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The Basics of Air Ionization for High-Technology Manufacturing Applications

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Several techniques for changing the ambient air's burden of ions are effective for controlling static charge on insulating materials.

Controlling static charge is essential for maximizing yield, quality, and profit in high-technology industry. Such control enhances semiconductor production and has become a necessity in the manufacture of hard disk drives and flat-panel displays (FPDs). Failure to control static charge leads to product losses from static-attracted particle contamination and from electrostatic discharge (ESD).

Control programs to assist in mitigating static-charge problems are available from several sources, among them the ESD Association and Semiconductor Equipment and Materials International.[1,2] The primary method employed for dealing with both conductive and static-dissipative objects—including people—is direct connection to ground to dissipate the static charge.

But products and work areas both may contain materials that are insulators. When these insulators are part of the product itself, they cannot be eliminated. For example, high-technology manufacturing makes use of oxide-coated silicon wafers, epoxy-packaged semiconductor devices, insulation on component leads, glass epoxy printed circuit boards, and glass panels for FPDs. In addition, materials such as Teflon, quartz, and many plastics necessary for resisting high temperatures or chemicals or providing cleanroom compatibility are insulators. Grounding has no effect on the levels of static charge on insulators. The only practical method for neutralizing static charge on most insulators is air ionization.[3,4]

The use of air ionizers is recommended in most published static-control programs, but those documents contain little explanation of the physics of the air ionization process or of the effects of using ionizers in the manufacturing environment. Because marshalling air ions for static-control purposes is important in many industries, this article attempts to fill in the missing information for users of air ionization technology.

Air Ions Defined

The word *ion*, derived from a Greek verb suggesting motion, has the sense of "a traveler." The term was first used to describe the effects observed when electrical currents were passed through various solutions; molecules in the solutions would dissociate and migrate—that is, travel—to electrodes of opposite polarity. A theory advanced by the Swedish researcher S. A. Arrhenius that the migrating ions were electrically charged atoms was substantiated by the later discovery of the electron and its nature.

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Ions are defined as atoms or molecules that have lost or gained electrons. (Electrons are the only easily available charge carriers.) When an atom or molecule has an equal number of electrons and protons it is electrically balanced, or neutral. If an electron is lost, the atom or molecule becomes positively charged and is a positive ion. Gaining an electron makes it a negative ion.

What is called an *air ion*, or a charged air molecule, is really no such thing. Air is a mixture of gases, including nitrogen, oxygen, carbon dioxide, water vapor, and other trace gases, any one or more of which may be ionized. Sometimes a diatomic gas molecule, such as nitrogen or oxygen, will gain or lose the electron. Sometimes it will be a more complex gas such as carbon dioxide. In any case, when molecules of one or more of the gases in air gain or lose electrons, the result is conventionally called air ions. Air ions differ from ions in solution in that energy is needed for their formation.

In normal, unfiltered air, air ions are molecular clusters consisting of about 10 neutral gas molecules around a charged oxygen, water, or nitrogen molecule. These are called small air ions. Small air ions are relatively mobile and soon encounter ions of the opposite polarity or a grounded surface, at which point they lose their charge and become neutral molecules again. Small air ions have a life span of a few seconds to a few minutes in clean air.

Under the right conditions, these ions attach to particles or other large molecular clusters in the air, resulting in large air ions. The relative proportion of small and large air ions present generally depends on the cleanliness of the air. Large quantities of particulate matter or aerosols in the air lead to a depletion of small air ions.

However, any discussion of neutralizing static charge on insulators in a static-control program, as here, will deal primarily with the production and effects of small air ions.

Air Conductivity and Charge Neutralization

If an ion is exposed to an electric field, it will move at a speed dependent on the magnitude of the field and in a direction dependent on both the direction of the field and the polarity of the ion (either of which may be positive or negative). The motion of ions in an electric field constitutes an electric current whose density depends on the number of ions in the air and the rate at which they move away from or toward the source of the electric field. The relationship between the current density and the electric field is known as the conductivity of the air. This conductivity may vary with the polarity.

If an object is charged, an electric field is established around it. The field strength will vary from point to point but is always proportional to the charge. If the object is surrounded by air ions of both polarities, a current carried by the ions of polarity opposite to its charge will flow toward the object. This neutralization current is proportional both to the charge on the object and to the relevant conductivity of the surrounding air. Stated simply, a charged object attracts ions of the opposite polarity.

An ion exposed to an electric field E will move with an average drift velocity v proportional to E, that is,

$$v = kE, \tag{1}$$

where k is the mobility of the ion.

Small air ions have mobilities in the range of 1.0–2.0 $cm^2/V\cdot s$ (centimeter^2 per volt-second). This means that a small air ion moves at a velocity of about 1 cm/sec when it is exposed to an electric field strength of 1 V/cm. It can be shown experimentally that the mobility of negative ions is approximately 15% higher than the mobility of positive ions.

If the air has a concentration n of positive ions with the mobility k and charge e, an electric field E will cause an electric current to flow in the direction of E with the density j.

$$j = enkE = \lambda E \tag{2}$$

The constant λ, which is equivalent to enk, is called the positive conductivity of the air or, more precisely, the polar conductivity due to the positive ions.

Negative ions will move in the opposite direction of the field. However, Equation 2 can still be used to calculate current density from negative ions when e is taken as the numerical value of the ion charge.

If a body is given a charge q of either positive or negative polarity, an electric field is established around the body. If the body is surrounded by air containing air ions of both polarities, opposite-polarity air ions will flow toward it and ions of the same polarity away from it. While the field will vary from point to point in space, it is always proportional to q. The movement of charge is an electric current. The current toward the body, carried by ions of polarity opposite to that of q and known as the neutralization current, is proportional to the charge and to the relevant opposite conductivity of the surrounding air.

If the air conductivity does not change, then the relative rate of charge neutralization is constant, and the charge will decay exponentially with a time constant τ that depends on the air conductivity. In other words, given an initial charge q_0, the charge remaining at a later time is given by

$$q = q_0^{-t/\tau}, \tag{3}$$

where the time constant τ is equal to the permittivity of the air ε_0 divided by the air conductivity, λ.

$$\tau = \varepsilon_0/\lambda; \tag{4}$$

thus, referring to Equation 3,

$$q = q_0^{-t(enk/\varepsilon_0)}, \tag{5}$$

making the rate of charge neutralization proportional to the ion concentration.

Practically, it is difficult to maintain constant air conductivity. Many factors cause variations in the rate of charge decay These factors include airborne-particle concentrations, depletion of ions in the vicinity of a charged object, the inhomogeneity of ionized air, and nonuniform electric fields due to irregularities in the charged object or nearby objects. Making corrections for all deviations from the simple case in order to calculate the time constant is an impractical approach. It is generally more reasonable to measure the neutralizing properties of an ionizer experimentally.

Natural Air Ions

Ions are present naturally in the air, with positive ions usually exceeding negative ions by a ratio of 1.2:1. Typically, clean outdoor air contains 2000–3000 ions per cubic centimeter. Inside a building with natural ventilation, the number drops below $500/cm^3$, and in most buildings with ducted air-conditioning systems, air ion levels above $100/cm^3$ are rare.

These natural air ions are formed primarily by the decay of trace radioactive elements in the air, ground, or building materials. Other sources include the triboelectric charging caused by waterfalls or ocean waves (mostly small negative ions), lightning storms (temporary increases), and, in the upper atmosphere, the passage of cosmic rays and solar radiation.

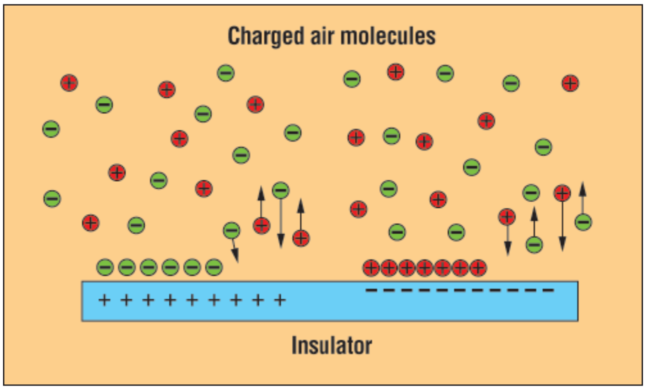

Figure 1. Neutralizing a surface through bipolar air ionization.

In clean air, ions last no longer than a few minutes, the rate of depletion depending on various factors. The higher the ion density, the more likely an ion of one polarity will find one of the opposite polarity. When this happens, charges are exchanged in a process known as recombination, and the result is two neutral molecules. Recombination also occurs when ions contact grounded surfaces. Thus, ions used for static neutralization must be produced in a way that minimizes interaction between ions of opposite polarity and must be isolated from large grounded objects.

Also, large air ions, when they form, move much more slowly than small air ions. The value of k becomes smaller (see Equation 2). Large air ions have much less effect on air conductivity and are not of interest for purposes of charge neutralization.

Small air ions can be removed from air by the electrostatic fields that emanate from statically charged surfaces. An electrostatic field interacts with the charged air molecules, attracting air ions of polarity opposite to the charge that created the field (see Figure 1). Ions are drawn to the opposite-polarity surface charge until that charge is neutralized and the electrostatic field it created ceases to exist. This important phenomenon is the basis for using air ions for static control.

However, natural sources of air ionization produce insufficient quantities of ions of both polarities to control static charge effectively. Much higher ion concentrations are needed for area static neutralization, typically 100,000 to 1 million ions per cubic centimeter of air.

Air Ionization

Creating air ions artificially requires adding electrons to or removing them from the gas molecules in the air. Two basic methods are used to achieve this: alpha ionization and corona ionization.

Alpha Ionization. Alpha ionizers utilize a nuclear source, polonium 210, which is an alpha particle emitter. The alpha particle, a helium nucleus, collides with air molecules, knocking out electrons over a travel distance of about 3 cm. Gas molecules that lose electrons become positive ions. The dislodged electrons do not exist freely for very long before they are captured by neutral gas molecules, forming negative ions (see Figure 2).

Alpha ionizers always produce balanced quantities of positive and negative ions. Each electron knocked out leaves behind a positive ion and, when captured, creates a negative ion. This is advantageous in certain applications involving extremely ESD-sensitive components. Equal numbers of positive and negative ions means that the ionizer is always balanced to 0 V and neutralizes everything in the work area to zero.

Alpha ionization is used commercially for applications involving explosive or flammable environments, or in applications requiring precise balance of ionization. The process is expensive because alpha ionizers lose half their strength every 143 days (the half-life of a radioactive source). Usually they must be replaced annually. Although alpha ionizers have more than a 25-year record of safety, they are subject to government regulation. Anything radioactive makes people nervous. For these reasons, alpha ionization use is not as widespread as that of corona ionization.

Corona Ionization. Corona ionizers use strong electric fields created by applying high voltage to a sharp ionizing point to move the electrons. Due to the decay of trace radioactive elements in soil and air, a few free electrons are always present in the atmosphere. Creation of a high positive electric field accelerates these electrons toward the ionizing point. They collide with air molecules and knock out more electrons on the way, leaving behind many molecules that have lost electrons and become positive ions in a high positive electric field. This field repels them from the ionizing point, presumably toward the area where they are needed for charge neutralization. Similarly, a negative electric field sends free electrons away from the ionizer point into collisions with gas molecules that generate more free electrons that are captured by neutral gas molecules near the ionizing point. The negative ions created are repelled by the negative electric field.[5]

Corona ionization generally does not provide the intrinsic balance of ion polarities that alpha ionization does. Methods do exist, however, to ensure that closely matched quantities of positive and negative ions are delivered to the work area despite differences in ion mobilities and ion production rates for each polarity. Also, some ionizers include monitoring and feedback capabilities to provide adequate long-term stability of the ion balance in the work area. Ion balance is important because an imbalance in the ionizer can induce voltages on isolated conductors, an outcome just the opposite of that for which the ionizer's use is intended.

The Ionization Standard. Ionizer balance, or offset voltage,

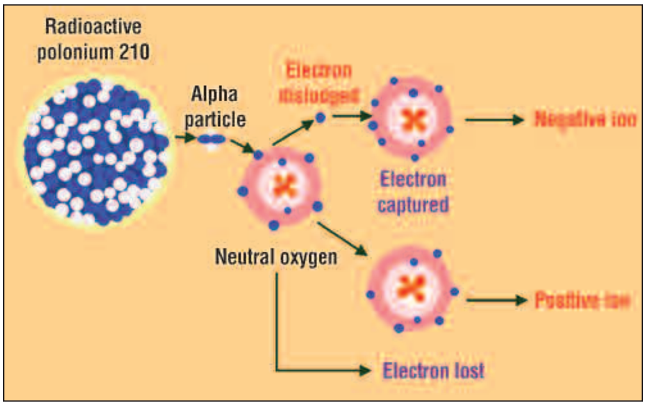

Figure 2. In alpha ionization, polonium 10 collides with air molecules and knocks out electrons.

is measured with a charged-plate monitor (CPM) using procedures defined in the ESD Association's standard on air ionization.[3] ANSI ESD STM3.1 is the only ionization standard recognized worldwide and has been referenced in many international static-control standards. As a standard test method, it defines only an instrument and test methodology for comparing either different systems or the same system over time; it does not specify required performance because of the variety of conditions under which air ionization is employed. To solve the static-charge problem, discharge times should always be specified by the end-user.

Selecting a Method. The ESD sensitivity of the product being protected generally determines the type of ionization that is best to use. The more sensitive the product, the more precise must be the ionizer's ability to maintain balance and long-term stability in ion production. However, problems such as particle attraction to charged surfaces and ESD-related equipment difficulties can be solved by almost any commercially available air ionizer. Solving these problems does not require ionizer balance to better than a few hundred volts, as measured with the CPM.

Few human technological activities lead to an increase in air ionization. Most cause depletion.

Selecting an ionizer may involve consideration of several other issues as well. These include available airflow, distance from the ionizer to the work area, and the cleanroom compatibility of the ionizer.

Types of Corona Ionizers

Several methods of corona ionization are available to create and deliver bipolar ionized air to the work area. These methods differ mainly in whether high-voltage ac, dc, or pulsed dc current is used to create ions.

Ac Ionization. In alternating-current technology, high voltage is applied to a number of closely spaced emitter points that cycle negative and positive at the line frequency of 50 or 60 Hz. Ionization efficiency is low because the points remain above the ionization threshold voltage for each polarity only a small percentage of the time.

Ac technology is widely used in ionization bars that control static charge on low- and medium-speed moving material webs. It is used also with ionizing blowers and blowoff gun devices. In electronics manufacturing, ac ionizers are commonly employed to protect components during assembly. Because of their dependence on the power line, with its often unbalanced and noisy characteristics, ac ionizers are rarely used in applications requiring precision balance (within ±15 V). And because of the high ion currents necessary to make up for high levels of ion recombination, particle levels associated with ac ionizers usually make them unsuitable for cleanroom applications.

Steady-State Dc Ionization. High voltage of both polarities is continuously applied to pairs of positive and negative emitter points in standard direct-current technology; thus, the efficiency of ion production is better than that of ac ionizers. Because lower operating currents can be used, steady-state dc ionizers are more applicable to cleanroom use. The availability of separate positive and negative high-voltage supplies makes it possible to employ various schemes for monitoring and feedback control of ion balance to better than ±5 V. Steady-state dc ionizers can be used in high-airflow rooms and in high-speed web applications. This technology is also applied in ionizing blowers, ionizing bars, and blowoff gun devices. In addition, it has wide application for controlling static charge in room systems, on work surfaces and flow hoods, and in equipment at the point of use.

Pulsed Dc Ionization. Positive and negative high-voltage currents to the emitter points are alternately turned on and off in pulsed systems, creating clouds of positive and negative ions that mix together in the work area. The result is a dramatic lowering of the recombination rate. This allows ionizers to be placed on the ceilings of rooms 5 m high or higher.

Pulsed dc ionizers are used in rooms with low airflow and are the most common type of ionizer employed in cleanrooms and laminar-flow hoods. The advantage of this type of ionizer is its flexibility and versatility, as cycle timing can be adjusted to the specific airflow conditions. Since the polarity of the ionizer output varies with the cycle timing, a voltage swing is produced that must be limited in order to protect ESD-sensitive devices.[5]

The Effect of Air Ions on People

Whenever something is to be added to the air people breathe, the natural response is to ask what effects it may have. Since the 18th century, scientists have been pursuing this question with respect to what are now called *charged air molecules*. Research on the effects of air ions on all sorts of biological systems conducted through the 20th century found that these included the killing of microorganisms, the stimulation of plant growth, and the shift of chemical levels in the blood and brains of animals. Both adding ions to the normal environment and removing them affected biological systems.

Investigations into the effects of air ions on human beings have followed from the anecdotal evidence that naturally occurring air ions do affect human activity. Certain hot dry winds, for example, cause a shift in the balance of positive to negative air ions, to which increases in illness and the alteration of mood have been attributed.

Despite an absence of true double-blind clinical trials, several conclusions regarding the effects of small air ions on people have been reached. One is that not all people notice or react to changes in the level of air ions. More important, for those who are affected, a decrease in the air ion level is more significant than an increase or a shift in the ratio of positive to negative ions.

Few human technological activities lead to an increase in air ions. Most activities cause depletion. Industrial air pollution, stray electrical fields, and ventilation ducts are some factors that effectively strip air ions from the environment. Such ion depletion can cause sleepiness, attention deficit, discomfort, and headaches, effects that artificially increasing air ion levels has been reported to reverse. Ion generators have been used to mitigate these problems. However, there is no general agreement that employing these devices to restore or increase environmental levels of air ions has beneficial health effects. Studies have shown, on the other hand, that for certain tasks, worker performance improves in an ionized environment, particularly relative to an ion-depleted work area. People whose performance or moods are affected by ion levels seem to prefer a negatively ionized environment.

One thing is common to all studies of the effects of air ions on people: no researcher has reported any adverse effects from even high concentrations of balanced or monopolar negative ionization.

Conclusion

Air ions have other uses besides the neutralization of static charge. Among these are paint spraying, bag filling, and surface coating. Also, electrostatic precipitation, which involves using a monopolar ionizer to generate many charged large air ions of one polarity that are drawn by electrostatic forces to oppositely charged collection plates or grounded surfaces, removes particles from industrial, office, and home air. Designed for industrial process pollution control, this air-cleaning technology, and all air ionization techniques, may have the additional effect of reducing respiratory problems in workers and instilling in them a greater sense of well-being. Anecdotal evidence suggests as much.

Air ionization is already important for delivering static control in high-technology manufacturing, but researchers around the world are continuing to investigate new applications for air ionization in both industrial processes and biological systems. Innovative uses for nanotechnology, biotechnology, and other life science applications are being developed.

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