

GaAs Schottky Diodes for Atmospheric Measurements at 2.5 THz

Perry A. D. Wood, David W. Porterfield,
William L. Bishop and Thomas W. Crowe

*Semiconductor Device Laboratory
Department of Electrical Engineering
University of Virginia
Charlottesville, VA 22903*

ABSTRACT

OH is an important molecule in the chemistry of the upper atmosphere, and is most easily observed at 2.5 THz. GaAs Schottky diodes are currently the most sensitive heterodyne receiver elements for applications above 1 THz.

The 1T15 is a whisker contacted 0.25 micron anode diameter Schottky diode with an epilayer doping and thickness of 10^{18} cm^{-3} and 300 Å, respectively. At 2.5 THz and an LO pump power of 6 mW, the 1T15 achieved a DSB mixer temperature of 9300K and conversion loss of 13.2 dB. The LO power can be reduced to 3.4 mW with only a 5% increase in receiver noise temperature. It can be further reduced to about 2 mW and still maintain a receiver noise temperature of less than 15000K.

A discussion of improvements for whisker contacted diodes is presented. The use and fabrication of planar diodes at 2.5 THz is also considered.

BACKGROUND

In recent years studies of the upper atmosphere have become a priority for the scientific community. This has come about in part due to concerns about ozone depletion. There are many chemicals and processes involved in the ozone depletion cycle and each one of these must be studied. OH is a particularly important molecule which has yet to be studied on a global basis. This molecule can be most easily measured at 2.5 THz. NASA has planned a Microwave Limb Sounder (MLS) which will be flown as part of the Earth Observing System (EOS) [1]. This mission will require receivers at 215 GHz, 440 GHz, 640 GHz and 2.5 THz. It is the latter frequency that this paper will address.

SIS receivers have made tremendous improvements recently and now outperform Schottky mixers at frequencies up to around 600 GHz [2][3][4]. However, whisker contacted Schottky diodes mounted in a corner cube are the most sensitive detectors at 2.5 THz. The 1T15 Schottky diode, fabricated by the Semiconductor Device Laboratory of the University of Virginia, is a whisker contacted Schottky diode designed for mixing applications above 1 THz. The anode diameter has been reduced to 0.25 microns to reduce the junction capacitance. The epilayer doping density was increased to offset the increase in series resistance that would have resulted from the smaller anode as well as increasing the current where hot-electron noise begins to dominate. Also the epilayer thickness was reduced to

more closely match the thickness of the depletion layer during normal operation. The fabrication and design of the submicron anode diameter diodes is discussed in the literature [5][6].

Planar diodes offer an attractive alternative to whisker contacted diodes. They are inherently more rugged and allow for easier integration of antennas and matching structures. Bishop et al [7] have described the fabrication of such devices. Fabrication issues for 2.5 THz will be presented in a later section.

RESULTS

Three 1T15 diodes were tested at 2.5 THz. The physical specifications for these diodes are given in Table 1. The series resistance was calculated using a three point voltage measurement at 10, 100 and 1000 μA .

The video responsivity for these diodes was measured using a Keating PM103 power meter as a reference. Fig. 1 is a schematic of the optical layout used to measure video

Table 1. Physical specifications of the tested 1T15 diodes.

Diode	Epilayer Thickness (\AA)	Epilayer Doping (cm^{-3})	Series Resistance (Ω)	Zero-Bias Capacitance (fF)	ΔV at 10-100 μA (mV)	Ideality Factor
1T15#47	300	10^{18}	18	0.22	105	1.6
1T15#12	300	10^{18}	20	0.25	102	1.6
1T15#50	300	10^{18}	20	0.27	99	1.6

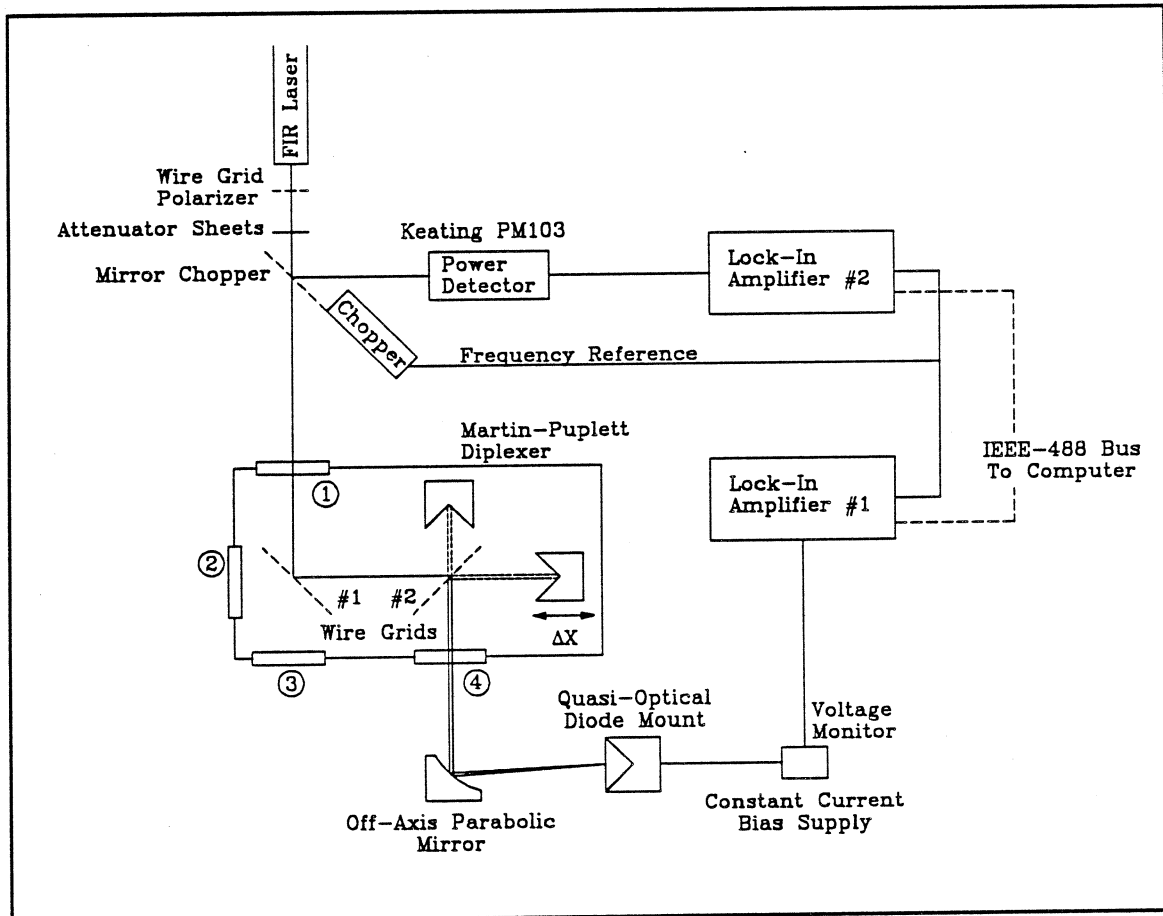


Figure 1. Optical schematic for video responsivity measurements.

responsivity. The distance to the Keating PM103 and to the diode mount were kept the same so that the incident power would be the same on both. All video responsivities were measured with a bias current of $1 \mu\text{A}$. The video responsivities for the three diodes are: 1T15#47, $R_v = 111 \text{ V/W}$; 1T15#12, $R_v = 102 \text{ V/W}$; and 1T15#50, $R_v = 87 \text{ V/W}$. We expect that a diode with a higher junction capacitance will have a lower video responsivity and our data fits this expected trend. However, because of the uncertainties in the capacitance and video responsivity measurements, this trend may be fortuitous.

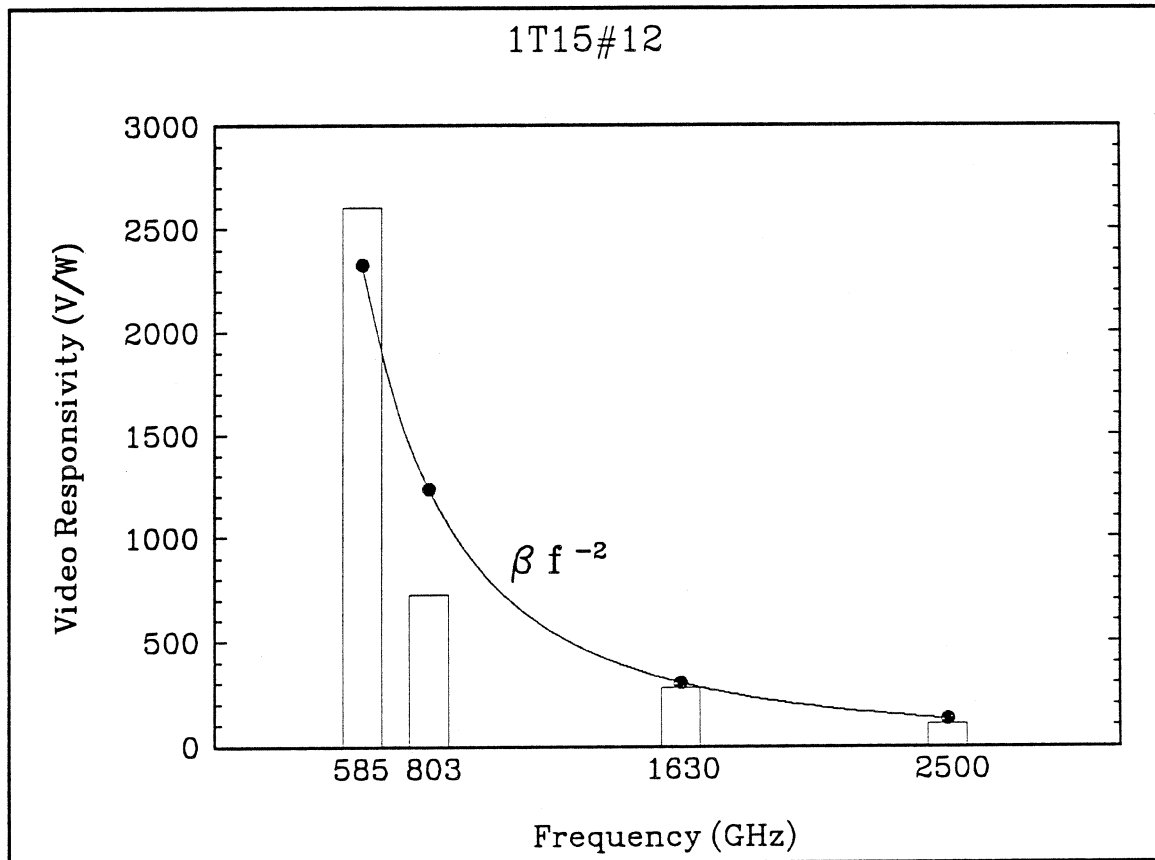


Figure 2. Video responsivity versus frequency for the 1T15#12 diode.

Video responsivity data for the 1T15#12 diode at lower frequencies is shown in Fig. 2. There is an approximate $1/f^2$ decrease in the responsivity as the frequency increases. Video responsivity is a good indicator of LO power requirements as we shall see that the required LO power increases as f^2 .

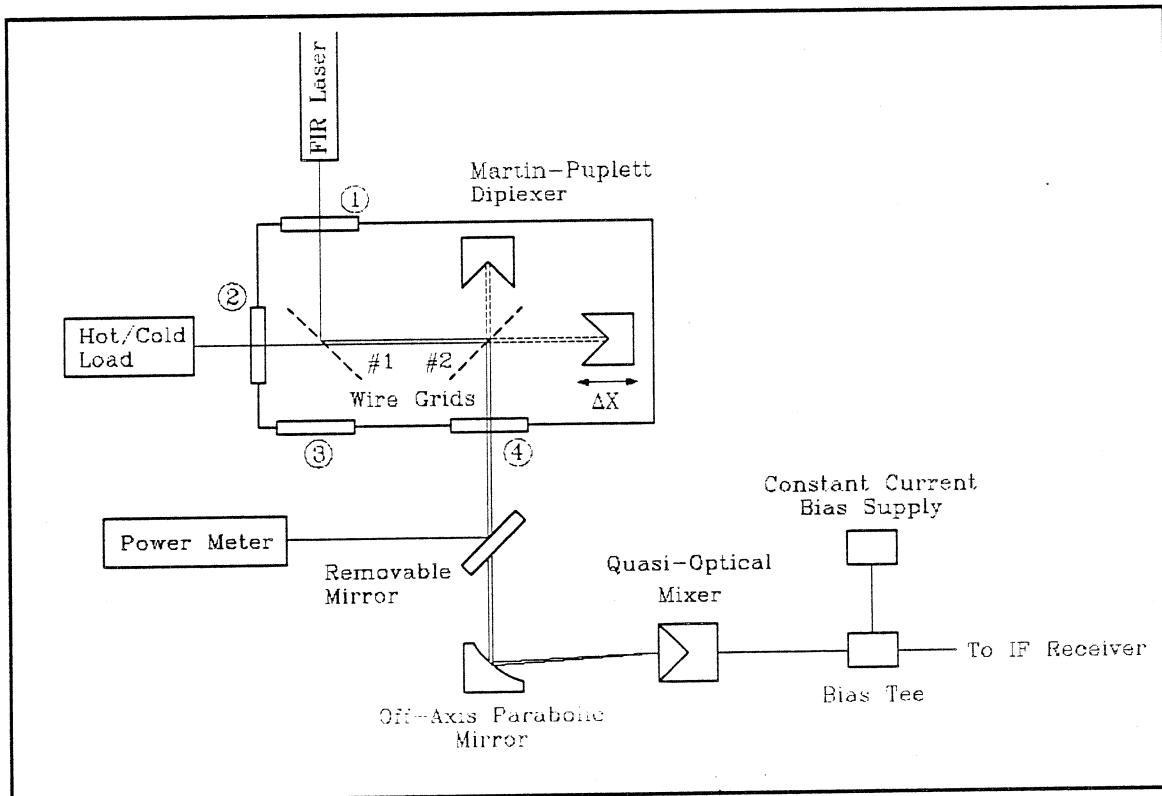


Figure 3. Optical layout used to measure receiver noise temperature.

Receiver noise measurements were made using the optical layout shown in Fig. 3. A Scientech 365 power meter was used because the noise measurements require an unchopped LO and the Scientech 365 meter, unlike the Keating PM103 meter, requires an unchopped signal. The Scientech 365 meter was placed so that the distance from the laser to the power meter was the same as the distance from the laser to the diode. Receiver noise temperature as well as mixer conversion loss and temperature were double sideband measurements. The IF receiver was operated at room temperature and had a noise temperature of 103K. An atmospheric absorption of 1 dB was measured over the signal path. This was calculated from the power difference as measured by the Scientech 365 meter over a 50 cm path length. The

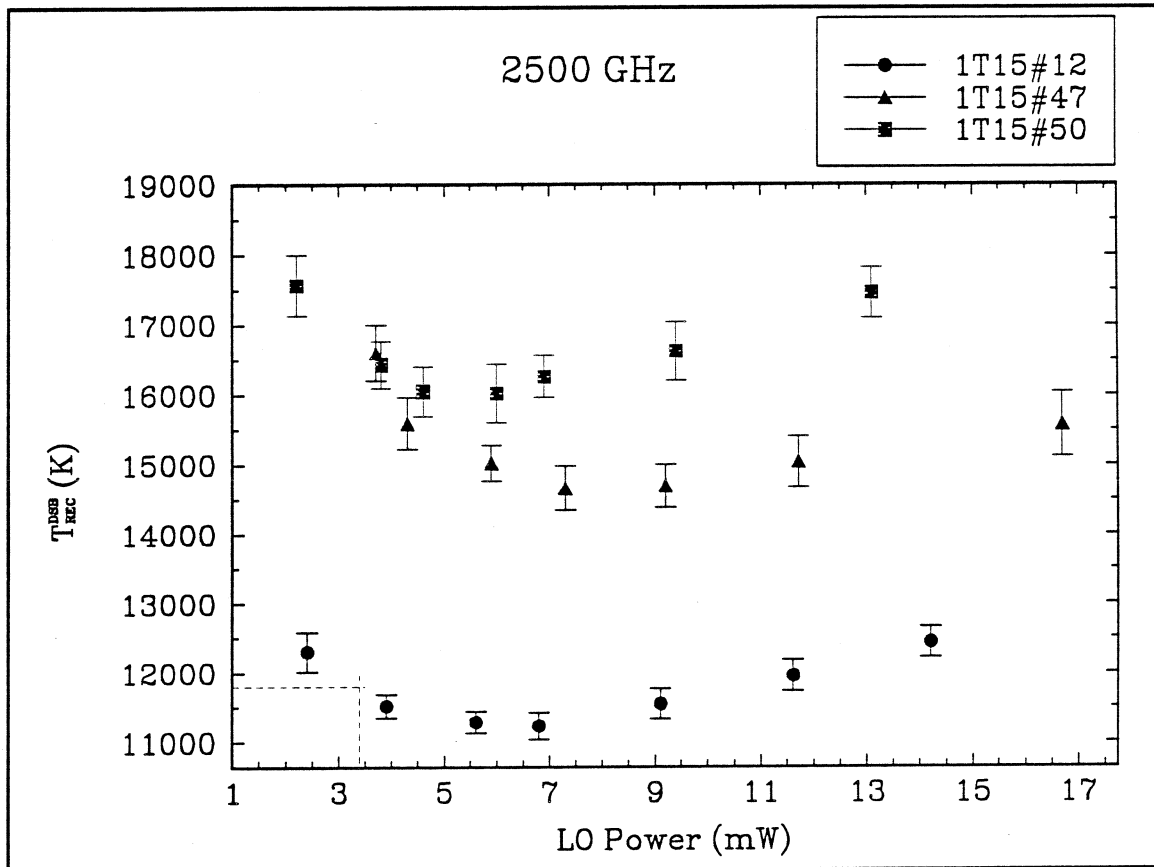


Figure 4. Graph of receiver temperature versus LO power for three 1T15 diodes. The dashed line in the lower left corner represents the minimum LO power for a 5% increase in receiver noise temperature.

hot/cold load was made from room temperature FIRAM (Far Infrared Absorbing Material) and 77K FIRAM. FIRAM, developed at the University of Massachusetts Lowell, is a silicone based anechoic with low reflection at 2.5 THz [8].

The goals for these measurements were to achieve a receiver noise temperature of less than 15000K [9] and to determine the minimum LO power required to realize that result. A graph of LO power versus DSB receiver noise temperature is shown in Fig. 4. The 1T15#12

diode achieved the lowest receiver noise temperature, 11400K. Fig. 4 represents the best contacts out of three attempts for each diode. For the 1T15#47 and 1T15#50, these results were obtained once, while for the 1T15#12 these results were achieved with two different contacts. For all the diodes there was evidence of LO saturation because of the increase in receiver noise temperature at the higher power levels. The dashed lines in the lower left corner of Fig. 4 represent the power level (3.4 mW) where the receiver noise temperature of the 1T15#12 is only 5% higher than the minimum (11400K). We define this as the minimum

Table 2. Mixer results at 2.5 THz

Diode	P_{LO} (mW)	L'_m (dB)	T'_m (K)	T_{rec} (K)
1T15#47	9.6	14.1	12000	14700
	4.9	13.8	11600	14200
	2.3	14.4	12200	15000
1T15#12	6.2	13.1	9300	11400
	2.4	14.1	9900	12600
1T15#50	6.0	15.0	12900	16200

required LO power for optimum performance. Table 2 shows a breakdown of mixer temperature and conversion loss for different power levels. Both the 1T15#47 and 1T15#12 achieve a receiver noise temperature below 15000K even down to power levels near 2 mW. While the 1T15#50 diode had a receiver noise temperature greater than 15000K, it would have been less than 15000K had the IF noise temperature been 65K rather than 103K.

Fig. 5 shows the minimum LO power requirement versus frequency for the 1T15#12 diode. The required LO power increases approximately as the frequency squared. This is the inverse of the video responsivity trend. From this data we conclude that diodes with higher video responsivity generally have lower LO power requirements.

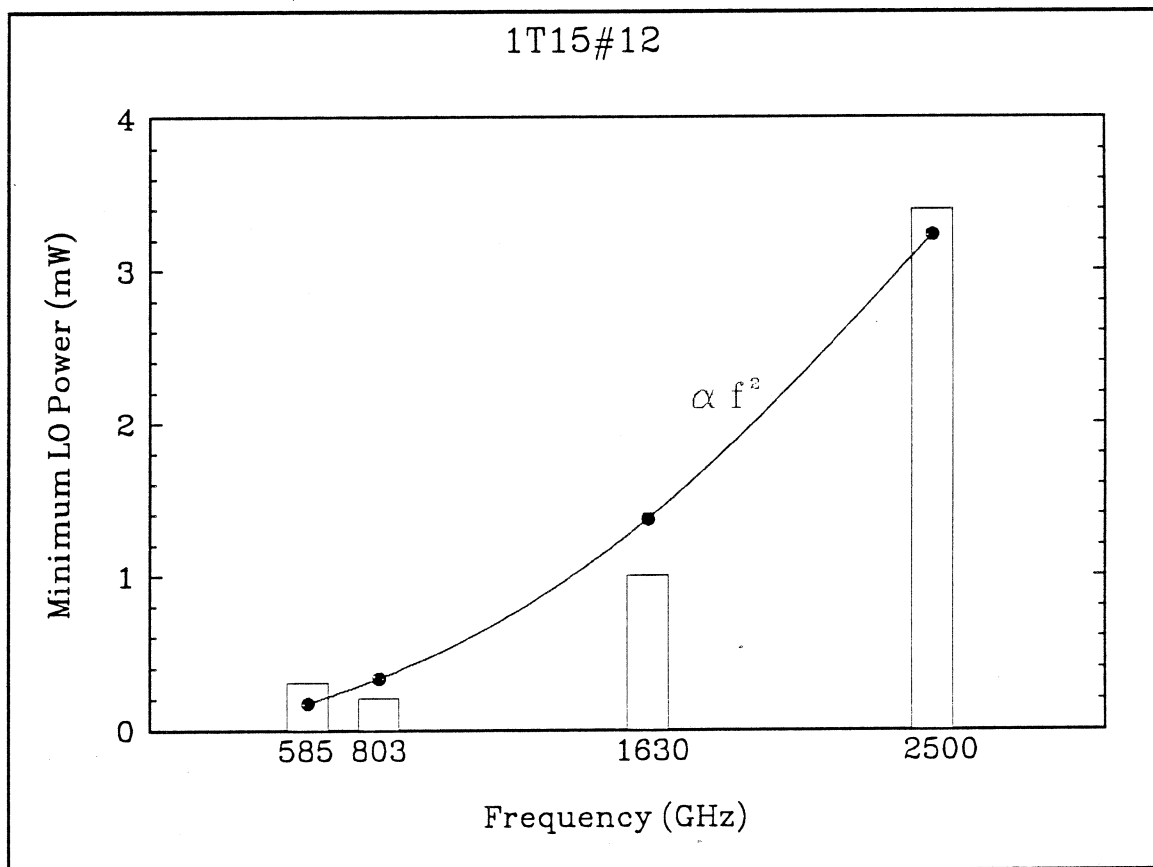


Figure 5. Minimum LO power versus frequency for the 1T15#12 diode.

The corner cube mixer mount has been designed with an IF impedance transformer. This transformer was designed for lightly doped ($2-4 \times 10^{17} \text{ cm}^{-3}$) and higher capacitance diodes. For the 1T15, S_{11} is about -7 to -9 dB. This mismatch was measured for each diode at the optimum operating point (lowest receiver noise temperature). Using the analysis of

Harris et al [10], we can remove the effect of the IF mismatch. To remove only the effect of the IF mismatch, we will assume that the optical coupling is perfect. Then we have;

$$T'_m = L'_m \Gamma^2 T_{t,r} + T_m$$

$$L'_m = \frac{L_m}{1 - \Gamma^2}$$

where L'_m and T'_m are the uncorrected mixer conversion loss and temperature, respectively (see Table 2). $T_{t,r}$ is the temperature of the circulator resistor (300K), Γ is the reflection coefficient and L_m and T_m are the corrected mixer conversion loss and temperature, respectively. This analysis is shown in Table 3. The corrected mixer temperatures are about 10% lower, while the corrected conversion losses are about 0.6 to 0.9 dB lower.

Table 3. Correction for IF mismatch

Diode	Zero Bias C_p (fF)	Receiver Noise T_{rec} (K)	Mixer Noise T_m (K)	Mixer Loss L'_m (dB)	S_{11} (dB)	LO Power (mW)	Corrected Mixer Noise T_m (K)	Corrected Mixer Loss L_m (dB)
1T15#12	0.25	11500	9300	13.2	-8.7	6.2	8500	12.6
1T15#47	0.22	14200	11600	13.9	-7.2	4.9	10300	13.0
1T15#50	0.27	16300	13000	15.1	-9.2	6.0	11800	14.5

DISCUSSION: PLANAR DIODES

Planar diodes are very attractive for space applications because of their inherent ruggedness compared to whisker contacted Schottky diodes. However, they are currently unable to be used at 2.5 THz. To achieve results comparable to whisker contacted diodes, the planar diodes need to be constructed using the same ideas, i.e., decrease the anode diameter to 0.25 microns or less and increase the epilayer doping. Fabricating sub micron anodes is possible, but the fabrication of the integrated antenna and the substrate present a challenge.

The radiation from an antenna on a substrate will be strongest through the higher dielectric substrate. The planar diode is made on a semi-insulating GaAs substrate. Between the metal antenna and substrate is a layer of n+ material. This n+ layer is conductive and therefore introduces losses. As the frequency of operation is increased this layer becomes a more significant parasitic. The n+ layer can be removed or thinned, except in a small area around the anode. This would bring the antenna structure closer to the semi-insulating substrate.

Decreasing the anode diameter is also important. This will present a challenge for alignment during fabrication. The finger across the air gap should be no larger than the anode itself to minimize parasitic capacitance.

CONCLUSIONS

The 1T15 diode is a very sensitive mixer at 2.5 THz. We measured a mixer temperature of 9300K and mixer conversion loss of 13.2 dB with an LO power of 6.2 mW. The minimum LO power for an increase of 5% in the minimum receiver noise temperature is 3.4 mW. The LO power can be further reduced to 2 mW for a receiver noise temperature of 15000K. Operation with small LO powers is important for satellite work where power is tightly budgeted.

Possible changes and improvements for the 1T15 include;

- Decrease the anode diameter: It is possible that a further reduction in anode diameter will improve noise performance and will certainly reduce LO power requirements.
- Improve the IF match: This can decrease the noise by about 10% and the conversion loss by 0.6 to 0.9 dB.
- Better coupling: The corner cube couples about 1/2 of the incident power. Improving the coupling will decrease the LO power requirements and decrease the noise temperature and conversion loss.
- Cooling: Cooling the 1T15 does not appear to alter the IV curve. Since the IV curve has not changed, then the diode should not be any more efficient as a mixer than it was at room temperature.

Planar diodes, though not currently viable at 2.5 THz, will no doubt be improved. The challenges to making efficient planar diodes at 2.5 THz are solvable and are being actively investigated.

ACKNOWLEDGEMENTS

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