February/March/1961

INTERNATIONAL RECTIFIER CORPORATION

SYMBOL OF QUALITY IN SEMICONDUCTORS

RECTIFIER NEWS

PUBLISHED BY INTERNATIONAL RECTIFIER CORPORATION • EL SEGUNDO • CALIFORNIA

RELIABILITY!

Anyone can claim it... but this stack has proved it in more than 100,000 hours of continuous operation!

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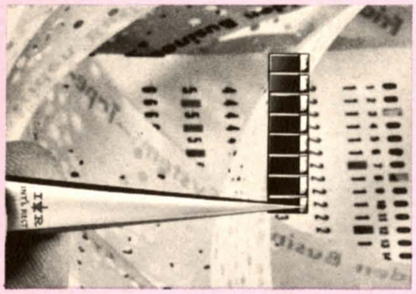
new developments

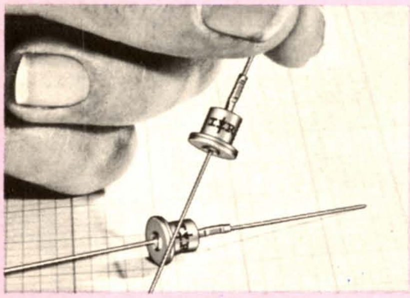


SILICON READOUT PHOTOCELLS CAPABLE OF READING 10,000 CHARACTERS PER SECOND

A new series of silicon readout photocells providing very fast response time (from 5 to 20 microseconds) are capable of reading 10,000 characters per second in perforated tape and punched card data reading systems. Cells are available with 5, 6, 8, 9 or 10 readout positions, an active cell area (per cell segment) of 0.128 x 0.067″, and center-to-center spacing of 0.087″.

All units provide high sensitivity and very low noise output. Typical current generated is 350 microamperes for 0.01 square inch of active cell area at 1000 footcandles illumination. An additional series of readout cells previously announced features 5 to 9 readout positions, typical output of 290 μa per segment at 1000 fc and center-to-center spacing of 0.100″. Dimensions, spacing and number of readout positions of individual cells may also be designed to meet special system requirements.

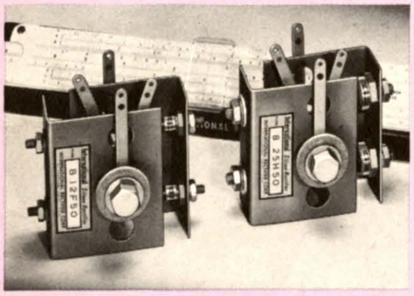
For detailed data on these devices, request Bulletin SR-280.



1.8 AMP RATED SILICON RECTIFIERS FEATURE LOW LEAKAGE, HIGH SURGE CURRENT CAPACITY

Rectified dc output currents up to 1.8 amperes per rectifier cell along with extremely low reverse leakage (500 ua at rated PRV at 150°C) are now available in a new diffused junction 'top hat' rectifier series. Designated types X10B1 through X10B6, the new series will provide forward currents up to 1.8 amperes (when mounted on heat sink) or 1.3 amperes (without heat sink in air) over a peak reverse voltage range from 100 to 600 volts.

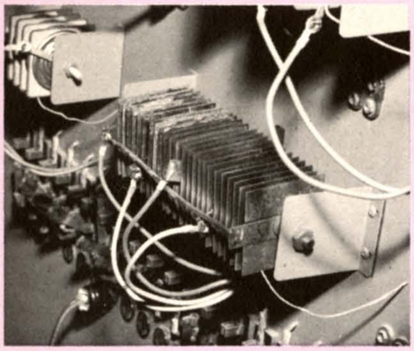
All units are particularly suited for magnetic amplifier applications where low leakage is a design parameter. Additional characteristics include very low forward voltage drop (1.10 volts max. at rated current at 25°C) and high surge current capabilities (40 amps peak at .01 sec.). All types have an operating temperature range from −65°C to +175°C, and feature rugged, hermetically sealed, welded construction. For additional data, request Bulletin XSR-217.



COMPACT 5 TO 50 AMP RATED SILICON RECTIFIER STACKS FOR 'CLOSE-QUARTER' CIRCUITRY

A new series of single phase bridge silicon rectifier stacks are mounted on compact dual-fin heat sinks designed to save space and weight in applications which do not permit a large volume for mounting. Measuring only 3 x 3¾″ overall, they are available with current ratings ranging from 5 to 50 amperes, and with peak reverse voltage ratings from 50 to 500 volts. Mounting is rapidly accomplished by a ⅜-16 mounting stud, and by connecting leads to terminal lugs on the stack.

Component diodes in this stack series include 6 and 12 amp rated diffused junction cells providing very low forward voltage drop characteristics, and 25 amp rated rectifier cells with low forward voltage drop and low reverse leakage characteristics. For detailed data, request Bulletin SR-331.



ON THE COVER: The stack pictured on the cover is unique in several ways. It is the very first rectifier of many thousands placed on life test by International Rectifier during its 13 years of semiconductor experience. Life Test Report #1, containing entries for more than 12 years, reveals that this rectifier, placed on test in June, 1948, has been operating continuously for 105,816 hours, during which time it has converted 21,586 kwh of power! Its long, uninterrupted life test was disturbed only recently when the stack was removed from its mounting to be placed in new life test faciilties. At that time this example of the sheer dependability of International Rectifier selenium power rectifiers was operating at 88.7% of its original voltage output. This fact speaks for the kind of reliability we build into every product we make.

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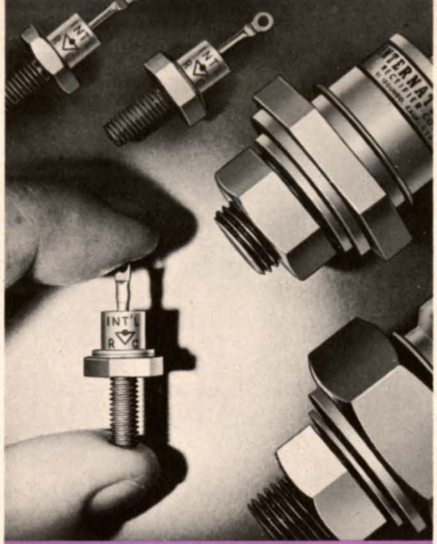

International Rectifier silicon power rectifier cells span a current range from 1 amp to 250 amps per junction, offering the widest, most versatile selection of configurations in the semiconductor industry.

For technical bulletins on each of the basic diode series, specify bulletins as follows: 1 amp pigtail lead types, XSR-217; 6 to 12 amp stud types, SR-308 and SR-311; for 25 to 35 amp Quad-Sealed types, SR-310; for 25 to 45 amp hermetically sealed types, SR-304; for 45 to 150 amp Quad-Sealed types, SR-312; for 45 to 150 amp hermetically sealed types, SR-300; 70 to 250 amp Quad-Sealed types, SR-313; 70 to 250 amp hermetically sealed types, SR-305.

Forward Voltage Drop and Power Loss in Silicon Rectifiers

WERNER LUFT, *Chief Electrical Design Engineer, International Rectifier Corp.*

Synopsis: The instantaneous forward voltage drop of silicon diodes of different sizes and processes is investigated over four magnitudes of current density. The temperature influence is determined. An equation relating the instantaneous forward voltage drop to current density and junction temperature is given. An expression of the average forward voltage drop and power loss as function of current density and conduction angle is developed.

TO EVALUATE the current-carrying capacity of a semiconductor diode, it is necessary to know the power losses within the diode as a function of the current. The power losses are forward conduction losses and reverse blocking losses. The former are generally of much greater magnitude than the latter, which depend on the reverse voltage and leakage current. The leakage currents are usually held to such limits that the blocking losses are the same for diodes of different voltage grades. Therefore, only the forward conduction losses will be discussed.

The instantaneous forward power loss is a function of instantaneous current, junction area, kind of junction, and operating temperature. The average power loss is, therefore, also a function of the current waveshape. For an a-c power supply and a load giving sinusoidal current through the diode, the average power loss will thus vary with the conduction angle.

The average power loss can be determined from the instantaneous current versus forward voltage-drop characteristic of the rectifier. This can be done graphically for any current waveshape, but a mathematical method is preferable. For the most common case, sinusoidal voltage supply, such a method is presented here.

The temperature influence on the forward voltage drop has been investigated and is considered in the developed equations.

Nomenclature

$\bar{I}_{\phi_1\phi_2}$ = average current over 2π for conduction from ϕ_1 to ϕ_2, amperes (amp)
s = instantaneous current density, amperes/centimeter^2 (amp/cm^2)
$\hat{S}$ = peak current density, amp/cm^2
$\bar{S}_{\phi_1\phi_2}$ = average current density over 2π for conduction from ϕ_1 to ϕ_2, amp/cm^2
e = instantaneous forward voltage drop, volts
$\bar{E}_{\phi_1\phi_2}$ = average forward voltage drop over 2π for conduction from ϕ_1 to ϕ_2, volts
ϕ_1 = angle at start of conduction, radians
ϕ_2 = angle at end of conduction, radians
α = variable angle, radians
f_1 = constant, volts cm^{2g} C/amp^g
$f = f_1/T$ resistance (exponential), volts cm^{2g}/amp^g
g_1, g_2 = exponents
$g = (g_1T - g_2)$, exponent
h_1 = resistance (exponential), volts cm^{2m}/amp^m
β = temperature coefficient, K^{-1}
$h = h_1\ (1+\beta T)$, resistance (exponential), volts cm^{2m}/amp^m
m = exponent
F = area of junction, cm^2
$\bar{P}_{\phi_2\phi_2}$ = average power loss over 2π for conduction from ϕ_1 to ϕ_2, watts
T = junction temperature, degree Kelvin (K)
$\psi_{\phi_1\phi_2}$ = form factor

Forward Voltage Drop

The forward voltage drop as function of current was measured with an oscilloscope in a circuit as shown in Fig. 1. To limit the temperature rise of the junction for current densities up to 3,000 amp/cm^2, a capacitor discharge of approximately 0.5 millisecond duration was used. The temperature rise caused by the current pulse was calculated by a method described by Diebold.[1] Tests were performed on alloyed-junction diodes of several sizes and on diffused-junction diodes of one size.

Variations in the voltage drop for diodes of the same type and size, and at the same temperature, depend mainly on three factors: 1. variation in thickness of the silicon wafer, 2. variation in the junction area, and 3. variations in the ohmic con-

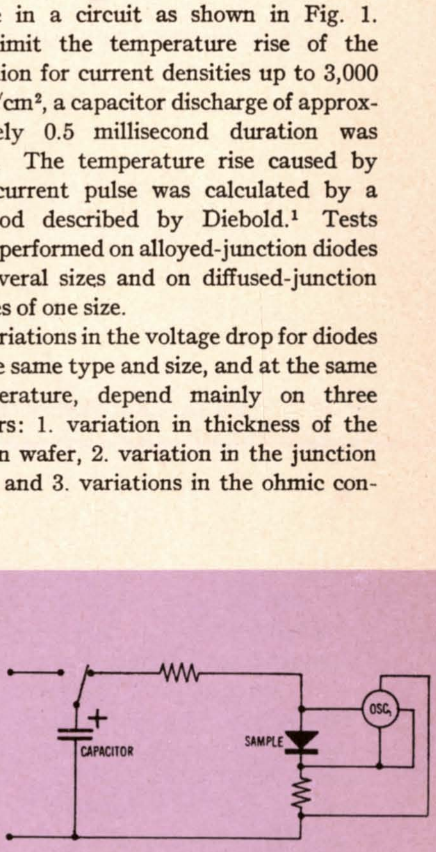

Fig. 1. Circuit for forward voltage drop measurements

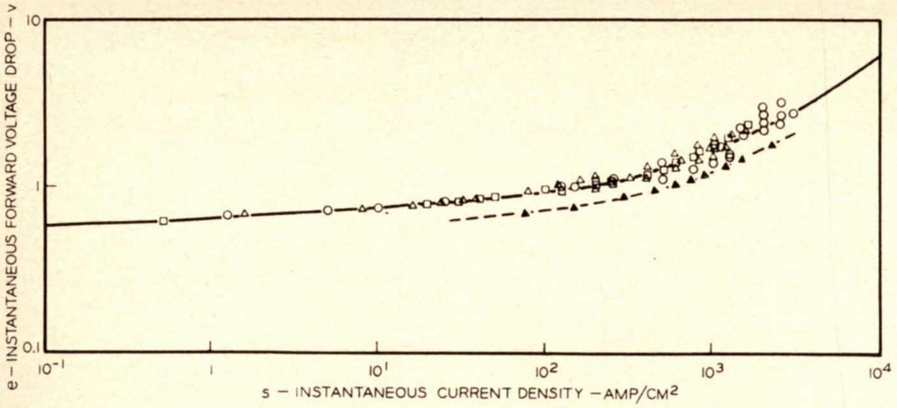

Fig. 2. Instantaneous forward voltage drop versus instantaneous current density for alloyed-junction diodes and for diffused-junction diodes

Symbol	F(cm²)
Alloyed-Junction Diodes	
○	0.396
△	1.263
□	1.98
Diffused-Junction Diodes	
▲	0.067

T = 323 K

tacts within the rectifier. During the manufacture of the diodes the first factor is controlled within 0.002 inch. For diodes of the area-alloyed type, the junction area is determined by the size of the alloying material and the alloying time. The area of the alloying material is held within 3%. The main variations of the forward voltage drop are thus caused by variation in the ohmic contact. The contact may be unsatisfactory between the silicon and the materials to which it is bonded; between this material and the base, or where the terminal lead enters the diode and where it is attached to the junction.

The higher forward voltage drop caused by poor ohmic contact is most easily seen at high current densities. To eliminate such diodes, production tests are made on all diodes with short pulses of high current. The current-voltage characteristic is viewed on an oscilloscope, and diodes having a drop above a certain value are rejected.

Fig. 2 illustrates diode forward characteristics plotted as logarithm of instantaneous forward voltage drop versus logarithm of instantaneous current density in the junction. Both alloyed-junction and diffused-junction diodes are represented. The junction areas for the alloyed diodes, which are all of aluminum-silicon-type alloy, are 0.396, 1.263, and 1.98 cm² and for the diffused diodes 0.067 cm². The junction temperature during the measurements was held constant at approximately 50 degrees centigrade (C).

It is seen that the alloyed-junction diodes follow closely the same characteristic curve for all investigated sizes of junction area. Data from other investigators indicate that the shape of the curve is maintained to about 10^{-2} to 10^{-3} amp/cm² before an inflexion occurs.[2]

The diffused-junction diodes have the same general characteristic, but the voltage drop at each current density is lower as shown by the dashed line in Fig. 2. The spread in test points reflects the variation in forward characteristics attributable to production tolerances and depends, as mentioned, mainly on the differences of ohmic contacts within the diode.

Analytical Expression

Many trials were made to find a simple equation which would closely match the test data for a wide range of current densities. The result is the analytical expression

$$e = f(s)^{g} + h(s)^{m} \qquad (1)$$

This equation has the advantage that the forward voltage drop goes to zero when the current density goes to zero, and does not assume a positive value as in equations containing a constant term or a negative value as in equations including a term in which the logarithm of the current occurs.

Numerical values of equation 1, giving the best matching to the test points, are for the alloyed-junction diodes

$$e = 0.645(s)^{0.561} + 1.45(10^{-3})(s)^{0.8932}$$

and for the diffused-junction diodes

$$e = 0.48(s)^{0.0682} + 8(10^{-4})(s)^{0.918}$$

How close matching has been obtained for current densities between 0.1 and 10,000 amp/cm² can be seen by the solid line in Fig. 2.

The relative magnitude of the two terms varies greatly with current density. At 10 amp/cm² the second term is only about 1% of the first; at approximately 1,500 amp/cm² the two terms assume the same magnitude and at still higher current densities the second term becomes dominant.

The physical meaning of equation 1 is that the diode is equivalent to two nonlinear resistors in series. The degree of nonlinearity is described by the exponents, which theoretically cannot exceed unity. The numerical values suggest that the first term represents the semiconductor junction and the second term the other metallic parts of the diode. For a pure metallic resistor the second exponent should be unity, and in effect a rather good matching can be obtained for exponent $m = 1$ if the other constants in the equation are altered accordingly.

Equation 1 can easily be differentiated and integrated, and lends itself well for analytical work (see the appendix). The additive terms facilitate separation of ef-

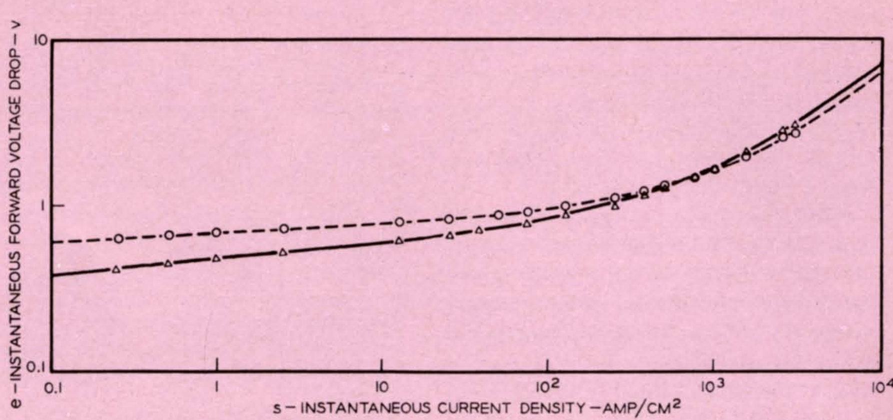

Fig. 3. Temperature influence on instantaneous forward voltage drop for alloyed junction diodes

△ Solid line: $e = 0.49(s)^{0.0931} + 1.64(10^{-3})(s)^{0.8932}$, T = 423 K
○ Dashed line: $e = 0.70(s)^{0.0468} + 1.40(10^{-3})(s)^{0.8932}$, T = 298 K
F = 0.396 cm

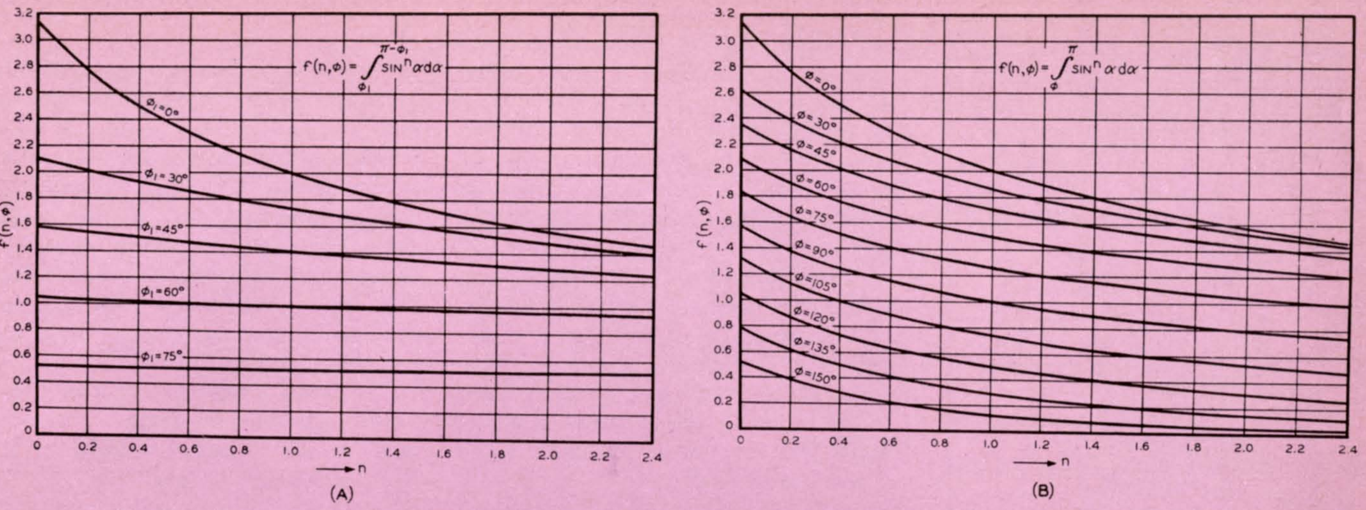

Fig. 4. Average forward voltage-drop integral $\sin^n \alpha d\alpha$

A— $\int_{\phi_1}^{\pi-\phi_1} \sin^n \alpha d\alpha$ B— $\int_{\phi_1}^{\pi} \sin^n \alpha d\alpha$

fects caused by the junction and by other parts of the diode.

Temperature Influence

To study the influence of the junction temperature, tests were made at 25 C and 150 C junction temperature with alloyed diodes having 0.396-cm² junction area. The result is shown in Fig. 3. The test points follow the equations given in the figure. These two equations and the one just given for the alloyed diodes can can be expressed in the general form

$$e=(f_1/T)(s^{g_1T}/s^{g_2})+h_1(1+\beta T)s^m \qquad (2)$$

Numerical values of the constants and exponents for the alloyed diodes are: $f_1=208$, $g_1=3.70\times10^{-4}$, $g_2=6.35\times10^{-2}$, $h_1=8.3\times10^{-4}$, $\beta=2.31\times10^{-3}$, $m=0.8932$

Further test data seems to indicate that the temperature limits of validity for equation 2 are 25 C and 150 C, but that still rather good approximation can be obtained over the temperature range −50 C to 200 C by using a slightly lower value of f_1 than previously given.

As the second term in equation 2 is much smaller than the first term at a current density of 1 amp/cm², the forward voltage drop at this current density is nearly inversely proportional to the absolute temperature. This relationship holds approximately true between 0.1 and 10 amp/cm² within the temperature limits given. The influence of the temperature in the exponent of the first term is rather small, even at high current densities. Increasing the temperature from 25 to 150 C increases the factor s^{g_1T} about 10 amp/cm² and 40% at 1,000 amp/cm².

The second term includes a positive temperature coefficient as for a metallic resistor. The magnitude of the coefficient is, however, lower than for the metals composing the diode.

The result of the addition of both terms is that within a certain range of current density the forward voltage drop is nearly independent of temperature, and that there is a cross-over point as seen in Fig. 3.

Average Forward Voltage Drop

It is often desirable to determine the average forward voltage drop at a given junction temperature and for a specified conduction angle and average current. For sinusoidal current flow the average forward voltage drop over a full cycle is

$$\bar{E}_{\phi_1\phi_2}=\frac{1}{2\pi}\left[f(\hat{S})^g\int_{\phi_1}^{\phi_2}\sin^g \alpha d\alpha + h(\hat{S})^m\int_{\phi_1}^{\phi_2}\sin^n \alpha d\alpha\right] \qquad (3)$$

The integral $\int_{\phi_1}^{\phi_2} \sin^n \alpha d\alpha$ has been determined for the two most usual cases; $\phi_2=\pi-\phi_1$, and $\phi_2=\pi$, and is represented in Figs. 4(A) and 4(B), for values of n from 0–2.4. The average forward voltage drop for various conduction angles corresponding to the instantaneous forward characteristic of the alloyed diodes from Fig. 1, but for 140 C junction temperature, is shown in Fig. 5. The junction temperature of 140 C was chosen, because it is a representative value for usual industrial applications

Forward Power Losses

The forward power loss at a constant junction temperaure is

$$\bar{P}_{\phi_1\phi_2}=\frac{F}{2\pi}\left[f(\hat{S})^{g+1}\int_{\phi_1}^{\phi_2}\sin^{g+1} \alpha d\alpha + h(\hat{S})^{m+1}\int_{\phi_2}^{\phi_2}\sin^{m+1} \alpha d\alpha\right] \qquad (4)$$

In Fig. 6 the forward power loss is

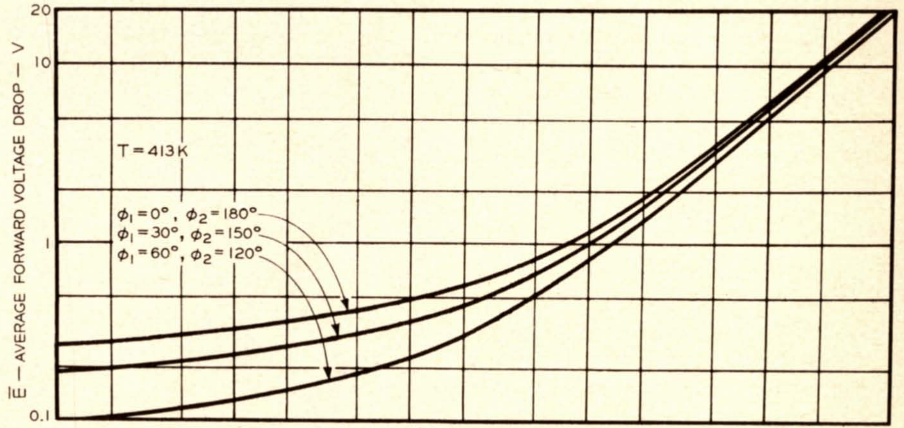

Fig. 5. Average forward voltage drop versus average current density for several conduction angles

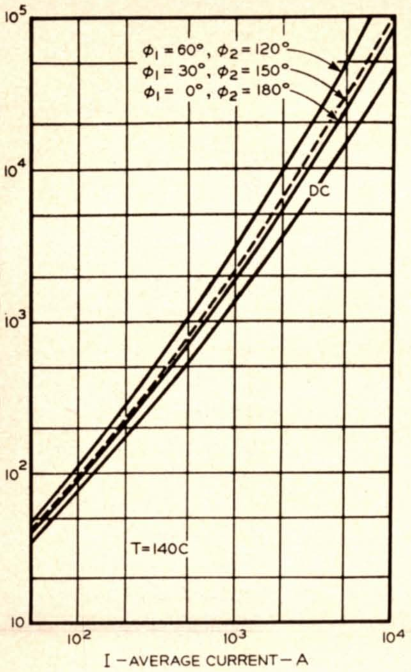

Fig. 6. Forward power loss versus average current at several conduction angles for a alloyed diode with 1.98-cm² junction area

shown for a diode having 1.98-cm² junction area and a junction temperature 140 . At a given average current the power loss for 120 degrees (deg) conduction (from 30–150 deg, is only approximately 10% higher than for 180-deg conduction, whereas for 60-deg conduction (from 60–120 deg) corresponding percentage is 30%. It should be observed that the power loss for a small conduction angle $\phi_2 - \phi_1$ varies considerably with ϕ_1. It makes a great difference if the conduction is from ϕ_1 to $\pi - \phi_1$, or from ϕ_1 to π, the losses in the latter case for the same average current density being much higher.

Frequently, the average forward voltage drop as function of average current has been determined for a diode by direct measurements, and it is desired to establish the power losses from these data. This can be done by introducing the form factor ψ from equation 13 (see the appendix). The average power loss for any conduction angle can then be expressed by

$$\bar{P}_{\phi_1\phi_2} = (\bar{E}\bar{I}\psi)_{\phi_1\phi_2} \tag{5}$$

The form factor ψ is a weak function of current density and temperature, but varies strongly with the angles ϕ_1 and ϕ_2. Once the form factor has been determined for one type of diode, e.g., alloyed-junction diodes, it can be used for calculating the power losses in such diodes, even if the characteristics of the same vary considerably from sample to sample. For the alloyed-junction diodes investigated, ψ has been calculated at two temperatures, and for the three most common conduction angles. The result is shown in Fig. 7. For 3-phase and 6-phase operation ψ is nearly constant for current densities from 1 to 10^4 amp/cm², whereas for single-phase operation there is an increase in ψ of about 10% between 50 and 10^4 amp/cm².

The form factor ψ for the diffused-junction diodes, with the forward characteristic shown in Fig. 2, has also been calculated. The average discrepancy between these values and the one shown in Fig. 7 for the alloyed-junction diodes is less than 1%, and the maximum deviation is less than 3%.

Pulse Load

For continuous operation an average current density of 130 amp/cm² (corresponding to a peak density of about 400 amp/cm²) is rarely exceeded in large area devices. However, under surge current conditions of short duration, a diode may be subject to current densities of the order of 10^4 amp/cm². To determine the momentary temperature rise of the junction under such conditions, it is necessary to know the power loss. Test data of the average forward voltage drop are not often available for such high-current densities. The equations previously given allow calculation of the power loss at any current density of interest. In order to give a clear picture of the behavior of the characteristics at high-current densities, all curves are shown for current densities up to 10^4 amp/cm².

Conclusions

For silicon diodes manufactured by the same process, but of different junction area, the forward voltage drop at equal current densities and junction temperature is very closely the same. The instantaneous forward voltage drop can be expressed as a power function of current density and the average forward voltage drop for any conduction angle and over a certain temperature range can be calculated.

The power losses can either be determined from the instantaneous characteristics or from measured values of the average forward voltage drop and the current. In the latter case a form factor must be introduced, which varies only slightly with the forward characteristics and the junction temperature.

Appendix

Assume

$$s = \hat{S} \sin \alpha \tag{6}$$

$$e = f(s)^g + h(s)^m \tag{1}$$

Then by definition and equation 5

$$\bar{S}_{\phi_1\phi_2} = \frac{1}{2\pi} \int_{\phi_1}^{\phi_2} s\,d\alpha = \hat{S}\,(\cos \phi_1 - \cos \phi_2)/2\pi \tag{7}$$

By definition

$$\bar{E}_{\phi_1\phi_2} = \frac{1}{2\pi} \int_{\phi_1}^{\phi_2} e\,d\alpha \tag{8}$$

Substituting equations 6 and 7 in equation 8 gives

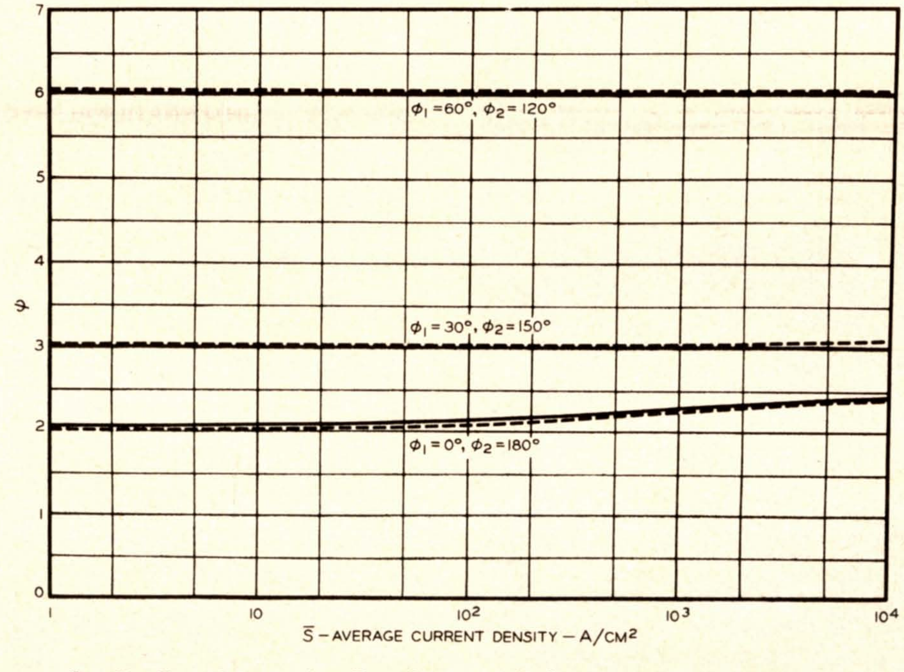

Fig. 7. Form factor ψ for alloyed-junction diodes at two junction temperatures

$$\bar{E}_{\phi_1\phi_2}=\frac{1}{2\pi}\left[f\left(\frac{2\pi\,\bar{S}_{\phi_1\phi_2}}{\cos\phi_1-\cos\phi_2}\right)^{g}\times\int_{\phi_1}^{\phi_2}\sin^{g}\alpha d\alpha+h\left(\frac{2\pi\,\bar{S}_{\phi_1\phi_2}}{\cos\phi_1-\cos\phi_2}\right)^{m}\int_{\phi_2}^{\phi_1}\sin^{m}\alpha d\alpha\right] \quad (9)$$

By definition

$$\bar{P}_{\phi_1\phi_2}=\frac{F}{2\pi}\int_{\phi_1}^{\phi_2} esd\alpha \quad (10)$$

Substituting equations 5, 6, and 7 in equation 10 yields

$$\bar{P}_{\phi_1\phi_2}=\frac{F}{2\pi}\left[f\left(\frac{2\pi\bar{S}_{\phi_1\phi_2}}{\cos\phi_1-\cos\phi_2}\right)^{g+1}\times\int_{\phi_2}^{\phi_1}\sin^{g+1}\alpha d\alpha+h\left(\frac{2\pi\,\bar{S}_{\phi_1\phi_2}}{\cos\phi_1-\cos\phi_2}\right)^{m+1}\int_{\phi_2}^{\phi_1}\sin^{m+1}\alpha d\alpha\right] \quad (11)$$

Rearranging equation 11 gives

$$\bar{P}_{\phi_1\phi_2}=(\bar{E}\bar{S}\psi)_{\phi_1\phi_2}/F \quad (12)$$

Where

$$\psi_{\phi_1\phi_2}=\frac{2\pi}{\cos\phi_1-\cos\phi_2}\times\frac{\int_{\phi_1}^{\phi_2}\sin^{g+1}\alpha d\alpha+\frac{h}{f}(\hat{S})^{m-g}\int_{\phi_1}^{\phi_2}\sin^{m+1}\alpha d\alpha}{\int_{\phi_1}^{\phi_2}\sin^{g}\alpha d\alpha+\frac{h}{f}(\hat{S})^{m-g}\int_{\phi_1}^{\phi_2}\sin^{m}\alpha d\alpha} \quad (13)$$

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1. TEMPERATURE RISE OF SOLID JUNCTIONS UNDER PULSE LOAD, E. J. Diebold. *AIEE Transactions*, pt. I (*Communication and Electronics*), vol. 76, Nov. 1957, pp. 593–98.

2. PROPERTIES OF SILICON POWER RECTIFIERS, E. F. Losco. *Ibid.*, vol. 74, Mar. 1955, pp. 106–11.

REPRINTS OF THIS ARTICLE,

which originally appeared in the AIEE Transactions, Vol. 79, Part 2 (Applications and Industries), July, 1960, are available upon request.

Other technical articles available are:

"Thermal Impedance of Cooling Fins" by Edward J. Diebold and Werner Luft,

"Voltage Distribution of Series Connected Semiconductor Devices" by Edward J. Diebold.

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INTERNATIONAL RECTIFIER MIL-APPROVED ZENER TYPES

SIGNAL CORPS TYPE*	NOM. ZENER VOLTAGE, VOLTS	DISSIPATION WATTS	MIL SPEC.
USA1N1777	18	1	MIL-E-1/1235(SigC)
USA1N1781	27	1	MIL-E-1/1235(SigC)
USA1N1804	6.2	10	MIL-E-1/1236(SigC)
USA1N1807	8.2	10	MIL-E-1/1236(SigC)
USA1N1353	12	10	MIL-E-1/1236(SigC)
USA1N1358	22	10	MIL-E-1/1236(SigC)
USA1N1361	27	10	MIL-E-1/1236(SigC)

*These zener diodes should not be confused with like-numbered JEDEC devices currently available. The above series conforms to the Signal Corps specifications. They are electrical equivalents to JEDEC devices with like numbers, but are opposite in polarity.

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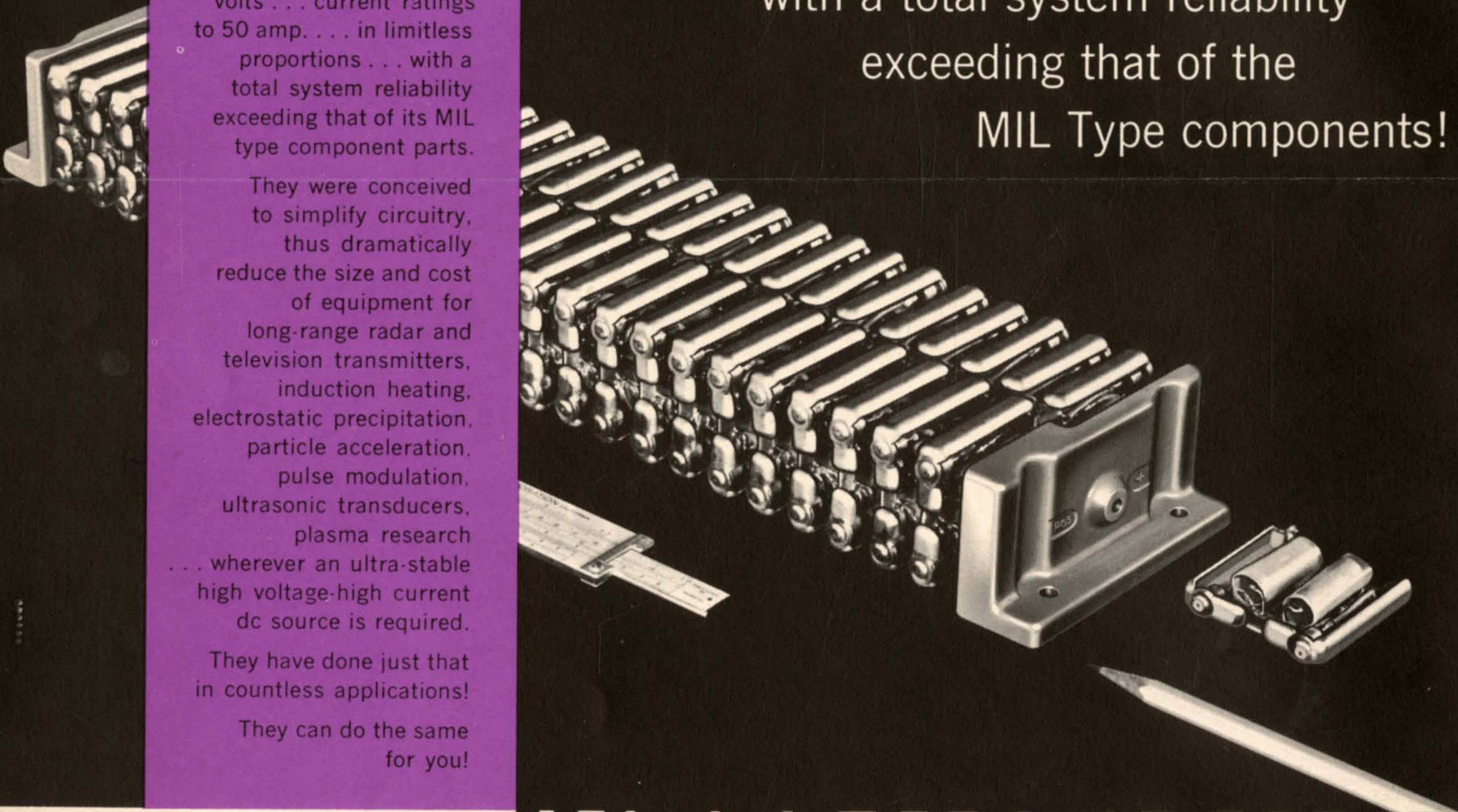
They have done just that in countless applications!

They can do the same for you!



WRITE FOR 16-PAGE BULLETIN SR-370 describing these new high voltage, high current devices in technical detail . . . Truly the most advanced design of its type available to industry!

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