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Second Breakdown in Germanium Gold-Bonded Diodes

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By
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20 JUNE 1972

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NAVAL ORDNANCE LABORATORY, WHITE OAK, SILVER SPRING, MARYLAND

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NAVAL ORDNANCE LABORATORY
White Oak, Maryland

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20 June 1972

Second Breakdown in Germanium Gold-Bonded Diodes

This report describes the high voltage pulse tests and post-damage analysis performed on gold-bonded germanium diodes. Further second breakdown studies will be conducted on other discrete and integrated solid state devices.

This work has been accomplished under the sponsorship of the Naval Ships Systems Command in support of their task SHIP 15221/S4814 as part of the continuing study of radiation effects on solid state electronics.

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Captain, USN
Commander

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By direction

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INTRODUCTION

Early germanium diodes were of the point-contact variety. A small germanium chip, usually n-type, was placed in contact with a tungsten wire cat whisker, bent so that its tip exerted pressure on the germanium chip. Rectification was only possible at certain points on the chip, and it was frequently necessary to adjust the contact for satisfactory performance.[1]

The adjustment problem and also the power dissipation problem were cured when the contacts were bonded to the germanium surface. A properly doped gold wire is brought into contact with the germanium chip, as in the point contact diode. A typical wire is two mils in diameter and is sharpened to a very fine point. The chip and wire are then bonded by passing a dc current through the contact point and heating the area to at least 358°C, the gold-germanium eutectic temperature. Typical values for the current pulse range from a few amps for tens of milliseconds to several hundred milliamps for about 10 seconds. The resulting germanium gold-bonded diode is mechanically and electrically stable.[2] Figure 1 is a cross-sectional view of such a diode.

Second breakdown in transistors was discovered by Thornton and Simmons[3] in 1958 and was observed as a sudden decrease in the voltage and an increase in the current when a transistor is subjected to high current levels. It is the purpose of this report to describe and, where possible, explain the phenomenon of second breakdown in germanium gold-bonded diodes.

EXPERIMENTAL TECHNIQUE

The test arrangement is shown in Figure 2. Voltage pulses from a Spencer-Kennedy Laboratory Model 503-A pulse generator were applied to a 1N277 germanium gold-bonded diode. The current was measured by a Tektronix CT-2 current probe connected to a Tektronix oscilloscope, and the voltage across the diode was measured with a voltage probe and an oscilloscope. Various oscilloscopes were used during the course of the investigation. The forward and reverse characteristics of each diode were measured before testing and after each pulse test.

Each sample was pulsed at increasing power levels to enable observation of progressive damage with increasing power and the determination of burnout power. This method has obvious advantages over testing each component only once, especially when the great variability in nominally identical devices is considered. Although the method does have the possible disadvantage of degrading device parameters with multiple sub-burnout level pulses,[4] this is not considered to be a significant source of experimental error.

OBSERVATIONS

DECREASE OF REVERSE BREAKDOWN VOLTAGE. The bulk of the testing was done with 100 nanosecond square pulses. In both the forward and reverse tests, the most obvious consequence of high power pulsing was a decrease in the reverse breakdown voltage. The breakdown voltage prior to testing was read at the specified 80 microamps reverse current. A typical before-and-after characteristic is shown in Figure 3. The reverse breakdown voltage was usually reduced by almost an order of magnitude. There is also a change in the forward conductivity; Figure 4 shows a decrease in the conductivity but both increases and decreases were observed.

Except for the 10 percent change in reverse current due to sub-burnout level pulses, no intermediate values of breakdown voltage were observed. For 100 nanosecond pulses, reverse breakdown voltages were changed either by 10 percent or by nearly an order of magnitude. In contrast, shorter pulses (10 nanoseconds) were capable of causing all gradations of damage, from near zero through total damage.

The average power required to damage the diode (major change) in the reverse direction was 325 watts. As the power was increased the amount of damage increased i.e., the breakdown voltage decreased. In the range of one to two kilowatts, the diode lost its nonlinear characteristic and became an ohmic resistance. This effect also increased with increasing power, i.e., the resistance decreased as the power increased. Typical values were 1000Ω at one kilowatt and 5Ω at two kilowatts. At power levels above two kilowatts the diode became an open circuit. Typical current and voltage traces for reverse biased pulse testing are shown in Figure 5. A decrease in voltage with an increase in current, characteristic of second breakdown, is evident. Figure 6 is an atypical trace clearly showing that second breakdown has occurred in the diode.

Similar results were obtained in forward pulse testing. Damaging power levels for a 100 nanosecond forward pulse averaged 95 watts - less than the power required to produce damage in the reverse biased case. Another difference is that reverse damage was caused by an average current of 5.5 amps while the corresponding current for the forward direction was 7.2 amps. In almost all cases in reverse testing there was no current (i.e., less than 0.1 amps) up to the damaging pulse while forward testing, as expected, showed several amps at all test levels with no evidence of second breakdown action.[5] Thus the voltage and current traces for forward pulsing look the same whether or not damage occurs, and a measurement of the diode parameters is necessary to determine damage.

LIFETIME AND RECOVERY TIME CHANGES. While the decrease in reverse breakdown voltage is the most obvious, and perhaps the most important result of damage through secondary breakdown, it is by no means the only result. Measurements were made on the reverse recovery time and on the effective lifetime of minority carriers. Both were measured on a Tektronix type "S" plug-in unit and were found to decrease after the application of a damaging pulse.

The reverse recovery time was measured at 0.1 milliamp reverse current and 2 milliamps forward current, and was arbitrarily chosen as the time required to reach a reverse bias of one-half volt after conducting in the forward direction. The average decrease in reverse recovery time was 20 percent, typical values being from 0.5 to 0.4 microseconds (heavily damaged units, with breakdown voltages of 10 to 15 volts). The current and voltage traces of the damaging pulses indicated that reverse recovery time decreased with increasing power.

The effective lifetime of minority carriers is the time required for the number of minority carriers to decrease to 1/e of their original number after termination of the forward current. Immediately after the forward current has ceased, i.e., at times small compared to the effective lifetime, and for diode voltages larger than kT/q (.026 volts at room temperature), it can be shown[6] that the effective lifetime of minority carriers, τ, is approximately given by

$$\tau = (.026)/(\Delta V/\Delta t),$$

where k is Boltzman's constant; q, the electronic charge; T, the temperature; and $(\Delta V/\Delta t)$ is the time rate of change of voltage across the diode. Using this approximation, the average decrease in effective minority carrier lifetime was found to be about 10 percent, typical changes being from 80 to 70 nanoseconds. All measurements were performed at room temperature and one milliamp forward current. As the damage pulse was increased in amplitude and the reverse breakdown voltage decreased, the effective lifetime approached zero as the diode became an ohmic resistance. Indeed, zero minority carrier lifetime distinguishes resistors from barrier junctions.[7]

It was mentioned that the forward current-voltage characteristic suffered only minor changes during pulse damaging. Figure 7 shows a unit in which the forward characteristic was considerably changed. There is no conduction in the forward direction until the forward voltage is greater than two volts, and the suddenness with which conduction begins is worthy of notice. Normal diodes are carrying very large currents at two volts forward bias. Note also the linear slope once conduction has begun.

Normal forward characteristics of diodes have linear voltage-current relationships above a certain current due to the IR drop across the bulk material, i.e., the germanium or silicon which is outside the junction. This voltage drop becomes larger than that across the junction in forward bias and thus becomes the limiting factor for high current conduction. The onset of this linear relationship in the diodes under test normally occurred at slightly under one volt bias. Typical bulk resistances were one to two ohms. From Figure 7 and Figure 3 the resistance in series with the junction of the damaged diode is seen to be 100 times larger after pulsing than before pulsing. In this case, the resistance went from 1.6Ω to 160Ω.

Another very interesting observation is not apparent from Figure 7. The trace was photographed on a Tektronix type 575 Transistor Curve Tracer, which applies a voltage across the diode that is continuously swept from zero to an adjustable maximum and back to zero. As the maximum forward voltage was increased, the voltage at which conduction began was seen to move continuously toward increasing voltage levels while the slope of the conducting part of the trace (i.e., the resistance) remained essentially unchanged. When we returned to these diodes a few months after pulsing to remeasure some parameters, we found that the damage in the forward characteristic had disappeared, while the decreased reverse breakdown voltage was still evident and unchanged. During that interval the diodes were stored at room temperature. These units had been pulsed at 800 watts in the reverse direction, considerably higher than the average of 325 watts.

In most of the units tested, the change in the linear part of the forward I-V curve was very slight and could be seen only upon close inspection. Mostly decreases in forward conductivity were seen, and they were typically no larger than 10 percent. There were occasional forward conductivity increases, too. We also attempted to measure any changes in junction capacitance resulting from damage. Both a pulse and a dc technique were employed, and in neither case was any change in junction capacitance observable.

TEMPERATURE MEASUREMENTS. Before and after pulsing, several units were tested to determine the reverse current as a function of temperature at a constant one volt reverse bias. Figure 8 shows the results. The most striking feature is that the two curves are approximately parallel when the current is plotted on a logarithmic scale. Thus at all temperatures tested the current at one volt reverse bias after pulsing is larger than the current before pulsing by a constant multiplicative factor of 1.3.

Another current-voltage measurement was performed at constant (room) temperature. The ratio of post- to pre-damage current was a constant (1.37) in the reverse-bias millivolt range, i.e., from one to one hundred millivolts. The same ratio, taken at voltages above one volt, was emphatically not a constant. The change of this ratio with voltage was so rapid above one volt that we attempted to fit the current ratio versus voltage curve to an exponential function containing the voltage. A least squares fit to the data, assuming a simple exponential variation, yields

$$I_2/I_1 = 1.37 \exp (.252V)$$

where I_2 and I_1 are the currents after and before pulse induced damage, and V is the voltage across the diode. The fit is excellent from one millivolt to 20 volts, at which point the exponential function increases much more rapidly than the current ratio. This is due to the voltage drop in the bulk of the diode. The curve is shown in Figure 9. The slow variation of the exponential function in the millivolt range explains the apparent constancy of the current ratio at low voltages. The previous statement about the constancy of the current ratio at one volt reverse bias shows that the above equation is approximately valid to 100°C for this biasing level.

ANNEALING OF DAMAGE. One final and rather unexpected phenomenon was observed. When the damaged diodes were checked approximately six months after pulse testing, it was found that the damage in most samples, which had not been short circuited or open circuited, annealed out. Of the 15 samples which were examined so long after testing and which showed this annealing, all but one were within the original manufacturer's specifications (less than 100 microamps at 100 volts reverse bias) after conducting more than 100 microamps at only 20 volts reverse bias.

The anneal is definitely a long-term effect. Samples examined one week after pulse testing were still damaged. All were stored at room temperature with their glass cases still intact. It becomes difficult to construct a theory of damage which is consistent with this observation.

DISCUSSION

DAMAGE MECHANISMS. Several phenomena relating to second breakdown in germanium gold-bonded diodes have been described. While many of these can be explained, we are unable to account for some of our observations.

The most obvious consequence of second breakdown induced damage is a marked decrease in the reverse breakdown voltage as measured at a given current. The usual explanation for this occurrence is that local melting produces filamentary shorts across the junction. While this satisfactorily explains the increase in reverse leakage current, it cannot explain the unusual phenomenon pictured in Figure 7, i.e., greatly increased forward resistivity. We can include this effect by describing the damage as a filamentary short through (i.e., in parallel with) the junction plus a smaller resistance in series with the junction.

Even this combination, or any other combination of series and parallel resistances, is unable to explain all the experimental observations. The series resistance, while it can explain the increase in forward resistance, cannot explain why forward conduction does not begin before the application of approximately two volts forward bias. Nor can the parallel resistance explain the phenomenon shown in Figure 10, where we show the reverse current-voltage characteristic before and after damage. In both cases there exists a range of constant current with varying voltage*, i.e., $dI/dV = 0$. With a parallel resistance the current would always be expected to increase at least linearly with voltage. Finally, as shown in Figure 9, the ratio of reverse currents before and after damage varies exponentially with the applied voltage over five decades. Such behavior is hardly characteristic of a shunt resistance. Thus the addition of ohmic resistances is clearly unable to explain the experimental observations.

One experimental result which greatly aids the explanation of some of our observations is the decrease of effective minority carrier lifetime. We can explain the increase in reverse current as follows.[8] If the lifetime of holes in the n-type germanium semiconductor is short, the diffusion gradient will extend a short distance into the germanium, thus presenting a higher gradient than would be the case for a longer minority carrier lifetime. Since the value of the gradient is higher for short carrier lifetimes, the diffusion current of holes passing under the junction barrier will be larger and the reverse resistance of the diode will decrease. This seems especially reasonable when we recall that the reverse current in a germanium pn junction is primarily a diffusion current.[9]

The same phenomenon is responsible for the increase in the forward resistance of the diode. Holes below the top of the valence band give rise to an excessively large number of minority carriers in the n-type semiconductor. These extra holes diffuse into the semiconductor and provide extra current carriers in the neighborhood of the contact. In order to neutralize the space charge of these extra holes, there must be an equal number of excess electrons in their immediate vicinity. This is the phenomenon of injection of minority carriers, and its effect is to increase greatly the number of current carriers near the contact. In germanium gold-bonded diodes, most of the resistance to

*This result occurs after a current equal to $2 \times 10^{-6}V$ amps is subtracted from the current reading at an applied voltage V. This same linear component of current is present both before and after pulsing, and is apparently due to surface effects.

forward current flow is localized in a very small volume of the crystal in the immediate vicinity of the contact (the spreading resistance region). Since the spreading resistance is localized so near the point of contact, the effect of current carrier injection is to decrease the spreading resistance markedly, often by more than an order of magnitude. Indeed, the diodes tested had measured resistances of 1.6Ω, two orders of magnitude less than the 160Ω calculated for a hemispherical junction of 2Ω-cm material and a .002 cm radius gold contact. This is the measured resistance for the sample in Figure 7. Thus the pure resistance characteristic after the onset of forward conduction is due to the decrease in the minority carrier lifetime and the concomitant decrease in conductivity modulation of the spreading resistance by injected minority carriers. Briefly stated, an injected carrier whose lifetime is not long enough to allow it to traverse most of the spreading resistance region will not be able to have a significant effect on lowering the forward resistance.

Unfortunately, all samples exhibiting a voltage threshold for forward conduction annealed, and no equivalently damaged samples could be produced. Thus we were unable to perform lifetime measurements on samples suspected of having extremely short minority carrier lifetimes.

These ideas explain why the samples tested showed an increase in reverse conductivity and why many showed a decrease in forward conductivity. However, many diodes showed an increase in forward conductivity. In addition, calculations show that the 10 percent change in lifetime is not enough to account for all the increase in the reverse current, though it is a factor. It is also the only mechanism which can account for a small decrease in forward conductivity.

We now turn our attention to the often mentioned phenomenon of a high forward conduction threshold voltage for some damaged samples. A reasonable explanation is as follows. Suppose that during pulse testing the thin gold wire bonded to the germanium is melted near the contact point, and the contact point is slightly displaced. (This melting explains why the power required for damage was 800 watts, much higher than the average of 325 watts.) What results is a thin layer of GeO_2 (previously present) sandwiched between an n-doped germanium chip and a p-doped gold wire. It is observed that forward conduction occurs at approximately two volts at room temperature, and we propose that this is due to dielectric breakdown in the oxide layer. The breakdown electric field for amorphous GeO_2 is a strong function of many parameters, including thickness, uniformity, continuity, and especially the concentration of water vapor. Depending on these parameters, the breakdown electric field of GeO_2 can be anywhere from 10^5 to almost 10^7 volts per centimeter.[10] Taking an average value of 10^6 volts/cm, this would imply an oxide layer 200 angstroms, or 40 GeO_2 molecules thick, a not unreasonable number. This would certainly account for the suddenness with which conduction begins, and the intervening oxide layer explains why the effective lifetime of minority carriers, and thus minority carrier injection, is near zero.

We can even explain why the threshold voltage increases with increasing voltage sweep on the curve tracer. This effect is due to a larger power dissipation (i.e., a higher temperature) at higher voltage sweeps. Naturally occurring GeO_2 invariably assumes either an amorphous or a hexagonal crystalline structure. In either case, the breakdown voltage of a thin film would be expected to increase with temperature for the following reasons.[10] As mentioned, the breakdown voltage of a thin film of GeO_2 is heavily dependent on the concentration of water molecules in the film. As the sample is heated by the current passed after breakdown, any water in the film is evaporated, and the breakdown voltage is increased. As the sweep voltage is decreased, the water vapor returns to the film (due to the very high absorption and adsorption rates of GeO_2 for water vapor) and the breakdown voltage is decreased.

An alternative explanation makes use of the decreased path length of current carriers due to production of optical phonons at higher temperatures.[11] Even in damaged diodes, the reverse current at two volts is small enough so that the breakdown effect would not be noticed in the reverse direction.

DAMAGING POWER LEVELS. It is generally assumed (and measured) that it is harder to damage a diode in the forward direction; the higher currents involved in this direction produce a voltage drop across the bulk of the germanium chip with the consequent power dissipation in a region far from the device junction. Thus more power is needed to raise the junction to the same critical temperature.[12]

While the same reasoning applies in the case of germanium gold-bonded diodes, we cannot reach the same conclusion because of the unusual hemispherical geometry, Figure 1, as opposed to the more usual planar geometry of diffused diodes. In order to explain the mechanism responsible for this, we give first, an approximate mathematical, and then a more physical description of a diode undergoing second breakdown.

The following discussion is by no means intended to be rigorous. Indeed, the problem is not soluble in closed form, and we therefore employ some drastic approximations. We do this because our sole intent is to show that although the total power dissipations in forward and reverse cases are quite different and are opposite from the order expected; nevertheless, the power densities at the junction are nearly equal.

Plans are underway to solve the problem more exactly with the IBM-developed DTRAN computer code.[13] For the present, we assume ambient temperature throughout the diode and low field mobility values for holes and electrons.

Since the second breakdown observed in these diodes is a thermal phenomenon, it is clear that the power dissipation per unit volume will be an important parameter. The power dissipation per unit volume can be expressed as

$$\frac{P}{V} = J^2 \rho \tag{1}$$

where P is the power; V, the volume; J, the current density; and ρ, the resistivity.

The current density of interest is that measured at the junction (since it there has its largest value) and is equal to the total current divided by the area of a hemisphere,

$$J = \frac{I}{2\pi a^2} . \tag{2}$$

Using the previously stated average current values of 7.2 amps in the forward direction and 5.5 amps in the reverse direction, and the measured value a = .002 cm, we find J forward = 3×10^5 amps/cm^2 and J reverse = 2.3×10^5 amps/cm^2.

To find the resistivity ρ, we first compute the volume density of charge carriers, n, from

$$J = nev \tag{3}$$

where e is the electron charge and v is the velocity of current carriers. We first consider the use of forward conduction.

For the large currents and electric fields involved,[13] the velocity of carriers is equal to the saturation drift velocity of holes in germanium, $v = 1.2 \times 10^7$ holes/cm^3. The corresponding resistivity is .04Ω-cm.[15] Substituting into Equation (1) yields a forward power density of 3.6×10^9 watts/cm^3.

The calculation proceeds somewhat differently in the reverse direction. The large current is due to avalanching in the depletion region. During avalanche, an electron or a hole gives up a part of its kinetic energy to a neutral atom, forming an additional electron-hole pair. We thus expect that in heavy reverse conduction, the number of current-carrying electrons and holes will be equal.

A rough calculation of the electric field in reverse conduction yields an average value for the electric field of 50,000 volts/cm, well above the field required for saturation drift velocity. Since the saturation velocity is the same for both electrons and holes in germanium,[14] we proceed as in the forward case to find the number of carriers. The result is $n = 1.2 \times 10^{17}$ carriers/cm^3, i.e., 6×10^{16} each of holes and electrons per cm^3. The hole component of resistivity is .09Ω-cm and the electron resistivity is .05Ω-cm.[15] The conductivities are additive with a resultant resistivity of .032Ω-cm. Substituting appropriate values into Equation (1) yields a power density of 1.7×10^9 watts/cm^3 in reverse conduction, about half the value found in the forward case. We note, however, that the forward direction, which had the lower total power dissipation, had the higher power density at the junction. Thus, it seems quite reasonable that a more exact calculation would show the two power dens ties in the vicinity of the junction to be approximately equal. This result can be understood physically as follows.

The germanium chip is 2Ω-cm n-type germanium with a doping level of 8×10^{14} carriers/cm^3. Since the carrier density, as shown above is greater than 10^{17} carriers/cm^3, the mobility varies by less than a factor of two. Thus the conductivity varies nearly linearly with the carrier density. However, as shown, the carrier density varies with the current density. It follows that the conductivity varies with the current density. Unfortunately due to the variation of the conductivity, the problem cannot be solved in closed form; nevertheless, we can determine the general form of the solution from the physics of the situation.

As the current spreads out from the contact, the current density decreases. The smaller number of carriers causes a decrease in the conductivity, or, equivalently, an increase in the resistivity ρ. However, the power dissipation per unit volume is $J^2\rho$, which varies as the square of J and linearly with ρ. Thus the variation in J will be dominant, and the power dissipation per unit volume will decrease with distance away from the junction. This behavior is to be contrasted with planar junction diodes, where the current density is nearly uniform, so that the resistivity is constant and the power dissipation per unit volume is constant.

To get some idea of how the power dissipation per unit volume decreases, we perform here a necessarily crude calculation. We assume that the current flow from the contact is radial only. This will be an excellent approximation very near the contact, and a very poor approximation at the back surface of the chip where the current flow lines will all be parallel. We further assume that the conductivity is proportional to the current density due to the large number of carriers. Thus ρ is inversely proportional to J. Combining,

$$\frac{P}{V} = J^2\rho \propto J^2 \cdot \frac{1}{J} \propto J \propto 1/(r + a)^2 \qquad (4)$$

since radial flow of current means J falls off as $1/(r+a)^2$, where "r" is the distance out from the surface of the hemisphere, and "a" is the radius of the hemisphere. Since P/V falls off rapidly with distance, the poor radial flow approximation at the far end of the chip is not very damaging to our general result. We note again the crudeness of the above calculation.

The large power dissipation in the area of the contact will raise the junction temperature, but the above general arguments of power density decrease with distance from the contact, with small modifications, hold true even if the temperature rise is high enough to cause the intrinsic carrier density to be larger than 10^{17} carriers/cm^3. The current spreading is the dominant factor which distinguishes gold-bonded diodes from planar diodes. Indeed, if ρ is a constant, i.e., temperature, not current density, is the dominant factor in the resistivity; then $J^2\rho$ falls off as $1/(r+a)^4$, a very rapid decrease.

It is now clear why, unlike planar diodes, gold-bonded diodes can be damaged with less total power in the forward direction than in the reverse direction. In planar diodes, a larger total power is required for forward conduction damage because of power dissipation in the bulk. In gold-bonded diodes, however, the power dissipation per unit volume falls off rapidly with distance and power dissipation in the bulk of the device is of only limited importance. More important is the voltage across the depletion layer; this was approximately 60 volts in the reverse direction and only about one-half volt in the forward direction (since the depletion region widens under reverse bias and narrows under forward bias). In both forward and reverse cases, the voltage drop across the bulk was only five to 10 volts because of current spreading. Since the two currents differed by only 30 percent, the result is a larger total power in the reverse direction.

Gold-bonded diodes are not the only examples of pn junction devices with a higher probability of forward failure than reverse failure. Habing[16] observed that the forward and reverse current levels required to cause junction failure were nearly equal in the presence of ionizing radiation. He also attributes this effect to conductivity modulation, although the modulation mechanisms are obviously quite different in the two cases.

With the power densities now known, we are now in a position to further analyze the mechanisms by which damage is produced. The thermal constants in the following semiquantitative discussion are based on a device temperature of 300°K. Although the actual temperature during second breakdown is undoubtedly higher, the qualitative results will remain unchanged when the elevated temperatures are taken into account.

Calculations show that a uniform power dissipation per unit volume is not enough to raise the temperature of the gold-germanium contact to its melting point, but can only raise its temperature by about 150°C. (The melting point of gold is 1063°C; of germanium, 960°C.) Gold is, however, an excellent conductor of heat, and the gold contact in the present problem may be treated as a fair heat sink; its temperature would increase by less than 150°C in the case of uniform power density over the entire junction area.

Clearly, then, there must be a current constriction with localized heating, since, as seen in Figure 11, some melting does occur at the junction. The figure is a scanning electron microscope photograph of a diode damaged to the point of having a pure resistance characteristic. The photograph is looking at the hole left by the gold contact on the germanium chip after the contact had been removed. (The resulting hole, which should be roughly circular, does not appear so because the sample was mounted at an angle.) Inside the hole another smaller hole can be seen, and this is the area where melting took place and shorted out the junction.

Melting also occurs in open circuited diodes. In this case, the gold wire generally melts, resulting in electrical isolation of the chip and contact.

Figure 11 shows melting in a diode damaged to the point of being a pure resistance. In only partially damaged diodes, i.e., diodes which still rectify but have a much increased leakage current, we are unable to determine the exact mode of damage. Any melting which did occur would change the impurity profile by means of liquid state diffusion. The consequent increase in entropy would render the change irreversible and would not allow for annealing of the damage, although we are presently investigating the possibility that such a change may be reversible because of the segregation coefficients of the elements involved.

TENTATIVE THEORY

Any theory of second breakdown in gold-bonded diodes must be capable of explaining all the observed phenomena. We propose here a theory which, despite its simplicity, accounts correctly for a large fraction of the experimental results.

We propose that due to the difference in the coefficients of thermal expansion of gold and germanium (Au = $14.3 \times 10^{-6}/^{\circ}C$ and Ge = $6.1 \times 10^{-6}/^{\circ}C$) and the elevated temperatures, the gold germanium bond is weakened and perhaps disconnected at points. Any gap thus produced would be subject to oxide formation, water vapor, etc. This idea allows a qualitative explanation of several phenomena.

Lifetime and recovery time changes, for example, are easily explained by the increased surface recombination velocity at the side of the small gap.

Annealing of the damage can be explained as a result of the pressure exerted by the gold wire on the contact; over a period of time, the contact could be pushed far enough to close the gap. Alternatively, evaporation or surface diffusion of the water vapor could be an important factor.

Since the surface area of the contact remains unchanged, and the width of the gap is microscopic, the junction capacitance would be expected to show a negligible change. Other results can also be explained.

Perhaps the most important piece of supporting evidence for this theory is the behavior of the diode immediately after pulse testing. When a damaged sample was first viewed on a curve tracer there were indications that the bond was unstable. Several different characteristics could be seen in rapid succession at low voltage levels without changing the voltage setting. Once high currents (100 microamps) were allowed to flow, only one stable characteristic was seen. Apparently, even a small amount of heat was enough to stabilize the bond, though it could not return the bond to its previous configuration.

We are still unable to explain why the ratio of post- to pre-damaged reverse current varies exponentially with the applied voltage at constant temperature; why the reverse current at one millivolt after damage was first larger than and then smaller than the reverse current before damage as the temperature was increased; and other phenomena. However, we know of no other theory which can explain long-term annealing of the damage. Clearly, much work remains to be done in determining the damage mechanisms involved in second breakdown.

IMPROVING BURNOUT RESISTANCE

The discussion on heat transfer gives some hints as to how burnout resistance may be improved. Since much of the heat flow is toward the gold contact, it follows that increasing the size of the contact would leave less heat near the junction to cause damage. The steps necessary to produce a larger contact are clear; one merely performs the bonding step with either a longer or a higher amplitude current pulse, or some combination of the two. This allows more melting and hence a larger contact and a better heat sink.

The method does have its disadvantages. In particular, all other parameters being equal, the current will increase directly with the area of the junction. The area of a hemisphere of radius "a" is $2\pi a^2$; thus, the reverse leakage current will increase as the square of the radius of the hemisphere.

To a good approximation, which holds well for short pulse widths and larger contact areas, the same reasoning holds true for the heat flow into the contact, i.e., it increases as the square of the radius of the hemisphere.

Clearly, then, the reverse leakage current increases in direct proportion to the heat flow away from the junction. If the circuits can tolerate the additional reverse current, the larger contact will provide an enhanced degree of burnout protection.

CONCLUSION

Second breakdown in germanium gold-bonded diodes differs from that in diffused diodes. The concept of filamentary shorts through the junction has been shown to be invalid except at very high power levels. The power required to cause damage in the forward direction is less than that required in the reverse direction; this is due to the hemispherical geometry of these devices. The device geometry also indicates that the junction area may be increased to improve burnout resistance; however, the reverse leakage current increases proportionally.

The damage mechanisms are still not completely understood. Our tentative theory is unable to account for several of the observed phenomena, and it is difficult to construct a complete theory consistent with all the results of second breakdown, especially annealing of the damage.

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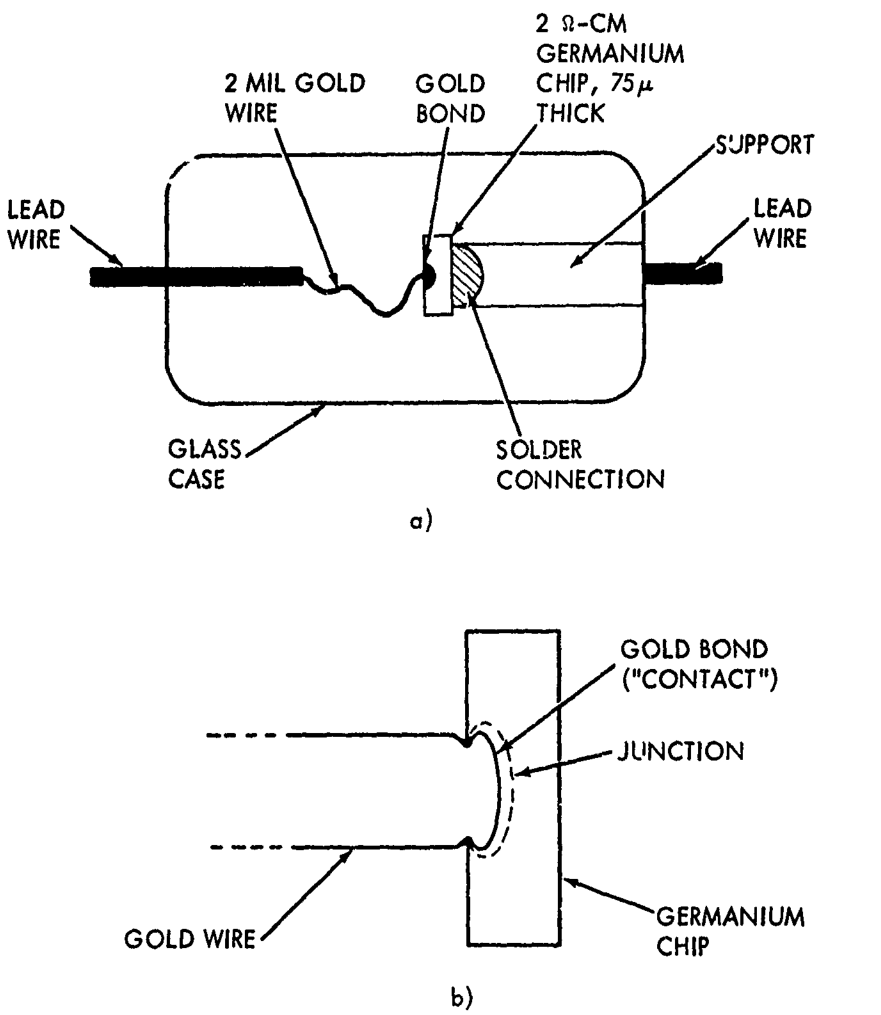
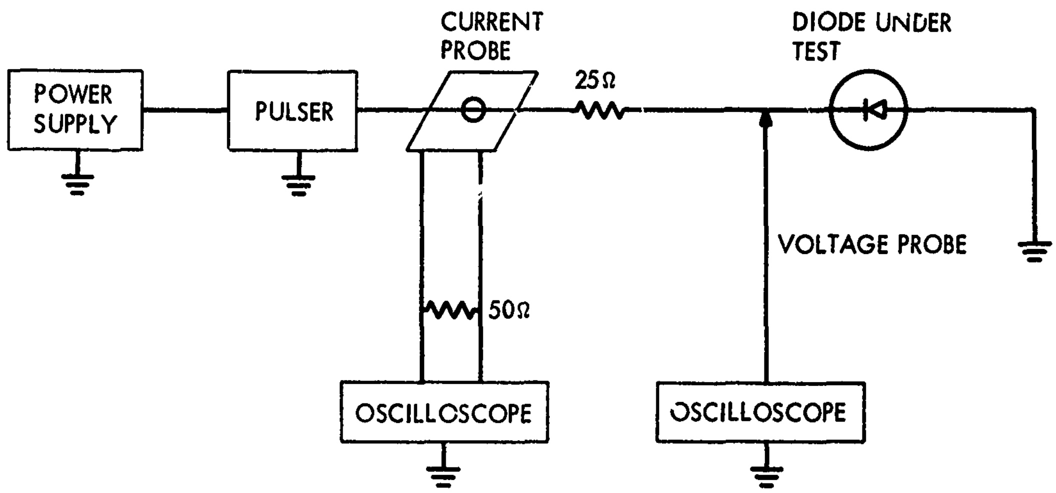


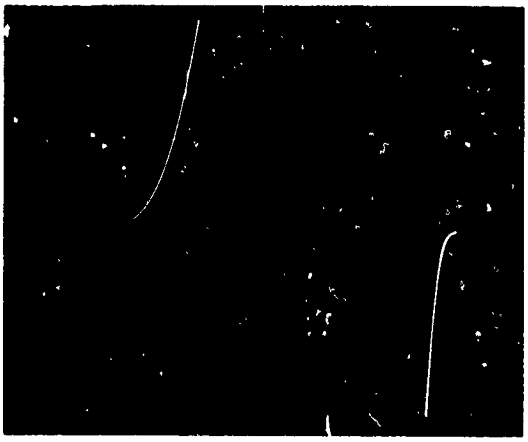
FIG. 1 a) CROSS SECTION OF A GERMANIUM GOLD-BONDED DIODE.
b) ENLARGED CROSS SECTION OF ACTIVE PART OF DIODE SHOWING THE HEMISPHERICAL GEOMETRY OF THE JUNCTION.



POWER SUPPLY - HEWLETT PACKARD MODEL 625-A
PULSER - SPENCER KENNEDY LABS MODEL 503-A
CURRENT PROBE - TEKTRONIX CT-2
VOLTAGE PROBE - TEKTRONIX P-6006
OSCILLOSCOPES - VARIOUS TEKTRONIX OSCILLOSCOPES

FIG. 2 TEST CIRCUIT

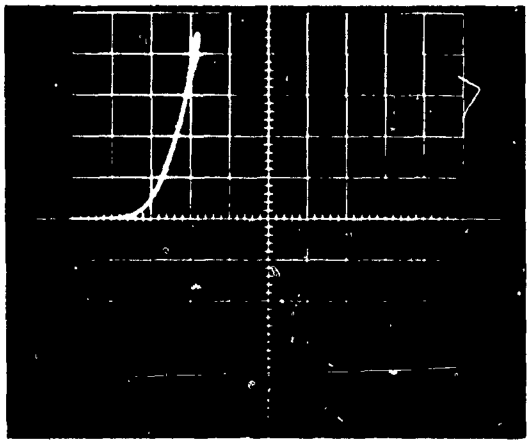
(a)



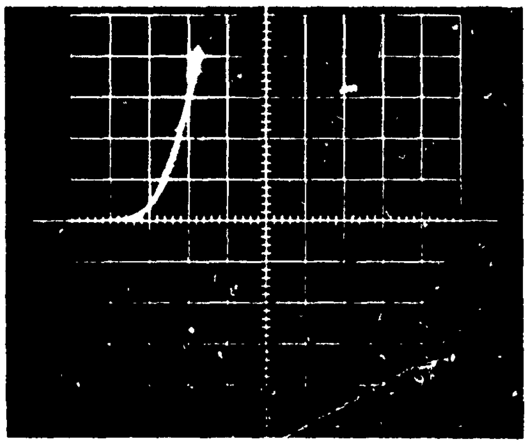
(b)

FORWARD: HORIZONTAL = 0.2 V/DIV, VERTICAL = 50 mA/DIV (LEFT)
REVERSE: HORIZONTAL = 20 V/DIV, VERTICAL = 20 μA/DIV (RIGHT)

FIG. 3 FORWARD AND REVERSE DIODE CHARACTERISTICS (a) BEFORE PULSE TEST AND (b) AFTER PULSE TEST



a) BEFORE PULSE TESTING

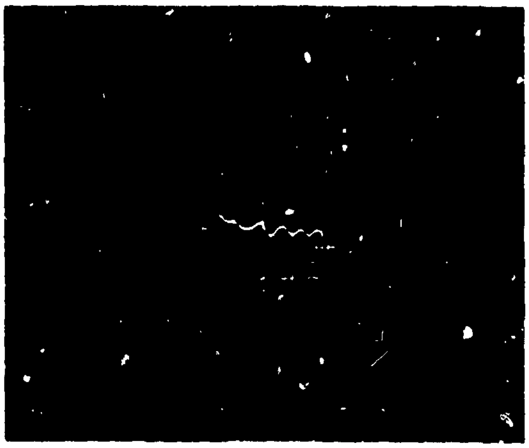


b) AFTER PULSE TESTING

HORIZONTAL = 0.2 VOLTS/DIV
VERTICAL = 50 MILLIAMPS/DIV

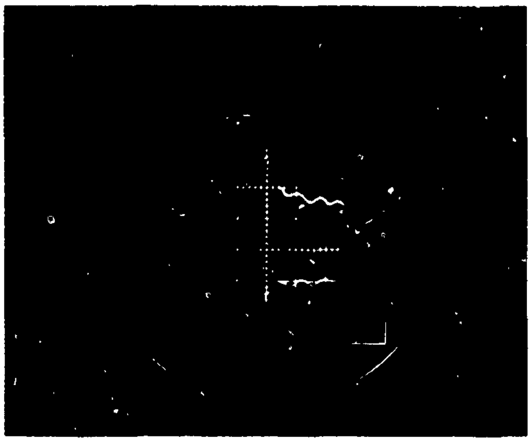
THE REVERSE BREAKDOWN VOLTAGE DECREASED FROM 130 VOLTS TO 16 VOLTS AT 80 μAMPS REVERSE CURRENT

FIG. 4 DIODE FORWARD CHARACTERISTIC



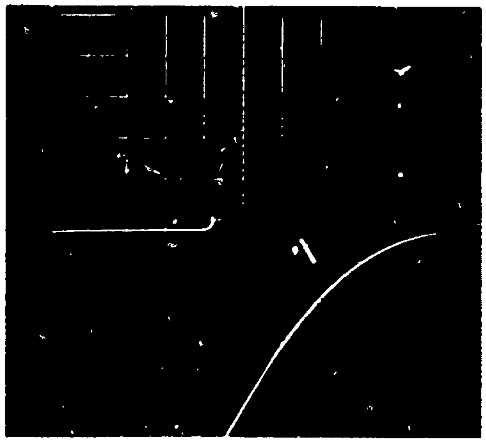
TOP: DIODE VOLTAGE = 100 VOLTS/DIV
BOTTOM: DIODE CURRENT = 5 AMPS /DIV
SWEEP SPEED: 20 NSEC/DIV

FIG. 5 CURRENT AND VOLTAGE TRACES DURING PULSE TESTING (REVERSE BIAS)

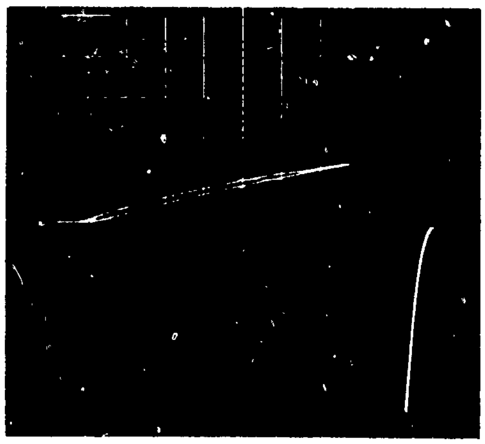


TOP: DIODE VOLTAGE, 100 VOLTS/DIV
BOTTOM: DIODE CURRENT, 5 AMPS/DIV
SWEEP SPEED: 20 NSEC/CM

FIG. 6 CURRENT - VOLTAGE TRACES DURING PULSE TESTING. THE SUDDEN DECREASE IN VOLTAGE AND INCREASE IN CURRENT MAKES IT CLEAR THAT SECOND BREAKDOWN HAS OCCURRED.



a) LEFT: FORWARD CHARACTERISTIC
HORIZONTAL = 0.5 V/DIV
VERTICAL = 20 μAMPS/DIV
RIGHT: REVERSE CHARACTERISTIC
HORIZONTAL = 2 V/DIV
VERTICAL = 20 μAMPS/DIV



b) LEFT: FORWARD CHARACTERISTIC
HORIZONTAL = 2 V/DIV
VERTICAL = 50 mA/DIV
RIGHT: REVERSE CHARACTERISTIC
HORIZONTAL = 20 V/DIV
VERTICAL = 20 μAMPS/DIV

FIG. 7 DAMAGED DIODE WITH FORWARD CONDUCTION THRESHOLD

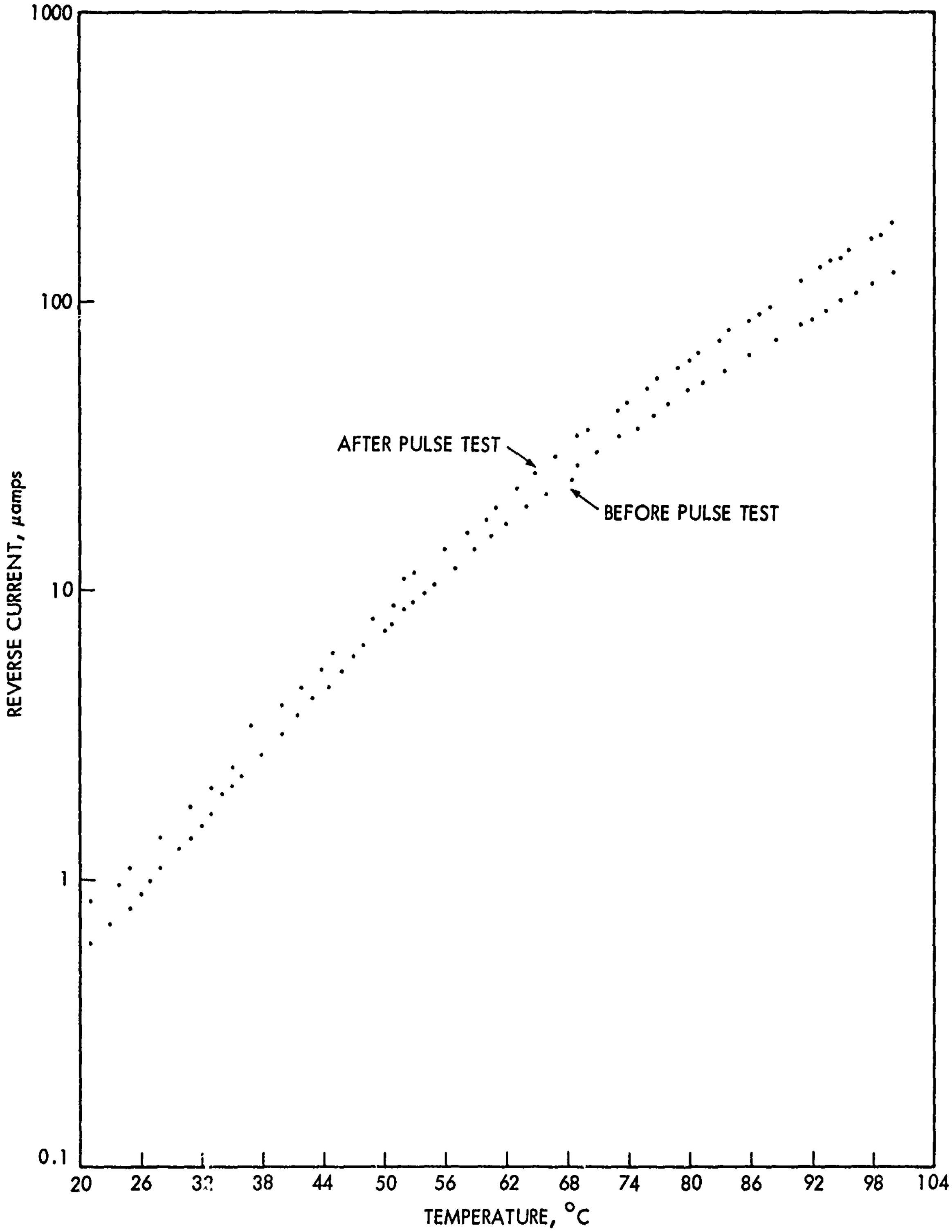


FIG. 8 REVERSE CURRENT VS. TEMPERATURE AT 1 VOLT BIAS

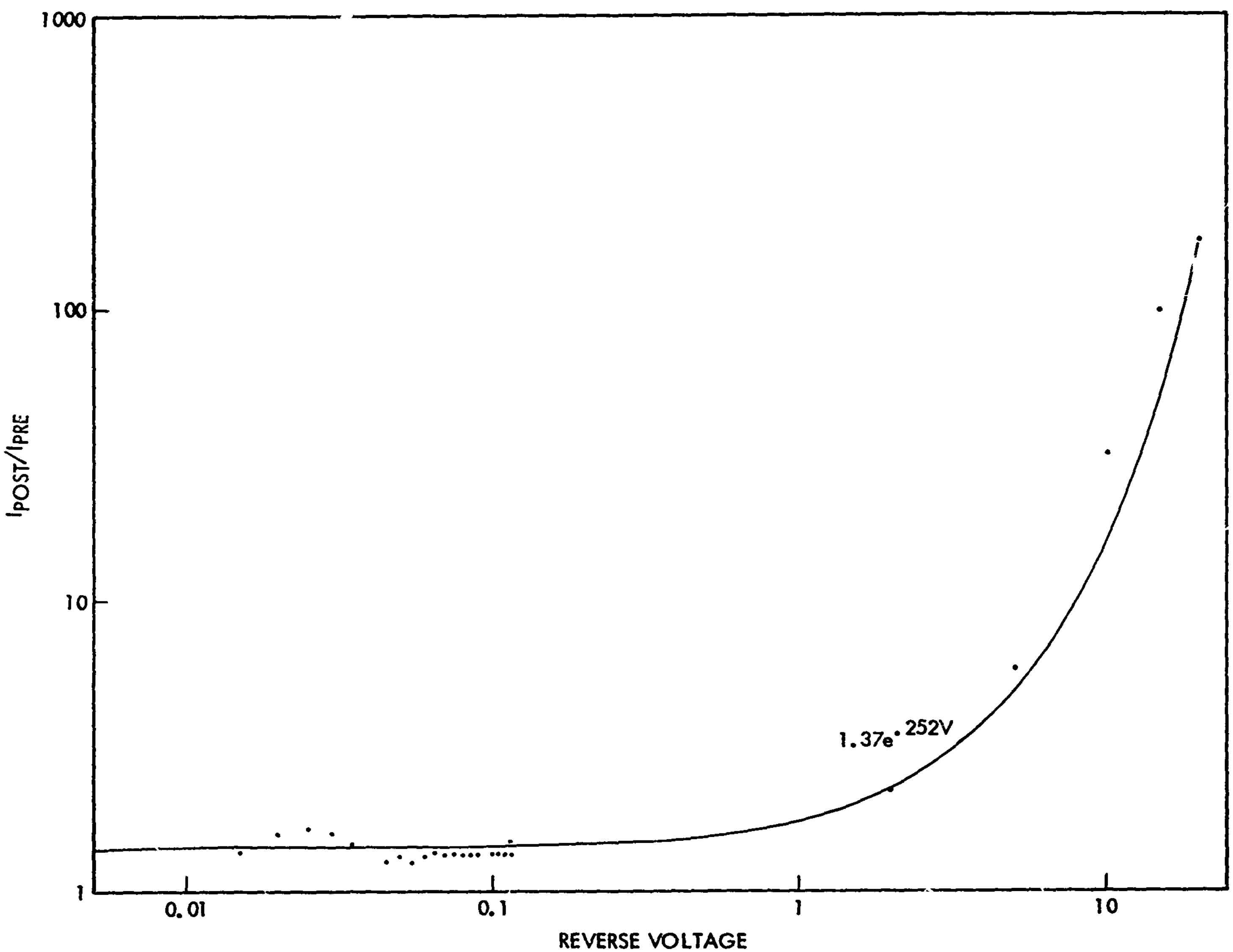


FIG. 9 (I_R POST-PULSE/I_R PRE-PULSE) VS. REVERSE VOLTAGE. EXPERIMENTAL POINTS AND LEAST SQUARES FIT CURVE (SOLID LINE).

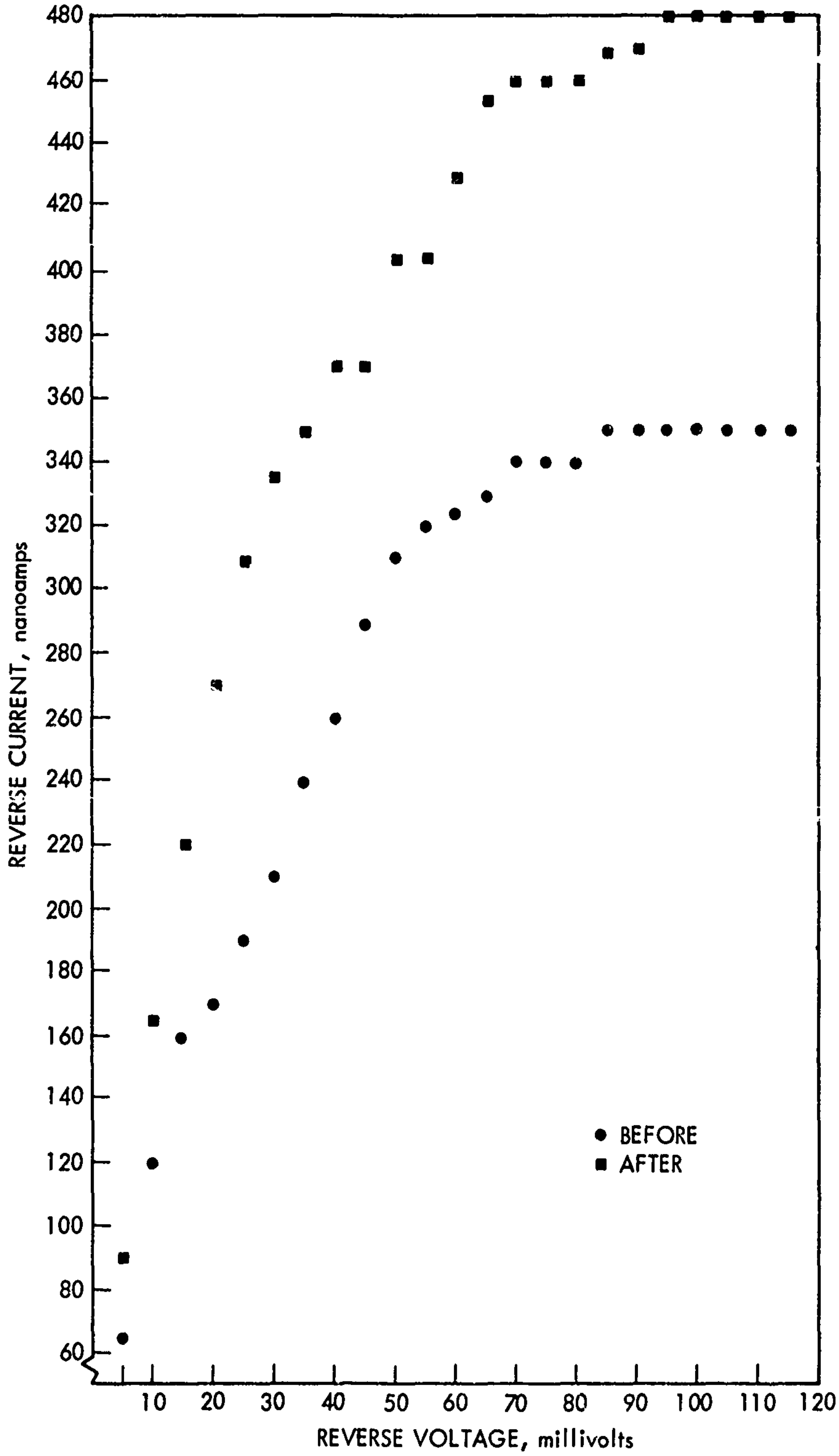


FIG. 10 LOW CURRENT-VOLTAGE TEST, BEFORE AND AFTER PULSE TEST

FIG. 11 SHORT CIRCUITED DIODE WITH GOLD CONTACT REMOVED. MAGNIFICATION = 400 X.