

1 Ω Disk Resistor Full-Wave Modeling for JS-002 Standard

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- **Abstract** –A 1 Ω disk resistor is specified in the CDM standard as the current sensing element. However, its transfer impedance is frequency dependent which is not considered in the standard. In this work, a full-wave model and a simple equivalent circuit model is provided to explain the root cause of the variation the transfer impedance of the 1 Ω disk resistor.

I. Introduction

When the pin or pad of a charged IC approaches an external metal object, and the breakdown voltage is exceeded a Charged Device Model (CDM) event occurs. During CDM testing, the discharge current of the CDM event is measured by a 1 Ω disk resistor sensing element that is located at the top of a pogo pin probe as described in the industry standard ANSI/ESDA/JEDEC JS-002 [1]-[3]. The resistance of this element is specified to have a value of $1.0 \Omega \pm 10\%$ and a transfer impedance that does not have a deviation relative to the DC value greater than 3 dB up to 9 GHz [3]. The standard does not consider frequency variations of the transfer impedance when calculating the current from the measured voltage. This work investigates this assumption by characterizing the sensing element (1 Ω disk resistor) of a field induced CDM tester in the frequency domain. Additionally, a simple circuit model and a full-wave model are presented to explain the variation of the transfer impedance up to 27 GHz.

II. CDM tester

A. Discharge Circuit

The cross section of a CDM tester [3] is shown in Figure 1.

To charge the device, the field plate is brought to the specified charge voltage, then the pogo pin is lowered to contact the DUT pin. A spark is initiated and the current flows via the pogo pin to the 1 Ω disk resistor (Figure 2). The transfer impedance, properties of the oscilloscope and cable losses will determine the voltage that is displayed at the scope. The voltage is measured across the 1 Ω disk resistor from which the discharge current waveform is then calculated. However, the transfer impedance of the 1 Ω disk resistor is not constant over the frequency range and deviates from the DC value of the 1 Ω resistor [5].

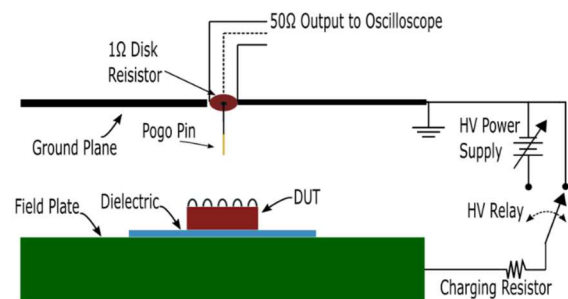


Figure 1: Cross Section of a JS-002 CDM Tester [4].

B. 1 Ω Disk Resistor Measurement

As shown in Figure 2, the disk resistor consists of a resistive sheet on one side and a ceramic substrate made from beryllium oxide (BeO) on the other side that

provides mechanical strength. In a CDM test head, the resistive sheet can be mounted downward (Figure 3a, resistive sheet towards pogo tip) or upward (Figure 3b, resistive sheet towards coaxial line).

Figure 4a shows a fixture to measure the disk resistor. The fixture is composed of two 50 Ω surface mountable connectors and a plate that aligns the disk resistor. The thickness of the plate was chosen to prevent any gap between the 50 Ω connectors and the surface of the disk resistor. The surface mount connectors were connected to ports 1 and 2 of a VNA and port extensions were performed up to the connector surfaces (Figure 4a). Figure 4b shows the definition of current and voltage of the two-port measurement setup (disk resistor setup measured with VNA). Knowing the S-parameter across the disk resistor, the transfer impedance of the disk can be calculated as in [6]:

$$Z_{Disk\ Down} = \frac{V_2}{I_1} = \frac{50 \times S_{21}}{1 - S_{11}} \quad (1)$$

$$Z_{Disk\ Up} = \frac{V_1}{I_2} = \frac{50 \times S_{12}}{1 - S_{22}} \quad (2)$$

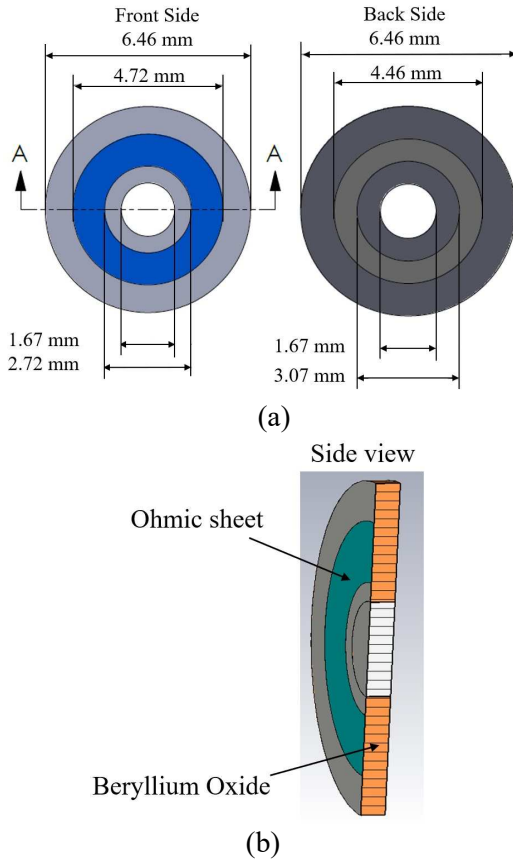


Figure 2: Cross section of the 1 Ω disk resistor. a) front and back view, b) side view.

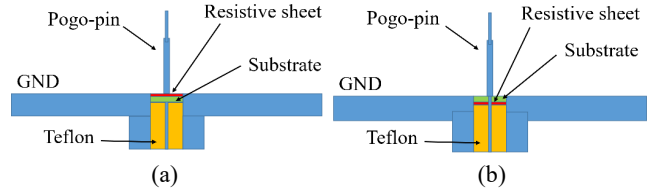


Figure 3: CDM test head with 1 Ω disk resistor. a) resistive sheet down, b) resistive sheet up.

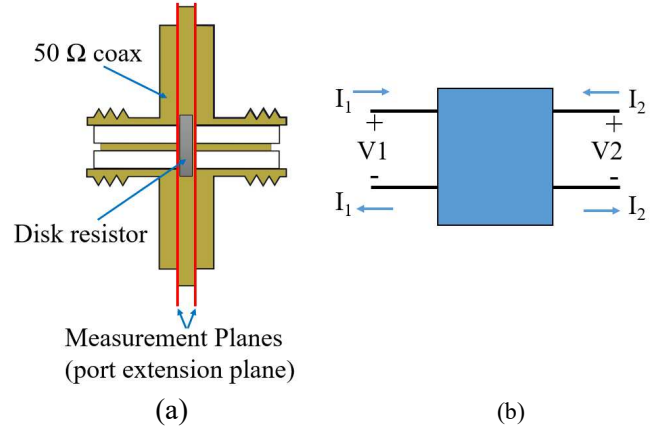


Figure 4: Measurement setup for the 1 Ω disk resistor. a) 50 Ω coax connectors with measurement planes, b) the definition of current and voltage of the disk resistor setup [6].

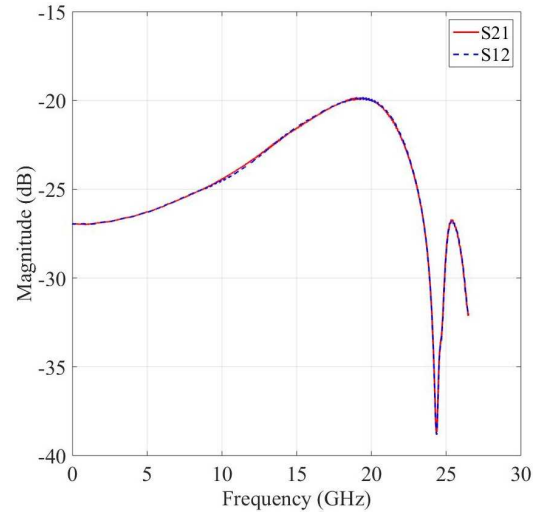


Figure 5: Measured S21 and S12 of a 1 Ω disk resistor.

As shown in Figure 5, the S21 and S12 of the disk are nearly identical which gives evidence for the accuracy of the measurement. However, the S22 and S11 are different (Figure 6). Port 1 of the measurement fixture (Figure 4) is toward the resistive sheet of the disk resistor, and port 2 is connected to the ceramic side of the disk. The reflection coefficient S11 is nearly flat but S22 has lower value at higher frequencies. The difference between S11 and S22 is important in understanding the CDM system behavior at high frequencies. Ringing was observed in the time domain

discharge waveform if the substrate is mounted toward the pogo-pin but it reduced if the disk was flipped. The ringing will be discussed in Section IV of this paper.

At low frequencies, the transfer impedance equals the disk resistance. Thus, the impedance measured with VNA should match the measurements obtained by an LCR meter ($1\ \Omega$ @ 1kHz).

As shown in Table I, both LCR Meter (@ 1kHz) and disk measurements (Figure 4) show about $1\ \Omega$ for different orientations of disk (up to 1GHz). For each sample, both methods showed nearly identical low frequency values (Figure 7). At higher frequencies, the transfer impedance obtained using (1) is increasing with frequency (Figure 8) for all disks. Additionally, manufacturing tolerances lead to variations between disk samples. The behavior of the S21 can be explained using a simple circuit model in the next section.

III. Device Modeling

A. Simple Circuit Model

Although different disk resistors showed slightly different transfer impedance values versus frequency, they all behave similar (Figure 8). The transfer impedance of the disks increased with frequency from $1\ \Omega$ @ 1 MHz to about $3\ \Omega$ @ 20 GHz. This behavior can be explained by the influence of the ceramic substrate. It forms a short, 13 ps delay transmission line (see Figure 2) which acts as transmission line transformer and changes the match of the $1\ \Omega$ disk side to the $50\ \Omega$ system. The substrate has a relative permittivity of around 7. However, the structure is not easy to model in 3D due to possibility of higher order modes if they are excited. Only considering TEM modes, a simple circuit model is created in Advanced Design System (ADS) [7] to evaluate the influence of the short ceramic transmission line (Figure 9).

Based on the geometry and permittivity of the Beryllium Oxide (BeO) substrate, the characteristic impedance of the ceramic portion was calculated to be roughly $17\ \Omega$. A 13 ps long $17\ \Omega$ $\lambda/4$ transmission line transformer converts $50\ \Omega$ to transfer impedance of about $3\ \Omega$ at 20 GHz which can be calculated with (1).

This transmission line behavior explains the observed increase of S21 and transfer impedance. As shown in Figure 10, S11 is almost flat over the entire frequency range whereas S22 decreases with frequency as the short transmission line changes the match to $50\ \Omega$. A comparison between measured impedance and calculated from the simple circuit model will be discussed in the next section.

Table I: Low Frequency Measurement of Disk Resistors.

	LCR Meter (Ω @ 1 kHz)	Network Analyzer (Ω up to 1 GHz)
Disk1	1.02	1.03
Disk2	1.03	1.01
Disk3	1.06	1.06

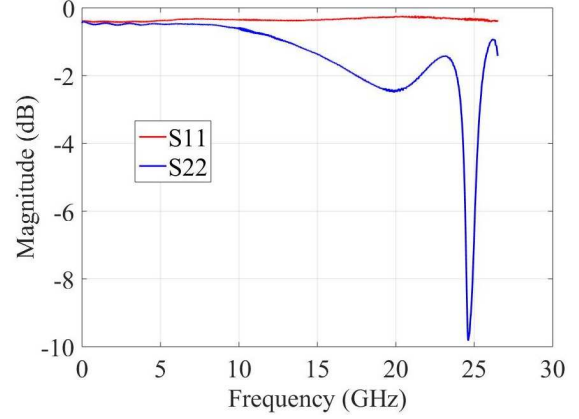


Figure 6: S11 and S22 of a $1\ \Omega$ disk resistor.

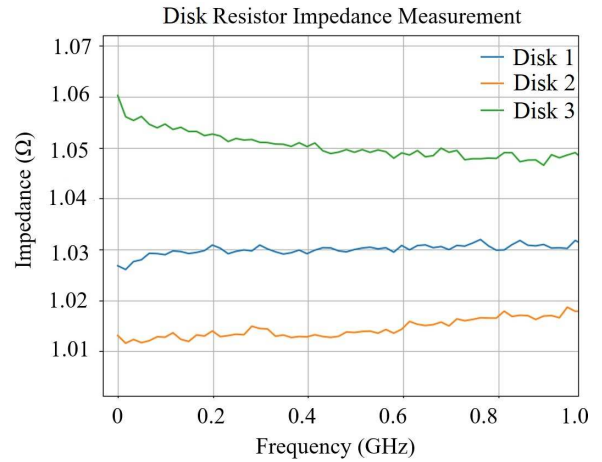


Figure 7: Transfer impedances of $1\ \Omega$ disk resistors calculated using (1) up to 1 GHz.

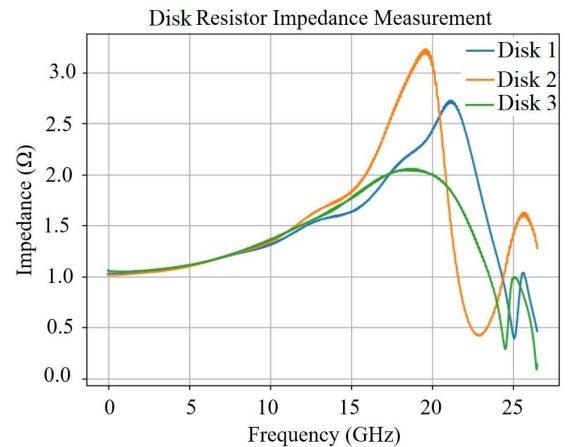


Figure 8: Measured transfer impedances of $1\ \Omega$ disk resistors calculated using (1) up to 26 GHz (resistive sheet down).

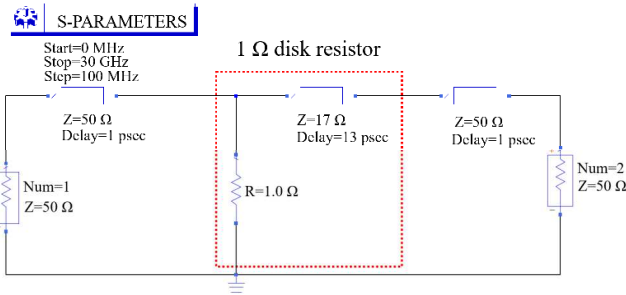


Figure 9: Simple circuit model of a 1 Ω disk resistor.

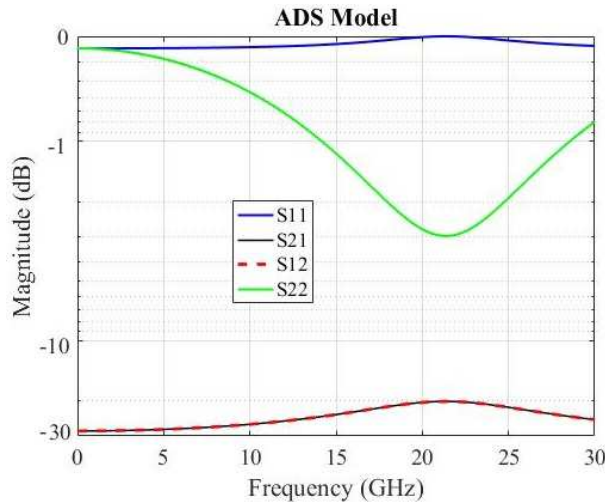


Figure 10: S-parameter results of the circuit simulation.

B. Full-wave Model

The simple circuit model gives a qualitative insight into only the dominating effects, excluding the influence of the skin effect, higher order modes, and details of the geometry. A full-wave model can reveal additional details about the frequency-dependent impedance. Figure 11 shows the core elements of the full-wave model: the 50 Ω connectors, the geometry of the disk resistor, and two waveguide ports which are placed across the 50 Ω connectors. Two short 50 Ω connectors are placed on both sides of the disk. As shown in Figure 2, the 1 Ω disk resistor has a resistive sheet on one side and a ceramic carrier made of beryllium oxide on the other side. A thin resistive sheet material (this does not model skin effect) and BeO were imported from the library of CST Studio Suite [8].

C. Comparison Between Measurement and Simulation

Figure 12 and Figure 13 compares the magnitude and phase variation data for the measured, circuit model, and full-wave model of the 1 Ω disk resistor. Both models and the data agree on the increase of the impedance above 1 GHz and the peak around 20 GHz.

This increase and the peaking may cause some error in the peak current measurement for CDM if the actual current contains relevant spectral content in this frequency range.

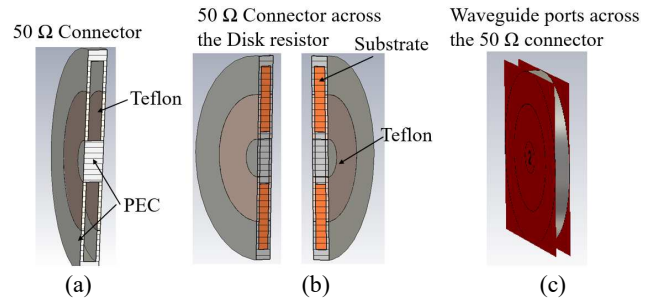


Figure 11: Full-wave model of the disk resistor. a) Section of the 50 Ω connectors b) disk resistor in between two 50 Ω connectors. c) Two waveguide ports are used to excite the 50 Ω connectors in TEM mode.

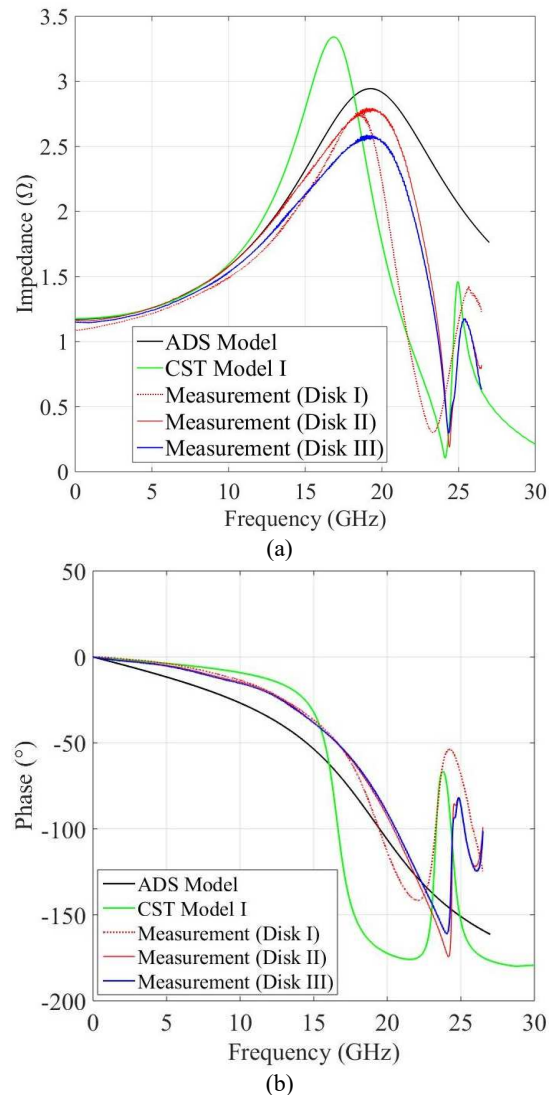


Figure 12: Transfer impedance of the 1 Ω disk resistor versus frequency for resistive sheet down (Figure 3a). a) magnitude, b) phase.

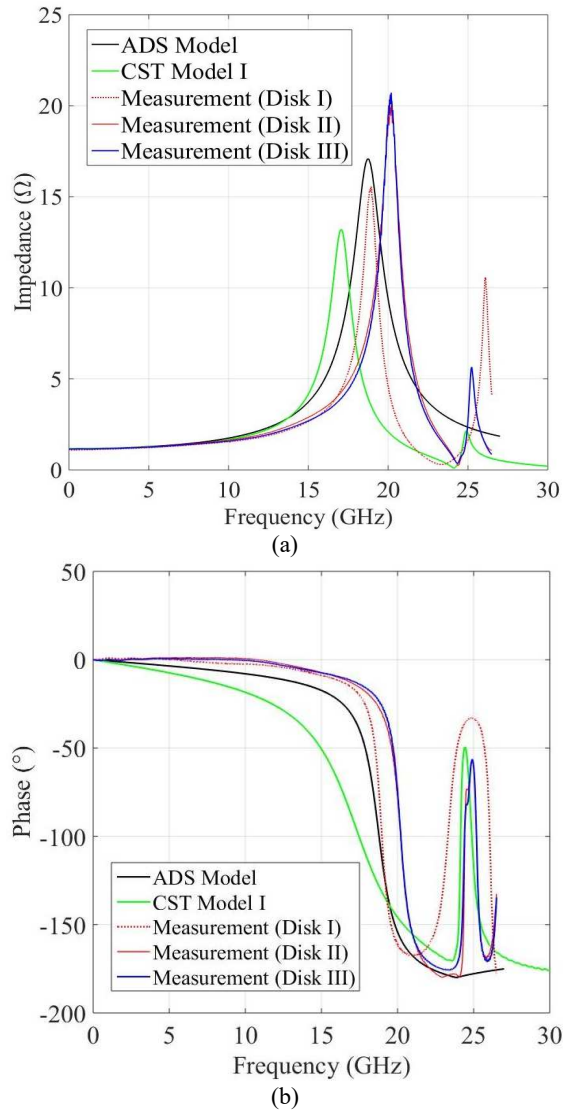


Figure 13: Transfer impedance of the 1 Ω disk resistor versus frequency for resistive sheet up (Figure 3b), a) magnitude, b) phase.

The fact that the simple circuit model and the measured data match up to 20 GHz can be seen as indicator that the short transmission line is the dominating reason for the observed increase in transfer impedance and the behavior of S11 and S22. The full-wave model predicted a higher peak value, 3.3 Ω relative to 2.6 Ω in the measurements (Figure 12 for resistive sheet down). The reason is not known, but as the frequency matches the other data one can be assured that the dielectric constant of the BeO was correctly estimated from literature data. The full-wave simulation shows additional resonant behavior around 25 GHz which is also seen in the measurements in the same frequency range. We have not investigated the field distribution at these frequencies within the full-wave results to identify the nature of these resonances. Furthermore,

the transfer impedance of the disk may decrease at higher frequencies when skin effect starts to decouple the front and the back side of the very thin resistive sheet. As the authors do not know the exact thickness and material of the resistive layer, it is not known above which frequency the decoupling effect of the skin effect would reduce S21. The data indicates that this is not the case below 20 GHz, as the simple ADS model matches the measurement in its principle behavior. Our full-wave model is also not able to simulate skin effect as an infinitely thin electrical layer was used to model the resistive sheet. The metallization of the resistive layer may not be fully homogeneous. This would cause a current flow that is not radially symmetric. As known from current shunts, this would increase the mutual inductance between both sides of the resistive disk. Such a behavior is not observed which leads to a tentative conclusion that the resistive sheet is homogeneous within the boundaries of the analysis.

IV. Effect of Disk Orientation on CDM Event

To investigate the effect of disk orientation, both measured and simulated results have been compared in a CDM test setup.

A. Effect of Disk Orientation on Measured Discharge Current

CDM classification levels have been reduced [9] and that further reductions are to be expected. This will lead to a faster rise time in CDM. This, paired with faster I/O on ICs may lead to measurement problems in CDM testing due to the mounting direction of the disk resistor. To investigate the effect of disk orientation, CDM discharge tests have been measured using a 23 GHz bandwidth oscilloscope [10] with different orientations of disk resistor as shown in Figure 3. One disk resistor was used within one test head by flipping the orientation between tests to prevent any unwanted effects or variation in the test setup. Discharge data from multiple pogo-pins with different length and discharge currents have been captured for charge voltage of 500 V (Figure 14 through Figure 17).

As shown, all plots have a low frequency component around 1 GHz which is the main CDM discharge current. However, there are some high frequency components as well which create ringing waveform over the low frequency waveform. As shown, high frequency ringing was observed in discharge current when the resistive sheet of disk resistor was mounted upward (Figure 3b).

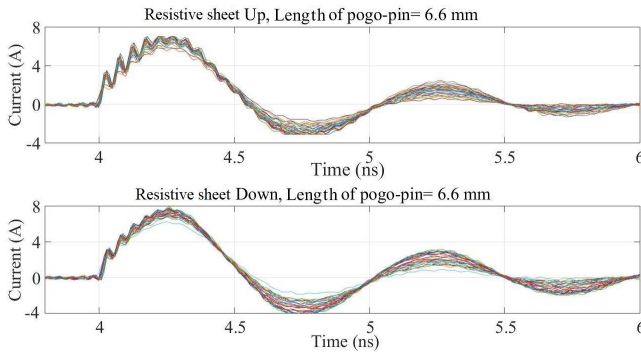


Figure 14: Thirty discharge currents with charge voltage of 500 V and small coin (8.89 mm), pogo length = 6.6 mm.

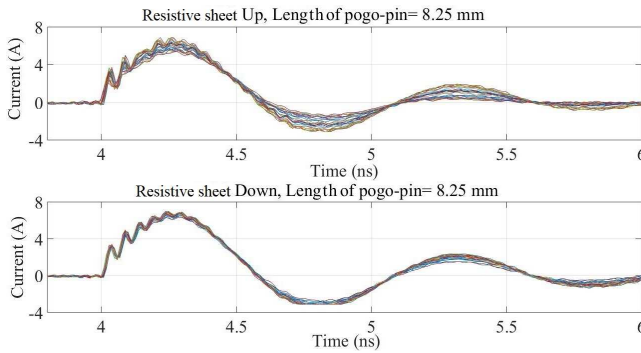


Figure 15: Thirty discharge currents with charge voltage of 500 V and small coin (8.89 mm), pogo length = 8.25 mm.

However, the ringing is weaker if the resistive sheet of disk resistor is mounted downward (substrate toward oscilloscope and the resistive sheet toward DUT as shown in Figure 3a). To isolate the ringing from the familiar low frequency response, a Maximum Overlap Discrete Wavelet Transform based Multiresolution Analysis (MODWT MRA) was used [11]. This method yields excellent decomposition and reconstruction while maintaining sharp edge definition and minimizing non-causality introduced by traditional high pass filtering. The high frequency ringing signal was found to be well isolated from the rest of the signal by using the db7 wavelet with a scaling factor of 2. Furthermore, the Wigner-Ville distribution [12] of ringing is used to visualize the time dependent frequency composition of the time dependent current.

The time domain signal, the power spectral density and time-frequency scalogram of ringing for different pogo-pins and for resistive sheet up and down is shown in Figure 18 and Figure 19. As indicated in time-frequency spectra of Figure 18, when the disk resistor is mounted upward for pogo pin length of 8.25 mm, 9.4 mm and 10.5 mm, there are two main high frequency component which make up the ringing with the corresponding interference term between the two main components.

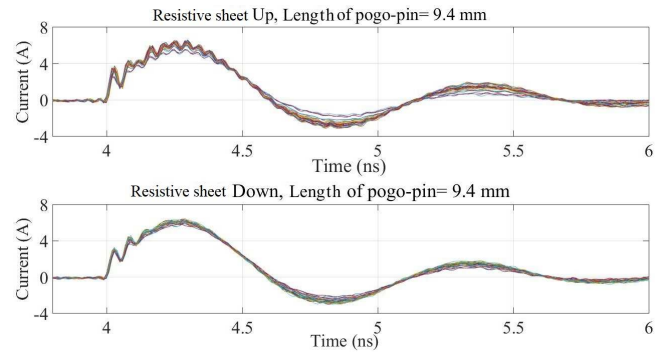


Figure 16: Thirty discharge current waveforms at voltage 500 V using the small coin (8.89 mm), pogo length is 9.4 mm.

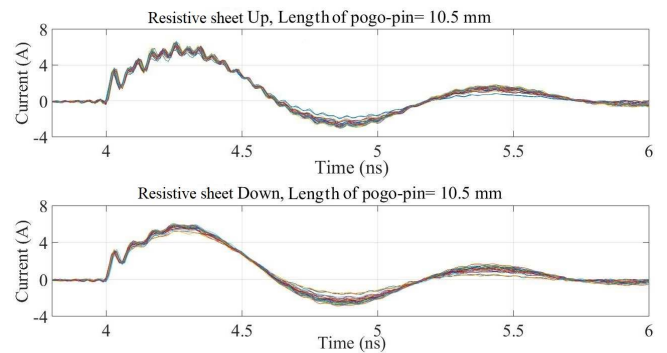


Figure 17: Thirty discharge currents with charge voltage of 500 V and small coin (8.89 mm), pogo length = 10.5 mm.

However, in all time-frequency spectra of Figure 19, there is only one frequency component. Similarly, when the resistive sheet of disk resistor is mounted upward the power spectrum has two main frequency components for pogo pin length of 8.25 mm, 9.4 mm and 10.5 mm. Table II summarizes the two observed frequencies if the resistive sheet of disk is mounted upward (Figure 18).

Two sinusoidal signals are used in Figure 20 to reconstruct the ringing for pogo pin of 10.5 mm (blue curve in Figure 20) and is compared with the original ringing (red curve in Figure 20).

Therefore, it is possible to reconstruct the ringing by summing two sinusoidal signals e.g., f1 and f2 as shown in Figure 20. This motivates us to consider the nature of ringing and determine the physical agents which correspond to these responses.

Table II: Pogo Pins and Different Resonance Frequency.

Pogo-pin Length (mm)	f1 (GHz)	f2 (GHz)
6.6	21	-
8.25	16.5	23
9.4	14.5	23
10.5	13	22-23

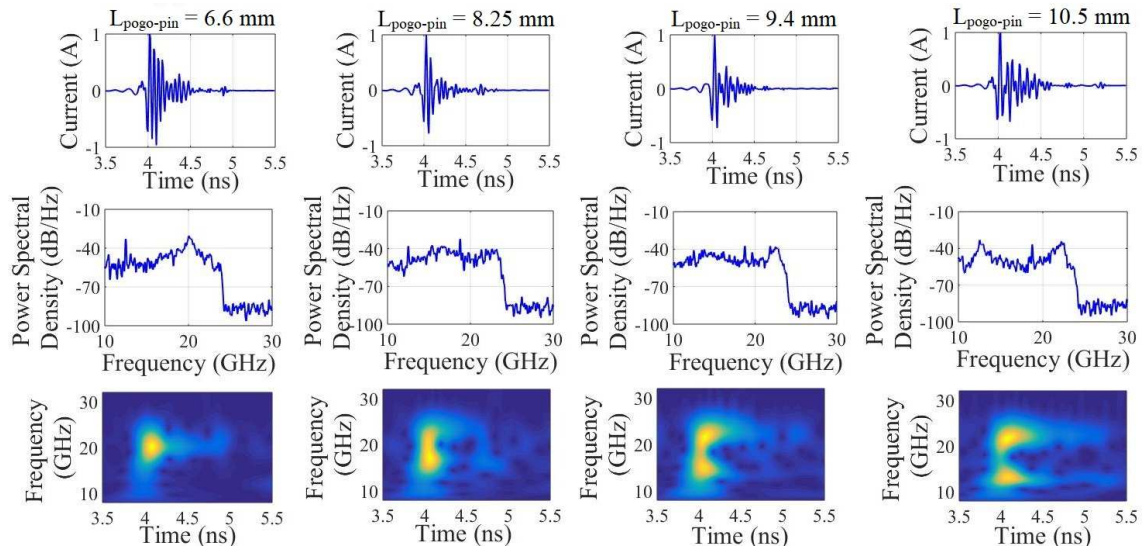


Figure 18: Time-frequency spectrum of ringing for resistive sheet up.

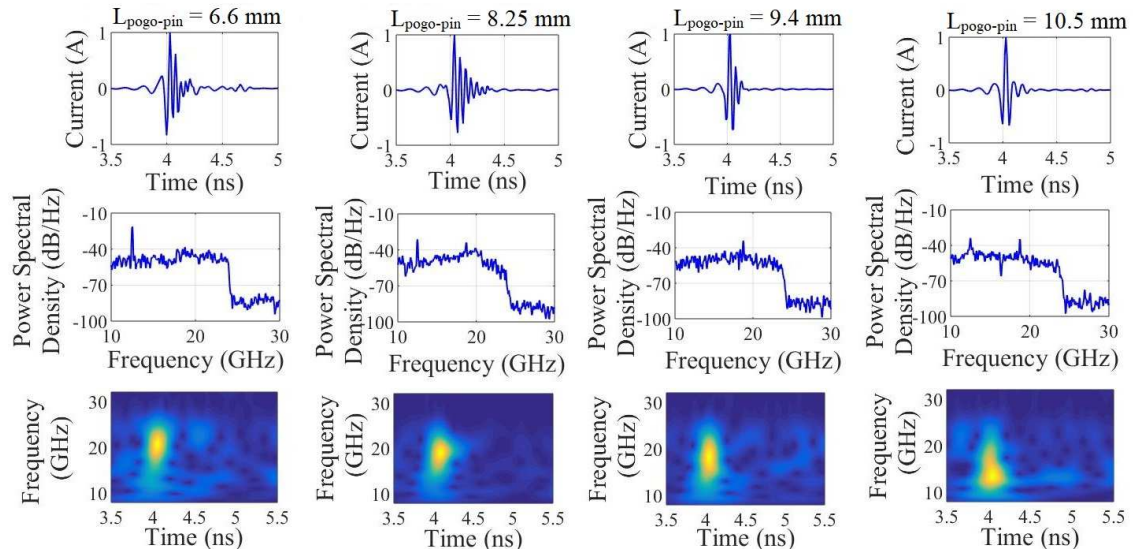


Figure 19: Time-frequency spectrum of ringing for resistive sheet down.

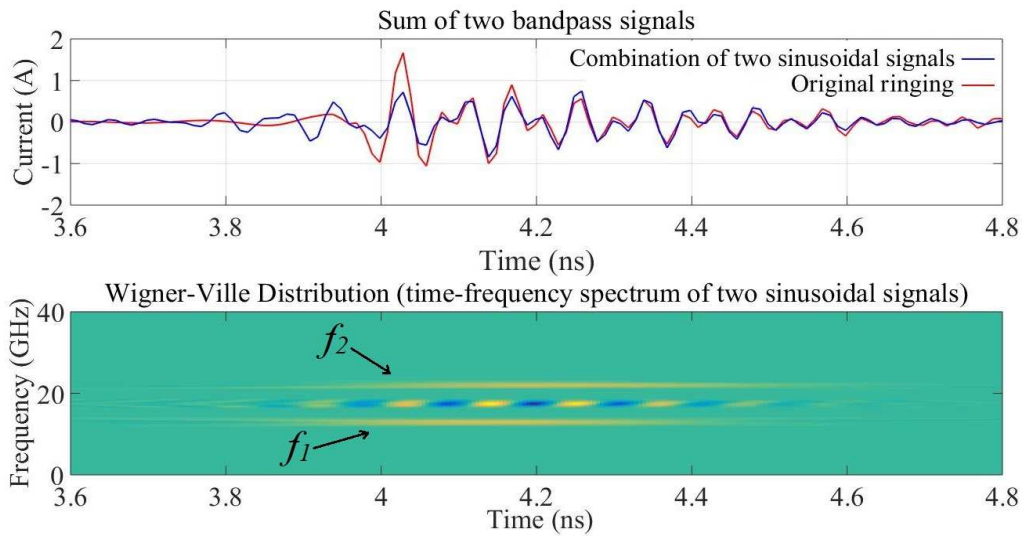


Figure 20: Time-frequency spectrum of power spectrum using Wigner-Ville Distribution.

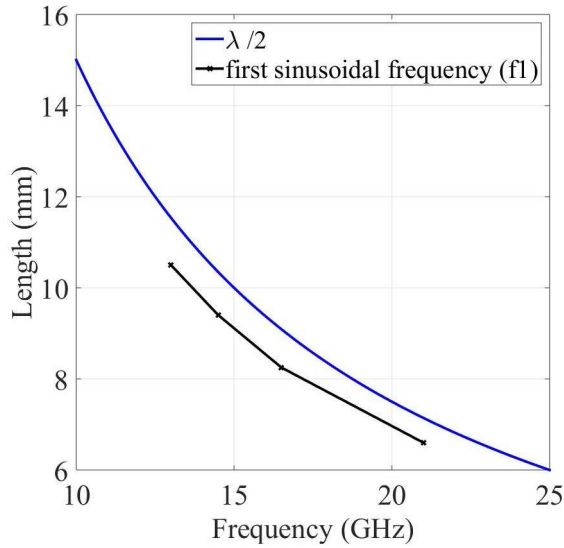


Figure 21: Wavelength versus frequency of first sinusoidal frequency for different pogo-pins.

Figure 21 shows the half wavelength versus frequency (blue curve) and is compared with the length of the pogo pins versus the first sinusoidal signal (f1) from Table II (black curve). As shown, the first sinusoidal signal (f1) is directly related to the length of pogo pin and can be calculated relative to the length of the pogo pin. The second sinusoidal component is related to the disk orientation. As shown in Figure 18 and 19, the second sinusoidal signal (f2) exist for resistive sheet upward for pogo pin 8.25 mm, 9.4 mm and 10.5 mm. However, this signal disappears when the resistive sheet is mounted downward. For the pogo pin 6.6 mm, two sinusoidal signals cannot be distinguished since f1 is very close to f2. When the resistive sheet of disk

resistor is mounted downward (resistive sheet toward DUT), only one frequency can be observed in time-frequency spectrum of ringing signal (Figure 19) which indicate the effect of disk orientation.

B. Effect of Disk Orientation in Simulation

As shown in Figure 18 through Figure 20, two sinusoidal signals contribute to the high-frequency ringing of the CDM discharge current. A full-wave model is created for CDM test setup (Figure 22) to obtain a qualitative insight into the dominating effects up to 30 GHz. Two discrete ports are placed on both sides of the pogo pin providing the corresponding connection for co-simulation simulation in ADS which is shown in Figure 23. Measured S-parameters of the $1\ \Omega$ disk resistor from Section II or simulated S-parameter file from Section III can be imported into ADS model of Figure 23. It is also possible to use the simple circuit model of the disk resistor (Figure 9) into the circuit model of Figure 23. As shown in Figure 24 and Figure 25, if the orientation of the disk is changed, the high frequency ringing also changes. The first ringing in the discharge current relates to the length of the pogo pin which exists in the discharge current regardless of disk orientation. However, the second ringing corresponds to the disk orientation and will disappear if the resistive sheet of the disk is mounted toward the DUT (red curve of Figure 24 and Figure 25). If the substrate of the disk is mounted toward the DUT (blue curve in Figure 24 and Figure 25), the waveform has more ringing (high frequency contents).

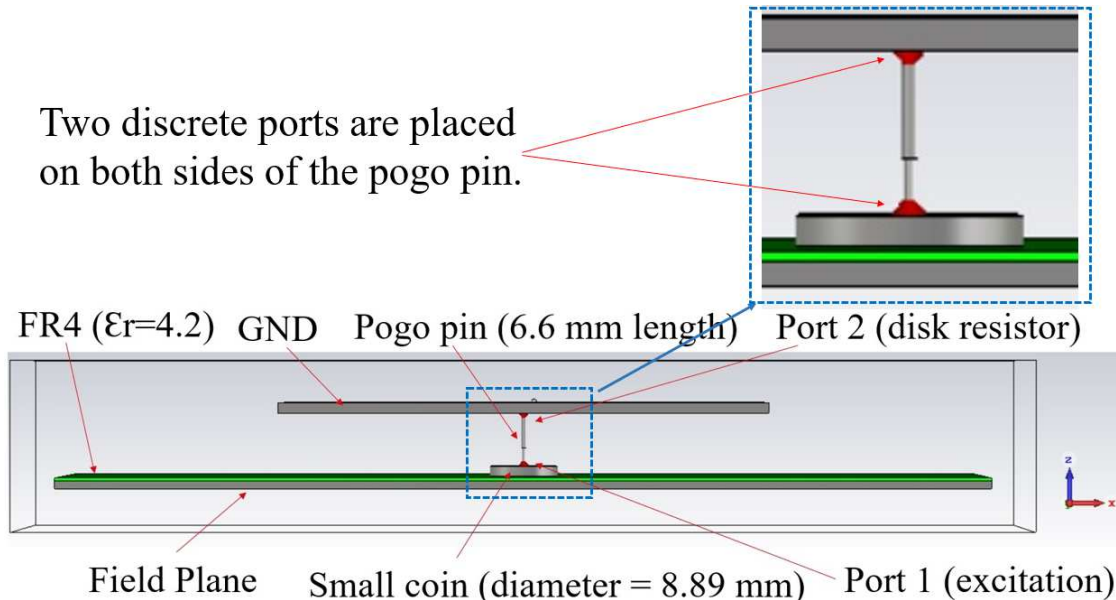


Figure 22: Full-wave model of CDM test setup.

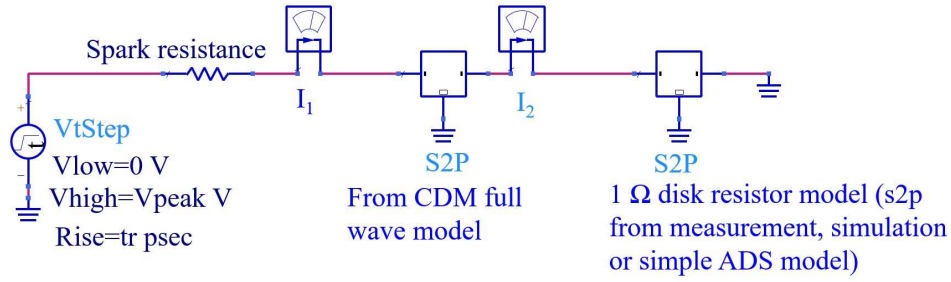


Figure 23: Schematic of ADS model for CDM test setup.

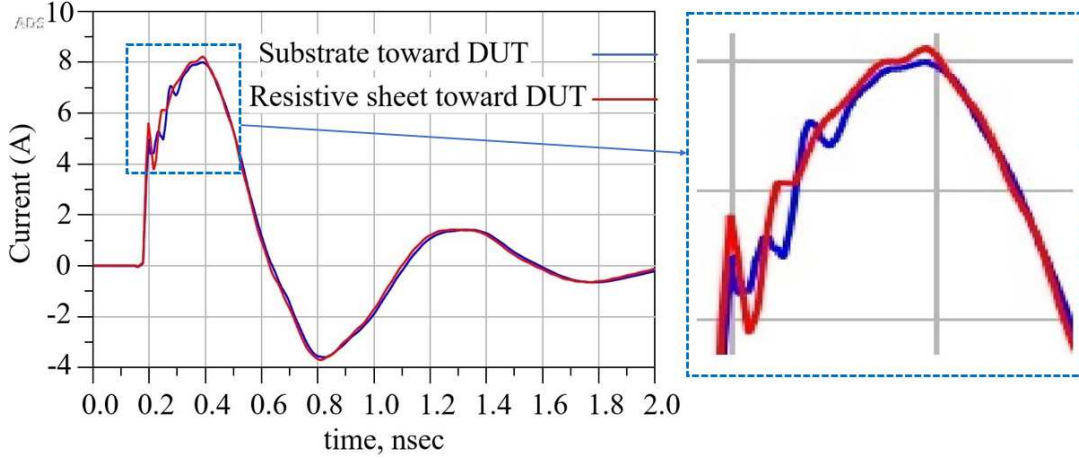


Figure 24: Simulated CDM discharge current using simple circuit model of a 1 Ω disk resistor (Figure 9).

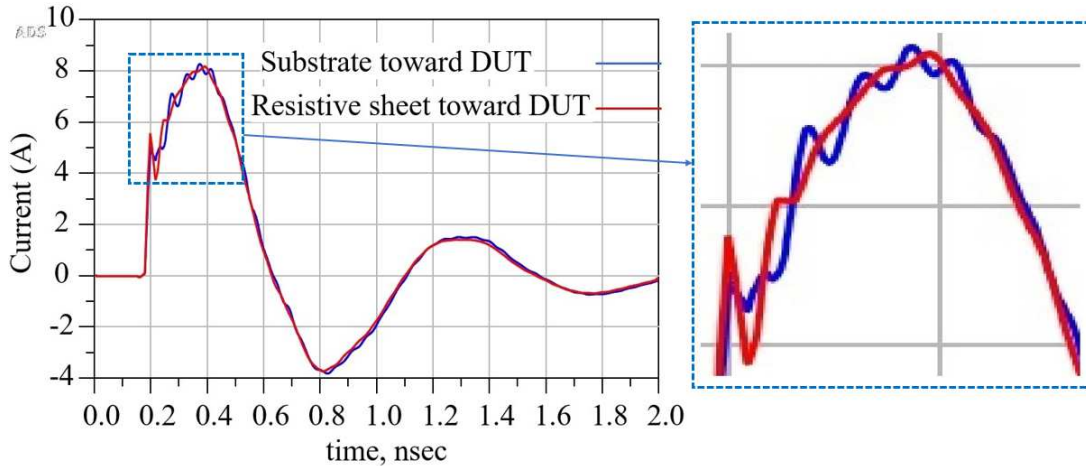


Figure 25: Simulated CDM discharge current using S-parameter of 1 Ω disk resistor from full-wave model (Figure 11).

The effect of disk orientation in simulated data (Figure 24 and Figure 25) is not as strong as the measured waveform (Figure 14 through Figure 17), but in principle they follow the same behavior, i.e., ringing is stronger if the ceramic substrate is mounted toward the DUT and gets weak if the resistive sheet is mounted toward the DUT.

It is known that the current measured at disk is not necessarily equal to the current at the DUT [13]. Ultimately, the current at the DUT is the stress that the device experienced. For accurate comparison between

measured and simulated data in this paper, only current at the disk resistor was studied. Future work should incorporate current at the DUT to get a more accurate measurement of the stress that the device experiences.

A. Discussion

The fundamental question is how important is the frequency response of the transfer impedance of the disk resistor above 10 GHz?

Present ICs have data rates up to 50 GHz and more. Thus, their I/O can be damaged by high frequency

content of every strong signal [14]. The charge voltages of CDM will be further reduced such that the rise times will further reduce [9]. Thus, the importance of the larger than 10 GHz spectral content will increase. Right now, CC-TLP testers can be based on a 40 ps or less transmission line pulser [14]. A 30 ps rise time equates to 10 GHz. To avoid problems in testing of future ICs and for comparing test methods, the analysis > 10 GHz is suggested.

V. Conclusion and Further Investigations

The frequency response of the transfer impedance of a 1 Ω disk resistor has been investigated through measurement, full-wave modeling, and a simplified equivalent circuit. The transfer impedance increases with frequency and shows a maximum of about 3 Ω at 20 GHz for disks mounted downward (resistive sheet toward DUT). However, the transfer impedance increases with frequency and shows a maximum of about 15-20 Ω around 20 GHz for a disk mounted upward (resistive sheet toward oscilloscope).

This is explained by considering the inner structure of the 1 Ω disk resistor. Only one side of the resistor's ceramic carrier contains the resistive sheet material. Thus, it is asymmetric. The thin ceramic carrier creates a short transmission line. The effect of this short transmission line section is clearly visible in measurement, simplified and full-wave simulation both in S11, S22 and S21 data. It cannot match the 1 Ω but it strongly changes the match and causes an increase of the transfer impedance. The CDM current has been captured with different pogo pin lengths. High frequency ringing was observed. It can be explained as the sum of two sinusoids. The first sinusoidal signal was directly related to the resonance frequency of the pogo pin structure, i.e., its length and the second one was created due to the transfer impedance of the disk orientation.

VI. Acknowledgements

We would like to thank Dr. David Johnsson and Dr. Timothy Maloney for their useful discussions and comments.

VII. References

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