Static electricity in cleanrooms

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Introduction

Static electricity is often overlooked in cleanroom environments and the results of this oversight can cause a reduction in profitability. In some factories where the effects are not studied and understood, they are dealt with by budgeting a reduction in production yield for unforeseen issues. Static charge and its effects certainly can be understood and it can be kept in check. The purpose of this article is to remove the "black magic" from the issue, explain how it affects the manufacturing process and discuss remedies available.

What is special about a cleanroom?

A cleanroom is a unique environment. For many applications it is regulated to a low relative humidity (RH) to optimise the process. Much of the particulate contamination is excluded by massive amounts of air filtration involving high efficiency particulate air (HEPA) filters. Objects in the cleanroom are wiped down before they can enter into the room. As it turns out, these actions are very good for maintaining an ultra clean environment but they are also the prescription for achieving massive levels of static charge in the room.

It is well known that static charge is created efficiently in a low humidity environment. It is commonplace for individuals to get stung by a spark when they reach for a doorknob in the winter time. Buildings are heated and lower RH results from the temperature rise. This same effect causes the rate of static charge generation to be higher in a cleanroom, especially a low RH cleanroom, than in a conventional room.

Once static charge has been generated by contact with other materials (see below for discussion of this effect), nature has several methods to dissipate the charge. The first mechanism is conduction of this electrical charge to ground through any surface contamination on the object. Normally, such contamination , for example oil from a person's hands, is removed from the object before it enters the cleanroom and the object remains clean because the products are only handled by gloved hands.

The only mechanism remaining for natural dissipation of surface charge is the presence of ions in the air. These ions are created by naturally occurring radioactivity and by other items like running water and electrical motors. Unfortunately, ions cannot pass through a HEPA filter – they are attracted electrostatically to the materials of the HEPA filter – so they are removed from the air entering the cleanroom.

To complicate matters further, most cleanrooms employ many insulators such as glass and plastic. Teflon™, for example, is an incredibly effective insulator and holds onto its static charge aggressively. Glass and other plastics are also very effective insulators. As a consequence of the above argument, cleanrooms allow static charge to be generated very efficiently and dissipated very poorly. The result is levels of static charge which far exceed those in conventional rooms[i].

Effects of static charge

Electrical Charge creates a force field around itself which attracts objects with the opposite charge and repels objects with the same charge. In the case of cleanroom contaminants, this force can be extremely significant. Static charge causes microcontamination issues through attraction and repulsion. Electrostatic discharge causes physical damage to small devices, most commonly electronic devices. In addition, these discharges radiate high frequency electrical pulses throughout the cleanroom. These pulses can corrupt microprocessor-controlled operations and create effects that mimic software bugs. Most often, the controlled item affected, for example a robot, halts and displays an error message requiring operator intervention.

Microcontamination - It is well known in everyday life that television screens collect dust which needs to be removed regularly (at least all of the generation of televisions before LCD technology became so popular). The picture tube on these TVs is a cathode ray tube and is bombarded by an electron beam which charges it, resulting in electrostatic attraction of dust.

The same effect that causes dust to be attracted to a television screen causes contaminants to be moved through a cleanroom. There have been many articles published on attraction of particles to the surface of a semiconductor wafer or to the surface if an IV bag[ii,iii]. In addition, static charges on objects in the cleanroom other than the product are also serious contamination issues. A good deal of effort is put into establishing airflows which entrain the small amount of contamination in the cleanroom so it

Figure 1. Dust electrostatically bonded to a television screen

moves past the product without settling out. The electrostatic forces on a particle in a cleanroom that does not have charge control are much greater than the aerodynamic forces on that particle and cause it not to follow the engineered airflow direction. This means that the microcontamination safeguard of engineered airflow has been defeated.

The effect of static charge on powders is of great significance. When the product is in the form of a powder, it is often seen to stick to the walls of a container. Trying to shake out the powder or to blow it out is most often fruitless. The powder adheres to the walls of the vessel tenaciously and cannot be removed. This is referred to as electrostatic bonding. The only way to avoid this issue is through electrostatic charge control.

As mentioned above, like charges repel each other. As a result, when a powder becomes highly charged and is put into a vessel of like charge, the powder will be repelled and much of it will spray out of the vessel. Similarly the repulsion effect can cause pills to refuse to sit in their assigned locations in blister packs.

Physical damage - In some applications, the product can be quite sensitive to damage from electrostatic discharge. This is true of most products which contain electronics. Pacemakers often contain sensitive electronics which can be damaged or destroyed by an accidental discharge to the product during handling. For products that consist of powders, a discharge to the product or near the product could cause a fire or an explosion.

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Interference with automation systems - Electrostatic discharges are fast. In fact, a metal-to-metal discharge typically takes place in under one nanosecond. While approximately half of the energy in a discharge becomes local heating of the two objects involved, the remaining half is radiated as electromagnetic interference (EMI) in the form of high frequency radio waves and microwaves (~100 MHz-5 GHz). Such short wavelength bursts are extremely difficult to shield against. They squeeze through cracks and permeate ground wires. By one means or another, they can result in short, large amplitude pulses (glitches) in microprocessor circuits. One such discharge is shown in Figure 2. Note that the signal is quite fast and 'rings' for ~20 nanoseconds. The ringing is an artefact of the antenna itself but the width of the first oscillation is representative of the actual discharge.

When such a discharge induces a pulse on a bus within a nearby microprocessor, it usually causes no effect upon the circuit. On the rare occasion that the pulse is present in the microprocessor circuitry exactly at the same time as a "latch strobe," an erroneous digital word will be latched into the microprocessor and either a corrupted instruction or data value will be processed by the microprocessor[iv]. In the case of a bad instruction, the processor will identify the instruction as bad and stop. This shuts down production until the fault is cleared. In the case of bad data, a microprocessor controller will cause abnormal behaviour. For example, in the case of a robot, the product may be dropped or an arm may crash into a wall.

Although the discharges might happen every few seconds, only occasionally will they happen at exactly the same time as the latch strobe, so most of the discharges do not cause an effect. When the two signals do align, the resulting automation anomaly mimics a software bug. Often such an

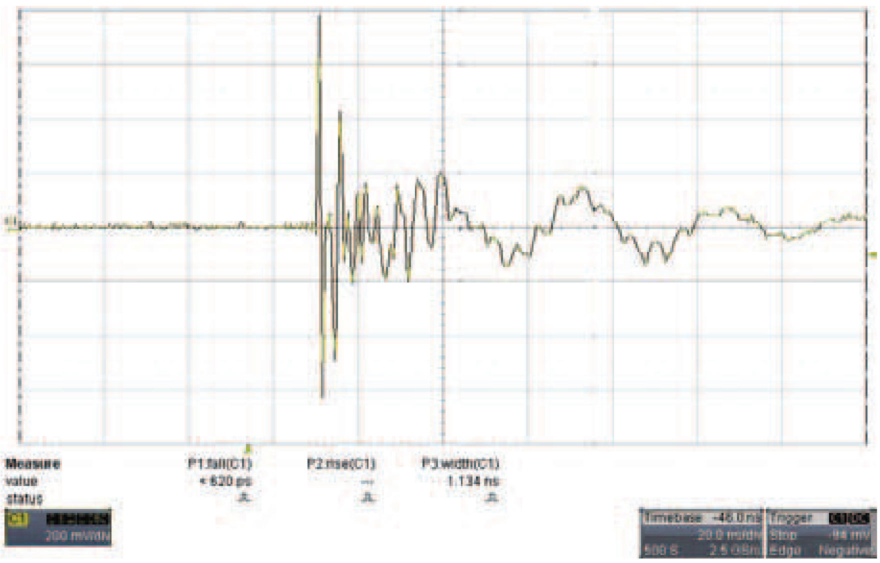

Figure 2. A waveform captured on an antenna near a small electrostatic discharge

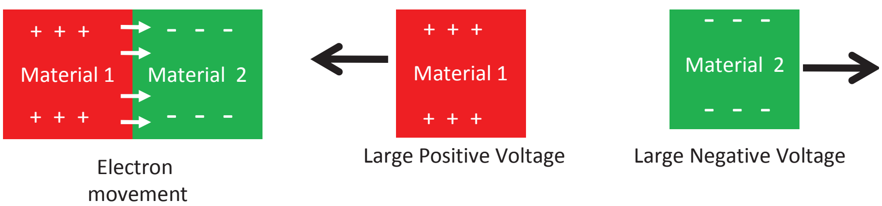

Figure 3a, Figure 3b

apparent bug takes weeks or months to sort out, but is ultimately identified as arising from ESD induced EMI. The key attributes of the effect are that

1. The effect looks like a software bug
2. It happens only occasionally and randomly
3. While there may be many identical process tools, all with the same software revision level, not all of them demonstrate the effect.

Generating static charge

All matter is made up of atoms and molecules. In solids and liquids, some of the electrons are attached to the solid or liquid rather than to individual atoms. Some materials readily give up some of their electrons while others easily take on additional electrons. This is related to the binding energy and the surface condition of the material. Thus when two different materials make contact (Figure 3a), a small transfer of electrons will necessarily occur. When the two charged materials are separated (Figure 3b), a voltage difference is generated. These materials can be either electrical conductors or insulators.

Materials can be ranked according to their tendency to accept or give up electrons. This is called the triboelectric series. Figure 4 shows a number of items that might be present in the production area of a factory. There are, of course, many other materials that might be important in a particular factory. Note that most organics tend to be electro positive, metals tend toward neutrality and plastics tend toward electro negativity. This is not a firm and fast rule but just a generalization. The further apart two materials are in the triboelectric series, the larger the charging effect will be. The semiconductor industry, for example, sees very large charges because they routinely place electropositive wafers in electro negative Teflon™ cassettes.

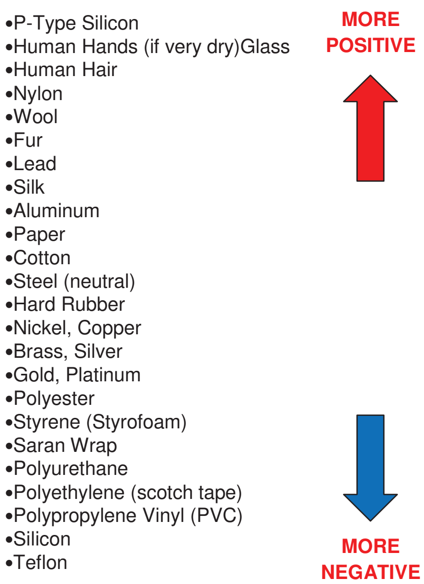

Figure 4 Triboelectric series

Since the triboelectric charging effect is a phenomenon that involves surfaces, it is no surprise that the relative humidity of the environment will affect the rate of charging. At high RH, a monolayer of water is deposited on the surface of materials in the room. This serves to reduce the contact of the intrinsic materials and minimise the triboelectric effect. At low RH, this effect is reduced and the triboelectric effect is increased.

The static charge will be developed triboelectrically no matter what solids or liquids are involved (gasses cannot cause this effect but any particles entrained in a gas flow can cause charging at a modest rate.) For example, materials at the ends of the triboelectric series left in airflow for days or weeks will show an appreciable charge. The materials can be conductors or insulators. If contact and separation occur, the charge transfer will also occur. If one or both of the materials is a conductor, its charge will be shunted to ground but if it is electrically floating, it will remain charged. The one case which is often misunderstood is the case of a grounded metal robotic arm which handles an insulator. When a conductor contacts an insulator, triboelectric charging (charge exchange) occurs. If the metal part is grounded, it transfers its charge to ground but the charge on the insulator is captive and remains. Thus the arm ends up uncharged and the insulator (e.g. a test tube or beaker) comes away charged.

Using the prescription of contact and separation of dissimilar materials, it is clear to see that significant charging can occur when glass or plastics are dipped into liquid and removed. Inserting into the liquid represents the contact process and the drip dry of the object after it is removed from the liquid represents the separation. Another example is when a powder is poured from one container into another. This gives two charging opportunities. The first is the contact of the powder with the walls of the first container and the second is the contact with the second container.

Thus, from the above discussion several rules emerge for the control of static charge. These are

1. Ground electrical conductors wherever possible
2. Avoid the use of insulators whenever possible
3. Use dissipative plastics wherever possible and remember to ground them

It is clear that in high temperature processes, glass must be used and in caustic chemical applications, Teflon™ is often the only choice; but in many applications, these materials can be replaced by similar materials which provide some electrical conductivity. Materials which have low electrical resistance $<10^4$ Ω are called conductors. For materials which have very high electrical resistance $>10^{11}$ Ω are considered insulators. Those in between these limits are called dissipative materials. Conductors and dissipative materials can be grounded to be made electrically neutral. Insulators can be sufficiently high in resistance so as to be impossible to discharge.

Most plastics fall into this category although there is a class of plastic which is doped chemically to become dissipative. Such materials are used extensively to control static charge. In addition, metal tools often are given dissipative tips so that they can dissipate static charge slowly (milliseconds instead of sub-nanosecond discharges) – see Figure 5. This is a technique to allow handling of sensitive parts without fear of damaging them due to a discharge. Another important rule for ESD control emerges:

- For products which can be damaged due to electrostatic discharge, eliminate all metal-to-metal contact and replace one of the two surfaces that make contact with dissipative materials.

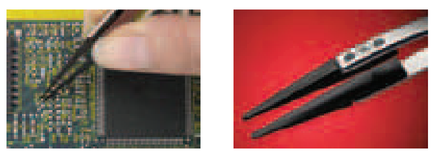

Figure 5. Tweezers with dissipative tips. Photograph courtesy of TDI, Inc.

Another area in which product can be damaged by discharge is on work surfaces. If the product is susceptible to discharge to ground, using metal work surfaces is dangerous. Using insulating surfaces is always a microcontamination hazard and may be a discharge hazard because fields from a charged insulating surface can induce voltages in adjacent conductors and then spark. The correct solution is to place a grounded dissipative mat on surfaces that will be used with highly sensitive parts.

Elements of a static charge control program

The measures to take to control static charge in production areas are simple to write down but there is a good deal of detail to consider in the execution. Which measures to take will depend upon the details of the production facility. For example, in a process which is mostly manual, a good deal of attention must be paid to grounding of operators. In an automated process, the robots and the walls of the process chambers near the product are of major concern.

The global grounding issue

There are many mobile objects within a clean room. Of note are personnel and carts which need to be grounded. While it would be nice to attach an umbilical cord to every mobile object (a wrist strap, for example), this is not a practical solution for objects that move throughout the cleanroom. The conventional solution is to use a specially designed floor which is electrically continuous to ground potential. Typically these floors have a resistance of 106 to 109 Ω to ground (RTG or resistance to ground) and are referred to as ESD floors. Note that lower RTG values can be used, but the values selected make it impossible for an operator to receive a painful or dangerous electric shock from exposed wiring. The RTG of the floor, and correspondingly of the operator, is high enough to substantially limit the current through the operator to a safe amount.

Personnel grounding

People represent a significant static charge issue. Fields from charged operators move contaminants out of the unidirectional airflow and therefore defeat its cleansing effect. Also, people making contact with product can damage it through a discharge. This is an issue for electronic products and many medical devices. There are a number of choices for grounding personnel. These include

1. A full ESD "bunny suit" used in conjunction with a floor which has continuity to ground. The entire suit contains conducting threads and continuity exists from the body of the garment to the boots and from the boots to the soles of the boots. See Figure 6. Note that this method for grounding is useless if the floor does not provide conductivity and a path to ground (a so-called ESD floor.)

Figure 6. Full cover clean room suit with ESD threads for continuity to the soles of the boots. Photo courtesy of Vidaro Corporation.

   Since the suit contacts the operator (either by direct contact or through a small amount of sweat), the operator is grounded and remains neutral.

2. Conventional shoes are insulators and make no contact between the operator and ground. Therefore, if an ESD bunnysuit is not worn, ESD shoes (designed to provide electrical conductivity between the floor and the operator's feet through a sweat layer in his socks), ESD heel grounders (see Figure 7) or ESD booties are required to provide a path to ground. ESD booties or heel straps are worn over the operator's shoes and have a wick that is placed into the shoe to provide a path to ground. In the case of either a non ESD bunnysuit or an operator with a smock or street clothing but without ESD footwear, the action of an ESD floor is defeated. In the case of an operator wearing an ESD smock and ESD footwear, the operator and the smock become neutral. If the clothing is insulating (as most synthetics are), the clothing remains charged but the smock acts as a Faraday shield to block any electric fields from the clothing.

Figure 7. Heel grounder on an operator's shoe. These devices should be used with either an ESD floor or with grounded ESD mats placed at each work area. Photo courtesy of Transforming Technology Inc.

3. ESD chairs are special chairs that provide continuity from the seat to ground. These can be used if operators wear ESD smocks because the smock contacts the operator and the chair grounds him or her.

4. Wrist straps are another way to ground operators. A bracelet (either cloth or metal) is put on the operator's wrist and is connected to ground at the work station. This is a very popular method of personnel grounding where there is no ESD floor. It requires that the operator remember to plug in at the work station. Also, there are sometimes issues with operators wearing the wrist strap over a sleeve which defeats the grounding. Also, operators with unusually dry skin may not be reliably grounded. Wrist strap testers will detect this issue and it can be solved with "ESD lotion" which improves the strap to wrist contact.

Note that there is no need to use all of these personnel grounders. It is up to the ESD program manager to determine which of these methods should be implemented.

Hardware grounding

Carts and shelves need to be grounded. Carts require ESD wheels which provide continuity to ground for the cart. At least two wheels need to be an ESD wheel to ensure that at least one wheel has contact with the ground. Again, ESD carts are only useful if the floor is of the ESD type. It is also possible to ground the carts by strategically placing grounded ESD mats. Note that very often both carts and shelving employ black plastic bushings to hold the shelves in place. These are most often insulating so that the shelves remain floating. It is necessary to replace at least one bushing per shelf with dissipative bushings.

It is surprising that process equipment with metal walls often has large panels which are not grounded. The reason for the grounding failure can be as simple as non contact due to paint on the surfaces. Every panel needs to be checked for ground integrity and, as required, ground straps should be installed to correct any faults.

Windows

Windows can be plastic or glass. Of particular importance are windows in process equipment which are close to the product. As a rule of thumb, "close" means the distance to the product from the window is within a length or width dimension of the window. These windows represent a contamination issue. They may also represent a discharge hazard by inducing voltages in adjacent conductors which, in turn can create a spark. The window material can be replaced with dissipative plastic which looks just like the original clear plastic but provides some electrical conductivity. It is important to remember to provide a ground to the new window. Typically, this is automatic if the window mounting material is metal and contacts the window. As an alternative, it is possible to use dissipative film with adhesive backing or to apply a dissipative coating. Coatings can be quite effective but, in time, they do wear off if there is any appreciable contact with the window, for example, by operators.

Required insulators and ungroundable conductors

Some insulating materials cannot be practically replaced by dissipative ones. For example, many acids will attack most plastics but they will not attack Teflon™. For that reason, and because it is particularly clean, Teflon™ is frequently found in cleanrooms. Unfortunately, as it is at the very end of the triboelectric series, it charges (negatively) extremely easily and holds its charge tenaciously. There are some metal structures that cannot practically be grounded owing to mechanical issues. The solution for these special circumstances is the use of air ionization.

Air ionization is used to convert some of the air molecules to air ions which in turn, find their way to the surface of objects which are charged and exchange charge with them, thereby neutralizing them. See Figure 8.

It is tempting to use ionizers as the complete static control program. Ionizers do eliminate static charge but they do so at a cost. All ionizers require some form of maintenance which can become a major personnel drain when ionizers are used extensively.

Ionizer technologies

The most common technology for air ionization generation employs the corona effect. These ionizers use high voltage (5 to 15 kV) on sharp needle points, called emitters. Various AC and DC technologies are used with several emitters per ionizer. These ionizers all act as precipitators, extracting chemical contaminants from the air and need to be cleaned regularly. Cleaning cycles can be as frequent as weekly or as long as quarterly, depending upon the technology and the type and concentration of contaminants (airborne molecular contaminants or AMCs[1]) in the air.

Corona ionizers need to be adjusted at installation and at each cleaning. The adjustment sets the rate of negative ion generation and positive ion generation to be equal. If this adjustment is not done, the ionizer will discharge objects to a voltage other than zero. The adjustment is done using a specialised instrument called a charge plate monitor, available from a variety of commercial sources.

Corona ionizers can be made to mount on the ceiling and provide a modest discharge rate (~30-60 sec) to all objects in an area of ~ 3 x 3 m. These ionizers are called ceiling emitters and can be strategically located over individual work or process areas. They use the unidirectional airflow of the cleanroom to deliver the ionization to the items to be discharged. Without unidirectional airflow, they cannot be used.

A second form of ionization is used within process equipment which is enclosed. This uses pre- existing airflows within each machine to discharge objects within the machine.

Corona ionizers also are made in the form of blowers. They look like small electrical fans and they make ions which are driven to the object to be protected using the airflow of the blower. These can be quite clean but they will perturb unidirectional airflow in a cleanroom. Blower type ionizers are mounted on a work surface or within a piece of process equipment and deliver substantially faster discharge than ceiling ionizers which use unidirectional airflow to deliver ionization.

A second technology that is used is alpha technology. Alpha ionizers use Po^{210} as a source of 5 MeV alpha particles. Each alpha particle that is emitted from the source travels through the air, colliding with air molecules and ionizing them along the way. The range of such alpha particles is approximately

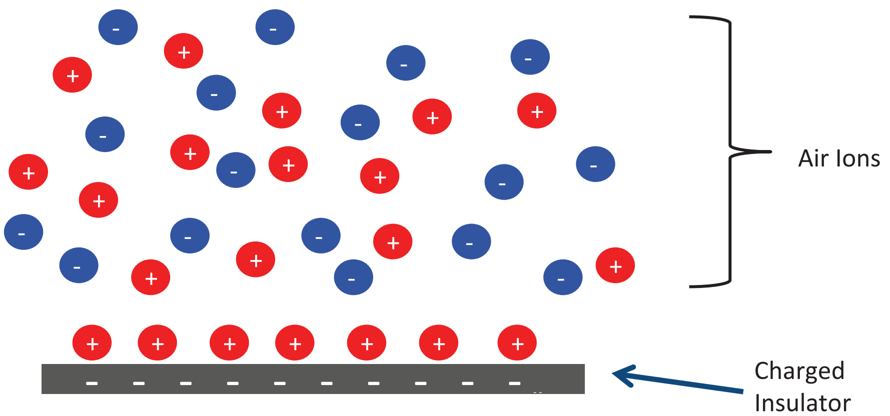

Figure 8. Air ions remove static charge from surfaces of insulators and isolated conductors.

1. This will become known as airborne chemical contamination or ACC in the next revision of ISO 14644-8 which should be published by summer 2011.

2.5 cm in air. A single alpha particle of this energy creates approximately 200,000 air ions which are inherently balanced (plus and minus.) Such an ionizer can be used very close to the product (2.5-10 cm.) Beyond that distance the alpha ionizer requires driven airflow (a blower) to be effective. These ionizers come in the form of small discs (the size of a coin) or bars with alpha elements (~ 5 mm x 25 mm). Alpha ionizers about the size of a postage stamp are routinely located in pan balances to eliminate the issue of static cling of powder in the instrument.

Alpha ionizers require government licensing and must be replaced once a year owing to the fact that they have a half life of 138 days, so their ionization power is substantially reduced by the end of a year. Alpha ionizers require no cleaning or adjustment which is a big plus. Annual replacement is the only maintenance required of alpha ionizers. Unfortunately, operators fear them which is a big negative. Inherently, they are quite safe. If they are eaten they are fatal, but any contact of the ionizer or its alpha particles with the operator's skin is completely safe.

Reference Documents

There are many documents which review the requirements for development of an ESD control program. A good overview is the IEST recommended practice RP CC 022 (http://www.iest.org/i4a/pages/index.cfm?pageid=3835) which discusses the entire discipline of establishment of an ESD control program. The document ANSI/ESDA S20.20 provides guidance on levels required for ESD controlled facilities. This document is available at no charge and can be downloaded by following the link http://www.esda.org/s2020.html. Additionally, there are numerous documents available from a variety of sources but one of the most complete sources of documents to purchase on ESD control can be located at http://www.esda.org/documents/PressCatalog.pdf.

Personnel training

No ESD control program will succeed without the support of its workers. The purposes of the elements of a program are not obvious to uneducated workers. It is common to see workers failing to wear their wrist straps. It is not a surprise that workers routinely turn off blower ionizers because they make them cold. When a factory is rearranged, it is easy to forget to ground the work stations, shelves and process equipment.

"No ESD control program will succeed without the support of its workers."

The only protection that can be provided against these failures is through education of the workers. Once they are aware of the reasons for the strange additions to their work environment, they become cooperative and supportive of the program. Education can be in the form of an online course or through a short (1 to 2 hour) seminar. Most companies with successful ESD control programs require new employees to take such a course and pass a simple examination before they are allowed to move into their work environment in the factory. Note that the worst offenders of ESD protocol are the engineers who are responsible for the operation of the facility. Do not forget to train them too.

Summary

ESD control is important for profitable manufacturing in a variety of cleanroom disciplines. Issues of contamination control, physical damage, electrostatic repulsion and automation interruption are issues that can be addressed by a static control program.

The basic elements of the program include the elimination of insulators wherever possible, establishing a comprehensive program of grounding, and employing grounded dissipative materials. Also important on the list is the use of air ionizers for those items which cannot be addressed in any other way. Because ionizers of all types require maintenance, they should never be used as the entire static control program but only for those items which cannot be dealt with in any other way.

i. LB Levit and J Menear, "Measuring and Quantifying Static Charge in Cleanrooms and Process Tools," Solid State Technology 41, no. 2 (1998): 85—92.

ii. Frank Curran, MS thesis, "The Effects of Static Charge on Silicon Wafers in the Semiconductor Industry," The Engineering Council of England, Nov. 1997.

iii. RP Donovan, AC Clayton, and DS Ensor, "The Dependence of Particle Deposition Velocity on Surface Potential," in Proceedings of the Institute of Environmental Sciences (Mount Prospect, IL: Institute of Environmental Sciences, 1987), 473—478.

iv. L.B. Levit, A. Steinman, "It's The Hardware, No, Software, No, It's ESD!" Solid State Technology Supplement, May 1999.

Larry Levit, Ph.D. got his graduate training in High Energy Physics. Over the last decades he has provided a variety of ESD consulting services under the name LBL Scientific (www.LBLScientific.com) . His background includes Global ESD program Manager for Finisar Corporation and Chief Scientist for MKS, Ion Systems, He has over 17 years of experience in the field of ESD control. He is a NARTE Certified ESD Engineer. His specialty has been ESD control in high technology cleanrooms. His work has taken him into a large fraction of the semiconductor, disk drive and flat panel cleanrooms worldwide. He is a senior member of the IEST and has provided ESD consulting and auditing to many manufacturers on three continents.

Levit is recognized as a problem solver, having identified problems and improved microcontamination control. He has successfully devised solutions to manufacturing problems to reduce ESD yield loss, contamination issues and photomask damage.