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Low-Noise Diodes and Mixers for the 1–2-mm Wavelength Region

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Abstract—Ultralow capacitance low-noise Schottky-barrier diodes have been developed for use in the 1–2-mm-wavelength region. The diodes have been fabricated using both photolithographic and electron-beam lithographic techniques. Use of the latter technique to make diodes shaped as crossed stripes of width 0.25 μm and 0.4 μm on epitaxial GaAs resulted in a 30-percent reduction in spreading resistance over that of photolithographically formed circular diodes with approximately the same junction area and capacitance. Because of this reduction, it is suggested that in order to minimize receiver noise figure at frequencies greater than about 200 GHz, it will prove advantageous to use such shaped diodes rather than the conventional circular ones.

The diodes were used in mixers operating at 140, 175, and 230 GHz. At 140 and 175 GHz the diodes were mounted in conventional Sharpless wafers. At 230 GHz, in addition to Sharpless wafers, a mixer of unique design was used which incorporated an RF matching element, low-pass filter, and IF output transmission line, all on stripline, whose performance was optimized using low-frequency scaling techniques. Mixer double side-band (DSB) noise figures of 3.8, 8.1, and 12.6 dB were measured at the three frequencies, respectively. At 175 and 230 GHz, however, mixer performance is degraded due to a lack of sufficient local oscillator (LO) power and this is currently the principal limitation to their performance.

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I. INTRODUCTION

CURRENT interest in extending the techniques of coherent detection to the wavelength region between 1 and 2 mm has focused attention on the twin problems of: 1) producing high-quality Schottky-barrier diodes for use at very high frequencies, and 2) mounting these diodes in mixer networks (with extremely small dimensions at these wavelengths) in such a way that good electrical performance is combined with a reasonably sturdy and mechanically realistic configuration. In this paper these two problems will be discussed, methods of overcoming them will be proposed, and experimental results obtained from prototype diodes and mixers will be presented.

II. DIODES

A. General

Planar Schottky-barrier diodes, fabricated on n-type epitaxial gallium arsenide and characterized by their low noise, are now commonly used as the nonlinear element in millimeter-wave receivers. The principal factors limiting their performance are the barrier capacitance (C_0) and the spreading resistance (R_s). The former is merely the capacitance of the space-charge limited region, and effectively shunts the nonlinear diode resistance (R_j). The spreading resistance (R_s) mainly consists of the resistance of the undepleted portion of the epilayer lying below the junction, and it is thus in series with the parallel combination of C_0 and R_j. The deleterious effect of these two parasitic elements on the conversion efficiency of a Schottky-barrier diode are immediately apparent: C_0 allows current to bypass R_j, while R_s is a source of power dissipation, heat production, and, consequently, excess diode noise.

Conduction in GaAs Schottky-barrier diodes at room temperature is mainly by thermionic emission over the potential barrier. The current–voltage characteristic for the intrinsic ($R_s = 0$) diode is given by $I = I_0[\exp(qV/\eta kT) - 1]$ and the intrinsic diode noise temperature [1], $T_D \simeq \eta T/2$ for $I \gg I_0$ where η the diode slope parameter is close to unity and T is the physical temperature of the diode.

It is an extremely complex problem to quantitatively relate mixer performance to η, R_s, and C_0. It can be shown [2], however, that for small signals the conversion loss L_0 of a diode is inversely proportional to its detection sensitivity, i.e.,

$$L_0 \sim \frac{1}{dI/dP} \tag{1}$$

where dI is an increment of detected current for an increment dP in incident power. Also [2],

$$\frac{dI}{dP} \simeq \frac{\alpha}{2} \frac{1}{1 + \omega^2 C_0{}^2 R_j R_s} \tag{2}$$

where

$$\alpha = \frac{q}{\eta kT}.$$

A cutoff frequency at which dI/dP equals half of its maximum value can be defined by

$$f_c = \frac{1}{2\pi C_0 (R_j R_s)^{1/2}}. \tag{3}$$

Equations (2) and (3) show how the high-frequency performance of a Schottky-barrier diode can be limited by the presence of the parasitics R_s and C_0. Other debilitating effects caused by these parasitics, such as an increase in the diode noise temperature due to I^2R heating of R_s, which is present at all frequencies, also exist, however. Clearly, it is important to find ways of reducing the values of C_0 and R_s in order to extend the range of usefulness of Schottky-barrier diodes to higher frequencies and to improve, if possible, their performance as mixers at all frequencies.

Schottky-barrier diodes are normally made photolithographically using a mask consisting of an array of circular dots, each of which defines a single diode. If r is the radius of such a diode, then $C_0 \sim r^2$ and $R_s \sim 1/r^n$ where n lies between 1 and 2 depending on the thickness of the epilayer and the diameter of the diode [3].

From (3) it is seen that the detection sensitivity high-frequency cutoff can be increased by decreasing the diode radius, i.e.,

$$f_c \sim 1/r^m$$

where

$$1 < m < 1.5.$$

In practice, however, one cannot keep decreasing r indefinitely in order to obtain diodes with higher and higher cutoff frequencies. In the first place, diffraction effects impose a limit of about 1 μm on the diameter of photolithographically produced diodes. In the second place, even when using relatively highly doped epitaxial material, before this limit of 1 μm is reached the spreading resistance has already reached an unacceptably high value.[1] These effects are illustrated in the following paragraphs.

B. Diodes Made Using Photolithography

Planar Schottky-barrier diodes were fabricated on n-type epitaxial GaAs supplied by both Monsanto Corporation and Plessey, Ltd. In order to achieve small junction capacitance the diode area was made as small as was compatible with current photolithographic techniques. To minimize the concomitant increase in diode spreading resistance, GaAs with an extremely thin (<3000 Å) relatively highly doped (>10^{17} cm^{-3}) epilayer was used. Briefly, the diode processing was carried out as follows. An SiO_2 passivating layer was RF sputtered onto the surface of the semiconductor to a thickness of about 4000 Å. The wafer was then lapped to a thickness of 150 μm and a plated gold tinnickel layer was alloyed into the back to obtain the ohmic back contact. Photolithographic and etching techniques were then employed to open up an array of holes with a diameter of 1 μm up to 2 μm spaced about 5 μm apart in the sputtered silica layer. Finally, after gold had been electroplated into the holes to form the gold–GaAs Schottky junctions, the wafer was cut into chips, 200 μm × 200 μm. Table I shows the measured dc characteristics of the various diode types which were produced. Type numbers 1 and 3, the circular diodes, were made using the photolithographic technique which has just been described.

When these two diode types were used in mixers at 140 and 230 GHz the performance of type 1 was inferior to

[1] Of course, nonepitaxial or bulk GaAs could be used so that this effect would not occur. This, however, would cause an increase in C_0 as well as a reduction in the back-breakdown voltage. This latter effect could lead to an increase in diode noise due to reverse current flow during the negative half of the local oscillator cycle.

TABLE I
DC CHARACTERISTICS OF CIRCULAR AND CROSS-SHAPED SCHOTTKY-BARRIER DIODES

Type Number	Diode Description	Spreading Resistance R_s (1)	Junction Capacitance C_o (1)	Diode Quality Factor η	Cut-off Frequency (2) $f_c = \frac{1}{2\pi C_o (R_j R_s)^{1/2}}$
1.	1µm diameter circular	20 Ω	.003 pF	$1.15 < \eta < 1.25$	1677 GHz
2.	Cross shaped 2µm x 0.25µm	14 Ω	.0027 pF	$1.2 < \eta < 1.25$	2228 GHz
3.	2µm diameter circular	10 Ω	.0120 pF	$1.1 < \eta < 1.18$	593 GHz
4.	Cross shaped 4µm x 0.4µm	7 Ω	.0123 pF	$1.15 < \eta < 1.2$	692 GHz

Notes: (1) Represents average value of many measurements on each diode type; $\sigma \simeq 10$ percent. (2) Diode biased so that $R_j = 50\ \Omega$. (3) Diode types 2, 3, and 4 were made from the same epimaterial (supplied by Monsanto, Inc.) with nominal characteristics as follows: epicarrier density 3.56×10^{17}/cc, epithickness 0.24 µm. Diode-type 1 was made from epimaterial (supplied by Plessey, Ltd.) with nominal characteristics as follows: epicarrier density 1.8×10^{17}/cc, epithickness 0.3 µm. These characteristics are nominal in that they are defined differently by different manufacturers. Thus comparing the rather exact manner in which R_s and C_0 scale with area for diode types 1 and 3, it is obvious that for purposes of making diodes, the overall epilayer properties of both types of GaAs were very similar.

that of type 3 (see Section V). That is, a reduction in diode size while resulting in an increased cutoff frequency (see Table I) gave a degraded RF performance. This degradation is thought to be due to two factors: 1) the higher value of spreading resistance which, combined with the smaller diode area, leads to excessive ohmic heating at the junction resulting in increased diode noise, and 2) the fact that the performance of the 230-GHz mixer was limited by the low level of local oscillator (LO) available at the mixer. Thus doubling the spreading resistance doubles the amount of LO power dissipated in it, leaving that much less available for the mixing process, and consequently increasing the conversion loss. Currently, because of a lack of suitable generators, *all* diode mixers operating above about 160 GHz do so with less than the optimum amount of LO power. In addition at 200 GHz, a 2-µm-diameter diode with a cutoff frequency $f_c = 593$ GHz has already added almost 0.5 dB to its minimum conversion loss. Clearly, a diode with a higher cutoff frequency is needed. However, if this is achieved by reducing the diameter of the diode any resulting decrease in conversion loss will be more than offset by an increase caused by a reduced level of LO power. It is thus desirable to prevent this concomitant increase in spreading resistance as the cutoff frequency is increased.

C. Diodes Made Using Electron Lithography

The spreading resistance of a diode in addition to being directly related to material constants is also likely to be affected by any current "bunching" which might occur due to the geometrical profile of the junction. Thus if it were possible to reduce this bunching, for instance by increasing the ratio of the perimeter of the diode to its area, a reduction in spreading resistance might also be obtained. This procedure has been implemented using electron-beam lithography to fabricate diodes in the form of crossed stripes [4]. These diodes have been made in two sizes, 2 µm × 0.25 µm and 4 µm × 0.40 µm, and are thus approximately equal in area to the 1-µm-diameter and 2-µm-diameter circular diodes described previously. The electron resist used was polymethylmethacrylate—a relatively insensitive positive electron resist described by Haller, Hatzakis, and Strimivason [5]. The resist was exposed using a commercial scanning electron microscope (SEM) (Cambridge Scientific Instruments, Sterescope IIA) with 20-kV electrons at a dose of 3×10^{-5} cm^{-2}. The beam of the SEM was controlled by a simple digital pattern generator and the resulting format was that of arrays of orthogonally crossed stripes 0.25 µm × 2 µm spaced at about 10 µm, and 0.4 µm × 4 µm spaced at about 15 µm. Following resist development, as with the circular diodes, the SiO_2 was etched through, the resist stripped, the GaAs surface cleaned, the diodes gold plated, and the wafer cut into 200-µm × 200-µm chips. Fig. 1 is an electron micrograph of the 0.25-µm × 2.0-µm diode array after developing the resist and Figs. 2 and 3 are photographs of the same array before and after gold plating.

The measured dc characteristics of these diodes are again shown in Table I (diode types 2 and 4). From Table

Fig. 1. Electron micrograph of the 0.25-µm × 2-µm cross diodes after development of the electron-sensitive resist.

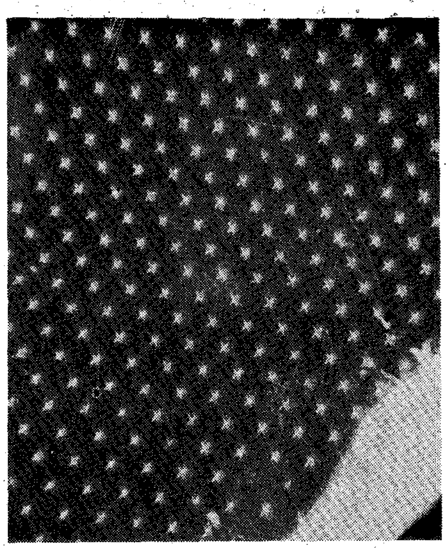

Fig. 2. Electron micrograph of the 0.25-μm × 2-μm cross diodes before gold plating.

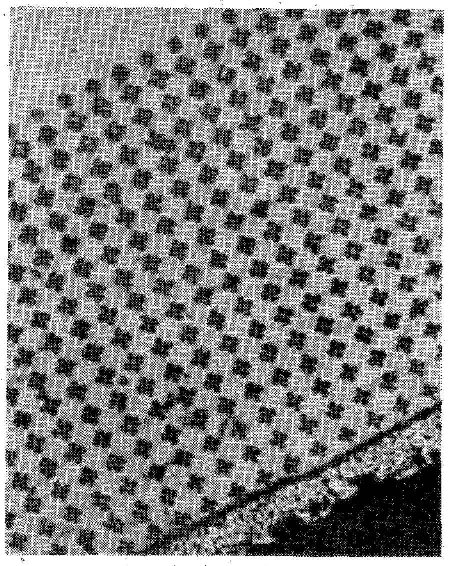

Fig. 3. Electron micrograph of the 0.25-μm × 2-μm cross diodes after gold plating.

I it is seen that increasing the perimeter to area ratio of a diode (i.e., by using a cross shape) results in a reduction of 30 percent in spreading resistance over circular diodes of approximately the same area and capacitance. This reduction is effected without any significant degradation in the diode quality factor.

III. MIXERS

The diodes were mounted in mixers operating at 140, 175, and 230 GHz. The waveguide types, and their inner dimensions (millimeters), used for each frequency were, respectively, RG-138 (2.03 × 1.02), RG-136 (1.65 × 0.83), and RG-137 (1.09 × 0.55). For the mixers operating at 140 and 175 GHz the diodes were mounted in conventional Sharpless wafers [6]. An excellent description of the construction of millimeter wave mixers using Sharpless-wafer mounted diodes is given by Penzias and Burrus [7].

At 230 GHz, however, it was felt that given the increasingly small dimensions of the mixer, a new method of construction should be attempted which would allow greater control over the more critical dimensions. Because of the successful application of millimeter integrated circuit techniques at lower frequencies [8], it was decided to incorporate some of these techniques to build a mixer at 230 GHz [9]. A great advantage of this approach is that it is possible to optimize a scaled low-frequency version of the circuit for which measurements and circuit adjustments are much simpler. Fig. 4 is a photograph of the mixer shown split down the center of the waveguide E plane.

The mixer consists of a waveguide input and a waveguide-to-stripline transition to which a 20-μm-diameter 150-μm-long eutectic Au–Cu wire, shaped to form a spring, is bonded. The other end of the spring-contact wire is etched to form a point and is used to contact one of an array of diodes on the surface of a 200-μm × 200-μm chip of semiconductor mounted on a screw in the broad face of the waveguide. The stripline circuit is evaporated

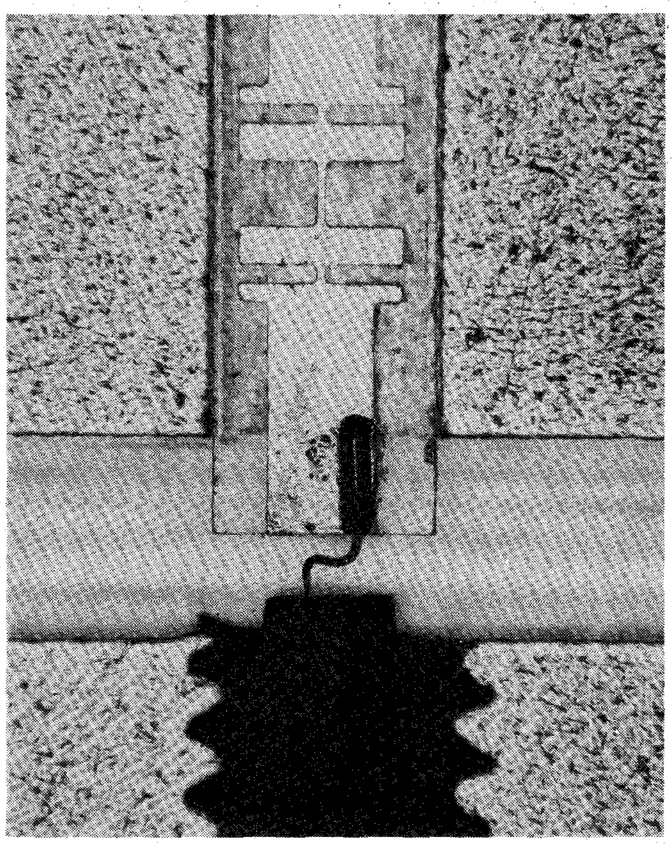

Fig. 4. View of 230-GHz stripline mixer diode mount shown split down the center of the waveguide E plane. The width of the waveguide channel shown is 0.55 mm. The 200-μm × 200-μm × 80-μm gallium arsenide diode chip is seen mounted on a 0.75-mm OD screw. Also seen is the contacting C spring bonded to the stripline low-pass filter on a 50-μm-thick silica substrate. The smallest dimension seen in the filter (the width of the inductances) is 25 μm.

and photoetched on a 50-μm quartz substrate and is suspended in a channel with cross-sectional dimensions of 250 μm $\times$ 500 μm. One end of the circuit protrudes into the waveguide to form the waveguide-to-stripline transition. Following this is a low-pass filter and a 50-Ω line to the IF output APC connector. This millimeter-wave integrated circuit was originally built and optimized at 6 GHz, approximately 37 times lower in frequency, using a diode whose junction capacitance and parasitics were appropriately scaled from those of the diodes which were finally used.

The detector itself consists of two halves split along the waveguide E plane. In assembling the detector, the stripline circuit is put in place before the two halves are screwed together. The screw with the semiconductor chip mounted on it is then screwed in until electrical contact is made with one of the diodes. Should this diode be burned out or contact otherwise be lost, contact can be made to another diode on the chip by simply screwing the screw in a little further. This construction has been found to be quite sturdy and rugged.

IV. RECEIVER ASSEMBLY

In order to measure the RF performance of the diodes and mixers which have just been described, they were incorporated into simple broad-band receivers. Each receiver utilized a cylindrical cavity operating in the TE_{011} mode with two noncontacting movable shorts to couple the LO into the signal line. At 140- and 175-GHz Varian klystrons were used to supply the LO signal.

At 230 GHz, however, no klystron was available and the LO signal is proved by a frequency doubler pumped by a Varian klystron operating at 115 GHz. The doubler consists of a four-port E plane waveguide junction, a Sharpless wafer mount, and a sliding short for matching purposes. The diode which is mounted in a Sharpless wafer is a diffused GaAs junction varactor supplied by C. A. Burrus [10]. The efficiency of the doubler was not measured because devices for measuring low levels of millimeter-wave power above 100 GHz are not available. However, a crude estimate based on the amount of the second harmonic current gives an efficiency of about 3–4 percent.

In order to give any output at all at 230 GHz, the varactor diode used had to have extremely small capacitance and area ($\sim$3-μm diameter). This in turn limited the amount of incident power at 115 GHz to about 150 mW. The resulting low level of second harmonic meant that a relatively low Q coupling cavity with a (Q loaded/Q intrinsic) = 0.5, (7-dB transmission loss), had to be employed. With approximately 150 mW into the multiplier, the 230-GHz mixer detector measured 2.5 mA directly at the output of the multiplier. However, with the coupling cavity in place the detected LO current was 0.3 mA.

All three receivers used a Micromeg room temperature parametric amplifier operating at 1.4 GHz with a noise figure of 0.8 dB as the first IF stage. Fig. 5 is a block diagram of the complete 230-GHz receiver and Fig. 6 shows this receiver mounted for use in the 36-ft millimeter-wave telescope of the National Radio Astronomy Observatory at Kitt Peak [11].

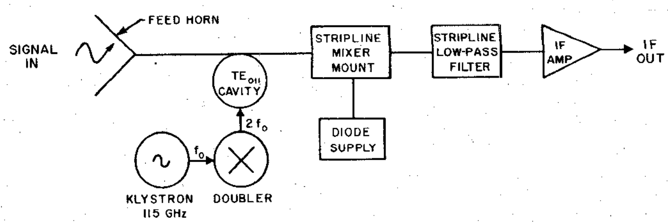

Fig. 5. Block diagram of the 230-GHz receiver including feed horn, klystron source, and IF amplifier. The waveguide components are in rectangular waveguide RG-137 with inner dimensions 1.09 $\times$ 0.55 mm.

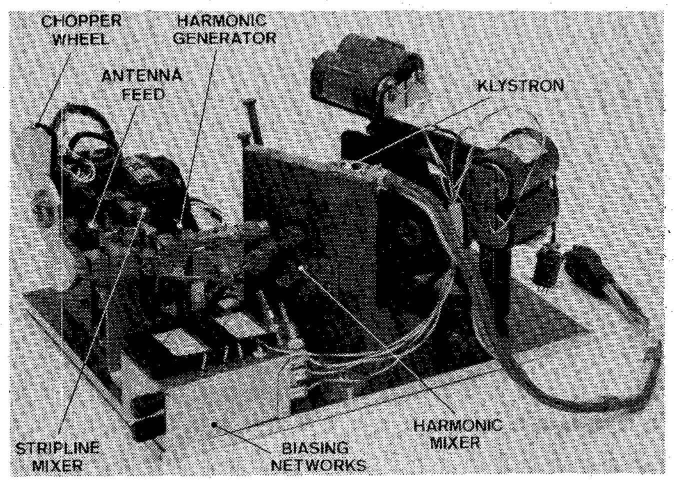

Fig. 6. Photograph of the 230-GHz receiver including chopper wheel to modulate the calibration signal input. The large connector Type PM6P on the far right connects to the klystron power supply, the small connector Type ACX which hangs over the KS 14711 Bell System dry cell batteries connects to the fan which cools the klystron mounted behind the vertical plate.

V. RF MEASUREMENTS

A. General

For all three receivers, the noise figure (N) was measured by noting the difference in receiver response when an absorber consisting of carbon-loaded polyurethane foam (Emerson–Cuming microwave absorber AN-72) at ambient temperature was placed in front of the feed horn and then replaced by one at liquid nitrogen temperature. In addition, for the 175-GHz receiver, the conversion loss (L) and the noise temperature ratio (t) were measured using a method similar to that described by Weinreb and Kerr [12].

It should be borne in mind when interpreting the following results that to mount and contact a diode in a mixer at these high frequencies, in such a way that RF performance is limited only by the *electrical* characteristics of the diode and mixer, is in general an extremely difficult process. This is a direct consequence of the very small dimensions involved and the ensuing dependence on extremely precise mechanical tolerances and finishing. Thus for instance, optimum noise and conversion loss performance will not be obtained from a Sharpless wafer mounted diode unless the following hold true.

1) The dimensions are precise enough to allow exact alignment of the waveguide portion of the wafer with that of the block into which it is inserted.

2) The mechanical finish inside the waveguide portion of the wafer, where the diode is mounted and contacted, is such that it allows unimpeded flow of current in this very critical region.

3) The diode itself is not damaged by overheating during mounting.

4) Good electrical and mechanical contact is made with the diode via as short (<200 μm, usually) an etched "whisker" as is possible.

It is usually difficult to optimize all these factors simultaneously so that in practice different Sharpless wafers containing exactly the same type of diode chip may show a distribution in measured noise figures of perhaps up to 1 dB, skewed toward the lowest noise figures indicating the closest to ideal mounting. Since in this paper we are concerned with the electrical performance of diodes and mixers, uncontaminated as much as possible by mechanical considerations, the results which are quoted are the best which were measured for the particular diode and mixer configuration under discussion.

B. 140 GHz

At this frequency diode types 1 and 3 (1-μm-diameter and 2-μm-diameter circular diodes) were mounted in Sharpless wafers. The best DSB mixer noise figures which were obtained with these diodes were 4.8 and 3.8 dB for types 1 and 3, respectively (mixer noise temperatures of 1000 K and 400 K).

C. 175 GHz

The receiver at this frequency was used for a comparison of the cross and circular shaped diodes. The comparison was made at 175 rather than at 230 GHz as at 175 GHz more power was available (from a klystron) to supply the LO signal. However, as it turned out, because of the relatively low output of the klystron (~35 mW) and the high loss through the coupling cavity to the diode (~13 dB) insufficient LO power was incident on the diode to achieve optimum conversion loss. Even so the situation was much better than at 230 GHz where even less power was available. A number of type 3 and type 4 diodes were mounted in Sharpless wafers and used for the comparison. Both the double side-band (DSB) conversion loss (L) and the noise temperature ratio (t) were measured for these diodes. Table II gives the results. It is seen that the minimum mixer noise figure (N) that was achieved ($N = Lt$) was ~8.1 dB (noise temperature 1570 K).

TABLE II
DSB CONVERSION LOSS AND NOISE TEMPERATURE RATIO FOR 4-μm × 0.4-μm CROSS DIODE AND 2-μm-DIAMETER CIRCULAR DIODE OPERATING AS MIXERS AT 175 GHz

Diode Type Number	DSB Conversion Loss (L)	Noise Temperature Ratio (t)
4. (4.0μm x 0.4μm Cross diode)	8.3 db	0.95
3. (2μm diameter circular diode)	8.8 db	0.96

TABLE III
DSB NOISE FIGURE OF 230-GHz MIXERS

Diode Type Number	Stripline Mixer	Sharpless Wafer Mount
1. (1μm circular)	13.4	13.9
2. (2μm circular)	12.6	13.2

D. 230 GHz

A number of stripline mixers and Sharpless wafers were measured at this frequency in which diode types 1 and 3 were mounted. The results are shown in Table III. The lowest mixer noise figure, which was achieved with a 2-μm circular diode in a stripline mount, is 12.6 dB (~5000 K).

VI. DISCUSSION

A. Diodes

From (2) and the data of Table I, the conversion loss of a 2-μm circular diode is expected to be about 0.1 dB greater than that of a 4-μm × 0.4-μm cross diode at 175 GHz. From Table II it is seen that in fact a difference of 0.5 dB was measured. However, with the uncertainties in the RF measurements, due mainly to the mechanical difficulties mentioned previously (Section V), the measured difference of 0.5 dB may only be marginally significant. In spite of this it is clear from the dc parameters that the cross diodes are as good (and most likely better) than their circular counterparts at 175 GHz.

As the 2-μm circular diodes give excellent performance at 140 GHz, much better than the 1-μm circular diode, it seems reasonable to propose an upper limit of about 10 Ω on the value of a diode's spreading resistance if the diode is to be useful at millimeter wavelengths. If this is so, then at frequencies greater than about 200 GHz where, from (2), the conversion loss of such a diode (e.g., the 2-μm-diameter circular diode) has already increased by about 0.5 dB, a real advantage can be gained by using a cross diode to achieve a higher cutoff frequency without a concomitant increase in series resistance. Use of cross diodes in mixers above 200 GHz will be even more important when such mixers are cooled in order to decrease the effect of the diodes intrinsic noise [12]. This follows since, assuming sufficient LO power is available, the main effect of a larger series resistance is to increase ohmic heating and also, consequently, the noise output of the diode.

B. Mixers

First, a general comment might be made that at present the main limitation to the performance of low-noise mixers in the 1–2-mm wavelength region is not a lack of suitable diodes or mixer networks but rather a lack of sufficiently powerful sources to deliver adequate LO power to the diode. This was the case with the 175- and 230-GHz mixers. In addition it should also be noted that at 230 GHz because of the low-Q coupling cavity which had to be used and the relatively low IF frequency (1.4 GHz), some klystron and multiplier noise was incident on the mixer and also the signal suffered some attenuation in passing the cavity. These problems could be partially alleviated by raising the IF frequency, however, the fundamental problem of low LO level remains.[2]

If at 140 GHz, where sufficient LO power is available, the LO signal is attenuated to provide the same value of rectified current as is obtained at 175 and 230 GHz, then about 1.5 and 3 dB, respectively, are added to the mixer noise figure. Thus as a first approximation, if sufficient LO power were available at 175 and 230 GHz, then using the present diodes and mixers noise figures of about 6.6 and 9.6 dB would be expected at these frequencies.

From that data of Table III it seems that the performance of the stripline mixer is superior to that of Sharpless wafer mounts at 230 GHz. This is not unexpected since the conductor pattern of the stripline detector, which is fabricated by photolithographic processing steps, can be more accurately designed and reproduced than the machined parts of the Sharpless wafer. Thus for the 1–2-mm region this technique certainly deserves further exploration. Perhaps in the future it may also be combined with harmonic down-converter techniques [13] to additionally solve the LO problems at these frequencies.

[2] When cooled mixers become practical at these frequencies the problem will be less severe because, as well as lowering diode noise, a cooled mixer needs less LO signal to achieve minimum conversion loss [12].

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