The Convergence Characteristic of the Forward *I-V* Characteristic Curves of a Semiconductor Silicon Barrier at Different Temperatures*

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Abstract: The *I-V-*(*T*) characteristic curves of p-n junctions with the forward voltage as the independent variable, the logarithm of forward current as the dependent variable, and the junction temperature as the parameter, almost converge at one point in the first quadrant. The voltage corresponding with the convergence point nearly equals the bandgap of the semiconductor material. This convergence point can be used to obtain the *I-V* characteristic curve at any temperature.

Key words: semiconductor barrier; bandgap; convergent point; forward *I-V* characteristic curves
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1 Introduction

In output characteristics of common-emitter configurations, the collector current I_C of the transistor increases as the collector-emitter voltage V_{CE} increases. Extrapolated output curves corresponding to different base currents almost meet at one point on the axis of V_{CE}, and the corresponding voltage V_A is called early voltage[1]. This phenomenon is called the early effect. In addition to the convergent point of the early effect, there is another convergent point about the performance of the transistor. The forward voltage of a p-n junction with constant current is a temperature sensitive parameter and has been used in the thermal resistance standards IEC 747 and IEC60747-7.[2,3] The *V-T-*(*I*) characteristics of a p-n junction with the junction temperature as the independent variable, the forward voltage as the dependent variable, and the forward current as the parameter have been the emphasis of research.[4~7]

A new analysis method[8] for infrared thermogram of transistors has been invented and important progress[9] on the *V-T-*(*I*) characteristics of a p-n junction has been reached with this method. The excessive thermotaxis effect of low current can be used to study the uniformity of the junction temperature distribution. The relationship between the forward voltage and the temperature with a constant current when the temperature ranges from 0 to 150℃ is nearly a beeline. One beeline corresponds to one current, and, extending the beelines corresponding to different currents, these beelines will almost converge at a point whose temperature is near absolute zero. The coordinate of the convergent point ranges because of differences in the semiconductor material.

This convergence characteristic was used to measure the junction temperature of a transistor on special equipment. Similar to this convergence characteristic, we found a new convergence characteristic of a p-n junction. The curve with the forward voltage as the abscissa, and the logarithm of the corresponding current as the ordinate at the same temperature is nearly a beeline if the series-wound resistance is ignored. If we extend the beelines for different temperatures, these beelines will almost converge at a point in the first quadrant.

2 Experimental results

A STS 2103B discrete semiconductor device test system (Beijing Huafeng Test & Control Technology Co., Ltd) was used for measurements. To connect the base and the emitter of a transistor to the apparatus, low current flows from the base to the emitter, and then measures the base-emitter voltage V_{BE}. The value of the current can be set by the computer. We put the transistor in a constant temperature oven and set the temperature. Different values of V_{BE} corresponding to different I_{BE} are measured after the temperature stabilized. The current values of 1, 2, 5, 10 and 20mA were taken, and measurements were performed every 30℃ from 25 to 145℃. The data we obtained was called the base data.

Figure 1 shows the characteristic curves measured with the voltage as the abscissa and the common log-

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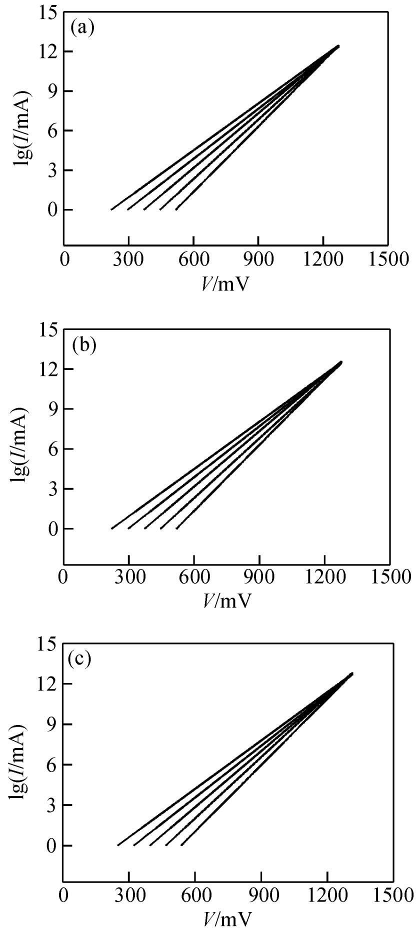

Fig. 1 Convergence characteristic of I-V characteristic curves of different transistors (The temperatures corresponding to the five lines in figure (a) are 145, 115, 85, 55, and 25℃ from left to right in order.) (a) 3DD15; (b) 3DD102; (c) 2SD850

arithm of the current as the ordinate and junction temperature as the parameter. If we extend the five curves corresponding to the values of the temperature, these curves almost converge at a point in the first quadrant. The points of intersection corresponding to the different curves do not overlap well, but are dispersed. Because the difference of the abscissa of every two convergent points is relatively small, we can consider that they converge at one point, and the average of the abscissa of all convergent points is the abscissa of the holistic convergent point.

The types of the three transistors measured are 3DD15, 3DD102, and 2SD850, respectively. 3DD15 and 3DD102 are widely used low-frequency and high-power transistors made in China. They are commonly used in TV, audio, and UPS as power supply adjust transistors, switch transistors, and power output transistors. 2SD850 is a high-negative-voltage and high-power switch transistor. It is mainly used in color TVs and computer displays as a switch power supply transistor and row output transistor. The package types of the three types of transistors used in this experiment are all F-2. Dealing with their base data with the method mentioned above, Fig. 1 is obtained. Fig. 1 shows that the voltage is nearly 1272mV corresponding to the convergent point for 3DD15, the voltage is nearly 1260mV corresponding to the convergent point for 3DD102, and the voltage is nearly 1300mV corresponding to the convergent point for 2SD850.

3 Theoretical analysis

For an ideal p-n junction, the relationship between its forward current I_F and its forward voltage V_F is

$$I_F = I_s\left(\exp\left(\frac{qV_F}{nkT}\right) - 1\right) \tag{1}$$

where q is the electron charge, k is Boltzmann's constant, T is the temperature of the p-n junction, n is the injection ratio, and I_S is the reverse saturated current, which is a function of the bandgap of the semiconductor material and the temperature and its approximate expression is

$$I_s = BT^{\gamma}\exp\left(-\frac{qV_{g0}}{nkT}\right) \tag{2}$$

where B is the structure factor of the device, which is a constant for the device. Gamma is a constant and is larger than 2.5. In the range of $0\text{K} \leqslant T \leqslant 423\text{K}$, $V_F \geqslant 10^2\text{mV}$, $\exp\left(\frac{qV_F}{nkT}\right) \gg 1$, so

$$I_F = I_s\left(\exp\left(\frac{qV_F}{nkT}\right) - 1\right) \cong I_s\exp\left(\frac{qV_F}{nkT}\right) \tag{3}$$

Substituting Eq. (2) into Eq. (3) gives

$$I_F = BT^{\gamma}\exp\left(\frac{q(V_F - V_{g0})}{nkT}\right) \tag{4}$$

Calculating the logarithm of Eq. (4) and we obtain

$$\ln I_F = \ln B + \ln T^{\gamma} + \frac{q(V_F - V_{go})}{nkT} \tag{5}$$

Then, the two equations corresponding to temperatures T_1 and T_2, respectively, are

$$\ln I_F = \ln B + \ln T_1^{\gamma} + \frac{q(V_F - V_{go})}{nkT_1} \tag{6}$$

$$\ln I_F = \ln B + \ln T_2^{\gamma} + \frac{q(V_F - V_{go})}{nkT_2} \tag{7}$$

The solution for V_F and $\ln I_F$ can be obtained from Eqs. (6) and (7) and is given by

$$V_F = V_{go} + \frac{nkT_1T_2\gamma}{q(T_2 - T_1)}\ln\left(\frac{T_2}{T_1}\right) \tag{8}$$

$$\ln I_F = \ln B + \gamma\frac{T_2\ln T_2 - T_1\ln T_1}{T_2 - T_1} \tag{9}$$

Thus, the coordinate of the point of intersection is $(V_F, \ln I_F)$, and the abscissa V_F relates to T_1, T_2, n, and γ, and the ordinate $\ln I_F$ relates to T_1, T_2, B, and γ. If $T_1 = 25℃ = 298.15\text{K}$, $T_2 = 145℃ = 418.15\text{K}$, $k = 1.38 \times 10^{-23}$, $n = 1.1$, $\gamma = 4$, the solution obtained

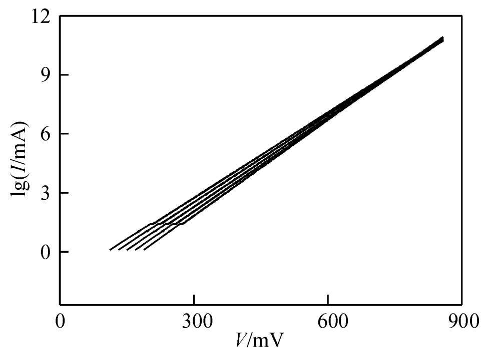

Fig. 2 Convergence characteristic of *I-V* characteristic curves of the Schottky diode The temperatures corresponding to the five lines in Fig. 2 are 65, 55, 45, 35, and 25℃ from left to right.

from Eq. (8) is: $V_F = V_{g0} + 133\text{mV}$. When T_1 and T_2 are nearly the same, Equations. (8) and (9) can be reduced to

$$V_F = V_{go} + \frac{nkT_1\gamma}{q} \tag{10}$$

$$\ln I_F = \ln B + \gamma + \gamma \ln T_1 \tag{11}$$

From Eq. (10), V_F increases as T_1 increases. When $T_1 = 25℃ = 298.15\text{K}$, $V_F = V_{g0} + 113\text{mV}$; when $T_1 = 145℃ = 418.15\text{K}$, $V_F = V_{g0} + 158\text{mV}$. From this result, we find that V_F equals the summation of the value of the bandgap V_{g0} and $nkT_1\gamma/q$, and the latter in proportion to V_F is very small.

From the manual, we obtained the breakdown voltages of the three transistors, which differ from each other. The breakdown voltage of 3DD15 is higher than that of 3DD102, but lower than that of 2SD850. The differences in the breakdown voltages mean a difference in the doping concentration in the base, and when the breakdown voltage is lower, the doping concentration is higher. So the bandgap of 3DD15 is higher than that of 3DD102, but lower than that of 2SD850. According to the result of the theoretical analysis and Fig. 1, the bandgap of 3DD15 is 1140mV.

We performed similar measurements for a Schottky diode. The values for current of 1.25, 2.5, 5.0, 10.0, 12.5, and 25.0mA were selected. Measurements were taken every 10℃ from 25 to 65℃, and the base data of this Schottky diode was obtained. The characteristic curves with the voltage as the abscissa, the common logarithm of the current as the ordinate, and the junction temperature as the parameter are shown in Fig. 2. If we extend the five lines in Fig. 2 corresponding to the five temperatures, these lines will almost converge at a point in the first quadrant. Fig. 2 shows that the voltage is 860mV, corresponding to the convergent point. The value of the voltage is close to the Schottky barrier height of silicon, which is about 800mV, and the difference can be considered as the value of $nkT_1\gamma/q$. The value of $nkT_1\gamma/q$ in proportion to the forward voltage V_F corresponding to the convergent point is very small, which is similar to the case of the p-n junction. The result of the Schottky diode proves the physical meaning of the convergent point again.

4 Application

The convergent point of the *I-V* characteristic curves in the first quadrant can be used to obtain base data at any temperature. The type of the transistor that we used is 3DD15. Measuring the base data every 15℃ from 25 to 130℃, the curve corresponding to a temperature is a beeline approximately with the voltage as the abscissa and the common logarithm of the current as the ordinate. If we extend the eight beelines corresponding to the eight temperatures, these beelines will almost converge at a point in the first quadrant. The figure demonstrates that the abscissa is 1273mV and the ordinate is 12.45, corresponding to the convergent point. Regarding the temperature as the independent variable and the slope of each beeline with corresponding temperature as the dependent variable, a group of regression coefficients is obtained. The relation between the slope and the temperature can be expressed with the group of regression coefficients shown in Eq. (12)

$$n = -4.026978 \times 10^{-10} \times T^3 + 2.131939 \times 10^{-7} \times T^2 - 6.523500 \times 10^{-5} \times T + 0.018013 \tag{12}$$

where n is the slope, T is the temperature. The slope of the beeline corresponding to 145℃ can be obtained from Eq. (12). In this way, we not only know the slope of the beeline, but also know that this beeline passes the convergent point, so the *I-V* characteristic curve corresponding to 145℃ can be drawn. The forward voltage corresponding to the different forward currents can be calculated with the slope and the coordinate of the convergent point, which can be seen in Eq. (13).

$$V_F = 1273 - (12.45 - \ln I_F)/n_1 \tag{13}$$

In Eq. (13), the units of V_F and I_F are mV and mA, respectively, and n_1 represents the slope of the beeline corresponding to 145℃. In Table 1, the calculated value is the forward voltage calculated with the slope and the coordinate of the convergent point, and the measured value is the forward voltage measured at 145℃. The table indicates that the largest error of the calculated values is only 1.325mV. It is feasible to calculate the base data with this method.

We have delivered papers to demonstrate an error in the principle figure and the waveform figure of the thermal resistance standard IEC747-7, which de-

Table 1 Contrast of the measured value and the calculated value of the forward voltage corresponding to the different forward current

Forward current /mA	Forward voltage (measuring value) /mV	Forward voltage (calculating value) /mV	Error /mV
1	220.0	218.675	1.325
2	245.0	244.168	0.832
5	278.0	277.867	0.133
10	304.0	303.360	0.640
20	330.0	328.853	1.147

scribes the relation between the *I-V* curves and the temperature[10]. In fact, we can demonstrate this error more simply with the convergence characteristic in this paper. The thermal resistance standard in IEC747-7 is widely accepted and has been used until now. Fig. 3 shows the corresponding Figs. 23 and 24 in IEC 747-7. Fig. 3(a) has two *I-V* curves, which are *I-V* curves of the emitter current (I_E) and emitter-base voltage (V_{EB}) at the junction temperatures $T_j^{(1)}$ and $T_j^{(2)}$, $T_j^{(1)} > T_j^{(2)}$. ΔV_{EB} is defined as the horizontal distance between the two curves. Fig. 3(b) in IEC747-7 is the waveform of the heating current, measuring current, and emitter voltage for measuring the thermal resistance corresponding to Fig. 3(a). In Fig. 3, V_1 and V_4 is the emitter-base voltages when the emitter current is I_M and the junction temperatures are $T_j^{(1)}$ and $T_j^{(2)}$, respectively. V_2 and V_3 is the emitter-base voltages with the emitter current being $I_M + I_H$

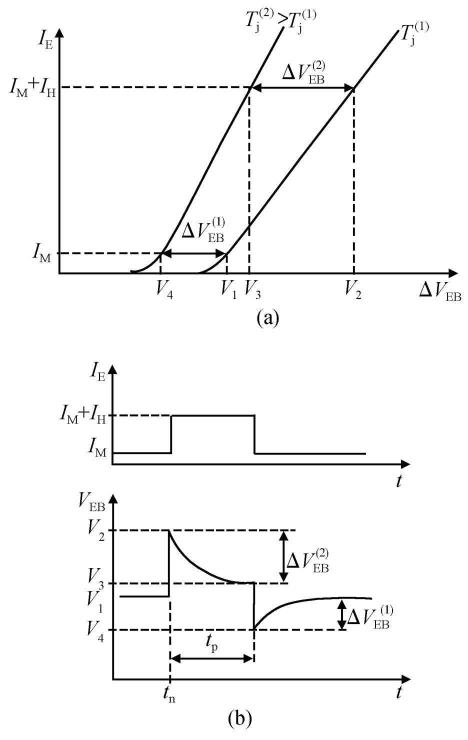

Fig. 3 Transistor *I-V* character curves and the waveform figure for measuring the thermal resistance in IEC standard (a) Fig. 23 in IEC747-7; (b) Fig. 24 in IEC747-7

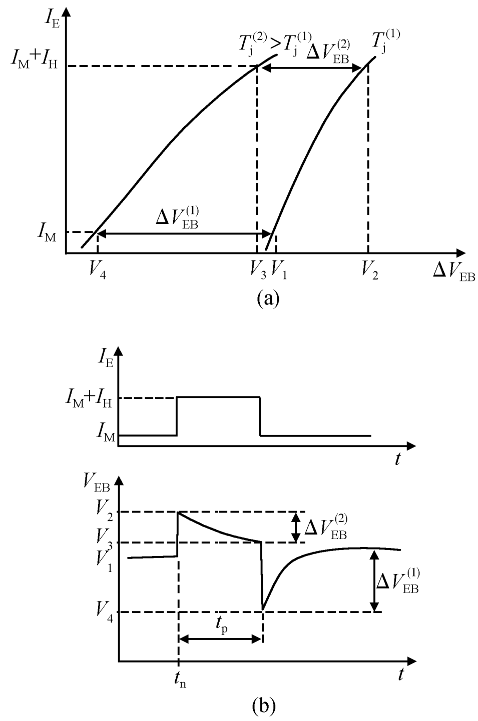

Fig. 4 Transistor *I-V* character curves and the waveform figure for measuring the thermal resistance after our correction (a) Fig. 23 in IEC747-7; (b) Fig. 24 in IEC747-7

and the junction temperatures being $T_j^{(1)}$ and $T_j^{(2)}$, respectively. $\Delta V_{EB}^{(1)} = V_1 - V_4$, $\Delta V_{EB}^{(2)} = V_2 - V_3$. The shape and position of the two curves in Fig. 3(a) in IEC747-7 show that $\Delta V_{EB}^{(2)}$ is larger than $\Delta V_{EB}^{(1)}$. Similar to Fig. 3(a), the waveform of Fig. 3(b) also shows the same result. That ΔV_{EB} increases with the current implies that the trend of the two curves' space is spread. However, this falls short of the theory and experimental findings that $\ln I_F$-V_{BE} curves converge at one point in the first quadrant. The corresponding figures to support our correction are shown in Fig. 4.

5 Conclusions

(1) The *I-V* characteristic curves of p-n junction with the voltage as the independent variable, the logarithm of the current as the dependent variable, and the temperature as the parameter, almost converge at a point in the first quadrant.

(2) The physical meaning of the coordinates of the convergent point is that the forward voltage V_F corresponding to the convergent point equals the summation of the value of the bandgap V_{g0} and $nkT_1\gamma/q$, which varies with the temperature. The $nkT_1\gamma/q$ is far less than V_{g0}.

(3) Though the points of intersection corresponding to the different curves do not overlap completely, because the difference of the abscissa of every two convergent points is relatively small, we can con-

sider that they converge at one point. The average of the abscissa of all convergent points is the abscissa of the holistic convergent point. There are differences in the bandgaps of semiconductor materials in different transistors, so there are differences in the abscissas of the convergent points.

(4) The convergent point of the *I-V* characteristic curves in the first quadrant can be used to calculate the *I-V* characteristic curve at a given temperature. The error is very small for calculation of concrete instances, which proves that calculating the base data with this method is feasible.

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不同温度下半导体硅势垒的正向 *I-V* 特性曲线的汇聚特性*

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摘要：以正向电压为自变量，以正向电流的对数为应变量，以温度为参数得到的 p-n 结的 *I-V*-(*T*)特性曲线在第一象限中近似汇聚于一点. 汇聚点对应的电压近似等于半导体材料的禁带宽度. 汇聚点可以用来获取任意温度下的 *I-V* 特性曲线.

关键词：半导体势垒；禁带宽度；汇聚点；正向 *I-V* 特性曲线

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