ESD (electrostatic discharge)—the sudden and momentary electric current that flows between two objects at different electrical potentials—causes equipment failure and network downtime, thus causing production losses of multiple billions of dollars annually. From portable consumer electronics to industrial-automation, process-control systems, and military and aerospace applications, every electronics manufacturer must consider ESD during equipment design. Myriad testing standards exist for addressing the range of technical requirements of the various industrial segments.

To help you select the correct testing standard for a design, you need to understand the main ESD standards and the differences between device- and system-level testing. ESD protection includes a range of protection schemes, the most common of which are steering-diode arrays, TVS (transient-voltage-suppressor) diodes, and zener diodes. No matter which protection scheme you select, you must perform a final EMI (electromagnetic-interference) test and a test of the protection circuit itself.

**HBM testing**

The HBM (human-body-model) device-level test is the most common model for ESD testing. It is used to characterize the susceptibility of an electronic component to ESD damage. The test simulates an electrical discharge of a human onto an electronic component, which could occur if a human has built up residual charge—for example, by dragging his feet, in socks, across a carpet and then touching an electronic device. The failure modes for the HBM testing of ICs typically comprise junction damage, metal penetration, melting of metal layers, contact spiking, and damage to the gate oxides.

You set up the test procedure by applying a high-voltage supply in series with a 1-MΩ resistor and a 100-pF capacitor. After the capacitor is fully charged, a switch is used to remove it from the high-voltage supply and series resistor and to apply it in series with a 1.5-kΩ resistor and the DUT (device under test). The voltage thus fully dissipates through the resistor and the DUT (Figure 1). Values for the high-voltage supply range, according to the test level, from 0.5 to 15 kV.
Figure 2 shows a typical oscilloscope readout with an initial current spike as large as 1.4 to 1.5A when the capacitor starts discharging and the ramp-down until it asymptotically approaches 0A at approximately 500 nsec. The DUT can experience a maximum power of 22.5 kW at a single discharge event on a traditional HBM. Keep in mind that power equals the current times the voltage.

MM testing

The MM (machine-model) device-level test, which emerged in the 1990s, is now less common than the HBM test. Industrial-automation-manufacturing sites became increasingly popular in the ’90s to increase output. These machines become electrically charged after turn-on and discharge into an electronic component after making contact. Thus, MM tests became a model for testing this type of ESD event. Failure modes in MM testing are similar to those in HBM testing. These failure modes include junction damage, melting metal layers, and gate-oxide damage.

You set up the test procedure for MM testing with a high-voltage supply in series with a resistor and a 200-pF capacitor. After the capacitor fully charges, a switch is used to remove it from the high-voltage supply and series resistor and then apply it in series to a 0.5-μH inductor and the DUT. The inductor with the capacitor voltage dissipates through the DUT (Figure 3). Traditional values for the high-voltage supply can vary, but the most common range is 50 to 400V.

When looking at an oscilloscope measurement of current over time, you can see that the RLC (resistance/inductance/capacitance) circuit creates an alternating current (Figure 4). The current reaches approximately ±3A, which is about four times higher than the HBM’s peak-to-peak current amplitude. Furthermore, the dissipation is much longer for the MM test because it is still asymptotically approaching 0A at 900 nsec (Figure 4). The DUT experiences a maximum power dissipation of approximately 1.2 kW during an MM discharge event.

MM testing requires that you test each pin on the DUT to its standard. The electronic chip is
mounted on a specially designed load board that interfaces with an automated ESD tester. You ground the other pins on the board and then individually test each pin. You continue this procedure until all pins have been tested.

CDM testing

The CDM (charged-device-model) device-level testing procedure is a simulation for situations that often happen in automated-manufacturing environments in which machines often remain on indefinitely, causing the electronic ICs to electrically charge over time. When the part comes into contact with a grounded conductor, the built-up residual capacitance discharges. For the CDM test, the DUT is placed on its back facing upward on a testing board.

Separate the metal field plate and the DUT with an insulating material, which acts as a capacitor between the two objects. You then connect the metal field plate to a high-voltage supply and increase its voltage to the required CDM-test-voltage level. A probe then approaches the pin under test where an ESD event occurs. Monitoring the ground connection of the pin under test verifies this action. Repeat this test on each pin of the DUT for three positive and three negative pulses. The result is six total discharges per pin (Figure 5).

Figure 6 indicates that the CDM discharge takes place over 2 nsec at most, which makes it difficult to test and to model. This test results in a current of 5 to 6A discharging in less than 1 nsec. The current dissipates within 5 nsec, making this part of the test succinct but volatile. Due to this fast transient, the failure modes typically seen in CDM tests are gate-oxide damage, charge trapping, and junction damage. Figure 6 shows the current waveform during a CDM test.

The HBM, MM, and CDM are the most common ESD device-level testing procedures for electronic components. Table 1 summarizes their similarities and differences.
The system-level ESD-immunity test simulates the ESD of a human onto an electronic component (Figure 7a). Electrostatic charge on a human can develop in low relative humidity, on low-conductivity carpets, and on vinyl garments. To simulate a discharge event, an ESD generator applies ESD pulses to the EUT (equipment under test) in two ways. The first is through contact discharge, or direct contact with the EUT, in which something makes physical contact with the EUT. The second is through air-gap discharge, or indirect contact with the EUT, in which the discharge occurs through the air. The IEC (International Electrotechnical Commission) defines this test in the IEC61000-4-2 ESD-immunity-test specification.

Characteristics for this test are a rise time of less than 10 nsec and a pulse width of approximately 100 nsec, indicating a low-energy, static pulse. The ESD-immunity test requires that you administer at least 10 discharges of both positive and negative polarity at 1-sec intervals. Thus, you test the EUT at least 20 times for the ESD-immunity system-level specification (Figure 7b).

EFT immunity

The system-level-testing standard of IEC61000-4-4 is the EFT (electrical-fast-transient) immunity-testing model (Figure 9a). The EFT-, or burst-, immunity test simulates transients that can happen in everyday environments due to switching off inductive loads, relay-contact bounce, and the

<table>
<thead>
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<th>Table 1 Comparison of HBM, MM, and CDM Testing</th>
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<tr>
<td><strong>Model</strong></td>
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<tr>
<td>Test levels</td>
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<tr>
<td>Peak current (A)</td>
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<tr>
<td>Pulse width (ns)</td>
</tr>
<tr>
<td>Rise time</td>
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<td>Typical ESD failures</td>
</tr>
</tbody>
</table>

**Figure 7** The system-level ESD-immunity test simulates the ESD of a human onto an electronic component (a). You test the EUT at least 20 times for the ESD-immunity system-level specification (b).

**Figure 8** The IEC ESD test typically has an eight-times-higher testing voltage than CDM and a 20-times-higher testing peak current than HBM.

**Figure 9** The system-level-testing standard of IEC61000-4-4 is the EFT (electrical-fast-transient) immunity-testing model (a). The EFT-, or burst-, immunity test simulates transients that can happen in everyday environments due to switching off inductive loads, relay-contact bounce, and the
operation of dc or universal motors. This test is performed on all power, signal, and earth wires. A burst is the sequence of pulses with a finite duration. In the EFT-immunity test, a burst generator produces a sequence of test pulses that attenuate to 50% of their peak values in less than 100 nsec. The next adjacent pulse typically occurs 1 μsec later. A burst typically lasts for 15 msec, and the burst period, the time from one burst’s start to the next burst’s start, is 300 msec. This cycle repeats for 10 sec, after which there is no testing for 10 seconds. This scenario represents one test cycle. The test cycle must repeat six times, taking 110 sec. The significance of the EFT-immunity test is its short pulse rise times, high repetition rates, and low energy content.

Although the fast rise time and the low energy content of an EFT are somewhat similar to those of an ESD pulse, the number of pulses per test cycle is not. Assuming a 1-μsec interval between one pulse front and the next, a 15-msec EFT burst contains at least 15,000 pulses. Multiplying the number of bursts within a 10-sec window yields 10 sec/300 msec=33.3 bursts and 500,000 pulses per 10-sec window. Thus, the application of six 10-sec windows with a 10-sec pause interval results in 3 million pulses within 110 sec.

Because EFT testing involves no direct contact of conductors but instead the indirect application through a capacitive clamp, proper, industrial-grade cabling with internal shielding can produce great results to the DUT by drastically attenuating the coupling of EFT energy into the conductors (Figure 9b).

**Surge immunity**
The surge-immunity, or lightning, test, IEC61000-4-5, represents the most severe transient-immunity test in current and duration (Figure 10a). However, testers often employ it on signal and power lines longer than 30m. The surge-immunity test simulates switching transients due to direct lightning strikes; induced voltages and currents due to indirect strikes; or switching the power systems, including load changes and short circuits.

The test specifies the surge generator’s output waveforms for open- and short-circuit conditions. The ratio of the open circuit’s peak voltage to the short circuit’s peak current is the generator’s output impedance. High current due to low generator impedance and pulse duration approximately 1000 times longer than the ESD- and EFT-immunity tests characterize this test, indicating a high-energy pulse.

This test requires five positive- and five negative-surge pulses with a time interval between successive pulses of one minute or less. A common procedure is to shorten the pause intervals to 12 sec, thus reducing total test time to less than two minutes. Although this approach intensifies the surge impact due to the protection circuits’ reduced recovery time between pulses, it contributes to a significant reduction in test cost (Figure 10b).

**System-level testing**

The IEC compiles the system-level-testing standards according to IEC61000-4. This family of standards includes approximately 25 system-level-testing specifications for transient-immunity testing: IEC61000-4-2 for ESD, IEC61000-4-4 for EFT, and IEC61000-4-5 for lightning. Table 2 compares these tests.

<table>
<thead>
<tr>
<th>Immunity test</th>
<th>Standard</th>
<th>Lines tested</th>
<th>Voltage (kV)</th>
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<tbody>
<tr>
<td>ESD</td>
<td>IEC61000-4-2 air gap</td>
<td>Power, signal</td>
<td>±15</td>
</tr>
<tr>
<td></td>
<td>IEC61000-4-2 contact</td>
<td>Power, signal</td>
<td>±15</td>
</tr>
<tr>
<td>EFT/burst</td>
<td>IEC61000-4-4</td>
<td>Power</td>
<td>±4</td>
</tr>
<tr>
<td>Surge/lightning</td>
<td>IEC61000-4-5 (6 and 20 μsec, 42Ω, 0.5 μF)</td>
<td>Signal</td>
<td>±0.5</td>
</tr>
<tr>
<td></td>
<td>IEC61000-4-5 (6 and 20 μsec, 2Ω, 18 μF)</td>
<td>Power</td>
<td>±1</td>
</tr>
</tbody>
</table>

Today’s rising demands for system-level testing renders inadequate device-level testing at the low voltage/current levels of HBM, MM, and CDM. A strong distinction exists between system ESD and burst/surge-level testing between consumer products and industrial equipment and systems, however. In consumer designs, ESD testing assumes a high priority due to the increased probability of human contact with electronic components through cable connectors.

In strong contrast, industrial designers rate the burst- and surge-immunity tests higher than ESD
testing. In this case, the daily bombardment of electrical transients due to electric motors and other inductive switching loads poses far greater risks to the system than ESD, whereas human contact occurs only during system installation and maintenance and even then only when the operator is wearing ESD-protection gear. For more information about ESD and testing, visit www.ti.com/esd-ca.

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