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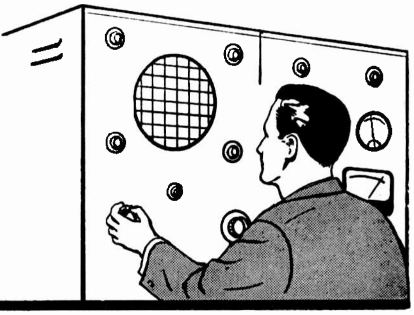

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Silicon Rectifiers

By the Engineering Department, Aerovox Corporation

IN the seventeen years preceding World War 2, the only semiconductor power rectifiers exploited commercially in significant numbers in the United States were of the copper oxide or magnesium-copper sulphide types. These rectifiers were restricted, for the most part, to low-voltage applications such as battery charging, engine starting, electroplating, loudspeaker field supply, and relay or solenoid operation. Miniature copper oxide rectifiers were, and still are, employed to convert d-c meters for a-c operation. Right after the war, the selenium rectifier, popular for some time in Europe, began to be manufactured here. Because a single selenium rectifier plate of given area and thickness of its active elements provides higher forward and reverse operating voltages than the copper oxide and magnesium-copper sulphide types, several such plates could be stacked in series for higher-voltage operation, fewer being required than with the two earlier types of rectifiers. It was natural therefore that this rectifier found its first widespread application in this country in transformerless radio receivers and amplifiers.

Selenium rectifiers soon began to be supplied in a wide variety of sizes with different current and voltage ratings. By stacking a number of small rectifier "cells" in series, kilovolt ratings were achieved. Large-area plates provide output currents up to several thousand amperes. The merits of all solid-state rectifiers are obvious: instant operation since there is no heat-up interval, freedom from the heat caused by filament operation, increased mechanical ruggedness compared with that of tubes, unlimited operating life, smaller size than tubes in some instances, ability

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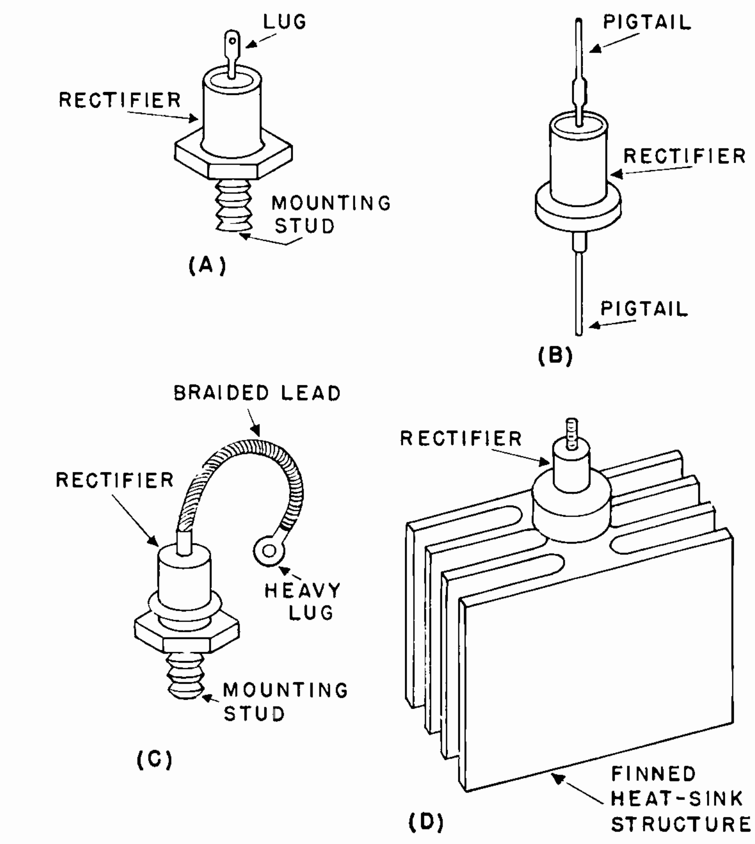
to operate at lower voltages, simplicity, greater current capability, and higher over-all efficiency because of the absence of filament power. Disadvantages of the selenium rectifier are its large physical size for high current ratings, restriction to lower-frequency operation, sensitivity to high ambient temperatures, and relatively low peak inverse voltage ratings per rectifier plate. These disadvantages, of course, are relative to performance of later solidstate rectifiers of other types. A further peculiarity of the selenium rectifier is its generation of a foul odor when accidentally burned out.

Following the development of the transistor, the germanium junction power rectifier appeared. This rectifier has the advantages of smaller size than the selenium unit, higher rectification efficiency, lower forward voltage drop, superior front-to-back current ratio, and considerably higher operating frequency. However, it is sensitive to high ambient and junction temperatures; and, because it is essentially a low-voltage device, several such units must be wired or stacked in series for high-voltage operation.

The silicon junction rectifier is the latest in the series of commercial semiconductor power units. Its characteristics suit it to many applications in industrial, military, and entertainment-type electronic equipment. In addition to power rectification, the silicon rectifier, because of its unique d-c characteristics, is utilized in other types of service such as voltage regulation, sequential switching, and equipment protection. In some applications, this unit is replacing selenium and germanium rectifiers just as the selenium unit earlier supplanted the copper oxide type in many applications.



SILICON RECTIFIER CONFIGURATIONS

FIG. 1

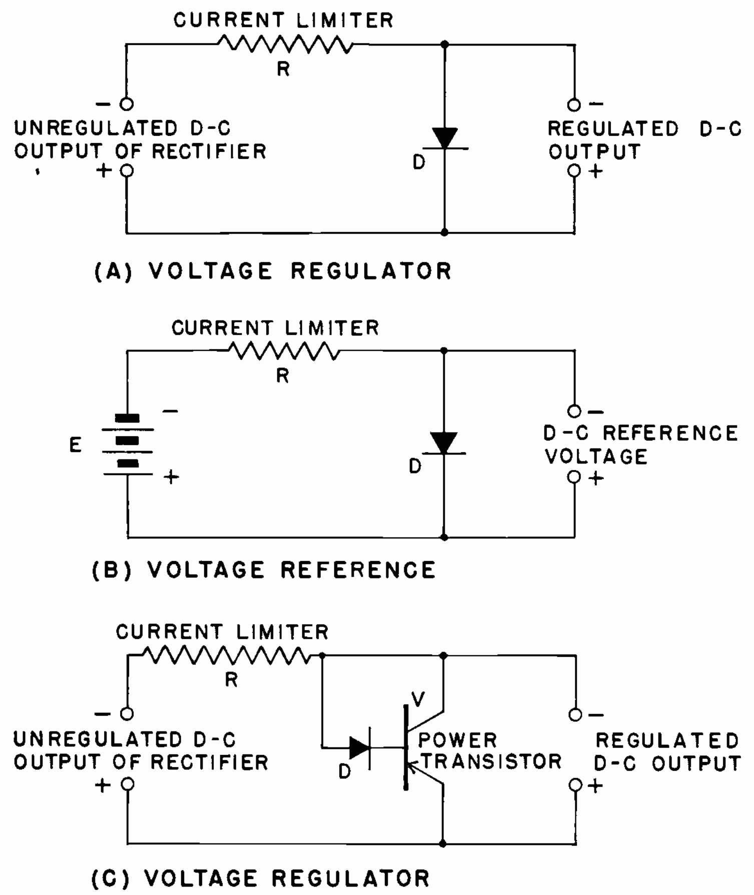
Silicon Rectifier Characteristics

The following features are representative of contemporary, production-type silicon rectifiers. In making comparisons with the selenium rectifier, the Editors have no intention of disparaging the latter. It so happens that the selenium rectifier and its characteristics are well-known to a number of readers, since this rectifier has been so widely used.

1. **Small Size.** Since the silicon rectifier consists of a single junction, the absence of stacks for simple low- and medium-current units (and some high-current ones as well) and the ability of the single junction to dissipate significant amounts of power keeps the unit small. A modern 3.5-ampere, 600-volt rectifier, for example, is only approximately 7/16″ in diameter and ⅞″ high, with a 10-32 mounting screw less than ½″ long on one end. Compare this with a 500-ma, 120-volt selenium rectifier which for one-fifth of the voltage and one-sixth of the current of the silicon rectifier is 3″ long, 1½″ high, and 1¼″ thick (over 14 times the volume of the silicon unit).

2. **High Power Capability.** The higher power handling capability per unit volume of the silicon rectifier will be evident from a comparison of a silicon with a selenium rectifier of nearly comparable rating: A typical 100 v, 750 ma silicon rectifier having a volume of approximately 0.4 cu. in. supplies 74 watts of d-c power. A 120 v, 400 ma selenium rectifier with 5.6 cu. in. volume supplies 57.5 watts. Thus, this silicon rectifier delivers 185 w/in^3 against 10½ W/in^3 for the selenium.

3. **High Efficiency.** Rectification efficiency (n) is defined as 100 times the ratio of d-c output voltage (e_0) to peak a-c applied voltage (e_1): n =



ZENER UNIT APPLICATIONS

FIG. 5

single-phase and polyphase half-wave and full-wave arrangements. Single rectifier cells may be connected in series for higher operating voltage, and in parallel for higher current. Voltage multiplier circuits, such as doublers, triplers, and quadruplers also may be used.

In addition, high-current silicon rectifier stacks are available in the following arrangements: (1) single-phase full-wave center-tap, (2) single-phase bridge, (3) Single-phase magnetic amplifier bridge, (4) three-phase half-wave, (5) three-phase bridge, and (6) six-phase star. These arrangements are shown in Figure 4. To prevent repetition, the complete power supply circuitry, including transformer, filter, and load, is not shown here, since this circuitry is standard and may be found in any electrical handbook.

Single high-current silicon rectifier cells are commercially available for single-phase half-wave operation with resistive or inductive loads to deliver up to 293 amperes output and up to 1120 volts rms input. For resistive or inductive loads, single-phase center-tap stacks are available up to 438 amperes and up to 280 volts rms input, single-phase bridges 219 amperes and 250 volts, single-phase magnetic amplifier bridges 219 amperes and 250 volts, three-phase half-wave stacks 380 amperes and 186 volts, three-phase bridges 190 amperes and 376 volts, and six-phase stars 338 amperes and 188 volts.

Zener Unit Applications

Figure 5 shows typical applications of silicon rectifiers designed and fabricated for specified values of reverse-voltage breakdown (Zener point).

Figure 5(A) is the circuit of a simple d-c voltage regulator. In this arrangement, the Zener rectifier, D, behaves in a manner comparable to that of the VR-type of gaseous regulator tube. The current-limiting resistance, R, is chosen such that the diode reverse current is held within the Zener region (that is, between E_Y and E_Z in Figure 2). The voltage drop across the diode consequently is fairly constant for large changes in the d-c voltage applied to the circuit and for load current changes. The d-c output voltage accordingly is regulated.

Figure 5(B) shows a simple d-c voltage reference ("standard cell") circuit. This arrangement behaves similarly to the voltage regulator in Figure 5(A). That is, the voltage drop across the Zener rectifier, D, is constant for large changes in the supply voltage, E. This diode voltage constitutes the stable d-c output. For best results, Voltage E should be large with respect to the d-c output voltage (Rectifier Zener voltage), resistance R should be high, and external loading should be light with reference to the Zener current flowing through the rectifier.

Figure 5(C) shows a regulator of the amplifier triode type employing a power transistor, V. The d-c base current of this transistor is supplied through the Zener rectifier, D, which is held in its Zener conduction region by the current-limiting resistance, R. Small changes in the rectifier current produce large changes in the collector output resistance of the transistor, as a result of the latter's high current amplification factor. Since the collector-emitter resistance shunts the d-c output terminals, this resistance variation has a regulating effect on the output voltage of the circuit.

tifier manufacturer's literature shows derating figures where these are applicable.

9. **Good Packaging.** Commercial silicon rectifiers are supplied in enclosed casing, principally of the stud (mounting-screw) and wire-in (pigtail) types. They often are hermetically sealed. Figure 1(A) illustrates the stud type and Figure 1(B) the pigtail type. Figure 1(C) shows a stud-mounting high-current type provided with a flexible-braid lead and lug for heavy duty. High-current types sometimes are provided with one-piece cooling structures, as shown in Figure 1(D).

Voltage-vs-Current Characteristic

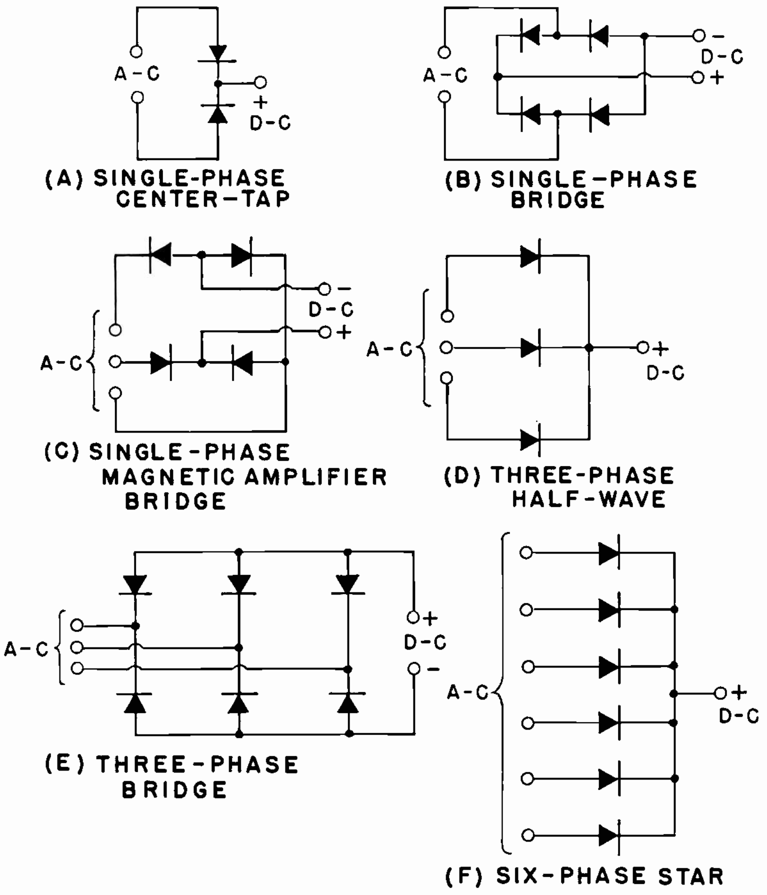
Figure 2 shows the typical plot of voltage vs current for a silicon rectifier. Note from this curve that the slope of the forward current is steep from zero to maximum, reaching a point I_f when the forward voltage is at the maximum permissible forward peak, E_f. The reverse current is notably small; at first being only a few microamperes in low-current types and a few milliamperes in medium and high-current types, from zero to the reverse voltage level E_z. At the potential E_z (termed the Zener voltage), the reverse current increases sharply, reaching a high level, I_z, during the small voltage increment E_x-E_z. While this sudden increase in current resembles a breakdown, and often is so termed, it causes no damage to the rectifier if the maximum current and dissipation ratings are not exceeded.

This "breakdown" is of especial interest in silicon rectifier applications: Because the increase in voltage drop across the rectifier from E_z to E_x is virtually negligible as the current makes a rather heavy excursion to I_z, the silicon rectifier operated at its Zener point may be employed as a voltage regulator or as a voltage reference. The resistance and dynamic impedance of the rectifier are very low in the Zener region. Some rectifiers are fabricated especially for such applications and are termed **Zener diodes.** In these units, the breakdown point occurs at a specified voltage. In standard rectifiers, Point E_z is sufficiently higher than the maximum rated peak inverse voltage of the units that the negative half-cycle of applied voltage never swings into the Zener region in normal operation. The desirable high front-to-back current ratio of the rectifier accordingly is maintained.

Figure 3 shows the static resistance characteristics of the silicon rectifier. This plot corresponds to the EI conduction characteristic depicted by Figure 2. The resistance axis in Figure 3 is assumed to be logarithmic and to cover the range from less than 1 ohm to several megohms. As forward voltage applied to the rectifier is increased from zero, the rectifier resistance decreases sharply to a low value (A) at maximum permissible forward voltage. When the reverse voltage is increased from zero, the rectifier resistance rises rapidly to a high value (B) and then decreases almost imperceptibly as the voltage is increased to C. As the voltage is increased a very small amount higher than at Point C, the resistance drops abruptly to a low value (D), since C represents the Zener point.

Silicon Rectifier Assemblies

Low, medium, and high-current silicon rectifiers are supplied in single-diode units which may be operated singly or in multiples with high efficiency in conventional power supply circuits. The latter include



(A) SINGLE-PHASE CENTER-TAP

(B) SINGLE-PHASE BRIDGE

(C) SINGLE-PHASE MAGNETIC AMPLIFIER BRIDGE

(D) THREE-PHASE HALF-WAVE

(E) THREE-PHASE BRIDGE

(F) SIX-PHASE STAR

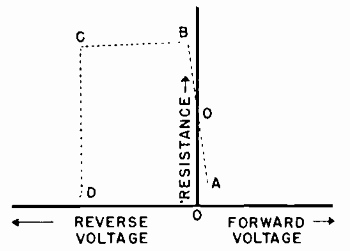
STACKED RECTIFIER ARRANGEMENTS

FIG. 4

$100\ (e_o/e_1)$. For resistance-loaded half-wave rectifiers, n may be as high as 99% for silicon rectifiers and 68% for selenium at light loading. These figures vary of course with selenium rectifiers under various operating conditions and the gap may not be as great in some instances. The voltage drop introduced by the rectifier when it is passing rated forward current is a function of the forward resistance at the operating voltage level. This voltage drop influences the rectification efficiency in an inverse manner and contributes directly to internal heating of the rectifier. In a silicon rectifier, the forward voltage drop may be of the order of 0.6 volt at 140 v rms operating potential; in a small selenium rectifier consisting of 5 stacked plates, the drop may be 5 volts.

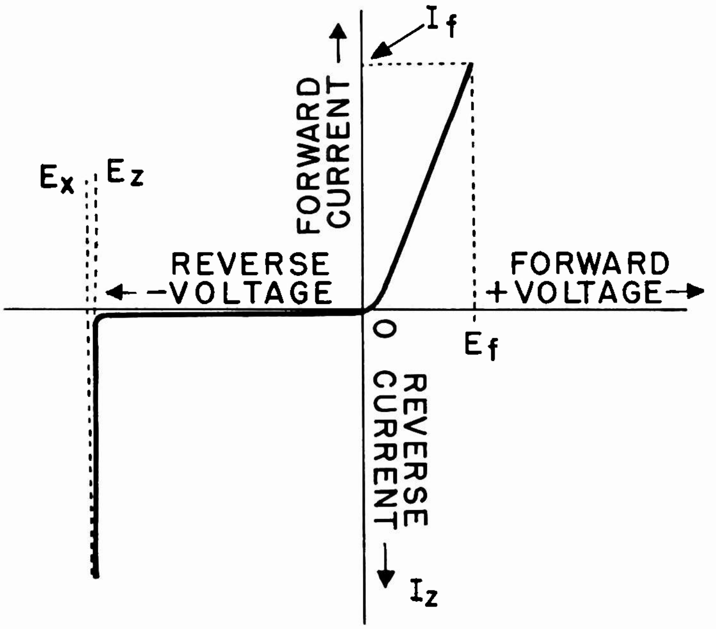
4. **High Reverse (Leakage) Resistance.** The maximum reverse (leakage) current through a silicon rectifier during the blocking period of the a-c half-cycle of applied voltage is lower than that through a comparable selenium rectifier. Thus, the reverse resistance of the silicon unit is the higher. Like forward voltage drop, reverse (leakage) current affects the rectification efficiency inversely and contributes to internal heating in the rectifier. In the low-current class, a typical silicon rectifier rated at 600 PIV and 3.5 amp d-c output has a leakage current of only 2 microamperes at the rated operating voltage. For a commercial 85-ampere, 210-volt silicon unit, the maximum leakage current is specified as 50 ma. In the first case, the front-to-back current ratio is more than 1 million to 1.

5. **Reduced Heating.** It follows from (3) and (4) that internal heating will be lower in the silicon rectifier because of the low forward voltage drop and low reverse leakage current, provided all other factors and standards of comparison are equal. Low heating prolongs rectifier life and simplifies equipment packaging problems.



SILICON STATIC RESISTANCE CHARACTERISTIC

FIG. 3



SILICON CONDUCTION CHARACTERISTIC

FIG. 2

6. **High-Voltage Operation.** Special silicon rectifiers provide high-voltage operation in single units without stacking. Use of such compact units simplifies equipment packaging and circuit design. Maximum peak inverse voltage ratings up to several kilovolts are obtainable in some types. Like other solid-state rectifiers, small-sized silicon cells also may be wired in series for higher-voltage operation.

7. **High-Frequency Operation.** The internal junction capacitance of the silicon rectifier is considerably lower than that of the wider-area, flat plate or disc of the selenium rectifier. It is principally because of this feature that the silicon rectifier may be operated at higher frequencies than other solid-state types. 100-kc operation is possible with silicon units, while the selenium rectifier (in power sizes, not small diodes) is restricted to power frequencies (e. g., 20 to 1000 cps).

8. **Good Temperature Characteristics.** Silicon rectifiers are specified for safe operation from —65°C to +200°C. Storage temperatures are specified for the same range. Some high-current types are provided with ventilating fins in single or stacked assemblies, and heat-sink mounting or forced-air ventilation is recommended for some applications. Rec-

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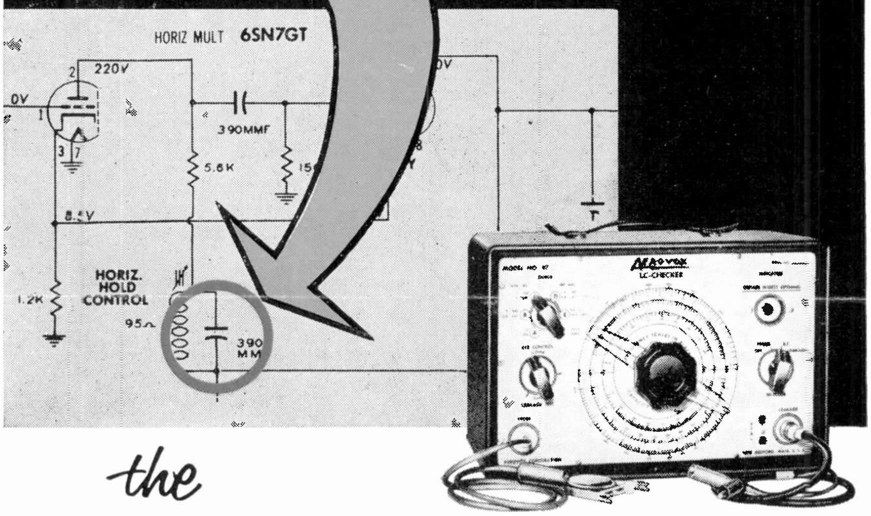

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