Fundamentals of Electrostatic Discharge

Part One--An Introduction to ESD

History & Background

To many people, static electricity is little more than the shock experienced when touching a metal doorknob after walking across a carpeted room or sliding across a car seat. However, static electricity has been a serious industrial problem for centuries. As early as the 1400's, European and Caribbean forts were using static control procedures and devices to prevent electrostatic discharge ignition of black powder stores. By the 1860's, 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.

The age of electronics brought with it new problems associated with static electricity and electrostatic discharge. And, as electronic devices became faster and smaller, their sensitivity to ESD increased. Today, ESD impacts productivity and product reliability in virtually every aspect of today's electronics environment. Many aspects of electrostatic control in the electronics industry also apply in other industries such as clean room applications and graphic arts.

Despite a great deal of effort during the past decade, ESD still affects production yields, manufacturing costs, product quality, product reliability, and profitability. Industry experts have estimated average product losses due to static to range from 8-33%[1] (Table 1). Others estimate the actual cost of ESD damage to the electronics industry as running into the billions of dollars[2] annually. The cost of damaged devices themselves ranges from only a few cents for a simple diode to several hundred dollars for complex hybrids. When associated costs of repair and rework, shipping, labor, and overhead are included, clearly the opportunities exist for significant improvements.

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[1]Stephen A. Halperin, "Guidelines for Static Control Management," Eurostat, 1990.
[2]Lonnie Brown and Dan Burns, "The ESD Control Process is a Tool for Managing Quality," *Electronic Packaging and Production*, April 1990, pp 50-53.

Table 1 Informal Summary of Static Losses by Level			
Static Losses Reported			
Description	**Min. Loss**	**Max. Loss**	**Est. Avg. Loss**
Component Manufacturers	4%	97%	16-22%
Subcontractors	3%	70%	9-15%
Contractors	2%	35%	8-14%
User	5%	70%	27-33%
Source: Stephen Halperin, "Guidelines for Static Control Management," Eurostat, 1990.			

This first in a series of six articles on the fundamentals of ESD and its control focuses on how electrostatic charge and discharge occur, how various materials affect the level of charge, types of ESD damage, and how ESD events can damage electronic components. Future articles will cover various ways to control the problem.

Static Electricity: Creating Charge

Static electricity is defined as an electrical charge caused by an imbalance of electrons on the surface of a material. This imbalance of electrons produces an electric field that can be measured and that can influence other objects at a distance. *Electrostatic discharge* is defined as the transfer of charge between bodies at different electrical potentials.

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. Another problem caused by static electricity occurs in clean rooms. Charged surfaces can attract and hold contaminants, making removal from the environment difficult. When attracted to the surface of a silicon wafer or a device's electrical circuitry, these 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. 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 generated.

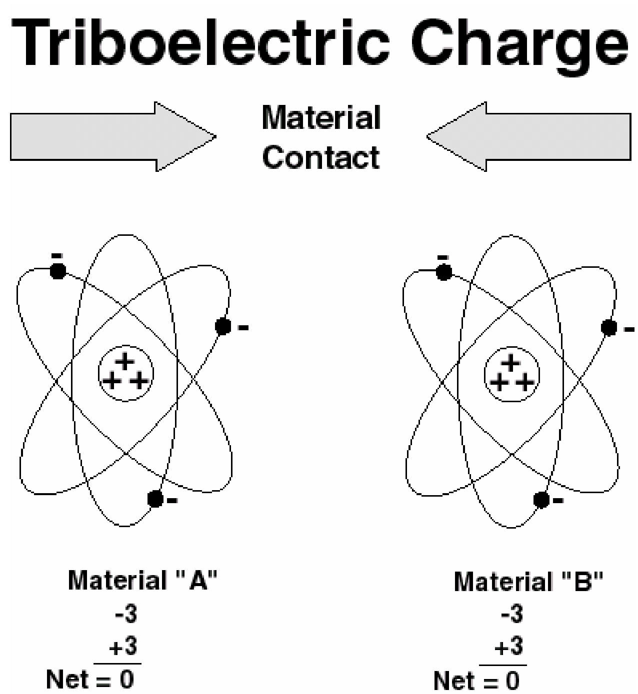

Figure 1 The Triboelectric Charge. Materials Make Intimate Contact

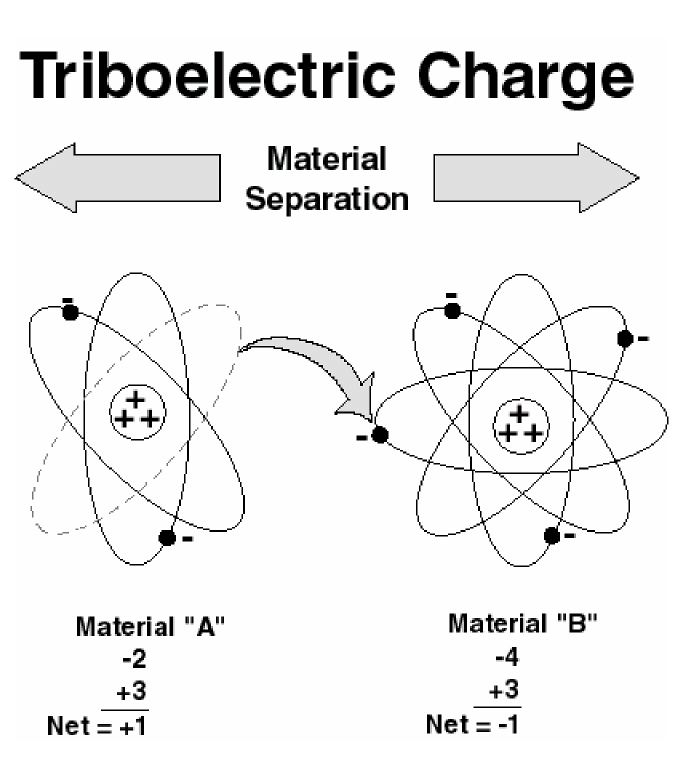

Figure 2 The Triboelectric Charge - Separation

Creating electrostatic charge by contact and separation of materials is known as "triboelectric charging." 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 really a 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 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 can cause damage.

Table 2

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 the *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 3.

Table 3

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
	Polyester
	Celluloid
Negative	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 materials' 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, generally greater than 1×10^{12} ohms/sq (surface resistivity) and 1×10^{11} ohm-cm (volume resistivity). 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, generally less than 1×10^{5} ohms/sq (surface resistivity) and 1×10^{4} ohm-cm (volume resistivity). 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 transfer between the materials quite easily. If the second conductor is attached to an earth 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 or nears 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 x 10^5 - 1 x 10^{12} ohms/sq (surface resistivity) and 1 x 10^4 – 1 x 10^{11} ohm-cm (volume resistivity). 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 conductors.

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*. 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 touched to ground while polarized, charge will flow from or to ground to compensate for the charge imbalance. If the electrostatic field is removed and the ground contact disconnected, the charge will be trapped 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 cannot be charged by induction.

ESD Damage—How Devices Fail

Electrostatic damage to electronic devices can occur at any point from manufacture to field service. 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 fail. Such failures usually can be detected when the device is tested before shipment. If the ESD event occurs after test, the damage will go undetected until the device fails in operation.

Latent Defect

A latent defect, on the other hand, is more 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 dramatically. 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 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. Damage to an ESDS device by the ESD event is determined by the device's ability to dissipate the energy of the discharge or withstand the voltage levels involved. This is known as the device’s "ESD sensitivity.

Discharge to the Device

An ESD event can occur when any charged conductor (including the human body) discharges to an ESDS (electrostatic discharge sensitive) device. The most common cause of electrostatic damage is the direct transfer of electrostatic charge from the human body or a charged material to the electrostatic discharge sensitive (ESDS) device. When one walks across a floor, an electrostatic charge accumulates on the body. Simple contact of a finger to the leads of an ESDS device or assembly allows the body to discharge, possibly causing device 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. The model used to characterize this event is known as the Machine Model.

Discharge from the Device

The transfer of charge *from* an ESDS device is also an ESD event. Static charge may accumulate on the ESDS device itself through handling or contact 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 device is referred to as the Charged Device Model (CDM). The capacitance and energies involved are different from those of a discharge to the ESDS device. In some cases, a CDM event can be more destructive than the HBM for some devices.

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 another conductive surface, a rapid discharge occurs from the device to the metal object.

Field Induced Discharges

Another event 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 device is placed in that electrostatic field, a charge may be induced on the device. If the device is then momentarily grounded while within the electrostatic field, a transfer of charge from the device occurs as a CDM event. If the device is removed from the region of the electrostatic field and grounded again, a second CDM event will occur as charge (of opposite polarity from the first event) is transferred from the device.

How Much Static Protection is Needed?

As noted earlier, damage to an ESDS device by the ESD event is determined by the device's ability to dissipate the energy of the discharge or withstand the voltage levels involved—its ESD sensitivity. Defining the ESD sensitivity of electronic components is the first step in determining the degree of ESD protection required. Test procedures based on the models of ESD events help define the sensitivity of components to ESD. These procedures will be covered in a future article in this series.

Many electronic components are susceptible to ESD damage at relatively low voltage levels. Many are susceptible at less than 100 volts, and many disk drive components have sensitivities 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. Tables 4 and 5 indicate the ESD sensitivity of various types of components.

Table 4
ESD Sensitivity of Representative Electronic Devices
Devices or Parts with Sensitivity Levels of 0-1,999 volts (HBM)

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
AMR and GMR Disk Drive Recording Heads
Laser Diodes
Hybrids
Very high speed integrated circuits (VHSIC)
Silicon controlled rectifiers (SCRs) with Io <0.175 amp at 10̃°C ambient

Table 5 **ESD Sensitivity of Representative Electronic Devices** **Devices or Parts with Sensitivity Levels of 2,000 to 3,999 volts (HBM)**
Device or Part Type
Discrete MOSFET devices
JFETs
Operational Amplifiers (OP Amps)
Integrated circuits (ICs)
Very high speed integrated circuits (VHSIC)
Precision resistor networks (type RZ)
Hybrids
Low power bipolar transistors, PT £100 milliwatts with Ic <100 milliamps

Summary

In this introductory article on electrostatic discharge, we have discussed the basics of electrostatic charge and discharge, types of failures, ESD events, and device sensitivity. We can summarize this discussion as follows:

1. Virtually all materials, even conductors, can be triboelectrically charged.
2. The level of charge is affected by material type, speed of contact and separation, humidity, and several other factors.
3. Electrostatic fields are associated with charged objects.
4. Electrostatic discharge can damage devices so they fail immediately, or ESD may result in latent damage that may escape immediate attention, but cause the device to fail prematurely once in service.
5. Electrostatic discharge can occur throughout the manufacturing, test, shipping, handling, or operational processes.
6. Component 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 to ESD.

Protecting your products from the effects of static damage begins by understanding these key concepts of ESD. Armed with this information, you can then begin to develop an effective ESD control program. In *Part Two* we will focus on some basic concepts of ESD control.

References

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ESD TR20.20, Handbook, ESD Association, Rome, NY.

ESD ADV 11.2, Triboelectric Charge Accumulation Testing, ESD Association, Rome, NY.

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