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Technical Information Note

MEASUREMENT OF THERMAL PROPERTIES OF SEMICONDUCTORS

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The power ratings of semiconductors are established on the basis of maximum operating junction temperatures and the thermal resistance of the devices. Thermal resistance is used consistently as a design characteristic from which the design engineer can determine the junction temperature of semiconductor devices under operating conditions. Its importance can hardly be over-emphasized. This note describes the techniques used by Motorola to obtain the thermal resistance of transistors, rectifiers, and thyristors.

MOTOROLA Semiconductor Products Inc.

INTRODUCTION

Power ratings of semiconductors are established on the basis of the maximum operating junction temperature and thermal resistance of the devices. Thermal resistance is also used consistently as a design characteristic with which the design engineer can determine the junction temperature of a semiconductor device under operating conditions. The importance of thermal resistance can hardly be over-emphasized; it is, therefore, necessary that it be accurately measured.

This report describes the method and the equipment used by the Motorola Applications Engineering Department to obtain thermal resistance measurements of transistors, rectifiers, and silicon controlled rectifiers (thyristors). Also described is a method employing modified thermal resistance measuring equipment to obtain the thermal response of a semiconductor device.

REVIEW OF BASIC PRINCIPLES: THERMAL RESISTANCE

The power dissipation in a semiconductor device and its junction temperature are related by a coefficient called thermal resistance. The term arises from converting the thermal properties of semiconductor devices to an equivalent electrical analogy. This analogy is given in Figure 1. For steady state conditions, the equivalent electrical circuit yields the following equation:

$$T_J = P_D(\theta_{JC} + \theta_{CS} + \theta_{SA}) + T_A \tag{1}$$

where

θ_{JC} is the thermal resistance - junction-to-case

θ_{CS} is the thermal resistance - case-to-heatsink

θ_{SA} is the thermal resistance - heatsink-to-ambient

T_J is the junction temperature

P_D is the power dissipated in the device

T_A is the ambient temperature

Equation (1) is also the controlling equation with which the thermal resistance of a device is determined. By monitoring the junction, case, sink, and ambient temperatures as well as the power dissipated in the device, the various thermal resistances can be calculated. Equation (1) can also be written:

$$\theta_{JC} = \frac{T_J - T_C}{P_D} \tag{2}$$

where

θ_{JC} is the thermal resistance -(junction to case)and T_C is the case temperature.

Since the ambient temperature is generally the uncontrolled variable, the junction temperature of a semiconductor device with a power rating greater than a few watts must be controlled by mounting the device to a heatsink. [Because semiconductor manufacturers have no control over device applications or how devices are mounted, manufacturers usually establish only a junction-to-case thermal resistance for power devices. The design engineer must design or select the best possible method for dissipating the heat from the case of a power transistor, rectifier, or a thyristor.]

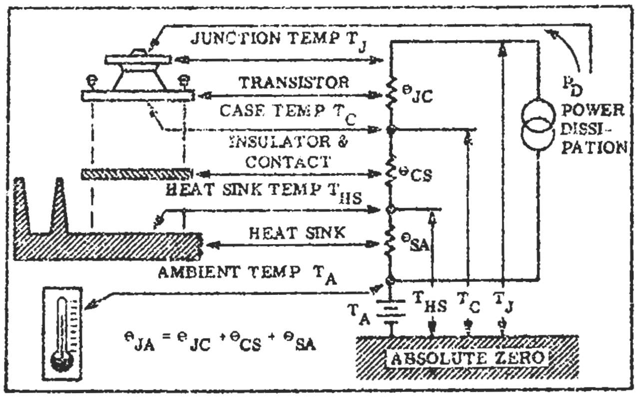

FIGURE 1 – THERMAL TO ELECTRICAL ANALOGY

The junction temperature of semiconductor devices can not be measured directly but must be obtained by monitoring some temperature sensitive parameter of the device. Parameters such as $V_{CE(SAT)}$, V_{BE} or V_{CB} for transistors; anode-cathode voltage drop for diodes or thyristors; the reverse leakage current (any semiconductor) can be used; but the recommended parameter is the forward voltage drop of a single P-N junction. This characteristic shows a more linear dependence on temperature and is more readily reproducible at low levels of current. Thus, in general, the forward voltage drop of rectifiers and the voltage drop of the forward-biased collector-base junction in transistors are used as the sense parameter. The collector-base junction is selected because most of the power is dissipated in the device at this junction. For thyristors, the anode-cathode drop was used (even though the drop is measured across 3 junctions) because significant power is dissipated in all junctions.

The reference junction temperature is established by elevating and monitoring the case temperature and sensing the collector-base junction forward voltage drop. The junction temperature is assumed to be equal to the case temperature if power dissipation from the voltage sensing current is negligible; the case temperature is then held at some measured low temperature while power is dissipated in the device until the collector-base forward voltage drop reaches the reference value. From this simple procedure, the junction temperature and the case temperature of the device is obtained.

Under most resistance test conditions, steady state power is dissipated in the test unit for long periods of time but pulsed to the low current sense conditions for short periods (usually less than one per cent of duty cycle). Under such conditions, the power dissipated in a rectifier or a thyristor is the product of the high forward current and the forward voltage drop of the device. The power dissipated in a transistor may be calculated with reasonable accuracy as the product of the collector-emitter voltage and the collector current. The collector current is slightly less than the emitter current, and the small error is usually neglected. Knowing the junction temperature, case temperature and the power dissipated in the device, the thermal resistance (θ_{JC}) can easily be calculated from Equation (2).

Previous methods of obtaining thermal resistance required a calibration curve relating the forward voltage drop to the junction temperature, a time consuming procedure which has been eliminated by the technique just described. The new method monitors the voltage drop at one junction temperature; therefore, the need for a calibration curve is eliminated.

THERMAL RESPONSE

When power is applied to a semiconductor device, the junction temperature does not rise as a step function, but rather rises as a complex exponential curve. The response is similar to a number of parallel R-C networks in series. Here R is analogous to the thermal resistance from the junction of the device to the case, and C is analogous to the thermal capacitance of the silicon die and the thermal path through the metal.

The fact that the thermal response does not follow a simple time constant, but that instead the time constant is complex is illustrated in Figure 2. Curve A is an exponential curve utilizing a single time constant of 30 milliseconds. Curve B is the actual thermal time response of the device. In 30 milliseconds, the junction temperature of the device has reached 63 per cent of its final value but for short periods of time the junction temperature raises much faster than an exponential function with a single time constant would indicate.

Because of the nature of the thermal response, an analytical expression would necessarily be complex and of little value to the circuit designer. Therefore the data of Figure 2 can be expressed as the effective transient thermal impedance as shown in Figure 3. With this information and the following equation, the designer can calculate the temperature rise of the junction in a semiconductor device under pulse power conditions.

$$\Delta T = T_J - T_C = P_D\,\theta_{JC(t)}$$

where $\theta_{JC(t)}$ is the transient thermal impedance of the device.

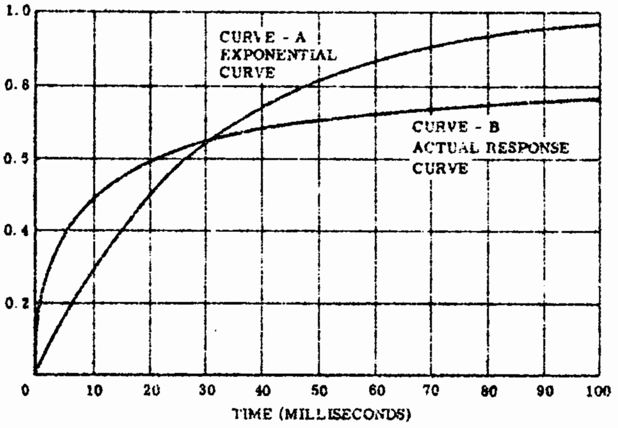

FIGURE 2 - THERMAL RESPONSE CHARACTERISTICS

Measurement of thermal time response can be obtained by sensing the same voltage used for thermal resistance measurements. Data is obtained by dissipating power in the devices under steady-state conditions until the junction temperature has stabilized and then removing the power and monitoring the junction temperature as the junction cools. Junction temperature sensing is accomplished as described in the thermal resistance tests below.

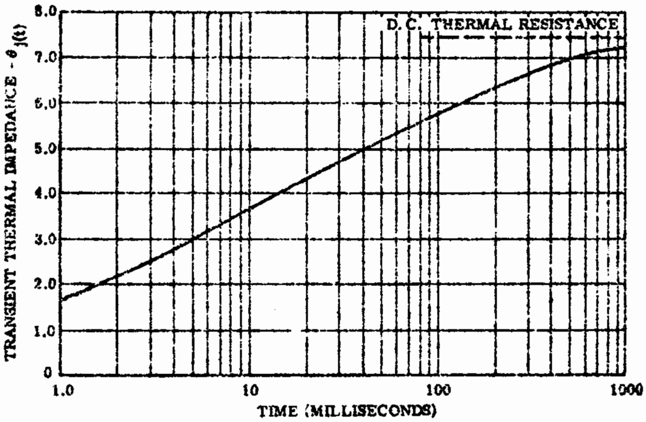

FIGURE 3 - TRANSIENT THERMAL IMPEDANCE
FOR TRANSISTOR OF FIGURE 2

THERMAL RESISTANCE TEST EQUIPMENT:

The thermal resistance test fixture (for measuring the junction-to-case thermal resistance (θ_{JC}) of high power semiconductor devices) was designed to simulate an infinite heat sink. This same device may also be used to measure the case-to-sink thermal resistance (θ_{CS}) and the transient thermal impedance with only slight modifications. To simulate an infinite heat sink, a water flow system which employs a motor control circuit, and a hot water temperature control system was developed. Switching circuits are necessary to alternately apply power and sense current to the device under test. Because of the nature of the various semiconductor devices, different switching circuits are used, depending upon whether transistors or rectifiers (and thyristors) are being measured. The systems employed in the thermal resistance test fixture are discussed individually on the following pages and the composite system is described in a later section.

HYDRAULIC SYSTEM:

The water flow diagram for the test fixture is shown in Figure 4. The system employs hot and cold water tanks, three pumps, a valve network, and a glass fixture upon which a three-by-three inch copper plate is placed. Test units are mounted on the copper plate. The minimum capacity of the tanks is 10 gallons; larger capacity tanks, in general, will improve the performance of the system. Jabsco type CJ 1/2'08 pumps are used and the speed of the input circulating pumps is 1725 rpm. The output pump, which pumps water from the fixture to the tanks, rotates at approximately 2000 rpm. Thus, the pumping action of this pump is greater than that of the input circulating pumps. The output pump removes water faster than it can be pumped in, consequently, a partial vacuum condition is created in the glass fixture. The thermal resistance test fixture requires the use of deionized water for proper performance since the terminals of some test units protrude through the copper plate.

The glass fixture is fitted with a soft pliable gasket so that a water and air tight seal can be maintained between the fixture and the copper plate when measurements are being made. The vacuum created within the jar also activates a switch to the input circulating motors so that these motors always start a short time after the higher speed output motor is running.

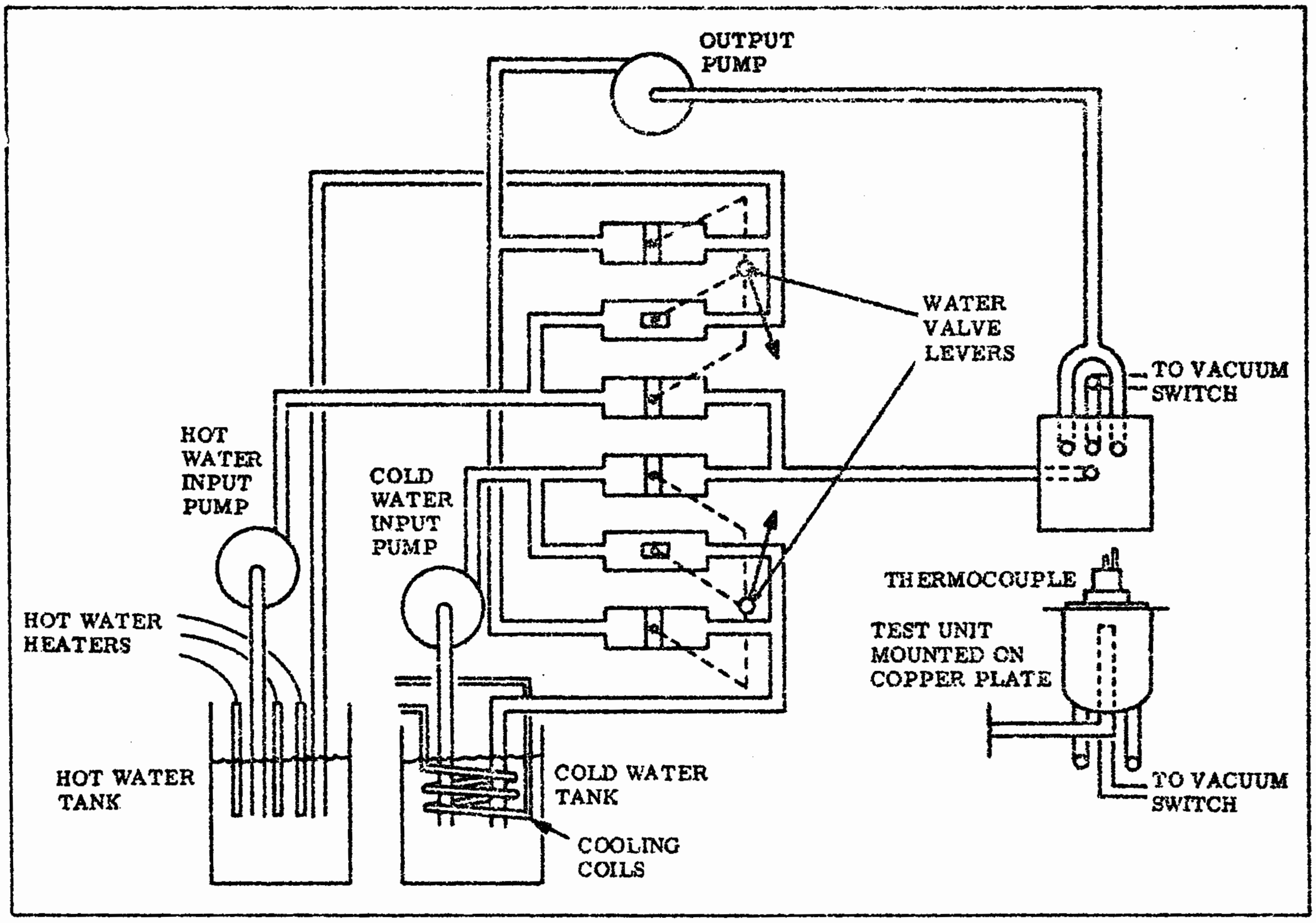

FIGURE 4 - WATER FLOW DIAGRAM

Figure 4 also shows the placement of the water heaters and cooling coils. The cooling coils are required to stabilize the temperature of the cold water tank since the temperature of this water will rise as more and more units are tested. Ordinary tap water is used in the cooling coils.

TEMPERATURE CONTROLLER:

The circuit diagram for the hot water heater and temperature controller is shown in Figure 5. This controller handles three 400-watt heating elements connected in parallel. The control element is a thermistor located in the hot water tank. Generally, five heaters are used in the warm-up period, two directly from a.c. outlets and three from the control unit. Initial heating of the water requires one to two hours.

MOTOR CONTROL CIRCUIT:

A silicon controlled rectifier circuit is used to control the motors which drive the water pumps in the hydraulic system. This circuit is shown in Figure 6. The gate signal is applied to the devices through microswitches which are located on or near the levers attached to the valves of the hydraulic system. Thus, the position of these valves conveniently controls the motors and the sequence of operation.

The high speed motor is energized when the levers of the water valves are brought together. Switch #1 is mounted on the lever arrangement of Figure 4. Once switch #1 is closed, the high speed motor is energized; he vacuum created in the bell-jar activates the vacuum switch which energizes the circulating pumps. Switches #2 and #3 are mounted on posts near the valve levers and energize the circulating pumps when the levers are in the position shown in Figure 4. Thus water is circulated within each tank when no unit is being tested. Without this circulation, temperature gradients would develop within the system.

SWITCHING CIRCUITS:

Switching circuits were designed for use on the thermal resistance fixture so that power could be applied to the device under test for periods of long duration and interrupted for very short intervals (1% of the time). During these short intervals, the sense current is applied to the device to effectively monitor the junction temperature. Two switching circuits are employed – one for power transistors and one for rectifiers and thyristors.

The switching circuit for measuring the thermal resistance of rectifiers and thyristors is shown in Figure 7. In this circuit, the 2N3447 transistor is the driver for four 2N2834 high current transistors in parallel. With the power switch closed and no pulse out of the pulse generator, the drive is biased "on" and the four parallel transistors are also biased on. Current to the test unit is controlled by the high current power supply. Test currents as high as 50 amperes may be applied to the test unit.

When a negative pulse is applied to the base of the driver transistor, the potential at the collector of this transistor rises in value and switches off the parallel high current transistors. Under these conditions, the low I_{CER} current is all that flows through these units. Effectively, only the sense current set by the sense supply and R_B flows through the test unit for the brief time that the transistors are off.

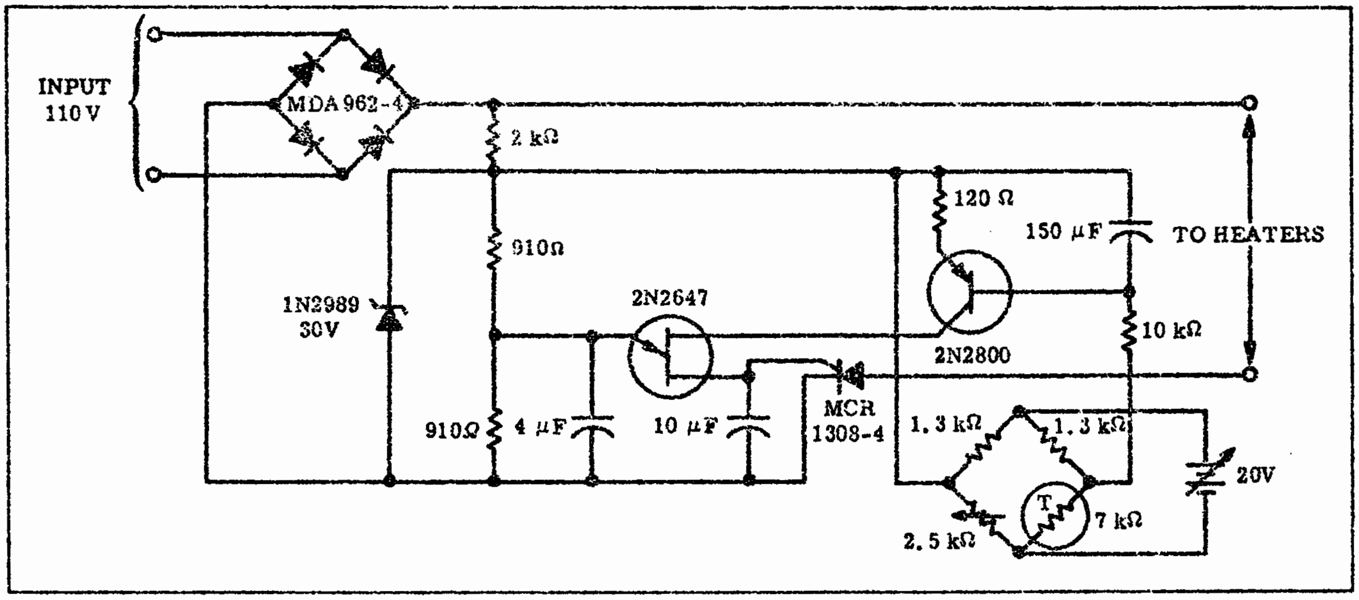

FIGURE 5 - WATER TEMPERATURE CONTROLLER

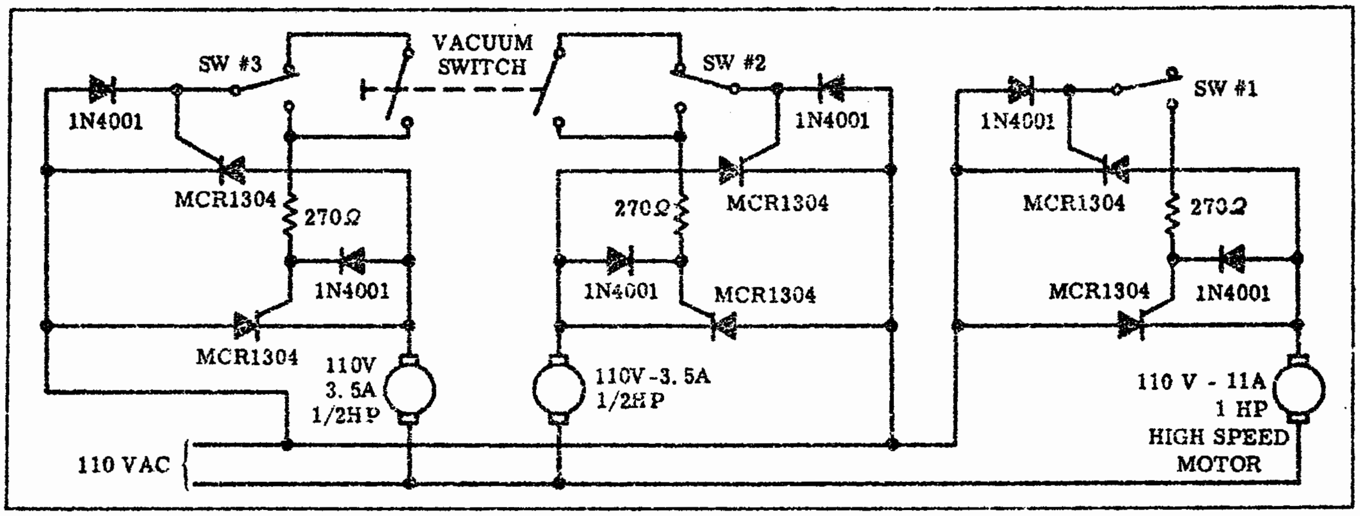

FIGURE 6 - WATER PUMP CONTROL CIRCUIT

The load current of the test unit is monitored across the 50 milliohm meter shunt and the average voltage is monitored directly across the terminals of the device. A constant current source is simulated for the sense current. For rectifiers, this current may range from 10 to 50 mA; however, for silicon controlled rectifiers this sense current must be greater than the holding current of the device. The SCR is gated on at the beginning of the test and then power to the gate is removed.

The reference voltage and the chopper relay provide a means of superimposing the sense signal and the reference signal on the oscilloscope. With the power switch open and a sense current flowing through the unit under test, the forward voltage drop is monitored on the oscilloscope. With the chopper relay, a signal from the reference voltage can be superimposed on the monitored voltage drop signal of the device. In this manner, the voltage drop of the device need not be monitored absolutely but only aligned with the reference voltage.

The transistor test circuit shown in Figure 8 is similar in operation to the rectifier test circuit but is of necessity more complex due to the fact that both PNP and NPN transistors can be tested in the circuit. Switch positions are shown in Figure 8 for testing NPN transistors. As noted in the schematic, the test transistor is driven in the common base configuration. With the disconnect switch in the sense position, the collector supply voltage is impressed across the device. Then the base supply voltage is increased until the pre-determined sense current flows through the collector of the test device. Thus, this voltage supply overrides the collector supply.

When the disconnect switch is closed, power can be applied to the device under test. Study of the circuit will show the control transistors Q_1 and Q_2 are normally biased on and increasing the emitter supply voltage will increase the collector current through the test unit while the collector voltage remains constant. When a negative pulse is applied to the transformer, the control transistors are turned off and sense current again is imposed on the test unit. Monitoring the voltage drop under sense conditions and power conditions is accomplished in the same manner as with rectifiers and thyristors.

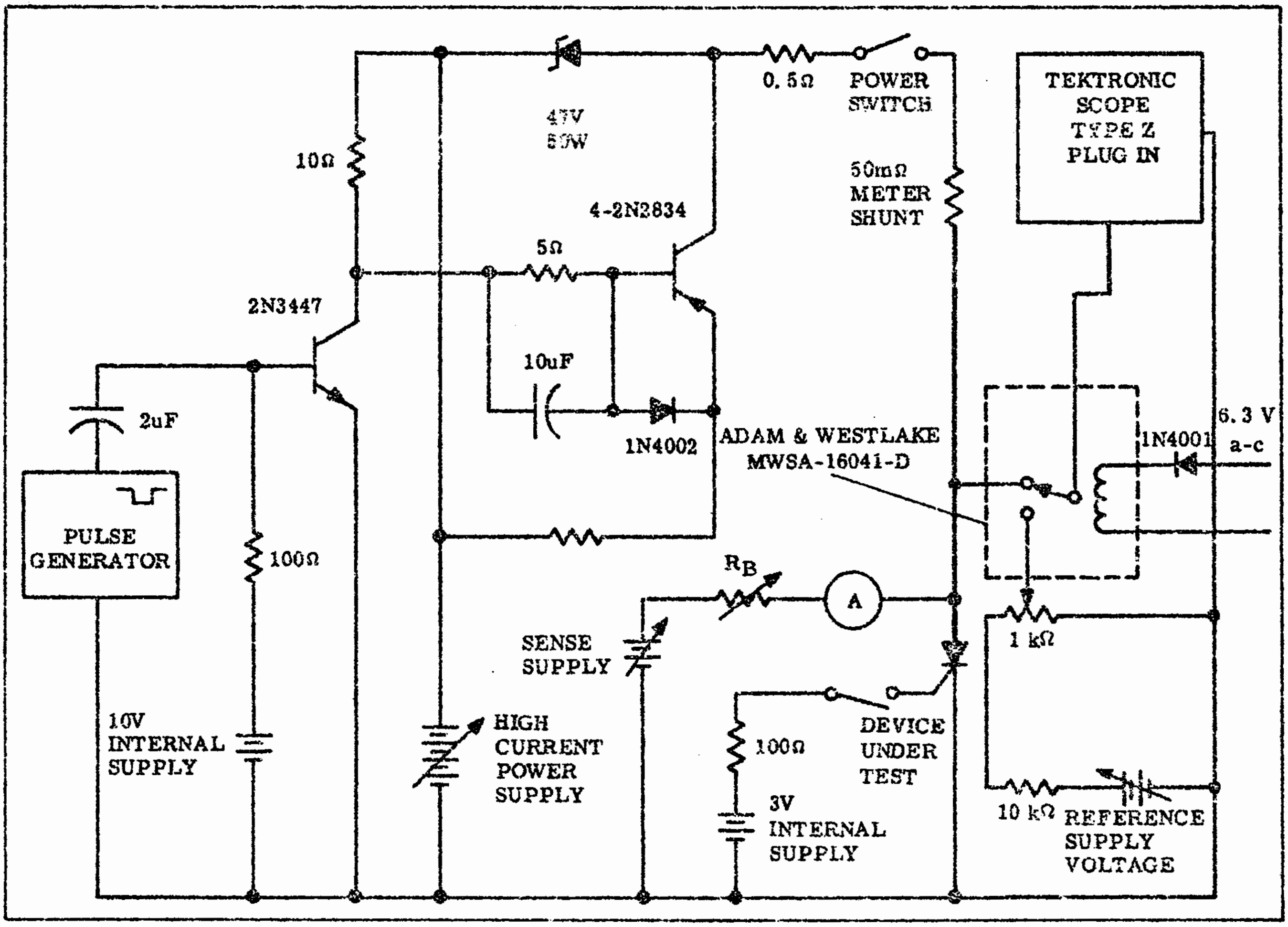

FIGURE 7 - RECTIFIER AND THYRISTOR THERMAL RESISTANCE TEST CIRCUIT

THERMAL RESISTANCE MEASUREMENTS:

Now that the individual elements have been described, the system as a whole needs to be considered. Initial steps in obtaining thermal resistance measurements require heating the water, connecting thermocouples to the devices, and mounting the devices to the copper plates as shown in Figure 4. Tap water is circulated through the cooling coils of the cold water tanks, and all external power supplies are connected to the system. Thermal resistance measurements may be made after water temperatures are stabilized.

Some consideration must be given to the temperature of the hot water and mounting of the thermocouples. The temperature of the hot water is determined by safe area of the devices tested. Silicon power transistors with adequate safe areas can be tested with water at 78 to 80 degrees centigrade. Germanium devices, however, may have to be measured at some lower temperature. When testing rectifiers and thyristors, the voltage drop is generally 1 to 2.5 volts. Thus, when the temperature change is great ($T_J - T_C \geq 50°C$), large currents must be available to provide the necessary power.

Thermocouples must be carefully mounted to the semiconductor devices. These thermocouples must be placed at specific points on or in the case of the device. Placement of the thermocouple should be as near the semiconductor material as is feasible.

TESTING THYRISTORS AND RECTIFIERS

After the rectifiers or thyristors are mounted on suitable copper plates as indicated in Figure 4, and a thermocouple is properly attached to the device package, thermal resistance measurements are ready to be made. Devices are connected into the test circuit as illustrated in Figure 7.

Hot water is sprayed on the bottom of the copper plate by changing the position of the set of valves shown in the upper portion of Figure 4. As previously stated, the position of these valves activates the pump motors.

Sense current is established in the rectifier or thyristor by adjusting the sense supply and R_B of Figure 7. In the case of thyristors, the devices are gated into conduction and then the gate is chosen so that operation is in the linear portion of the diode characteristics. For thyristors, the sense current must be greater than the holding current of the device. The case temperature is monitored with a thermocouple and a temperature bridge.

From Equation 1, the monitored case temperature is equal to the junction temperature of the device if the sense current and thus the power dissipated in the device is chosen small enough that it can be considered negligible. The voltage drop of the test unit is displayed on the oscilloscope. A differential type W plug-in is used so that adequate sensitivity can be obtained. The reference supply is adjusted so that this voltage is superimposed

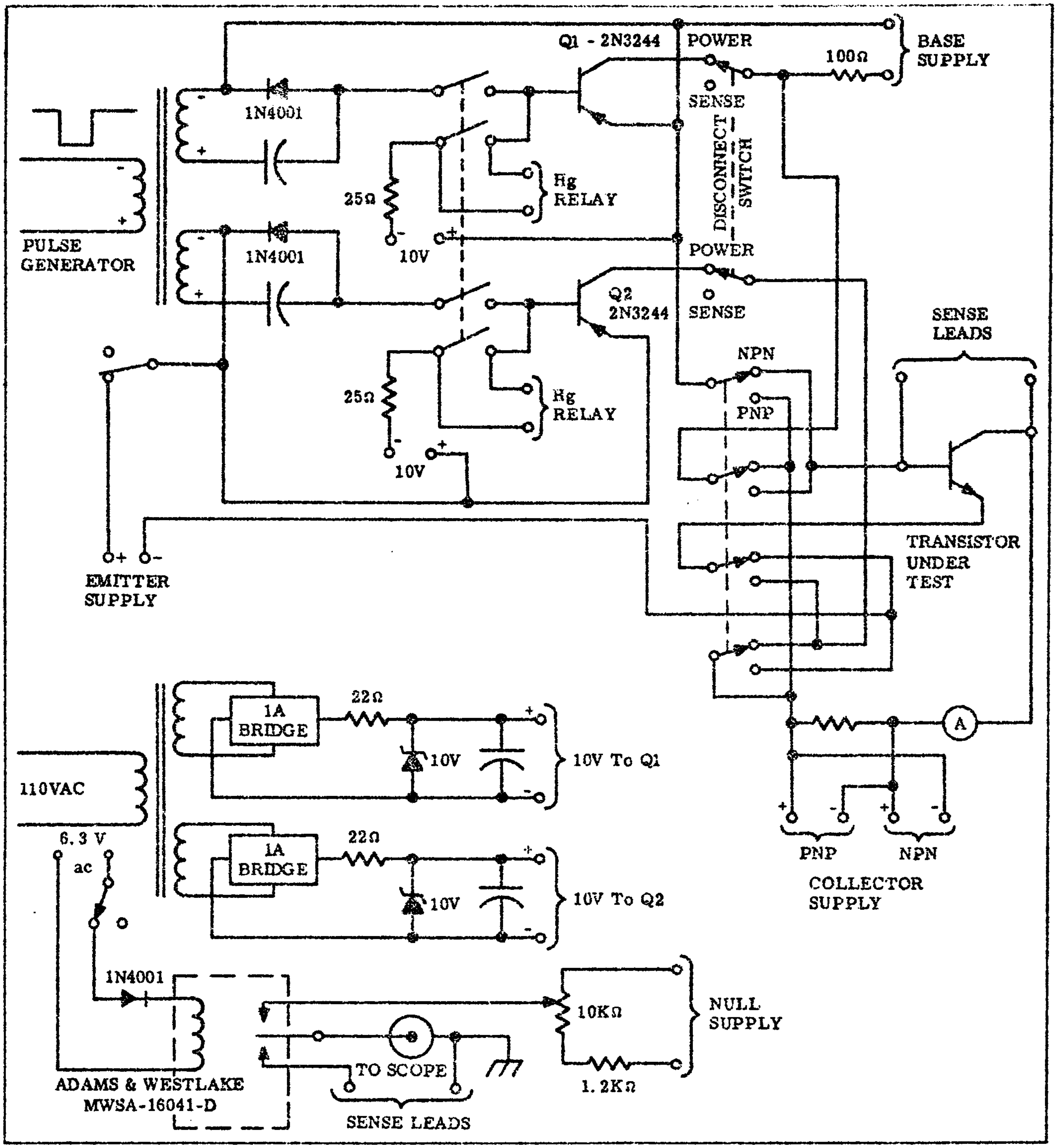

FIGURE 8 - TRANSISTOR THERMAL RESISTANCE TEST CIRCUIT

over the voltage drop of the test unit. The relay is a break before make type so that the reference voltage does not affect the test circuit.

The hot water is turned off and cold water is sprayed on the plate. With the same sense current, the forward voltage drop of the test unit will increase to a higher level. Thus, the reference voltage and the new voltage drop will differ by approximately 2 mV per degree C of the case temperature change. The power switch is closed and high current is applied to the device. The pulse generator switches the high current off so that only sense current flows in the device (for less than one per cent of the time). The scope display is shown in Figure 9. As more power is applied to the device, the junction temperature will rise until the voltage drop under sense conditions will align with the reference voltage on the oscilloscope. When this occurs, the junction temperature is the same as the hot water case temperature (T_j).

The DC current through the device is obtained with a meter across the 50 mV shunt. The product of the DC current and the DC voltage dropped across the device (under high current conditions) is the power dissipated in the device. Now if the case temperature is monitored, the thermal resistance can be computed from Equation (1) as T_j, T_c, and P_d are all known.

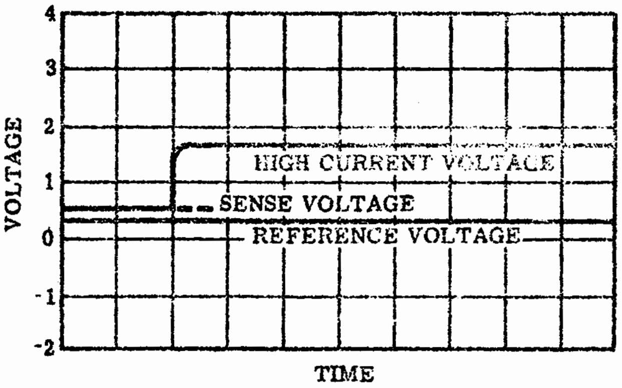

FIGURE 9 - OSCILLOSCOPE DISPLAY FOR RECTIFIER TESTS

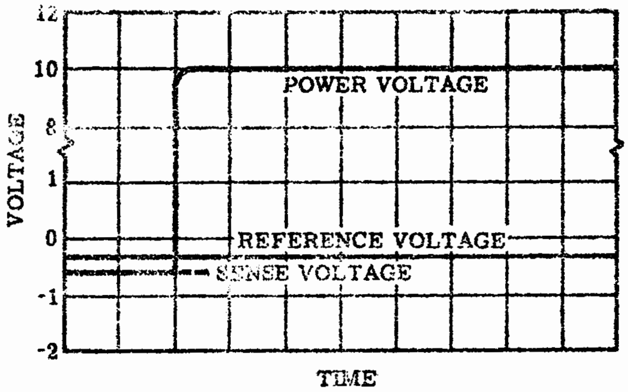

FIGURE 10 - OSCILLOSCOPE DISPLAY FOR TRANSISTOR TESTS

TRANSISTOR TESTING

Thermal resistance of transistors can be measured using the test circuit of Figure 8. Again the transistor must be mounted on a copper plate, thermocouple attached to the case and connections made to the test circuit. Hot water is sprayed on the copper plate as described for testing rectifiers and thyristors. With the disconnect switch in the sense position, the collector supply voltage is set to some reasonable value (usually 10 volts). The base supply voltage is increased until the sense current flows in the forward biased base-collector junction of the test unit. The sense current is established in the same manner as in testing rectifiers. The resulting voltage drop is displayed on the oscilloscope with the W type plug-in. The reference voltage is superimposed over the sense voltage and the case temperature of the test unit is monitored. Thus, it is very similar to the method used in testing rectifiers and thyristors.

Next, cold water is sprayed on the copper plate. The bias switches to Q_1 and Q_2 are closed (Mercury relay contacts are open) and the disconnect switches are changed to the power position. The pulse generator is energized and set for a one percent duty cycle. As the emitter voltage supply is increased, the collector current will increase, but in a direction opposite to the sense current. The collector voltage remains essentially constant. The pulse generator and the switching transistors pulse the test transistor off, and only sense current flows in the test unit. The voltage waveform as displayed on the oscilloscope, is shown in Figure 10.

As more power is dissipated in the device, the junction temperature will rise until the voltage drop of the collector-base junction under sense conditions, aligns itself with the reference voltage displayed on the oscilloscope. At this point, the junction temperature is known.

The case temperature is now monitored, the collector current and the collector-emitter voltage is metered and the thermal resistance can be computed from Equation (1).

FINDING THERMAL RESPONSE

The thermal response of a semiconductor device can be obtained with slight modifications to the switching circuits of the thermal resistance fixture. For transistors this is illustrated in the circuit of Figure 8. Here the bias switches to Q_1 and Q_2 are open, and a mercury relay driven by a pulse generator is used to bias the switching transistors.

To obtain thermal response, cold water is sprayed on the copper plate as before. A sense current is applied to the transistor as before with the collector voltage set at some power level. The mercury relays are then closed, power is dissipated in the test transistor until the case temperature, and, therefore, the junction temperature is stabilized. Once stabilization has been attained, power to the device is removed. The voltage across the P-N junction under sense current conditions will increase exponentially with time. This exponential wave shape is photographed or stored on a memory scope.

The voltage change recorded above is normalized as shown by curve 3 of Figure 2. Thus, the need to know the actual junction temperature is eliminated. If the thermal resistance of the device is known, the normalized data of Figure 2 can be used to construct the transient thermal impedance curve of Figure 3.

CONCLUSION

The test equipment and procedure described gives a technique for accurately measuring thermal resistance and thermal response. Results are consistent and quite reproducible – usually to within 10 percent. Mounting of the devices usually requires time, which tends to slow the operation, however, actual measurements are obtained quickly and accurately.

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