Characterizing ESD Stress Currents in Human Wearable Devices

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Abstract – Currents induced on an I/O of a human wearable device IC are predicted using a test IC as a wearable device capable of transient event detection and level sensing. ESD on this pseudo wearable device using the test IC is characterized for different test scenarios and compared to the prediction.

I. Introduction

Wearable electronics are becoming ubiquitous. Smart phones, watches and glasses located on the human body experience severe stress events due to ESD. These ESD events can be quite complicated and the range of events that the wearable device must be immune to or how to adequately test them is poorly understood. IEC-61000-4-2 [1], for example, specifies that the device under test (DUT) is subjected to ESD when it is placed on an insulated surface above a ground plane. This setup does not accurately represent conditions seen by human wearable technology as the wearable device (DUT) is now mounted on the charged human body.

Previous studies have investigated the maximum possible potential and currents that body worn equipment may experience under certain test situations, though experimental characterization of ESD to wearable electronics is still lacking. The authors in [2] measured the voltage waveforms induced on a human worn device. The study concluded that the electrical stress induced by the ESD event on a wearable device depends on the circuit structure and its impedance. An extensive study of the characteristics and generation of long ESD pulses to wearable electronics was studied in [3]. Both the device and its wearer were charged together, or the device was kept within a certain proximity of the discharge event. This study helped show the test conditions which might cause a long discharge current. A long discharge is more likely to cause thermal damage to an IC than a short discharge of the same magnitude. Another study [4] investigated the worst case discharge current that would occur when a human worn device approaches a grounded conductor. The authors measured the currents through a hand-held metal probe or a semi-spherical metal device attached to the human at different locations. The hand-held metal probe or the semi-spherical device were considered as replicants of the charged wearable device. The peak current through the worn semi-spherical device depended on its location on the body and was higher than the current experienced by the hand-held probe. The event duration also depended on the type of discharge performed. Although these studies give an idea of the intensity and shape of the ESD current that might be experienced by wearable electronics, there are no measurements of the actual transient disturbance experienced by the electronics inside the wearable device.

This article studies the current levels an IC in a wearable electronic device must withstand. This is done by monitoring the discharge current through an I/O pin of an IC in a wearable device which is mounted on a human.

II. Wearable Device Under Test

A metal enclosure containing a single IC was used as a replicate of a wearable electronic device. This particular IC has added circuity with the capability to detect the occurrence and peak levels of transient events it is exposed to, so long as the event is above a certain threshold (~1 A). Separate characterization of the test IC has shown successful detection for both positive and negative events as well as repeatable detection of the level of the event. The design and characterization of the test IC is described by the authors in separate articles [5,6]. The IC will provide the number of transient overstress or understress events experienced by the IC and level of each event upon query from the user.

The test IC is housed in a well shielded box and is battery powered. The enclosure prevents any direct coupling to the pins of the IC. The power line from the battery pack is filtered before entering the shielded box. The only other port defined from within the box to the outside environment is through an audio jack to which external headphones can be connected. Inside the box the audio jack is connected to a single I/O pin of the test IC as shown in Fig. 1, and constitutes the device test port. This box can be considered equivalent to a wearable device, which may be worn by a human during ESD level testing.

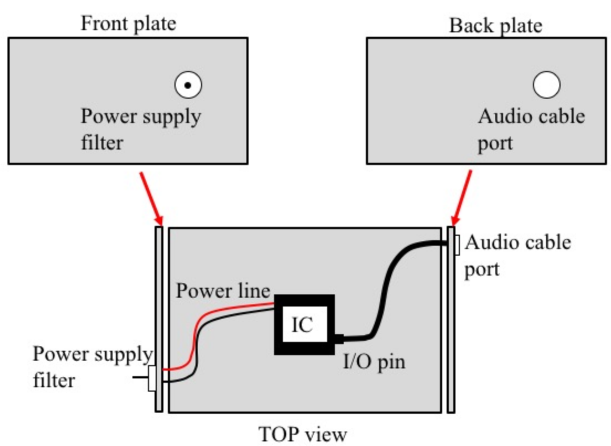

Figure 1. Test IC housed in a metal shielding box - pseudo wearable device.

The IEC standard for ESD testing subjects devices to a different test case than is typically experienced by a human worn device. The ESD events experienced by a human worn device are closer to a "brush-by" case where the discharge currents are significantly higher than those seen in the human-metal discharge case, since the device itself can provide a lower-impedance discharge path than can be provided by a hand-held conductor.

III. Test Scenarios

The currents induced in the I/O of the wearable DUT are characterized under different test scenarios. The test scenarios are grouped based on the different discharge situations that a wearable device may be subjected to. The different groups are:

A. Brush-by contact discharge.

B. Cable plugin to user interface of device.

C. Daily activity in a laboratory environment.

A Brush-by contact discharge represents the scenario where the wearable device is on the human while the human charges up and discharges through different locations of the body. It is necessary to have the cable close to the discharge point so that part of the discharge current is coupled through the cable to the I/O of the DUT. The cable in this scenario is associated with headphones which are often connected to a smartphone or portable audio player.

Cable plug into an user interface like an audio, USB, power or other interface cables represents a cable discharge event (CDE). Cables can easily accumulate charge by being dragged on the floor or over another surface and through other handling situations. This triboelectric charging results in charge accumulating on the inner signal wires. When this cable is subsequently plugged into a user interface there is a discharge path based on the lowest inductance path. This scenario is replicated by plugging in an intentionally charged cable into a user interface connected to the I/O of the IC. This arrangement can estimate the currents the I/O of a wearable device can experience for a CDE. This is a complete non-intrusive method to estimate the currents in a fully functional system where no additional hardware is added to monitor the stress levels.

The final scenario for evaluating the currents induced on a wearable device is to have a test subject perform daily activities while wearing the DUT. In this test case, the human body along with the DUT charges up while walking on the carpet flooring. The discharge occurs when the human comes in contact with metal planes or objects such as door knobs, metal doors, etc.

A. Brush-by contact discharge

1. Test Setup

The test setup showing the human wearing the DUT, the high voltage (HV) charging source, the discharge plane, and the shielded measurement setup is illustrated in Fig. 2. A headphone is connected to the audio jack on the DUT and is wrapped along the human arm. When the human charges up to a certain potential, the DUT potential rises along with the potential of the host human body. During the discharge to a grounded conductor, the audio cable provides a low impedance conduction path forcing the current through the I/O pin of the IC. This current is measured using a current clamp and an oscilloscope. The IC in the DUT observes the same current and records this value, which is later read out by the user.

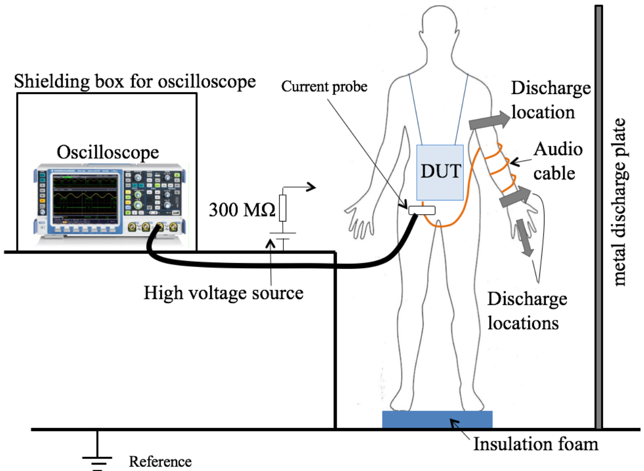

Figure 2. Test setup for characterizing ESD to wearable electronics under different discharge cases.

To simulate the "brush-by" ESD case, the discharge was performed through a body-mounted semi-sphere metal probe held at different locations on the human body. Tested locations included:

a) Hand held metal rod
b) Wrist mounted
c) Arm mounted
d) Waist mounted

as these are the most common locations of discharge to a grounded conductor by a "brush-by" action. The test cases study events that might occur on a daily basis as a person performs typical activities like walking or standing up from a chair. For each test case, the headphones are routed close to the discharge location so as to carry most of the current. Fig. 3 shows the mounting of the discharge sphere and the hand-held metal rod for the test cases studied in this article. The routing of the audio cable is shown for the hand-held discharge case.

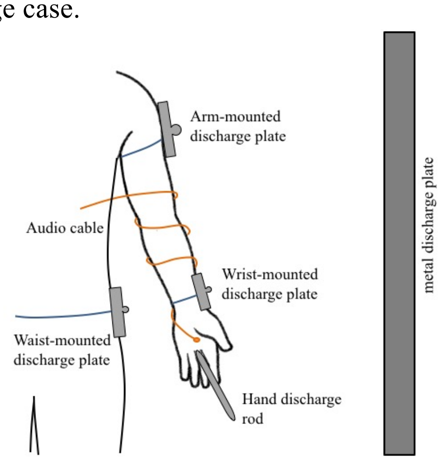

Figure 3. Discharge locations showing the metal sphere and hand-held metal rod.

2. Test Procedure and Results

For testing, the human in Fig. 2 first charges himself by touching the high voltage electrode momentarily and lets go of the electrode while simultaneously discharging into the vertical ground plane through the metal semi-sphere or the hand-held metal probe. The peak current during this discharge is recorded through the audio cable using a FCC-F-65 current clamp. This induced current is measured using an oscilloscope and is then corrected with the transfer impedance of the probe to obtain the current on the wire connected to the I/O of the IC. The transient waveforms for the current on the audio cable for a 3 kV charge is demonstrated in Fig. 4 for different discharge locations on the human body. Each of the current waveforms was produced with the same charge setting of the high voltage source. At the same setting, the maximum discharge current through the arm is larger than the maximum discharge current through the hand-held metal probe. The current induced on the audio cable is lower than the discharge current through the body connected metal electrode and grounded conductor.

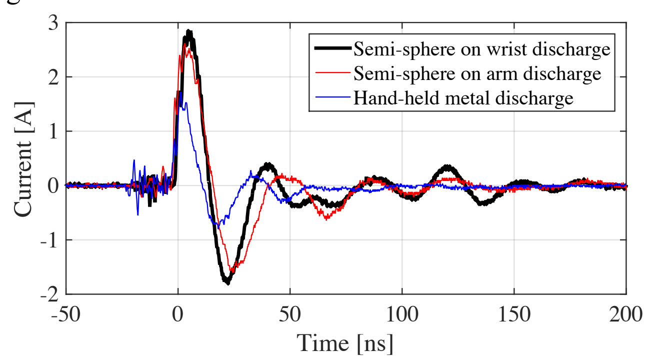

Figure 4. Transient current waveforms induced on the audio cable under different discharge scenarios.

The repeatability of the shape and amplitude of the discharge currents were verified by observing these parameters on the oscilloscope over many discharge events. Once the repeatability was established, the magnitude of the events was read from the IC in the DUT using an external computer. Upon query, the DUT successfully detected and recorded the transient event. The IC is capable of reporting the magnitude as well as the polarity of the transient event. The DUT correctly detects the transient disturbance on the pin to which the wire of the audio cable was connected. When there is a positive and negative swing in the current (Fig. 4) beyond the threshold, the DUT reported back both positive and negative event detection on the correct I/O. The voltage value received from the DUT is plotted against the measured current through the single wire of the audio cable. These results are shown in Fig. 5.

The red curve in Fig. 5 shows a calibration transfer curve that gives the relationship between the injected current and the voltage read from the internal transient level sensor. This curve was obtained by injecting a 30 ns TLP pulse into the I/O pin while monitoring the voltage readout from the IC [6]. The voltage and current readouts for different test cases are plotted on Fig. 5 as well.

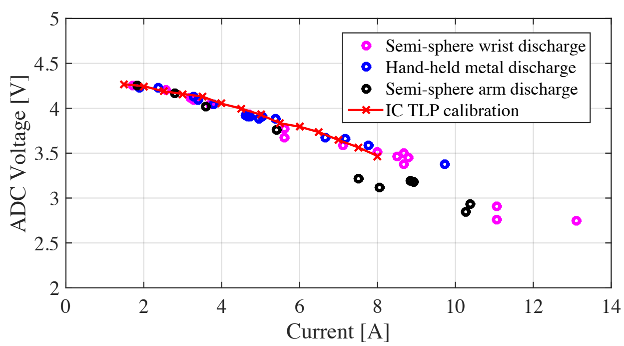

Figure 5. Comparison of current on audio cable as measured by oscilloscope and by test IC.

The ability of the test IC to accurately predict the peak current of the transient event is demonstrated in the figure. The voltage readout from the IC is used along with the IC TLP calibration curve to back calculate the current the I/O of the IC experienced. This estimation of the current using the TLP characterization curve correlates well with the measured currents using the current clamp as shown in the figure. The maximum error between the measured (current clamp method) and estimated (using voltage readout and TLP calibration curve) transient level current was less than 0.5 A. In a scenario where the user has a wearable device mounted and experiences an ESD event, the test IC will record the voltage proportional to the current flowing in the I/O. A test performed with the human charged at 3 kV who discharges through his arm (here through the semi-sphere mounted on his arm), the IC reported a voltage of 4.2 V. Now using the calibration curve of the IC, it was predicted that the ESD event caused 2.5 A of current through the I/O. This correlates well with the current observed earlier using the current clamp on the audio cable (Fig. 4). For all the test cases, the trend between the current and voltage readouts follow the calibration curve well up to 9 A of peak current.

For a 5 kV charge, the voltage readout from the DUT for a hand-held discharge will be higher than the voltage readout for an arm mount or a wrist mount discharge. This is due to the fact that the discharge current is lowest for the hand-held discharge case. A lower discharge current induces lower currents on the audio cable which results in a higher voltage readout from the IC. The current clamp measurements showed that the currents induced in the audio cable followed the expected trend. The voltage readout from the IC used along with the calibration curve supported this measurement.

B. Cable plug in to user interface of device

1. Test Setup

Wearable devices frequently come into contact with the user especially through user interfaces. This includes headphone jacks, USB interfaces, data cards, etc. A charged cable being plugged into a device is a classical representation of a CDE. An alternate situation could be the DUT is charged up and is plugged into a cable. In this article, a CDE where the cable is charged and plugged into the DUT has been demonstrated. The test setup is shown in Fig. 6. The test is performed with an audio cable which has a twisted pair configuration.

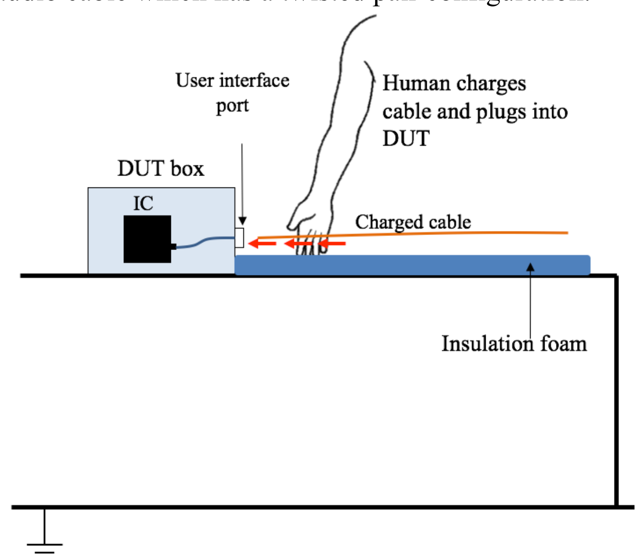

Figure 6. Test setup for cable plugin test.

2. Test Procedure and Results

The test procedure is similar to earlier test cases. The human stands over an insulating surface and charges the cable with himself by holding a HV charging source simultaneously. For discharging, the HV source is let go and the cable is plugged into the DUT immediately. This was performed at different HV source settings for different layout arrangement of the audio cable on the insulation foam. Once the cable is plugged in, the data of the recorded events from the DUT is retrieved. The DUT successfully detected the I/O location as well as returned a voltage value which is then used with the

TLP calibration curve to estimate the current. This is demonstrated in Fig. 7. Initial tests were performed with a current clamp on the audio cable which was compared with the estimated current peak value using the voltage value returned from the DUT. When the DUT returned 4.1 V, the estimated current from the calibration curve is 3.2 A while the current measured using the current clamp is 3.6 A. The current clamp is removed after validation for a few discharge events. This test was repeated with different head phone cables and showed similar results. This scenario can be extended to different type of cable-connector interfaces. When using USB cables for plugin tests, the shield quality along with termination of the cable determined the currents induced in the inner wire and the I/O. This is being investigated in a different study. This test setup can therefore non-intrusively measure the peak currents which an I/O of a wearable device may experience during CDE.

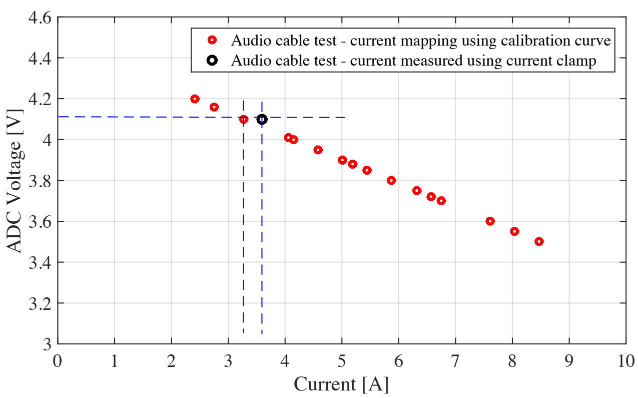

Figure 7. Estimation of current using the ADC voltage and TLP calibration curve for cable plug in tests.

C. Daily activity in a laboratory environment

This test deals with the daily activities a human may perform while wearing a wearable electronic device. The audio cable was connected to the I/O throughout the tests. In this test case the charging of the human and the DUT was not controlled. In the previous test cases a HV source was used to charge the human or the human along with the cable. Here the charging of the human/DUT is solely based on activities such as walking on a carpet floor, sitting down and standing up from a chair, and getting in and out of a car. Because the DUT is battery powered and compact, the human being could move around performing his daily activities, during which he randomly discharges through the wearable device.

The data from the DUT is measured at regular intervals. Fig. 9 shows the results after mapping the voltage readout from the DUT with the TLP calibration curve. The correct I/O is identified by the DUT. For some readouts there is only a positive or negative detector flagged, which indicates that the discharge current was either a unidirectional current or the peak was less than the negative or positive detector thresholds. This is valuable information which is now possible to retrieve from a wearable device without addition of an oscilloscope or a current clamp, which would thwart daily activities and alter the system.

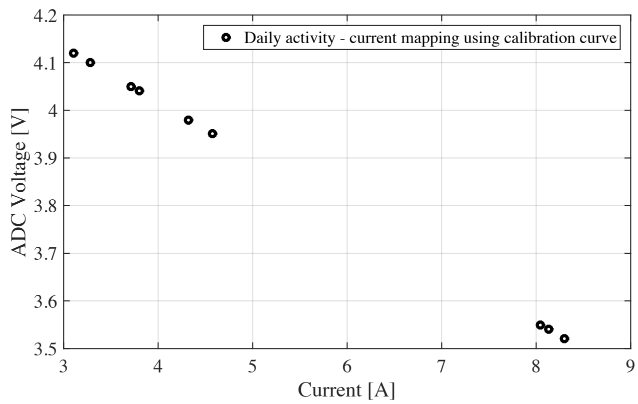

Figure 8. Estimation of current using the ADC voltage and TLP calibration curve for daily activity tests.

In this case it is important to route the audio cable close to the discharge location. This was done so as ensure there was enough current coupled into the I/O.

IV. Discussion and Conclusions

Using the test IC, it is now possible to get an estimate of the induced current through the I/O pin of an IC of a wearable device without altering the system. Based on the test scenarios discussed, a relation between the charge voltage and current on the I/O of an IC can be estimated. This information is important so that design improvements can be made to the overall ESD protection and software stability on wearable devices. Using the current pseudo wearable DUT, studies for the statistical distribution of the number and level of ESD events experienced by the wearable device during normal human activity can be investigated. Discharge electrodes at different locations on the human body can be connected to different I/O's on the test IC and monitored for the number of events triggered. Such studies can be expanded to include relative humidity, different flooring conditions, different apparel material types, and more.

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