The Application of Spark gaps on Audio Jack for ESD Protection

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***Abstract* – ESD strikes can be suppressed by placing ESD protection devices along ESD current paths. As primary ESD protection on PCBs, spark gaps are cheap and take little space, but the breakdown voltage is not low enough and the lag time can be too long to protect the circuit. The effect of adding carbon and non linear polymers to the spark gap is investigated in this paper.**

***Index Terms* – ESD protection, spark gaps, breakdown voltage, time lag, polymer, VSD.**

I. INTRODUCTION

The electrostatic discharge (ESD) protection design for an IC is critical for safe production and handling. The control method techniques for ESD Protected Areas (EPA) have progressed and now ICs only require the minimum specified protection levels. Typical IC level (or component level) ESD protection requirements, addressing both the Human Body Model and Charged Device Model, commonly specify 1 kV and 250 V, respectively. However, system-level ESD protection has become very important in today's world as devices become more portable, contain multiple interface connectors, have touchscreens, and are continually exposed to the external world. Increasing the IC ESD protection to a level sufficient to protect against system-level ESD has potential disadvantages: increased IC area, possibly reduced functional performance, and higher cost [1].

One way of reducing the risk of hard failures is to place ESD protection devices in the path of the ESD current. To reduce cost and save die space, a spark gap might come in mind as a good choice [2]. Different ESD protection structures used inside ICs or on PCB have been reported, e.g., the spark gaps protecting components during PCB assemblies using "finger shape" ground [3] or some "tooth-like" protrusions along the length of conductor path [4,5]. However, the breakdown voltage of spark gaps is not low enough, and the time lag is too long. Voltage switchable dielectric (VSD) material reduces the time lag [7]. This paper analyzes ESD protection of a microphone/earphone jack. "Tooth-like" spark gaps are placed along each "finger-shape" signal/ground traces, as shown in Fig. 1, which replaces 5 TVS diodes on the audio jack connector. The ESD suppression performance of the spark gaps, with and without time lag modifying materials, is evaluated.

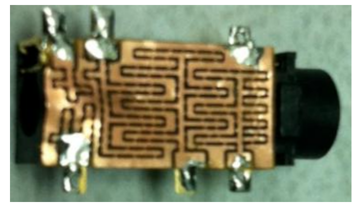


Fig. 1 Spark gaps applied on audio jack connector

II. OVER-VOLTAGE PROTECTION COMPONENTS

A. Spark gaps

1) A spark gap is a mechanically simple, but electrically complex device. Important aspects of spark gaps are:

- DC breakdown voltage:

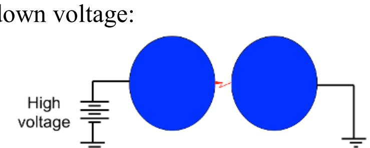


Fig. 2 Spark between two electrodes

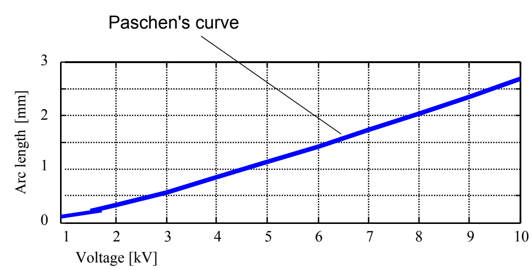


Fig. 3 Paschen's curve

The Paschen curve (Fig.3) depicts the breakdown voltage of a gap with different arc lengths, under the following conditions: normal pressure in air, homogeneous field. It has been shown that the Paschen curve is also a good predictor for small gaps that have an inhomogeneous electric field, such as a gap on a PCB. For a 0.1 mm gap the static breakdown voltage is around 1000 V.

- Turn on delay (Statistical time lag):

The breakdown may not occur instantaneously after applying a voltage larger than the static breakdown voltage. The breakdown is delayed until electrons can start the avalanche process, which is called the "statistical time lag". Fig. 4 shows the response of the spark gap at two different voltage levels. The left half shows a pulse that is about three times the DC breakdown voltage. In this case the spark gap breaks down earlier. The right half shows a pulse that is about two times the DC breakdown voltage. The delay is longer. If we want to protect a circuit, the spark gap will have no effect as protection device until after the time lag. Thus, the time lag should be as short as possible, and the breakdown voltage as low as possible. The stronger the "overvoltage" on the spark gap is, the faster the breakdown will be initiated.

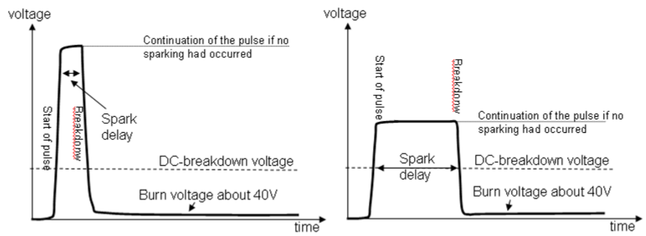


Fig. 4 Turn-on delay of the spark gap, illustrated at different voltage levels across the gap

- Burn voltage:

  The burn voltage is often in the range of 25-40V. The consequence is that the gap cannot clamp the voltage to any voltages lower than the burn voltage.

- Advantages and disadvantages for using spark gaps:

  The advantages are: they are cheap, small, can handle very high currents, and do not add capacitance.

  The disadvantages are: 1) breakdown voltage is high; 2) long time lag, which can be reduced by: Carbon electrodes, radioactive charge carrier generation, humidity, rough surfaces, dielectric interfaces, etc. [8]; 3) until the spark gap breaks down, it has no effect as a protection device.

A non-linear polymer has two main differences: it clamps the voltage to 200-400V even before it breaks down, and its time lag is much shorter [7].

B. Non-linear polymer

A polymer's electrical characteristics exhibit "snap-back" in their current versus voltage curve, as shown in Fig. 5, at high voltage, arcs between the particles creates a low resistance path resulting in a drop in voltage. Measurements of different polymers showed trigger voltages between 100 V and 1000 V. Relative to spark gaps, the statistical time lag is much shorter (often < 1ns), and the clamping voltage is usually 20 to 50 V.

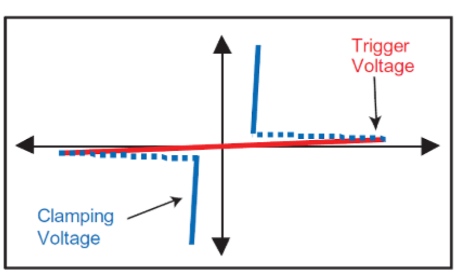


Fig. 5 V-I curve of polymer devices

III. ESD Measurement for Spark Gaps

A. Spark gaps in air

1) ESD test scenario 1

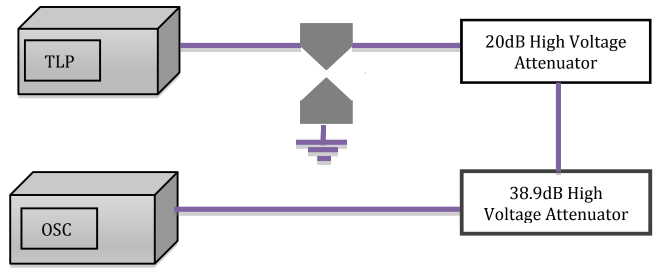


Fig. 6 Equivalent circuit for test setup scenario 1

Test scenario 1 is used to evaluate the performance of the breakdown voltage and time lag for the spark gaps (see also Fig.8). The test setup up is shown in Fig. 6. A transmission line pulser (TLP) is used as an excitation for the test due to the simplicity of its waveform. An equivalent circuit for this TLP is shown in Fig. 7. The 12.5 pF capacitance and 50 Ohm resistance are used to increase the fall time of the pulse, forming a reverse termination. The output voltage into a 50 Ohm load is ½ of the charge voltage minus the drop across the relay contact which is often in the range of 25-40 V (burn voltage). The voltage across the spark gap is measured via a high voltage pulse attenuator connected to a 4 GHz oscilloscope.

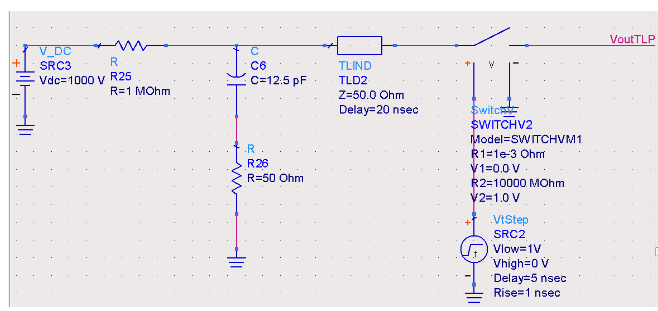


Fig. 7 Equivalent circuit for the TLP

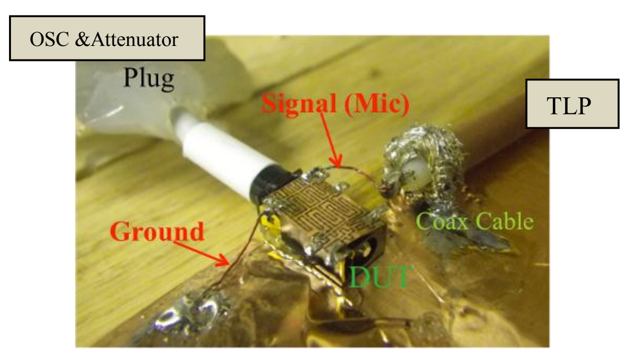
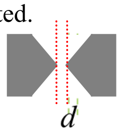


Fig. 8 Spark gaps under test

Using Paschen's law the DC breakdown voltage is calculated.



$$V_{Bd} = 25.4 \times d + 6.64 \times \sqrt{d}$$

$$d = 0.1mm, V_{Bd} = 918V$$

d is limited by the manufacturing process.

Fig. 9 Calculation of approximate breakdown voltage

As shown in Fig. 10, up to a voltage of about 1500 V using about 12 ns pulse width, no breakdown occurred.

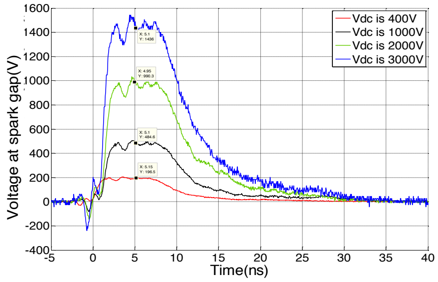


Fig. 10 Voltage at the spark gap for test scenario 1 (no breakdown)

At about 2000 V across the gap, using a 12 ns wide pulse, the first breakdowns are observed. For a voltage of 3100 V nearly all pulses lead to a breakdown. At average field strengths of 300 kV/cm the time lag is usually very short. While an average field strengths of 100 kV/cm only lead to short time lags if the electron emission is strongly enhanced, for example, by using carbon electrodes. Fig. 11 shows different waveforms, all taken at 2250 V gap voltage. This data illustrates the variability of the time lag, which is governed by the probability of an electron being in the right place at the right time to trigger an avalanche. Even applying a voltage of 2.5 times the static breakdown voltage cannot ensure a reliable breakdown of such a gap within 8 ns.

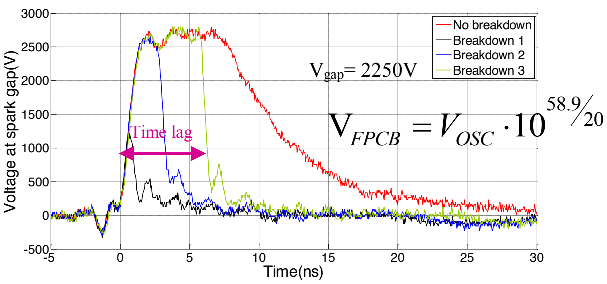


Fig. 11 Voltage at the spark gap for test scenario 1 with Vgap=2250 V

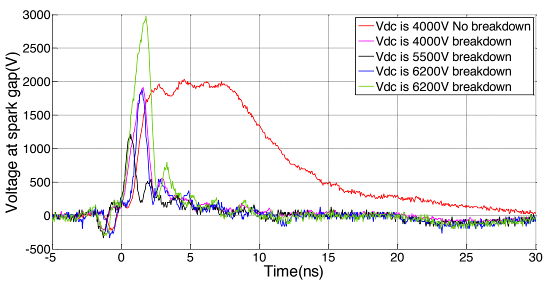


Fig. 12 Voltage at the spark gap for test scenario 1 for selected discharges for 4000 V to 6200 V charge voltage.

Higher voltages reduce the average time lag further, as shown in Fig. 12. The electrons that initiate the breakdown are drawn from the cathode surface by field emission if no other sources provide them. Here the field emission is enhanced by surface roughness at the atomic scale. Other possible sources are detachment from water molecules (which cause a strong reduction of the time lag in humid conditions), detachment for surface contaminations and dielectric surfaces parallel to the field strengths.

2) ESD test scenario 2 – Measuring current flowing on IC

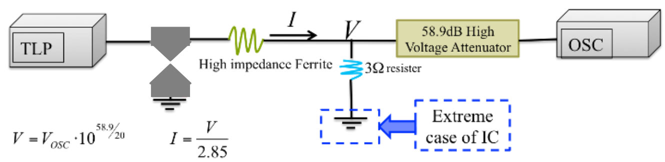


Fig. 13 Block diagram for "scenario 3", measurement of current flow into an "IC"

If the spark gap breaks down, it reduces the voltage at the IC. However, it can only break down if a sufficiently high voltage is present across the gap for a sufficiently long time. If the IC's internal ESD protection prevents this from happening, the spark gap will be "protected" by the IC. As most ESD protections clamp around -1V for negative pulses, a series impedance should be placed between the IC input and the spark gap. The voltage drop across this series impedance must be large enough to trigger the spark gap. The current which flows into the IC before the breakdown or after the breakdown (limited by the burn voltage) must be low enough to avoid damage to the IC. Assuming that the IC can only pass 2 kV HBM, then the maximum current cannot surpass 1.3 A. This is a very conservative assumption, as many I/O pins that connect to ESD endangered connectors, such as audio, will probably contain stronger ESD protection. Next the -1V drop at the IC input can be ignored by simply assuming the IC acts as a short, as shown in Fig. 13. The test setup is shown in Fig. 14.

From the voltage measured at the oscilloscope in Fig. 13, the current is measured by placing a 3 Ohm resistor into the current path. The voltage across the resistor is used to estimate the current using equation 1:

$$V = V_{OSC} \cdot 10^{58.9/20} \qquad I = \frac{V}{2.85} \qquad (1)$$

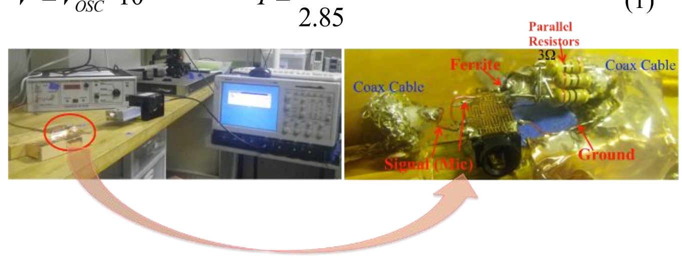


Fig. 14 Test setup for test scenario 3 to measure the current flowing into IC

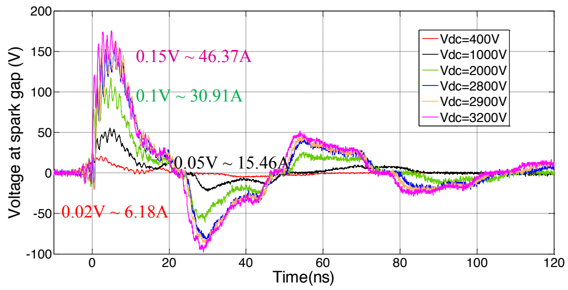


Fig. 15 Voltage at spark gap for test scenario 2

For test scenario 2, the breakdowns have been observed for voltages larger than 1400 V. Breakdowns are always observed at 1600V as shown in Fig. 15. If there is no breakdown, the current into the IC is too large, and the IC would be destroyed.

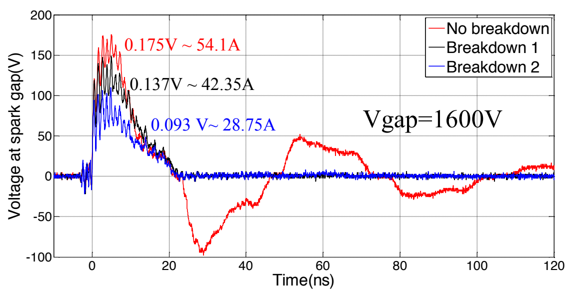


Fig. 16 Voltage at spark for test scenario 2 at DC voltage 3200V

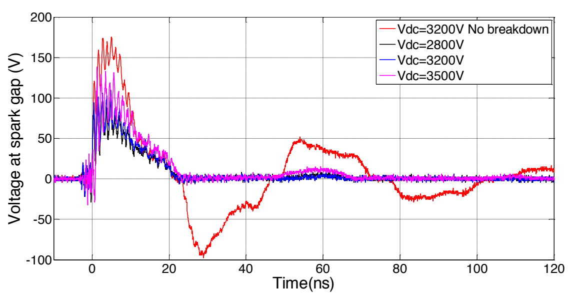


Fig. 17 Voltage at spark for test scenario 2 with higher DC voltage

From Fig. 16 and Fig. 17, we can see that even after a breakdown, the current flowing in the IC is still too high, which usually cannot be handled by the IC, since TLP used in this experiment has an output impedance of 50 Ohms, for a given voltage the TLP will provide a current larger than the current obtained from an HBM discharge at the same voltage.

As mentioned, the problems in using spark gaps are that the static breakdown voltage is not low enough and the time lag is too long. To decrease time lag, carbon and some modified polymer are coated on the gap structure in the following two test scenarios.

3) Protection Spark gaps coated with carbon

Fig. 18 Spark gaps with added carbon for test scenario 1

Carbon electrodes have been used for spark gaps due to the low time lag for hundreds of years to protect telegraph lines. According to [9], the edges of the carbon layers enhance the field emission strongly, reducing the time delay and its variability [8] [9].

With carbon applied on the surface of spark gaps as shown in Fig. 18, breakdowns have been observed for voltages larger than 849V. Due to the strongly reduced time lag, we observed the breakdown for gap voltages bigger than 1kV is always within 7 ns, as we can see from Fig. 19.

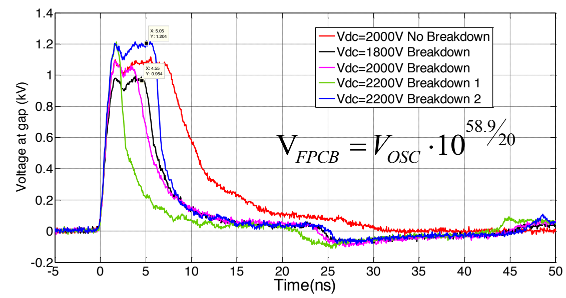


Fig. 19 Voltage at spark for test scenario 1 with carbon at higher voltage

Using 2200 V charge voltage, which corresponds to 1061 V at the spark gap, most of the pulses are observed causing a breakdown within 7 ns.

4) Spark gaps filled with modified polymer

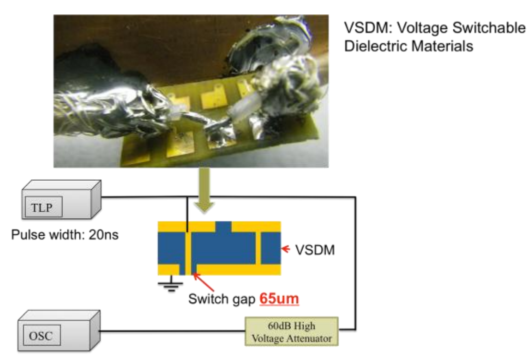
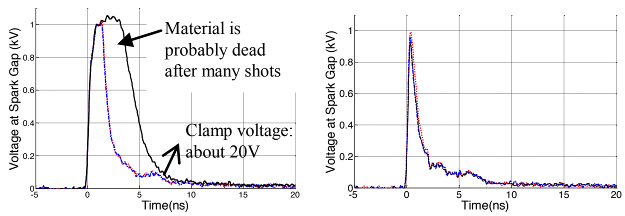


Fig. 20 Test setup (upper) and block diagram (lower) for test scenario 1 having a polymer placed into the spark gap

A VSDM (voltage switchable dielectric material) is a polymer nano-composite insulator that acts somewhat similar to spark gap. While a spark gap does not clamp the voltage before it breaks down, a modified polymer will clamp the voltage at levels of a few hundred volts. A possible explanation for the clamping is tunneling between conductive particles within the polymer. After a very short time lag, the electrons liberated by the tunneling cause a breakdown. It returns to its insulating stage after the current is removed.

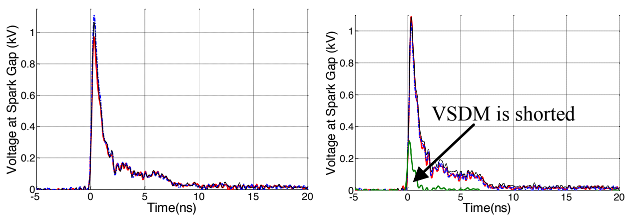
Two samples of VSDM were tested using the test setup for scenario 1. Test samples and test setup are shown in Fig. 20.



2kV charge voltage   3kV charge voltage

Fig. 21 Repeating test (3 times) for test sample 1

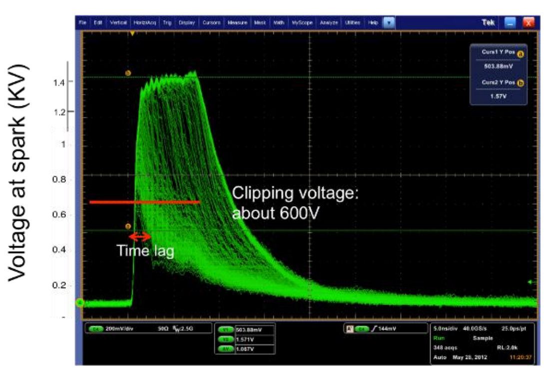
From Fig. 21, at a level of 750 V breakdowns are observed, indicating a time lag that is even less than compared to the case in which carbon had been used. Also we can see that time lag is smaller at V_{dc}=3kV than at V_{dc}=2kV.



4kV charge voltage   5kV charge voltage

Fig. 22 Repeating test (3 times) for test sample 1 with higher voltage

When the DC voltage at TLP is 5kV, we tried one more case to short the spark gap with a wire, the result is shown as a green curve in Fig. 22, which is comparable to the VSDM result, showing that the resistance of VSDM is very small when it is conducted.



Vdc at TLP = 3000V

Fig. 23 Repeating test 100 times for VSDM test sample 2

At typical ESD current levels of < 50A a spark gap will not erode fast. However, the VSDM material is based on a polymer. To understand its degradation, multiple pulses have been applied. At a TLP setting of 6000V, a current of 120 A will flow through the material, this can be considered as an extreme case. The data presented in Fig. 23 show the degradation that was observed while applying 100 pulses. As the number of ESDs to an audio jack will be limited, and currents will be much lower, one can conclude that no relevant degradation would occur for the protection of an audio jack.

IV. Conclusion

Spark gaps have been tested for breakdown voltage and time lag. The spark gaps have been created on a flex PCB to protect an audio jack from ESD. Without additional measures the time lag is long. To reliably break down a gap having 1000 V static breakdown voltage within 20 ns, a voltage of about 3100 V need to be applied. Carbon coating reduces the time lag strongly. Using of a modified nonlinear polymer coating reduces not only the time lag, but also the maximal voltage across the gap even before a breakdown.

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