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Sub Title	
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Publisher	慶応義塾大学藤原記念工学部
Publication year	1965
Jtitle	Proceedings of the Fujihara Memorial Faculty of Engineering Keio University (慶応義塾大学藤原記念工学部研究報告). Vol.18, No.69 (1965.) ,p.42(18)- 49(25)
JaLC DOI	
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Notes	
Genre	Departmental Bulletin Paper
URL	https://koara.lib.keio.ac.jp/xoonips/modules/xoonips/detail.php?koara_id=KO50001004-00180069-0018

The Transient Temperature Measurement of Transistor Junctions under Pulse Operation

(Received September 30, 1965)

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Abstract

During the recess time of the repetitive power pulses, the measuring pulses of I_{cbo} (reverse saturation current) which can be arbitrarily varied in their phase, width and height are put into the collector of the transistor under test. Then, the transient temperature of the junction at any instant during the recess interval can be measured successively. With this method, we could know the period from switch-in of the power pulse up to thermal steady state of the junction and the behavior of the temperature decay during the recess of the power pluses. Also we could estimate the maximum temperature rise of the junction right after the power pulses are off in the duration.

Consequently, it is found that there occur local spots in the junction more highly heated than expected.

At first, for the temperature measurements, we must make a calibration curve with I_{cbo} vs. T_j (junction temperature) corresponding to each one of transistors using a constant temperature bath.

I. Introduction

Recently high power transistors have been widely used in various purposes, especially in pulse circuitry. Under the pulse operation it is not enough to design such circuits with d. c. consideration on temperature rise. But we must consider transient temperature rise to their circuit applications.

Each transistor having its temperature limit we should not disregard its thermal resistance accompanied with physical geometry, ambient temperature and cooling devices. Moreover, it happens once in a while that local heating becomes remarkable and it would tend to cause deterioration and sometimes to lead to break-down. Thus, to know the feature of its temperature rise and also its thermal time constant experimentally under the pulse operation has significant advantage.

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II. Temperature sensitive parameters

There are three methods to detect junction temperature of transistor by means of its electrical characteristics.

They are

(1) Temperature dependence of I_{cbo} (reverse saturation current through collector to base)

(2) Temperature characteristics of V_{be} (potential difference between emitter and base when the forward emitter current is kept constant)

(3) Temperature characteristics of the input impedance between emitter and base

In the present paper, we have chosen I_{cbo} temperature dependence as the temperature sensitive parameter.

I_{cbo} is known as follows [1]

$$I_{cbo}=AT_j{}^3 \exp\left(-\frac{E_g}{kT_j}\right) \tag{1}$$

where

A : A constant depending on geometry and material of transistor

E_g : Energy gap of transistor material (for Ge, ~0.65 eV)

k : Bolzmann's constant

T_j : Junction temperature in degree Kelvin

From equation (1), we obtain

$$\ln I_{cbo} = \ln(AT_j{}^3) - \left(\frac{E_g}{kT_j}\right) \tag{2}$$

$\ln AT_j{}^3$ and E_g are nearly constant in the range concerned, therefore $\ln I_{cbo}$ is proportional to $1/T_j$, and we get a straight line between I_{cbo} and T_j in semi-logarithmic plots as shown in Fig. 1 (*a*) or in Fig. 1 (*b*).

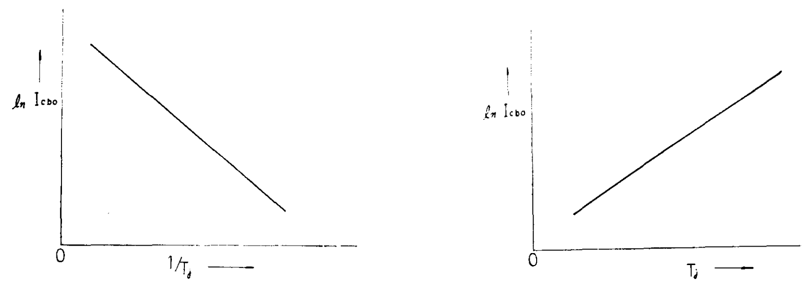

Fig. 1. (*a*) **Fig. 1.** (*b*)

Relation between ln I_{cbo} and $1/T_j$ or T_j.

1) Greiner, R. A.; Semiconductor Devices and Applications, McGraw-Hill Book Co., 1961, p. 122.

However, each transistor should be measured of its I_{cbo} by varying temperature within a certain range in a constant temperature bath prior to the experiment. Thus, we have obtained each calibration curve between I_{cbo} vs. T_j. Therefore, when I_{cbo} is measured by our equipment, it is easy to know the junction temperature from these curves.

III. Measurement circuits [2)]

The block diagram of the equipment is shown in Fig. 2 and also phase relations among the wave forms of output of each unit are illustrated in Fig. 3.

Let us consider how to operate the units of the diagram in Fig. 2.

Wave-form Generator is to drive each pulse generator in the range of repetition period 0.1 ms to 10 sec. Pulse Generator 1 produces positive or negative pulses of about 25 volts in its maximum synchronized by the output of Wave-form Generator and its pulse width can be varied in the range of 1 μs to 100 ms. The output of Generator 1 is given to Pulse Amplifier which raises up to 200 volts in negative value when a pnp transistor is used. The amplifier output obtained is applied to the collector of a transistor to be tested.

Meanwhile, through Delay Circuit 2, the trigger pulse of Wave-form Generator delayed at least as much as the output pulse width of Generator 1 is applied to Generator 2 which produces pulses of 1 μs$\sim$100 ms width and 25 volts to be added to Bias Cutoff Circuit. It makes possible to measure I_{cbo} with the emitter current of the transistor under test being off for a certain time right after the output power pulse is cut off.

A part of the output power pulse of Amplifier is applied to I_{cbo} Pulse Generator through Delay Circuit 1 of which the delay time can be adjustable. I_{cbo} pulse produced from I_{cbo} Pulse Generator is added to the collector of the specimen to

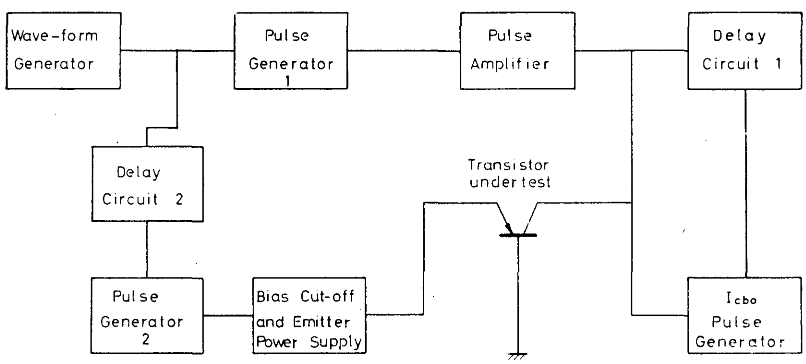

Fig. 2. Block diagram of transient junction temperature measurement circuits.

2) Suzuki, T. et al.; IEE of Japan Convention, #1065, Apr., 1962.

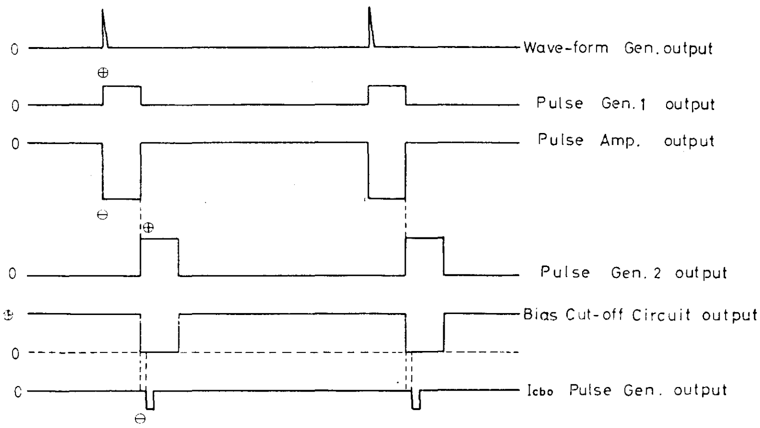

Fig. 3. Phase Relations among the wave forms of output of each unit in Fig. 2.

know the junction temperature during the recess period of the negative power pulses. I_{cbo} pulse is less than 10 volts in height and about 10 μs in width (variable up to 100 μs), and its position or phase is changeable through the recess time of the power pulses.

These phase relations among the pulses could be well-understood refering to Fig. 3.

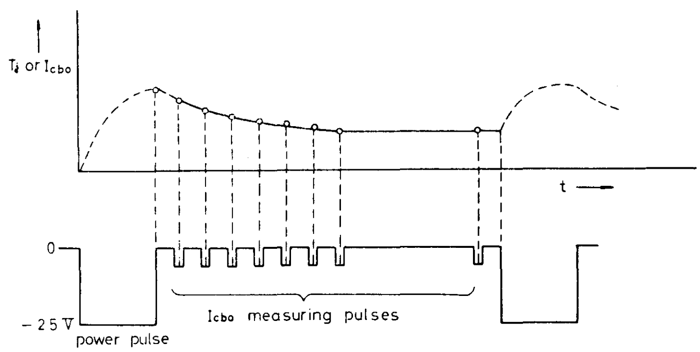

Fig. 4. Transition of the junction temperature T_j (or I_{cbo}) and phase relation between power pulses and I_{cbo} measuring pulses.

The junction temperature T_j or I_{cbo} increases as the power pulse is added, and decreases with a time constant when the power pulse is at recess as shown in Fig. 4. I_{cbo} corresponding to T_j is obtained by shifting the position or phase of I_{cbo} pulse manually during the recess time of the power pulse.

Wave-form Generator, Pulse Generator 1, 2 and Pulse Amplifier are constructed with vacuum tubes.

The output impedance of Amplifier should be made lower i. e., 100 to 500 [Ω] in order to avoid excess voltage drops of the power pulse output. Also its duty ratio should be kept less than 1/2 and its pulse width less than 50 ms.

When we measure I_{cbo} by adding I_{cbo} measuring pulse, not only the power pulses but the emitter current of the specimen should be off in advance. Bias Cutoff Circuit of the emitter is used for this purpose and the circuit is shown in Fig. 5.

A positive pulse from Pulse Generator 2 is added to the base of T_1 in Fig. 5. The base of T_1 has been negative so as to flow a rating amount of the emitter current of T_2 by R_1. According to the positive pulse applied to the base of T_1, the potential of the base is inverted to reverse direction during the pulse width and the emitter current is cut off. Thus, the emitter current of T_2 does not flow. Then a little later, I_{cbo} pulse will be applied to the collector of T_2. From the potential difference between E and F, with a differential amplifier of an oscilloscope, we can get the value of I_{cbo}.

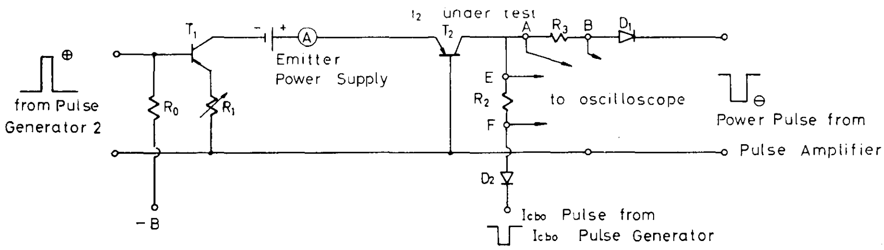

Fig. 5. Emitter Bias Cut-off Circuit.

Estimation of the input power to the collector of T_2 is done by measuring the potential drops between A and B with a differential amplifier set in an oscilloscope.

Resistance R_3 connected between A and B should be as low as possible, while Resistance R_2 inserted between E and F is adjusted to I_{cbo} value so as to make correct measurement.

Diodes D_1 and D_2 are inserted to inhibit mutual interference between the power pulses and I_{cbo} pulses.

The emitter current of T_2 is restricted by the rating of T_1. Therefore, Bias Cut-off Circuit and Emitter Power Supply including T_1 may be changed for higher power transistors.

Now, I_{cbo} Pulse Generator is transistorized because small output is sufficient.

IV. Examples of measurement

100 mW, pnp (2SB113) Ge transistors have been used as specimen for measuring the junction temperature and their typical results are shown in Fig. 6 and Fig. 7.

Fig. 6 shows the temperature decay with time after the power pulse is off. Conditions are as follows

(1) Pulse widths are 0.5, 1.0, 2.0, 3.0 and 5.0 ms.

(2) Pulse duration is 11 ms.

(3) The ambient temperature is kept constant 24°C in the bath.

(4) I_{cbo} pulse voltge is $-2[V]$ and its width is 10 μs.

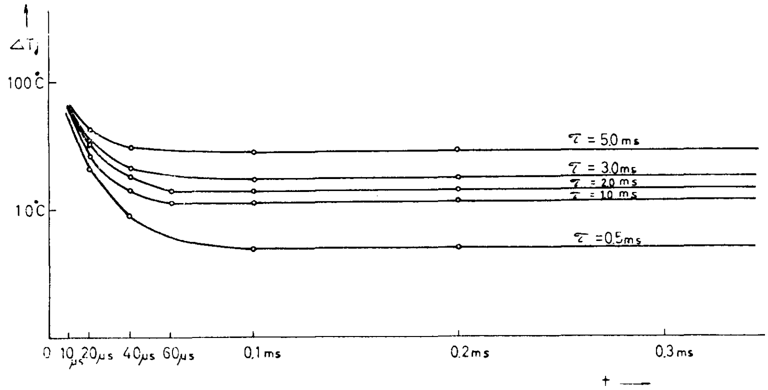

Fig. 6. The temperature decay with time (difference between junction and ambient temperature, ΔT_j)

2SB113 (pnp Ge alloy type)

Applied peak power	: 100 mW
Pulse duration	: 11 ms
Pulse width τ	: 0.5, 1.0, 2.0, 3.0, 5.0 ms
Ambient temperature	: 24°C
I_{cbo} pulse voltage	: -2 V

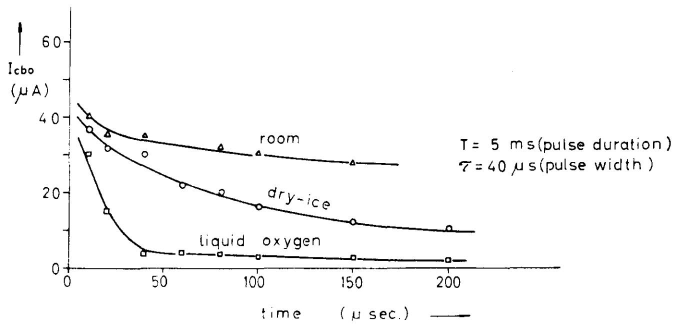

Fig. 7. Comparison of three ambient temperatures : room, dry-ice, and liquid oxygen.

It should be noted that I_{cbo} pulse width is to be as narrow as possible, but it depends upon the scanning speed during the pulse duration, characteristics of a Braun-tube of an oscilloscope used and amounts of I_{cbo} current. If I_{cbo} pulse becomes wider, we would read the average temperature of the decay lasting during I_{cbo} pulse width. Therefore, we could get correcter instant value as I_{cbo} pulse becomes narrower, and so we have chosen about 10 μs as the width.

It might be better to know the temperature soon after the power pulses are taken off, but there was the pulling phenomenon observed so that we had to make the time lag between the power pulse and I_{cbo} pulse apart more than 5 μs.

Fig. 7 shows the comparison of the three ambient temperatures such as that of room, of dry-ice and liquid oxygen.

One of the I_{cbo} vs. T_j calibration curves is illustrated in Fig. 8 measured by the same I_{cbo} pulse which has been used for the experiment in the constant bath.

In the case of Si transistors which have very small values of I_{cbo}, say 0.01 μA at room temperature, it is necessary to use high resistance for R_2 in Fig. 5, or a differential amplifier with high amplification, less ripple, less noise and less drift.

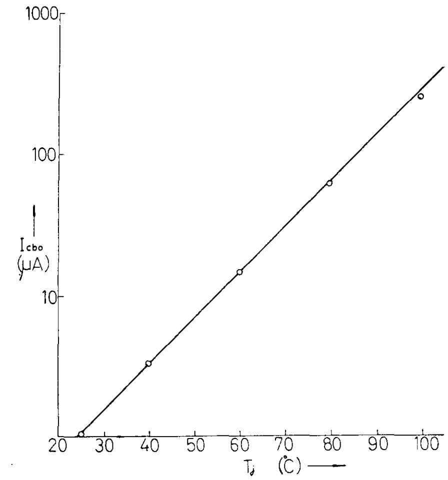

Fig. 8. I_{cbo} vs. T_j calibration curve for the transistor used in the experiment of Fig. 6.

V. Discussion and conclusion

The transient behavior of the junction temperature between the successive power pulses has been observed with high reliability by measuring I_{cbo} pulse.

If we notice a certain position of recess time of the power pulses, with use of photo-technique, we may observe how the temperature goes from the instant of power pulse switch-in till the stationary state.

With our equipment, one may obtain the characteristics of temperature rise at the junction when the power pulses are varied successively in their widths.

Besides the thermal time constants, transient thermal resistances of various transistors may be obtained from these results.

At the experiment, we have noticed the existence of locally heated spots at the junction which is hardly detected by V_{be} method as it will be discussed later in another report.

The junction temperature soon after the power pulses off could be estimated by extrapolating the obtained results.

To get more precise temprature measurement, the equipment should be adjusted to kill the jittering effect or pulling phenomenon. At the same time, the differential amplifier should be with high gain (adjustable), high stability, low noise and low ripple to reduce errors of the results. The error estimated is within 10 % in total.

Choosing higher power pulses, we must pay attention to deterioration and breakdown of transistors under test. Once these occur, no more correct temperature is available corresponding to I_{cbo} vs. T_j calibration curves made in advance and we could know only the temperature tendency with time.

Acknowledgements

The authors are greatly indebted to Prof. T. Suezaki for many valuable advices and to students who helped us in constructing the units and carrying out the experiments.