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Problems of the human body model and electrostatic discharge part 1: discharge from LSIs held by a charged person

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Abstract. The nanosecond transient response between a pin of a large-scale integrated circuit (LSI) held by a charged person and the ground plane showed a very sharp impulse and high peak current. This response could not be represented using the human body model (HBM), and it was caused by the parasitic capacity between an inner conductor in the LSI and the ground plane. However, the conventional HBM tester could not control the low capacitance. Consequently, the machine model (MM) using a low capacitance or the charged device model (CDM) with low device capacitance should be used. Moreover, the capacitanc of charged objects including LSIs can be determined by a Coulomb meter. Practical use of these data will give us the methods to prevent electrostatic discharge troubles for quarter-micron LSIs.

1. Introduction

Experiments to evaluate the electrostatic discharge (ESD) sensitivity of LSIs have consisted of three kinds of methods: the human body model (HBM) [1, 2], the machine model (MM) [3] and the charged device model (CDM) [4]. The history of these models has been described in detail by McAteer [5]. However, the early data observed with the oscilloscope did not show the nanosecond transient response precisely, since the design of the HBM was too old electronically. Of the three models, the HBM test has been most widely adopted. However, the nanosecond response in the HBM test should be studied in order to prevent ESD troubles with quarter micron very large-scale integrated circuits (VLSIs).

Recently, we investigated the relationship of the CDM failure voltage V_D to the device capacitance C_{LG} between an inner conductor in a Logic MOS LSI and the ground plane [6]. Simultaneously, we defined the charge in the C_{LG} as the excessive mobile charge Q_{EM}. As a result, it became clear that the CDM sensitivity of the LSI should be represented by an inherent quantity of mobile charge, Q_D, when the LSI failed in the CDM test. By analogy, it can be presumed that a hand-held LSI has a low C_{LG}, and a charged person may be regarded as the voltage source charging the C_{LG}.

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Therefore, the Q_{EM} in the low C_{LG} will flow out rapidly just like in the CDM test when a pin of the LSI held by a charged person touches the ground plane.

The purpose of this paper is to verify that the major cause of ESD accidents due to a charged person should be represented by the MM using a low capacitance or the CDM with low device capacitance. First, focusing on the nanosecond current transient, we will investigate the discharge characteristics between a pin of an LSI held by a charged person and the ground plane. Next, we will determine the capacity C_{LG} by using an apparatus for measuring excessive mobile charge (the Coulomb meter) discussed in a previous paper [6]. Then, we will be able to express the discharge characteristic as the L–C–R series circuit. Subsequently, as a supplementary experiment to prove the existence of the low capacity, we will show the transient response characteristic between a terminal of a high resistor supplying high voltage to another terminal and the ground plane.

2. Experiment for ESD of LSIs

2.1. Preliminary experiment

The HBM [1, 2] has long been generally adopted as a standard specification. However, we have often experienced that HBM accidents in the manufacturing lines showed the following curious characteristics that are inconsistent with each other. When a pin of an LSI was in

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contact with the ground plane, if a charged person touched some other pins, the LSI did not fail easily. The person had to be charged to at least 4 or 5 kV to damage the LSI under such conditions. At the moment of the discharge, a strong electric shock was received. HBM failure voltages of this kind of LSI were 2.0–2.8 kV. However, the LSIs often failed when a charged person at low electric potential (1–2 kV) handled them.

In order to elucidate the above-mentioned phenomena that could not be explained using the HBM alone, we re-examined the relationship between the HBM and the MM and CDM. The discharge current in the HBM test has been represented by equation (1) since it was a C–R circuit [1]. However, considering that the impedance of a person is expressed by the distributed constant circuit consisting of the skin resistance and capacitance, the current discharging between the LSI held with the fingers of a charged person and the ground plane cannot be represented just by equation (1) since the inner conductor of the LSI has an inherent low capacitance

$$I = \frac{V}{R}\exp\left(-\frac{t}{CR}\right) \tag{1}$$

at $R = 1.5$ kΩ, $C = 100$ pF.

2.2. Experimental procedure

We carried out the following experiment, as shown in figure 1, in order to explain the phenomena described in section 2.1. A person who held the LSI touched a voltage source, and a pin of an LSI was immediately attached to a terminal of a grounded resistor (1 Ω: disk type resistor with a parallel capacitance (about 0.5 pF): 135D375P-01R0K, Florida RF Labs Inc). The package of the LSI was a 42 pin dual in line package (DIP) and the LSI chip was a Logic MOS LSI with gate length of 0.5 μm. The person was on an insulator plate. The LSI was held with the fingers or with metal tweezers, and the fingers or the tweezers touched a few pins. The two conditions (fingers and tweezers) were investigated. The discharge current was converted into a voltage through a resistor (1 Ω), and it was observed with an oscilloscope (Tektronix SCD 5000 with maximum frequency range 3.5 GHz).

Additionally, if any pin or all pins except a discharged pin later and non-wired pins of the LSI were chosen as the held pin, each discharge current showed practically the same transient characteristics. This means that all the elements constituting the inner conductor in the LSI are at a uniform electric potential in supplying the high voltage to a pin of the LSI. The phenomenon has previously been verified by experiments [7]. However, the peak current and the pulse width depended on the device size, for example the area of the inner conductor in the LSI package. Moreover, to be exact, the transient characteristics depended on the device size, and were varied a little with the contact area between the LSI and the fingers or the exposed area of the LSI.

As supplementary experiments, the next discharge phenomena that might often occur in the manufacturing lines was measured using a current monitor unit (a resistor and an oscilloscope as shown) in figure 1. That is, the discharge current characteristics from a terminal of a high resistor (100 MΩ) were observed. A terminal of the high resistor touched a pin of the LSI (the above-mentioned 42 pin DIP) that was in contact with the resistor (1 Ω) in figure 1. Then the other terminal of the resistor was connected to the high-voltage source (0.5 kV or 1 kV) and the other pins of the LSI were grounded.

3. Experimental results and discussion

Figure 2 shows the discharge current characteristics when a charged person held the LSI (A) with her fingers and (B) with her tweezers, and one of pins of the LSI touched the low resistance. This figure simultaneously includes the calculated curve from equation (1). These transient responses by the charged person could not be represented merely by the conventional HBM.

It was considered that these responses were caused by the discharge from a pin of the LSI to the ground plane after the low capacity C_{LG} was charged by the person's electric potential. When the LSI was held with tweezers, the time constant of the circuit must increase in proportion to the sum of C_{LG} ($\simeq$5 pF) and the capacity C_{TW} ($\simeq$5 pF) of the tweezers. These capacities were obtained immediately by measuring the mobile charge Q_{EM} with the Coulomb meter using the method of a previous paper [6] after having supplied the same voltage as the charged person to the pair of isolated tweezers or the isolated LSI. The time constant of the transient response for a very short time, of the order of a nanosecond, is described with $C = 5$ pF instead of $C = 100$ pF. Therefore, equation (1) should be replaced by

$$I \simeq \frac{V}{R}\exp\left(-\frac{t}{CR}\right) \tag{2}$$

at $R = 1.5$ kΩ, $C = C_{LG} \simeq 5$ pF or $C = C_{LG} + C_{TW} \simeq 10$ pF.

However, the time constant in equation (2) was 5 pF × 1.5 kΩ = 7.5 ns and did not fit to the characteristic in figure 2(a). Moreover, the peak current was 1.33 A (at $V = 2$ kV) and did not reach 12 A. Consequently, a transient response of the L–C–R series circuit in figure 3(a) was calculated with the equation

$$L\frac{\mathrm{d}I}{\mathrm{d}t} + RI + \frac{1}{C}\int I\,\mathrm{d}t = V. \tag{3}$$

The discharge current I in figure 2 was not oscillating, therefore it was calculated on a condition of $R > 2(L/R)^{1/2}$. R and L were the fitting parameters for resistor and inductor respectively and $C = C_{LG} = 5$ pF was fixed. From the result, a similar characteristic curve was obtained for $R = 150$ Ω and $L = 7$ nH shown in the equation

$$I = \frac{V}{\sqrt{(R/2)^2 - (L/C)}}\exp\left(-\frac{R}{2L}t\right) \times \sinh\sqrt{(R/2L)^2 - (1/LC)}t \tag{4}$$

at $R = 150$ Ω, $V = 2$ kV, $C = C_{LG} = 5$ pF, $L = 7$ nH. Figure 3(b) shows the calculated curve from equation (4)

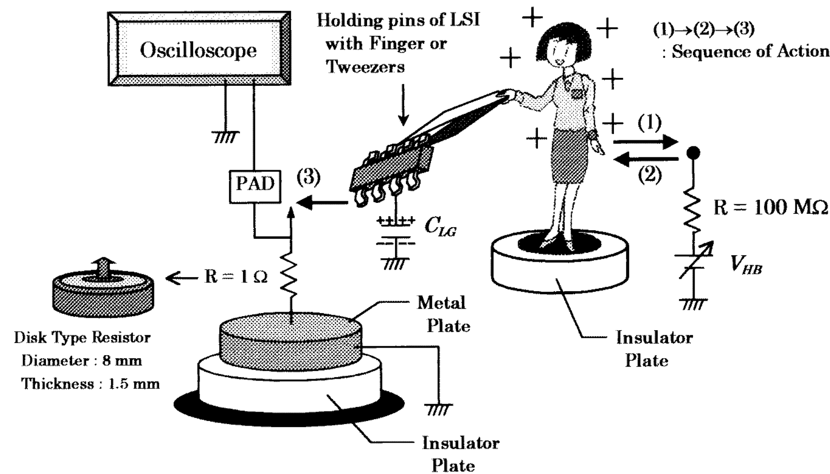

Figure 1. Transient response experiment in discharging from a pin of an LSI held with fingers or tweezers to the ground plane.

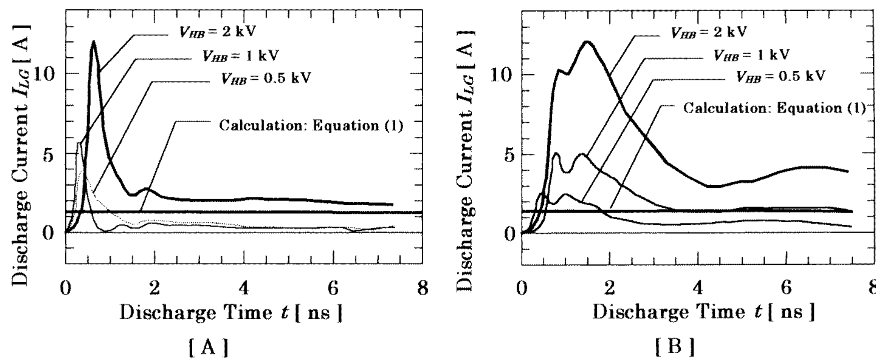

Figure 2. Discharge current characteristic when a charged person holds an LSI (*a*) with her finger and (*b*) with her tweezers and a pin of the LSI touched a low resistance (1 Ω).

and the experimental characteristics for $V = 2$ kV, shown in figure 2(*a*).

A sharp increase of current was not observed for the experimental curve in figure 3(*b*), and the residual current (approximately 2 A) was found after 1.5 ns. These two characteristics would not appear with the transient response analysis of the lumped constant circuit. It was considered that the sparking or arc discharge occurred while the LSI held by the person came slowly near a terminal of the resistor (1 Ω) in figure 1. Furthermore, the inductance (7 nH) on internal wires and leads of the LSI was a reasonable value for their thickness and length. However, we could not judge whether $R = 150\ \Omega$ was for the internal resistance of the LSI or for the resistance in the sparking gap.

In the CDM test, the discharge current generally shows the damped oscillation response [4–6]. However, figure 2 showed merely the single impulse response. For this reason, it is considered that the spark or arc discharge in the gap between a pin of the LSI and the ground plane occurred because of the slow action of the person.

Figure 4 shows the discharge current characteristics after a pin of the LSI touched a terminal of a high-voltage resistor. This characteristic resembled the discharge characteristic in figure 2. The low capacity was formed between a metal terminal of the resistor and the ground plane. It was estimated that the high-speed discharge occurred in the moment when the mobile charge discharged from the terminal to the pin of the LSI. This experimental result has proved the data in figure 3 to be reasonable, since the human body and the inner conductor of the LSI can be regarded as the resistor and the metal terminal respectively. It should be noted that the high-speed discharge occurred between a metal plate (or piece) on charged objects (person, insulator, conductive mat, etc) with high resistance and a pin of the LSI.

Obviously, the experimental results in this paper show that the conventional HBM cannot represent the discharge phenomenon between a pin of a hand-held LSI and the ground plane. Although the HBM failure voltage for the LSI was 2.3–2.5 kV, the failure voltage for the hand-held LSI was 1.0–1.7 kV, nearly equal to 0.9–1.2 kV of the CDM test. The detailed CDM test method has been mentioned elsewhere [8]. This result agreed well with the above-mentioned preliminary experiments.

After the discharge between an input pin (the weakest pin) of a hand-held LSI and the ground plane, failure analysis was carried out; an inferable damage point was

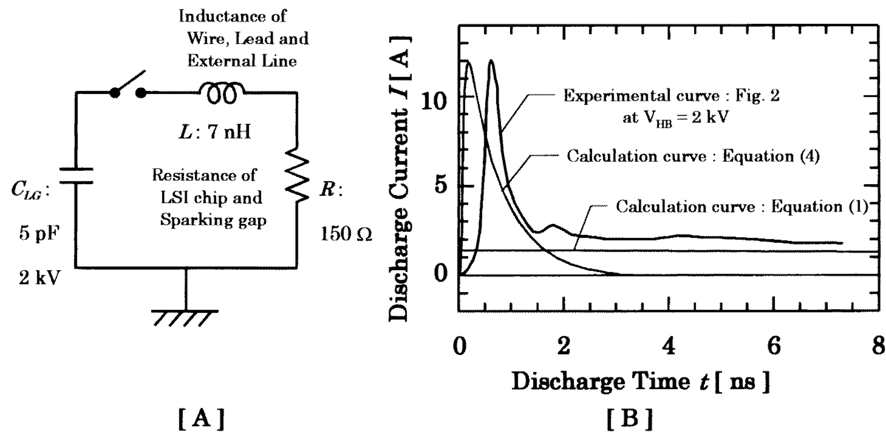

Figure 3. Equivalent circuit in discharging between C_{LG} and the ground plane, and result of the calculation of the transient response.

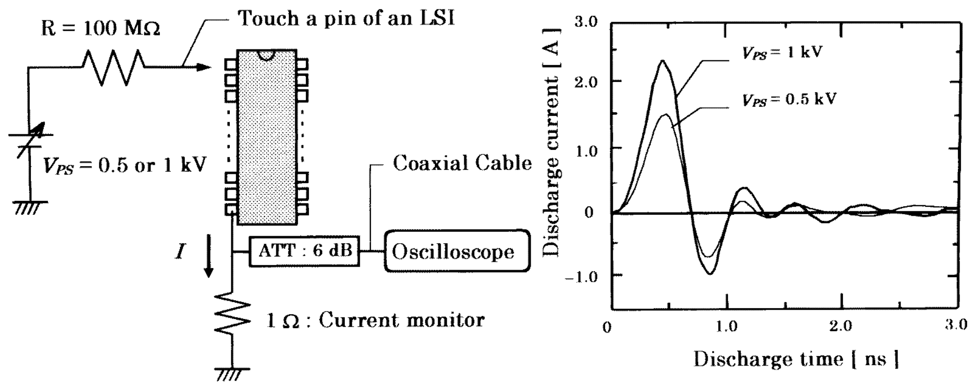

Figure 4. Discharge from a metal terminal of the high-voltage supplied resistor to a pin of the LSI.

then observed on the gate SiO_2 of the protection circuit. Regrettably, the damage point could not be distinguished from the original grain boundaries of the gate SiO_2 and poly-silicon by any photographic method using an advanced scanning electron microscope (SEM). Similarly, the analysis result after the CDM test was also indistinct. By contrast, the damage in the HBM test extended to the whole surface of the protection circuit.

Clearly, ESD events with this nanosecond transient response have often caused accidents. The ESD events should be remodelled into the MM using a low capacitance (about 5–10 pF) or the CDM with low device capacitance. Additionally, the two models must have a series resistance of about 150 Ω. However, the resistance should be examined closely since we could not judge whether 150 Ω was the internal resistance of LSI or the resistance in the sparking gap.

Although the robustness of the conventional ESD has been specified by merely the voltage V, the capacitance C is an important factor in order to prevent the many ESD accidents for current VLSIs. The Q, C and V of the charged objects including LSIs can be determined by the application of the above-mentioned method [6, 7]. We expect that the experimental results in this paper will contribute greatly to progress with quarter-micron VLSIs.

4. Conclusions

The nanosecond transient response between a pin of an LSI held by a charged person and the ground plane showed a very sharp impulse and a high peak current. This phenomenon could not be represented by the conventional HBM. Moreover, the discharge between the metal terminal of the resistor connected to a high-voltage source and the pin of the LSI also showed a high-speed transient response.

Clearly, these two phenomena were due to the inherent low capacitance. The discharge between the hand-held LSI and the ground plane should be represented by the MM using a low capacitance or the CDM with low device capacitance. However, conventional MM and CDM testers could not be varied to measure the capacitance. Using a Coulomb meter and a CDM tester with variable capacitance can solve the problem, and application of the Coulomb meter can prevent ESD accidents for quarter-micron VLSIs.

Acknowledgments

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