# MEASUREMENT OF JUNCTION TEMPERATURE

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# JUNCTION TRANSISTORS

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## ABSTRACT

Measurement methods of junction temperature for the triode junction transistor, such as the switching methods and the continuous methods, are described and discussed.

A sweep method using a sweep circuit of full-wave rectified sinusoidal pulses is proposed. Junction temperature variation during the sweep period is mathematically analyzed.

Measurements of the junction temperature of a silicon transistor were performed employing both the sweep method and the continuous method, and the results were compared.

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# CHAPTER I

## INTRODUCTION

Transistors are inherently temperature sensitive devices. Their operation is greatly affected by the junction temperature. Having fully recognized the importance of an accurate determination of such a property, many measurement methods have been proposed. However, up to the present time, great differences still exist among the results obtained from the existing methods.[1*] Even those values accepted as the standard ones are regarded as being optimistic.[2,3] Further exploration in the development of a more satisfactory method of measurement seems necessary.

The existing measuring methods take advantage of the fact that the transistor is itself an electrical thermometer. Some electrical parameters of the transistor, under certain conditions, vary directly with the junction temperature. A transistor parameter which can be measured and used to indicate the junction temperature is called a temperature sensitive parameter, abbreviated TSP.

As is well known, the collector reverse saturation current $I_S$, the intrinsic emitter-base forward-biased voltage $V'_{EB}$, and the intrinsic common-base short circuit input impedance $h'_{ib}$ show definite variations with the junction temperature. $I_S$

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* The numeral denotes the reference number as listed in the bibliography.

increases exponentially with junction temperature; $V_{EB}'$ has a negative temperature coefficient of approximately -2 to -2.5 mv/°C; and $h_{ib}'$ is directly proportional to junction temperature.

In practical measurements, however, second order effects may predominate when the applied electrical stresses (bias voltages or bias currents) are large. The leakage current may mask the reverse-biased saturation current $I_S$; the transverse voltage drop across the base region (the product of base current $I_B$ and d.c. base resistance $R_B$) may overshadow the intrinsic $V_{EB}'$; and the incremental base resistance $r_b'$ may constitute a large portion of the measured extrinsic input impedance $h_{ib}$. Hence, in order to assure that second order effects are negligibly small, the measured parameter should fall within the values estimated from theoretical considerations.

Furthermore, during the measurement of junction temperature, the applied electrical stress must be varied (as described in the next paragraph). An electrical parameter of a transistor, besides its relationship with junction temperature $T_J$, is inevitably influenced by the variation of the applied electrical stress. If the transistor under test is connected in a common-base configuration, a d.c. constant emitter current $I_E$ is injected, and a d.c. reverse-biased constant collector voltage $V_{CB}$ is applied, the TSP is then a function of $I_E$, $V_{CB}$ and $T_J$, or TSP = $f(I_E, V_{CB}, T_J)$. The dissipation of electrical power inside the transistor, (approximately equal to $V_{CB}I_E$), will cause $T_J$ to rise. Therefore, the TSP is affected by both direct electrical effects and indirect thermal effects of the applied electrical stress. Measuring techniques must be devised such that the electrical effects of the electrical stress on the TSP can be kept constant when the electrical stress is varied. In the following description of the measurement principle, the TSP will be assumed to be capable of indicating $T_J$. The measuring techniques will be discussed in detail in the following chapters.

Methods for the measurement of $T_J$ under conditions of thermal equilibrium fall into two categories, the constant junction temperature method (or substitution method[4,5]) and the constant reference temperature method.[6] These two methods are described as follows:

(a) The constant junction temperature method.

This method is based on the concept of thermal resistance, $\theta$, of a transistor. The thermal resistance of a transistor is defined as the effective junction temperature rise per unit power dissipation above the temperature of a stated external reference point under conditions of thermal equilibrium.[7*]

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* Thermal equilibrium has been reached between the junction and the external reference point when the difference of the junction temperature and the external reference temperature does not change with time.[8]

This definition may be expressed in mathematical form as:

$$\theta_{JR} = \frac{T_J - T_R}{P} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1.1)$$

where $T_J$ is the junction temperature of either the junction between collector and base or the junction between emitter and base,

$T_R$ is the reference temperature measured at a specified reference point outside the transistor under test. $T_R$ may be $T_A$, the ambient temperature; or may be $T_C$, the transistor case temperature,

P is the electrical power dissipated at the junction of the transistor, P is approximately equal to the measurable electrical operating power applied to the test transistor,

$\theta_{JR}$ is the thermal resistance between the junction and the specified reference point determined under conditions of thermal equilibrium. $\theta_{JR}$ may be $\theta_{JA}$, the thermal resistance between junction and the ambient thermal reference point, or it may be $\theta_{JC}$, the thermal resistance between junction and the case of the transistor.*

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* Hereafter, 'the case' stands specifically for 'the case of the transistor'.

Therefore, the junction temperature $T_J$ can be obtained from the following relationship:

$$T_J = P\theta_{JR} + T_R \quad \text{......................} \quad (1.2)$$

or $$T_J = P\theta_{JA} + T_A \quad \text{......................} \quad (1.2a)$$

or $$T_J = P\theta_{JC} + T_C \quad \text{......................} \quad (1.2b)$$

From equation (1.2a), it can be seen that $T_J$ comprises two components, $T_A$ and $(P\theta_{JA})$. $T_A$ is due to the external ambient thermal stress. $(P\theta_{JA})$ is due to the internal thermal stress which results from the applied electrical stresses. Varying the external electrical and thermal stresses at a constant $T_J$ value as indicated by the measured TSP, $\theta_{JA}$ can be determined.

The measurement of the thermal resistance is carried out by placing the test transistor in a temperature controlled environment (e.g., an oven). The temperature of the reference point $T_R$ is then adjusted by regulating the temperature controlled environment. At the same time, an adjustable electrical power P is also applied. The junction temperature $T_J$ is thus indicated by the TSP measured.

The measurement procedure consists of two steps. P and $T_R$ are first set at arbitrary values $P_1$ and $T_{R_1}$ within the operating limitations of the test transistor. The TSP which is then measured and denoted as $(TSP)_1$ will indicate the junction temperature $T_{J_1}$.

$$T_{J_1} = P_1\theta_{JR} + T_{R_1} \quad \text{....................} \quad (1.3)$$

P is then increased (or reduced) to $P_2$, and $T_R$ is lowered (or raised) to $T_{R_2}$, such that the measurement of $(TSP)_2$ is maintained at the same value as $(TSP)_1$, i.e., $(TSP)_1 = (TSP)_2$. Therefore,

$$T_{J_1} = T_{J_2} \quad \text{.................................} \quad (1.4)$$

and

$$T_{J_2} = P_2\theta_{JR} + T_{R_2} \quad \text{.........................} \quad (1.5)$$

The thermal resistance $\theta_{JR}$ can thus be determined from the measured quantities:

$$\theta_{JR} = \frac{T_{R_2} - T_{R_1}}{P_1 - P_2} = \frac{\Delta T_R}{\Delta P} \quad \text{................} \quad (1.6)$$

The junction temperature under conditions of thermal equilibrium can then be calculated from the knowledge of the electrical operating power P, the reference temperature $T_R$ and $\theta_{JR}$ determined by the above measurement, provided that $\theta_{JR}$ is a constant, or at least that the variation of $\theta_{JR}$ is small with the variation of the applied electrical and thermal stresses.

(b) The constant reference temperature method.

In this method, the test transistor is placed in a temperature controlled environment, and electrical power is applied to the test transistor as in the case of the constant junction temperature method. The TSP is measured to indicate junction temperature. The measurement procedure consists of two steps.

In the first step, a constant electrical stress of small size is applied to the test transistor. Since the electrical stress introduces a negligibly small thermal effect, the reference temperature (in this case, the same as the temperature of the temperature controlled environment) can be taken as the $T_J$ of the test transistor and a calibration curve of $T_J$ against the measured TSP can be plotted.

In the second step, the test transistor is operated under electrical and thermal stresses within the range of the transistor. The TSP is then measured. The junction temperature $T_J$ for these operating conditions can be inferred from the measured TSP of the second step using the calibration curve of the first step.

This method may be viewed as a limiting case of the constant junction temperature method. As from equation (1.3), it is obvious that $T_{J_1}$ will be approximately equal to $T_{R_1}$, if the temperature rise due to the electrical power ($P_1 \theta_{JR}$) is much smaller than $T_{R_1}$. Therefore, the only difference in the measurement procedure of the constant junction temperature method and the constant reference temperature method is that in the latter case the electrical power $P_1$ approaches zero, and the $\theta_{JR}$ can be determined as follows. In equation (1.6), $T_{R_1} = T_{J_1} = T_{J_2}$, and $P_1 << P_2$, therefore $\theta_{JR} = (T_{J_2} - T_{R_2})/P_2$. Dropping the numeral 2 in the subscript of each symbol,

$$\theta_{JR} = \frac{T_J - T_R}{P} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1.7)$$

where P and $T_R$ are respectively the electrical operating power and the reference temperature measured in the second step of the measurement procedure. $T_J$ as represented by the TSP measured in the second step, can be deduced from the $T_J$ vs TSP calibration curve as obtained in the first step.

In both the constant junction temperature method and the constant reference temperature method, the electrical operating power P may be produced by either direct-current or periodically varying electrical stresses, according to measuring techniques. When periodically varying electrical stresses are employed, another thermal parameter of the transistor, the thermal time constant $\tau$ must be taken into consideration. $\tau$ is the product of thermal resistance and thermal capacitance $C_{th}$, i.e., $\tau = \theta C_{th}$. The thermal equivalent circuit of the transistor illustrates the physical implication of $\tau$ in the measuring techniques.

Equations (1.2a) and (1.2b) may be represented by thermal equivalent circuit in its electrical analog form in Figure 1.1.[9] $T_J$ is analogous to electrical potential at the junction; $T_C$, electrical potential at the case; P, electrical constant current source; $T_A$, electrical constant voltage source; and $\theta$, electrical resistance. The static thermal equivalent circuit shown in Figure 1.1 is only valid for the internal electrical power dissipation P constant with respect to time.

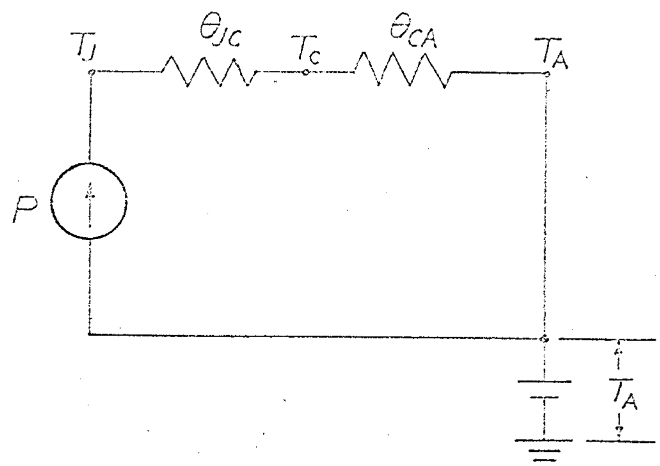


Figure 1.1. Static thermal equivalent circuit of transistor.

When P(t) varies with time, the thermal time constant $\tau$ affects the thermal operation as illustrated in Figure 1.2,[10] where $C_{JC}$ is the thermal capacitance between the junction and the case; and $C_{CA}$, the thermal capacitance between the case and the ambient environment. $\tau_{JC} = \theta_{JC}C_{JC}$; $\tau_{CA} = \theta_{CA}C_{CA}$. The circuit in Figure 1.2 is a lumped model of the transistor thermal equivalent circuit.

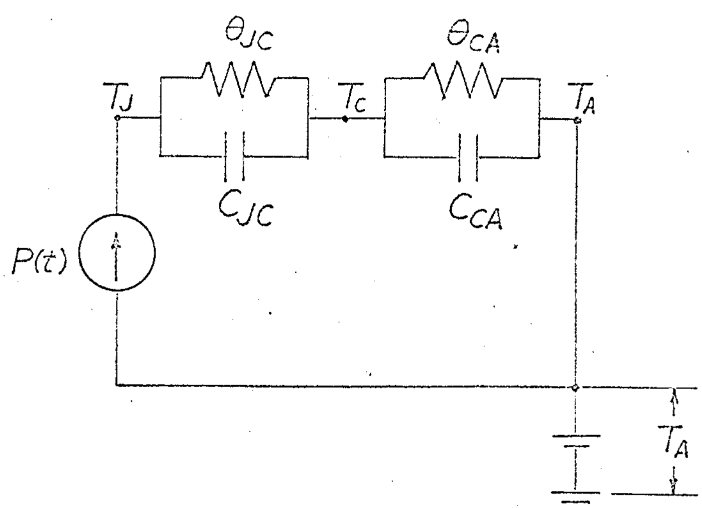


Figure 1.2. Dynamic thermal equivalent circuit of transistor.

In practical devices, both $\theta$ and $C_{th}$ are thermal parameters of a distributed nature, and may be represented by the circuit shown in Figure 1.3.[11]

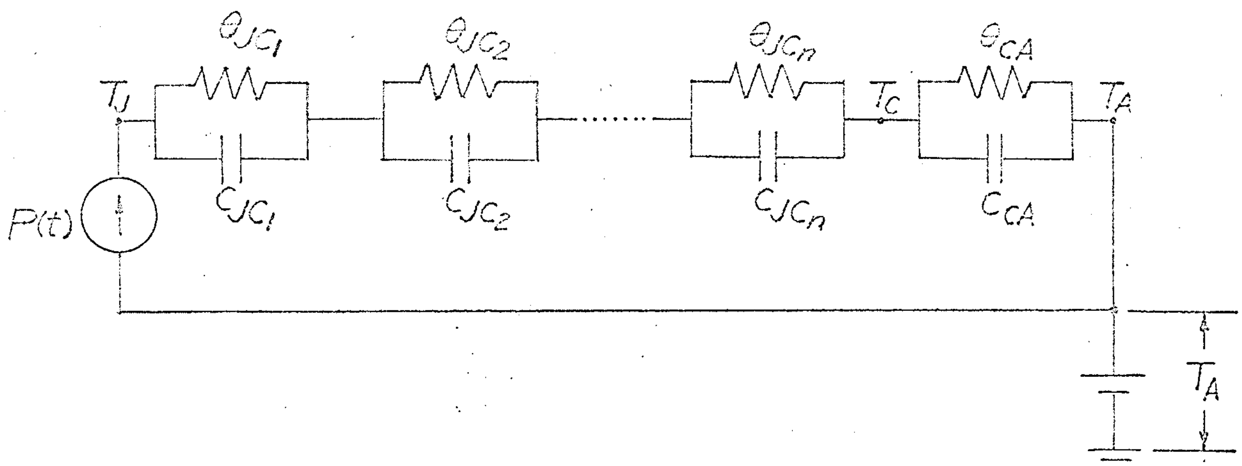


Figure 1.3. Multiple-lumped thermal equivalent circuit of transistor.

During the measurement, if d.c. electrical stresses are applied to the test transistor, the final junction temperature will certainly be constant with respect to time and independent of $\tau$. However, if periodically varying electrical stresses are applied, the variation of the junction temperature with respect to time should be maintained as small as possible such that thermal equilibrium between the junction and the external reference point can be established. It can be seen in Figures 1.2 and 1.3, that as P is varying, the magnitude of $\tau$ will affect the variation of $T_J$ during each cycle of operation, and determine the accuracy of the results obtained by the measuring technique.

The requirements that a measuring technique must meet can then be summarized as follows. Firstly, an electrical parameter can be selected as a TSP such that a theoretical relationship between the selected TSP and the $T_J$ can be formulated. Secondly, the selected TSP must be measured under the condition of thermal equilibrium. Thirdly, the selected TSP must be electrically independent of the variation of the applied electrical stress. If a measuring technique, on the basis of either the constant junction temperature method or the constant reference temperature method, can be devised to meet these requirements, then the $\theta_{JR}$ can be determined; and hence the $T_J$ under thermal equilibrium can be predicted.

CHAPTER II

# SWITCHING METHODS

For an electrical parameter to be suitable as a TSP, it must have a definite relationship with the junction temperature. The functional relationship between TSP and junction temperature can be theoretically formulated for a sufficiently small electrical stress. However, experimental evidence shows that for certain types of transistors when the applied electrical stresses are large, such a relationship becomes complicated beyond the theoretical formulation.[12] Since the magnitude of junction temperature can only be inferred indirectly from the direct measurements of TSP, it is necessary that the determination of junction temperature be conducted with a small electrical stress. Usually a transistor is operated under a large applied bias. Therefore, the determination of the junction temperature produced in such circumstance becomes a delicate problem. For the switching method, the problem is dealt with by using two electrical sources: one of larger operating power for electrically heating the test transistor and the other small constant electrical stress for temperature (or TSP) measurement. A switching device should be included in the circuit, to switch between the heating and measurement cycles alternately. The time interval of the heating period (power-on period) is usually much longer than that of the cooling period (power-off period or measurement period). The TSP is thus measured during the power-off period, or in the switching cooling cycle to indicate the junction temperature.

## 2.1 Military Standard (Rectangular Power Pulses Method)

The switching method has been adopted as a military standard.[2] This method is also recommended in Gates and Johnson's work sponsored by the Electronic Industries Association.[6] The TSP proposed are emitter-to-base forward-biased voltage $V_{EBf}$, collector-to-base forward-biased voltage $V_{CBf}$, and collector-cutoff-current $I_{CBO}$. The measuring circuits using $V_{EBf}$, $V_{CBf}$, and $I_{CBO}$ as TSP are shown respectively in Figures 2.1a, 2.1b, and 2.1c.

In Figures 2.1a, 2.1b, and 2.1c, switches $S_1$ and $S_2$, ganged together, are switched alternately between their respective heat positions $H_1$ and $H_2$ and their respective measurement positions $M_1$ and $M_2$.

When the switches are in their respective heat positions for a heat interval of time $t_{on}$, the circuit connection is the same for either $V_{EBf}$, or $V_{CBf}$, or $I_{CBO}$ used as a TSP. A test transistor is connected in a common-base configuration. Electrical heating power which is applied to the test transistor is produced by a forward-biased emitter current flowing into the emitter from a d.c. constant current source and a reverse-biased collector voltage of a d.c. constant voltage source applied across collector and base. The junction temperature rise above the external reference temperature is caused by the electrical heating power applied during $t_{on}$.

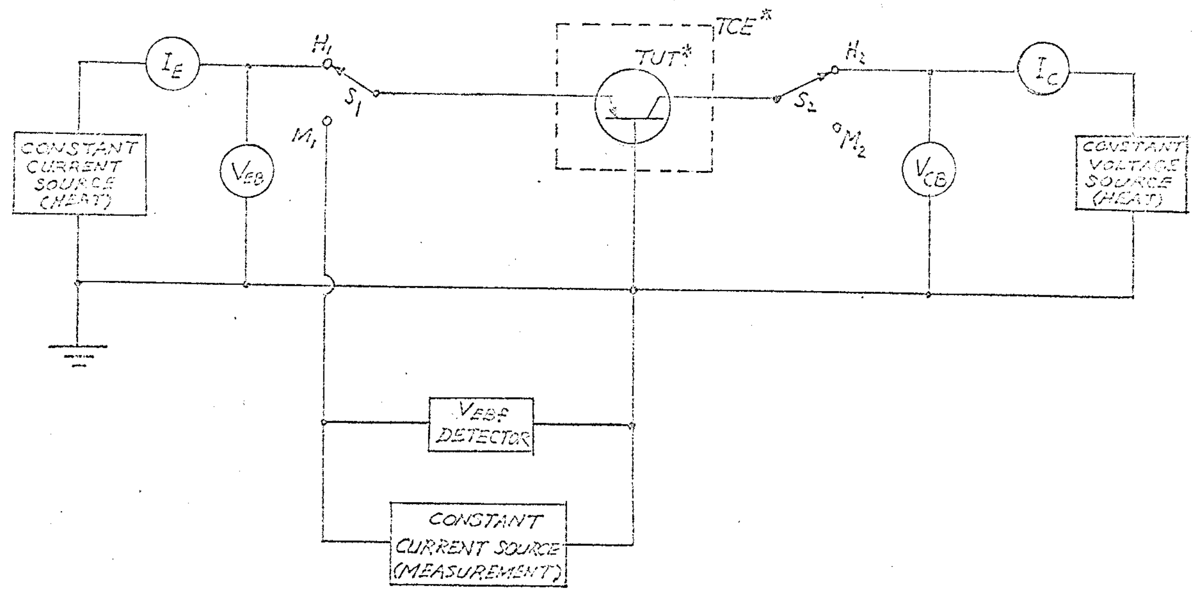


Figure 2.1a. Measuring circuit of switching method using $V_{EBf}$ as TSP.

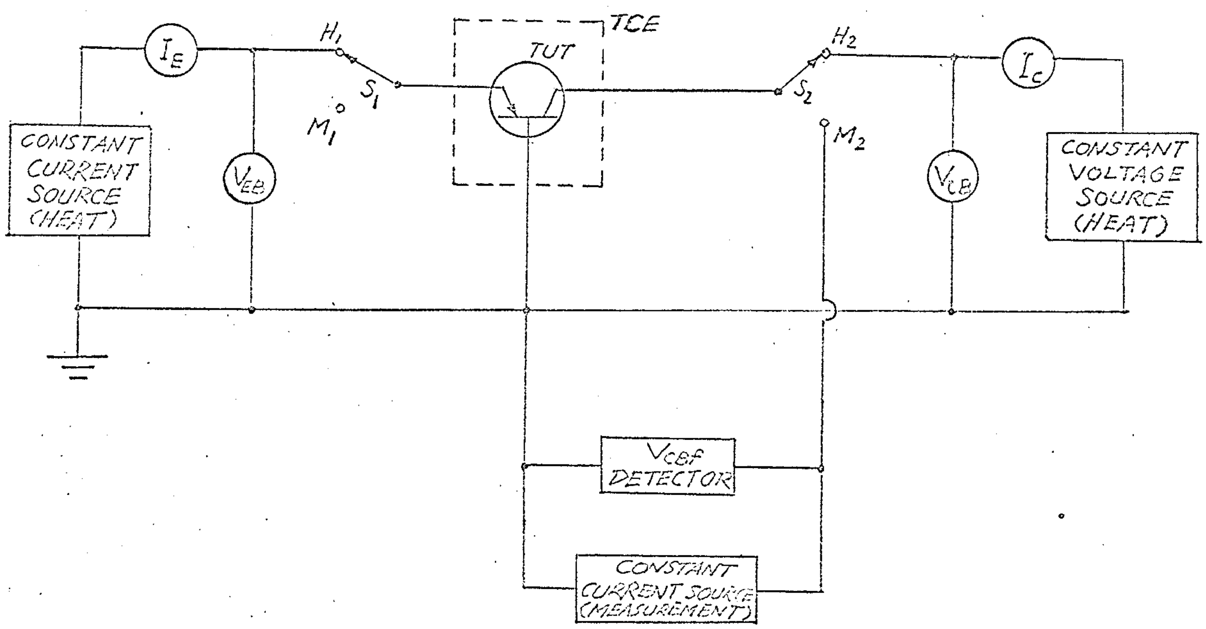


Figure 2.1b. Measuring circuit of switching method using $V_{CBf}$ as TSP.

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* TUT and TCE in Figure 2.1a and in all Figures hereafter stand for the abbreviation of Transistor Under Test and Temperature Controlled Environment respectively.

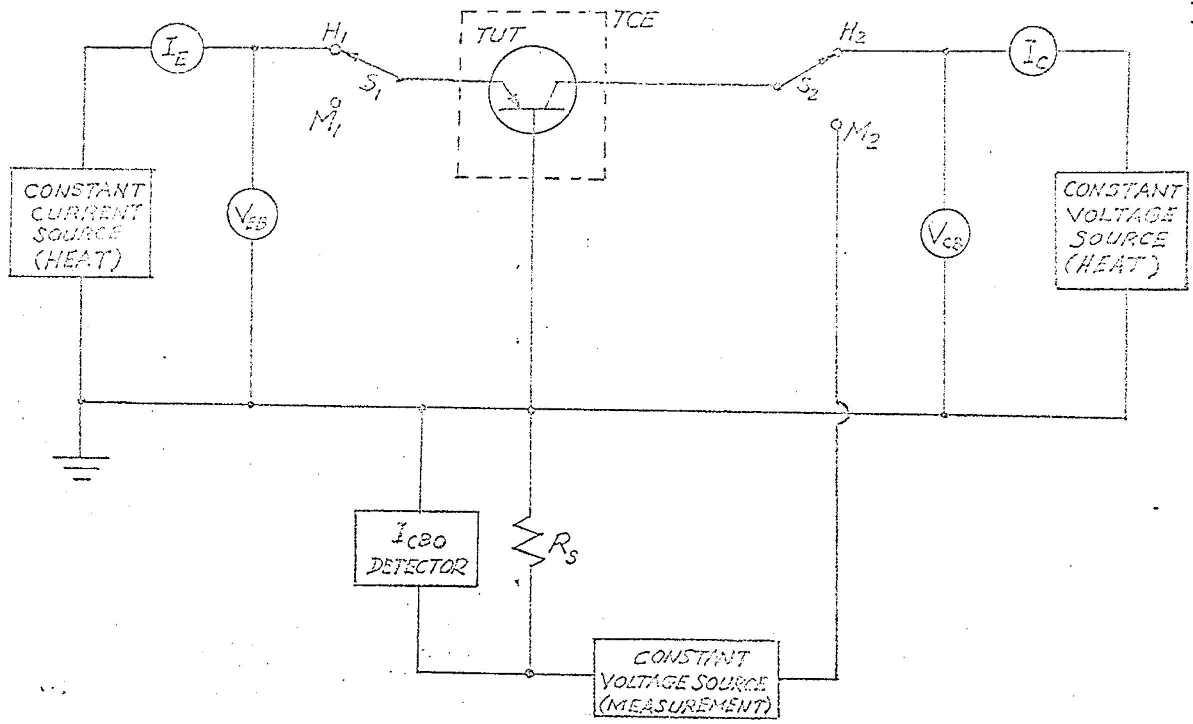


Figure 2.1c. Measuring circuit of switching method using $I_{CBO}$ as TSP.

When switches are in their respective measurement positions for a measurement interval of time $t_{off}$, the electrical heating power is cut off, a small d.c. constant voltage or current source for measurement purposes is applied to the test transistor. When $V_{EBf}$ (or $V_{CBf}$) is used as a TSP, as shown in Figure 2.1a (or Figure 2.1b), the collector (or emitter) is open-circuited, and a small forward-biased emitter (or collector) current is injected into the emitter (or collector) from the current source for measurement purposes. $V_{EBf}$ (or $V_{CBf}$) is read by a detector (e.g., an oscilloscope) connected across the emitter (or collector) and the base. When $I_{CBO}$ is used as a TSP as shown in Figure 2.1c, the emitter is open-circuited, a small reverse-biased voltage of the voltage source for measurement purposes is applied across the collector and the base to cause $I_{CBO}$ to flow. $I_{CBO}$ is read as a voltage drop across a sensing resistor $R_s$ by a detector.

As the electrical heating power is turned on and off alternately, a sequence of rectangular electrical power pulses of average power $P_{avg}$ is thus formed and is applied to the test transistor. $P_{avg}$ may be varied by varying the electrical heating power source (either the voltage or the current source). The test transistor as shown in Figures 2.1a, 2.1b and 2.1c is placed in a temperature controlled environment, the temperature of which is adjustable. By varying $T_R$ and $P_{avg}$, $\theta_{JR}$ $(= \Delta T_R/\Delta P_{avg})$ can then be determined according to the measurement procedures of the constant junction temperature method or the constant reference temperature method as fully described in Chapter I.

The average power $P_{avg}$ of the electrical heating power pulses is equal to $(V_{EB}I_E + V_{CB}I_C)$, where $V_{EB}$, $I_E$, $V_{CB}$, and $I_C$ are respectively the average values of the forward-biased emitter-to-base voltage, emitter current, reverse-biased collector-to-base voltage, and collector current as measured by the meters shown in Figures 2.1a, 2.1b and 2.1c. $T_R$ may be measured by a thermocouple or any temperature-sensitive device.

TSP ($V_{EBf}$, $V_{CBf}$, or $I_{CBO}$) which indicates $T_J$ is read instantaneously at the start of the measurement interval.

As specified in the military standard[2], the duty cycle* should be as large as possible, i.e., $t_{on} >> t_{off}$, and the $t_{off}$ should be much shorter than the thermal response time** of the test transistor, such that the thermal equilibrium will be reached during whole cycle of operation, i.e., $(T_J - T_R) \approx$ constant. Furthermore, a small d.c. voltage is used for the measurement of TSP during $t_{off}$. The TSP thus indicates the $T_J$ and is electrically independent of the variation of the electrical stress for heating purposes. The measuring technique of the switching method therefore satisfies the requirements as mentioned in the last paragraph of Chapter I.

## 2.2 Sinusoidal Power Pulses Method[13,14]

The measurement principle of this method is the same as that of the military standard method, except that during the $t_{on}$, sinusoidal power pulses, instead of rectangular power pulses, are applied to a test transistor. Therefore, the measuring circuits for the military standard method shown in

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* The duty cycle of a sequence of rectangular pulses is equal to $t_{on}/(t_{on} + t_{off})$.

** The thermal response time of a test transistor is defined as the time required for the junction of the test transistor to reach 90% of the final value of junction temperature change following application of a step function of power dissipation under specified conditions.[2]

Figures 2.1a, 2.1b and 2.1c can also be used for the measurement in the sinusoidal power pulses method.

Since in the sinusoidal power pulses method, a condition of thermal equilibrium is maintained by applying a sequence of sinusoidal power pulses of average power $P_{avg}$, the determination of $\theta_{JR}$ ($= \Delta T_R/\Delta P_{avg}$) can be carried out by employing the same measurement procedures as described in the military standard method.

## 2.3 Discussion

In the development of switching methods, the voltage drop across the forward-biased junction has been gradually accepted as the most useful TSP for both germanium and silicon devices.[6] $I_{CBO}$ has been disregarded as a TSP, especially for silicon transistors, because leakage current of silicon transistors varies in an unpredictable manner with respect to temperature.[15]

In the description of the switching methods, the end of the heat period and the start of the measurement period are assumed to occur at the same instant. In the practical measurements, on-and-off switching of electrical power will produce electrical transients. The basic premise of the switching methods is that there will be no appreciable cooling during the interval of the electrical transient immediately after the heating power is switched off. The argument is that the magnitude of the thermal time constant is usually in the order of milliseconds,[10,14,16] while the duration of the electrical transient is usually much smaller, so any masking effect of the electrical transient would induce no serious error in the measurement during the cooling cycle. However, according to some experimenters, the thermal time constant is in the order of microseconds.[17,18] One manufacturer states that for devices with long electrical transient characteristics, accurate thermal measurements will be difficult.[19] Furthermore, considering the distributed nature of thermal characteristics of transistors, Strickland takes a different view of the electrical transient problem.[11] The thermal equivalent circuit of distributed thermal networks is shown in Figure 2.2*; there are n thermal networks. When electrical heating power P is

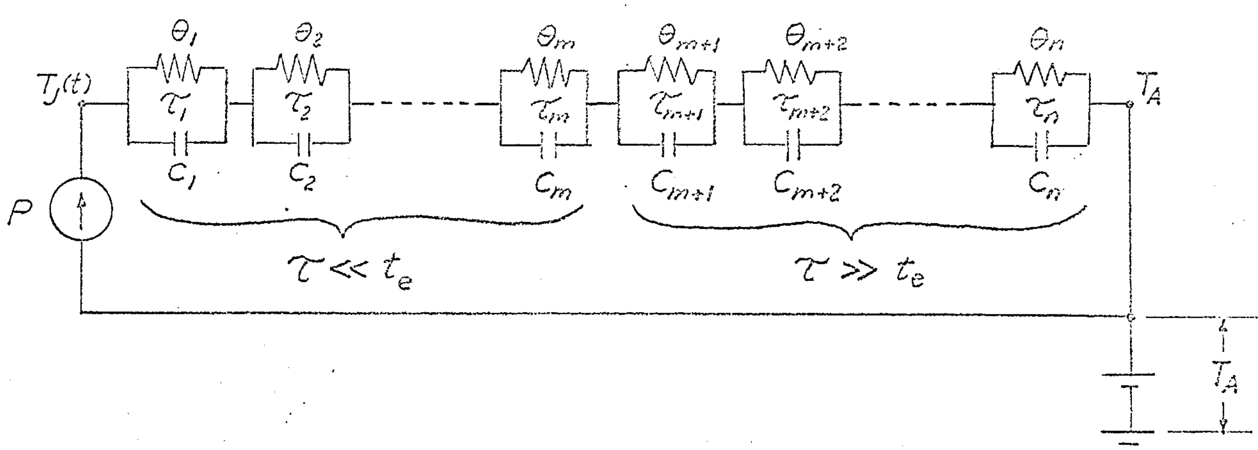


Figure 2.2. Thermal equivalent circuit of distributed thermal networks.

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* Figure 2.2 differs from Figure 1.3 in notations, for clarity in explanation.

suddenly switched off at time $t = 0$, $T_J$ decays exponentially according to the $\tau$ of each thermal network.

$$T_J(t) = P\sum_{n=1}^{n}\theta_n \exp(-\frac{t}{\tau_n}) + T_A \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2.1)$$

If the duration of the electrical transient is $t_e$, then

$$T_J(t_e) = P\sum_{n=1}^{n}\theta_n \exp(-t_e/\tau_n) + T_A \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2.1a)$$

where $T_J(t_e)$ is the junction temperature at the end of the electrical transient. Thus $T_J(t_e)$ not only depends upon $\tau$ and $t_e$, but also varies directly with $\theta$. To evaluate the effect of $\theta$ on the junction temperature drop during the electrical transient period, it is assumed that in m of the n thermal networks the $\tau$ of each m thermal network is much larger than $t_e$, then equation (2.1a) becomes

$$T_J(t_e) = P\left[\sum_{m=1}^{m}\theta_m \exp(-t_e/\tau_m) + \sum_{n=(m+1)}^{n}\theta_n \exp(-t_e/\tau_n)\right] + T_A \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2.1b)$$

for $\tau_n >> t_e >> \tau_m$, $[n = (m+1), (m+2), \ldots, n;\ m = 1, 2, \ldots, m.]$

$$T_J(t_e) = P\sum_{n=(m+1)}^{n}\theta_n + T_A \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2.1c)$$

The junction temperature at $t=0$ is equal to $P\left[\sum_{m=1}^{m}\theta_m + \sum_{n=(m+1)}^{n}\theta_n\right]$, then the junction temperature drop at the end of the electrical transient will be $P\sum_{m=1}^{m}\theta_m$. Admitting the fact that there could be m thermal networks with $\tau$ of magnitude as low as microseconds, Strickland opines that $\sum_{m=1}^{m}\theta_m$ would constitute only a small portion of total $\sum_{n=1}^{n}\theta_n$, and the temperature drop at the end of the electrical transient would be negligible. In any case, no reliable experimental data is available for the period immediately following the power pulse because the electrical and the thermal effects have not yet been separated for this portion of the cycle.[20,21] That is, the amount of error introduced in the measurement of $\theta$ due to the temperature drop during the electrical transient interval is uncertain.

# CHAPTER III

## CONTINUOUS METHODS

In the switching method, the possible error of the measured results is due to the cooling effect during the electrical transient interval of time. To avoid this cooling effect, the electrical heating power must not be interrupted. Thus the electrical stresses used for heating purposes must be simultaneously utilized for measuring the TSP.

The electrical stresses for heating purposes are usually of large size. When a large value of electrical stresses is applied to a test transistor, the second order effects in the measured TSP may become predominant, and the theoretical relationship between the TSP and $T_J$ may no longer hold true. Therefore, in continuous methods, the experimental results must be verified for their agreement with the theoretical values.

According to the measurement principle of the constant junction temperature method and the constant reference temperature method, during the measurement the applied electrical stress is varied from one value in the first measurement step to another value in the second measurement step. The purpose of varying the electrical stress is to vary the internal thermal stress. The reading of the TSP should indicate only the variation of the internal thermal stress. However, the variation of both the indirect thermal effect and the direct electrical effect of the electrical stress will cause the TSP to vary. Measuring techniques must be devised so that either the electrical stress is kept at a constant value or the electrical effect on the TSP should be much smaller than the indirect thermal effect.

In the switching method, the TSP is produced by a small constant electrical stress, thereby keeping the electrical effect on the TSP constant. Continuous methods described in this Chapter are the pulse method, the d.c. method and the small signal method. In the pulse method, rectangular electrical pulses of constant amplitude are employed. Varying the pulse duration of the pulses, the thermal effect is varied, while the electrical effect is kept constant. D.C. electrical stress is used in the pulse method, since d.c. electrical stress is a rectangular electrical pulse of infinite pulse duration. In the d.c. method and the small signal method, if a test transistor is connected in a common-base configuration, $V_{CB}$ is varied while $I_E$ is kept constant. The selected TSP must be electrically independent of $V_{CB}$.

## 3.1 Pulse Method

This method has been developed by Nelson and Iwerson,[18] who have pointed out the possible error during the cooling period in the switching method, and emphasize that the pulse method is the one in which the temperature is measured during the heating period. One more feature mentioned by Nelson and Iwerson is that the d.c. current gain $h_{FE}$ is used as a TSP.

In the pulse method, d.c. electrical stresses are used for heating, and a sequence of rectangular electrical pulses is utilized to calibrate the relationship between TSP and $T_J$ of a test transistor. During calibration, the electrical power of the electrical pulses should be negligibly small to avoid heating the test transistor. Therefore, the pulse repetition rate should be as low as possible, and the pulse duration should be as short as practicable. Since there is always an electrical transient phenomenon during off-on pulses, the pulse duration should be sufficiently long to ensure negligible distortion due to electrical capacitance effects and the hole storage effect of the test transistor, but short enough to minimize the temperature rise during the pulse-on period.

The measurement circuits in Figure 3.1a and 3.1b are shown for illustration of the measurement procedure of the pulse method. The circuits may be connected in common-base configuration. For the common-emitter configuration shown in Figures 3.1a and 3.1b, the d.c. source may be applied across collector and emitter. Two synchronized pulse power sources may be used instead of one d.c. source and one pulse source. $h_{FE}$ is used as the TSP by Nelson and Iwerson. Other electrical parameters may also be used as the TSP according to circuit arrangement.

The measurement procedure is described as follows. There are two measurement steps, the test transistor is connected in a common-emitter configuration in both steps and $h_{FE}$ is used as the TSP. Since $h_{FE} \approx I_C/I_B$, and for common-emitter configuration $I_B$ is kept constant, therefore, $I_C$ is actually used as the TSP.

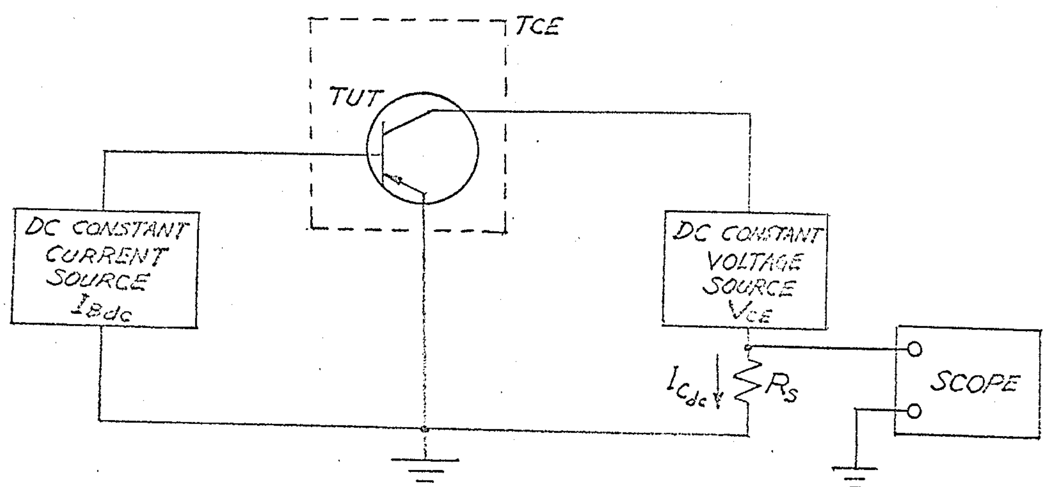



Figure 3.1a. Measurement circuit of the pulse method (First measurement step).

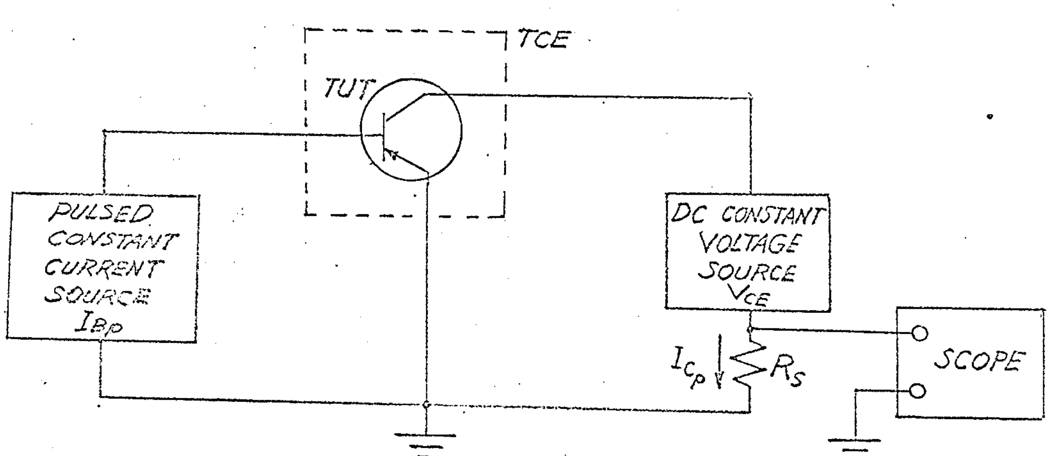



Figure 3.1b. Measurement circuit of the pulse method (Second measurement step).

In the first step, the measurement circuit is shown in Figure 3.1a, a d.c. base current $I_{B_{dc}}$ flows from a d.c. constant current source into the base of a test transistor, and a d.c. collector voltage $V_{CE}$ of a d.c. constant voltage source is applied through a sensing resistor $R_s$ across the collector and the emitter. The d.c. electrical heating power, P, applied to the test transistor is approximately equal to $(V_{CE}I_{C_{dc}})$. The d.c. collector current $I_{C_{dc}}$ is read as a voltage drop $(I_{C_{dc}}R_s)$ across the sensing resistor $R_s$ by an oscilloscope. The $(I_{C_{dc}}R_s)$ drop should be much smaller than $V_{CE}$. The test transistor is placed in a temperature controlled environment, the temperature of which is kept at a constant value, usually the room temperature. $T_A$ and $T_C$ are measured.

In the second step, the measuring circuit as shown in Figure 3.1b is the same as that in the first step, except that the d.c. constant current source is replaced by a pulsed constant current source. A pulsed base current of peak value $I_{B_p}$ is flowing from the current source to the base; a pulsed collector current of peak value $I_{C_p}$ will then flow through $R_s$. $I_{B_p}$ is kept at a value equal to $I_{B_{dc}}$, i.e., $IB_p = I_{B_{dc}}$. $V_{CE}$ in the second step is also equal to $V_{CE}$ in the first step. When the temperature of the temperature controlled environment is first at room temperature, the value of $I_{C_p}$ will be smaller than that of $I_{C_{dc}}$ measured in the first step. The temperature of the temperature controlled environment is then raised, until the value of $I_{C_p}$ increases up to the same value as $I_{C_{dc}}$.

The pulse power is negligibly small, therefore, the temperature of the temperature controlled environment is the same as the junction temperature $T_J$.

Since $I_{C_p} = I_{C_{dc}}$, $I_{B_p} = I_{B_{dc}}$, and ($V_{CE}$ in first step) = ($V_{CE}$ in second step), therefore, the electrical effects are the same in both steps. $I_C$, the TSP, then indicates the thermal effects, i.e., the $T_J$. Since $I_{C_p} = I_{C_{dc}}$, the $T_J$ measured in the second step should be equal to ($P\theta_{JA} + T_A$) or ($P\theta_{JC} + T_C$), where P, $T_A$ and $T_C$ are measured in the first step. $\theta_{JA}$ or $\theta_{JC}$ is thus determined.

Any possible error in the pulse method is due to an initial exponential junction temperature rise during the electrical transient period when an electrical pulse is applied. As could be seen from Figures 1.2 and 2.2, the initial temperature rise during the electrical transient period $t_e$ depends upon ($t_e/\tau$) and $\theta$. From the discussion in Chapter II, the initial temperature drop during the electrical transient period in the switching method has exactly the same relationship with ($t_e/\tau$) and $\theta$. The arguments for or against the switching method apply equally well to the pulse method. Since in the experimental results, the electrical transient masks the thermal behaviour when a power pulse is switched on or off, the amount of error introduced in the measurement of $\theta$ of the pulse method will be as uncertain as in the switching method.

## 3.2 D.C. Method

As deduced from the principle of the pulse method, Reich devised the d.c. method.[22] In Reich's method, only d.c. sources are required. Either forward emitter-to-base d.c. voltage $V_{EB}$ or static value of the common-emitter forward current transfer ratio $h_{FE}$ is taken as the TSP. In a measurement circuit of common-base configuration, $I_B$, instead of $h_{FE}$, is actually used as the TSP, since $h_{FE} \approx I_C/I_B \approx (\text{constant})/I_B$.

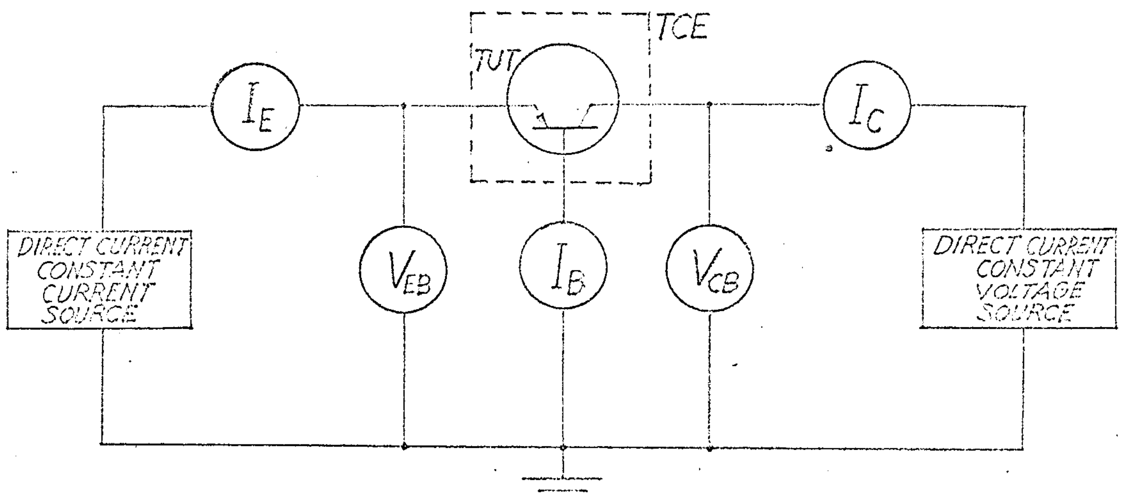



Figure 3.2. Measurement circuit of d.c. method.

The measurement circuit of the d.c. method is shown in Figure 3.2. A test transistor is connected in a common-base configuration, and placed in a temperature controlled environment. An emitter current $I_E$ flows from a d.c. constant current source into the emitter, and a d.c. collector voltage of a d.c. constant voltage source is applied across the collector and the base. Meters shown in Figure 3.2 measure the d.c. values of $I_E$, $V_{EB}$, $I_B$, $V_{CB}$, and $I_C$ respectively. $I_B$ or $V_{EB}$

is used as the TSP. The electrical heating power is equal to $(V_{EB}I_E + V_{CB}I_C)$; and is approximately equal to $(V_{CB}I_C)$, if $V_{CB} >> V_{EB}$. $T_A$ or $T_C$ can be measured by a thermocouple or any temperature sensitive device.

Since $T_R$ ($T_A$ or $T_C$) can be varied by varying the temperature of the temperature controlled environment, and the d.c. electrical heating power P can be varied by varying the $V_{CB}$, $\theta_{JR}$ $(= \Delta T_R/\Delta P)$ can thus be determined in accordance with the measurement procedures described in Chapter I.

The TSP ($V_{EB}$ or $I_B$) will indicate the $T_J$, provided that the TSP is electrically independent of the variation of $V_{CB}$, and that a theoretical relationship between the TSP and the $T_J$ can be formulated. The thermal equilibrium is maintained during the measurement of the TSP, as d.c. power is applied. Therefore, the requirements for a measuring technique are fulfilled. $I_E$ is always kept constant, as all TSP available are elctrically dependent on $I_E$.

## 3.3 Small-Signal Method

In Gates and Johnson's work,[6] the measurement during the cooling cycle with $V_{CBf}$ as TSP is recommended. In recognition of the fact that $h_{ib}$ is electrically independent of $V_{CB}$, the continuous method has also been mentioned with $h_{ib}$ as the TSP. An 1000-Hz oscillator is used for the measurement of $h_{ib}$, the principle of operation is exactly the same as the d.c. method.

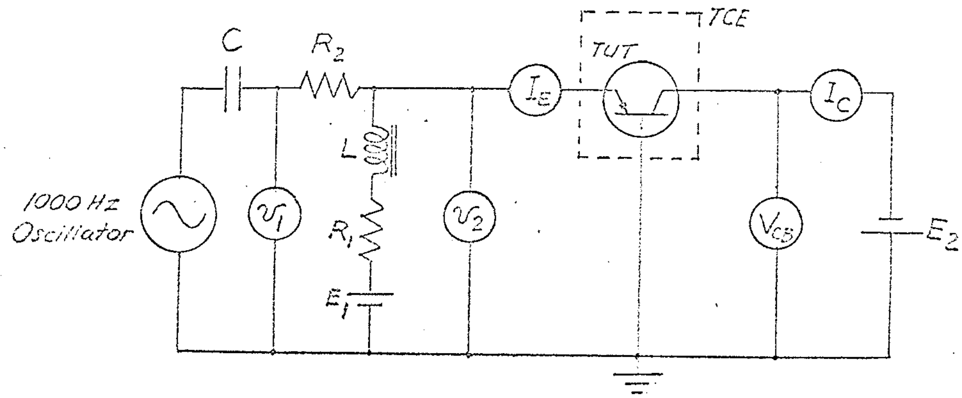



Figure 3.3. Typical measurement circuit for small signal method with $h_{ib}$ as TSP.

The test circuit used by Gates et al is shown in Figure 3.3. The capacitor C blocks the d.c. voltage, while the inductor L blocks the 1000 Hz frequency. $I_E$ (set by $R_1$ and $E_1$) remains at a fixed value during the measurement. If $R_2 >> h_{ib}$, then

$$h_{ib} = \frac{v_2}{i_{ac}} = \frac{v_2}{\dfrac{v_1}{R_2 + h_{ib}}} \approx \frac{R_2}{v_1} \times v_2 = (\text{constant}) \times v_2,$$

where $v_1$ and $R_2$ are kept at constant values to give an almost a.c. constant current source, $h_{ib}$ will thus be directly proportional to $v_2$. The measurement procedure is identical with that in Reich's method.

The importance of this method lies in its physical implication. With a d.c. source to raise the junction temperature of the test transistor to a constant value, the a.c. signal serves as a probe to explore the junction temperature simultaneously. The a.c. voltage across the emitter and the base at any instant will indicate the junction temperature caused by the d.c. electrical heating. It could be visualized then, that the instantaneous value of electrical parameter may be used to indicate the junction temperature as effective as the d.c. value.

3.4 Discussion

A comparison between the pulse method and the d.c. and small-signal methods shows that on the former one imposes no restriction of $V_{CB}$ independence of TSP. Another distinction between these two methods is that, the pulse method applies the principle of the constant reference temperature method, while the d.c. and small-signal methods employ that of constant junction temperature method.

The constant junction temperature method is applicable only when $\theta$ is constant. If $\theta$ varies with the variations of applied stresses, then $\theta$ in the equations (1.3) and (1.5), obtained from two measurement steps with equal junction temperature, must be replaced by $\theta_1$ and $\theta_2$, i.e.,

$$(T_J =)\ P_1\theta_1 + T_{R_1} = P_2\theta_2 + T_{R_2} \quad\ldots\ldots\ldots\ldots\ldots\ldots\ (3.1)$$

Mathematically this equation (3.1) with two unknowns $\theta_1$ and $\theta_2$ can not be solved. Therefore, $\theta$ determined from equation (1.6) by assuming $\theta_1 = \theta_2$ will result in error. With a view to estimating the error, the equation (3.1) is re-written in the following form:

$$I_C(V_{CB_1} + V_{EB})\theta_1 + T_{R_1} = I_C(V_{CB_2} + V_{EB})\theta_2 + T_{R_2} \quad\ldots\ldots\ (3.2)$$

by neglecting the change in $V_{EB}$ in the two measurement steps ($V_{EB} = V_{EB_1} = V_{EB_2}$), taking $I_C \approx I_E$, and substituting

$P_1 = I_C V_{CB_1} + I_E V_{EB_1} \approx I_C(V_{CB_1} + V_{EB})$, and

$P_2 = I_C V_{CB_2} + I_E V_{EB_2} \approx I_C(V_{CB_2} + V_{EB})$ into equation (1.6).

Let $\theta_1 = \theta_2 - \Delta\theta_{12}$, $\theta_2$ is then derived as follows:

$$\theta_2 = \left[\frac{T_{R_1} - T_{R_2}}{P_2 - P_1}\right] - \left[\frac{P_1}{P_2 - P_1} \times \Delta\theta_{12}\right] \quad \text{.............. (3.3a)}$$

$$= \left[\theta \text{ determined from equation (1.6)}\right] - \left[\frac{V_{CB_1} - V_{EB}}{V_{CB_2} - V_{CB_1}} \times \Delta\theta_{12}\right] \quad \text{.............. (3.3b)}$$

It could thus be seen, in the d.c. and small-signal methods, if $\theta$ is not a constant, $V_{CB_1}$ should be made as small as possible, or the difference of $V_{CB_2}$ and $V_{CB_1}$ be kept as large as practicable. In order to ascertain its constancy, $\theta$ should be determined for several values of $V_{CB}$ using a fixed value of $I_E$. In the pulse method, since the pulse power is much smaller than the d.c. power dissipation ($P_1 << P_2$ in (3.3a)), the error due to the variation of $\theta$ is negligibly small.

In a comparison of the switching method and the d.c. method, the latter has a definite advantage of eliminating the probable error due to cooling effect, but presents the difficulty in selecting a TSP which can indicate exactly the $T_J$.

If $\theta$ of a test transistor is a constant, then the d.c. method will be quite satisfactory for the measurement of $\theta$ by applying small electrical stresses. However, the variations of $\theta$ with external electrical stresses have been reported by experimenters.[1,3,23,24,25] Hot spots produced inside the transistor are considered to be the cause of the variations of $\theta$.[26] Therefore, the knowledge of the value of $\theta$ under the operation of large electrical stresses is important.

However, when electrical stresses are large, second order effects of a selected TSP may be predominant. Under such condition, the theoretical relationship between the TSP and the $T_J$ can not be formulated; consequently, an error of an uncertain amount will be introduced in the measurement of $\theta$.

# CHAPTER IV

## SWEEP METHOD

As a result of examining the existing methods, it can be seen that the switching method introduces an error in the measurement results due to the cooling effect; and that in the continuous method the application of a large electrical stress may invalidate the theoretical relationship of a TSP with $T_J$. To overcome the above weaknesses in the existing methods, the author proposes in this Chapter a sweep method, in which under the thermal equilibrium the TSP is measured when the electrical stress of sinusoidal pulses is at a small instantaneous value.

### 4.1 Principle of the Method

The measuring technique of visually displaying a family of characteristic curves of a transistor on a CRO (cathode ray oscilloscope) screen has been adopted as a standard method.[27] Usually this is done (e.g., for a common-emitter configuration) by applying half-wave or full-wave rectified 60-Hz sinusoidal pulses as a constant voltage source across collector and emitter, and stair-case pulses as a constant current source through base and emitter. Circuits for displaying a single contour curve have also been designed for the measurement of electrical parameters of transistors.[9] The circuits of a single-curve tracer are essentially the same as that of the tracer for displaying a family of curves, except that a d.c. constant current source, instead of stair-case pulses, is used.

The circuit of a single-curve tracer was used for the sweep method. The full-wave rectified sinusoidal pulses were used for the following two purposes. First, based upon the principle of the sinusoidal power pulses method in Chapter II, these sinusoidal pulses together with a d.c. constant current source generate a constant junction temperature $T_J$ in the test transistor. The condition of thermal equilibrium is thus established. Secondly, according to the principle of the small signal method in Chapter III, an instantaneous TSP can be used to indicate the $T_J$. As a small instantaneous value can always be pre-selected for sinusoidal pulses of all peak values, a TSP can then be measured at this pre-selected small value, and is independent of the variation of the peak value. Consequently, the requirements of a measuring technique are fulfilled. $\theta_{JR}$ $(= \Delta T_R/\Delta P_{avg})$ can thus be determined according to the measurement procedures as described in Chapter I.

## 4.2 Thermal Analysis

A mathematical analysis on temperature variation during the sweep period is to be made with the following assumptions:

1) $V_c$ are sinusoidal pulses of period k and peak value $V_{cp}$,
2) $I_C$ and $T_A$ remain at constant value, and
3) electrical charge storage and electrical capacitance effects do not exist.

Mathematical derivation of a single lumped thermal network shown in Figure 1.2 is worked out. From the thermal equivalent circuit, the following equation can be obtained by analogy:

$$P(t) = \frac{\Delta T(t)}{\theta} + C_{th}\frac{d(\Delta T(t))}{dt} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.1)$$

where $\Delta T(t) = T_J(t) - T_A$,

therefore,

$$\frac{d(\Delta T(t))}{dt} + \frac{1}{\tau}(\Delta T) = \frac{\theta}{\tau}P(t) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.2)$$

This equation (4.2) can be solved by applying the Laplace transform, with initial condition $\Delta T|_{t=0} = 0$,

$$s(\Delta T(s)) + \frac{1}{\tau}(\Delta T(s)) = \frac{\theta}{\tau}P(s) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.3)$$

i.e.,

$$\Delta T(s) = \frac{\theta P(s)}{s\tau + 1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.4)$$

where

$$P(s) = \frac{\int_0^k V_{cp} I_C \sin\omega t \exp(-st)dt}{1 - \exp(-ks)}$$

$$= P_p \times \frac{\omega}{s^2 + \omega^2} \times \frac{1 + \exp(-ks)}{1 - \exp(-ks)} \quad \ldots\ldots\ldots\ldots (4.5)$$

where $\omega = \pi/k$, $P_p = V_{cp}I_C$.

Substituting equation (4.5) into (4.4),

$$\Delta T(s) = \theta P_p \times \frac{\omega}{s^2 + \omega^2} \times \frac{1}{s\tau + 1} \times \frac{1 + \exp(-ks)}{1 - \exp(-ks)}$$

$$= P_p\theta \times \frac{\omega}{1 + \tau^2\omega^2} \times \frac{1 + \exp(-ks)}{1 - \exp(-ks)} \times \left[\frac{\tau^2}{s\tau + 1} + \frac{1 - s\tau}{s^2 + \omega^2}\right]$$

$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.6)$$

Using the inverse Laplace operation and some mathematical manipulation, the steady-state value of $\Delta T(t)$ within any period from 0 to k (or from nk to (n+1)k; n=0,1,2,.....) is obtained:

$$\Delta T(t) = P_p \theta \cos\phi \times \left[ \frac{2\sin\phi \exp(-t/\tau)}{1 - \exp(-k/\tau)} + \sin(\omega t - \phi) \right] \quad \ldots\ldots. (4.7)$$

where $\phi = \tan^{-1}(\omega\tau)$.

For infinite numbers of thermal networks, as shown in Figure 2.6, $\Delta T(t)$ may be deduced readily:

$$\Delta T(t) = P_p \sum_{n=1}^{\infty} \theta_n \cos\phi_n \left[ \frac{2\sin\phi_n \exp(-t/\tau_n)}{1 - \exp(-k/\tau_n)} + \sin(\omega t - \phi_n) \right] \quad ..(4.8)$$

Physical information may be envisaged from the equation (4.7). For $0 \leqslant t \leqslant k$, $\Delta T(t)$ is composed of a sinusoidal waveform with its phase determined by $\omega\tau$, and an exponential decay. If the $V_c$ sweep of sinusoidal pulses is plotted against $\Delta T(t)$, there will be a hysteresis loop in the $V_c$-$\Delta T(t)$ curve. This hysteresis loop is due to the phase difference $\phi = \tan^{-1}(\omega\tau)$ between $V_c$ and $\Delta T(t)$, or physically due to the thermal capacitance effect. In practice, both the thermal and the electrical capacitance effects exist. A hysteresis loop can be observed in the $V_c$-(TSP) curve on a CRO screen.

The average temperature $T_{J_{avg}}$ can be solved as:

$$T_{J_{avg}} = P_p \theta \frac{1}{k} \left\{ \int_0^k \cos\phi \left[ \frac{2\sin\phi \exp(-t/\tau)}{1 - \exp(-k/\tau)} + \sin(\omega t - \phi) \right] dt \right\} + T_A$$

$$= \frac{2}{\pi} P_p \theta + T_A$$

$$= P_{avg} \theta + T_A \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.9)$$

If there are many thermal networks, then

$$T_{J_{avg}} = P_{avg}\sum_{n=1}^{\infty}\theta_n + T_A$$

$$= P_{avg}\theta_{total} + T_A \quad \text{.............................} \quad (4.10)$$

When $\tau$ is very much larger than k, the second term on the right-hand side of the equation (4.7) vanishes, the first term approaches to $2/\pi$.

$$\lim_{\omega\tau\to\infty} \Delta T(t) = \frac{2}{\pi} P_p\theta \quad \text{..........................} \quad (4.11)$$

This indicates that $\Delta T$ is a constant (i.e. independent of time), and approaches the average value $T_{J_{avg}}$.

If $\tau$ is very short as compared with k, then the first term vanishes, the second term approaches $\sin\omega t$, and

$$\lim_{\omega\tau\to 0} \Delta T(t) = P_p\theta\sin\omega t \quad \text{........................} \quad (4.12)$$

The temperature thus varies in phase with $V_c$, and the condition of thermal equilibrium will not be satisfied.

From equations (4.11) and (4.12), it can be seen that the temperature variation during the sweep cycle could be reduced by increasing the frequency of the sinusoidal pulses.

In the above analysis, $V_c$ is assumed to be a sequence of sinusoidal pulses and $I_C$ is a constant, such that

$$P(t) = V_c(t)I_C = V_{c_p}I_C\sin\omega t. \qquad (0 \leq t \leq k)$$

The same analytical result will be obtained, if

$$P(t) = V_C I_c(t) = V_C I_{c_p}\sin\omega t, \qquad (0 \leq t \leq k)$$

i.e., a sequence of sinusoidal pulses is inserted into emitter and base, while a d.c. constant voltage is applied across collector and base.

## 4.3 Methods of Measurement

The principle of the measurement procedure is based upon that of the constant junction temperature method. Suppose that $h_{FE}$ be taken as a TSP, the test transistor is connected in a common-emitter configuration. A constant d.c. current $I_B$ is injected into the base, and full-wave sinusoidal pulses of peak value $V_{cp}$ are applied across the collector and the emitter. The test circuit is shown in Figure 4.1.

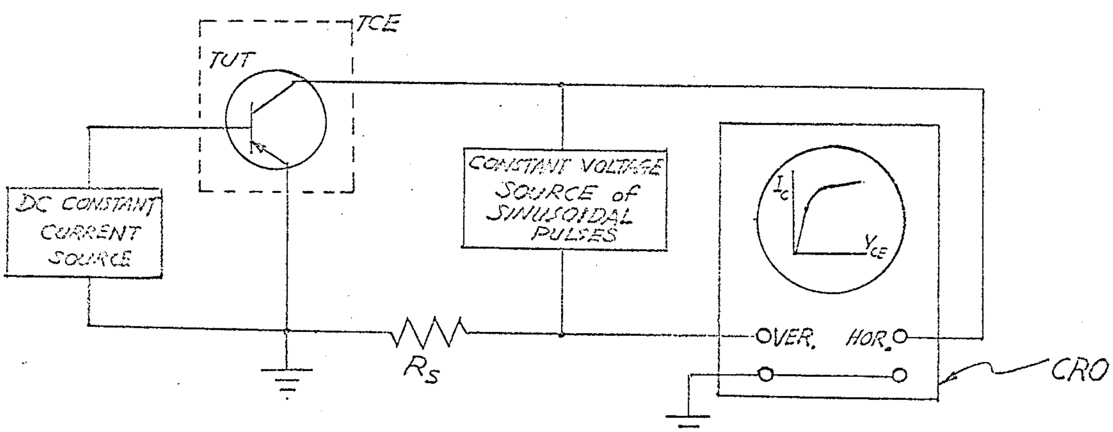



Figure 4.1. Measurement circuit of sweep method.

The measurement procedure consists of two steps:

In the first step, with $V_{cp} = V_{cp1}$, an arbitrary set of instantaneous $V_{cref}$ and $I_{cref}$ within the active region of the characteristic curve is selected as TSP, and their values are recorded accordingly. The reference temperature reading is taken as $T_{R1}$. Then, $I_{cmax1}$ and $I_{cmin1}$ are measured to determine $I_{cavg1}$ using the expression:

$$I_{cavg1} \approx (I_{cmax1} + I_{cmin1}) / 2 \quad \ldots\ldots\ldots\ldots\ldots \quad (4.13)$$

In step (2.a), with $V_{cp}$ value reduced from $V_{cp1}$ to $V_{cp2}$, the curve will be seen dropping due to reduced power dissipation. In other words, $I_{cref}$, corresponding to the same $V_{cref}$ as pre-selected in the first step, will decrease to another value. As a reference point, $V_{cref}$ so chosen should be less than both $V_{cp1}$ and $V_{cp2}$.

In step (2.b), the temperature is raised externally until the $I_{cref}$ reading equals the original value as in the first step. The readings of $T_{R2}$, $I_{cmax2}$ and $I_{cmin2}$ are taken at the same time.

This measurement procedure is illustrated in Figure 4.2 with a solid line as the characteristic curve measured in the first step; a dash line, in step (2.a). The characteristic curve measured in step (2.b), which is drawn in a heavy solid line, coincides with that part in the first step.

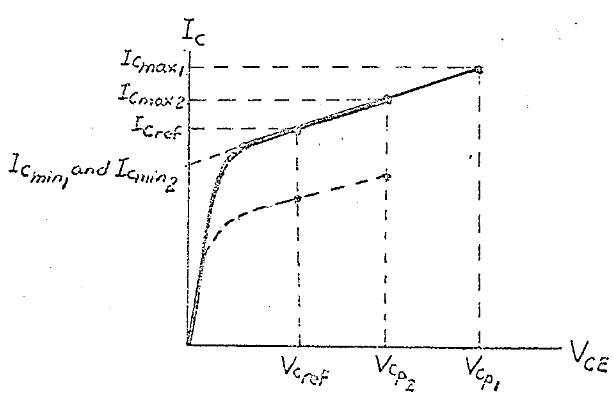



Figure 4.2. Typical characteristic curve display of the sweep method.

The average power dissipation will be approximately:

$$P_{avg} = \frac{2}{\pi} V_{cp} I_{cavg} \quad \text{.............................} \quad (4.14)$$

The thermal resistance can thus be calculated:

$$\theta_{JR} = \frac{\Delta T_R}{\Delta P_{avg}} = \frac{T_{R2} - T_{R1}}{P_{avg1} - P_{avg2}} = \frac{\pi}{2} \frac{T_{R2} - T_{R1}}{V_{cp1} I_{cavg1} - V_{cp2} I_{cavg2}} \quad \text{.............................} \quad (4.15)$$

If the slope of the characteristic curve is fairly flat, then:

$$\theta_{JR} = \frac{\pi}{2} \frac{T_{R2} - T_{R1}}{(V_{cp1} - V_{cp2}) I_c} = \frac{\pi}{2} \frac{\Delta T_R}{(\Delta V_{cp}) I_c} \quad \text{................} \quad (4.16)$$

The circuit connection in the common-emitter configuration as shown in Figure 4.1 is included as an illustration of the measurement principle. The circuit can also be connected in common-base configuration. In case that $h_{ib}$ is used as TSP, a constant sinusoidal pulse current is sent through emitter and base while a d.c. constant voltage is applied on collector and base.

The circuit of the sweep method can be modified by adding a d.c. source in series with the sinusoidal pulse source, as shown in Figure 4.3. This modified method is essentially a combination of Reich's method and the sweep method.

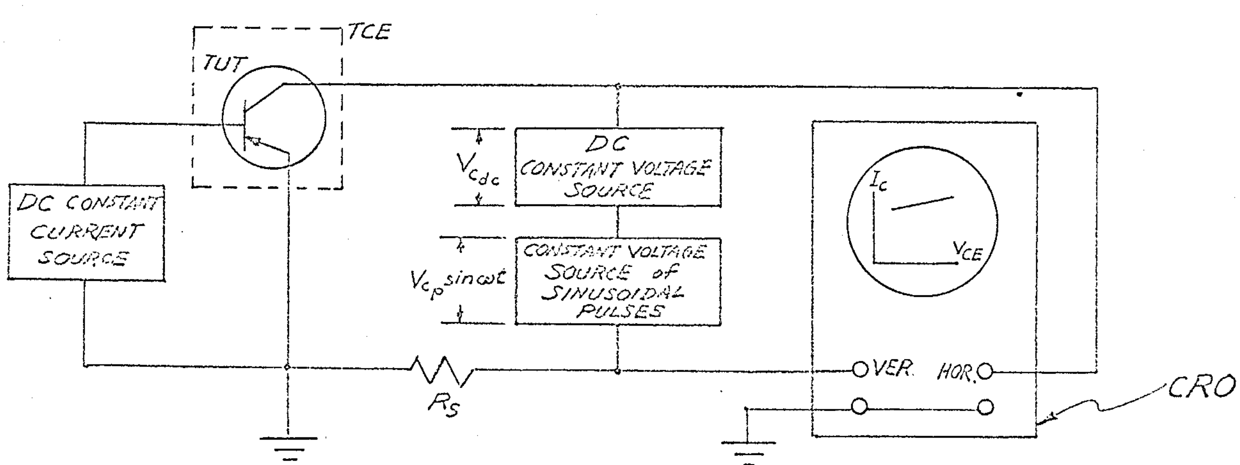



Figure 4.3. Modified circuit of the sweep method.

The d.c. source is used to keep the transistor operating within its active region. Power dissipation in this case can be easily derived from Figure 4.4. The average power dissipation due to sinusoidal pulses is:

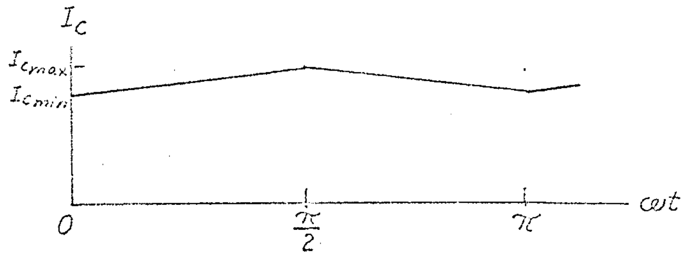



Figure 4.4. One of the possible waveform of $I_c$ vs $\omega t$ in the modified sweep method.

$$P_{avg1} = \frac{2}{\pi}\int_0^{\pi/2} V_c I_c d(\omega t)$$

$$= \frac{2}{\pi}\int_0^{\pi/2} (V_{c_p}\sin\omega t)\left[\frac{2(I_{c_{max}} - I_{c_{min}})}{\pi}(\omega t) + I_{c_{min}}\right] d(\omega t)$$

$$= \frac{2}{\pi} V_{c_p} \frac{2I_{c_{max}} + (\pi - 2)I_{c_{min}}}{\pi}$$

$$= \frac{2}{\pi} V_{c_p}\left[I_{c_{min}} + \frac{2}{\pi}\Delta I_c\right] \qquad (4.17)$$

The average power due to d.c. voltage is:

$$P_{avg2} = V_{c_{dc}} \times \frac{I_{c_{max}} + I_{c_{min}}}{2} \qquad (4.18)$$

The total average power is the sum of $P_{avg1}$ and $P_{avg2}$. If $I_c$ vs $\omega t$ waveform looks like that in Figure 4.5, when $I_c$ current is small and the electrical collector capacitance effect is pronounced,[28] there will be no error introduced in the equation (4.14) in the calculation of $P_{avg}$ (= $V_{c_{avg}} I_{c_{avg}}$).

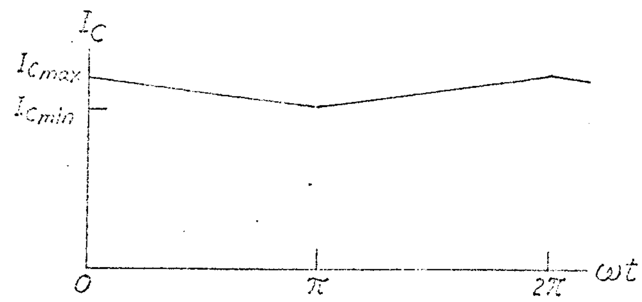



Figure 4.5. Another possible waveform of $I_c$ vs $\omega t$ in modified sweep method.

## 4.4 Experiment

The accuracy in the measurement of the sweep method was verified by comparing its experimental results with those of the d.c. method. The measurement should thus be carried out within the restrictions imposed upon the d.c. method. Therefore, in the experiment, a test transistor of which $V_{EB}$ (TSP) is electrically independent of $V_{CB}$ was selected, and a small emitter current $I_E$ was applied. An identical experimental circuit as shown in Figure 4.6 was used for both sweep and d.c. methods. The test transistor was connected in a common-base configuration. $V_{EB}$ was used as a TSP.

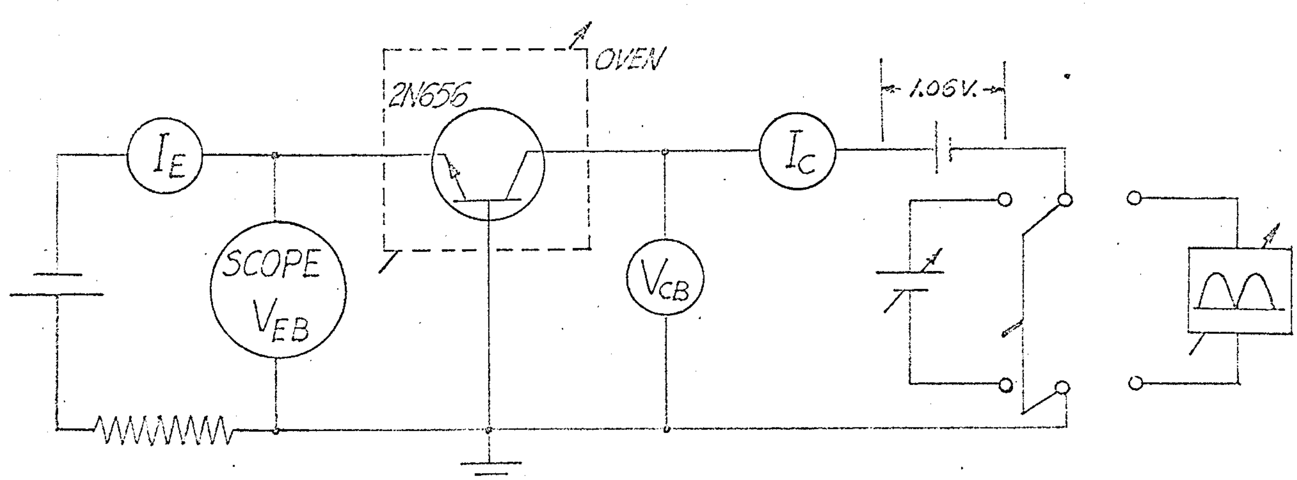



Figure 4.6. Experimental setup for the comparison of the sweep method with the d.c. method.

A silicon transistor, G.E. type 2N656, was tested. $I_E$ was kept constant at 9.4 ma. The temperature controlled environment was a thermostatically controlled oven. The temperature of reference point $T_R$ was measured at an arbitrary fixed point inside the oven by an iron-constantan thermocouple by means of a potentiometer. Room temperature, read from a glass thermometer, was used as a reference. $V_{EB}$ was read by an oscilloscope with maximum voltage sensitivity of 1 mv/cm. Both readings of $V_{CB_{dc}}$ (of the d.c. method) and $V_{CB_{avg}}$ (of the sweep method) were taken from a single D.C. voltmeter, while the readings of $I_{C_{dc}}$ (of the d.c. method) and $I_{C_{avg}}$ (of the sweep method) from a single D.C. milliammeter. $V_{CB_{dc}}$ and $V_{CB_{avg}}$ were both varied from 1.06 volts to 46 volts in steps.

The experiment was conducted in two steps, the first step was calibration of TSP ($V_{EB}$) vs $T_J$; the second step was the measurement of junction temperature due to internal electrical power dissipation in terms of TSP ($V_{EB}$). During calibration, the junction temperature rise, $(T_J - T_R)$, due to internal electrical power dissipation, P, was estimated as only 1.1°C, (with $I_E = 9.4$ ma, $V_{CB} = 1.06$ V, $V_{EB} = 0.6$ V, and $\theta_{JR} = 72°C/W$; $P = (1.06+0.6)x9.4 = 15.6$ mw; $(T_J - T_R) = 72x15.6/1000 = 1.1°C$). Therefore, the measurement procedure of the constant reference temperature method was followed, and calibration was proceeded with, bearing in mind that the junction temperature directly measured in this experiment will be 1.1°C lower than the actual value.

1) Calibration

With $V_{CB} = 1.06$ V, $I_E = 9.4$ ma, $V_{EB}$ was calibrated against $T_R$ as the oven temperature was varied in steps. The calibration curve of $V_{EB}$ in millivolts vs $T_R$ (or approximately $T_J$) in millivolts was plotted in Figure 4.7 as a dashed line.

2) Measurement of Junction Temperature

2a) Measurement using the D.C. Method

With $I_E = 9.4$ ma, $V_{CB_{dc}}$ was varied from 1.06 V to 46 V in steps. Corresponding $V_{EB}$ and $I_{C_{dc}}$ values were recorded. $V_{EB}$ in millivolts against $V_{CB_{dc}}$ in volts was plotted as a solid line as shown in Figure 4.7. The experimental data were marked as small triangles.

2b) Measurement using the Sweep Method

With $I_E = 9.4$ ma, $V_{CB_{avg}}$ was varied from 1.06 V to 46 V in steps. $V_{EB}$ at $V_{CB} = 1.06$ V was taken as an instantaneous TSP. Corresponding $V_{EB}$ and $I_{C_{avg}}$ values were taken. $V_{EB}$ in millivolts vs $V_{CB_{avg}}$ in volts was plotted as a solid line as shown in Figure 4.7. The experimental data were identified by means of small circles.

The Determination of the Thermal Resistance $\theta_{JR}$

$\theta_{JR}$ may be determined by using the experimental results of comparison and a calibration curve, and is simply the ratio of the slopes of the solid line and the dashed line in Figure 4.7 times a constant of proportionality.

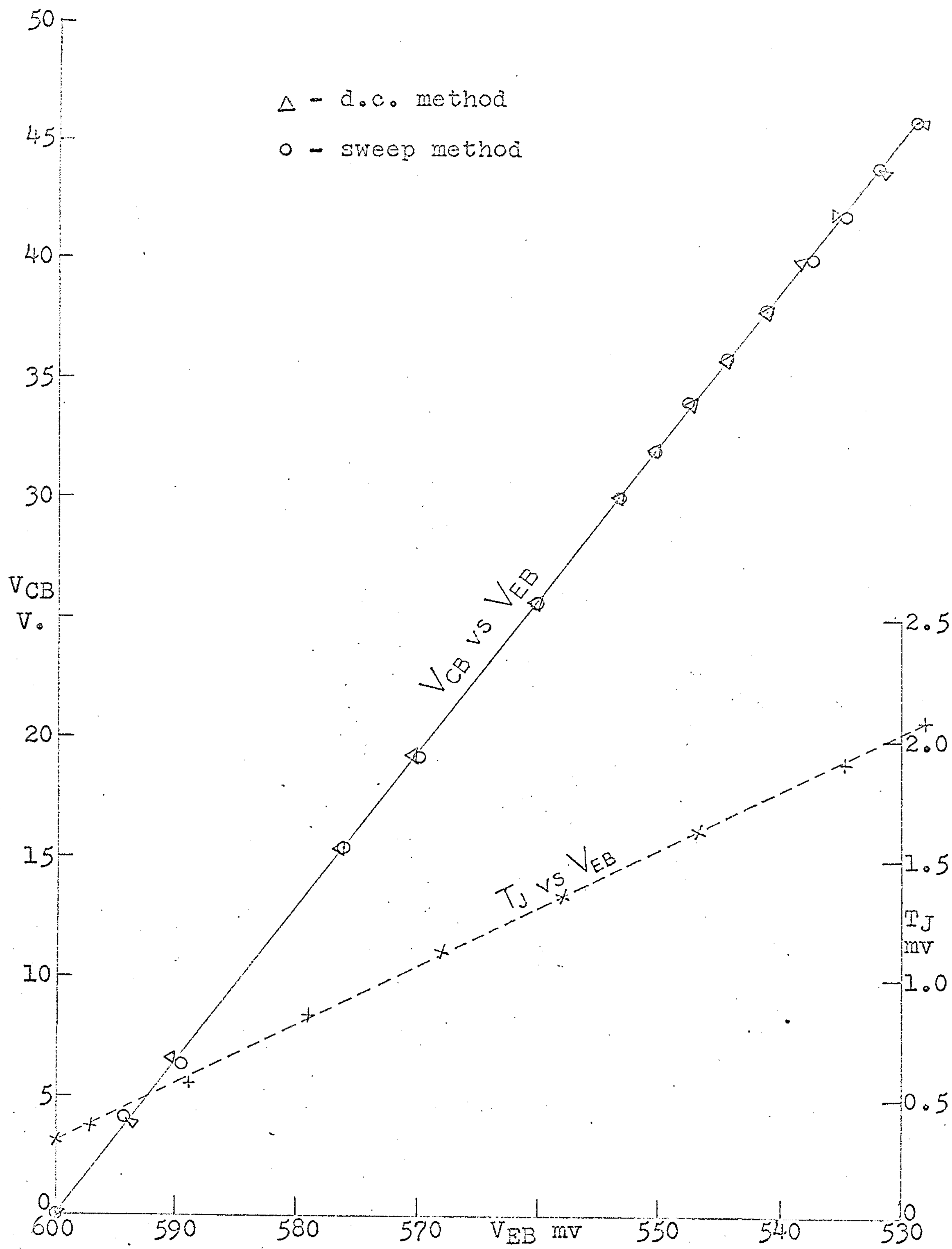



Figure 4.7. Comparison of experimental data of the sweep method with that of the d.c. method.

$$\theta_{JR} = \frac{\Delta T_R \text{ in } ^\circ C}{\Delta P \text{ in } W} = \frac{\dfrac{\Delta T_R\ ^\circ C}{\Delta V_{EB}\ mv}}{\dfrac{\Delta P\ W}{\Delta V_{EB}\ mv}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.19)$$

where $\Delta P = I_C \Delta V_{CB}$,

$$\Delta T_R \text{ in } ^\circ C = \frac{1}{0.056\ mv/^\circ C} \times \Delta T_R \text{ in mv.}$$

(from Table of Iron-Constantan Thermocouple,[29] the voltage potential increase of the thermocouple with the increase of temperature is 0.056 mv/°C, within the temperature range from 0°C to 100°C.)

$$\theta_{JR} = \frac{\dfrac{1}{0.056\ mv/^\circ C} \times \dfrac{\Delta T_R \text{ in mv}}{\Delta V_{EB} \text{ in mv}}}{I_C \text{ Amp.} \times \dfrac{\Delta V_{CB} \text{ in V}}{\Delta V_{EB} \text{ in mv}}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (4.20)$$

$$= \frac{(1\ /\ 0.056\ mv/^\circ C) \times (\text{slope of dashed line in Figure 4.7})}{I_C \times (\text{slope of solid line in Figure 4.7})}$$

From the measurements, $I_C = 9.3$ ma; and from Figure 4.7,

$$\frac{\Delta T_R \text{ in mv}}{\Delta V_{EB} \text{ in mv}} = \frac{1.7 \text{ mv}}{70 \text{ mv}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.21)$$

$$\frac{\Delta V_{CB} \text{ in V}}{\Delta V_{EB} \text{ in mv}} = \frac{45 \text{ V}}{70 \text{ mv}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.22)$$

Therefore, $\theta_{JR} = 72^\circ C/W = \text{constant.}$

The Determination of Junction Temperature $T_J$

The junction temperature at any power dissipation corresponding to a point on the solid line in Figure 4.7 could be read directly from the corresponding point on the dashed line with the same $V_{EB}$ reading.

## The Variation of $I_E$

Before proceeding with the measurement, the constancy of the d.c. constant current source was first checked when the $V_{CB}$ sinusoidal pulses varied continuously from 1.06 V to 71 V peak. From the results of measurement by a zero-suppression method, $I_E$ variation due to the variation of $V_{EB}$ was measured to be 2.3 μa. The slope of input characteristic curve ($I_E$ vs $V_{EB}$) was measured by applying constant sinusoidal current pulses through emitter and base and a d.c. constant voltage source of 70 V on collector and base. At $I_E = 9$ ma, the slope $\Delta V_{EB}/\Delta I_E$ (or approximately $h_{ib}$) was measured as about 25 ohms. Therefore, the variation of $V_{EB}$ due to the variation of $I_E$ was (2.3 μa) x (25 ohms) = 0.60 mv. As $\Delta V_{EB}/\Delta T_J$ measured for the test transistor was -2.32 mv/°C, the error introduced in the temperature measurement due to this variation of $V_{EB}$ would be about 0.03°C and was negligible.

## Suitability of $V_{EB}$ as a TSP for $T_J$ Measurement

$\Delta V_{EB}/\Delta T_J$ obtained from the calibration curve was a constant, equal to -2.32 mv/°C. This data was close to the theoretical calculation of $\Delta V_{EB}/\Delta T_J$ for a silicon transistor as approximately -2 mv/°C.[6] Therefore, $V_{EB}$ indicated $T_J$. To further confirm the agreement with the theoretical result, a smaller current of $I_E = 1$ ma was sent through the emitter, $\Delta V_{EB}/\Delta T_J$ was measured as -2.36 mv/°C.

## The Comparison of Experimental Results of the Sweep Method with Those of the D.C. Method

Two curves plotted from observed experimental data of step 2a and 2b were coincident with each other, therefore only a single solid line was drawn as seen in Figure 4.7. This result would lead to the suggestion that the sweep method is as effective as the d.c. method.

The purpose of this experiment was the comparison of the experimental results of the sweep method with those of the d.c. method. Therefore, the measured $\theta_{JR}$ of the d.c. method, (abbreviated as $\theta_R$), was taken as a reference value, i.e., an accurate value without error. The comparison error, $\delta\theta$, in the measured $\theta_{JR}$ of the sweep method, (abbreviated as $\theta_S$), as compared with $\theta_R$ will be:

$$\delta\theta = \frac{\theta_S - \theta_R}{\theta_S} = 1 - \frac{\theta_R}{\theta_S} \quad \text{.................... (4.23)}$$

As $\theta_R$ was taken as a reference value without error, $\theta_R$ was equal to the determined $\theta_{JR}$ (72 $^{o}C/W$). Therefore, the equation (4.19) on page 47 for $\theta_{JR}$ applied equally well for $\theta_R$. The $\theta_S$ with the comparison errors, $\delta T_R$, $\delta V_{EB}$ and $\delta P$, taken into account may be deduced from equation (4.19):

$$\theta_S = \frac{\dfrac{\Delta T_R \pm \delta T_R}{\Delta V_{EB} \pm \delta V_{EB}}}{\dfrac{\Delta P \pm \delta P}{\Delta V_{EB} \pm \delta V_{EB}}} \quad \text{........................ (4.24a)}$$

Since a single calibration curve of $T_R$ vs $V_{EB}$ curve was used for both methods, therefore the comparison error due to the calibration of $V_{EB}$ vs $T_R$ (i.e., the comparison error in the slope of $\Delta T_R/\Delta V_{EB}$) was zero. Thus,

$$\theta_S = \frac{\dfrac{\Delta T_R}{\Delta V_{EB}}}{\dfrac{\Delta P \pm \delta P}{\Delta V_{EB} \pm \delta V_{EB}}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4.24b)$$

Substituting equations (4.19) and (4.24b) into equation (4.23),

$$\delta\theta = 1 - \frac{1 \pm \dfrac{\delta P}{\Delta P}}{1 \pm \dfrac{\delta V_{EB}}{\Delta V_{EB}}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4.25a)$$

The maximum probable comparison error, $(\delta\theta)_{max}$ will then be:

$$(\delta\theta)_{max} = 1 - \frac{1 - \dfrac{\delta P}{\Delta P}}{1 + \dfrac{\delta V_{EB}}{\Delta V_{EB}}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4.25b)$$

where $\delta P = I_C \delta V_{CB} + V_{CB} \delta I_C$ ........................ (4.26)

$\Delta P = I_C V_{CB} = 9.3 \times 45 = 420$ mw.

$\Delta V_{EB} = 70$ mv.

$\delta V_{EB}$, $\delta V_{CB}$, and $\delta I_C$ were estimated respectively as 3.5 mv, 2 V., and 0.2 ma, as will be explained in the following paragraphs. Substituting the values of $V_{CB}$, $\delta V_{CB}$, $I_C$, and $\delta I_C$ into equation (4.26), $\delta P$ can be calculated as 29 mw. Further substituting the values of $\Delta P$, $\delta P$, $\Delta V_{EB}$, and $\delta V_{EB}$ into equation (4.25b), the maximum comparison error, $(\delta\theta)_{max}$ is thus obtained as 11%.

## Estimation of Comparison Errors

### Error in Power Measurement

#### 1) Error in Voltage Measurement

The instrument error of the Model 8 Universal Avometer Mk II was 2% of the indication between full-scale and half-scale deflection, and 1% of the full-scale value below half-scale deflection.

For $V_{CB}$ = 46 V, which was the maximum value of $V_{CB}$ used in the experiment, the error in the $V_{CB}$ reading was taken as 2 volts, i.e. $\delta V_{CB} = 2$ V.

#### 2) Error in Current Measurement

The milliammeter used for the measurement of $I_E$ was calibrated as 9.74 ma at its full-scale reading of 10 ma; while that for $I_C$ was calibrated as 9.9 ma.

For $I_C$ = 9.3 ma as measured in the experiment, the error in the $I_C$ was taken as 0.2 ma, i.e. $\delta I_C = 0.2$ ma.

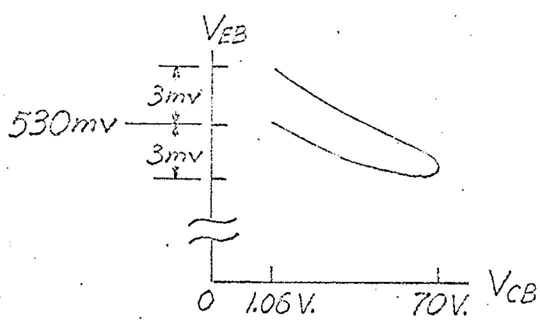
### Error in $V_{EB}$ as a TSP in the Indication of $T_J$

#### 1) Error in $V_{EB}$ as a TSP due to the Sensitivity of the CRO

If $V_{EB}$ was read as 0.6 V (600 mv) by using the 0.1 V/cm scale on the CRO, then the maximum error due to scale reading could be 0.1 V/10, or 10 mv, i.e., $V_{EB}$ = (600 ± 10) mv. Since 10 mv would indicate a temperature difference for the test transistor of (10 mv)/(2.32 mv/°C), or 5°C, therefore, the sensitivity of 0.1 V/cm of CRO was not high enough for the indication of $T_J$. By suppressing the zero, the 5 mv/cm voltage sensitivity scale was used, and the maximum possible error due to the CRO was reduced to (0.5 mv)/(2.32 mv/°C) = 0.3°C. $\delta V_{EB}$ due to the CRO sensitivity was taken as 0.5 mv.

2) Error in $V_{EB}$ as a TSP due to the Hysteresis Loop

Due to the electrical capacitance effect* and the thermal capacitance effect** during the sweep cycle, a hysteresis loop in the $V_{EB}$ vs $V_{CB}$ characteristic curve could be observed on a CRO screen display, as sketched in Figure 4.8.




$I_E$ = 9.4 ma,

$V_{CB}$ = 1.06 + 70sinωt volts,

$(n\pi \leqslant \omega t \leqslant (n+1)\pi)$.

Figure 4.8. The hysteresis loop in the $V_{EB}$-$V_{CB}$ characteristic curve.

The instantaneous $V_{EB}$ was selected as a TSP at $V_{CB}$ = 1.06 V. From Figure 4.8, for a single-valued $V_{CB}$ = 1.06 V, there were double values of $V_{EB}$, the difference of which was 3 mv. That is, the vertical size of $V_{EB}$ of the

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* The electrical capacitance effect is largely due to the charging and discharging of the electrical collector-to-base capacitance[28] when the applied electrical stress varies periodically.

** The thermal capacitance effect is described on page 37. This effect causes the temperature fluctuation during the sweep cycle.

hysteresis loop at $V_{CB}$ = 1.06 V was 3 mv. In the measurement, the lower value was used as the TSP. The maximum error was taken as ±1.5 mv. Or the error in the indication of the $T_J$ would be ±(1.5mv)/(2.32mv/°C), or ±1°C. $\delta V_{EB}$ was estimated as 1.5 mv.

Moreover, $V_{EB}$ varied during the sweep cycle. The difference of the instantaneous value of $V_{EB}$ taken as the TSP and the minimum value of $V_{EB}$ during the sweep cycle was observed as 3 mv, as shown in Figure 4.8. The causes of the variation of $V_{EB}$ during the sweep cycle could be attributed to either the electrical capacitance effect, or the thermal capacitance effect, or the combined effects of both. Taking the possible thermal capacitance effect into consideration, $\delta V_{EB}$ due to the $T_J$ variation during the sweep cycle was estimated as 1.5 mv.

In this experiment, the electrical capacitance effect on the hysteresis loop was considered to be predominant. According to the literature,[28] the electrical capacitance effect will be pronounced when $I_E$ is small and $V_{CB}$ sweep is large; while in this experiment, a small $I_E$ of 9.4 ma and a large $V_{CB}$ sweep of peak value of 71 V were used. To justify the above statement, the author further reduced the value of $I_E$ to 0.4 ma such that the thermal capacitance effect became negligible, (since the $T_J$ rise = (72°C/W)x(45V)x(0.4/1000Amp) = 1.3°C, the $T_J$ fluctuation during the sweep cycle was negligible,) the hysteresis loop of approximately the same size as that of $I_E$ = 9.4 ma was observed in the $V_{EB}$-$V_{CB}$ curve.

## 4.5 Discussion

As compared with the d.c. method, the sweep method has the advantage of bypassing the difficulties involved in the selection of a TSP. In the sweep method, a TSP is instantaneously measured at a pre-selected small value of sinusoidal pulses of all sizes. The peak value of sinusoidal pulses determines the magnitude of the electrical heating power which causes the rise of the $T_J$. The TSP will thus exactly indicate the $T_J$. In the d.c. method, the d.c. electrical stress serves dual purposes of determining the magnitude of the electrical power and of measuring the TSP. In consequence, the selected TSP must be electrically independent of the variation of the d.c. electrical stress. Therefore, in the d.c. method, the emitter current is always kept at a constant value during the measurement, since the variation of the emitter current will electrically affect the selected TSP. In the sweep method, no such restrictions are imposed. A constant current source of sinusoidal pulses can be connected across the emitter and the base, while a d.c. constant voltage source is connected across the collector and the base. An instantaneous $V_{EB}$ can then be selected as a TSP at a pre-selected small instantaneous value of the emitter current during the $I_E$ sweep cycle.

On the other hand, the applicability of the sweep method is limited by the existence of a hysteresis loop in the selected TSP vs $V_{CB}$ sweep (or $I_E$ sweep) characteristic curve, due to the electrical capacitance effect and the thermal capacitance effect. It has been reported that a hysteresis loop due to the thermal capacitance effect will be formed when the characteristic curves extend into high power regions.[30] A hysteresis loop due to the electrical capacitance effect will result when a test transistor is operated in the small current and large voltage region.[28] Actually, the hysteresis loop is always present to a greater or lesser extent as could be observed if the characteristic curve is 'magnified' or expanded by using higher voltage sensitivity scale on the CRO, and by zero-suppressing the waveform.

In principle, the modified sweep method can improve the accuracy of the measurement results by reducing the electrical capacitance effect. In the sweep method, during the transition period (from the end of one sweep cycle to the beginning of the next one), first $I_C$ drops from its maximum value $I_{C_{max}}$ to zero, then rises from zero to $I_{C_{max}}$ again. In other words, in the curve of $I_C$ vs time t, there are discontinuities in the slope of the curve at $\omega t = n\pi$. The rapid change of $I_C$ during the transition period causes the electrical capacitance effect to be more pronounced.[28] In the modified sweep method, the test transistor is operated within its active region, $I_C$ is approximately constant. Therefore, the size of hysteresis loop due to the electrical capacitance effect will be much reduced. The accuracy of the measurement will thus be improved.

Furthermore, since the sweep waveform of the electrical stress $V_{CB}$ used in the modified sweep method is of sinusoidal pulses which have a maximum change at the transition period in a manner like the change of $I_C$ in the sweep method as described in the previous paragraph, therefore, the electrical capacitance effect will also be pronounced at the transition period.[28] In other words, in the curve of $V_{CB}$ vs t, there are discontinuities in the slope of the curve at $\omega t = n\pi$, jumping from $-(V_p\omega)$ to $+(V_p\omega)$,* where $V_p$ is the peak value of $V_{CB}$ sinusoidal pulses. If these discontinuities in the slope be eliminated, the electrical capacitance effect will be much reduced. Consequently, it is recommended that an electrical stress of a sweep waveform without discontinuities in its slope be used in the modified sweep method. For example, an electrical stress ($V_{CB}$ or $I_E$) of a sinusoidal source and a d.c. source with a waveform of

$$V_{CB}(t) = V_{dc} + V_p \sin\omega t, \qquad (V_{dc} = V_p; \quad -\infty \leqslant t \leqslant +\infty)$$

or $$I_E(t) = I_{dc} + I_p \sin\omega t, \qquad (I_{dc} = I_p; \quad -\infty \leqslant t \leqslant +\infty)$$

may be attempted as the sweep in the modified sweep method, (where $V_{dc}$ (or $I_{dc}$) is the d.c. voltage (or current) of the d.c. source, and $V_p$ (or $I_p$) is the peak value of the sinusoidal voltage (or current) of the sinusoidal electrical source.)

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* The magnitude of the jump of slope is deduced as follows:

$$\frac{dV_{CB}(t)}{dt} = \frac{dV_p \sin\omega t}{dt} = V_p\omega\cos\omega t, \qquad (n\pi \leqslant \omega t \leqslant (n+1)\pi);$$

$$V_p\omega\cos\omega t = -V_p\omega, \qquad (\text{at } \omega t = n\pi, \quad n \text{ odd})$$

$$V_p\omega\cos\omega t = +V_p\omega, \qquad (\text{at } \omega t = (n+1)\pi, \quad n \text{ odd}).$$

Since the modified sweep method is in fact the combination of the d.c. method and the sweep method, its principle of operation may be exploited to advantage. As is evident from equation (4.12), the variation of temperature during the sweep cycle, (i.e., the thermal capacitance effect,) is proportional to the peak power $P_p$ of the sinusoidal pulses. Also the electrical capacitance effect varies as the peak value of $V_{CB}$ sinusoidal pulses.[28] Therefore, the hysteresis effects can be reduced by reducing the peak voltage of the sinusoidal pulses while increasing the d.c. voltage of the d.c. constant voltage source as shown in Figure 4.3.

# CHAPTER V

# CONCLUSION

From the foregoing expositions and discussions, it can be seen that the existing methods have both advantages and disadvantages. In the switching method, a selected TSP is measured by applying a small electrical stress to a test transistor; therefore, the TSP indicates $T_J$ exactly, because the theoretical relationship between the TSP and the $T_J$ can be formulated. However, there is a possible error in the switching method due to the transient temperature drop during the cooling period. Due to the uncertainty of the size of the transient temperature drop, a corresponding uncertainty of the validity of the switching method arises (see Sec. 2.4). On the other hand, in the continuous method, a selected TSP is measured when the thermal equilibrium is established by applying d.c. electrical stresses. However, when the applied electrical stresses are large, the second order effects may be predominant in a selected TSP, such that the theoretical relationship between the TSP and the $T_J$ can not be formulated. Thus, an uncertainty in the error will be introduced if the TSP is used to indicate the $T_J$. Consequently, the common short-coming in the existing methods is due to the fact that the amount of error introduced is uncertain.

In the sweep method, a selected TSP is measured when an applied electrical stress of sinusoidal pulses is at a preselected small instantaneous value, while the condition of thermal equilibrium is established under the operation of the electrical stress of sinusoidal pulses and a d.c. electrical stress. The sweep method avoids the common shortcoming in the other two methods, in that the error introduced in the sweep method is measurable from the vertical size of the hysteresis loop (as explained in Sec. 4.4). The size of the hysteresis loop can further be reduced by employing the modified sweep method. The electrical capacitance effect upon the hysteresis loop can be diminished by changing the sweep waveform (as recommended in Sec. 4.5). The thermal capacitance effect upon the hysteresis loop can be minimized by increasing the sweep frequency (as mentioned in Sec. 4.2). From the above statement and the measurement results in the experiment, the sweep method is therefore proposed to be the most satisfactory method in the measurement of $\theta$.

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