EVALUATION OF AN EXPERIMENTAL REGULATOR (ZENER) DIODE

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SYNOPSIS:

Regulator diodes, recently developed at Hughes R & D, have been received at Customer Service for evaluation. This work is in progress and interim results are contained in this progress report. The mechanism and philosophy of the new device is explained and recommendations indicated.

INTRODUCTION:

Before discussing the characteristics of regulator diodes, it may be helpful to consider the terminology employed (see the author's I.D.C. to C. D. Schumacher dated September 9, 1958). As in other rectifying diodes, there are two directions of current flow—forward and reverse. Contrary to the common diode, the forward and reverse direction cannot be discerned from the magnitude of the currents in one or the other direction, because the regulator current which flows in the opposite direction from the forward current is also of high magnitude. We define, therefore, within a P-N junction, the current flowing from the P-material (anode) to the N-material (cathode) as the forward current and the current flowing in the opposite direction as the reverse, inverse-and breakdown-or regulator current.

The sudden breakdown effect in silicon P-N junction has been observed in a very early stage of silicon diode development. Pearson and Sawyer[1] describe their observations made in this respect and McKay has discussed a possible explanation of the breakdown[2].

The breakdown or regulator voltage is proportional to both temperature and current, and these variations constitute a source of systematic deviations in the reference potential. The amount of such error contributed by the internal resistance (herein called dynamic impedance or resistance) can be called "slope error" and the amount contributed by temperature variations is considered the "temperature coefficient" of the device.

It is desirable, in general, to minimize these internal errors in reference devices. However, there are circumstances where a known internal error may be used to compensate for a known error, external to the reference device.

It is possible, in principal, to manufacture regulator diodes with a regulator voltage up to several thousand volts. However, it is not practical to do so. Therefore, we are only concerned with a limited voltage range, probably from 2 to 30 volts. Any value beyond this can be made by a combination of several diodes.

It seems to be appropriate here to mention some important factors which have to be considered when evaluating the design or the quality of a regulator diode.

Probably the most interesting dependent variable to be controlled in designing a regulator diode is the breakdown voltage. Since this voltage is the voltage just sufficient to bring the maximum electric field within the junction region to a critical value and to cause the avalanche, one would think that the resistivities of the material on each side of the junction is all that affects the outcome. Unfortunately, it is not so. Some other factors are also affecting E_Z, and to control these is not too simple.

Another important characteristic to control is the reverse current. Being directly related to the number of traps in the space-charge region, the factors leading to "softness" of the reverse characteristic may also cause some increase in the reverse current.

The geometry of the junction has definitely an important bearing on some properties of the diode.

The area of the junction itself is important in that all of the currents through the junction, forward, reverse and regulator, will vary in proportion to this area.

The capacity of the junction, which must be at a minimum when the diode is supposed to operate in high frequency circuit configurations, will also vary in proportion to the junction area, and applied potential.

A series resistance is existent due to the bulk silicon resistivity. This value may become appreciable compared to the forward and dynamic resistance of the junction, especially when the resistivity of the material is high. A means to control this characteristic is: The areas of the ohmic contacts, the distance of these contacts from the junction and, naturally, the resistivity of the bulk of the junction materials, the silicon.

As it is shown, the manufacture of a regulator device is just complicated enough to justify utmost care and understanding of the problems involved. The fact that an excellent device has been constructed in the laboratory area does not imply units coming off mass production lines have to be so excellent in all cases without any particular effort. Since we cannot inspect and test quality into a product, we have to build it in.

CONCLUSIONS AND RECOMMENDATIONS:

1.1 The tests, so far as they have been conducted, indicate that the regulator diode developed in R & D is an excellent device and, to a great extent, competitive with similar devices on the market.

1.2 Relating the test results to each other, we can conclude that the important properties of the device can be controlled to a considerable extent, i.e. it is possible to fabricate regulator diodes for a predetermined regulator voltage with an appreciable yield.

1.3 Systematic changes in the regulator voltage are probably closely related to the physical aspects of the device, the regulator current and the environmental temperature.

1.4 The lack of time, personnel and facilities did not permit the determination of time-dependent variations. For the same reasons, any realistic and reasonable prediction of the life expectancy of the device is difficult.

1.5 From competitors' publications, we discern, however, that the regulator diode is not likely to exhibit any random, or time dependent variations in reverse, regulator or forward current or voltage, when operated within its thermal ratings.

1.6 Through the judicious use of several diodes connected in series, some forward and some reverse, it is possible to "tailor-make" voltage standards having close to a zero temperature coefficient, a net positive, or a negative temperature coefficient.

1.7 The electrical characteristics are:

Regulator voltages range from 3.0 to 50.0 volts.

The spread in voltage among one lot is ±10% or better

The maximal regulator current is 40.0 mA

The maximal dissipation has been estimated at 250 mW

The temperature coefficient varies with regulator voltage and is from -0.03 to +1.03%/°C.

The dynamic resistance is 1.8 to 220 ohm

The temperature range (tested) is -55°C to +150°C

The capacitance ranges from 8 μμf at E_Z to a value beyond 300 uuf at zero bias

2.1 The future of this device depends greatly on its cost and the demand of the market.

The market's capacity, at the present about ten million units per year, is far from being saturated and good commercial results should be expected from a new product in this line.

2.2 The cost is closely related to the way a device is manufactured, classified and tested. The concepts presently governing the manufacture, classification and testing of the SA1, which is a similar device, will not help to make the story of the regulator diode a successful one.

2.3 In order to obtain the maximum yields, at least in respect to regulator voltages, the nominal regulator voltages should be such that the ± 10% tolerances (spread in regulator voltage inevitable in any production) of the nominal values at a specified current overlap. This would also be in concurrence with the EIA standards.

2.4 An extension of this line of devices toward a higher dissipation rating (4 - 500 mW; 1 Watt and 10 Watts), for example, is desirable because of similar devices on the market as a consequence of great demand.

2.5 This extension in ratings can be attempted by providing larger heat paths from both materials of the junction to the outside of the package. This concept is even more valid when a heat sink can be directly connected to the terminal.

2.6 The fabrication of regulator diodes in a large scale should be considered only after more extensive tests and statistical analysis of the units is obtained by experimental production with production-facilities and production people. Units produced in the laboratory and by laboratory people are not indicative of the quality obtainable in mass-production.

DIODES RECEIVED FOR EVALUATION

The regulator voltages and dynamic resistances noted here have been indicated by the R & D department.

Quantity	Lot #	Reg. Voltage	Dyn. Res.	Test Sample #
29	619	6.8	4	1-10
27	620	4.4	64	11-20
20	627	10.5	4	21-30
175	629A	6.5 - 7.1		31-40
257	629B	7.1 - 7.8		41-50
143	630A	6.5 - 7.1		51-60
167	630B	7.1 - 7.8		61-70
171	631A	6.5 - 7.1		71-80
179	631B	7.1 - 7.8		81-90
15	657	42.0		91-100
21	658	30.0		101-110
22	661	5.4	55	111-120
20	680	4.0		121-130

TABLE 1

PHYSICAL CHARACTERISTICS

CONSTRUCTION AND PACKAGE:

The regulator diode is a silicon junction diode identical to the SA1. The envelope is the hermetically sealed glass package also used for all other "Hughes" Signal Diodes.

The dimensions are 0.265" maximum length and 0.130" maximum diameter. The leads are dumet .020" thick and 1 1/8" long.

The die is N-type silicon .037" x .037" and about .012" thick. The material resistivity is from .01 to .5 ohm-centimeter to cover a regulator voltage range from 3 to 50 volts. In a tape furnace is a small, approximately .005" diameter, aluminum button fused into the die to form a P-N junction.

The die is placed into the glass body using baked-in gold paste for electrical contact. A platinum spring welded to the other lead makes a pressure contact to the P-type aluminum.

This glass package insures an excellent hermetic seal which enables the diode to operate over a temperature range from -78°C to +200°C.

ELECTRICAL AND OTHER CHARACTERISTICS

DISSIPATION AND THERMAL CONDUCTANCE:

The maximal dissipation of the regulator diode is determined by the geometry of the junction and the construction of the diode for the following reasons.

1. The area of the junction itself is especially important in that all of the currents through the junction, forward, reverse and regulator will vary in proportion to this area.
2. The construction of the device is significant in that it determines the thermal conductance. It has to be noted, however, that the use of a heat sink (and the position of it in respect to the junction) affects this factor considerably, as well as the substance and the temperature of the ambient.

Since the power is directly related to the heat dissipation in the device, the thermal conductance expressed in W/°C is also the measure of deration of power with increase in temperature. The thermal conductance is the reciprocal of the thermal resistance in °C/W.

It is felt that a correct, but sometimes misunderstood concept should be explained at this point.

Since heat causes undesired effects in a junction, it is expedient to transfer this heat away from the junction as fast and as effective as possible.

The ability of a device to do so is the thermal conductance "G". The thermal conductance is inverse proportionals to the thermal resistance R_{th}.

$$G = \frac{1}{R_{th}} \quad W/^{o}C \qquad (1)$$

R_{th} can be also expressed as the relationship between the change in temperature and the power dissipated.

$$R_{th} = \frac{\Delta T}{P} \quad ^{o}C/W \qquad (2)$$

From that it could be concluded that the device with a small thermal resistance (R_{th}) and consequently a large thermal conductance is preferable to the device with an opposite characteristic.

The consequence of the foregoing is, however, that we reach a stipulated, fixed power level much faster with a small R_{th} when we raise the temperature than we do with a device with a large R_{th}.

It means, also, that we can or have to dissipate more power in a device before we reach a stipulated and fixed temperature level.

For the proper evaluation of these considerations, the following may be of help.

The most important factor determining the ratings of a semiconductor junction device is, without any doubt, the temperature the junction and the materials involved can withstand. This characteristic, which is a physical one, is controlled by the specific properties of the materials. Manufacturing processes or construction of the device have very little to do with it.

The temperature, a silicon-aluminum alloyed junction should be able to withstand, is slightly below the alloying temperature, which is in our case about 630°C.

It is unfortunate that also the electrical characteristics of the junction and the other related materials have to be considered. (We are aware of the fact that these electrical characteristics are no lesser physical ones than the others named as such. But it seems to be easier to separate them according to the way of how they are apparent.) As far as the electrical characteristics are concerned, we know from experiments made by different people during the years of diode development that we cannot expect to have a silicon device such as ours working above 400°C. It should be stressed, however, that this temperature is mentioned in respect to the junction and its material. The difference between 400°C assumed possible and the value of 200°C accepted as maximum junction temperature by many manufacturers is partly due to the inadequate construction, and manufacturing of the various devices, yet, more due to the phlegmacy toward scientific investigation and the ultra-conservativism encountered in many places related to the subject.

In order to evaluate what is the desirable characteristic of a device in respect to temperature and power, we have to consider the following:

At an ambient temperature of 25°C our objective is to transfer the heat created by the applied power in the junction to the ambient. The small temperature resistance or high temperature conductance we want, therefore, permits a rapid flow of heat from the junction to the ambient and we can consequently dissipate more power (or transfer power in heat) in the junction, than we can with a large R_{th}. In this case, of course, we also have to derate a larger amount of our applicable power for each degree °C we raise the ambient temperature. In fact, an amount of power which is directly proportional to the thermal conductance or inverse proportional to the thermal resistance.

If the power or temperature handling capability of the device is determined by the rule of thumb, and is consequently lower than the actual value, it is obvious that with a relatively small increase in ambient temperature the applicable power has to be derated to almost zero.

This, of course, gives the impression that the device is of lesser quality, or, more specific, can't stand up against competitive devices. This is entirely wrong, because the other device may have an actual limit much lower than the device in question.

Would it then be better to have a device with a large thermal resistance, where the amount of power to be derated is to be much smaller?

One is bound to say, yes, in all cases where power and temperature level has been established arbitrarily. Because with a lower thermal conductance the amount of power to be derated per degree °C is smaller and the device appears to be of better quality.

As usual, industry has made a compromise and adapted deratings which satisfy the physical and electrical requirements by relying on the "hidden" reserves in power handling capability. These adapted values for derating are low enough to have the appeal to the customer, without the need to step up the power ratings of devices to a level, which is suspicious to the customer because he does not know better. To solve the whole problem it is necessary to investigate whether the maximum temperature or power level can be raised or not.

For this, it is necessary to establish by experiments:

1. The maximum temperature level of which the device is still operative, for example, with 20% of its rated power at 25°C;
2. The temperature at which thermal runaway occurs.

These investigations have not been made on silicon devices, at least to the knowledge of the author.

A concept has been adapted by industry that at a junction temperature of 200°C the power applicable to the device has to be derated to zero. This seems to be very conservative and is not in concurrence with, what has been opinioned by some scientists. However, +150°C is the value for the maximum junction temperature which is considered at Hughes, and also used for the evaluation of the regulator diode.

We know of several methods which are used to establish the value of R_{th} and G. The thermal conductance of the device can be *calculated*, according to a theory developed by M. Cutler (See SR-58), when knowing

Breakdown Voltage	E_Z
Temperature Coefficient	β
Dynamic Resistance	R_Z

Values which can be obtained experimentally. It is then

$$G = \frac{E_Z^2 \cdot \beta}{R_Z} \quad \text{Watts/}^{o}\text{C} \qquad (3)$$

The thermal conductance of the device can also be determined by *computation* of the thermal resistance for the various materials involved. Assuming that heat flows linearly between two parallel surfaces of the material, the thermal resistance is then

$$R_{th} = \frac{1}{G}$$

$$\text{or } R_{th} = R_{Dumet} + R_{others} \qquad (4)$$

$$\text{We know } R_{Dumet} = \frac{1}{k \cdot A} \qquad (5)$$

when $k =$ thermal conductivity in $\left(\frac{\text{cal}}{\text{sec deg cm}} \right)$

$A =$ area in cm^2

$l =$ distance between conducting surfaces

$$\text{and } R_{\text{others}} = \frac{R_{pt} \, (R_G + R_{si})}{R_{pt} + R_G + R_{si}} \qquad (6)$$

where R_{pt}; R_G; R_{si} are the thermal resistances of the platinum, the glass body and the silicon respectively.

Using for R_{si} a value which is normally found in handbooks implies that the heat develops uniformly over the area in question.

A concept opinioned by Rose[3] does not agree with that assumption. According to this theory, the existence of so-called "hot spots" or microplasmas is to be considered. These are individual spots at which the breakdown in silicon occurs.

Rose[3] points out that the temperature rise and the rate of approach to temperature equilibrium in the ionizing regions can be only estimated.

If we assume all the power P to be dissipated uniformly in a sphere of diameter l, we find that the equilibrium temperature rise at the center is given by

$$T = 3 \, \Gamma \left(\frac{3}{2} \right) P / 4 \, \pi^{\frac{3}{2}} \, k \, l \qquad (7)$$

where k = heat conductivity
(for silicon 0.836 joule/sec cm °C)

P = power in Watt

l = diameter of sphere

For an ionizing region with 50 uA current we have for example

$$P \approx 2 \times 10^{-4} \text{ Watt}$$

assuming $l = 500\ \mathring{A}$

$$T = 12^{\circ}C$$

Rose also stresses that this value is an absolute lower limit. First, because the current may be twice as large. Second, heat diffusion from other ionizing "hot spots" and the surrounding resistivity cannot be ignored. A temperature rise three times as large, i.e. 36°C is probably more realistic.

The thermal conductance of a point contact (or hemisphere) on an infinite slab is given by

$$G_m = 2 \pi k r$$

where k = thermal conductivity

r = the radius of the contact

As a result of this theory, the heat is considered to be developed at these hot spots and the thermal resistance will be larger for the uniform area

$$G_{sl} = n. G_m \qquad (8).$$

The thermal conductance can also be determined experimentally by measuring the thermal resistance. This is done by putting the device in an ambient of known and unvariable temperature, and then driving a DC current through the device. The current times the voltage across the device constitutes a power which will heat the junction and establish a certain temperature.

A relationship has been established in previous measurements between power dissipated in the junction and junction temperature. It is therefore possible, now, to conclude the temperature at the junction.

Knowing the junction temperature enables us to solve for the thermal resistance

$$R_{th} = \frac{T_1 - T_0}{P} \tag{9}$$

However, this method may be adequate when applied for conditions prevailing for the forward characteristics of the device, because the heat created by the applied current seems to be evenly distributed over the entire junction area and the average temperature is equal to the maximal temperature. In the breakdown region, due to the existence of microplasmas, the calculated temperature does not indicate the actual value of heat created at specific points of the junction area. This may be the reason for a discrepancy in values for G as shown in a recent report (SR-58).

E. Benko shows that different values for G can be obtained, depending what method is used. We can discern from this report, that values obtained with different methods differ by a factor of two (2). This discrepancy is explained, and a difference by a factor of two between theory and experiment considered acceptable.

> From the commercial and marketing point of view, an uncertainty by a factor of two is unbearable. It means a difference in power ratings and power handling capability of 100%.

In order to determine the power handling capability of a device, the maximum temperature has to be known which the device can stand. This information can be only obtained by destruction tests and temperature resistance measurements. Since the regulator diode has the same physical properties as the SA-1, the values for the latter could be used. Unfortunately, the SA-1 never underwent such tests. At least no records are available.

Since the thermo-conductance of a device is a dominant factor, by controlling the power handling capability in respect to changes in temperature, it seems to be appropriate as pointed out already to investigate this subject more thoroughly.

For the purpose of evaluation of these regulator diodes, the power rating at 25°C has been postulated with 250 milliwatts. This corresponds to a value for

$$G = 2.0 . 10^{-3} \ W/^{o}C$$

REGULATOR VOLTAGE

All diodes tested are in the range from 3 to 50.0 volts. Arriving at the regulator voltage is indicated by the characteristic increase in reverse current to several milliamperes. It is seen that in this region very small changes in voltage provoke relatively large changes in current, Figure 1 shows the forward and reverse V-I characteristics of some sample diodes.

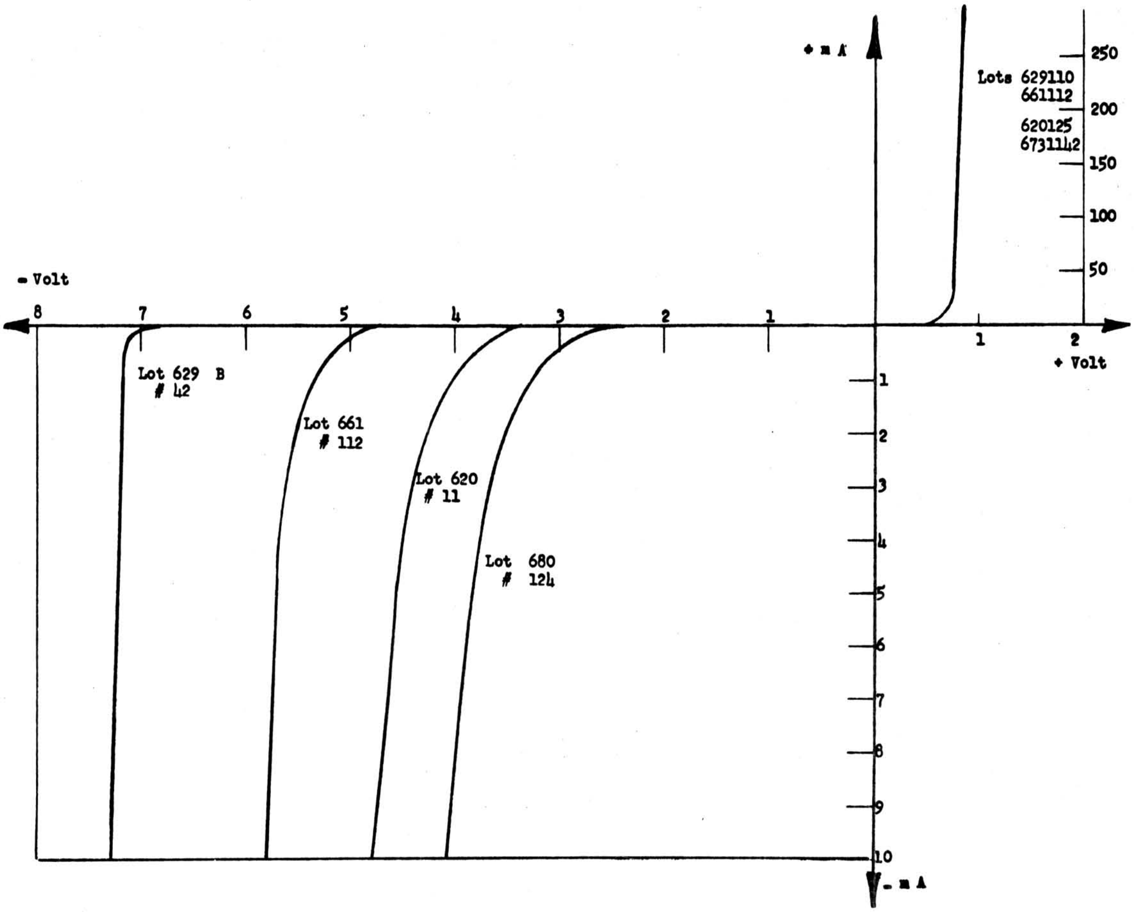


FIGURE 1

If we, on the other hand, change the regulator current considerably, we notice only small changes in regulator voltage. See Figure 2.

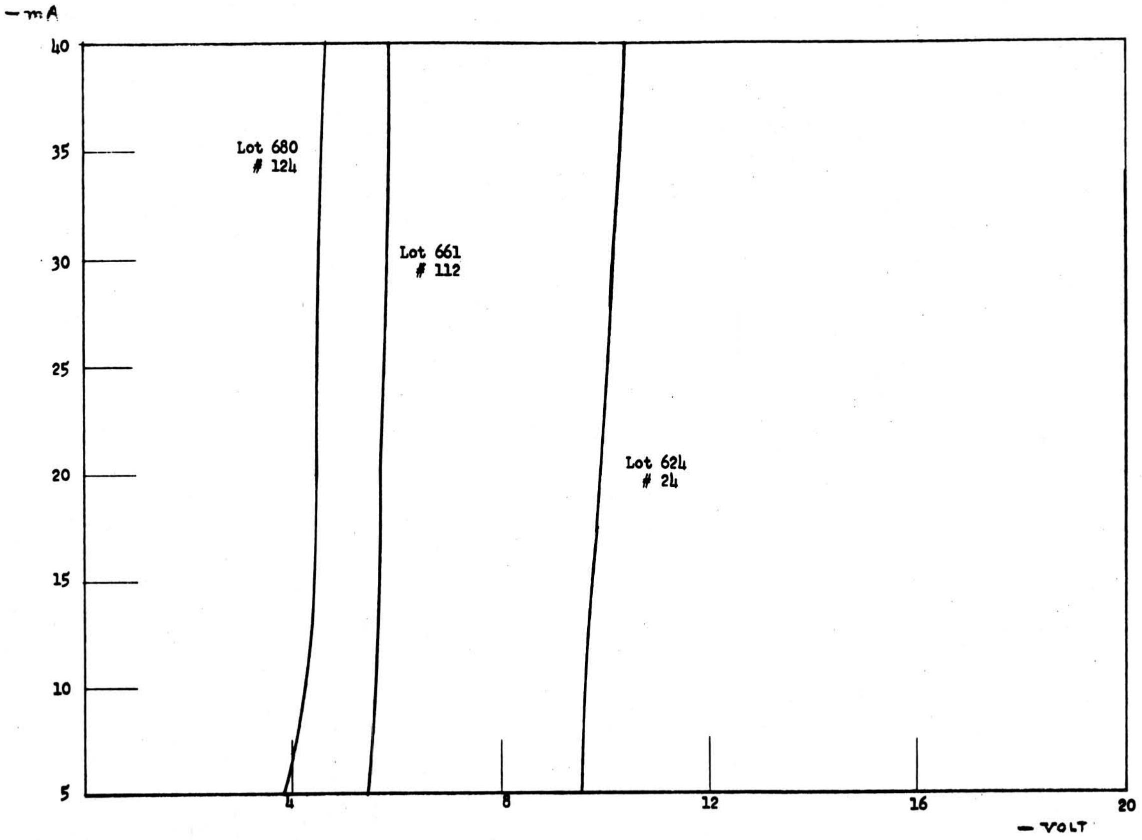


FIGURE 2

Figure 3 shows some individual V-I curves of regulator diodes. The pictures marked "a" are the reproduction of photos taken from the scope with an expanded V-I scale; whereas the pictures "b" represent the V-I characteristic over the full current and voltage scale.

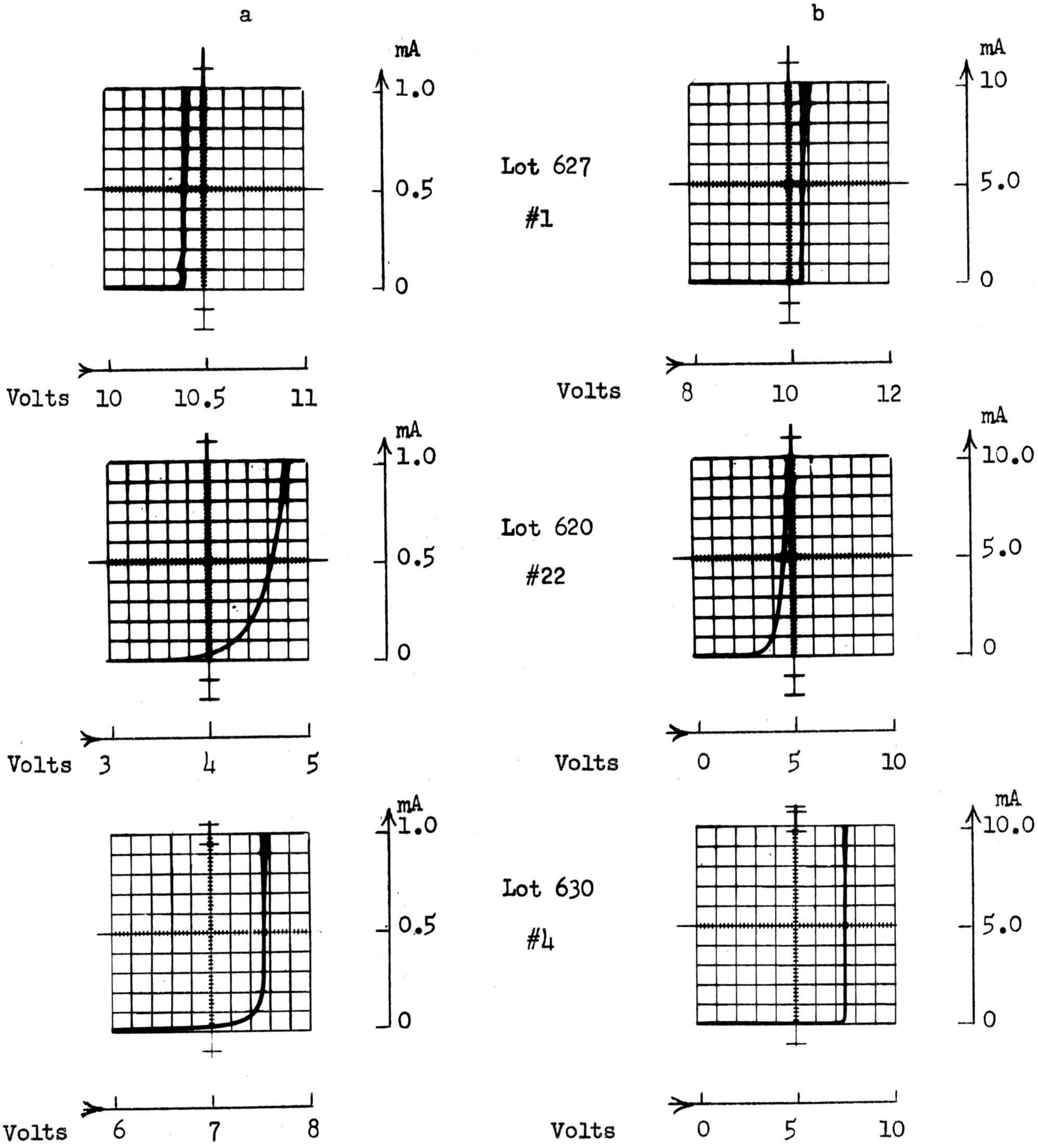


FIGURE 3

SPREAD IN REGULATOR VOLTAGE

The Table shown on the next page is merely a compilation of the ± tolerances from the nominal voltages as indicated by the R & D department for each particular lot. The writer has been informed that the units have not been pre-selected.

The number of diodes tested is too small that the result should be used as an established reference for quality. However, taking into consideration that the test units have been taken out of a number of hundreds final seals made from the same wafer, without any selection, we can say the result does have some significance and the high yields to the nominal regulator voltage are very encouraging.

Only statistical analysis with a calculated number of samples from a production line may indicate the true merit of these figures.

Considering that the regulator voltage is mainly determined by the resistivity of the semiconductor material used, it becomes obvious that close supervision has to be exercised from the moment the single crystal is cut in wafers, and the resistivity determined, until the manufactured device is color-coded.

It also becomes apparent that it is cheaper to store wafers (1 wafer $\approx$ 300 diodes) instead of finished goods and use some automatic tester and selector for the wafers and store the so obtained information on punch cards. This will enable constant observation of yields over any period of time.

SPREAD IN REGULATOR VOLTAGE

Lot#	Ez nom.	Calculated value for ± 5% toler.		Measured values		Yield in % for a tolerance of		Number of units tested
		min.	max.	min.	max.	± 5 %	± 10 %	
619	6.8	6.5	7.1	6.82	6.95	100	100	10
620	4.4	4.2	4.6	4.11	4.70	80	100	10
627	10.5	10.0	11.0	9.67	10.97	70	100	10
629A	6.8	6.5	7.1	6.69	7.06	100	100	10
629B	7.45	7.1	7.8	7.12	7.53	100	100	10
630A	6.8	6.5	7.1	6.72	7.18	90	100	10
630B	7.45	7.1	7.8	7.27	7.58	100	100	10
631A	6.8	6.5	7.1	6.66	7.14	90	100	10
631B	7.45	7.1	7.8	7.18	7.57	100	100	10
657	42.0	39.9	44.1	42.60	44.41	90	100	10
658	30.0	28.5	31.5	29.40	31.00	100	100	10
661	5.4	5.13	5.67	5.33	5.47	100	100	10
680	4.47	4.26	4.53	4.18	5.00	100	100	10

TABLE 2

REGULATOR CURRENT

The range of regulator current is in principle determined by two facotrs: The so-called dynamic resistance R_Z and the power dissipation P.

The dynamic resistance limits at a determined maximal change in voltage ΔE_Z the current range ΔI_Z to

$$\Delta I = \frac{\Delta E_Z}{R_Z} \tag{10}$$

The maximal current for a given voltage is also limited by the maximal dissipation P. I_{Zmax} has always to be

$$I_{Zmax} \leqq \frac{P}{E_Z} \tag{11}$$

As previously mentioned the maximum dissipation was stipulated with 250 mW.

The diodes under test had nominal regulator voltages in the range from 3.0 to 50.0 volts. For a particular device the regulator voltage versus regulator current were plotted at 0°C; +25°C and +150°C. The regulator current was varied in the diode from 5 mA to a value representing a power dissipation of approximately 250 milliwatts, the tentative full power rating of these diodes.

Then, issodissipative lines were superimposed on each set of curves at power levels of 125; 187.5 and 250 milliwatts, representing 50%, 75% and 100% of the power rating.

25°C was established as rated room temperature and 187.5 milliwatts, corresponcing to 75% dissipation, as nominal operating power.

The intersection of the 187.5 milliwatt-line and the 25°C curve was noted, and the coordinated of this point were termed E_{Z_0} and I_{Z_0}, the rated regulator voltage and current respectively. It was established that these values will be the design center for the regulator diodes. This process is demonstrated in Figure 4 for a typical 10.0 Volt diode from lot #627.

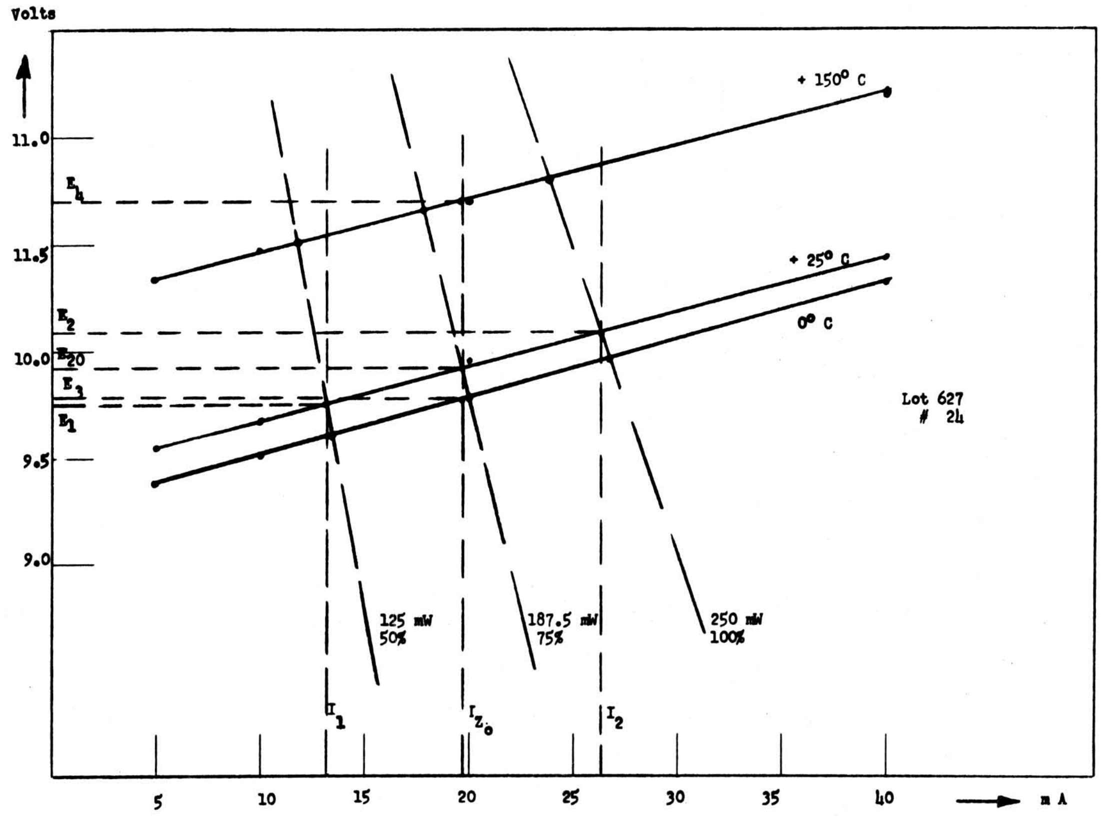


FIGURE 4

TEMPERATURE COEFFICIENT

One of the most important properties of a regulator diode is the temperature coefficient.

As McKay points out, the temperature coefficient of α_i (α_i is solely a function of E, the electric field) can be determined either from breakdown data or multiplication data provided the appropriate relations are established.

The temperature dependence of the avalanche breakdown voltage for linear gradient junctions can be described approximately by

$$V_{BT} = V_{BO} \left[1 + \beta \; (T-T_o) \right] \qquad (12)$$

where by V_{BT} = Breakdown Voltage at temp. T

V_{BO} = Breakdown Voltage at ref. temp.

β = Temperature Coefficient

$T-T_o$ = Change in temperature

It has to be considered, however, that for step junction the temperature coefficient may be 50 per cent greater than in a linear-gradient junction[3].

Tests conducted in the early stage of diode development showed already that the temperature coefficient increases with increase in regulator voltage. An almost zero temperature coefficient has been observed at voltages around 5 Volts and a negative temperature coefficient is noted with lower voltages.

This phenomenon may have its reason in the fact that at low voltages the breakdown is caused by what is known as the Zener effect, whereas at higher voltages the avalanching is the controlling factor.

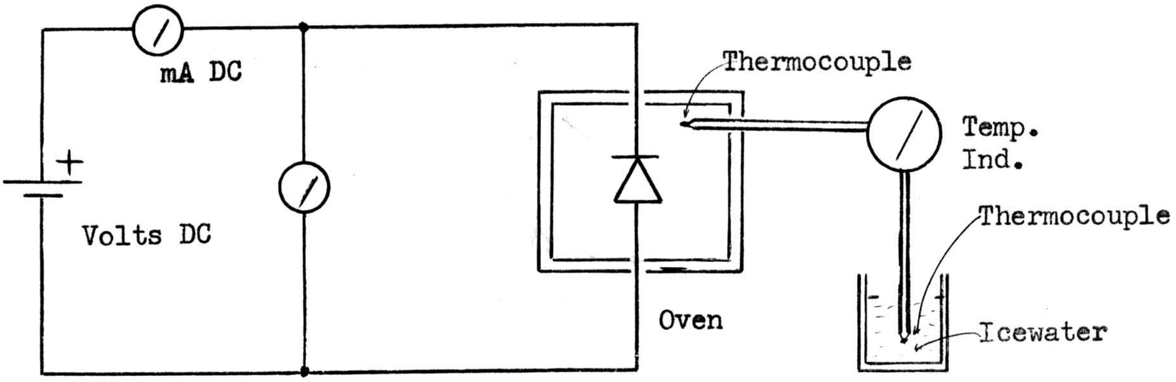
For all practical purposes the temperature coefficient is the value expressing the systematic change in regulator voltage with temperature at a constant current. We can write

$$\text{T coeff.} = \frac{E_{Z2} - E_{Z1}}{E_Z} \Big/ (T_1 - T) \, . \, 10^{-4} \Big/ \quad {}^{o}C \qquad (13)$$

It is common practice to express the temperature coefficient in % per ^{o}C by multiplying with 100.

$$\text{T coeff.} = \frac{\Delta E_Z}{E_Z} \cdot \frac{100}{\Delta T} \quad \%/{}^{o}C \qquad (14)$$

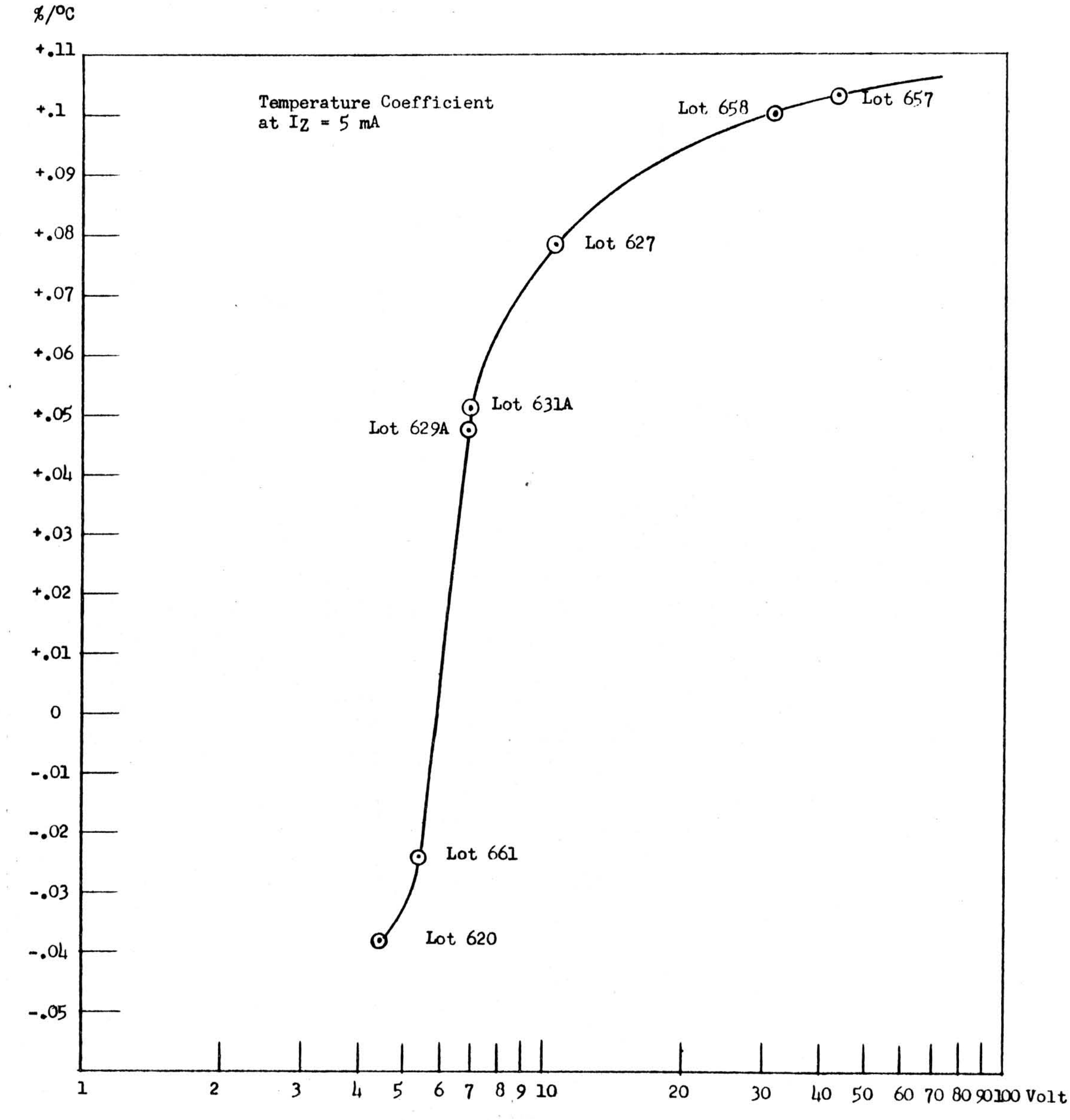
The test setup used to determine the temperature coefficient of our regulator diode is shown in Figure 5



The devices under test were placed in an oven where the temperature could be controlled within a half degree °C. With an oven temperature at 25°C ± ½°C, the diode under test was brought in the breakdown region with an appropriate DC voltage derived from a constant current power supply. The current was maintained constant ± 1% at an arbitrarily set value of 5 mA. Time was allowed for the diodes to set at the oven temperature. Then the regulator voltage of the diodes were measured with an accuracy of ± 1%. Regulator voltages were tested at -55°C; 0°C; +25°C and +150°C.

Figure 6 demonstrates the temperature coefficient in %/°C plotted for diodes with different regulator voltages at a specified current.

FIGURE 6



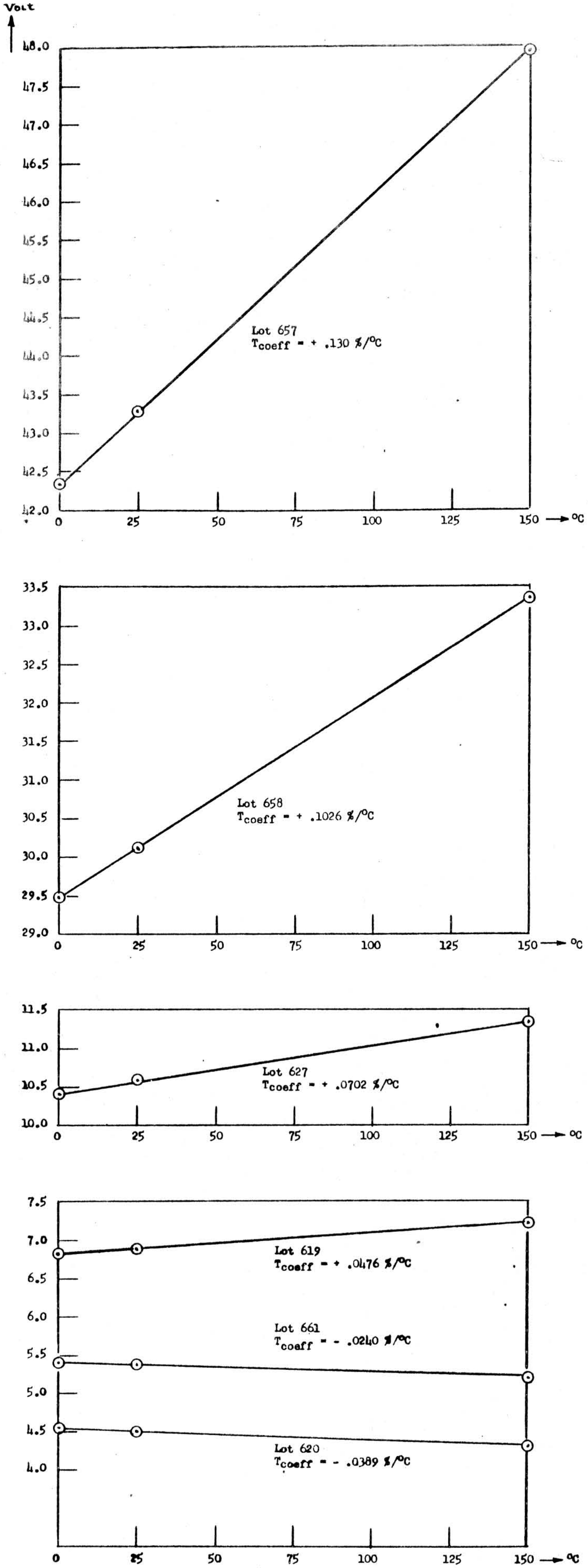


Figure 7 shows the different slopes, indicating the change of regulator voltage in respect to temperature, for diodes of various regulator voltages.

DYNAMIC RESISTANCE:

The so-called dynamic resistance or dynamic impedance is de facto a slope error of regulator voltage. It is determined by plotting the change of terminal voltage over a given current range in the breakdown region, and dividing the change in voltage by the change in current.

$$R_Z = \frac{\Delta E}{\Delta I} \quad \text{ohms} \qquad (15)$$

It is common practice to determine R_Z by the following method:

The device under test is brought in the breakdown region with an appropriate DC voltage derived from a constant current power supply. The current is maintained constant at a 20% value of the value called out as the maximum regulator current of the device.

An AC signal current being 10% of the value of the DC current, is now superimposed upon the DC current flowing through the device. This voltage developed across the device by the signal current is measured.

Dividing the obtained value for the AC voltage by the value of the AC current results in the value for the dynamic or AC resistance expressed in ohms. The test setup is shown on the following page.

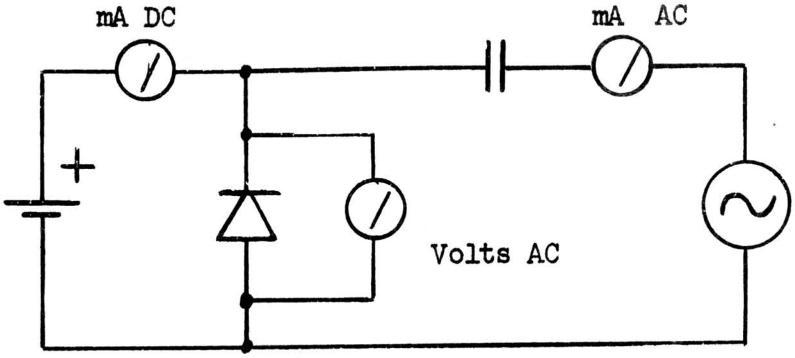


FIGURE 8

$$R_Z = \frac{V_{ac}}{I_{ac}} \quad \text{ohms} \qquad (16)$$

It should be noted, that the value obtained with the described procedure is not be confused with the absolute resistance which can be interpolated from a V-I plot.

Figure 9 shows curves indicating the change in R_Z for diodes of different regulator voltages for +25°C and +150°C respectively.

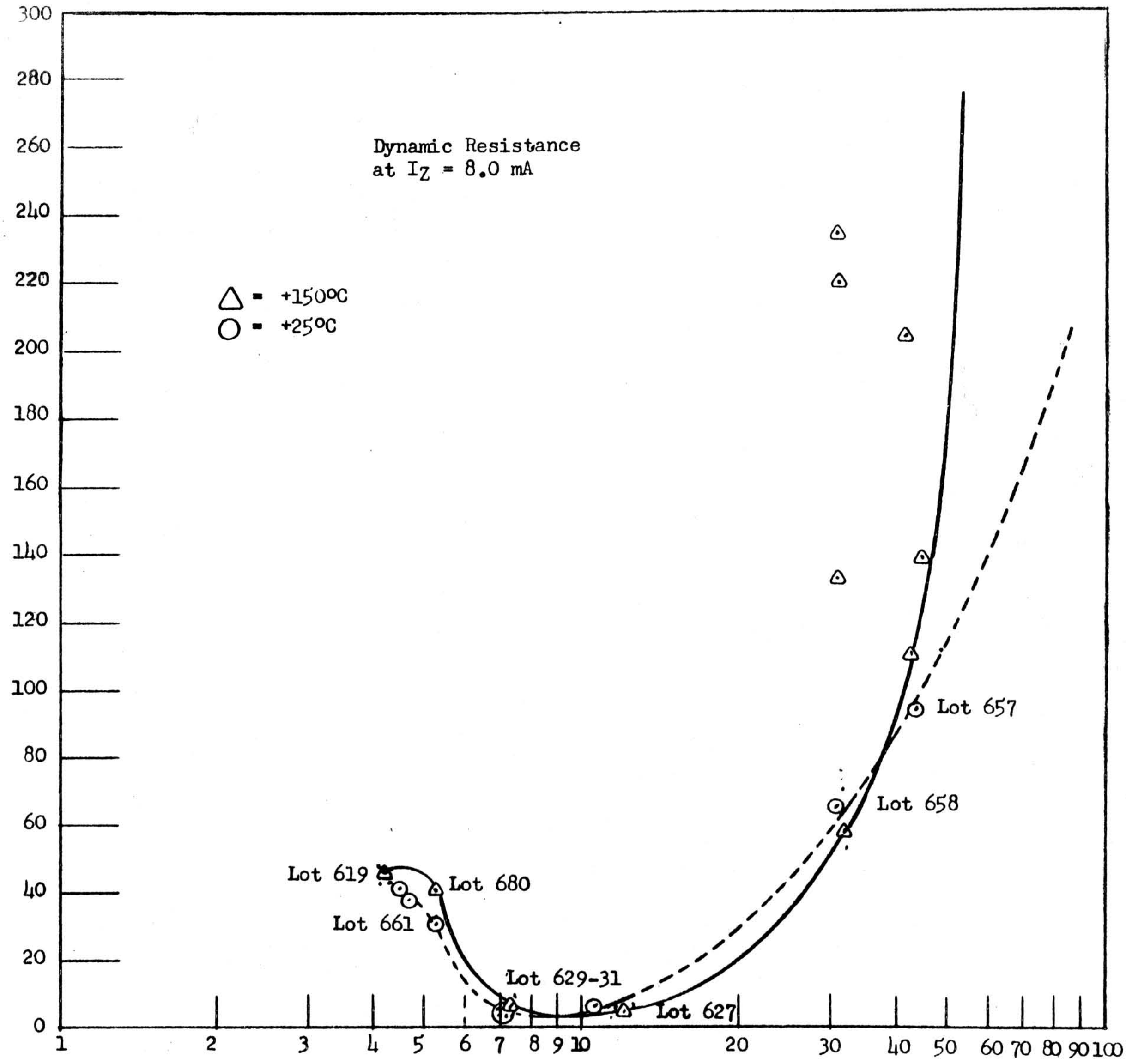


FIGURE 9

REVERSE CURRENT

The current flowing in the reverse direction at a potential below the regulator voltage is very low and in the microampere range. Therefore, one could think that for regulator diodes where high currents are flowing in the reverse direction in the breakdown condition, the low reverse current before breakdown is of no or little consequence. Unfortunately this is not so. The efficiency of a circuit is, among other things, determined by the losses due to high reverse current. The proper function of a circuit may depend on the stability of the reverse current, particularly with increase in temperature.

By investigating the reverse current characteristic, we observe two distinctively different conditions. The "soft" and the "hard" reverse characteristic.

Several factors contribute towards the softness of the reverse characteristic.

Chynoweth and McKay[4] indicate that the multiplication factor $M=1$ up to reverse biases of about 1.5 volts. (M is defined as the ratio of the photo current at a given voltage to its constant value at small values of the reverse bias.)

Even over this range, the reverse current grows rapidly with the voltage. It has been also shown, that considerable carrier generation by internal field emission is possible even at $V_a = 0$ in which case, the current will increase with V_a right from $V_a = 0$. This is so because for zero or small reverse voltages the top of the valence band on the p side will be only slightly higher than the bottom of the conduction band on the n side, so that only a few electrons will be available for the emission transitron. As the reverse voltage is increased, the number of such available electrons will increase also.

From their investigation the authors[4] conclude that the onset of a more rapidly increasing current represents multiplication produced by carriers originally field-excited from sites in the valence band between the edge and the center of the junction. Thus it is apparent that internal field emission (Zener-effect) rather than multiplication dominates the breakdown characteristics in very narrow junctions. In very wide junctions, breakdown occurs by the avalanche process before the field gets sufficiently high to produce appreciable internal field emission. An intermediate situation may exist with both processes occurring side by side in junctions of intermediate width. Reverse characteristics which seem to fit this picture are frequently observed.

At low voltages the current shows a gentle increase with V_a but at a well-defined value of the bias (called the hardening point) the current increases rapidly with the voltage, leading into a sharply defined breakdown.

On the following page we have a table of values for the reverse current at -1.0 Volts, -2.0 Volts and at a value $0.7 \cdot E_Z$ at room temperature and at +150°C.

It can be noted, that the reverse current at room temperature is within a range appropriated for good devices. The values determined at +150°C also are within practical and commercially interesting limits.

However, a consistently apparent instability (change of reverse current from the lowest to the highest level within one order of magnitude) for almost all lots is undesirable and worth to be investigated with all deliberate speed.

From our experience with the SA-1 we know, that instability in the reverse characteristic at elevated temperatures is a major headache.

REVERSE CURRENT

Lot	Diode #	+25°C			+150°C			E_Z nom.
		-1.0 V µA	-2.0 V µA	$0.7 \cdot E_Z$ µA	-1.0 V µA	-2.0 V µA	$0.7 \cdot E_Z$ µA	
619	1	.0001	.0022	1.45	.030 U	.084 U	16.0 U	6.8
	9	.017	.020	.75	4.8	6.2	41.0	
	2	.095	.250	54.0	.275 U	1.0 U	120.0 U	
620	18	.006	2.0	67.5	.166 U	5.2 U	150 U	10.5
	15	.065 U	4.7 U	130.0	.025 U	7.7	215.0 U	
	20	.025	8.0	250.0	.200	17.0	335.0	
627	21	.0002	.0006	.120	.380 U	.450 U	10.5	10.5
	22	.0003	.0006	.128	.390 U	.500 U	1.0	
	25	.0005	.0005	.077	.720	.800	1.25	
629 A	31	0	.0001	1.35	.021	.061	8.1	6.8
	33	.0003	.005	.53	1.0 U	7.0 U	25.0 U	
	35	.012	.013	.480	4.9 U	5.2 U	12.5 U	
629 B	41	0	.0005	.55	.088	.112	3.4	7.45
	47	.0003	.0047	.490	.114	.220	4.3	
	44	.0021	.0036	.184	2.2 U	2.5 U	5.4	
630 A	51	0	.0004	1.1	.038	.072	4.5	6.8
	55	0	.0004	0.9	.039	.052	3.9	
	60	0	.0009	2.2	.120 U	.170 U	8.1	
630 B	63	0	.0003	2.1	.007 U	.083 U	1.45	7.45
	67	.0007	.0014	2.7	.600	.700	2.85	
	61	.225	.640	16.0	2.8 U	5.8 U	41.0 U	
631 A	71	0	.0004	1.5	.082	.100	6.6	6.8
	80	.0002	.0052	0.7	.045	.082 U	3.4	
	77	.0016	.007	3.6	.140 U	.250 U	7.5	
631 B	85	0	.0011	1.4	.148 U	.150 U	1.8	7.45
	90	.0001	.0009	4.7	.245 U	.275 U	4.3	
	81	.065 U	.300 U	118.0 U	.225 U	3.5 U	45.0 U	
657	96	0	0	.0002	.245 U	.300	.400	42.0
	100	.0003	.0004	.0053	.420	.500	.900	
	95	.063	.0013	156.0	1.7	2.0	524.0	
658	105	0	0	.0014	.225 U	.250	.350	30.0
	108	.0001	.0001	.00035	.410 U	.437 U	.600	
	101	.0005	.0006	.0011	.500	.780	.900	
661	113	.0002	.098	59.0	.055 U	.470	67.0	5.0
	119	.0006	.098	57.0	.034 U	.495	65.0	
	120	.0013	.106	59.0	.094 U	.500	67.0	
680	124	.0021	.062	59.0	.305	1.8	64.0	4.0
	121	.0091	3.5	267.0	.085	7.1	280.0	
	130	.011	2.6	225.0	.164	6.2	245.0	

U = Unstable

TABLE 3

FORWARD CURRENT:

The minimum forward current of the regulator diodes under investigation was tested in the same manner as used for the SA1, and at 25°C.

The forward current starts increasing quite steeply as soon as the treshold voltage of about .7 Volts is passed, as shown in the reproduction of photos taken from curves displayed on the scope.

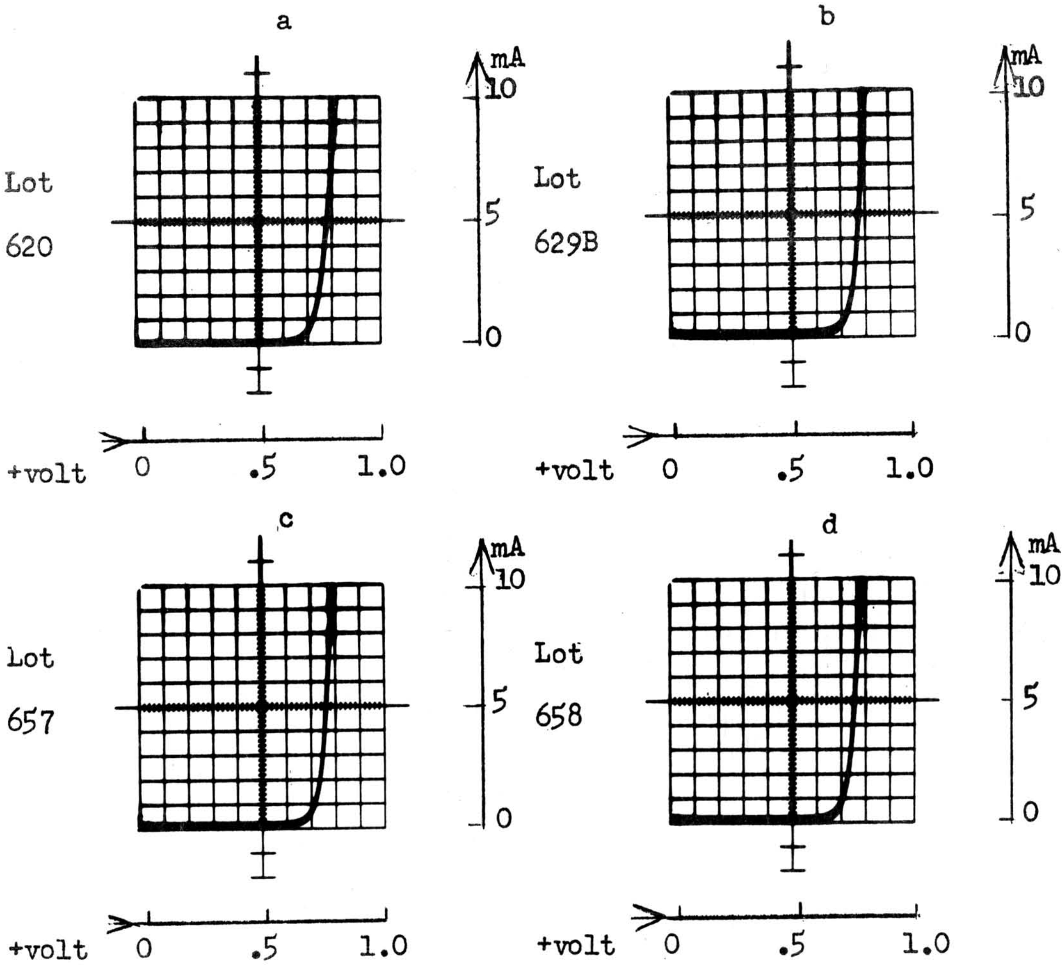


FIGURE 10

FORWARD VOLTAGE

The forward voltage known also as the "voltage drop" was measured at +25°C and +150°C with a load (forward) current of 100 and 150 mA respectively. The values obtained spread from .8 to 1.2 Volts at +25°C and from .6 to 1.0 Volts at +150°C.

These relatively low, forward voltages for the applied currents agree with the theory and allow the application of the device with good efficiency in respect to its forward characteristic.

TEMPERATURE RANGE

As mentioned before, no attempt has been made to establish actual maximal values by tests. The temperature maxima and minima governing the application of the SA-1 have been adapted.

The temperature range of the regulator diode, therefore, has been stipulated with -68°C to +200°C.

SHUNT CAPACITANCE

For better understanding of the obtained test results, we will recapitulate the phenomena controlling the junction capacity.

We have to consider the regulator diode controlled by an abrupt transition of the charge density, and we assume that the space-charge zone is fully depleted and that there is an abrupt transition between the depleted zone and the rest of the crystal, where electrical neutrality prevails. A consequence of these assumptions is the existence of the sharply defined regions of charge which establish an electric field confined to those regions. The depletion zones extend into two regions in inverse relation to the impurity - concentrations of those regions and in proportion to the square root of the breakdown voltage. In our case the impurity concentration of one of the regions is very much larger than that of the other. Consequently, the depletion region extends almost entirely within the region of lower impurity-concentration, that is, the region of the higher resistivity.

The width of the depletion zone therefore is closely related to the resistivity.

We write:

$$W_B = (2 \epsilon \rho \mu V_B)^{\frac{1}{2}} \qquad (17)$$

Junction capacitance

$$C = \frac{d\,Q}{d\,V_B} = \frac{d\,Q}{d\,W} \cdot \frac{d\,W}{d\,V_B},$$

$$C = \left(\frac{\epsilon}{2\,\mu\,\rho}\right)^{\frac{1}{2}} \cdot V_B^{-\frac{1}{2}} \qquad (18)$$

For silicon

$$C = 1.06 \cdot 10^4 \,(\rho\, V_B)^{-\frac{1}{2}} \quad \mu\mu\text{fd/cm}^2 \qquad (19)$$

where

C = capacitance per unit area (uufd/cm^2)

ϵ = dielectric Constant

μ = mobility

ρ = resistivity

V_B = breakdown voltage + built-in voltage

We have to consider that the value V_B contains the junction built-in voltage of approximately 0.7 Volts.

From the foregoing we discern that besides the junction size the resistivity of the material and the applied potential are the dominant factors governing the shunt capacitance.

For many applications is the shunt capacitance of little or no consequence. However, in some specific applications of the more sophisticated type like computers, modulators, or other frequency-dependent circuits, the capacitance of the device becomes important. This not only at zero bias but at all points of the reverse voltage scale until to the breakdown point.

This is the reason the measurements of the shunt capacitance have been made at three reverse voltage levels. The measurements have been taken with a "Tektronix" L-C meter at a frequency of 140 Kc and the bias voltage as stated.

Average values from 10 samples for each lot have been listed in Table 4.

Capacitance in uufd at 140 Kc and +25°C

Lot	O-bias	-2.0 Volt	0.7 • EZ
619	380	205	151
620	490	265	251
627	212	107	60
629A	333	180	126
629B	356	195	145
630A	345	185	131
630B	290	154	105
631A	277	148	104
631B	288	155	108
657	49	23	8
658	67	32	11
661	350	223	208
680	300	266	250

TABLE 4

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