A novel electrical measurement method of peak junction temperature based on the excessive thermotaxis effect of low current*

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Abstract: It has been a scientific and technological problem in the field of microelectronics for several decades that the electrical method is used to measure the peak junction temperature of power transistors. Based on the excessive thermotaxis effect of low current, a novel electrical measurement method of the peak junction temperature is presented in this paper. The method is called the thermal spectrum analysis method of transistors, simply designated TSA (thermal spectrum analysis method). Unlike the common method which uses a single measuring current, TSA uses multi-step currents to measure temperature-sensitive parameters. Based on the excessive thermotaxis effect of low current and the sub-transistor parallel model, the peak junction temperature and non-uniform property of junction temperature distribution are analyzed successfully.

Key words: peak junction temperature; multi-step current; excessive thermotaxis effect of low current; power transistor

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1. Introduction

Junction temperature is a very important physical quantity to determine the reliability of semiconductor devices. It is still a parameter that must be measured in reliability analysis experiments of devices, especially power devices. Currently, there are two common ways to measure junction temperature—the standard electrical method and thermal infrared method, dessignated SEM and TIM respectively. TIM is the most exact measurement method of the peak junction temperature and temperature distribution. However, it cannot be used to measure finished products with hermetically packaged chips, due to the measuring principle based on optical infrared images. Therefore, TIM cannot be used for finished products as a conventional measurement. However, SEM is in widespread use because of its non-destructive character, not only for finished products but also semi-finished products[1−3].

For TIM, the advantage is that it can accurately detect junction temperature distribution and peak temperature of the chip; the disadvantage is that it is destructive for the measurement of finished products. For SEM, the advantage is that it is simple and non-destructive for the measurement; the disadvantage is that the measured single temperature value (average junction temperature) obliterates and obscures the non-uniform property of the junction temperature distribution of the whole chip. Thus, a new measurement method, which has the advantages of both these methods, will be very significant for reliable investigation of semiconductors. The new method can use electrical non-destructive measurement to finally obtain the peak junction temperature. This investigation was begun in the 1970s[4,5]. However, today, it is still a scientific and technological problem in the field of microelectronics[4−8].

In this paper, a novel measurement method based on the excessive thermotaxis effect of low current, different from other reported methods, is presented. The method uses multi-step currents to measure the temperature-sensitive parameter V_F (or V_{BE} or V_{SD}) to successfully analyze the peak junction temperature of devices. The method is called the thermal spectrum analysis method, simply dessignated TSA (thermal spectrum analysis method).

2. Theoretical basis

2.1. Dual sub-transistor parallel model

A power transistor is made up of many parallel cells. Therefore, the sub-transistor parallel model is often used in electrical and thermal simulation of power transistors[5,8]. To simplify calculation and simulation, the dual sub-transistor parallel model is used in the thermal spectrum analysis method in this paper, shown in Fig. 1.

In Fig. 1, from A1/B1/C1 to A2/B2/C2 to A3/B3/C3, the junction temperature distribution varies with increasing dissipation power condition. In the dual sub-transistor parallel model, the mother transistor is made up of a main stream and tributary steam sub-transistor. The temperature distribution of each sub-transistor is uniform; however, the temperature of each sub-transistor is different. Due to the thermotaxis of current in a PN junction, for the current passing

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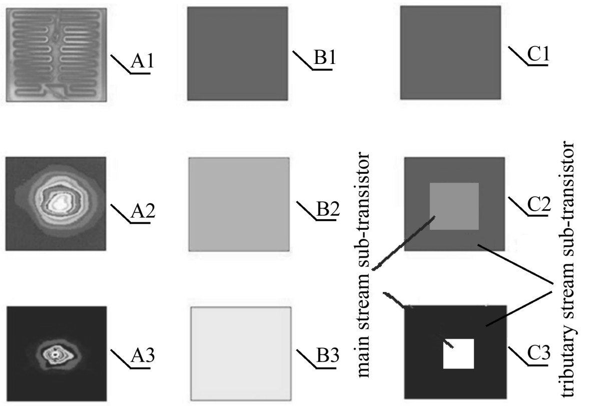

Fig. 1. Three different physical models in TIM, SEM and TSA respectively. A: Infrared images of a transistor; B: Model of uniform junction temperature distribution in SEM; C: Dual sub-transistor parallel model in TSA.

through the mother transistor, the great mass of the current passes through the sub-transistor with higher temperature, namely, the main stream sub-transistor, and less current passes the tributary stream sub-transistor with lower junction temperature. The more sub-transistors that are used in the model, the more the analysis result approaches the level of the infrared image. However, the calculation and simulation will become more complicated. Compared with the standard model of uniform junction temperature distribution, the dual sub-transistor parallel model represents a great advancement.

2.2. Excessive thermotaxis effect of low current

As a novel physical effect of semiconductor devices, the excessive thermotaxis effect of low current has been rigorously proved by theory and verified by experiment, with the correlated papers represented in the Chinese Journal of Semiconductors[9,10]. This effect is the most essential and pivotal theoretical basis of the TSA method. It describes the type of current distribution characteristic when the current passes through a PN junction barrier with non-uniform temperature distribution. For the same non-uniform temperature distribution, when less current passes through the junction, the current distribution will become more non-uniform, and more of the current will go to the higher temperature region in the junction. In other words, for the same non-uniform temperature distribution, when less current passes through the junction, the thermotaxis of the current will be more distinct. Hence, different currents, used in measurement, will obtain different temperature information of the junction. Through comprehensive analysis of all the information, peak junction temperature and the effective area of the junction can be obtained.

2.3. Background data of the transistor

For power semiconductor devices, the I–V–T characteristic curve is the most essential physical attribute and the most important calorific characteristic of the transistor. It is called the background data of the transistor in TSA, shown in Fig. 2.

In thermostatic apparatus with a high degree of accuracy, the temperature-sensitive parameter (forward voltage of measured junction) of DUT is measured with high speed by a multi-step constant current. Then, the I–V–T curve cluster with wide temperature interval is obtained in the experiment. In Fig. 2(a), the temperature range in the experiment is from ambient temperature to 150 °C. Then the V–T curves with different I are regressed to 0 K via a linear function. The arrow indicates the increasing direction of current. In Fig. 2(b), the I–V curves with different T are shown in single logarithmic coordinates. The arrow indicates increasing direction of temperature.

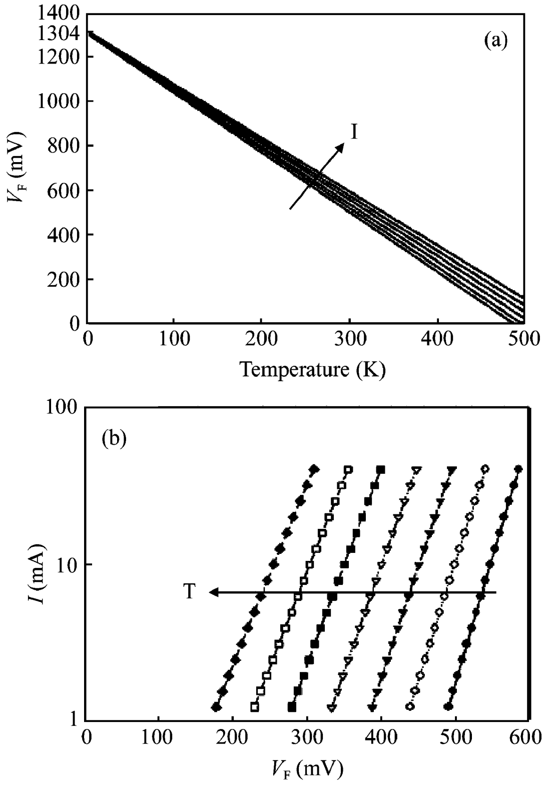

Fig. 2. Background data of the transistor: (a) V–T curves with different currents; (b) V–I curves with different temperatures in single logarithmic coordinates.

Via a fitting function, voltage, corresponding to random temperature and random current, is obtained from the I–V–T curves as in Fig. 2. Background data are regarded as the database of the thermal spectrum analysis, and the data have a high degree of accuracy. Temperature is accurate to 0.1 °C and voltage is accurate to 10 μV. The background data are integrative, and include thermal conductivity, thermal capacitance, series resistance, and injection ratio, etc. Therefore, if background data are used directly to calculate and analyze, the uncertainty in these parameters can be avoided[5].

3. Experimental results and analysis

For comparison among TIM, SEM and TSA, the respective corresponding testing instruments, QFI InfraScope II thermal infrared imager, BJ2984 transient thermal impedance testing instrument and NC2992 semiconductor reliability analytical instrument, are associated to measure the same samples. The type of sample in the experiment is a 3DD102 bipolar transistor.

Table 1. Comparison of peak junction temperature given by the three different methods 3DD102_10# sample.

I_E @ V_{cb} (A @ V)	A_E (%)	Measured junction temperature			Error with reflect to infrared (°C)	
		SEM (°C)	TSA peak (°C)	Infrared peak (°C)	SEM	TSA peak
1@10	100.0	79.4	81.3	80.8	–2.2	0.5
1@20	100.0	90.3	95.4	93.5	–5.3	1.9
1@25	100.0	96.5	102.9	103.0	–6.9	–0.1
1@30	100.0	104.5	110.0	111.3	–7.9	–1.3
1@40	67.0	111.7	129.7	134.8	–21.9	–5.16
1@50	54.0	125.5	151.6	157.5	–27.4	–5.9
1@55	11.8	175.2	260.6	264.1	–103.2	–3.5
1.375@40	65.0	128.0	158.6	172.16	–42.8	–13.5

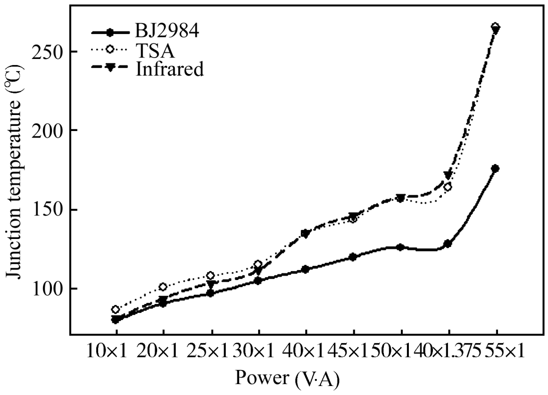

Fig. 3. Comparison of peak junction temperature among the three methods for the 10# sample.

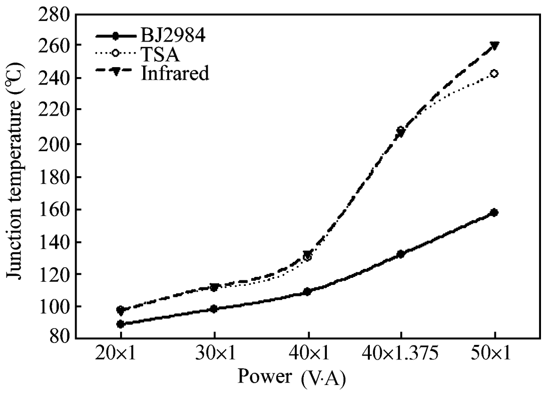

Fig. 4. Comparison of peak junction temperature among the three methods for the 17# sample.

The peak junction temperature measured by the three instruments corresponding to different power conditions is obtained from the experiment, and is shown in Table 1 and Fig. 3. For simplicity, the result of TIM based on the QFI InfraScope II is designated the infrared peak; the result of SEM based on the BJ2984 testing instrument is designated BJ2984; and the result of TSA based on the NC2992 analytical instrument is designated the TSA peak. Note that the infrared peak in Table 1 is not the highest temperature in the thermal images, but the inner average temperature of the effective area (A_E) transformed from the whole chip area[11]. The purpose of transformation from the whole chip to the effective area obtained in TSA is to compare expediently between TIM and TSA.

From the data of Table 1 and the curve of Fig. 3, with increasing power, i.e. with rising junction temperature, it is evident that the difference in peak junction temperature between that obtained in SEM and the actual value (obtained in TIM), becomes larger. In other words, with rising junction temperature, the result measured by SEM deviates more from the actual status. However, the junction temperature measured by TSA surrounds the actual values better, and the deviation is smaller. This indicates that the TSA gets better anastomosis with TIM, and is more preponderant than SEM. In Fig. 4, another device, the 17# sample, is measured by the three methods, and the result is same with the above 10# sample.

From the above comparison, it indicates that the TSA method, as an electrical measurement method, can get a result close to the actual peak junction temperature of the device. Therefore, TSA is better than TIM at non-destructive measurement, and more scientific, more reasonable and more exact than SEM at measuring peak junction temperature and non-uniform property.

4. Conclusion

TSA of transistors, presented in this paper, is a completely electrical measurement method of peak junction temperature and non-uniform property of a transistor. It inherits the advantage of electrical measurement, i.e. non-destructive measurement, to measure both finished and semi-finished devices. Moreover, it also has the advantage of the thermal infrared method, i.e. that it can measure peak junction temperature and the non-uniform property. In the associated experiment among TSA, SEM and TIM, the result of TSA gets better anastomosis with TIM.

In the paper, the simplest parallel model, the dual sub-transistor parallel model, is used in the TSA method. With an increase in the amount of sub-transistors in the model, the analytic complexity increases hugely; however, the analytic result of junction temperature distribution will be more exact, closer to the real status, and have higher resolution. If actual applications are considered, the dual sub-transistor parallel model is more applicable than the multi sub-transistor parallel model.

The least number of physical quantities, only peak junction temperature T_P and effective area A_E, are required to characterize distribution status of junction temperature[5]. Based on the above two parameters of TSA, the reliability analysis and assessment will not only be simpler to use but also more exact, more scientific, and more reasonable than that based only on the average junction temperature of the standard electrical method. Therefore, the thermal spectrum analysis method will be one of the future trends in the development of reliable analysis technology.

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