ESD Back-to-Basics

When Coulomb and Priestly observed and measured the attractive and repulsive forces between two charged balls, and Coulomb subsequently formulated his famous Coulomb's Law, little did he know that he laid the foundation on which much of modern Physics is built. Electrostatic charging (ESC) and discharging (ESD) phenomena, already observed and described by the Greeks in 600 BC, can be directly related to Coulomb's observations.

Charged elementary particles of like polarity, electrons in our case, repel each other. This is actually an understatement. Electrons forced to live together on a small conductive object repel each other with, proportionally speaking that is, unimaginable strong forces. Matter of fact, if enough electrons are present on this object, the expulsion force may be so great that they create an escape path in the form of an arc.

The Electrostatic Discharge or Event

An electrostatic discharge is basically a more or less sudden and violent redistribution of electrons between bodies such that in their new spatial equilibrium position, the electrons end up as far away from each other as they could possibly get. Because of the repulsion between like charges, the charges will always position themselves at the outside skin of a conductive body, which is ultimately as far away from each other as they can possibly get.

If the path for this sudden electron rush happened to include sensitive electronic devices, destruction or latent damage may well be the result. If, in their quest to redistribute, they forced themselves through an arc, and if this happened in an explosive atmosphere, the damage could be far more than just a dead electronic component or system.

The suddenness, or better, the time duration during which such a charge redistribution or ESD event takes place depends on numerous parameters. If for example, the interacting bodies are excellent metallic conductors suddenly touching each other, the electrons are probably redistributed in a matter of picoSeconds, and the peak current during the sudden massive flow is substantial. It is not readily understood how fast ESD events really are because of bandwidth limitations of today’s existing equipment.

The electromagnetic fields associated with an impulsive current of this magnitude are simply huge, and have the ability to upset electronic circuits quite easily. Measured frequency spectra of fast discharges extend all the way up to 40 to 50 Ghz. If on the other hand, there is resistance or impedance in the path between the interacting bodies, the electrons will require more time to work themselves through these obstacles. The peak current will hence be lower, and the duration of the discharge longer. Most ESD protective gear such as wrist straps, conductive footwear, and the like, attempt to do just that. By inserting known resistive paths, the currents are kept to the microAmpere levels, and the duration are extended to the millisecond or second range.

Note that redistribution of charge, whether sudden or not, always involve dissipation of energy. Slowing the flow of the electrons with a resistor is but converting some of their kinetic energy into heat. Other forms of released energy are of electromagnetic and mechanical nature, and if an arc is involved, acoustic, and light as well.

Charge is the Enemy

The culprits in ESD events, are electrons, either too much or not enough of them, and the bodies on which they reside. The term body is obviously not restricted to the human body. It is a standard expression in Electrostatic Physics, used to describe an isolated entity of matter, conductive or not, surrounded by either vacuum or an infinite mass of a different matter. For a Physicist, an integrated circuit is a body, a shoe is another one, an elephant is a third one.

As stated earlier, on conductive bodies the charges will end up at the outer skin of that body, because that is as far as they can possibly go. If the body is irregular in shape, the electrons will not be equidistantly positioned. They will spread themselves around the surface such that all repulsive forces on each individual electron are in equilibrium. In other words, a giant balancing act frequently involving billions of players. Only on a perfect conductive sphere will the electrons be spaced equidistantly. For example, a charge of I microCoulomb is typically found as a result of an interaction between a pair of shoe soles and a floor, distributed over a perfect sphere with 1 meter diameter involves 6.2 trillion electrons, each spaced 0.7 micrometer apart.

One of the implications of this electron behavior is that any randomly shaped body can be fairly accurately modeled as a sphere with a diameter such that its skin surface equals the total skin surface of the body being modeled. A typical human body, for example, becomes a 1 meter diameter conductive sphere. A 64 pin Dual In Line IC becomes an 18 mm sphere. And, taking it one step further, the electrostatic properties of a sphere can be easily described and predicted with well understood mathematical expressions. Also, the interaction betweenmultiple spheres, when a charged human picks up the IC for example, and between a sphere and a plane, a human and the earth for example, can be readily described and predicted.

Capacitance

Probably the most important property of the sphere is its capacitance. Note that a "capacitor", seen through the eyes of a physicist, is a totally different kind of animal then the "capacitor" seen by most electrical engineers. There is a very important distinction, and some electrical engineers have a hard time understanding and visualizing what a capacitor in the electrostatic physics sense of the word really is. As a result, a fair amount of ESD related products and test equipment designs are based on debatable and erroneous (concepts and models of capacitance).

For a physicist, a capacitor is basically a physical body with certain dimensions, composed of real molecules, and immersed in a dielectric of a certain capacity. If the total number of electrons contained in the molecular structure of that body exceeds the total number of protons, then the body is negatively charged, or, expressed differently, its capacitance holds a negative charge.

From the electrostatic physics point of view, there is thus no need for a second plate parallel in close proximity of a first one to make a capacitor. This is the device that the electrical engineer usually thinks of when he hears the word capacitor. In fact, the parallel plate capacitor is for the physicist but a special case in the general field of electrostatic physics.

The following examples will illustrate the notion of spherical capacitor as the physicist sees it. The capacitance of the earth in the solar planetary context equals 710 microFarad. A 1 meter diameter sphere, which is the model for the human body, has a free space capacitance of approximately 110 pF. By free space is meant far away from any other body or plane. If the same 1 meter sphere comes down to earth and floats approximately 5 centimeter above it, it's capacitance will have increased by 2.5 times.

Charge, Capacitance and Potential Difference

If charge is stored in a body, it will develop a potential difference with respect to the body from which the charge was extracted. For example, when a person with conductive footwear walks over a non conducting floor surface, the shoe sole to floor interaction will result in electrons being extracted by one from the other. Assuming it is the shoe soles that get the electrons, then the extracted electrons will end up distributed over that person's body. In other words, stored in his/her body capacitance. Since potential difference, charge and capacitance, are related by the equation $U = Q/C$, we can calculate that a 1 microCoulomb charge stored into the 110 picoFarad of the human body would result in a 9010 Volt potential difference. And, since the capacitance at 5 cm from the ground plane is 2.5 times higher, the potential would drop to 3600 Volts at that distance.

The potential difference on an unprotected human body in motion will vary continuously. It varies because the body bobs up and down above the ground plane, it varies because the dimensions and the geometry of the body are continuously changing, it varies because of different amounts of charge being extracted at each shoe sole to surface interaction, and it varies because of dozens of other interfering parameters. Predicting the potential difference of a human body in motion and interacting with its environment is a nearly impossible task. It is important to realize that ESD damage is in the first place caused by the amount of electrons that suddenly flow, rather than by the potential differences being so high as to cause an arc. An arc is nothing but an unusual form of a low resistance conductive path through which the excess electrons can rush and redistribute themselves. In the electronics industry, it is not so much the arc that is the culprit, it is in the first place the electron rush. In an ammunition plant, one might be tempted to say that the arc is more important.

In a way, potential difference plays somewhat in our favor. Electrostatic physics shows that field strength and curvature of a body are related, the field is always more intense at sharp protrusions. If the field becomes sufficiently high as to cause ionization and corona, charge will be able to escape into the ambient air, thus limiting the potential difference excursion on the human body. It would however not be prudent to rely on this phenomena as a protection against ESD. Another interesting aspect of potential difference excursion on the human body is that it can be easily measured with a suitable Voltmeter. This can be non-contact Electrostatic Voltmeters or Electrometers. Potential differences due to charge on the human body can be made with a Novx Electrometer for example.

Electrification

In the Electronics Industry, charged human bodies are the component or system killer, and the charges come almost invariably from the interaction between shoe soles and the floor. Seldom does charge come from friction in clothing. Matter of fact, the clothing worn in most electronic factories are relatively thin, and from the electrostatics point of view, it is "drenched" in highly conductive compounds containing bromine and chlorine. Clothing actually becomes the effective conductive outer skin of the human, and that is where the excess charges will ultimately end up. It also has serious implications on the magnitude of the equivalent body capacitance.

Probably one of the biggest misconceptions about electrostatics was planted in the minds of factory workers and engineers alike by high school science teachers, demonstrating electrostatics by rubbing a comb, or something on their shirt sleeves. Rubbing an object on ones shirt sleeves has become the stereotype for electrostatics. Although there is nothing wrong with that demonstration from the pure electrostatic physics point of view, it has been totally misunderstood, and it must have cost, and is still costing the industrialized world an untold fortune to unteach and reteach the true basics of electrostatics as they apply to the industrial establishment.

Rubbing the handle of a screwdriver on a shirt sleeve seldom is detrimental to your electronic circuits. Shuffling your feet on the floor while sitting in a chair at the workbench very likely is. Good self explanatory, back to basics teaching tools are sorely needed in the industry as well as in the science classes of our high schools and institutions of higher learning.

Protective Equipment

"The best protection against ESD obviously is to eliminate ESC. If there are no electrons lost or gained in an interaction between bodies, there can be no electron rush in between them. How can we reliably and acceptably cost protect ourselves from ESC? The easiest solution is to rely on the electron backflow phenomena. When two materials physically interact, whether they are different or the same, or whether they are in their gaseous, liquid or solid states, one of them is likely to loose electrons to the other. The amount of electrons lost is, amongst others, a function of a materials property called the workfunction. There is also a table classifying the materials according to a Tribolectric Series, attempting to predict which one of the materials will gain the electrons and thus become negatively charged. If the interacting materials are both conductors, then electron backflow occurs at the moment of separation, and no net charge exists on the interacting bodies.

Foot Straps and Conductive Shoes

The interaction between conductive footwear and conductive flooring is an example of electron backflow in action. To be noted, a conductive pair of shoes on a conductive floor works. A conductive pair of shoes on a non-conductive floor does NOT work. A non-conductive pair of shoes on a conductive floor does NOT work either. And a non-conductive pair of shoes on a non-conductive floor is totally out of the question. Conductive shoes work well as long as the person wearing them does not use insulating inserts. Some workers frequently object against wearing them because they tend to be clumsy and unfashionable. ESD shoe suppliers typically cater to the steel toe crowd and fashion is obviously the least of their concern. Foot straps on BOTH feet on a conductive floor work as long as the foot straps are touching the conductive floor. Heel straps do NOT work when a person stands on her/his toes, and toe straps do not work when a person stands on his/her heels. These conditions happen more often them one thinks. The best foot straps cover both toes and heels. They are widely used in ammunitions plants for example. Velcro on the foot straps often interferes with the shoe laces. Foot straps frequently loosen on the heels of personnel sitting at workbenches.

Wrist Straps

Nothing rivals a wrist strap when it comes to protection against ESC. It clearly is the uncontested winner. The biggest problem is that wearers frequently forget to connect them when they arrive at their workstations, and then it does not really matter whether the wrist strap is a dual conductor type connected to an appropriate continuous workstation monitor or just a standard ground strap. The wrist strap grounding cords frequently are a source for aggravation. They tend to be in the way, snag, and sweep tools and components off the workbench.

Smocks

A smock is basically a conductive outer skin or Faraday Cage. One has to be careful with smocks as they can become the equivalent of a concentric spherical capacitor around the human body, able to store enough charge and with sufficient capacitance to become a threat of comparable magnitude to that of an unprotected human body. This occasionally happens when they are worn over thick winter clothing in dry weather and when the smock does not make reliable contact with the skin of the person wearing it. Friction between the smock and the clothing causes the smock to become charged with respect to the human body, which, in turn, can have a charge of its own. Contact with the skin of the human body is very important and is usually done at the cuffs of the smock. The electrical connection between the sleeves and the body of the smock is another source for concern.

Conclusion

We have attempted to put ESD and ESC related phenomena into a slightly different perspective. ESC is in the first place electrostatic in nature, whereas ESD belongs more in the domain of electromagnetism. For the longest time, ESC and ESD were a neglected, poorly understood, under funded and stigmatized niches of physics and electrical engineering. This is changing rapidly and dramatically, as dense IC structures and MR Heads become more and more prone to ESD induced damage. Remember, if there is no ESC, there is no ESD.