Transistors and Junction Diodes in Telephone Power Plants

By F. H. CHASE, B. H. HAMILTON and D. H. SMITH

(Manuscript received November 30, 1953)

This paper describes the use of junction diodes, reference voltage diodes, and junction transistors in regulated rectifiers for telephone power plants. It discusses the pertinent characteristics of these semiconductor devices, together with illustrative circuits in which they are used to control the flow of direct current power.

1. INTRODUCTION

Recent articles in the literature have treated the theory and properties of semiconductor devices. In particular, papers by Messrs. Shockley, Ryder, Wallace and others have emphasized the theoretical aspects of the new devices; their reliability, reproducibility and performance at high frequencies to name only a few.[1, 4, 5, 6, 7] In addition many papers have been published concerning their applications in the transmission and computer fields. There is also a field of application for these devices in the conversion and control of power, and this paper discusses some of these power applications.

1.1. *Scope*

The first three groups of sections in this discussion review the pertinent characteristics and practical engineering aspects of junction rectifier diodes (Section 2.1), reference voltage diodes (Section 2.2) and junction transistors (Section 2.3). The second three groups of sections concern respectively shunt transistor regulators (Section 3.1), series transistor regulators, (Section 3.2) and power regulating circuits employing magnetic amplifiers in combination with transistors and junction diodes (Section 3.3). The last two groups of sections treat specific applications (Sections 4.1 through 4.3).

2. DEVICE CHARACTERISTICS

2.1. *Junction Rectifiers*

A junction rectifier is made from a wafer cut from a single crystal of semiconductor material. The materials now being used for this purpose are germanium and silicon, but to date the use of germanium is more common than silicon. Pure germanium in its undisturbed or intrinsic state is a poor conductor; but its conductivity can be increased by disturbances such as cosmic rays, photons of light, external potentials, or by the addition of very small amounts of selected impurities. We are concerned here only with the addition of impurities. There are two classes of these impurities, called "donors" and "acceptors." The physical mechanism by which pure germanium becomes conductive depends on which of these two classes of impurities are present. Donor impurities result in a surplus of free electrons which can conduct current by negative charges passing through the germanium crystal. Thus the addition of donor impurities to pure germanium creates "n" type material. Presence of acceptor impurities results in a shortage of electrons creating "holes," which have positive charges. These holes are mobile and they can conduct current through the crystal.[7] Thus the addition of acceptor impurities to pure germanium creates "p" material.

When an abrupt change is made from p to n type material inside the crystal a rectifying junction exists at the boundary between the two materials. This p-n junction exhibits rectifier action in that it will conduct current every easily from p toward n; but, in its rectifier operating range, only minute currents can be made to flow from n toward p. We say that this junction has a low forward resistance and a high reverse resistance. All rectifiers have these characteristics to a greater or lesser degree and the p-n junction rectifier characteristics have been compared elsewhere to other rectifier devices.[2]

There are two methods of producing the junction inside the crystal. It can be obtained by growing part of the crystal from p type material and part from n type. This is called a "grown" junction. It can also be obtained by diffusing impurities into the crystal after it has been grown. This has been called an "alloy" process, a "fused junction" process, or a "diffused junction" process.

2.11. *Junction Rectifier Terminology*

Before discussing the characteristics of junction diodes, it may be helpful for the reader to consider the terminology employed. As in other rectifying cells, there are two directions of current flow, forward and reverse. Each diode has a positive and a negative terminal, and we define the positive terminal as that terminal towards which forward current flows *within the diode.* Likewise, the negative terminal is that terminal towards which reverse current flows *within the diode.* In Fig. 1(a), terminal 1 is the negative terminal and terminal 2 the positive. The circuit convention for the diode is a shorthand method of indicating the polarity of the diode to the engineer. If a battery is connected to a diode as shown in Fig. 1(b), forward current will flow, and if connected per Fig. 1(c), reverse current will flow. If the battery is replaced by a source of alternating current, forward current will flow through the diode during the half cycle that terminal 1 is positive, and reverse current will flow during the half cycle that terminal 2 is positive. The rectifier is said to "conduct" during the first half cycle and to "block" during the second half cycle, for the resistance in the conducting direction is very much less than the resistance in the blocking direction.

The figure of merit of a diode is a measure of this ease of conduction and the effectiveness of the blocking action. The ease of conduction can readily be determined on a static basis by applying a dc voltage to the diode as shown in Fig. 1(b) and plotting forward current through the diode as a function of applied voltage. Likewise, the blocking characteristic can be determined if a circuit per Fig. 1(c) is employed.

2.12. *Typical Junction Rectifiers*

Fig. 2 is a photograph of several sizes of typical junction diodes. The diodes shown have a range of forward current from several milliamperes (Diode I) to hundreds of amperes (Diode IV). Diode I is made from a crystal of silicon and the balance are made from germanium. Most rectifying diodes have a particular field of use dictated mainly by their power handling capacity in the forward direction of current flow, although Diode I is of interest because of its unusual reverse or blocking characteristic, as will be pointed out later in this paper.

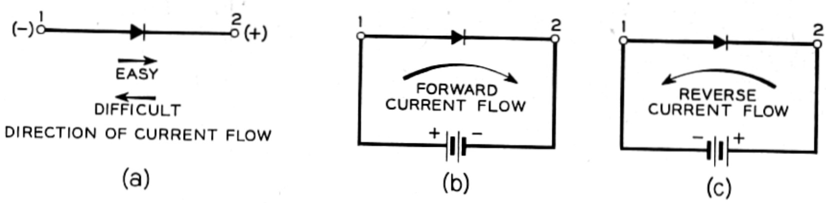

Fig. 1 — Rectifier terminology.

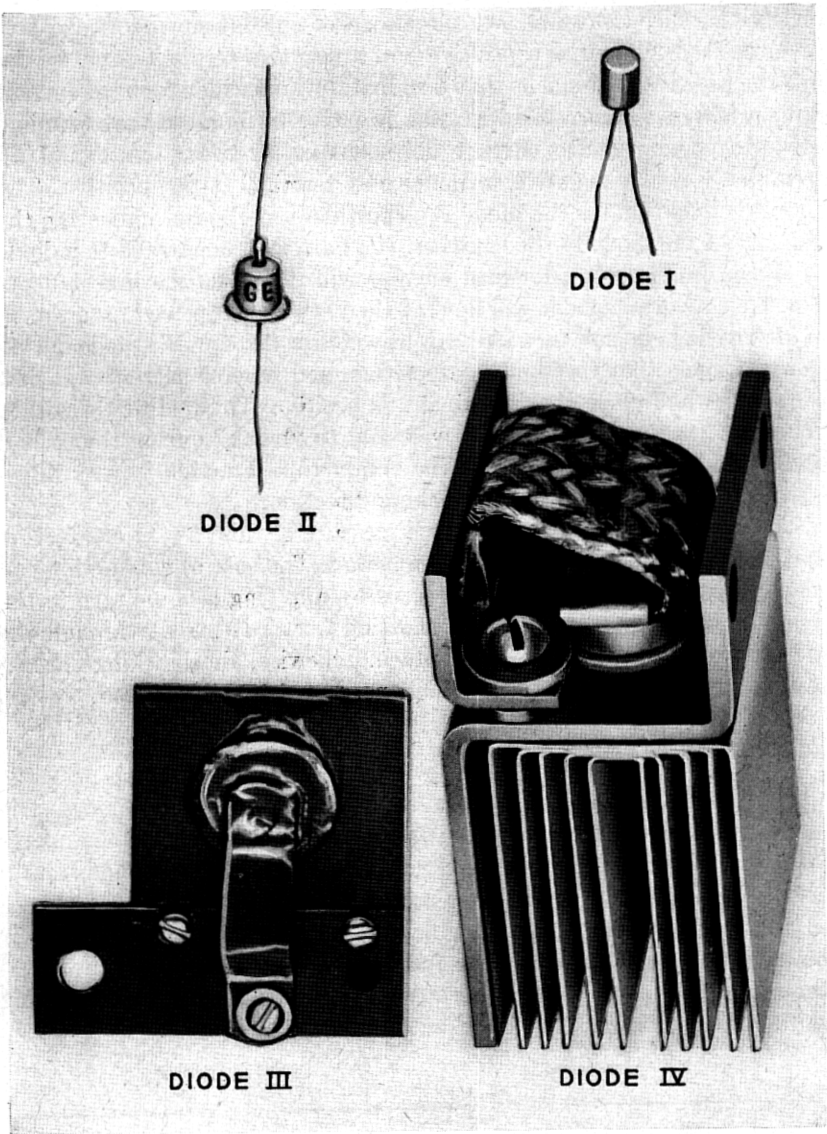

Fig. 2 — Typical junction rectifiers. Diodes II, III and IV, courtesy of the General Electric Company.

Fig. 3 is a plot of the static forward and reverse characteristics of the four diodes shown in Fig. 2. The characteristics were obtained using the circuits in Figs. 1(b) and 1(c), respectively, measurements being made in still air at room temperature. The curves in the first quadrant, $(+E + I)$ are the forward characteristics and the curves in the third quadrant $(-E \ -I)$ are the reverse characteristics. Notice that the scales are different in these quadrants. In general, at any other temperature the curves would shift their positions with respect to the reference axes. This must be taken into account by the circuit designer.

2.13. *Junction Temperature*

We will limit further discussion of general characteristics to those of Diode IV, for in many respects this is the most interesting rectifier for

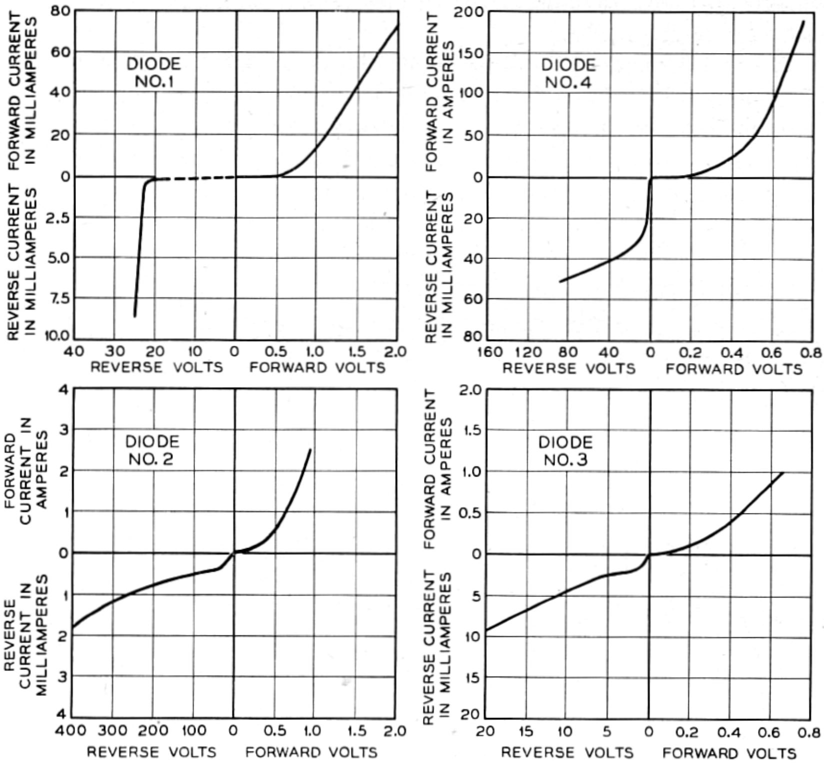

Fig. 3 — Junction rectifier static characteristics.

power applications. Laboratory experience indicates that it is not desirable to operate the junction of this diode above 65° to 70° centigrade. The value of this critical temperature is not accurately known on account of the difficulty in measuring the junction temperature inside of the crystal. However, below the critical temperature, those changes in characteristics which are associated with changes in junction temperature are reversible, that is, if the temperature is raised and then reduced, the characteristics will shift back to values previously experienced at the reduced temperature. Beyond the critical junction temperature any change in the reverse characteristics is permanent and has the effect of reducing the reverse resistance. In an operating circuit, this effect leads to progressively greater permanent damage to the diode. Lowered reverse resistance allows more reverse current to flow, increases the reverse power dissipation and elevates the temperature of the junction causing further reduction of the reverse resistance, and so on until the diode no longer blocks.

Thermal damage to the junction can be prevented by removing heat. This method is employed with the diode under discussion by forcing air through the cooling fins at a high velocity. The quantity of air needed depends on the amount of heat generated in the junction, the efficiency of the cooling fins and the temperature of the air employed for cooling. In most Bell System applications, the maximum temperature of the

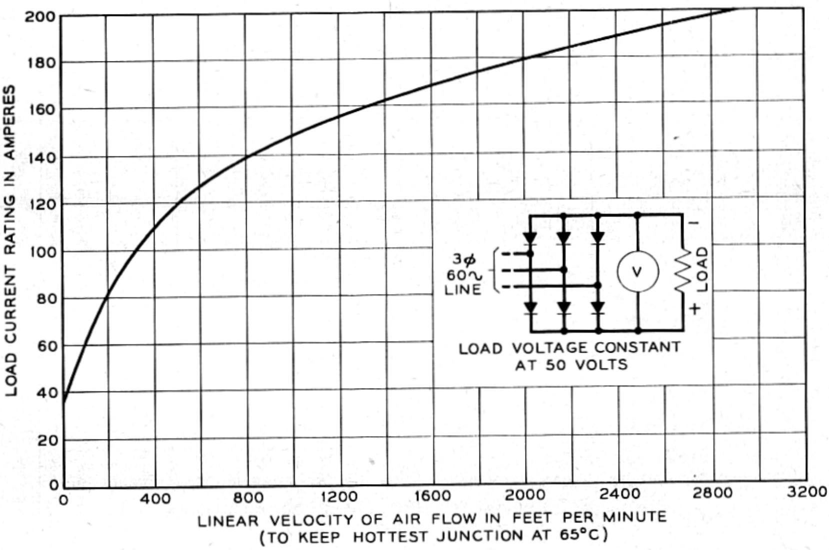

Fig. 4 — Junction rectifier forced cooling characteristics.

ambient air is 40°C, which permits the junction temperature to be 25 to 30°C above the air temperature before the critical value is reached.

A typical load-current versus air velocity curve is shown in Fig. 4. The curve is based on a 65°C junction temperature measured by thermocouples attached to the radiating structure near the junction and 40°C ambient air. Notice that the curve is taken with a working circuit composed of six diodes in a three-phase full wave bridge arrangement. In general, engineers developing rectifier circuits find that curves showing the properties of combinations of rectifying diodes are more useful than single diode characteristics, except where the properties of the diode are such as to make it useful as a valve, or as a reference standard, as is the case of Diode I in Fig. 2. This leads directly to a more detailed consideration of the blocking or reverse characteristics of junction rectifiers.

2.2. *Reference Voltage Diodes*

2.21. *General*

In the case of silicon junction diodes it has been possible to reduce the reverse current to a very low value for reverse voltages up to a value called the "saturation voltage." When the saturation voltage is reached the electrons and/or holes which comprise the leakage current are given sufficient energy to create other electron-hole pairs which add to the original reverse current. This process is cumulative and leads to large increases in current for small further increases in voltage. The effect is illustrated by the reverse voltage-current characteristic for Diode I in Fig. 3. This curve shows the reverse current to be quite low for voltages less than 22 volts. This portion of the characteristic is called the "high resistance region." As voltage is further increased the curve goes through a "transition region" to the "saturation voltage region" at 23 volts where voltage is nearly constant over a wide range of current. The voltage saturation characteristic makes the diode suitable for use as a source of reference potential in the control of power. Those readers who wish to study the basis of these properties will find the theory covered elsewhere in the literature.[3,8]

The rectifier selected for study in this Section is Diode I. This is a p-n junction rectifier made from silicon. It has been constructed to obtain a reasonably constant saturation voltage as shown in Fig. 5. In order to show the wide range of current values where this voltage is substantially constant, Fig. 5 is plotted to a logarithmic scale. In this connection it is interesting to note that the saturation voltage can be controlled in manufacture from a few volts to several hundred volts. This

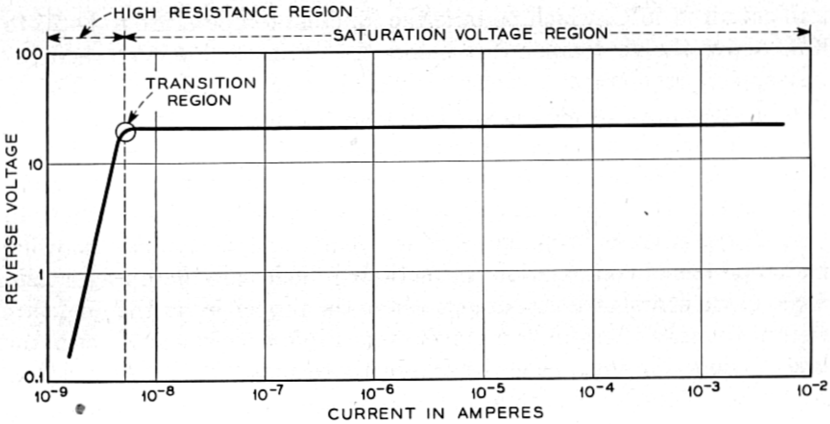

Fig. 5 — Reverse characteristics of a reference voltage diode.

range can be compared to the 60 to 150 volts range of cold cathode voltage regulator tubes which are also used as sources of reference potential.

2.22. *Saturation Voltage Utilized in Regulating Circuits*

In all check back (feedback) regulating circuits the potential to be regulated is compared to a reference potential. This comparison is a form of subtracting the two values so that the changes in the potential to be regulated produce a large percentage change in the difference or error voltage. The methods by which this is accomplished in direct current circuits are illustrated in Section 3. A stable source of reference potential is required for this type of regulation. When the saturation voltage of a silicon junction diode is used for this purpose, we have called the device a "reference voltage diode."

2.23. *Effect of Temperature on Saturation Voltage*

In order to evaluate the stability of Diode I in its saturation voltage region a small section of Fig. 5 has been redrawn in Fig. 6 using a linear scale. Additional curves are included in Fig. 6 to show the change of voltage with ambient temperature variations. The slope of the 30 degree curve in Fig. 6 is equivalent to a resistance of 200 ohms in series with a 23-volt battery with current flowing through this combination from an external source. The change of potential with ambient temperature is equivalent to a 0.07 per cent change per degree C. It should not be inferred that these are limiting values, for diodes have been tested which exhibit slopes of less than 10 ohms and temperature coefficients of less than 0.01 per cent per degree C. The specific applications covered later in this discussion show methods to compensate for slope and temperature variation when necessary.

2.3. *Junction Transistor Action*

2.31. *Two-Rectifier Analysis*

In junction transistors there are two p-n junction rectifiers contained in the semiconductor material. Of the materials now in use germanium is the more prevalent. Remembering the results of adding donor and acceptor impurities to obtain n and p type materials covered in section 2.1 these two rectifiers are obtained by interposing a layer of p type material between two layers of n type making an *n-p-n transistor* or interposing a layer of n type material between two layers of p type making a *p-n-p transistor*. The electrical connections are designated as the collector terminal, the emitter terminal and the base terminal. Both types of transistors (n-p-n and p-n-p) have a rectifying junction between the collector and base terminals and another rectifying junction between the emitter and base terminals. The polarity of the collector and emitter rectifying junctions determines whether the transistor is n-p-n or p-n-p.

Figs. 7(a) and 7(b) are simplified diagrams illustrating respectively the internal circuits of n-p-n and p-n-p transistors. The figures show the characterizations of transistors by means of a two-rectifier analogy. Although a transistor may be somewhat over-simplified by this method of characterization, the analogy permits the power engineer to approximate the operation of transistors in familiar terms. Experience in the development of the circuits described later in this article has proven that the analogy is valid under circumstances where the operation of the transistor as a dc amplifier is of interest.

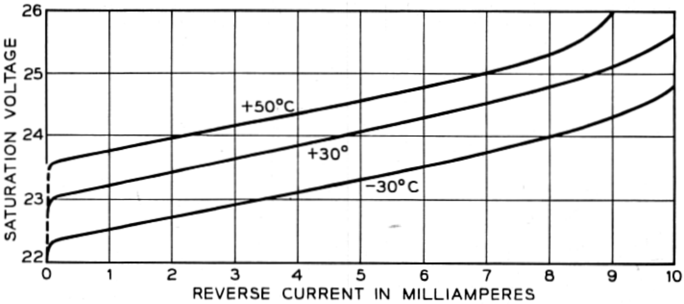

Fig. 6 — Saturation voltage characteristics of a reference voltage diode.

In an n-p-n transistor the collector and emitter terminals are the positive electrodes of the rectifiers, see Fig. 7(a), and in a p-n-p transistor the collector and emitter terminals are the negative electrodes of the rectifiers, see Fig. 7(b). The base terminal is the common point of the two rectifiers. In a given transistor each rectifier has a saturation voltage, usually stated in the characteristics, which must not be exceeded in normal operation. Thus, the saturation voltage of the collector rectifier determines the maximum instantaneous collector potential. The emitter rectifier also has a saturation voltage which determines the maximum potential which can be applied between the base and the emitter. The saturation voltage of the collector rectifier usually differs from the saturation voltage of the emitter rectifier.

2.32. *Transistor Action*

If a source of potential, E_{ce} in Figs. 7(a) and 7(b) is connected between the collector and emitter terminals, the resulting current will flow in series through the collector rectifier in its reverse direction and through the emitter rectifier in its forward direction. This is the direction of current flow for transistor action to take place. In Fig. 7 the reverse resistances of the collector rectifiers are shown and the forward resistances of the emitter rectifiers are also shown.

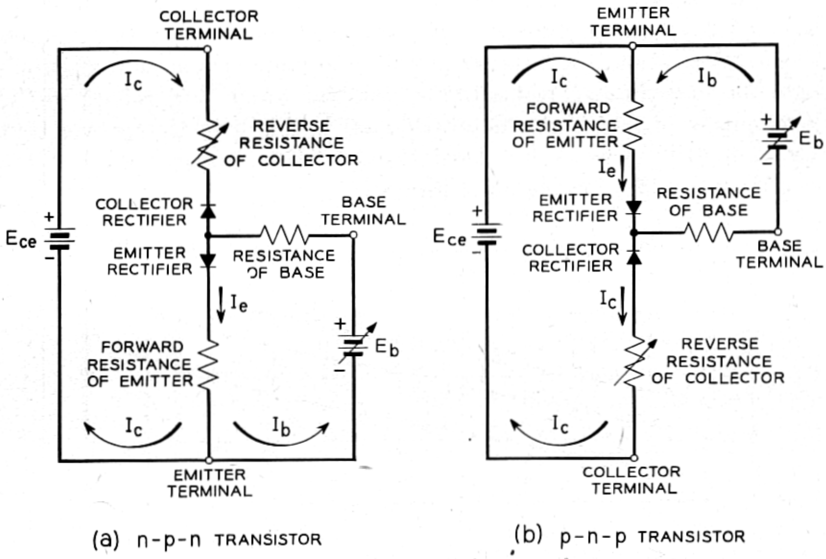

Fig. 7 — Junction transistor analogy.

2.33. *Current Gain*

Now when a second relatively small potential is connected between the base and emitter rectifier (E_b in the sketches) additional current, I_e will flow through the emitter rectifier in the forward direction and I_c will also increase. This increase in I_c caused by the increase in I_e is transistor action. The increase in I_c is related to the increase in I_e by the factor alpha (α) as written below:

$$\Delta I_c = \alpha \Delta I_e . \tag{1}$$

The application of Kirchoff's current law to the sketches in Fig. 7 gives the change in I_b as follows

$$\Delta I_b = \Delta I_e - \Delta I_c . \tag{2}$$

By combining equations (1) and (2), ΔI_c can be written as a function of ΔI_b only

$$\Delta I_c = \frac{(\alpha)}{(1 - \alpha)} \Delta I_b . \tag{3}$$

The usual value of α for junction transistors is near but slightly less than unity. In a typical case α might be 0.98. This value when substituted in equation (3) shows the current gain of the transistor, $\Delta I_c/\Delta I_b$ to be 49. Most of the circuits discussed in this paper are based on equation (3).

It has been shown how a small change in base to emitter potential with a small change in base current effects a large increase in collector current at a higher voltage. This explains how large power gains, of the order of 60 db, can be obtained from the junction transistor.

The sketches in Fig. 7 do not show why this transistor action takes place. The reasons for it involve the use of such solid state physics terms as the migration of electrons and holes through a crystal lattice, and the interposition of junction barriers. The "why" for transistor action is very important in the manufacture of transistors, and it has been thoroughly covered in the literature.[1, 7] For present purposes it is only necessary to examine the static characteristics of an n-p-n transistor as shown in Fig. 8. This figure presents transistor characteristics in a manner which simplifies the explanation of the operation of the transistor control circuits covered later in this paper.

Referring to the curves in Fig. 8, it will be seen that in the straight portion of the 1.5-volt curve, a change of 50 microamperes in the base current will result in a change of about 2 milliamperes in the collector current. This illustrates the current amplification of transistors and the

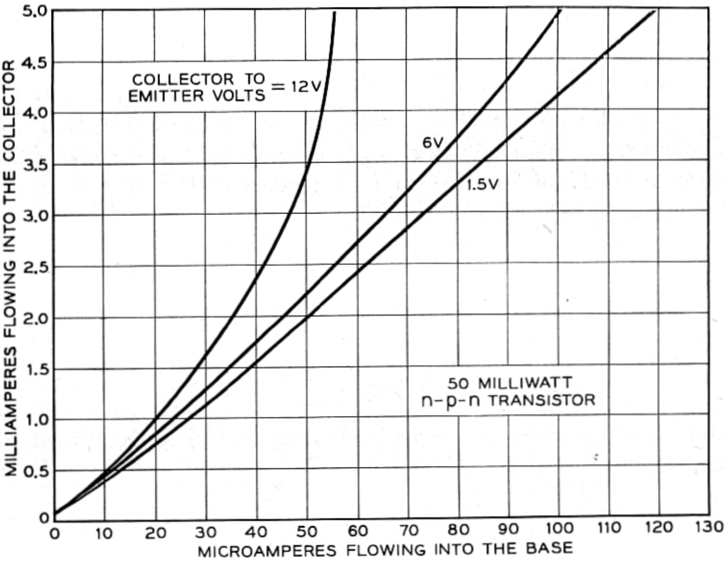

Fig. 8 — Junction transistor static characteristics.

current gain of this transistor is equal to 40. The measured α for this transistor was 0.976. Substituting in the current gain formula, equation (3) above, the calculated current gain is 40.6 which agrees with Fig. 8 within the accuracy of the measurements.

2.34. *Low Voltage Characteristics*

Again referring to the curves in Fig. 8, it will be seen that transistors operate at low collector to emitter potentials. The 1.5-volt curve is not the minimum potential at which this transistor will operate. Some transistors have good current amplification at potentials as low as two-tenths of a volt. When the base current is reversed, the characteristics in Fig. 8 can be extended to smaller collector current values. One might assume that the collector current can be reduced to zero by causing enough current to flow out of the base. This is not true. There is a minimum collector current, called the saturation current, and increasing current flow out of the base will not decrease the collector current below this value. This saturation current is assigned the symbol I_{c0}. This I_{c0} current is usually a few microamperes but it increases at the rate of 7 or 8 per cent per degree Centigrade increase in temperature of the collector junction. Transistors also have a critical junction temperature which should not be exceeded under any operating conditions, and this must be kept in mind during the design of the regulating circuits.

2.35. *Equivalent Circuit of a Transistor*

Ryder and Kircher[4] have shown that it is possible to convert the sketches shown in Fig. 7 into a small signal equivalent circuit using alpha and the three characteristic resistances of the transistor. These resistances are the emitter resistance r_e, the base resistance r_b and the collector resistance r_c. Two forms of equivalent circuit are shown in Figs. 9(a) and 9(b). In the equivalent circuit in Fig. 9(a) the active portion of the transistor is characterized as a current generator. This equivalent circuit is more directly related to the physical processes occurring inside the transistor than the equivalent circuit in Fig. 9(b) which characterizes the active portion of the transistor as a voltage generator. Although both equivalent circuits are useful the one in Fig. 9(a) is preferred in power work because r_c is much larger than the load resistance in many cases and can be neglected. Typical values for the equivalent circuit parameters are given in the caption of Fig. 9. The use of the equivalent circuits are further discussed in some of the articles listed at the end of this paper. The article[5] by R. L. Wallace Jr. and W. J. Pietenpol is of particular interest in this connection.

2.36. *Typical Junction Transistors*

Fig. 10 is a photograph of two Bell System junction transistors made from germanium. The smaller one will dissipate 50 milliwatts, and the larger one is an exploratory model that will dissipate 2 watts when it is attached to a suitable heat sink. These transistors are hermetically sealed to protect them from the infiltration of moisture. The characteristics shown in Fig. 8 were measured using the smaller unit.

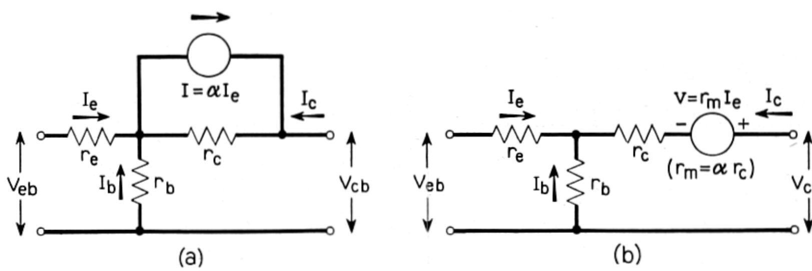

Fig. 9 — Junction transistor equivalent circuits. Typical values for a 50-milliwatt transistor: r_e, 25 ohms; r_b, 500 ohms; r_c, 5 megohms; α, 0.98; and r_m, 4.9 megohms.

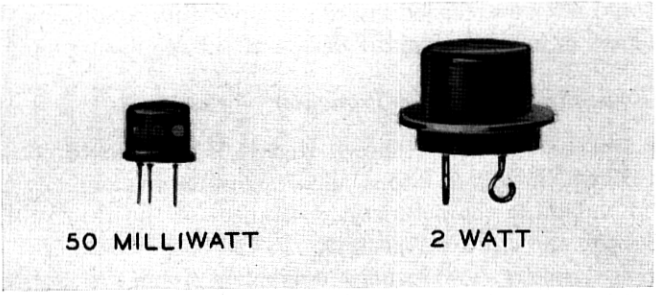

Fig. 10 — Typical junction transistors.

Thus, note that there are two kinds of transistors with respect to the polarity of the electrodes. The n-p-n transistor operates with positive collector potential and the p-n-p requires negative potential on the collector. Both will amplify current changes in the base circuit into much larger current changes in the collector circuit. The transistors have similar equivalent circuits and parameters but all of their operating potentials and currents are reversed. It is also significant that the normal direction of current flow is out of the base terminal of the p-n-p transistor and that the normal direction of current flow is into the collector terminal of the n-p-n transistor. Likewise, the normal direction of current flow is out of the collector terminal of the p-n-p transistor and into the base terminal of the n-p-n transistor. This relationship between direction of current flow in n-p-n and p-n-p transistors is called reversed or complementary symmetry, and enables the circuit designer to cascade direct coupled transistors, alternating n-p-n and p-n-p. This is not possible with vacuum tubes because there is no tube that will operate with negative plate potential. It will be shown how this complementary symmetry can be used to advantage in multistage direct current amplifier circuits.

3. TYPICAL REGULATING CIRCUITS

3.1. *Shunt Regulators*

3.11. *Simple Diode Regulator*

If a load is connected to a source of power, the current through the load and thus the voltage drop across the load will depend on the potential of the source of power, the internal impedance of the power supply and the load impedance. The voltage drop across the load can be made very nearly independent of these three parameters by employing a circuit known as a shunt regulator.

A shunt regulator is a variable current device, connected in parallel with the load. Both the load and the shunt regulator draw current from the source of power through a common impedance. The operating requirement for a good shunt regulator is that the voltage drop across it must remain constant over a certain range of current. Certain types of cold cathode tubes such as the VR-150-30(0D3) exhibit this effect. It has been determined that certain semiconductor junction diodes exhibit the same effect. Note that diode No. 1 that is shown in Fig. 3 has a reverse voltage drop of about 24 volts over a range of reverse current from less than 1 milliampere to almost 10 milliamperes. If such a device is connected in parallel with a load as in Fig. 11, shunt regulating action will take place. Consider the operation of the circuit in Fig. 11, first assuming that the load impedance is constant and that the potential of the power source increases. Additional current tends to flow from the source, but since the potential of the reference voltage diode designated "*s*" in Fig. 11 is fixed, this additional current develops an increased voltage drop across the regulating resistor, and the load voltage does not change. Similar reasoning can be applied to the case of a decrease in source voltage. Next assume constant source voltage and an increase or decrease in load resistance. This would normally tend to cause a change in the voltage drop across the load, but the shunt element draws respectively more or less current than normal and the load voltage again does not change.

The value of the regulated load potential in Fig. 11 is controlled by the saturation voltage of the diode and it cannot be adjusted to any other value. The accuracy of regulation is controlled by the slope of the reverse characteristics shown in Fig. 6. An additional limitation is that the usefulness of this type of regulator is controlled by the power handling capacity of the diode. The next section shows how these limitations can be circumvented by the addition of transistors.

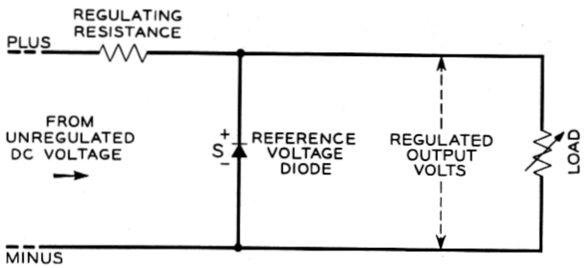

Fig. 11 — Simple shunt regulator.

3.12. *Transistor-Diode Regular*

To examine the operation of shunt transistor regulators consider the circuit shown in Fig. 12. In this, the transistor is shown by its standard convention where the upper slanting line represents the collector rectifier shown in Fig. 7 and the lower slanting line with the arrow on it represents the emitter rectifier. The direction of the arrow shows that, in this transistor, current flows out of the emitter, so it is an n-p-n transistor. The (*c*), (*b*) and (*e*) designations also help to locate the collector, base and emitter. Notice that the emitter current, shown by the arrow I_e, flows through the reference voltage diode in its reverse direction. The rectifier symbol with an adjacent "*s*" is a convention for this diode.

In Fig. 12 a portion of the load voltage is applied to the base of the transistor by means of the adjustable potentiometer. The potential of the emitter is held constant with respect to the negative output potential by the saturation voltage of the diode. The base-to-emitter voltage is thus equal to a proportion of the load voltage minus the saturation voltage. The potentiometer is adjusted so that the base potential is slightly positive with respect to the emitter when the desired value of voltage appears across the load. This value of load voltage is called the regulated voltage. Current I_b then flows into the base, current I_c flows through the regulating resistance, and $I_b + I_c$ combine to form I_e. Now assume that the regulated voltage (E) increases by an amount ΔE. The base voltage becomes more positive with respect to the negative terminal by the proportion of ΔE developed across points 1 and 2 of the potentiometer. Since the emitter potential is held constant by diode "*s*" and cannot change, the net effect is to increase the base to emitter potential. This change in base to emitter potential causes an increase in collector current,

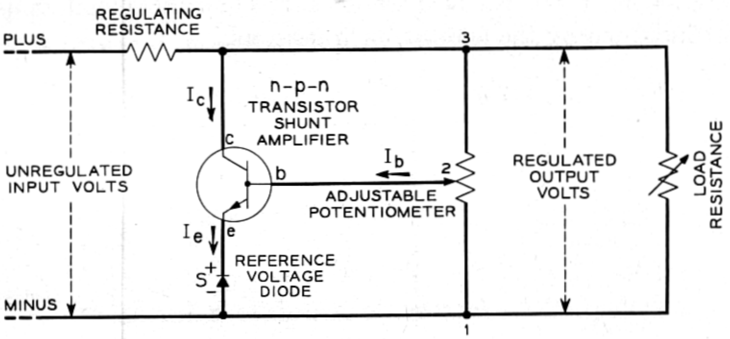

Fig. 12 — Transistor shunt regulator using one transistor.

a consequent increase in voltage drop in the regulating resistor, and a decrease in the load voltage. The correcting process continues until the load voltage returns to the regulated value, and takes only a small fraction of a second. The process is essentially the same for a decrease in load voltage, except that the base to emitter potential decreases, the collector current decreases, the voltage drop across the regulating resistor decreases and the load voltage rises to the regulated value.

The value of the regulated output voltage is determined by the adjustment of the potentiometer. Of course in a practical shunt regulator circuit, the adjustable range of the potentiometer would have to be limited to correspond with the operating range of the transistor. The maximum allowable positive potential between the base and the emitter is limited by the safe value of the maximum collector current. The maximum allowable negative potential between the base and the emitter is limited by the saturation voltage of the emitter rectifier.

The accuracy of this shunt regulator circuit is restricted by the slope of the characteristic curves for the reference voltage diode. All of the changes in base and collector currents required for regulation flow through this diode and cause changes in the saturation voltage. The addition of the transistor does not increase the accuracy of regulation but only allows adjustment of the regulated output potential to a value which is greater than the standard potential. However additional stages of transistor current amplification minimize the reference potential changes by restricting the range of current excursions through the diode. An example of a multistage shunt regulating circuit is given in Fig. 13.

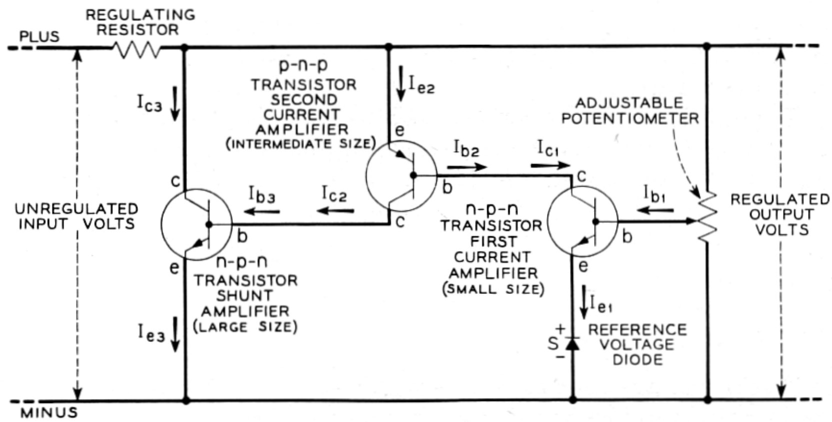

Fig. 13 — Transistor shunt regulator using three transistors.

3.13. *Multistage Transistor Shunt Regulator*

In Fig. 13 two additional transistors have been added to the simple shunt regulator of Fig. 12 in order to increase the accuracy of regulation. The first stage (subscript 1 is used for the transistor currents in this stage) compares the output potential to the reference voltage, drives the second stage (subscript 2) which in turn drives the third stage (subscript 3). The first stage transistor operates in a similar fashion to the transistor in Fig. 12, except that its collector current now is the base current of the second transistor. The collector current of the second transistor is the base current of the third transistor. The second and third stage transistors amplify the collector current of the first transistor. The shunt regulating current is the sum of the currents in all three transistors. An examination of Fig. 13 will reveal that the first transistor is an n-p-n, the second transistor is a p-n-p, and the third transistor is an n-p-n and that no coupling networks are used. This illustrates the advantages of complementary symmetry.

In Fig. 13 different sizes are specified for the three transistors. The transistor shown for the first current amplifier might be a 50-milliwatt transistor operating at a collector potential of about 10 volts. Then the maximum base current of the second stage p-n-p transistor should not exceed 5 milliamperes and, with an assumed current amplification of 20 times, the maximum collector current of the second stage could be 100 milliamperes Such a transistor has been developed. With 100 milliamperes flowing into the base of the large n-p-n transistor and an assumed current amplification of 20 times the maximum shunt regulator current would be about 2 amperes which would compensate for considerable load current variations. Large size transistors such as would be necessary in the third stage are now under exploratory development within the industry.[6]

The circuit in Fig. 12 can be modified to use a p-n-p transistor and several other modifications can be made. Similar modifications can be made in the circuit shown in Fig. 13. It is not within the scope of this article, however, to show all the permutations and combinations of transistor regulator circuits that are usable. Section 3.2 below covers some typical transistor series regulator circuits.

3.2. *Series Regulators*

Precise voltage control can be obtained with shunt regulators but series regulator circuits are usually more efficient. This comes about because the shunt regulator wastes the shunt current plus the voltage drop across the regulating resistance whereas the series regulator wastes only the voltage drop across the series device. At light load the power dissipated in the shunt current is usually greater than the power dissipated in the series circuit. With a transistor used as the series regulator device this difference in efficiency is more pronounced because of the small collector voltage that can be used for the full load current. This collector voltage is the voltage drop across the series transistor as shown in Fig. 14.

3.21. *Simple Series Regulator*

Fig. 14 shows a simple transistor series regulator circuit. A p-n-p transistor is shown connected so that all the load current must pass through it. The comparison of the output voltage to the reference potential in the current amplifier of Fig. 14 is accomplished by holding the emitter at a constant potential with respect to the *positive* output terminal. Note the difference between this method and that covered in the previous section on the shunt regulator 3.12, where the emitter was held at a constant potential with respect to the *negative* output terminal. Now, when the output potential increases by an amount ΔE, the base voltage becomes more *negative* with respect to the positive terminal by the proportion of ΔE developed across points 2 and 3 of the potentiometer. Since the emitter cannot change with respect to the point of reference (the positive terminal), the net effect is to *decrease* the base to emitter potential and the collector current for an increase in output voltage. The collector current decrease is amplified by the current gain of the p-n-p series transistor to decrease the load current, reducing the output

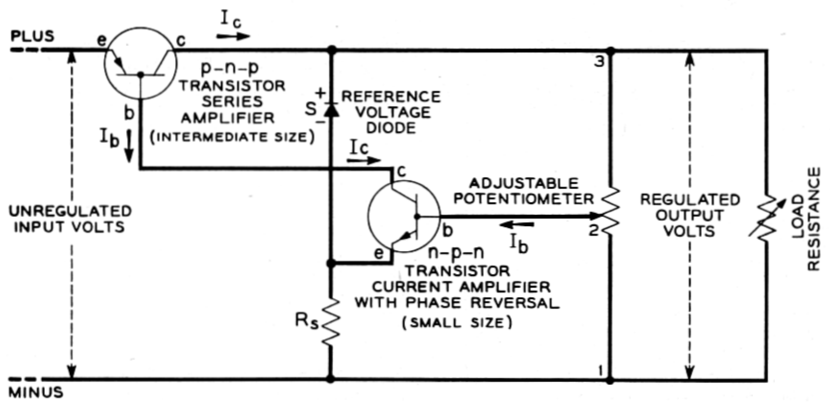

Fig. 14 — Transistor series regulator constant voltage regulation.

voltage, and thus regulating it. The value of the regulated output voltage is again determined by the adjustment of the potentiometer. The ohmic value of the R_s resistor in Fig. 14 is selected to keep the current flowing through the reference voltage diode in its saturation voltage region.

Fig. 14 is the simplest form of a transistor series regulator circuit. It requires two transistors whereas the most simple form of a transistor shunt regulator shown (Fig. 12) requires only one transistor. But the added current gain of the second transistor in Fig. 14 results in better regulation than can be obtained with Fig. 12. If desired the circuit in Fig. 14 can be modified to change the series transistor to the negative output lead by using the complementary p-n-p first current amplifier and an n-p-n series transistor. This illustrates another advantage of the complementary symmetry of the two types of transistors. Also, if more gain is required, additional transistor stages can be used employing the principles outlined above.

3.22. *Series Current Regulator*

The circuits covered so far regulate for constant output voltage. Similar transistor regulator circuits can be developed which will regulate for constant output current. One of these is shown in Fig. 15. In this circuit the load current produces a voltage drop across the regulating resistance and, in the n-p-n transistor, this voltage drop is compared to the reference voltage. The difference between these two potentials controls the n-p-n transistor base current and this base current is amplified by the current gain of both transistors to control the load current.

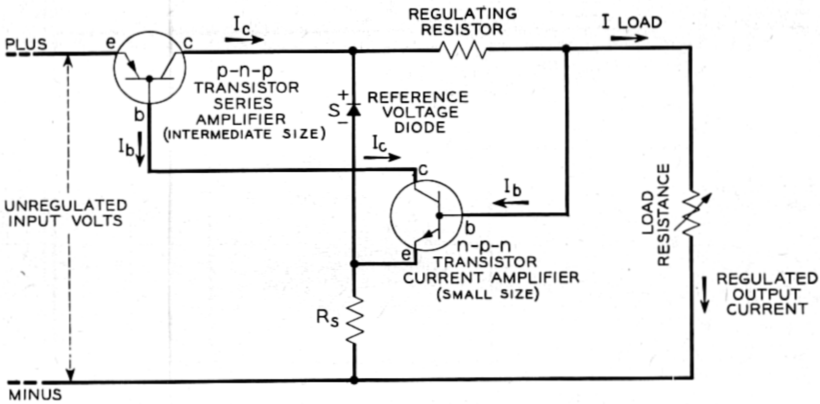

Fig. 15 — Transistor series regulator constant current regulation.

This circuit is phased so that the load current will be increased when it is too small and decreased when it is too large. The values of the regulating resistor and the reference voltage determine the value of the regulated load current. Additional current amplifier stages can be included or the circuit can be modified to change the series transistor to the minus lead as covered above.

3.3. *Transistors Combined With Magnetic Amplifiers*

3.31. *General*

Transistors can be used to control directly the flow of power to a load as pointed out in the sections on series and shunt regulators. However, their direct use is limited to moderate voltages (below 100 volts) or moderate currents (up to 1 ampere) with transistors now contemplated.

3.32. *Transistors as DC Preamplifiers*

In cases where regulation of higher power is required, it is expedient to combine transistor circuits with other devices having higher power-handling capacity. One type of combination is shown in Fig. 16, where a transistor is used to amplify weak dc error signals to a magnitude sufficient for driving a magnetic power amplifier.

In Fig. 16, emitter (*e*) of the n-p-n transistor is held at a fixed negative voltage with respect to the positive output of the power supply by the reference voltage diode ("*S*"). Another negative voltage derived from the output voltage of the power supply through potentiometer (*P*) is applied

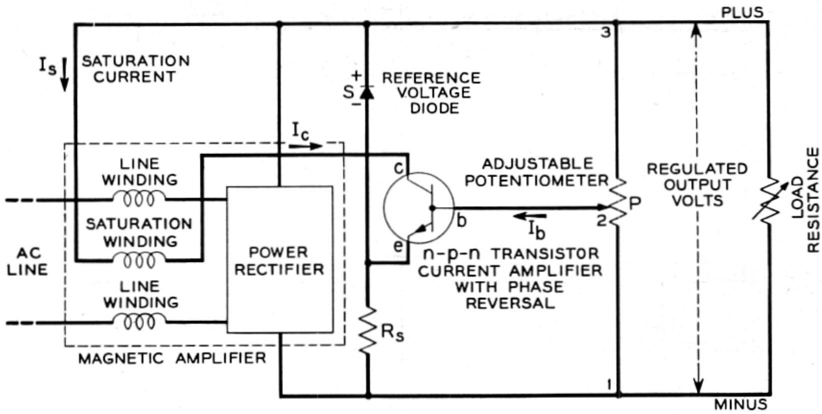

Fig. 16 — Transistor control circuit for a magnetic amplifier regulated rectifier with constant voltage regulation.

to base (b) of the transistor. This latter voltage is made a little smaller than the emitter voltage so that the base (b) is positive with respect to the emitter. Now assume that the load voltage increases for some reason such as an increase in the line voltage or a decrease in the load current. A portion of the increased load voltage appears across points 2 and 3 of potentiometer (P), and tends to make the base voltage more negative. Since the base is slightly positive with respect to the emitter, the net effect of making the base more negative is to decrease the base-to-emitter voltage. Through transistor action, the collector current, which is also the saturation current of magnetic amplifier, decreases and the ac impedance of the line windings rises. The line windings absorb more input voltage and the output voltage is brought back very nearly to the original value before the change.

The circuit of Fig. 16 is of interest because it can control larger amounts of power than can be handled by transistors alone and, in addition, it is capable of faster regulating action than an all-magnetic regulating circuit with the same loop gain. The use of the transistor in this circuit eliminates the need for one or more stages of milliwatt-size magnetic preamplifiers.

3.33. *Increased Gain in Voltage Regulators*

Additional amplification to improve the regulation can be added to Fig. 16 in two ways. Several stages of transistor current amplification can be added or more magnetic amplifier stages can be used. Of course

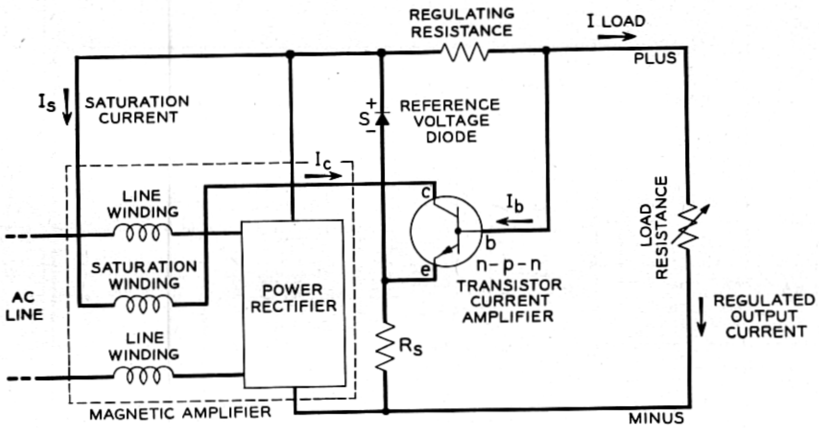

Fig. 17 — Transistor control circuit for a magnetic amplifier regulated rectifier with constant current regulation.

a combination of the two methods is also feasible. Additional magnetic amplifiers have the disadvantage of adding time delay. Transistor action likewise is not instantaneous because it takes a finite amount of time to move the charge over a finite distance in the crystal lattice. However transistor action is much faster than the time required to change the current in practical magnetic amplifiers.

3.34. *Current Regulators*

Fig. 17 shows a simple transistor control circuit to obtain constant current regulation with a magnetic amplifier regulated rectifier. The operation of this circuit is similar to Fig. 15 and its description will not be repeated.

3.35. *Temperature Effects*

One limitation of the foregoing transistor regulating circuits is the sensitivity of collector current to ambient temperature variations. The collector current increases with increasing temperature even if the base-to-emitter bias is held constant. This is the result of three factors. (1) I_{c0}, the uncontrolled portion of I_c increases greatly as covered in Section 2.34; (2) the emitter resistance (r_e) decreases causing I_b to increase, and (3) alpha changes. The effect of the temperature sensitivity of the collector can be greatly reduced by using a differential or push-pull circuit of the type illustrated in Fig. 18.

3.36. *"Push-Pull" DC Amplifier*

The push-pull circuit uses two emitter-coupled n-p-n transistors and is in many respects similar to a cathode-coupled vacuum tube amplifier.

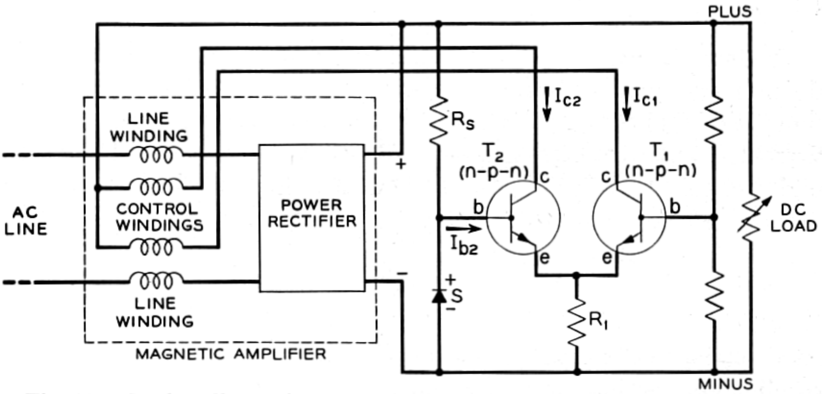

Fig. 18 — Push-pull transistor control circuit for a magnetic amplifier regulated rectifier with constant voltage regulation.

A voltage proportional to the regulated output is connected to the base of transistor (*T1*). Fixed resistors are shown in the base circuit of (*T1*) in Fig. 18, but a variable potentiometer could be used. The reference voltage diode "*s*" applies a constant reference voltage to the base of transistor (*T2*). If the output voltage tends to increase, more collector and emitter current flows in transistor (*T1*) due to the increase in its base-to-emitter voltage. This increase in emitter current of transistor (*T1*) flows through resistor (*R1*) and tends to raise the emitter voltage of transistor (*T2*). Since the base potential of transistor (*T2*) is fixed, the effect is to decrease the base-to-emitter voltage of (*T2*) and its collector and emitter currents decrease. The result is an increase in I_{c1} and an almost equal decrease in I_{c2}. If the two saturation windings on the magnetic amplifier are oppositely poled, the changes in I_{c1} and I_{c2} represent a net decrease in the control ampere turn input to the magnetic amplifier. As before, the magnetic amplifier responds by absorbing more voltage. If, however, I_{c1} and I_{c2} both increase equally due to an increase in ambient temperature, no net change is made in the control ampere turn input to the magnetic amplifier. Thus if the two transistors are perfectly matched, and the reference voltage diode has a low temperature coefficient, temperature changes will have little effect on the output regulated voltages.

A further advantage is the reduced variations in the current through the reference voltage diode. As in the case of the other circuits additional stages of transistor or magnetic amplification can be added to increase the loop gain and the precision of regulation.

4. APPLICATIONS

4.1. *General*

The last sections of this discussion cover some specific applications of the principles discussed above. Section 4.21 covers a one-stage transistor shunt regulated rectifier as a grid battery eliminator for phase controlled thyratron tube rectifiers. Section 4.22 covers a transistor voltage amplifier circuit as a grid battery eliminator for magnitude controlled thyratron tube rectifiers. A two-volt, three-ampere regulated rectifier covered in Section 4.31 illustrates how a low voltage, high current, regulated rectifier with a transistor and magnetic amplifier control circuit can be obtained. Section 4.32 covers a 65-volt, 200-ampere regulated rectifier for telephone central office battery charging. It uses the p-n junction rectifier devices covered in Section 2.1 and a modification of the transistor control circuits for magnetic amplifier regulation covered in Section 3.36.

4.2. *Grid Battery Eliminators*

4.21. *Phase Controlled Thyratron Tube Rectifiers*

In thyratron tube regulated rectifiers the standard potential for the checkback regulator is often obtained from dry cells. The annual replacement of dry cell batteries is an appreciable maintenance expense, particularly in those cases where the rectifiers are installed in isolated or unattended locations. This section covers a transistor shunt regulated rectifier as a substitute for the dry batteries. Its circuit is illustrated in Fig. 19.

The circuit in Fig. 19 is the same as Fig. 12 with the addition of the compounding resistor and the thermistor. The compounding resistor is added to compensate for the slope of the reference voltage diode in its saturation voltage region (see Fig. 6). The thermistor is added to compensate for ambient temperature varitions of this diode and the transistor.

The compounding resistor adds ac line voltage compounding. The transistor base current regulating signal in Fig. 19 is increased by the compounding resistance whenever the ac voltage is increased. By selecting the proper ohmic value of the compounding resistor, the circuit in Fig. 19 can be arranged so it will deliver constant output voltage into a constant resistance load when the ac voltage is varied from 85 per cent

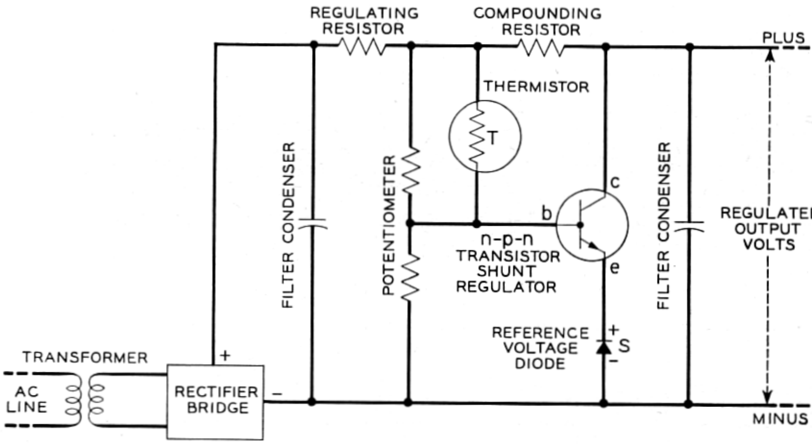

Fig. 19 — Grid-battery eliminator for phase-controlled thyratron rectifier.

to 115 per cent of its normal value. In the thyratron tube rectifiers, the circuit of Fig. 19 operates into a constant resistance load of several megohms. With such a high value of load resistance, the addition of the compounding resistor on the load side of the regulating resistor does not cause appreciable error. In fact, laboratory measurements on an experimental unit show that the compounding can be adjusted to obtain *improved* regulation of the thyratron tube rectifier when the grid battery eliminator is used in place of the normal grid battery. This is because the grid battery eliminator can be adjusted to over-correct for line voltage variations and thus compensate for the slight amount of residual line regulation error in the thyratron circuit.

The thermistor in Fig. 19 is a shunt element across one of the resitors in the potentiometer and a change of its resistance is equivalent to changing the potentiometer adjustment. The thermistor decreases its resistance with an increase of ambient temperature so it will change the output voltage when the temperature is changed. This output voltage change is opposed to the voltage changes resulting from the temperature effects in the reference voltage diode and the transistor. By selecting the proper thermistor and the proper ohmic values for the potentiometer resistors, these temperature variations will nearly cancel and the regulated output voltage will be temperature compensated.

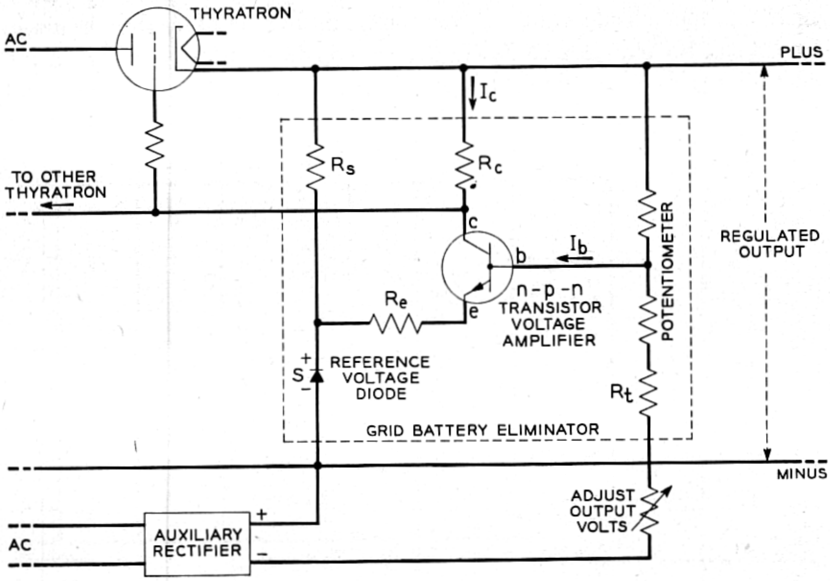

Fig. 20 — Grid-battery eliminator for magnitude controlled thyratron rectifier.

4.22. *Magnitude Controlled Thyratron Tube Rectifiers*

The grid battery eliminator covered in Section 4.21 is also usable in magnitude controlled thyratron tube regulated rectifiers but a simple, less expensive circuit can be used for this application. It is illustrated in Fig. 20. A simplified schematic of the thyratron rectifier is also shown in Fig. 20 and the grid battery eliminator is the portion of the circuit enclosed by the dotted line. It is actually a transistor voltage amplifier circuit. This type of circuit has not been covered previously in this discussion so its operation is described in some detail below.

Referring to Fig. 20 a portion of the output potential is compared to the reference potential by the base and emitter connections to the transistor. The difference between these two potentials causes the base current I_b to flow. This base current is amplified by the current gain of the transistor and it results in flow of collector current I_c, through the R_c collector resistance. The voltage drop across R_c is the negative grid potential applied to the thyratron tube. Now when the output potential is increased the base current is increased, the collector current is increased, the voltage drop across the R_c resistor is increased and the negative grid potential at the thyratron tube is increased. This will delay the firing of the thyratron and thus reduce the output potential.

If the ohmic value of the R_e resistor in Fig. 20 is zero the voltage amplification of this transistor circuit will be about 10, or a small change in the output potential will result in about 10 times this change in the thyratron grid potential. This is voltage amplification added to the circuit by the grid battery eliminator and a voltage gain of 10 is more than present circuits can use. The emitter resistance R_e reduces the voltage amplification of the grid battery eliminator to reasonable proportions.

The R_t resistance in the potentiometer circuit of Fig. 20 is wound with nickel resistance wire. Its positive temperature coefficient of resistance compensates the grid battery eliminator circuit for the temperature effects in the reference voltage diode and the transistor. This nickel wire resistance accomplishes the same result as the thermistor in Fig. 19. This is another method of compensating transistor regulator circuits for ambient temperature variations.

The "Adjust Output Volts" potentiometer and the auxiliary rectifier shown in Fig. 20 are part of the present magnitude controlled thyratron tube rectifiers. The auxiliary rectifier adds some ac line voltage compounding to the rectifier regulation. It is also used with a time delay relay circuit, not shown, to bias the grid potential of the thyratron tubes so that they will not fire during the required rectifier starting time interval.

4.3. *Magnetic Amplifier Regulated Rectifiers*

4.31. *2-Volt, 3-Ampere Regulated Rectifier*

The control of direct current at low voltage levels has been complicated by the lack of inexpensive low voltage reference standards, and by the very poor efficiencies of most rectifiers at low voltage. The new semiconductor devices have made important contributions in this field. Germanium diodes with their relatively low forward resistance seem naturally suited for use at low voltages, and the high sensitivity of junction transistors likewise makes them an almost ideal amplifier of small dc potentials.

Fig. 21 illustrates the use of junction diodes, junction transistors and a magnetic amplifier combined to furnish a regulated 2-volt, 3-ampere dc power supply. It will be noticed that the circuit of Fig. 21 is very

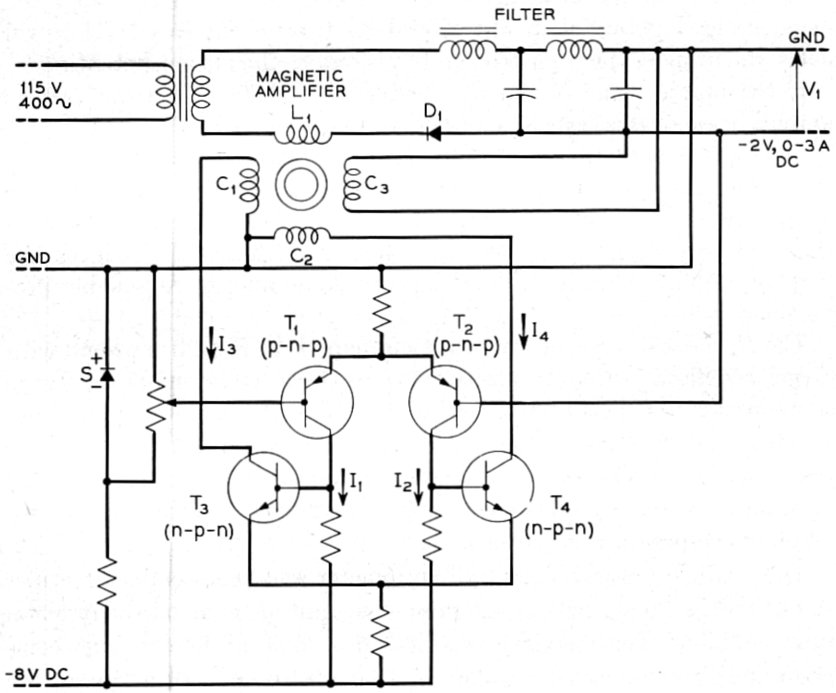

Fig. 21 — Two-volt three-ampere magnetic amplifier regulated rectifier.

similar to that in Fig. 18, except that an additional stage of current amplification has been added to the basic push-pull circuit.

Briefly, the regulating action is as follows. (1) The currents I_1 and I_2 respond in push-pull fashion to changes in output voltage $V1$ as covered in Section 3. 36, (2) currents I_1 and I_2 are amplified by the 2-watt n-p-n transistors (T_3) and (T_4), (3) the amplified currents (I_3) and (I_4) flow in control windings (C_1) and (C_2) of the magnetic amplifier to control the voltage absorbed by the power winding ($L1$), (4) this action regulates the average value of the voltage rectified by the germanium diode ($D1$), thus completing the feedback loop. Tests show that this circuit is capable of ± 1 per cent accuracy of the output voltage with a ± 15 per cent change in the line voltage and with load current variations of from 10 to 100 per cent of rated output current.

4.32. *65-Volt, 200-Ampere Germanium Rectifier*

Fig. 22 is a circuit sketch of a 65-volt, 200-ampere regulated rectifier suitable for charging and floating central office storage batteries. This rectifier employs six of the power rectifying cells with forced air cooling

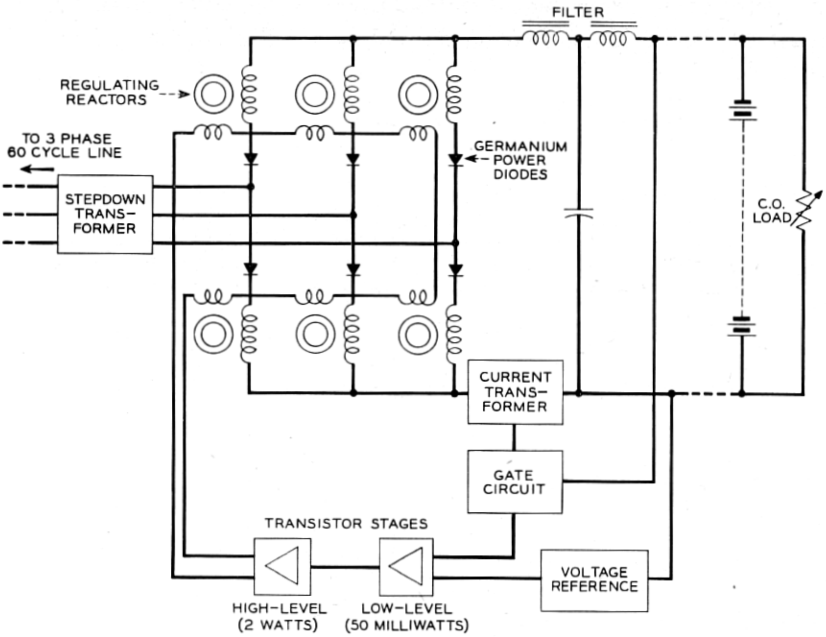

Fig. 22 — Sixty-five volt two-hundred ampere magnetic amplifier regulated rectifier.

described earlier (Diode IV, Fig. 2), a reference voltage diode (Diode I, Fig. 2), two 50-milliwatt, and two 2-watt junction transistors.

The dc output voltage of the rectifier is controlled by a high gain self saturating magnetic amplifier. High gain in the magnetic amplifier is achieved by using tapewound gapless nickel-iron cores having rectangular hysteresis loops. The control current for the magnetic amplifier is provided by 2, 2-watt n-p-n transistors acting in push-pull. The 2-watt transistors are driven by 2, 50-milliwatt p-n-p transistors also acting in push-pull. The circuit is similar to Fig. 21. Again, the reference potential is furnished by a reference voltage diode.

Where the rectifier is connected to storage batteries an additional feature known as "current droop" is needed to protect the rectifier. The output characteristic of the rectifier with current droop is shown in Fig. 23. This characteristic is obtained by coupling a signal proportional to load into the first stage transistor amplifier through a gating circuit. This signal is provided by a dc current transformer which is another form of magnetic amplifier. At currents below the "droop" value the current signal is blocked from the amplifier. At full load the gating circuit allows the current signal to take over and hold the output current constant over a wide range of output voltage. In Fig. 23, the performance

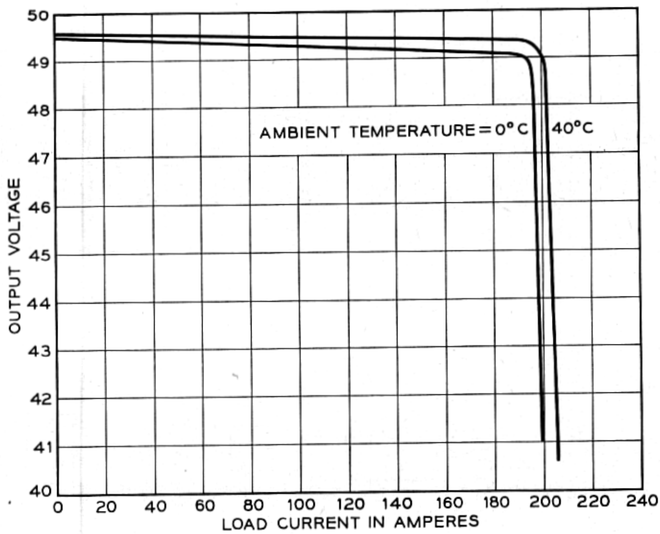

Fig. 23 — Output characteristics of experimental 65-volt 200-ampere germanium rectifier.

is shown over the range of ambient temperatures normally encountered in central offices.

5. CONCLUSIONS

It is seen from the above discussion that semiconductor junction diodes and transistors have a wide field of application in power conversion and control. Certain difficulties remain to be overcome, among which the variation of the device characteristics with ambient temperature appears to be the most troublesome at the present time. It has been shown that these variations with temperature can be minimized by two methods. First through the use of thermistors (negative temperature coefficient) or nickel-wire resistors (positive temperature coefficient) and second, through the employment of circuits in which the temperature variations of one element are balanced out by similar temperature variations in a complementary element. Thus, errors due to temperature changes can be minimized by further reduction of the sensitivity of the device characteristics to ambient temperature changes and by improved uniformity of the devices.

Another important aspect of the circuits covered in this paper is their freedom from dependence on auxiliary sources of dc potential. In most cases it is possible to power the regulating circuit directly from the regulated output, thereby eliminating the necessity for the transformers, rectifiers and filters usually needed to furnish plate potential for the regulating tubes and voltage standards.

The regulating circuits discussed in this paper are of the checkback type. In all of them, there must first be an error in the load voltage to start and maintain the regulating action. The load voltage will only return to precisely the original value if the regulating amplifier has infinite gain. These effects, however, are common to all closed-loop feedback regulating systems. Transistors and junction diodes, at their present stage of development seem well suited for use in checkback circuits having a high quality reference potential, for the feedback principle helps to minimize residual errors due to changes in the device characteristics with changes in ambient temperature.

Of course, the small size, long life and high efficiency of these semiconductor junction devices will also be very gratifying to the design engineers.

6. ACKNOWLEDGMENTS

The authors wish to acknowledge the assistance of C. W. Van Duyne of Bell Telephone Laboratories and the personnel in his group,

who were instrumental in obtaining the experimental data upon which this paper is based.

7. REFERENCES

1. W. Shockley, The Theory of p-n Junction in Semiconductors and p-n Junction Transistors, B.S.T.J., **28,** p. 435, 1949.
2. C. L. Rouault and G. N. Hall, A High-Voltage, Medium-Power Rectifier, I.R.E. Proc., **40,** p. 1519, Nov., 1952.
3. G. L. Pearson and B. Sawyer, Silicon p-n Junction Alloy Diodes, I.R.E. Proc., **40,** p. 1348, Nov., 1952.
4. R. M. Ryder and R. J. Kircher, Some Circuit Aspects of the Transistor, B.S.T.J. **28,** p. 367, 1949.
5. R. L. Wallace, Jr., and W. J. Pietenpol, Some Circuit Properties and Applications of n-p-n Transistors, B.S.T.J., **30,** p. 530, 1951.
6. R. N. Hall, Power Rectifiers and Transistors, Proceedings of the I.R.E. Proc., **40,** p. 1512, Nov., 1952.
7. W. Shockley, *Holes and Electrons in Semiconductors*, D. Van Nostrand, 1950.
8. K. G. McKay, Avalanche Breakdown in Silicon, Phys. Rev., **94,** p. 877, May 15, 1954.