EMP injection damage effects of a bipolar transistor and its relationship between the injecting voltage and energy*

Xi Xiaowen(席晓文)†, Chai Changchun(柴常春), Ren Xingrong(任兴荣), Yang Yintang(杨银堂),
Zhang Bing(张冰), and Hong Xiao(洪潇)

*(Key Laboratory of Ministry of Education for Wide Band-Gap Semiconductor Materials and Devices,
School of Microelectronics, Xidian University, Xi'an 710071, China)*

Abstract: The response of a bipolar transistor (BJT) under a square-wave electromagnetic pulse (EMP) with different injecting voltages is investigated. Adopting the curve fitting method, the relationship between the burnout time, the damage energy and the injecting voltage is obtained. Research shows that the damage energy is not a constant value, but changes with the injecting voltage level. By use of the device simulator Medici, the internal behavior of the burned device is analyzed. Simulation results indicate that the variation of the damage energy with injecting voltage is caused by the distribution change of hot spot position under different injection levels. Therefore, the traditional way to evaluate the trade-off between the burnout time and the injecting voltage is not comprehensive due to the variation of the damage energy.

Key words: BJT; square-wave EMP; injecting voltage; damage energy
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1. Introduction

Electronic systems tend to failure under the effect of an electromagnetic pulse (EMP) inducing voltage and current surges, which is directly related to the damage of the components that make up the systems. The authors have reported the damage effect and mechanism of silicon and GaAs low-noise amplifiers (LNA) in the pre- and post-injection signal[1−3]. Experimental results show that the bipolar devices of LNAs are particularly susceptible to destruction from external electrical stresses. The damage to the device under the EMP is one of the main failure mechanisms in the modern microelectronic device. Although the response of bipolar devices under the EMP effect is a complex problem, it has an important significance for the development of reliability. The study in this aspect is not only applicable to EMP problems but is also applicable whenever high transient voltages appear in a circuit whether the pulse origin is EMP, or a transient transform within the system itself[4, 5].

In order to test the EMP damage, generally there are two methods with the electrostatic discharge (ESD) and square-wave EMP to conduct the injection experiment[6, 7]. Due to the complex EMP model, the failure thresholds are used to perform the EMP assessment and hardening of the electronic systems[8−11]. Comparing with the ESD method, the application of square-wave EMP to perform the failure thresholds can easily obtain the power by calculating the responsive voltage waveform and the current waveform. Also, it is easy to obtain the damage energy absorbed by the device. However, in actual practice the complex overstress resulting in failure of the device can not be described in a simple square-wave EMP. Considering that the biggest damage mechanism is an energy dependent process, it is necessary to build up a relationship between the square-wave injecting voltage and the damage energy.

There were early studies on the subject of the damage energy of the devices under the EMP effect. Wunsch and Bell *et al.* studied the pulse power failure levels of semiconductor junctions through an extensive experimental program, and established a semi-empirical formula based on experimental data and on a simple thermal failure model, which can make order of magnitude estimates of the failure level as a function of pulse length for many silicon diodes or transistors[8]. Tasca assumed that the device model was a spherical geometry, and divided the damage energy by the burnout time into three phases: a constant energy phase for short pulse widths; a one half power of time dependence for longer pulse widths; a direct time dependence at thermal equilibrium[9]. These papers represent some formula to make estimates of junction failure in the semiconductor reliability study.

However, no related literature has reported the damage energy of the device under the EMP effect directly based on the special device structure. This study is distinctively different from the traditional methodology of the EMP study that is based on the two-dimensional thermal model or the spherical geometry model, and directly uses the typical BJT structure as the model.

In this paper, an EMP damage analysis of an n^+–p–n–n^+ bipolar transistor is presented with the device simulator Medici employed. The relationship between the burnout time, the damage energy and the injecting voltage is obtained using the curve fitting software Origin. It is demonstrated that the damage energy is not a constant value, but changes with the injecting voltage magnitude due to the burnout hotspot position varying with the magnitude of the injecting voltage. Thus the traditional way

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† Corresponding author. Email: xixiaowen523103@163.com

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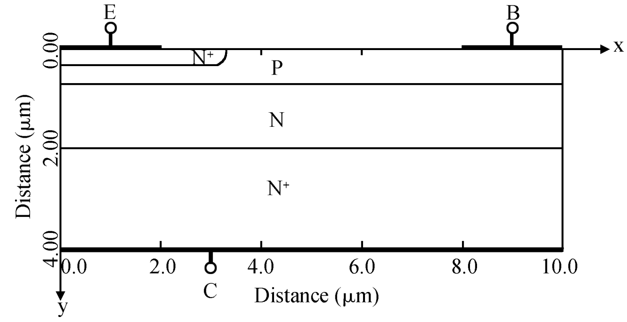

Fig. 1. Structure diagram of BJT.

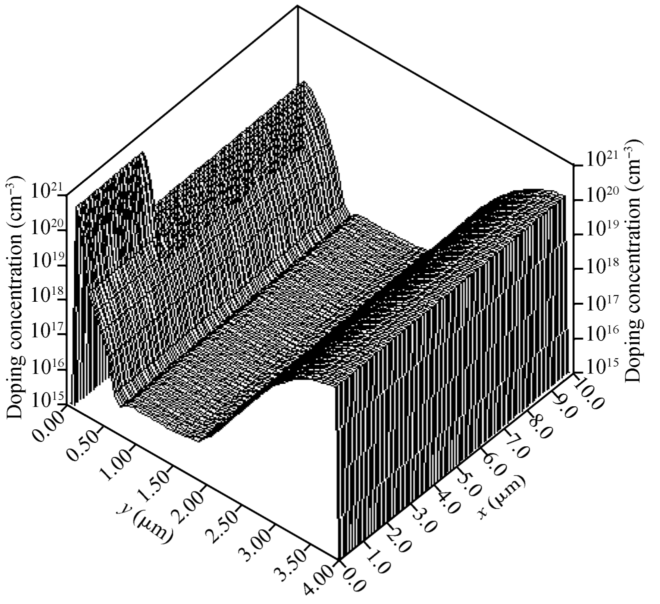

Fig. 2. Doping profile of BJT.

to evaluate the trade-off between the burnout time and the injecting voltage is not comprehensive on account of the variation of the damage energy.

2. Device structure

The structure of a typical BJT is given in Fig. 1, and only half an emitter finger is analyzed considering the symmetry, where B, C, and E stand for its base, collector, and emitter respectively; P and N represent the p- and n-type silicon regions, respectively; N^+ denotes the heavy doped regions of the n-type silicon. The two-dimensional doping profile of the typical BJT is illustrated in Fig. 2. The thermal electrode is at the bottom of the transistor where the lattice temperature remains at 300 K, and the thermal boundary conditions at all boundaries are adiabatic.

3. Results and analysis

The collector undergoes voltage injection from 50 to 140 V at $t = 100$ ps with the emitter and the base connected to the ground for a device with the structure shown in Fig. 1. In order to consider the effect of the external circuit and the energy absorbed by the device, a 50 Ω resistor is connected to the collector. By the use of 2D-Medici simulation software, device failure is indicated when the lattice temperature reaches the melting point of silicon at 1688 K[8, 9]. The relationship between the burnout time, the damage energy and the injecting voltage is obtained and analyzed. Figure 3 shows the current and voltage response of the device under a square-wave EMP with a magnitude of 50 V. There is a second breakdown point where the device begins to show abrupt reduction in collector-emitter voltage as the collector current increases. A high voltage makes the junction instantaneously enter into avalanche breakdown, which causes the current to increase and build up sufficiently to forward-bias a portion of the emitter. The BJT becomes unstable and the second current breakdown happens when the emitter is injecting[12]. Device response is exhibited as a low sustaining voltage-high current mode of operation. With the duration of the operation, the device is burned when it absorbs a certain amount of energy.

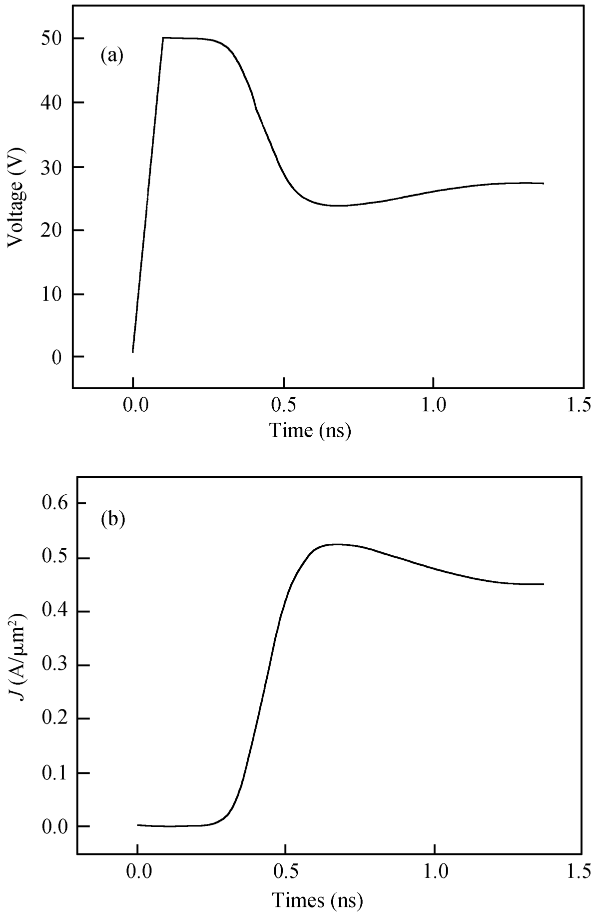

Fig. 3. (a) Voltage and (b) current response of BJT.

3.1. Variation of the burnout time with the injecting voltage

In order to analyze the dependence of the burnout time on the magnitude of the injecting voltage, the authors simulated the burnout processes of the BJT under different injecting voltage magnitudes based on the model shown in Fig. 1. Figure 4 depicts the relationship between the burnout time and the injecting voltage. It is seen that the burnout time decreases with increasing injected voltage as the whole, which shows that the device failure mechanism is an energy dependent process. However, the damage energy is not a constant value; when the injecting voltage is between 80 and 100 V, the burnout time

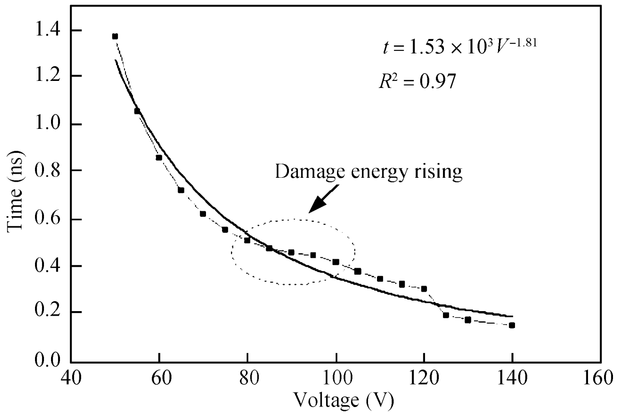

Fig. 4. Dependence of the burnout time on the injecting voltage.

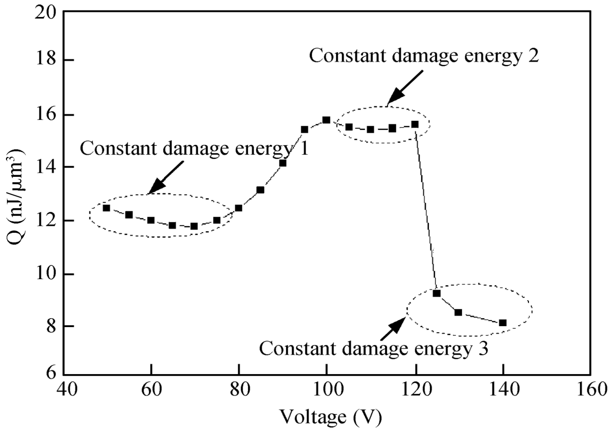

Fig. 5. Dependence of the damage energy on the injecting voltage.

almost remains constant with the variation of the injecting voltage due to the rising energy.

Adopting the curve fitting method to fit the data points, the relationship between the burnout time and the injecting voltage meets the function of $t = 1.53 \times 10^3 V^{-1.81}$ (ns) shown in Fig. 4, the correlation coefficient of which, $R^2 = 0.97$, is close to 1 and provides an especially good fit to the relationship between the burnout time and the injecting voltage.

3.2. Variation of the damage energy with injecting voltage

Under the effect of the EMP, the collector current of the BJT includes the transfer current which makes a contribution to heat up the device and the charging current which has hardly any effect on the damage to the device. The charging current is in direct proportion to the change rate of the injecting voltage with time and accounts for the main component of the collector current in the rising stage of the injecting voltage. In this paper, the rising time of the injecting voltage is only 100 ps, and the current in the rising stage of the injecting voltage shown in Fig. 3(b) is so trifling that it can be neglected compared with the current which consists mostly of the transfer current after the injecting voltage reaches a steady value, thus the energy of the device is mainly caused by the transfer current. In the present work, the authors do not conduct a more in-depth study on the relationship between the transfer current and the charging current due to the complexity of the model, and define the energy obtained by calculating the instantaneous voltage and current waveform as the damage energy when the energy makes the device lattice temperature reach 1688 K. Figure 5 shows the dependence of the damage energy on the injecting voltage. There are three constant damage energy phases and a damage energy rising phase. When the injecting voltage is in the constant damage energy phases, the burnout time varies inversely with injecting voltage (Fig. 4); when the injecting voltage is between 80 and 100 V, the damage energy increases linearly with the increase of the injecting voltage, which causes the burnout time to almost remain constant in this phase (Fig. 4).

3.3. Simulation analysis and discussion

The variation of damage energy with injecting voltage is no coincidence, and is relevant to the internal variation of the device at the burnout. By use of the device simulator Medici, the temperature distributions of the damage device under different injecting voltage levels are given in Fig. 6.

When the injecting voltage is relatively low, the hot spot locates near the n^-–n^+ interface under the center of the emitter region (Fig. 6(a)). The damage energy is invariable (constant damage energy 1) due to only a hot spot. As the injecting voltage increases, the hot spot near the emitter can not be overlooked due to the large current density (Fig. 6(b))[13], which increases along with the increase of the injecting voltage and causes the damage energy to increase (damage energy rising phase). When the hot spot near the emitter reaches saturation (Fig. 6(c)), the damage energy can not change by a wide margin (constant damage energy 2).

When the injecting voltage reaches a certain value, “double peak” phenomena[14] happen in the PIN structure composed of the base-epitaxial layer-collector. Figure 7 depicts the electric field distribution of the device at 203 ps under 125 V. The maximum electric field locates at the edge of the base near the emitter. The corresponding current density distribution is shown in Fig. 8, and there is a peak current density appearing at the edge of the base near the emitter. Because the edge of the base electrode is both the peak electric field and the peak current density, the hot spot (Fig. 6(d)) at this point rises faster because the heat generation is centralized[15], which causes the damage energy to drop quickly (constant damage energy 3).

3.4. Comparison with experimental results

Experimental studies reported in Ref. [16] have shown that the crystal damage is at the n^-–n^+ interface under the center of the emitter as the device is subjected to high voltage and high current operating conditions. It is believed from Ref. [16] that the crystal damage is due to local heating. Figure 9 is the cross-sectional view of the device showing the defect location. This result coincides with the simulation results in this paper. However, when the magnitude of the pulse is sufficiently high, the damage may happen firstly at the edge of the base near the emitter; this aspect still needs further experimental studies.

4. Summary

The damage characteristics of semiconductor devices under an EMP are very complicated in nature. Due to the complex EMP wave shape, generally the devices were injected by

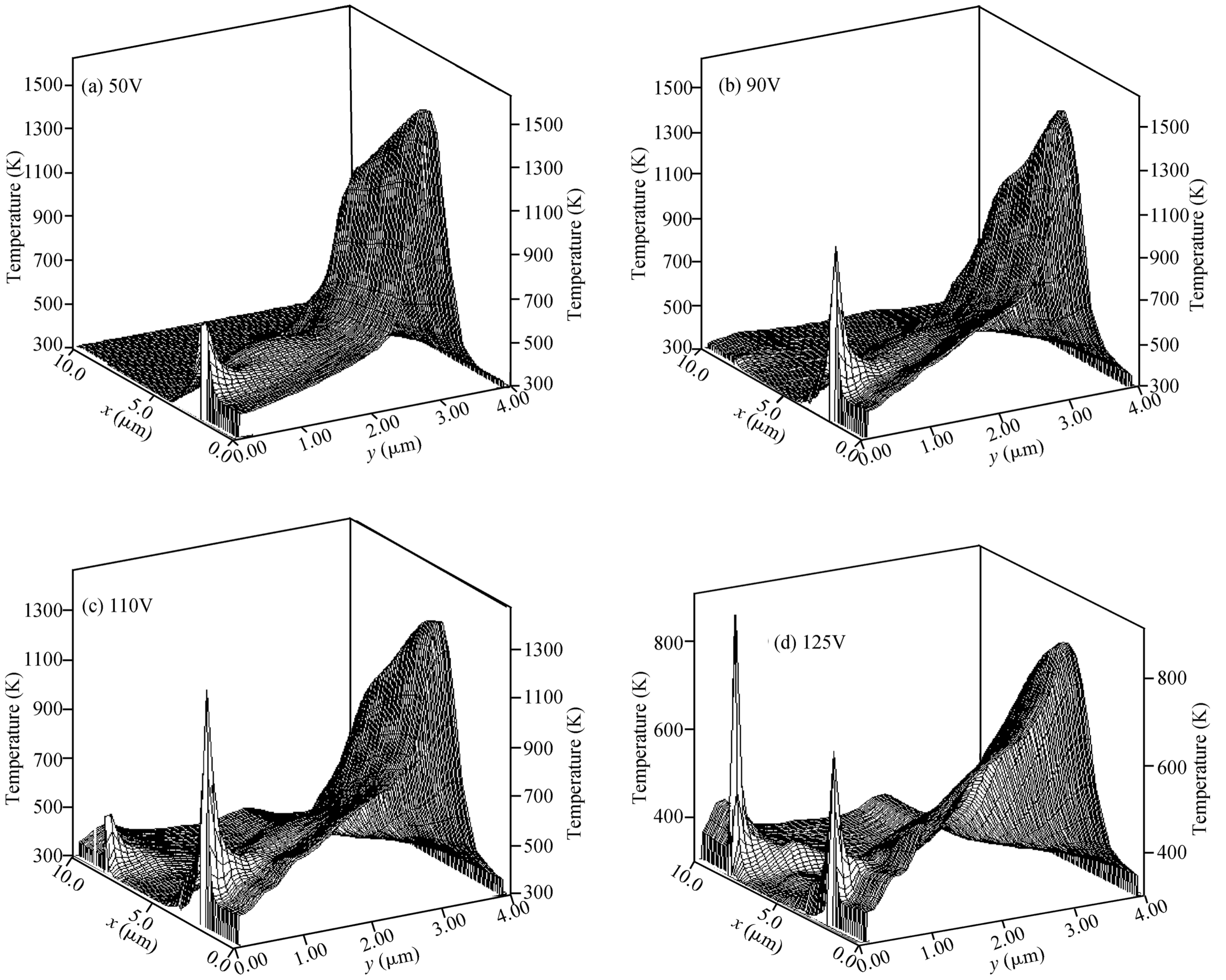

Fig. 6. Temperature distributions of the device under different injecting voltage levels. (a) 50 V. (b) 90 V. (c) 110 V. (d) 125 V.

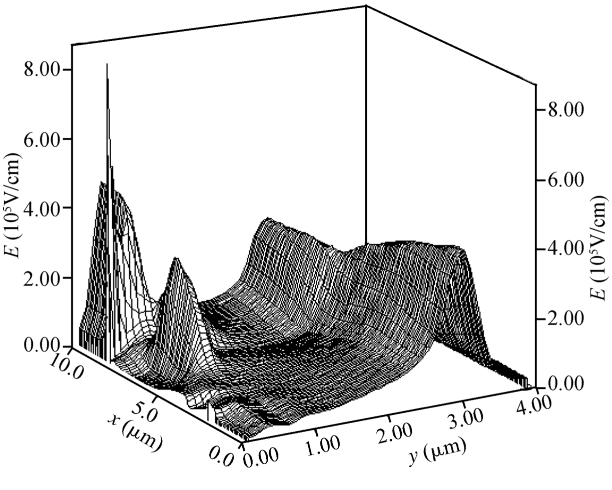

Fig. 7. Distribution of the electric field at 203 ps under 125 V.

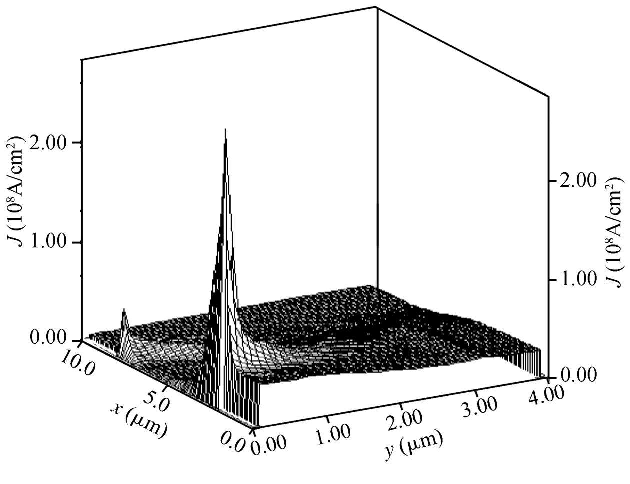

Fig. 8. Distribution of the current density at 203 ps under 125 V.

ESD or rectangular pulse to study the damage effects. In this paper, the authors' attention is focused on the response of the BJT under the impact of a square-wave EMP. Through analysis of the relationship between the burnout time, the damage energy and the injecting voltage, the important conclusion follows that the damage energy changes under different injecting voltage levels.

In Fig. 4, the burnout time decreases with the increase of the injecting voltage, which indicates that energy may be the main factor leading to device damage. However, the damage energy is not a constant value, and has three constant damage energy phases and an energy rising phase (Fig. 5). Due to the distribution change of the peak electric field and the peak current density with injecting voltage, the position of the device

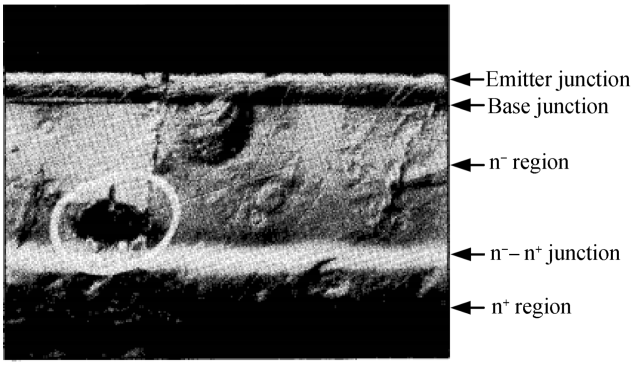

Fig. 9. Cross-sectional view of power transistor chip showing internal crystal damage[4].

damage is not fixed in one place, which causes the damage energy levels to change with the injecting voltage levels.

This conclusion provides experience in the design of the source of the strong electromagnetic pulse. Traditionally, it is believed that shortening of the burnout time goes with simultaneous increase of the injecting voltage. But as seen in Fig. 4 the increase of the injecting voltage has little influence on the variation of the burnout time in the range of 80 and 100 V, and in this range the damage energy increases as the injecting voltage increases. In the design of the strong electromagnetic pulse, it is judicious to avoid the magnitude of the pulse falling into the energy raising phase.

From the weakness areas of the device, this study finds that the damage energy is not a constant value, which provides a certain theoretical basis to the EMP assessment and hardening of the electronic systems.

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