

FINAL REPORT
PROJECT A-1068-001

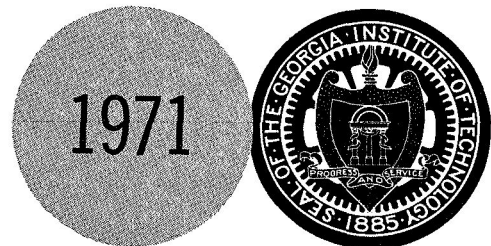
TECHNIQUES FOR REDUCING MIXER CONVERSION
LOSS IN MILLIMETER WAVE RECEIVERS FOR
COMMUNICATIONS AND RADIOMETRY

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ABSTRACT

The performance of point-contact mixers utilizing ion bombarded crystals has been investigated at 94 GHz. Calculations were made to evaluate the effects of parasitic impedances on the conversion loss of mixers utilizing p-type silicon and n-type gallium arsenide. These calculations have shown that a non-homogeneous crystal consisting of a high resistivity surface layer on a low resistivity chip can be employed to minimize the conversion loss of a millimeter wave mixer.

Ion bombardment was employed to form the low resistivity surface layer, and the conversion losses of mixers utilizing the non-homogeneous crystals were measured as a function of the ion bombardment parameters. It was found that a relative improvement of 5-15 dB in the conversion loss could be obtained for mixers formed on boron-doped silicon which had been annealed during the ion bombardment process. It was also found that rectifying junctions could only be formed on low carrier density aluminum- and boron-doped silicon which had been ion bombarded and annealed. No improvements in conversion loss were obtained for mixers formed on the ion-bombarded gallium-arsenide crystals.

The measured changes in DC and RF performance of the mixers are discussed in terms of the ion bombardment process. Effects of crystal surface preparation on the measurements are considered, and recommendations for further investigations are given.

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I. Introduction

Although millimeter wave component technology has advanced significantly during the last twenty years, the performance of millimeter wave detectors continues to lag behind that of detectors designed for operation in the microwave region. Typically, the conversion loss of a good millimeter wave mixer is about 5-7 dB higher than its microwave counterpart, and its stability and shelf life are reduced because of the high doping levels required for low conversion loss at millimeter wavelengths. Stability and shelf life have been improved in hermetically sealed point-contact mixers,^{1,2} and in Schottky barrier diodes³ with small area junctions; however, the mixer continues to be a restraining factor in the choice of a millimeter wave system.

The reasons for poor performance in the millimeter wave region center around the parasitic junction capacitance which is too large for proper impedance matching of the local oscillator when microwave mixer design criteria are employed. This limitation has been partially overcome by employing gallium arsenide, whose charge carrier mobility is large enough to compensate for the low doping level required for the proper junction capacitance. A suggestion for further improvement in mixer performance based on a two layer crystal structure has been advanced by Petit.⁴ The creation of a shallow layer of low carrier density on a highly doped crystal substrate by ion bombardment has been employed by Petit as a means of providing the proper values of junction capacitance with reduced conversion

loss in a silicon mixer at 70 GHz. His work provides a plausible explanation for the empirical results reported by Ohl^{5,6,7} showing improved performance of harmonic generators and video detectors fabricated with ion bombarded silicon.

The excellent stability of point defects created in a crystal by ion bombardment, and the inhibition of surface oxide growth on the higher resistivity surface layer should result in a long shelf life for mixers fabricated from ion bombarded materials. The promise of low conversion loss with increased lifetime provides a strong rationale for a thorough investigation of ion bombardment techniques.

The work reported herein concerns the investigation of ion bombardment as a means of preparing mixer crystals with low conversion loss and extended shelf life at the millimeter wavelengths. Included in the investigation was the preparation of mixer crystals by ion bombardment, the fabrication of point-contact mixers utilizing the ion bombarded crystals, and the measurement of their conversion losses at 94 GHz. This work is the extension of an earlier research program performed under Research Grant NGR-11-002-065,⁸ which was concerned with the performance of mixers fabricated with ion bombarded crystals at 35 GHz.

Although calculations were made to determine the ion beam parameters necessary to produce the optimum surface layer, the results are empirical since diagnostic equipment was not available for determining the density profile of ions in the implanted layer, or the resulting carrier density. The bombarded crystals were, however, annealed in an attempt to better understand the role of substitution and radiation damage in changing the bulk resistivity of semiconductors.

II. Design Consideration for Millimeter-Wave Mixers: Impedance

Matching and Conversion Loss of Metal-Semiconductor Junctions formed on Ion Bombarded Silicon and Gallium-Arsenide

A. The Effect of Junction Capacitance on Conversion Loss at 94 GHz

The conversion loss of a mixer operating at frequencies higher than X-band is a monotonically increasing function of the product of the barrier capacitance and spreading resistance⁹ ($C_b R_s$), although each can be made to predominate by adjusting the local oscillator drive level. Bauer et al.¹⁰ have shown that the minimum conversion loss is given by

$$L_c(\omega)_{\min} = L_o (1 + 2\omega C_b R_s) \quad (1)$$

where L_o is the conversion loss with zero spreading resistance, and the local oscillator drive level is adjusted so that the barrier resistance, $R_b = \frac{1}{\omega C_b}$. Thus, in general, it is desirable for $\omega C_b R_s < 1$ for minimum loss in a given mixer junction.

In a point-contact mixer junction, the parasitic impedance elements are related to the semiconductor characteristics and contact radius by

$$R_s = \frac{1}{4aNe\mu b} \quad , \quad (2)$$

and

$$C_b = \frac{\pi a^2}{2} \left[\frac{e e N}{\Phi_o - V} \right]^{\frac{1}{2}} \quad (3)$$

where

a = contact radius (cm),

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

e = electronic charge (1.6×10^{-19} coulomb),

b = carrier mobility ($\text{cm}^2\text{-volt}^{-1}\text{-sec}^{-1}$),

ϵ = dielectric constant (farad- cm^{-1}),

Φ_0 = junction potential barrier (volts),

V = junction voltage

It should be noted that, as a rule, some of the area under the whisker point does not conduct, and hence equations (1) and (2) represent lower and upper limits respectively on R_s and C_b .

Multiplying equations (1) and (2), the product $C_b R_s$ becomes, in terms of the junction parameters,

$$C_b R_s = \frac{\pi a}{8b} \left[\frac{\epsilon}{eN(\Phi_0 - V)} \right]^{\frac{1}{2}} \quad (4)$$

For operation at a frequency where the reactance of C_b can be ignored, the minimum conversion loss is found for the maximum value of $\frac{b}{a} \sqrt{\frac{N}{e}}$; however, in applying this criterion, one must remember that chance of burnout increases and mechanical strength of the junction decreases as (a) decreases. Since the width, W , of the rectifying junction is given by

$$W = \left[\frac{2\epsilon}{Ne} (\Phi_0 - V) \right]^{\frac{1}{2}}, \quad (5)$$

an upper limit on N is also determined for that value of W for which tunneling results in loss of rectification. Within these bounds, the minimum conversion loss may be determined for any semiconductor whose physical properties are known.

As the operating frequency is increased into the millimeter wavelength region, the reactance of C_b can no longer be ignored, and the criterion of minimizing the product $C_b R_s$ for low conversion loss must be carefully applied. For RF matching purposes, the maximum value of C_b is determined by the generator impedance, which from equation (3) also determines the maximum value of carrier density N . For a given contact radius, the upper limit on N sets a lower limit on R_s , and hence the conversion loss is essentially determined by the carrier mobility and dielectric constant of the semiconductor. From equations (2) and (3), it can be seen that a low value of dielectric constant and a high value of carrier mobility are desirable properties for a mixer crystal.

The effect of impedance matching requirements on millimeter wave mixer design can be shown by calculating $X_c = \frac{1}{\omega C_b}$ and R_s at a frequency of 94 GHz for various doping levels in the commonly used mixer crystals, silicon and gallium arsenide. These calculations are presented graphically for p-type silicon and n-type gallium arsenide in Figures 1 and 2. If we require, for example, a minimum generator impedance of 400 ohms for efficient local oscillator drive, the resulting values of R_s can be found from the intersection of the vertical lines drawn from the 400 ohm point on the X_c curves

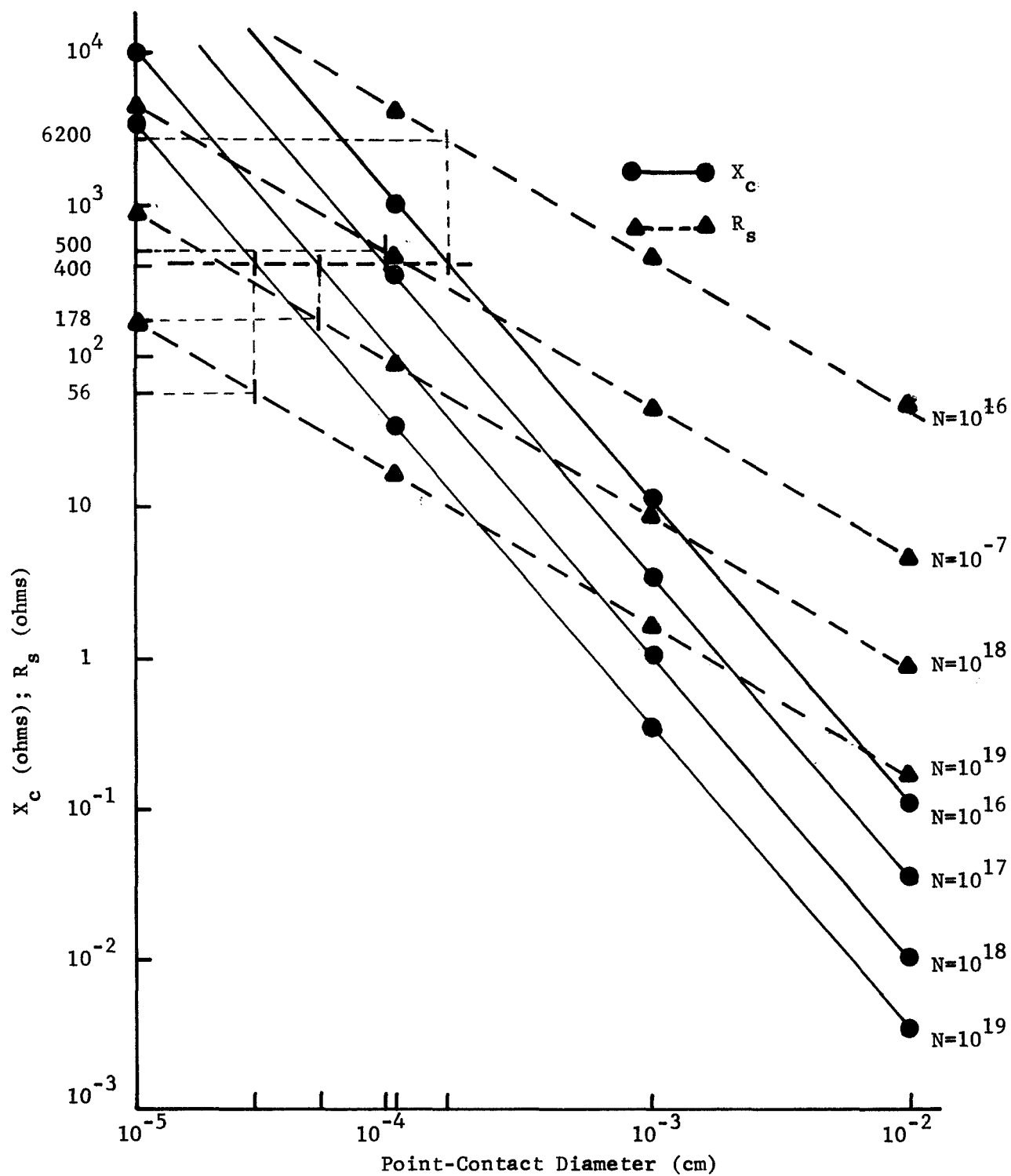


Figure 1. Barrier Reactance and Spreading Resistance of Boron-Doped Silicon Mixers.

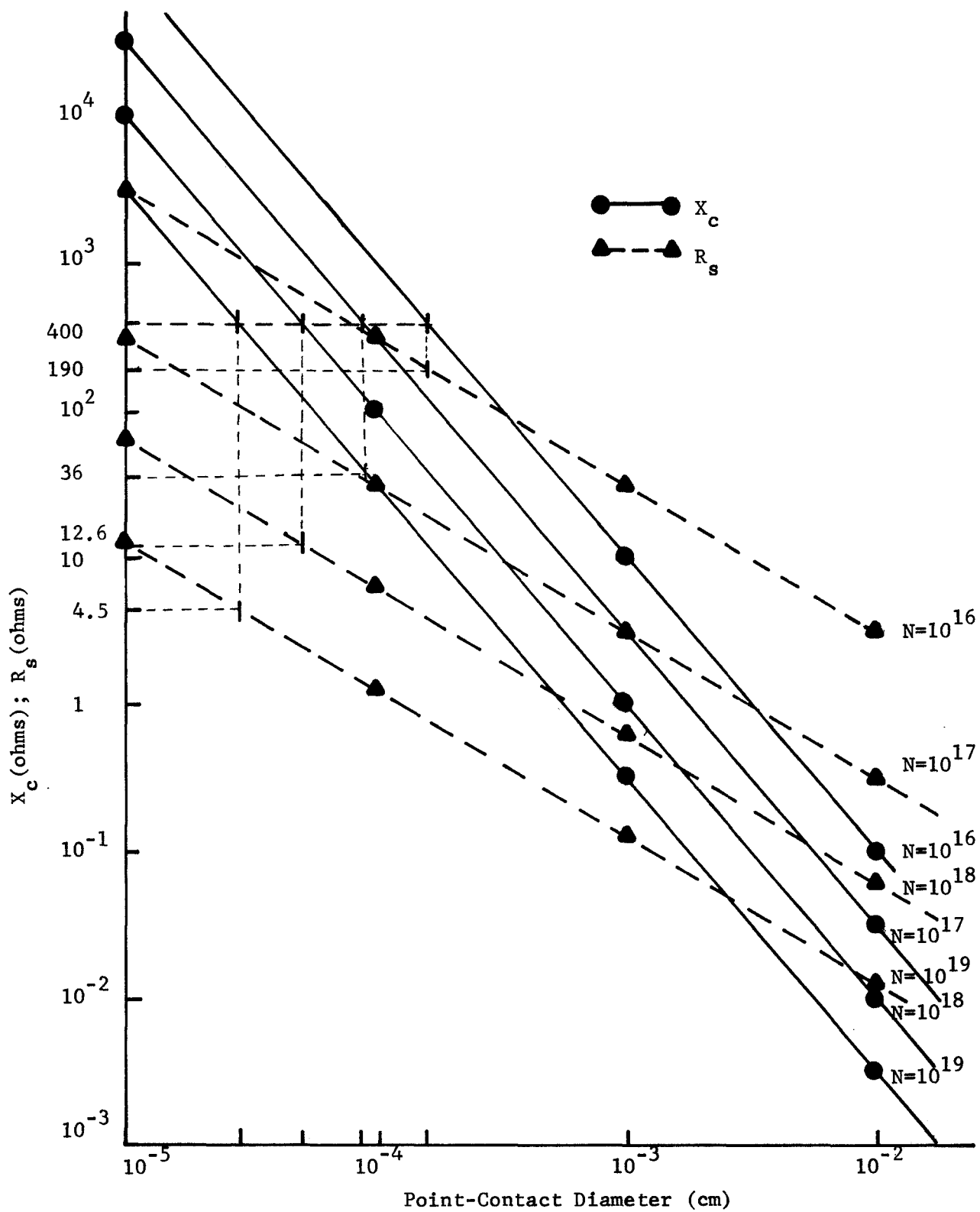


Figure 2. Barrier Reactance and Spreading Resistance of Tellurium-Doped Gallium Arsenide Mixers.

for corresponding values of N . The values of R_s , C_b , $\omega C_b R_s$, and the contact diameter, $2a$, are compiled in Table I.

Although the dependence of conversion loss on R_s and C_b is complicated by terms involving R_s alone and other involving the product $R_s C_b$, for a given value of C_b the losses always decrease with decreasing values of $\omega C_b R_s$, and in general, from equation (1), low values of conversion loss require that $\omega C_b R_s < 1$. If there were no restrictions on the contact diameter of the whisker, it can be seen from Table I that the criterion of $\omega C_b R_s < 1$ is achieved for $N > 10^{19}$ in silicon, and $N > 10^{17}$ in gallium arsenide. Since the onset of tunneling in p-type silicon occurs at $N = 5 \times 10^{18}$, and the minimum contact diameter is about 4×10^{-4} cm for adequate burnout protection,¹¹ it is hard to envision good mixer performance on silicon at 94 GHz. On the other hand, the calculations show that good performance should be possible with gallium arsenide, although some degree of burnout protection would be sacrificed for increased performance with highly doped crystals.

Table I. Calculated Values of R_s , C_b , and $\omega C_b R_s$ for a
Fixed Reactance $X_c = 400\Omega$ in Point-Contact
Silicon and Gallium Arsenide Mixers at 94 GHz

Crystal	$N(\text{cm}^{-3})$	$C_b(\text{fd.})$	$R_s(\Omega)$	$\omega C_b R_s$	$2a(\text{cm})$
Silicon	10^{16}	4.2×10^{-15}	6,200	15.5	3.1×10^{-4}
	10^{17}	"	500	1.25	1.9
	10^{18}	"	178	0.45	1.0
	10^{19}	"	56	0.14	0.6
Gallium Arsenide	10^{16}	"	190	0.48	3.1×10^{-4}
	10^{17}	"	36	0.09	1.7
	10^{18}	"	12.6	0.03	1.0
	10^{19}	"	4.5	0.01	.6

B. The Conversion Loss of Non-Homogeneous Crystal Mixers at 94 GHz

Petit⁴ has shown that conversion losses of 9 to 12 dB can be obtained with a point contact mixer fabricated on non-homogeneous silicon at 75 GHz. His mixer utilizes a silicon wafer with a high value of bulk carrier density N_B ($\sim 10^{19} \text{ cm}^{-3}$) and a low value of surface carrier density N_S ($\sim 10^{17} \text{ cm}^{-3}$), which is created by ion bombardment of the surface with low energy helium ions. For low conversion loss with the two layer crystal, Petit applies the criterion

$$\omega C_b R_d < 1 \quad (6)$$

where
$$R_d = \frac{\rho_S W}{\pi a} + \frac{\rho_B}{4a} \quad , \quad (7)$$

ρ_S = surface resistivity (ohm-cm),

ρ_B = bulk resistivity (ohm-cm),

and W is given by equation (5). The total series resistance in equation (7) consists of a cylindrical term within the surface layer, and a spreading term within the highly doped zone. If we have assumed that the space charge is limited to the surface region, the barrier capacitance may be expressed as

$$C_b = \frac{\epsilon \pi a^2}{W} \quad , \quad (8)$$

and using equations (5), (7), and (8), the product $\omega C_b R_d$ becomes

$$\omega C_b R_d = \omega \left[\frac{\epsilon^2 \pi^2 a^4}{2 b_s C_b} + \frac{\rho_B C_b}{4a} \right] \quad , \quad (9)$$

where b_s is the mobility of the surface layer.

The significance of equation (9) is that the creation of a higher resistivity surface layer on a low resistivity crystal results in a minimum in $\omega C_b R_d$ for a value of the contact radius which depends on C_b and the crystal parameters. The surface layer is used to establish the proper value of C_b for matching into the local oscillator while the highly doped bulk regions tends to keep the series resistance low. The contact radius $a_{\min}$ which results in a minimum for $\omega C_b R_d$ is found by differentiating equation (8) to be:

$$a_{\min} = \left[\frac{4b_s C^3 \rho_B}{\epsilon \pi^2} \right]^{1/5} \quad (10)$$

The depth of the surface layer is then calculated from

$$W = \frac{\epsilon \pi a_{\min}^2}{4C_b} \quad , \quad (11)$$

and the carrier density of the substrate is determined by applying equation (5) with the result:

$$N_s = \frac{4C_b^2}{\epsilon \pi^2 a_{\min}^4} \quad , \quad (12)$$

where $(\Phi_0 - V)$ has been set equal to unity for this calculation.

Calculated parameters for non-homogeneous point-contact mixers are presented in Table 2. These calculations, which were performed for $X_c = 400\Omega$ at 94 GHz, show that the required reactance is achieved in the surface layer

Table 2. Calculated Parameters for Non-Homogeneous Crystal

Mixers with $X_c = 400\Omega$ at 94 GHz

Crystal	N_b (cm ⁻³)	$2a_{\min}$ (cm)	$W(\text{\AA})$	N_s (cm ⁻³)	$R_d(\Omega)$	$\omega C_b R_d$	V_c (volts)
Silicon	10^{17}	5.56×10^{-4}	1,585	7.1×10^{15}	305	0.76	3.07
	10^{18}	4.04×10^{-4}	810	2.5×10^{16}	84	0.22	1.62
	10^{19}	2.90×10^{-4}	420	9.5×10^{16}	22	0.04	0.84
Gallium Arsenide	10^{17}	9.08×10^{-4}	3,240	1.3×10^{15}	68	0.17	6.48
	10^{18}	6.58×10^{-4}	1,702	4.6×10^{15}	19	0.05	3.40
	10^{19}	4.74×10^{-4}	883	1.7×10^{16}	2.2	0.006	1.77

with a significantly larger contact diameter than is possible for the homogeneous geometry, and hence the product $\omega C_b R_d$ is smaller for the same doping level. It would appear from these calculations that reasonably low loss mixers could be formed on silicon with doping levels between 10^{17} and 10^{18} , while it should be possible to form very low loss mixers on gallium arsenide in the same doping range.

It should be noted, however, that the thickness of the surface layer could result in electrical breakdown with high local oscillator drive levels. Assuming a dielectric strength of 20×10^6 V/m for both crystals, the breakdown voltage, V_c , is shown for each doping level in Table 2. An inverse voltage of about 2V would be just sufficient to withstand local oscillator drive levels up to 10 mW, and hence an adequate margin of safety might require operation at a thickness other than that which gives the minimum value of the product $\omega C_b R_d$ in silicon.

Determination of the ion beam parameters for creation of the desired surface layer is not as simple as for the preceding calculations. The depth of penetration of the ion is dependent on the type of material, its orientation and surface state, the energy of the ion, and the ion species. Gibbons¹² has shown that the depth of penetration is significantly increased if the crystal is oriented so that the ion beam impinges along a crystal axis. For example, data from Gibbon's experiments have been plotted in Figure 3 and show that the projected range for light ions begins to show much greater penetration in the channeled direction. Since the lower limit of Gibbon's data is mass number 10, however, there is considerable uncertainty involved in extending the curves to determine the depth of penetration for helium.

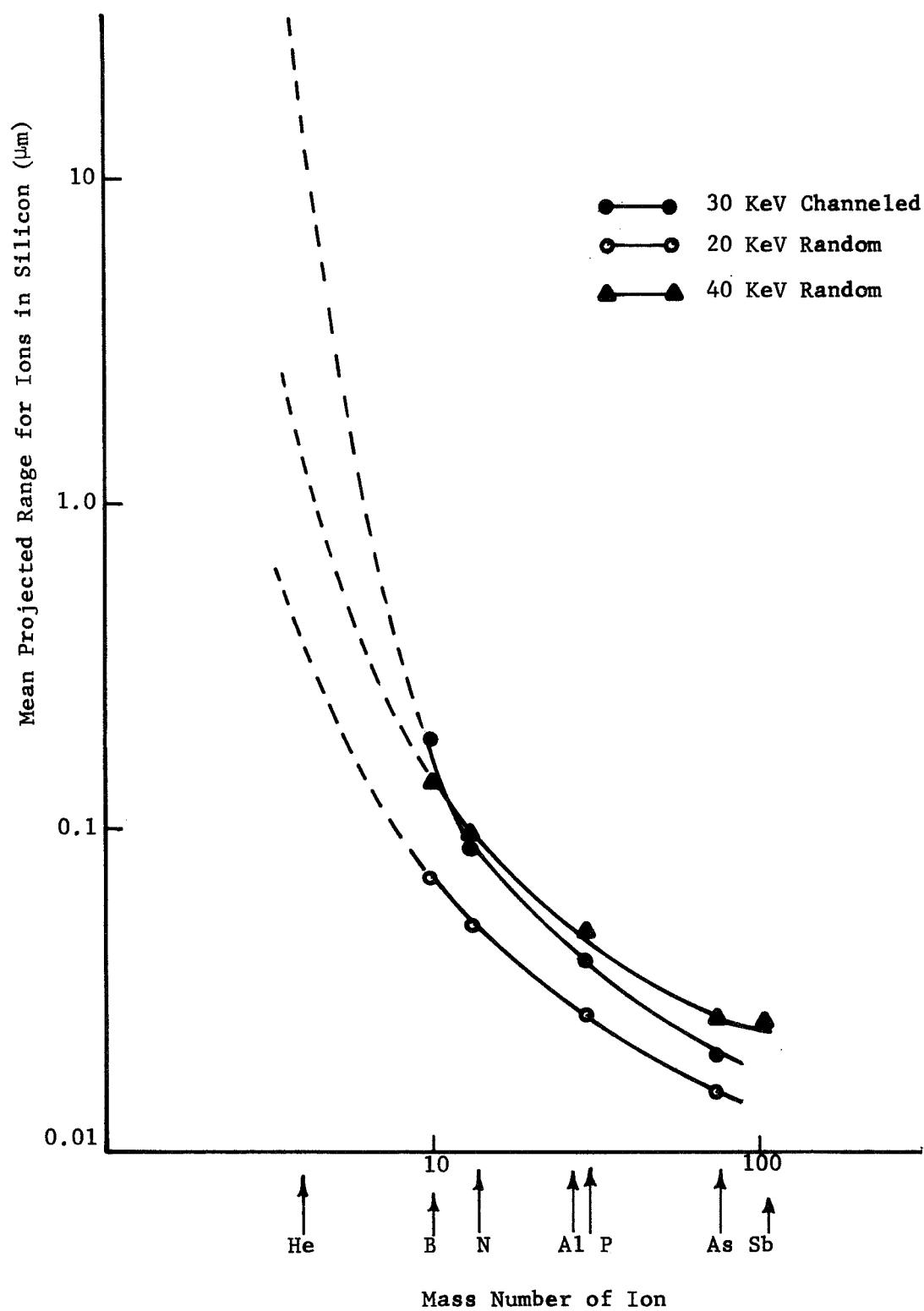


Figure 3. Depth of Penetration of Ions in Silicon.

The ion energies employed in this study were based on the empirical results of Ohl's⁷ experiments which, from the projections in Figure 1, would cover a range of approximately 500 - 13,000 Å.

The number of ions necessary to create the desired surface resistivity is difficult to estimate. The dominant physical mechanism responsible for the increase in resistivity is the decrease in carrier mobility resulting from scattering by the damage sites which are caused by the implanted ions. Although there is also some carrier neutralization caused by trapping of electrons at the interstitial ion locations, an order of magnitude calculation shows that this effect is small. For example, the number of charge carriers which must be removed from the surface layer is given by $(N_B - N_S)V_s$, where N_S represents the carrier density of the surface layer corresponding to a resistivity ρ_s , and V_s is the product of the surface area under ion bombardment and the depth of penetration of the ions. We shall assume that the profile of the ion distribution in the surface layer is constant, and that each implanted ion results in the removal of one charge carrier. The last assumption depends on the temperature of the crystal during bombardment since it is possible to anneal most of the damage sites above 300°C. As a specific example, from Table 2, the minimum number of ions necessary to reduce the carrier density in gallium arsenide from 10^{18} to 4.6×10^{15} in a surface layer of 1702 Å depth is approximately 10^{13} which represents a total charge of 1.6μ coulombs. It was found, however, during the course of this research program that a total charge several orders of magnitude greater than the calculated values were required to produce any measurable changes in the RF or DC properties of the mixer.

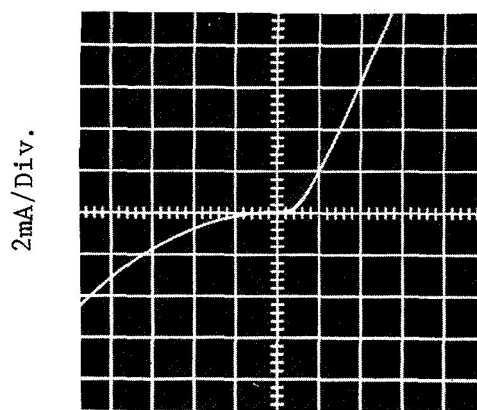
Thus the decrease in mobility caused by implantation sites is easily the larger effect.

Ohl⁷ has shown that the effects of ion bombardment on the I-V junction characteristic reach a saturation point when the ion flux is such that approximately one ion is incident on the surface for each unit cell. Using this empirical result as an upper limit, there is a range of about two orders of magnitude between the threshold for observable effects and saturation of these effects. This range was experimentally investigated during this study, and the desired improvements in conversion loss were found to be obtained for values of ion flux near the saturation point.

III. DC Characteristics of Mixer Junctions Formed on Silicon and Gallium Arsenide

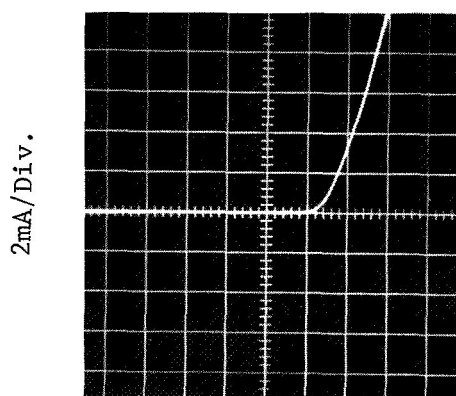
A standard "run-in" mixer similar to that described by Wentworth, et al.¹ was employed in fabrication of the test junctions. Experience gained in forming mixer junctions at 35 GHz has shown that a proper DC rectification characteristic is a necessary but not sufficient condition for good RF performance. The desirable properties of the DC characteristic are a low reverse current and large reverse breakdown, a sharp breakpoint or "knee" in the forward direction, and a low forward resistance. A transistor curve tracer is used to monitor the I-V characteristic while the junction is being formed, with the desired characteristic serving as an indication of successful ohmic contact between the pointed whisker and the surface of the semiconductor chip. This method is not, however, foolproof. Since the spreading resistance is inversely proportional to the contact diameter, and the junction capacitance is proportional to the square of the contact diameter, mixer junctions with large contact diameters resulting in good I-V characteristics and very poor RF performance are easily formed. Typical I-V curves for tungsten on aluminum-doped silicon and gold-copper on tellurium-doped gallium arsenide are shown in Figure 4. These characteristics are compared with junctions formed on ion-bombarded silicon and gallium arsenide in Section V.

A detailed description of the forming techniques for point contact junctions on silicon and gallium arsenide was presented in the final report on Research Grant NGR-11-002-065 (FR-I).⁸ Tungsten whiskers were employed



0.5 V/Div.

(a) Tungsten-Silicon Junction



0.5 V/Div.

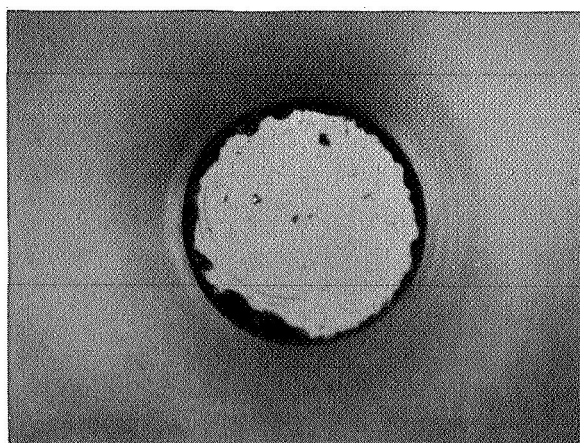
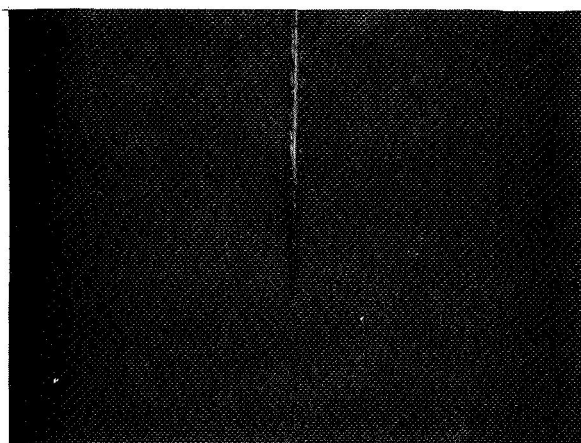
(b) Gold-Copper-Gallium Arsenide Junction

Figure 4. Typical I-V Characteristics of Silicon and Gallium Arsenide Mixer Junctions

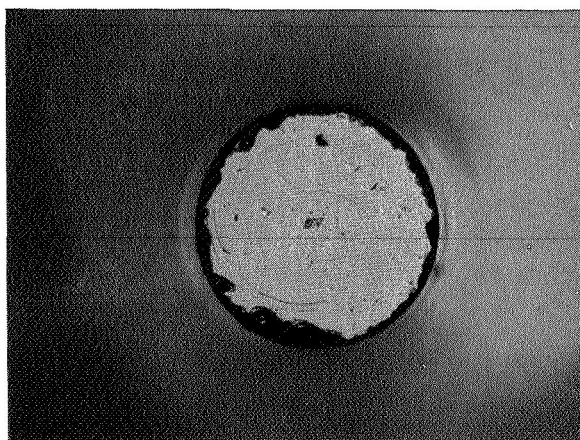
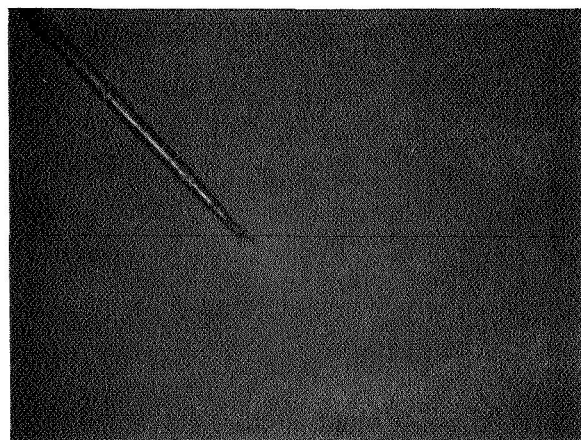
with silicon while gold-copper alloy and phosphor bronze whiskers were used with gallium arsenide. The whiskers were pointed electrolytically, and a combination of mechanical and chemical techniques were employed to prepare the crystal surface. The semiconductor wafers were etched before ion bombardment and immediately before forming the point-contact junction to remove the surface oxidation and ion damaged layers. The chemicals used and the immersion times involved in the pointing and etching processes were given in reference 8 (hereafter referred to as FR-1).

Instead of attempting to correlate the measured conversion loss of the junction with the constants A and α of the I-V characteristic as was done in the previous study, the I-V characteristics on the subject work were used primarily as a means of estimating the contact diameter of the formed junction. This approach was taken because of the questionable correlation of these parameters to conversion loss observed in the previous work at 35 GHz, and because of the increased sensitivity of the conversion loss to the junction capacitance at 94 GHz.

A microscope with calibrated reticle and movable stage was used to examine the whisker and crystal surface before and after formation of the junction. A typical set of "before" and "after" photomicrographs for tungsten-silicon and gold-copper-gallium arsenide junctions are shown in Figures 5 and 6 respectively. Using a high power objective and the calibrated reticle, the radii of the whisker points were found to be 2.5×10^{-4} and 1.5×10^{-4} cm before, and 6×10^{-4} and 6×10^{-4} cm after contact, respectively, for silicon and gallium arsenide.

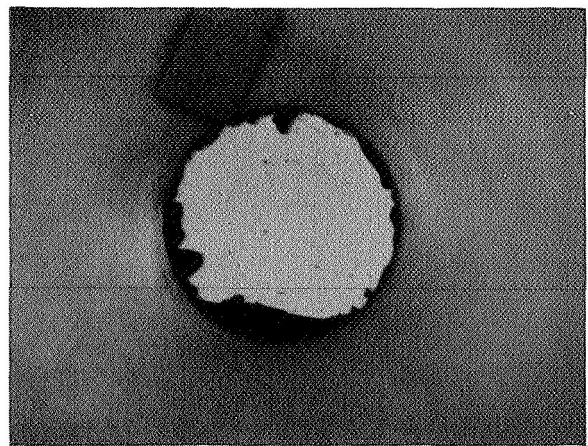
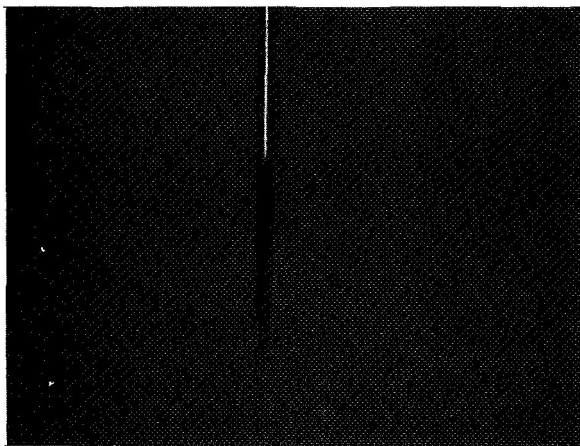


(a) before contact

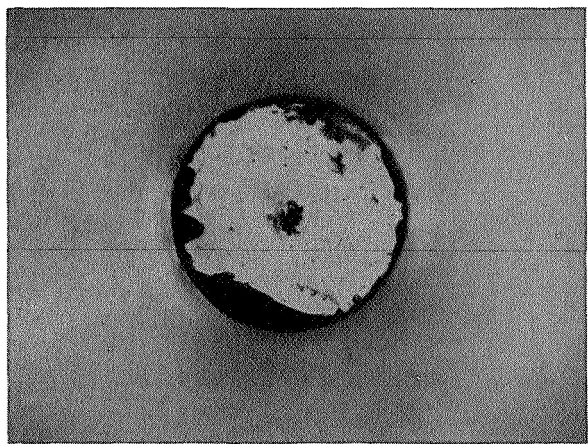
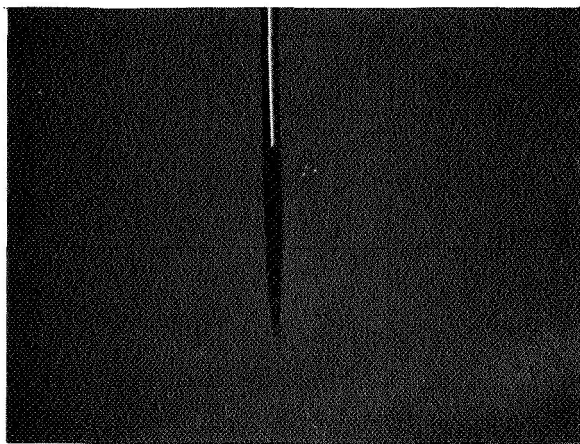


(b) after contact

Figure 5. Photomicrographs of Tungsten-Silicon Junction Elements Before and After Contact.



(a) before contact



(b) after contact

Figure 6. Photomicrographs of Gold-Copper-Gallium Arsenide Junction Elements Before and After Contact.

Note that the tungsten whisker appears to have more residue attached to its point after contact than the gold-copper whisker, although the disturbed spot on the silicon crystal surface is smaller than that on the gallium arsenide surface. Viewed obliquely, very little difference was observed in the depth of the disturbed spots on either crystal surface. Instead, the spots would appear to be very fine scratches that could result from the pointed whisker tracing out a pattern while skidding across the crystal surface. This hypothesis is very reasonable for the tungsten-silicon mixer whose junction is formed by advancing the crystal surface against the whisker until the proper DC characteristics are obtained. If the whisker is not exactly perpendicular to the crystal surface, it is possible for the whisker point to skid along the surface until some irregularity in the surface results in penetration. This reasoning, however, would not seem applicable to the gold-copper-gallium arsenide mixer whose junction is welded by applying a current pulse in the forward direction through the junction as soon as ohmic contact is made.

Many junctions were examined, and good RF performance was consistently associated with the pattern of surface disturbance shown in Figure 5. Examination of junctions with good DC characteristics and poor RF performance almost always revealed a large contact radius and, consequently, a large junction capacitance, while junctions with poor DC characteristic usually were a result of severe damage such as cracking or pitting of the crystal surface. Occasionally, a tungsten whisker tip would bend or a gold-copper whisker tip would burn off during the formation of the junction, but these occurrences were readily detected without microscopic examination.

To remove surface oxides, etching of both the crystal surface and the whisker immediately before forming the junction was found to be absolutely essential in creating a good mixer. An aqueous solution of 50 percent hydrofluoric acid was used to etch the silicon crystal and the whiskers, while an aqueous solution of 17 percent hydrofluoric plus 50 percent nitric acid was found to produce the best results with gallium arsenide. Etching times of 2 minutes for silicon and 30 seconds for gallium arsenide produced good results when followed with a thorough wash in water and methyl alcohol. The methyl alcohol is thought to be weakly bonded to the crystal thus inhibiting formation of oxides.

It was found that etched and polished crystal surfaces which had been exposed to air for a period of several months required repolishing before a satisfactory junction could be formed. This effect was more noticeable in the highly doped crystals which tend to form surface oxides much quicker than do the lower doped crystals. Both whisker and crystal should be stored in an evacuated environment or in a dessicator cabinet, if possible, to prevent rapid deterioration of surfaces.

During the two-year program, several hundred mixer junctions were formed, and while the yield of acceptable mixers was greatly improved, no uniform procedures could be found which guaranteed results. It has been suggested by Ohl⁷ that repeatable junctions can only be formed on surfaces where the mechanical damage incurred in the grinding and polishing steps has been oxidized and removed by chemical etching. The mechanically disturbed layer which is about $1000\text{\AA}$ deep can be removed by a fifteen-minute

exposure to steam at 1000° C; however, the necessary equipment for performing this procedure was not available during this research program. Successive run-ins on the same crystal produced wide variations in RF performance; however, the minimum conversion loss for a particular whisker and crystal could be repeated if enough junctions were formed. Since the goal of this program was to obtain comparative performance for crystal materials which were altered by ion bombardment, the minimum conversion loss junction was chosen in each case as the basis of comparison.

IV. Modification of the Ion Bombardment Apparatus for

Beam Purity and Annealing of the Ion Bombarded Crystals

The ion generator and sample chamber employed in this program have been previously described in FR-1. Two major modifications to the ion bombardment apparatus were undertaken for the present work. The first modification involved the addition of a complementary beam port to provide for mass selection of the desired He^+ ions, while the second modification was performed on the sample holder to provide for annealing of the sample during bombardment.

A. Modified Ion Generator

A diagram of the modified ion bombardment apparatus illustrating the location of the complementary beam port and the analyzer port is shown in Figure 7. Note that the axes of the analyzer port and the complementary port are at the same angle with respect to the ion generator axis. The beam spectrum is measured at the analyzer port, and the magnetic current corresponding to the He^+ ion beam is established. The direction of current through the magnet is then reversed, and the previously established value of magnet current is employed to direct the He^+ beam along the axis of the complementary port.

The method used to control the total charge incident on the sample during bombardment was also changed for the present work. Previously, the total charge was approximately determined by measuring the ion current and manually controlling the time between opening and closing of the valve

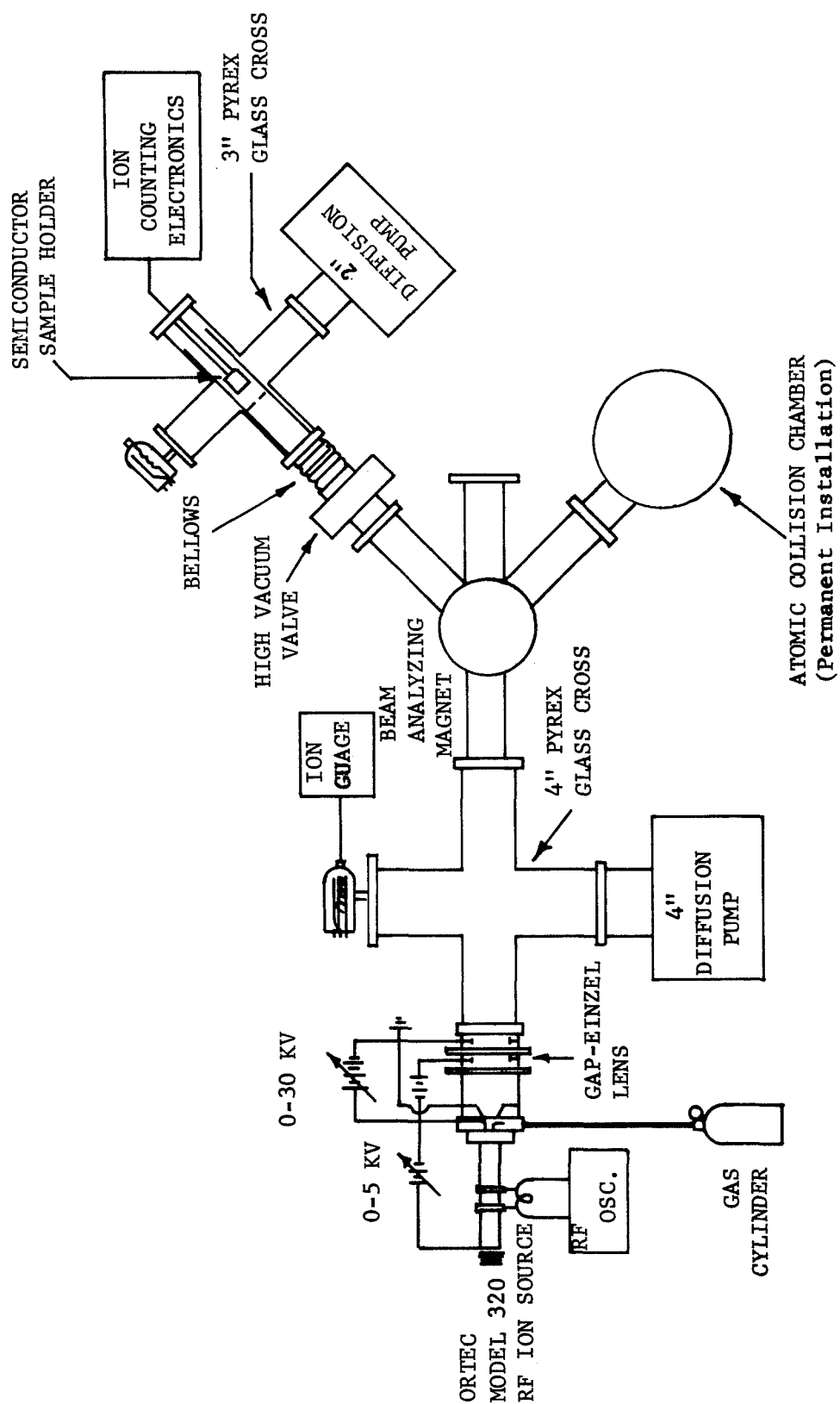


Figure 7. Modified Ion Bombardment Apparatus with Complementary Beam Port.

between the sample chamber and ion beam port. Since it takes about 3 seconds to open or close the valve, and the exposure time for the desired current and total charge is in the range of 20-25 seconds, an error in charge estimation of about 15 percent can be expected using this technique.

A voltage to frequency converter and a scaler preset to the desired charge was employed in the present work to integrate the ion current falling on the sample and cut the ion generator off when the preset charge level was reached. Figure 8 shows a block diagram of the modified system which measures the ion current, total charge, and elapsed time for the bombardment.

B. Modified Sample Holder for Annealing Studies

The sample holder used in the previous work employed a target cup which would accept the post mounted mixer crystals and permit simultaneous bombardment of four posts. It did not, however, have any provisions for temperature control of the sample during bombardment. Since there was danger in diffusing some of the bonding compound into the crystal at the annealing temperature, unmounted crystal wafers were obtained for the subject research program.

The target cup was redesigned to permit heat transfer to the crystal wafers of varying sizes with minimum sputtering from the mounting block. A photograph of the resulting assembly is shown in Figure 9(a). The original sample holder with one of its mounting plates removed is shown for comparison in Figure 9(b). Note the size of the semiconductor wafer in Figure 9(a) as compared to the post-mounted semiconductor chip in Figure 9(b). A stainless

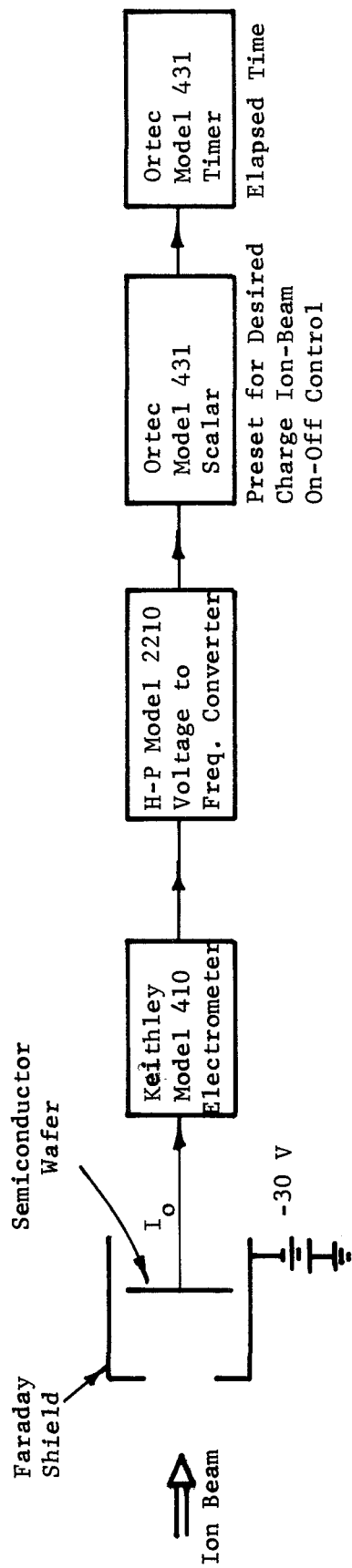
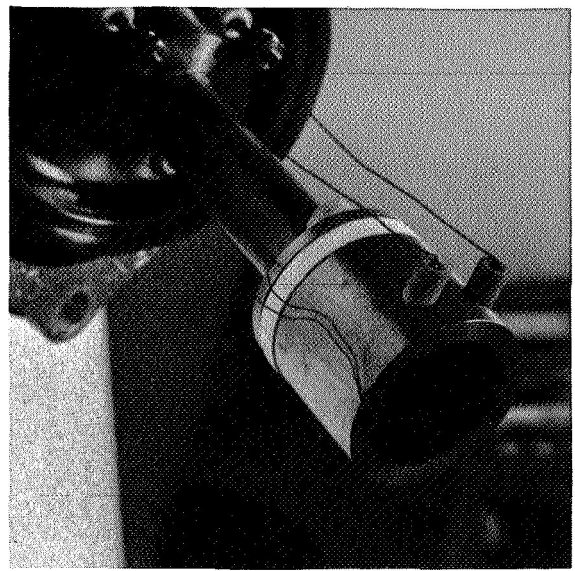
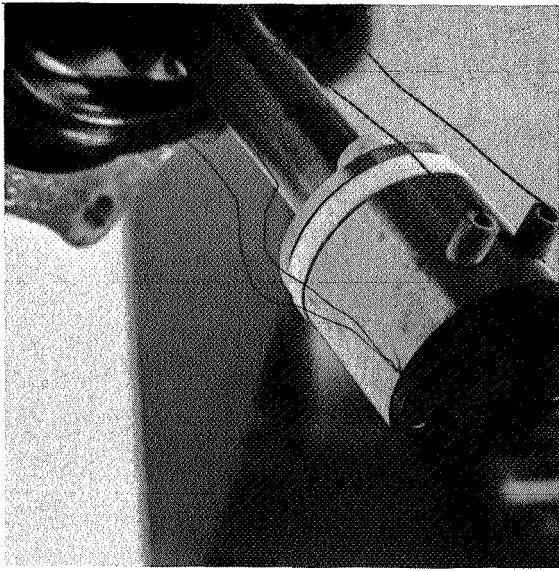
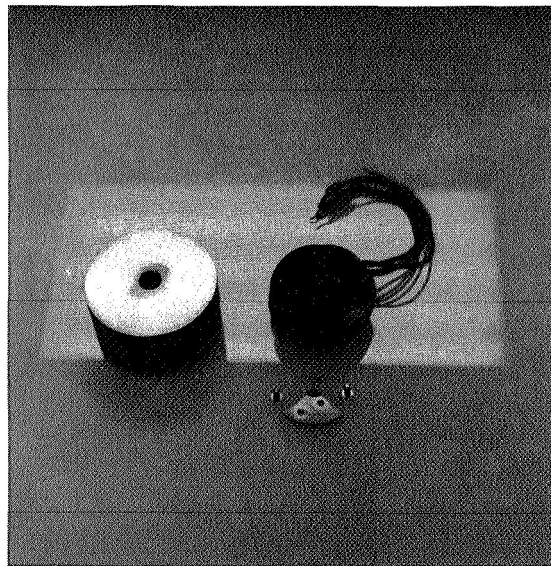


Figure 8. Block Diagram of Electronics Used to Measure Ion Current, Total Charge, and Bombardment Time.



(a) Modified Sample Holder with Heater



(b) Original Sample Holder

Figure 9. Photographs of Ion Beam Sample Holders.

steel cup was employed as an oven with heating coils consisting of 14 turns of No. 32 Nichrome wire wound on two $\frac{1}{4}$ -inch diameter alumina rods situated in the cup. A carbon block with a dovetail cross section "V" cut in the surface served as the mounting block. The "V" cut allowed use of wafers of varying diameters with good contact between the wafer and the mounting block.

Heat transfer was accomplished by radiation and conduction to the carbon block and by conduction from the carbon block to the crystal wafers. The mounting block was coated with a layer of silicone grease before the wafer was mounted to improve the heat transfer and to reduce time required to achieve the desired bombardment temperature. A thermocouple junction was mounted on the carbon block to monitor the temperature and to provide a means for measuring the time required for the wafer to attain thermal equilibrium at the desired temperature. Figure 10 shows the AC heater voltage required to reach the anneal temperature of 300°C. It was found that a stable operating point at the anneal temperature could be reached in about one hour.

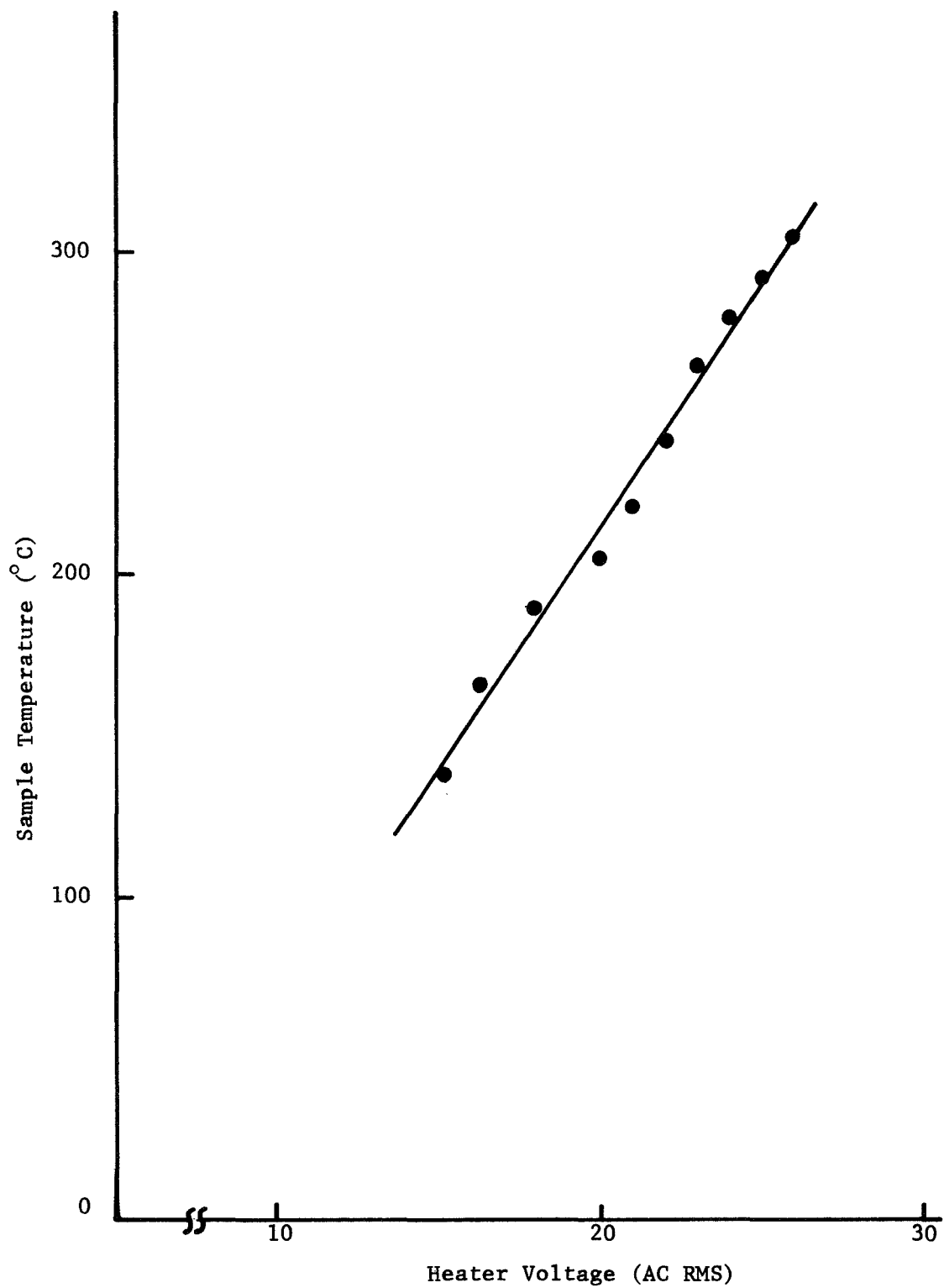


Figure 10. Temperature of the Sample Block as a Function of AC Heater Voltage.

V. Conversion Loss of Mixers Formed on Ion Bombarded Silicon and Gallium Arsenide at 94 GHz

A variety of semiconductor materials of types which have been successfully employed in microwave and millimeter wave mixers were obtained in wafer form for preparation by ion bombardment. Mixer junctions were formed on the ion bombarded crystals, and their conversion losses measured at 94 GHz as a function of ion energy and temperature during bombardment. A list of the test crystals and their physical properties are presented in Table 3. In addition to the samples listed in Table 3, a gallium arsenide crystal with a carrier density of 10^{18} cm^{-3} was ordered from Wacker Chemical Corporation at the beginning of the program, but was never delivered.

All the test samples with the exception of the SA18 (IN53 diode chips) were obtained with the orientation (111), and ground surfaces. Final polishing was accomplished with 600 grit abrasive and Linde-0.3 micron polishing compound. Immediately before ion bombardment, the wafers were etched for 2 minutes to remove surface oxides. After the ion bombardment was completed, a final etch of 15 minutes was employed to remove the shallow insulating layer created by the impinging ion beam. The wafer was then diced and the chips attached to a brass post suitable for mounting in the "run-in" mixer. This process, which was described in detail in FR-1, was very tedious and required the efforts of a highly skilled technician.* To prevent any possibility of

* All crystal posts and whiskers used in the 35 and 94 GHz "run-in" mixers were fabricated by Mr. Emory Horvath, Custom Microwave Corporation, Longwood, Florida.

Table 3. Physical Properties of Semiconductor Test Samples

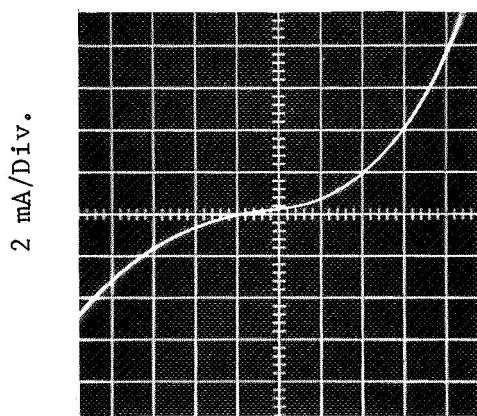
Designation	Supplier	Type	Dopant	$N(\text{cm}^{-3})$	$b(\text{cm}^2 \cdot \text{V}^{-1} \cdot \text{sec}^{-1})$	$\rho(\text{ohm-cm})$
GT17	¹ W	Gallium Arsenide	Tellurium	1.4×10^{17}	3630	0.0124
SA17	² GDC	Silicon	Aluminum	10^{17}	--	--
SA18	³ S	Silicon	Aluminum	10^{18}	--	--
SB17	⁴ GDC	Silicon	Boron	10^{17}	367	0.170
SB18	⁵ GDC	Silicon	Boron	10^{18}	183	0.034
SB19	⁶ GDC	Silicon	Boron	10^{19}	96	0.0065

1. Wacker Chemical Corporation -- Crystal No. 67901
2. General Diode Corporation -- Crystal No. 0012353
3. Sylvania -- Chip from IN53 Diode
4. General Diode Corporation -- Crystal No. 0012276
5. General Diode Corporation -- Crystal No. 0013414
6. General Diode Corporation -- Crystal No. 0013262

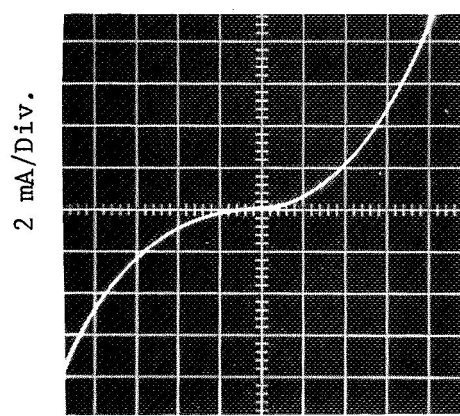
erroneous results from thermal migration of the implanted ions and damage sites, the semiconductor chips were not soldered to the brass post. Instead, a silver loaded epoxy with a very low impedance was employed.

Immediately preceding formation of the mixer junction, both the semiconductor surface and metal whisker were again etched and thoroughly washed in water and methyl alcohol. The silicon junctions were formed with a combination of mechanical pressure and reverse junction current in a process which was dubbed "reverse forming" and which was described in FR-1. The gallium arsenide junctions were welded using a forward current pulse in the manner described by Wentworth, et al.¹ The I-V characteristic was observed on an oscilloscope as the junction was formed, and served primarily as an indication of good ohmic contact on the first run-in. Several run-ins were sometimes required to achieve an acceptable junction; however, it was found that only two run-ins could be made on the silicon crystal without repointing the whisker, while the whisker employed in the gallium arsenide junction required inspection after each run-in because of the tendency for the whisker point to burn off during the welding process.

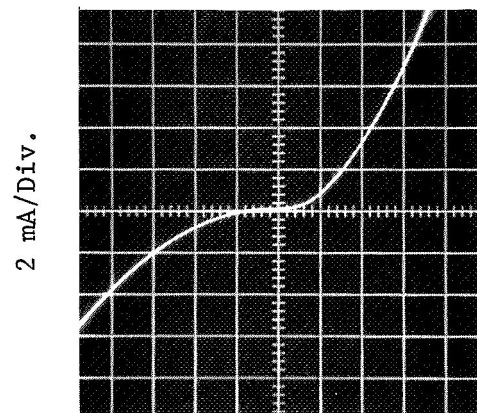
The effects of ion bombardment at room temperature on the I-V characteristics of the test crystals produced no surprises from the results reported in FR-1. For the same carrier density, the I-V characteristics of junctions formed on the aluminum- and boron-doped crystals were almost identical, while the gallium arsenide junctions showed practically no changes for the range of ion energies employed in the tests. Figure 11 shows the oscillographs taken on an aluminum-doped silicon mixer with a carrier density of 10^{18} cm^{-3} , and a



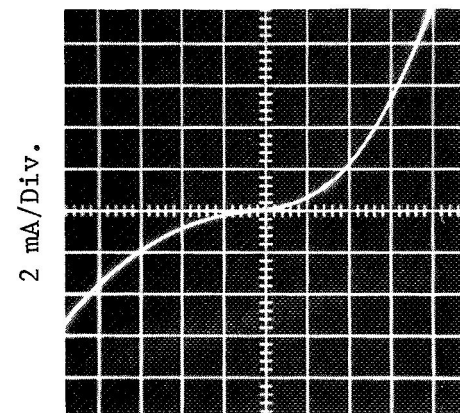
0.5 V/Div.
(a) SA18-24°C-10 KeV



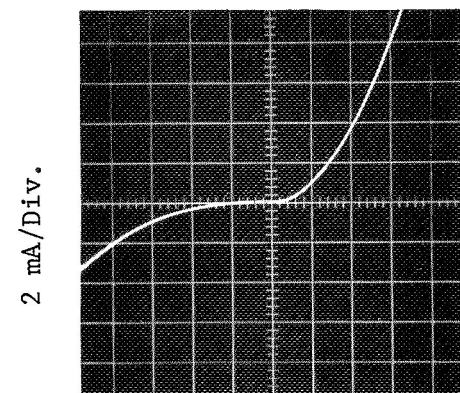
0.5 V/Div.
(d) SB19-24°C-10 KeV



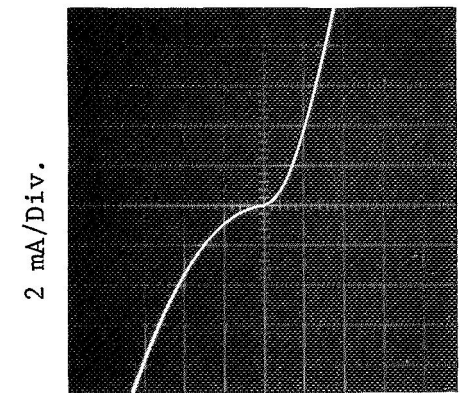
0.5 V/Div.
(b) SA18-24°C-20 KeV



0.5 V/Div.
(e) SB19-24°C-20 KeV



0.5 V/Div.
(c) SA18-24°C-30 KeV

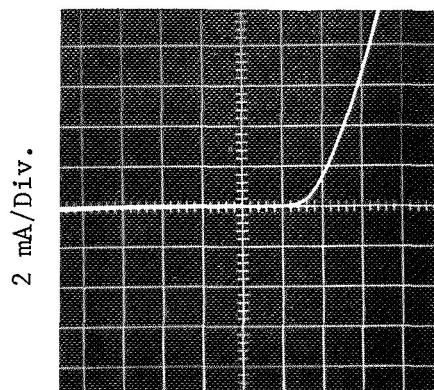


0.5 V/Div.
(f) SB19-24°C-30 KeV

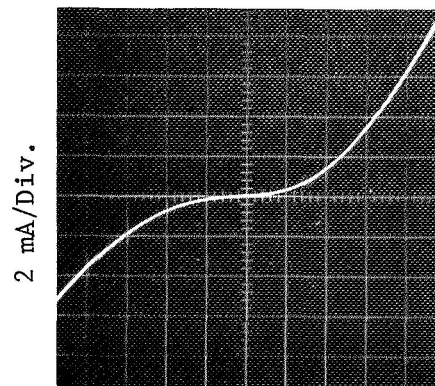
Figure 11. I-V Characteristics of Ion Bombarded Silicon Mixers.

boron-doped silicon mixer with a carrier density of 10^{19} cm^{-3} . Qualitatively, the effect of increasing the energy of the ion beam is, in general, to reduce the forward resistance and sharpen the knee of the forward characteristic. Mixers formed on the ion bombarded silicon crystals with densities of 10^{17} and 10^{18} cm^{-3} showed an increase in reverse resistance; however, on the boron-doped crystal with a density of 10^{19} cm^{-3} , the reverse impedance was consistently reduced for an ion beam energy of 30 KeV. Quantitatively, the above effects were characterized in terms of the constants A and α relating to the I-V characteristic equation for the aluminum-doped silicon mixers and presented in FR-1.

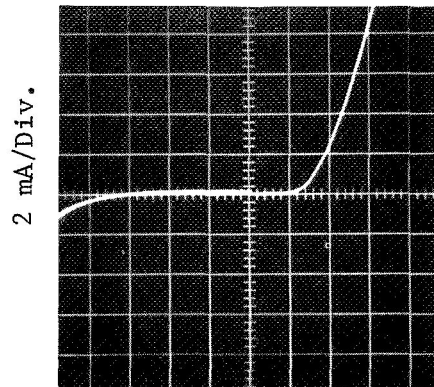
The effect of crystal bombardment temperature was found to be relatively insensitive to both the dopant species and the carrier concentration, but highly dependent on the host crystal. Figure 12 shows the results of sample temperature on the I-V characteristics of boron-doped silicon and tellurium-doped gallium arsenide junctions. It can be seen that the forward characteristic of the gallium arsenide junction was virtually unaffected over the range of approximately 300°C , while the reverse breakdown point was progressively reduced as the temperature was increased. Both the forward and reverse impedance was reduced as the temperature of the silicon samples were increased. The aluminum-doped silicon junctions behaved in a similar manner, with results which in general were very close to those published by Ohl.⁷ Several interesting anomalies occurred in which junction characteristics radically different from those shown in Figures 11 and 12 were produced. Since these effects were not repeatable, RF testing of the anomalous junctions was not attempted. It was



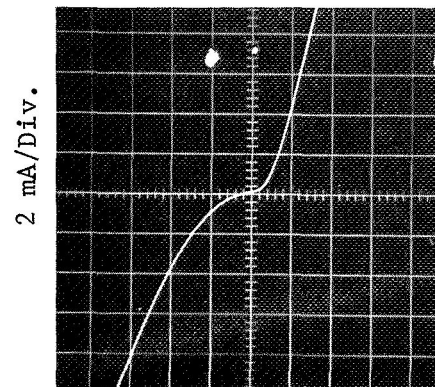
0.5 V/Div.
(a) GT17-24°C-20 KeV



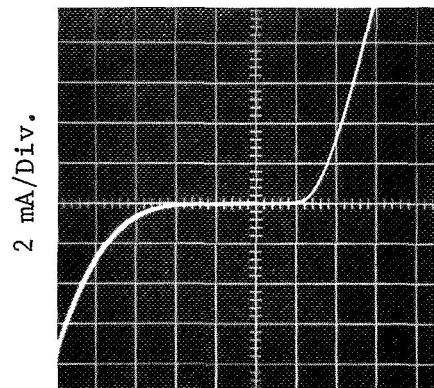
0.5 V/Div.
(d) SB18-24°C-20 KeV



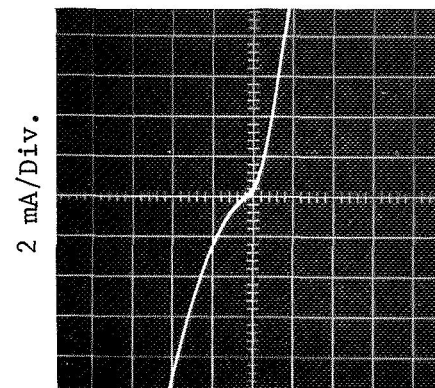
0.5 V/Div.
(b) GT17-200°C-20 KeV



0.5 V/Div.
(e) SB18-200°C-20 KeV



0.5 V/Div.
(c) GT17-320°C-20 KeV



0.5 V/Div.
(f) SB18-320°C-20 KeV

Figure 12. I-V Characteristics of 20 KeV Ion Bombarded Silicon and Gallium Arsenide Mixers Showing Effects of Sample Temperature During Bombardment.

interesting to note, however, that rectifying junctions could not be formed on either the unbombarded aluminum- or boron-doped silicon with carrier density of 10^{17} cm^{-3} . A respectable junction characteristic could only be formed on the 10^{18} cm^{-3} silicon which had been bombarded by 20 KeV ions. This result would seem to be at odds with the theory which would predict a lower mobility for carriers near the surface, and hence no improvement in the I-V characteristics. There is the possibility, however, that the ion beam is being stopped at the surface by sputtering the surface oxide and damage layers thus resulting in a clean surface which would improve the junction contact.

The conversion losses of point-contact junctions formed on the test materials listed in Table 2 were measured at 94 GHz as a function of ion energy and total charge. The initial measurements were performed on aluminum-doped silicon and compared with the results reported in FR-1 which were performed at 35 GHz on similar junctions. The minimum conversion loss obtained on unbombarded silicon (SA18) at 35 GHz was found to be 15 dB, whereas the minimum conversion loss on the same material at 94 GHz was found to be 18.6 dB. From equation (1), it can be shown that for $\omega C_b R_s > 1$,

$$L_c(\omega' C_b') \approx \frac{\omega' C_b'}{\omega C_b} L_c(\omega C_b), \quad (13)$$

and

$$10 \text{ Log } L_c(\omega' C_b') \approx 10 \text{ Log } \frac{\omega'}{\omega} + 10 \text{ Log } \frac{C_b'}{C_b} + 10 \text{ Log } L_c(\omega C_b) \quad (14)$$

Thus, for identical mixer junctions (same values of R_s and C_b), equation (14) would predict a difference of $10 \text{ Log } \frac{\omega'}{\omega} = 4.3 \text{ dB}$ between operation at 35 and

94 GHz. This calculation is in close agreement with data presented in Figure 13 which show conversion losses taken from measurements of 35 and 94 GHz on junctions with the same spreading resistance and different junction capacitance. The junction capacitances were calculated by combining equations (2) and (3) and using the measured values of spreading resistance, carrier mobility, and carrier density. It should be noted that the junction capacitance, C_b , was the only calculated or measured parameter which could be reliably correlated with conversion loss.

Figures 14, 15, and 16 show the conversion loss of mixer junctions formed on ion bombarded silicon and gallium arsenide as a function of ion energy. Satisfactory junctions could not be formed on the aluminum-doped silicon with a density of 10^{17} cm^{-3} or the boron-doped silicon with densities of 10^{17} cm^{-3} and 10^{18} cm^{-3} although the I-V characteristics of all three samples were radically improved with ion bombardment.

At a sample bombardment temperature of 24°C , no improvement in conversion loss was obtained over the range of total charge and energy employed although some improvement in the I-V characteristic were noted. Three crystal posts were fabricated from each bombarded wafer, and a wide range of etching times were employed in an attempt to improve the junction performance. The results presented in Figures 14, 15, and 16 represent typical performance from mechanically acceptable junctions for each crystal.

Following the initial ion bombardment experiments carried out at room temperature, the sample holder was modified to permit bombardment at temperatures up to about 300°C . At room temperature, lattice disorder increases with ion

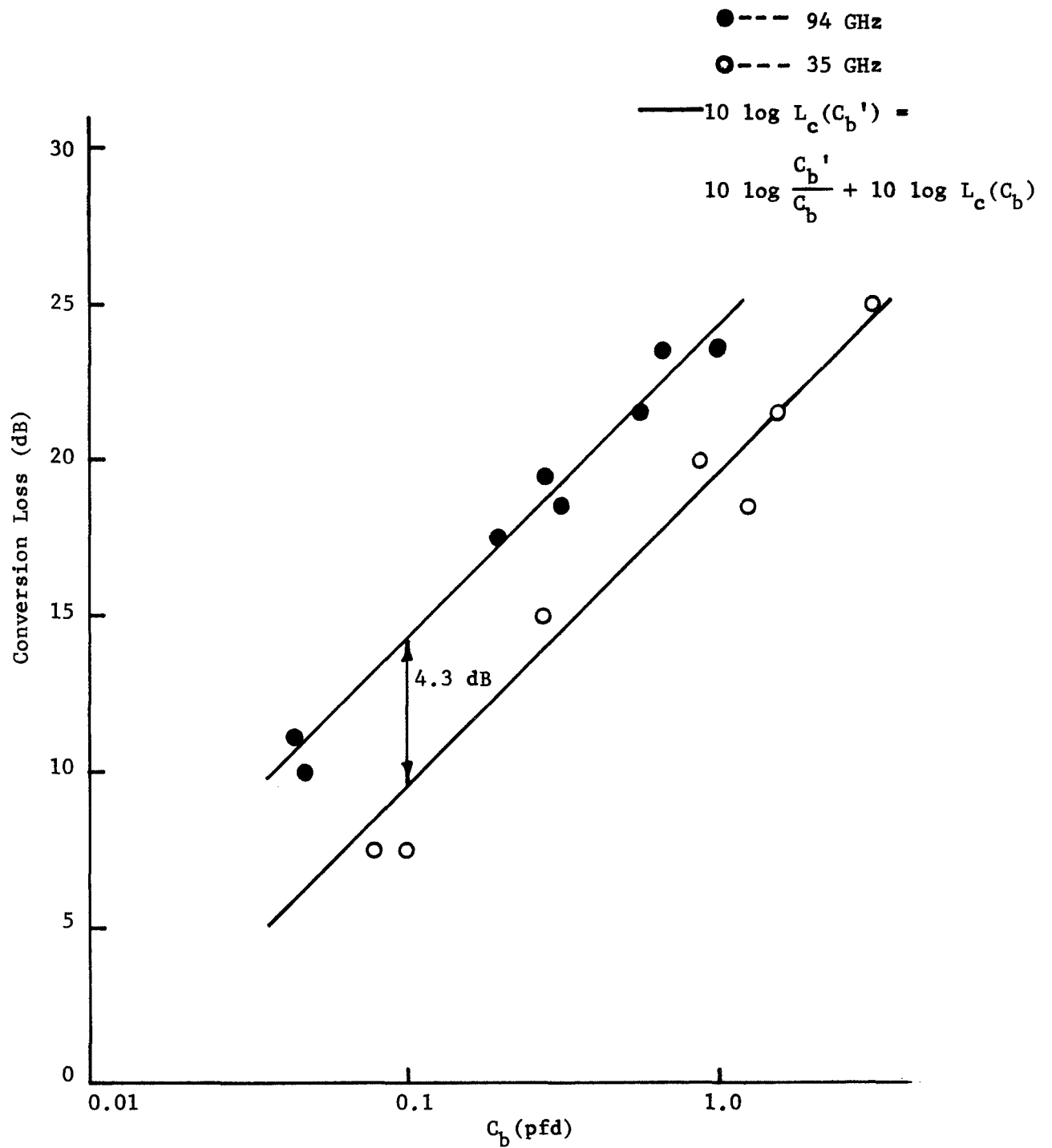


Figure 13. Conversion Loss as a Function of Junction Capacitance for Silicon Mixers at 35 and 94 GHz.

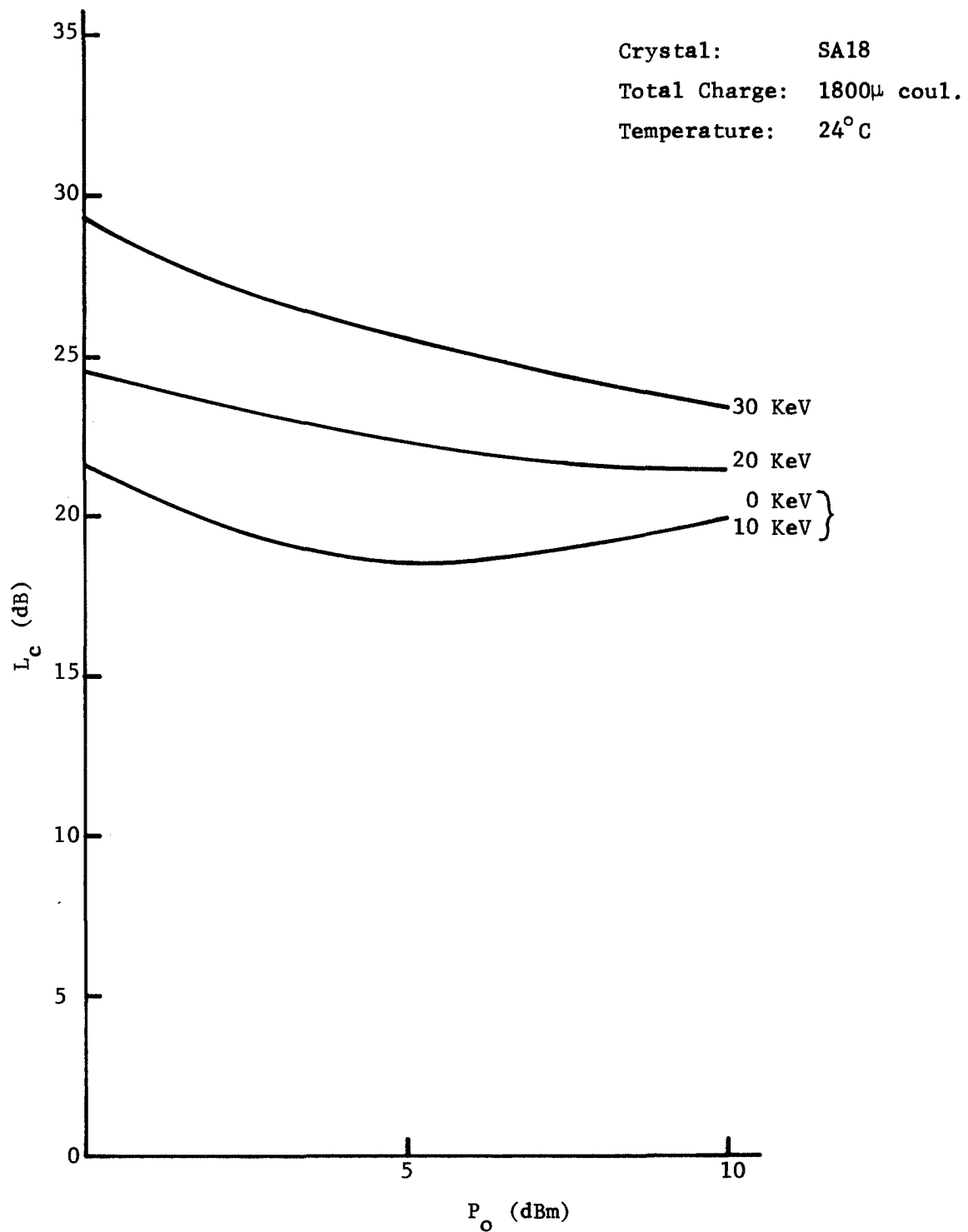


Figure 14. Conversion Loss of a "Run-In" Mixer Employing Ion Bombarded Aluminum-Doped Silicon at 94 GHz.

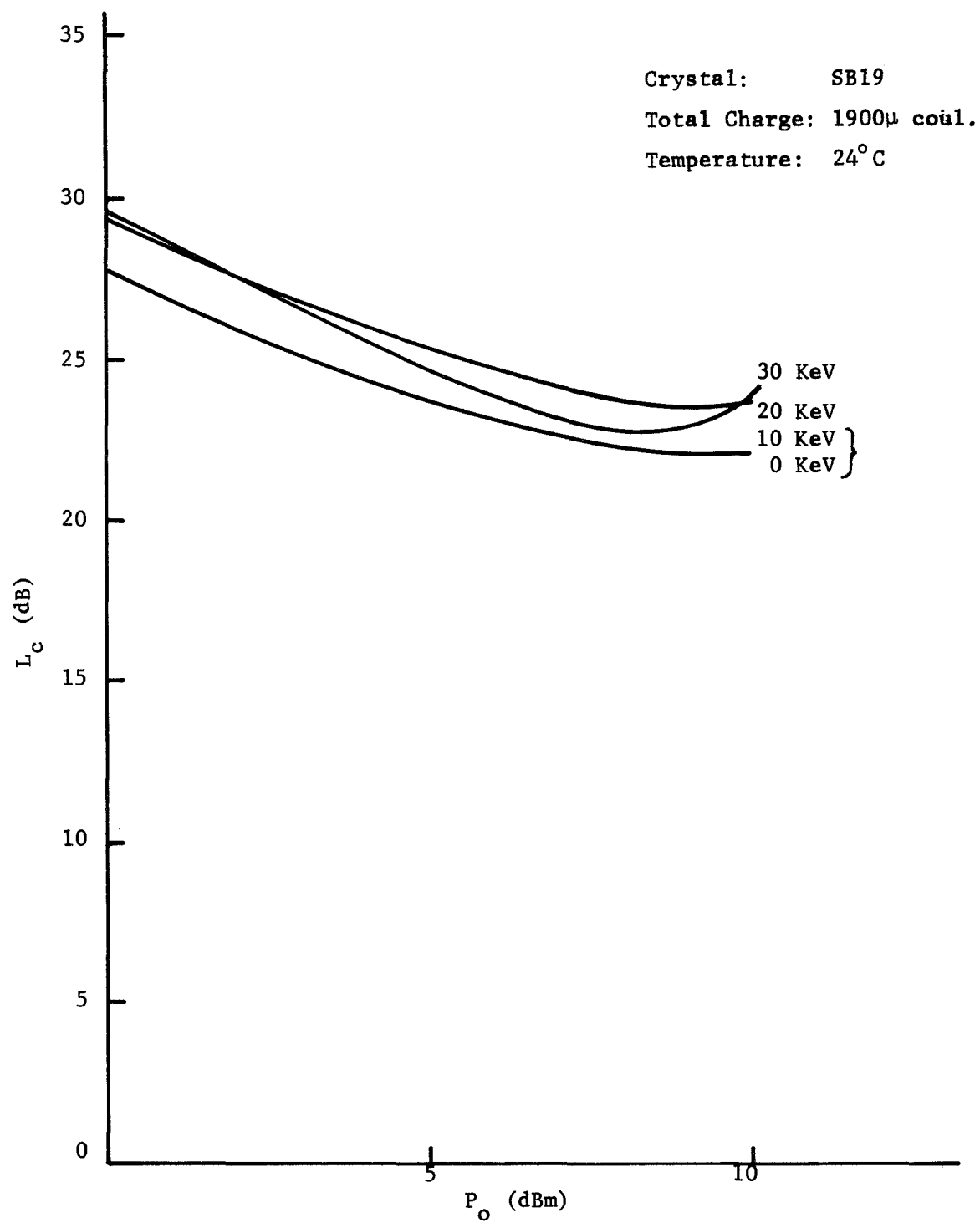


Figure 15. Conversion Loss of a "Run-In" Mixer Employing Ion Bombarded, Boron-Doped Silicon at 94 GHz.

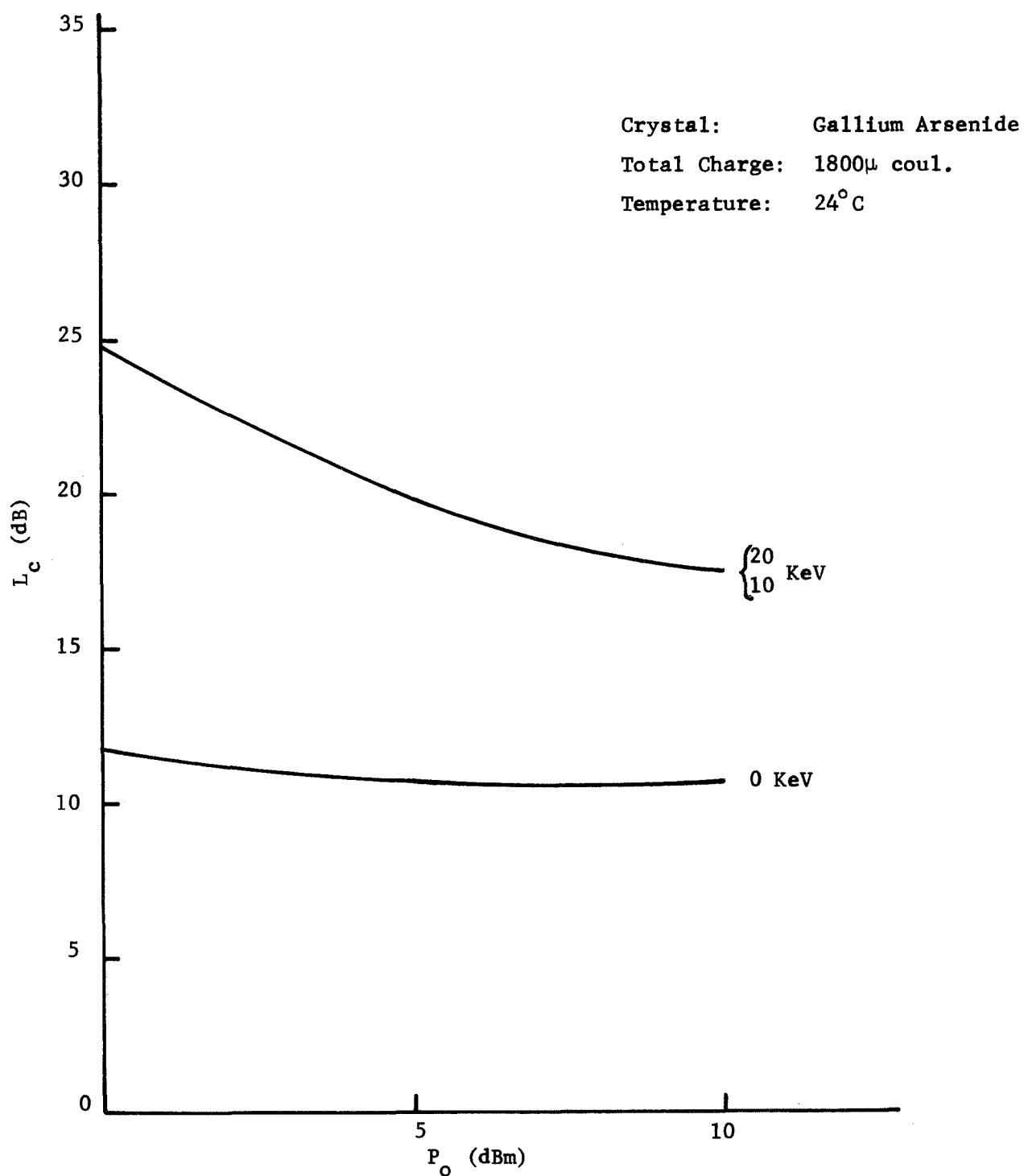


Figure 16. Conversion Loss of a "Run-In" Mixer Employing Ion Bombarded, Tellurium-Doped Gallium Arsenide at 94 GHz.

dose, and a completely amorphous layer can eventually be obtained. The lattice disorder can be annealed by raising the temperature of the sample during bombardment, and Eriksson, et al.¹³ have shown that for group III and V dopants implanted in silicon, approximately ninety percent substitutional and interstitial levels occur for implantation temperatures exceeding 300°C. One would expect the anneal temperature to be somewhat lower for helium implanted in silicon since the mass of the helium ion compared to the ions of group III and V elements is small.

Silicon and gallium arsenide wafers were bombarded at temperatures of approximately 200 and 300°C, and "run-in" mixers were fabricated from these samples. The results of conversion loss measurements on these mixers at 94 GHz are presented in Figures 17 through 20. The ion bombardment parameters for each junction are also given in Table 4. The same testing procedure was followed for the annealing experiments as was followed for the initial ion bombardment experiments. Three mixer posts were fabricated from each wafer, and various junction forming and surface preparation techniques were employed to obtain the best mixer performance.

The conversion loss of most junctions formed of the annealed semiconductors was better than that of junctions formed on the wafers which were bombarded at room temperature. The exception to this trend was the gallium arsenide material for which no acceptable junctions could be formed on the annealed wafers. It was found, however, that a significant improvement in conversion loss resulted from the annealing process in mixers formed on silicon with low carrier density. Junctions with less than 20 dB conversion loss were formed on both 10^{17} cm^{-3} and

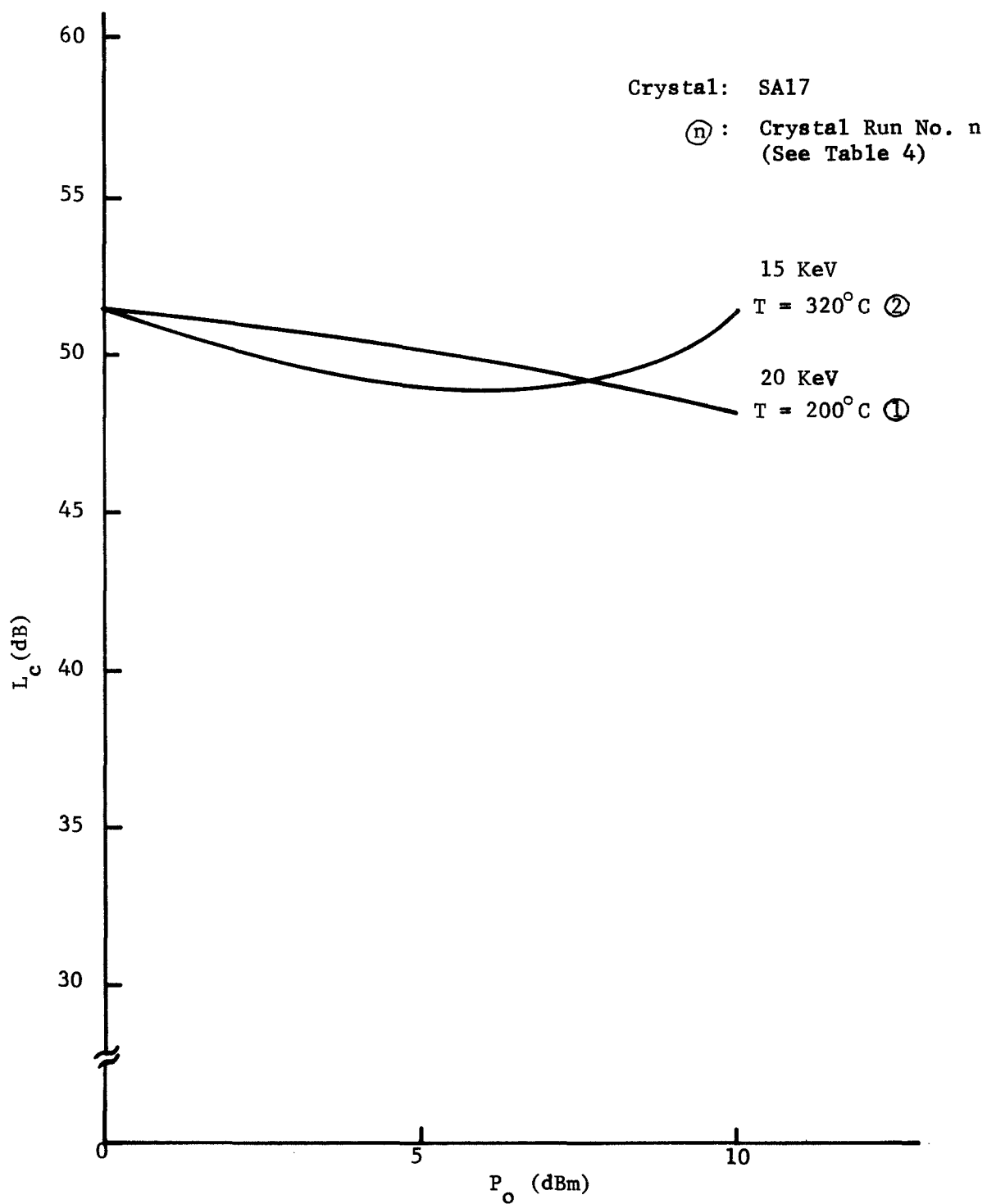


Figure 17. Conversion Loss of Aluminum-Doped ($N = 10^{17}\text{ cm}^{-3}$) Silicon Junctions as a Function of Bombardment Temperature.

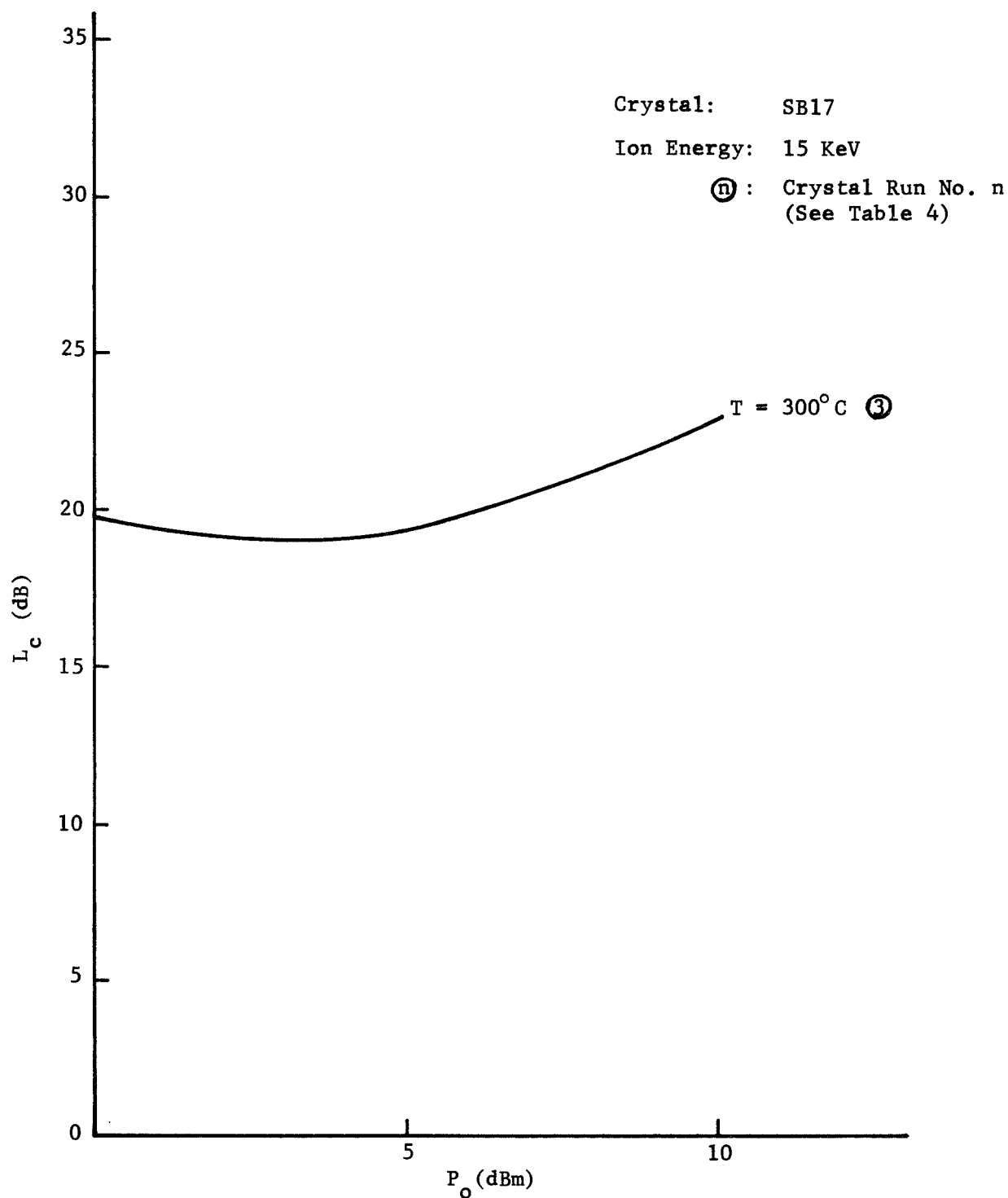


Figure 18. Conversion Loss of Boron-Doped ($N = 10^{17} \text{ cm}^{-3}$) Silicon Junctions as a Function of Bombardment Temperature.

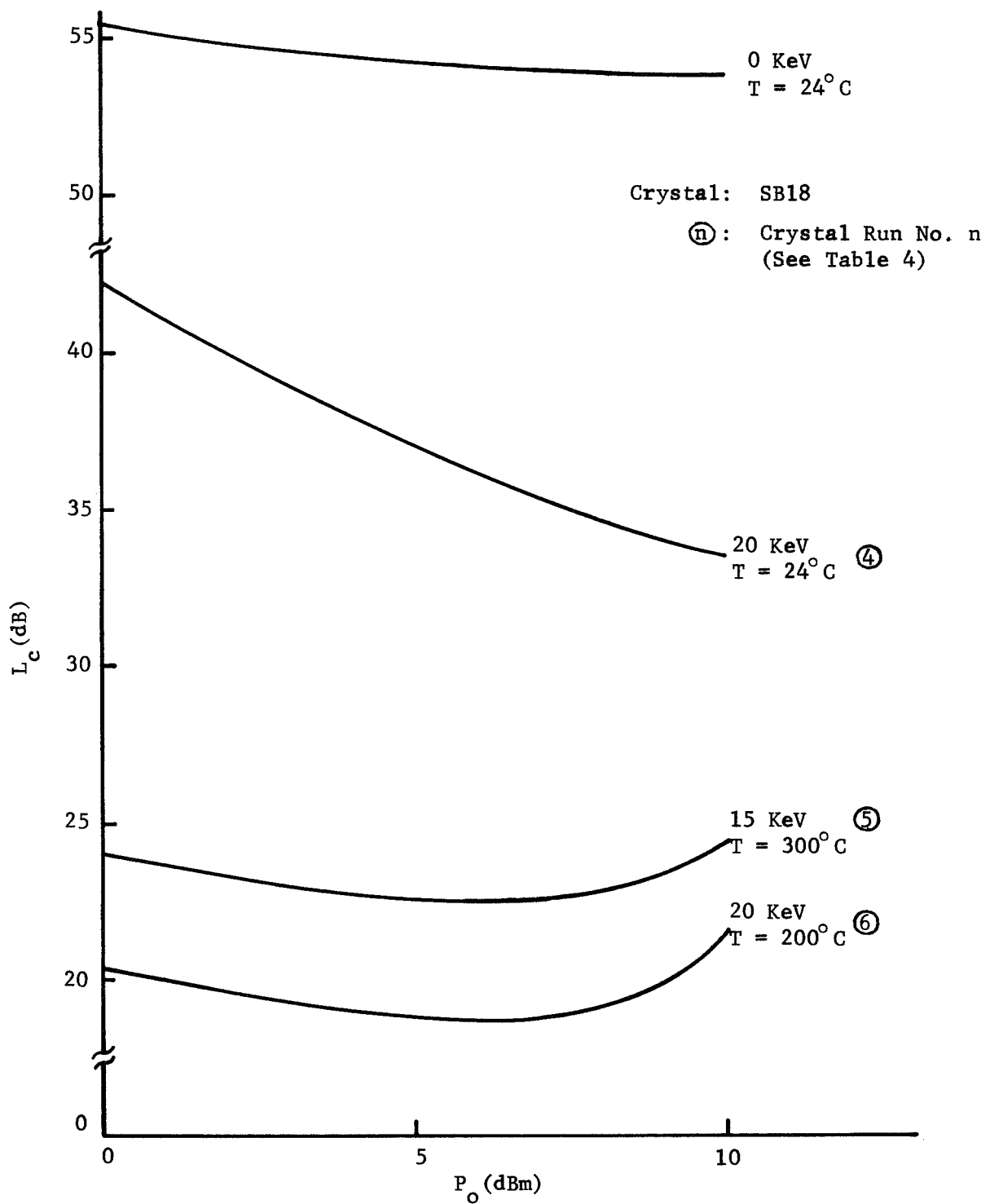


Figure 19. Conversion Loss of Boron-Doped ($N = 10^{18}\text{ cm}^{-3}$) Silicon Junctions as a Function of Bombardment Temperature.

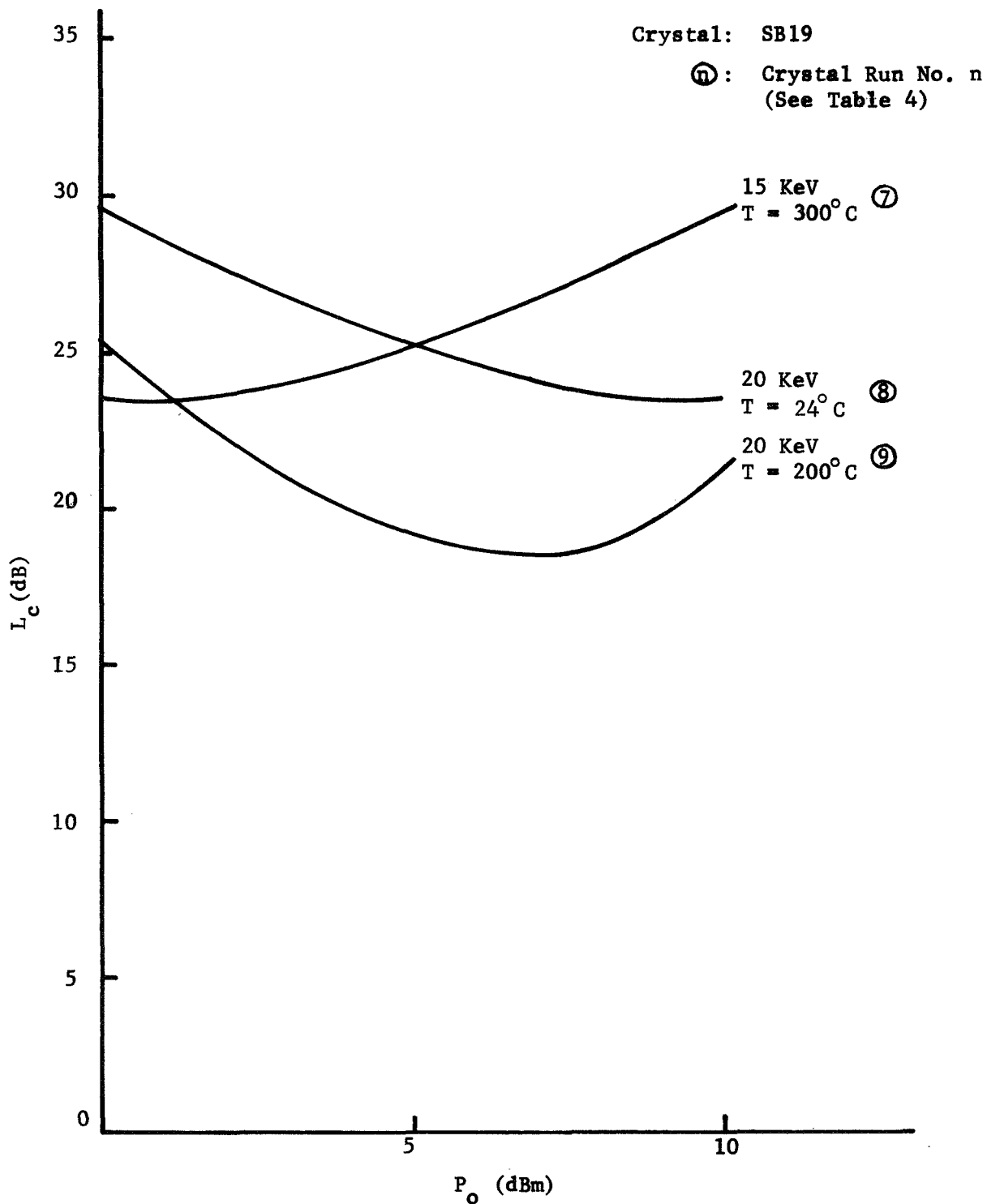


Figure 20. Conversion Loss of Boron-Doped ($N = 10^{19} \text{ cm}^{-3}$) Silicon Junctions as a Function of Bombardment Temperature.

Table 4. Ion Bombardment Parameters for Annealed Samples

Run No.	Sample Temperature (°C)	Ion Energy (KeV)	Ion Current (μ A)	Δt (sec)	Total Charge (μ coul.)
1	200	20	80	34.0	1800
2	320	15	85	24.2	2000
3	300	15	90	23.5	2000
4	24	20	65	--	1800
5	320	15	87	23.2	2000
6	200	20	90	20.6	1800
7	300	15	88	23.6	2000
8	24	20	95	--	1800
9	200	20	45	44	1800

10^{18} cm^{-3} boron-doped silicon, and a junction with measurable tangential sensitivity was formed on 10^{17} cm^{-3} aluminum-doped silicon. The lowest conversion losses were found to occur at a bombardment temperature of 200°C for the 10^{18} cm^{-3} and 10^{19} cm^{-3} boron-doped silicon, and at 300°C for the 10^{17} cm^{-3} boron-doped silicon. Since only one 94 GHz "run-in" mixer was available for these experiments, extended shelf life tests could not be carried out. Measurements extending over a period of several days revealed a tendency for a slight initial change in the junction characteristics followed by a stable operating point. During this time, the junction was subjected to a nominal power level of 1 mW for eight hours each day, and the conversion loss checked as a function of power level over the range of 1 to 10 mW at 2 hour intervals. Shelf life observations made by Ohl^{5,7} have shown that excellent lifetime can be expected from ion bombarded materials with no degradation in performance noted over a two-year period.

VI. Conclusions

Calculations based on a non-homogeneous point-contact mixer configuration first proposed by Petit⁴ have shown that the conversion loss of a millimeter wave mixer can be minimized by modifying the near surface layer of the mixer crystal. Ion bombardment has been employed by Petit and others to affect the desired near surface parameters although the exact physical mechanisms responsible for the changes produced are still in question. The objective of this work has been to investigate the use of ion bombardment in the preparation of millimeter wave mixer crystals by experimentally determining the effects of the ion beam parameters and sample bombardment temperature on the conversion loss measured at 94 GHz.

It has been shown that desirable changes in mixer performance occur for ion doses of about one ion per unit cell over the crystal surface, and for energies between 10 and 30 KV. Relative improvements in the conversion loss of 5 to 15 dB have been measured for ion bombarded crystals which were annealed at temperatures of 200 and 300°C. A minimum conversion loss of about 18 dB was obtained for the silicon mixers and about 9 dB for the gallium arsenide mixers, although no improvement from ion bombardment was observed for the gallium arsenide mixers.

The large parasitic loss corresponding to the minimum conversion loss of 18 dB for the silicon junctions is thought to be a result of the high series resistance as determined from the I-V characteristics. This supposition is supported by the correlation between the conversion loss and the junction

capacitance, and the calculated values of spreading resistance which are about an order of magnitude less than the measured series resistance. Ohl⁷ has suggested that a mechanically disturbed high resistance surface layer is created during the grinding and polishing stage, which can only be removed by high temperature steam oxidation followed by chemical etching. Since the necessary equipment for this process was not available, several attempts at repolishing and chemical etching were employed in an effort to reduce the series resistance. These attempts were not successful, and thus it would seem that the mechanical polishing step creates a limitation which can only be overcome with the steam oxidation procedure suggested by Ohl.

In summary, it has been shown that relative improvements in the conversion loss can be obtained from mixers utilizing semiconductor crystals prepared by ion bombardment. It was, however, necessary to anneal the crystal during bombardment to achieve these improvements. Evidently, the reduction of resistivity in the near surface layer by increased scattering from substitutional levels is preferable to reduction of resistivity by increased lattice disorder. Diagnostic equipment for determining the ion density profile and surface resistivity was not available, and hence direct correlation between the measured improvements in conversion loss and the calculations on non-homogeneous crystals could not be made. These correlations are necessary to determine the ultimate usefulness of ion bombardment in crystal mixer design, and should comprise the primary effort in any future research program in this field.

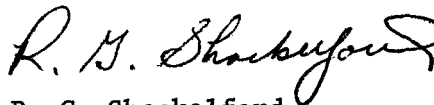
VII. Acknowledgments

The work reported herein was under the general supervision of Dr. A. P. Sheppard, and several other staff members of the Electronics Division contributed to the experimental program.

The author gratefully acknowledges the efforts of Mr. Albert McSweeney and Mr. W. T. Anderson who shared the difficult task of forming the point-contact junctions and determining their performance as millimeter wave mixers.

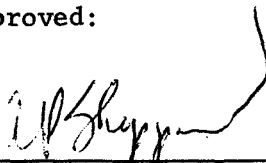
The modification and use of the ion source was made possible by the cooperation of Dr. E. W. Thomas of the School of Physics. The operation of the ion source and the ion beam analysis was performed under the guidance of Mr. R. L. Fitzwilson, also of the School of Physics.

Respectfully submitted,



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Approved:



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