FINAL REPORT

PROJECT A-1068

TECHNIQUES FOR REDUCING MIXER CONVERSION LOSS IN MILLIMETER WAVE RECEIVERS FOR COMMUNICATIONS AND RADIOMETRY

R. G. SHACKELFORD

RESEARCH GRANT NGR-11-002-065

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Engineering Experiment Station
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ABSTRACT

The design and construction of an apparatus capable of bombarding semiconducting materials with H^+, He^+, and Ar^+ at energies up to 30 KeV is discussed. Measurements of the junction characteristics of metal-semiconductor point-contact diodes fabricated from He^+ bombarded silicon and gallium-arsenide are presented and compared to a 1N53 cartridge diode at the frequency of 35 GHz. The effects of various junction forming techniques on both the I-V characteristics and the conversion loss were investigated. It was found that electrically formed junctions on gallium-arsenide utilizing a copper alloy whisker were stable and exhibited repeatable conversion losses at 35 GHz. While mechanical or pressure forming produced the best results on the unbombarded silicon, an electrical forming technique utilizing a current limiting resistor at the reverse breakdown voltage was found to improve the performance of He^+ bombarded silicon. The conversion loss of the point-contact silicon mixers was found to be considerably higher than the best 1N53 mixer, probably because of the low doping level of the P-type silicon material and incomplete surface treatment. The best gallium-arsenide mixers were found to have conversion losses slightly better than the 1N53 diode even though measurements of their spreading resistances indicated a moderately low doping level. A consistently lower conversion loss was obtained for the junctions utilizing He^+ bombarded silicon at 10 KeV although no improvement could be found for He^+ bombarded gallium-arsenide. These preliminary results suggest the need for further research to determine the specific physical phenomena responsible for the change in characteristics of mixers employing ion-bombarded

semiconductors, and if these phenomena, once identified, can be used to lower the conversion loss or increase the stability of millimeter wave mixers.

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I. INTRODUCTION

Since World War II there has been a steady effort to extend microwave technology to higher frequencies. The frequencies of the millimeter wavelength region make it possible to consider systems of unusually high angular resolution with antennas of manageable size. Components themselves are reduced in size and weight so that it is also easier to design light, compact systems for applications where this is a factor. In terms of communication links, the potential modulation bandwidth is greater for the millimeter region than for lower frequencies.

For radiometric observations, the millimeter region is very interesting because it encompasses the molecular rotational transitions of various gases. Oxygen, for example, has a cluster of 24 lines that occur near 60 GHz. When scanning from above the earth's atmosphere, a millimeter radiometer will reveal some fifty degrees temperature difference between the peak of an oxygen line frequency and a non-resonant frequency, thus illustrating the utility of the millimeter radiometer for remote atmospheric probing. Water vapor, the methane series, ozone, ammonia, nitrous oxide, and sulfur dioxide are but a few planetary atmospheric gases that have strong characteristic absorption spectra in this frequency region which may lend to radiometric identification.

Components are currently available for coverage of the entire 30 to 100 GHz part of the millimeter spectrum, as are klystron and backward wave sources. A communications or radiometric superheterodyne receiver can be implemented with relative simplicity for the region, but to date sensitivity comparable to that available in the microwave region is difficult to obtain because of the problems associated with the millimeter mixer diodes. For example, in the atmospheric window near 95 GHz, mixer conversion loss presently is about 7 dB higher than ideal, and 5 dB higher than good low frequency point-contact diode mixers for field type conditions. In addition, the yield for low conversion loss diodes is small and the shelf life is unpredictable and sometimes very short. A highly doped point-contact mixer can deteriorate in a matter of hours if care is not taken to prevent oxidation of the junction area.

The design of mixer diodes with proper impedance match to both the RF structure and the IF amplifier has been satisfactorily solved by Meredith and Warner of the Royal Radar Establishment-Malvern[1], and by Cohn, et al., of ADTEC.[2] Therefore, it appears that the greatest improvement in millimeter receivers in the near future will result from improved diode materials. Two similar directions being pursued to achieve this end are the "hot-carrier" diode research and the Schottky Barrier epitaxial diode investigations by Harrison of Sylvania[3] and Young at Bell Labs[4], respectively. Another attractive approach, which is the subject of this report, is the investigation of particle-bombarded diodes.

Ohl of Bell Laboratories reported work, prior to his retirement around 1960, on the positive ion bombardment of silicon diodes for millimeter wave harmonic generation.[5,6,7] Various positive ions ranging in energies from a few hundred to 80,000 electron volts were tried on various dopings of silicon. As an example of the results obtained by Ohl, irradiation of high purity P-type silicon with 0.002% boron doping resulted in at least an order of magnitude power increase for higher harmonics over that normally obtained with silicon diodes. The bombarding particles in this case were phosphorous ions accelerated to 30 KV with a total dosage of 300-400 μcoulombs/cm^2. Improvement of video detectors has also been noted.[8] Carbon ions from 1 to 5 KV irradiating 0.02% boron-doped silicon gave better results for video detectors than did the lower percentage boron-doped silicon bombarded with phosphorous ions that were successful harmonic generators. The characteristics of millimeter wave mixers fabricated from helium-bombarded silicon has been reported by Petit.[9] Although the conversion loss was found to lie between 9 and 12 dB at 70 GHz, remarkable stability was noted under any storage conditions.

The typical point-contact junction used in millimeter wave diode devices is often unstable; that is, even while sitting on the laboratory shelf, the diode characteristics will change significantly over a relatively short time. An explanation of this behavior lies partly in the tendency for the semiconductor surface oxidation to increase with increasing dopant concentration. The highly doped semiconductor also causes a reduced barrier width which encourages tunneling. Both Ohl and Petit noted that the irradiated materials used in point-contact junctions resulted in a long-term stable contact that could not otherwise be obtained. Ion bombardment creates a thin surface layer whose resistivity can be made considerably higher than the bulk resistivity of the semiconductor material. The increased diode stability probably results from the inhibition of surface oxides caused by the low conductivity surface layer, and the stability of the damage centers and dopant profile created by the ion bombardment. Others have used irradiated silica, supplied by Ohl, for both video detection and harmonic generation with greatly improved results over conventional materials.[10,11]

This report concerns the design and construction of an ion bombardment apparatus and the results of conversion loss measurement made on helium bombarded silicon and gallium-arsenide mixers at 35 GHz. The ion bombardment apparatus was designed specifically for the irradiation of post mounted semiconductor wafers with singly ionized hydrogen, helium or argon at energies up to 30 KeV.

The primary orientation of this grant was to set up an ion bombardment apparatus, establish reproducible and accurate millimeter wave conversion loss measurement techniques and to make a preliminary evaluation of the performance of a millimeter wave mixer utilizing ion-bombarded silicon and gallium arsenide. All the above goals were accomplished with the preliminary mixer evaluation confined to helium bombarded wafers. The data included in this report represent a typical sampling for each mixer type and in most cases may be treated in terms of a small number approximation to Gaussian statistics.

II. ION BOMBARDMENT APPARATUS

The experimental apparatus which was used to bombard the silicon and gallium-arsenide wafers with high energy positive ions is shown in Figure 1. The ion generator consists of an Ortec Model 320 RF ion source which is capable of generating and extracting positive ions to mass 40 with a maximum energy of 5 KeV. Gas is emitted from a controlled leak into the ion source base where an intense plasma is created in the anode region by the field of an RF oscillator and the dc field of the magnet coil. Ionization proceeds by electron collision with neutral gas atoms and the available current is approximately inversely proportional to the square root of the mass. Typical ion currents would be about 1 mA for H^+ and 150 μA for Ar^+.

Positive ions extracted from the source are accelerated and focused by a gap-Einzel lens system which follows the RF ion source. The gas pressure confronting the extracted beam is controlled by a four-inch diffusion pump connected to the side arm of the glass cross following the Einzel lens assembly. Operating pressure in the extractor lens and glass cross is about 1.5 microns as contrasted with the source pressure of about 35 microns. The ion source is used in a permanent installation with other experiments employing singly ionized hydrogen as the bombarding particle. A dual gas supply is employed for convenience of operation at the expense of some contamination of the ion beam for different experiments. A mass analyzer was permanently appended to the ion source for other experiments and served in addition the useful function of analyzing the particle content of the ion beam. If future

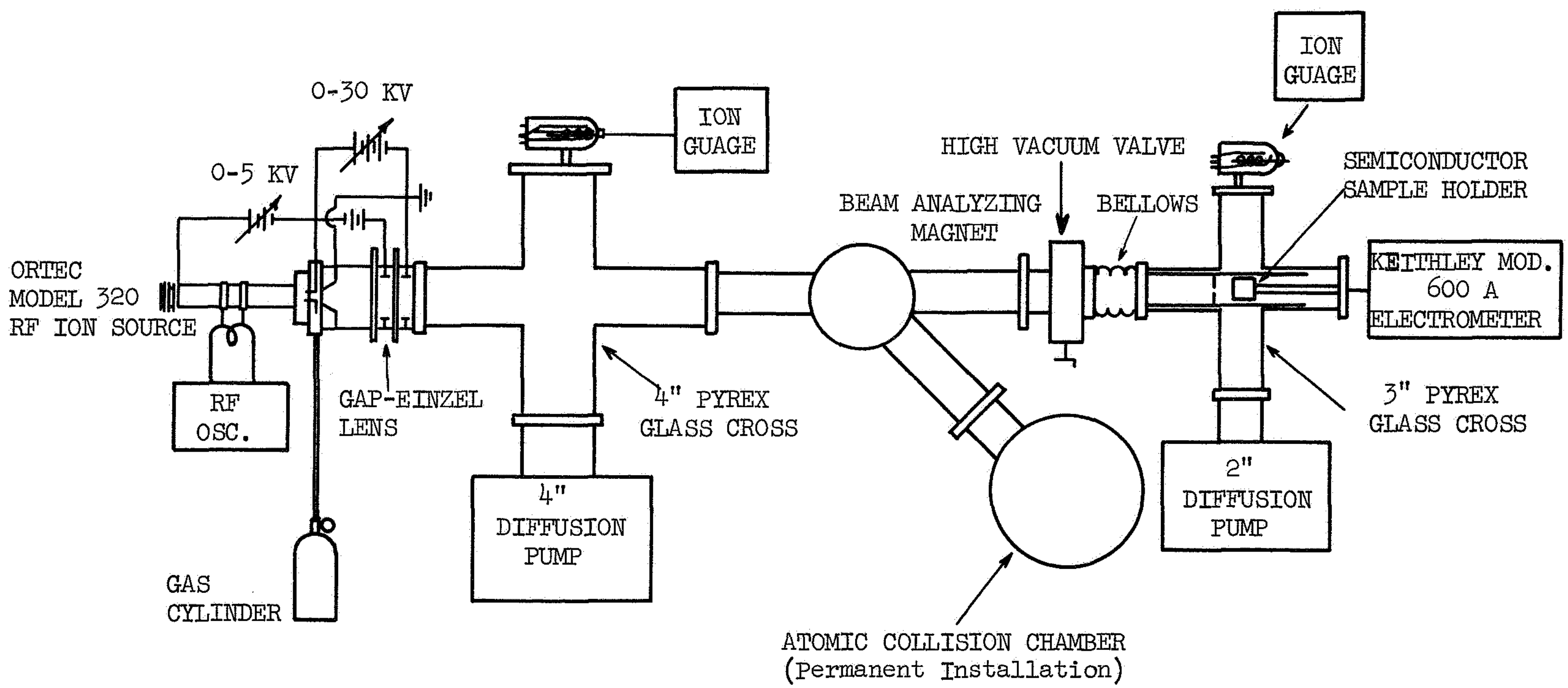


Figure 1. Block Diagram of Ion Bombardment Apparatus

work is initiated, a complementary port will be installed providing a mono-energetic ion beam for use in the bombardment of the semiconductor wafers.

The bombardment chamber is connected to the beam analyzer through a high vacuum slide valve so that the irradiated samples may be retrieved without cycling the entire system. Back pumping of the chamber is provided by a two-inch diffusion pump connected to the chamber sidearm.

A photograph of the sample holder and ion source is shown in Figure 2. The sample holder is made to accommodate post mounted semiconductor wafers. The beam cross section incident on the semiconductor is defined by two apertures. The first aperture confines the ion beam to a circular cross section of about 1.8 cm^2 and prevents ions from entering the area behind the sample holder assembly. A second aperture in the sample holder cap limits the ion beam to a cross section of 0.71 cm^2 on the surface of the disc containing the post mounted semiconductor wafers. The posts are pressed into the two front discs of the assembly in such a manner that the surface of the wafer is flush with the outer disc and presents a smooth planar surface to the ion beam. Two saw cuts are made at right angles through the center of each disc and the four pieces of the disc are insulated from each other by a thin strip of mylar. The ion current is conducted from each quarter disc by wires running through the supporting tube and disc assembly to four high vacuum feed-throughs mounted on the sample holder end plate. A drawing illustrating the details of the sample holder construction is shown in Figure 3.

An electrometer is connected to each terminal to determine the ion density on the four quarter plates. Secondary electron emission from the target disc

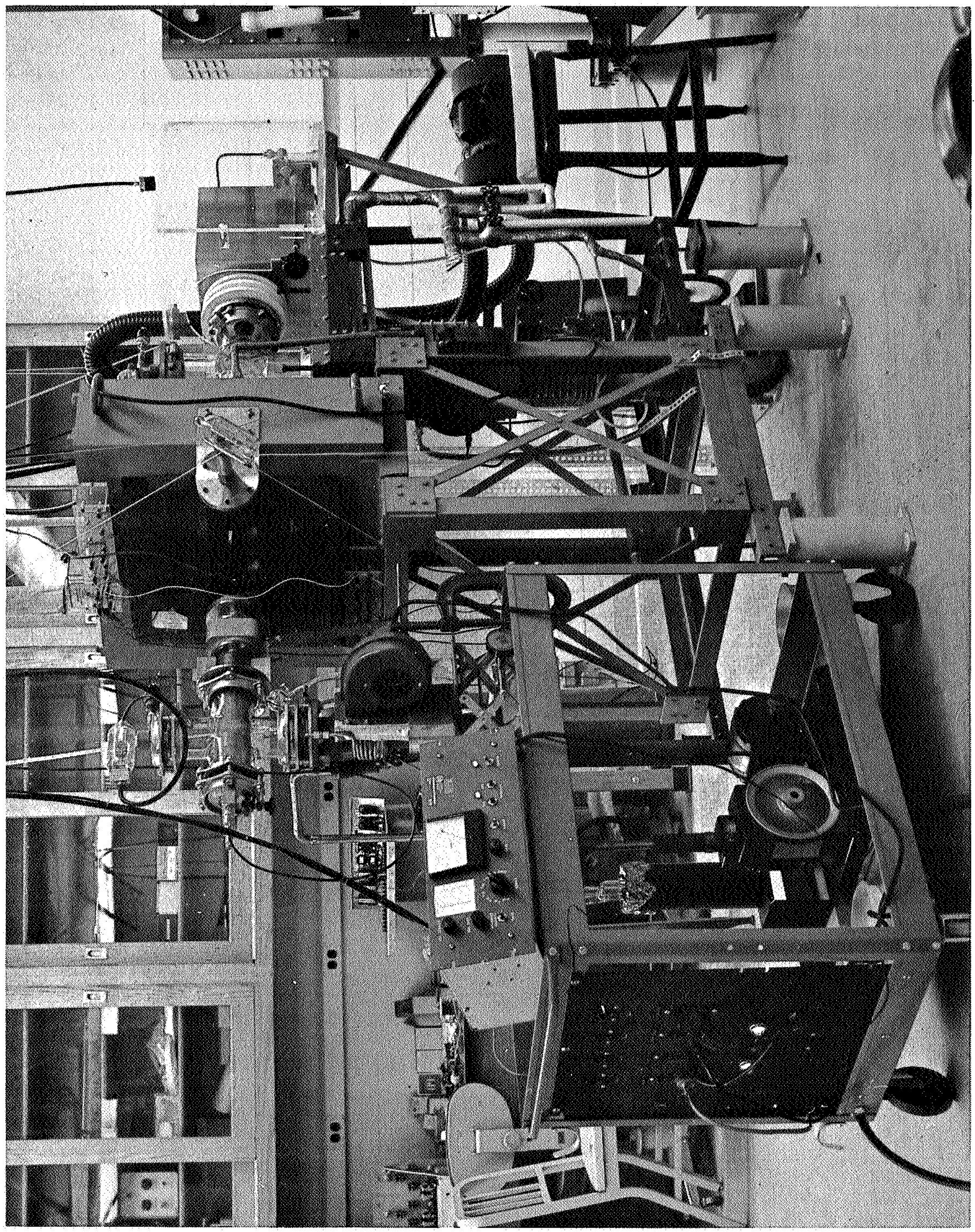


Figure 2. Photograph of Ion Source and Sample Holder

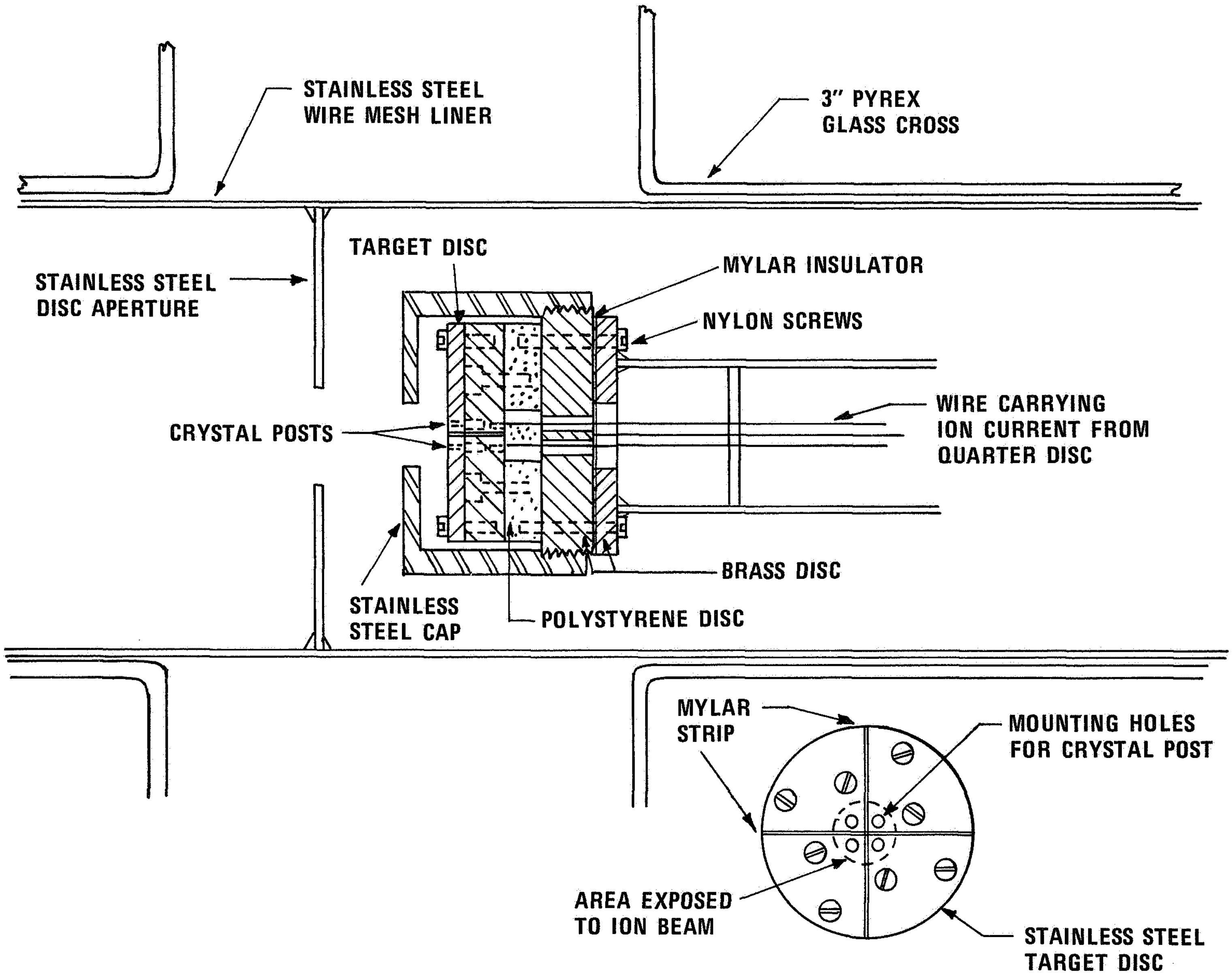


Figure 3. Semiconductor Sample Holder for Bombardment Chamber.

is controlled by the application of a retarding potential between the disc and the sample holder cap.

The target sample holder provides for simultaneous bombardment of four semiconductor wafers and the measurement of beam homogeneity over a small area near the beam center. Bombardment of a single wafer is accomplished by filling the remaining holes in the target disc with blank posts. The ion current was selected to give the highest percentage of He^+ in the ion beam, and the bombardment time was calculated to give a total dose of 300 μcoul/cm^{-2}. In a homogeneous ion beam this represents approximately one ion per lattice site on the silicon surface whose nearest neighbor distance is approximately 2.3 Å. An analysis of the ion beam content is given in Table I for the ion energies employed in the bombardment of the silicon and gallium arsenide wafers. The percentage of He^+ in the total ion beam is between 60 and 70 for 5, 10, and 20 KeV but only 43% for the 15 KeV beam. The presence of a measurable amount of H_3^+ and a large H^+ component indicates contamination with hydrogen in the ion source. This was not considered serious since the effects of bombardment by H^+ and He^+ have been shown by Ohl[7] to be very similar. The current corresponding to the H_2^+, He^{++} have the same charge to mass ratio. It is reasonably certain, however, that the He^{++}component is larger in view of the small amount of H^+ present and the small ionization probability associated with the formation of H_2^+. The ion currents listed in Table I were obtained by placing a Faraday cup on the mass analyzer port, and are different from the currents collected at the target holder; however, the ratio of the various species are the same at either location.

TABLE I

ION CURRENT AS A FUNCTION OF ION ENERGY FOR THE VARIOUS SPECIES COMPRISING THE TOTAL ION BEAM

Ion Species	Ion Current (μA) 5 KeV	10 KeV	15 KeV	20 KeV
He^+	0.63	0.90	1.30	0.70
H_3^+	< 0.01	< 0.01	0.10	< 0.01
H_2^+, He^{++}	0.35	0.50	0.95	0.26
H^+	0.01	0.05	0.70	0.01
Total Ion Current (μA)	0.99	1.45	3.05	0.97
Percentage of He^+ in Ion Beam (%)	63	62	43	72

III. FORMATION OF POINT-CONTACT RECTIFYING JUNCTIONS ON SILICON AND GALLIUM-ARSENIDE

The techniques of forming millimeter wave point-contact rectifying junctions have received a broad coverage in the literature.[12-18] These techniques may be divided roughly into two categories: mechanical forming and electrical forming. The objective of the forming process is to create a barrier layer between two materials of different work functions. To accomplish this objective both the metal whisker and the semiconductor wafer must be prepared such that mechanical imperfections, surface oxidation, and bulk impurities are minimized. The metal whisker is pointed electrolytically and etched to remove any oxide coating before the junction contact is formed. The surface of the semiconductor is ground flat and optically polished to insure a small area contact. The semiconductor surface is also etched to remove any oxide formation.

In a mechanical forming process, the proper junction characteristics are obtained by applying the correct force to the whisker contact. The diameter of the whisker-wire is determined largely by the force required to form the junction, and the whisker is made with a loop near its base to prevent damage to the point. For operation in the millimeter wave region, the whisker-wire diameter is usually chosen to be 1-5 mils while the contact force is approximately 10-20 grams. The optimum pressure is a compromise between good electrical properties which occur at the lower pressures and good stability which is obtained at the higher pressures. The technique of mechanical shock or "tapping"[19] is sometimes employed to enhance the pressure contact. In this process the whisker is brought into ohmic contact with the semiconductor and tapped lightly while observing the dc characteristics displayed on an oscilloscope. This technique requires a high level of experience to achieve consistent results, since the whisker point is easily bent, and the semiconductor wafer can be caused to crack if a grain boundary or other imperfection runs across the surface.

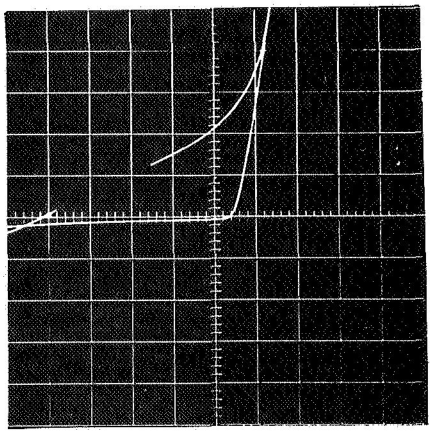
Electrical forming is usually accomplished by passing a series of current pulses through the junction in the forward direction. If a capacitive discharge source is employed, the peak current and pulse duration are controlled by the amount of stored charge and the RC time constant of the discharge circuit. The current density at the point is very high for a supply voltage which exceeds the forward breakdown, and burnout may result unless a current limiting resistor is employed. The effects of electrical forming vary greatly depending on the composition of the metal and semiconductor materials. The major effect on the silicon mixer, which employs a tungsten whisker, seems to be the creation of a clean junction resulting from the melting of a small part of the whisker point and its adjacent semiconductor contact; however, reverse forming has produced some unusual effects which will be discussed in Section IV. The electrically formed or "welded" junction produces a quite different effect in the gallium-arsenide mixer. Welding a copper alloy wire such as phospor-bronze or gold-copper to an N-type gallium-arsenide wafer results in the diffusion of copper into the junction area. Since copper is an acceptor in gallium-arsenide it is thought that a planar P-N junction is created provided the amount of copper in the whisker exceeds several percent. If this supposition is true, the whisker wire serves as simply an electrical lead from the planar junction, and a very stable diode is formed.

Indication of correct junction formation is usually given by a characteristic relationship between the dc junction current and the forward and reverse junction voltage. However, since the RF properties depend strongly on the junction capacitance and hence the contact area, achieving the proper dc characteristics is a necessary but not a sufficient condition for obtaining good RF performance. The relationship between the dc characteristics and conversion loss will be discussed in Section V.

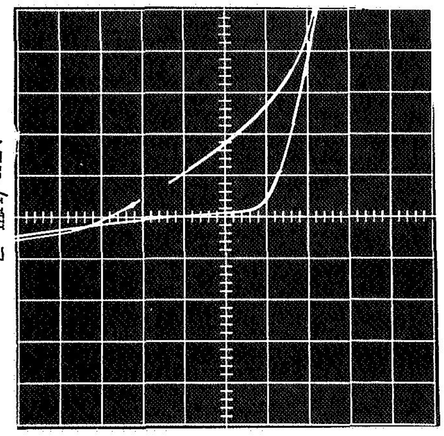
Figure 4 shows the dc characteristics of several 1N53 diodes of widely different age. The 1N53 diode is a point contact junction device fabricated from a tungsten whisker and a P-doped silicon wafer. It is designed for operation in the frequency region of 35 GHz and was chosen as a basis of comparison for the point-contact silicon mixers constructed during this research effort. It is evident from Figure 4 that shelf life can have a degrading effect on the junction properties. This is due in part to the formation of oxide coatings on both the metal whisker and the semiconductor surface, and the instability of diffusion-doped semiconductors at the surface layer. An enlarged log-linear plot of the dc characteristic of a new 1N53 mixer diode is shown in Figure 5. Both the diode and diffusion theories of rectification predict a forward I-V characteristic of the form

$$I = A\left[\exp(\alpha V_J) - 1\right] \qquad (1)$$

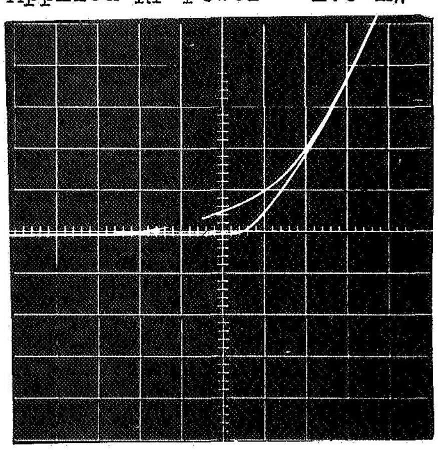
where I is the current, V_J the junction voltage, and A and α are constants.



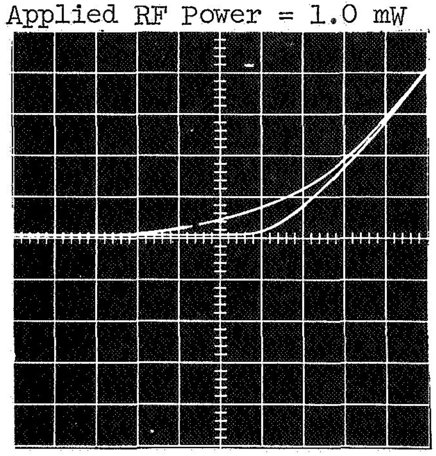
New 1N53 Diode
Applied RF Power = 1.0 mW



1N53 ≈ 3 years old
Applied RF Power = 1.0 mW



1N53 ≈ 7 years old
Applied RF Power = 1.0 mW



1N53 ≈ 7 years old
Applied RF Power = 1.0 mW

Figure 4. Oscillographs of the I-V Characteristics of Several 1N53 Diodes Showing Aging Properties

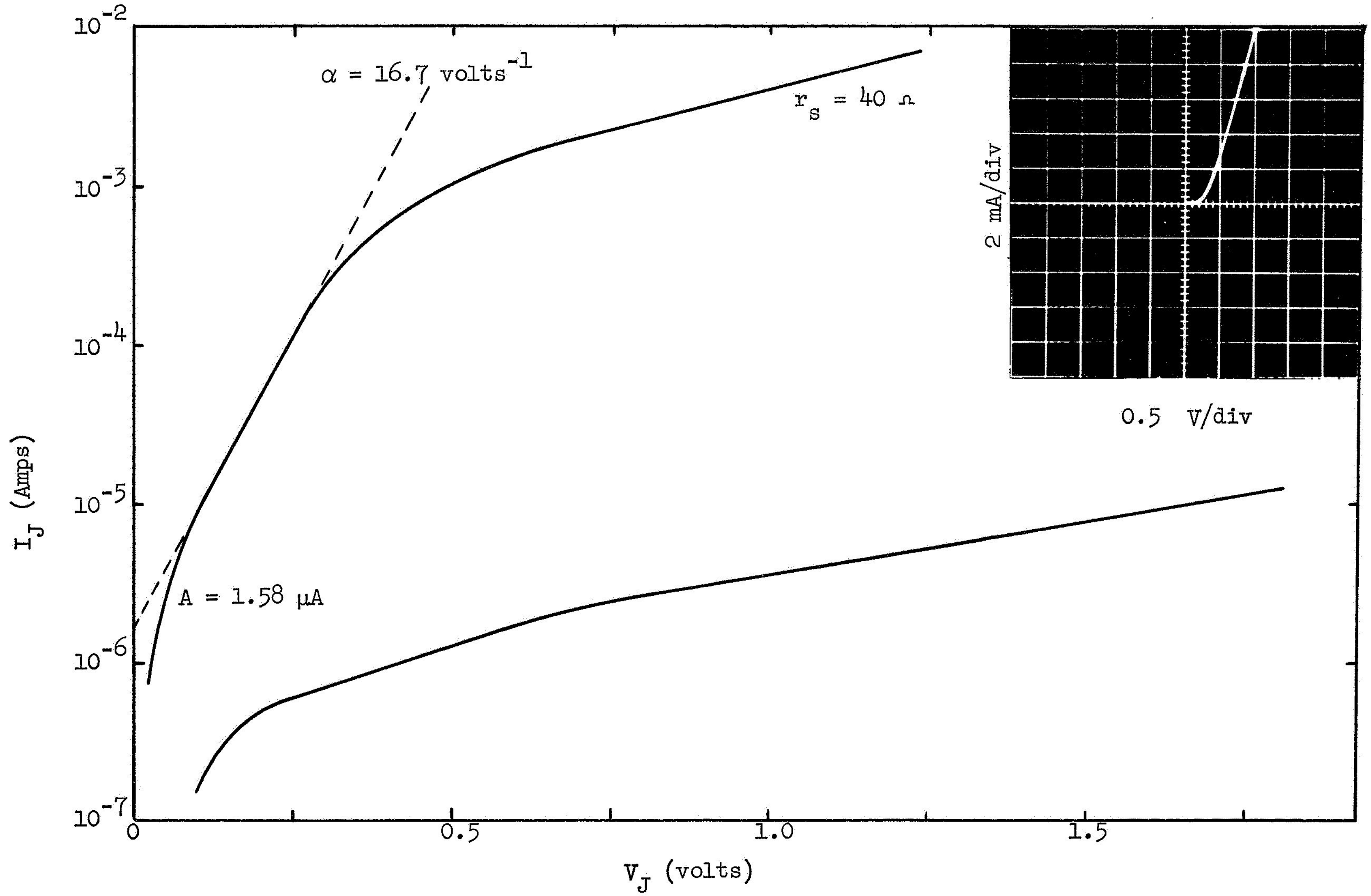


Figure 5. I-V Characteristics of a New 1N53 Diode

The voltage applied to the rectifier leads is greater than V_J by the drop in contact spreading resistance r_s plus the bulk resistance r_B which is usually much smaller than r_s. For a circular contact of radius a, the spreading resistance is given by

$$r_s = \frac{1}{4\sigma a} \qquad (2)$$

where σ is the conductivity of the semiconductor. If equation (1) is fitted to the forward I-V characteristic in Figure 5, the constants are:
$A = 1.58\mu$ amp, $\alpha = 16.7$ volts^{-1}, and $r_s = 40$ ohms.

The constants may be expressed in terms of the physical parameters of the junction and the properties of the diode materials.[18]

$$A = \tfrac{1}{2}\,\bar{v}\pi a^2 Ne \quad \exp\left(-e\Phi_o/kT\right) \qquad (3)$$

$$\alpha = \frac{e}{kT} \qquad (4)$$

The symbols in equation (2) and (3) are defined as follows:

a = radius of whisker contact (cm)

N = carrier density (cm^{-3})

e = charge on an electron (1.602×10^{-9} coulomb)

T = temperature ($^{\circ}K$)

$\bar{v}$ = average carrier drift velocity (cm/sec^{-1})

Φ_o = height of barrier (volts)

k = Boltzman's constant

At room temperature, equation (4) predicts that α will be 39 volts^{-1}. It has generally been found that α lies between 10 and 30 volts^{-1} for silicon diodes. Several theories have been advanced to explain this discrepancy. One is the multicontact theory of Yearian[20], while Culter[21] has attempted an explanation based on the surface layer drop theory. The overall problem of reconciling the rectification theory and the experimental evidence was attempted by Bethe.[22] While none of these attempts has been completely successful, it has been shown that a perfect area junction does not exist between the point of the whisker and the semiconductor surface.

The point-contact mixers studied in this research program were formed on aluminum-doped silicon and tellurium-doped gallium-arsenide. A standard "run-in" mixer was employed with the whisker mounted so that it extends vertically into the waveguide through the top wall and the semiconductor wafer mounted in a differential screw so that it extends into the waveguide through the opposite wall. The rectifying junction is formed by advancing the differential screw until contact is established between the pointed whisker wire and the surface of the wafer. The point of contact is made at a position just above the bottom wall of the waveguide. The means of attaching the silicon and gallium-arsenide to the brass post are different. Nickel is electroplated onto one side of the roughly polished silicon wafer so that it may be soldered to the mounting post while the gallium-arsenide wafer is attached with a conducting silver epoxy cement. The final polishing of the surface is performed after the wafer is attached to the post.

A graph of the I-V characteristics for a typical silicon mixer is shown in Figure 6. A tungsten whisker was used because its work function and mechanical properties are complementary to the P-type silicon. It was found

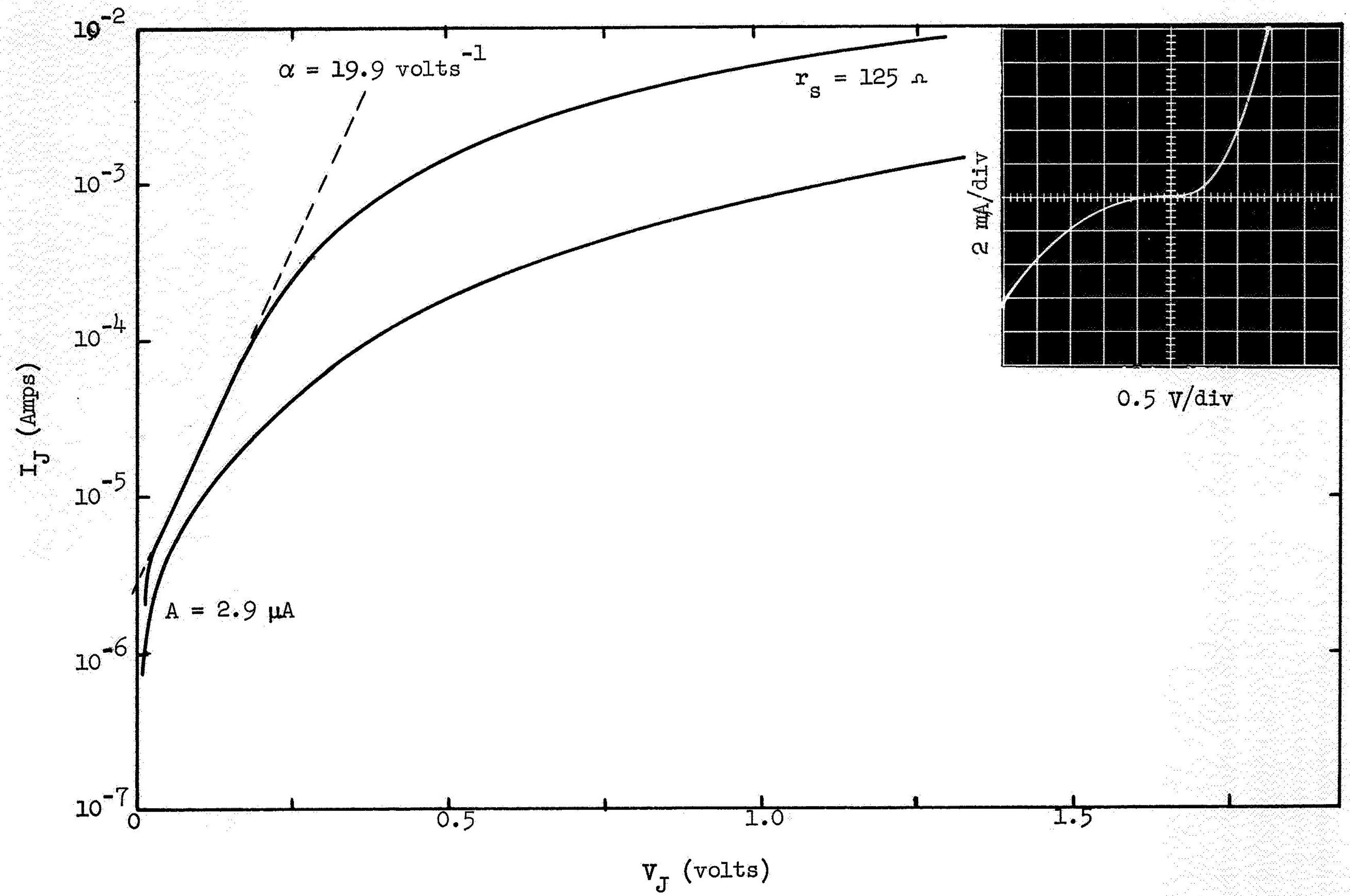


Figure 6. I-V Characteristics of a "Run-In" Mixer Employing a Tungsten Whisker and a P-Doped Silicon Chip.

that mechanical forming alone produced the best results. Electrical forming did not significantly improve the forward or reverse characteristics and usually ended in burnout at a level of about 4-6 volts. A comparison of Figures 5 and 6 shows the reverse current to be several orders of magnitude higher than for the 1N53 diode. In addition, the forward break point or "knee" is not sharp but rises in a continuous arc. It was felt that this behavior was probably due to surface contamination of the silicon. P-doped silicon wafers were obtained from two other sources and the results were all similar. In all, approximately thirty wafers were examined with the same result. In the interest of improving the forward characteristic, several surface cleaning techniques were investigated. These included the use of etching solutions for removal of surface oxides, and grinding and polishing techniques for exposing a clean surface layer. The variation in I-V characteristics as a function of etching time are shown in Figure 7. The etching solution used in this experiment consisted of 10 ml HF plus 10 ml H_2O, and an etching time of about 2 minutes was found to produce the best results. After each successive etch the tungsten whisker was repointed electrolytically in a 3 normal solution of KOH and the dc characteristics were again measured. At least three run-ins were made on each trial to insure a good contact. A more powerful etch consisting of 5 ml HNO_3 plus 10 ml KOH plus 15 ml CH_3COOH was tried and resulted in such severe pitting for exposures of about 5-10 seconds that the surface has to be repolished. Two different means of grinding and polishing the surface of the wafer were tried. One technique involved the use of a fine abrasive stone in the grinding process while the other involved the use of 600 grit

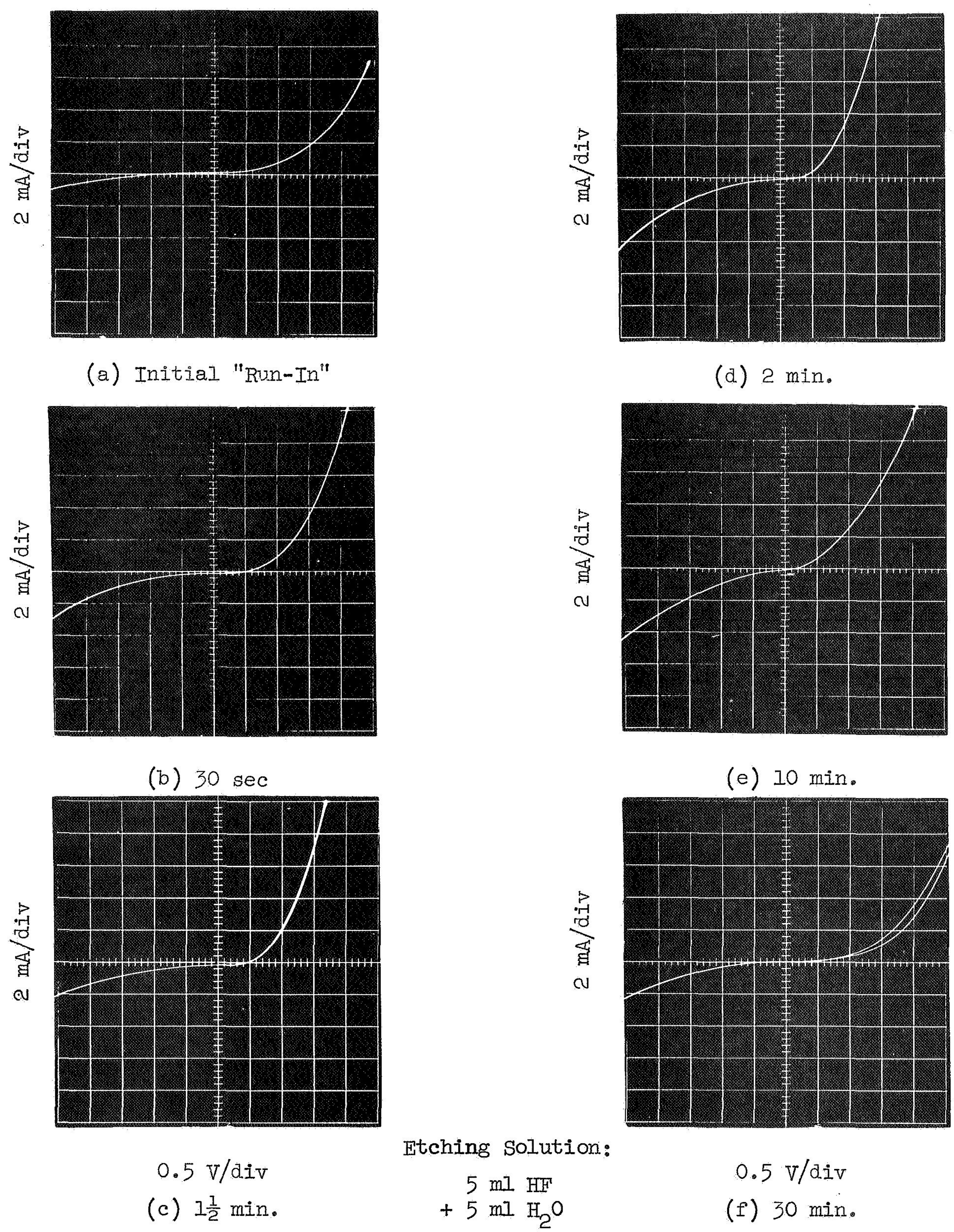


Figure 7. I-V Characteristics of a "Run-In" Silicon Mixer as a Function of Etching Time.

grinding compound. Polishing was accomplished in both techniques by mounting the differential screw in an inverted channel whose runners were ground and polished to ride on an optical flat. The polishing compound (Linde-0.3 micron) was rubbed into a small square of bond paper which was placed on the optical flat. The surface of the wafer was lowered into contact with the impregnated paper and polished with the standard figure eight pattern. Significant changes were not observed as a result of grinding and polishing a new surface layer. There is indication from the work of Ohl[5] that an optimum contact cannot be made directly to a polished silicon surface because of the damage layer incurred in the grinding and polishing process. Removal of this damaged layer requires oxidation at a temperature of approximately 1000° over a time interval of about 15 minutes. An experiment of this nature was not possible during this research program since facilities were not readily available and the silicon was obtained soft soldered to a brass post.

The formation of point-contact junctions on gallium-arsenide was straightforward and no difficulties were encountered. The whisker wire used was either phosphor-bronze or a gold-copper alloy; both worked equally well. Figure 8 shows the dc characteristics of a typical junction formed with a gold-copper alloy whisker on gallium-arsenide. The ratio of forward to reverse current is very high past the "knee" of curve and the constants of equation (1) are: $A = 1.26 \times 10^{-9}$, and $\alpha = 22.6 \text{ volts}^{-1}$. Preparation of the gallium-arsenide surface was similar to that of the silicon surface. An etching solution consisting of 15 ml HNO_3 plus 10 ml H_2O plus 5 ml HF was followed by a water rinse and finally a rinse in methyl alcohol. The

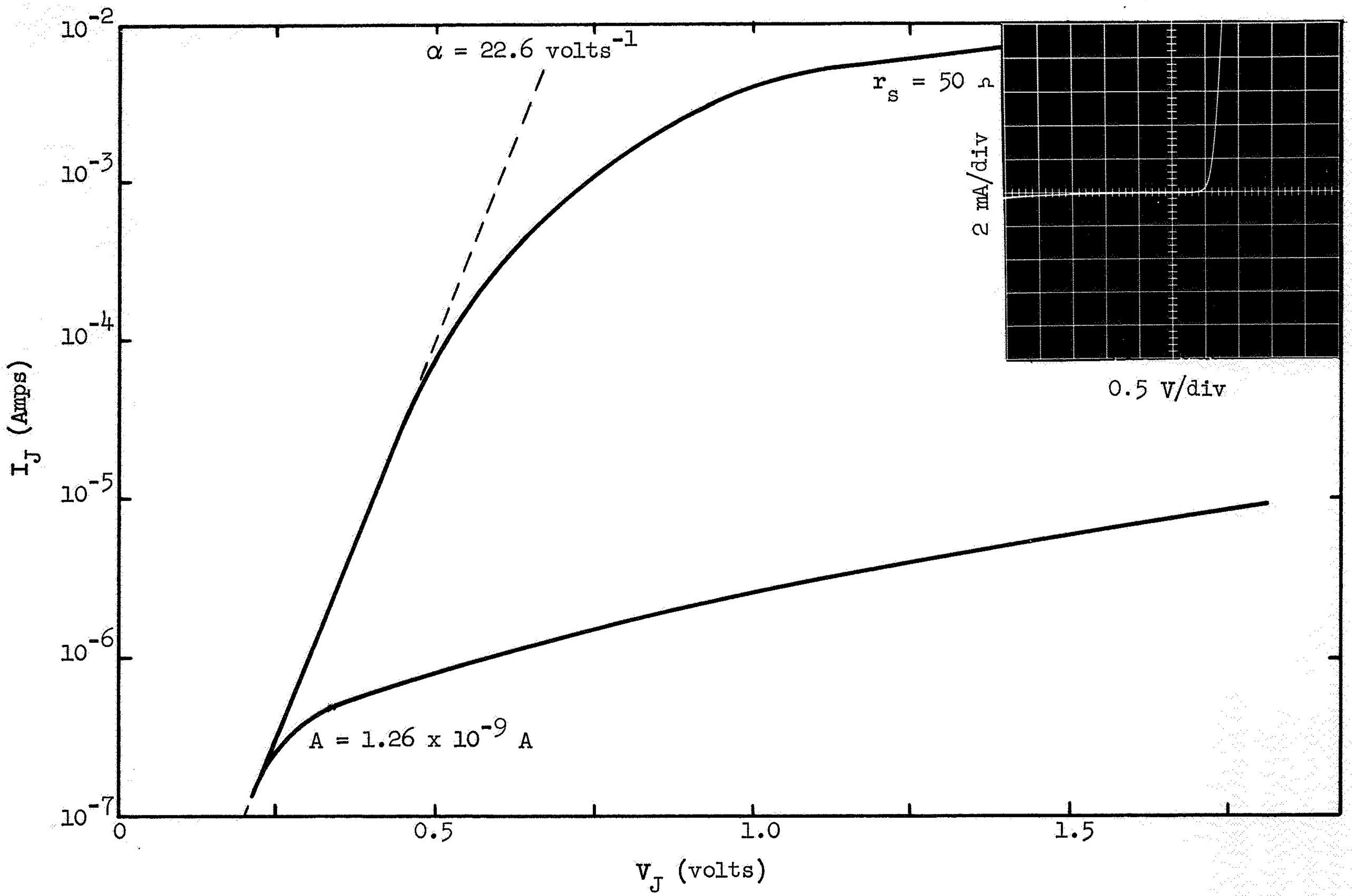


Figure 8. I-V Characteristics of a "Run-In" Mixer Employing a Gold-Copper Alloy Whisker and an N-Doped Gallium-Arsenide Chip.

whiskers were pointed in an undiluted solution of phosphoric acid. Electrical forming was used to "weld" the junction resulting in a very stable diode. A series of current pulses derived from a 1 μf capacitor were employed in the forming process. The charging voltage was initially set at 3 volts and increased in 0.5 volt increments until the desired characteristic was obtained.

IV. DC CHARACTERISTIC OF ION BOMBARDED SILICON AND GALLIUM-ARSENIDE

The effects of ion bombardment on a semiconductor surface can be characterized by a damage layer whose conductivity is considerably different from the rest of the semiconductor. The penetration of ions into the crystal lattice produces a variety of damage centers whose end result is measurable as a change in conductivity. Near the surface to a depth of several tenths of a micron the conductivity may be so low that the layer loses its semiconducting properties. The profile of implanted ions and damage centers tends to peak in this region, then flatten out and may fall off quite abruptly, particularly if the direction of incidence of the ion beam is parallel to a crystal axis and channeling takes place. It is desirable to etch away the insulating surface layer leaving a well-defined semiconducting layer with a lower conductivity than that of the remaining bulk material. It was shown by Ohl[7] and confirmed in this work that the two primary changes in the I-V characteristic caused by ion bombardment are a much higher back resistance and reverse breakdown and a higher effective contact potential. For example, the I-V characteristics of a point-contact mixer fabricated from a silicon wafer bombarded with 10 KeV He^+ ions is shown in Figure 9. It is obvious that this characteristic is not desirable for a mixer application. The "knee" of the forward characteristic has been moved out to about 2 volts and is a smooth continuous arc instead of a sharp break. The reverse breakdown has been moved out to about -10 volts and the back resistance is very

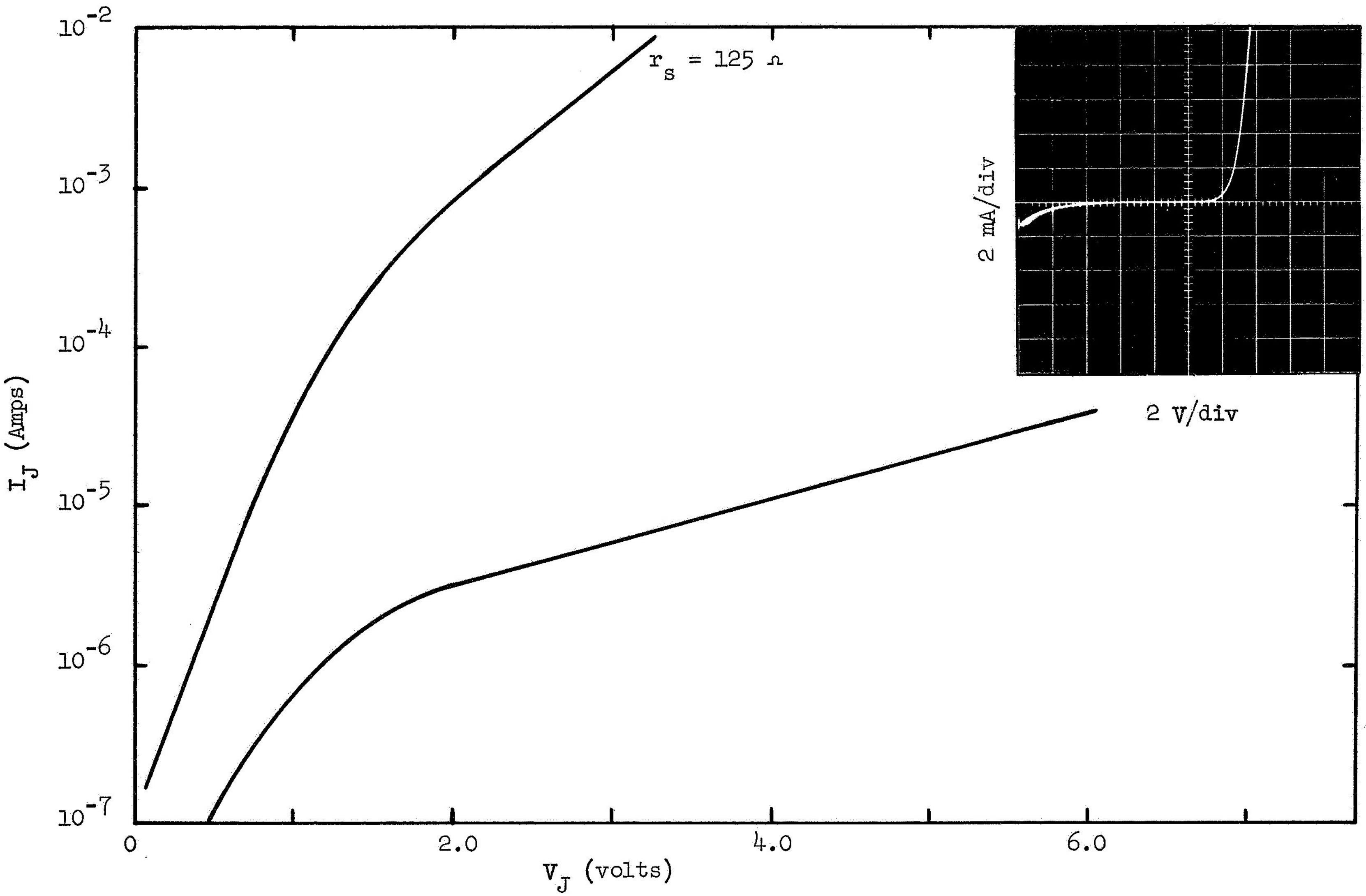


Figure 9. I-V Characteristics of a "Run-In" Mixer Employing 10 KeV He^+ Bombarded Silicon.

high--approximately one megohm. There is evidence in some of Ohl's work[7] that these characteristics, particularly the forward breakdown, can be improved by an annealing procedure performed simultaneously with the ion bombardment. Even if this were possible, it is likely that certain noise mechanisms would be enhanced since operation as a mixer would require a dc bias to establish the operating point at the "knee" of the curve and hence the energy of the injected charge carriers would be greatly increased.

In the process of forming junctions on the ion bombarded silicon wafers, it was found that improved I-V characteristics could be obtained with electrical forming in the reverse direction. In this process, 10 volts dc was applied in series with a current limiting resistor in the reverse direction across the junction. While observing the I-V characteristics on an oscilloscope, the series resistor was varied until the desired results were obtained. Figures 10 through 13 show the I-V characteristics of reverse-formed junctions on ion-bombarded silicon at energies of 5, 10, 15 and 20 KeV. The constants pertaining to equation (1) of Section III are presented for these curves in Table 2 to provide comparison with junctions formed on unbombarded silicon. Also listed in Table 2 are the ion bombardment parameters and the spreading resistance of the junction. Reverse forming produced a junction with the same contact potential as for unbombarded silicon with a sharp "knee" in the forward direction. The reverse breakdown, however, was marginal when compared with the 1N53 diode. It is important to stress that these characteristics are representative of the particular materials used to form the junction in the sense that they might be one of 10 or more similar

TABLE 2

CHARACTERISTICS OF POINT-CONTACT JUNCTIONS

FORMED ON SILICON BOMBARDED WITH He^+ IONS

(Total dose 300 μcoulomb cm^{-2})

Ion Energy (KeV)	Ion Current (μA)	α ($Volts^{-1}$)	A (μA)	r_s (ohms)
0	0	19.9	2.9	125
0 (1N53)	0	16.7	1.58	40
5	0.32	40.0	2.50	56
10	0.47	15.5	2.00	83.5
15	0.98	31.4	1.78	62.5
20	0.31	24.6	1.00	125

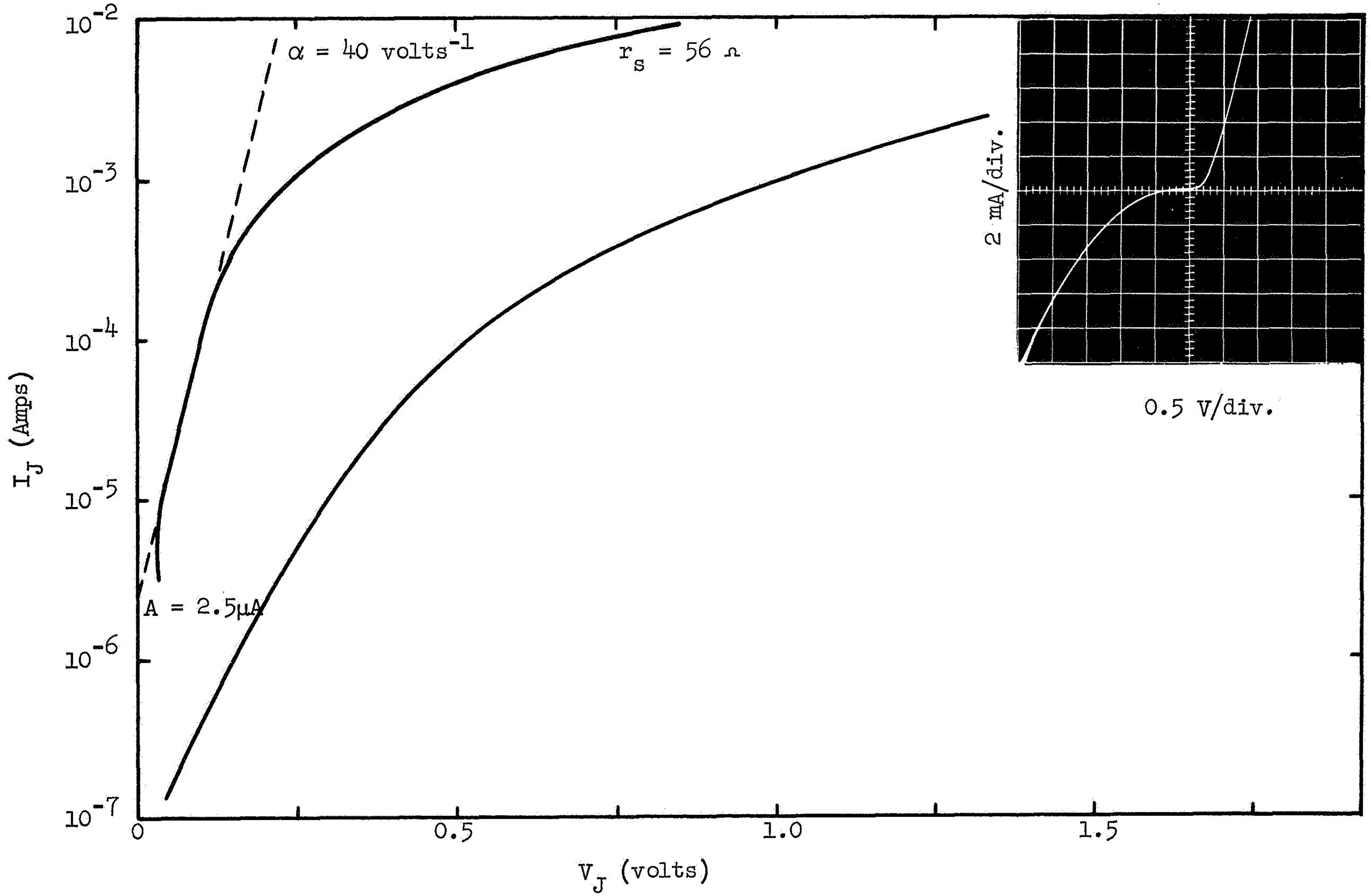


Figure 10. I-V Characteristics of a "Run-In" Mixer Employing 5 KeV He^+ Bombarded Silicon in a Reverse Formed Junction.

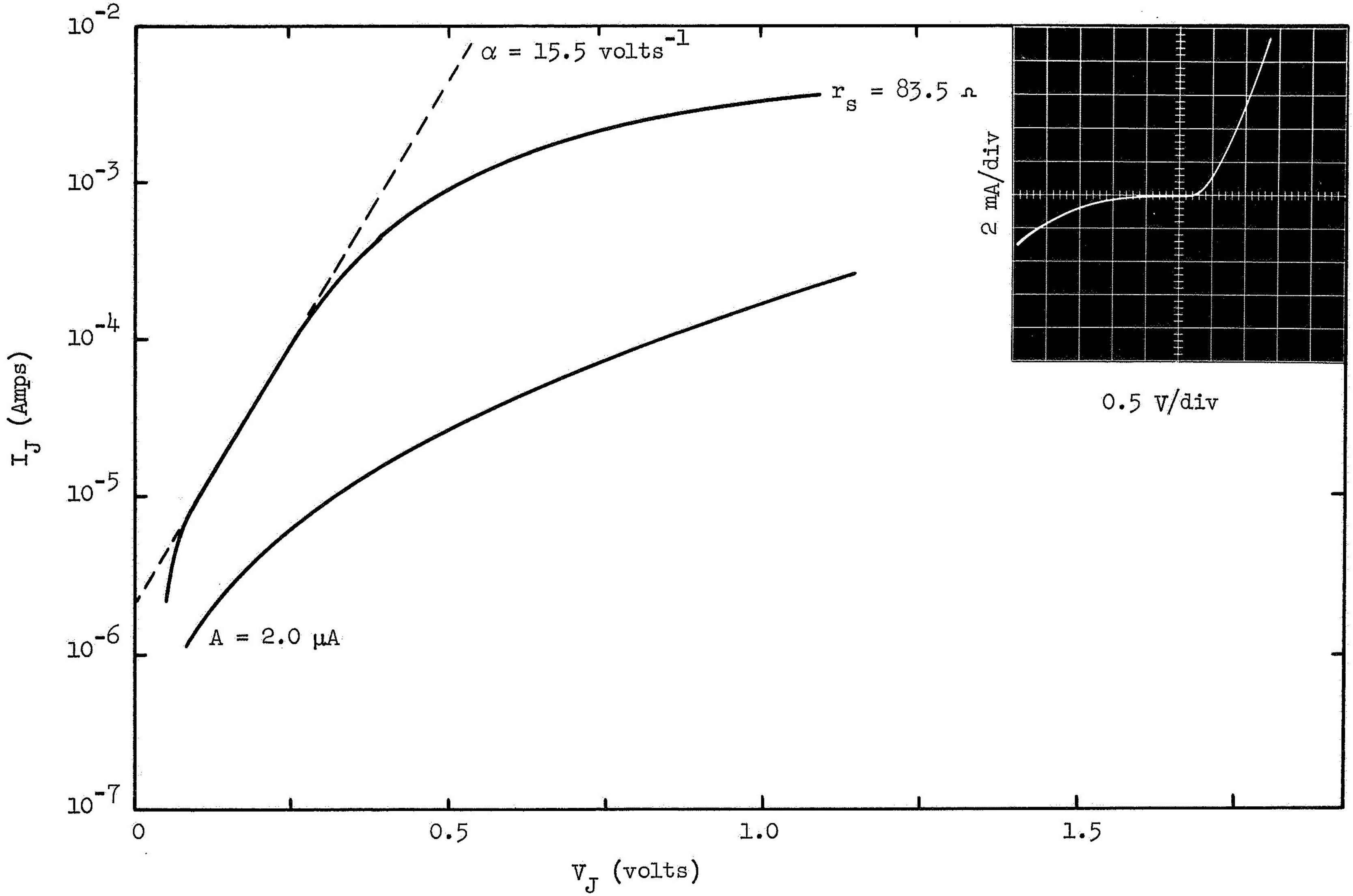


Figure 11. I-V Characteristics of a "Run-In" Mixer Employing 10 KeV He^+ Bombarded Silicon in a Reverse Formed Junction.

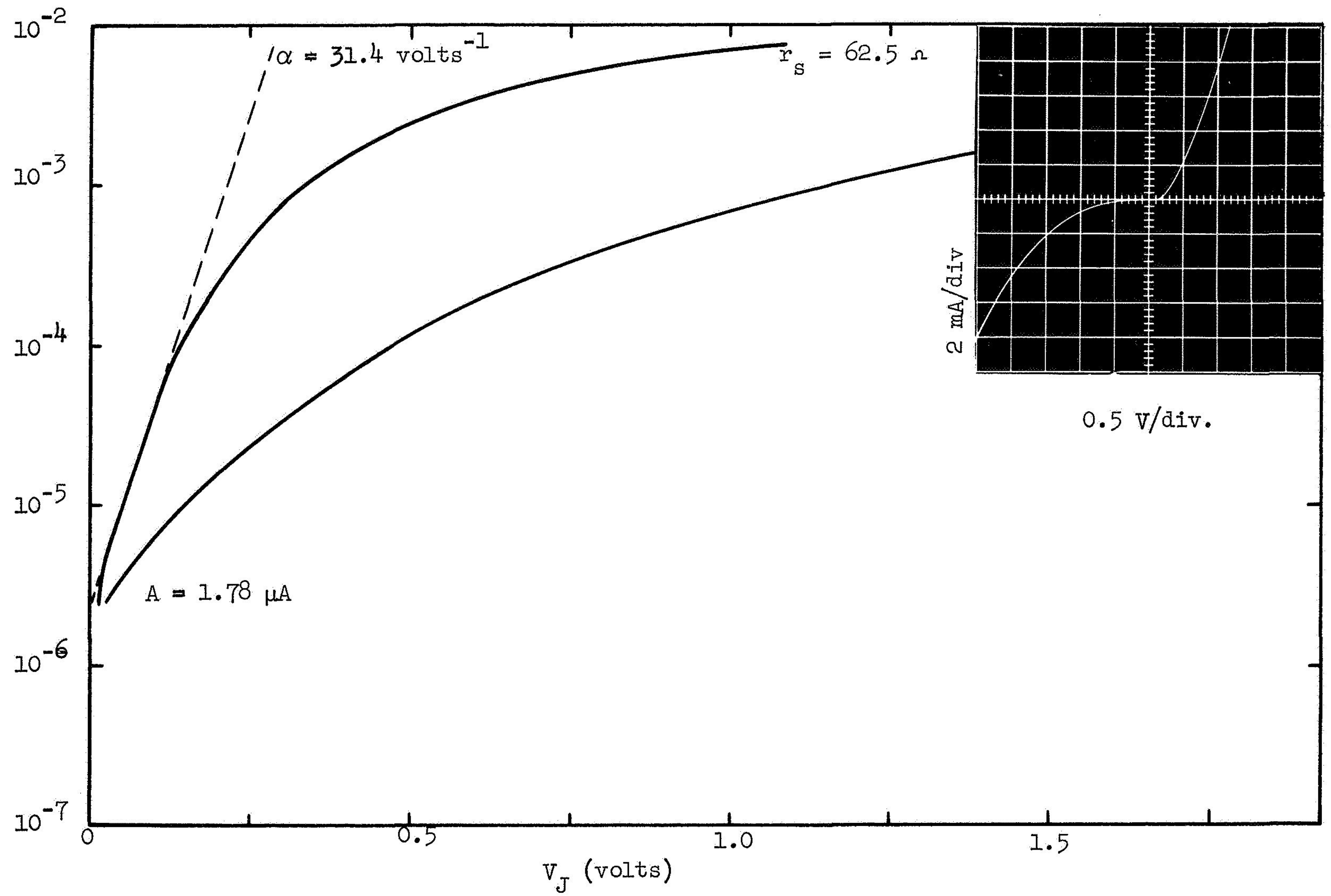


Figure 12. I-V Characteristics of a "Run-In" Mixer Employing 15 KeV He^+ Bombarded Silicon in a Reverse Formed Junction.

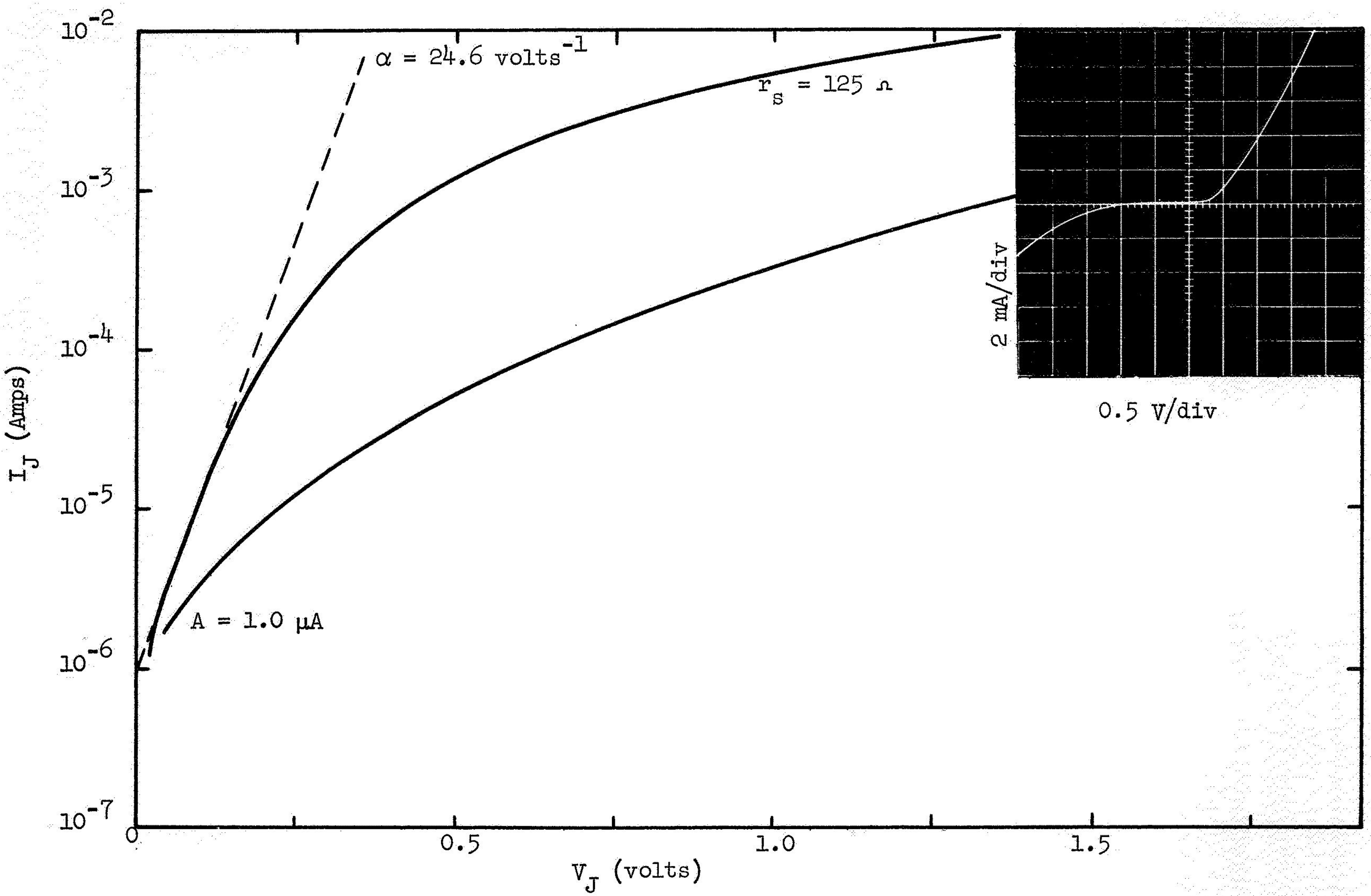


Figure 13. I-V Characteristics of a "Run-In" Mixer Employing 20 KeV He^+ Bombarded Silicon in a Reverse Formed Junction.

"run-ins" made on the particular wafer. Although exact repeatability is practically impossible to achieve, considerations of material costs make a true statistical analysis prohibitive. Another means of comparison may be obtained by plotting the ratio of forward to reverse current as a function of junction voltage. This ratio is compared in Figure 14 for several of the silicon junctions previously discussed. Although higher ratios were obtained with the ion-bombarded silicon than with the unbombarded silicon, none of the "run-in" junctions could match the commercial 1N53 diode.

The effects of ion bombardment on gallium-arsenide were more difficult to analyze. With the exception of the 5 KeV sample, a successful junction could not be formed. The I-V characteristic for the junction formed on gallium-arsenide bombarded with 5 KeV He^+ ions was virtually identical to that shown in Figure 9. For higher energies, the I-V characteristics deteriorated with a typical junction illustrated in Figure 15.

The reason for this behavior has not been determined although it is possible that the penetration and damage in the gallium-arsenide is more extensive than in silicon because of reduced stopping power. It would appear from the results obtained that the surface insulating layer is much deeper than for silicon. Grinding and polishing of the surface was tried, but the results were the same even after a considerable depth had been removed. A comparison of the ratio of forward to reverse junction current as a function of junction voltage is shown in Figure 16 for the gallium-arsenide mixers and reveals the similarity of the two curves for the unbombarded and 5 KeV He^+ bombarded wafers.

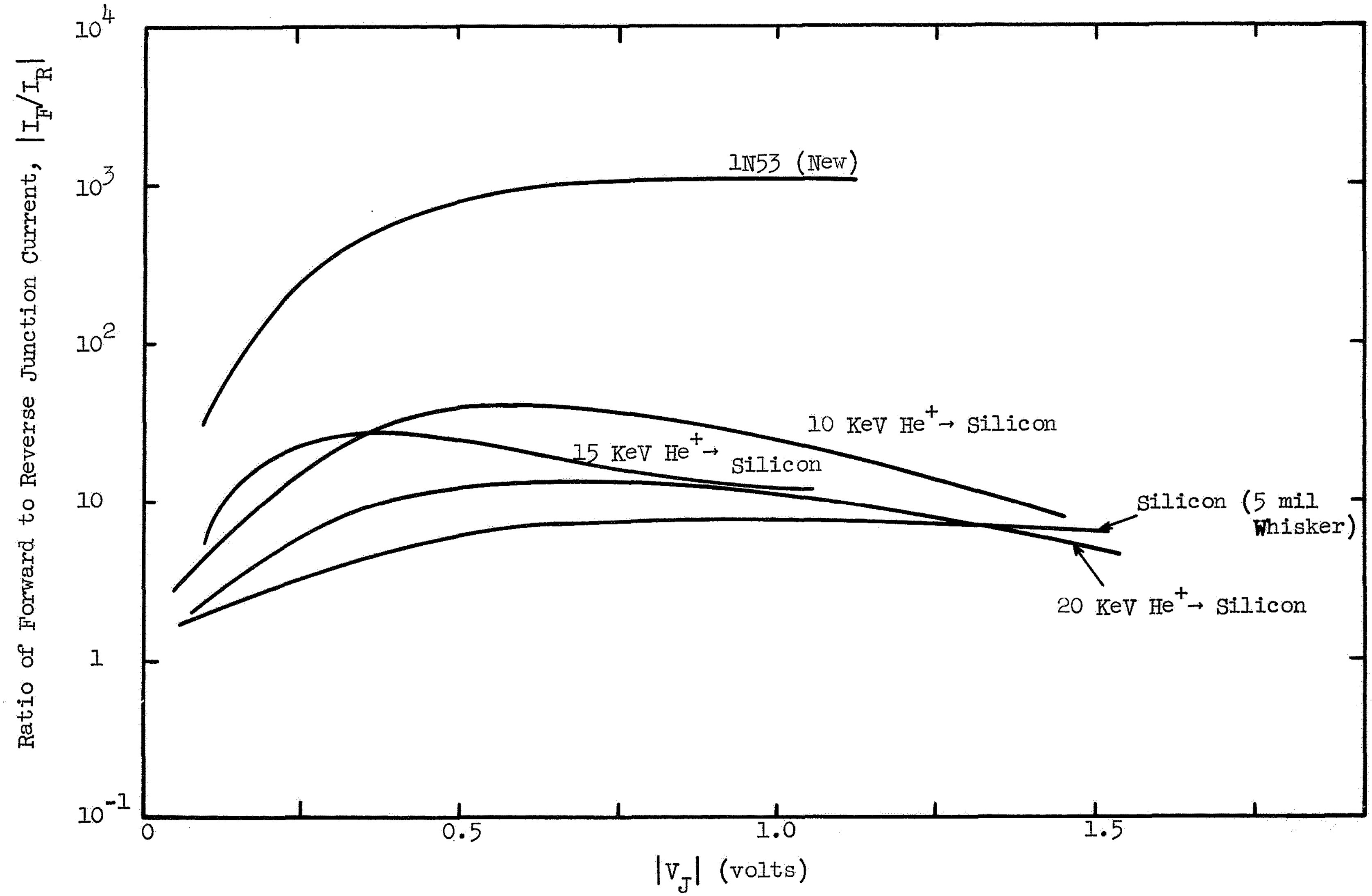


Figure 14. Ratio of Forward to Reverse Junction Current as a Function of Junction Voltage for Silicon "Run-In" Mixers.

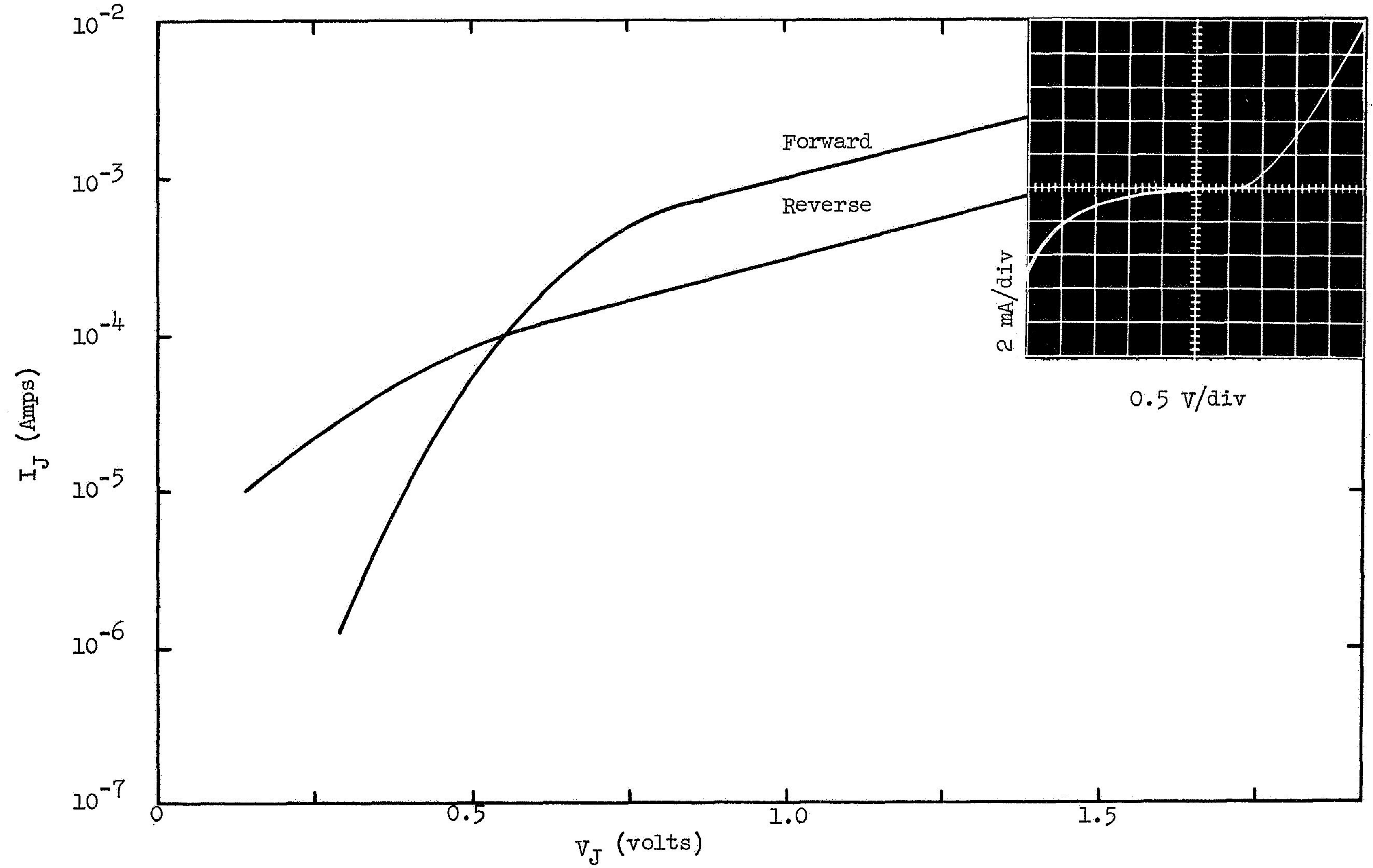


Figure 15. I-V Characteristics of a "Run-In" Mixer Employing 10 KeV He^+ Bombarded Gallium-Arsenide.

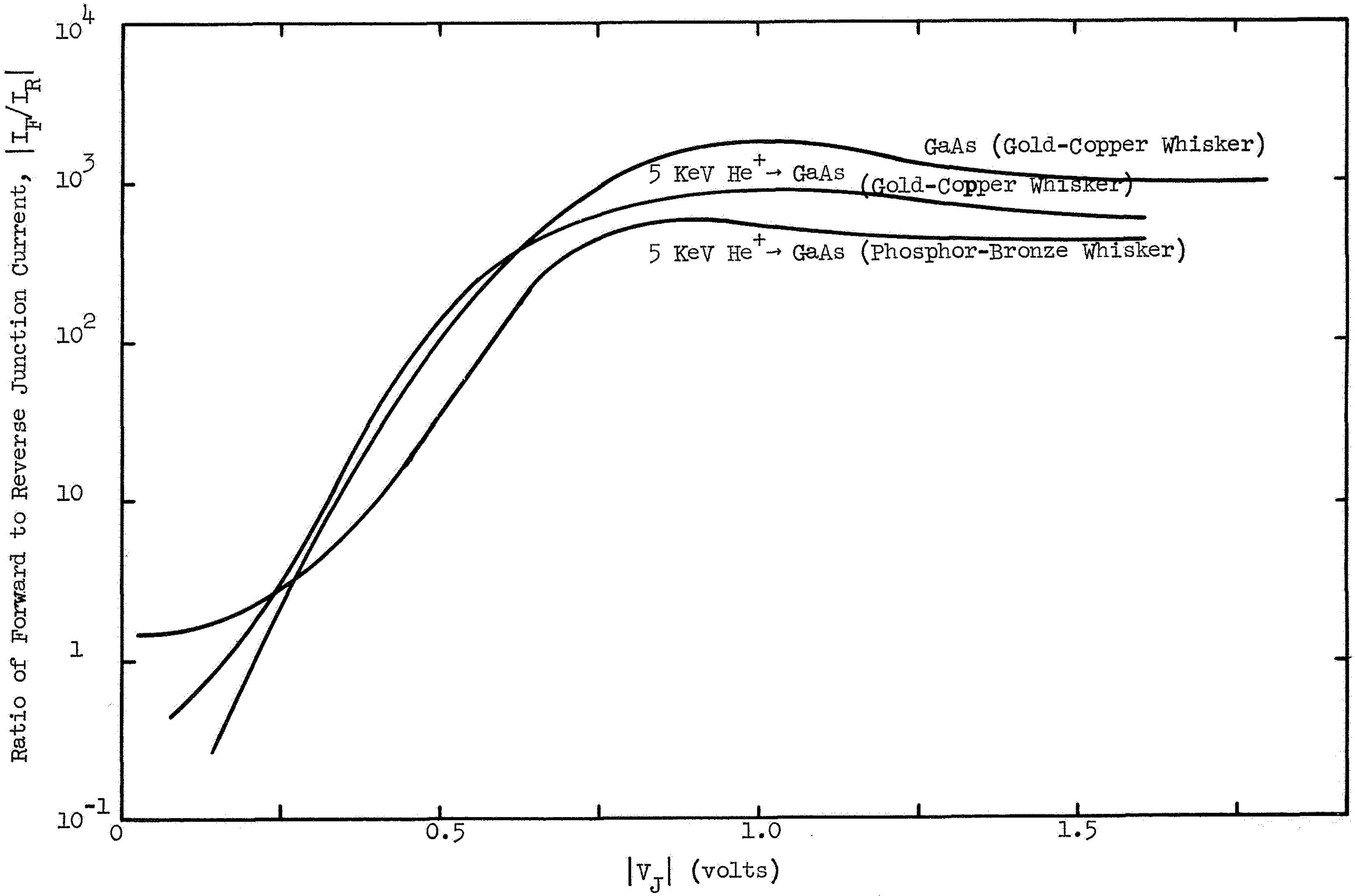


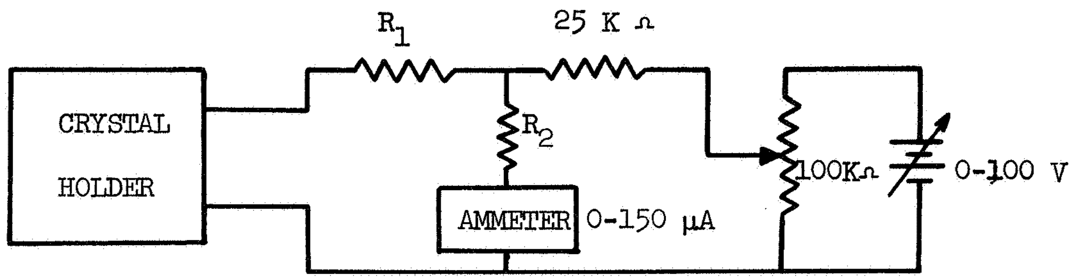
Figure 16. Ratio of Forward to Reverse Junction Current as a Function of Junction Voltage for Gallium-Arsenide "Run-In" Mixers.

V. CONVERSION LOSS OF ION-BOMBARDED SILICON AND GALLIUM-ARSENIDE MIXERS

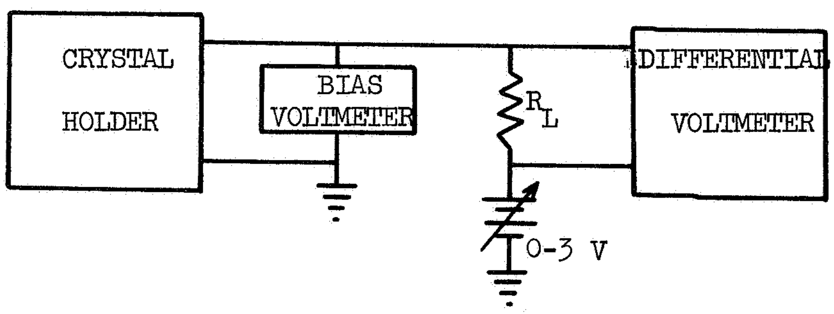
The performance of the point-contact junctions formed during this research was evaluated by measuring their conversion loss. No attempt was made to measure the noise temperature ratio--an important parameter in determining the noise figure of a receiver employing a mixer. The measurements of conversion loss were made using a modification of the dc incremental method described by Torrey and Whitmer[23]. It was found advantageous to modify their circuit and employ a differential voltmeter to determine the change in dc current corresponding to an incremental change in RF power incident on the junction. Figure 17 shows a block diagram of the measurement set-up as found in Reference 14, and also a block diagram of the measurement set-up as modified for use in this work. The procedure is straightforward and involves the determination of two quantities: (1) the change in dc current ΔI through a known load resistor R_L, and (2) the change in RF power ΔP incident on the mixer. The calculation of conversion loss proceeds from the expression

$$L_0 = \frac{1}{2P_0 R_L \left(\frac{\Delta I}{\Delta P}\right)^2} \tag{5}$$

The measurements of L_0 were all made at 35 GHz with R_L chosen to match the IF impedance of the mixer. It was found that certain errors could be incurred with the set-up shown in Figure 17(a). This occurs in the measurement procedure when the ammeter arm is unbalanced and causes a change in the input VSWR



(a) Standard Incremental Power Set-Up for Measuring Conversion Loss.



(b) Modified Incremental Power Set-Up for Measuring Conversion Loss.

Figure 17. Block Diagram of Standard and Modified Conversion Loss Measurement Set-Up.

and the actual power absorbed by the crystal. This effect was significant for measurements at power levels below about 10 mW and under certain conditions could account for changes of about 1.5 dB in the conversion loss. This potential error along with the desire to make measurements with a variable dc bias led to the choice of the modified set-up of Figure 17(b).

A new 1N53 diode was chosen as a standard for comparison, and Figure 18 shows a family of conversion loss curves as a function of power level for this diode with the dc bias as a parameter. For bias levels exceeding 0.1 volt, the conversion loss of the 1N53 assumes its minimum value of 7.5 dB between 0 and + 5 dBm and rises slowly for power levels on either side of this range. This behavior is typical of point contact diodes and can be explained in terms of the tradeoff in power loss caused by the spreading resistance and the shunting effect of the barrier capacitance with increasing RF power. Ten 1N53's were tested with the new diode exhibiting the lowest conversion loss and the value of L_0 generally increasing with increasing deterioration in the I-V characteristics of the remaining units.

As one might expect from the measurement of their I-V characteristics, the conversion loss of the typical silicon "run-in" mixer was much worse that that of the 1N53 diode. A statistical evaluation was not attempted because of the relatively small number of junctions formed and the high probability of forming an obviously atypical junction. The emphasis was placed on achieving the minimum repeatable conversion loss for a given wafer by making a series of "run-ins" with all the parameters controlled as carefully as possible. Even with an extreme amount of care taken in making a "run-in" and an experienced technician in control, the results were not always consistent. On many occasions the I-V characteristics will look promising but the RF measurements will reveal a very high conversion loss with very poor tangential sensitivity. Often examination of the whisker under a microscope will reveal a bent or blunt point, but just as often the whisker point will be found in excellent condition. Figure 19 shows the results of conversion loss measurements on a typical silicon "run-in" mixer. These junctions were formed on a P-doped silicon wafer using a 1 mil tungsten whisker. The minimum conversion loss ranged from about 12 to 20 dB with 15 dB representing the most probable value. It was found generally that the lower conversion loss junctions were unstable and some would degenerate within a day's time. Junctions were also formed using a 5 mil tungsten whisker, allowing a much higher force to be applied to the contact. The minimum conversion loss of this mixer was about the same as for the mixer using the 1 mil whisker; however, as shown in Figure 20, the variation of conversion loss with RF power was considerably different.

Along with RF power level and dc bias, the minimum conversion loss is also a function of the load resistor R_L. Figure 21 shows the dependence of conversion loss on R_L for both the silicon and gallium-arsenide mixers at a fixed RF power level. These measurements reveal the optimum load resistance to be approximately 450 ohms for the silicon mixer and 900 ohms for the gallium-arsenide mixer.

The formation of point-contact junctions on gallium-arsenide yielded much better conversion losses than their silicon counterparts. Figure 22 shows a family of conversion loss curves obtained with a mixer whose junction

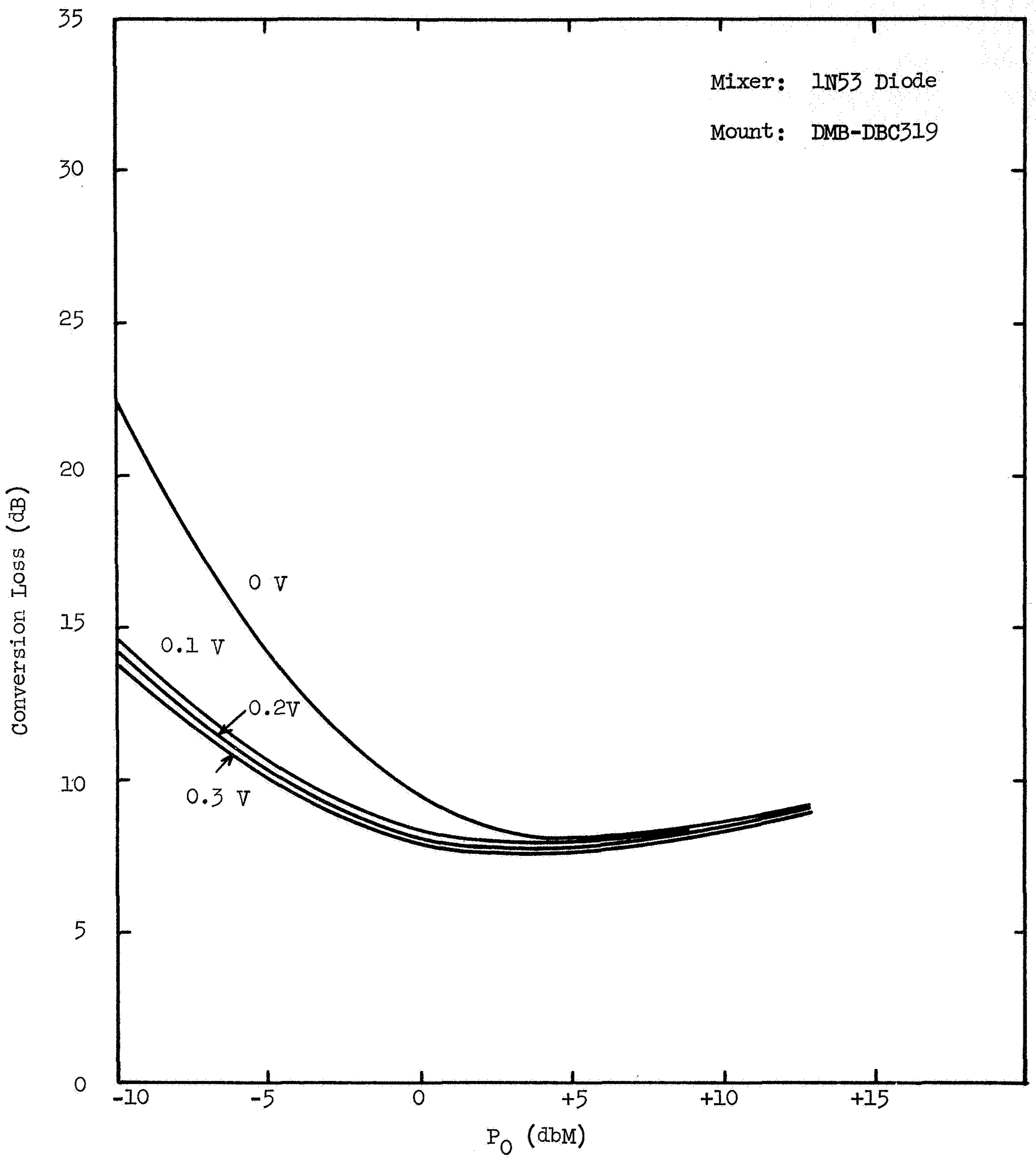


Figure 18. Conversion Loss as a Function of RF Power and DC Bias for a 1N53 Diode at 35 GHz.

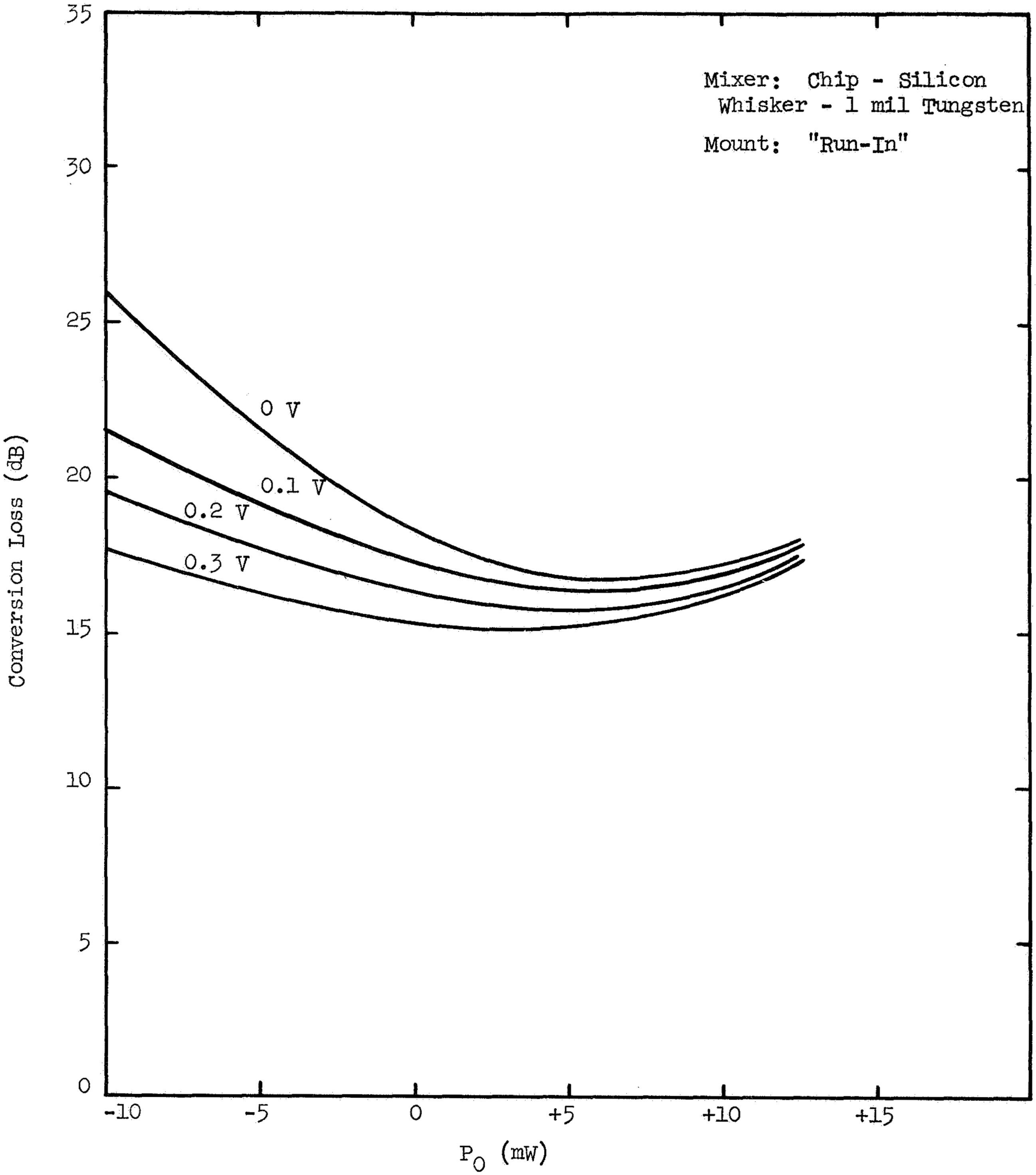


Figure 19. Conversion Loss as a Function of RF Power and DC Bias for a Silicon "Run-In" Mixer at 35 GHz.

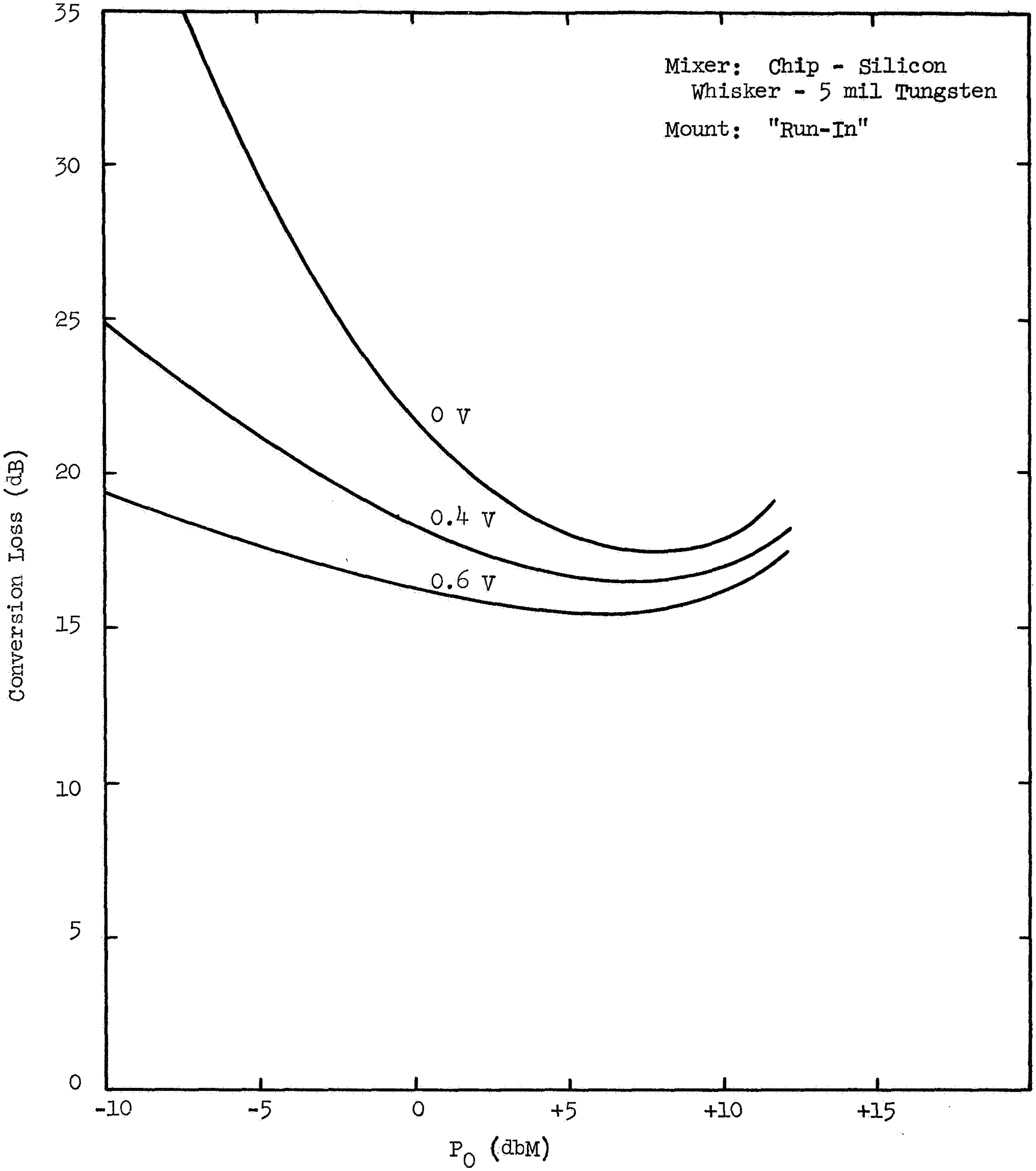


Figure 20. Conversion Loss of a Silicon "Run-In" Mixer Employing a 5 mil Tungsten Whisker at 35 GHz.

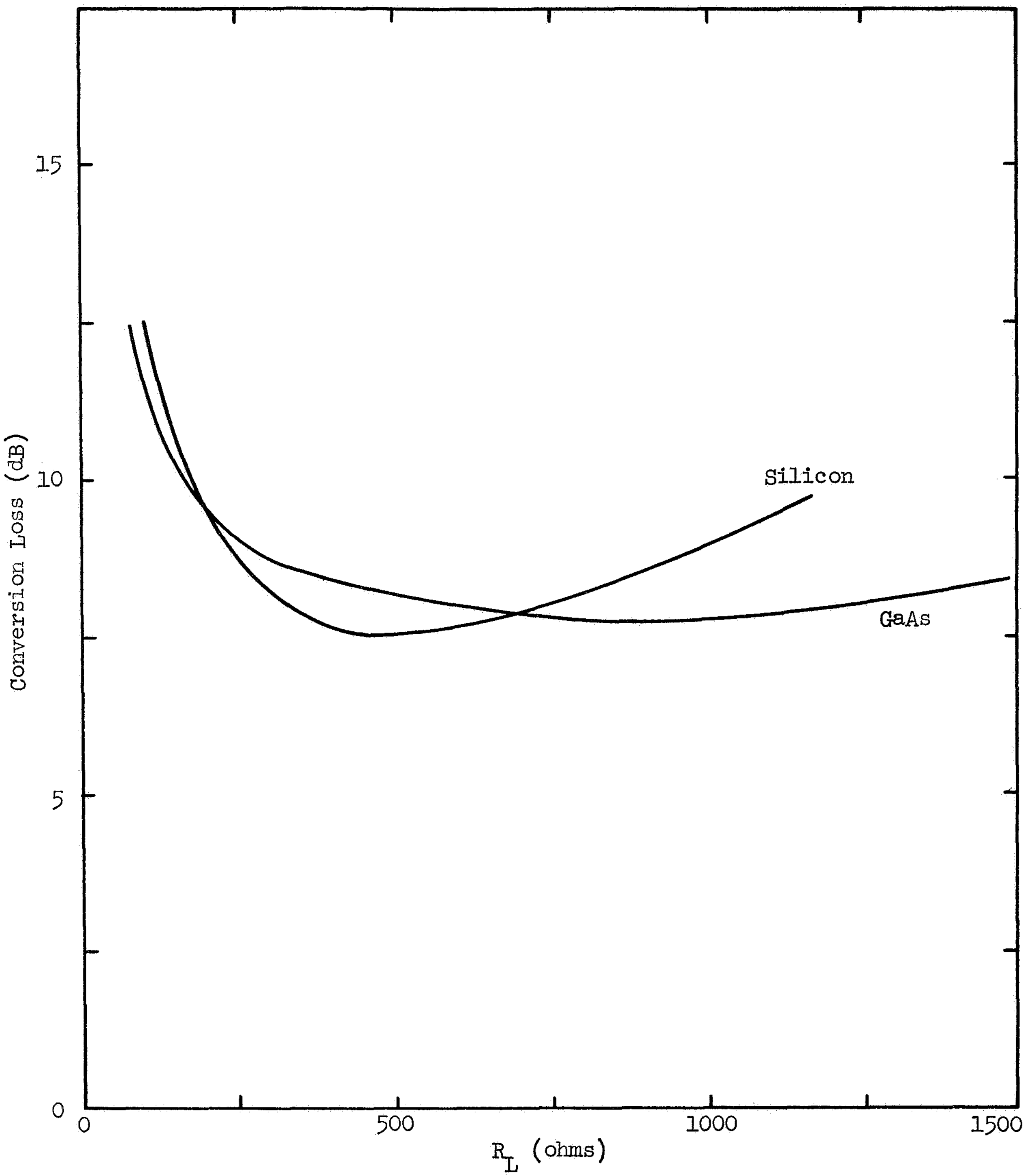


Figure 21. Conversion Loss as a Function of R_L for Silicon and Gallium-Arsenide "Run-In" Mixers.

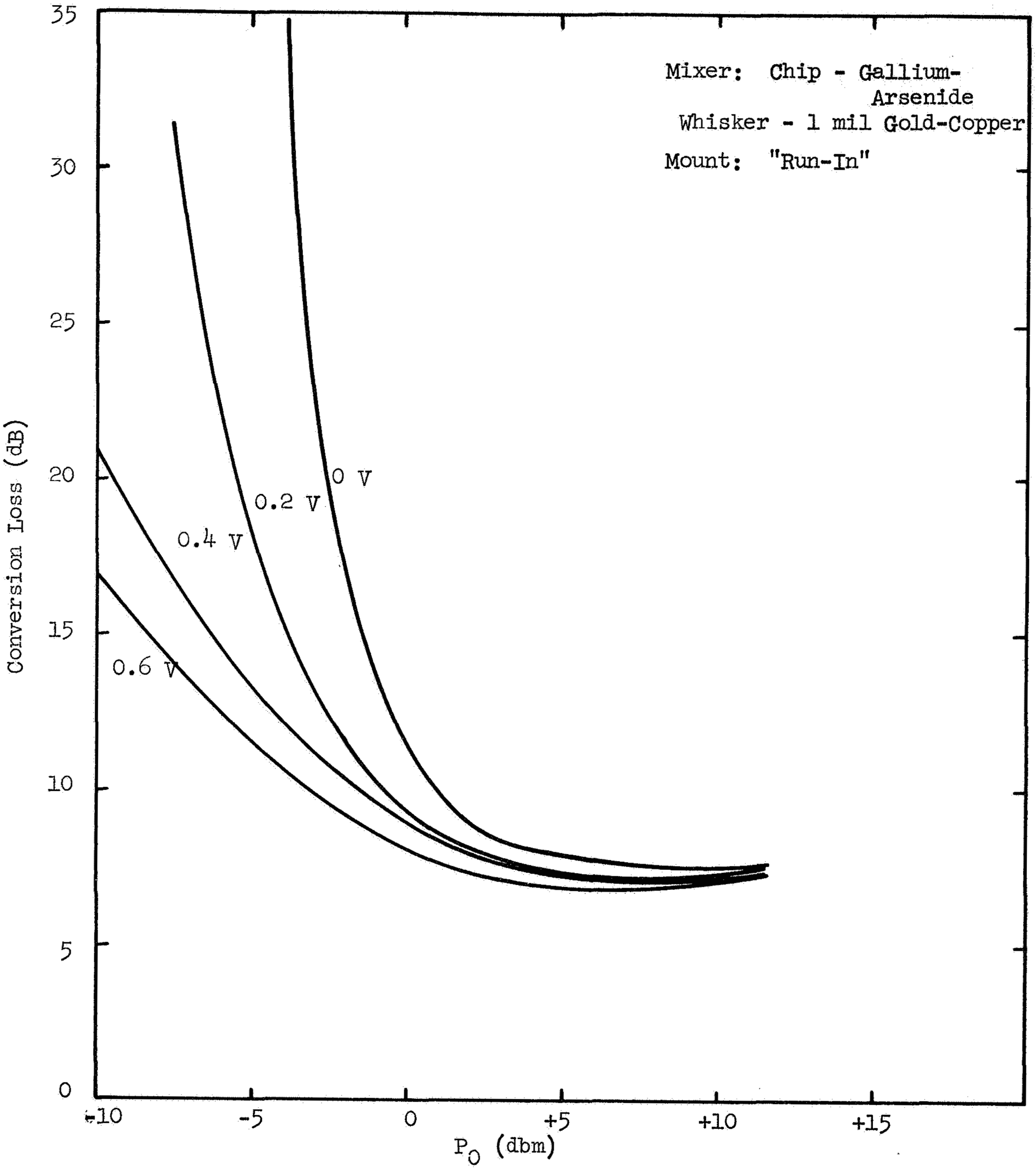


Figure 22. Conversion Loss as a Function of RF Power and DC Bias for a Gallium-Arsenide "Run-In" Mixer at 35 GHz.

was formed with a phosphor-bronze whisker on gallium-arsenide. The minimum conversion loss for this mixer was 7 dB and similar results were obtained with a gold-copper alloy whisker. The range of minimum conversion loss for the gallium-arsenide "run-in" mixer was about 7 to 10 dB with reproducibility much higher than the silicon mixer. It was also found that the gallium-arsenide mixer with low conversion loss was much more stable in terms of shelf life and reaction to mechanical shock probably because of the welding technique used to form the junction.

The conversion loss of the ion-bombarded silicon mixers fell, with one exception, in the same range as the unbombarded silicon mixers. Figures 23 through 26 show the conversion loss of those junctions whose I-V characteristics were shown in Figures 11 through 14. The minimum conversion loss of the 10 KeV mixer was about 10 dB and could be reproduced within ± 1 dB by forming junctions with similar I-V characteristics. Correlation of the conversion loss with several parameters derived from the I-V characteristics was attempted. The spreading resistance was examined because of its dependence on the junction area and conductivity. No meaningful correlation was found even between mixers whose bulk conductivity was identical. Since the spreading resistance is a function of the conductivity and junction area, one would expect to find some correlation between samples having the same conductivity. The junction capacitance is related to the conductivity by the expression

$$C = \frac{\pi a^2 (\epsilon q N)^{\frac{1}{2}}}{2(\Phi - V_s)^{\frac{1}{2}}} \tag{6}$$

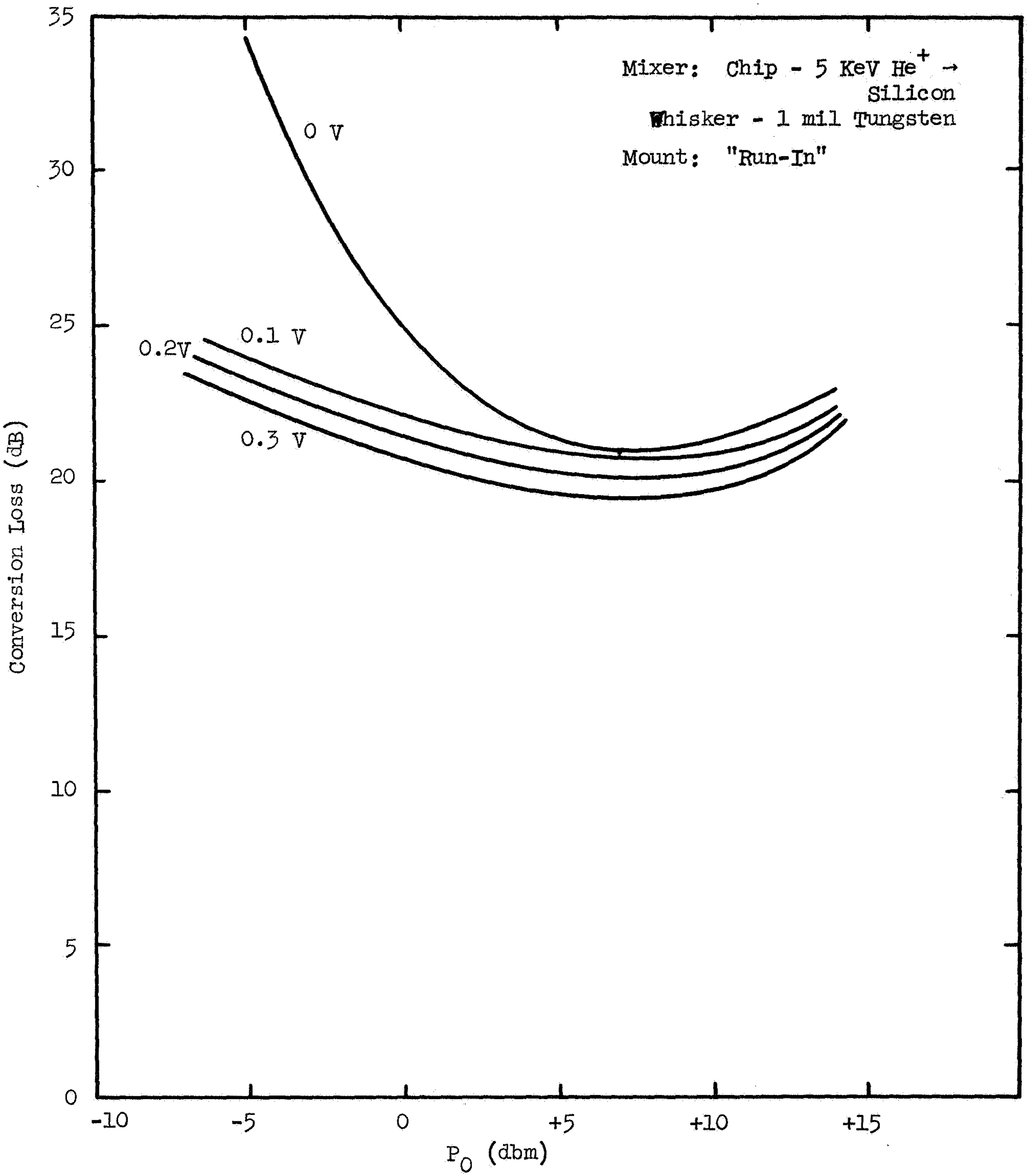


Figure 23. Conversion Loss of a "Run-In" Mixer Employing 5 KeV He^+ Bombarded Silicon.

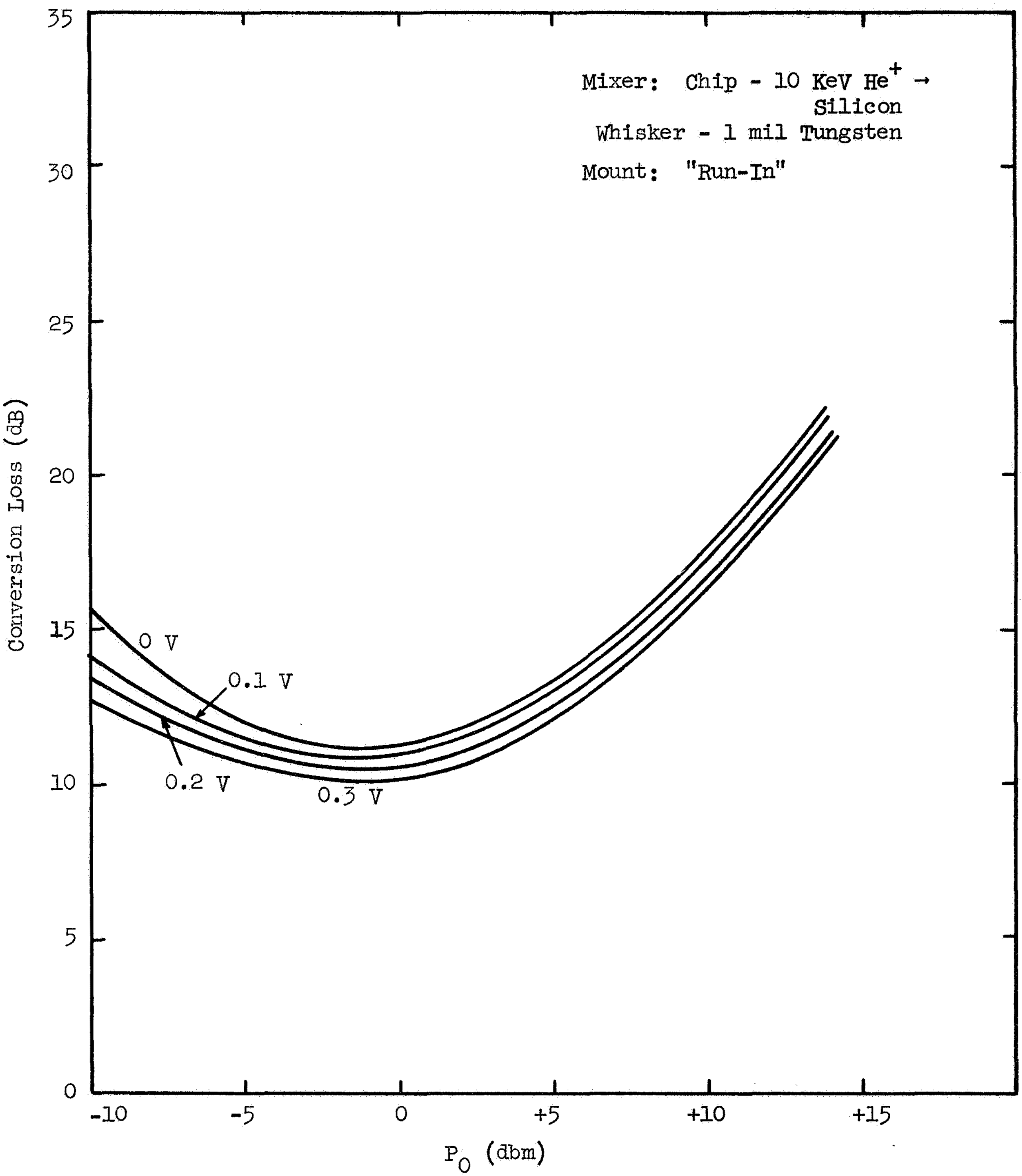


Figure 24. Conversion Loss of a "Run-In" Mixer Employing 10 KeV He$^+$ Bombarded Silicon.

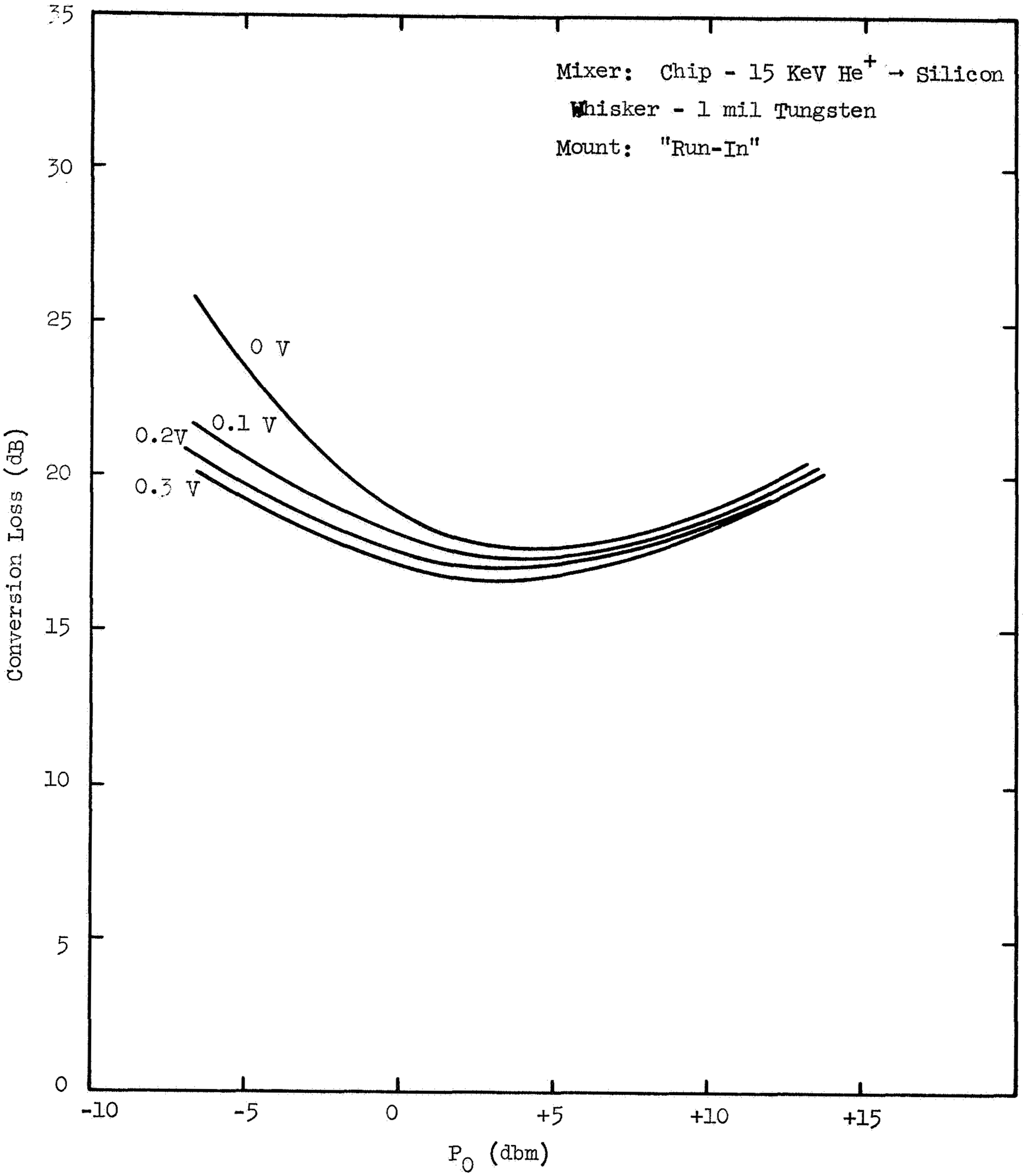


Figure 25. Conversion Loss of a "Run-In" Mixer Employing 15 KeV He^+ Bombarded Silicon.

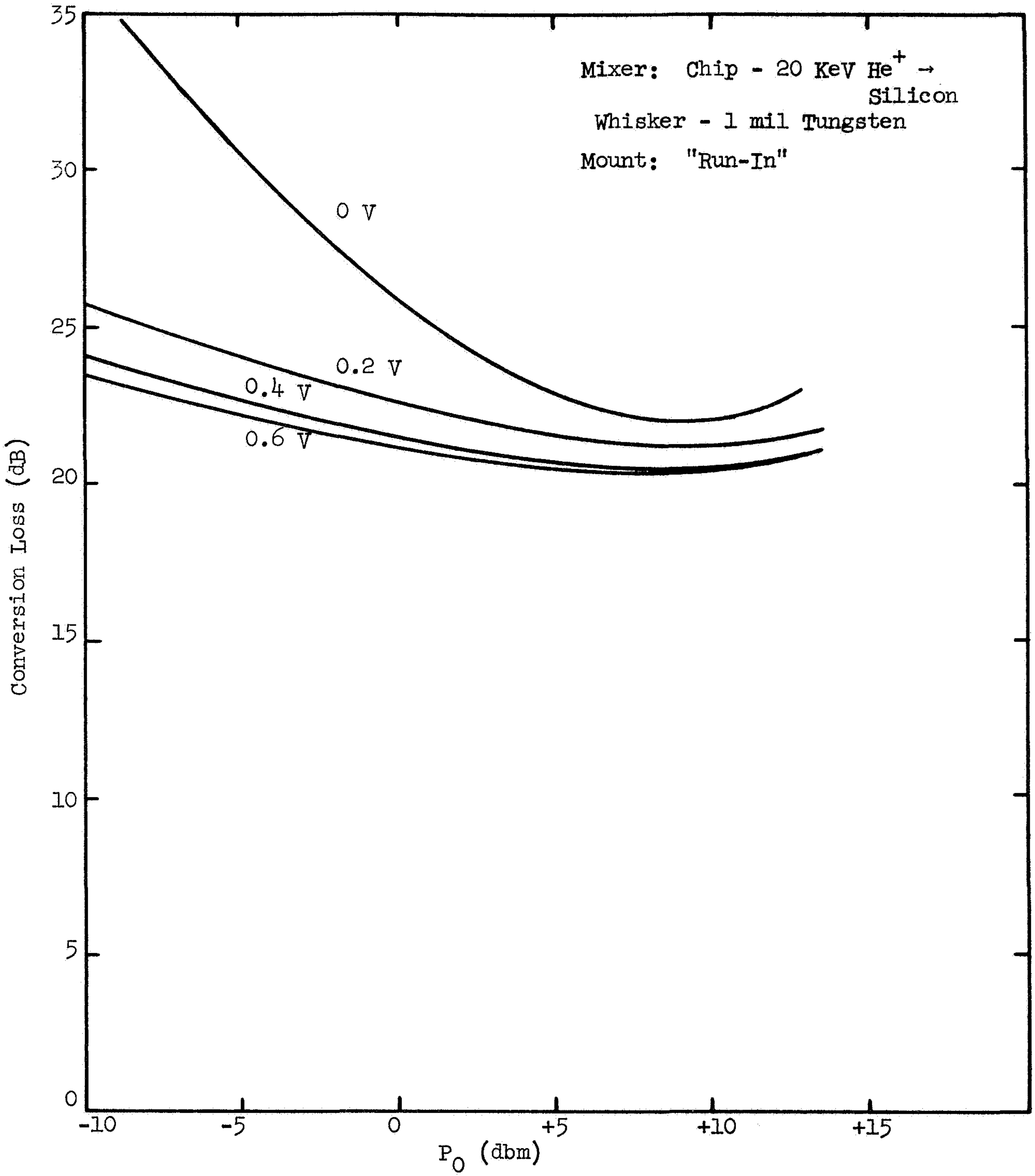


Figure 26. Conversion Loss of a "Run-In" Mixer Employing 20 KeV He^+ Bombarded Silicon.

and a commonly used figure of merit for mixer performance is

$$\frac{C r_s a \epsilon^{\frac{1}{2}}}{N^{\frac{1}{2}} b} \qquad (7)$$

where b is the carrier mobility, ϵ is the dielectric constant of the semiconductor materials, and the other symbols were defined in Section III. It is desirable to minimize equation (7) for optimum conversion loss bearing in mind that "a" must be chosen as a compromise between reducing the conversion loss and providing adequate burnout protection and stability. The fact that the spreading resistance of junctions formed from the same semiconductor material could not be used to predict a trend in conversion loss leads one again to the conclusion that the junction has been altered by surface contamination.

The ratio of forward to reverse junction current at a fixed junction voltage revealed a general trend although variations in the junction capacitance and spreading resistance undoubtedly prevented a direct correlation. Figure 27 shows the distribution of points on a graph of the ratio I_F/I_R as a function of conversion loss. It is important to note that junctions were formed with high I_F/I_R ratios and low conversion losses; however, no junctions were formed with low I_F/I_R ratios and low conversion losses. One is again led to the conclusion that the proper I-V characteristic with a sharp knee in the forward direction and a high back resistance is a necessary condition for achieving low conversion loss but by no means does it furnish a sufficient condition.

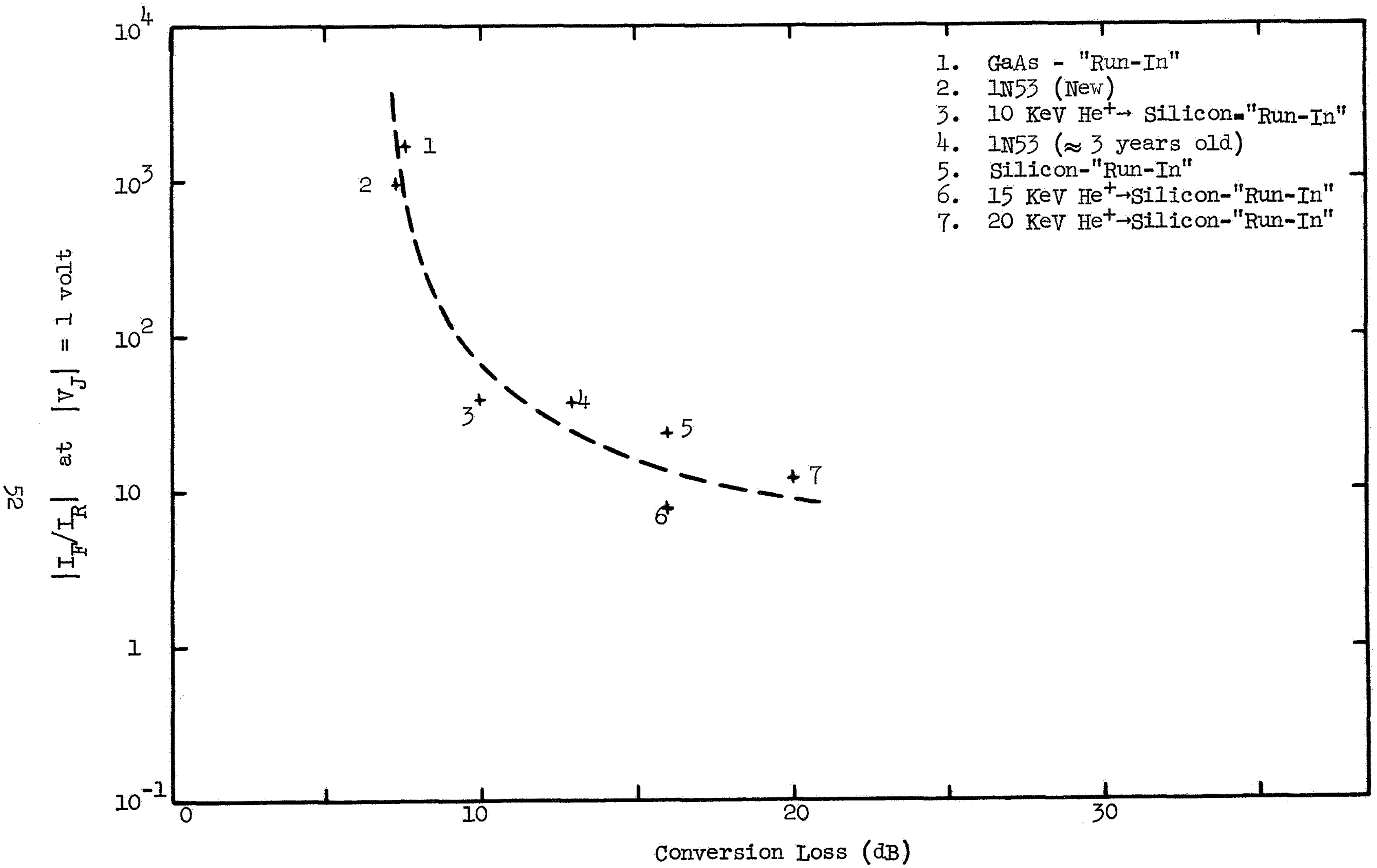


Figure 27. Conversion Loss as a Function of I_F/I_R for Cartridge and "Run-In" Mixers at 35 GHz.

VI. CONCLUSIONS

It has been demonstrated by this work and others preceding it that definite changes can be made in the rectifying properties of a point-contact diode by bombarding the semiconductor material with positive ions. The simplest explanation of the effects of ion bombardment are to consider the irradiated semiconductor to be an inhomogeneous substance with highly stable well defined layers of different conductivity. Petit[9] has shown that the proper use of the lower conductivity layer can result in an improved conversion loss at 70 GHz. His analysis reveals that one must be able to control both the thickness of the lower conductivity layer and the bulk conductivity of the semiconductor to achieve the desired result. It is also evident that the preparation of the semiconductor surface is critical to the formation of a good point-contact junction, particularly at the millimeter wavelengths.

As initially proposed, the major portion of this program was devoted to constructing an experimental facility to carry out the ion bombardment, and in making preliminary measurements to evaluate the performance of a millimeter wave mixer fabricated from the ion bombarded semiconductor. Progress was made in understanding the factors contributing to the formation of low conversion loss mixers and the enhancement of these factors by the process of ion bombardment. The measurements were preliminary in nature, and full use could not be made in this work of the effects of varying certain material parameters; however, the junctions formed on ion bombarded silicon were shown to have some promising characteristics. For example, the conversion loss of a mixer employing helium bombarded silicon was found to have the lowest conversion loss of any silicon junction formed during this work. The relative improvement shown by this mixer whose junction was formed on silicon bombarded by 10 KeV He^+ ions could be the result of several radically different phenomena. It has not yet been established whether the internal damage sites caused by the ion bombardment, the actual implanted ion, or the surface damage is the primary cause of the change in RF characteristics. In view of the improved I-V characteristic obtained for this mixer, it is possible that bombardment with low energy ions (1-10 KeV) might play a major role in surface cleaning by the sputtering process. The preliminary measurements also served to point up several changes in the semiconductor preparation techniques which will benefit future research. These changes would involve the operations of final surfacing and ion bombardment on the unmounted wafer instead of a premounted wafer.

A definitive answer to the question of whether ion-bombardment can be used to enhance conversion loss in the millimeter wave region will require very careful control and flexibility in preparing the semiconductor for use in the mixer. One should be able to specify accurately the dopant concentration and impurity levels in the semiconductor and be equipped to perform high temperature oxidation of the surface to expose the crystal lattice. In addition it would be desirable to have the capability of carrying out an annealing procedure simultaneously with the ion-bombardment. Heavier ions should be investigated to determine whether penetrability or momentum transfer is the most effective means of creating a stable well defined low conductivity layer. It is possible that conversion loss measurements made at higher frequencies will be more meaningful since the conversion loss would be more sensitive to the junction capacitance and hence the bulk conductivity in this region.

The measurements begun during this research effort should be pursued to the point of definitely establishing the value of ion bombardment as a possible technique for reducing the conversion loss of millimeter wave mixers. The promise of greatly increased stability for devices utilizing ion bombarded semiconductor material would in itself provide justification for further investigation.

VII. ACKNOWLEDGMENTS

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The modification and use of the ion source was made possible by the cooperation of Dr. E. W. Thomas of the School of Physics. The operation of the ion source and the ion beam analysis was performed under the guidance of Mr. R. L. Fitzwilson, also of the School of Physics.

Respectfully submitted,

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Approved:

A. P. Sheppard, Head
Special Techniques Branch

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