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Analysis of charge injection processes including ESD in MEMS

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ABSTRACT

The effect of charge injection due to human body model (HBM) electrostatic discharge (ESD), charged device model (CDM) ESD and triboelectrification in capacitive microelectromechanical systems' (MEMS) structures is analyzed. The results show that as feature size is reduced, the effect remains constant for charging by triboelectrification. However, HBM ESD injected charge produces a change which is inversely proportional to the square of the gap separation and CDM ESD injected charge produces a change which is inversely proportional to the square of the plate area.

1. Introduction

Electrostatic discharge (ESD) can cause direct, indirect and latent damage to semiconductor devices and electronic systems. There is evidence that devices will become more sensitive through the year 2010 [1]; scaling of CMOS devices and process technology is projected to continue through 2019 [2,3]. Emerging technologies such as microelectromechanical systems (MEMS) and nanoelectromechanical systems (NEMS) which include microgap and nanogap assemblies [4] will inherently be extremely sensitive to ESD. Since ESD is effectively a charge injection source, it is to be seriously considered as a major reliability issue in MEMS [5,6]. Parasitic charging of the dielectrics in MEMS devices including microphones and switches results in undesired electrostatic forces on these actuators; studies have shown that this is a serious performance issue [7–10]. It can be concluded that microgap devices can face a serious challenge due to electrical breakdown during manufacturing, handling and operation [11].

2. Objectives

The objective of this work is to analyze the relative effect of charge injection due to human body model (HBM) ESD and charged device model (CDM) events on capacitive microelectromechanical systems (MEMS). The influence on the operating characteristics as a function of feature size is studied for small gaps where the modified Paschen's curve applies. For comparison purposes, the relative effect of charge injection due to triboelectrification is also assessed.

3. Charge injection

3.1. HBM ESD

Electrostatic discharge is a charge-driven phenomenon [12]. Maxwell's method to formulate multi-body capacitances for a system of conductors [13] can be used to study the various models. Consider the two-body problem shown in Fig. 1; an analysis of this system can be used for HBM [14] ESD events. Body 1 is the charged source representing the charged human body; body 2 is the target, an uncharged floating system containing a MEMS device. In this paper, spheres will be used to illustrate the bodies in the various models. It is to be noted here and described in more detail in the later discussion on capacitive MEMS characteristics that the MEMS device situated in one of the system bodies does not exist in a spherical form given the planar nature of all MEMS fabrication methods.

The system equations are

$$Q_1 = c_{11}V_1 + c_{12}V_2 \quad (1)$$

$$0 = c_{12}V_1 + c_{22}V_2 \quad (2)$$

where V_1 and V_2 are the potentials of body 1 and body 2 respectively; the initial charge on body 1 is Q_1 while body 2 is initially uncharged.

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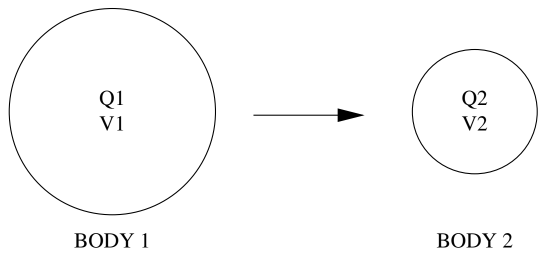

Fig. 1. Two-body problem for HBM ESD events: static analysis.

A coefficient of self-capacitance is of the form c_{ii} and is defined as the charge on body i when body i is raised to a potential of 1 V with all other conductors in the system grounded. A coefficient of mutual capacitance is of the form c_{ij} and is defined as the charge on body j when body i is raised to a potential of 1 V and all other conductors (including j) are grounded. Thus, c_{ii} is the amount of flux per volt from conductor i with all other conductors grounded while c_{ij} is the amount of flux per volt from body i which terminates on body j. Before the discharge, Eqs. (1) and (2) are solved to give the body potentials.

$$V_1 = \frac{Q_1}{c_{11} - c_{12}^2/c_{22}} \tag{3}$$

$$V_2 = -V_1\frac{c_{12}}{c_{22}} \tag{4}$$

$$V_1 - V_2 = \frac{Q_1}{[c_{11} - c_{12}^2/c_{22}]}\left[1 + \frac{c_{12}}{c_{22}}\right] \tag{5}$$

This result demonstrates that the potential difference between the two bodies, $V_1 - V_2$, is directly proportional to the charge Q_1 on the source. A discharge event occurs when the electric field between the two bodies exceeds the breakdown strength of air which is approximately 30 kV cm^{-1}. Since the electric field between the two bodies at a separation d is approximately $(V_1 - V_2)/d$, it can be seen that the probability of a discharge event is proportional to the potential difference $V_1 - V_2$. Furthermore, the effect of the relative sizes of the two bodies is to be noted. If the size of body 2 is much smaller than the size of body 1, all of the electric flux associated with body 2 will terminate on body 1 or $c_{12} = -c_{22}$. From Eq. (4), the potential V_2 of the small body will float to the potential V_1 of the large body; from Eq. (5), $V_1 - V_2 \to 0$.

Let the discharge be modelled by a fine conductor which joins the two bodies. This filamentary path allows the transfer of charge to be effected between the two bodies; the path is assumed to have negligible resistance and capacitance. After the ESD event, both bodies are at the same new potential V and the original charge Q_1 is distributed on the two bodies. It can be shown that the amount of charge transferred to body 2 in the discharge is

$$\begin{aligned} q_2 &= V(c_{12} + c_{22}) \\ &= \frac{Q_1(c_{12} + c_{22})}{(c_{11} + 2c_{12} + c_{22})} \end{aligned} \tag{6}$$

The severity of the discharge is proportional to Q_1 and is reduced for cases where body 2 is smaller than body 1. In the limit, for a very small body 2 with respect to body 1, $c_{12} = -c_{22}$; $q_2 \to 0$ and $i_2 \to 0$. In this study, only cases where body 2 is smaller than body 1 are examined; in application, this models the charged human body handling small floating electronic systems. The work has practical use in understanding the effect of ESD on the reliability of the increasing number of miniature mobile electronic devices containing MEMS.

The effect of the size of body 2 relative to body 1 on system potentials is shown in Fig. 2 for the two-sphere model shown in Fig. 1. Sphere 1 has a fixed radius r_1 (0.5 m) while the radius r_2 of sphere 2 varies from 0.05 m to 0.5 m; the charge Q_1 on body 1 is 1 μC; the body separation is 0.5 mm. The charge q_2 transferred to body 2 during the discharge event is shown in Fig. 3.

Maxwell's method using system equations (1) and (2) gives a complete solution to the generalized two-body ESD problem since it includes the effect of any electric flux coupled to ground planes. A comparison of Maxwell's approach (employing capacitance coefficients) and the engineering approach (using conventional capacitors) has been presented [15].

The lumped element equivalent circuit shown in Fig. 4 can also be used for analysis purposes. C_1 is the capacitance of the human body, R_1 is the resistance associated with the discharge path and C_2 is the capacitance of the target or system under test. Standard values used in the HBM test method [16] are $C_1 = 100$ pf, $R_1 = 1.5$ kΩ, $V_1 = 250$–8000 V; the maximum charge Q_1 is then 0.8 μC. In the test method C_1 models the capacitance of the human body and R_1 models the resistance of the skin associated with the finger, assumed to be the discharge point from the human body. The relative effect of the size of C_2 with respect to C_1 on the charge q_2 transferred in a discharge event is shown in Fig. 5. As the size of body 2 (C_2) decreases relative to the size of body 1 (C_1), the amount of charge q_2 transferred in the discharge is reduced.

3.2. CDM ESD

3.2.1. Package charging

An integrated circuit can become charged by triboelectrification after contact and separation of the insulating package with another body. The system geometry for the charged device model (CDM) is shown in Fig. 6. Body 1 is composed of the device pins, lead frame and circuit die; body 2 represents the package which has a charge Q_2 due to triboelectrification. The device approaches another conductor body 3 which can be floating or grounded; it is assumed that body 3 is much larger than the device which is typically the case. It has been shown [17] that during a discharge between body 1 and body 3, a charge equal in magnitude and opposite in polarity to Q_2 will be transferred to the device.

3.2.2. Pin charging

In this situation, the pins of the integrated circuit become charged by triboelectrification between the pins and another body; the system geometry for this CDM is shown in Fig. 7. Q_2 is the charge on the pins of the device due to triboelectrification. It

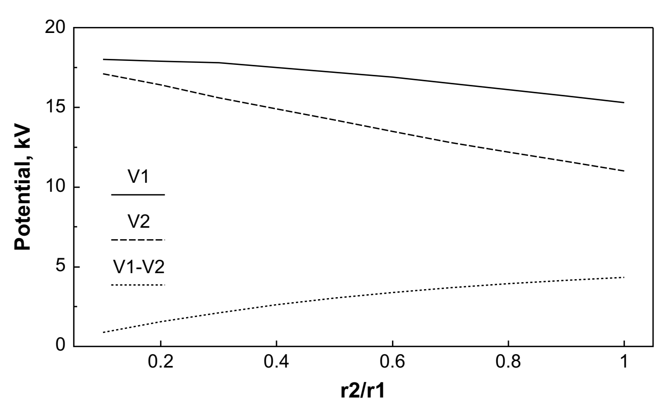

Fig. 2. Distribution of potential for two-body problem.