RF Performance of a Novel Planar Millimeter-Wave Diode Incorporating an Etched Surface Channel

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Abstract **—A new whiskerless millimeter-wave mixer diode has performance comparable to that of the highest quality whisker-contacted diodes. The diode uses an etched surface channel and planar air bridge to obtain greatly reduced parasitic capacitance. At 94 GHz the room-temperature diode exhibited a conversion loss of 5.3±0.5 dB and an equivalent input noise temperature of 518±50 K SSB.**

I. Introduction

Over the past two decades the mixing element of choice for most millimeter- and submillimeter-wavelength receivers has been the whisker-contacted GaAs Schottky barrier diode. Although this configuration provides the lowest possible shunt capacitance, the whisker-contacted structure lends itself poorly to inclusion in integrated circuits, requires reduced height waveguide mounts which are extremely difficult to machine, and is not well suited to space applications.

A number of laboratories have proposed and fabricated whiskerless diodes intended to circumvent these limitations [1]–[11]. The diodes used in the present work incorporate an etched surface channel and an associated air bridge. This approach permits precise photolithographic definition of the air bridge and uses conventional etching technology, thereby eliminating the need for costly and inherently lower resolution proton bombardment. Fabrication technology and preliminary results for such a mixer have been described previously [10].

This paper describes a mixer for 90–110 GHz using a planar surface-channel diode. A novel waveguide mixer structure with two tuners was used, which permitted optimized impedance matching of the diode to the mount at RF. Measured results are compared with those of other whiskerless and back-contacted diodes as described in the literature.

II. Diode Structure and DC Characteristics

The surface channel diode is depicted in Fig. 1 The structure includes a semi-insulating GaAs substrate supporting a 3.5 μm n^+ buffer layer ($N_D > 2\times10^{18}/cm^3$) and a 1.0 μm active layer ($N_D = 2–5\times10^{17}/cm^3$), where N_D is the donor impurity density. Chip dimensions are approximately 390 μm×130 μm×130 μm. Bonding sites are provided at opposite ends of the chip by a 130 μm square ohmic contact and a 100 μm×200 μm anode contact pad. Electrical contact to the Schottky junction is established with a 50 μm×4 μm gold finger which spans the air-filled surface channel.

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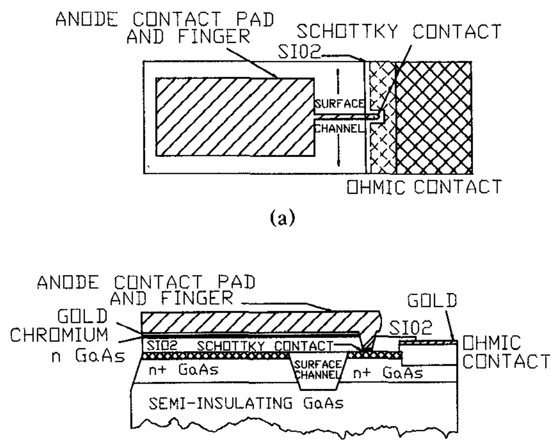

Fig. 1. Schematic diagram of the surface channel diode showing (a) top view and (b) cross sectional view (not to scale). The chip dimensions are 390 μm length×130 μm width×130 μm thickness.

Inclusion of the surface channel substantially reduces parasitic capacitance by interrupting the conducting path between the anode and cathode pads through the active GaAs dielectric (Fig. 2). Surface channel formation as one of the final processing steps permits definition of critical device features on a planar surface. Consequently, highly accurate pattern transfer is achieved during photolithography and etching of the Schottky junction and contact finger.

Table I presents the measured dc electrical characteristics of surface channel diodes from two batches: SC2R1 and SC2R2. Also presented are dc characteristics of a similarly doped whisker-contacted diode, TE-12, whose mixer performance is compared with that of the surface channel diode in Section IV.

The whiskerless diodes described above measured 130 μm×390 μm in dimension and were lapped to a thickness of 130 μm. At present, our laboratory is able to fabricate diodes measuring 75 μm×75 μm×75 μm, which approaches the smallest size practical for handling during the mounting procedure. Scale-model measurements of such diodes show a

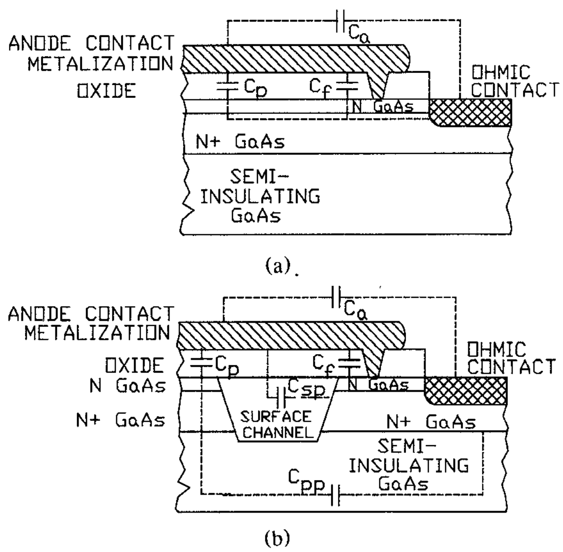

Fig. 2. Cross section showing capacitance components in (a) a basic planar diode and (b) the surface channel diode.

TABLE I
DC CHARACTERISTICS OF SURFACE CHANNEL DIODES AT 298 K

Diode	SC2R1	SC2R2	TE-12
Anode diameter	2.5 μm	2.5 μm	2.0 μm
ΔV(10–100 μA)	71–73 mV	70–72 mV	67 mV
Ideality factor	1.2	1.1	1.1
R_s^*	5–6 Ω	4.5–5.5 Ω	6.8 Ω
V_{br} (@ 1 μA)	4.5–5.5 V	4.5–5.5 V	6.5 V
C_{j0}	5–6 fF	5–6 fF	—
C_{shunt}^{**}	13–15 fF	15–21 fF	—
C_{total}^{**}	18–21 fF	20–27 fF	6.6 fF

*Series resistance was calculated from the dc I–V curve taking $R_s = \Delta V_{(10\ mA-1\ mA)} - \Delta V_{(100\ \mu A-10\ \mu A)/(10\ mA-1\ mA)}$.
**Measured in an open capacitance test fixture.

minimum free-space shunt capacitance of 5.44 fF. It should be noted that the capacitance measurements quoted were made at 1 MHz using an open test fixture. The values of C_{shunt} and C_{total} are therefore much larger than they would be in a millimeter-wave circuit with a grounding plane present beneath the chip (e.g. in microstrip).

III. Mixer RF Measurement System

A. The Mixer Block

The NASA/GISS type-D mixer mount [12] was used to evaluate mixer performance. Individually tuned series and parallel reactance components associated with this mount design permitted impedance matching to the device under test at the signal frequency over most of the Smith chart. A small unattainable region was not significant in the present work. The gold-plated brass block contained two parallel quarter-height WR-10 waveguides. Each waveguide was fitted with a contacting spring-finger-type sliding backshort. The device under test was mounted in a rectangular opening in a fused quartz substrate with a gold stripline circuit pattern. The substrate was supported in a suspended stripline configuration allowing the diode to be positioned across the main waveguide, as shown in Fig. 3. The two waveguides were coupled through this suspended stripline.

B. The RF Measurement System

The system used to determine mixer conversion loss and noise temperature is shown in Fig. 4. Both LO and RF input power were coupled to the mixer block using a resonant-ring diplexer [13]. Local oscillator power was supplied from a Gunn oscillator tunable from 85 to 110 GHz. A gas discharge tube coupled through a 9 dB directional coupler provided a broad-band RF input signal for tuning the mixer. An impedance transformer at the IF output of the mixer block helped to match the mixer output impedance (typically 200 Ω) to the IF power measurement system (50 Ω). The 1.4 GHz output of the transformer was coupled through a 50 Ω coaxial cable to an IF noise radiometer/reflectometer system.

IV. Surface Channel Diode Characterization

A. DC-Excited IF Noise Temperature

The noise temperature of the dc-biased diode, T_D, was measured as a function of bias current using the IF radiometer system depicted in Fig. 4 connected directly to the IF port of the mixer block. Correction for the IF power reflection coefficient, $|\Gamma|^2$, was according to the relation

$$T_D' = T_s|\Gamma|^2 + (1-|\Gamma|^2)T_D \qquad (1)$$

where T_D' is the measured noise temperature and T_s is the equivalent temperature of the noise power from the IF test system incident on the diode under test. A minimum diode noise temperature, T_D, of 220 K was measured at a forward bias current of 0.5 mA.

B. Mixer Conversion Loss and Noise Temperature

Whiskerless diodes from two batches were measured as mixers and the results compared with those of a conventional, whisker-contacted diode (TE-12) of similar epitaxial layer doping which exhibited excellent dc and RF performance. The double-sideband conversion loss and noise temperature of the mixer (and IF transformer) were determined using a measurement method similar to that described by Weinreb and Kerr [14], in which a microwave absorber at ambient and liquid nitrogen temperatures served as input sources to the radiometer shown in Fig. 4. Correction for the mismatch between the mixer output and the 50 Ω IF test set was according to (1). The conversion loss (DSB) is given by

$$L = \frac{T_{in(298\ K)} - T_{in(77\ K)}}{T_{out(298\ K)} - T_{out(77\ K)}}. \qquad (2)$$

The double sideband mixer noise temperature is given by

$$T_{mxr} = LT_{out(298\ K)} - T_{in(298\ K)}. \qquad (3)$$

Results obtained for the surface channel diode, SC2R2, and the TE-12 whisker-contacted diode are shown in Figs. 5 and 6. In each case the LO power and dc bias voltage were adjusted for minimum overall noise temperature (T_{rcvr}). Single-sideband values were determined by multiplying the double-sideband values by 2, assuming a broad-band response.

V. Comparison with Other Mixer Diodes

Tables II and III show published results for mixers operating near 100 GHz using other whisker-contacted and planar

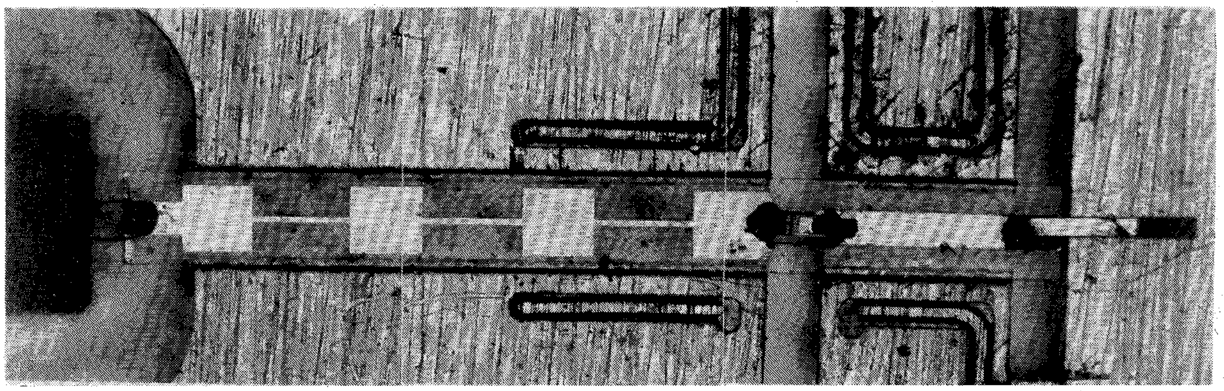

Fig. 3. Photograph of the surface channel diode mounted in the larger quartz substrate. The chip is positioned across the main waveguide channel. The quartz substrate is 580 μm wide.

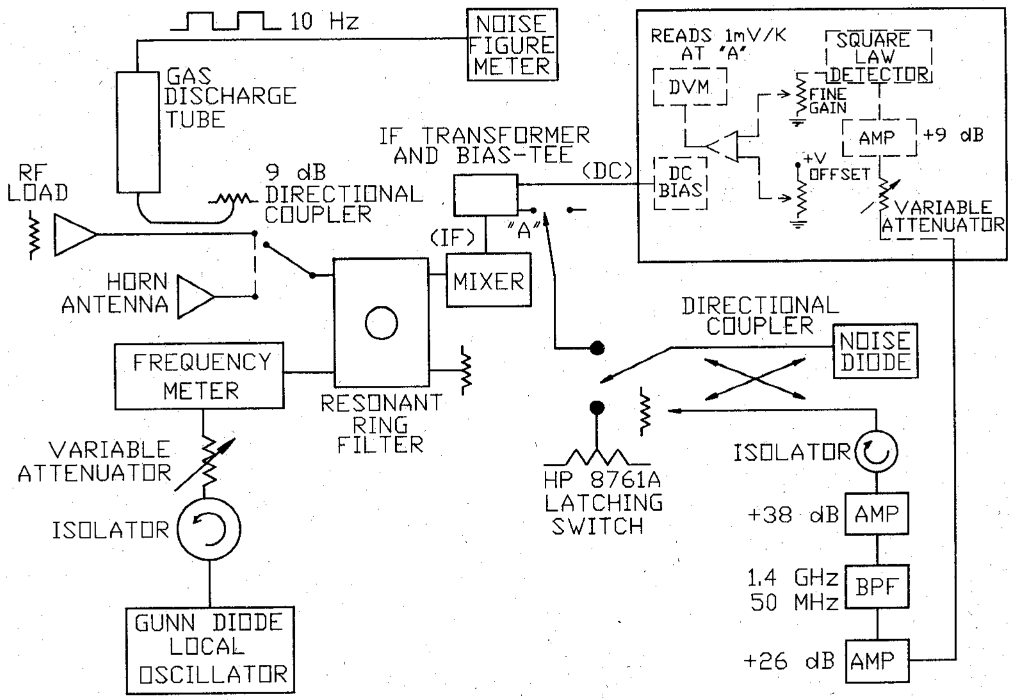

Fig. 4. Schematic diagram of the test system used for mixer noise temperature and conversion loss measurements. The noise figure meter and gas noise tube are used for optimization of the overall receiver noise temperature. Precise measurements of L_{mxr} and T_{mxr} are made using the calibrated DVM temperature readings with liquid nitrogen (77 K) and room-temperature loads in front of the input horn.

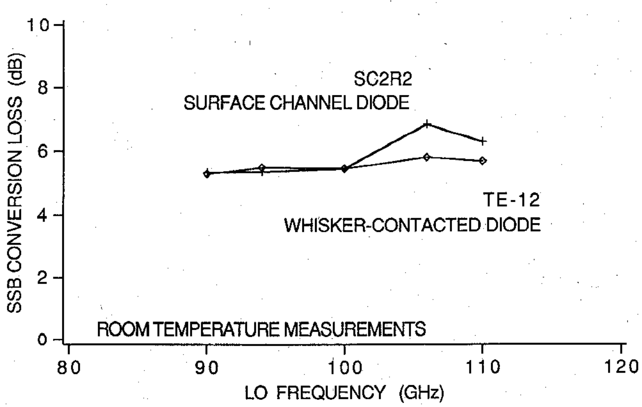

Fig. 5. SSB mixer conversion loss versus frequency for (♦) whisker-contacted TE-12 and (+) surface channel SC2R2 diodes (matched IF). LO power and bias voltage were optimized for minimum T_{rcvr}.

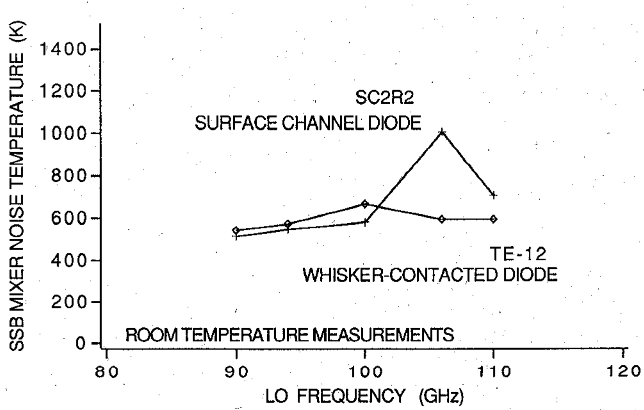

Fig. 6. SSB mixer equivalent input noise temperature versus frequency for (♦) whisker-contacted TE-12 and (+) surface channel SC2R2 diodes (matched IF). LO power and bias voltage were optimized for minimum T_{rcvr}.

TABLE II
SUMMARY OF PERFORMANCE OF ROOM-TEMPERATURE MIXERS OPERATING NEAR 100 GHz USING WHISKER-CONTACTED GaAs SCHOTTKY BARRIER DIODES

Mixer/Diode Type*	LO or Sig. Freq. (GHz)	L_{MXR} (SSB) (dB)	T_{MXR} (SSB) (K)	Date	Reference
WG, SE/BC	115	5.5	500	1975	Kerr [15]
WG, SE/BC	90	5.4	600	1977	Wilson [16]
WG, SE/BC	115	6.2	700	1977	Wilson
WG, SE/BC	106.6	6.2	600	1977	Zimmermann and Haas [17]
WG, SE/BC	112.4	6.1	760	1977	Zimmermann and Haas
ShP, St, Ba/NF	98	7.4	390	1978	Carlson *et al.* [18]
WG, SE/BC	115	5.3	440	1979	Cong *et al.* [19]
WG, SE/BC	113.3	6.3	660	1979	Keen *et al.* [20]
Q, WG, SE/BC	~100	5.6	310	1984	Predmore *et al.* [21]

*Q, quasi-optical; ShP, subharmonically-pumped; M, microstrip; St, suspended stripline; WG, waveguide; SE, single-ended; Ba, balanced mixer; IA, imaging array; BC, back-contacted; NF, notch-front; MIC, monolithic IC; H, hybrid.

TABLE III
SUMMARY OF PERFORMANCE OF ROOM-TEMPERATURE MIXERS OPERATING NEAR 100 GHz USING PLANAR GaAs SCHOTTKY BARRIER DIODES

Mixer/Diode Type*	LO or Sig. Freq. (GHz)	L_{MXR} (SSB) (dB)	T_{MXR} (SSB) (K)	Date	Reference
ShP, St, Ba/H	98	7.7	1600	1978	Carlson *et al.* [18]
St, Ba/H	94	6.0	760	1979	Cardiasmenos [22]
Q, SE/MIC	110	6.8	680	1981	Clifton [6]
(Not described)	94	4.5	440	1981	Calviello *et al.* [5]
(Not described)	110	5.2	670	1981	Calviello *et al.*
M, Ba/MIC	94.5	—	1045[1]	1984	Bauhahn *et al.* [4]
M, SE/H	94	5.9	1030[2]	1984	Mills *et al.* [7]
Q, IA/MIC	91	8.0[3]	—	1985	Zah *et al.* [8]
WG, Ba/MIC	93.7	6.5	—	1986	Jarry *et al.* [23]
WG, SE/H	106	6.2	430	1990	Archer *et al.* [11]
Shp, St, Ba/MIC	86	8.9	1525	1990	Archer *et al.*
WG, SE/H	94	5.3	520	1990	This work

*Q, quasi-optical; ShP, subharmonically-pumped; M, microstrip; St, suspended stripline; WG, waveguide; SE, single-ended; Ba, balanced mixer; IA, imaging array; BC, back-contacted; NF, notch-front; MIC, monolithic IC; H, hybrid.

[1]Bauhahn *et al.* did not state T_{MXR} explicitly. This value was estimated from the receiver noise figure and IF noise contributions given, assuming a SSB conversion loss of 6.0 dB, according to the formula $T_{RCVR} = T_{MXR} + LT_{IF}$.

[2]Mills *et al.* did not state T_{MXR} explicitly. This value was estimated from the receiver noise figure, the IF noise contribution, and the SSB conversion loss given using the formula $T_{RCVR} = T_{MXR} + LT_{IF}$.

[3]Zah *et al.* did not calculate L_{MXR} explicitly. This value was estimated from the data by subtracting coupling losses from overall measured loss so that results could be compared on a uniform basis.

mixer diodes respectively. Each table chronologically lists measured values of single-sideband mixer noise temperature and conversion loss for room-temperature GaAs mixer diodes. In some instances, published double-sideband results have been converted to single-sideband values by multiplying by 2 so that results can be compared on a uniform basis.

VI. CONCLUSIONS

The GaAs surface channel diode has very low parasitic capacitance owing to its unique construction. As a mixer in the vicinity of 100 GHz, it has demonstrated excellent performance: a conversion loss of 5.3 ± 0.5 dB and a mixer noise temperature of 518 ± 50 K at 94 GHz. This compares favorably with the best whisker-contacted mixers in the same frequency range.

While recent experimental development has focused on the mixer diode, other applications for this diode are possible. In particular the surface channel diode is well suited for GaAs microwave and millimeter-wave integrated circuits. Development of varactor multipliers, balanced mixers, and MMIC devices incorporating the surface channel structure is in progress.

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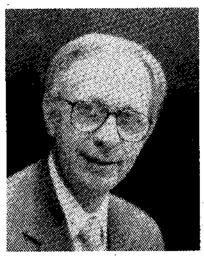

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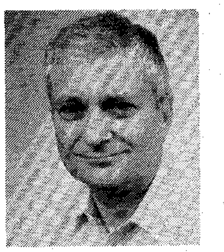

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