Thermal Modeling for Input Protection Circuit

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입력보호회로설계를 위한 열모델링

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요 약

반도체 소자에 정전기 방전으로 인한 소자내의 온도 상승을 알기 위해 열전달 방정식으로부터 열모델을 유도하였다. 그리고 열파괴 문턱전류를 얻고 시간에 따른 온도 변화를 열모델로부터 해석하였다. 여기서 유도한 열모델은 Wunsch－Bell모델에 지수 항을 추가한 형태이다. 이 모델의 유효성을 증명하기 위해 실험결과와 비교한 결과 매우 잘 일치하였으므로 이 열모델의 함수는 입력보호회로의 반도체소자를 설계하는데 매우 유용하다.

SYMBOLS AND ABBREBIATIONS

A_j : Junction area.
B : Wunsch-Bell coefficient.
C_B : Human body capacitance.
D : Thermal diffusivity $\left(=\frac{K}{\rho}C_P\right)$.
Io : Peak current.
I(t) : Current.
I_{th} : ESD threshold current, i, e., the value of I_o at threshold.
K : Thermal conductivity.
$P_{(t)}$: Power.
P_f : Failure power.
R_B : Human body resistance.
R_D : Semiconductor resistance.
t : Time.
t_f : Failure time.
t_L : Lower failure time.
t_U : Upper failure time.
T_o : Ambient temperature.
T(t) : Temperature function.
V_j : Junction voltage.
V_{th} : ESD threshold voltage, i.e., the value of Vo at threshold.
V(t) : Voltage.
ρ : Density.
τ : Disharge time constant.

Ⅰ. INTRODUCTION

Electrostatic discharge(ESD) thermal runaway has been identified as one of the failure mechanisms in semiconductor devices. Thermal runaway has been modeled by a localized heat source, where the instantaneous power, voltage and current are related by $P(t) = V(t)I(t)$. The heat generated raises the temperature at the hottest point to some critical value T_C, where T_C may be the melting temperature which causes thermal failure.

The earliest analytical models of thermal breakdown are those of Wunsch and Bell[1] and Tasca[2]. Wunsch and Bell described junction breakdown in Si p-n diodes under constant power stress by a simple one-dimensional heat flow analysis. Tasca derived a thermal model in which the heat source may be regarded as a sphere in an infinite medium.

In the case of a transient ESD pulse, Speakman[3] applied the Wunsch and Bell(W-B) model for constant pulses to exponential ESD pulses. Power is dissipated in the device in Fig. 1 by the voltage drop of the junction(V_j) and the resistance of the device(R_D). It is assumed that the junction voltage V_j and the resistance R_D are constant in the equivalent circuit shown in Fig. 1. The discharging current profile is expressed by the exponential function with decay time constant. Speakman assumes that threshold failure occurs toward the end of the pulse and after a time 5τ, the exponetial is replaced by a constant pulse of length 5τ, which contains the same average power as the exponential pulse over the failure time. However, Speakman's result underestimates the maximum temperature rise by about 20% when compared to the exact result obtained from Lin[7].

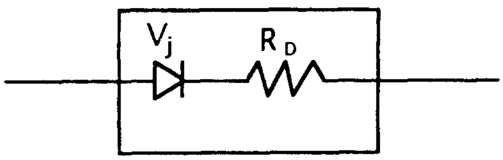

Fig. 1. Device circuit model.

To determine the best relationship between the constant power model and the ESD power model without estimation using an average power, Pierce *et al.* did a test on a 256K UVEPROM to collect data for developing a waveform conversion model[4]. This test translates a device threshold measured with one type of electrical overstress transient into an equivalent threshold with a different transient. That is, a test on a constant pulse is used to obtain the energy consumed by the device, and then this energy is used to relate the ESD power by solving the Dawson integral for the ESD damaging peak device current I_o. This damaging current is used to multiply the resistance 1.5 kΩ of the human body model(HBM) simulator to obtain the HBM ESD voltage.

Dwyer *et al.* extended Pierce's work and obtained the failure current/voltage threshold using the Dawson integral and the time interval of the pulse which causes the damage[5]. Existing thermal models are normally based on constant power pulses. An extension to a ESD pulse may be achieved by use of the Duhamel formula and may be used to analyze the heating effects of ESD pulses based on a knowledge of constant power results.

The objectives of this paper are to derive an approximate closed-form temperature function for the excitation caused by human body electrostatic discharge and determine the thermal failure threshold current in semiconductor devices. The closed-form model is compared with the experimental results in literatures.

Ⅱ. ANALYTICAL THERMAL MODEL

The human body model widely accepted as industry reference consists of a precharged 100pF capacitor discharging through a 1.5 kΩ resistor into the device under test, as shown in Fig. 2. Power is dissipated in the device due to voltage drop V_j across the junction and the internal resistance R_D of the device[3]. The equivalent circuit is shown in Fig. 1 with V_j and R_D taken as constants. This circuit model has now become a general starting point for thermal runaway modeling[4,6]. The current equation for the device is assumed to be exponetial and given by

$$I(t) = I_0 \exp\left(-\frac{t}{\tau}\right) \tag{1}$$

where

$$I_o = \frac{V_o - V_D}{(R_B + R_D)} \tag{2}$$

and

$$\tau = C_B(R_B + R_D) \approx 150\ ns \tag{3}$$

The instantaneous power disssipated in the device is given by[4]

$$P(t) = V_j I_o \exp\left(-\frac{t}{\tau}\right) + R_D I_o^2 \exp\left(-\frac{2t}{\tau}\right) \tag{4}$$

This power is the heat source in the heat flow equation. The solution for the temperature at the hottest point is given by[5,7]

$$T(t) = T_o + \frac{1}{A_j\sqrt{4\pi\rho C_p K}} \int_0^t \left[\frac{V_j I_0}{\sqrt{\lambda}} \exp\left(-\frac{(t-\lambda)}{\tau}\right)\right.$$

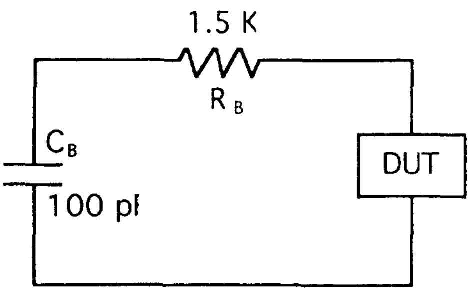

Fig. 2. Human body circuit model with device under test.

$$\left. + \frac{R_D I_o^2}{\sqrt{\lambda}} \exp\left(-\frac{2(t-\lambda)}{\tau}\right)\right] d\lambda \tag{5}$$

The integral terms in equation (5) are simplified in order to obtain a closed－form temperature function. Integrating these terms, a series expansion yields

$$\int_0^t \frac{\exp\left(\frac{\lambda}{\tau}\right)}{\sqrt{\lambda}} d\lambda = 2t^{\frac{1}{2}} \exp\left(\frac{t}{\tau}\right) \left[1 - \frac{2t}{3\tau} + \frac{2\cdot2}{3\cdot5}\left(\frac{t}{\tau}\right)^2 - \frac{2\cdot2\cdot2}{3\cdot5\cdot7}\left(\frac{t}{\tau}\right)^3 + \frac{2\cdot2\cdot2\cdot2}{3\cdot5\cdot7\cdot9}\left(\frac{t}{\tau}\right)^4 - \cdots\cdots\cdots\right] \tag{6}$$

and

$$\int_0^t \frac{\exp\left(\frac{\lambda}{\tau}\right)}{\sqrt{\lambda}} d\lambda = 2t^{\frac{1}{2}} \exp\left(2\frac{t}{\tau}\right) \left[1 - 2\frac{2t}{3\tau} + 2\frac{2\cdot2}{3\cdot5}\left(\frac{t}{\tau}\right)^2 - 2\frac{2\cdot2\cdot2}{3\cdot5\cdot7}\left(\frac{t}{\tau}\right)^3 + 2\frac{2\cdot2\cdot2\cdot2}{3\cdot5\cdot7\cdot9}\left(\frac{t}{\tau}\right)^4 - \cdots\cdots\cdots\right] \tag{7}$$

For small t/τ these integrations have approximately the form of a Taylor series for an exponential function. Subsituting this dependence yields

$$T(t) = T_0 + \frac{1}{A_j\sqrt{\pi\rho C_p K}} t^{\frac{1}{2}} \left[V_j I_0 \exp\left(-\frac{2t}{3\tau}\right) + R_D I_0^2 \exp\left(-\frac{4t}{3\tau}\right)\right] \tag{8}$$

To obtain a better approximation for the exponential terms, constant values for the coefficients in the exponential argument of 0.6 and 1.2 are chosen. These values are obtained by curve fitting as shown in Fig. 3, where $V_j = 20$ V, $R_D = 4\ ohm$, $I_o = 1\ A$ and $A_j = 500\ \mu m^2$. Hence, the modified expression is given by

$$T(t) = T_0 + \frac{1}{A_j\sqrt{\pi\rho C_p K}} t^{\frac{1}{2}}$$

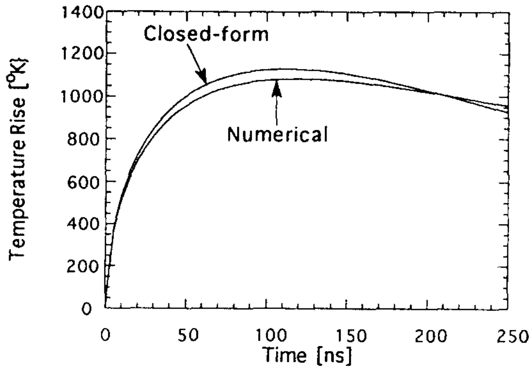

Fig. 3. Temperature rise for p – n junction.

$$\left[V_j I_0 \exp\left(-0.6\frac{t}{\tau}\right) + R_D I_0^2 \exp\left(-1.2\frac{t}{\tau}\right)\right] \quad (9)$$

The temperature rise given in equation (9) is understood in the following way. For shorter times, the temperature of a component rises as the power of the pulses sufficient to overcome the cooling effect of thermal diffusion. This process is dependent on $t^{\frac{1}{2}}$. For longer times, the diffusion losses dominate and the temperature of the device drops toward room temperature. For a p – n junction under reverse bias conditions, $R_D=0$ is a good approximation. The temperature rise function of the reverse bias junction for ESD is then given by

$$T(t) = T_{W-B}(t)\exp\left(-0.6\frac{t}{\tau}\right) \quad (10a)$$

$$T_{W-B}(t) = \frac{1}{A_j\sqrt{\pi\rho C_p K}} V_j I_o t^{\frac{1}{2}} \quad (10b)$$

where $T_{W-B}(t)$ is the W – B model temperature function.

The relationship between the time of the maximum temperature and the threshold current is important. The maximum temperature time (t_m) is obtained as follows :

$$\frac{d}{dt}\left(\frac{1}{A_j\sqrt{\pi\rho C_p K}} V_j I_o t^{\frac{1}{2}} \exp\left(-0.6\frac{t}{\tau}\right)\right) = 0$$

and $t=t_m$, for reverse bias (11a)

$$\frac{d}{dt}\left(\frac{1}{A_j\sqrt{\pi\rho C_p K}} R_D I_o^2 t^{\frac{1}{2}} \exp\left(-1.2\frac{t}{\tau}\right)\right) = 0$$

and $t=t_m$, for forward bias (11b)

Solving these equations yields $t_m=0.833\ \tau$ for reverse bias and $t_m=0.417\ \tau$ for forward bias.

The maximum temperature at $t=t_m$ and $R_D=0$ for reverse bias is obtained by substitution into (9) as

$$T_m = 0.553\frac{V_j I_o}{A_j\sqrt{\pi\rho K C_p}}\sqrt{\tau} \quad (12)$$

This result has only 2% error in comparison with the exact solution form Lin's results[7].

If the current threshold is expressed as a function of failure times, we can define t_L and t_U to be the limiting times for the failure time range, where t_L and t_U are given by[4].

$$\frac{d}{dt}\left(\sqrt{t_U}\exp\left(-0.6\frac{t_U}{\tau}\right)\right) = 0$$

$$\text{and } \frac{d}{dt}\left(\sqrt{t_L}\exp\left(-1.2\frac{t_L}{\tau}\right)\right) = 0$$

or

$$t_L=0.417\ \tau \quad (13)$$

and

$$t_U=0.833\ \tau \quad (14)$$

This time window is similar to that of Dwyer *et al.*[5]. The threshold current I_{th} must satisfy equation (9) with the threshold time to failure t_f restricted to the defined range. Rearranging equation (9), we have

$$\frac{B}{t^{\frac{1}{2}}\exp\left(-0.6\frac{t}{\tau}\right)} = \left[V_j I_o + R_D I_o^2 \exp\left(-0.6\frac{t}{\tau}\right)\right] \quad (15)$$

where B is the W – B coefficient given by

$$B = (T_m - T_o) A_j \sqrt{\pi\rho K}\, C_p \quad (16)$$

The denominator term of the left side of (15) and the exponential term of the right side is approximated by taking the average at both ends, t_L and t_U. The average values are 0.5275 and 0.6926 for the two functions. The current threshold, the least value of I_o which causes thermal failure, is obtained as follows by solving equation (15) :

$$I_{th} = \frac{V_D}{1.444R_D}\left[\sqrt{1+\frac{2\frac{B}{\sqrt{\tau}}1.444}{0.5275\frac{V_D^2}{R_D}}}-1\right] \quad (17)$$

For the forward bias case, the threshold current may be easily solved for by applying $V_j=0$ and $t=t_f$ in equation (15), yielding

$$I_{th}^2 = \frac{B\exp(1.2t_f/\tau)}{R_D\sqrt{t_f}} \quad (18)$$

where $t_f=0.417\ \tau$ is the maximum temperature time for the fowrard bias which causes thermal failure and by substitution

$$I_{th}^2 = 2.55\frac{B}{R_D\sqrt{\tau}} \quad (19)$$

Similarly, for the reverse bias case, $R_D=0$ in equation (15), the current threshold is obtained as

$$I_{th} = 1.805\frac{B}{V_D\sqrt{\tau}} \quad (20)$$

The results for the forward and reverse bias are quite similar to those of Dwyer *et al.*[5]. Hence, simple expressions for the threshold current and voltage for transient ESD pulses are obtained with only a small sacrifice in accuracy.

Ⅲ. Comparison with Experimental Results

In this section, a comparison of the close form threshold equation is made with ESD threshold data from the literature[8]. A thick field input protection structure similar to that shown in Fig. 4 was the human body model tested by Rountree and Hutchins[8] for a variety of device widths and overlaps.

The assumption is made that the area conducting the overstress current is the drain - substrate junction between the drain contact and the channel. Referring to Fig. 4, that area is,

$$A_j=\pi dW/2+DW \quad (21)$$

where D is the overlap, W is the width and d is the depth of the drain diffusion. The Wunsch - Bell coefficient for a reverse biased thick field input transistor is given by

$$B = (T_m - T_o)\sqrt{\pi D}\rho C_p A_j$$

and by substitution

$$B=3.67\times 10^3(\pi dW/2+DW)(W - s^{1/2}) \quad (22)$$

where

K=Si thermal conductivity=1.45 W/(cm - C)

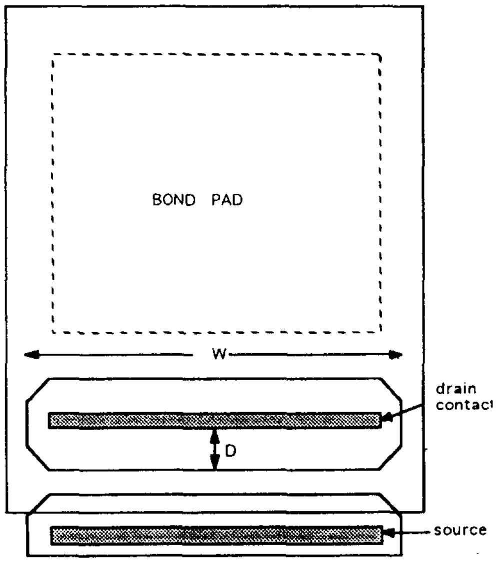

Fig. 4. Layout of thick field transistor.

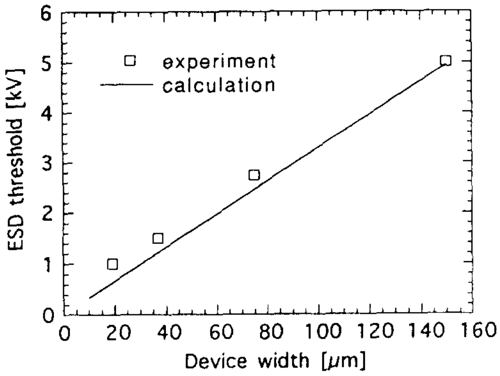

Fig. 5. Failure threshold as a function of device width(diffusion overlap of contact = 4.7 μm).

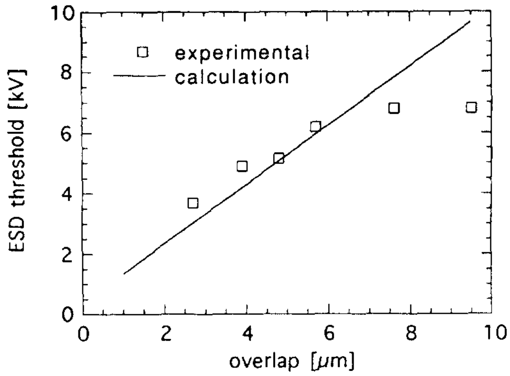

Fig. 6. Failure threshold as a function of overlap (device width is 148 μm).

ρ = Density of Si = 2.33 g/cm^3

C_p = Specific heat of Si = 0.65 J/(g - C)

T_m = Melting point of Si = 1420 C

and

T_m = Starting temperature = 22 C

The quantities needed to calculate the threshold voltage for HBM ESD voltage are the device resistance R_D and the junction voltage V_D. V_D depends only upon the doping profiles which are assumed constant across the devices. R_D is given by

$$R_D = \rho L / A \qquad (23)$$

where ρ is the resistivity, L the length and A the area of the active region. The value of R_D in Fig. 4 for reverse biased inputs is given by the scaled resistance expression as[8]

$$R_D = (10^{-4}\Omega - cm^2)/DW \qquad (24)$$

If it is assumed that the ESD source is an ideal source, then the failure current, I_o, is obtained from equation (17). This gives the HBM ESD threshold voltage as

$$V_{th} = (1.5k\Omega) I_o \qquad (25)$$

This method was applied to the data in reference (8). The first comparison is shown in Fig. 5, where the ESD failure threshold is plotted versus device width, W, for a device overlap, D. The data is shown as circles for 4.7 μm overlap. The line is the predictions using the threshold equation. Overall agreement is good, which supports the assumption that the area dissipating is between the drain contact and channel. Fig. 6 shows ESD threshold data from Reference (8) versus device overlap for constant device width. Agreement with data is good until device overlaps are on the order of about 6 μm. The ESD threshold starts to roll off, while the calculation continues along the linear trend. The roll - off suggests the HBM ESD excites a differnt channeling mechanism at overlaps greater than 6 μm.

Ⅳ. CONCLUSION

An ESD pulse due to an electrostatic discharge at the p - n junction was studied using the heat flow equation and the device circuit model. In this paper, a simple and straightforward derivation from heat flow analysis without the use of any constant power results yields a closed - form expression for the temperature function. A closed - form thermal model is used to obtain directly the current threshold and failure time. Since ESD is a three - dimensional problem, the one - dimensional closed - form temperature function is only valid for large junction area and relatively small junction depletion length. However, this is the practical situation in most instances. The thermal model has a good agreement with experimental results. The closed - form thermal model should be useful for the ESD protection structure design.

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