

A Comparison of High-Frequency Voltage, Current and Field Probes and Implications for ESD/EOS/EMI Auditing

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Abstract – High-frequency voltage, current and field probes are used to characterize charged device model ESD. The relationships between voltage, current and field measurements are explored. A “unified theory of ESD auditing” that connects voltage, current and field measurements is described for comprehensive high-frequency ESD/EOS/EMI auditing.

I. Introduction

Measurement of voltage, current, and electromagnetic fields can be highly useful during ESD/EOS/EMI auditing. For example, high frequency voltage, current and E-field probes have been used to characterize charged device model (CDM) events in automated IC handlers [1,2], handling of extremely ESD sensitive Class 0 devices [3,4], and testers and tools with electrical ground noise [5,6].

But there are many different types of current, voltage and field probes and each probe has its own bandwidth, measurement challenge and useful application. These measurements are also often reported individually, e.g. only current or only voltage, which leaves the relationship *between* voltage, current and electromagnetic field measurements unclear. These factors, combined with the inherent difficulty of high-frequency measurements, can lead to confusion as to which measurement technique or probe is best to completely understand the voltage, current or field threat in a manufacturing process step.

The purpose of this work is to compare and contrast measurements of a charged device model (CDM) event using a variety of high-frequency voltage, current and field probes. Measurement challenges and pitfalls are highlighted and a unified approach for high-frequency ESD/EOS/EMI auditing is discussed.

II. Experimental

Figure 1 shows a schematic representation and picture of a floating IC device that is held by a charged metal holder. Due to the electric field on the holder, the device will have an induced voltage and a CDM ESD event will occur upon grounding of a pin. A single pin of the IC was grounded using either a 1 cm long wire to the metal block, or a 60 cm long wire to the grounded chassis of a LeCroy 5005A (5 GHz 20 GS/s) digital oscilloscope.

Table 1 lists the model and bandwidth for the three voltage, five current and two field probes used. The use of at least two probes of each type enabled

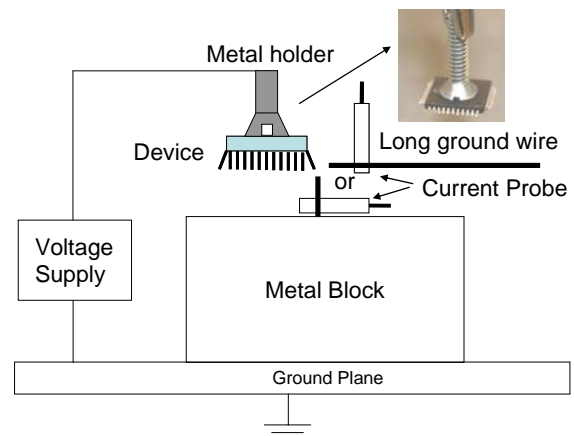


Fig. 1. Schematic representation of experimental setup for CDM event to IC device.

Type	Model	Bandwidth
Voltage	Keithley 6517A electrometer	DC-10 kHz
Voltage	HP1140A FET active differential (200 MHz, 7pF, 1M Ω)	DC-200 MHz
Voltage	LeCroy AP20 FET active single ended (1 GHz, 1.3pF, 1M Ω)	DC-1GHz
Current	TEKTRONIX (TEK) CT6	250 kHz-1 GHz
Current	TEK CT1	25 kHz-1 GHz
Current	TEK CT2	1.2kHz-200kHz
Current	Coaxial Resistive [7]	DC-500 MHz
Current	Fischer Communications F65	100 kHz-1GHz
E-Field	Credence EMEye	1 MHz-2 GHz
E-Field	Credence CTS001	1 MHz-2.6 GHz
E-field	Dipole antenna	500 MHz resonance

Table 1. Properties of the voltage, current and electric field probes used in this study.

comparison measurements under both similar and different test conditions and bandwidths. Figure 2 shows photographs of some of the probes. The CT-2 probe is shown with a 3 cm long wire to the braid of the coax, which was grounded at the scope. It was also used with the short, 1 cm long ground wire to the grounded block. The coaxial current probe was made using the design given in ref. 7.

III. Results

1. Current

Figure 3 shows the current waveforms when the same pin of the IC with an induced voltage of 50V was grounded using different current probes. The waveforms using the CT6, CT1 and CT2 probes were obtained using the short, 1cm long ground wire to the metal block. The “CT2 gnd” waveform used a 3 cm long wire to the 2-foot long ground braid of the coax (see Fig. 2). A 60 cm ground wire using the braid from a coax cable was used with the F65 clamp-on current probe.

Note that the waveform shape and peak current are similar using the CT6, CT1 and CT2 probes with the same short ground wire. The CT2 probe worked extremely well, considering that its bandwidth is only 200 MHz. The reduced current and broader pulse width for the CT2 gnd, coaxial, and F65 probes are attributed to the increased impedance in the discharge

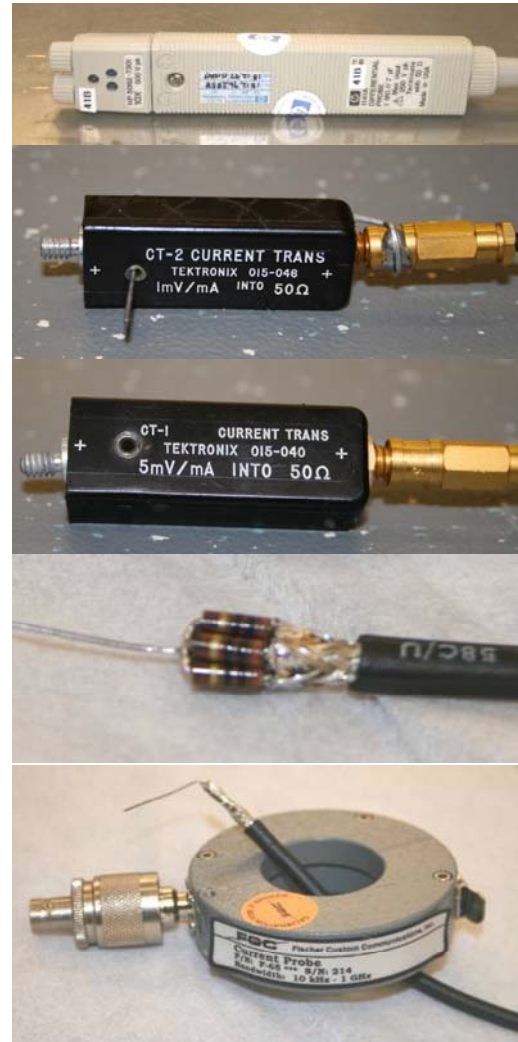


Fig. 2. From top to bottom: HP1141A active differential voltage probe, TEK CT1, TEK CT2, coaxial and Fischer Communications F65 clamp-on current probe with ground wire.

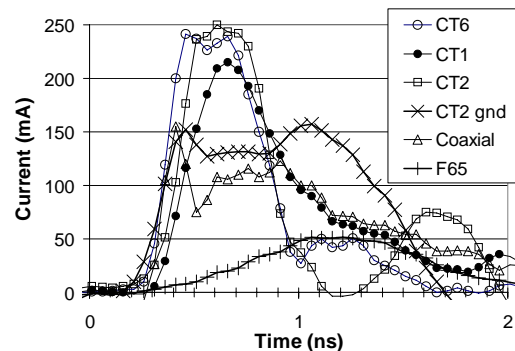


Fig. 3. Current waveform when same pin of IC at 50V was grounded using each current probe.

path due to the longer ground wires. It is important to note that the peak current for the CT2-gnd waveform, which used the coax braid as the ground, has a peak current that is 40% lower than when the CT-2 probe used the short wire to the grounded block. Therefore, significantly different current transients can be measured using the same probe when a different length or type of ground wire is used.

Since the ESD current depends on the impedance in the discharge path, the longer ground wires, with more inductance and impedance, resulted in reduced peak current and broader waveforms. This highlights the importance of understanding the effect of the ground wire used with any current probe, since it strongly influences the waveform amplitude and pulse width.

Figure 4 shows the average peak current for 10 measurements using each probe for a device voltage of 50V. Again, the dramatic reduction in peak current in the CT-2 with ground wire, coaxial, and F-65 probes is due to the longer ground wire used with these probes.

If the use of a long ground wire is required, a scale factor could be used to convert the lower peak current reading to the larger one that would have been measured if a short wire was used. For example, the CT-2 waveform could be taken as close to worst case using the 1 cm long ground wire. But it is much easier to use the braid of the coax of the CT2 as the ground return, and the “CT2-gnd” waveform shown in Fig. 3 would then be measured. Using a scale factor of 1.7 (260mA/155mA), the peak current measurement using the CT2 with coax braid as the ground return can be converted to the “worst case” current.

Figure 5 shows that the average peak current vs. device voltage using the CT6 probe with a 1cm-long wire to ground. The peak current depends linearly on device voltage. This suggests that if a ground wire with known impedance is used, and if the device capacitance is known and kept constant, then the current probe measurement could be used to determine the initial *voltage* on the device. Thus, the current probe can be “calibrated” to determine the device voltage in certain special cases.

2. Voltage

It is important to measure the voltage on the device prior to metal contact during processing to determine the threat to ESD damage from a CDM event. In situations where current is measured, but the device capacitance and impedance in the discharge path is

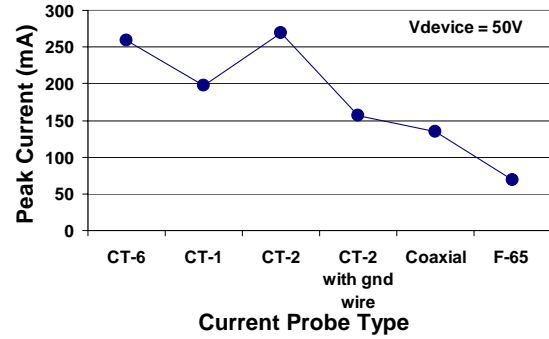


Fig. 4. Peak current for CDM event during grounding of IC for each current probe.

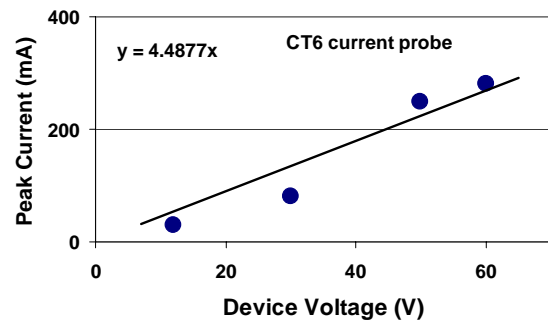


Fig. 5. Peak current vs. device voltage for the CDM event using TEK CT6 current probe.

not known, direct voltage measurements would be required.

The use of an electrometer to continuously measure voltage during processing has been reported [8]. In this section voltage measurements on the floating IC using the electrometer are compared to measurements using the active voltage probes.

Figure 6 shows the voltage on the device using a Keithley 6517A electrometer vs. time as one input of the HP1141A active differential voltage probe made contact to the device pin and was then removed.

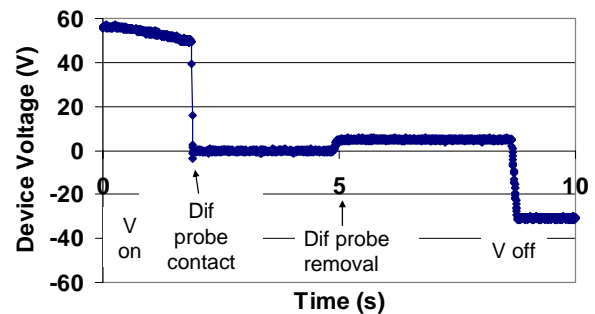


Fig. 6. Voltage on device, as measured by Keithley 6517A electrometer, vs. time as the differential voltage probe made contact and was then removed.

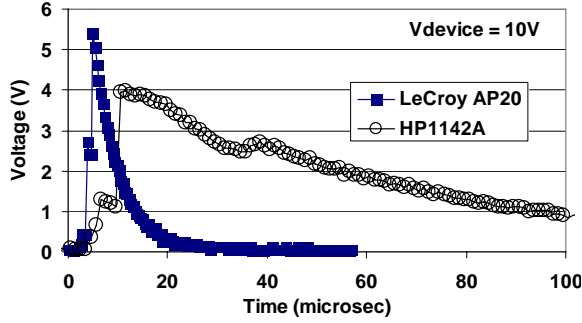


Fig. 7. Voltage probe signal vs. time when the LeCroy and HP active voltage probes were touched to device pin at 10V.

When the voltage probe touched the pin, the device voltage dropped to zero. This behavior is consistent with the $1M\Omega$ input impedance of the probe allowing charge to flow from ground into the $\sim 1pF$ device in about $1\mu s$. When the probe tip was removed from the device pin and the voltage on the IC holder turned off (V_{off}), the device voltage went negative, proving that the device was charged by induction due to the contact by the active voltage probe.

The voltage pulses when the device pin at 10V was touched by the LeCroy AP20 and HP1141A active voltage probes are shown in Fig. 7. The difference in voltage pulses is explained by the different input capacitance of the two probes (see Table 1). The waveform measured using the LeCroy probe, with its smaller input capacitance ($1.8pF$), had a faster time constant and greater peak voltage than the waveform measured by the $7pF$ HP probe. In both cases, the peak voltage of the active probe was somewhat less than the initial voltage ($10V$) on the device.

The waveform measured by the voltage probe is easily understood in terms of charge sharing between the device and probe at first contact. The ratio of the initial peak voltage measured by the voltage probe (V_{probe}) and initial voltage on the device (V_{device}) is given by

$$\frac{V_{probe}}{V_{device}} = \frac{C_{device}}{C_{device} + C_{probe}}, \quad (1)$$

where C_{device} and C_{probe} are the capacitance of the device and probe, respectively. Therefore, V_{probe} approaches V_{device} only when $C_{probe} \ll C_{device}$.

SPICE modeling is often useful to better understand high frequency circuit behavior. In order to simulate the signal measured by the active voltage probe, the

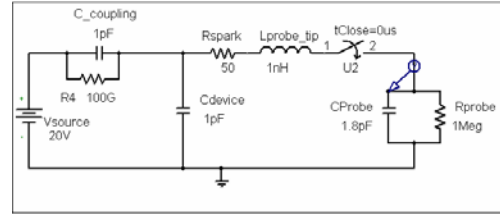


Fig. 8. SPICE model for $1pF$ charged device touched by LeCroy AP020 active voltage probe.

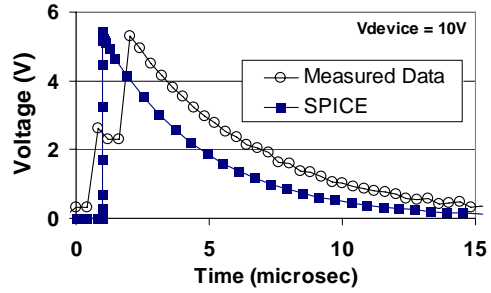


Fig. 9. Comparison between measured and SPICE simulated voltage vs. time waveform.

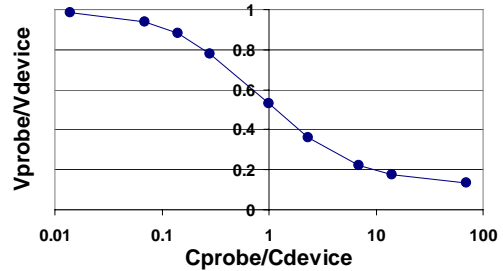


Fig. 10. SPICE simulation result showing the ratio of probe to device voltage vs. the ratio of probe to device capacitance.

SPICE model shown in Fig. 8 was used. The probe is modeled as a simple resistor and capacitor in parallel.

Figure 9 compares the measured and SPICE model voltage waveforms vs. time. There is excellent agreement in peak voltage and time constant.

Figure 10 shows SPICE modeling results for the ratio of the ratio of the probe to device peak voltage vs. the ratio of the probe to device capacitance. It is seen that the peak probe voltage measured by the probe depends strongly on the relative capacitance of the device and probe, as expected from Eqn. 1. Only when the probe capacitance is much less than the capacitance of the device will the probe measure close to the initial device voltage just before contact.

Figure 11 shows the HP1141A probe peak voltage vs. device voltage. Although the FET probe does indeed measure a voltage that is smaller than the initial device voltage, there is a linear relationship. This

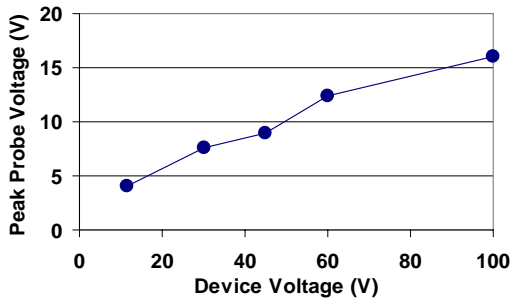


Fig. 11. Peak voltage probe signal vs. voltage on device at time of contact.

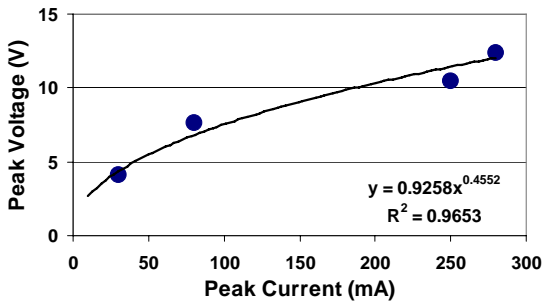


Fig. 12. Plot of peak voltage for CDM event using voltage probe vs. peak current for CDM event using current probe. Each point was measured at the same voltage. Device voltage ranged from 12V to 60V.

suggests that the active voltage probe could be “calibrated” to measure the initial voltage on a device with known capacitance.

Taken one step further, Fig. 12 shows the peak voltage, as measured by the active voltage probe, vs. the peak current, measure by the current probe, for CDM events at the same device voltage. This graph was generated by plotting the y-axis data from Fig. 5 vs. the y-axis from Fig. 11. The usefulness of Fig. 12 is that the peak CDM current can be determined from a voltage measurement. This is only valid for current and voltage measurements on a device at the same capacitance.

Finally, the active voltage probe can be used to measure charge flow from the device to the probe. If Q is the initial charge on the device, then

$$Q = c \int V(t) dt, \quad (2)$$

where c is a scaling factor proportional to the impedance to ground, $V(t)$ is the voltage waveform and t is the time. This is because V is proportional to the current. Thus, integration of the voltage waveform in the scope would yield a measure of the initial charge on device, turning the active voltage probe into a small capacitance, high-bandwidth, but “leaky” nanocoulombmeter.

Thus, the voltage probe can be used to determine the device voltage, peak current for a CDM event and even the initial charge on the device.

3. Electromagnetic (EM) Fields

EM fields can be measured using a variety of passive monopole or dipole antennas, or active near E-field or H-field antennas. The advantage of an active probe is a flat response vs. frequency.

Figure 13 shows a simultaneous comparison between ESD current using a CT6 and simultaneous E-field transients using an active (CTS001) probe and passive 12 inch dipole antenna, for a 30V CDM event 5 cm away. The delay in time for the active CTS-001 probe is likely due to the amplifier. The ringing in the dipole antenna signal is due to its resonance at about 500 MHz.

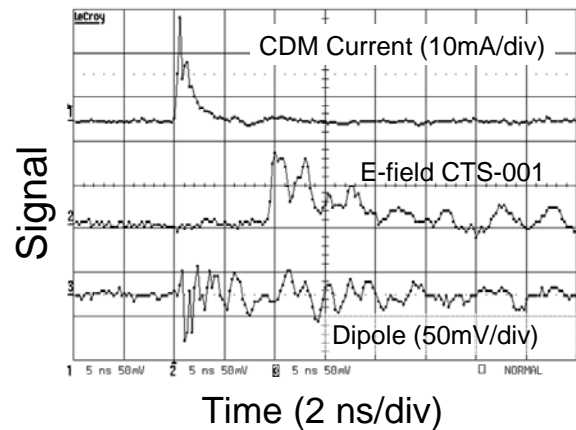


Fig. 13 Comparison between ESD current using CT6 and simultaneous E-field transients using an active (CTS001) probe and passive dipole antenna for a 30V CDM event 5 cm away.

IV. Implications for ESD/EOS/EMI Auditing

Measurements of voltage, current and fields are related through impedance, capacitance and other factors. In principle, it would be possible to use a single probe measurement of one type to determine another type of measurement. For example, one could measure the peak current, and determine the device voltage and initial charge using conversion factors. This calculation would involve knowing the impedance to ground, device and probe capacitance and impedance, calibration coefficients, and other factors.

In practice, one or more of the factors that affect the current-to-voltage and voltage-to-current conversion can change from one process step to the next, so it may be difficult and/or time consuming to convert from one measurement type to another. It is far simpler and more accurate to simply measure charge, current, voltage and fields directly, rather than trying to convert from one to the other. Nonetheless, it is important to understand the connection between each measurement to better understand the meaning of each measurement.

V. Unified Theory of ESD/EOS/EMI Auditing

A “unified theory of ESD auditing” is now proposed to fully characterize the ESD/EOS/EMI threat to devices during handling. All measurements are assumed to be “high bandwidth”, from DC to at least 200 MHz, preferably to 1 GHz.

1. VOLTAGE

- Measure device voltage, continuously if possible, or at least prior to any metal-to-metal contact to a pin.
- Measure voltage on any conductive surface that the device inputs can touch.

2. CURRENT

- Measure device current to ground just prior to possible metal contact to device inputs. Use a ground wire with known and repeatable impedance to ground, and use the scale factor back to worst-case current with minimal impedance.
- Measure current to ground for all conductive tools or surfaces that can touch device inputs.

3. FIELDS

- Measure E-fields near device and any conductive surfaces that come near or into contact with device inputs. This should include the radiated fields from sparks using an EMI event detector.

While measurements of voltage, current and field are often redundant, the extra information is useful to confirm the other types of measurements and to gain a more complete picture of all types of transients.

VI. Summary and Conclusions

1. Since the impedance to ground strongly affects current and voltage probe measurements, it must be understood and controlled when comparing voltage and current probe measurements.
2. A current probe measurement can be used to determine the initial *voltage* on the device if the impedance of the ground wire and capacitance of the device are known.
3. SPICE modeling can be useful in understanding the measurement of current and voltage probes.
4. A “Unified Theory of ESD/EOS/EMI Auditing” involves voltage, current and field measurements on the device and tooling from DC to ~ 1GHz to characterize the threat of overstress to the device.

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