1 Fundamentals of Electrostatics

1.1 INTRODUCTION

We are all familiar with electrostatic discharge (ESD): shuffle your feet across a shag carpet in your favorite sneakers, touch a piece of metal, and zap! For a human being, we let out an "ouch!"; but for micro-electronics to nano-electronics, this can lead to product failures [1].

But, today, and in the future, static charge will remain an important industrial issue for the production of both electronic devices to systems. It is also an issue in fields of munitions, explosives, chemical, and material industries. Any industry where there is a risk of impact to quality, yield, degradation, or physical harm will be concerned with electrostatic discharge (ESD), electrical overstress (EOS), electromagnetic interference (EMI), and electromagnetic compatibility (EMC).

In this book, a short survey of ESD from manufacturing to product use will be shown. The text will discuss fundamentals of electrostatics, manufacturing electrostatic issues, component level issues, system level issues, to design.

So, where did all this all begin?

1.2 ELECTROSTATICS

The discovery of electrostatic attraction and electrostatic discharge is one of the world's earliest understandings of scientific thought and analysis. Its first discovery goes back to the early foundation of the problem of the nature of matter, astronomy, mathematics and foundation of Greek philosophy, and pre-dates the nature of matter.

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1.2.1 Thales of Miletus and Electrostatic Attraction

Thales of Miletus, born in 624 B.C.E and died in 546 B.C.E, was the founder of the Ionian School (or Milesian School) and one of the Seven Wise Men of Ancient Greece in the Pre-Socratic era. Thales was an astronomer, mathematician, and philosopher. He was an inventor and an engineer. Thales of Miletus established a heritage of searching for knowledge for knowledge sake, development of the scientific method, establishment of practical methods, and the conjecture approach to questions of natural phenomenon. The Milesian School is regarded as establishing the critical method of questioning, debate, explanation, justification and criticism. The students of Thales included Euclid, Pythagoras, and Eudemus [2].

It was Thales of Miletus who was accredited with the discovery of the electrostatic attraction created after the material amber was rubbed. Thales noted after amber was rubbed, straw was attracted to the piece of amber. It was from this event, the Greek word for amber, ελεκτρον (trans. *electron*) became associated with the electrical phenomenon.

Knowledge of Thales' ideas was common through writings of his disciples and notary Greek Philosophers. In *De Anima 411 a7-8*, Aristotle stated "Some think that the soul pervades the whole universe, when perhaps came Thales' view that everything is full of gods." [3].

Electrostatic phenomenon pre-dated early thoughts of the nature of physical matter. Thales of Miletus's ESD experiments and study of electrostatic attraction was before the atomic schools of matter in Greece and Rome. Electrostatic phenomena and thought began before the Greek atomistic schools of Democritus (420 B.C.E.), and Epicurus (370 B. C.E.), and Roman School of Lucretius (50 B.C.E). Thales was deceased by the time the schools of atomic thought were active. On his tomb read, "Here in a narrow tomb Great Thales lie; Yet his renown for wisdom reached the skies [4]."

Robert A. Millikan, in the Introduction of his 1917 edition of "The Electron" [5] stated,

> *"Perhaps it is merely a coincidence that the man who first noticed rubbing of amber would induce in it a new and remarkable state now known as the state of electrification was also the man who first gave expression to the conviction that there must be some great unifying principle which links together all phenomena and is capable of making them rationally intelligible; that behind all the apparent variety and change of things there is some primordial element, out of which all things are made and the search for which must be the ultimate aim of all natural science. Yet if this be merely coincidence, at any rate to Thales of Miletus must belong a double honor. For he first correctly conceived and correctly stated, as far back as 600 B.C., the spirit which has actually guided the development of physics in all ages, and he also first described, though in a crude and imperfect way, the very phenomenon the study of which has already linked together several of the erstwhile isolated departments of physics, such as radiant heat, light, magnetism, and electricity, and has very recently brought us nearer to the primordial element than we have ever been before."*

J.H. Jeans, in the 1925 Fifth Edition of *The Mathematical Theory of Electricity and Magnetism* [6], wrote

> *"The fact that a piece of amber, on being rubbed, attracted to itself other small bodies, was known to the Greeks, the discovery of this fact being attributed to Thales of Miletus"*
>
> *"A second fact, namely, that a certain mineral ore (lodestone) possessed the property of attracting iron, is mentioned by Lucretius. These two facts have formed the basis from which the modern science of Electromagnetism has grown."*

1.2.2 Electrostatics and the Triboelectric Series

With the death of Thales of Miletus, little progress proceeded on ESD phenomenon. Although history moved forward, the advancement of tribo-electric charging and electrostatic discharge phenomenon was slow relative to the time that passed. In Europe, mankind saw the Roman Empire, the Golden Age of Islam, the Middle Ages, the Black Death, the Renaissance, the Reformation, and the advancement of nation states. ESD phenomenon was discovered by Thales while China was undergoing the Zhou Dynasty. Asia underwent tremendous change with the Qin, Han, Sui, Tang, and Song, Yuan, and Ming dynastic periods, but there was no advancement of this field of knowledge.

With all this social change, insignificant growth in the understanding of electrostatic phenomenon increased until the eighteenth century. The interest in tribo-charging and electrostatic phenomenon became the luxury of scientists supported by the courts of Europe and laboratories of France and England.

So, how does tribo-charging happen?

When two materials come into contact, the atoms contained within the materials come into close contact. Figure 1.1 shows an example of two atoms of different materials. The nucleus is tightly bound, with neutrons and protons, and is positively charged. Strong interactions hold the neutrons and protons together. According to the Bohr model, the electrons orbit around the nucleus, and are drawn to the nucleus by the electrostatic attraction between the negative electrons and the positive nucleus. In a neutral un-charged atom, the number of protons and electrons are equal in number.

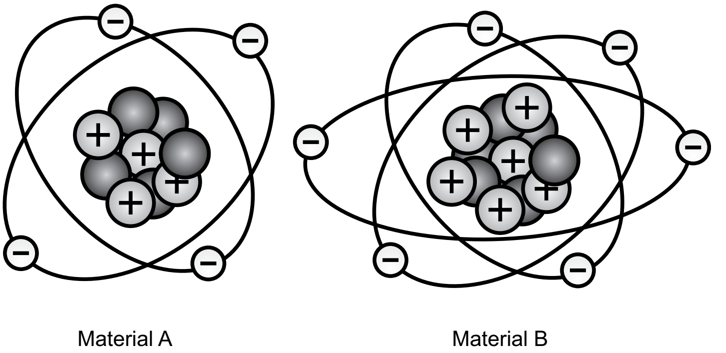

Figure 1.1 Tribo-charging of materials – physical contact

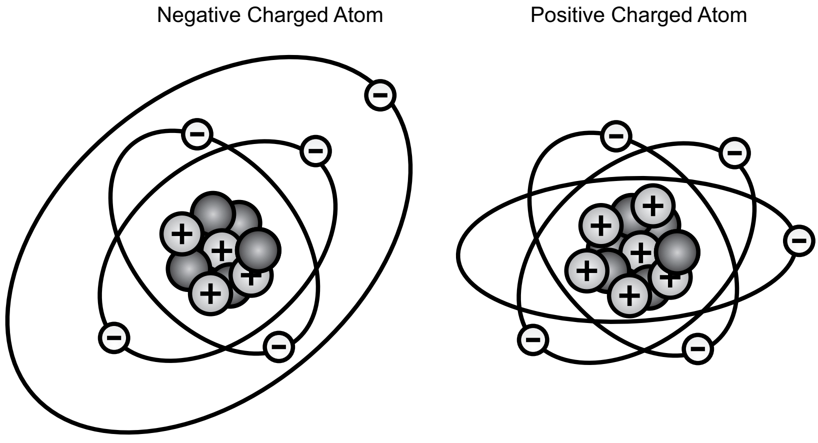

Figure 1.2 Tribo-charging of materials – separation

When two materials are in contact, charge transfer occurs through the friction or physical contact. An electron of the outer orbitals can transfer from one material to the second material. Figure 1.2 shows an example after the two materials are separated. In this case, the material that loses the electron becomes positively charged, and the material that gains the electron becomes negatively charged.

1.2.3 Triboelectric Series and Gilbert

Gilbert, in the seventeenth century, noted that interaction between a glass rod and silk produced the same phenomenon discussed by Thales of Miletus – materials when rubbed with silk became "*amberized*" [5]. Gilbert began construction of the earliest list of tribo-electrification.

1.2.4 Triboelectric Series and Gray

In the same period, Stephen Gray (1696–1736) thought of the concept of the division of materials according to its nature of removing or sustaining electrification [5]. He defined a class of materials which remove "amberization" as conductors, and the class of materials which allowed a body to retain its electrification as non-conductors, or insulators.

1.2.5 Triboelectric Series and Dufay

This work was followed by French physicist Dufay in 1733 discovering the same effect can be achieved with sealing wax and cat's fur and noted the effect was different from the glass rod [5]. Dufay first noted that there was an attractive and repulsive phenomenon between different materials, naming the opposite processes as "vitreous" and "resinous."

1.2.6 Triboelectric Series and Franklin

Benjamin Franklin – the first American ESD engineer, in 1747, also identified two processes, which he divided into "positive" and "negative" processes. The "positive" process was the first process, discovered by Gilbert, any physical body was electrified positive if repelled by a glass rod which was rubbed with silk. The "negative" process is any body repelled from sealing wax which was rubbed with cat's fur, extending the work of Dufay.

In this time frame, many electrostatic scientists began recording the relationship of one body to another in the electrification process. Lists of materials of the times were ordered to construct the early tribo-electrification chart [6]

> . . . *"It is therefore possible to arrange any number of substances in a list such that a substance is charged with positive or negative electricity when rubbed with a second substance, according as the first substance stands above or below the second substance on the list. The following is a list of this kind which includes some of the most important substances:*
>
> *"Cat's skin, Glass, Ivory, Silk, Rock Crystal, The Hand, Wood, Sulphur, Flannel, Cotton, Shellac, Caouthouc, Resins, Guttapercha, Metals, Guncotton.""*
>
> J.H. Jeans D.Sc, LL.D, F.R.S
>
> *The Mathematical Theory of Electricity and Magnetism Cambridge*, England, 1925

1.2.7 Electrostatics – Symmer and the Human Body Model

In this time frame, some electrostatic scientist and engineers explored phenomenon around them, and were the early root of electrostatic discharge (ESD) phenomenon of garments, and possibly early influences on the "human body model."

Robert Symmer (1759) would do experimental studies in the dark, exploring the electrical discharge phenomenon of removal of his stockings and the interactions of two different sets of stockings, placing two white stockings in one hand and two black stockings in the other [5].

1.2.8 Electrostatics – Coulomb and Cavendish

Coulomb (while other ESD scientists were still enjoying the ESD phenomenon with their stockings and rubbing things together) developed the Torsion Balance, in 1785, beginning a series of processes to understand the relationship of force, charge and physical distance. The experiments of Coulomb were also performed by Cavendish at an earlier date but not published until 1879 by James Clerk Maxwell [7].

1.2.9 Electrostatics – Faraday and the Ice Pail Experiment

At this time, the relationship of positive and negative electrification was not fully understood. In 1837, Michael Faraday performed the "ice-pail experiment" involving glass rod and silk which showed that "positive and negative electrical charges always appear simultaneously and in exactly equal amounts."

Faraday, in his lecture *Forces of Matter – Lecture V Magnetism-Electricity* would provide demonstrations of electrostatic charging phenomenon demonstrating the phenomenon and the relationship of positive and negative charging effects [8]. He would close his lecture on electrical phenomenon with ". . . *This, then is sufficient, in the outset to give you an idea of the nature of the force which we call ELECTRICITY. There is no end to the things from which you can evolve this power.*"

1.2.10 Electrostatics – Faraday and Maxwell

Even at this time frame, the relationship of matter, electrical charging and electrical force was not well understood. Different models were proposed from single electrical fluid models, and two fluid models to explain the charging process. Electrical phenomenon models were established to explain this phenomenon as related to a stress or strain of the medium, moving the thoughts from an atomistic perspective to a field representation. It was in this time frame that Faraday and James Clerk Maxwell began addressing the understanding of electricity and electrical forces in terms of a field perspective, and electrical charge was viewed as a "state of strain in the ether." James Clerk Maxwell, *in Electricity and Magnetism* in 1873, created the modern formulation of electricity and magnetism as we understand it today [7].

1.2.11 Electrostatics – Paschen

In 1889, Paschen began an analysis of breakdown phenomenon in gases trying to explain the relationship between gas pressure and electrode spacing [8]. Breakdown phenomenon in media took a great leap forward influencing electrostatic discharge (ESD) understanding in today's devices. Even today, the Paschen breakdown curve is important for understanding the electrical breakdown in air gaps and nano-structures.

1.2.12 Electrostatics – Stoney and the "Electron"

In 1891, the word "electron" as a natural unit of electricity was suggested by Dr. G. Johnstone Stoney, connecting the ideas of Faraday's Law of Electrolysis [5]. At this time, the understanding of the connection to physical matter was not understood, but was used as a measure or unit. Dr. G. Johnstone Stoney reconnected the idea to the Greek word for amber, connecting the early work of Thales of Miletus to the modern day concept of an electrical unit, later to be proven to be connected to matter and atomic theory.

From this brief history, it can be seen that electrostatic attraction pre-dates the earliest thoughts of the understanding of matter. From 600 B.C.E to even as late as the 1890s the relationship of the discovery of Thales of Miletus was not understood as connected to the transfer of electrons which were made of matter.

1.3 TRIBOELECTRIC CHARGING – HOW DOES IT HAPPEN?

Tribo-electric charging occurs when two bodies of materials come into physical contact, followed by separation of the two bodies. (Table 1.1) As discussed before, the word electron comes from the Greek word for "amber." The word "tribo" also comes from Greek, meaning "to rub." Tribo-charging has to do with two items that come into contact, followed by their separation. In the process of tribo-charging, electrons transfer from one material to another. Atoms are made of a nucleus which consists of positively charged protons, and neutrally charged neutrons. Outside of the nucleus, electrons establish standing wave orbitals around the nucleus. Electrons are negatively charged. When there are two dissimilar materials of different electric potentials, electrons can transfer from one material to another. After material separation, the material with the extra electron becomes negatively charged, whereas the material that lost the electron becomes positively charged.

So, the material property influences whether the electrons transfer. As discussed by Jeans [6], a chart can be constructed predicting the direction of charge transfer.

> "*It is therefore possible to arrange any number of substances in a list such that a substance is charged with positive or negative electricity when rubbed with a second substance, according as the first substance stands above or below the second substance on the list. . .* "

Table 1.1 Triboelectric series

Positive (+)	Materials
	Rabbit Fur
	Glass
	Human Hair
	Nylon
	Wool
	Fur
	Silk
	Aluminum
	Paper
	Cotton
	Steel
	Wood
	Amber
	Nickel
	Gold
	Polyester
	Silicon
	Teflon
Negative (−)	

1.4 CONDUCTORS, SEMICONDUCTORS, AND INSULATORS

The electrical engineer likes to draw some defining boundary lines between insulators, semiconductors, and metals on the basis of such conductivity,

$$\textit{Insulators}\ \sigma < 10^{-9}\ \textit{ohms}^{-1}\ \textit{cm}^{-1}$$

$$\textit{Semiconductor}\ 10^{-9} < \sigma < 10^{2}\ \textit{ohms}^{-1}\ \textit{cm}^{-1}$$

$$\textit{Metals}\ \sigma > 10^{2}\ \textit{ohms}^{-1}\ \textit{cm}^{-1}$$

Arthur Von Hippel "Building from Atoms" Chapter 2
The Molecular Designing of Materials and Devices, MIT Press, 1965

The physicist Professor Arthur Von Hippel simplifies the matter of what is an insulator, semiconductor, and metal based on the conductivity of a solid [9]. In layman's terms, an insulator is a material that limits the flow of electrons within the bulk volume or surface of the material, and a conductor is a material that allows free flow of electrons within the bulk or surface of the material. An insulator can have a surface resistance of $\rho_s = 10^{11}$ ohms and bulk resistance of $\rho = 10^{11}$ ohms-cm; whereas conductors can have a surface resistance less than $\rho_s = 10^4$ ohms and bulk resistance less than $\rho = 10^4$ ohms-cm. The boundaries between them are not well defined.

From a practical perspective, an insulator does not allow the free flow of electrons on its surface, or through its bulk, where in the case of semiconductors and metals, carriers can flow on and within the materials.

In semiconductor devices, components, and systems, the material properties can be a good thing, or a problem. In the case where a material does not allow the free flow of carriers, charge will build up, and can lead to the establishment of electric fields. High electric fields can lead to electrical breakdown, and electrical overstress. In the case where the material allows the free flow of carriers, high currents can establish. High currents can lead to high discharge currents, electrostatic discharge events, self-heating, thermal breakdown, and melting of components, packaging and systems.

1.5 STATIC DISSIPATIVE MATERIALS

In the field of electrostatic discharge protection, it is advantageous to have materials that are not highly insulating, and also not highly conducting. These materials are referred to as static dissipative materials. Static dissipative materials are the materials which are between the insulators and conductors. Hence, we can define them as materials in the range of $\rho_s = 10^4$ ohms to 10^{11} ohms surface resistance, and the range of $\rho = 10^4$ and 10^{11} ohms-cm bulk resistance. The advantage of having materials that are neither insulators or conductors is the avoidance of static charge buildup or high currents.

1.6 ESD AND MATERIALS

Unfortunately, components and systems are not that simple. Both electrical components and systems contain insulators, semiconductors, and metals. Semiconductor components comprise of insulating dielectrics, semiconductors, and metals.

Insulating dielectrics exist as inter-level dielectrics, thin film oxides, and buried oxide films in the substrate. Insulator films in the MOSFET gate dielectric are very thin films whose thickness is dependent on the technology generation. Inter-level dielectric films exist between the wiring levels in a semiconductor chip whose thickness is in the order of the metal wiring film thickness. Electrical breakdown of the dielectrics is a failure mechanism from electrical overstress (EOS), or electrostatic discharge (ESD) events. Insulators are used in systems for cards, boards, supports, and other components.

Metal films exist in semiconductor components as interconnects between the electronic circuits. Semiconductor components contain wire films consisting of aluminum and copper. Refractory metals, such as titanium, cobalt, tantalum, and tungsten are also used for contacts, vias, silicide films, to cladding for the wiring. In systems, metals are used for the system chassis, and shielding.

Semiconductor materials are used throughout semiconductor components as the base wafer for semiconductor devices. The conductivity varies dramatically through semiconductor devices using dopants, from resistive to conductive regions.

As a result, semiconductor components are a stratified medium of layers that consists of metals, insulators, and static dissipative materials. Hence, controlling the conduction and dissipative nature of a semiconductor component can be quite difficult with regions of high conducting and high insulating properties.

1.7 ELECTRIFICATION AND COULOMB'S LAW

> *"The force between two small charged bodies is proportional to the product of their charges, and is inversely proportional to the square of their distance apart, the force being one of repulsion or attraction according as the two charges are of the same or of opposite kinds."*
>
> Coulomb, 1785

From Coulomb's law, it is understood that the force between two objects is associated with the product of the charges, and inversely proportional to the square of the distance. Hence the electric field associated with a force on a "test charge" is the charge of the object, and inversely proportional to the square of the distance between.

1.7.1 Electrification by Friction

"Bodies may be electrified many other ways, as well as by friction"

Part I Electrostatics Chapter I: *Electrification by Friction*
A Treatise on Electricity and Magnetism
James Clerk Maxwell, 1891

Electrification can be caused by rubbing two objects together. It is through friction between the surfaces (e.g., the materials touching) that can lead to the charge transfer and charging. When two materials are rubbed together, friction is assisting in the charge transfer process [7,10].

1.7.2 Electrification by Induction

"No force, either of attraction or of repulsion, can be observed between an electrified body and a body not electrified. When, in any case, bodies not previously electrified are observed to be acted on by an electrified body, it is because they have become electrified by induction"

Part I Electrostatics Chapter I: *Electrification by Induction*
A Treatise on Electricity and Magnetism
James Clerk Maxwell, 1891

From an ESD perspective, charged materials and charged surfaces generate electric fields. These electric field lines start at the positive charge, and end at the negative charge.

Hence a system or component placed near a charged surface can be polarized where negative charges are formed on the surface. In this process of "induction", given that the object is electrically connected to a ground potential, polarization will occur. When the ground connection is removed, this object will be charged. Charge will flow either to or from the ground connection. In the "induction process", given that the ground connection and the electric field is removed, the component or system will remain charged [7,11].

Induction charging is a concern in semiconductor components which have been charged by external fields, and is not electrically grounded. As will be discussed, this is a concern for the "charged device model." When it is charged there is no concern; but, when the charge is rapidly discharged to a ground connection, high currents can lead to component damage.

1.7.3 Electrification by Conduction

James Clerk Maxwell noted that electrification can occur by placing a "wire" between a first object and a second, where the current flows from the first object to the second. In that time, Maxwell referred to this as "Electrification by Conduction [7]." Today, this would be regarded as charging a body through a voltage source and an electrical circuit. Hence, there are many ways to "charge" a body.

Today, in the manufacturing environment, electrical components, and systems, these charging processes occur and are part of the "events" that must be monitored, controlled, and eliminated.

1.8 ELECTROMAGNETISM AND ELECTRODYNAMICS

Electromagnetism has three branches, namely Electrostatics, Magnetostatics, and Electrodynamics. Electrostatics and Magnetostatics are independent of each other and address only states of rest. On the other hand, electrodynamics deals with the motion of electricity and magnetism [6].

1.9 ELECTRICAL BREAKDOWN

Although we regard electrostatic discharge (ESD) as an electrostatic phenomena, since charge is moving, and currents are flowing, it is electro quasi-static. Electrostatic discharge can be initiated by an arc from a person to an object. The electrostatic discharge event occurs as a result of the breakdown of the air in the gap between the person and the object. The discharge process is a function of spacing of the gap, the geometry of the gap (e.g., curvature, radius of electrodes), cleanliness of the surface, relative humidity, and speed of approach.

So, what is electrical breakdown?

1.9.1 Electrostatic Discharge and Breakdown

As a young graduate student at the MIT High Voltage Research Lab, my professor Markus Zahn had to do some research at Exxon in Linden New Jersey; so we were brought along to do some experimental work on the breakdown of oil . . . the researcher had a lab with a 200,000 Volt charging source, a large Corona ring, and a metal pipe to connect to the sample of oil. The breakdown of oil is a function of the oil purity, dirt, and oil degradation from discharge events. We were there to isolate the electrical instability after the oil breakdown occurrence and capture the signal during the event. We used an electro-optical isolating Kerr cell – nitrobenzene, two polarizers and a laser. The researcher worked six months to find this electrical oscillation of oil after breakdown . . . we were given 5 days – we found it after 4 days of exploration for the signal . . . Understanding the fundamentals of breakdown is important in gases, liquids and solids! . . . So this is what you do at MIT on your summer breaks!

Electrostatic discharge involves the breakdown in gases, liquids and solids [12]. Breakdown in gases, liquids or solids can be initiated by a feedback induced by the acceleration of carriers leading to secondary carriers. Breakdown phenomenon in air is important for ESD applications for spark gaps, ESD simulators, and magnetic recording industry. Today, there is a focus on the understanding of breakdown phenomenon for charged device simulators.

In the magnetic recording industry, breakdown can occur between the magneto-resistor (MR) element and the shields across the air bearing surface. Hence the physics of breakdown in air is relevant to today's problems. At very high speeds, the ability to provide semiconductor devices may be limited. As a result, field emission devices and spark gaps may play a role in air bridge applications and micro-machines.

1.9.2 Breakdown and Paschen's Law

Paschen, in 1889, studied the breakdown physics of gases in planar gap regions [13]. The result of Paschen showed that breakdown process is a function of the product of the gas pressure and the distance between the electrodes. Paschen showed that

$$pd \approx \frac{d}{l}$$

where p is the pressure, d is the distance between the plates and l is the mean free path of the electrons. From the work of Paschen, a universal curve was established which followed the same characteristics independent on the gas in the gap. The Paschen curve is a plot of the logarithm of the breakdown voltage, V_{BD}, as a function of the logarithm of the product of the pressure and gap distance,

$$V_{BD} = f(pd)$$

At very low values of the p-d product, electrons must accelerate beyond the ionization limit to produce an avalanche process because the likelihood of impacts is too few. In this region, the breakdown voltage decreases with increasing value of the pressure-gap product. This occurs until a minimum condition is reached. At very high values of the pressure-gap product, the number of inelastic collisions is higher and the breakdown voltage increases. This U-shaped dependence is characteristic of gas phenomenon. At the high gas pressure, secondary processes, such as light emissions occur. Figure 1.3 shows the Paschen curve highlighting its U-shaped characteristic.

1.9.3 Breakdown and Townsend

Avalanche phenomenon is important to understand the breakdown process in semiconductors and other materials. Townsend, in 1915, noted that the breakdown occurs at a critical avalanche height [12,14],

$$H = e^{\alpha d} = \frac{1}{\gamma}$$

In this expression, the avalanche height H, is equal to the exponential of the product of the probability coefficient of ionization (number of ionizing impacts per electron and unit

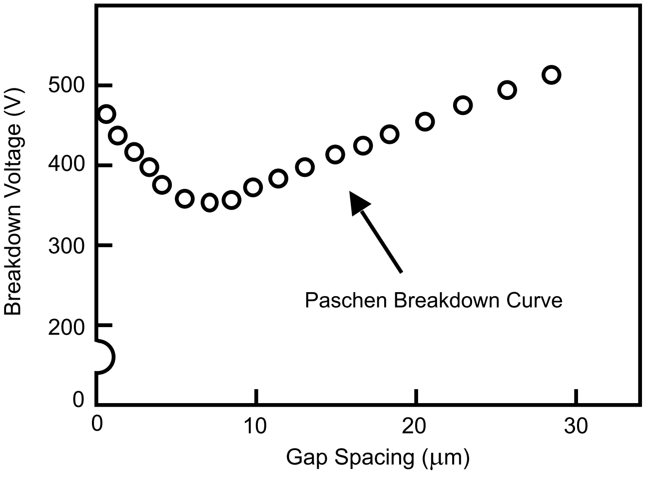

Figure 1.3 Paschen breakdown relationship

distance in the direction of the electric field) and electrode spacing. The avalanche height, H can also be expressed as the inverse of the probability coefficient of regeneration (number of new electrons released from the cathode per positive ion).

1.9.4 Breakdown and Toepler's Law

Evaluation of the resistance of arc discharges are important in ESD phenomenon since these events are evident in ESD simulation, such as charged device model (CDM), machine model (MM) for components and other ESD gun simulators for systems.

Toepler, in 1906, established a relationship of the arc resistance in a discharge process [15]. Toepler's law states that the arc resistance at any time is inversely proportional to the charge which has flowed through the arc

$$R(t) = \frac{kTD}{\int_0^t I(t')dt'}$$

where $I(t)$ is the current in the arc discharge at time t, and D is the gap between the electrodes. The value k_T is a constant whose value is 4×10^{-5} V-sec/cm.

1.9.5 Avalanche Breakdown

Avalanche breakdown plays an important role in the understanding of electrostatic discharge issues. Avalanche breakdown can lead to physical failure of semiconductor components.

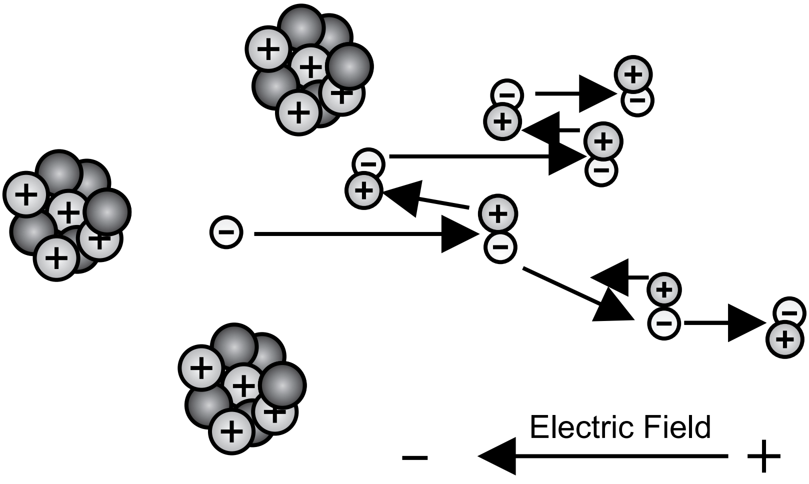

Figure 1.4 Avalanche breakdown

Avalanche breakdown also is used intentionally in semiconductors to serve as a trigger element to initiate turn-on of an ESD circuit. Avalanche breakdown plays a key role in semiconductor ESD elements and circuits which are intentionally reverse biased during functional operation of semiconductor chips, but are initiated at a voltage above the native operational voltage. This phenomenon is key to ESD networks in MOSFET and bipolar devices. It is utilized on input pin circuits, between common power rails in ESD power clamps, and between power rails. Hence, it is fundamental to the ESD discipline.

What is the avalanche process? Avalanche breakdown occurs when a carrier is accelerated by an electric field, where the collision with the material leads to a secondary carrier (Figure 1.4). The secondary carrier is then also accelerated, forming a third interaction. This is why it is called "avalanche multiplication."

To be more specific, it can involve energy transfer between the carriers, and the medium. As carriers are accelerated in a medium, energy is transferred from the electric field to the carriers. As the electric field increases, carriers approach a limiting drift velocity and further increases lead to thermal vibrations. As carriers are accelerated, there is a competition between energy transmitted to the electron and energy transmitted to the lattice. This is a function of the ionization threshold, the energy of the carrier, and mean free path of optical phonon scattering. To follow the cascade of carriers, the ionization rate is a function of the summation of probable events of cascades. The probability that a carrier contributes to ionization is a function of a first event where the carrier reaches the ionization and the probability that the first event is ionization. A second term is the probability that the carrier achieves the energy of a phonon and ionization event, and that the first event is phonon emission, followed by an ionization event. This is followed by a third term of the probability that an electron achieves the energy of two phonons and an ionization energy, where the probability is that two phonons are emitted followed by an ionization event. And on, and on. . . . From this collision process, we can derive an ionization coefficient associated with the avalanche collision processes.

Analysis of the breakdown in air is valuable for ESD protection to understand ESD simulators, and specifications. For example, D. Lin and T. Welsher related the phenomenon of air discharges to understand the physics of the first charged device model (CDM) test system [16].

Assuming a simple geometry of a gap with a gap spacing d, charge Q, and voltage V, we can evaluate the voltage, electric field, peak current, rise and fall time using the Townsend avalanche relationship. Assume a breakdown voltage and breakdown electric field is achieved in the gap leading to the flow of current across the gap structure. Let the current be a function of the electron drift current term (neglecting diffusion current).

$$I = en_e v_d$$

and

$$v_d = \mu E$$

We can relate the current to the derivative of the charge Q as a function of time, letting $dQ = (env)\ dt$, and we can relate the drift voltage to the electric field, and we know that the electric field, E, is a function of the voltage and gap spacing $E = V/d = Q/Cd$.

Assuming a breakdown voltage, and breakdown electric field magnitude, as the initial condition to initiate the discharge, we can derive the equations to explain the phenomena. Voltage, electric field, charge and current can be obtained in the gap when the electron density as a function of time is evaluated. Hence, all the terminal information can be expressed as a function of the charge density in time. In this fashion, the current as a function of time can be evaluated from the electric field, carrier density, and impact ionization coefficients. The peak current is a function of the capacitance, the gap size, the mobility and the ionization at the maximum electric field.

Air breakdown is important in ESD phenomenon and the physics of failure. A key parameter of interest is the peak current of the air discharge since a number of ESD failure mechanisms is associated with the peak current magnitude. It can be shown that the peak maximum current is expressable as [16]

$$I_{Peak} = (\mu Cd) E_{\max}^2 \alpha(E_{\max})$$

The peak current is then a function of the capacitance, the gap size, the mobility and the ionization at the maximum electric field.

1.10 ELECTROQUASISTATICS AND MAGNETOQUASISTATICS

For static electric and magnetic fields, it is adequate to address evaluation in the electroquasistatic and magnetoquastatic approximation of Maxwell's equations. The approximation is a function of the charge relaxation time, magnetic diffusion time, and the time constant of interest.

1.11 ELECTRODYNAMICS AND MAXWELL'S EQUATIONS

James Clerk Maxwell showed that there exists a set of equations that explain the connection within electromagnetism between electric and magnetic fields [7]. Electric charge leads to static electric fields, and current leads to magnetic fields. Additionally, time varying fields lead to sources that influence electrical components, and systems.

In production and manufacturing, one must not only be concerned with static fields, but time varying fields that produce electromagnetic interference (EMI), and electromagnetic compatibility (EMC) issues.

1.12 ELECTROSTATIC DISCHARGE (ESD)

Today, the discipline of electrostatic discharge (ESD) is focused on the impact to components and systems. Prior to the 1990s, there were few texts associated with the field of electrostatic discharge. In the last twenty years, many texts have been written discussing the ESD design discipline and latchup design discipline [17–30].

As will be discussed further in the text, there are many new ESD test standards to qualify and evaluate both components and systems. Components tests consist of tests for human body model (HBM), machine model (MM), charged device model (CDM), transmission line pulse testing (TLP), and very fast transmission line pulse (VF-TLP) testing [31–43].

For system level evaluation, there are tests for cable discharge events [44–46], system test IEC 61000–2, and human metal model (HMM) [47–53].

1.13 ELECTROMAGNETIC COMPATIBILITY (EMC)

Electromagnetic compatibility (EMC) is the ability of an electronic system to function properly in its intended electromagnetic environment and not be a source of electronic emissions to that electromagnetic environment. Electromagnetic compatibility (EMC) has two features. A first feature is a source of emission of an electromagnetic field. A second feature is the collector of electromagnetic energy. The first aspect is the emission of an electromagnetic field which may lead to electromagnetic interference of other components or systems. The second aspect has to do with susceptibility of a component, or system to the undesired electromagnetic field. Today, there are many standards and tests on the subject of EMC [54–75].

1.14 ELECTROMAGNETIC INTERFERENCE (EMI)

Electromagnetic interference (EMI) is interference, or noise, generated from an electromagnetic field. Electromagnetic interference is electric and magnetic fields that interfere with electrical components, magnetic components, and electrical or magnetic systems. EMI can lead to both component level or system level failure of electronic systems. EMI can lead to failure of electronic components, without physical contact to the electronic system. In the industry, there is a significant number of standards and tests to address both EMC and EMI concerns [54–76].

1.15 SUMMARY AND CLOSING COMMENTS

In Chapter 1, a brief discussion of electrostatics, and triboelectrical phenomena was weaved into the individuals, dates, and history: Thales of Miletus, Gray, Dufay, Franklin, Toepler, Faraday, Cavendish, Coulomb, to Maxwell – just to mention a few. The chapter then quickly fast-forwards to today's issues of ESD, EMC and EMI, all today's concerns in components and systems.

In Chapter 2, the text discusses the manufacturing and factory environment, and how it is related to the discussion in Chapter 1. Today, the factory environment is established to address everything we learned in Chapter 1 about materials, conductivity and avoidance of discharge events. What will be observed is how it has been integrated and applied into the manufacturing environment and business process to reduce the impact of ESD phenomena.

. . . *Thales of Miletus would be shocked to see how far this has gone!*

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