WINTER 1959

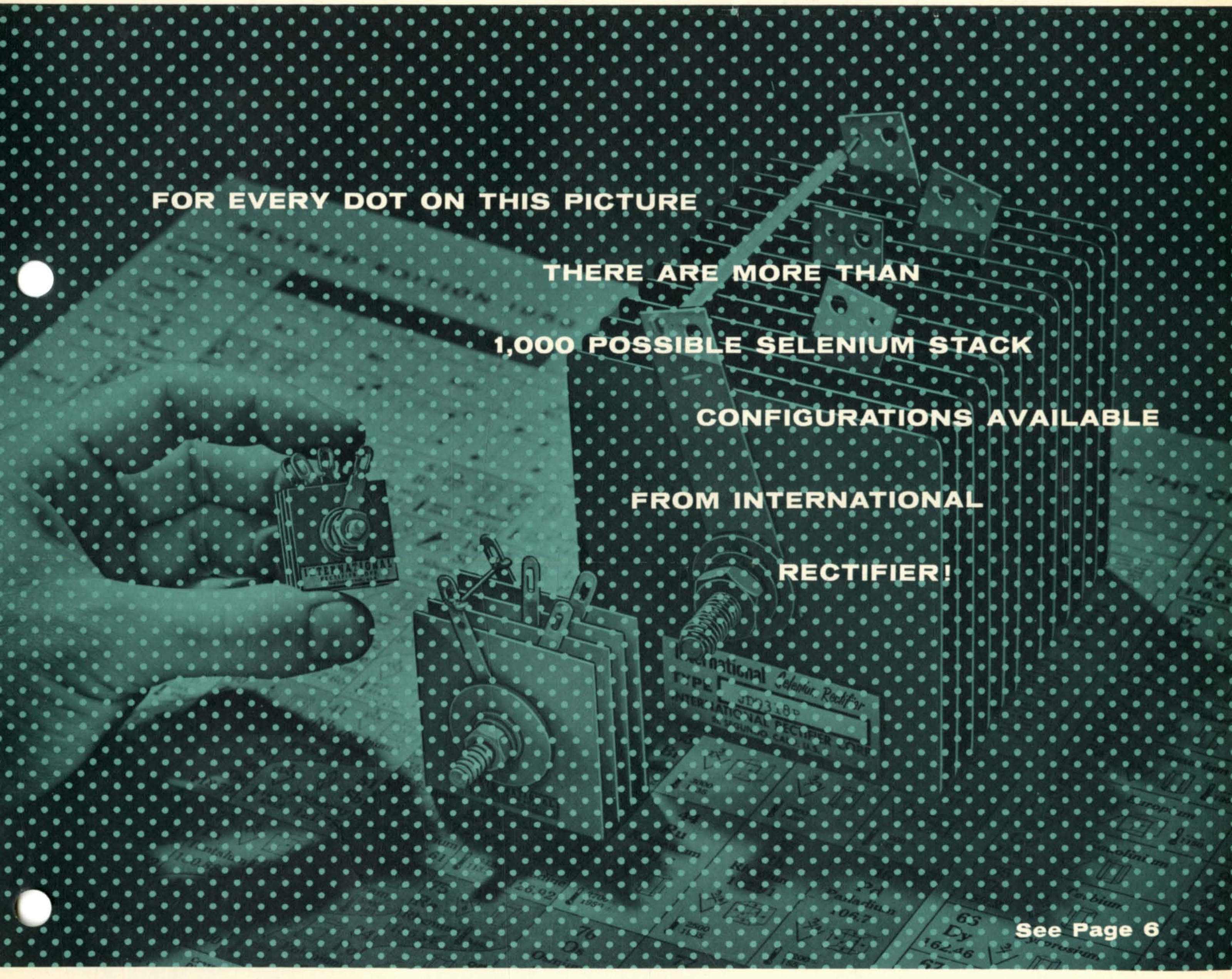
INTERNATIONAL RECTIFIER CORPORATION

A WORLD OF DIFFERENCE THROUGH RESEARCH

SYMBOL OF QUALITY IN SEMICONDUCTORS

RECTIFIER NEWS

PUBLISHED QUARTERLY BY THE INTERNATIONAL RECTIFIER CORPORATION • EL SEGUNDO, CALIFORNIA



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IN FULL PRODUCTION

10 AND 16 AMPERE TYPES

ACTUAL SIZE

The International Rectifier "Thyrode" Silicon Controlled Rectifier is a three-junction, hermetically sealed semi-conductor device that will block positive anode to cathode voltage as does a thyratron. When a signal is applied to its third (gate) lead, the device rapidly switches to a conducting state and provides the low forward voltage drop of a typical medium power silicon rectifier. Current flow may then be halted, by reversal or removal of the anode voltage. This simplicity of control makes the "Thyrode" applicable to a wide range of control and switching uses.

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Int'l Type Number	Max. Rep. PIV, Volts	RMS Input (Sin.) Volts	Average Forward Current Amps	Surge Current (1 Cycle) Amps	Min. Forward Breakover Voltage, Volts	Max. Forward & Reverse Leakage, Ma		Gate Power, Watts		Gate Current Ma,		Forward Gate Voltage, Volts		Max. Forward Volt. Drop, 1 Cycle Volts
						Peak	Average	Peak	Average	Peak	Max. to fire	Peak	Max. to fire	
10 Ampere Rated Series, Operating Temperature Range: —30°C to +85°C														
X10RC2	20	14	10	125	20	45	22	5	0.5	2000	85	10	5	1.25
X10RC3	30	21	10	125	30	40	20	5	0.5	2000	85	10	5	1.25
X10RC5	50	35	10	125	50	35	18	5	0.5	2000	85	10	5	1.25
X10RC7	70	50	10	125	70	30	15	5	0.5	2000	85	10	5	1.25
X10RC10	100	70	10	125	100	25	12.5	5	0.5	2000	85	10	5	1.25
X10RC15	150	105	10	125	150	13	6	5	0.5	2000	85	10	5	1.25
X10RC20	200	140	10	125	200	12	6	5	0.5	2000	85	10	5	1.25
16 Ampere Rated Series, Operating Temperature Range: —30°C to +105°C														
X16RC2	20	14	16	125	20	45	6.5	5	0.5	2000	50	10	3	.90
X16RC3	30	21	16	125	30	40	6.5	5	0.5	2000	50	10	3	.90
X16RC5	50	35	16	125	50	35	6.5	5	0.5	2000	50	10	3	.90
X16RC7	70	50	16	125	70	30	6.5	5	0.5	2000	50	10	3	.90
X16RC10	100	70	16	125	100	25	6.5	5	0.5	2000	50	10	3	.90
X16RC15	150	105	16	125	150	13	6	5	0.5	2000	50	10	3	.90
X16RC20	200	140	16	125	200	12	6	5	0.5	2000	50	10	3	.90

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PART ONE

OF A TWO PART ARTICLE CONCERNING A FUNDAMENTAL CIRCUIT PROBLEM

VOLTAGE DIVISION OF SERIES - CONNECTED SEMICONDUCTOR DEVICES

NEXT ISSUE — PART TWO "PROPERTIES OF RECTIFIER SYSTEMS AND MEANS TO IMPROVE VOLTAGE DIVISION"

Properties of Semiconductor Devices Affecting Voltage Division

BY EDWARD J. DIEBOLD, *Engineering Consultant, International Rectifier Corporation*

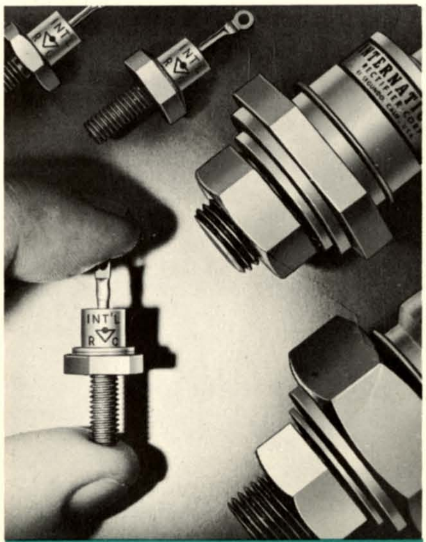
Synopsis

Flexibility in the application of semiconductor devices permits series and parallel connection in almost unlimited numbers. Their properties and the requirements of the equipment either limit the application or require special measures. Device characteristics affecting voltage distributation and different methods to achieve equality are discussed, analyzed and recommendations are made for the solution of specific problems.

* * *

Introduction

Semiconductor devices, compared to older switching devices, stand out by their small size, low power losses, immediate start-up, facility of mounting and low price. Their main advantage is the absence of a filament power supply, particularly whenever series connection is required. For high power applications it is customary to connect them either in parallel, series, or series-parallel. Facility and flexibility of multiple designs led to some misapplications by lack of understanding of the rules which are given by physical properties of both devices and systems.



International Rectifier manufactures a complete line of silicon power rectifiers rated from 6 amperes to 250 amperes per junction.

Correctly applied, the series connection of semiconductor devices is perfectly safe. Under this condition a number of semiconductor devices connected in series perform better than the individual devices, each of them operating at the same voltage. This is similar to the performance of gas discharge devices which have a lower probability of failure when operating in series. The method of application must, however, achieve this increased reliability by eliminating the causes of failure which are specific to series connection.

Any number of devices connected in series, as a so-called string, behaves as a single circuit element with a higher forward voltage drop and a higher peak inverse voltage capacity than the individual device. In the forward direction the string is subjected to a current causing in each device a stable forward voltage drop which is approximately equal for all of them. Thus in the forward direction the series connection leaves no uncertainty and the performance of a series string is just as good as for a single device. If one of the devices in a string fails by breakdown of the reverse characteristic, the forward performance is not affected. The only individual forward failure which affects the entire string is opening of the electric connection, which happens very rarely.

When an inverse voltage is applied to a string of series connected devices the behavior is quite unpredictable. Individual voltages are hard to measure correctly; they change their relative values with time, are disturbed by the observation and affected by temperature and air humidity. If the voltage increases to a value commensurate with the sum of the rated voltages of the devices in the string, the individual voltage will be excessive for some of them and very low for others. Overstressed devices may fail in the reverse direction and suddenly lose the reverse voltage, subjecting other devices to excessive voltages, causing more failures and thus, by a chain breakdown, destroy the entire string. This does not necessarily occur immediately, but represents an added risk which is far beyond the normal failure probability of the individual devices. Thus it is the main obstacle to be overcome if the application of semiconductor devices in series should be successful.

Reverse Characteristics of Semiconductor Devices

The behavior of semiconductor devices in a series string under voltage depends only on their reverse characteristics.

Devices of the monocrystalline type are characterized by almost ideal rectifier properties. In the forward direction the voltage drop is very small compared to the permissible reverse voltage. In the reverse direction the current is negligibly small; e.g., less than 1/10,000 of the forward current. The small reverse current is an advantage for heat dissipation, efficiency, and for control functions such as magnetic amplifiers. For reverse voltage division this current is too small and too poorly voltage dependent to be sufficient. This is also the cause for the undefined behavior due to other small leakage currents and for the unreliable measurement of the voltage distribution which is disturbed by the small current flowing through a measuring device.

Besides the low magnitude of the reverse current the curvature of the so-called reverse characteristic is of importance. Plotting the reverse current (vertical) versus the reverse voltage (horizontal) we obtain a curve similar to (a) on Figure 1. This shape is determined by many factors which are not necessarily equal for all the devices produced by one manufacturer. Generally the device is assumed to be satisfactory if the reverse current vs voltage curve is stable and the reverse current at the rated reverse voltage, within a specified temperature range, is below a specified maximum. Hence there is no limitation as to shape, which may show an infinite variety within the boundaries set by the specifications.

Figure 1 shows four reverse characteristics which are within the rated voltage (vertical dotted line) and the maximum permissible reverse current (horizontal dotted line). The four individual characteristics are designated (a), (b), (c) and (d). It is apparent that individual (b) is very different from the others because it represents a very definite avalanche breakdown behavior (similar to a so-called zener diode). Individual (a) has a relatively large reverse current below and a rapidly increasing current above the rated voltage. Even this "large" current is less than 1/10,000 of the forward current. Individual (c) has a so-called "soft knee" characteristic, with a very high voltage required to attain avalanche breakdown. Individual (d) has an extremely low reverse current at any voltage within the test range.

If the four devices shown in Fig. 1 are connected in series and subjected to a voltage which is approximately the sum of the rated voltages of the individuals, the series string carries a reverse current which is indicated by the dot-dash line. Devices (a), (b), (c) and (d) will be subjected to the voltages A, B, C and D respectively. This voltage distribution is very unequal and indicates how a small deviation of inverse characteristics may upset the voltage distribution. Thus device (d) is in danger of breaking down, whereas device (a) is perfectly safe. If device (d) breaks down, the reverse current of the string increases to the maximum reverse current (dotted line). Now device (c) will be subjected to a very high reverse voltage, whereas devices (a) and (b) will be subjected to a voltage which is only slightly above rated. If device (c) fails, the string fails completely, because devices (a) and (b) together should hold four times rated voltage which is far beyond their capacity, as shown by the characteristics. Thus we would witness a subsequent failure of device (d), device (c) and simultaneously device (a) and (b), although individually they are able to handle more than rated voltage.

As another example, consider the devices (b), (c) and (d) of Fig. 1. Subjecting them to a voltage corresponding to B, the reverse currents B, Bc, and Bd are only slightly different as compared to the maximum permissible reverse current (horizontal dotted line). Thus we may conclude that these reverse currents have been "matched" and that we may connect the three devices in series. Applying a high voltage to the new string will again cause a reverse current equivalent to the dot-dash line, and individual voltages given by B, C and D, which are much more unbalanced than the differences in reverse current seemed to indicate. The above example shows also that matching penalizes the best diode in the string whenever a transient overvoltage occurs. Thus diode (d) would have to absorb the major part of a transient overvoltage, whereas diode (b) would always be limited to a much smaller voltage.

Matching reverse currents at a fixed voltage is also deceptive because operating voltages are not fixed. Normal a-c crest voltages are usually far below the permissible peak inverse voltage. Transient over-voltages may assume any value, from normal crest voltage (continuously) to rated peak inverse voltage (rarely) and far beyond (exceptionally for extremely short transients). Obviously, due to the different shapes of the characteristics, matching at any one point cannot account for all the other conditions.

Another important property of semiconductor devices is the variation of the reverse characteristics with temperature. For germanium devices, the reverse current (saturation current) increases and the voltage of avalanche breakdown decreases with increasing temperature. In

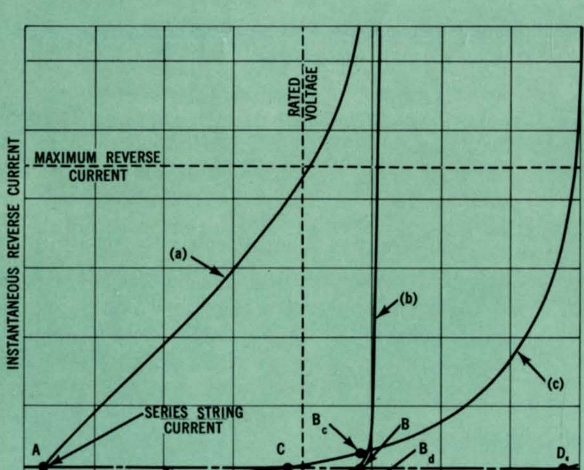
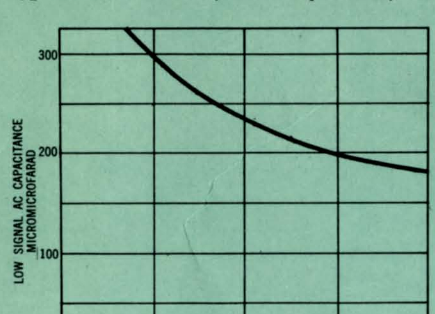


Figure 1. Reverse characteristics of four high voltage diodes meeting the same specifications.

Figure 2. Low-signal capacitance vs dc bias voltage of an alloyed junction device with ½" active diameter (room temperature).



silicon devices the reverse current decreases and the voltage of avalanche breakdown increases with increasing temperature. Thus, if correct voltage distribution is achieved at a certain temperature, this may not be the case at another temperature, if some devices operate in the region of linear reverse current and others are on the verge of avalanche breakdown. This behavior depends also on the type of device: it is different between alloyed and diffused junctions.

For devices which are manufactured and selected for equal temperature coefficients, equal shape of reverse characteristics, and equal reverse currents at the rated voltage, connection in series is no problem. However, manufacture of semiconductor devices with the specific purpose of equal voltage division in series connection does not seem practical at the present time. Many other characteristics, such as low forward drop at rated current, good performance under pulse load, high static and transient breakdown voltage, stability (electric, mechanical fatigue, thermal) and long service life, are of much greater importance and cannot be sacrificed for a special purpose. The simple means for successful series connection described in Part II of this paper allow the use of standard high quality devices.

Reverse Voltage Breakdown

Destruction of semiconductor devices in operation can almost always be traced to breakdown due to reverse voltage. This may have many other causes, such as excessive voltages applied to the system, poor voltage distribution and deterioration of the reverse characteristic of a device subjected to mechanical or thermal abuse. Breakdown or destruction of a device due to excessive reverse voltage should not be confused with avalanche breakdown (or zener breakdown), the latter being reversible and causing no destruction, unless the device is subjected to excessive heat produced by a high reverse current. The expectation that all semiconductor devices behave like "Zener" diodes is an error which has caused many severe misapplications.

Several mechanisms contribute to failure under high voltages, the most common being the dielectric perforation of the junction. This may occur because of excessive average dielectric gradients between very close layers, or because of localized high gradients due to slight crystal or junction defects. In Fig. 1, device (d) will probably be destroyed by dielectric perforation before its avalanche breakdown voltage is attained.

Germanium devices fail frequently

continued next page

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7 cell voltage ratings—including 22 and 26 volt standard cells, 22, 33 and 36 volt high density cells, and 40 and 45 volt high voltage cells.

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5 standard mounting configurations.

Continued

by thermal runaway, which is caused by insufficient cooling or excessive forward current, combined with excessive reverse voltage. Thermal runaway may also occur in small defects which escape detection in production testing. Such localized thermal runaway, localized surface flash-over, or localized dielectric perforation are eliminated by continuous improvement of manufacturing processes. The user should, however, bear in mind that high voltages applied over extremely short distances (as in semiconductor devices), cause high dielectric gradients which are always associated with sudden failures; particularly when only small imperfections are present, too small to be seen even by close visual inspection, and extremely hard to detect by electrical measurement.

Early devices, manufactured many years ago, had such high reverse currents that their thermal effect was a critical limitation of device performance, and thus the value of reverse current provided an indication of quality. Since then the typical reverse current has been drastically reduced (e.g. more than 100 times). Therefore, contrary to some previously available recommendations, it is of utmost importance that the instantaneous reverse voltage of each individual device be limited. When connected in series the voltage division counts. Equal reverse current per device, or "self-balancing" by reverse current limitation is not feasible with modern devices. Flexible voltage division, however, allowing the voltage to "collapse" whenever the reverse current of any one device rises far above a reasonable value, is desired because it allows continued operation even after one device in a series string has failed.

Dynamic Reverse Characteristics

Besides the static properties of the devices, correct application should also consider their dynamic characteristics.

Capacitance

Semiconductor devices have an inherent junction capacitance which depends on the applied voltage, following a negative exponential curve with equal exponent but different capacity values for individual junctions.

An example of junction capacitance vs voltage curve is shown in Fig. 2, for an alloyed silicon junction with an active diameter of ½ inch. Variations between individual junctions and at different temperatures may be substantial. Other junction sizes show different capacitances; e.g.:

¼" diameter alloyed — 70 to 100 micromicrofarad at 200 v.

.100" square, diffused — 15 to 20 micromicrofarad at 200 v.

.030" diameter alloyed — 1.5 to 2 micromicrofarad at 200 v.

The above values are tested as low excursion a-c voltage and current with a variable d-c bias voltage. At low voltages the junction capacitance is quite high, but this is without importance for the voltage distribution of high voltage devices. For a-c operation it is advisable to use an equivalent capacitance which encompasses all the capacitive effects from zero to full inverse voltage. This can be calculated as follows:

The junction capacitance C as a function of the bias voltage E can be written as

$$C = C_o\left(\frac{E_o}{E}\right)^{\alpha}$$

Wherein C_o and E_o are capacitance and voltage at the maximum voltage encountered during operation, and the constant α designates an exponent given by the measured curve (such as in Fig. 2).

From this equation we compute the charge Q_o stored at the maximum voltage E_o:

$$Q_o = C_oE_o^{\alpha}\int_0^{E_o} E^{-\alpha}\,dE = \frac{C_oE_o}{1-\alpha}$$

The equivalent constant capacitance C_e is the one which holds the same charge at the same voltage:

$$C_e = \frac{C_o}{1-\alpha}$$

Measurements show that α is approximately 0.35, or:

$C_e = 1.54\ C_e$

The equivalent linear capacitance for voltage division should be taken as 154% of the measured "small signal" capacitance at the crest value of the operating voltage.

Reverse Recovery

Another important dynamic characteristic is the reverse recovery time (also known as hole storage effect). Semiconductor junctions derive their switching properties from discontinuities (junctions!) within crystals, wherein the only variables are the distribution of positive or negative charges, introduced in each layer in controlled numbers, as so-called impurities. During forward conduction, the junction zone becomes flooded with movable charges provided by the adjacent layers of different polarity. The abundance of easily movable charges allows for passage of current at a small potential difference.

If the current stops and reverses

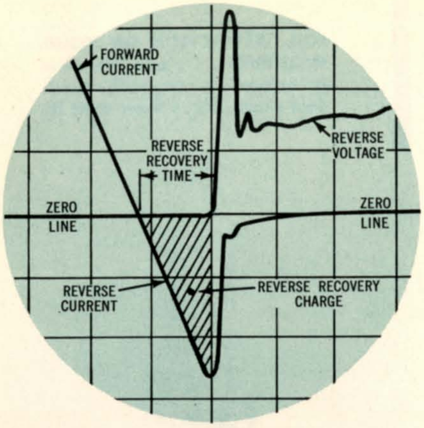

Figure 3. Dual beam oscilloscope traces of reverse recovery voltage and diode current versus time for a ¼″ diameter alloyed junction. Cross-hatched area represents the reverse recovery charge. Reverse recovery time approximately 7 micro-seconds.

within very short time (in the order of microseconds) the former abundance of charges is still present. A substantial reverse current flows until the movable charges of opposite polarity have recombined or have returned to their origin. Only at this time a reverse voltage can appear at the junction. For extremely fast current reversal, a finite and constant quantity of charge (reverse recovery charge) must flow before the reverse voltage can appear. For slow reversals, a lesser charge is required because time is available for recombination.

The reverse recovery charge is not equal for all individual devices and represents a major problem when many devices are connected in series. For example: Considering a string of diodes containing one individual which requires a very small reverse recovery charge; when the entire string is subjected to a reverse voltage, the charge determined by this diode flows freely through the entire string; afterwards, however, the entire recovery voltage of the string appears on this particular diode, while the other diodes are not yet capable of assuming any reverse voltage. In the other diodes the charge carriers are forced to recombine without the benefit of a substantial reverse current, which takes a relatively long time (compared to the time of current reversal but which is still a very short time compared to the duration of the cycle).

The first diode must hold the full voltage of the string until the slow recombination of another diode is terminated. Gradually all the diodes enter their reverse blocking stage and the string operates as expected. This sequence of events is not much affected by the distributed capacitances of the system, the junction capacitance and possibly the substantial reverse current of the first diode which is subjected to a very high voltage. When many diodes are connected in series, this effect can cause instantaneous voltage surges of a destructive magnitude on the first diode which assumes the reverse voltage.

Fig. 3 shows an oscillogram of the current reversal and the rise of the reverse voltage of an alloyed junction. The horizontal distances represent time, with the total width of the figure corresponding to 50 microseconds (1/20,000 of a second). The current curve is shown as coming from the direction of forward current, reversing into the negative and then suddenly returning to the zero line. At the break of the current, the reverse voltage rises from zero to a sharp peak, and then returns to its continuous value. The triangle described by the current reversal and the time during which the current is negative, until it suddenly drops back to zero (while the voltage recovers) is a measure for the quantity of charge, which is expressed in micro-ampere-seconds, or micro-coulombs. It is obvious that a sudden voltage rise, as shown in Fig. 3, requires also a certain amount of charging current for the reverse capacitance of the junction which adds to the apparent reverse current after the voltage has started to rise.

Examples of Reverse Recovery Charges:

¼″ diameter alloyed junction:
0.35 microcoulomb

1/10″ square diffused junction:
0.08 microcoulomb

Measured with a current rate of decay of 13,000 ampere per second.

It is important to note that the behavior of these two types of junctions is different; stable and unchanging between individual alloyed junctions, with few oscillations of the recovery voltage. The diffused junctions show pronounced oscillations ("ringing") and a broad distribution of reverse recovery times.

Conclusion

Semiconductor devices have several distinct properties which affect their performance when connected in series. Correct application must provide for equal voltage distribution under consideration of their static and dynamic characteristics.

Application examples and system properties which influence the series operation are discussed in Part II of this paper.

new developments

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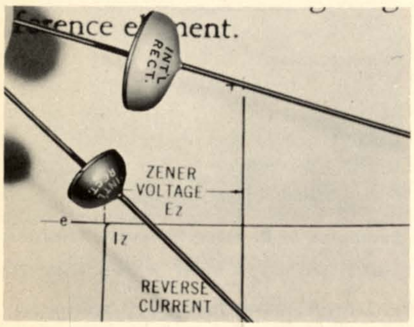
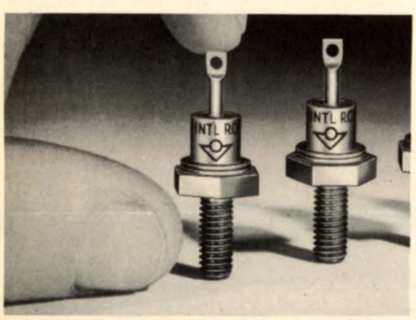


Economy Line Silicon Zener Diodes, 500 MW, 1 Watt Rated and 10 Watt Types

An economy line of "Tri-Sealed" silicon zener diodes substantially lower in cost than standard units is now available from International Rectifier Corporation. Designed specifically for commercial equipment applications, these diodes demonstrate low zener impedance values and very sharp zener "knees." They are available in 500 milliwatt, 1 watt rated and 10 watt series, and standard RETMA 10% voltage steps from 5.6 to 27 volts.

All types embody a new technical advancement in the sealing of zener diode junctions, termed "Tri-Sealed"—a three-layer seal assuring high resistance to humidity, shock, vibration, temperature extremes and other adverse environmental conditions.

For complete data, circle No. 8 on the Information Request Card.



High Temperature 6 and 12 Amp Diffused Junction Silicon Rectifiers Operate to 190°C.

Two new series of 6 and 12 amp rated silicon diffused junction rectifiers, designed specifically to meet rigid military specifications, are capable of operating to base temperatures of 190°C. The new 6 amp series is designated JEDEC Types 1N1341 through 1N1347, and the 12 amp series Types 1N1199 through 1N1205. Both series have peak inverse voltage ranges from 50 to 500 volts.

All units are manufactured by precision-controlled diffusion processes, assuring extremely low forward voltage drop, low leakage, and high uniformity of characteristics over the entire operating temperature range. Each diode is nickel-plated, to provide minimum contact resistance and prevent corrosion. A flattened-pierced end on the top (anode) lead assures fast, easy wiring into production assemblies.

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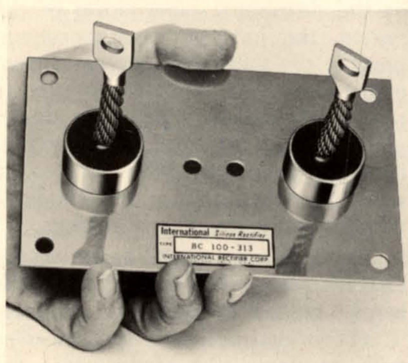

Low Cost 100 Amp Rated Silicon Rectifier For Battery Charging Applications

A low cost, 100 ampere rated silicon rectifier, complete with heat sink, is designed for rapid, easy installation on a wide variety of battery charging applications. The center-tap rectifier features single unit, compact construction, consisting of two silicon junctions mounted on a 4" x 6" nickel-plated copper cooling fin. Mounting holes are spaced to facilitate mounting to practically any battery charger.

All junctions incorporate the exclusive International Rectifier "Quad-Seal" process, including successive layers of humidity resistant, insulating resins and sealants assuring optimum operation over a temperature range from —20 to +130°C.

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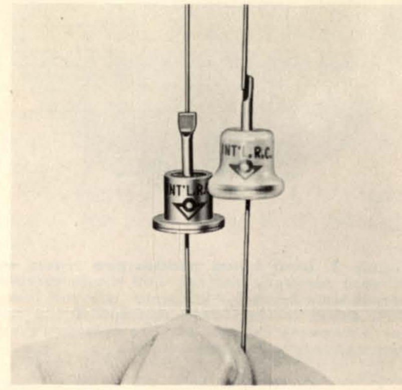

Teflon Jackets Provide Total Diode Case Insulation in "Close-Quarter" Circuitry

For circuitry where bank-mounting or other close-quarter mounting procedures are used, the entire range of International Rectifier Corporation silicon pigtail diodes are now available with an insulating Teflon coating over the diode case. In such applications as printed circuit boards, computers and data-processing equipment, the high temperature, chemical-resistant jacket permits extremely close positioning of diodes, while eliminating the possibility of diode cases shorting to other components or to chassis.

In addition to allowing reduced spacing of components, the transparent insulating jacket will maintain its electrical and mechanical properties from —67° to +250°C. The cost? Ten cents each above diode list price.

TECHNICAL ARTICLES

Information Theory, a Key to the Procurement of Reliable Parts, by R. F. Edwards.
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Electronic Equipment Reliability Competition, or "The Reliability Game," by R. F. Edwards.
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