Dr. Lawrence B. Levit

Microrite, Inc. San Jose, CA, USA, https://www.microrite.com

ELECTROSTATIC MEASUREMENTS IN A CLEANROOM

KEYWORDS

Micro-contamination, electrostatic charge, electrostatic discharge, ESD, EMI, ESA, robotics, electric field, voltage, cleanroom

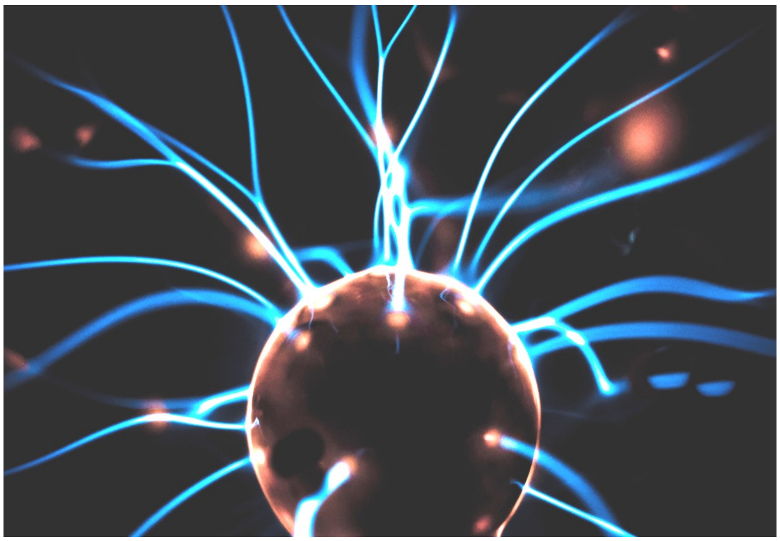
ABSTRACT

Electrostatic charge in the cleanroom grows to much higher levels than in a conventional room. It is responsible for a variety of negative consequences; including increased micro contamination, physical damage to devices and interference with operation of automation and robotics. There are a variety of measurements that can be performed to determine the presence of issues and to evaluate the efficiency of an electrostatic control program. Often, the user focuses on one type of measurements whereas the issue that needs to be addressed requires a different measurement. In this paper, the effects of static charge are related to the appropriate electrostatic parameter and the measurement instrument required for each is discussed.

CLEANROOMS AND STATIC ELECTRICITY

Why do cleanrooms have unusually high levels of static electricity? The static charge is attributable to the nature of a cleanroom, materials of construction of the room and the process tools as well as details of the product and the manufacturing process.

Low Humidity - There are a number of reasons why static charge levels are so much higher in a cleanroom than in a conventional room. The most obvious is the low humidity maintained in a cleanroom. Low humidity enhances the charge generation mechanism, called tribo-electric charging. Low humidity in the winter is well known to cause increased levels of static charge in everyday life. The most obvious example is that it is common to be shocked when touching a door knob in the winter but rarely in the summer. A study of charging in a chamber with regulated relative humidity of 0 to 70% was done to show the magnitude of the charging vs humidity effect[1]. The study showed 1000% higher charging at low humidity than at high humidity.



Super clean surfaces - The first defense against static charge generation is the electrical conduction path represented by surface contamination. Before an object can be taken into a cleanroom, it must be wiped down, eliminating the discharge path to ground for surface static charge.

Insulators – It is commonly understood that insulating materials are poor conductors of electricity. This turns out to be false. Insulators are not poor conductors, they are non-conductors. Surface charge on a clean insulator is trapped in place and will not dissipate. Once an insulator in the cleanroom becomes charged, it will remain so indefinitely.

Dr. Lawrence B. Levit

Microrite, Inc. San Jose, CA, USA, https://www.microrite.com

EFFECTS OF STATIC CHARGE

Electrostatic attraction/repulsion -A very important negative consequence of static charge in the cleanroom is its effect on contamination control. It is important to understand that for small particles, electrostatic movement of these particles is much greater than would be the case for macroscopic objects. A measure of the magnitude of various effects is the so-called deposition velocity. It is the speed at which particles "drift" through the atmosphere under the influence of each type of force. There is a gravitational deposition velocity, a diffusional deposition velocity (Brownian Motion) and an electrostatic deposition velocity. Each depends upon the size of the particle being studied. For example, the gravitational deposition velocity (sometimes called the settling speed) of a person jumping out of an aircraft is much higher than for the case of a person wearing a parachute, making him much larger of an object.

A microscopic particle is made up of atoms, each inherently neutral but in an aggregate, the charge of the particle while near zero, is not always exactly zero due to statistical effects. One particle may be slightly positive and another slightly negative. See Figure 1.

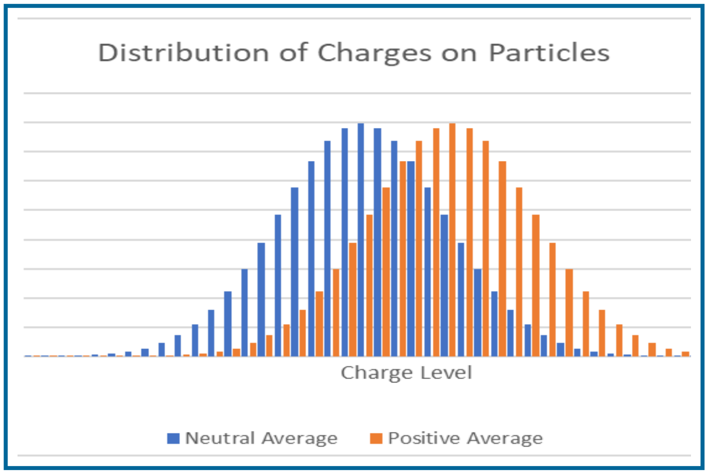


Figure 1

Examples of net charge on two populations of particles

It is that slight charge imbalance that causes particles to be driven by electric fields. A population of particles may not be charged on the average (blue distribution) or may be charged on the average (orange distribution). Calculations[2] show the effect of a net neutral particle source with a modest electric field of 500 V/cm.

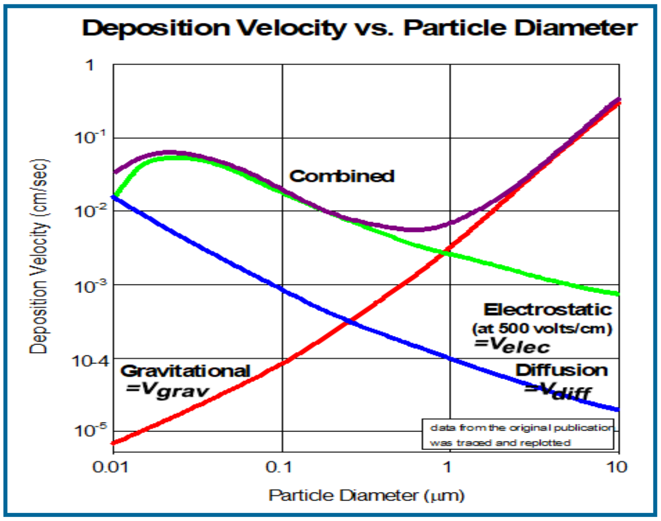


Figure 2

Deposition velocities for three different forces

The calculation employs a postulated distribution of charges similar to the blue one in figure 1 and calculates gravitational (settling velocity called V_{grav}), diffusional (called V_{diff}) deposition velocity and electrostatic deposition velocity (called V_{elec}). The results are shown in figure 2. Electrostatic (V_{elec}) and diffusional (V_{diff}) effects become smaller as the particle size increases but gravitational effects (V_{grav}) grow and dominate for larger particle sizes. Note that the calculation assumes an electric field of only 500 V/cm which is quite a modest field, very easily attainable in the neighborhood of a static surface charge. Since it is common to observe fields of >5000 V/cm in a cleanroom, electrostatic effects are the most important influence on microscopic particles (≤5 µm) in the air flow/ This means that microscopic particles do not follow the cleanroom's unidirectional air flow which is intended to keep particles from settling on the surface that is to be kept clean. This is discussed further below.

Dr. Lawrence B. Levit

Microrite, Inc. San Jose, CA, USA, https://www.microrite.com

EFFECTS OF STATIC CHARGE (CONTINUED)

The calculations described above were confirmed by an experiment involving a charged metal plate in a unidirectional flow field[3]. Polystyrene latex micro spheres (PSL) were introduced into the air stream and tracked with a laser. A summary of the results are redrawn here, illustrating the electrostatic effect. See figures 3a and 3b. The first figure clearly illustrates the movement of particles in a unidirectional flow field in the absence of any electric fields. The second figure shows the movement of particles in the same unidirectional flow field but with a voltage of 4000 V applied to the metal plate, thus simulating a statically charged object in the cleanroom. The particles are drawn off of their original trajectory along the stream lines and impact the plate.

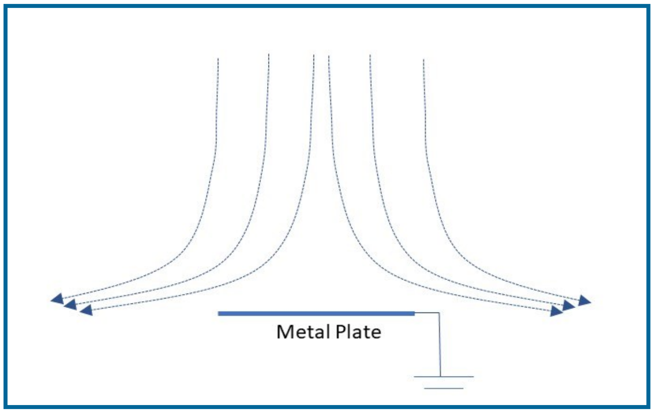


Figure 3a

Particles follow the airflow streamlines when no static charge is present

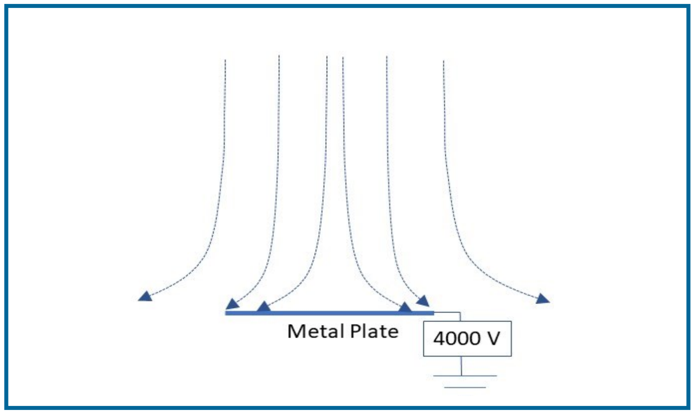


Figure 3a

Particles are pulled off the airflow streamlines by electrostatic attraction

This <u>electrostatic enhancement of micro contamination</u> is called electrostatic attraction (ESA). It is further enhanced by a second effect. When a particle comes within several radii of the charged surface (~ a few µm), the particle becomes polarized and is strongly attracted to the surface even if the particle is neutral. This effect is called dielectrophoretic attraction and the effect causes the particles to become strongly attached to the surface they impact. Electrostatically bonded particles are difficult to remove by any cleaning process and can only be efficiently removed by neutralizing the host object, in this case, the plate[4,5]. See figure 4.

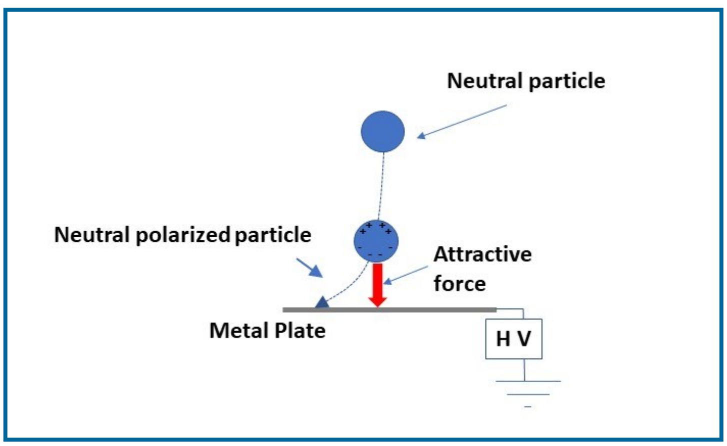


Figure 4

Dielectrophorisis holds particles fast to a charged surface

Dr. Lawrence B. Levit

Microrite, Inc. San Jose, CA, USA, https://www.microrite.com

ELECTROSTATIC ATTRACTION OF VIRUSES

The semiconductor industry is building transistors with ever smaller elements. Back in 1980, the industry entered the sub-micron regime meaning that transistor structures (features) became less than 1 micron in size. The industry has learned how to print much smaller size features. The state of the art today is feature sizes of <10 nm! Now particles even smaller than a virus can destroy a circuit! Because such small particles must be controlled, it is impossible to manufacture semiconductors without controlling static charge. Charge control has become an enabling technology in semiconductor manufacturing. This experience from semiconductor manufacturing can be applied to the medical product industries.

Considering figure 2 from a health science perspective and in light of the **COVID19** outbreak, it is important to consider the effects of electrostatics on the smallest viable micro contamination. Bacteria are between 0.2 and 2.0 µm[6] and most viruses are 1/100 the size of most bacteria[7]. Thus the physics of Electrostatic Attraction (ESA) on viruses is similar to dealing with particles in modern semiconductor cleanrooms.

Further, in the experience of the author, static charge in the cleanroom produces fields of 1-20 kV/inch (2.5 to 8.0 kV/cm), much larger than the ones in figure 2. Figure 2 was traced and digitized. Then a deposition velocity curve was calculated for 5 kV/cm, replacing the 500 V/cm curve. The size ranges for bacteria and viruses were also shown. The result is figure 5. The vertical axis was replaced by a linear one.

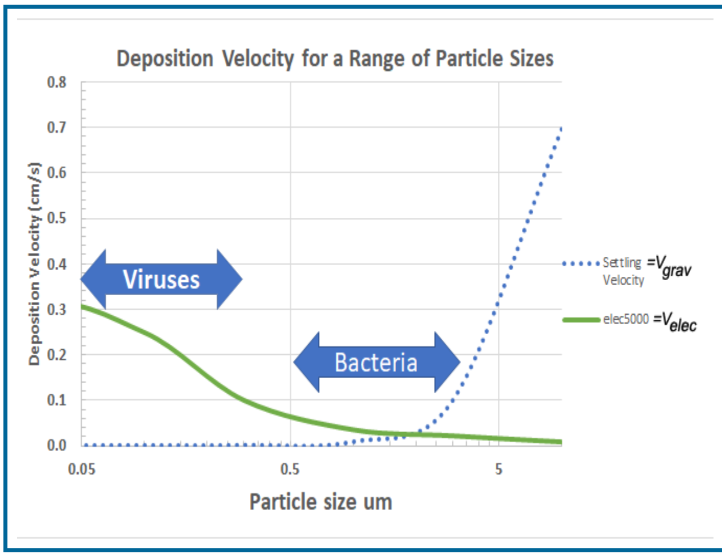


Figure 5

Deposition velocity in a typical cleanroom for both bacteria and viruses

> "Significantly charged surfaces such as a vial after wet cleaning will literally suck virus particles out of the air and bond them to their surface permanently!"

This figure is calculated using realistic values for the electric field in real cleanrooms derived from figure 2. The dashed curve is the calculated 5000 V/cm electrostatic deposition. To understand the effect of electrostatics on contamination for the bacteria and virus regimes, compare them to the gravitational deposition velocity. Figure 5 shows that a 1 µm bacterium, experiences an electrostatic deposition velocity is 10x that of gravity but for 50 nm virus, the effect has climbed to 10,000x that of gravity! Certainly not ignorable. That means that a significantly charged surface such as a vial after wet cleaning will literally suck virus particles out of the air and bond them (figure 4) to their surface permanently.

This effect should definitely NOT be ignored!

Dr. Lawrence B. Levit

Microrite, Inc. San Jose, CA, USA, https://www.microrite.com

EMI AND ESD

Electromagnetic Interference (EMI) – When a discharge occurs from a charged object to another (typically grounded) object, the discharge current is quite large for a very short time **(1/100,000 of a second!!)**. This is particularly so when the discharge is from a charged metal object to another metal object. In this case, the discharge is sub-nanosecond and typically is tens of Amperes. Such a fast discharge is very difficult to shield against and, as such, finds its way into nearby electronics. The path can either be through the air (radiated emission) or through wiring or a support structure (conducted emission). The microprocessors driving robotics near the discharge can be interfered with, resulting in anomalous robot behavior or process interruption. Much has been written about such strange robot behavior[8]. Such interference is hard to diagnose since the effect is not consistent owing to timing issues between the emi event and the microprocessor clock. Since the effect comes and goes erratically, it takes a very long time (as much as a year!) to diagnose.

Electrostatic Discharge Damage (ESD) – When a discharge occurs, it deposits half of its stored electrostatic energy as heat at the site of the discharge. The energy deposit can cause a microscopic volume of material to melt, often damaging the object receiving the discharge. For electronics and medical devices, this can mean a destroyed product or loss of yield. This is rarely an issue for healthcare products.

THE PARAMETERS OF ELECTROSTATICS

Static charge creates electric fields, and raises objects to a voltage. The three parameters that measure these effects are electric field, charge and voltage. Very often these three parameters are inaccurately used interchangeably. Often, this results in measurements using the wrong instrument to produce dubious results. In addition, air ionizers are sometimes used to dissipate static charge from insulating surfaces. A device called a Charge Plate Monitor (CPM) is used to measure the performance of the ionizer.

Figure 6

Using a portable fieldmeter to measure the field from plastic packing material

Electric Fields – are lines of force (force/unit charge) which extend from charged objects and terminate on grounded objects. A charged object in the field will experience a force proportional to the field strength and in the direction of the field. As such, the fields as discussed above drive micro contamination. Electric fields are measured using a hand held field meter which is placed 2.54 cm from the charged object. An example of a fieldmeter measuring the field from plastic packing material is shown in figure 6. Note that the field in this measurement is -4.7 kV/inch (-1.9 kV/cm).

Since electric fields terminate on grounded objects, the field intensity is related to the magnitude of the charge density on the surface and the presence of grounded objects nearby, for example a metal microscope or a person will result in a lower field reading at the object. The magnitude of the field determines how much the micro-contamination is enhanced by the charge.

Dr. Lawrence B. Levit

Microrite, Inc. San Jose, CA, USA, https://www.microrite.com

THE PARAMETERS OF ELECTROSTATICS (CONTINUED)

Voltage - The voltage on the object reflects the amount of electrostatic energy stored in the system. Voltage is energy/charge. The more voltage the greater the potential for damage in the event of a discharge. Electrostatic voltage cannot be measured using a simple voltmeter or a multi meter. The action of such a meter would provide a path to ground for the charge and discharge the object. Instead, a non-contacting electrostatic voltmeter must be used. See figure 7.

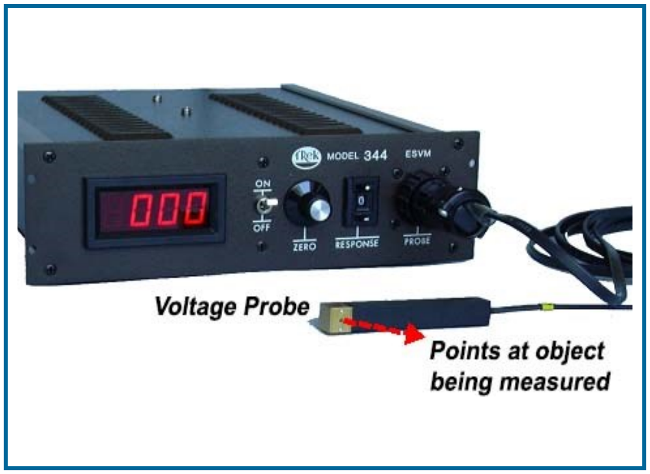


Figure 7

An electrostatic voltmeter and its sensor

Source: Advanced Energy, www.advancedenergy.com

An electrostatic voltmeter has much more bandwidth than a fieldmeter so it is a useful tool to determine whether an object moving though the production line is significantly charged. If the products coming off the production line with damage, the first tool for locating the issue is the electrostatic voltmeter.

Transient emi – Process interruption due to robotic problems is a difficult phenomenon to diagnose since it happens infrequently. It is true, however, that the emi accompanying the discharge occurs every time there is a discharge.

Unfortunately, the discharge often is not observable by the human eye. The best way to diagnose these types of problems is with a high frequency (>1 GHz) antenna and a suitably fast digital oscilloscope (see figures 8 and 9).

Figure 8

An oscilloscope and an antenna being used in a cleanroom

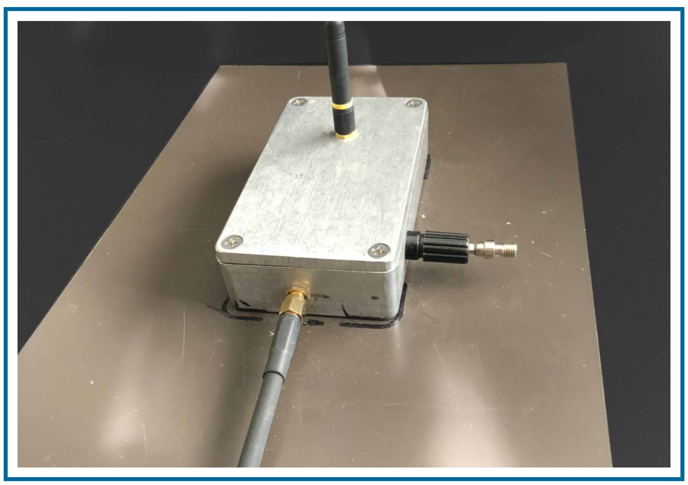


Figure 9

A ultra wide band antenna consisting of a whip antenna on a ground plane

Dr. Lawrence B. Levit

Microrite, Inc. San Jose, CA, USA, https://www.microrite.com

THE PARAMETERS OF ELECTROSTATICS (CONTINUED)

Figure 10 shows a single event in the laboratory recorded using a LeCroy 104MXi-A digital oscilloscope with a bandwidth of 1 GHz and a sampling rate of 10 GSamples/s. This signal is extremely fast, taking place in under 2 ns. An event taken on the manufacturing floor with an even faster16 GS/s 6 GHz Keysight 6004A digitizing oscilloscope is shown in figure 11. It was recorded using the same antenna shown in Figure 9. The lobes of the wave are each well under 1 nanosecond long!

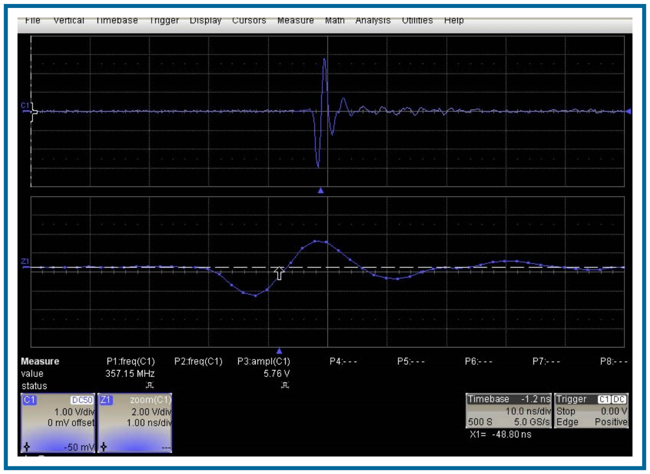


Figure 10

A single event captured from an esd discharge. Upper trace at 0 ns/div and lower trace is an expansion of the same event at 1 ns. /div

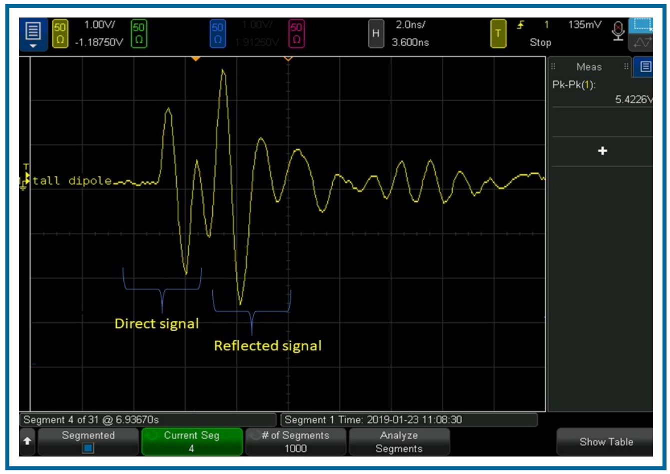


Figure 11

A fast electrical pulse arising from an esd event on the manufacturing floor. Note the reflection 2 ns. Into the pulse

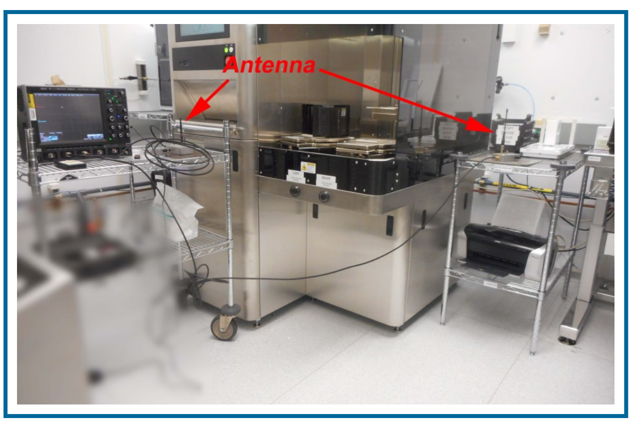


Figure 12

Two antennas used to find the location of an esd event

The pulse is in the range of frequencies called microwave. It is only about 5 nanoseconds long; incredibly fast and short lived. The oscilloscope shows that the pulse is made up of two components. The first component is the electromagnetic pulse traveling from the process tool directly to the antenna. The second one in the trace corresponds to the same pulse but delayed by just 2 nanoseconds and this can only come from a reflection off something 30 cm away from the discharge. Pulses in this frequency range bounce freely in their environment and find their way into the most sophisticated electronics in the factory, the microprocessor that drives the robot. With pulses that fast, it is actually possible to determine where they came from with a position resolution of less than 30 cm using two antennas and recording the time difference between them. See figure 12.

Dr. Lawrence B. Levit

Microrite, Inc. San Jose, CA, USA, https://www.microrite.com

THE PARAMETERS OF ELECTROSTATICS (CONTINUED)

Charge – when the object is small enough to handle, then the charge on it can be measured directly by placing it into a Faraday cup with an electrometer (nanoCoulomb meter). See figure 13.

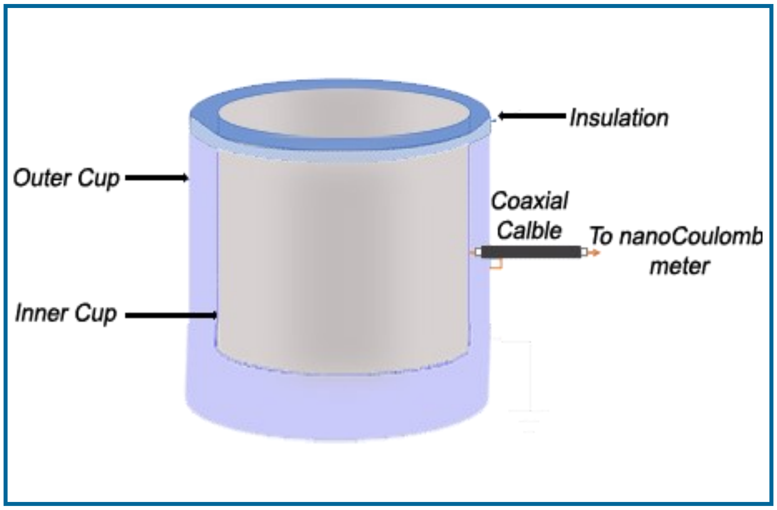


Figure 13

Diagram of a Faraday cup used to measure charge on an object placed within it

Resistance measurement – Insulators and conductors have very different resistivities. Resistivity is a property of a material which characterizes the its ability to limit the electrical current through a material. It is typically given the symbol ρ (rho). Resistivity has units of Siemens/meter or Ω-cm. A conductor has a resistivity of $<10^4$ Ω-cm and insulators have a resistivity of $>10^{11}$ Ω-cm. Most metals (all conductors) have a resistivity <1 Ω-cm. There is a mid-range of resistivity:10^4 Ω-cm$>\rho>10^{11}$ Ω-cm. Whereas ρ is a property of a type of material, resistance, R, is a characteristic of a given size and shape of a material of a given ρ. See figure 14.

These materials in the midrange are called dissipative materials. Dissipative materials play an important role in a static charge control program. They do conduct electricity, thus dissipate static charge but they present a large electrical resistance to the discharge so the current in the discharge is orders of magnitude lower than a discharge through a conductor. Dissipative material is used for protection against damaging discharge when objects contact a sensitive device being manufactured.

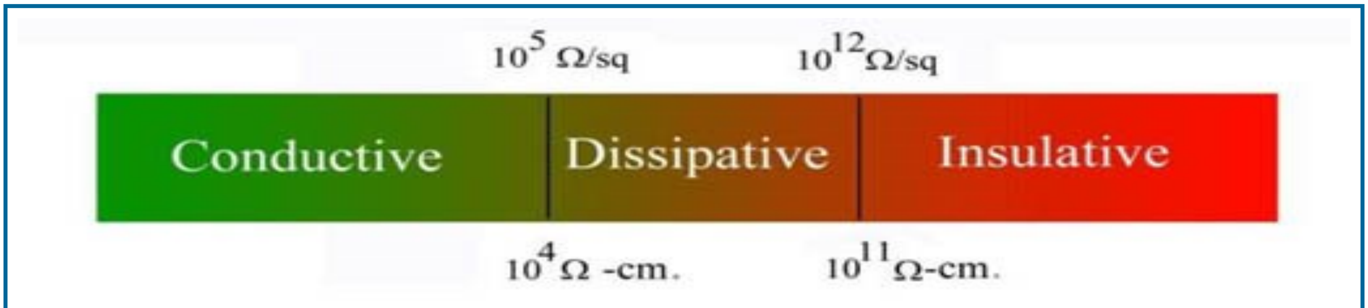


Figure 14

The spectrum of resistivities

Dr. Lawrence B. Levit

Microrite, Inc. San Jose, CA, USA, https://www.microrite.com

THE PARAMETERS OF ELECTROSTATICS (CONTINUED)

The resistance of an object is measured using a special static charge resistance meter. This is not the same instrument used in electronics measurements. Such a meter has the ability to employ a much higher voltage in the resistance sensor circuit of the meter. A typical resistance meter for ESD is shown in figure 15. The meter employs a pair of special 5 lb (2.3 kg) weight probes, also shown in the figure. The resistance to ground (RTG), of

Figure 15

An electrostatic voltmeter. Courtesy of Prostat Corporation

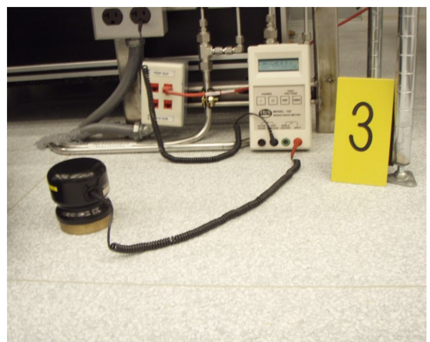


Figure 16

Measuring the resistance of an esd floor

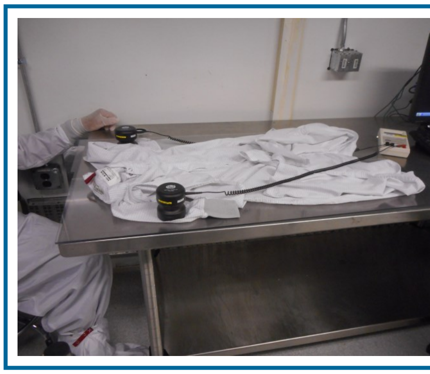


Figure 17

Measuring the sleeve-to-sleeve resistance of a coverall

a static dissipative floor (figure 16) and the resistance between panels of a cleanroom coverall (Figure 15) are typical uses for this specialized meter.

IONIZER MEASUREMENT

For those cases where an insulator is required for the process and cannot be replaced by electrically conducting material, the only solution is the use of air ionization. These devices emit positive and negative ions which are driven down to the charged insulator, called the target object. Delivery may be through built in blowers (fans) or they may use the cleanroom's unidirectional flow. The ionizer may be steady state, emitting both positive and negative ions at the same time. This type of ionizer suffers from much higher positive-negative ion recombination so a powerful fan is required. Another way to deliver the ions that does not require a powerful fan involves producing ions one polarity at a time, alternating positive and negative ion delivery at rather low frequency, typically 1-10 Hz. The performance of an ionizer is measured by putting an electrically floating plate into the ion stream. An instrument called a Charge Plate Monitor (CPM, Figure 18) includes the plate, a ±1000 V power supply to charge the plate and an extremely high impedance voltmeter. The CPM measures how fast the ionizer discharges an object (±discharge time) and the accuracy of ± balance of the ionizer (maximum offset and balance). How to make these measurements is published[9].

Figure 18

A charge plate monitor

Dr. Lawrence B. Levit

Microrite, Inc. San Jose, CA, USA, https://www.microrite.com

SUMMARY

The presence of electrostatic charge in a cleanroom has negative consequences. Which of the consequences are important depends on product type and product requirements. In any process that requires a cleanroom for manufacturing, electrostatically driven micro-contamination will be the most important one to deal with. To do so, stray fields from the product and from the environment must be controlled. Use of a field meter to perform an audit of the facility will identify sources of field to be eliminated. If the product is sensitive to electrostatic damage, a Faraday Cup is an ideal solution. If this is not practical for any reason, use of an electrostatic voltmeter to measure products as they move through the production line will be required. If issues from robotics are observed, a search for transient emi is required. This can involve an oscilloscope and antenna (figures 8-12) or an esd-emi event detector. Air ionization is a solution to some of the issues in a cleanroom but not all of them. In addition, ionizers require maintenance including periodic cleaning and electrical adjustment. Measuring the ionizer can be done with a Charge Plate Monitor. A full complement of instrumentation to perform ESD testing must also include a CPM. Such a device measures the performance of the ionizer and does not measure the product in the production line.

ABOUT THE AUTHOR

Lawrence B. Levit graduated with honors from Case Institute of Technology in 1964 and received a Ph.D. from Case Western Reserve University in 1970. He is a member of the American Physical Society, the Electrostatics Society of America, the Institute for Environmental Sciences Technology and the Electrostatic Discharge Association. At IEST, he chairs the Working Group RP-CC-022 on electrostatics in the cleanroom. He is a vetted instructor for the Electrostatic Discharge Association and the IEST on the subjects of Digital Oscilloscope operation, static charge control and Cleanroom Technology. He is a frequent lecturer on electrostatic charge control techniques in the United States, Europe and Asia. Dr. Levit was a faculty member at Louisiana State University (physics) and worked 20 years at LeCroy Research Systems as Chief Scientist. LeCroy provided high speed electronics to the High Energy Physics research community. He helped instrument 5 Nobel Prize winning experiments. His career also included 20 years at Ion Systems in Northern California as Chief Scientist where he developed static electricity control techniques for the semiconductor industry worldwide. More recently, he has focused on electrostatics in pharmaceutical and medical device manufacturing including a partnership with Microrite, Inc.

Microrite, Inc. is a USA based consulting and training firm assisting companies globally. Our clients include pharmaceuticals, biotechnology, medical devices, other healthcare related industries and high technology manufacturing facilities. We strive to provide our clients with a comprehensive approach and unparalleled expertise in the areas of facilities, validation, microbiology, quality assurance and quality control.

REFERENCES

[1]Larry B. Levit, Ph.D. and Wei Guan, Ph.D., Measuring Tribocharging Efficiency in Varying Atmospheric Humidity and Nitrogen, *Proceedings of the Annual Conference of the Electrostatics Society of America*, June 27-30, 2001

[2]R. P. Donavan, Particle Control for Semiconductor Manufacturing, Marcel Decker, Inc., New York, copyright 1990

[3]Inoue, M., Sakata, S., Chirifu, S., "Aerosol Deposition on Wafers", Proceedings of the 34th Annual Technical Meeting of the Institute of Environmental Sciences, May, 1988, p. 423

[4]Christopher W. Long James Peterman, and Lawrence B. Levit Implementing a static control program to increase the efficiency of wet cleaning tools, Micro, Feb. 2006

[5]https://www.ncbi.nlm.nih.gov/pubmed/12237547

[6]https://www.microscopemaster.com/bacteria-size-shape-arrangement.html

[7]https://en.wikipedia.org/wiki/Virus

[8]A. Steinman and L. B. Levit, It's the Hardware. No, it's the Software. No it's ESD! , *A Supplement publication to Solid State Technology*, May 1999.

[9]ANSI/ESD SP3.3-2012, ESD Association Standard Practice for the Protection of Electrostatic Discharge Susceptible Items – Periodic Verification of Air Ionizers,, Electrostatic Discharge Association, Rome, NY.