

$$Q = 2 \times V \times H \times \epsilon_0 A \quad \text{(Equation 2-14)}$$

$$\sigma = 2 \times V \times H \times \epsilon_0 \quad \text{(Equation 2-15)}$$

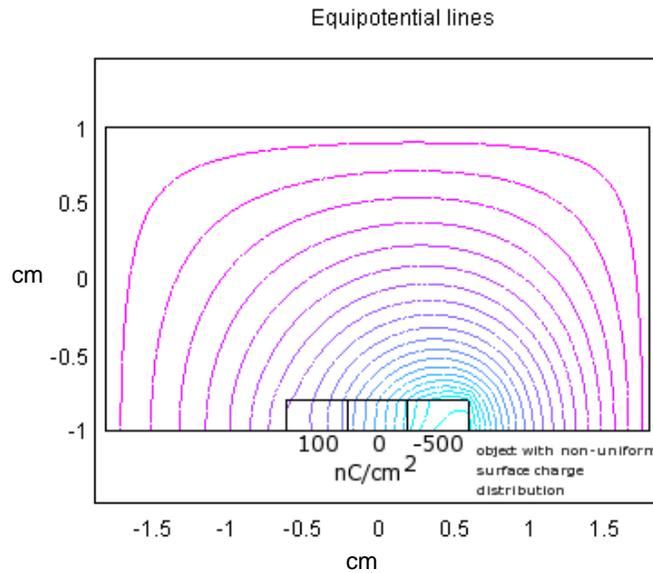
(Equation 2-14)

(Equation 2-15)



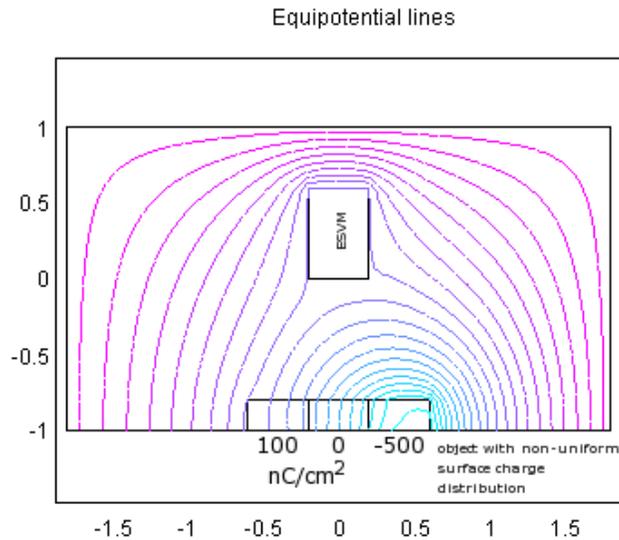
**Figure 23**  
**Electric Potential over the Finite Plane with a Uniform Surface Charge Distribution**

2.4.4 Consider again Example 3, where the surface that is being measured is of finite extent, in a form of a disc of radius R, and has non-uniform, random surface charge density  $\sigma$ .



**Figure 24**  
**Electric Potential Distribution for the Finite Plane with a Non-Uniform Surface Charge Distribution**

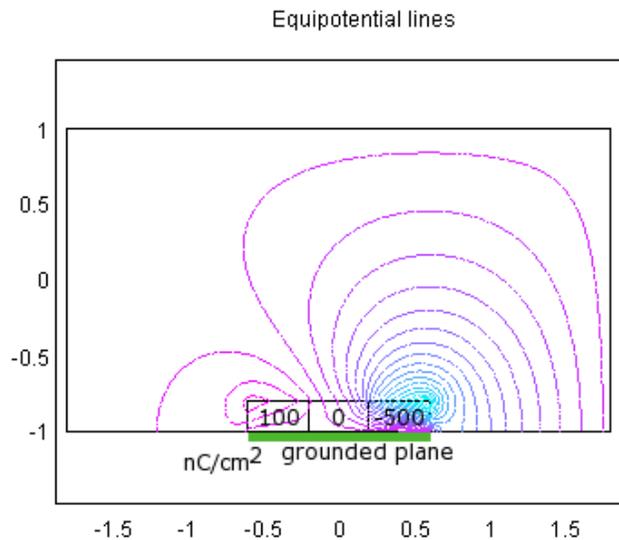
The electrostatic voltmeter readings in this case will depend on the capacitive coupling of the distributed charge to the surrounding objects and on coupling of the electrostatic voltmeter's sensor to the measured surface. In order to do any meaningful measurement in these conditions, all capacitance interactions should be well defined, which in practice is very difficult to obtain.



**Figure 25**  
**Influence of the Electrostatic Voltmeter on the Surface Potential Measurement**

The electrostatic voltmeter sensor is driven to the potential of the measured surface, and it shows the voltage resulting from the superposition of the existing electric fields.

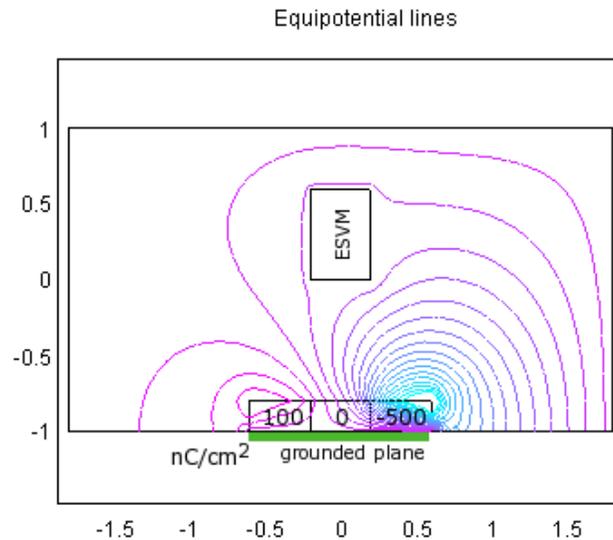
2.4.5 When the material with a non-uniform surface charge is backed by a grounded plane, as in example 4, the capacitance between the surface and the earth ground is constant and well defined by the geometry and the electric permittivity of the material.



**Figure 26**  
**Equipotential Lines for the Surface with Non-Uniform Surface Charge Distribution and a Backing Ground Plane**

2.4.6 If the capacitance between the charged surface and the ground can be defined, the calculation of the surface charge is very simple:

$$Q = C \times V \quad \text{(Equation 2-16)}$$



**Figure 27**  
**Influence of the Electrostatic Voltmeter on the Electric Potential of an Object with Non-Uniform Surface Charge Distribution with a Backing Ground Plane**

The electrostatic voltmeter allows for very close proximity of the sensor to the measured object. As the sensor is driven to the potential of the measured object there is a reduced possibility of arc-over. This capability makes it possible to do a very precise charge distribution mapping.

#### 2.4.7 Influence of Capacitive Couplings

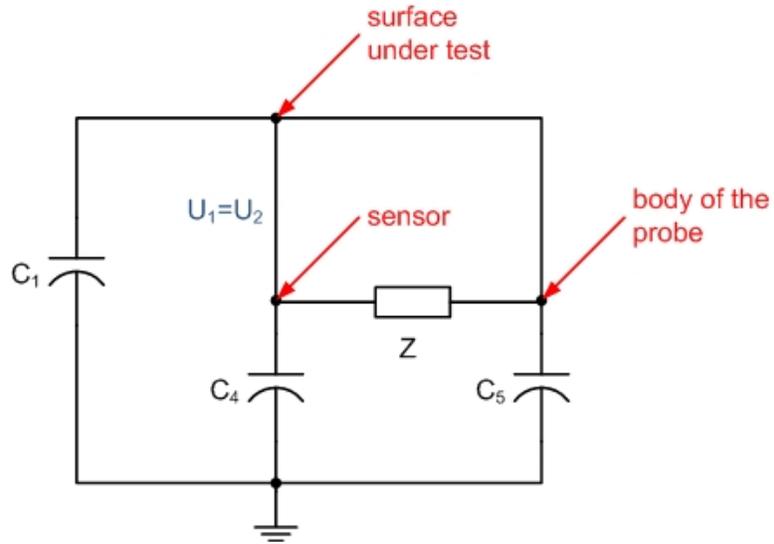
Analysis of capacitive couplings of the DC ESVM requires a brief description of the principle of operation of the voltmeter. In essence, the potential on the sensor and the body of the probe are identical, and are equal to the electric potential of the tested surface. In consequence, the capacitances  $C_2$  and  $C_3$  become equal to zero (or, in practice, negligibly small). The simplified diagram of capacitive couplings is presented in Figure 29. The potential  $U_1$  on the surface is, therefore, determined by the following dependence:

$$U_1 = \frac{Q}{C_1 + C_4 + C_5} \quad \text{(Equation 2-17)}$$

As long as  $C_1 \gg C_4$  and  $C_5$ , the measurement is free of the stray capacitance errors.

#### 2.4.8 Conclusions

- Electric potential measurements are affected by the geometry of the measurement setup.
- It is important to consider the size of the surface that is being measured and the distance between the sensor and the surface (influence of stray capacitances).
- The electrostatic voltmeter allows for precise measurements of charge distributions when charge is coupled to well defined electric potential reference point. Otherwise the measurement can be difficult.



**Figure 28**  
**Capacitive Couplings of a DC Feedback Electrostatic Voltmeter**

## 2.5 References

- [1] M. Horenstein, "Measuring Surface Charge With a Noncontacting Voltmeter", Conference Record of the 1993 IEEE Industry Applications Society Annual Meeting, 2-8 Oct. 1993, vol.3, pp. 1811–1816
- [2] M. Noras, A. Pandey, "Evaluation of Surface Charge Density with Electrostatic Voltmeter – Measurement Geometry Considerations", Conference Record of the 2008 IEEE Industry Applications Society Annual Meeting, 5-9 Oct. 2008, pp. 1–6