Fundamentals of Electrostatic Discharge

Part One—An Introduction to ESD

History & Background

To many people, Electrostatic Discharge (ESD) is only experienced as a shock when touching a metal doorknob after walking across a carpeted floor or after sliding across a car seat. However, static electricity and ESD has been a serious industrial problem for centuries. As early as the 1400s, European and Caribbean military forts were using static control procedures and devices trying to prevent inadvertent electrostatic discharge ignition of gunpowder stores. By the 1860s, paper mills throughout the U.S. employed basic grounding, flame ionization techniques, and steam drums to dissipate static electricity from the paper web as it traveled through the drying process. Every imaginable business and industrial process has issues with electrostatic charge and discharge at one time or another. Munitions and explosives, petrochemical, pharmaceutical, agriculture, printing and graphic arts, textiles, painting, and plastics are just some of the industries where control of static electricity has significant importance.
The age of electronics brought with it new problems associated with static electricity and electrostatic discharge. And, as electronic devices become faster and the circuitry getting smaller, their sensitivity to ESD in general increases. This trend may be accelerating. The ESD Association's "Electrostatic Discharge (ESD) Technology Roadmap", revised April 2010, includes "With devices becoming more sensitive through 2010-2015 and beyond, it is imperative that companies begin to scrutinize the ESD capabilities of their handling processes". Today, ESD impacts productivity and product reliability in virtually every aspect of the global electronics environment.

Despite a great deal of effort during the past thirty years, ESD still affects production yields, manufacturing cost, product quality, product reliability, and profitability. The cost of damaged devices themselves ranges from only a few cents for a simple diode to thousands of dollars for complex integrated circuits. When associated costs of repair and rework, shipping, labor, and overhead are included, clearly the opportunities exist for significant improvements. Nearly all of the thousands of companies involved in electronics manufacturing today pay attention to the basic, industry accepted elements of static control. ESD Association industry standards are available today to guide manufacturers in establishing the fundamental static charge mitigation and control techniques (see Part Six – ESD Standards). It is unlikely that any company which ignores static control will be able to successfully manufacture and deliver undamaged electronic parts.

Static Electricity: Creating Charge

Definitions for Electrostatic Discharge Terminology are in the ESD ADV1.0 Glossary which is available as a complimentary download at www.ESDA.org. *Electrostatic charge* is defined as "electric charge at rest". Static electricity is an imbalance of electrical charges within or on the surface of a material. This imbalance of electrons produces an electric field that can be measured and that can influence other objects. *Electrostatic discharge (ESD)* is defined as “the rapid, spontaneous transfer of electrostatic charge induced by a high electrostatic field. Note: Usually, the charge flows through a spark between two bodies at different electrostatic potentials as they approach one another”.

Electrostatic discharge can change the electrical characteristics of a semiconductor device, degrading or destroying it. Electrostatic discharge also may upset the normal operation of an electronic system, causing equipment malfunction or failure. Charged surfaces can attract and hold contaminants, making removal of the particles difficult. When attracted to the surface of a silicon wafer or a device's electrical circuitry, air-borne particulates can cause random wafer defects and reduce product yields.

Controlling *electrostatic discharge* begins with understanding how *electrostatic charge* occurs in the first place. Electrostatic charge is most commonly created by the contact and separation of two materials. The materials may be similar or dissimilar although dissimilar materials tend to liberate higher levels of static charge. For example, a person walking across the floor generates static electricity as shoe soles contact and then separate from the floor surface. An electronic device sliding into or out of a bag, magazine or tube generates an electrostatic charge as the device's housing and metal leads make multiple contacts and separations with the surface of the container. While the magnitude of electrostatic charge may be different in these examples, static electricity is indeed formed in each case.

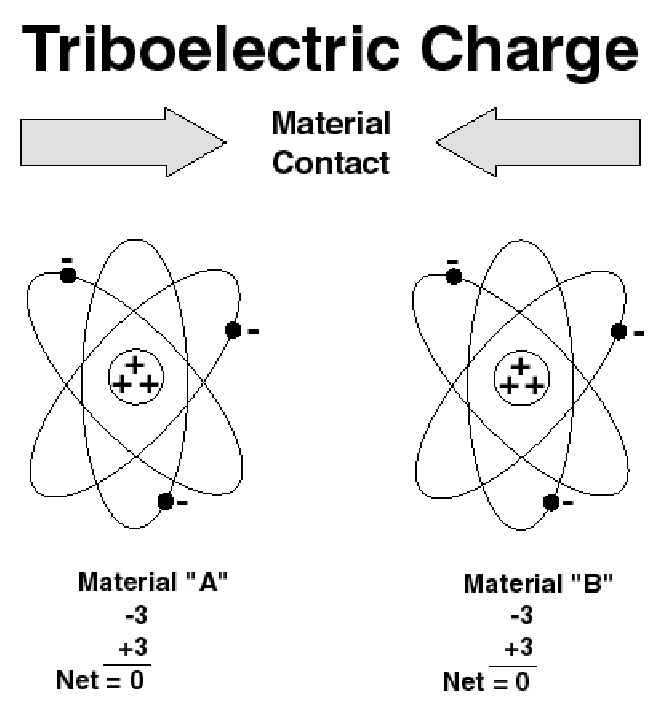

Figure 1 The Triboelectric Charge. Materials Make Intimate Contact

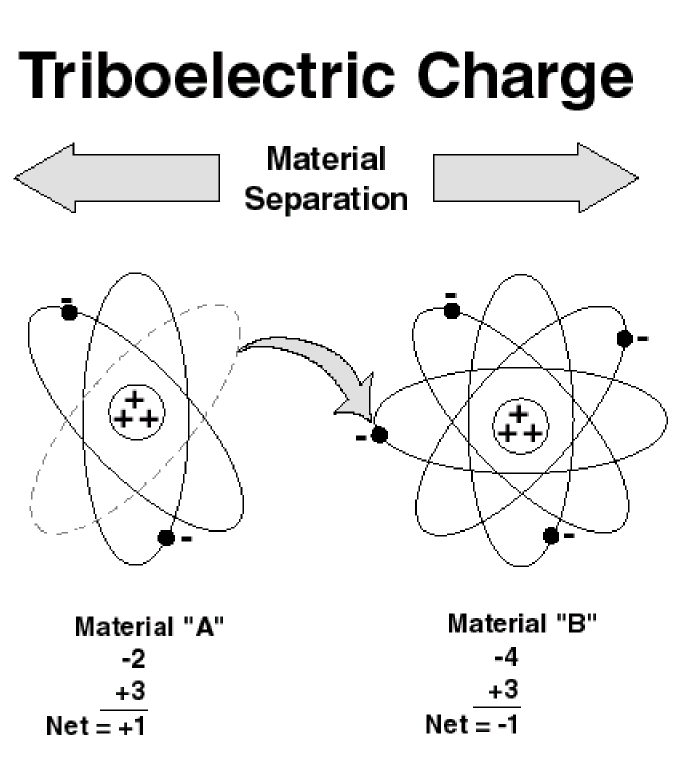

Figure 2 The Triboelectric Charge - Separation

Creating electrostatic charge by contact and separation of materials is known as "triboelectric charging." The word "triboelectric" comes from the Greek words, *tribo* – meaning "to rub" and *elektros* – meaning "amber" (fossilized resin from prehistoric trees). It involves the transfer of electrons between materials. The atoms of a material with no static charge have an equal number of positive (+) protons in their nucleus and negative (-) electrons orbiting the nucleus. In Figure 1, Material "A" consists of atoms with equal numbers of protons and electrons. Material B also consists of atoms with equal (though perhaps different) numbers of protons and electrons. Both materials are electrically neutral.

When the two materials are placed in contact and then separated, negatively charged electrons are transferred from the surface of one material to the surface of the other material. Which material loses electrons and which gains electrons will depend on the nature of the two materials. The material that loses electrons becomes positively charged, while the material that gains electrons is negatively charged. This is shown in Figure 2.

Static electricity is measured in coulombs. The charge "q" on an object is determined by the product of the capacitance of the object "C" and the voltage potential on the object (V):

$$q = CV$$

Commonly, however, we speak of the electrostatic potential on an object, which is expressed as voltage.

This process of material contact, electron transfer and separation is a much more complex mechanism than described here. The amount of charge created by triboelectric generation is affected by the area of contact, the speed of separation, relative humidity, and chemistry of the materials, surface work function and other factors. Once the charge is created on a material, it becomes an electrostatic charge (if it remains on the material). This charge may be transferred from the material, creating an electrostatic discharge or ESD event. Additional factors, such as the resistance of the actual discharge circuit and the contact resistance at the interface between contacting surfaces also affect the actual charge that is released. Typical charge generation scenarios and the resulting voltage levels are shown in Table 1. In addition, the contribution of humidity to reducing charge accumulation is also shown. It should be noted however that static charge generation still occurs even at high relative humidity.

Table 1

Examples of Static Generation

Typical Voltage Levels

Means of Generation	10-25% RH	65-90% RH
Walking across carpet	35,000V	1,500V
Walking across vinyl tile	12,000V	250V
Worker at bench	6,000V	100V
Poly bag picked up from bench	20,000V	1,200V
Chair with urethane foam	18,000V	1,500V

An electrostatic charge also may be created on a material in other ways such as by induction, ion bombardment, or contact with another charged object. However, triboelectric charging is the most common.

How Material Characteristics Affect Static Charge

Triboelectric Series

When two materials contact and separate, the polarity and magnitude of the charge are indicated by the materials' positions in a *triboelectric series.* The triboelectric series tables show how charges are generated on various materials. When two materials contact and separate, the one nearer the top of the series takes on a positive charge, the other a negative charge. Materials further apart on the table typically generate a higher charge than ones closer together. These tables, however, should only be used as a general guide because there are many variables involved that cannot be controlled well enough to ensure repeatability. A typical triboelectric series is shown in Table 2.

Table 2

Typical Triboelectric Series

+	Rabbit fur
	Glass
Positive	Mica
	Human Hair
	Nylon
	Wool
	Fur
	Lead
	Silk
	Aluminum
	Paper
	COTTON
	Steel
	Wood
	Amber
	Sealing Wax
	Nickel, copper
	Brass, silver
	Gold, platinum
	Sulfur
	Acetate rayon
Negative	Polyester
	Celluloid
-	Silicon
	Teflon

Virtually all materials, including water and dirt particles in the air, can be triboelectrically charged. How much charge is generated, where that charge goes, and how quickly, are functions of the material's physical, chemical and electrical characteristics.

Insulative Materials

A material that prevents or limits the flow of electrons across its surface or through its volume is called an insulator. Insulators have an extremely high electrical resistance, **insulative materials** are defined as "materials with a surface resistance or a volume resistance equal to or greater than 1 $\times 10^{11}$ ohms." A considerable amount of charge can be generated on the surface of an insulator. Because an insulative material does not readily allow the flow of electrons, both positive and negative charges can reside on insulative surface at the same time, although at different locations. The excess electrons at the negatively charged spot might be sufficient to satisfy the absence of electrons at the positively charged spot. However, electrons cannot easily flow across the insulative material's surface, and both charges may remain in place for a very long time.

Conductive Materials

A conductive material, because it has low electrical resistance, allows electrons to flow easily across its surface or through its volume. Conductive materials have low electrical resistance, less than 1×10^4 ohms (surface resistance) and 1×10^4 ohm (volume resistance) per Glossary ESD ADV1.0. When a conductive material becomes charged, the charge (i.e., the deficiency or excess of electrons) will be uniformly distributed across the surface of the material. If the charged conductive material makes contact with another conductive material, the electrons will be shared between the materials quite easily. If the second conductor is attached to AC equipment ground or any other grounding point, the electrons will flow to ground and the excess charge on the conductor will be neutralized.

Electrostatic charge can be created triboelectrically on conductors the same way it is created on insulators. As long as the conductor is isolated from other conductors or ground, the static charge will remain on the conductor. If the conductor is grounded the charge will easily go to ground. Or, if the charged conductor contacts another conductor, the charge will flow between the two conductors.

Static Dissipative Materials

Static dissipative materials have an electrical resistance between insulative and conductive materials ($1 \times 10^4 < 1 \times 10^{11}$ ohms surface or volume resistance). There can be electron flow across or through the dissipative material, but it is controlled by the surface resistance or volume resistance of the material.

As with the other two types of materials, charge can be generated triboelectrically on a static dissipative material. However, like the conductive material, the static dissipative material will allow the transfer of charge to ground or other conductive objects. The transfer of charge from a static dissipative material will generally take longer than from a conductive material of equivalent size. Charge transfers from static dissipative materials are significantly faster than from insulators, and slower than from conductive material.

Electrostatic Fields

Charged materials also have an electrostatic field and lines of force associated with them. Conductive objects brought into the vicinity of this electric field will be polarized by a process known as *induction* Figure 1. A negative electric field will repel electrons on the surface of the conducting item that is exposed to the field. A positive electric field will attract electrons to near the surface thus leaving other areas positively charged. No change in the actual charge on the item will occur in polarization. If, however, the item is conductive or dissipative and is connected to ground while polarized, the charge will flow from or to ground due to the charge imbalance. If the electrostatic field is removed and the ground contact disconnected, the charge will remain on the item. If a nonconductive object is brought into the electric field, the electrical dipoles will tend to align with the field creating apparent surface charges. A nonconductor (insulative material) cannot be charged by induction.

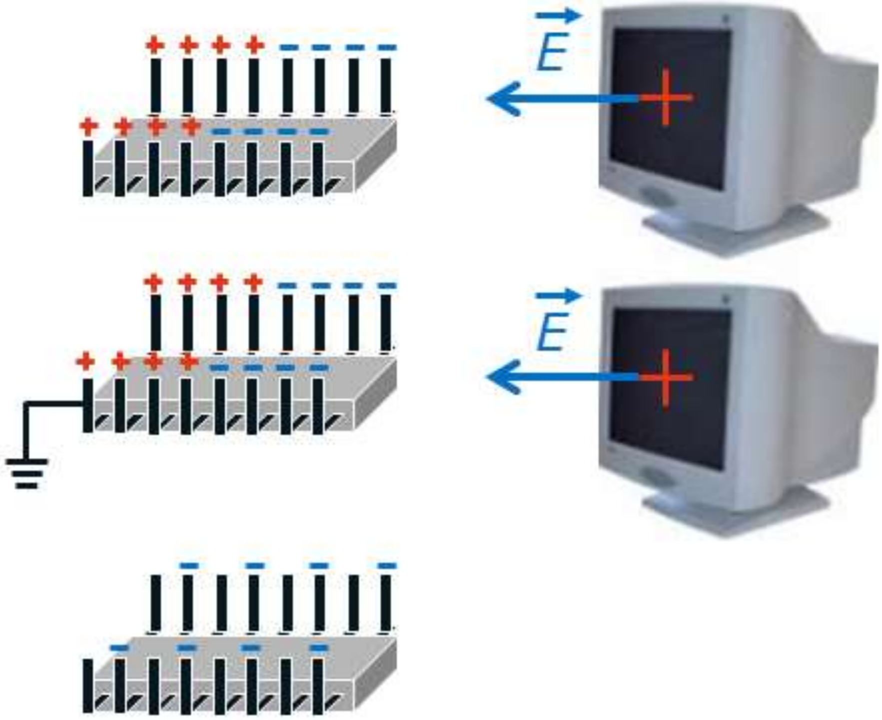

Figure 1: Induction

ESD Damage—How Devices Fail

Electrostatic damage is defined as "change to an item caused by an electrostatic discharge that makes it fail to meet one or more specified parameters." and can occur at any point from manufacture to field service. Typically, damage results from handling the devices in uncontrolled surroundings or when poor ESD control practices are used. Generally damage is classified as either a catastrophic failure or a latent defect.

Catastrophic Failure

When an electronic device is exposed to an ESD event, it may no longer function. The ESD event may have caused a metal melt, junction breakdown, or oxide failure. The device's circuitry is permanently damaged causing the device to stop functioning totally or at least partially. Such failures usually can be detected when the device is tested before shipment. If a damaging level ESD event occurs after test, the part may go into production and the damage will go undetected until the device fails in final test.

Latent Defect

Per ESD ADV1.0 latent failure is "a malfunction that occurs following a period of normal operation. The failure may be attributable to an earlier electrostatic discharge event. The concept of latent failure is controversial and not totally accepted by all in the technical community." A latent defect is difficult to identify. A device that is exposed to an ESD event may be partially degraded, yet continue to perform its intended function. However, the operating life of the device may be reduced. A product or system incorporating devices with latent defects may experience premature failure after the user places them in service. Such failures are usually costly to repair and in some applications may create personnel hazards.

It is relatively easy with the proper equipment to confirm that a device has experienced a catastrophic failure. Basic performance tests will substantiate device damage. However, latent defects are extremely difficult to prove or detect using current technology, especially after the device is assembled into a finished product.

Basic ESD Events—What Causes Electronic Devices to Fail?

ESD damage is usually caused by one of three events: direct electrostatic discharge *to* the device, electrostatic discharge *from* the device or field-induced discharges. Whether or not damage occurs to an ESD sensitive item (ESDS) by an ESD event is determined by the device's ability to dissipate the energy of the discharge or withstand the voltage levels involved. The level at which a device fails is known as the device's ESD sensitivity or ESD susceptibility.

Discharge to the Device

An ESD event can occur when any charged conductor (including the human body) discharges to an item. A cause of electrostatic damage could be the direct transfer of electrostatic charge from the human body or a charged material to the ESDS. When one walks across a floor, an electrostatic charge accumulates on the body. Simple contact (or close proximity) of a finger to the leads of an ESDS or assembly which is typically on a different electrical potential can allow the body to discharge, possibly causing ESD damage. The model used to simulate this event is the Human Body Model (HBM). A similar discharge can occur from a charged conductive object, such as a metallic tool or fixture. From the nature of the discharge, the model used to describe this event is known as the Machine Model (MM).

Discharge from the Device

The transfer of charge *from* an ESDS to a conductor is also an ESD event. Static charge may accumulate on the ESDS itself through handling or contact and separation with packaging materials, worksurfaces, or machine surfaces. This frequently occurs when a device moves across a surface or vibrates in a package. The model used to simulate the transfer of charge from an ESDS is referred to as the Charged Device Model (CDM). The capacitances, energies, and current waveforms involved are totally different from those of a discharge to the ESD sensitive item, resulting very likely in different failure modes.

The trend towards automated assembly would seem to solve the problems of HBM ESD events. However, it has been shown that components may be more sensitive to damage when assembled by automated equipment. A device may become charged, for example, from sliding down the feeder. If it then contacts the insertion head or any other conductive surface, a rapid discharge occurs from the device to the metal object.

Field Induced Discharges

Another electrostatic charging process that can directly or indirectly damage devices is termed Field Induction. As noted earlier, whenever any object becomes electrostatically charged, there is an electrostatic field associated with that charge. If an ESDS is placed in that electrostatic field, a charge may be induced on the item. If the item is then grounded while within the electrostatic field, a transfer of charge from the device occurs as a CDM event. If the item is removed from the region of the electrostatic field and grounded again, a second CDM event will occur as the charge (of opposite polarity from the first event) is transferred from the device.

How Much ESD Control Protection is Needed?

Damage to an ESDS by the ESD event is determined by the device's ability to dissipate the energy of the discharge or withstand the voltage levels involved—as explained previously these factors determine the parts ESD sensitivity or susceptibility. Test procedures based on the models of ESD events help define the sensitivity of components to ESD. Although it is known that there is very rarely a direct correlation between the discharges in the test procedures and real-world ESD events, defining the ESD sensitivity of electronic components gives some guidance in determining the degree of ESD control protection required. These procedures and more are covered in Part Five of this series.

The ESD withstand voltage is “the highest voltage level that does not cause device failure; the device passes all tested lower voltages.” Many electronic components are sensitive or susceptible to ESD damage at relatively low voltage levels. Many are susceptible at less than 100 volts, and many disk drive components withstand voltages even below 10 volts. Current trends in product design and development pack more circuitry onto these miniature devices, further increasing their sensitivity to ESD and making the potential problem even more acute. Table 3 indicates the ESD sensitivity of various types of components.

Table 3 ESD Sensitivity of Representative Electronic Devices Devices or Parts with Sensitivity Associated with HBM and CDM*
Device or Part Type

Microwave devices (Schottky barrier diodes, point contact diodes and other detector diodes >1 GHz)
Discrete MOSFET devices
Surface acoustic wave (SAW) devices
Junction field effect transistors (JFETs)
Charged coupled devices (CCDs)
Precision voltage regulator diodes (line of load voltage regulation, <0.5%)
Operational amplifiers (OP AMPs)
Thin film resistors
Integrated circuits
GMR and new technology Disk Drive Recording Heads
Laser Diodes
Hybrids
Very high speed integrated circuits (VHSIC)
Silicon controlled rectifiers (SCRs) with Io <0.175 amp at 10 °C ambient
*Specific Sensitivity Levels are available from supplier data sheets

Summary

In this "An Introduction to ESD", we have discussed electrostatic charge and discharge, the mechanisms of creating charge, materials, types of ESD damage, ESD events, and ESD sensitivity. We can summarize this discussion as follows:

1. Virtually all materials, including conductors, can be triboelectrically charged.
2. The amount of charge is affected by material type, speed of contact and separation, humidity, and several other factors.
3. Charged objects have electrostatic fields.
4. Electrostatic discharge can damage devices so a parameter fails immediately, or ESD damage may be a latent defect that may escape immediate detection, but may cause the device to fail prematurely.
5. Electrostatic discharge can occur throughout the manufacturing, test, shipping, handling, or operational processes, and during field service operations.
6. ESD damage can occur as the result of a discharge **to** the device, **from** the device, or from charge transfers resulting from electrostatic fields. Devices vary significantly in their sensitivity or susceptibility to ESD.

Protecting products from the effects of ESD damage begins by understanding these key concepts of electrostatic charges and discharges. An effective ESD control program requires an effective training program where all personnel involved understand the key concepts. See Part Two for the basic concepts of ESD control.

References

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