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Abstract	Previously we reported a method to measure the transient temperature of transistor junctions under pulse operation. The method was such that the transient temperature of the junction was measured through Icbo pulse current, but to know a whole temperature decay during the recess time of power pulses, Icbo pulses were shifted manually point by point in their phase with use of Delay Circuit. It leads to several diffculties such as in setting the phase shifts of Icbo pulses, in reading the junction temperatures correctly and also it takes a lot of time to complete the whole decay of the temperature of the transistor junction. This means we could not expect good accuracies. In this time, the temperature behavior during the recess time of the power pulses can be measured continuously and easily to be observed on an oscilloscope. The new method can take those diffculties away and gives good accuracies. At the same time, it becomes possible to observe both temperature rise of the junction after switch-in and temperature fall after switch-off of power pulses. Also it could easily obtain thermal time constants, the maximum and minimum temperatures of the transistor under pulse operation and the limit of thermal runaway conditions.
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Transient Temperature Measurement of Transistor Junctions under Pulse Operation (2)

(Received June 2, 1966)

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Abstract

Previously we reported a method[1),2)] to measure the transient temperature of transistor junctions under pulse operation. The method was such that the transient temperature of the junction was measured through I_{cbo} pulse current, but to know a whole temperature decay during the recess time of power pulses, I_{cbo} pulses were shifted manually point by point in their phase with use of Delay Circuit.

It leads to several difficulties such as in setting the phase shifts of I_{cbo} pulses, in reading the junction temperatures correctly and also it takes a lot of time to complete the whole decay of the temperature of the transistor junction. This means we could not expect good accuracies.

In this time, the temperature behavior during the recess time of the power pulses can be measured continuously and easily to be observed on an oscilloscope. The new method can take those difficulties away and gives good accuracies. At the same time, it becomes possible to observe both temperature rise of the junction after switch-in and temperature fall after switch-off of power pulses. Also it could easily obtain thermal time constants, the maximum and minimum temperatures of the transistor under pulse operation and the limit of thermal runaway conditions.

I. Introduction

I_{cbo}, the reverse saturation current between the collector and the base of the transistor is used as a temperature sensitive parameter. As mentioned in the previous paper,[2)] I_{cbo} is dependent on the temperature of the junction, that is

$$I_{cbo}=AT_j^3 \exp(-E_g/kT_j) . \qquad (1)$$

Logarithmic expression of Eq. (1) gives

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1) T. Suzuki *et al.*: I. E. E. of Japan Convention #1065, Apr., 1962.

2) T. Suzuki and H. Hirose: Proceedings of Faculty of Eng., Keio University Vol. 18, No. 69, p. 18, 1965.

$$\ln I_{cbo} = \ln (AT_j^3) - \frac{E_g}{k}\frac{1}{T_j}\ , \qquad (2)$$

while AT_j^3 and E_g are nearly constant in the range concerned. Fig. 1 shows the relations between temperature and I_{cbo} for three of 2SB110 Ge alloy type pnp transistors when I_{cbo} currents are measured at the pulse voltage of -2V. Therefore, I_{cbo} measurements afford the temperature behavior of the transistor junctions by means of the calibration curves of the transistors.

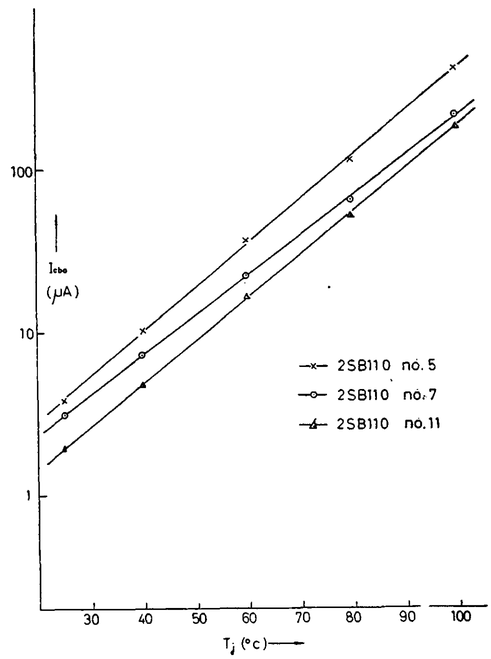


Fig. 1. I_{cbo} *vs* temperature (T_j) calibration curves.

II. Circuits of the apparatus

Fig. 2 shows the block diagram for the temperature measurement while Fig. 3 illustrates the phase relations between the pulses used in the measurement. The operation of the equipment will be clarified in detail on Fig. 2 as follows.

The repetition period T of the power pulses which are applied to the collector of the transistor under test can be set from 0.1 ms to 10 s by the trigger pulses from Wave-form Generator. τ is arranged at Pulse Generator that is also driven by the trigger pulses of Wave-form Generator. τ is continuously variable from 1 μs to 200 ms. Pulse Generator is available for both negative and positive output of 25V in its maximum. The Pulse Generator output is amplified to arbitrary amount through Pulse Amplifier up to 250V in its height. The transistor to be tested is applied to negative or positive power pulses (according to pnp or npn type) that are

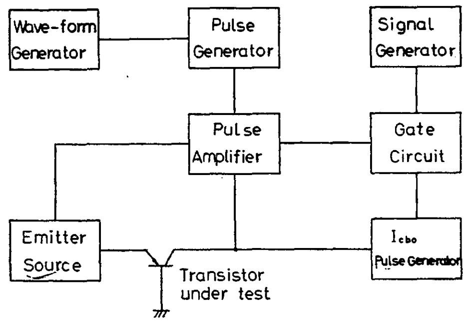


Fig. 2. Block diagram of transient temperature measurement circuits.

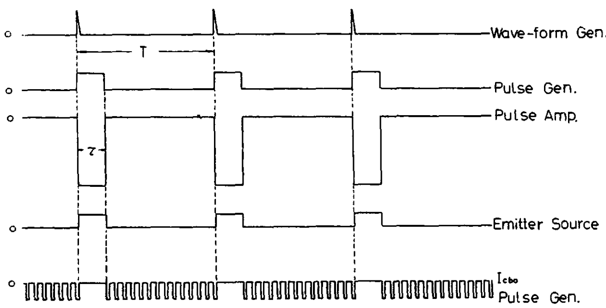


Fig. 3. Phase relations among pulses of output of each unit in Fig. 2.

adjusted with the repetition rate, pulse width and peak values required. While, by the constant positive pulses out of Schmitt Circuit in Pulse Amplifier, Emitter Source is driven to give a constant current to the emitter of the specimen when the power pulses are on to its collector. At the same time, the output pulses of the Schmitt Circuit are inverted in their sign and then applied to Gate Circuit. Another input to Gate Circuit is connected to Signal Generator. Only when negative gate signal from Pulse Amplifier is off, Signal Generator output is shaped through the Schmitt Circuit of Gate Circuit and added to I_{cbo} Pulse Generator. Accordingly, during the recess time of the power pulses, −2V pulse train is given to the transistor in order to measure its I_{cbo} current. The phase relations of each pulse are shown in Fig. 3.

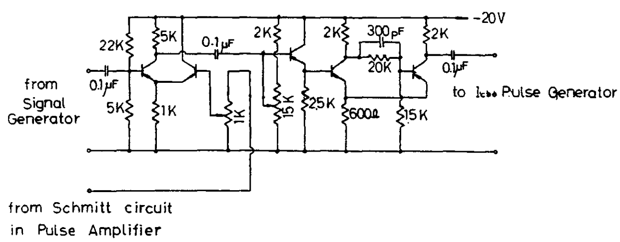


Fig. 4. Diagram of Gate Circuit.

Wave-form Generator, Pulse Generator and Pulse Amplifier are constructed with vacuum tubes, on the contrary Gate Circuit (Fig. 4), Emitter Source (Fig. 5) and I_{cbo} Pulse Generator (Fig. 6) are all transistorized.

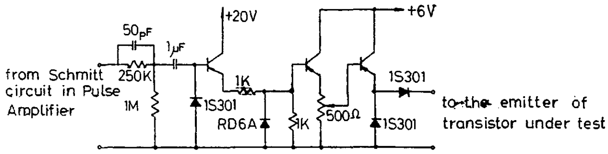


Fig. 5. Diagram of Emitter Source.

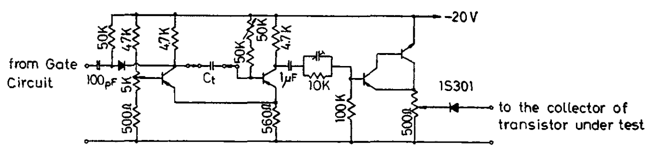


Fig. 6. Diagram of I_{cbo} Pulse Generator.

III. Method for measurements

The transient temperature measurements of the transistor junctions are achieved as follows.

The power pulses from Pulse Amplifier are applied to the collector of the transistor under test, while Emitter Source gives a certain amount of collector current. Therefore, the resultant peak power given to the collector junction is evaluated by the pulse voltage V_0 and the collector current I_0 (almost no phase difference is observed).

$$P_m = V_0 I_0 .$$

However, the average power is estimated from the product of P_m and duty ratio. The voltage V_0 is directly read from an oscilloscope, and with use of a differential amplifier, the current I_0 is indirectly known with the voltage ΔV across the series resistance R_p inserted in the collector circuit such as

$$I_0 = \Delta V / R_p .$$

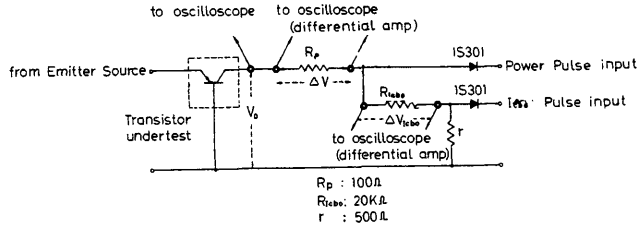


Fig. 7. Measuring points and circuit for measurement.

I_{cbo} current can be measured on an oscilloscope through the resistance R_{Icbo} when I_{cbo} pulse voltage V_{Icbo} from I_{cbo} Pulse Generator is given to the collector during the recess time of the power pulses.

With use of a differential amplifier and an oscilloscope, I_{cbo} is given as

$$I_{cbo} = \Delta V_{Icbo} / R_{Icbo} ,$$

where ΔV_{Icbo} is the voltage across the resistance R_{Icbo}.

R_{Icbo} value depends on an amount of I_{cbo} current and on the differential amplifier gain, but 20 kΩ is adopted here for the test transistors.

The reason why 1S301 diodes are inserted between I_{cbo} Pulse Generator and Pulse Amplifier is to avoid the interference between I_{cbo} pulses and power pulses. Resistance r is to improve the shape of the power pulses.

The circuit of measurements above mentioned are shown in Fig. 7.

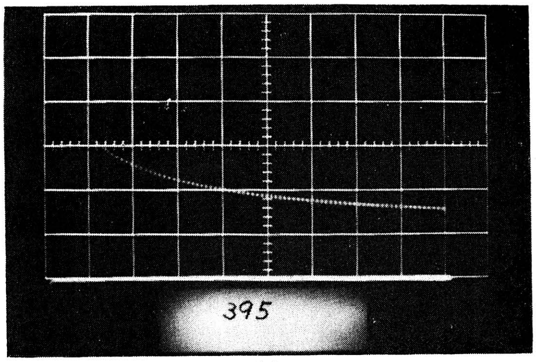
IV. Results

Three photographs (a, b, c) in Fig. 8 show I_{cbo} behavior of the dynamic quasi-steady state during the recess time of the power pulses. The dynamic quasi-steady state condition was achieved in sufficiently long time after the power pulses were switched in. In each case, the power pulse repetition period T is 100 ms, peak power=1 W ($V_0 I_0 = P_m = 40\,V \times 25\,mA$), vertical and horizontal sensitivities are 0.5 V/div. and 10 ms/div. and duty ratio d is set to 0.1, 0.08 and 0.06 for (a), (b) and (c) respectively.

Changing I_{cbo} values from the photographs to the corresponding temperatures through the calibration curve given in Fig. 1, then, ΔT_j, the differences between the room temperature 25°C and the junction temperatures are obtained. ΔT_j are shown in Fig. 9 with respect to the photographs (a), (b) and (c).

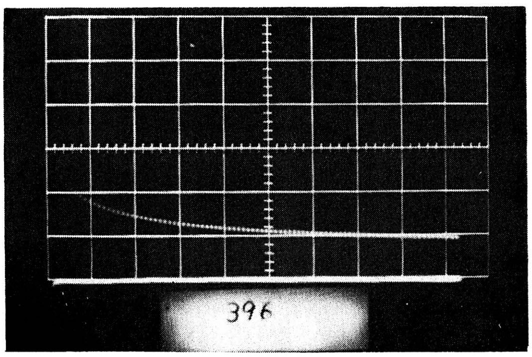
As shown in Fig. 10, the junction temperature takes the first maximum just after the power pulse is switched in, then, during the recess time of the power pulse the temperature falls down, next instant the power pulse becomes on duty again and causes the temperature rise of the junction. Repeating the cycle, the temperature rises until the dynamic quasi-steady state with a certain time constant. T_j(max) is the temperature just after the instant of the rear edge of the power pulses and T_j(min) is the temperature just before the front edge of the power pulses (in other words, T_j(min) is at the last position of the recess time of the power pulses). Those transitions are taken by photographs in Fig. 11 and Fig. 12 with different sweeps such as 0.5 s/div. and 2 s/div.

Fig. 13 gives the envelopes of T_j(max) and T_j(min), calibrated from the photographs. When the power pulses are switched off the junction temperature starts to fall down from the dynamic quasi-steady state to the ambient temperature as shown in Fig. 14.



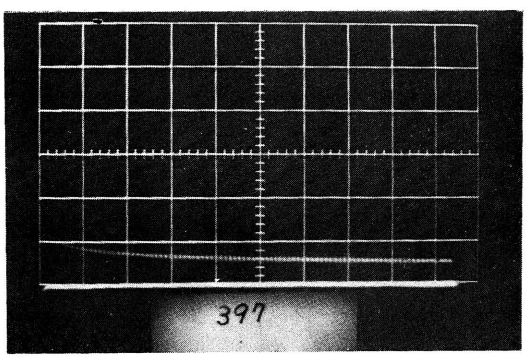
(a)

$P_m=1$ W, $T=100$ ms, $\tau=10$ ms, $d=0.1$



(b)

$P_m=1$ W, $T=100$ ms, $\tau=8$ ms, $d=0.08$



(c)

$P_m=1$ W, $T=100$ ms, $\tau=6$ ms, $d=0.06$

Fig. 8. I_{cbo} behavior during the recess time of power pulses.
V: 0.5 V/div, H: 10 ms/div

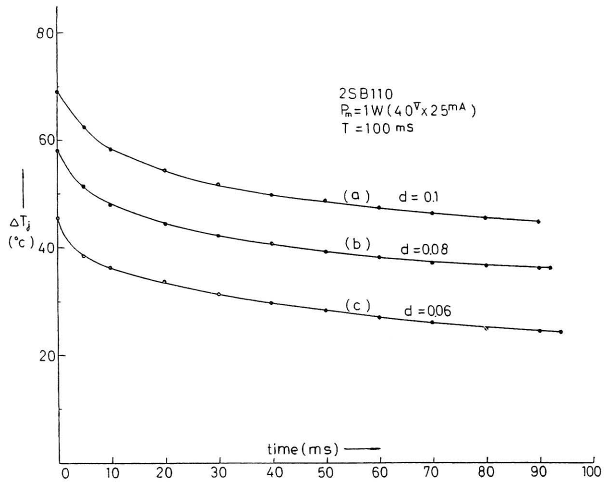


Fig. 9. Temperature decay during the recess time of power pulses calibrated from Fig. 8 using Fig. 1.

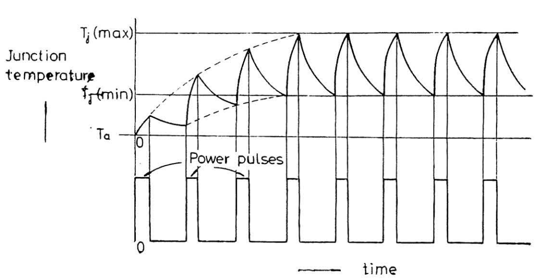


Fig. 10. Ideal temperature rise until quasi-steady state after switch-in.

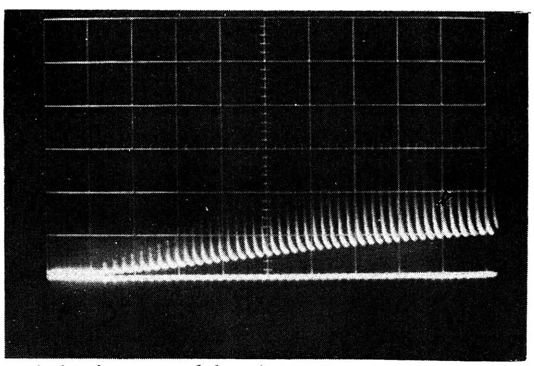


Fig. 11. I_{cbo} behavior caused by the temperature rise after switch-in, the upper envelope shows T_j(max) and the lower, T_j(min) (time sweep: 0.5 s/div.).

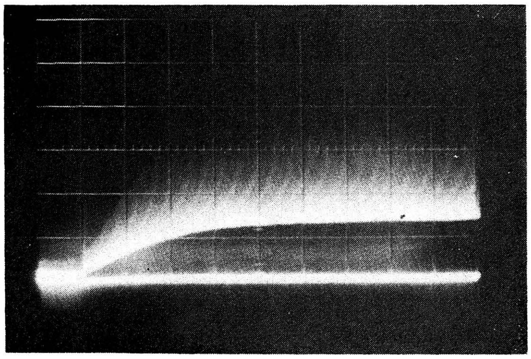


Fig. 12. The same one as Fig. 11 but time sweep is 2 s/div.

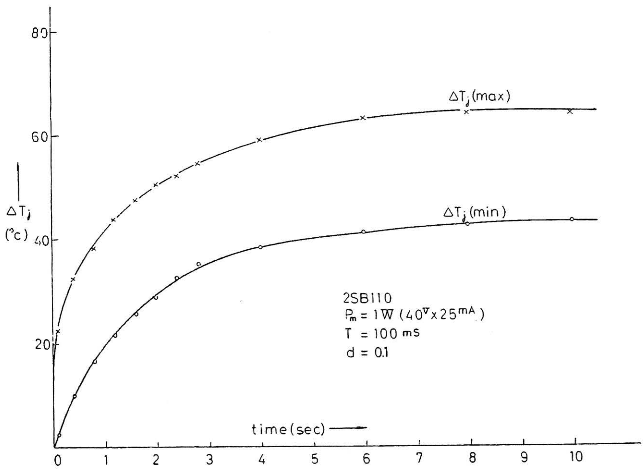


Fig. 13. Temperature rise after switch-in calibrated from Fig. 12.

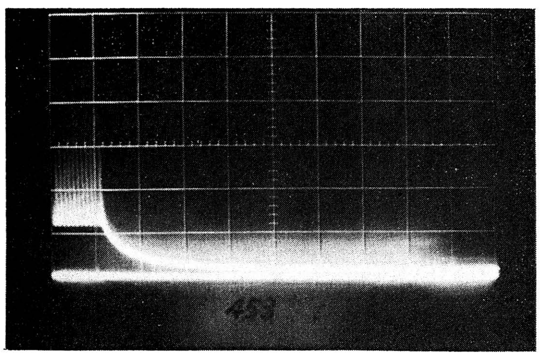


Fig. 14. I_{cbo} behavior caused by the temperature fall after switch-off.

V. Estimation of error and conclusion

Possible errors are

(1) errors concerned with the differential amplifier,
(2) reading error from the oscilloscope,
(3) temperature rise caused by I_{cbo} pulse train during the recess time,
(4) voltage regulation of the power supplies.

(1) Our differential amplifier has the rejection factor (ratio of common mode and differential mode) is 1/1000. Near the room temperature (25°C) I_{cbo} current has a value of 5 μA approximately, R_{Icbo} is 20 kΩ, therefore the differential mode voltage is given as 0.1 V. Now that the common mode voltage (I_{cbo} pulse voltage) is 2.0 V, the error is roughly estimated as 2%, but I_{cbo} at higher temperature is always larger than that of the ambient temperature, so the error is considered to be within 1% under operation.

(2) The largest is the reading error among the above classification. The diameter of the beam spot of the oscilloscope is about 1 mm in its minimum, and we assumed the center of the spot as the real value to get. In the case of sensitivity range 0.5 V/div., the beam diameter gives an error of 0.02 V at the maximum. When I_{cbo} is 5 μA the related error makes 20%, but larger I_{cbo}(>20 μA) gives an error within 5%.

(3) Nearly 500 μA is evaluated for I_{cbo} at the maximum temperature rise, then the power losses concerned with I_{cbo} pulses are about 1 mW because the I_{cbo} pulse voltage is 2 V.

(4) The power supplies are all stabilized and their regulations are below 1%, moreover, dc current of I_{cbo} Pulse Generator is supplied from dry cells so as to have negligible fluctuation.

The possible error will be estimated within 5%, but the reading error is the largest.

The same to the previous paper, the temperatures can not be known right at the beginning of the recess time, but at least 10 μs time lag is always remained. I_{cbo} pulse width is not the problem in the experiment and the transient temperature measurements are well carried out without any particular skill. The method proposed here can not afford temperature measurements during the power pulses are on duty, but if the power pulse width could be varied from the narrow one to the wider, then the maximum temperature T_j(max) in each width gives an envelope which possibly represents the real rise-up characteristic of the junction temperature.

As I_{cbo} pulses are not synchronized to the power pulses, they are free in the phase, but make no trouble to the measurement. If necessary I_{cbo} Pulse Generator could be synchronized to the power pulses.

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