ESD Packaging Considerations

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Understanding packaging terms and how they apply to specific situations is critical to implementing and maintaining an effective ESD control program.

Establishing and implementing successful ESD protective packaging procedures requires a basic understanding of how sensitive devices may be damaged during or after packaging and how protective procedures work. Two basic events, charging (either triboelectric or contact with charged source) and discharging, ultimately can result in the destruction of microelectronic devices. In theory, these events could be avoided by preventing the motion inherent in the triboelectric charging process, by minimizing contact between or with insulators, and by keeping all surfaces at equal potentials. In practice, however, it is not possible to effect these safeguards.

By its very nature, electronic manufacturing is a constant blur of motion. Devices must be moved from place to place and, in the process, they come into contact with a variety of materials. As a result, even highly visible controls, such as wrist straps, do not ensure that ESD-sensitive devices will be protected from damage. In the absence of air ionization and for Class 0 (less than 200 V), static-control materials and deployment of special ESD controls are essential.

This article outlines the basic concepts that must be considered when using special materials for ESD protective packaging and surfaces. These concepts apply to traditional packaging materials such as cartons, bags, and boxes, as well as to temporary packaging materials such as tote bags used during manufacturing. These concepts also apply to surfaces such as benchtops and rails that devices may come into contact with during manufacturing. Specific terms describe these materials according to the way they address a particular ESD problem. The precise definitions of these terms have evolved slightly over the years and are now as follows:

- *Antistatic.* Materials that effectively prevent the buildup of a static charge on themselves or on contacted materials.
- *Static Dissipative.* Materials that retard the otherwise extremely fast discharge involved in a charged-device model (CDM) event. The ESD Association and the Electronic Industries Association define these as materials having surface resistivities between 10^5 and 10^{12} Ω/sq. Antistatic and static-dissipative materials directly address the charging and discharging steps involved in most failures. Their use, in combination with other simple measures, provides broad protection for sensitive devices even in automated assembly factories. In some instances, however, conductive materials are used.
- *Conductive.* By definition, these are materials with surface resistivity of less than 10^5 Ω/sq. They are typically used for shunting of device leads to a common potential. In some applications, they are used for shielding an area from electrostatic fields.

In rare instances a part is sensitive to the mere presence of an electrostatic field. Experience has shown, however, that the use of conductive materials is necessary only for parts such as some surface acoustic wave (SAW) filters and integrated circuit photomasks that have very narrow air gaps over very sharp (field enhancing) metallic structures. Discrete metal oxide semiconductor (MOS) devices also can be made to fail in the presence of a field when unusually long antenna leads are attached to the device to amplify the effects.

There is considerable confusion as to the precise meanings of these three definitions. Many materials, for example, may be both antistatic and static dissipative. Furthermore, it is quite common for conductive materials to generate a charge on some insulators, and these materials cannot be considered to be antistatic.

Understanding these distinctions and how they apply to specific situations is critical to implementing and maintaining an effective ESD control program. It is also critical to properly evaluating vendor claims about the effectiveness of their products. Each of these material types must also have properties that will not interfere with standard manufacturing processes. In addition, abrasion resistance, thermal stability, contamination effects, and many other properties may be important aspects of the overall material specification.

Antistatic Materials

Insulators can become charged through contact with other materials. When such contact occurs, a number of physical processes take place that enable charges (electrons or molecular ions) to flow across the boundary between the materials. Antistatic materials minimize this charge flow. However, because the tendency to tribocharge results from the combined properties of two materials or objects, referring to a single material as *antistatic* is not totally accurate.

A more accurate description is that a particular material is antistatic with respect to another material. In practice, the other materials in question are insulators, such as an epoxy/glass printed wiring board (PWB) substrate or conductors, such as copper traces on the PWB, that may be charged during a specific process or handling procedure.

Therefore, most commercially successful antistatic materials are antistatic with respect to a significant percentage of other materials typically involved in the same process or procedure. These materials generally receive the generic designation, *antistatic*.[1] There are three types of commercial antistatic materials: those treated with a special agent known as a *topical antistat*; synthetic polymers impregnated with an antistatic agent that, because it is insoluble in the polymer, blooms to the surface; and those that are intrinsically antistatic.

Topical antistats are especially useful because they minimize charging between many widely different materials. They typically comprise a carrier or solvent and the active antistat, examples of which include quaternary ammonium compounds, amines, glycols, and amides of lauric acid. Application of a topical antistat produces a layer between materials that tends to dominate the interfacial properties. The mechanism by which these topical antistats, also known as *surfactants*, reduce tribocharging is not completely understood. It is known, however, that surfactants are hygroscopic. This means that they promote the absorption of water at the surface. In fact, their effectiveness is usually highly dependent on the ambient relative humidity. Topical antistats also reduce friction.

The resulting reduction of frictional heating may also be important. Furthermore, because the antistats are somewhat conducting, at least under moderate humidity conditions, they may dissipate or spread some of the charge being transferred. Although this latter characteristic may be useful, it should not be regarded as especially relevant when evaluating antistat material. Antistat materials should perform their intended function; that is, reduction of charge generation, without being grounded.

Static-Dissipative Materials

Because there are many instances where charge generation cannot be avoided, these charges must be safely eliminated. Many antistatic materials also can function in a static-dissipative manner when grounded or employed in large sheets, such as for flooring. Other static-dissipative materials may be homogeneous volume resistive or may be laminates with a conductive core, such as those used on benchtops. The term static dissipative was actually coined to describe a class of materials that limit the current that flows through a charged device when it comes in contact with the surface.

EIA and the ESD Association have defined this relatively vague property as "any material that has surface resistivity between 10^5 and 10^{12} Ω/sq." Bossard and others have shown that the 10^5 Ω/sq lower limit is appropriate for protecting energy-sensitive devices that adhere to a specific thermal model for device failure.[2]

In addition to surface resistivity, an important related property is the ability of static dissipative materials to safely remove a charge from an object. This property typically is referred to as *static decay*. Static decay should follow the exponential decay predicted for an RC circuit, $V(t) = V_0e^{-t/t}$, where t = RC is the time constant.

For a tote box used in PWB assemblies, the capacitance is approximately 50 pF. In a typical specification, the potential is required to decay to a fixed percentage of its original value, e.g., one percent, within a specified minimum time, e.g., two seconds. Consequently, the 50-pF tote box requires:

$$R < \frac{(t/c)}{\ln\,(V_0/V(t))} = \frac{(2/5 \times 10^{-11})}{\ln\,(100)} = 8.7 \times 10^9\ \Omega \qquad (1)$$

which is in the middle of the static-dissipative range. Again, as with antistatic materials, relative humidity is an important factor and should be controlled and recorded during the resistance and static-decay tests.

Conductive Materials

Materials with surface resistivity less than 1 X 10^5 Ω/sq are defined as *conductive*. Conductive materials may be used to contribute to the removal of charges from other conductors or from static-dissipative items such as a tote box on a conductive surface. The most common application, however, involves shunting device leads together in order to maintain common potentials between the leads.

When employing shunting strategies, there are two important points to remember. First, the ability of materials to maintain a common potential during a high-speed event is limited. This limitation is related to inductance. In one test case, it was observed that an 8000-V pulse could damage a device with a very low (less than 50 V) human body model (HBM) ESD threshold even when the device was placed in conductive foam.

Although the test confirmed that shunting the leads was sufficient to protect the device in the factory, it also demonstrated that shunting does not preclude the possibility of damage. Other experimental data have since been published confirming this conclusion. The second important point is that shunting must be applied as close as possible to the device leads. Many ESD events, especially charged-device model (CDM), occur in about 1 nanosecond. If a shunt is applied even a few inches away from a device, an ESD event at the device lead will damage the device before current can flow through the shunting materials to equalize potentials.

Conductive materials used in ESD applications typically are either polymeric materials loaded with some form of carbon particles, such as the foam referenced above, or laminated or vapor-deposited metallized structure such as those used in some ESD-protective bags. Although 10^5 Ω/sq has been established as a boundary between static-dissipative and conductive materials, it should not be considered the lowest boundary for protection from CDM damage. Being aware of variations can be of great practical advantage when the only available conductive materials are in the $10–10^4$ Ω/sq range, as is currently the case. Care must be exercised when using conductive materials due to the increased possibility of CDM damage.

Packaging Applications

Tape-and-Reel Packaging. With the introduction of surface-mount assembly processes, tape-and-reel has become the preferred method for packaging and handling integrated circuits. This method is rapidly replacing the IC shipping tube because tape-and-reel results in higher manufacturing throughput and reduced operator intervention. However, because the materials that make up these structures are in intimate contact with ESD-sensitive devices for extended periods, it is critically important that they are ESD-safe.

The tape-and-reel method was introduced for use with discrete passive devices, such as chip resistors. Because these devices generally are not ESD-sensitive, the earliest versions of tape-and-reel were not ESD protective. As a result, electrostatic potentials in excess of 10,000 V were generated when the cover tape was removed from the carrier prior to circuit board assembly. In response, the chip components rose up out of the carrier in unpredictable ways, including standing upright in the carrier. This wreaked havoc with the automated assembly process. It was also a clear indication that drastic reengineering of the material system was required before tape-and-reel could safely be used in conjunction with integrated circuits. Because of the potential for increased device damage, we conducted a systematic investigation of the materials available at the time. It was determined that devices were charged by tape-and-reel materials to much higher levels than was typical for shipping tubes. This was true despite the fact that the materials were advertised as ESD-safe or that they were compliant with then-current standards such as EIA 541.

Material	Typical Electrostatic Voltage (V)	Typical Charge on Device (nc)
Shipping tube	0	0.005
Conductive cover tape	50	0.725
Static-dissipative cover tape	50	0.611
Insulative cover tape	8000	1.020

Table I. Charge on devices packaged in shipping tubes and tape-and-reel.

For example, we determined that some cover tapes were indeed antistatic but only on the outer, nonadhesive side of the tape.[3] As shown in Table I, the charge appearing on the device after contact with the adhesive side of the cover tape was both high and unpredictable by category.

There also was a concern that, in the presence of this uncontrolled charging, an overly conductive carrier tape might lead to field-induced CDM failures. This deficiency resulted from the fact that, at the time, there was no adhesive technology compatible with typical antistatic reagents.

The effects of the carrier-tape conductivity were demonstrated in a series of experiments using a CDM-sensitive device (150 V). When a tape-and-reel assembly containing these devices was subjected to a controlled shake test to simulate shipping and handling, a statistically significant percentage of the devices showed serious degradation in their electrical properties (reduced breakdown voltage) when carrier tape of 1 or 100 Ω/sq resistivities were used. Conversely, even in the presence of an insulating cover tape, no degradation was observed when the carrier tape resistivity was 10^4 Ω/sq (Devices tested were packaged in tape-and-reel using insulative cover tape and conductive carrier.) The results are summarized in Figure 1.

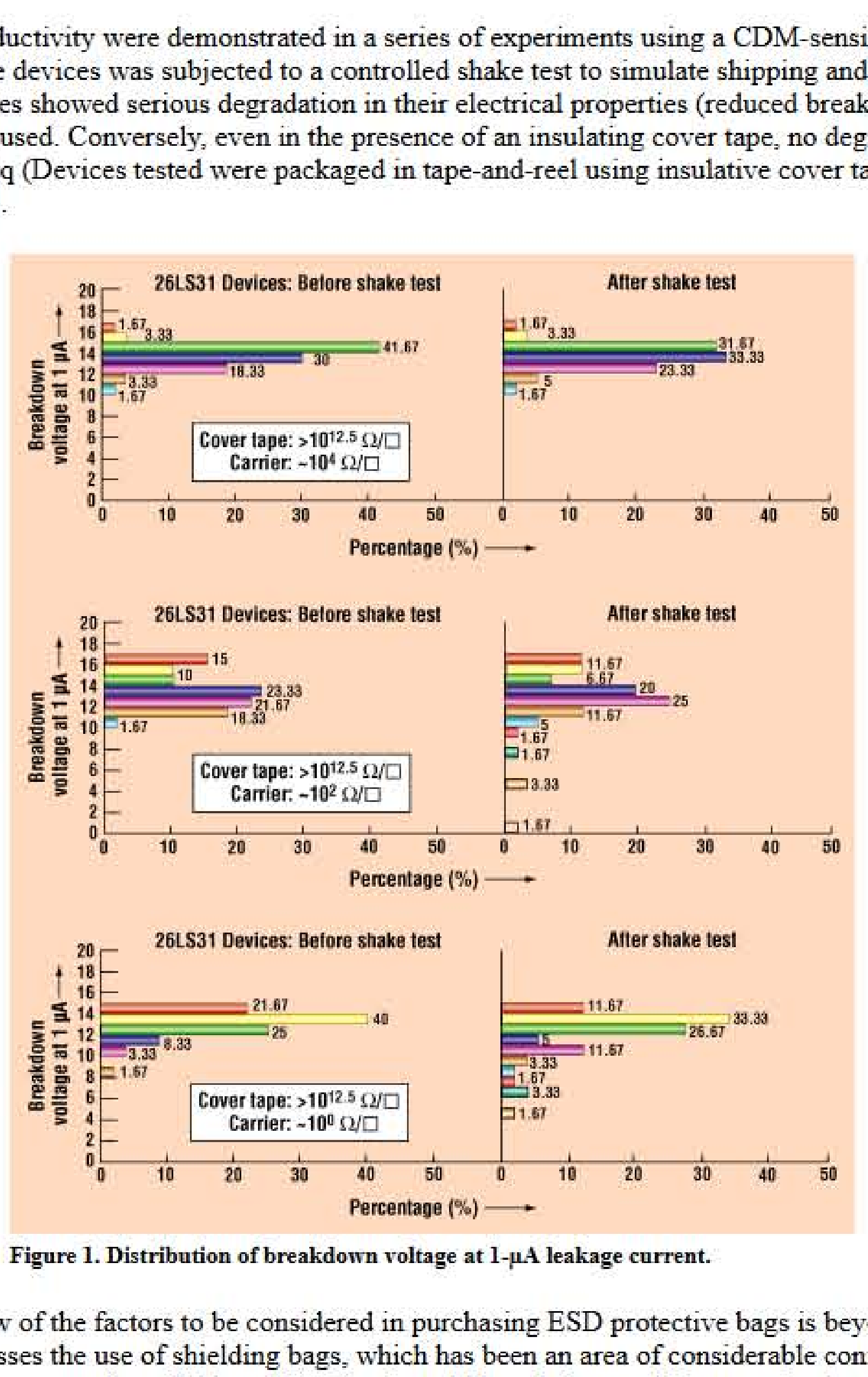

Figure 1. Distribution of breakdown voltage at 1-μA leakage current.

Protective Bags. A detailed review of the factors to be considered in purchasing ESD protective bags is beyond the scope of this article. However, this article briefly addresses the use of shielding bags, which has been an area of considerable confusion within the ESD industry. This confusion stems from early concerns about field-sensitive devices. Although the conditions required to cause failures in unprotected MOSFETs in an otherwise ESD protective environment are difficult to produce, it was commonly believed that these devices were routinely damaged by the mere presence of an electrostatic field.

Material	Damage Threshold Voltage (V)	
	New Bags*	Old Bags
Conductive cardboard	2500	—
Insulative bag	4000	—
Antistatic (pink poly) bag	4500	—
Static-dissipative bag	5000–6000	—
Antistatic bubble wrap	4500–6500	6000
Antitstatic foam wrap	6500	—
Shielding bags (three types)	6500–8000	5000–6000
* New bags were crimped or folded to simulate use.		

Table II. Device damage thresholds for various ESD bag types.

This concern was largely dismissed, but some in industry maintained that shielding was required. Although it is true that a voltage could be induced on a device due to the time-dependent E-field of the event and that shielding layers could be used to reduce the effect, these shielding layers are not the only solution. Nor are they generally the best solution. Test results are summarized in Table II. In this set of experiments, direct ESDs were allowed to occur between an HBM simulator and a bag containing a sensitive device (either an HBM with a threshold of 200 V or an event detector with equivalent sensitivity). The voltages indicate the level at which the device was damaged by direct discharge into the bag.

These data demonstrate that, in a controlled environment such as an electronics manufacturing facility, normal ESD controls allow use of any materials listed in the table because voltages are maintained well below the 2500-V level, the lowest damage threshold shown. Consequently, the apparent additional protection of the bag is of little value. The effectiveness of shielding bags is typically greatly reduced after initial use. Folding or crimping can cause pinholes and gaps in the metallic shielding layer. The most important properties of bags or packages are their antistatic and dissipative qualities and physical protection. The data in Table II also suggest that bags are not a good solution for handling electronics in uncontrolled environments. In those instances, rigid packaging, which provides an adequate air gap, is more effective for both ESD and physical protection.

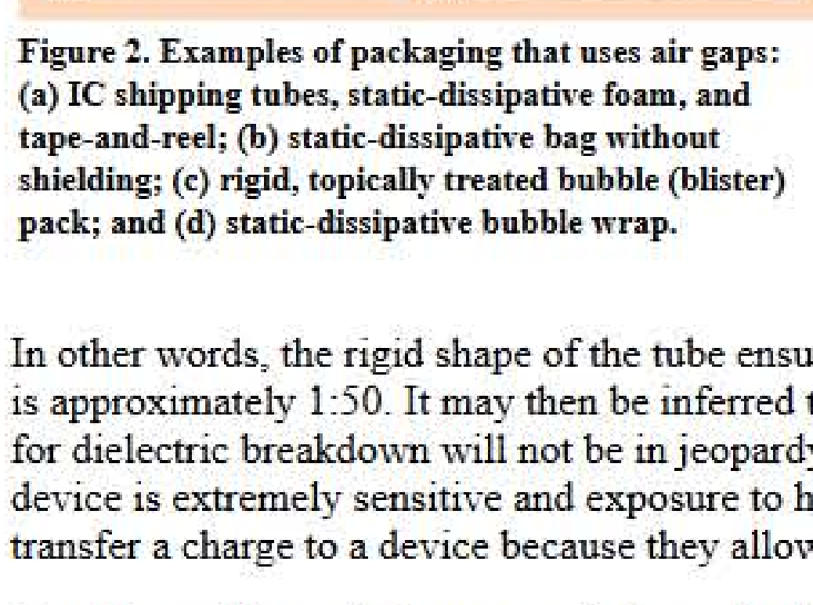

Figure 2. Examples of packaging that uses air gaps: (a) IC shipping tubes, static-dissipative foam, and tape-and-reel; (b) static-dissipative bag without shielding; (c) rigid, topically treated bubble (blister) pack; and (d) static-dissipative bubble wrap.

Capacitive Coupling and Air Gaps

One of the reasons that conductive or shielding materials are seldom necessary is that the orientation and position of a device with respect to the source of a static charge can be sufficiently restricted to minimize any detrimental effects. Examples of materials that use air gaps to achieve this objective are shown in Figure 2 and are reviewed in the following sections.

Integrated Circuit Shipping Tubes.

The potential exposure to ESD damage to which a device packaged in an integrated circuit (IC) shipping tube is subjected is illustrated in Figure 3. In this illustration, V_S is the potential on the source. C_C is the capacitance between the source and the device, and C_D is the capacitance of the device to ground. The voltage seen by the device is then given by:

$$V_D = \frac{V_S C_C}{C_C + C_D}\,. \qquad (2)$$

In other words, the rigid shape of the tube ensures there will be a gap, which will reduce V_D. Unger has argued that, typically, the ratio V_D/V_S is approximately 1:50. It may then be inferred that, as long as external voltages are held below about 5000 V, devices with 100-V thresholds for dielectric breakdown will not be in jeopardy.[4] Therefore, conductive or metallic IC shipping tubes appear to be unnecessary unless the device is extremely sensitive and exposure to high voltages is likely. In fact, Unger also has shown that conductive tubes are more likely to transfer a charge to a device because they allow the charge to distribute rapidly over the length of the tube.

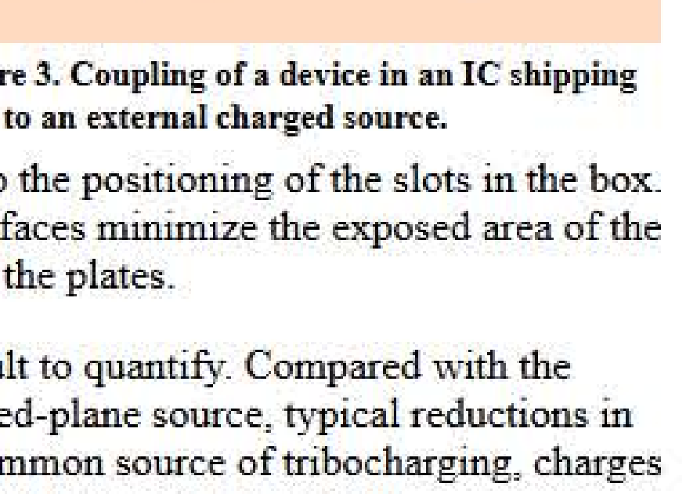

Figure 3. Coupling of a device in an IC shipping tube to an external charged source.

Tote Boxes. Figure 4 shows a typical anodized aluminum dissipative tote box used for circuit boards. (Anodized aluminum can be specified to have a surface resistivity of between 10^6 and 10^{10} Ω/sq.) Most tote boxes are made of a static-dissipative material so that any charge that might appear on them can be removed by grounding or by placing them on a static-dissipative or conductive work surface. Nevertheless, a charge may remain on an outer surface or on an object near the box. As illustrated in Figure 4, the orientation and position of the boards minimize coupling to these sources.

The surfaces of the tote box that are in contact with the circuit board have a relatively weak coupling because they are perpendicular to the plane of the board. Conversely, the surfaces that are parallel have reduced coupling because they are required to be approximately 1/2 in. away from the board due to the positioning of the slots in the box. In terms of the parallel plate capacitor model, the perpendicular surfaces minimize the exposed area of the plates, and the parallel surfaces have a maximum distance between the plates.

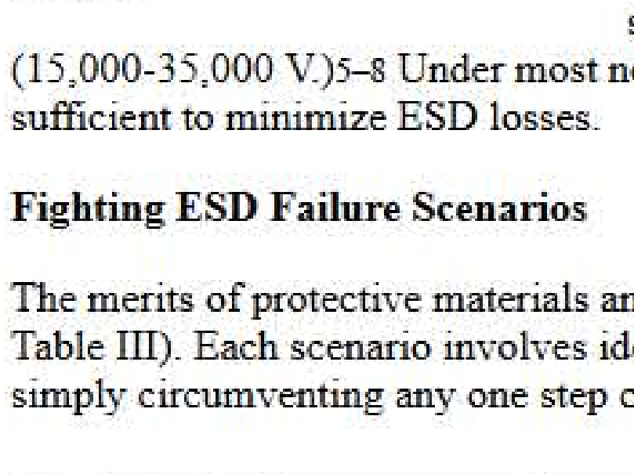

Figure 4. Schematic of the coupling of a printed wiring board assembly to the bottom, Cb, and parallel edge, Ce, of a tote box.

The degree of protection afforded by such an arrangement is difficult to quantify. Compared with the coupling seen by a circuit board mounted horizontally over a charged-plane source, typical reductions in coupling are about one-half. Because sliding the box is the most common source of tribocharging, charges most often reside on the bottom surface. As a result, the orientation in Figure 4 is forgiving.

Bubble Packs versus Bags. When a rigid or semirigid packaging material is used, air gaps can be maintained during shipping and handling. These air gaps simultaneously provide visibility and physical isolation and minimize field effects without resorting to conductive materials. Most studies conducted on shielding have involved bags in worst-case configurations with extremely high source voltages (15,000-35,000 V.)[5–8] Under most normal conditions, minimizing coupling through orientation combined with other protective measures is sufficient to minimize ESD losses.

Fighting ESD Failure Scenarios

The merits of protective materials and packaging procedures can be evaluated by analyzing the three most common ESD failure scenarios (see Table III). Each scenario involves identifiable steps where protection techniques can be applied. Because each process is sequential, in theory, simply circumventing any one step could eliminate the potential for ESD damage. In practice, however, this is not possible.

Scenario	Step	Remedy
A	1. Motion produces a charge on surface(s).	Antistatic material or agent on either surface.
	2. Devices moved near a charged surface.	Dissipative surface. Suppression by air gaps and/or shielding.
	3. Device is grounded while near a charged surface (CDM).	Air ionization. Static dissipation.
B	1. Motion produces a charge on the insulated package (lid) of device.	Antistatic material or agent on contacting surface.
	2. Charge remains on the device.	Air ionization.
	3. Device is grounded while charged (CDM).	Static dissipation.
C	1. Charge generated by the movement of a person.	Grounded wrist straps.
	2. Charge remains on the person.	Conductive or static-dissipative floors and shoes.
	3. Charge is transferred to device by touch.	Room air ionization. Isolation of the device. Static-dissipative package slowly discharged. Conductive shunt.

Table III. Implementation of ESD controls in three common ESD scenarios.

First, no technique is foolproof. Antistatic agents age and become ineffective, and ground contacts become intermittent or open completely. Second, other objectives of a process may preclude or limit the application of some safeguards. For example, the adhesive side of some tape-and-reel cover tapes must be insulated to provide good bonding with the carrier tape.

Scenario A. Two surfaces experience some motion, which produces a static charge; a sensitive device is then placed in the field of this charge; and the device is subsequently grounded.

The problems associated with step 1 can be minimized by using antistatic materials while the surfaces are in contact. Any remaining charge can be allowed to dissipate through use of a static-dissipative material, neutralized by air ionization, or suppressed by using air gaps or electrostatic shielding. The effect of step 3 can be minimized by using a static-dissipative material to ensure that any discharge is controlled and slow.

Scenario B. In Scenario A, there are a number of ways to minimize the probability of step 3 occurring. This is to be contrasted with Scenario B, where a static charge appears on a device because of contact with another surface. As in Scenario A, step 1 can be counteracted by using an antistatic agent on the contacting surface. Of course, the device cannot be made antistatic or static dissipative and continue to function properly. The ceramic or plastic body of the device must be highly insulated to satisfy electrical requirements as well as moisture- and corrosive-resistance requirements. This also limits the options for responding to step 2. Because the charge now resides on the device package, the only way to remove the charge, other than to wait for an extended period, is through air ionization. Step 3 is the failure step. The only viable means of protection is to avoid contact with the conductors and to discharge the device through a static-dissipative material.

A discharge through a lumped resistor of $10^5–10^{12}$ Ω is not a good substitute for a large sheet of material such as a work surface.[9] This is because discrete resistors have parasitic (shunt) capacitances that allow a significant flow of current at high frequency, as is seen in typical CDM ESD events.

Scenarios A and B are likely to occur because of the movement, often automated, of devices through a manufacturing operation. In this context, the familiar human threat is not a significant factor. Rather, it has been our experience that these scenarios represent the greatest potential for damage because they can produce static charges in a systematic fashion as part of the manufacturing process.

Scenario C. Because of the relative efficiency of personnel grounding in controlled manufacturing areas, the HBM threat tends to be sporadic. However, wrist straps do fail and, even in a well-audited program, some employees occasionally do not use them properly. Therefore, packaging must provide additional protection. This protection is even more important outside the factory when a circuit board may be subject to a somewhat less controlled repair or maintenance environment. Scenario C describes the interaction of a charged person with a device and the protection alternatives provided by various packaging. To prevent this, the charging mechanism must be eliminated. This, however, is seldom done. Even the most antistatic carpeting is actually static dissipative or conductive. The wrist strap actually applies to step 2, or removal of the charge from the individual. Another alternative is room air ionization, which is an expensive, incomplete, and rarely elected solution. Step 3 is the transfer of the charge to the device, either by removing the board or the device from its package or by touching the package directly. Assuming that dielectric breakdown of the device is not an issue at this stage, the following two remedies are required: Adequate insulation from the charged source to preclude rapid discharge, and sufficient conductivity (static dissipation) so that, when the source approaches, any discharge slowly leaks onto the package surface.

Most antistatic dissipative bag materials are sufficient. For very sensitive devices (below 100 V), however, more caution may be necessary. Using rigid materials to ensure a significant air gap and a reduced coupling with external charged sources may provide ample additional protection.

As these scenarios clearly illustrate, several opportunities are available for greatly reducing the threat of ESD failures through the use of antistatic and static-dissipative materials. These materials directly address the critical steps that can lead to failure. It is also clear that a considerable number of options are available in the design and implementation of an effective ESD control program. This point is often overlooked when dealing with vendors of ESD control materials and products.

One of the primary benefits of understanding the relative importance and effectiveness of the various options is the ability to critically evaluate claims that vendors make regarding their materials and products. When confronted with assertions that conductive materials are necessary, it is useful to keep the following seven points in mind:

- Devices that fail simply in the presence of a field due to dielectric breakdown rather than by ESD are extremely rare.
- Electrostatic fields can be addressed by using air gaps and subsequent minimal capacitative coupling.
- Arcing directly through a static-dissipative bag without shielding is unlikely below 5000 V.
- Published studies where shielding effectiveness is demonstrated often involve extreme, worst-case scenarios.
- Increasing conductors in the environment can increase device vulnerability to the CDM, i.e., greater conductivity is not necessarily better.
- Using conductive materials for the most sensitive devices cannot be implemented in a rational way if HBM thresholds are the only available data. This is because the voltage thresholds for unterminated devices are much higher than reflected in the available data (in the HBM test, devices are grounded); HBM data do not correlate with dielectric breakdown sensitivity; and selective implementation of shielding to prevent ESD due to static induction requires CDM data.
- Sound ESD programs have proven very successful without the broad use of shielding materials.

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