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A STUDY OF CURRENTS IN AVALANCHING MICROWAVE DIODES

Chih-Hsien Chien
Cornell University

TECHNICAL REPORT NO. RADC-TR- 68-554
January 1969

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FOREWORD

This is an interim technical report on research conducted at the School of Electrical Engineering, Cornell University, under Contract No. F30602-68-C-0042, Project 5573, Task 557303. The research is under the over-all direction of G. C. Dalman and L. F. Eastman.

The RADC Project Engineer is R. H. Chilton - (EMATE).

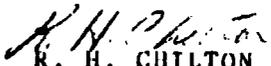
The major objective of this contract is to study active microwave bulk and transit time phenomena in solid-state materials. The purpose of these studies is to provide a better understanding of the phenomena and their application in the effective generation and amplification of high-frequency, high power microwave signals.

This report represents progress made in studies of currents in the avalanching zone of avalanche diode (IMPATT) oscillators.

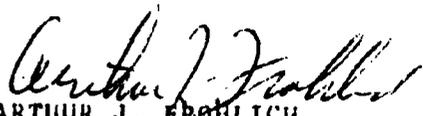
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This report has been reviewed and is approved.

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R. H. CHILTON
Project Engineer
Electron Devices Section

Approved:


ARTHUR J. FROHLICH
Chief, Techniques Branch
Surveillance & Control Division

ABSTRACT

A large-signal experimental study has been made on the wave shapes and phase relations of the current in an avalanching silicon diode excited by an external microwave signal source under different conditions of current bias. The objective of this study has been to obtain information helpful in the understanding of the factors determining the operating efficiency of microwave avalanche transit-time diode oscillators.

The experiments were conducted at 760 MHz on diodes that normally oscillated at 10 GHz so that the transit-time effects in the drift zone of the diode were negligible and so that the displacement currents in the diode could be reduced to the same order of magnitude as the convection current. By subtracting the displacement current from the total device current as viewed through a current viewing disc resistor in series with the diode, a display of the net avalanche current was obtained. The avalanche current wave shape looks like a half-wave rectified sinusoidal signal with its peak lagging the voltage signal by approximately 80 degrees. In general, the experimental result has been found in good qualitative agreement with theoretical analysis when the particular values of the various parameters characterizing the diode tested are taken into consideration.

The anomalous rectification effect in avalanche diodes has also been investigated. The variation of the rectified current agrees with the theoretical analysis even at perturbations as high as 22 percent of the bias voltage.

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I. INTRODUCTION

An impact-avalanche transit-time (IMPATT) diode oscillator which might operate at microwave frequencies was first proposed by Read¹ in 1958. The proposed structure was an $N^+P_i P^+$ which, under reverse bias, would result in a very high field intensity (of the order of several hundred kv/cm) at the N^+P junction. As a result of the impact ionization mechanism of electrons and holes within this region (the avalanche region) the thermally injected current will keep on building up as long as the field is maintained above a critical value. For steady state conditions if the junction is reverse biased at this critical field the current will continue to grow up during the reverse period of the a-c voltage. At the end of the reverse period, the current stops growing and begins to decrease. This implies that the peak of the avalanche current lags the a-c field by 90° in the avalanche region. As the holes leave the avalanche region and move into the relatively low field intrinsic region (the drift region) they proceed with scattering limited velocity (of the order of 10^7 cm/sec). This will result in an additional 90° phase lag of the induced current if the oscillator frequency and the width of the drift region are such that the transit time through the drift region is a half of the period of the oscillation. The device therefore presents a 180° negative resistance.

In his small signal analysis Read assumed equal ionization rates and saturated velocities for electrons and holes. As a result of the assumption of very thin avalanche region, the avalanche current appeared as very sharp spikes lagging the voltage signal by 90° . According to his estimation, Read predicted a 30 percent efficiency for this kind of structure. By taking into consideration the asymmetry of the ionization rates of electrons and holes, Lee et al.² have shown that efficiency of higher than 30 percent may be achieved. Because of technological difficulties in fabrication, this kind of structure had not been realized until recently when a npnp structure closely approximating Read's recommended structure was successfully fabricated at Bell Laboratories.³

On the other hand, microwave oscillations from simple P-N junctions utilizing the time dependent properties of the avalanche region and transit-time effect in the drift zone have been observed^{3,4,5} and analyzed^{6,7,8} recently. Efficiencies of only a few percent have been observed for transit-time mode oscillations in this kind of structure. However, microwave oscillation in a different mode of operation has been observed from this kind of structure recently with efficiency as high as 60 percent.⁹

In order to help in understanding the factors affecting the operating efficiency of microwave avalanche p-n junctions it is important to investigate the waveform of the particle current emerging from the avalanche region. The idea of the

present work is to measure the current waveform and its phase relative to the voltage signal as the junction is reverse biased at various levels and driven with an external microwave signal source at the same time. This is illustrated schematically in Figure 1.1 with cosine wave r-f signals superimposed on the d-c characteristic of the avalanche P-N junction. In this figure, V_b I_b and V'_b I'_b indicate the bias conditions and V_p and V'_p represent the peak value of the r-f voltage signals.

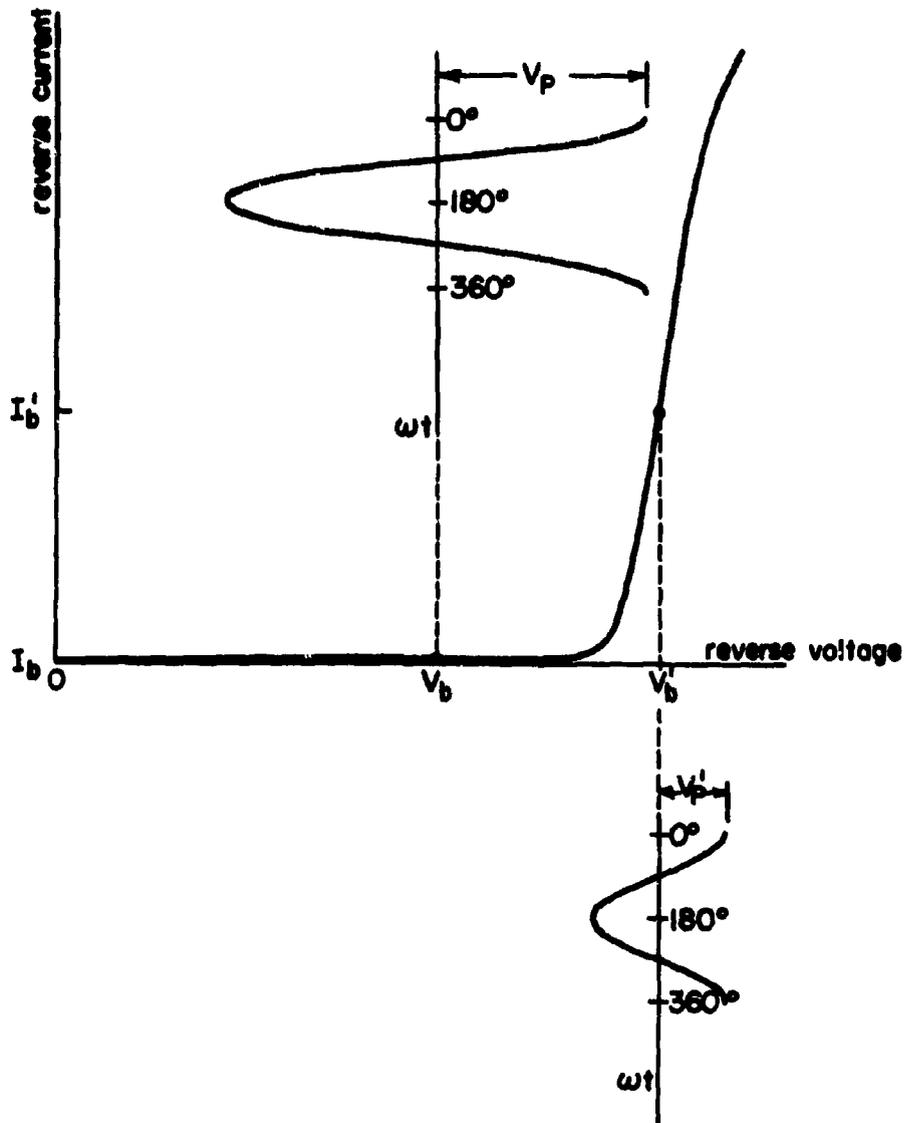


FIGURE 1.1. Diagram Showing the D-C Breakdown Characteristic of Avalanche P-N Junction with R-F Voltage Signal Superimposed on it.

II. EXPERIMENTAL CIRCUIT AND SAMPLE DESCRIPTION

A. Experimental Circuit and Apparatus

In order to investigate the properties of the avalanche region through measurements of the total device current and terminal voltage the effect of the drift region must first be minimized. This may be achieved by driving the device at frequencies much lower than the normal operating frequency of the diode. The diodes tested in this experiment normally oscillate at 10 GHz. At this frequency the essential effect of the drift region is a delay of the avalanche current by approximately 90 degrees relative to its phase at the end of the avalanche zone. The experiment is conducted at 760 MHz so that the phase delay through the drift region is reduced to only a few degrees. Therefore, the avalanche current observed at the end of the drift zone differs from that at the end of the avalanche zone only by a phase shift of a few degrees. A block diagram of the experimental circuit of a 50- Ω coaxial system is shown in Figure 2.1. The diode is biased with a regulated power supply and the biasing voltage and d-c current are monitored with a d-c voltmeter and a d-c milliammeter. A special Sperry SRL-17 L-band medium power reflex klystron is used to drive the diode. This tube was tuned at 760 MHz and gave a maximum output of about 1 watt into 50 Ω . A precision adjustable

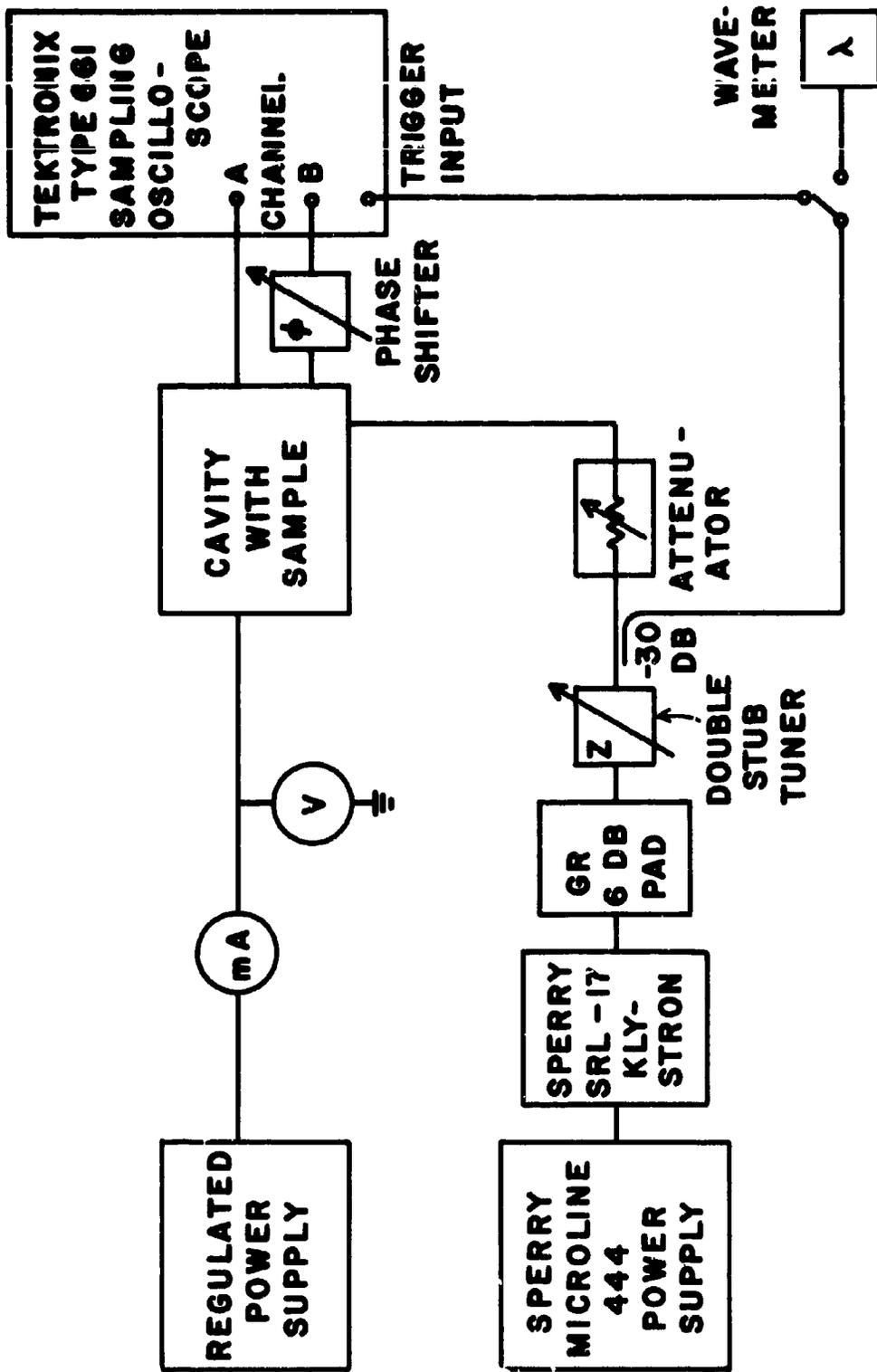


FIGURE 2.1. Block Diagram of Experimental Equipment.

attenuator is used to control the input r-f level.

Figure 2.2 shows the detailed structure of the cavity. The cavity consists of three sections. A modified GR 874-GAL adjustable attenuator is used as the input section. The 50- Ω matching resistor in the loop circuit of this unit is removed to reduce the loss. The center conductor is modified so that it provides an r-f bypass at one end where d-c bias is to be fed in. Another GR-874 GAL adjustable attenuator is used as the sample holder and output section. The diode is inserted in the center conductor at one end of the main line. A 0.4 Ω current viewing disc resistor is placed in contact with the diode so that the sample current may be observed by measuring the voltage across the disc resistor. The inductive loop coupler in the output branch of this unit is replaced by a capacitive disc for sampling the voltage signal across the diode. The two sections are connected together by a GR-874 LK10 constant-impedance adjustable line. This section is used so that critical adjustment for resonance will be much easier. The total length of the coaxial cavity can be varied from 44 cm to 54 cm. For most of the measurement it is set around 50 cm which corresponds to about one wavelength and a quarter at 760 MHz. The quality factor of the test cavity is about 50.

The equivalent circuit of the test equipment is shown in Figure 2.3. In this schematic diagram, the various symbols have the following meaning:

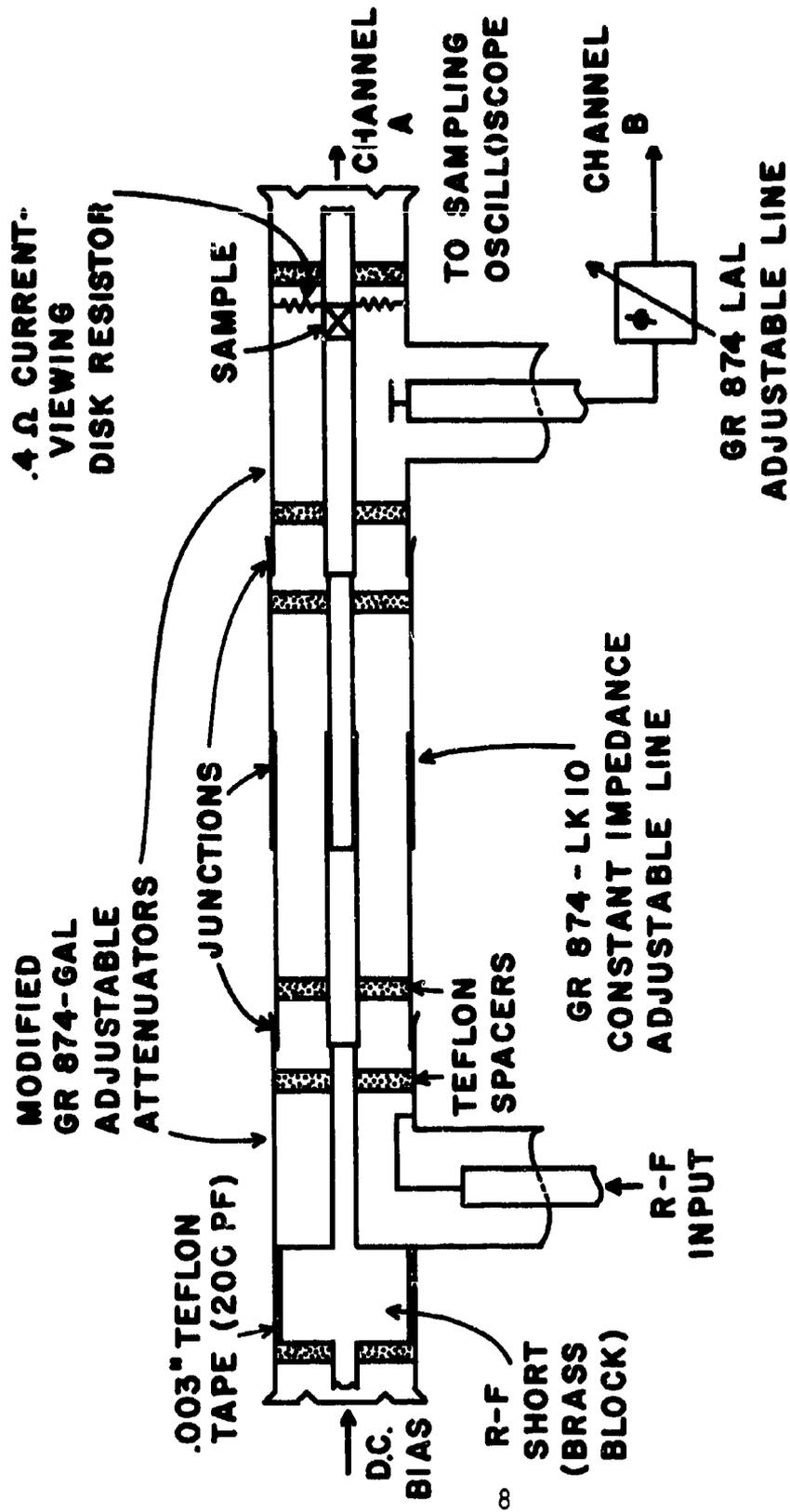


FIGURE 2.2. Detailed Structure of Test Cavity.

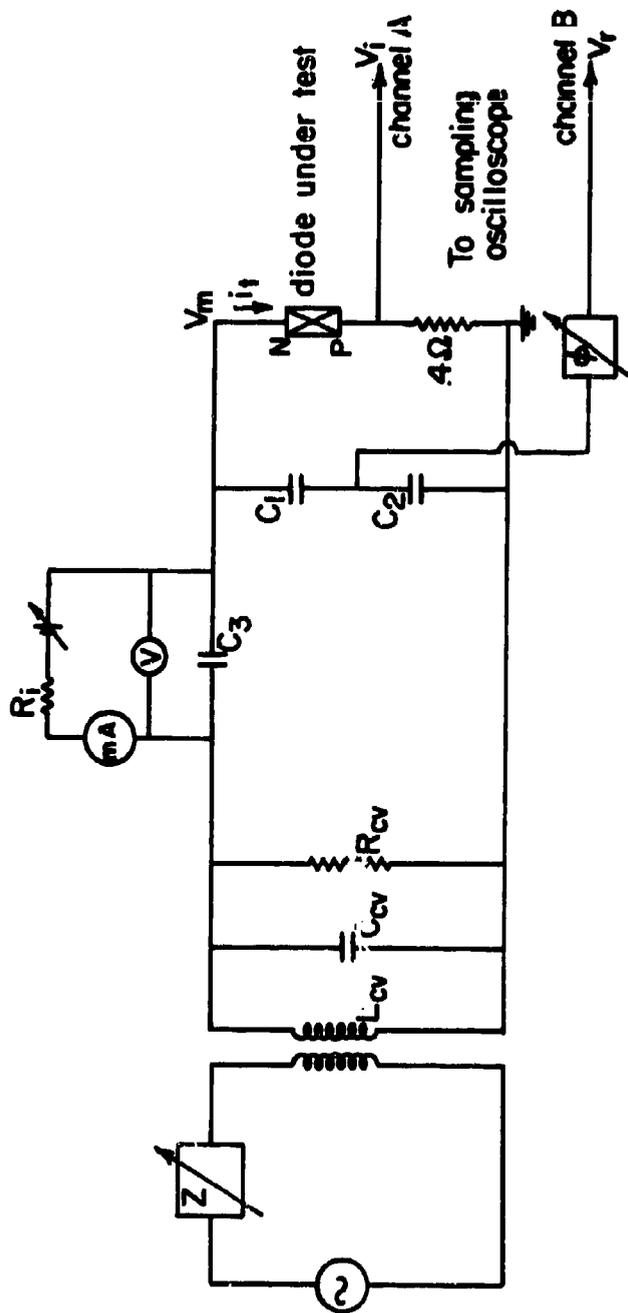


FIGURE 2.3. Equivalent Circuit of the Test Equipment.

- R_1 internal resistance of the power supply.
- Z representing the equivalent circuit impedance between the klystron and the input port of the cavity.
- C_3 200 pF r-f bypass capacitor.
- L_{cv}, C_{cv}, G_{cv} equivalent inductance, capacitance and conductance of the cavity referred to the sample.
- C_1, C_2 equivalent capacitance of the capacitive probe voltage divider.

The resistance of the 0.4Ω current viewing disc resistor is much smaller than the dynamic impedance of the mounted sample which is usually of the order of 100Ω at 760 MHz. Therefore, v_1 , equals to $i_t \times 0.4 \Omega$ and v_v is proportional to v_m which is approximately the voltage across the sample.

A block diagram of the circuit used for investigating the time response of avalanche to unit pulse inputs is shown in Figure 2.4. The lengths of the two branches are so adjusted that they have equal electrical length when the sample is replaced by a brass dummy diode.

B. Sample Description

The samples tested in this experiment are made of Semimetals', Inc. silicon wafers processed by the KMC Semiconductor Company. This wafer has a P^+NN^+ structure. The n-type layer was grown epitaxially on the N^+ substrate

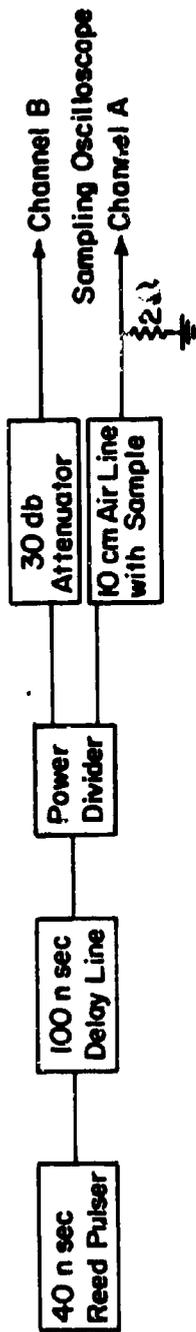


FIGURE 2.4. Block Diagram of the Circuit Used for Investigating the Time Response of Avalanche to a Unit Pulse Voltage.

and the epitaxial layer was then boron diffused to form the P⁺N junction. The thickness of the epitaxial layer is about 6 microns and has a resistivity of 0.8 Ω-cm. The P⁺ layer is about 3 microns thick. An aluminum contact of 5000 ~ 6000 Å thick is made on the P⁺ side and gold contact is made on the N⁺ side. The wafer is cut into squares 20 mils on a side and mesas of approximately 3 to 4 mils in diameter are formed. This corresponds to a junction area of about $0.6 \times 10^{-4} \text{ cm}^2$. Therefore, one milliampere of device current is equivalent to a current density of about 17 amp/cm².

Two types of diode mounts have been used in this experiment. One of them is a standard 1N23 cartridge. The N⁺ side is soldered on the mounting post and a cat-whisker provides a pressure contact to the P⁺ side. The cat-whisker has an inductance of 4.2 nh which corresponds to 20 Ω at 760 MHz. The cartridge capacitance is negligible in this experiment. The other type of diode mounting used is a very small varactor diode ceramic package, 80 mils in diameter and 40 mils high. The N⁺ side is soldered to one end of the package and gold wires bonded on the other end makes the contact to the P⁺ side. The capacitance of this cartridge is about 0.62 pF which corresponds to 340 Ω at 760 MHz. The reactance of the gold wires is negligible.

These junctions have a very good d-c breakdown characteristic with breakdown voltage around 50 volts. They may be operated CW at 25 ma bias.

III. PRINCIPLES OF MEASUREMENT

A. Calibration of the Measuring Circuit

Before any measurement could be made, the amplitudes of the current and voltage signals must first be calibrated. Also the relative phase between the voltage and current signals at the inputs of the sampling oscilloscope must be correctly adjusted.

The calibration of the amplitude of the current signal is both straightforward and accurate. Suppose the voltage measured on the sampling oscilloscope is v_1 and the resistance of the current viewing disc resistor is R_{disc} ohms, which is small compared to the diode impedance, then the total current in milliamperes through the disc resistor is

$$i_t = \frac{v_1}{R_{disc}} = F_1 v_1 \quad (3.1)$$

where $F_1 = 1/R_{disc}$ (ma/mv) is defined as the conversion factor for the current probe. The total current i_t consists of the avalanche current and the displacement currents due to the junction capacitance and the capacitance of diode cartridge.

To calibrate the voltage probe we need a reference impedance element. Because purely resistive microwave elements of the proper geometry are difficult to obtain, purely reactive elements are employed. A reference inductor

used in calibrating the voltage probe comes in the form of a short-circuited cat-whisker mounted in a standard 1N23 cartridge. The reactance of this element is measured with the ordinary slotted-line technique. It is then inserted into the cavity at the position where the test diode is to be situated. Now we display both the current signal and the voltage signal on the sampling oscilloscope with the x-y display. A straight line or an ellipse (or a circle, if the amplitudes of the inputs of the two channels happen to be the same and the length of the voltage channel is correctly adjusted) should be observed. Suppose the peak-to-peak voltage of the signal from the voltage probe as measured on the sampling oscilloscope is v_v° mV and that of the current channel is v_i° mV and the reactance of the reference inductor at the measuring frequency is X_{ref} ohms then with the help of Equation (3.1), we have

$$v_v^{\circ} F_v = F_i v_i^{\circ} \cdot X_{ref} \quad (3.2)$$

From this equation conversion factor for the voltage channel F_v is determined as

$$F_v = \frac{F_i v_i^{\circ} X_{ref}}{v_v^{\circ}} \quad (\text{mV/mV}) \quad (3.3)$$

The magnitude of the voltage signal is therefore calibrated and the voltage across the sample is simply F_v times the voltage at channel B as measured on the sampling oscilloscope.

The correct relative phase between the voltage and current signals is obtained by adjusting the length of the adjustable line in the voltage channel. With the reference inductor inserted into the cavity, the adjustable line should be set such that an ellipse circulating in the counterclockwise direction and with principal axes parallel to the coordinate axes is observed on the sampling oscilloscope. This method of setting the relative phase is not accurate since it is difficult to determine whether the principal axes are exactly parallel to the coordinate axes. A more accurate way of setting the relative phase with the reference inductor is to adjust the length of the voltage channel so that a positively sloped straight line appears on the sampling oscilloscope and then advance the voltage channel by a quarter wavelength. After this adjustment the i-v plot or dual trace display on the screen will have the correct relative phase between the voltage and current signals.

An empty diode-pill package is used as a reference capacitor for calibration. The procedure is exactly the same as that with an inductor except that the voltage channel is delayed rather than advanced by a quarter wavelength after a positively sloped straight line is observed on the oscilloscope.

B. Measurement of the Avalanche Current

As mentioned in Section III.A, the total current as measured at the disc resistor consists of the avalanche current and the displacement current due to diode junction capacitance and the capacitance of the diode cartridge. In order to be able to identify the avalanche component of the total current a special measuring technique has been employed. This method applies to measurements made with those samples mounted in the varactor pill type package. In this case the approximate equivalent circuit of the device under test is simply the capacitance of the diode junction and the cartridge paralleled by an avalanche branch. No series elements appear in the equivalent circuit. The magnitudes of the capacitive current and the avalanche current are of the same order even when the diode is biased well into breakdown. In order to separate the avalanche current from the capacitive current the voltage signal is advanced by 90 electrical degrees by reducing the length of the voltage channel by a quarter wavelength from the correctly calibrated length. Therefore, the $i-v$ plot of any linear reactive element modified in this manner will appear as a straight line. The slope of this straight line is positive for a capacitive element and negative for an inductive element. This process is shown graphically in Figure 3.1.

For r-f levels not too high, the device is practically a linear capacitor before breakdown and the modified $i-v$ plot

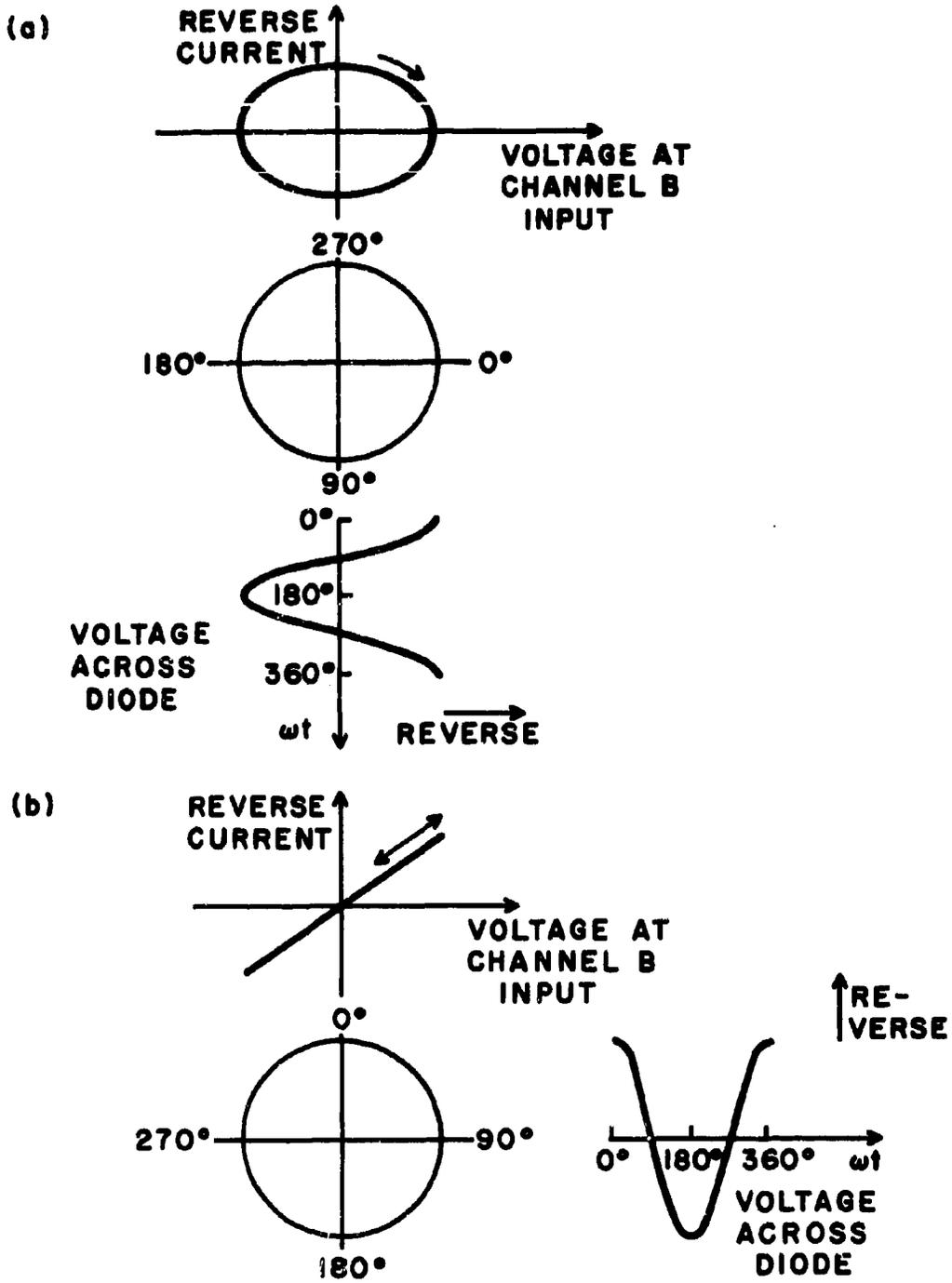


FIGURE 3.1. Diagram Showing the Phase of (a) the $i-v$ Plot and (b) the Modified $i-v$ Plot of the Reference Capacitor.

is a positively sloped straight line (as will be shown in Section IV). Any deviation from this straight line indicates the appearance of the avalanche current. This method allows us to determine the avalanche current more accurately and is especially convenient in determining the approximate phase of the avalanche peak relative to the voltage signal.

It is also interesting to see how the avalanche current grows up on the time display of the total current as we increase the d-c bias or the r-f level. This is made possible by displaying both the total current and the voltage signal on the sampling oscilloscope simultaneously. The latter is advanced by 90° and its gain is adjusted so that it has the same phase and amplitude as the pre-breakdown capacitive current. By comparing the total current with this modified voltage signal, the avalanche current can be distinguished from the total current very easily.

At this point, the net avalanche current may be displayed without any difficulty on the sampling oscilloscope with the help of the "Algebraic Sum" selector and the "invert" switch of the voltage channel. The results of these measurements will be shown in Section IV.

In investigating the anomalous rectification phenomena of the avalanche diode two minor modifications have been made on the circuit shown in Figures 2.1, 2.2, and 2.3, to allow more accurate measurement. First, the 0.4Ω

disc resistor is replaced by a short-circuit brass disk. Secondly, a regulated d-c source of about 40 V is inserted in series with the voltmeter to offset the reading of the bias voltage so that the voltmeter may be set at finer scales and the bias voltage can therefore be monitored more accurately. The amount of r-f excitation is monitored on the sampling oscilloscope with the calibrated voltage probe. The d-c breakdown characteristic is measured with various degrees of r-f excitation. The difference in d-c current between the case with certain r-f excitation and that without excitation is the rectified current and is plotted as a function of bias voltage.

IV. EXPERIMENTAL RESULTS AND COMPARISON WITH THEORIES

A. Introduction

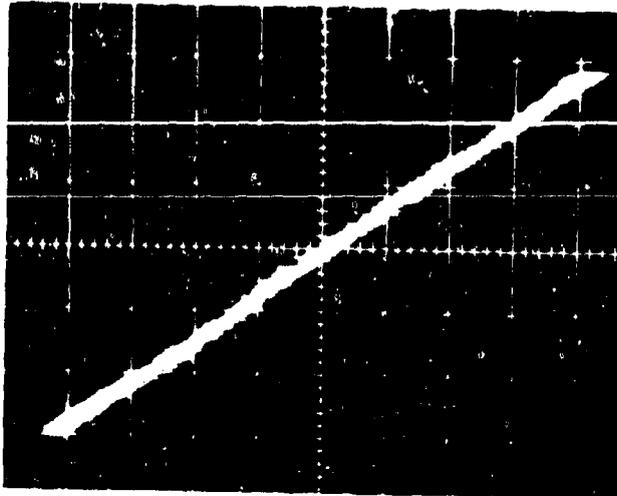
In this section the results of the measurements on the avalanche current, the anomalous rectification phenomena and the time response of avalanche to a unit pulse voltage are presented and compared with existing theories. The comparisons are made on a qualitative basis since none of the present theories have taken into consideration such complex factors as, for example, thermal effect which is encountered at high current levels. Besides, the extraordinarily large perturbation (up to 100 percent) involved in this large signal experiment makes it very difficult to make detailed qualitative comparison with the present theories. Although only those results obtained for diodes No. H-6 and No. H-9 in the varactor pill package and No. 2-112-U in ordinary 1N23 cartridge are presented because of their clean, noise-free character, similar results have been obtained from a number of other diodes made of the same material.

Moreover, the results are independent of whether the diodes are operated CW or pulsed. As a result of better triggering stability of the sampling oscilloscope the pictures of the diode under CW operation are usually clearer than those under pulsed condition.

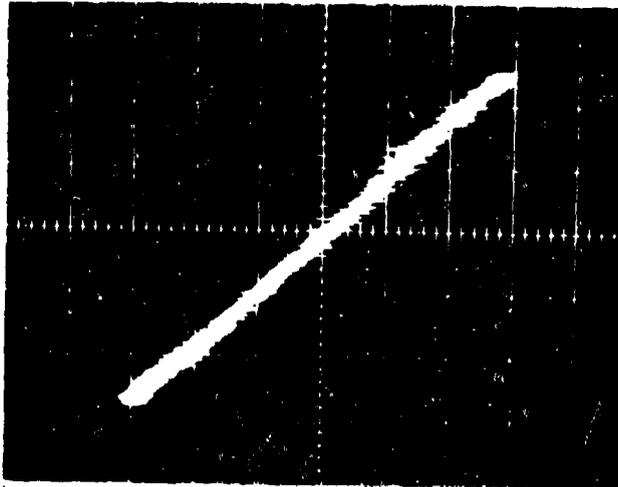
In the oscillograms shown in this section the coordinate axes are such that the positive y-axis corresponds to the reverse current. The phase of the voltage signal is illustrated in Figure 3.1.

B. Measurement of Avalanche Current Waveform

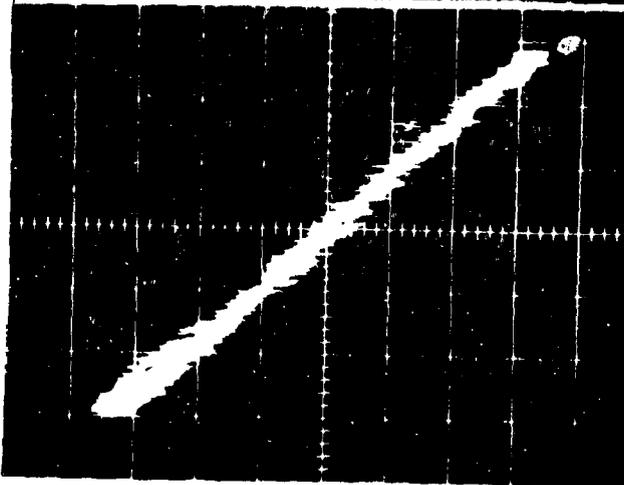
The best way to see how the steady state avalanche current starts is to observe the variation of the modified i-v plot (as described in Section III.3 and shown schematically in Figure 3.1) as the bias is increased from below breakdown into avalanche condition. Oscillogram 4.1(a) shows the modified i-v plot of an empty pill package with a capacitive reactance of 339Ω at 760 MHz. This empty package is used as a reference capacitor. From this picture the voltage conversion factor F_v is determined to be 0.561 volt at the diode per millivolt at the channel B input of the sampling oscilloscope. Oscillogram 4.1(b) is for diode No. H-6 biased at 40 volts. The fact that the trace is almost a perfect straight line shows that at this bias the junction may be approximated by a linear capacitor even with r-f signals as large as 30 volts peak-to-peak. From the slopes of oscillograms 4.1(a) and 4.1(b) the junction capacitance of this diode at 40 volts bias is determined to be about 0.17 pF (as compared to 0.62 pF for the empty cartridge). In oscillogram 4.1(c) the bias is raised to 45 volts and an a-c swing of about 30 volts peak-to-peak value (30 percent



(a)
 H. S. 5.61 v/cm
 V. S. 25 ma/cm



(b)
 H. S. 5.61 v/cm
 V. S. 25 ma/cm

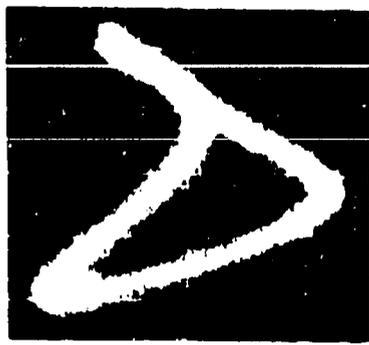


(c)
 H. S. 2.81 v/cm
 V. S. 12.5 ma/cm
 Counterclockwise

FIGURE 4.1. Modified i-v Plots of (a) Empty Diode Cartridge, (b) Diode No. H-6 at 40 v Bias and (c) Diode No. H-6 at 45 v Bias.

perturbation of the bias voltage) is applied. A small counterclockwise loop is seen forming at the lower left end of the trace. This indicates that the avalanche current begins to appear around the 70-degree point of the voltage signal (c.f. Figure 3.1(b) for the designation of the phase of the voltage signal). This agrees with the general understanding, as described in Section I, that the avalanche peak occurs near the end of the time period during which the junction is under avalanche condition. The spread of the traces in these pictures is a result of the noisy character of the sampling diode in channel B of the particular sampling oscilloscope used in this experiment when pulse-operated at low repetition rates.

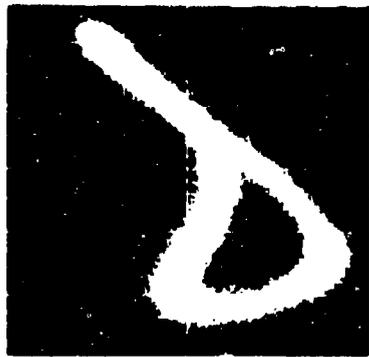
Oscillograms 4.2(a) through 4.2(h) show the modified $i-v$ plot of diode No. H-6 under CW operation at various biasing levels. All these pictures have a considerable length of straight sections (more than about 180°). During this time interval, the total current is purely reactive. These pictures are taken with increasing bias at 3 ma steps. The peak-to-peak r-f swing for the first four pictures is about 12 volts. As the bias is increased, it is seen that the avalanche current becomes larger and larger and the peak of the avalanche current shifts toward the left most end of the a-c swing which means that the avalanche peak occurs later and later until it eventually reaches the 90-degree



(a) 48.2 V, 3 MA



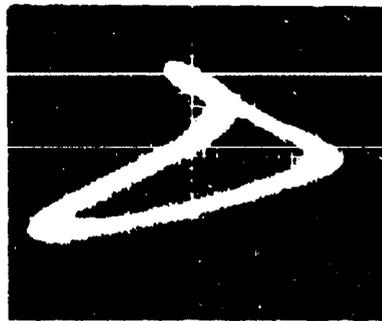
(b) 49.4 V, 6 MA



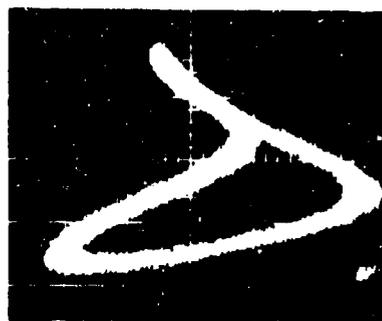
(c) 50.5 V, 9 MA



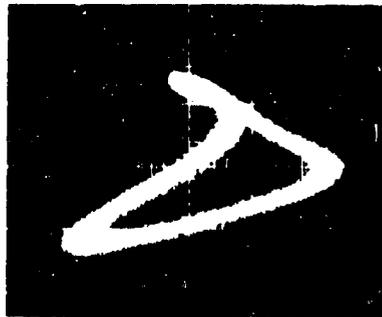
(d) 52.2 V, 12 MA



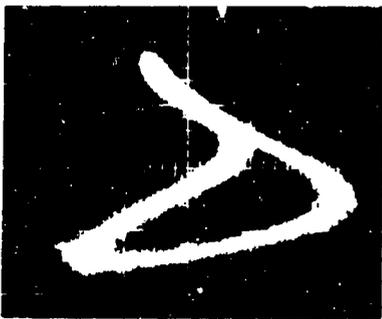
(e) 52.3 V, 24 MA



(f) 52.2 V, 21 MA



(g) 52.2 V, 21 MA



(h) 52.2 V, 18 MA

FIGURE 4.2. Modified i-v Plots of Diode #H-6 Under Various Bias Conditions. Scales (a) - (d) Vertical 12.5 ma/cm, Horizontal 281 v/cm; (e)-(h) Vertical 25 ma/cm, Horizontal 5.61 v/cm.

point. The series also shows that the avalanche current starts earlier and earlier. As the bias is increased to higher values it starts at about the 0-degree point in oscillogram 4.2(a) and shifts to about the -20 degree point in oscillogram 4.2(h). This is to be expected since the bias is being increased from (a) to (h) so that the avalanche condition is achieved earlier and earlier during each r-f cycle and the avalanche build up becomes faster and faster. From Gilden and Hines'⁶ theory, the small signal reactance of avalanche diode has the form

$$X = -\frac{1}{\omega C} \frac{1}{1 - \frac{\omega_a^2}{\omega^2}} \quad (4.1)$$

where C is the junction capacitance and ω_a is called the avalanche frequency and is proportional to the square root of the bias current density. As ω_a increases from zero up, X decreases from $-1/\omega C$ toward negative infinity. At $\omega_a = \omega$, a discontinuity occurs and X jumps to positive (inductive) infinity and then approaches zero asymptotically as ω_a tends to infinity. This is shown schematically in Figure 4.3.

The slope of the straight line section of the modified i-v plot may be used to estimate the small-signal reactance of the diode. From these oscillograms and the one for the 339 Ω empty package, the small-signal junction reactance

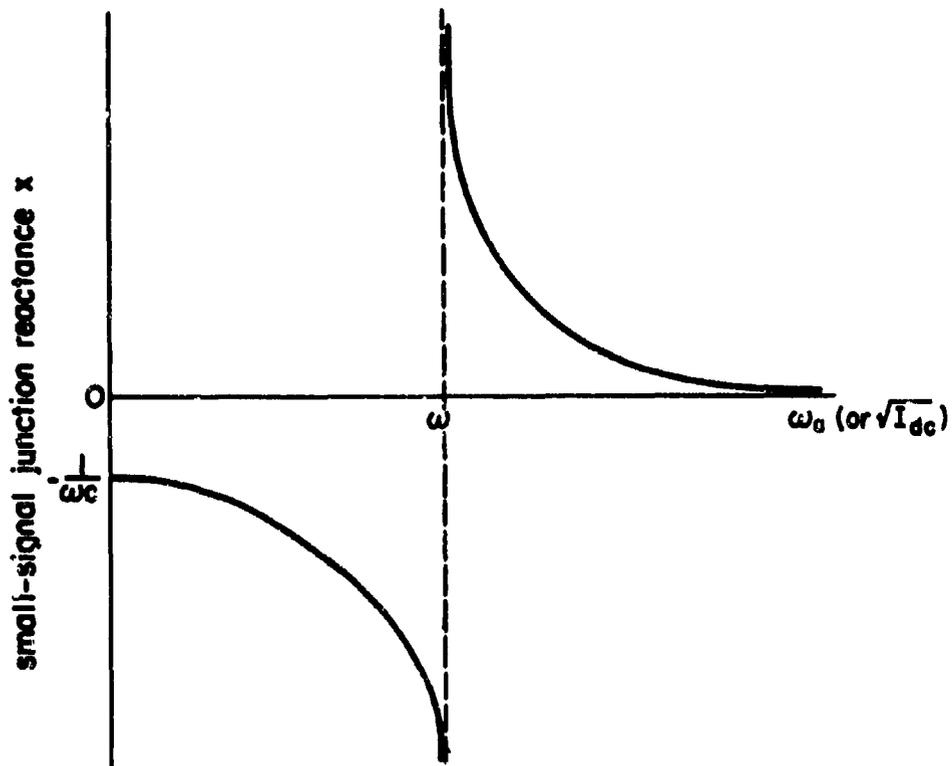


FIGURE 4.3. Schematic Diagram Showing the Theoretical Prediction of Small-Signal Junction Reactance of Avalanche Diode as a Function of Bias Current.

X of the diode under bias conditions corresponding to those shown in Figure 4.2 are tabulated as below:

	<u>Slope of Straight Line Section</u>	<u>X Ohms</u>
Empty Package	0.84	- 339
Oscillogram a	0.995	+ 1820
b	1.19	+ 813
c	1.38	+ 532
d	1.43	+ 480
e - h	1.80	+ 304

The fact that the junction reactance is positive for all these bias conditions shows that the ω_a 's corresponding to the various biases in Figure 4.2 all exceed the operating frequency of 760 MHz. In other words, a bias current of 3 ma (about 51 amp/cm²) corresponds to an avalanche frequency of higher than 760 MHz for this particular diode.

The curvatures near the upper right end of the traces in these oscillograms are believed to be due to the harmonics contained in the voltage signal as can be seen in the time display of the current and voltage signals later on.

Oscillograms 4.4(a) - (h) show the total device current superimposed on the displacement current for biasing conditions corresponding to those shown in Figure 4.2. The upper traces are the total device current. The lower trace is obtained by advancing the voltage signal by 90° so that it has the

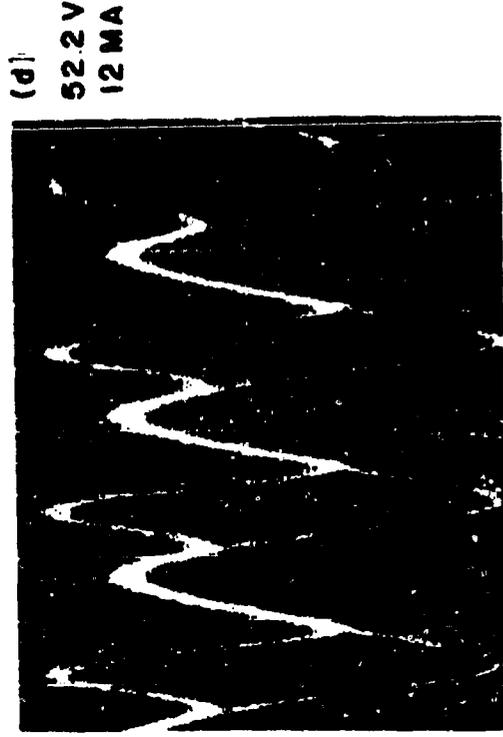
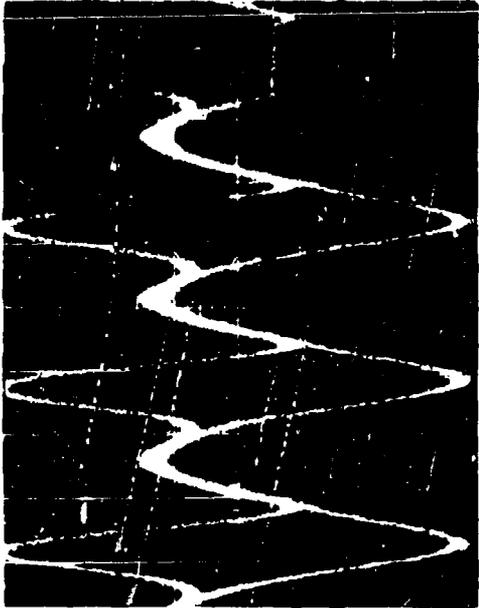


FIGURE 4.4. Total Device Current Superimposed on the Displacement Current.
Vertical Scale = 12.5 ma/cm. Horizontal Scale = .5 nsec/cm (760 MHz).

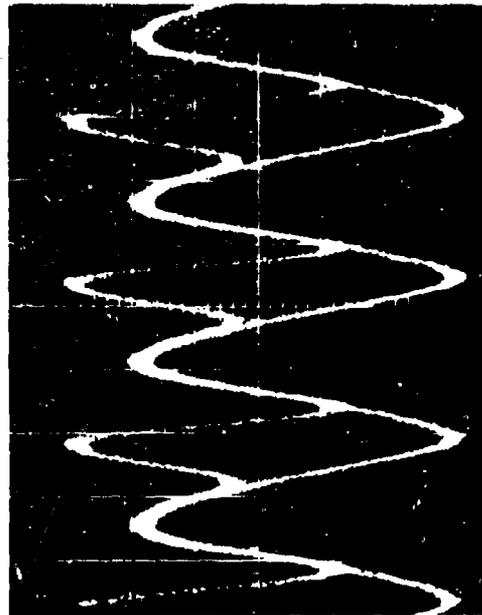
(f)
52.2 V
21 MA



(h)
52.3 V
24 MA



(e)
52.2 V
18 MA



(g)
52.2 V
21 MA



FIGURE 4. (Continued). Total Device Current Superimposed on the Displacement Current. Vertical Scale = 25 ma/cm. Horizontal Scale = .5 nsec/cm (760 MHz).

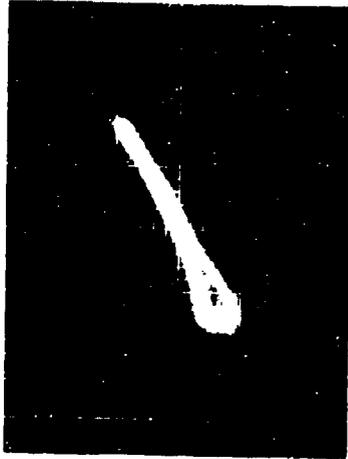
same phase as a capacitive current. The amplitude of this trace is so adjusted that it will fit the total device current during the portion of the cycle where the modified i-v plot in Figure 4.2 shows a straight line. From these oscillograms it is easy to see how the avalanche current builds up as the bias is increased. It is observed that for very low r-f excitations the avalanche current first appears near the negative peak of the capacitive current (i.e., a little bit earlier than the 90-degree point of the voltage signal) as the bias is raised from below breakdown into avalanche condition. This agrees with the small signal theory which says that the avalanche peak should lag the voltage signal by 90 degrees.

It is also noticed that the forward peak of the voltage signal is somewhat sharper than the reverse peak. This is thought to be the cause of the nonlinearity of the upper right end of the modified i-v plots shown in Figure 4.2.

Figure 4.5 shows the modified i-v plots for diode No. H-6 under different levels of current bias. This time a very wide range of bias conditions are covered. The bias is raised from far below breakdown up to 25 ma (approximately 425 amp/cm^2) well into the avalanche condition. In oscillogram 4.5(a) the diode is biased at 35 volts and an r-f excitation with a peak value of 25 volts (about 70 percent perturbation) is applied. The diode is below



(a) 35 V, 0 MA



(b) 47 V, 0 MA



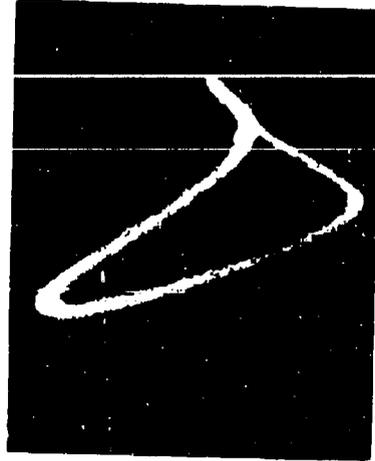
(c) 51 V, 10 MA



(d) 54.5 V, 15 MA



(e) 56 V, 20 MA

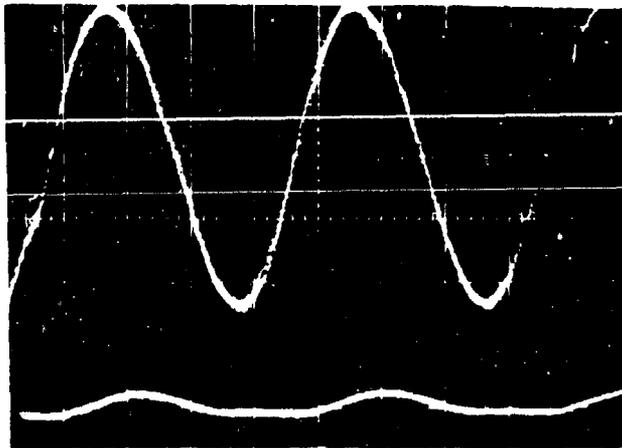


(f) 58 V, 25 MA

FIGURE 4.5 Modified $i-v$ Plots of Diode #H-6 Under Various Bias Conditions.
Scales: (a) H.S. 11.2 v/cm, V.S. 50 ma/cm; (b)-(f) H.S. 5.61 v/cm, V.S. 25 ma/cm.

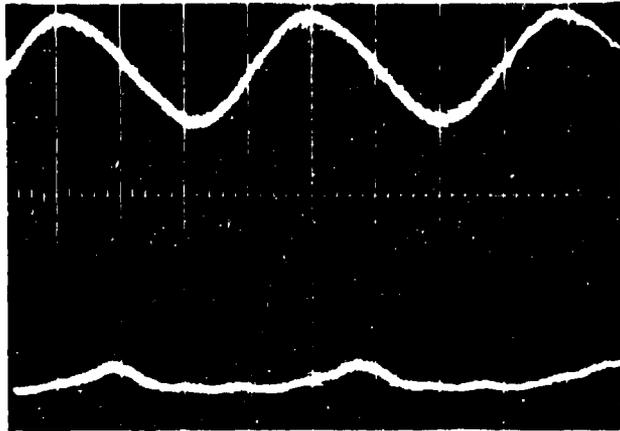
breakdown most of the time and is driven into avalanche condition around the peak of the reverse cycle. The modified i-v plot is essentially a straight line slightly opened up around the lower left end, (from about 0° point to 90° point). This counterclockwise rotating loop continues to grow up as the bias is increased from 0 ma (47 volts) in oscillogram 4.5(b) to 25 ma in oscillogram 4.5(f). It is clear that the straight line portion of the modified i-v plot of oscillogram 4.5(f) breaks into two pieces with different slopes. This is exclusively a large signal phenomena and may be understood easily when we look at the current waveform and notice its phase relative to the voltage signal as is shown in oscillogram 4.5(f) and discussed later on. The same phenomena is seen to start off if we trace back to oscillogram 4.5(e) which is biased at a lower current level.

The lower traces shown in Figure 4.6 are the net avalanche current waveforms corresponding to the modified i-v plots shown in Figure 4.5. The current scale for these traces is 50 ma/cm. The upper traces represent the r-f voltage applied across the diode. The relative phases between the upper and the lower traces are not very accurate since these pictures are obtained by making double exposures. The time scale for these traces is so adjusted that one centimeter on the horizontal axis represents approximately 90 degrees of the r-f swing.

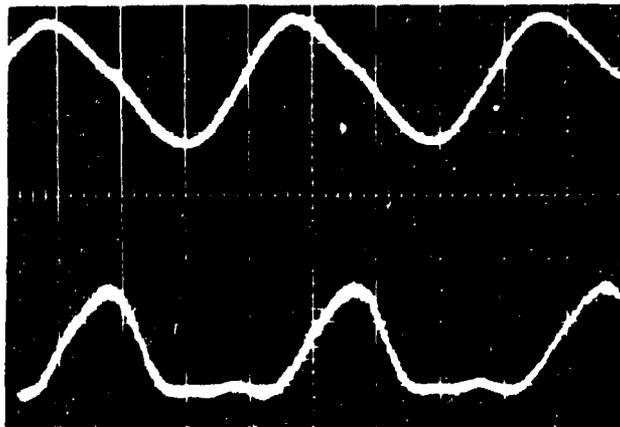


BIAS CONDITION:

(a)
35 V, 0 MA

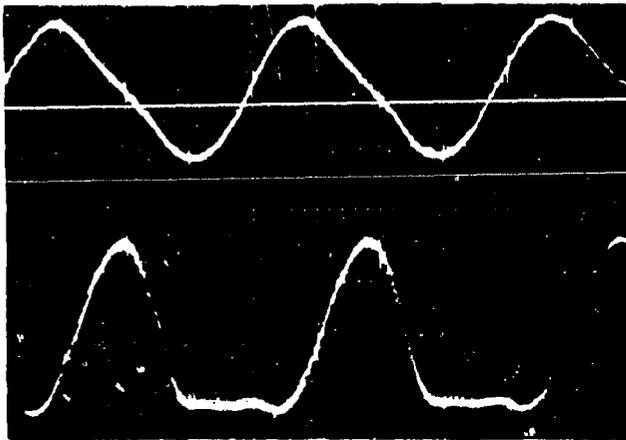


(b)
47 V, 0 MA

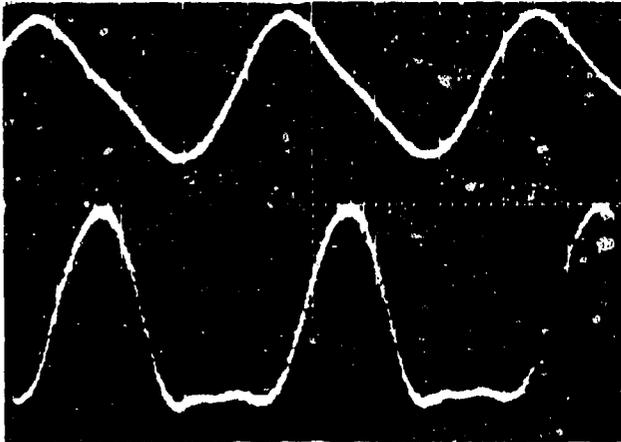


(c)
51 V, 10 MA

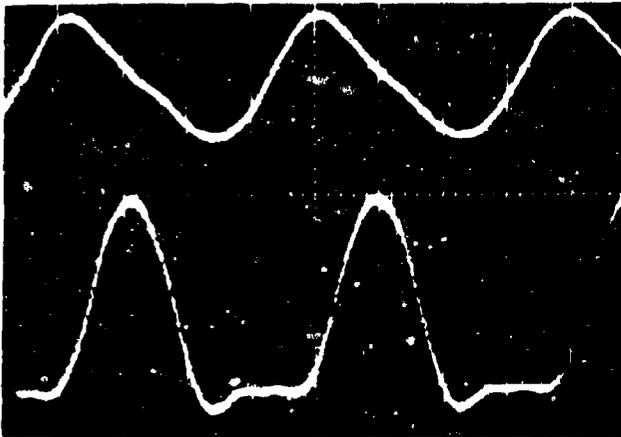
FIGURE 4.6. Net Avalanche Current Waveforms (lower traces) Corresponding to the Modified $i-v$ Plots Shown in Figure 4.5. Current Scale 50 ma/cm. Upper Traces Show the Voltage Signals. Voltage Scale = 11.2 v/cm. Horizontal Scale = 90 degrees/cm (at 760 MHz).



(d)
54.5 V, 15 MA



(e)
56 V, 20 MA



(f)
58 V, 25 MA

FIGURE 4.6 (Cont'd.) Net Avalanche Current Waveforms

In oscillogram 4.6(a) the diode is biased far below breakdown and is driven into the avalanche condition with a very large r-f signal. The avalanche peak is seen lagging the voltage signal by only about 45 degrees. The bias for this picture is 35 volts and the r-f peak value is 25 volts. Taking 47 volts to be the breakdown voltage this implies that the diode is driven back to below breakdown at about the 35-degree point of the r-f voltage signal. Therefore the avalanche peak occurs about 10 degrees later than the point where the diode is brought back to below breakdown for such cases of low bias and extremely large r-f excitation.

From oscillogram (b) through (f) in Figure 4.6, it is seen that the avalanche peak always lags the reverse voltage peak by about 80 degrees instead of 90 degrees as predicted by the theories for the small-signal analysis. Thus the avalanche peak occurs about ten degrees earlier than the point where the r-f swing brings the diode back to the bias level. This disagreement with the small-signal theoretical prediction that the avalanche peak should occur at the point where the r-f swing goes from reverse into forward direction might be expected when the space charge effect involved in such large signal operation is considered.

The general waveform of the net avalanche current obtained in this experiment looks like a half-wave rectified sinusoidal signal with a conduction angle of roughly 180

degrees and with its peak lagging the voltage signal by about 80 degrees. The theoretical analysis¹ on the other hand, predicts the avalanche effect to be a highly nonlinear phenomena with very sharp, exponentially growing avalanche peak lagging the voltage signal by 90 degrees. The fact that the experimental result does not agree perfectly with Read's qualitative prediction is expected when the following factors are taken into consideration:

1. Carrier space charge effect

This is a large signal experiment. The oscillograms in Figure 4.6 show that the avalanche peak current has reached a value of about 150 ma which corresponds to a current density of approximately 2550 amp/cm². The carrier charges in such high current density may tend to result in a sort of saturation phenomenon in the avalanche current and prevent its peak from growing very sharp. It also helps to explain why the peak occurs earlier than where it should be.

2. Effect of the drift region

The drift angle of the diodes tested in this experiment is about ten degrees at the operating frequency. The important effect of this non-zero drift angle would be that of causing the avalanche current pulse emerging from the avalanche region to spread out somewhat as viewed in the external circuit.

3. Thermal effect

The temperature rise in the avalanche region connected with high current density operation may also have some effect on the multiplication which will consequently affect the waveform of the avalanche current.

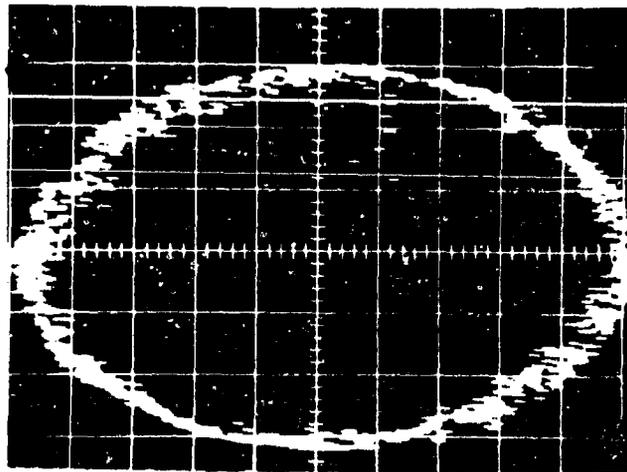
By choosing proper values for the various parameters, the experimental results have been proved¹⁰ to be in general agreement with the theoretical analysis made by Lee et al.¹¹ Experimentally, of course, the range of excitation exceeds the limits where the analysis is valid, but still qualitative differences in the conduction angle are small in this extended range. It is not thought that the conduction angle is necessarily large throughout this range of excitation but is a consequence of the particular parameters characterizing the diode tested.

In oscillogram 4.5(f) a dip from the bias level is seen in the current waveform. This occurs around the point where the voltage signal is at its forward peak. Because of the large amplitude (12 volts peak value) of the r-f signal, the junction is brought from the 25 ma bias level back to below avalanche breakdown as the voltage signal swings to its forward peak. A dip of about 25 ma in the avalanche current is therefore expected.

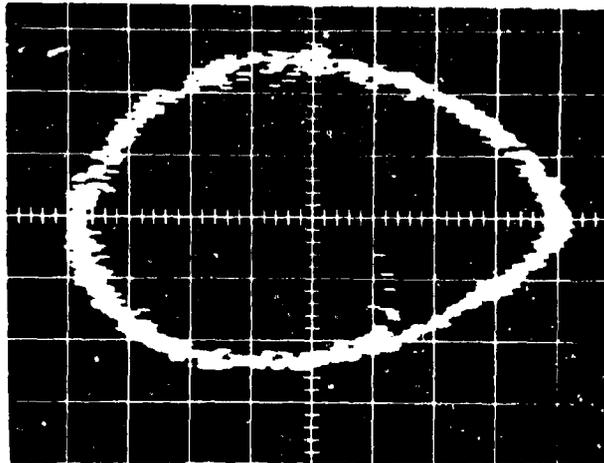
The small bumps on the horizontal portion of the current waveforms in oscillograms 4.6(b) through (f) are attributed to the defects in the waveform of the voltage signal.

C. Dynamic i-v Plots

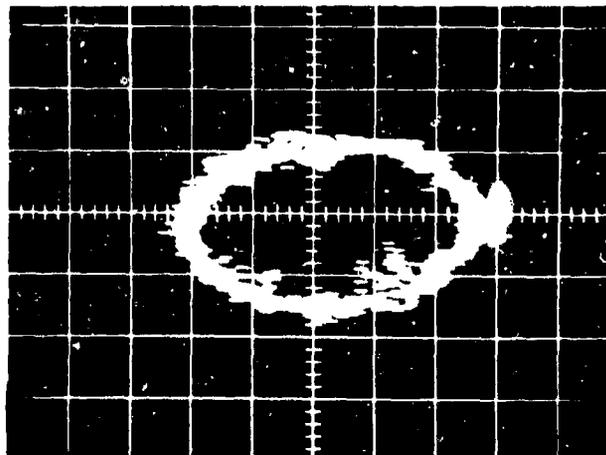
Figure 4.7 shows the i-v plots of diode No. 2-112-U under various bias condition and r-f excitation. This diode is mounted in an 1N23 cartridge with a cat-whisker of 20Ω at the operating frequency. Oscillogram 4.7(a) shows the i-v plot of a short circuited cat-whisker which is used for calibration. In oscillogram 4.7(b) the diode is biased at 35 v and is driven with a r-f excitation of 20 volts peak-to-peak. This trace circulates in a clockwise direction which means that the reactance of the junction capacitance at this bias is greater than that of the cat-whisker at the operating frequency. The loop is seen deviating from an ellipse around the lower right corner. This indicates that avalanche current is beginning to appear somewhere between the 0-degree point and the 90-degree point of the voltage signal. In oscillogram 4.7(c), the diode is biased near breakdown at 45 v. The r-f excitation is smaller than that in oscillogram (b). The trace is a well shaped ellipse rotating in the clockwise direction. The junction capacitance at this bias is calculated from this picture to be about 0.84 pF (about 250Ω at 760 MHz). In oscillogram 4.7(d), (e), and (f) the diode is biased at 8 ma, 11 ma, and 15 ma, respectively and the r-f excitations are of comparable magnitudes. In these oscillograms the avalanche current has grown so large that the lower half of the ellipse in



(a)
 H. S. 1.25v/cm
 V. S. 100 ma/cm
 Counterclockwise

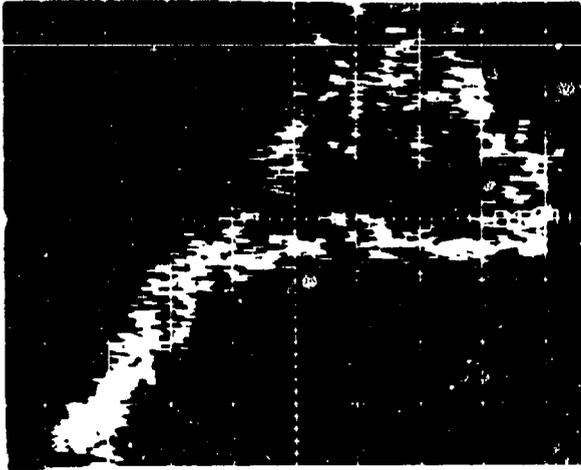


(b)
 H. S. 2.49 v/cm
 V. S. 20 ma/cm
 Clockwise

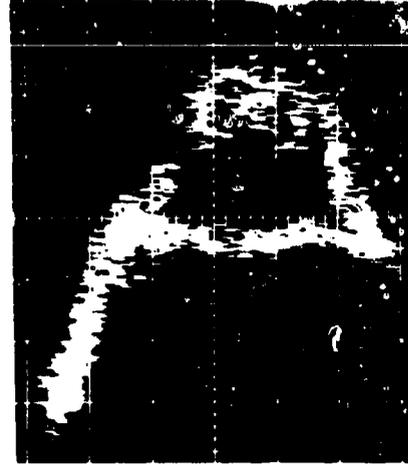


(c)
 H. S. 1.25 v/cm
 V. S. 10 ma/cm
 Clockwise

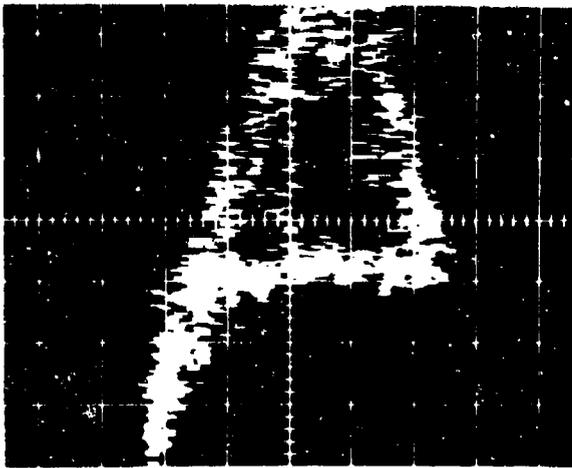
FIGURE 4.7. i-v Plots of (a) 20Ω "Cat-whisker," (b) Diode No. 2-112-U at 5v Bias and (c) Diode No. 2-112-U at 4v Bias.



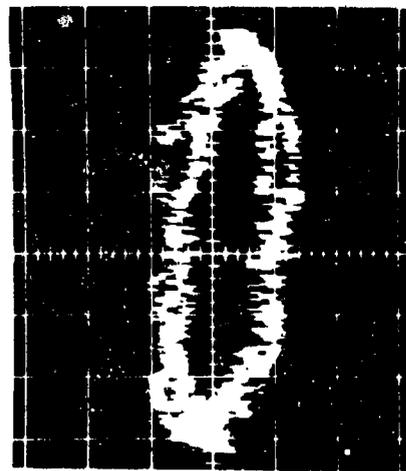
(d) Bias 8ma
H.S. .498v/cm V.S. 4 ma /cm
C.C.



(e) Bias 11ma
H.S. 1.25v cm V.S. 10ma cm.
C.C.



(f) Bias 15ma
H.S. 1.25v/cm V.S. 10 ma/cm
C.C.



(g) Bias 15 ma
H.S. .498v cm V.S. 4 ma cm
C.C.

FIGURE 4.7. (Cont'd.) i-v Plots of Diode No. 2-112-U.

oscillogram 4.7(d) rises above the upper half and a P-shaped loop tracing in the counterclockwise direction is resulted. These oscillograms again show a wide conduction angle. The proportionality of the horizontal scale to the vertical scale has been kept the same for these oscillograms. From these pictures we see that the impedance becomes smaller and smaller as the bias is increased. It must be mentioned that all these i-v plots have included the effect of the 20Ω reactance of the cat-whisker which is in series with the sample.

At biases of over about 3 ma, the i-v plot turns into an inductive (counterclockwise) ellipse for small r-f signals as illustrated by oscillogram 4.7(g).

D. Anomalous Rectification Phenomena

The measured d-c breakdown characteristic of diode No. H-9 under various r-f excitations is shown in Figure 4.8. The r-f excitation ranges from 17 percent to 40 percent. It is seen from this figure that the breakdown starts at lower d-c bias voltage for higher r-f excitation. Figure 4.9 shows the rectified current which is the difference between the d-c device current with r-f excitation and that without excitation. From this figure it is seen that the rectified current is always larger for higher r-f excitation. When the bias voltage is raised from below breakdown the

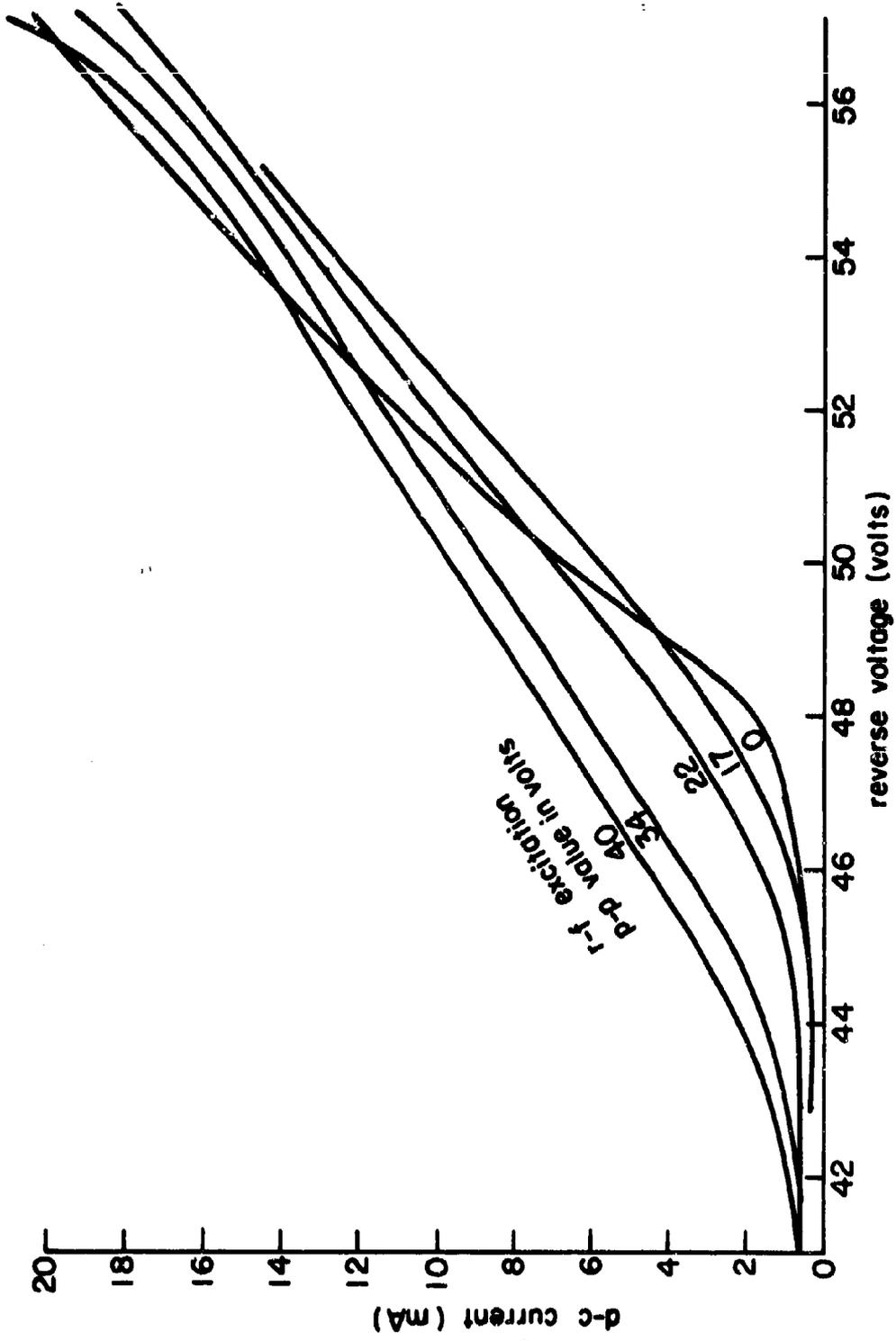


FIGURE 4.8. D-C Breakdown Characteristic of Diode No. H-9 under Different R-F Excitations.

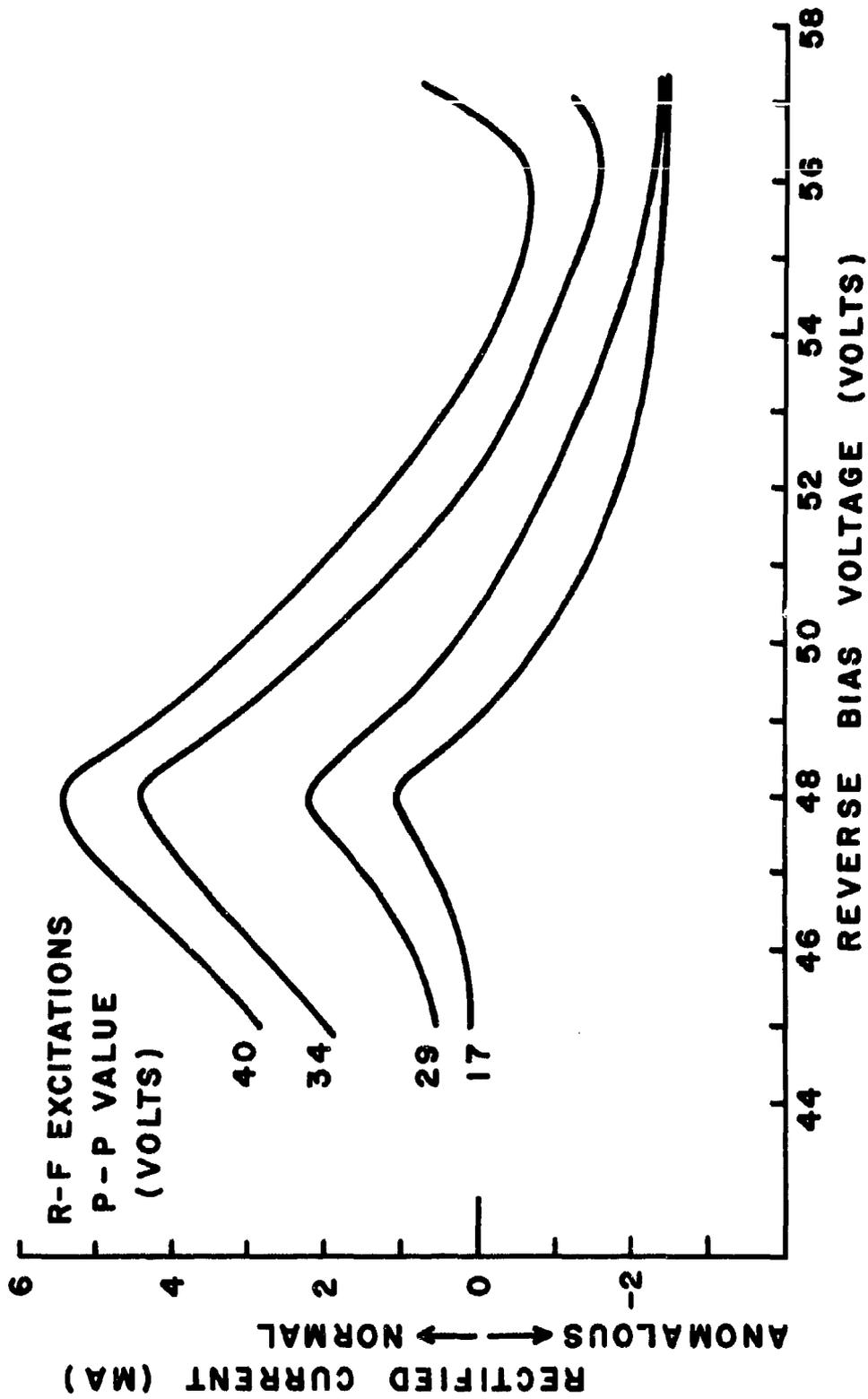


FIGURE 4.9. Rectified Current of Diode No. H-9 under Different R-F Excitations.

rectified current is positive and increases until it reaches a maximum. It then goes down to zero and continues to decrease to negative values, i. e., anomalous rectification appears. The tendency of the variation of the rectified current agrees with the theoretical prediction given by Lee et al.^{11,12} for a diode with positive a_2 coefficient. This figure shows that the voltage at which the rectification changes from normal into anomalous is higher for larger r-f excitation. It is also noticed that the maximum normal rectification always occurs at the same bias level for the various r-f excitations.

When the bias is increased further, the curve for the highest excitation (about 40 percent) reaches a minimum point and then goes up, passing the zero level and reaches into the normal rectification region again. The curve for the next highest excitation (34 percent) has the same tendency. It is believed that if the higher order terms had been retained in Equation (34) of the analysis of Lee et al.¹¹, this phenomena might have been predicted for such large-signal operations.

E. Time Response of Avalanche to a Unit Pulse Voltage Input

Oscillogram 4.10(a) shows the voltage pulse and the current at breakdown. The voltage is 46 volts on the top of the pulse. Oscillogram 4.10(b) is the same as oscillogram 4.10(a) except that the gain of the voltage channel is

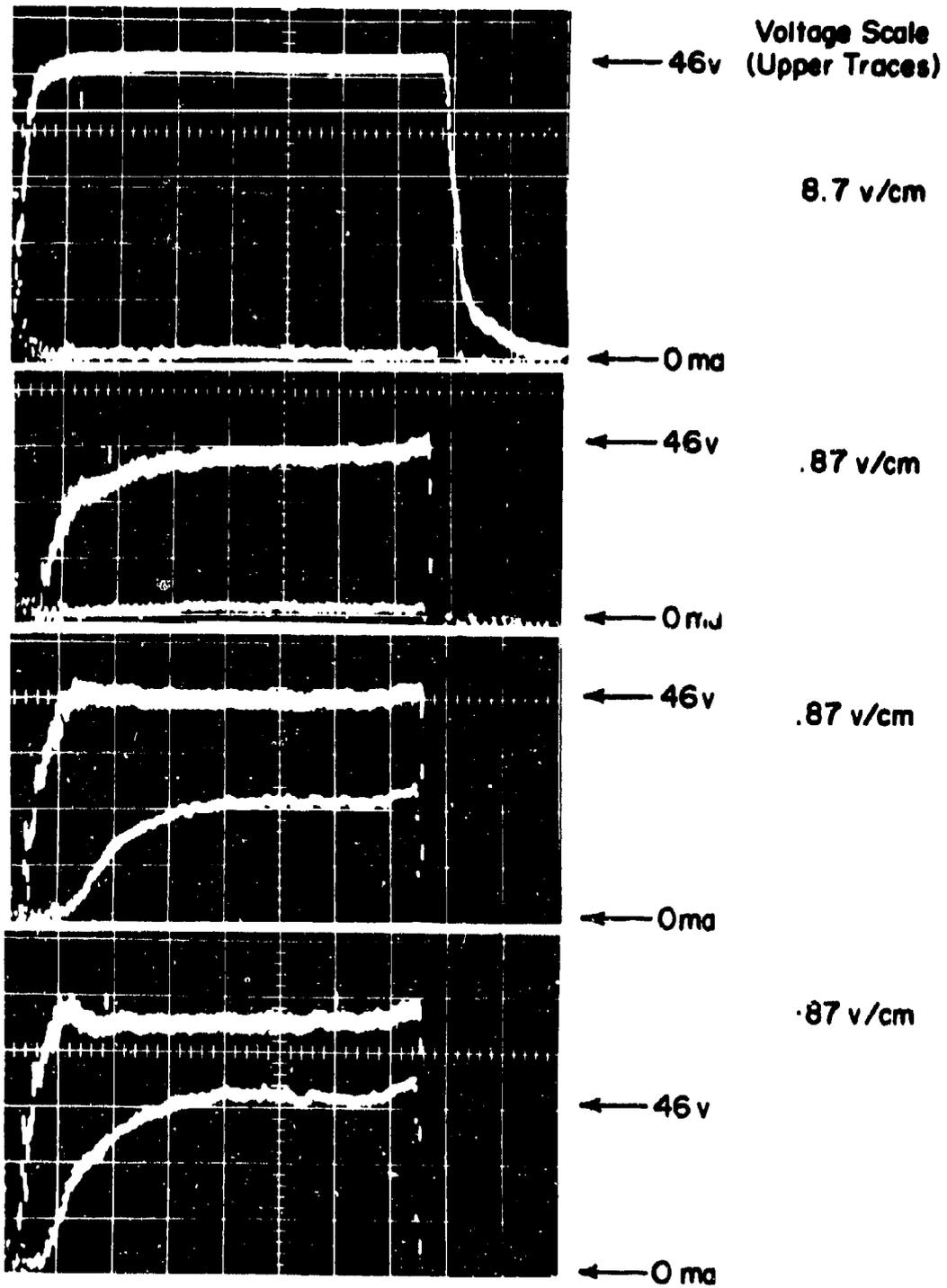


FIGURE 4.10. Time Response of Avalanche Diode to Unit Pulse Voltage. Current scale (Upper traces) 10 ma/cm. Time Scale 5 nsec/cm.

increased by ten times and the voltage wave shape is down shifted. Oscillograms 4.10(c) and 4.10(d) show the voltage and current at higher voltages. Comparing these two pictures with oscillogram 4.10(b), we see that a buildup time of about ten nsec does exist for the avalanche response. (The resolution of this circuit is not good enough to allow more detailed measurement).

V. SUMMARY AND CONCLUSION

The avalanche current waveform of an avalanching silicon P-N junction has been measured. The general waveform of the net avalanche current looks like a half-wave rectified sinusoidal signal having a conduction angle of roughly 180 degrees and with its peak lagging the voltage signal by about 80 degrees. The theoretical analysis given by Read predicts a very narrow current pulse lagging the voltage signal by 90 degrees. The disagreement between the experimental results and the theoretical prediction may be due to such factors as carrier space charge effect, effects of the transit angle of the drift region and the thermal effects. The particular value of the various parameters characterizing the diode tested also have some effect in the wideness of the conduction angle. If the experiment had been conducted at a lower frequency, at lower sample temperature and with a higher Q circuit possibly better agreement with Read's prediction might have been obtained. The measured results, however, have been proved to be in general agreement with the theoretical analysis of Lee et al.¹¹ with proper choice of the various parameters.

The results of the measurement of anomalous rectification effect show the same variation of the rectified current as predicted by Lee et al.¹¹, even at an excitation of as high as 22 percent. The result shows that the particular diode

tested has a positive a_2 coefficient. However, the result for the case with higher excitation (40 percent) shows that the avalanche junction turns from anomalous back into normal rectification at high bias levels. The experimental result shows that the maximum normal rectification always occurs at the same bias voltage for various r-f excitations.

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13. ABSTRACT A large-signal experimental study has been made on the wave shapes and phase relations of the current in an avalanche silicon diode excited by an external microwave signal source under different conditions of current bias. The objective of this study has been to obtain information helpful in the understanding of the factors determining the operating efficiency of microwave avalanche transit-time diode oscillators. The experiments were conducted at 760 MHz on diodes that normally oscillated at 10 GHz so that the transit-time effects in the drift zone of the diode were negligible and so that displacement currents in the diode could be reduced to the same order of magnitude as the convection current. By subtracting the displacement current from the total device current as viewed through a current viewing disc resistor in series with the diode, a display of the net avalanche current was obtained. The avalanche current wave shape looks like a half-wave rectified sinusoidal signal with its peak lagging the voltage signal by approximately 80 degrees. In general, the experimental result has been found in good qualitative agreement with theoretical analysis when the particular values of the various parameters characterizing the diode tested are taken into consideration. The anomalous rectification effect in avalanche diodes has also been investigated. The variation of the rectified current agrees with the theoretical analysis even at perturbations as high as 22 percent of the bias voltage.			

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