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VALVES FOR HIFI

PART 1 — INPUT TYPES

By M. Y. Epstein

RCA Electron Tube Division, Harrison N.J.

RCA has recently introduced into its line several new valve types intended specifically for high-fidelity audio service. Some of these types are already being used in equipment manufactured by RCA and other companies. This paper discusses these types from a valve designer's viewpoint and shows how their design, as well as the design of others still in development, is influenced by the special requirements of high-fidelity applications.

In high-quality audio systems, the input signal is often as low as 3 millivolts (or even 1 millivolt for the latest 4-track stereo-tape pickup head). Because a signal-to-noise ratio of about 60 db is desired for high-fidelity applications, the input valve and its associated components must contribute total noise* of less than 3 microvolts.

The most significant feature of an input valve, then, is low noise level. Electrically, the valve should have relatively high gain to raise the low input signal well out of the noise region of the following valves. Because the 12AX7 high-mu twin triode has been very satisfactory in input-circuit designs, RCA recently brought out the 7025 having equivalent electrical characteristics but designed specially for low-level signals and carefully controlled for low noise.

The 7199 medium-mu triode—sharp-cutoff pentode is also designed and controlled for low noise, but not to the same degree as the 7025. This valve can be used in practically all the stages (except the output) of a complete audio system. Except in very critical low-level applications, the 7199 performs satisfactorily as a preamplifier, a tone-control amplifier, and the phase splitter for the push-pull power-output stage.

Noise

The sources of noise in a vacuum valve are varied. For convenience, different valve noises may be grouped together and discussed under three headings: microphonics, hum, and hiss (with hiss being a general term that includes thermal, shot, partition, and leakage noise).

Microphonics

Microphonic noise is a result of fluctuations or modulations of the electron stream caused by varying electrode spacings. The valve elements are caused to vibrate by external mechanical forces applied to the valve directly through the air from the loudspeaker or through the chassis from switches, motors, and turntables.

The amplitudes and frequencies of these forces felt by the valve depend on such variables as the Q factor of the coupling elements between the tube and the mechanical-force sources, and the moduli and phase angles of the forces appearing simultaneously at the valve. Consequently, microphonic noise can be avoided to a great extent by proper design of the valve environment.

For the valve designer, however, the problem is to reduce both the amount of electrode vibra-

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* Valve noise is measured in terms of equivalent volts at the grid input, i.e., the noise output, without signal, divided by the gain of the valve. This measurement permits direct noise comparison between valves having different sensitivities.

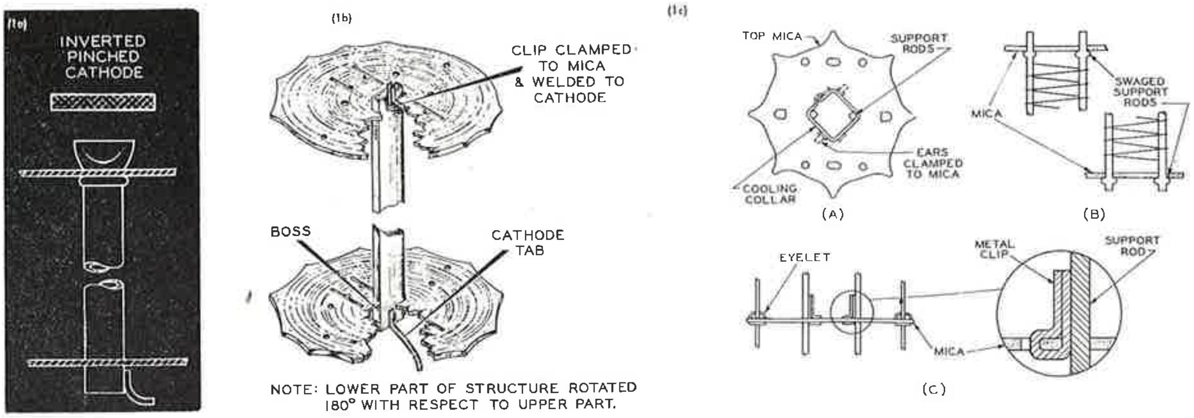

Fig. 1—Various methods used to fix electrodes tightly and eliminate rattle noise in electron valves. Figs. 1a and 1b show cathode-"fixing" methods and Fig. 1c shows "grid-fixing" methods.

tion and the sensitivity of response of the valve to external vibrating forces. Vibration of the valve elements consists of two forms—rattle and resonance. The former is due to the looseness of fit between the electrodes and their supporting and fixing members, and the latter is due to the natural resonant frequency or frequencies of the particular electrode or group of electrodes. Because the resonant frequency depends on the form and the tightness of fixing of a part, the two forms of vibration are related. The difference, however, is that it is theoretically possible to eliminate rattle completely, whereas resonant frequencies are impossible to avoid but may be shifted to reduce their microphonic noise effects.

Fig. 1 shows several well-known methods used to fix electrodes and eliminate rattle noise.[1] These methods include pinched cathodes, embosses on the cathode, mica eyelets, grid swages, and grid stitches. Because these methods add cost to the valve, however, the real question involved in the avoidance of rattle noise is to determine what devices are absolutely necessary to provide the proper margin of safety.

As mentioned above, resonant frequencies cannot be completely eliminated, but can be adjusted. In general, the resonant frequencies of the valve elements vary inversely with the square of their length and density, and directly with their diameter, the square root of their moduli of elasticity, and the tightness of fit. The amplitude of vibration varies inversely with the frequency.

Changes made to improve either rattle or resonance, therefore, benefit both. Tightness of fit to reduce rattle also raises the resonant frequency; higher frequencies reduce the amplitude of vibration resulting from a given mechanical shock, and also make the valve less liable to excitation from mechanical sources (which usually vibrate at low frequencies).

Both the 7025 and the 7199 are designed with short cages and rigid connectors to provide overall mount structures which reduce both rattle and resonance. Cathodes have a tendency to warp or bow at high temperatures if they are fixed too tightly and cannot expand. Because this tendency limits the tightness of cathode fixing, the cathode is often the worst offender in the production of microphonic noise. A new valve is presently being developed which will be even shorter than the 7025 and also have a larger-diameter cathode. The increased structural strength of the shorter, larger-diameter cathode will allow the use of tighter fixing.

A desirable approach to the reduction of microphonic noise is to make the valve less sensitive to changes in its electrode spacings. Valve symmetry is important in this respect. Conventional valves are built around a cathode, as shown in Fig. 2,

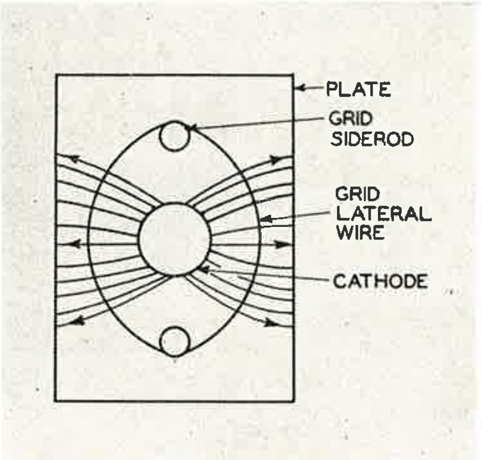

Fig. 2—Diagram illustrating formation of two separate sections in a valve as a result of the effect of grid siderods.

and may be considered as two separate valves connected in parallel. Movement of a given electrode structure increases the spacings on one side of the cathode while reducing them on the other. With good symmetry of spacings, the effects of such changes on valve characteristics tend to cancel. This simple-sounding requirement, however, is very difficult to achieve under quantity-production conditions.

A very interesting technique for reducing microphonics that is presently being evaluated is based on the "inselbildung" phenomena and its effect on amplification factor.[2] At very small grid-cathode spacings, the control grid begins to lose its control over portions (islands) of the cathode, as shown in Fig. 3, because of excessive penetration of the plate equipotential lines through the control-grid lateral wires. Effect upon amplification factor is shown in Fig. 4. Microphonic noise is also affected because current (I) varies inversely with both amplification factor (μ) and grid-cathode spacing (D_{g1k}), as follows:

$$I = f \left[\frac{1}{(\mu) \ (D_{g1k})} \right]$$

Depending upon the region of operation in Fig. 4 (A or B), electrode displacements will produce changes in both D_{g1k} and μ that either add or tend to cancel the changes produced in I. In region A, the "inselbildung" region, the effects add to make microphonics worse.

Because of the need for high transconductance and cathode efficiency, modern-day valves are invariably designed with small grid-cathode spacings and operate in region A. However, the electrical compromises necessary to move the valve design from region A to region B are not too critical in valves for audio applications, and it is hoped that this technique will help to reduce microphonic noise in inexpensive, high-quality valves of the future.

Hum

Hum noises are contributed by the effects of the ac current flowing in the valve heaters.[3] This type of noise is conveyed from the heater to the valve output by essentially four different mechanisms: (1) electrostatic hum due to capacitive coupling between the heater and other elements, (2) inductive hum caused by mutual inductance between the heater and other elements, (3) magnetic hum caused by the influence of the magnetic field of the heater on the electron stream, and (4) insulation hum caused by the leakage currents from the heater to the cathode through the heater insulation. Use of dc in the heater will eliminate all these noises.

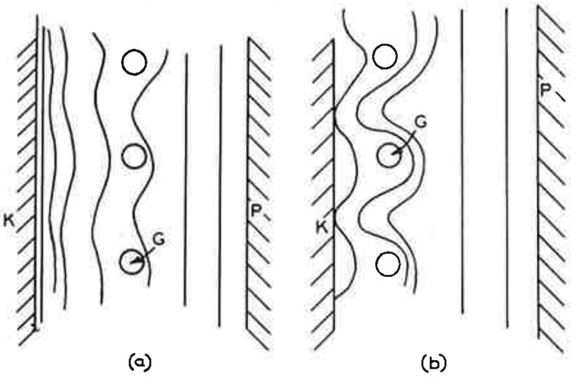

Fig. 3—Effect of grid-cathode spacing on uniformity of electrostatic fields at the surface of the cathode.

The first two noise sources represent shielding problems. Because the cathode metal sleeve acts as a shield between the heater and other electrodes within the mount cage of the valve, most of the coupling occurs between the stem leads. Proper selection of basing arrangement is effective to reduce coupling effects, as is the use of shields to isolate the heater leads. Electrostatic hum between the heater and the control grid can be significantly reduced by the use of a potentiometer, as shown in Fig. 5. The electrode capacitances and conductances form a bridge network, with the external grid resistance as the cross-arm. Although inductive hum cannot be corrected in this manner, careful positioning and twisting of the socket heater leads is generally sufficient to avoid this source of noise.

The magnetic field of the heater affects the space charge in front of the cathode, producing noise both by modulation of the cathode-current density and by deflection of the electrons from their normal paths and resulting variations in

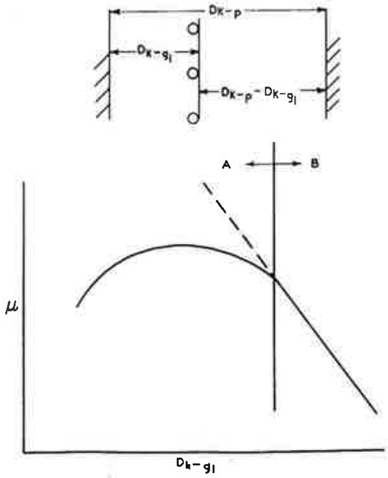

Fig. 4—Variation of amplification factor as a function of grid-cathode spacing.

their rate of arrival at the plate. The 0.002-to-0.003-inch nickel cathode sleeve is no protection against this low-frequency magnetic field because the cathode is operated above the curie temperature of nickel. Pentodes are more susceptible to this form of noise than triodes because the presence of even a weak varying magnetic field usually increases the level of partition noise (see section on hiss below).

Fortunately, it is possible to design heater configurations that confine the magnetic field almost completely within the heater itself. Fig. 6 shows three forms of heaters. The folded heater produces a magnetic field which is directed into the cathode space charge and can be very troublesome. When the heater is folded so that the current in adjacent strands flows in opposite directions, the magnetic fields cancel. During insertion of the heaters into the cathode, however, the strands are aligned randomly. Consequently, the distribution of hum noise output with folded heaters is very wide.

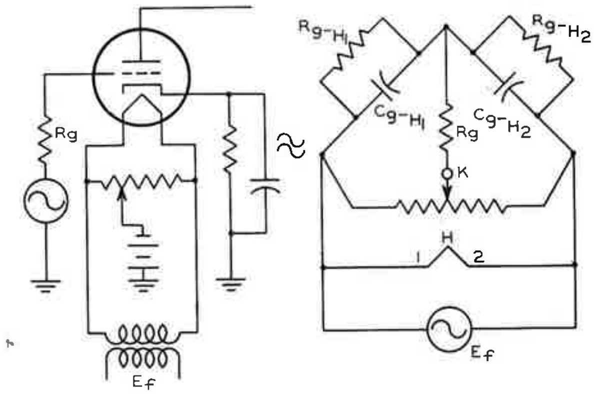

Fig. 5—Bridge network using potentiometer (with external grid resistance as cross arm) to reduce electrostatic hum.

The single-helix heater confines most of the magnetic field inside the heater, with only a weak field directed into the space charge. The double-helix heater is the best of all in this respect, with practically no fields outside the heater turns. The 7025 uses a single helix and the 7199 a double helix, both with very low hum noise. The shorter developmental valve previously referred to will also use the double-helix coil. At present, a double-helix heater cannot be made small enough to fit into the small-diameter 7025 cathode.

Varying leakage current between the heater and cathode through the heater insulation produces a noise voltage when it flows through the cathode-biasing resistor. Even when this resistor is completely bypassed, there is an internal cathode resistance of the order of 0.1 ohm due to cathode interface, fusing of the cathode, and contact resistance between the valve leads and the socket. With excessive heater-cathode current, several microvolts of noise can be developed across even this small resistance.

Heater-cathode current depends strongly on temperature, as shown in Fig. 7. It is desirable, therefore, to operate the heater at as low a temperature as possible. If the cathode temperature becomes too low, however, excessive shot noise will develop, as described below.

Fig. 8 shows the current-voltage characteristics of the insulation coating between heater and cathode. Positive biasing reduces the effect of the ac heater voltage on noise output because of the saturated current conditions. The slope of the curves in Figs. 7 and 8 suggests that, in addition to insulation leakage, there is also direct emission (with characteristics similar to the usual diode emission) from heater to cathode. Although positive bias supposedly reduces or causes saturation of the emission component of the total current, there are instances[3] where negative biasing achieves the same results.

The most satisfactory method to reduce heater-cathode hum in the 7025 and 7199 is to insure that materials used for the heater insulation are as pure and as effective as possible, that care is taken during valve assembly not to chip or scrape off the insulation, and that as much insulating material as possible (consistent with heater power and cathode size) be used on the heater.

Hiss

The general term hiss includes those noises produced by the flow of the electron stream itself. Thermal noise, although generally included, should not be directly associated with the input valve because it is caused by the thermally agitated random motion of electrons in conductors external to the tube.

Shot effect is the noise associated with random emission in a valve whose emission is temperature-limited. Although this noise is probably the loudest of the electron-valve noises,[4] it is greatly reduced when the cathode is hot enough to operate outside the temperature-limited region. Space-charge operation also tends to smooth out the effects of shot noise because emission of more than the average number of electrons in an instant results in an increase in space charge and, consequently, a compensating decrease in current

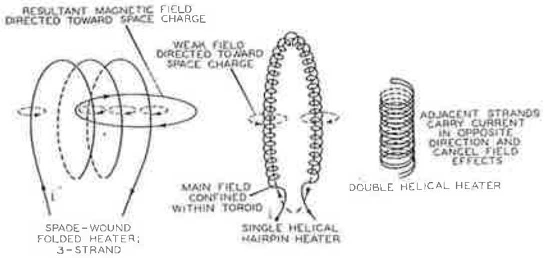

Fig. 6—Effect of heater configuration on heater magnetic fields.

in the next instant. With proper cathode temperature and valve operation, shot noise can be reduced below one microvolt.

For critical low-level applications, triodes have less hiss output than tetrodes and pentodes because of partition noise, i.e., noise due to random variations in the division of space current to the plate and screen grid. This noise is generally the dominant noise of a multi-positive-electrode valve. The noise output of a pentode is often three to five times higher than when the valve is operated as a triode (screen grid tied externally to plate).

Leakage noise is lumped together with other hiss noises because it is caused by current flow between electrodes, although not directly along the cathode electron stream. The leakage current flows along conductance paths on the mica spacers or through the glass separating the electrode-connecting leads. The greatest leakage occurs across conductance paths formed on the micas by metallic deposits driven from the hot electrodes and the getter (the barium deposit flashed onto the inside glass walls to adsorb gas during the life of the valve). Although the cathode is usually the largest contributor of these leakage-forming elements, inclusion of these materials in the cathode is essential for proper operation of the oxide-coated cathode. Consequently, a balance must be reached between low leakage and proper cathode performance.

Cathodes which have low levels of contaminants have been developed for low-noise valves. The necessary environments for these cathodes are very critical, however, and great care must be taken to use clean parts and electrode materials that are compatible with the delicate cathode.

High-fidelity valves are processed and operated at the lowest possible temperatures to avoid excessive evolution of particles from the electrodes. Processing of the 7025 and 7199 is delicately balanced between temperatures high enough to drive off gases from the electrodes during exhausting of the valve and to burn out contaminants in the heater insulation that might cause heater-cathode leakage, and temperatures low enough not to cause leakage paths due to the volatilization of materials from the electrodes.

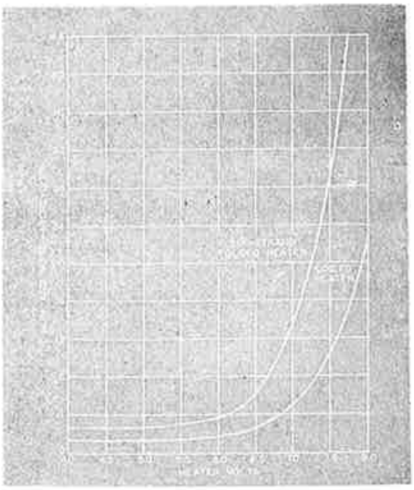

Fig. 7—Variation of heater-cathode leakage (hum noise) with temperature (heater voltage).

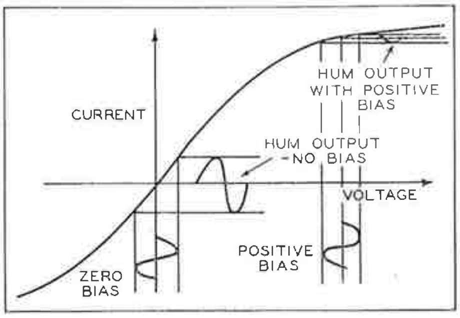

Fig. 8—Current-voltage relationship of heater-cathode insulation coating showing effect of positive bias on hum output.

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THERMAL IMPEDANCE OF SILICON RECTIFIERS

by N. Smith and J. Neilson

RCA Semiconductor and Materials Division
Somerville, N.J.

The single greatest cause of failure in silicon rectifiers to date has been thermal failure. Because electrical characteristics alone give no indication of thermal performance, it is important to understand and investigate thermal characteristics. This paper discusses the various factors that determine the thermal impedance of silicon rectifiers and describes the limitations of several techniques for measuring such impedance. A practical method based on forward-voltage-drop characteristics is presented.

INTRODUCTION

As silicon rectifiers and other semiconductor devices become more and more widely used, and as their operating requirements are raised, greater emphasis must be placed on the proper design and application of these devices. The life of a semiconductor element is very long; in fact, no life end point has yet been established. Because the crystal structure of semiconductor material remains unchanged throughout years of operation, it would seem that the devices should continue to operate satisfactorily. However, a great many devices fail in service even when it seems that they are being operated well within the manufacturer's ratings. This paper discusses some of the causes of failure and provides information on determining how well a silicon rectifier is constructed and on choosing a safe rating for the device. Although the paper deals exclusively with silicon rectifiers, the information can also be applied to other types of semiconductor devices.

TEMPERATURE EFFECTS IN RECTIFIERS

The predominant cause of failure in silicon rectifiers is excessive temperature. (A rectifier is assumed to have "failed" when either the forward voltage drop or the reverse leakage has increased to a point where the device can no longer fill its requirements in the application.) The excessive temperature may be the result of various causes, such as localized heat within the device, external ambient heat, or excessive applied voltage or current.

Consequently, the thermal characteristics of a rectifier are at least as important as its electrical characteristics. In most cases, however, there is no correlation between the thermal and electrical characteristics of a given device. For example, when two units rated for an average forward current of 20 amperes were tested recently, they had identical forward voltage drops at 100 amperes and very closely matched dynamic and static leakages. When they were placed in service, however, one unit failed from thermal fatigue after only 10 hours of operation while the other successfully completed 1,000 hours.

Although it has been shown that silicon rectifiers are very susceptible to inverse voltage transients, excessive temperature causes failure more often than the momentary increase in voltage itself. When the normal peak inverse voltage of a rectifier is exceeded, the reverse current increases rapidly until the power in the inverse direction is of the order of watts instead of the normal milliwatts. This increased power causes a substantial increase in temperature at the rectifying element which induces failure.

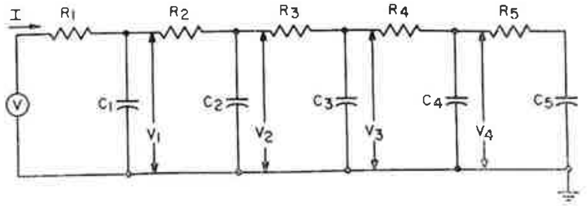


Fig. 1—Electrical analog circuit used to describe thermal properties of silicon rectifier.

A silicon rectifier should be capable of dissipating as much power internally in the reverse direction as in the forward direction without damage to the unit. Often, however, a rectifier fails when subjected to an inverse voltage transient which results in much lower dissipation than that produced by the normal forward current. Such failures may be caused by the reverse current being localized at one spot on the surface or within the bulk material, rather than being distributed uniformly over the junction. A uniform, smooth junction (such as those obtained by diffusion techniques) is more likely to be free from localized heating within the crystal than an irregular junction and can therefore handle excessive transient inverse voltage more safely.

Because the inverse voltage in a p-n junction is of necessity blocked by a very thin section, the reverse bias causes a very high electrical field or voltage stress. This stress is intensified by irregularities in the junction or on the surface of the crystal. Such irregularities cause excessive localized reverse currents and localized overheating. Although heat from forward current is not usually localized on the crystal surface, it may be localized within the crystal by imperfections such as irregular junctions, cracked semiconductor pellets, or poor contacts to the pellet.

Each material in a silicon rectifier has its own specific temperature limitations. The upper limit for a given material is the temperature above which irreversible changes begin to take place in the material. The temperature limitations of the device itself are determined by the lowest of the various material limitations.

The materials contained in a typical silicon rectifier include the silicon crystal, an electrically insulating material, a solder or brazing alloy, and case materials such as glass, steel, nickel, copper, aluminium, epoxy resin, and the like. Because the semiconductor element of a silicon diffused-junction rectifier is originally formed at very high temperatures, it can be operated at temperatures as high as 400 degrees Centigrade for short periods without significant changes in performance. However, soldered contacts to the crystal may be weakened or destroyed if the temperature approaches their melting point. Thermal-expansion differences between the various components can destroy a device by fatigue of joints or contacts, or by actual cracking of the crystal.

The electrical characteristics of a semiconductor device are dependent on temperature. During operation, the amount of heat generated depends mainly on the characteristics of the semiconductor element itself, and most of the heat is generated within this element. The general temperature dependence of characteristics of a p-n junction will be discussed later (Figs. 6 and 7).

The bulk reverse saturation current I_s of a p-n junction is a function of temperature, as shown below:

$$I_s = kT_J{}^3 \exp - \frac{qV_g}{kT_J} \qquad 1$$

where q is the electronic charge, V_g is the inverse-voltage bias, k is Boltzmann's constant, and T_J is the absolute temperature of the junction.

Because leakage over the semiconductor surface adds to the reverse current, the actual current often does not conform to equation (1) and can only be determined empirically. At temperatures in the order of 300 or 400 degrees Centigrade, the reverse current in a silicon p-n junction increases very rapidly with temperature and causes a corresponding increase in the power developed by the reverse current within the crystal. This increased current causes failure only if it is allowed to continue to flow without removal of the resulting heat, so that the temperature exceeds the limitations of one of the components of the device.

A condition in which an increase in temperature causes an increase in power dissipation so that one continues to add to the other is known as "thermal runaway". Even under such conditions, failure generally occurs as a result of macroscopic changes such as carbonization or cracking of the resin, melting or fatigue of contacts, or cracks in the crystal caused by uneven heating or differences in thermal expansion long before the temperature is high enough to cause any change in the structure of the semiconductor crystal.

If failures are to be prevented, the heat must be removed rapidly enough so that all materials in the device are kept within their temperature limits. Because the semiconductor element itself is the source of heat, it has the highest temperature in the device, and other materials are at various lower temperatures.

Electrical	Thermal
Current generator	Heat generator (semiconductor crystal)
Resistance R (ohms or volts/ampere)	Thermal Resistance R_T ($^\circ$C/watt)
Capacitance C (ampere-second/volt)	Thermal Capacitance (C_T watt-second/$^\circ$C)
Potential difference V_1-V_2 (volts)	Temperature difference T_1-T_2 ($^\circ$C)
Potential above ground V-V_G (volts)	Temperature above ambient T-T_A ($^\circ$C)
Current I (amperes)	Power dissipation P (watts)
Impedance Z (volts/ampere)	Thermal impedance Z_T ($^\circ$C/watt)

Table I — Comparison of various electrical quantities and corresponding thermal quantities.

THERMAL CONSIDERATIONS

The temperature of the semiconductor element (or the junction temperature T_J) is related to the temperatures of the various other elements surrounding it by mathematical relations similar to those applying to an electrical circuit containing capacitance and resistance. Therefore, it is convenient to describe the thermal properties of a silicon rectifier in terms of thermal impedance, thermal capacitance, and thermal resistance.

The thermal properties of a device may be represented by an electrical analog circuit, such as that shown in Fig. 1, which consists of a current generator connected to a series of resistors that have capacitance to ground distributed along their length. The power P dissipated within the crystal of a semiconductor device results in a flow of heat outward from the crystal. This flow of heat (dissipated power P in calories per second or in watts) in a semiconductor device is analogous to the flow of charge (electrical current I in coulombs per second or amperes) in such a circuit. Thermal resistances and thermal capacitances of the device are analogous to the electrical resistances and capacitances shown in the circuit. The potential difference or voltage between any two points in the electrical analog circuit is analogous to the temperature difference between the corresponding two points of the device it represents. Table I shows the relationship between various electrical quantities and their corresponding thermal quantities.

Thermal impedance Z_T, like electrical impedance Z, is a complex variable because of the time dependance associated with the thermal capacitance C_T. Thermal resistance R_T is the reciprocal of thermal conductance G_T and is derived in the same manner as electrical resistance R. Thermal conductivity K is a basic property of the material itself and is independent of geometry.

Fig. 2 shows a layer of thermally conductive material which has a constant cross-sectional area A and a thickness L. If the surface S_1 is maintained at temperature T_1 and surface S_2 at temperature T_2, a given quantity of heat Q flows through the layer in a time t. The rate of flow P of heat through the layer is given by $P = Q/t$. The thermal conductance G_T of the layer is related to the thermal conductivity K of the material by the expression $G_T = KA/L$. The thermal resistance R_T of the layer is given by

$$R_T = l/KA\,(^\circ C/watt) \qquad 2$$

The thermal resistance of the layer can be measured experimentally by determination of the time rate of heat flow ($P = Q/t$) through the layer and the temperatures T_1 and T_2. Thermal resistance is then given by

$$R_T = \frac{T_1 - T_2}{P}$$

The thermal capacitance C_T, which is determined by the specific heat of the material, may be defined as the quantity of heat absorbed by the sample when its temperature rises one degree. Thus, if a given sample absorbs a quantity of heat Q when its temperature is raised from T_1 to T_2, the thermal capacitance of the sample is given by

$$C_T = \frac{Q}{T_2 - T_1}$$

Thermal capacitance for a given sample may be determined from the following expression:

$$C_T = HM \qquad 3$$

where H is the specific heat of the material and M is the mass of the sample.

Although both thermal resistance and thermal capacitance vary with temperature, the variation for most materials over the temperature range employed for most semiconductor devices is small enough that it may be neglected in thermal calculations.

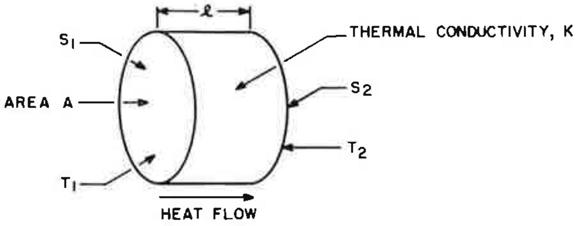


Fig. 2 — Diagram of a layer of thermally conductive material.

In the electrical or thermal analog circuit representing a semiconductor device, the thermal resistances closest to the heat source are large because the cross section of semiconductor element is small (all the heat generated flows through a small area). As shown in equation (2), thermal resistance varies inversely with cross-sectional area. In general, thermal resistances become progressively smaller as distance from the semiconductor element increases.

Equation (3) indicates that thermal capacitance varies directly with both mass and specific heat. Therefore, the small mass of the semiconductor element of a device causes the thermal capacitance to be smallest at the heat source and to become progressively larger as distance from the heat source increases. The final thermal capacitance in the series must be considered as an infinite capacitance, which electrically is the same as a direct short across the end of the line.

In the electrical analog circuit shown in Fig. 1, resistance can be measured by supplying a steady known current I through the resistors and measuring the voltage drop E across them. Thus, the resistances are given by

$$R_2 = \frac{V_1 - V_2}{I},\ R_3 = \frac{V_2 - V_3}{I}, \text{etc} \qquad 4$$

In the analogous thermal circuit, thermal resistance is measured by supplying a steady known amount of heat or power P through the resistors and measuring the temperature difference $(T_1 - T_2)$ across the thermal resistance R_T. Thermal resistances are then given by

$$R_{T2} = \frac{T_1 - T_2}{P},\ R_{T3} = \frac{T_2 - T_3}{P}, \text{etc}$$

In the electrical analog circuit, a steady current is essential for accurate measurement because any changes in current are accompanied by charging or discharging of the capacitors, which causes an unknown value of current to flow through the resistors. Because the equation R = V/I is used to solve for resistance, both V and I must be known.

Similarly, in the thermal circuit, there must be a steady heat flow because any charging or discharging of the thermal capacitances produces an unknown variation in the value of P. For example, if the thermal resistance between the semiconductor crystal or junction and the outer case of a semiconductor device is to be measured, the arrangement shown in Fig. 3 might be used. The device is mounted on a suitable heat sink, and a steady current I is passed through it. At the same time, measurements are made of the voltage drop V across the device, the temperature T_J at the junction, and the temperature T_C at the case. The power P dissipated as heat within the device, and hence the power passing out through the thermal resistances, is given by P = IV (watts). The thermal resistance R_T of the device is then given by

$$R_T = \frac{T_J - T_C}{P}\ (°C/\text{watt}) \qquad 5$$

Such a simple measurement of thermal resistance is applicable to measurement with a constant heat input only. If there is any change or fluctuation in heat-input rate, the change in temperature difference lags behind the change in heat input because some of the heat flows into or out of the thermal capacitances. Several disadvantages of this method are discussed later.

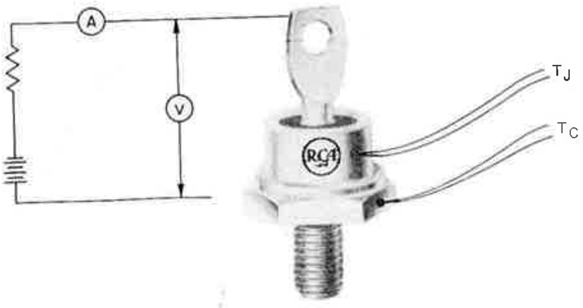


Fig. 3 — Suitable arrangement for measuring thermal resistance.

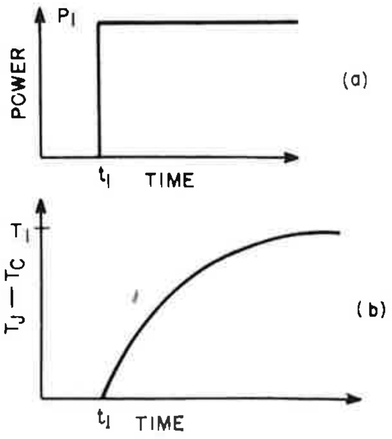


Fig. 4 — Temperature-rise curve obtained with step function of power.

If a step function of power is applied to the device (i.e., if the power input at time t_1 increases from $P = O$ to $P = P_1$), the temperature difference between junction and case rises as shown in Fig. 4, and approaches temperature T_1 asymptotically. This temperature-rise curve is similar to the voltage-rise curve which would be obtained in the analogous resistance-capacitance electrical circuit. The curve rises more steeply at first than in a circuit using a single resistor and a single capacitor because the thermal capacitance is very small near the junction but becomes progressively larger away from the junction and in the larger mass of the heat sink. The small capacitance near the junction is rapidly charged when the power is applied, but the larger capacitance further away from the junction charges much more slowly.

This temperature-rise curve can be misleading if it is described in terms of a single time constant, R x C. Because the thermal capacitance is distributed along the thermal resistance, as shown in Fig. 1, several different time constants must be used to describe the temperature rise. The time constants representing the region close to and within the semiconductor pellet might be several orders of magnitude smaller than those representing the case and heat sink. Fig. 5 shows a typical temperature-rise curve for a 20-ampere silicon rectifier, together with an exponential curve which takes the same time to reach temperature

$$T = T_o + 0.632\,(T_F - T_o)$$

Because the actual rise is initially steeper than that of the exponential curve, for a short time the temperature rise is higher than that predicted by the curve. Thus, if it is desired to know the junction temperature a very short time after a power pulse is applied (e.g., to determine the ability of the device to handle short surges of high power input) the temperature must be determined at the actual time desired rather than at some time after the operating temperature has stabilized.

MEASUREMENT OF DEVICE TEMPERATURE

As previously stated, measurement of thermal resistance is based on measurement of both the temperature T_C of the case and the temperature T_J of the crystal or junction of the device. The case temperature can be readily measured by use of a thermocouple, which can be attached directly to the case without affecting the operating characteristics of the device. Measurement of junction temperature presents more of a problem. A small temperature-sensing element such as a thermocouple or thermistor can be attached to the semiconductor material, and its leads brought out through a hole in the case. To have any degree of accuracy, the sensing element should be very small so that its thermal capacitance is low. It must also have a low-thermal-resistance connection to the semiconductor crystal so that, at least for a steady power input, it will assume the same temperature as the crystal. The leads from the element should be small, and have a high thermal resistance, so that they do not contribute to the removal of heat. Such measurements can be performed on specially fabricated devices, but cannot be performed non-destructively on conventional devices. Even with special devices the actual temperature T_J is not measured because the thermocouple is not actually at the junction.

A more convenient and more accurate way to measure T_J is to use the temperature-sensitive characteristics of the semiconductor element of the device itself. Because the electrical characteristics of all semiconductor devices are more or less sensitive to temperature, the problem then becomes one of calibrating a temperature-sensitive characteristic and using it to measure T_J.

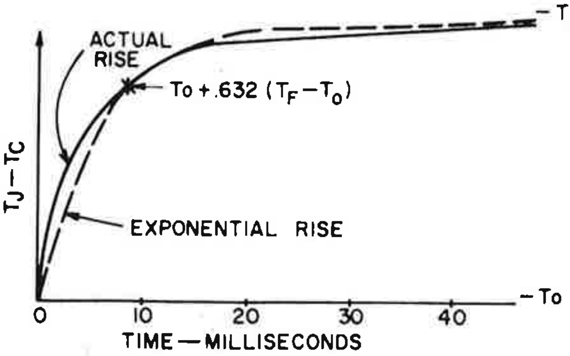


Fig. 5 — Typical temperature-rise curve for 20-ampere silicon rectifier, together with calculated exponential curve.

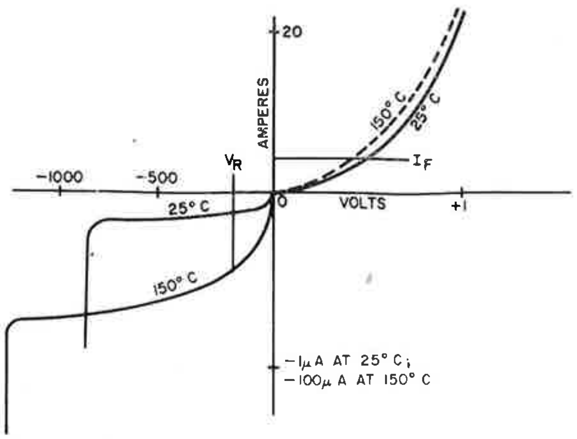


Fig. 6—Typical voltage-current characteristic of p-n junction.

A p-n junction in a semiconductor device has a voltage-current characteristic similar to that shown in Fig. 6. It should be noted that different scales are used for the forward and reverse directions in this curve. The numerical values shown are typical values obtained for the 1N248-C 20-ampere stud-mounted silicon rectifier. However, the general shape and the change with temperature are characteristic of any diffused p-n junction.

The voltage-current characteristic of the junction can be used in various ways to measure temperature. One way is to pass a constant current through the junction, in either the forward or reverse direction, and to measure the voltage drop across the junction at various temperatures. Another way is to apply a constant voltage across the device and measure current at various temperatures.

Although some junction-temperature measurements have been made by measuring the reverse current at a constant inverse voltage, the most convenient and most accurate method has been found to be the measurement of forward voltage drop at a constant small forward current. Because the reverse current does not vary linearly with temperature, and may vary greatly from one unit to another, each unit must be calibrated individually to obtain a curve of reverse current versus junction temperature for a constant inverse voltage. Several such calibration curves are shown in Fig. 7.

Forward voltage drop has been found to vary almost linearly with temperature over the range of interest. Consequently, a change in junction temperature may be determined by measuring the change in forward voltage drop and multiplying by the slope of the curve of forward voltage drop versus temperature. This slope has also been found to be nearly constant from one device to another. Once this constant has been measured for a family of units, therefore, the junction temperature may be measured without calibration of each individual unit.

In the calibration of the forward characteristic of a device for temperature measurement, a steady forward current is applied to the device and the forward voltage drop is measured as a function of temperature. If the forward current is low compared to the normal operating current of the device, the junction temperature may be considered to be equal to the ambient temperature. If the forward current is high enough to raise the junction temperature a measurable amount above ambient, the device can still be calibrated provided the change in forward voltage drop resulting from the change in ambient temperature is observed. The calibration may be made accurately if the device is placed in an oil bath with a thermocouple in the oil close to the unit. and the oil bath is heated on a hot plate. Fig. 8 shows some typical calibration curves obtained for a 20-ampere stud-mounted silicon rectifier (such as the 1N248-C) and for a 0.5-ampere flanged-metal-case rectifier (such as the 1N540) for several levels of forward current. The

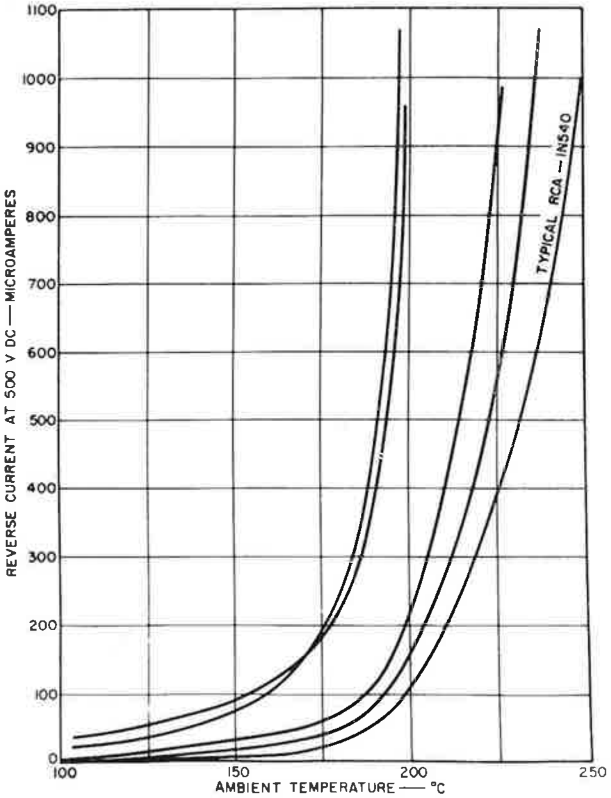


Fig. 7 — Calibration curves showing reverse current of several silicon rectifiers as a function of ambient temperature at a constant reverse voltage.

relation between temperature and forward voltage drop is a fairly straight line over the temperature range from 25 to 200 degrees Centigrade. The slope of this line, which is fairly constant for currents ranging from 1 to 10 milliamperes, is equal to 2 millivolts per degree Centigrade.

The slope is approximately the same for both the flanged-metal-case rectifier and the 20-ampere stud-mounted devices. Measurements on several different 20-ampere silicon rectifiers of various makes also indicated this same value for the slope over this temperature range. Consequently, it can safely be assumed that, over a wide range of pellet geometry, current density, and temperature, the forward voltage drop at a given forward current varies with temperature at the rate of approximately 2 millivolts per degree Centigrade. This slope can thus be used in measurements of junction temperature in a wide variety of silicon rectifiers without specific calibration of each unit. A change in junction temperature can then be related to a change in forward voltage drop by the following expression:

$$\Delta T_J = m \Delta V_f \qquad 6$$

where m is the slope of the calibration curve (2 mv/°C for small forward currents).

The problem of measuring thermal resistance then becomes one of measuring the change in forward voltage drop which occurs with a given change in dissipation (due to a change in forward current). A step increase in forward current can be applied and the forward voltage drop measured at the instant current is applied and again after the device has stabilized. Fig. 9 shows both the current pulse used to measure thermal resistance of a 20-ampere silicon rectifier by this method and the forward-voltage-drop curve obtained with this current pulse. Because the rise in temperature when current is applied is initially very rapid, as shown in Fig. 9 (c), the forward voltage drop must be measured within several microseconds of the time the current begins and again after the current has been flowing for several minutes. These measurements are difficult because of the initial rapid change in voltage drop and because the change in voltage drop is very small compared to the total voltage across the unit. Furthermore, the measurements must be taken instantaneously, but cannot be presented in a repetitive manner on an oscilloscope because the heating-cooling cycle of the unit is of the order of minutes.

In the method shown in Fig. 9, the change in forward voltage drop at the heating-current level is used to measure junction temperature. Another method, which is much simpler, is to use two current levels: a high-level current I_h for

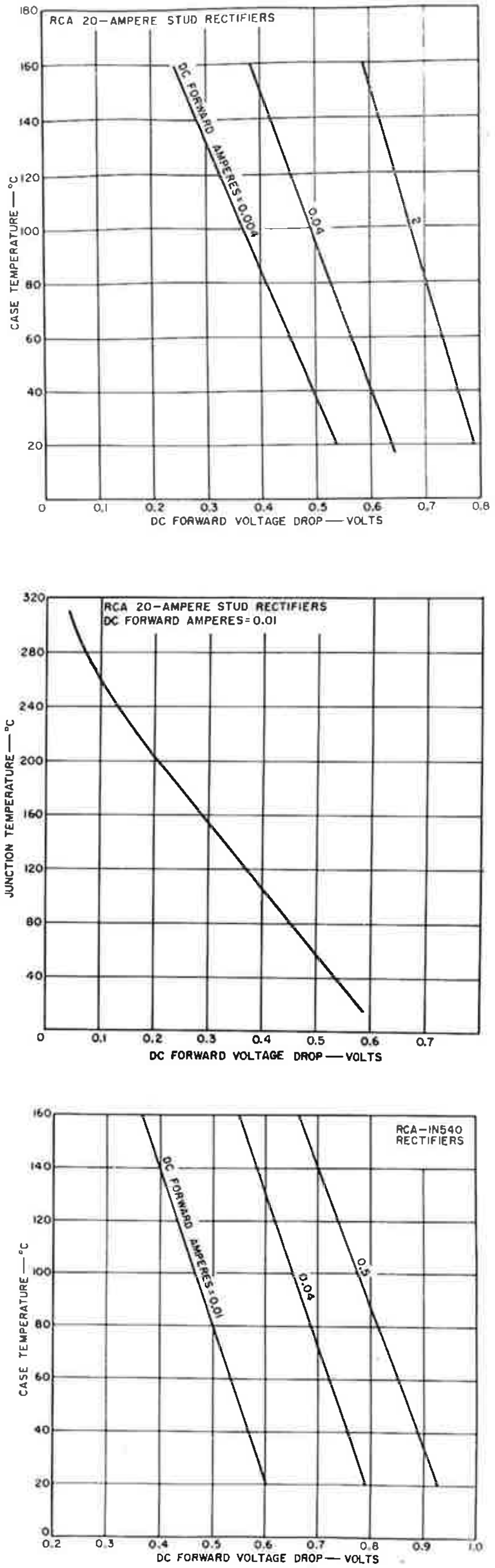


Fig. 8—Calibration curves for a typical 20-ampere stud silicon rectifier and a 0.5-ampere rectifier.

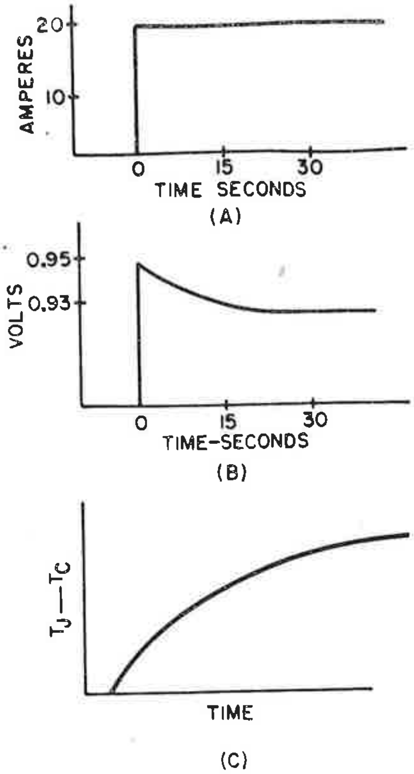


Fig. 9—(a) Current pulse used to measure thermal resistance of 20-ampere silicon rectifier. (b) Forward voltage curve obtained with current pulse of (a). (c) Temperature curve obtained with current pulse of (a).

heating, and a low-level current I_m to measure temperature. This method uses a current waveshape such as that shown in Fig. 10 (a), and produces a junction-temperature rise such as that shown in Fig. 10 (b). The final temperature T_F fluctuates up and down around the same final temperature which would be obtained with a steady current supplying the same power input as the fluctuating current.

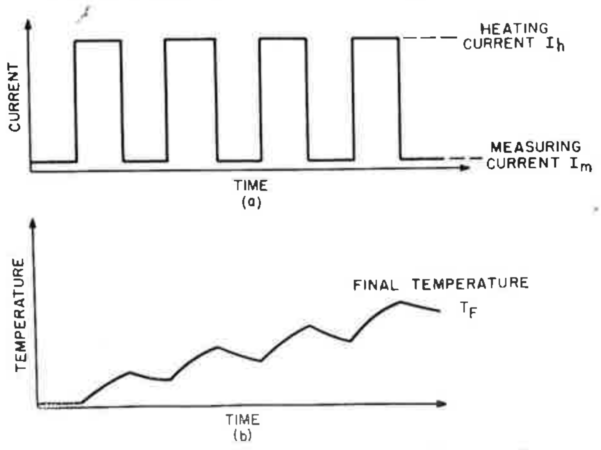


Fig. 10 — Current pulse (a) used to obtain fluctuating temperature curve (b).

Although the ratio of time at current I_h to time at current I_m is not limited to any particular value, optimum values may be chosen for a particular experiment. Theoretically, a cycle in which the time at current I_h is much longer than time at I_m should give the most accurate measurement of the steady-state thermal resistance of a device. If the time at measuring current I_m is increased, the peak-to-average value of the heating current I_h must also be increased. However, the higher peak current introduces additional error in the measurement due to the extremely rapid temperature changes of the pellet. The peak temperature observed immediately after the heating pulse is somewhere between the steady-state temperatures which would be obtained with a steady current at the peak value and with a steady current at the average value.

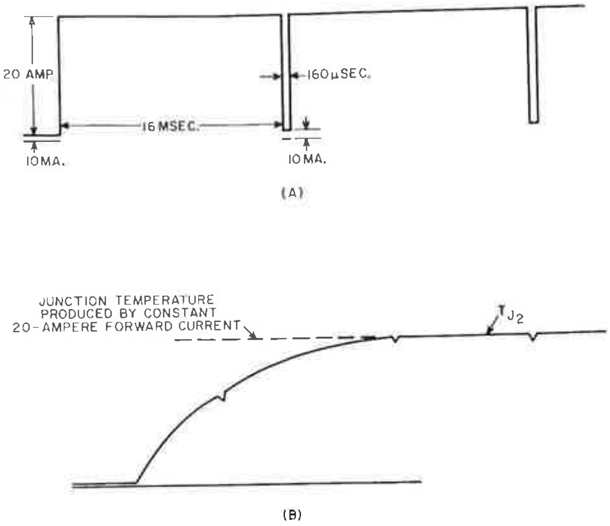


Fig. 11—Square 20-ampere pulse (a) used to obtain fluctuating temperature-rise curve (b).

For example, the pulse shown in Fig. 11 (a) might be used to measure the thermal resistance of a 20-ampere silicon rectifier. The 20-ampere heating-current pulse is 16 milliseconds long, and the 10-milliampere measuring pulse is 160 microseconds long. The junction temperature measured immediately after the heating pulse is very close to the value which would be obtained with a steady 20-ampere current, as shown in Fig. 11 (b).

The forward-voltage drop characteristic obtained with this cycle is shown in Fig. 12. For a measurement of junction temperature, the forward voltage drop must be accurately measured at various points on this curve. As shown, the heating current I_h is on for approximately 99 per cent of the time, and the measuring current I_m for approximately 1 per cent.

(Page 19 Please)

TRANSISTOR POWER SUPPLY

by B. J. Simpson

This unit arose out of the fact that I was putting a transistorized amplifier together, and at the crucial time when I wanted to make a few tests, I was unable to borrow a transistor power supply. So I sat down to make one, and this is the result.

The unit described here truly falls under the heading of test equipment, as it is intended to supply power to transistorized equipment whilst it is under development and test. It is of course true that batteries will fill the same need, and where the current consumption is small, it may be just as easy to use them. When it comes to the larger units however, with current drains of the order of 1 to 4 amperes, the batteries themselves become a problem, as they have to be kept charged. The battery could be "float charged", but with transistorized apparatus this method has several drawbacks.

This unit will provide regulated output voltages continuously variable from zero up to 15 volts, at up to 4 amperes. The instrument will therefore meet the needs of most units of transistorized equipment, and can also be used to power car radios and other units which normally operate from a 6 or 12 volt battery.

The regulation of the output voltage is suitable for most applications except the most critical. In the worst possible case, variation of the load from zero to 4 amperes, the output voltage, set at 12 volts under no load, falls to 11 volts at 4 amperes output. This corresponds to a fall of a little over 8%, and is of course proportionally better where the load variation is less.

For example, when testing an amplifier with a quiescent current of 800 ma and a full load current of 2 amperes, the unit showed a variation of —0.3 volt, a variation of 2.5%. At currents of this order, we are therefore getting close to the sort of voltage drop we may find in actual practice along the battery leads to a unit.

The ripple on the dc output of the unit varies according to the load current. The approximate limits of ripple voltage are 4 to 30 millivolts. This is quite satisfactory for most applications, 30 millivolts ripple on a 12-volt output being about 52 db down. Increasing the value of C2 will show a slight improvement in the ripple figure, but the improvement obtainable falls off rapidly each time the value of the capacitor is doubled. The value chosen for the model appeared to be a good compromise.

Circuit Description

The circuit hardly needs a blow-by-blow description, but there are a couple of interesting features. The first thing you will notice will probably be the four 2N301's used as a bridge rectifier. The emitters are not used, the base/collector junction being used as a diode. This is quite a legitimate use of the 2N301, as at the forward currents used in this unit, they offer a very satisfactory and economic solution to the question of what to use as a rectifier.

The transformer, which is a specially-wound unit (M.S.P. prototype G1741), provides 18 volts on the secondary, the unfiltered and unregulated dc output being 25 volts. A simple capacitor filter is used. Transistors Q7 and Q8 are connected in parallel, and form the series-regulating element of the unit. These transistors are used as variable resistors, the emitter/collector resistance being varied by the control signal fed into the base by Q6.

The reference voltage is provided by two SX75 zener diodes connected in series, thus providing a reference voltage (and maximum unit output voltage) of 15 volts. The voltage available across the voltage-setting potentiometer in the emitter lead of Q5 is also of course 15 volts, and is tapped off to the base of Q6 to control Q7 and Q8 as required. The output impedance of the power supply is about half an ohm.

Construction

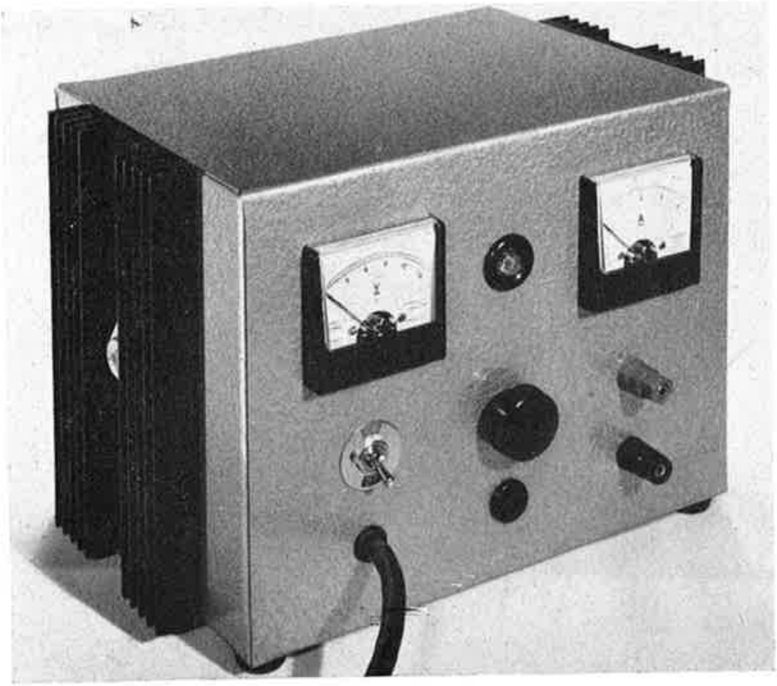
As in the case of the circuit, most of the constructional data can be gathered from the photographs and diagrams. A standard MC7 metal case is used to house the instrument, and is used back to front, i.e., the removable panel is used at the back. This facilitates construction considerably. The size of the case is 10 inches wide, 8 inches high and 7 inches deep.

The two series regulating elements, transistors Q7 and Q8, dissipate high powers, particularly when the unit is used at low voltages and high currents. Two large standard heat sinks are therefore provided for them. The heat sinks are type 7003, 4 inches by 8 inches, and provide 200 square inches of area. They are fitted vertically to the sides of the case so that maximum dissipation of heat will be achieved. Appropriate fixing holes are drilled in the sides of the box. Silicone grease is used under Q7 and Q8 when finally mounting them in order to improve conduction of heat away from the transistors.

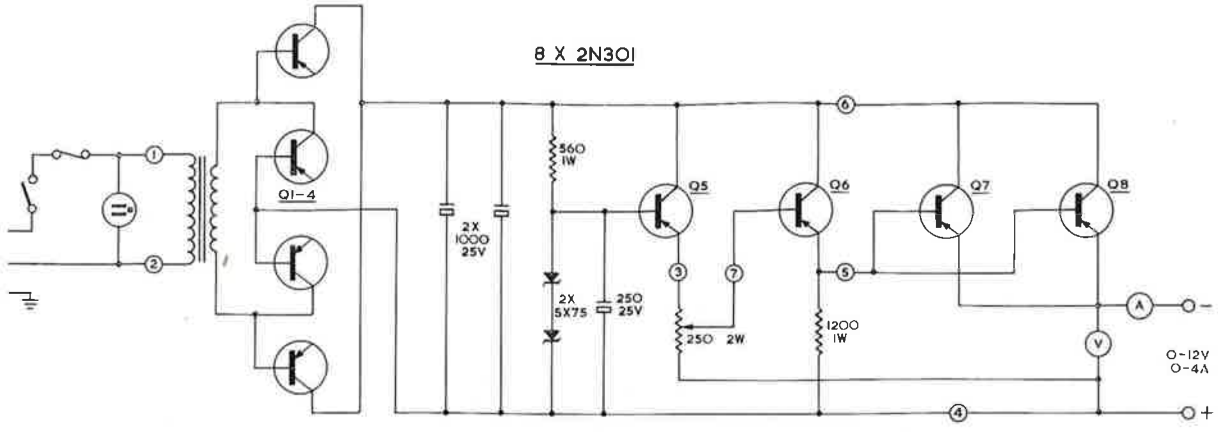
It was considered desirable to provide meters both for the output voltage and the load current. Two Master S225 matching meters of very neat appearance were used, one reading 0-15 volts, and the other 0-4 amperes. A mains fuse and lumolite warning lamp are used, the latter because it was considered essential to have a clear warning when the unit was switched on. No fuse is provided in the output of the unit, as standard fuses would not blow quickly enough. This point is discussed further below.

The photographs show the components which are mounted on the front panel, and the layout used. This could of course be changed if desired. The balance of the unit, consisting of the mains transformer, six transistors, capacitors and resistors, are mounted on a sub-assembly inside the box. A detailed drawing of the aluminium plate forming the basis of the sub-assembly is provided, and the assembly of components thereon will be seen from the illustrations. The interconnections between the sub-assembly and the rest of the unit are indicated by numbered circles inserted into the leads in the circuit diagram.

The eight 2N301's are mounted in the standard way for these types, as previously illustrated in these pages. Mica insulators, which should be ordered at the same time as the 2N301's, are used to insulate the cases (collectors) from the



The author's variable regulated transistor power supply unit, delivering 0-15 volts at up to 4 amperes.



Circuit diagram of the transistor power supply.

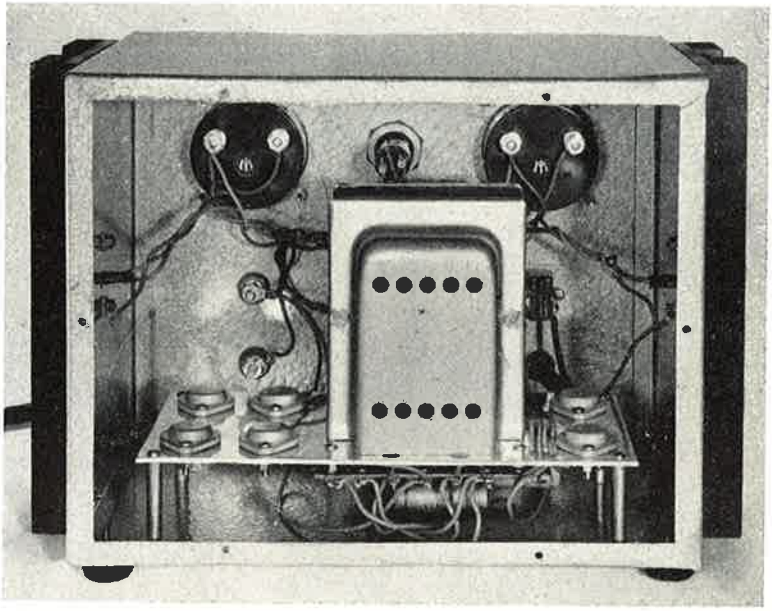
case of the instrument. The small insulating washers required on the other side of the panels are not supplied by the transistor makers, but are readily obtainable, or are easily made. These washers can be flat washers if a short length of insulating sleeving is slipped over the mounting screws where they pass through the panels. After mounting all the transistors, and before making any connections to them, check that the cases (collectors) are actually insulated from the framework. This is a wise precaution, as it needs only a small piece of wire or a shaving of metal to cause a short circuit in the mounting of the transistor.

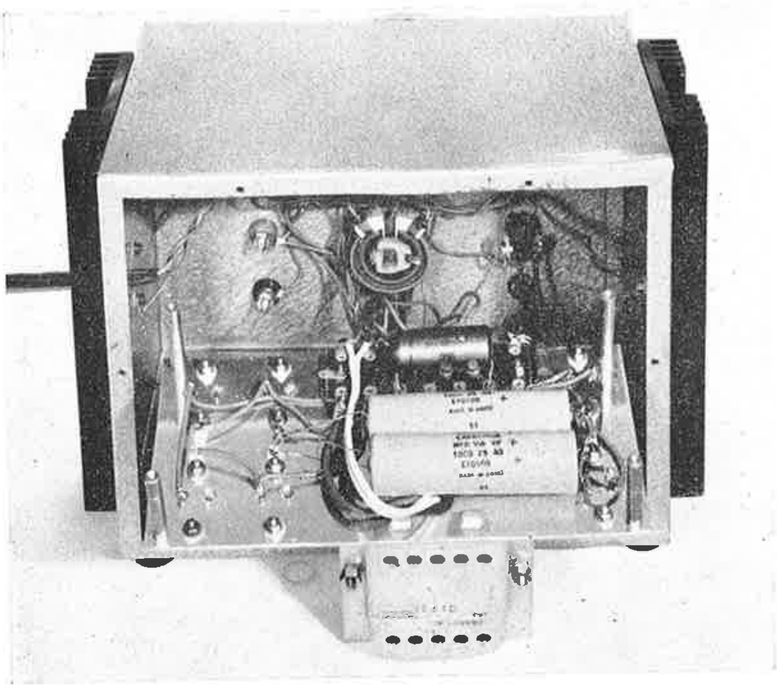
As an alternative to silicone grease, but less effective, lead washers can be used under the Q7 and Q8 transistors to assist heat conduction. These can be cut from a piece of scrap lead of about 20 gauge, shaped to the base outline of the transistor; four holes are needed, two for mounting the transistor and two clearance holes for the base and emitter pins. The lead washer should be inserted between the transistor and the mica insulator; when the transistor mounting screws are pulled up tight, the soft lead is moulded to form a very good thermal junction between the transistor and the mounting plate.

Testing and Using

After the unit has been completely wired and is ready for switching on, it is a good idea with transistor equipment to recheck the circuitry, including polarity of electrolytic capacitors and connections to the transistors themselves. Semi-

Rear view of the power supply showing the internal assembly.





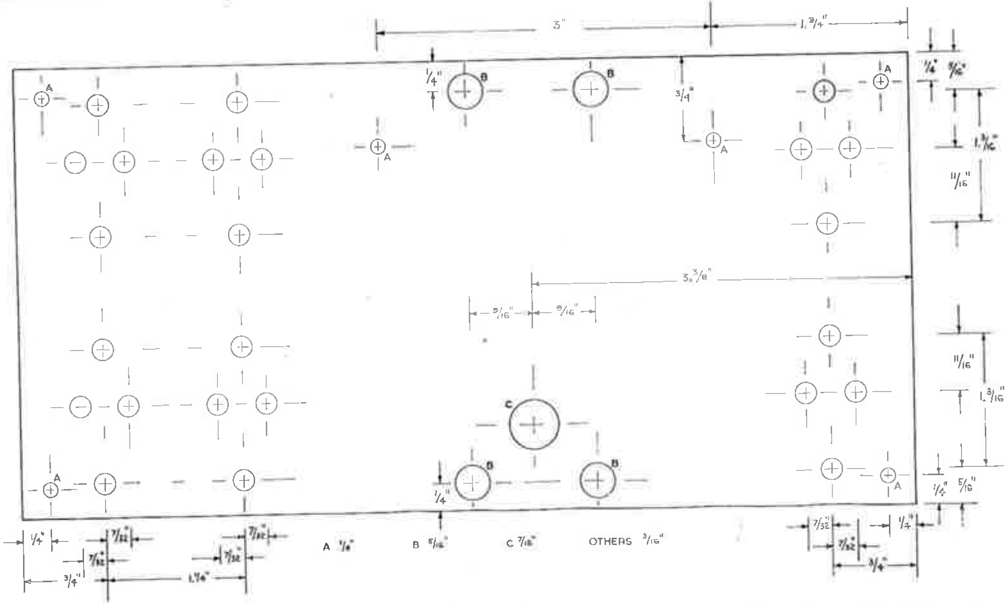
This view shows the rear of the power supply with the sub-assembly mentioned in the text withdrawn but still connected.

conductors, as we all know, are less tolerant of wiring errors than thermionic valves.

Check first of all that under no load, an output is obtained, and that it can be varied over the stated output range, i.e., the range of the voltmeter. Loads can then be applied to make sure the unit will deliver the stated current.

The use of the unit is obvious, but watch correct polarity when connecting apparatus to the power supply. It will be seen from the circuit that the output of the unit is completely isolated from the mains input and the casing. This means that either side of the output may be grounded as required. It is probably best practice to apply this ground at the unit under test, and not at the power supply. This avoids the possibility of accidentally shorting the output, perhaps through the ground lead of another piece of test gear on the bench.

As previously mentioned, no fuse is provided in the dc output circuit of the unit, as no normal fuse will operate quickly enough under short-circuit conditions to guarantee circuit protection. It is possible to devise electronic means of protecting a unit of this kind, but the protection



Mechanical drawing of the 12-gauge aluminium plate which forms the base of the sub-assembly.

circuit is quite involved and adds considerable complication and cost.

The best protection you can give this instrument as it stands, is to use it with caution, carefully checking connections and so on. Never connect a unit to the power supply without checking that there is no short circuit on the power input. If in doubt, or there is a possibility of a short being applied during test, a wise precaution is to insert a 3-ohm 60-watt resistor in series with the supply to the unit under test. With units using up to about 1 ampere, the IR drop can be compensated for in the setting of the output voltage control. This applies particularly to radios, small amplifiers and other low current consumption units. When the item being tested is operating properly, the series resistor can be removed and the voltage readjusted for final testing. This simple precaution cannot be used so successfully where high load currents are called for.

Conclusion

This unit forms an inexpensive workshop tool which would undoubtedly pay for itself in a short time, and is invaluable where large numbers of transistorized and other battery-driven items are handled. The unit has been successfully tested with all types of apparatus, and it is estimated that the supply could be constructed for about £35 list.

THERMAL IMPEDANCE OF SILICON RECTIFIERS (Cont.)

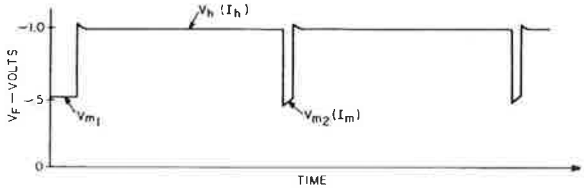


Fig. 12—Forward-voltage characteristic obtained with square pulse shown in Fig. 11.

The voltage level V_{m1} designates the forward voltage drop when only a steady current level I_m (in this case 10 milliamperes) is flowing through the device. The voltage level V_{m2} designates the forward voltage drop immediately after the current has dropped from level I_h to level I_m, as shown in Fig. 12. Although V_{m1} is the voltage at a steady current I_m, and can easily be measured on a meter, V_{m2} is an instantaneous value and must be measured on an oscilloscope by presentation of the forward-voltage waveshape.

(With acknowledgements to RCA)

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