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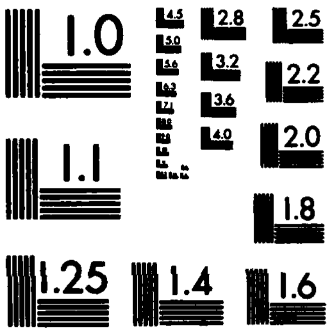


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# THE PHYSICS OF SECOND BREAKDOWN

Mark E. Snyder

November 1983

Final Report







AIR FORCE WEAPONS LABORATORY
Air Force Systems Command
Kirtland Air Force Base, NM 87117

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This final report was prepared by the Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico, under Job Order 37630155. First Lieutenant Mark E. Snyder (NTAT) was the Laboratory Project Officer-in-Charge.



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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This report details the phenomenology of Second Breakdown in semiconductor materials. This phenomenology is then investigated and explained in the light of solid state physics and known experimental results. The similarity between Second Breakdown and current controlled negative resistance is shown to lead to the conclusion that current and thermal mode breakdown is explained by plasma injection.

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## ILLUSTRATIONS

# I. INTRODUCTION

All solid state electronic systems are designed to operate with a margin of safety to prevent system impairment or failure due to electrical overstress (Ref. 1). To enhance the margin of safety, the environment surrounding most systems (e.g., shielding, leads, and ports of entry) is stringently controlled and electrically isolated. However, in some cases the enhancement provided by the environment may be minimal or nonexistent. Thus, if the system's margin of safety is small, a large electrical overstress caused by a nuclear electromagnetic pulse, lightning, or system-generated surges may jeopardize the system's operation.

Therefore, to maximize the margin of safety for a solid state electronic system, the designer must know the conditions under which individual semiconductor components will become unstable, degrade, or fail. With this information, the designer can choose the appropriate components to provide a margin of safety for the system at some acceptable level of confidence. Unfortunately, attempts to determine the conditions under which a semiconductor device is degraded or fails have met with limited success because the models developed for this purpose cannot adequately explain the actual physics of failure or the associated phenomena called Second Breakdown. The reason for this is brought out later in this report. Nevertheless, these models are still being used to determine the susceptibility of large scale weapons systems to transient electrical overstress. Thus, a strong impetus exists to further the scope of our knowledge in the area of device failure, and in particular, Second Breakdown.

Extensive research on Second Breakdown phenomenon started with its discovery in the 1950s (Ref. 2).

Initially this research was applied to new device design, but interest in device failure soon became the sole driving force for continued Second Breakdown investigations.

However, this concentration of Second Breakdown research in device failure soon led to a heavy reliance on first order empirical modeling, leaving progress toward a broader understanding of the physics of Second Breakdown elusive. This lack of understanding can be quantized by stating the two questions present research has failed to answer: (1) What are the processes and parameters that control Second Breakdown? and (2) under what conditions is Second Breakdown initiated?

This report attempts to answer these questions by qualitatively examining the basic experimental evidence on documented Second Breakdown phenomena and exploring the fundamental solid state physics that elicits this phenomena. A follow-on report will contain a more quantitative approach to the theories presented in this report.

## II. EARLY MODELS TO DETERMINE FAILURE LEVELS

Before presenting the experimental evidence on Second Breakdown, the two empirical models that strongly influenced the direction of Second Breakdown research are examined.

The first attempt to model failure levels in semiconductors was made in 1968 by D.C. Wunsch and R.R. Bell (Ref. 3). The Wunsch-Bell model is based on a semiempirical formula derived from experimental data and a simple thermal failure model. By using the appropriate experimental values and the device's junction area it was possible to determine, within an order of magnitude, an estimate of the thermal failure level of the device. The model did not attempt to explain any other related phenomena (such as Second Breakdown) that were observed before device failure.

This important deficiency was intentional since the model was only intended to be an approximation. As such, its applicability was limited only to those cases where:

1. The simple thermal model's geometry and thermodynamic conditions were applicable to the device being modeled.

2. Failure was thermally induced in the bulk of the device.

Further experimentation using the Wunsch-Bell model continued to confirm its limited ability to determine device failure levels and failure phenomena.

In 1970, D.M. Tasca published the results of a new model to determine device failure levels (Ref. 4). The Tasca model incorporated a more detailed thermal analysis than the Wunsch-Bell model in the belief that this would make the model more versatile in application. However, continued experimentation showed that the Tasca model suffered from the same limited approximate nature as the Wunsch-Bell model.

Although the success of these two models was limited, they were and are still used extensively to determine device failure levels. Their continued use led to more research along the same semiempirical vein in an effort to improve upon model precision. Thus, very few attempts to determine the actual physics of Second Breakdown were attempted.

The results of experimentation with the Wunsch-Bell and Tasca models appear to point future research in divergent directions. One direction points to pursuing the semiempirical approach in more depth in the hope that a larger number of tests, model refinements, or improved statistics may result in better model precision. But, the assumptions and inaccuracy of empirical models inherently fail to account for all the actual processes and causes of device failure. These drawbacks prevent these models from precisely portraying Second Breakdown or the actual thermal failure level of devices. Hence, a second more promising direction that originates from the results obtained for these two models involves determining the actual physics of Second Breakdown to predict device failure levels that are consistently based in known semiconductor device physics.

With this last thought in mind, the remainder of this report brings together those bits and pieces of the Second Breakdown puzzle to determine how they fit together within the framework of Solid State Physics.

## III. GENERALLY OBSERVED CHARACTERISTICS OF FAILURE/DEGRADATION OF SEMICONDUCTOR DEVICES

The original experiments of Wunsch-Bell and Tasca employed a device failure criteria defined as the point where the device is destroyed or permanently degraded. Theoretically, if semiconductor devices all failed according to a simple thermal model, then a repeatable trend would become obvious in plots of power versus pulse length. The results of their experiments generally verified this belief (Refs. 3, and 4), but with the added complication of a very significant scatter (i.e. wide standard deviation) in the data. Therefore, the simple thermal model was generally correct but the precision was poor at the individual device level.

Attempts to improve on model accuracy and precision led to the investigation of Second Breakdown phenomena as the criteria for device failure. Continued testing with these criteria did not improve upon model accuracy or precision and, in fact, resulted in a larger diversity of data for some devices that was difficult for experimenters to explain in terms of a thermal failure (Ref. 5). These new data showed some devices exhibiting Second Breakdown under two distinct conditions: (1) High power short pulse width (less than 0.1 μs), and (2) High power long pulse width (greater than 0.1 μs). The first condition was called fast breakdown or current mode breakdown. The second, was the more familiar thermal breakdown (Ref.5).

Postmortem examinations of devices under both failure criteria showed excessive localized heating that would either cause thermal shock or soldered leads to fall away from the semiconductor chip. This indicated that internal device temperatures were approaching and exceeding the melting point (MP) of the semiconductor materials (silicon's MP is 1420°C and germanium's MP is 936°C).

Together, these generally observed characteristics demonstrated that Second Breakdown was a more complex phenomenon than originally thought. Thus, determination of the physics of Second Breakdown will require an in-depth analysis of all the possible parameters and processes discerned from experimental results.

## IV. SPECIFIC EXPERIMENTAL INVESTIGATIONS OF SECOND BREAKDOWN

A singularly distinct characteristic of Second Breakdown is the formation of current constrictions inside a semiconductor sample or device. The increased current density in the constrictions induces strong localized heating (as noted in section III) which causes the region of the constriction to actually melt (Ref. 6). Experimenters referred to this melt, or current constriction, as microplasma. The microplasma can grow quickly in a semiconductor becoming a giant plasma or mesoplasma (Ref. 7) which can engulf the entire electrically active region of a device.

The formation of a microplasma occurs simultaneously with a rapid (sometimes discontinuous) drop in voltage with increasing current, as seen in Figure 1. When more than one microplasma formed experimenters found that an equivalent number of Second Breakdown transitions would occur in the I-V characteristics as shown in Figure 2 (Refs. 8, 9, and 10). Yet, no direct empirical connection between the type or magnitude of transitions and the microplasmas seemed apparent.

Further experiments determined that the microplasma was not occurring haphazardly in semiconductor devices or samples. The regions of formation were predictable enough to determine some of the major parameters that appeared to affect microplasma formation. Those factors are heating, high electric fields, and defects. Therefore, each of these factors are examined separately to determine their contribution in Second Breakdown phenomena.

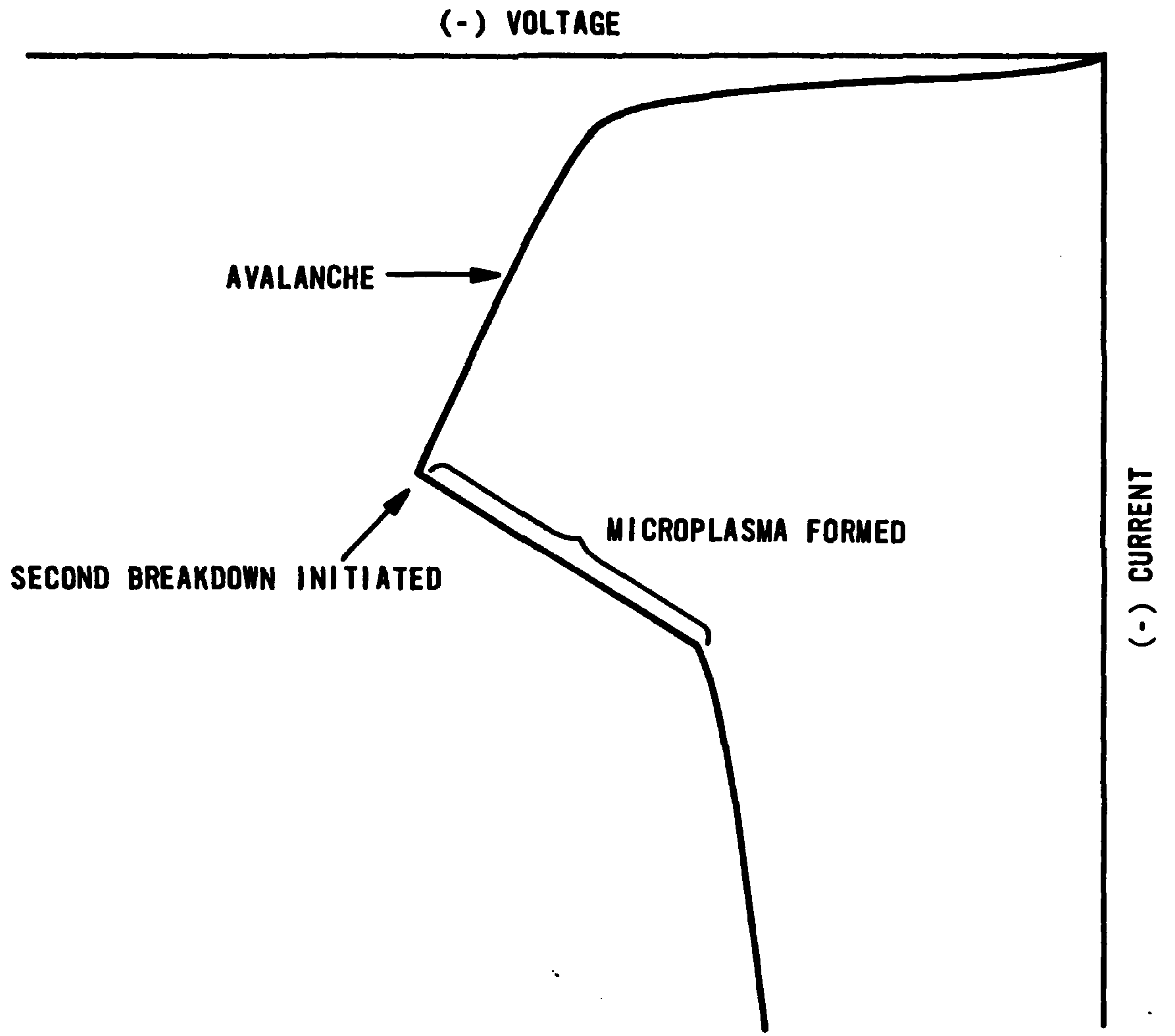


Figure 1. Formation of a single microplasma in a reverse-biased diode (not to scale).

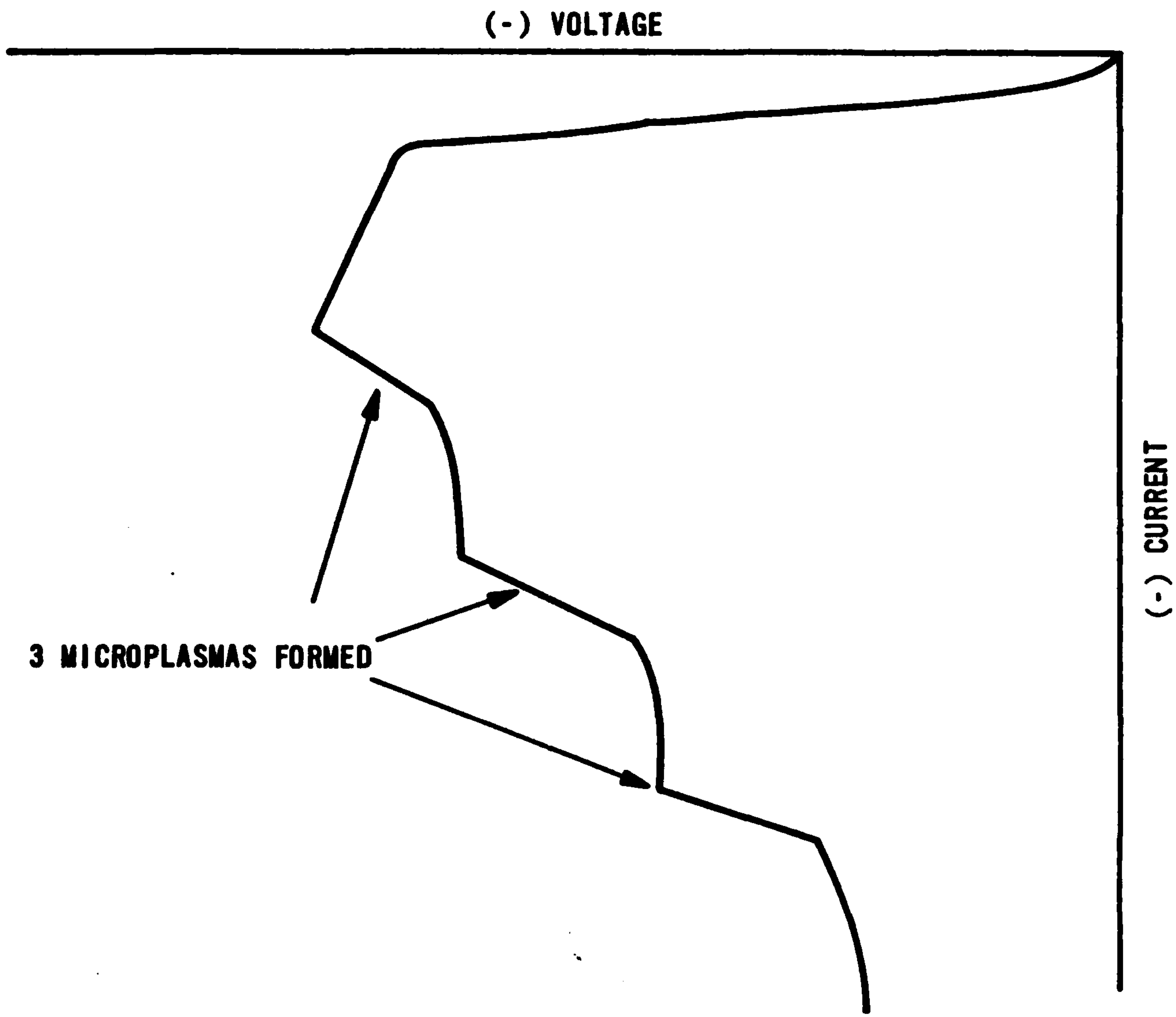


Figure 2. Formation of three microplasmas in a reverse-biased diode (not to scale).

## 1. HEATING

Heating occurs in the electrically active regions of all devices to some extent. It is in these regions that microplasmas form initially (Ref. 11). Proponents of early thermal failure models believed that a plausible explanation of this effect is obtained from observing Figure 3, a graph of the resistivity versus temperature of doped Silicon. Figure 3 shows for lightly doped material ($10^{13}$ carriers/cm$^3$), the resistivity begins to decrease after the intrinsic temperature of the material is surpassed. This is attributable to the increasing number of carriers available from the valence band due to thermal excitation, far outnumbering those available from the impurity levels. Hence, the resistivity falls (the conductivity rises) with increasing temperature.

Thus, certain regions of a device could possibly exhibit a lower resistivity and draw a higher current density possibly forming a microplasma (Ref. 13). This argument for microplasma formation appears to be less plausible when the material is highly doped ($\geq 10^{17}$ carriers/cm$^3$). The difference in resistivity on both sides of the intrinsic temperature becomes smaller as the doping increases, making microplasma formation via differences in resistivity very unlikely at high dopant levels.

However, it should also be noted that Figure 3 applies to a semiconductor sample experiencing ambient heating from an external source (such as an oven). Under high current injection levels and high internal electric fields (as a device would experience in Second Breakdown) this graph is not directly applicable. At high temperatures and high electric field the carrier mobility drops dramatically (Refs. 14 and 15) in semiconductor materials. This in

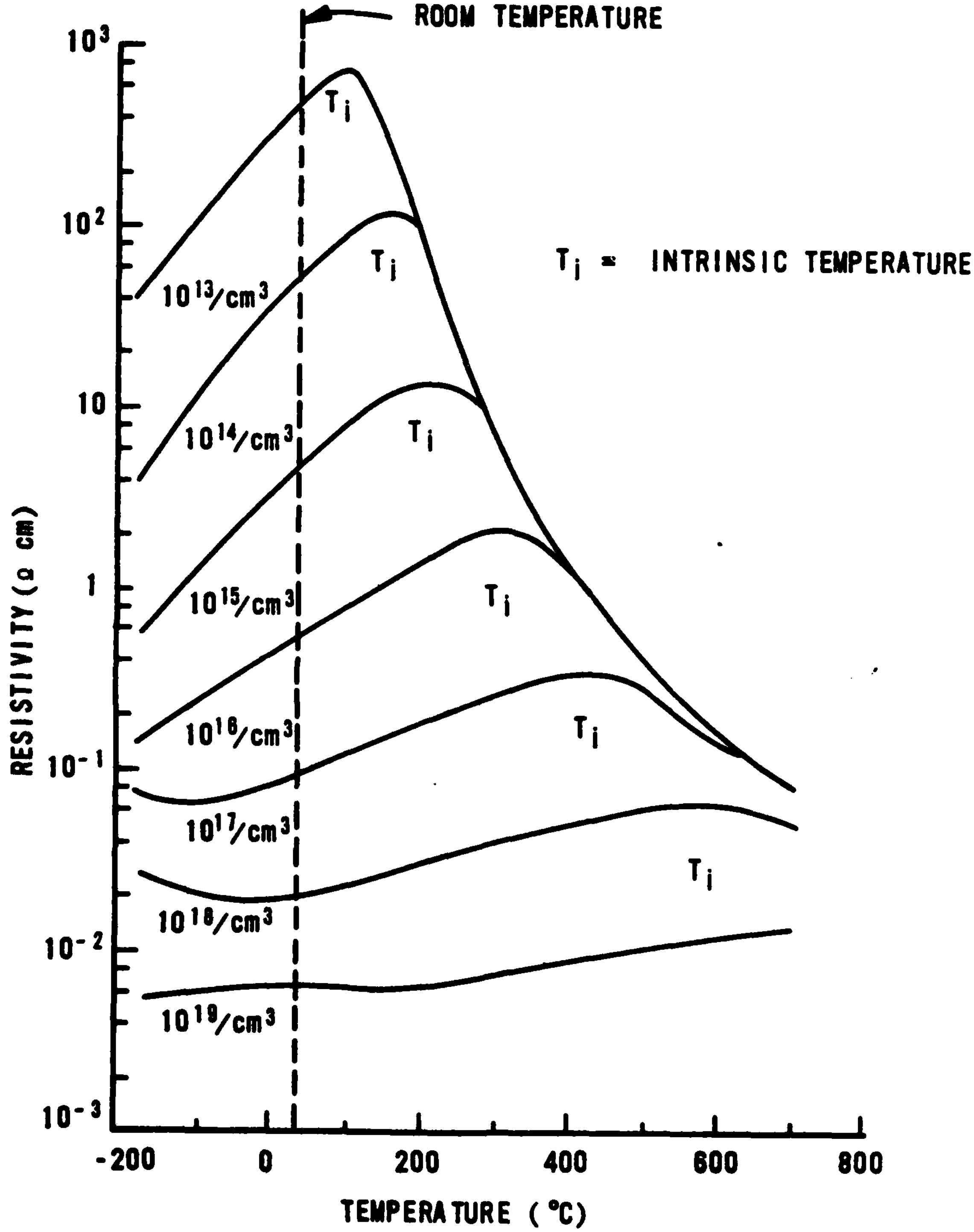


Figure 3. Silicon resistivity versus temperature (Ref. 12).

turn limits the increase in material conductivity (Ref. 15) due to thermal excitation of carriers, preventing a device from exhibiting the low voltage, high current, I-V characteristic normally seen in overstress testing to failure.

Thus, a semiconductor device experiencing high internal fields and strong heating would rapidly approach the voltage of the overstress simultaneously with a rapidly increasing current until an open circuit condition occurs due to device melting. Internal device heating provides no physical mechanism to pin the voltage at a low level as seen in Second Breakdown I-V characteristics. Additionally, no thermal mechanisms exist to explain the formation of multiple microplusmus in semiconductor materials or devices. Therefore, it appears that heating alone is inadequate to explain the initiation of Second Breakdown.

## 2. HIGH ELECTRIC FIELDS

Another parameter that appears to affect microplasma formation is high electric fields. Most semiconductor devices have regions that exhibit higher electric fields than the rest of the device. This can be due to abrupt diffusion profiles, angular metalizations (Ref. 16), or sharply curved depletion regions (Ref. 17), as shown in Figures 4 and 5. These figures show that as the device bevel angle increases, the bulk electric fields get much stronger. Since avalanche breakdown requires an electric field strength of at least $1 \times 10^5$ V/cm to occur, these regions of high electric fields can initiate local avalanche breakdown before the rest of the bulk material reaches avalanche. This creates regions of higher carrier concentration that could possibly draw a large amount of current, forming a microplasma and Second Breakdown. Since most of the bulk electric fields that occur in a device are near the surface

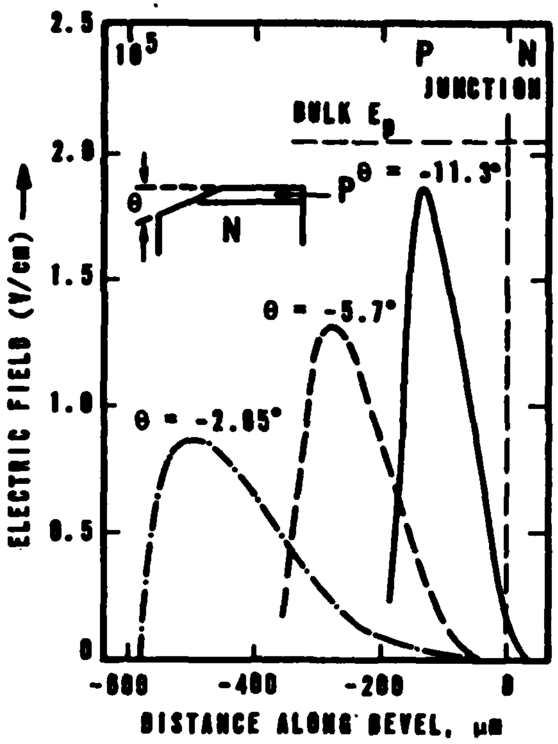


Figure 4. Field distribution on the surface for a 2000-V reverse biased P+N diode structure with three different bevel angles (Ref. 17).

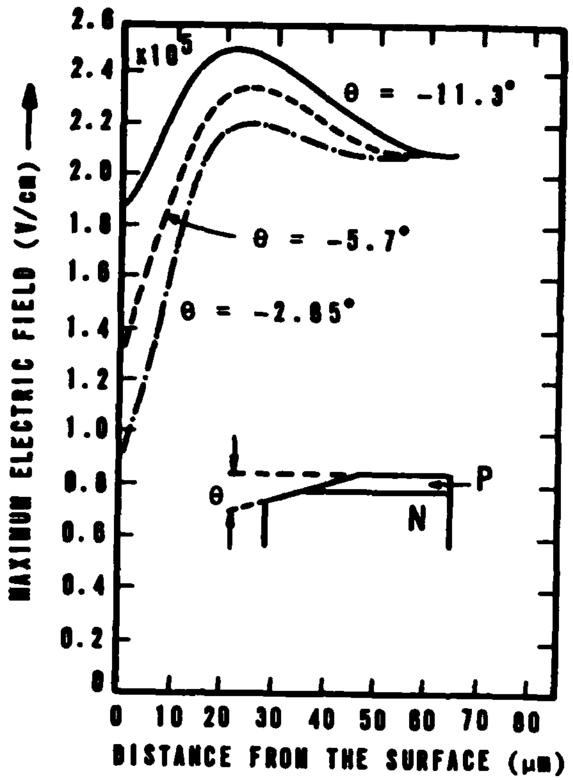


Figure 5. Maximum Field as a function of the distance from the surface for the above diode with three different bevel angles (Ref. 17).

due to device geometry and construction,this appears to explain the initiation and operant mechanism of surface Second Breakdown (early postmortem examinations by Tasca revealed failure at or near the surface of failed devices).

The only argument against avalanche breakdown as the sole operating mechanism of Second Breakdown in the bulk and surface is the temperature dependence of avalanche breakdown. As the local temperature increases the electric field necessary for a mobile carrier to create more carriers via impact ionization becomes larger. Since the carrier is losing so much energy to heat vibration (known as phonons) there is not enough energy left in the carrier to sustain impact ionization. Thus, avalanche breakdown dies out as the temperature increases.

Yet, it is plausible that the material's temperature dependent resistivity becomes dominant as avalanche dies off. This action, coupled with velocity saturation, develops into a somewhat unexplored regime of operation that may take on the qualities seen in Second Breakdown. However, the carrier mobility in a semiconductor decreases with increasing field. This action limits the current density with increasing field and makes Second Breakdown characteristics difficult to achieve at or beyond velocity saturation. In addition, the mechanisims at work here give no physical explanation of the difference between Thermal and Current mode Second Breakdown, nor do they provide physical support for microplasma formation.

## 3. DEFECTS

Defects occur in all semiconductor devices to various degrees (Ref. 18). The kind of manufacturing process and types of diffusions used normally determine the type and overall quality of defects present in a device (Refs. 19 20, and 21). Some device lines may have a wide variety of defects present, although the actual density of defects is not normally known with any accuracy. In solid state physics, a defect is defined as an imperfection in the periodic lattice of a semiconductor (i.e. a dislocation, interstitial or surface). Any impurity introduced into the lattice can interlace an imperfection creating a locally enhanced electric field which can interact with carriers or other nearby imperfections. The electric field associated with this defect can, under increasing electrical stress, induce highly localized impact ionization initiating localized avalanche breakdown or the defect can become a thermally activated source of carriers creating a localized high current density. Either of these situations may set-up the conditions necessary for Second Breakdown to occur before complete bulk avalanche breakdown is initiated. Physical support for this assertion is partially provided by an experiment that has shown highly localized defects are more likely to be locations for Second Breakdown (Ref. 22) to occur. This also implies that a homogenous distribution of defects would have less of an effect on initiating Second Breakdown since the initiation of electrical activity due to defects would be quite uniform in the device (Ref. 23).

In larger devices, defects normally play a more minor role in inducing avalanche breakdown, unless the defect is physically large. If the density of such defects is high, their role as thermally activated sources of carriers may be important in aiding microplasma growth once Second Breakdown is possibly initiated by bulk avalanche breakdown. Therefore, defects in a large device could play the role of initiating localized avalanche breakdown and supporting microplasma growth by thermal generation of carriers.

Other factors that affect Second Breakdown can be related to the three areas (heating, high electric fields and defects) already mentioned. For example;

1. The impurity profile determines what the magnitude and distribution of the electric field will be. It also affects the density and distribution of defects in the device. Thus, the type of impurity profile used in a device could affect Second Breakdown.

2. The geometry of a device determines essentially where the microplasma will occur, since the geometry affects both heating characteristics and electric field distribution.

3. The type of material also affects the occurrence of a microplasma. The basic electrical characteristics of semiconductor materials (e.g. silicon and germanium) are controlled by the width of the band gap. Wide band gap materials (e.g. silicon) exhibit a higher resistance to microplasma formation than narrow band gap materials, such as germanium (if other factors that affect Second Breakdown are excluded). A wide band gap material has a higher avalanche threshold and can be more extrinsic over a wider temperature range. Therefore, an extrinsic material will not become intrinsic until a much higher temperature is reached compared to a narrow band gap material. Also, the structure of the bands and band gaps of semiconductors and insulators may provide other nonlinear effects under high electric fields and temperatures.

Qualitatively, there are a number of facts known about Second Breakdown and microplasma formation. For example, careful observations show that the mechanisms for initiating Second Breakdown seem to be coherent, as explained previously, but explain little about the variation in breakdown found for a family of devices. Thus, questions concerning the operant mechanism of Second Breakdown and the relationship between thermal mode and current mode breakdown and their predictability, must be answered by discerning a basis in the framework of solid state physics using the facts learned from specific experiments on Second Breakdown.

## V. INTERPRETATION OF EXPERIMENTAL EVIDENCE

To review the major theses presented so far, it appears that in general;

1. Avalanche breakdown may set up the conditions for Second Breakdown (thermal or current mode).
2. Microplasmas form in current mode and thermal mode Second Breakdown.
3. Microplasmas occur at predictable points (i.e. the depletion region of a device).

The experimental evidence presented in Chapter IV supports these assertions, but a theoretical basis to explain them directly is lacking. Also, there are numerous auxilliary facts which must fit into any theoretical explanation of the phenomena.

From a solid state physics point of view, the microplasma is the most dominant phenomena that needs explanation, since understanding the microplasma may provide clues to the transport mechanism involved in Second Breakdown.

### 1. MICROPLASMA GROWTH

The most dominant driving force once a microplasma forms, is heat. Although the initial driving force may be electrical, this soon gives way to an exclusively thermal driving force, terminating in device degradation or destruction. This provides a clue to explain the rapid growth of the microplasma into a mesoplasma.

Most devices contain impurities, such as gold (Fig. 6), which reduces the lifetime of the carriers by acting as a recombination center (a sink for carriers) which increases the switching speed of a device. Devices also contain defects in varying proportions in and around the depletion regions. These defects have a tendency to form at midgap energies in the semiconductor band gap structure, where they act in the same capacity as a gold impurity (Fig. 6).

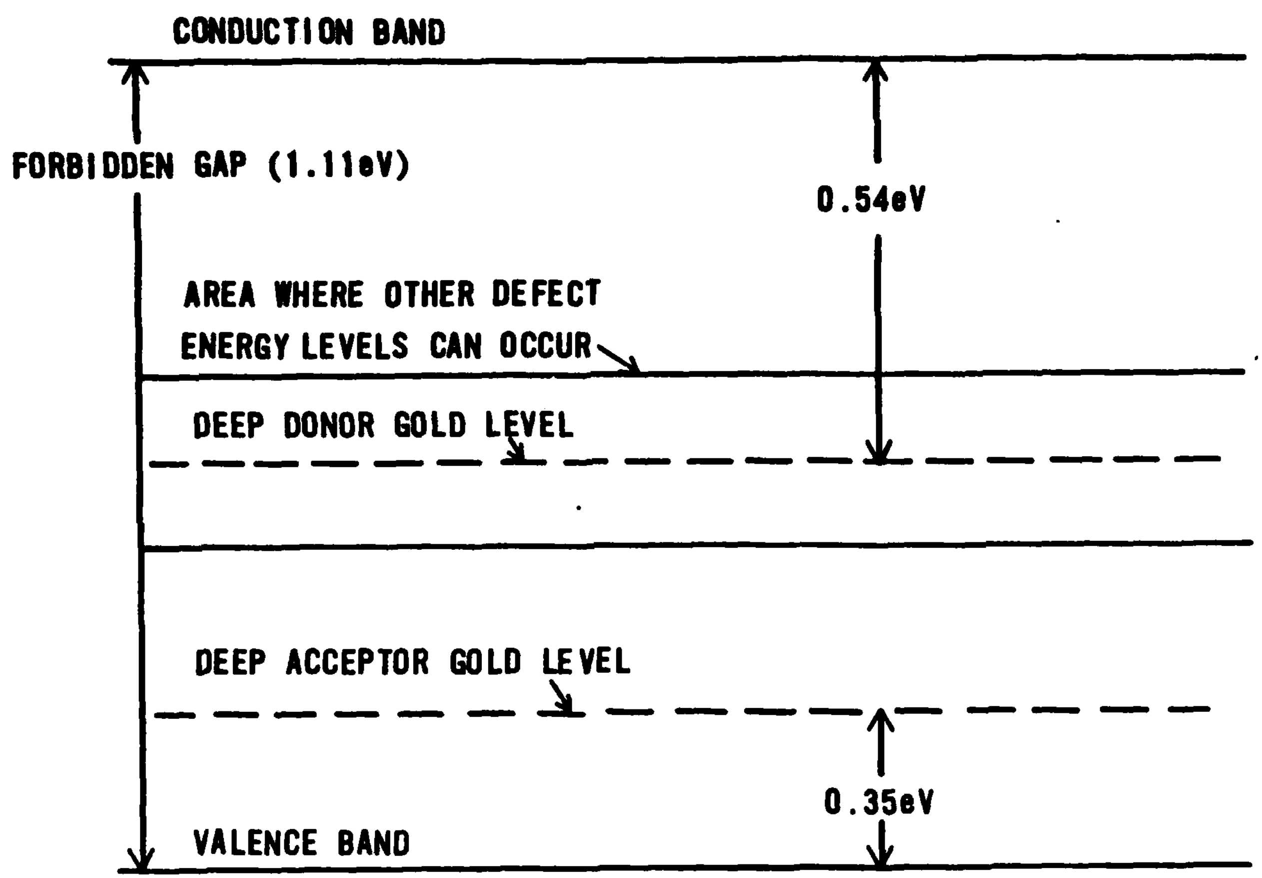


Figure 6. Energy band diagram for silicon showing the locations of energy levels for gold impurity and possible defect levels (Ref. 24).

These impurity or defect centers act as thermally activated sources for carriers in a reverse biased depletion region instead of a sink for carriers as occurs under forward bias conditions. Their presence is often noted in increased levels of reverse bias leakage current in diodes. As the temperature increases, the rate of carrier generation from impurity or defect levels increase very rapidly (doubling for every 11$^{o}$C temperature rise in silicon) (Ref. 25). Therefore, strong heating in the depletion region could provide a very large number of carriers to supply microplasma growth. Even if there are no impurity levels in the band gap, direct excitation of carriers from the valence band to the conduction band by heating would eventually supply a large number of carriers also, although the necessary temperatures would be much higher than the latter.

Thus, a microplasma, aided by device heating, would grow very rapidly to engulf the entire electrically active region of the device, assuming of course that thermal shock did not destroy the device first.

An interesting prediction of this concept of the microplasmas source of carriers portrays devices with gold doping or a high density of defect levels as exhibiting microplasma formation at lower levels of excitation than those devices that do not contain gold doping. Until recently, this prediction was untested, but newly published evidence has found that those devices with gold doping exhibited Second Breakdown at consistently lower levels than similar devices without gold doping (Ref. 16).

Although this concept of microplasma growth appears to meet with limited success, it does not give a clear description of all aspects of microplasma formation.

The strong temperature and field dependent qualities of the mobility restrict any rapid increase in a device's localized current density. And heating alone appears incapable of forcing a homogenous current distribution into a single channel. In other words, the temperature controlled negative resistance aspects of silicon (or any other semiconductor for that matter) does not appear to be adequate enough to support microplasma formation and growth alone.

To obtain a clearer picture of the aspects of microplasma growth and formation, a slight digression is made into basic Solid State Physics in the next subsection.

## 2. THE TRANSPORT PHENOMENA OF SECOND BREAKDOWN

The electrical characteristics of a semiconductor sample are usually determined by the type of charge or carrier transport. The two types of carrier transport are called double carrier injection and single carrier injection. As the names imply, either both types of carriers (holes and electrons) carry current or only one type of carrier participates.

In single carrier injection only one type of carrier handles the majority of current flow in the sample. This is normally due to trapping centers deliberately introduced to reduce minority lifetime (compared to the majority carriers lifetime) making them ineffective. Such single carrier currents are limited by the amount of excess space charge built up by the majority carrier near the opposite electrode in the sample.

If the voltage level is increased enough, the injection level of the nonparticipating carrier becomes high enough to fill the available trapping centers (increasing carrier lifetime) and allowing the excess minority carriers to participate fully in carrying current. This results in the initiation of double carrier injection.

Double carrier injection can also occur when impact ionization starts avalanche breakdown. If a carrier has enough energy it will impart this energy via impact ionization to create an electron-hole pair which then participates in current conduction and goes on to create more carriers. Thus, regions that are in avalanche before the bulk exhibits double carrier injection can carry more current than other areas using single carrier injection. Once double carrier injection occurs, via avalanche breakdown, it can be quenched by increasing the free carrier concentration throughout the sample. Using strong optical illumination, ambient heating or ionizing radiation will increase the number of available carriers and hence the conductivity throughout the sample. This increase in conductivity offsets the need for avalanche to provide carriers, thereby reducing or stopping avalanche in the sample.

Figure 7 shows a graph of the current density versus the voltage for a lightly doped semiconductor sample. A noticeable aspect of the curve is the region of negative resistance once double injection is initiated. This S-type I-V characteristic is known as current controlled negative resistance (CCNR) (Refs. 2, 26, 27,and 28) and has been directly associated with the appearance of current filaments (Refs. 29, 30, and 31) in semiconductors and insulators. This contention is further supported by the research efforts of B. K. Ridley (Ref. 29). Ridley employed the principle of least entropy production to show that a uniform current flow in a region of CCNR is unstable against filament formation. Although Ridley's efforts do not include external circuit parameters, his basic presentation demonstrates that microplasma formation is a continuous process that logically moves toward mesoplasma. Further experimental evidence of this contention was provided by a set of experiments performed by Barnett and Milnes (Ref. 30).

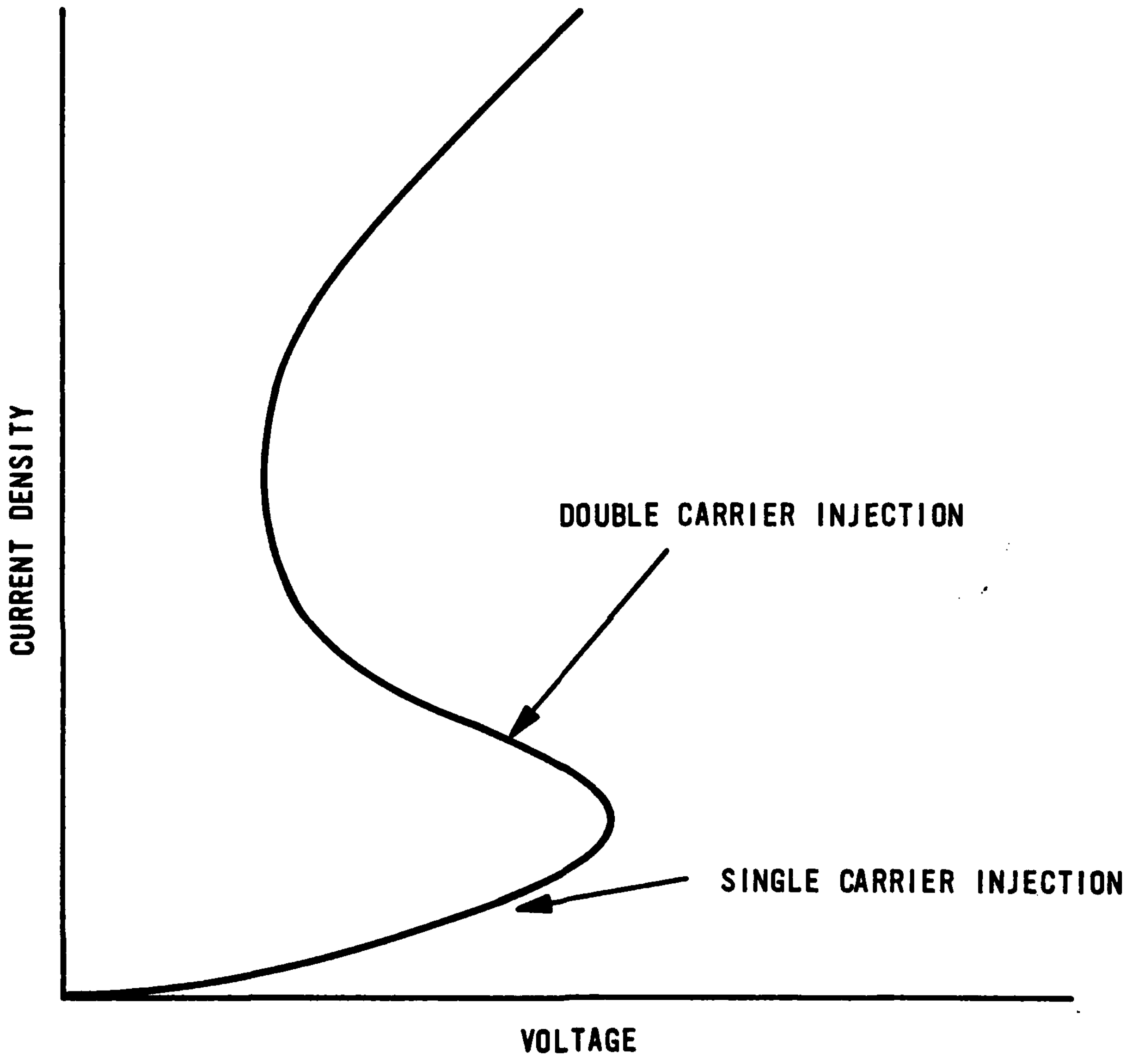


Figure 7. Current density versus voltage for a semiconductor sample.

These experiments performed on silicon P+-I-N+ devices at liquid nitrogen temperatures (to prevent destructive heating) displayed steady state microplasmas that developed and moved toward mesoplasma when CCNR occurred (see Figs. 8, 9, and 10). A further extension of this assertion shows that a number of microplasmas could form at relatively low current levels when CCNR is present. As the current level increases, the number of microplasmas may decrease until only one mesoplasma remains. This may verify the results obtained by a series of experiments performed by Sunshine and Lampert (Ref. 33). Their studies with lateral silicon on sapphire diodes demonstrated that at low current levels CCNR initiated the formation of multiple microplasmas. As the current level was increased, the number of microplasmas decreased to three or four mesoplasma. Thus, a cursory study of the evidence appears to support Ridley's ideas of microplasma formation.

However, Ridley's concepts do not give an adequate explanation of this phenomena in terms of a charge transport mechanism (a mechanism that forces carriers into microplasma formation). One clue that can be discerned from Ridley's work pertaining to charge transport is the time needed for a prominent microplasma to form. Ridley's calculations show that time is less than or equal to the dielectric relaxation time (the time necessary for bulk semiconductor to redistribute charge to maintain charge neutrality). This implies that higher order bulk semiconductor properties are controlling the filamentation phenomena under rapidly changing charge conditions (or injection level). In other words, microplasma formation is the dominating process in any semiconductor device. The only charge transport mechanism capable of inducing such phenomena in such short time intervals is high level current injection augmented by ballistic (collisionless) charge transport.

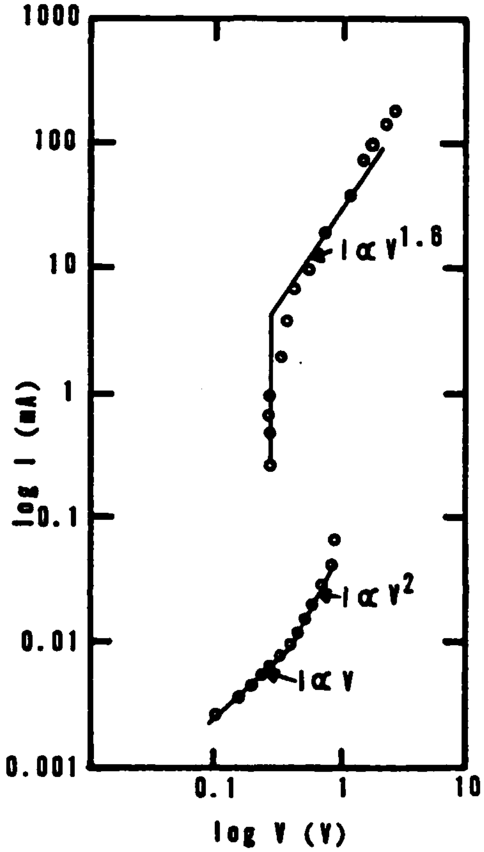


Figure 8. Current voltage characteristics for device No. 25-1 a PIN diode in reverse bias (Ref. 32).

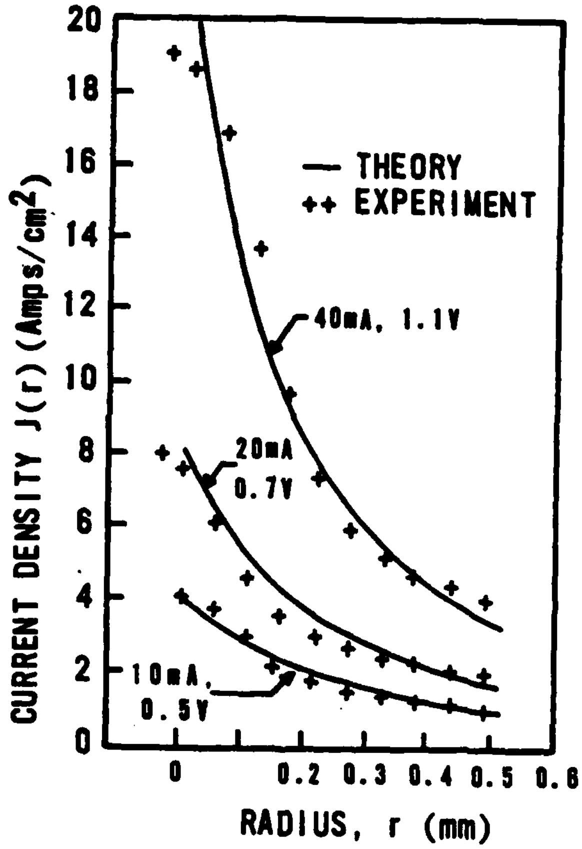


Figure 9. Current density versus distance across the 10, 20, and 40 mA filaments of device No. 25-1 a PIN diode in reverse bias (Ref. 32).

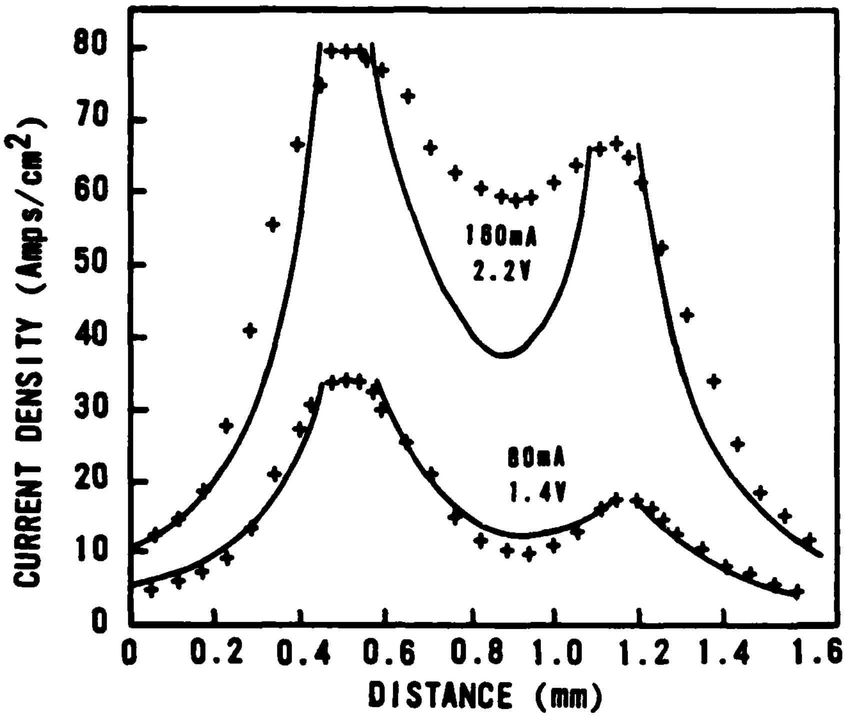


Figure 10. Current density versus distance for multiple filaments of device No. 25-1 (Ref. 32).

This is a form of double injection where injected electrons and holes remain free of trapping and approximately neutralize each other as they are injected. Since this is the limiting extreme of double injection, it has been termed "solid state plasma injection" because of the injected current's similarities to plasma (gaseous) discharge in low-pressure discharge tubes.

# VI. SOLID STATE PLASMA INJECTION

To explain solid state plasma injection in its proper context, a description of the type and magnitude of carrier injection experienced in semiconductor devices will prove helpful. In the last section both single and double carrier injection were discussed in some depth, a similar discussion can be given for simple semiconductor devices such as diodes and transistors.

Single carrier injection can occur in transistors or PIN diodes when punch-through conditions prevail (see Fig. 11). For the PIN diode in a punch-through condition (not yet in avalanche) the high electric field at the P+I interface causes the injection of electrons into the I region which dominates the reverse current flow in the device. Current flow under these circumstances is limited by space charge build-up near the IN+ interface. For a transistor (see Fig. 12) biased under conditions such that the depletion region at the collector junction reaches the emitter junction depletion region before avalanche occurs, the transistor is said to be punched-through. Single carrier injection conditions prevail now in the same way as for the PIN diode.

If the electric field in the depletion region for both devices is increased to a higher value impact ionization occurs causing avalanche breakdown and the onset of hole injection at the IN+ interface of the diode and the NN+ interface of the transistor. The conditions are now satisfied for double carrier injection, and the accompanying CCNR to initiate plasma injection.

The device can now be represented as a container with an enclosed plasma discharge in an unstable state. Initially, the plasma undergoes magnetic pinch creating a microplasma, but thermalization in the microplasma soon drives the plasma to a thermal instability or mesoplasma.

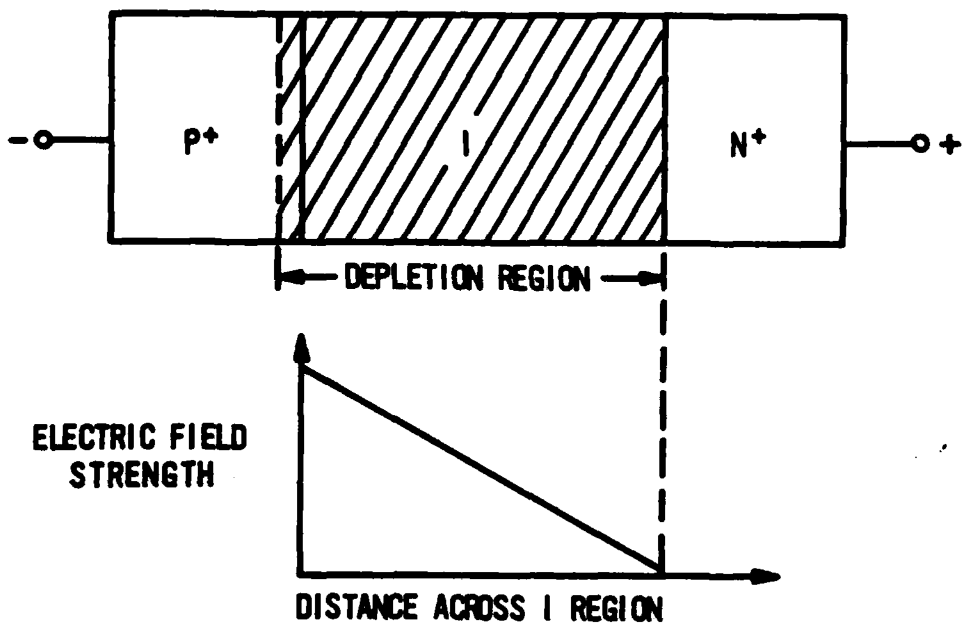


Figure 11. A PIN diode in a punched-through condition. Under normal operation the depletion region does not extend to the IN interface.

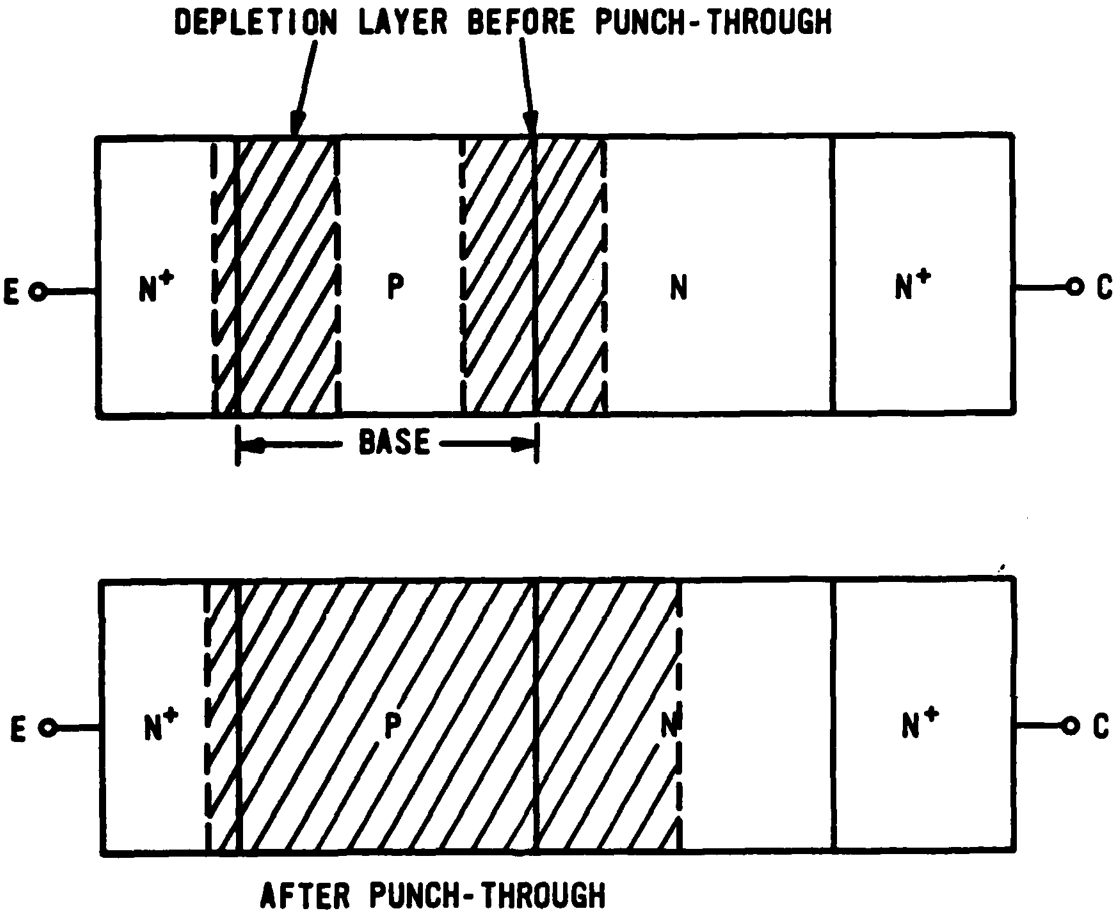


Figure 12. A punched-through NPN transistor.

The extensive heating that occurs in the microplasma is due to the vastly increased mobility of the carriers that can now efficiently transfer their kinetic energy via phonon production to the crystal lattice. Externally, the device's voltage potential will move quickly to that of the plasma, plus the remaining potential between the plasma and the depletion layer edge. As the plasma grows the device's potential assumes the plasma potential.

The explanation of Second Breakdown for forward-bias and reverse-bias (without punch-through) conditions in a diode and transistor is somewhat different than explained previously. Yet, the PN junction in these devices provides a common point for analysis to determine the conditions for Second Breakdown. A forward biased PN junction under an electrical overstress can be characterized as a small depletion region undergoing high level injection. Normally, the forward current is strongly limited by the number of minority carriers available for recombination, a situation similar to single carrier injection. As the electric field increases in strength, the number of minority carriers available begins to approach the limit of carrier doping and recombination kinematics for the device. This action reduces the carrier mobility increasing the electric field in the depletion region till complete double carrier injection proceeds via avalanche injection or mobility changes.

In a reverse biased junction, the onset of avalanche injection does not always initiate double carrier injection. Recombination kinetics can still maintain unequal mobilities for holes and electrons preventing CCNR from occurring. CCNR can only occur when increasing field levels overcome the depletion region's recombination kinetics causing equal mobility levels for holes and electrons.

If the injection level is somewhat below the level necessary for plasma injection, device heating prior to double injection can raise the injection level or lifetime of the carriers (by thermal activation of impurities) (Ref. 34) enough to initiate plasma injection. Additionally, if a device should happen to experience strong ambient heating, optical illumination or ionizing radiation before plasma injection occurs, the conditions inside the device would become more homogenous. Such actions would quench either plasma injection or avalanche as noted in some past experiments (Refs. 35, and 36).

Under the right circumstances plasma injection can be initiated in a semiconductor device without complete avalanche breakdown as a precursor. Since the concept of CCNR also occurs for pure semiconductor materials, a semiconductor device could form a plasma due to the rapid occurrence of a strong electrical overstress, optical illumination or ionizing radiation (Ref. 37).

This action is relatively straightforward to understand when Figures 13 and 14 are examined. Generally, the highest occupied energy level in a solid determines the carrier characteristics of that material. As figure 13 shows, the occupancy level of a energy band in conjunction with the size of the band gap gives a material the qualities of a metal, semimetal, semiconductor, or an insulator. By providing a suitable environment, a material's qualities or carrier dynamics can be drastically altered toward the extremes of a metal or an insulator. For example, a semiconductor tends to resemble an insulator near absolute zero, and under high level electrical stress begins to take on the characteristics of a metal. The physical phenomena evoked to initiate metallic-like conduction involves the transistion of carriers to a higher energy level in the conduction band which possesses a higher mobility than the average mobility measured in the bulk.

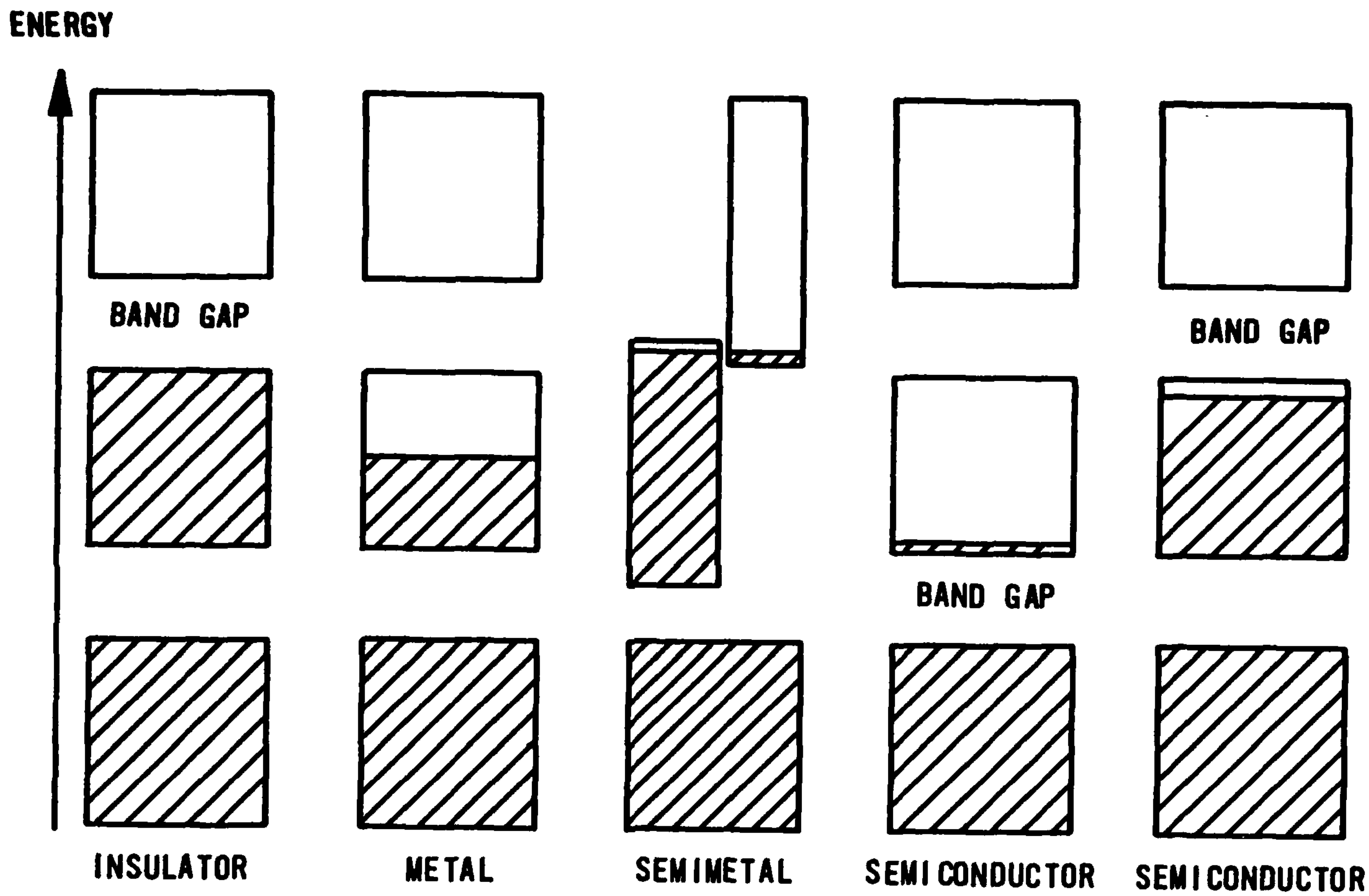


Figure 13. Schematic electron occupancy of allowed energy bands for an insulator, metal, semimetal, and semiconductor. The vertical extent of the boxes indicates the allowed energy regions: the shaded areas indicate the regions filled with electrons. In a semimetal (such as bismuth) one band is almost filled and another band is nearly empty at absolute zero, but a pure semiconductor (such as silicon) becomes an insulator at absolute zero. The left of the two semiconductors shown is at a finite temperature, with carriers excited thermally. The other semiconductor is electron-deficient because of impurities (Ref. 38).

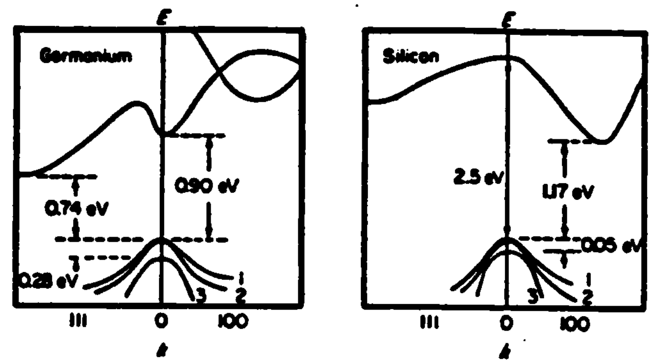


Figure 14. Energy bands $\vec{E}(k)$ versus $\vec{k}$ near the conduction and valence band extrema including spin orbit splitting energies for germanium and silicon. Energies given are for 0 K. $\vec{k}$ represents the crystal orientation in a three dimensional space (Ref. 39).

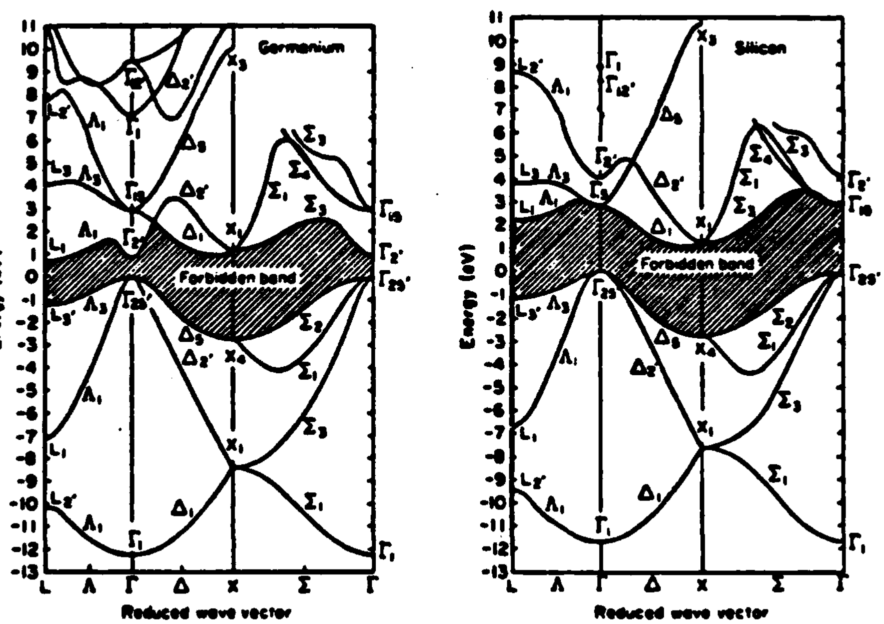


Figure 15. Energy bands $\vec{E}(k)$ versus $\vec{k}$ in different crystal directions for germanium and silicon. Spin orbit splitting energies are neglected (Ref. 39).

Normally, the average bulk mobility decreases with increasing electric field, but some carriers can still gain enough energy to transition to higher conduction bands and exhibit a highly localized change in mobility. The energy gap most often referred to in literature for silicon and germanium is the indirect (or phonon assisted) transition across 1.17 and 0.74 eV, respectively. This is normally a thermally assisted jump under low level injection conditions reflecting the base material parameters quoted in most semiconductor device books. However, the transitions to higher energy bands in germanium and silicon (see Fig. 15) are possible under extreme phonon production with high electric fields. These transitions place carriers in higher conduction bands that possess a different number of available states and carrier dynamics. In particular, carriers that transition to bands with sharper curvatures (See Figs. 14 and 15) always possess a higher mobility (Ref. 38). Hence, as the number of carriers transitioning increase; the mobility and current density in a particular area and crystallographic direction of the semiconductor can increase greatly, resulting in negative resistance (CCNR) and filamentation. Such behavior has been seen in gallium arsenide, a well known semiconductor with two differently curved conduction band minima close to each other (Refs 39, 40, and 41) that exhibits domain formation (due to transitions to bands with a low mobility) and filament formation (due to transitions to bands with a higher mobility).

This may account for such phenomena as current mode or fast breakdown, while plasma injection that is initiated due to avalanche and the resultant double injection may account for what is known as thermal mode breakdown. Other ways of arriving at plasma injection no doubt exist, depending on the material makeup and the charge dynamics of the device under study.

If failure in devices is caused by the formation of a solid state plasma due to plasma injection, is there proof positive that a plasma can form in a semiconductor sample or device? The results of previous experiments have shown without doubt, that an electron-hole plasma (a solid state plasma) can exist inside a semiconductor (Refs. 42, 43, 44, and 45).

The proof of plasma formation comes from an experiment performed in the Soviet Union (Refs. 46, and 47). Experimenters placed PIN diodes in a liquid nitrogen bath and put the diodes into quasi-static Second Breakdown. A transverse magnetic field of various strengths was then applied to the diodes to determine the effects on the microplasma. If a transverse magnetic field was applied to a gaseous plasma, the plasma's magnetic field would cause the plasma to move sideways. In this experiment the transverse magnetic field forced the microplasma to move to the side of the sample. This was accompanied by an increase in voltage and current across the diode to maintain the microplasma in its distorted shape. After the magnetic field was removed, the microplasma slowly returned to its original position with an accompanying decrease in voltage and current.

The experimenters then applied a strong magnetic field to the microplasma and observed plasma oscillations which died out eventually when the magnetic field strength was increased to a high level. This last observation can be explained by looking at the effect of a magnetic field on a gaseous plasma. A gaseous plasma can be characterized by a plasma pressure, which tries to make the plasma grow and a self-induced magnetic field that tries to contain plasma growth. If these competing mechanisms fluctuate, the plasma will oscillate. Therefore if the microplasma is a true plasma, a strong magnetic field can aid or constrict microplasma actions, as this experiment shows.

These concepts of the electron-hole plasma and its interaction with external magnetic fields have been further substantiated by the development in the 1950s and 1960s of the Cryosar and the Madistor (Refs. 48 through 51). These devices use the formation of solid state plasmas in semiconductors at liquid nitrogen temperatures to derive electrical characteristics that are observed today in devices experiencing Second Breakdown at room temperatures.

Microplasmas can also form by means other than plasma injection. For very small devices (in the LSI and VLSI range) charge transport effects occur that do not normally occur in discrete semiconductor devices (Ref. 52). At these small scales, consideration must be made for the effects of hot electrons, current saturation, ballistic (few or no collisions) transport, mobility changes and high phonon densities. These effects can work together to give rise to a mean free path between collisions that is larger than the device dimensions, resulting in Second Breakdown effects. Although this has not been characterized experimentally for such devices, the theory is quite explicit on detailing these effects (Ref. 53).

# VII. CONCLUSIONS

This report has attempted to sift through the extensive phenomenology of Second Breakdown to acquire a clearer understanding of the mechanisms involved in Second Breakdown.

The following paragraphs summarize the Physics of Second Breakdown and the ideas proposed in this report.

1. Early semiconductor failure models, such as the Wunsch-Bell and Tasca models, are generally correct for determining general failure levels of a large family of devices, but are too inaccurate to apply to specific devices. The models are limited to only those devices where the simple thermal model used is realistically applicable. Additionally, the models fail to explain any of the phenomena of Second Breakdown.

2. Present experimental evidence infers that microplasma formation and growth resembles gaseous plasma formation.

3. Microplasma formation and growth to mesoplasma occurs when a current controlled negative resistance condition occurs in a device due to double injection or the initiation of higher order bulk effects (interband transitioning in the conduction band).

4. Second Breakdown can be characterized as the initiation of CCNR in soild state semiconductor devices.

A follow-on report will contain an in-depth analyses of the major points brought out in this report. The objective of the follow-on report will be to obtain the mathematical expressions that will relate Second Breakdown (in a simple device) to external parameters.

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## GLOSSARY

AMPHOTERIC IMPURITIES - An impurity which when added to a semiconductor creates both a donor (electron source) and acceptor (hole source) level in the energy gap. Both or one of the levels is normally a deep level.

AVALANCHE BREAKDOWN - When the rate of carrier generation via impact ionization in a device proceeds at an infinite rate the device is said to be in Avalanche Breakdown. Also known as first breakdown.

BAND GAP - The gap in energy between the valence band and the conduction band. The band gap of Silicon is 1.12 eV, germanium is 0.68 eV and GaAs is 1.43 eV.

CARRIER LIFETIME - The average time a carrier remains free before it recombines with a carrier of the opposite sign or is captured by a trapping center.

CARRIER TRANSIT TIME - The average time it takes a carrier to traverse the depletion region or other electrically active region of a device or sample.

CONDUCTIVITY - A measure of the quality of current flow under an electric field impressed on a material. The conductivity is the inverse of the resistivity.

CURRENT CONSTRICTIONS - See Microplasmas.

CURRENT CONTROLLED NEGATIVE RESISTANCE (CCNR) - A mechanism produced by certain current injection and charge transport properties that allows the current to become multivalued with respect to the voltage.

CURRENT MODE SECOND BREAKDOWN - Second Breakdown initiated by a short (less than 0.1 us) but strong, electrical overstress. Device degradation is not necessarily by thermal shock under these conditions.

DEEP LEVELS - A donor or acceptor level that is far from the conduction or valence band respectively.

DEPLETION REGION - A region of charge neutrality created by the overlapping of two oppositely (P and N) doped semiconductor materials.

DIELECTRIC RELAXATION TIME - If an excess charge is injected into a semiconductor the semiconductor will redistribute its own free charge to compensate the injected charge in a time known as the dielectric relaxation time.

DIFFUSION PROFILE - A description of how the charge distribution in two oppositely doped semiconductors will appear once a depletion region is formed.

DOPANT - See Impurity.

ELECTRICAL OVERSTRESS - An uncontrolled voltage and/or current surge which induces a device to operate outside of its maximum normal operating parameters.

EXTRINSIC (material) - A material whose conductivity characteristics are determined by the impurity concentration in the material.

FAST BREAKDOWN - See Current Mode Second Breakdown.

HOT ELECTRONS - Electrons moving at high speeds in a material will have a high kinetic energy. The equivalent heat energy of such electrons corresponds to electrons having an equivalent high temperature. Thus, even if the lattice is at room temperature, the electrons may have an equivalent temperature that is much higher than the lattice, thus, hot electrons. Collisions with the lattice will eventually transfer this energy to the lattice, raising its temperature.

IMPACT IONIZATION - A hot electron can impact the lattice of a semiconductor and impart enough energy to create an electron-hole pair. This pair may then have enough energy to create other pairs. Thus, a multiplicative process is initiated resulting in Avalanche Breakdown.

IMPURITY - An elemental material added to a semiconductor to control the conductivity via the creation of additional carriers to aid conduction.

INTRINSIC (material) - A material whose conductivity characteristics are determined by the base material alone.

INTRINSIC TEMPERATURE - The temperature at which a semiconductor's conductivity is determined by the base material alone.

$\bar{k}$ or $\langle k \rangle$ - Refers to the orientation of the crystal lattice in terms of the miller indices.

MAJORITY CARRIER - The carrier (electrons or holes) which is most abundant in a device.

MESOPLASMA - A giant plasma. The point where the microplasma fills a major portion of the depletion region of a device.

MICROPLASMA - A narrow current channel caused by a devices attempt to remain electrically stable under the influence of plasma injection and CCNR.

MINORITY CARRIER - The carrier (electrons or holes) which is least abundant in a device.

MOBILITY - The velocity of a carrier in the direction of the electric field per unit field.

PHONONS - The quantization of the energy of lattice vibrations normally caused by heating.

PLASMA INJECTION - When the injected charge in a device crosses the depletion region in a time equal to or less than the dielectric relaxation time, plasma injection occurs. This type of injection is only limited by the rate of recombination of the injected electrons and holes with each other.

PUNCH-THROUGH - A mode of device operation where the depletion region expands across some intermediate region negating its electrical influence. Devices with three or more doped regions can experience punch-through.

RECOMBINATION CENTER - An impurity location where electrons and holes may recombine.

RESISTIVITY - The inverse of conductivity. The amount of resistance to current flow in a material.

SECOND BREAKDOWN - The phenomena associated with the initiation of plasma injection in a semiconductor. This results in the I-V characteristics experiencing a rapid drop in voltage with increasing current, causing device degradation or destruction by thermal shock.

THERMAL MODE SECOND BREAKDOWN - Second Breakdown believed to be initiated by electrical heating, during a short electrical overstress or a strong electrical overstress of long duration (greater than 0.1 us). Device degradation or destruction is almost always by thermal shock.

THERMAL SHOCK - A damaging of a material by either a rapid rise in temperature or the existence of internal temperatures near the melting point of the material.

TRAPPING CENTER - A center that collects carriers of only one type and releases them by thermal excitation.

VELOCITY SATURATION - When the carriers in a device reach their maximum velocity and further increases in the electric field can not increase the speed of the carriers.

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