Can ElectroStatic Discharge Sensitive electronic devices be damaged by electrostatic fields?

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Abstract. In recent years the susceptibility of ElectroStatic Discharge Sensitive devices (ESDS) to electrostatic fields has been questioned. This paper proposes that very high impedance voltage sensitive ESDS such as MOSFETs or MOS capacitors can be damaged due to external field changes without making contact with other conductors in the presence of the field. A simple electronic model is proposed. In a practical evaluation of this risk, discharges are demonstrated to occur due changing external fields, as a result of breakdown of a voltage sensitive structure in a high impedance circuit with one terminal continuously grounded.

1. Introduction

ElectroStatic Discharge (ESD) is known to be a source of damage to unprotected ESD Sensitive devices (ESDS). Electrostatic fields are controlled in ESD Protected Areas (EPAs) designed for handling unprotected ESDS according to the standards such as IEC 61340-5-1 [1]. For many years electrostatic field shielding has also been seen as an important quality of ESD protective packaging specified according to standards IEC 61340-5-3 [2]. In recent years, electrostatic field shielding property of packaging has been specified as optional. There has been discussion amongst experts in standardization committees as to whether this property is necessary, and if it is currently correctly specified. To answer this question, it is necessary to have some understanding of how ESDS might be damaged by electrostatic fields. There are some specialist structures such as reticles used in photolithography that are known to be subject to field induced ESD between closely spaced conductors. More common types of ESDS such as circuit boards and electronic components are thought unlikely to be damaged by electrostatic fields alone. ESD damage can occur if the ESDS contacts another conductor at a voltage difference induced by electrostatic fields, creating an ESD event. Swenson showed that the voltage induced on an electrically isolated device can give damaging ESD if the device is subsequently connected to ground [3], due to the ESD current that flows at the moment of contact. It has been thought that without making contact in this way, the voltage differences created within the ESDS by external electrostatic fields equalise without damage. This paper examines whether it is possible for very high impedance voltage sensitive ESDS such as MOSFETs or MOS capacitors to be damaged due external field changes without making contact between the ESDS and another conductor in the presence of the field. A simple electronic model of this scenario is proposed. Breakdown of two voltage sensitive structures (neon bulb and MOSFET) are
demonstrated to occur in a high impedance circuit with one terminal continuously grounded due changing external fields.

2. Theory
An electrostatic field induces voltage on a conductor within the field. This behaviour can be modelled as the result of capacitance between the field source and the conductor, and the conductor and ground. The simple circuit model of Figure 1 examines whether damage could occur without making contact in the presence of the field. A simple ESD sensitive device, such as a MOSFET or MOS capacitor, is considered connected in a circuit with two nodes 1, 2. This has capacitance $C_d$ and is damaged if the voltage across it exceeds a breakdown voltage $V_{br} = V_1 - V_2$. Any real device mounted in a circuit board has parallel circuit resistance $R_c$ and capacitance $C_c$. In the model the source field capacitance to the circuit nodes are represented by $C_{s1}, C_{s2}$. The capacitance to ground from these nodes are $C_{g1}, C_{g2}$.

![Figure 1. A simple electronic model of an ESDS within an electrostatic field](image)

Initially we can consider that there is no link to ground via the oscilloscope. The field source is far away or has zero voltage and so there is no induced charge, and we assume no initial charge in the circuit so $V_1 = V_2 = 0$. The charges $Q_{s1}, Q_{s2}$ in the capacitors $C_{s1}, C_{s2}$ are given by $C_{s1} (V_1 - V_{s1}) = Q_{s1}$ and $C_{s2} (V_2 - V_{s2}) = Q_{s2}$. We can induce charge in the circuit by changing the capacitance $C_{s1}, C_{s2}$ or the source voltage $V_s$. If the source is distant and is charged to $V_s$ and then brought nearby, charges are injected by the change in capacitance $C_{s1}, C_{s2}$. If the source is already close and $C_{s1}, C_{s2}$ are significant, a change in $V_s$ will result in charge injection. The charge injection represents an injected current proportional to the rates of change of capacitance $C_{s1}, C_{s2}$ and voltage $V_s$. In a practical situation both may occur simultaneously. A voltage difference will result across the device capacitance $C_d$, and if sufficiently great the device may break down and be damaged.

In practice the voltage difference is temporary or limited because the parallel device and circuit capacitance $C_c + C_d$ discharge through the circuit resistance $R_c$ with a time constant $\tau = R_c (C_c + C_d)$. The time constant made by $C_{g2}$ and the leakage resistance across it may also need to be considered. If $\tau$ is much less than the time taken to change the source capacitance or voltage, the voltage across the device is limited by voltage equalization by conduction through the $R_c$. If $\tau$ is very long, this effect can be neglected. So, the model suggests that damage to a voltage sensitive device could be possible for a changing field source if the circuit resistance is high and time constant long compared to the rate of change in source field.

The circuit is simplified if a ground link is made at circuit node 2. In this case $C_{g2}$ is shorted and $C_{s2}$ can be neglected, and $V_2$ is held at 0 V. Capacitance $C_{g1}$ is now in parallel with $C_c$ and $C_d$. If the link is made via a 50 $\Omega$ coaxial cable to a 50 $\Omega$ oscilloscope input and discharge current due to breakdown of the device $C_d$ can be detected. Assuming $V_I << V_s$ and $C_{s1} << (C_{g1} + C_c + C_d)$ the charge $Q_{s1}$ injected by a changing field is approximately $Q_{s1} = C_{s1} V_s$. The charge injection current is $d Q_{s1}/dt = d (C_{s1} V_s)/dt$. This current charges the parallel capacitance $(C_{g1} + C_c + C_d)$, with a proportion passing through the parallel resistance $R_c$. For damage to occur $V_I$ must exceed $V_{br}$ and so $Q_{s1}$ must exceed $(C_{g1} + C_c + C_d) V_{br}$ and $dQ_{s1}/dt$ must exceed $V_{br} / R_c$. If breakdown occurs, the charge stored at node 1 $Q_I$ is discharged and detected by the oscilloscope.
3. Experimental
A simple circuit was constructed in which the device under test was a neon lamp in the place of the ESD sensitive device, in a socket to allow replacement with MOSFET components if desired. The neon lamp has the characteristic of remaining open circuit until the voltage across it reaches the breakdown value around 50 – 100 V. At this point it switches to a low resistance state and discharges the circuit. After the discharge, the device switches again to the high resistance state. Repeated breakdown and discharge events can then be detected without changing damaged components. Node 2 of the circuit was effectively earthed via a 50 Ω coaxial cable and monitored using a LeCroy Waverunner LT4372 oscilloscope. The leakage resistance $R_c$ was measured at 100 V as 370 GΩ at 60 %rh.

Figure 2. Experimental arrangement.

![Image of experimental setup](image1)

![Image of oscilloscope](image2)

Figure 3. Typical ESD current due to breakdown of the neon lamp on collapse of plate voltage +500 V (left) and -500 V (right)

Node 1 of the circuit was connected to the plate of a Charged Plate Monitor (CPM). This allowed measurement of the voltage of the node. The total node 1 capacitance $C_{c} + C_{d} + C_{g1}$ and was measured to be 17 pF using charge transfer measurement techniques with the field plate grounded. With the leakage resistance this gave a calculated time constant $\tau$ of 0.64 seconds. The field source was provided by a metal plate mounted at 5 mm distance parallel to the CPM plate. The CPM plate size was 60 x 60 mm, giving a calculated value of 6.4 pf for $C_{s1}$. The metal field plate could be charged from a BM80 high resistance meter that had test voltages of 50, 100, 250, 500 and 1 kV. The charged field plate was discharged abruptly to create a sudden field change by touching with an earthed finger. Charging and discharging the field plate with a metal wire was found to create high electromagnetic interference and false triggering of the oscilloscope.

Figure 3 shows typical breakdown waveforms recorded with a source plate voltage of ± 500 V. Discharge waveforms did not occur when the neon lamp was removed from the circuit, confirming that breakdown of this device was the source of the transient. The charge transferred in these
discharges was -1.7 nC and +2.4 nC respectively, consistent with exceeding the lamp breakdown voltage with the measured capacitance. No discharges were detected while using a field plate voltage of 250 V.

In a follow-up experiment, two specimens of a 2N4351 MOSFET were subjected to stress applied between the gate and source pins. This device had 5 pF data sheet input capacitance and ±125 V maximum gate-source voltage. The MOSFETs were handled with ESD control precautions. The integrity of the device as installed could be tested by measuring resistance from the CPM plate to ground using a Beckman 4410 resistance meter on 20 MΩ range. The CPM plate was grounded during the field plate charging process, then CPM plate resistance to ground verified to be > 20 MΩ showing the device gate oxide was undamaged. The field plate was then discharged. The CPM plate resistance to ground measurement was then repeated. The first specimen MOSFET survived a field plate discharge of 250 V. After discharge of 500 V on the field plate, the CPM plate resistance to ground was 2.1 MΩ confirming gate oxide damage. The second MOSFET specimen survived 250 V and 500 V field plate discharge. After 1 kV the CPM resistance to ground reduced to 1.5 MΩ confirming gate oxide damage.

4. Discussion and Conclusions
It has been demonstrated that a voltage sensitive device in a high resistance circuit can be made to break down by application of a fast-changing electrostatic field without the need for making contact with the device in the presence of the field. In the experiment one node of the circuit was continuously earthed through measurement equipment. This situation could arguably simulate a real-world situation where an ESDS were, for example, resting on a conductive surface.

Swenson [3] used in his experiments 3N157 MOSFETs which have datasheet input capacitance of 5 pF and absolute maximum gate voltage of ± 50V. The lower breakdown voltage of this device implies that that it could be damaged below the stress levels creating damage in this experiment.

The model suggests that field strength is not the only important factor. For breakdown to occur induced charge must exceed the amount required to charge circuit and device capacitances $C_c$, $C_d$ to the device breakdown voltage. This depends on the coupling of the field to various parts of the circuit and so is likely to be dependent on circuit geometrical factors. The induced current transient must exceed the breakdown voltage divided by the circuit resistance. The field must change in a short time compared to the time constant of the circuit $R_c (C_c + C_d)$. Risk of breakdown is predicted to be greatest for circuits that contain low breakdown voltage devices having high circuit resistance $R_c$ and low circuit capacitance $(C_c + C_d)$. The risk is increased for high field and strong field coupling (high $C_s1$) and fast changing field. The model suggests that the risk situation could be simulated by application of a controlled charge impulse, e.g. by application of a controlled voltage waveforms via a small value capacitance to the node under stress. This approach may assist further modelling and experimentation.

It cannot be ruled out that some very sensitive devices could be at risk of breakdown with no earthed node if suitable conditions could arise (such as fast changing electrostatic fields). This would be a lesser risk due to reduction of the voltage appearing across the device due to capacitive division. High capacitance $C_{s2}$ could increase this risk. This could be envisaged if, for example, circuit node 2 were a printed circuit board ground or supply plane in close proximity to a grounded surface.

One challenge in repeating the non-destructive experiment in non-earthed mode is to detect breakdown when it occurs. Future work will examine whether breakdown can be detected in this circumstance, and attempt further destructive experiments.

References
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