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INTERFACE STATES IN SCHOTTKY BARRIER DIODES

Rensselaer Polytechnic Institute

This research was supported by the Defense Nuclear Agency under Subtask Z99QAXTB056, Work Unit 52, entitled "Radiation Effects on Solid State Microwave Device Structures"

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This technical report has been reviewed and is approved.

Donald A. Neamen

DONALD A. NEAMEN
Contract Monitor

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The change in the electrical characteristics of Al-GaAs Schottky barrier diodes with neutron fluence has been determined. Al-nGaAs Schottky barrier diodes, fabricated from epitaxial and bulk material with carrier concentration in the range of between 7×10^{15} to 8×10^{16} cm^{-3}, were exposed to fast neutron irradiation at fluences where the change in free carrier concentration was less than 20%. In the lighter doped diodes, there was a slight change in the forward and reverse bias I-V characteristics after irradiation. The changes in the I-V characteristics indicate that the

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20. Abstract (Continued)

density of interface states changes during irradiation. The interface state density is approximated by a sharp peak of between 3×10^{13} to 10^{14} cm^{-2} eV^{-1} located at near the zero bias Fermi level before irradiation and after the low irradiation the density of interface states change by a factor of 2 to 5 and becomes less peaked. In the higher doped diodes, the reverse current change by at least an order of magnitude while the forward I-V characteristics remained essentially the same. The increase in reverse current is caused by high field emission from a trap whose energy for free carrier emission is of the order of 0.3 eV and it is similar to the one found previously in Au-nGaAs diodes.

The photo current of the Schottky junction, biased near and at avalanche breakdown, was measured under transient ionizing radiation, at dose rates between 10^{8} to 10^{10} rads/sec. The photoresponse of the Al diodes to ionizing radiation is similar to the one observed in diffused pn junctions and it is not affected by the neutron irradiation at the low fluence used. These results indicate that IMPATT diode oscillator aftereffects observed under transient ionizing radiation are not due to the Schottky junction.

The effect of RF circuit tuning and of bias curcuit tuning in producing IMPATT diode oscillator aftereffects under transient ionizing radiation were experimentally evaluated. Half watt Si and GaAs X-band IMPATT diode oscillators were tested under transient ionizing radiation in a tunable disc-and-post type waveguide cavity. The results indicate that the principal cause of the aftereffects is a device-circuit interaction and is related to the impedance of the RF circuit and not the bias circuit impedance. Of the several devices tested, the GaAs Schottky IMPATTs were more prone to the aftereffects than the diffused devices.

FOREWORD

Under Air Force Cambridge Research Laboratories, Contract No. F 19628-74-C-0102, sponsored by the Defense Nuclear Agency, the Electrical and Systems Engineering Department of Rensselaer Polytechnic Institute has been carrying out research toward studying the effect of neutron irradiation on the metal-semiconductor interface and the resultant performance of Schottky barrier diodes (including with transient ionizing radiation). This final report presents the results obtained during the last six months of the 18 months research program.

The authors wish to acknowledge the help given by J. Floyd in the neutron irradiations at Brookhaven National Laboratory and D. E. Lapierre and J. R. Capelli during the transient ionizing irradiations at AFCRL. Special thanks are given to our contract monitor, Dr. D. A. Neamen, for the many technical discussions and suggestions throughout the program. The extra effort and diligence of Ms. Ardell Deane while typing the several reports and communications prepared during the program are gratefully acknowledged.

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1.0 INTRODUCTION

1.1 Overview

Gallium arsenide Schottky barrier junctions have become increasingly important in a wide variety of high performance GaAs microwave devices such as IMPATT diodes, Schottky gate FETs and RF detectors. Although neutron irradiation effects on silicon Schottky barrier junctions are well documented ~~(1,2,3)~~ no detailed results have been reported for GaAs Schottky junctions. ~~(4)~~ The purpose of this program was to explore the effect of fast neutron irradiation on the metal semiconductor interface and the resultant performance of Schottky barrier (including with transient ionizing radiation). Device changes at neutron fluences where the reduction in free carrier concentration is less than 20% were emphasized, as larger reductions in free carrier concentration lead to gross changes in junction properties that cannot be tolerated in most applications. Gold and aluminum were selected as the metals for forming the Schottky junctions since there is a large variety of results for Au-GaAs Schottky junctions reported in the literature, which could be used for comparison purposes, and because the Al-GaAs junction has a lower barrier height and appears to be more stable than the Au-GaAs interface.

The research program was divided into two parts. The first part of the program was concerned with the study of the Au-GaAs interface and lasted 12 months. It was also used for developing an appropriate device test structure, which eliminated surface leakage current effects, and for developing automated I-V and C-V measurement test set-ups which permitted fast and accurate measurement of the electrical characteristics of the devices tested from 77°K to 400°K. The second part of the program, which lasted 6 months, was concerned with the changes in the Al-GaAs interface as well as with experimental study of the influence of the RF and bias circuits on producing anomalous aftereffects on IMPATT diode oscillators observed previously.(5)

1.2 Summary of the First Part of the Program

As mentioned above, the first part of the program was concerned with the study of the changes that take place at Au-nGaAs interface with neutron irradiation and the results have been reported previously.(6,7) The following summarizes the main results for Au-nGaAs Schottky barrier diodes.

The reverse I-V characteristics are greatly affected by neutron irradiation at fluences where the change in free carrier concentration was less than 10% while the forward characteristics are less sensitive to neutron irradiation. Typically the n factor at forward bias changed from 1.01 in unirradiated devices to 1.1 after irradiation. For forward bias and for small reverse bias the current in Au-nGaAs diodes is caused by thermionic emission and any changes in the I-V characteristics can be accounted for by a change in the density of interface states. The experimental results before and after neutron irradiation indicate that the interface state density model of Levine(8) has a small range of validity when carrier concentration and temperature are varied. In particular, the energy distribution of interface states changes from a highly peaked distribution near the zero bias Fermi level (peak value $\sim 10^{14}/\text{cm}^2$ eV) before irradiation to a more uniform distribution of lower value ($\sim 10^{13}/\text{cm}^2$ eV) after irradiation.

The observed increase in reverse current (at voltages larger than 2 volts) after low fluence irradiation was found not to be due to conventional generation-recombination as has been found in silicon Schottky barriers.(1) The changes observed in the reverse current is larger in diodes with higher doping than in diodes with lighter doping. Furthermore, the reverse current was found to be more voltage dependent and less temperature dependent after irradiation than before irradiation, indicating that the increase in reverse current is due to a high field effect process. Consideration of several high field effect processes showed that enhanced field emission from a trap is a likely source of the reverse current.

Transient ionizing radiation measurements showed that the behavior of reverse biased Schotttky diodes under transient ionizing radiation operating below or in the avalanche regime, is not affected by neutron irradiation and it is similar to that reported previously for silicon pn junction diodes.(9) Comparable transient ionizing radiation data on Schottky barriers GaAs IMPATT oscillators indicated that aftereffects observed in their devices are not exclusively a junction effect but that device-circuit interactions are a likely cause.

1.3 Second Part of the Program

The second part of the research program had two objectives. The first one was to determine if the effects observed in neutron irradiated

Au-nGaAs diodes are sensitive to the type of metal used for forming the Schottky barrier. Aluminum was chosen as the metal to be used because it gives a lower barrier height and it appears to form a more stable interface in GaAs than gold does. The second objective was to determine the effect of the RF and bias circuits on the occurrence of aftereffects under transient ionizing radiation of IMPATT diode oscillators. This final report presents the results obtained during this final phase of the program.

Chapter 2 contains the radiation results in Al-nGaAs diodes. The test instrumentation, the interface state model for the Schottky barrier and the data reduction scheme used for interpreting the results obtained are similar to the ones used for Au-nGaAs diodes, it is not repeated here since it has been reported previously.(6) Chapter 3 describes the tests and results obtained in determining the effect of RF and bias circuits on causing aftereffects during transient ionizing radiation of commercial silicon, diffused and Schottky GaAs IMPATT diode oscillators. The last chapter, Chapter 4, summarizes the results obtained during the whole program.

2.0 RADIATION RESULTS IN Al-nGaAs DIODES

2.1 Device Fabrication and Test Instrumentation

The device structure used was the same as the one developed for the Au-nGaAs diodes and consists of four diodes on a 0.100" x 0.100" chip.(6) Three of the diodes had a guard ring in order to prevent surface currents from affecting the I-V measurements. An enlarged photograph of the device chip is shown in Fig. 2.1. The center dot is 15 mils in diameter which corresponds to an area of 1.1×10^{-3} cm^2.

The fabrication procedure used was similar to the one used for the Au-nGaAs devices with a few minor modifications. The starting material was either n bulk GaAs or nn$^+$ epitaxial (100) GaAs wafers with carrier concentrations in the range of 7×10^{15} to 8×10^{16} cm^{-3}. The fabrication sequence used was as follows: the back contact was formed by evaporating 6000 A$^\circ$ indium on the back of the wafer followed by alloying at 350°C for two minutes in a forming-gas atmosphere. The Schottky barrier contact was formed by evaporating 1000-2000 A$^\circ$ of Al with the wafer heated at 150°C. Before the aluminum evaporation the GaAs surface was carefully cleaned with HCl, rinsed with methanol and blown dry with filtered air. The device test structure was defined by etching the aluminum film from the unwanted areas using photolithographic techniques. The etch used for removing the aluminum was Transene Type D Aluminum etchant which is nitric acid free and does not attack the GaAs. The photoresist was removed with Trichloroethylene by scrubbing the wafer with a Q-tip. The next step was scribbing the wafer to separate the 0.100" x 0.100" chips. The chips were mounted on TO-5 headers with a silver epoxy and

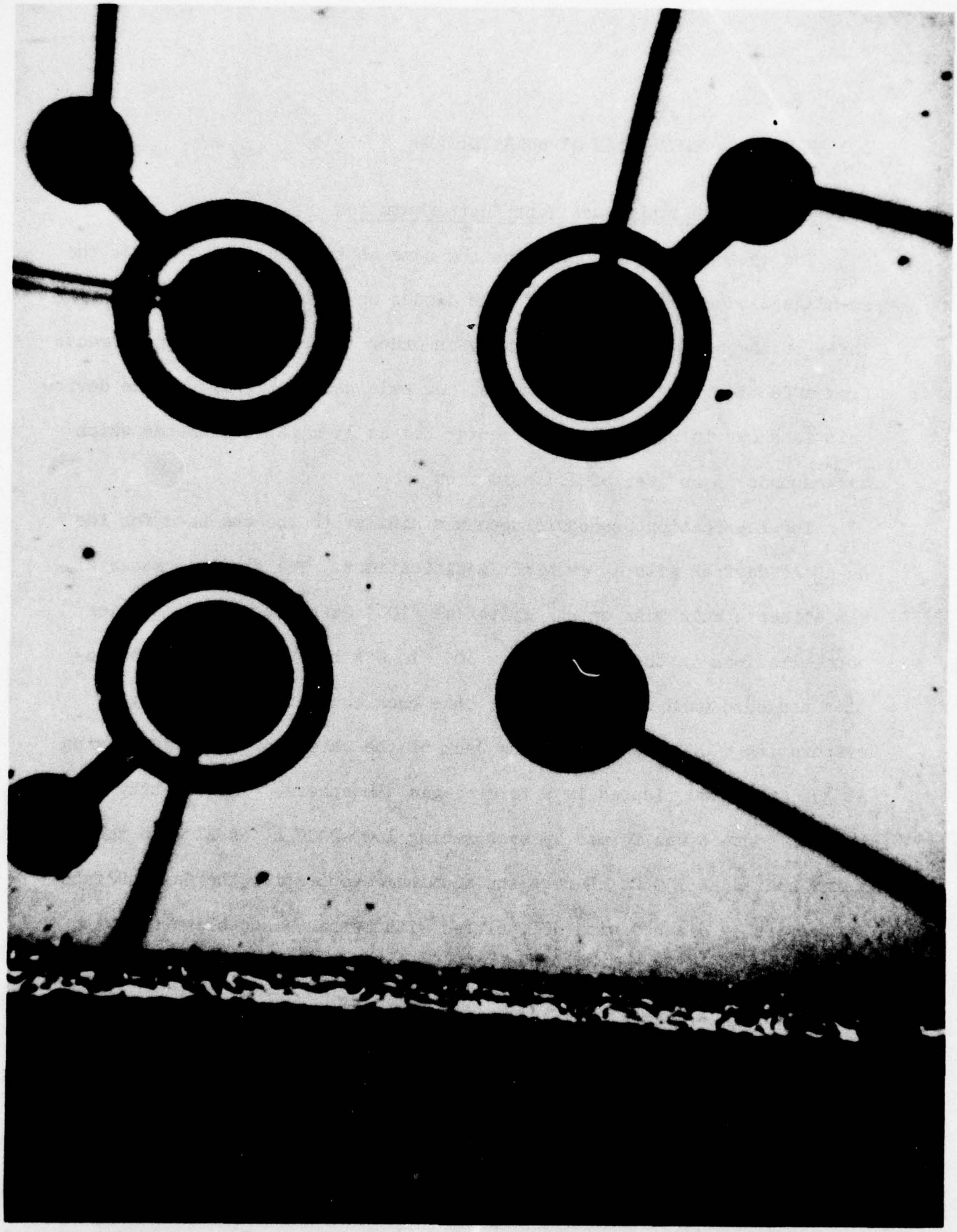


Fig. 2.1. Photograph of top surface of Schottky barrier device chip

cured overnight at a temperature between 100 and 125°C. Gold wires were bonded between the terminals of the TO-5 headers and the device terminals.

Using the above procedures Al-nGaAs were fabricated with forward and reverse current characteristics comparable to or better than the ones reported in the literature.(10) Table 2-1 presents a summary of the room temperature characteristics of the three series of Al devices fabricated during this part of the program.

The electrical characteristics of the devices before and after irradiations were determined using the test facilities developed during the first part of the program and described in detail in a previous report.(6) The facilities allowed automated swept DC I-V and 1 MHz C-V characteristics to be measured between 77°K to 400°K with great rapidity and high resolution in current, voltage and capacitance.

The fast neutron irradiations were carried out at the BMR reactor at BNL. The devices were irradiated to two different neutron fluences. A low neutron fluence of 3.6×10^{14} n/cm^2 was used in the lightly doped devices and a high neutron fluence of 2.2×10^{15} n/cm^2 was used in the highly doped devices. With the above neutron fluences the change in free carrier concentration was less than 20% and it will be described in detail later in the report.

Transient ionizing radiation testing was performed at the linear accelerator facility at AFCRL. The accelerator generated a 10 MeV electron beam of 100 nanosecond duration with dose rates between 10^8 to 10^{10} rads/sec. The photocurrent and voltage across the diode during the radiation pulse were recorded with the diodes in an evacuated chamber to

Table 2-1 - Room Temperature Characteristics of Al-nGaAs Schottky Diodes with Different Starting Material

Device Series	Starting Material	Carrier Concentration (cm^{-3})	n-factor (over 10^{-8} - 10^{-6} A)	Saturation Current (A) (extrapolated from forward I-V data)	Reverse Current (A)	Zero Bias Capacitance (pF)
Al/316	Bulk	7.2×10^{16}	1.04	1.7×10^{-10}	6.8×10^{-9} at 3 V	114
Al/1E16	Epitaxial (4 μm)	1.2×10^{16}	1.03	3.7×10^{-10}	2×10^{-9} at 4 V	50
Al/7E15	Epitaxial (6 μm)	6.8×10^{15}	1.014	2×10^{-10}	2.3×10^{-9} at 7.5 V	39

prevent air ionization from affecting the measurements. The electron beam dose rate was determined using a calibrated PIN diode radiation detector. During the testing the radiation pulse was monitored by means of a Faraday cup. The results of these tests are described in Section 2.6 of this report.

2.2 I-V Characteristics

The forward and reverse bias I-V characteristics for device series 1E16-1 before and after the low fluence irradiation are shown in Figs. 2.2 and 2.3. The data shows that the forward characteristics changed slightly with the low neutron fluence, the n factor changed from 1.02 before irradiation to 1.03. Figures 2.4 and 2.5 are Richardson plots of I_s/T^2 vs. 1/T where T is the absolute temperatures and I_s is the leakage current obtained by extrapolating the forward bias I-V characteristics to the V = 0 intercept. Before irradiation the barrier height ϕ_B is 0.725 eV and the Richardson constant A^* has a value of 9.1 $A/cm^2\text{-}^oK^2$, which corresponds very closely to the theoretical value of 8 assuming a reduced effective mass of 0.067. After irradiation, the barrier height ϕ_B is 0.733 eV and A^* is close to 10. The above results indicate that Al-nGaAs diodes are less sensitive to low neutron irradiation than Au-GaAs.

The reverse current characteristics above room temperature did not change after irradiation. At lower temperatures and reverse voltages larger than 2 volts, the reverse current increased typically by a factor of 2 to 3 after the low neutron fluence. The large change observed previously in the reverse characteristics of Au-nGaAs and not observed in the Al-nGaAs diodes at low neutron fluence is due to the smaller

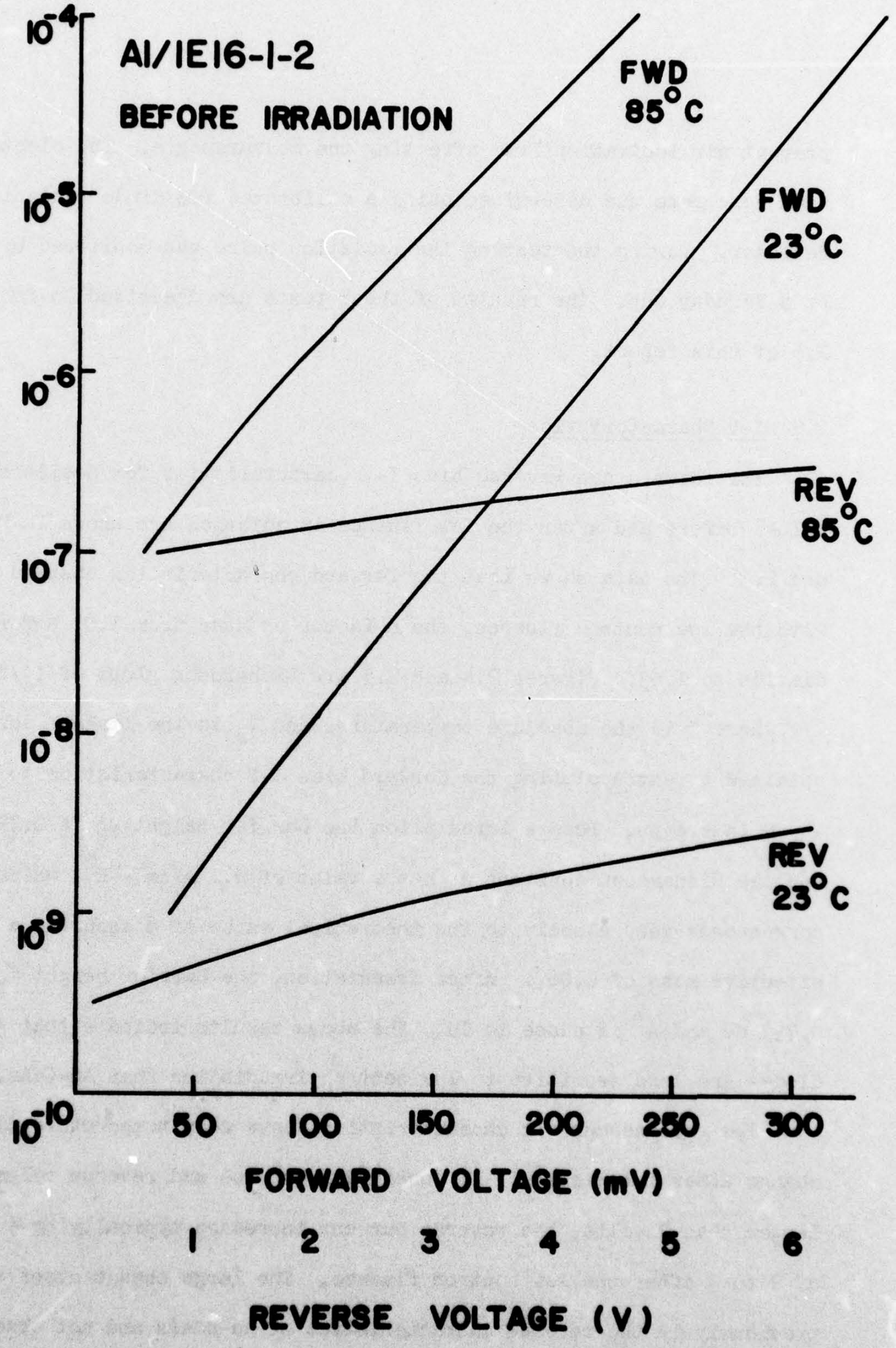


Fig. 2.2. Forward and reverse bias I-V characteristics of 1E16-1 before irradiation

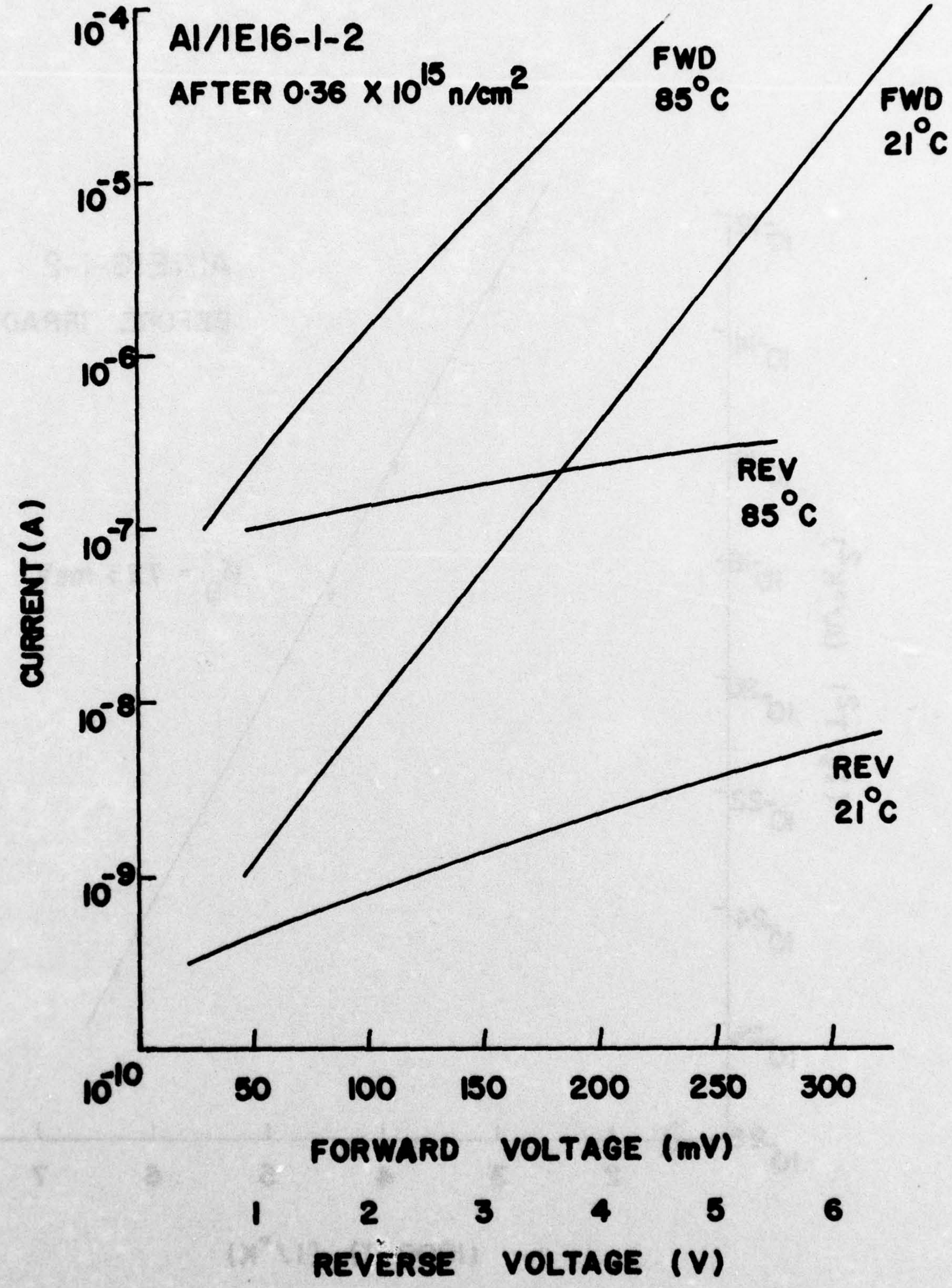


Fig. 2.3. Forward and reverse bias I-V characteristics of 1E16-1 after irradiation

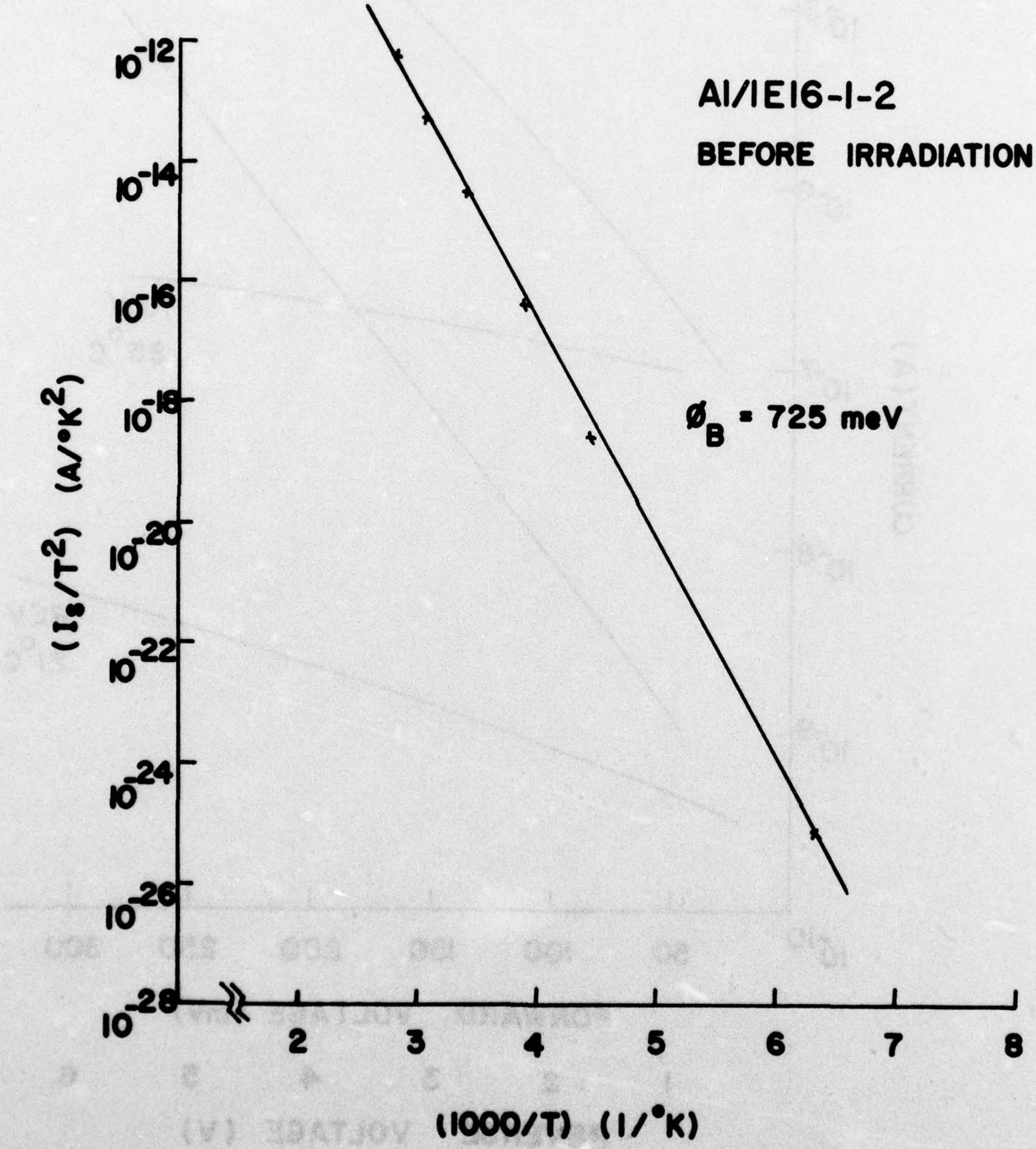


Fig. 2.4 Richardson plot of I_s/T^2 vs. 1/T of 1E16-1 before irradiation

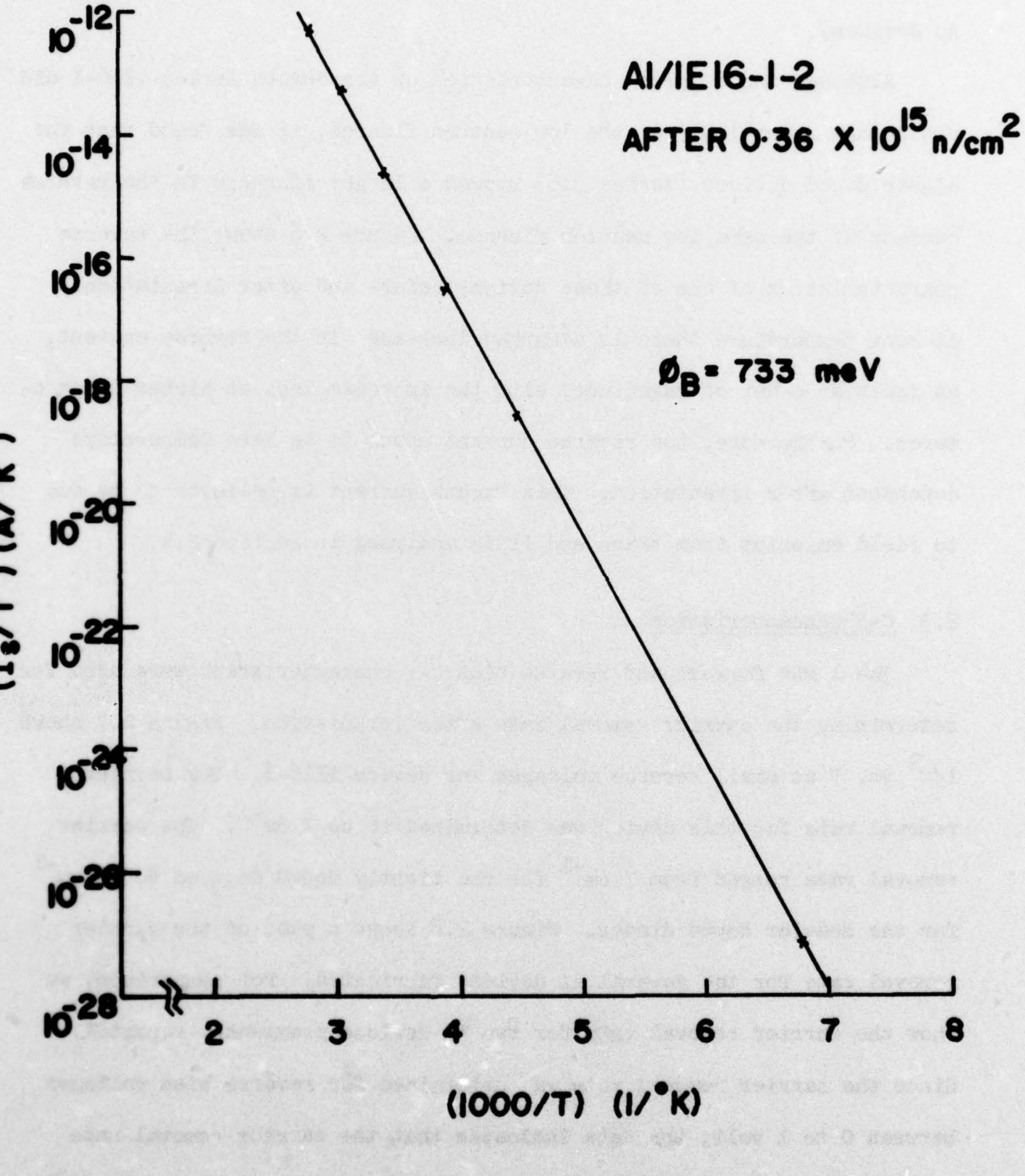


Fig. 2.5 Richardson plot of I_s/T^2 vs. 1/T of 1E16-1 after irradiation

barrier height of the Al devices (0.72 eV as compared to 0.9 eV for the Au devices).

Although the reverse characteristics of the device series 1E16-1 did not change appreciably at the low neutron fluence, it was found that the higher doped devices (series 316) showed a larger increase in the reverse current at the same low neutron fluence. Figure 2.6 shows the reverse characteristics of one of these devices before and after irradiation. At room temperature there is a marked increase in the reverse current, at least an order of magnitude, with the increase less at higher temperatures. Furthermore, the reverse current shows to be less temperature dependent after irradiation. This excess current is believed to be due to field emission from traps and it is analyzed in Section 2.4.

2.3 C-V Characteristics

The 1 MHz forward and reverse bias C-V characteristics were used for determining the carrier removal rate after irradiation. Figure 2.7 shows $1/C^2$ vs. V at small reverse voltages for device 1E16-1. The carrier removal rate for this device was determined to be 7 cm^{-1}. The carrier removal rate ranged from 7 cm^{-1} for the lightly doped devices to 13 cm^{-1} for the heavier doped diodes. Figure 2.8 shows a plot of the carrier removal rate for the several Al devices fabricated. For comparison, we show the carrier removal rate for two Au devices previously reported. Since the carrier removal rate was determined for reverse bias voltages between 0 to 1 volt, the data indicates that the carrier removal rate close to the metal-semiconductor interface depends upon the nature of the interface, although more data would be desirable to confirm this conclusion.

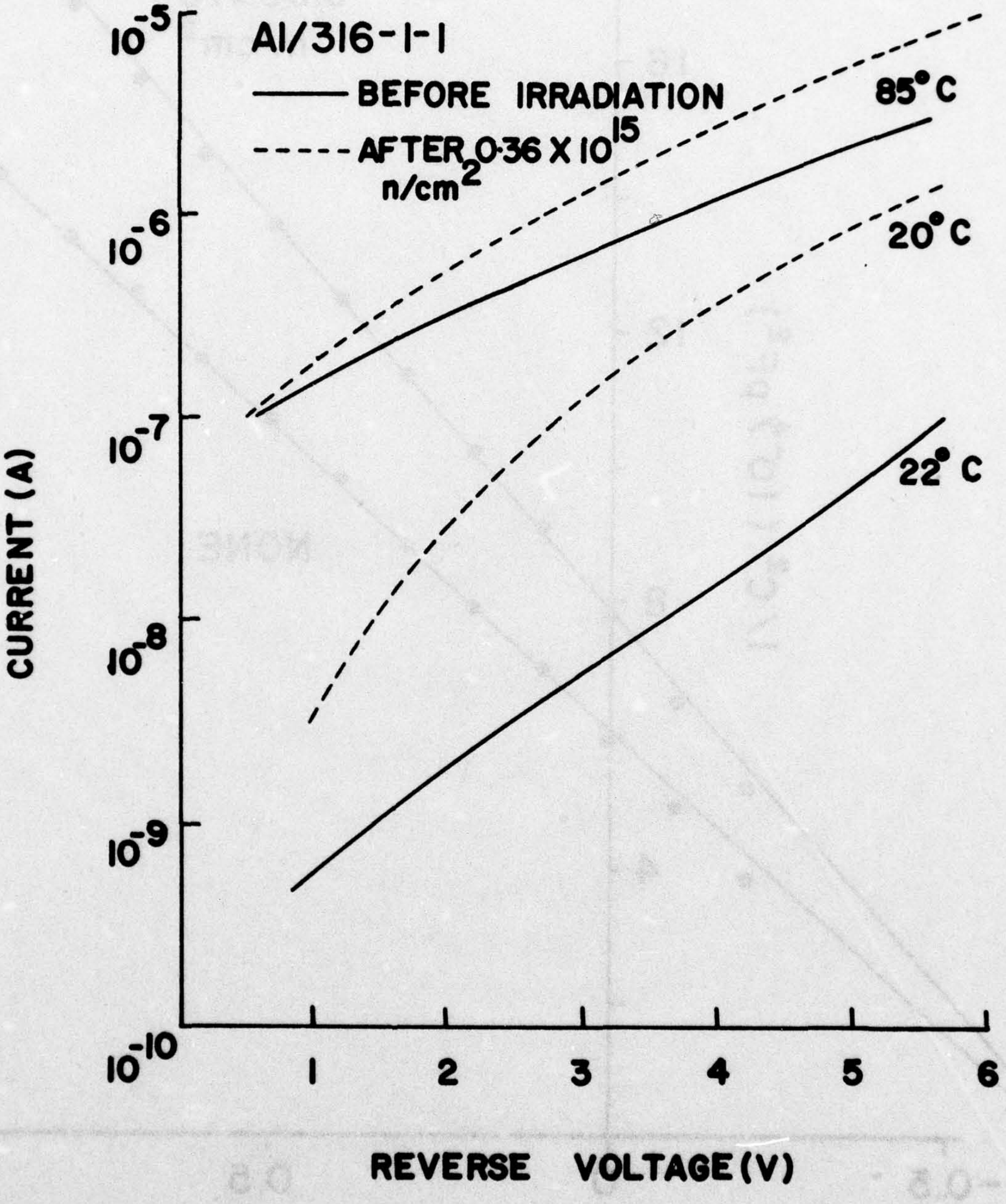


Fig. 2.6 Reverse bias I-V characteristics of 316 before and after irradiation

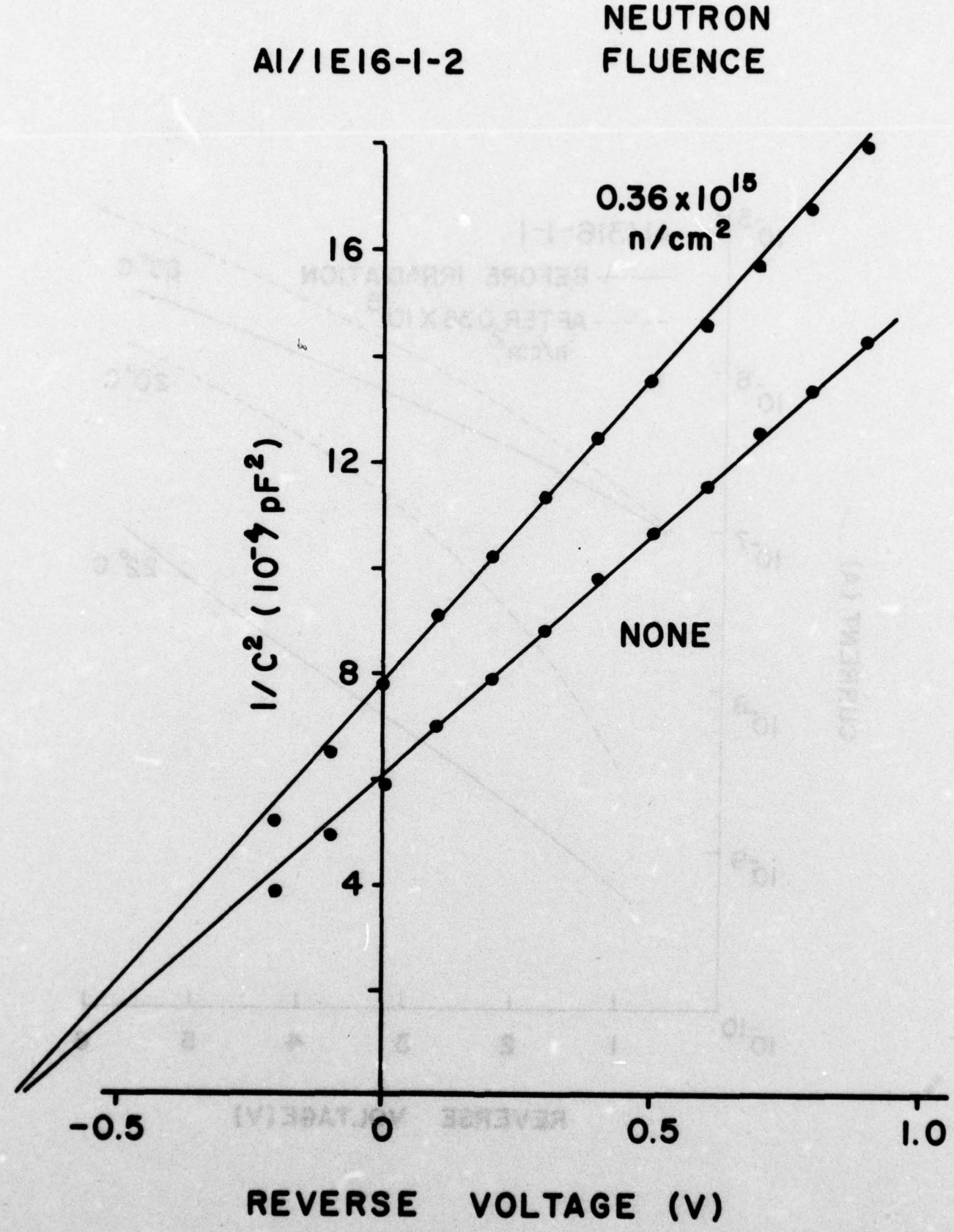


Fig. 2.7 $1/C^2$ vs. V near zero bias for 1E16-1 before and after irradiation

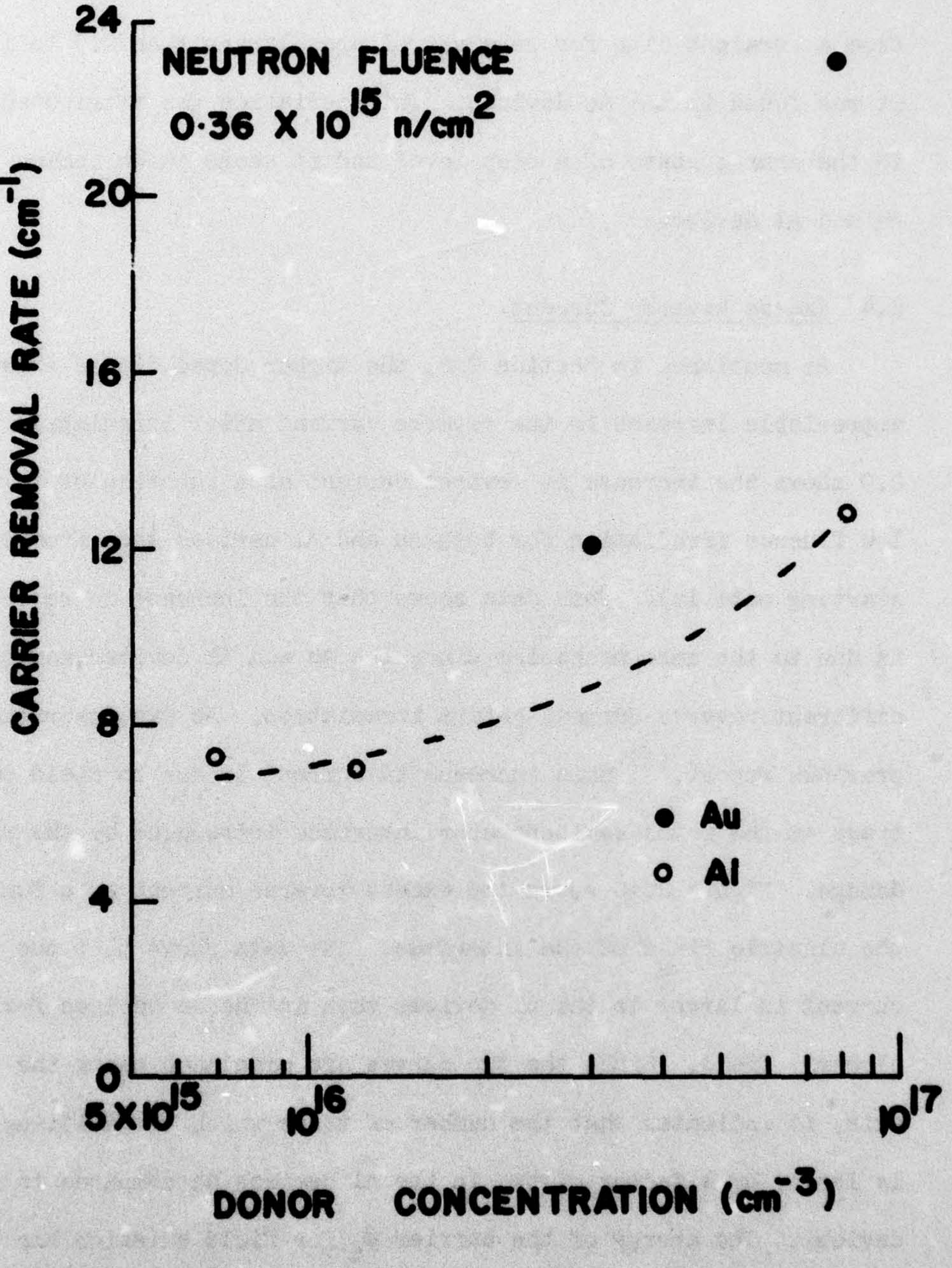


Fig. 2.8 Carrier removal rate as a function of free carrier concentration

The $1/C^2$ vs. V. plot for the 316 series of devices shows a deviation from a straight line for reverse voltages larger than 0.5 to 1 volt, as it was found in the Au devices. This deviation was attributed to a change in the charge state of a deep level and it seems to be common to both the Au and Al devices.

2.4 Excess Reverse Current

As mentioned in Section 2.2, the higher doped diodes showed an appreciable increase in the reverse current after irradiation. Figure 2.9 shows the increase in reverse current as a function of voltage after low fluence irradiation for both Au and Al devices made from similar starting material. This data shows that the increase in reverse current is due to the same mechanism since the Au and Al devices had quite different reverse current before irradiation. As was described in a previous report,(6) this increase in current is due to field emission from traps at the metal-semiconductor interface introduced by the radiation damage. Figure 2.10 shows the excess reverse current as a function of the electric field at the interface. The data shows that the excess current is larger in the Al devices than in the Au devices for the same electric field. Since the two curves are displaced along the current axis, it indicates that the number of traps which are emitting the carriers is larger by a factor of two in the Al devices as compared to the Au devices. The energy of the barrier ϕ_t for field emission for the Al devices was found to be very close to the barrier ϕ_t found previously in the Au diodes ($\phi_t \approx 0.3$ eV at room temperature).

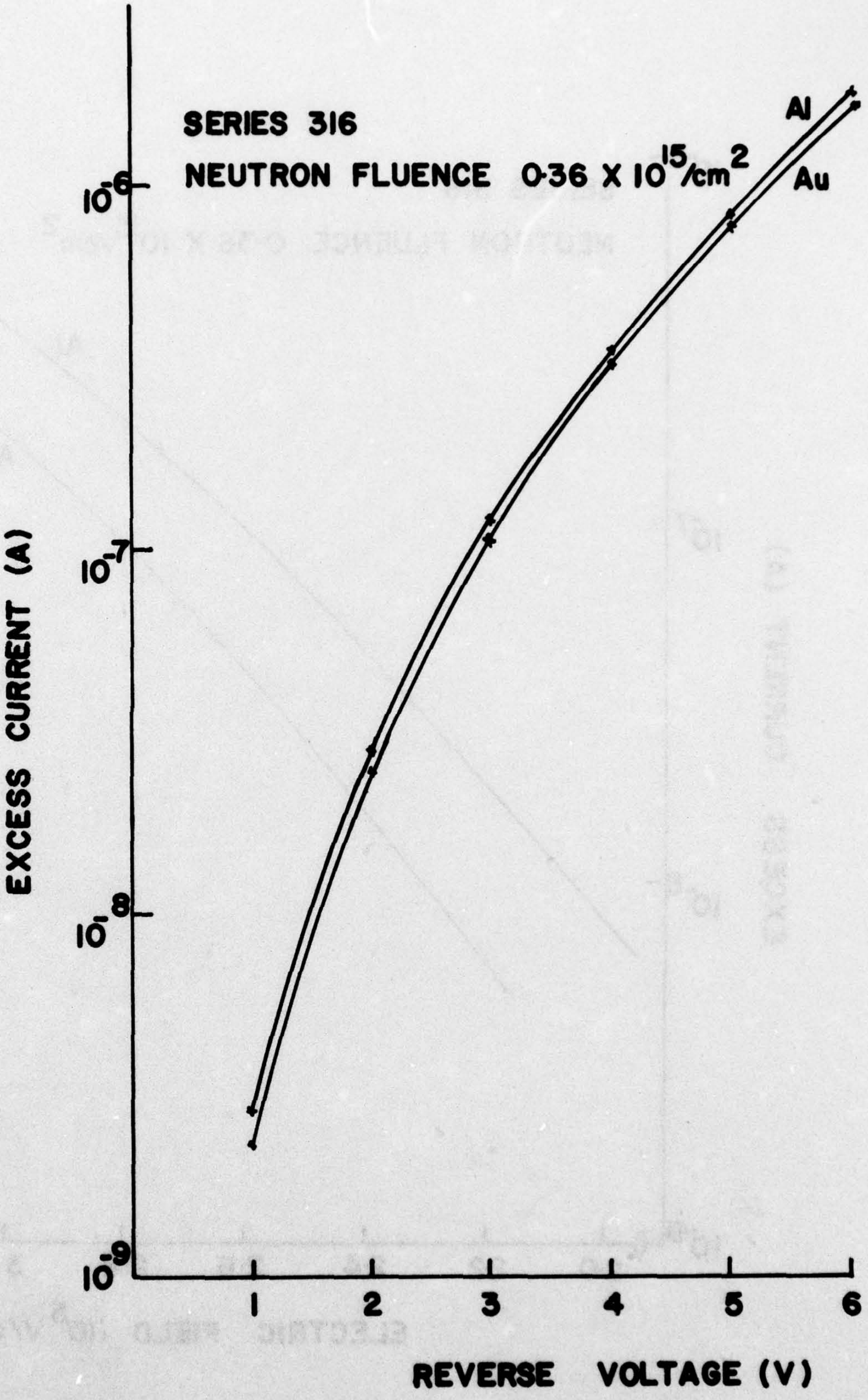


Fig. 2.9 Increase in reverse current as a function of voltage after irradiation

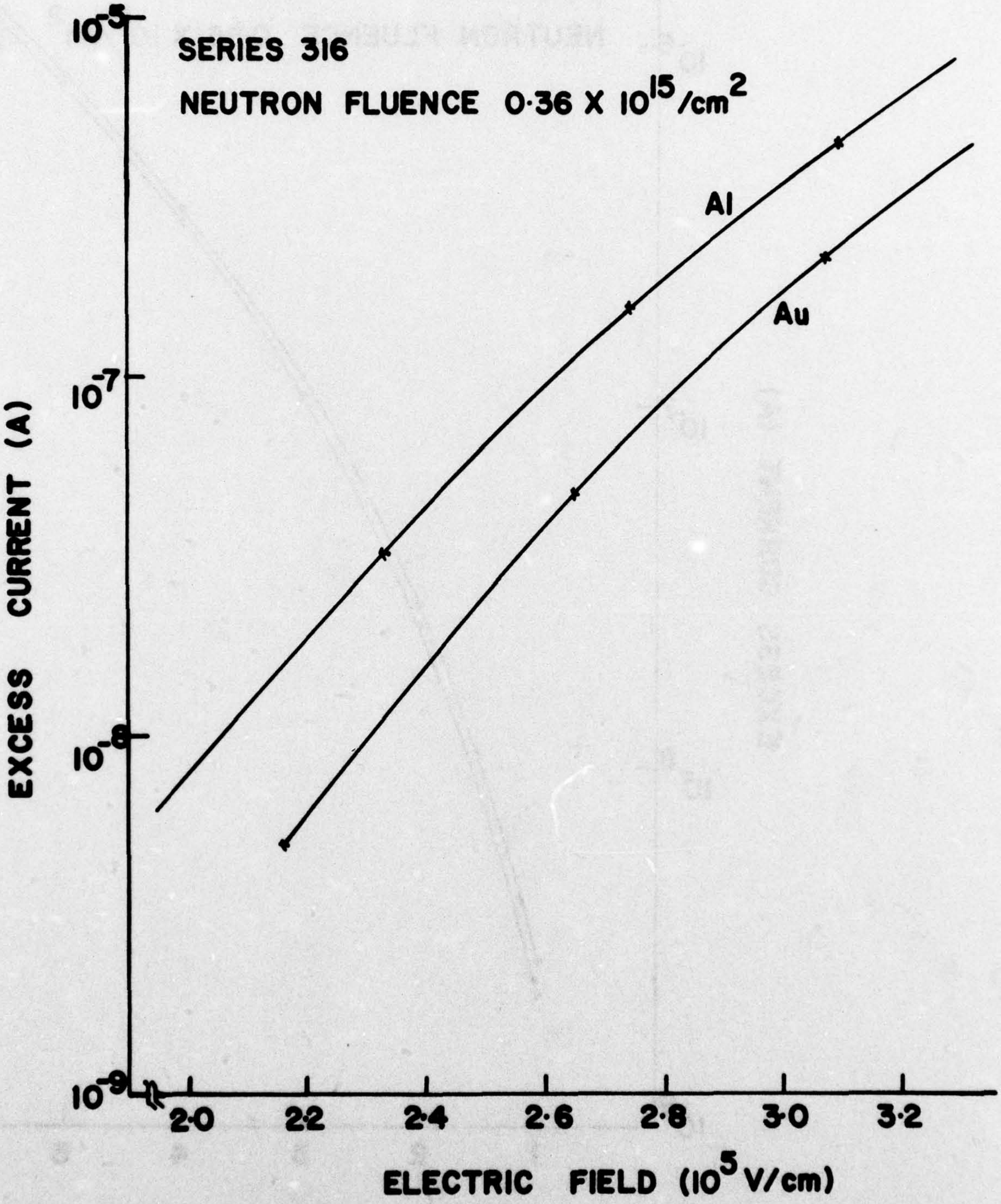


Fig. 2.10 Increase in reverse current as a function of peak electric field at the interface

Since the lowest doped diodes like the 1E16 series of devices did not show the increase in reverse current observed in the 316 series of devices, we conclude that it is necessary to have both neutron damage and donors in order to produce traps capable of increasing the reverse current by field emission. This appears to be more critical in the Al devices since the lower barrier height gives a larger reverse current before irradiation.

2.5 Density of Interface States

Using the I-V and C-V characteristics of the devices, we determined the interface state density before and after irradiation using the techniques described in a previous report.(6) A computer program developed for reducing the data to obtain the electric field at the interface, the change in barrier height and the density of interface state is given in Appendix I. Figure 2.11 shows the electric field at the interface E_s as a function of change in barrier height $\Delta\phi_B$, corrected for image force barrier lowering, before and after irradiation for device 1E16-1. The density of interface states N_{ss} as a function of $\Delta\phi_B$ is shown in Fig. 2.12 for the same device. The curves show the same features as the one previously found for the Au-GaAs devices. Before irradiation the N_{ss} is highly peaked at the zero bias Fermi level. After irradiation the distribution is less peaked and of reduced value.

2.6 Transient Ionizing Radiation Results

Transient ionizing radiation photocurrent measurements were taken with the aluminum devices in an evacuated chamber, with results in

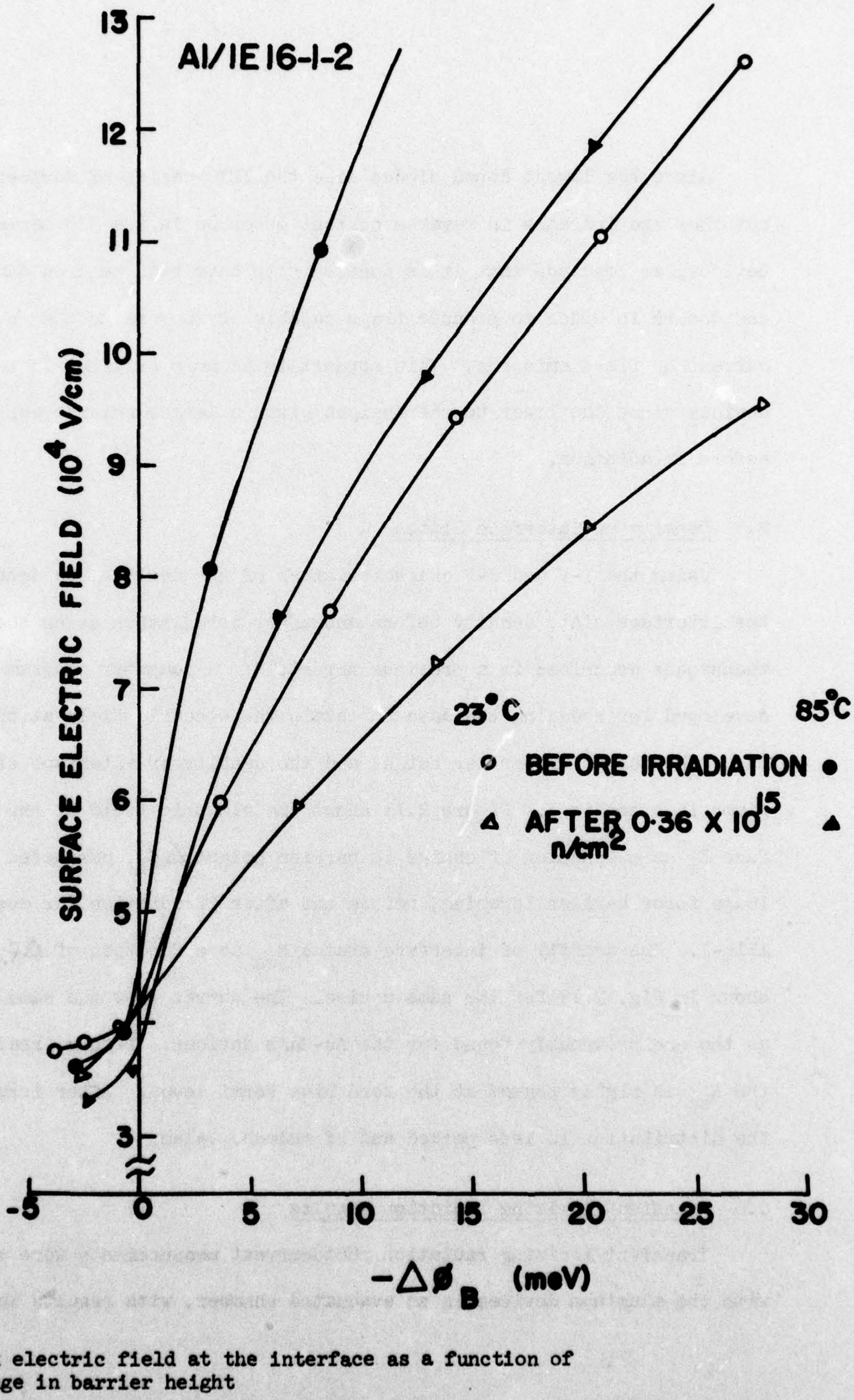


Fig. 2.11 **Peak electric field at the interface as a function of change in barrier height**

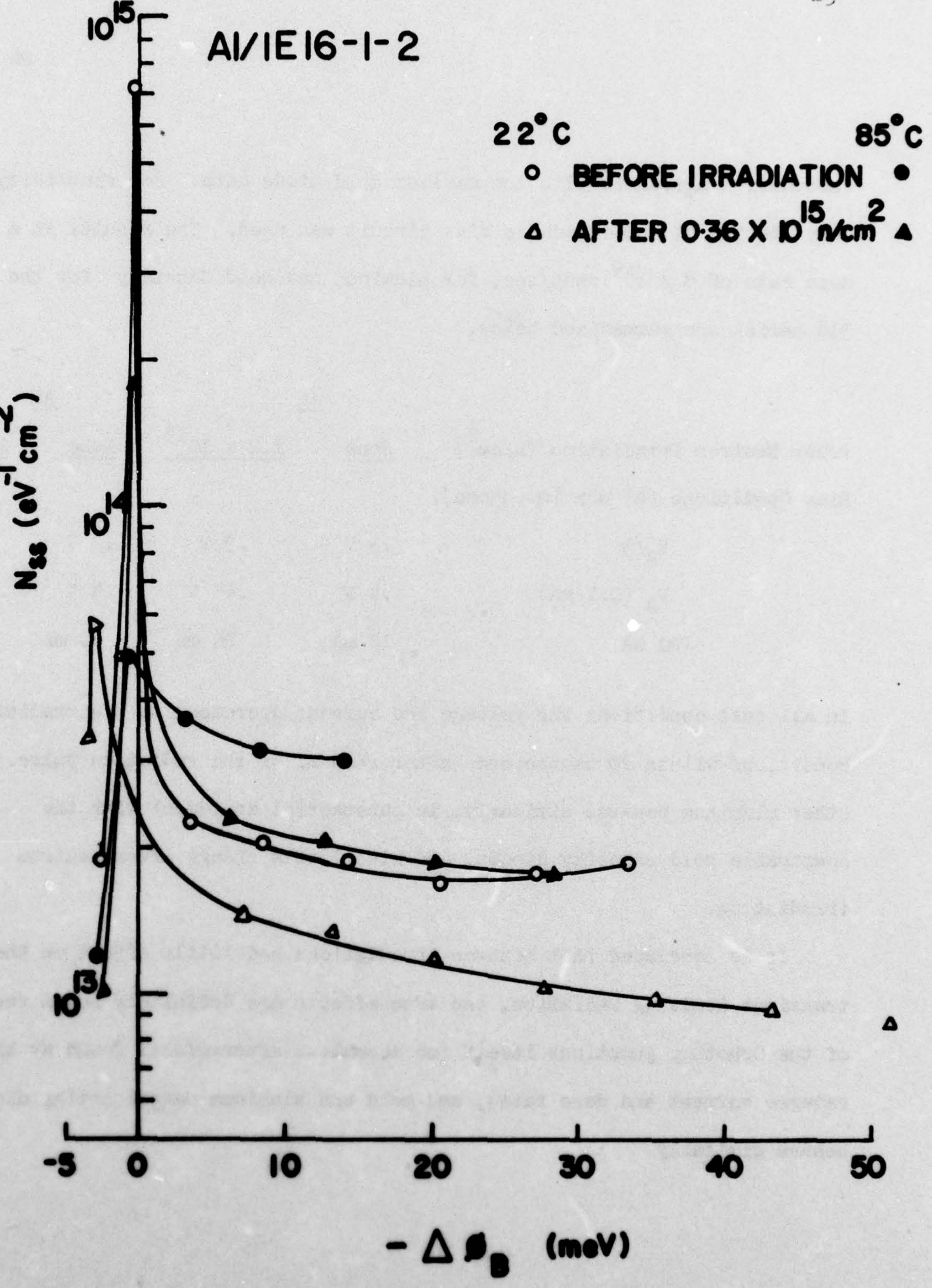


Fig. 2.12 Density of interface states before and after irradiation as a function of change in barrier height

substantial agreement with the earlier gold diode data. For simplicity, only the low 47 ohm impedance bias circuit was used. The results at a dose rate of 8×10^9 rads/sec. for aluminum and gold Schottky for the 316 series are summarized below.

	Au		Al	
Prior Neutron Irradiation (n/cm^2)	None	2.2×10^{15}	None	2.2×10^{15}
Bias Conditions (47 ohm impedance)				
$V_B/3$	.3 V	.3 V	.3 V	.3 V
V_B (0.1 mA)	.4 V	.45 V	.4 V	.4 V
100 mA	10 mA	20 mA	20 mA	20 mA

In all test conditions the voltage and current decreased to preirradiation conditions within 20 nanoseconds after removal of the radiation pulse. Other aluminum behaved similarly, in substantial agreement with the comparable gold Schottky diodes, and with little change after neutron irradiation.

It is concluded that neutron irradiations had little effect on the transient ionizing radiation, the aftereffects are definitely not a result of the Schottky junctions itself (no anomalous aftereffects found at high reverse current and dose rate), and gold and aluminum GaAs Schottky diodes behave similarly.

3.0 IMPATT DIODE AFTEREFFECTS

Although many of the effects of transient ionizing radiation on IMPATT oscillators are well documented,(11) anomalous aftereffects have been occasionally reported(5,12) that are not well understood. If these solid state microwave sources are to be used in reliable radiation hardened systems, the aftereffects must be controlled. The term "aftereffects" is used whenever the oscillator does not regain preirradiation characteristics following the ionizing radiation pulse, even though irreversible device changes need not occur. Unlike previous investigations, we have been able to control the occurrence of these aftereffects by RF circuit tuning and by bias circuit tuning during this program. Although necessary and sufficient conditions for the aftereffects are still not known, these measurements of the relationship between IMPATT diode, RF cavity and bias circuit indicate that transient ionizing radiation can be detrimental to some IMPATT oscillators at dose rates above 2 x 10^9 rads/sec. These experimental results are a key contribution to the understanding of aftereffects in IMPATT diodes as well as the eventual control of the phenomenon.

3.1 Devices Tested and Test Set-up

In this work 500 milliwatt silicon and gallium arsenide X-band IMPATT diodes were evaluated, with typical diode characteristics given in the table below:

Diode No.	Diode Type	V_{br} (volts)	C_{br} (pfd)	I_{max} (mA)
301B	Si-double epi	78	0.76	93
22A4	GaAs-diffused	64	1.26	100
1B10	GaAs-Schottky	49	0.83	105

One or two devices of each type was tested as described below, although previous experience with these devices(11) indicates that the devices are representative of those commercially available.

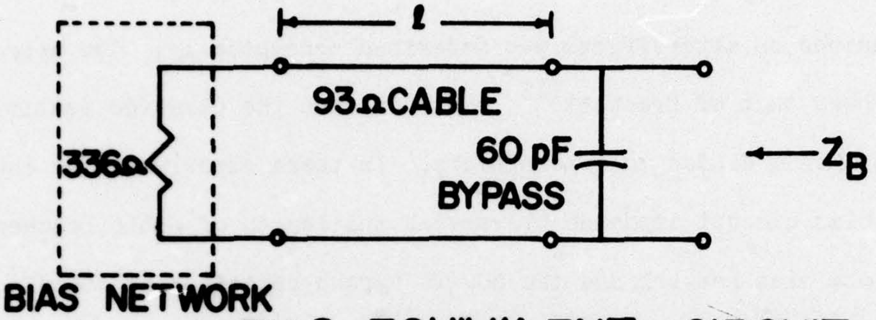
The RF test set-up is similar to that described in detail previously.(6,11) The disc-and-post type waveguide cavity was tuned by changing the length of a sliding short "behind" the diode (additional tuning by changing disc diameter was also used but kept fixed during the testing reported). The bias circuit impedance was adjusted by inserting lengths of coaxial cable between the diode and the bias box (consisting of passive circuit components used to provide the proper DC resistance and to allow diode voltage monitoring during the irradiation pulse). With this variable length of cable, the bias circuit impedance at the diode terminals was adjustable in the frequency range of 10 to 100 MHz, where bias circuit oscillations usually occur.(13) In all these experiments, the circuit parameters were carefully adjusted until the RF and frequency of oscillation varied smoothly with bias current while maintaining a clean RF spectrum, that is, the IMPATT oscillators were well-behaved prior to irradiation.

3.2 Influence of Bias Circuit

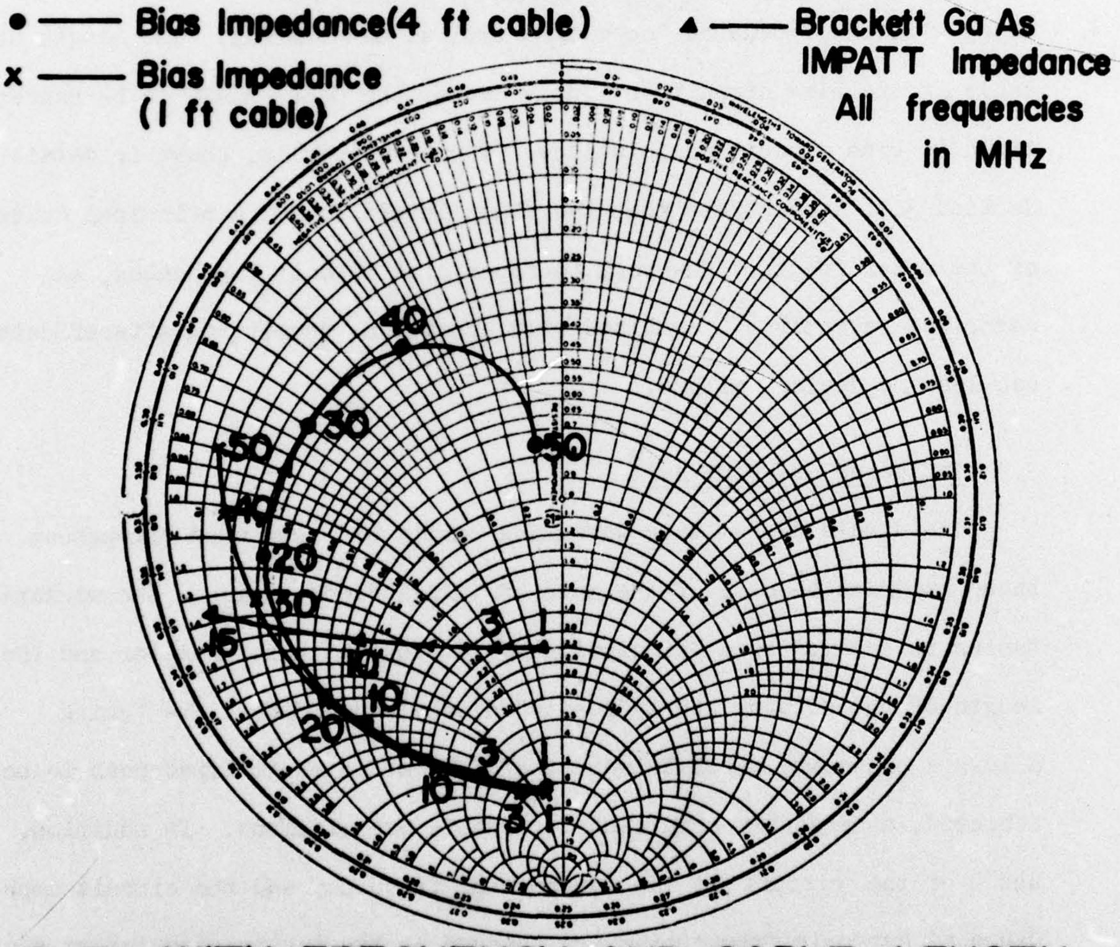
In a recent scientific report,(6) the possible effect of bias circuit impedance on aftereffects was described conceptually. The approach followed that of Brackett(15) and indicated the observed sensitivity of GaAs IMPATT diodes to aftereffects. In these experiments we controlled the bias circuit impdance by varying the length of cable between the 325 ohm bias network and the 60 pF bypass capacitor at the diode. The bias circuit impedance as a function of frequency is shown in Fig. 3.1 along with the impedance locus of a typical GaAs IMPATT. The length of cable in the bias circuit obviously causes the GaAs IMPATT to be susceptible to bias circuit oscillations. The test results, shown in detail in Section 3.3, demonstrate that the bias circuit is NOT a principal cause of the aftereffects. However, improper bias circuit impedances, as described recently,(6) combined with conditions permitting aftereffects can lead to device failure.

3.3 Influence of RF Circuit

The disc-and-post type waveguide cavity has been used throughout these programs because of the ease of IMPATT diode tuning. The mechanical tuning is accomplished principally by varying the disc diameter and the length of the sliding short "behind" diode-loaded disc. The tuning allows a conjugate match between the diode and circuit impedances to be achieved, a necessary condition for stable oscillations. In addition, the Q of the circuit at the fundamental frequency and the circuit impedance at harmonic frequencies are changed as the tuning adjustments are varied. In this section, we report on measurements taken with only the sliding short position varied (by about a half guide wavelength at the frequency of oscillation), i.e., the disc diameter is unchanged.



A. BIAS EQUIVALENT CIRCUIT



B. Z_B WITH FREQUENCY AND CABLE LENGTH AS PARAMETERS(Brackett GaAs IMPATT superimposed)

Fig. 3.1 IMPATT diode bias circuit impedance as a function of frequency

The gallium arsenide Schottky diode (1B10) was tuned with the sliding short close to the diode with the oscillator being well-behaved as described in Section 3.1 (short position .750 cm). Aftereffects did not occur at the highest dose rate used, 7 x 10^9 rads/sec. as shown in Fig. 3.2. The RF power reduces to near zero during the radiation pulse due to the effective leakage current generated by the ionizing radiation and cavity ionization. All microwave testing was done with air-filled cavities, the difference between evacuated and air-filled cavities being previously reported.(11) Although there is a small time delay required before the RF amplitude builds up to the steady state value after the radiation pulse, the RF power clearly returns to its preirradiation value (as does the RF frequency, bias voltage and other electrical characteristics). This lack of aftereffects was observed for all cable lengths inserted in the bias circuit at this sliding short position, indicating that the bias impedance could not induce the aftereffects.

After extending the sliding short by one-half guide waveguide, almost identical preirradiation RF tuning was observed. However, after the irradiation pulse the RF power reduced from 280 mW to 120 mW while the frequency increased from 9.54 to 9.95 GHz and the bias voltage increased by 0.7 volt. The RF power change is shown in Fig. 3.3A and the bias voltage change in Fig. 3.4A. The slight increase in bias voltage after the radiation pulse (compared to the preirradiation value) is consistent with the lower amplitude of RF oscillation. With a 5 foot coaxial cable inserted between the diode and the bias box, 25 MHz bias circuit oscillations were observed in addition to the power and frequency

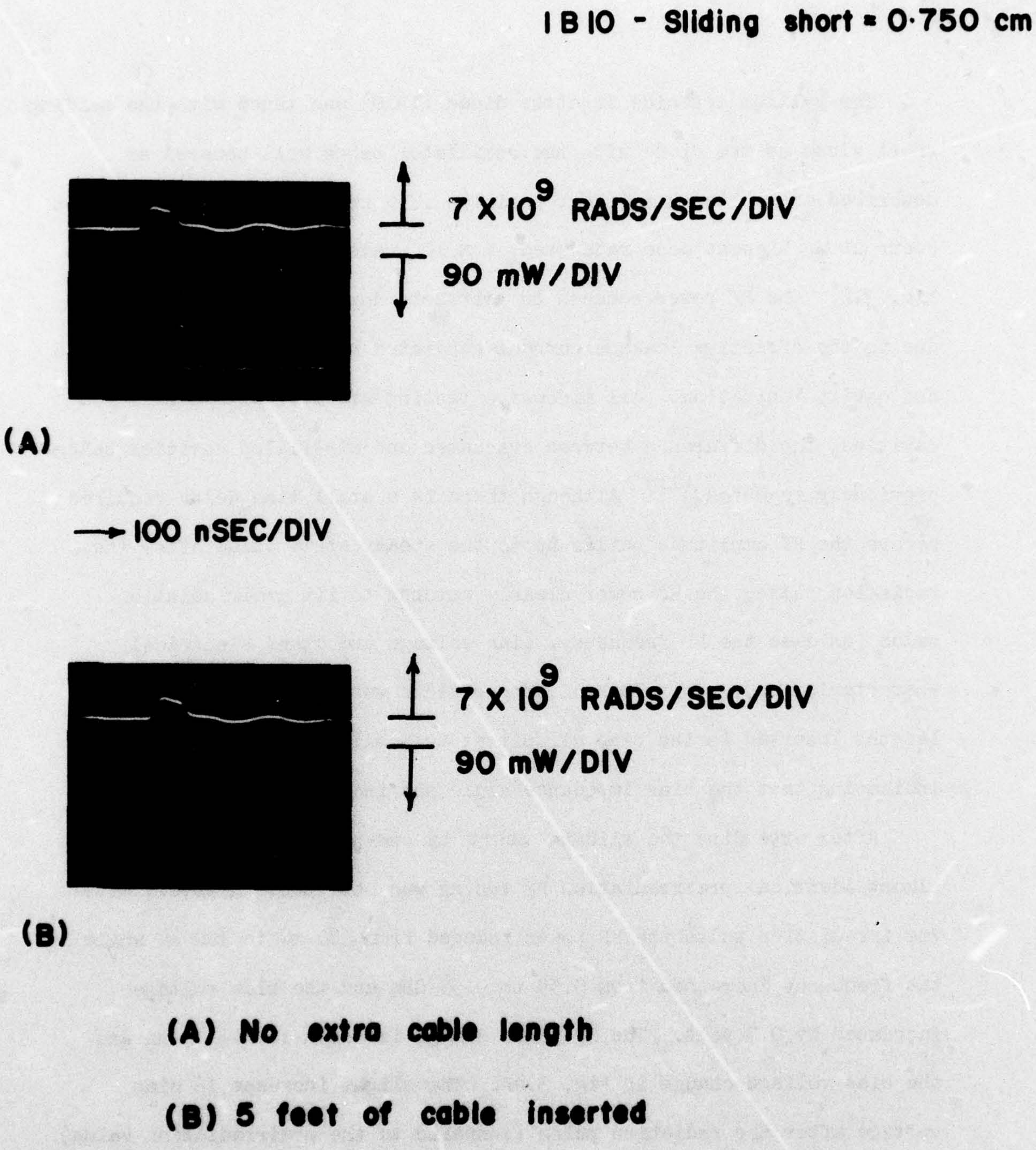
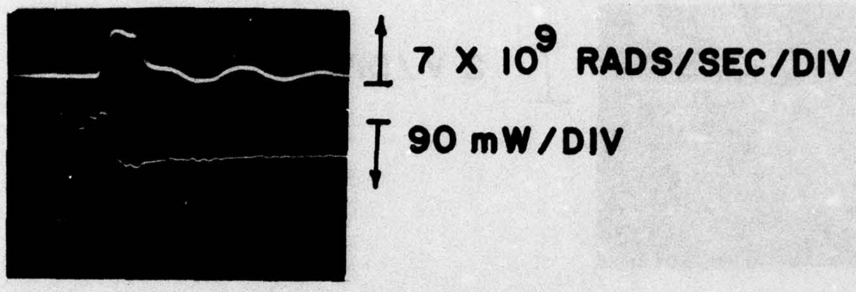


Fig. 3.2 RF power of GaAs Schottky tuned without aftereffects

A. No extra cable between diode and bias box

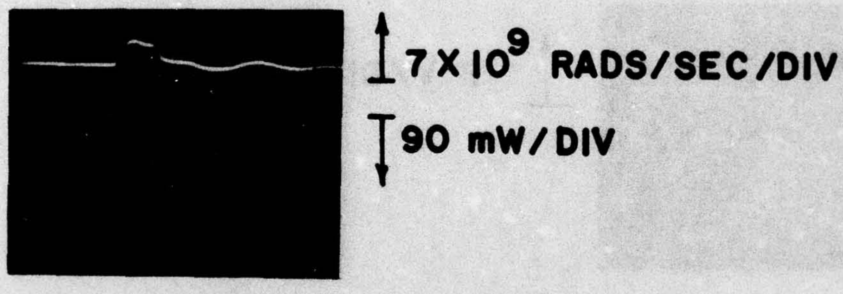
B. Five feet of cable inserted

IB 10 - Sliding short = 2·880 cm



(A)

→ 100 nSEC/DIV



(B)

(A) No extra cable length

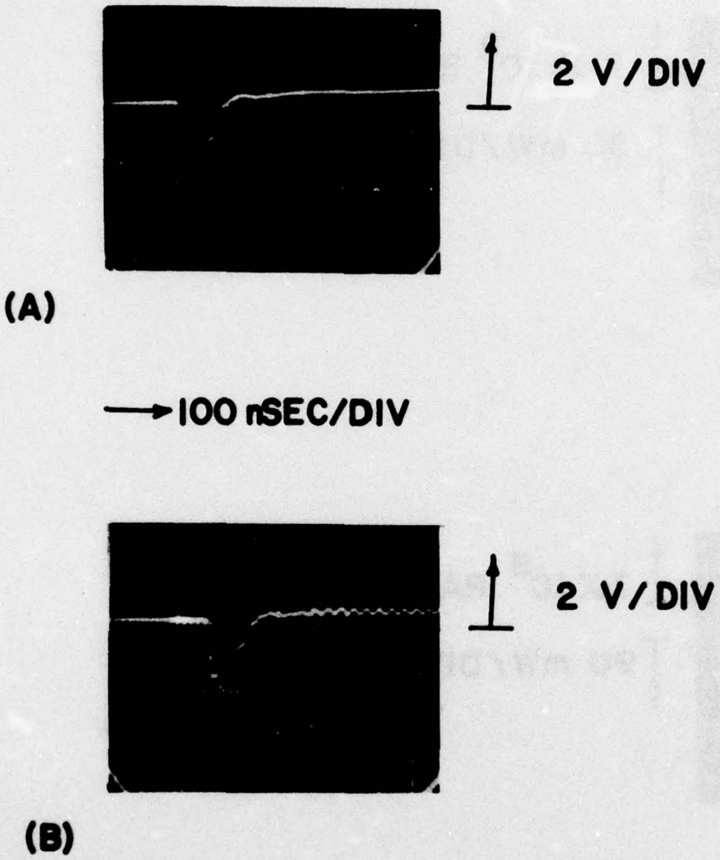
(B) 5 feet of cable inserted

Fig. 3.3 RF power of GaAs Schottky tuned with aftereffects

A. No extra cable between diode and bias box

B. Five feet of cable inserted

I B 10 - Sliding short = 2·880 cm



(A) No extra cable length

(B) 5 feet of cable inserted

Fig. 3.4 Bias voltage of GaAs Schottky tuned with aftereffects

A. No extra cable between diode and bias box

B. Five feet of cable inserted

change. The bias oscillations are apparent in the RF power photograph shown in Fig. 3.3B, as well as in the diode voltage photographs in Fig. 3.4B. In addition, the classic bias oscillation spectrum was observed after radiation using a spectrum analyzer. The spectrum was "clean" otherwise and was not noisy with, or without, the bias circuit oscillations.

In all cased where aftereffects were observed, the original RF characteristics could again be obtained by lowering the bias current. In particular, there were no diode failures as sometimes reported.(5) It should be emphasized that (1) the RF power and frequency tuned smoothly with bias current while maintaining a clean spectrum prior to irradiation at all test conditions used and (2) these irradiation aftereffects could then be reproduced without difficulty. The aftereffects were obtained reproducibly with preirradiation RF powers greater than 200 mW and dose rates greater than 2 x 10^9 rads/sec.

Similar RF and bias circuit tuning and irradiation testing was done with the GaAs diffused diode (22A4) and the Si diffused diode (301B). Although less dramatic and potentially less harmful, aftereffects (RF power reduction and frequency change) could be observed if (1) the diode bias current was set only slightly below the value for power saturation and/or spectrum deterioration and (2) high dose rates (~8 x 10^9 rads/sec) were imposed. The GaAs diffused diode was more prone to aftereffects than the Si diffused diode, although the aftereffect susceptibility was much greater in the GaAs Schottky IMPATT than either of the diffused diodes. The dependence of the aftereffects upon sliding short position was observed, but bias circuit oscillations were not observed for these diodes. In fact, the extra cable length had little effect on these aftereffects.

At the power levels near power saturation and at high dose rates, aftereffects in these two diffused diodes were sensitive to bias current level and tuning. As shown in Figures 3.5 and 3.6 for the GaAs diffused and Si diffused diodes, aftereffects were not observed with the extra cable length for the particular test conditions shown. This data should not be interpreted as implying that the cable tends to quench the aftereffects (additional data not shown confirms these conclusions), but only that (1) the occurrence of aftereffects was sensitive to circuit parameters near power saturation and at high dose rate and (2) the bias circuit impedance locus in the 10-100 MHz frequency range is not a principal cause of the aftereffects.

In addition, the data with the Si and GaAs diffused diodes confirms the IMPATT diodes are prone to the aftereffects with the sliding short far from the diode in the disc-and-post type RF circuit. Less extensive testing performed at sliding short positions near the diode with diodes 22A4 and 301B did not yield aftereffects under similar drive levels and dose rates.

3.4 Phenomenological Explanation of Results

We have demonstrated experimentally that (1) bias circuit instability is not a principal cause of the aftereffects and (2) aftereffects depend upon "second order" effects of the RF cavity (i.e., on sliding short position of the waveguide disc-and-post cavity either though similar

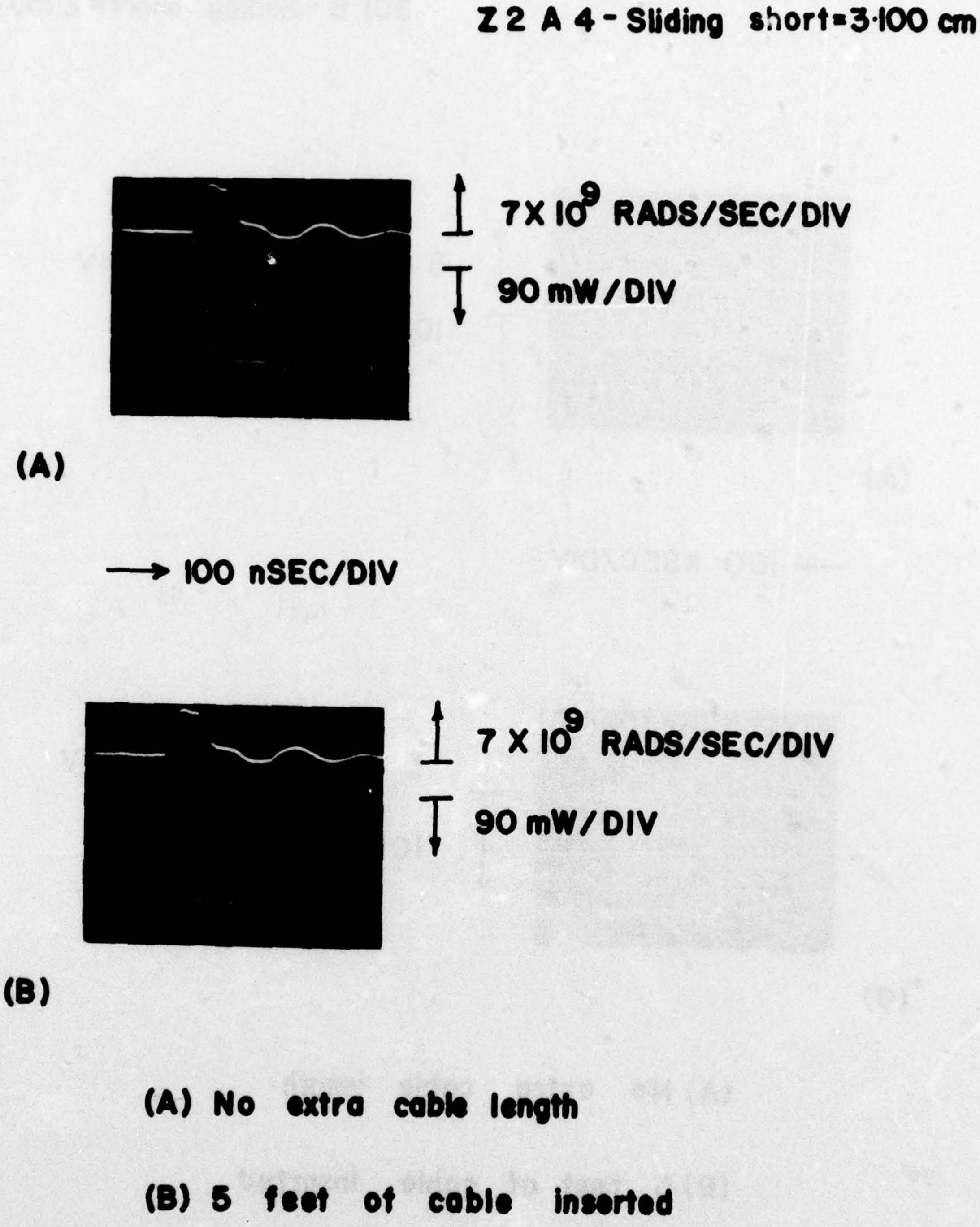


Fig. 3.5 RF power of GaAs diffused tuned with aftereffects

A. No extra cable between diode and bias box

B. Five feet of cable inserted

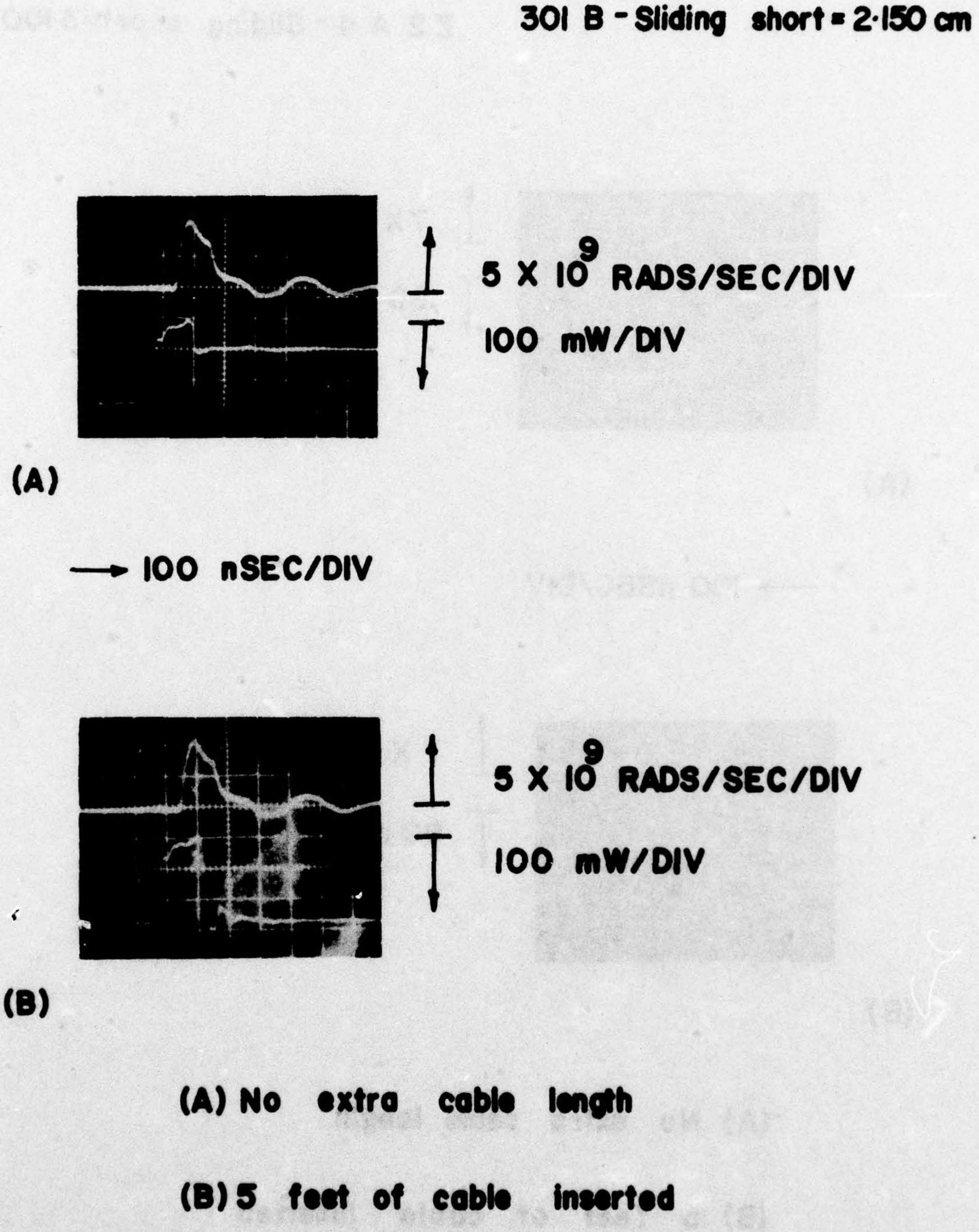


Fig. 3.6 RF power of Si tuned with aftereffects

A. No extra cable between diode and bias box

B. Five feet of cable inserted

preirradiation oscillator characteristics are observed). Three reasonable explanations can be put forth which have been observed previously in IMPATT oscillators.

1. parametric stabilities as described by Hines(14) and Schroeder.(15)
2. frequency jumping as described originally by Slater(16) and recently by Kurokawa.(17)
3. harmonic effects as described by Mouthaan(18) and Brackett.(19)

In this section we present a brief description of each effect and discuss the feasibility of each phenomenon being a principal cause of the aftereffects with transient ionizing radiation.

Parametric instabilities are generally ascribed to the nonlinear inductive reactance effect in the avalanche process. Besides the main oscillator output (considered as a pump in theoretical treatments(14)), a low level auxiliary signal or noise is required. Due to the nonlinear inductance, the usual parametric effects (normally desired with the nonlinear capacitance of a varactor such as mixing, up conversion, etc.) occur. Since the waveguide disc-and-post type waveguide cavity is still not well characterized the stability requirements developed by Schroeder(15) cannot be applied directly. However, parametric instabilities are usually accompanied by auxiliary spectral responses and/or noisy spectrum. Since the RF spectrum observed after the irradiation induced aftereffects was clean, i.e., the main spectrum line was narrow and there were no auxiliary responses (except for the classic bias oscillation spectrum with the GaAs Schottky and the 5 foot cable in the bias circuit) across the band

(8.2-12.4 GHz), we conclude that parametric instabilities are an improbable cause of the aftereffects.

Frequency jumping is usually a result of the diode impedance and the microwave circuit locus intersecting in more than one stable operating point. As a result, the actual operating point depends upon the history of the oscillator.(16,17) In the case of interest, the circuit impedance locus is expected to be a stronger function of frequency as the sliding short is positioned further from the diode (higher Q circuit). The device impedance is known to be dependent upon level of oscillation and leakage current as required. When the oscillator is normally tuned, the bias current is slowly increased, and as required in the tuning procedure, no frequency or power jumps occur. However, after the irradiation pulse the leakage current is rapidly decreased(10) and the circuit Q is rapidly increased (air ionization decay) so that the RF amplitude builds up differently than in the preirradiation tuning and a different level of operation is possible. Network analyzer measurements of the waveguide cavity from the diode terminals indicate a classic looping circuit impedance confirming the plausibility of this explanation.

The effect of higher harmonics, in particular the second harmonic, has been considered by Mouthaan(18) and Brackett(19) among others. Harmonic content is expected to increase with drive level and one can easily show that the phasing of any harmonic of significant amplitude, particularly the second, can effect the power output.(18) The conditions developed in the literature are difficult to invoke without a detailed equivalent circuit at the fundamental and harmonic frequencies. Network analyzer measurements up to 18 GHz (near the second harmonic frequency) indicate a difference between the two sliding short positions. However, accurate characterization is difficult and has not been accomplished.

In summary, either (1) frequency jumping due to multiple stable operating points or (2) higher harmonic phasing changes is expected to be a principal cause of the aftereffects. Additional testing, with different diodes and cavities, is needed to completely characterize the mechanism.

3.5 Conclusions

From these experiments and our earlier work(5,6) we have concluded the following:

1. The principal cause of the aftereffects is a device-circuit interaction and is related to the RF circuit impedance locus at the fundamental frequency(16) and/or the harmonic loading impedance at the diode.(18)
2. The principal cause of the aftereffects is NOT the bias circuit impedance causing bias circuit oscillations,(13) although it is believed that improper bias circuit impedance combined with aftereffects can cause diode failure with pulses of ionizing radiation.(6)
3. The GaAs Schottky diode is more prone to the aftereffects, with the occurrence at power levels above 200 mW and dose rates above 2×10^9 rads/sec. in the diode tested. The aftereffects in the Si and GaAs diffused diodes only occurred with the diode operated slightly below power saturation and/or spectrum deterioration and at the higher dose rates ($\sim 8 \times 10^9$ rads/sec.).

Although these conclusions, obtained from experimentally controlling the aftereffects for the first time, enhance our understanding appreciably, more work is needed to fully understand and control this phenomenon. In particular, we are uncertain why the GaAs Schottky diode is more prone to the aftereffects, as the Schottky junction itself behaves similar to a diffused junction under transient ionizing radiation.(6) (See also Section 2.6). The demonstrated effect of RF tuning in disc-and-post type cavities should be evaluated in other types of waveguide, coaxial and microstrip cavities. The aftereffects must be measured and evaluated in hi-lo and lo-hi-lo high efficiency GaAs diodes (as well as flat profile GaAs IMPATTs as used in this work) before they are incorporated in high performance radiation hardened applications.

4.0 SUMMARY AND CONCLUSIONS OF OVERALL PROGRAM

In this last chapter we summarize the main results obtained during the research program.

4.1 Neutron Radiation Results

Au-nGaAs and Al-nGaAs Schottky barrier diodes, fabricated from epitaxial and bulk material with carrier concentrations in the range of 7×10^{15} to 8×10^{16} cm^{-3}, were exposed to fast neutron fluences of 3.6×10^{14} and 2.2×10^{15} n/cm^2. At neutron fluences where the reduction in free carrier concentration is less than 20%, the following results were obtained:(20)

1. The forward characteristics are slightly changed at the low neutron fluences. Typically the n factor changed from 1.01 before irradiation to 1.05 after irradiation. The Al Schottky diodes exhibited a smaller increase in the n factor.
2. The current flow in the forward direction is due to thermionic emission with the metal-semiconductor barrier height remaining unchanged after irradiation.
3. The changes observed in the I-V characteristics at forward and small reverse bias (less than 2 volts) indicate that the density of interface states changes with irradiation. The density of interface states is reasonably approximated by a sharp peak of between 3×10^{13} to 10^{14} cm^{-2} eV^{-1} located at near the zero bias Fermi level before irradiation and after the low irradiation the density of interface states changes by a factor of 2 to 5 and becomes less peaked.

4. The reverse characteristics are greatly affected at the low neutron fluences. The increase in reverse current was more than an order of magnitude for the Au diodes at room temperature. The increase in reverse current in Al diodes was less than in the Au devices due to the higher initial reverse current because of the lower barrier height.
5. The excess reverse current is not due to generation-recombination with a constant lifetime. The reverse current after irradiation is strongly dependent upon voltage and relatively temperature independent. This characteristic indicates that thermionic emission is not the principal source of the observed increase in the reverse current and that it is due to a high field effect process. Considerations of the several possible field emissions processes showed that field emission from a trap has the appropriate field dependence exhibited by the data obtained and that the trap energy for field emission is of the order of 0.3 eV.
6. The increase in reverse current is higher in the highest doped diodes which indicates that the trap centers which cause the increase in reverse current by field emission are produced by a combination of the neutron damage and the doping in the material. In the highest doped diodes, the excess reverse current had almost the same value in the Au diodes as in the Al diodes indicating that it is independent of the metal used for forming the Schottky barrier.

4.2 Transient Ionizing Radiation Behavior

Transient ionizing radiation photocurrent measurements were taken with the gold and aluminum Schottky diodes before and after neutron irradiation in an evacuated chamber. The results support the following conclusions:

1. IMPATT diode oscillator aftereffects are definitely not a result of the Schottky junction per se as there were no anomalous aftereffects at the highest bias currents (200 mA) and dose rates (8×10^9 rads/sec) used.
2. The gold and aluminum diodes have similar photoresponse indicating that the response is not critically dependent on the details of the rectifying junction. Further, the photoresponse results are in substantial agreement with results in the literature for diffused diodes.
3. Neutron irradiation does not effect the photoresponse of the Schottky diodes at low neutron fluences where the depletion layer remains unchanged. This is further confirmation that the photoresponse is unrelated to the details of the interface and is controlled by photogeneration of carriers in and near the depletion region.

Thus, Schottky junction devices should perform adequately in transient ionizing radiation environments UNLESS THERE ARE SYNERGISTIC EFFECTS IN THE PARTICULAR APPLICATION.

4.3 IMPATT Diode Aftereffects

In this work we have been able to control the occurrence of these aftereffects by RF circuit tuning and have also been able to control the occurrence of bias circuit oscillations by bias circuit tuning. This is the first time that results have been reported with aftereffects having been experimentally controlled.(21) Although necessary and sufficient conditions for the aftereffects are still not known, the demonstrated relationships between IMPATT diode, RF cavity and bias circuit indicate that transient ionizing radiation can be detrimental to some IMPATT oscillators at dose rates above 2×10^9 rads/sec.

In particular, the following conclusions have been reached:

1. The principal cause of the aftereffects is a device-circuit interaction and is related to the RF circuit impedance locus at the fundamental frequency and/or the harmonic loading impedance at the diode.
2. **The principal cause of the aftereffects is NOT the bias circuit impedance causing bias circuit oscillations, although it is believed that improper bias circuit impedance combined with aftereffects can cause diode failure with the ionizing radiation pulse.**
3. **The GaAs Schottky diode is more prone to the aftereffects with the occurrence at power levels above 200 mW and dose rates above 2×10^9 rads/sec in the diode tested. The aftereffects in the Si and GaAs diffused diodes only occurred with the diode operated slightly below power saturation and/or spectrum deterioration and at the higher dose rates (8×10^9 rads/sec).**

4. The principal cause of the GaAs Schottky susceptibility to after-effects is NOT caused only by the Schottky junction, as photo-response evaluations indicate similar results under transient ionizing radiation as diffused junctions.

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21. R. J. Gutmann and J. M. Borrego, "Experimental Evaluation of After-effects in IMPATT Oscillators with Transient Ionizing Radiation", submitted for presentation at the 1976 IEEE Nuclear and Space Radiation Effects Conference.

APPENDIX

SR-52 Calculator Program to Determine Surface State Density

Definitions of Symbols

A	Area of diode (cm^2)
a	$1/\{1 - \exp(-11.605\, V_{j,j-1}/T)\}$
C_j	Small-signal capacitance of diode at voltage V_j (pF)
$C_{j,j-1}$	Small-signal capacitance of diode at voltage $V_{j,j-1}$ (pF)
$\mathcal{E}_j$	Peak junction electric field at voltage V_j (V/cm)
$\mathcal{E}_{j,j-1}$	Peak junction electric field at voltage $V_{j,j-1}$ (V/cm)
N'_{ss}	$1/\{a - \frac{1}{n} - \beta \left\vert\frac{\Delta\sqrt{\mathcal{E}_j}}{\Delta V_j}\right\vert$ for FWD bias $1/\{\frac{1}{n} - \beta \left\vert\frac{\Delta\sqrt{\mathcal{E}_j}}{\Delta V_j}\right\vert\}$ for REV bias
n	Ideality factor
T	Temperature (^{O}K)
V_j	Applied voltage of diode (mV)
$V_{j,j-1}$	$(V_j + V_{j-1})/2$ (mV)
V_{j-1}, V_j	Successive diode voltages for decade(FWD bias) or 1/6 decade (REV bias) change in current (mV)
ΔV_j	$(V_j - V_{j-1})$ (mV)
β	Image-force barrier height reduction constant $\left(\frac{q}{4\pi\,\epsilon_d}\right)^{1/2} = 1.149 \times 10^{-4}$ $(eV\text{-}cm)^{1/2}$ for GaAs
ϵ_d	Optical dielectric constant for GaAs = 9.65×10^{-13} F/cm
$\Delta\phi_B$	Change in barrier hieght (meV)
$\mathcal{E}_o$	Zero-bias electric field (V/cm)
$\Delta\mathcal{E}_j$	$\sqrt{\mathcal{E}_j} - \sqrt{\mathcal{E}_{j-1}}$ $(V/cm)^{1/2}$
N_{ss}	Surface state density ($eV^{-1}\ cm^{-2}$)

TITLE Surface State Density from I-V and C-V PAGE ______ OF ______
PROGRAMMER ______________________ DATE ______________

SR-52 Coding Form

LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS
000 112		*LBL =				RCL 2				STO RCL	
		A INV				0 =				1 1	
		STO *if flg		040 152		1 SUM				2 5	
		0 0				X 1				*LBL HLT	
		5 cos				RCL 4		080 192		+	
005 117		HLT +/-				0 RCL				INV	
		*LBL *LBL				7 0				*if flg	
		B cos		045 157		= 0				0	
		STO +				STO −				sin	
		0 RCL				1 RCL		085 197		RCL	
010 122		6 1				1 1				1	
		HLT 2				HLT 0				1	
		*LBL *1/x		050 162		*if flg *√x				STO	
		C =				0 X				1	
		STO *1/x				+ RCL		090 202		2	
015 127		0 HLT				(0				*LBL	
		7 X				1 3				sin	
		HLT RCL		055 167		− =				(	
		*LBL 0				(*if flg				RCL	
		D 9				RCL 0		095 207		0	
020 132		STO X				0 tan				5	
		0 RCL				2 +/-				*√x	
		8 0		060 172		X *LBL				−	
		HLT 4				RCL tan				RCL	
		*LBL =				0 +		100 212		0	
025 137		E HLT				8 RCL				6	
		STO (				) 1				*√x	
		0 RCL		065 177		INV 4				)	
		9 0				lnx =				X	
		HLT 8				) STO		105 217		RCL	
030 142		*LBL −				*1/x 1				0	
		*A' RCL				− 5				3	
		STO 1		070 182		RCL RCL				+	
		1 3				1 0				RCL	
		0)				1 8		110 222		0	
035 147		HLT ÷				*1/x STO				7	
		*LBL RCL				= 1					
		*B' 1		075 187		*1/x 3					

TEXAS INSTRUMENTS
INCORPORATED

LABELS
A ε_j
B ε_{j-1}
C ΔV_j
D $V_{j,j-1}$
E $C_{j,j-1}$
A' $\varepsilon_{j,j-1}$
B' START
C'
D'
E'
REGISTERS
00 $\beta\sqrt{\varepsilon_0}$
01 $\frac{5.04006}{T(°K)}$ or ×6
02 $\frac{-11.605}{T(°K)}$
03 11.49
04 $10^{-12}/qA$
05 ε_j
06 ε_{j-1}
07 ΔV_j
08 $V_{j,j-1}$
09 $C_{j,j-1}$
10 $\varepsilon_{j,j-1}$
11 n
12 n'
13 $V_{j,j-1}$ * previous values
14 $\Delta\phi_B'$
15 $\Delta\phi_B$
16
17
18
19
FLAGS
0   0 for FWD bias 1 for REV bias
1
2
3
4

SR-52
User Instructions

TITLE Surface State Density from I-V and C-V PAGE ______ OF ______

◄A◄				
$\mathcal{E}_{j,j-1}$				
$\mathcal{E}_j$	$\mathcal{E}_{j-1}$	ΔV_j	$V_{j,j-1}$	$C_{j,j-1}$

◄B◄				

STEP	PROCEDURE	ENTER	PRESS			DISPLAY
1	ENTER PROGRAM (A & B)	$\beta\sqrt{\mathcal{E}_0}$ in 10^4 V/cm	STO	0	0	
2	ENTER CONSTANTS	5.04006/T(°K) for FWD 30.24/T(°K) for REV	STO	0	1	
		−11.605/T(°K)	STO	0	2	
		$\beta = 11.43$	STO	0	3	
		$10^{-12}/qA$	STO	0	4	
3	FLAG FOR FWD/REV BIAS		INV *st flg	*st flg 0	0	← FWD ← REV
4	INITIALIZE $V^{\bullet}_{j,j-1}$ & $\Delta\phi'_B$	0	STO	1	3	
		0	STO	1	4	
5	ENTER VARIABLES	$\mathcal{E}_j$ in 10^4 V/cm	A			
		$\mathcal{E}_{j-1}$ in 10^4 V/cm	B			
		ΔV_j in mV	C			
		$V_{j,j-1}$ in mV	D			
		$C_{j,j-1}$ in mV	E			
		$\mathcal{E}_{j,j-1}$ in 10^4 V/cm	*A'			
6	START & COMPUTE n		*B'			n
	COMPUTE N'_{ss}		RUN			N'_{ss}
	COMPUTE N_{ss}		RUN			N_{ss} in $eV^{-1}cm^{-2}$
	COMPUTE $\Delta\phi_B$		RUN			$\Delta\phi_B$ in meV

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