DIELECTRIC CHARACTERISTICS OF MATERIALS - ELECTROSTATIC DISCHARGE

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12 November, 2002

MatE 210, Experimental Methods in Materials Engineering
Fall 2002

Prof G. Selvaduray

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I. INTRODUCTION:

Electrostatic discharge (ESD) is a physical phenomenon that we all have frequently encountered in our everyday lives. The consequences of ESD in each circumstance, however, have ranged from the harmless, yet sobering shock from the touch of a metal doorknob on a cool, dry winter day to the entire loss of multi-million dollar spacecraft[1]. Professionally, an understanding of the physical fundamentals of ESD and the material characteristics that influence ESD behavior are essential in this world of ubiquitous sensitive electronic equipment. This paper explains the physical principles of ESD in the context of material dielectric properties as well as the testing required to categorize these ESD events.

II. SIGNIFICANCE:

According to NASA[1], "Total losses have occurred on several satellites in Earth geostationary orbits…attributed to the effects of ESD." While this is an extreme situation, defects from ESD events cost the semiconductor industry millions of dollars every year and ESD considerations are becoming increasingly important as IC device dimensions are shrinking.

The electric field that is associated with ESD is a function of distance, so as dimensions of insulating layers in semiconductor devices get smaller, they will become more susceptible to breakdown in dielectric layers given the same electric field. Extremely localized temperatures resulting from ESD events may be greater than 1500 degrees Celsius, which is higher than the melting temperatures of most metals and dielectrics commonly used for conductors and insulators in computer chips.[2] The introduction of Copper, which has a much higher melting temperature than current conductors used in devices will help marginally. However, even at lower temperatures the thermal inputs can cause unwanted dopant diffusions that adversely affect device electrical operations.

Catastrophic and Latent Damage

ESD damage is classified as either catastrophic or latent. Catastrophic damage means that permanent and immediate damage has been done such as a material has melted. Figure 1 shows an example of catastrophic damage to chrome lines in a photomask. It is typically easy to identify when catastrophic damage has occurred.

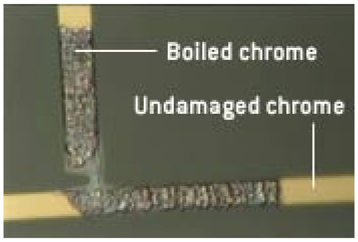


FIGURE 1: ESD damage to chrome lines in photomask
Source: Lightning Rods for Nanoelectronics, Steven H. Voldman, Scientific American magazine, October, 2002. Originally from: KLA-Tencor Corporation

Latent damage means that a structure has only partially degraded but that it still performs as specificied. The operating life of a component that has incurred ESD damage will be substantially reduced, however. Latent damage is a major concern because it is usually difficult to detect on systems that are in operation. The device may operate for a long time after an ESD event and then fail during operation, posing potential safety concerns.

III. FUNDAMENTALS:

Essentially, electrostatic discharge is a high voltage, high frequency transfer of electrons from a surface of a relatively negatively statically charged (high electron concentration measured in Coulombs) surface to a relatively positively statically charged (low electron concentration measured in Coulombs) surface. For ESD to occur, the following conditions must be met;

1. An electrostatic charge imbalance must be present between the surfaces (this is represented as the amount of work required to move a unit of charge between the objects and it is called electrostatic potential difference which is measured in Volts or Joules/Coulomb).
2. The electrostatic potential difference must exceed the dielectric breakdown threshold of the medium between the surfaces.
3. The ESD path must be the path of least resistance for charge stabilization.

Understanding of the underlying physical principles of these conditions will be essential to developing effective ESD countermeasure plans.

A. ELECTROSTATIC CHARGE:

The term “electrostatic” implies that relatively stationary electrons are being addressed. Electrons are always in motion on an atomic scale, but in this case, the term refers to a macroscopic scale such as electrons trapped in an ungrounded conductor or trapped in an insulator material. The lack of electron mobility is key to ESD. If the electrons had a path of lower energy to equilibrium such as a conductive path to ground, then they would not have to jump across surfaces during ESD events which requires a lot of energy. It can be inferred then, that material electrical properties such as electron mobility dictate the capacity for electrostatic charging and therefore, the capacity for ESD.

There are two fundamental properties of charge that are essential to understanding the role that it plays in ESD.

1) It is a conservative entity that can not be created or destroyed, only transferred.

2) It is a quantized entity that must be an integer of the basic unit of +1.6 X 10^{-19} Coulombs for protons or -1.6 X 10^{-19} for electrons.

Neutral entities have an equal number of protons and electrons so that the net charge on the entity is essentially zero. Negatively electrostatically charged objects have an excess of electrons that can not escape. Positively electrostatically charged objects have an excess of holes that can not escape.

Electrostatic charge sources

Electrostatic charge build-up can originate from exotic to common sources. The energy of the electron flux in the earths magnetosphere is high enough to penetrate the skin of spacecraft and embed in cable insulation, thermal blankets and circuit boards.[3] This creates charging environments that can potentially cause arcing to nearby conductors affecting control systems or damaging components.

Ion or electron beam bombardment can also create electrostatic charge fields, but the most common and far reaching type of electrostatic charge build up is triboelectric charging. As the prefix tribo- implies, this charging results from friction or contact between objects. Examples of triboelectric charging are the charge build up that human bodies experience from walking on carpets on dry winter days. The shock that we feel when we then touch a doorknob is ESD as the oversupply of electrons in our body created from our interaction with the carpet is transferred to the metal conductor doorknob. This ESD event is typically equivalent to approximately 3000 Volts, which is the threshold at which ESD shock can be felt or heard. Though it sounds like a lot of voltage, we are not catastrophically damaged because the amount of current carried in the transient is very small.

Other triboelectric systems are listed in Triboelectric Series tables. One Example of a triboelectric table from the Electrostatic Discharge Association is shown in Table 1. When materials closer to the top of the table contact materials closer to the bottom of the table, the material on top assumes a positive charge and the material near the bottom takes a negative charge. The farther apart on the table the materials are, the greater will be the resulting charge build up.

TABLE 1: Triboelectric Table

Source: Electrostatic Discharge Association (www.esda.org)

Typical Triboelectric Series

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

B. DIELECTRIC BREAKDOWN:

Once an electrostatic field imbalance has been developed, then for an ESD event to occur, the magnitude of the existing electrostatic charge imbalance must exceed the dielectric breakdown threshold of the medium material between the surfaces.

Dielectric Constant (Relative Permittivity)

Insulator materials are commonly called dielectric materials because all insulators have a dielectric constant. The dielectric constant determines the ability of the material to become electrically polarized. There are three types of polarization possible in dielectric materials;

1) Electronic polarization occurs when electrons are displaced relative to the nucleus.
2) Ionic polarization occurs when cations and anions are displaced relative to each other.
3) Orientation occurs when permanent dipoles, such as H_2O are aligned.

Only the low mass bodies of the electrons can polarize in response to very high frequency electric fields. Ions and permanent dipoles move too slowly and can only be polarized by lower frequency electric fields. The time needed for a specific polarization to occur is termed the relaxation time.

Materials with a high dielectric constant have a strong ability to become polarized. The dielectric constant is equal to the permittivity of the material (ε) divided by the permittivity of a pure vacuum (ε_o). Permittivity is a proportionality constant that relates the displacement of a charge in relation to an electric field. Dielectric materials, therefore, have a dielectric constant greater than unity and are strong supporters of electrostatic fields.

Polarization of positive and negative charges presents an electrostatic potential energy that is associated with opposite charges being held apart from each other. This is the material property that is exploited in capacitors to create power supplies.

Dielectric Strength

While the dielectric constant determines a materials ability to hold an electrostatic field, a the dielectric strength of a material is a measure of the material resistance to breakdown. Breakdown of a dielectric occurs when electrons or holes break molecular bonds in the dielectric medium during and ESD event creating micro-defects which can propagate through the medium. The units of dielectric strength are Volts/material thickness which represents the Voltage required to breakdown a certain thickness of the subject material.

Avalanche

Strong electric fields, such as ESD may free electrons from atoms and accelerate them to energies high enough to free other electrons from atoms which creates an avalanche of electron interactions. This is known as dielectric breakdown and the energy required to cause this breakdown is the dielectric strength. In many instances, the medium between two surfaces in an ESD situation is air, but in the case of semiconductor devices, the medium could be a thin insulating layer of the device. Because the electrical field is defined as Voltage per distance, thin layers are particularly susceptible to breakdown given a particular field strength. This is a major challenge in proceeding toward shrinking semiconductor device dimensions.

Electro-current constriction

In addition to avalanche events and dielectric breakdown, electro-current constriction can aggravate damage to an IC.[3] When a localized region of a conductor material is heated to high temperatures as the result of an ESD event, the electrical resistance in that localized region is reduced. When resistance is reduced in a localized region, more current will flow through that region than the unheated regions and the heating will thereby increase to an even greater extent.

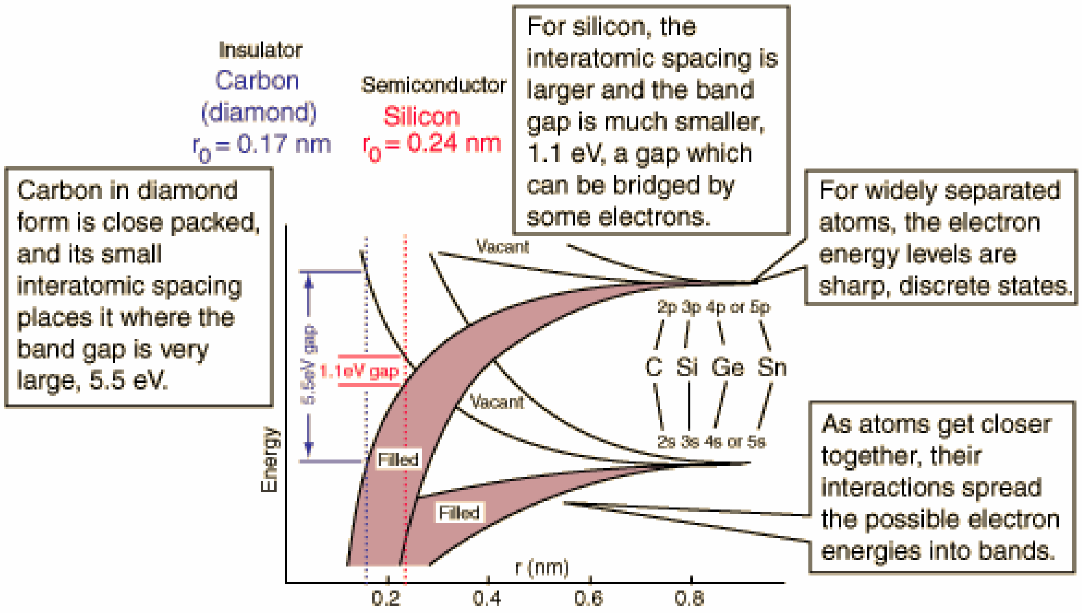
C. MATERIALS CONSIDERATIONS:

It was stated in section IV of this document that electron mobility within a material is a controlling factor in ESD considerations. In the context of electrical properties, materials are distributed into three categories based on electron mobilities.

1) Conductors, such as metals, have a high electron mobility.
2) Semiconductors have a low electron mobility that can be altered by adding dopants to the semiconducting substrate.
3) Insulators have very low electron mobility. The generally accepted dividing line between insulators and semiconductors is that semiconductors can be made to be electrically conductive at ordinary temperatures.

Energy Bands

The difference in electron mobilities between categories can best be described in the context of energy bands. When individual atoms are isolated and free from environmental influences, each electron has a discrete energy following Pauli's exclusion principle. As atoms are brought together in a solid, electrons in valence shells interact with each other, with their nucleus and with surrounding atoms. The net effect is that the electron shells of atoms are compressed. Heisenbergs uncertainty principle indicates that if the width of the spatial spectrum of an atoms valence electron shell is compressed, then the width of the momentum spectrum in the band will increase. This, in combination with Pauli's exclusion principle will lead to electron energy bands in solids rather than the discrete energy levels found in isolated atoms. Implicit from this information is that the atomic distance in a material will determine the width of energy bands and band gaps between valence and conduction bands as shown in Figure 1.



Carbon in diamond form is close packed, and its small interatomic spacing places it where the band gap is very large, 5.5 eV.

For silicon, the interatomic spacing is larger and the band gap is much smaller, 1.1 eV, a gap which can be bridged by some electrons.

For widely separated atoms, the electron energy levels are sharp, discrete states.

As atoms get closer together, their interactions spread the possible electron energies into bands.

At low temperatures, electron energy levels are filled up to the Fermi level. For insulators and semiconductors, the Fermi level is in a band gap so that outer electrons are not free to move through the material in response to an electric field.

FIGURE 2: Band Gap Development in Semiconductors

Source: Sproull, R. L., and Phillips, W. A., Modern Physics: The Quantum Physics of Atoms, Solids and Nuclei, Wiley, (1980). Comments courtesy of Carl Nave, Department of Physics and Astronomy, Georgia State University

Conductor Materials

In conductor materials electron conduction occurs easily because the energy band gap between the valence electron shell and the conduction band is infinitely small or they may overlap. In either case it takes very little to no energy to promote an electron from the valence shell to the conduction band. This small amount of energy can easily be supplied by any thermal energy above 0 Kelvin. Conductive surfaces will, therefore, have uniform charge distributions as electrons are easily transported from regions of high concentration to areas of low concentration. When two conductive surfaces touch, electrons are easily transported back and forth across the interface and there is no electrostatic charge build-up on either side. Conductive surfaces can, however, build up charge if they are isolated and have no conductive route to ground reference.

Insulating Materials

In insulating materials, electrons are not able to redistribute from the negatively charged area to the positively charged area due to the large band gap required to move electrons from the valence band to the conduction band. Conduction is therefore inhibited to the extent that localized positive and negative charged areas may exist simultaneously at different locations on a surface. It is insulating surfaces and ungrounded conducting surfaces that are most susceptible to electrostatic charge build-up and therefore electrostatic discharge due to their lack of electron mobility.

Semiconductor and Static Dissipitive Materials

Semiconductor materials have electron mobility properties between the properties of conductor and insulator materials. Electrons and holes in these materials are more mobile than they are in insulators, but less mobile than they are in conductors. The moderate electron/ hole mobility quality of these materials makes them ideal for circuit board packaging applications where a lot of friction is created from sliding parts in and out of bags, which builds up triboelectric static charge fields. Because of their moderate electron/ hole mobility they are able to discharge extra charges at a more controlled dissipitive rate, rather than a discharge rate. The International Electrotechnical Commission (IEC) defines materials with a surface resistance between $1 \text{ X } 10^5\ \Omega$ and $1 \text{ X } 10^{11}\ \Omega$ as static dissipitive.[4]

ESD Robustness of materials

In addition to the material characteristics that define susceptibility to ESD events, other material characteristics must be considered in the context of resistance to ESD damage. Materials with high thermal conductivity and melting temperature and low coefficient of thermal expansion are more capable of dissipating thermal energy without incurring structural damage to the victimized device.

D. OTHER CONSIDERATIONS:

The likelihood of an ESD event occurring is also influenced by geometrical and environmental factors present.

Geometrical Factors;

Large distances between electrostatically charged surfaces or volumes require a large voltage to jump across the gap. These large voltages will typically result in higher temperatures and more likely visible damage. Smaller distances will require smaller voltages that are still sufficient to breakdown the dielectric, though no visible indications of damage may be present.

Environmental Factors;

Surface resistivity is highly sensitive to environmental humidity. High humidity environments promote lower resistivity (i.e. better conduction of electrons and holes), lowering the chances of ESD event occurrence. The upper limit of environmental humidity in manufacturing environments is generally accepted to be around 60%, which is determined more by hygienic and ergonomic factors. Above 60% humidity, human comfort level deteriorates and materials are more subject to environmental degradation. Very dry environments inhibit electron/ hole mobility and increase the liklihood of ESD events. The lower limit for environmental humidity is typically about 40%.

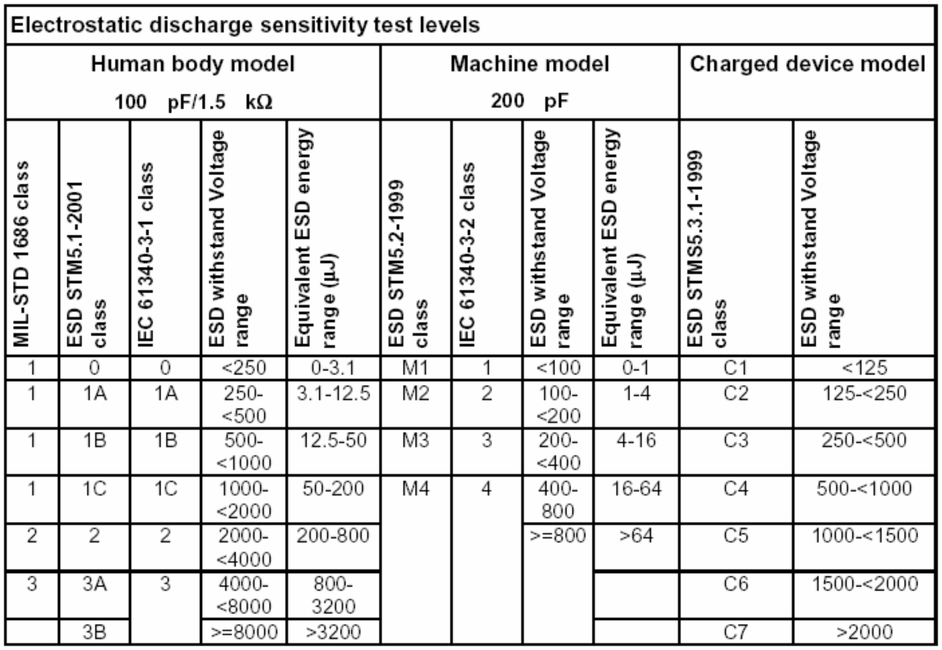
IV. ESD TESTING AND STANDARDS:

The concepts that have been discussed in sections I through III of this document imply that there are several considerations to take into account when testing for ESD susceptibility. Device sensitivity must be tested to understand what level of protection must be planned. Additionally, dielectric properties of materials must be tested to understand the role they play in ESD events.

A. SENSITIVITY TESTING

Three standard models of ESD events are used for rating ESD sensitivity of devices. Each model represents a different mode of discharge. Since a device may be susceptible to any one of the modes, a properly tested device would be rated with all three models. The general concept is that a subject device is placed into a circuit and tested through a range of discharge voltages until the circuit is catastrophically damaged by an ESD. Then a sensitivity category is assigned to the device. Table 2 provides a reference of the different sensitivity rating categories by various standards.

TABLE 2: STANDARD CLASSIFICATIONS OF ESD SENSITIVITY TESTS [6]



Electrostatic discharge sensitivity test levels										
Human body model 100 pF/1.5 kΩ					Machine model 200 pF				Charged device model	
MIL-STD 1686 class	ESD STM5.1-2001 class	IEC 61340-3-1 class	ESD withstand Voltage range	Equivalent ESD energy range (µJ)	ESD STM5.2-1999 class	IEC 61340-3-2 class	ESD withstand Voltage range	Equivalent ESD energy range (µJ)	ESD STMS5.3.1-1999 class	ESD withstand Voltage range
1	0	0	<250	0-3.1	M1	1	<100	0-1	C1	<125
1	1A	1A	250-<500	3.1-12.5	M2	2	100-<200	1-4	C2	125-<250
1	1B	1B	500-<1000	12.5-50	M3	3	200-<400	4-16	C3	250-<500
1	1C	1C	1000-<2000	50-200	M4	4	400-800	16-64	C4	500-<1000
2	2	2	2000-<4000	200-800			>=800	>64	C5	1000-<1500
3	3A	3	4000-<8000	800-3200					C6	1500-<2000
	3B		>=8000	>3200					C7	>2000

Human Body Model

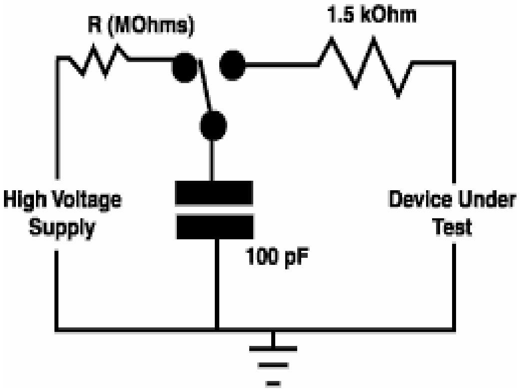


FIGURE 3. HUMAN BODY MODEL[7]

The Human Body Model (HBM) simulates a discharge from a standing individual delivered to a galvanicaly grounded victim device. The circuitry of the discharge model is depicted in Figure 3. The size of the resistor and capacitor in the model vary among different standards, but the general circuit structure remains unchanged. The capacitor in the circuit is an average representation of human body capacitance, which can get up to thousands of pF, but is typically between 50 and 250 pF. The resistor in the circuit models the resistance of a human body. Since the resistance of the human body is a function of contact area, pressure and salt and oil concentrations, the resistance of a human body may range from 100 to 10000 Ω, but is usually around 1000 to 1500Ω.[5] These are the values found in the standardized models used by ANSI and the ESD Organization. The other resistor in the HBM circuit as seen in the upper left corner of Figure 3 represents the surface resistance between the device and ground potential. This resistance is equal to zero in the case of an electrical short. Note that adding a static dissipitive material between the device and the ground potential is representative of increasing this resistance, thereby increasing the impedence across the discharge path and reducing the electrical current discharge rate to a more controlled dissipitive rate that is less damaging to the material.[6]

Machine Model

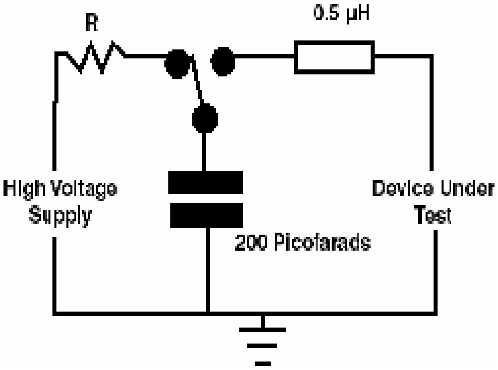


FIGURE 4. MACHINE MODEL[7]

The Machine Model (MM) circuit represents an ESD mode of charge transfer from an ungrounded metal object to the victim device. It is similar to the HBM circuit, except that the electrical components representative of the human body are replaced with electrical components representative of an ungrounded metal object. Circuitry of the model is depicted in Figure 4. In the MM, a 0.5 µH inductor replaces the human impedence resistor of the HBM model representing the lower resistance of the metallic object in comparison to a human body. The lower resistance in the MM leads to a much faster rise time (i.e. more current transfer per unit time) than the HBM and is considered similar to a worst-case HBM ESD incident.

Charged Device Model

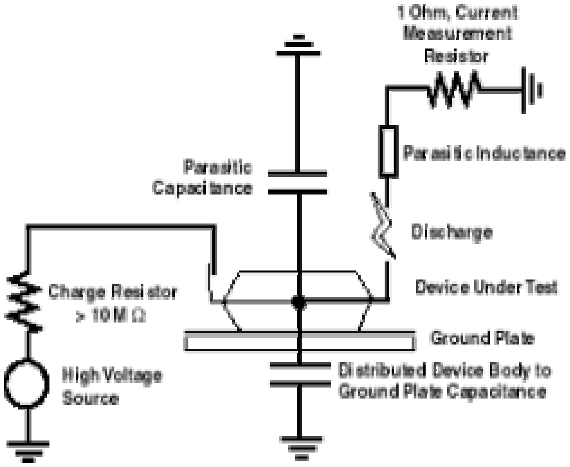


FIGURE 5. CHARGED DEVICE MODEL[7]

The Charged Device Model (CDM) is different from the HBM and the MM in the respect that it simulates the charge transfer from a device, rather than to the device. Charging of the device can occur tribo-electrically from the friction as the device slides down the feeder of an assembly line for example. The CDM circuitry is shown in Figure 5. The schematic is more complex than the HBM or MM, though it essentially describes the following; A high voltage power supply supplies a charge to a victim device. Capacitors hold the charge at the device. A spark gap to a grounded conducting target acts as the path for the ESD event to occur when the voltage potential is sufficiently accumulated.

B. DIELECTRIC TESTING

As previously mentioned in section III B of this document, one important consideration in materials related to ESD prevention is the dielectric strength of a material. If a material of high dielectric strength is introduced between the anode and the cathode of the ESD circuit, a very high voltage potential would be required to break down this dielectric medium and ESD would be less likely.

ASTM 149 and IEC 80243 describe the method for testing the dielectric strength of a material. The basic test setup consists of simply placing an insulating material of a known thickness between two electrodes and altering the voltage potential across the electrodes until the material breaks down from an ESD event. The results of the test are given simply in units of Volts/mil representing the amount of voltage potential required to breakdown a given thickness of material. The three methods for implementing this test are the short-time method, the slow rate-of-rise method and the step-by-step method.

In the short-time method, the voltage is increased linearly and relatively rapidly from zero until the dielectric breakdown voltage. This method determines an approximate dielectric breakdown voltage. The slow rate-of-rise method then uses 50% of this approximate dielectric breakdown voltage as a starting point and increases the voltage linearly at a slower rate to determine more accurately what the dielectric breakdown voltage is. The step-by-step method also uses 50% of the short-time method breakdown voltage as a starting point, but the voltage is increased in stepped increments, rather than linearly until breakdown.

V. ESD MITIGATION:

The first step in mitigating ESD events is to understand the risk of the subject environment through testing such as that described in the previous section. Once the risk has been quantified, then mitigation techniques can be selected appropriately. The most effective ESD mitigation technique requires that all bodies in a work environment are kept at equal electrical potential. Without an electrical potential difference, there is no need for electrons to jump from one surface to another. This may not always be possible however and other mitigation techniques can be implemented as well. Workers around ESD sensitive devices can wear ankle and wrist straps that bleed off excess charge to ground. Highly resistive material should be shielded to prevent electron impregnation in the material. All conductive bodies should be properly grounded so that excess charge can easily bleed off to the ground potential. Ionizing devices that emit alternating positive and negative ions can be used to counter electrical charging effects in dielectric materials. Finally, ESD dissipation can be structured into semiconductor circuits.

VI. CONCLUSION:

The fundamental principles of electrostatic discharge were presented in this paper and related in the context of materials considerations with an emphasis on dielectric properties and different modes of ESD discharge. It was explained that ESD events originate from electron/ hole concentration imbalances that result from the lack of electron/ hole mobility to ground reference in materials. How devices are tested to classify them in a certain category of ESD sencitivity was explained. Then, ESD Mitigation techniques based on the physical principles were suggested.

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[1] Electrostatic Discharge Test Practices, NASA Preferred Reliability Practices, Impact of Non-Practice, Practice # PT-TE-1414.

[2] Lightning Rods for Nanoelectronics, Steven H. Voldman, Scientific American magazine, pp90-97, October, 2002.

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[3] Thick Dielectric Charging/ Internal Electrostatic Discharge, NASA Preferred Reliability Practices, Practice # PD-AP-1316.

[4] Standard IEC 61340-5-1: Electrostatics, Part 5-1, Protection of Electronics devices from electrostatic phenomena-General Requirements, 1998.

[5] MIL-HDBK-263B, "Electrostatic Discharge Control Handbook for protection of electrical and electronic parts, assemblies and equipment", 1994.

[6] "Ideal Surface Resistance of ESD Protective Materials in Intimate Contact with ESD Sensitive Devices", Jaako Paasi, VTT Industrial Systems, Technical Research Center of Finland.

[7] Electrostatic Discharge Association, www.esda.org