GaAs Schottky Diodes for Mixing Applications Beyond 1 THz †

Thomas W. Crowe and W.C.B. Peatman

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

ABSTRACT

In the frequency range from about 600 GHz to over 3 THz, GaAs Schottky barrier diodes are the most sensitive mixer element for use in heterodyne receivers. Although there is hope that superconductor-insulator-superconductor (SIS) junctions will soon replace semiconductor diodes over all, or part, of this frequency range, there are many technological challenges, and perhaps fundamental problems, that must be overcome before this can be achieved. Since there are many scientific research programs that require receivers in this frequency range, and a variety of NASA missions are planned for the near future, it is imperative that the performance and reliability of GaAs diodes be increased to the highest level possible. This paper reviews the performance of heterodyne receivers in this frequency range, discusses qualitatively how the mixer diode limits the receiver performance, considers potential improvements to receiver performance, and overviews research at the University of Virginia. The paper begins with a very brief overview of the previous research that has lead to the present Schottky technology.

I. BACKGROUND

A great deal of research has been necessary to bring GaAs Schottky technology to the point where it is suitable for use in THz receiver applications. Although it is beyond the scope of this paper to outline this research in detail, it is helpful to acknowledge several of the major milestones. The first such milestone was the initial development of the "honeycomb" Schottky diode by Young and Irvin in 1965 [1]. This work used modern photolithographic technology to

define the metal-semiconductor junction in a reproducible and controlled manner. Their basic chip design, shown in Fig. 1, is still in use today, mainly because the whisker contact adds minimal series resistance and shunt capacitance to the diode circuit. In addition, microwave engineers have used the whisker to couple the high-frequency radiation into the diode, and have even used the whisker inductance to tune out part of the shunt capacitance.

Once the basic chip design of Young and Irvin was recognized as a suitable structure for high-frequency receivers, many groups began investigations to determine the optimum design for the GaAs epitaxial layers and to improve the fabrication technologies. Major contributions to this work were made by over a dozen research teams including those at Bell Labs, MIT, University College in Ireland, Chalmers University in Sweden, and the University of Virginia. Theoretical research has resulted in a great advance in the understanding of electronic conduction in the diode, including the effect of electron tunneling on the IV curve [2] and the increase in series resistance due to the skin effect [3] and plasma resonance [4]. The generation of noise in the diode was intensively studied by many groups, culminating in the *Unified Noise Theory* of Viola and Mattauch [5], which was later extended to include the so called hot-electron noise [6]. Modern fabrication technology allowed the reduction of the anode size and vastly improved control of the thickness and doping concentration of the epitaxial layer, reducing junction capacitance and series resistance. The fabrication of highly reliable metal-semiconductor
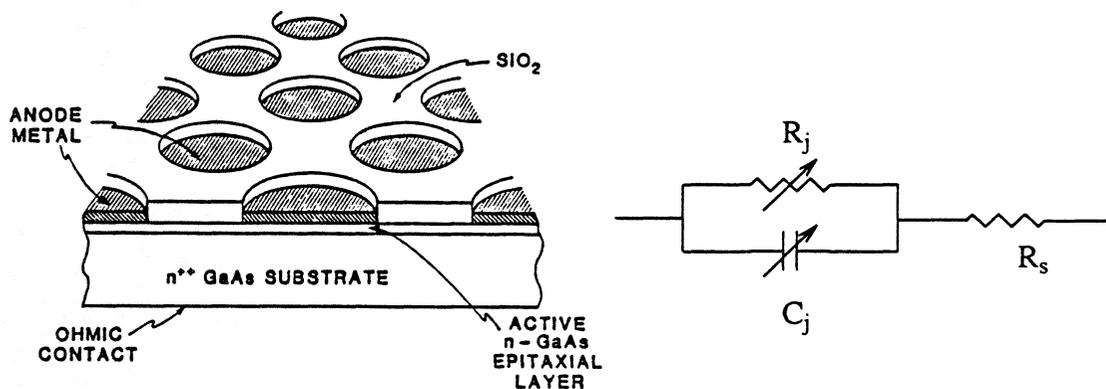
Fig. 1. A cross-section view of a typical Schottky diode chip and an equivalent circuit.

interfaces was seen as a major prerequisite to the fabrication of devices without excess noise, and many papers were written on this subject [7,8,9,10].

Research by Kerr and his colleagues lead to the development of a powerful computer program that predicts the performance of a heterodyne receiver once the fundamental properties of the mixer element and the RF circuit are known [11,12]. This analysis is used not only by receiver designers, but also by device designers, in an effort to understand how to optimize the mixer element for higher frequencies. The program has since been extended to incorporate greater understanding of the operation of the diodes at THz frequencies [13,14].

The coupling of RF radiation into the diode has always been a problem. The major advance that lead to the first THz receivers was the development of the corner-cube mixer, initially proposed by Kräutle [15]. Although the corner-cube is often maligned for its poor efficiency and difficult use, it remains the best structure for THz Schottky receivers, and minor changes have been made to improve reliability and coupling to the IF amplifier [16,17]. There have been several attempts to develop planar Schottky diodes that eliminate the whisker contact and use integrated antenna structures [18,19,20,21]. However, this work is only now becoming successful at millimeter and long-submillimeter wavelengths.

Molecular gas lasers have been developed as suitable local oscillators for heterodyne receivers throughout the submillimeter wavelength range [22,23]. Although these systems are large, power inefficient, and require excessive maintenance and tuning, lasers are the only sources available that generate sufficient power with low noise and high spectral purity throughout this wavelength range.

The current status of heterodyne receivers employing Schottky diodes is summarized in Table I. The frequency coverage is from 300 GHz through nearly 3 THz. It is clear that the noise temperatures are well above the quantum limit. It is important to ask why this is so and to determine what limits the sensitivity of these receivers.

II. LIMITATIONS TO THE PERFORMANCE OF SCHOTTKY RECEIVERS

A simplified block diagram of a heterodyne receiver is shown in Fig. 2. The receiver noise temperature is essentially determined by the signal losses and the noise generated within the system. The major losses occur between the antenna and the mixer, within the mixer itself, and between the IF amplifier and the mixer. The major sources of noise are the mixer diode, the IF amplifier and thermal noise from passive components. For the purposes of this paper, we will neglect noise and losses from passive components and the receiving antenna.

Table I: Submillimeter Wavelength Performance of Some Whisker Contacted Schottky Barrier Mixer Diodes					
ν_{RF}(GHz)	T_{rec}^{SSB} (K)[†]	ν_{IF}(GHz)	BW_{IF}(GHz)	Temp.(K)	Reference
326	1900	1.4	1	300	Röser, 1986 [17]
460-490	1740	1.45	0.3	20	Keen, 1986 [42]
693	4850	1.4	1	300	Röser, 1986 [17]
800	6300	6.4	1	77	Harris, 1989 [24]
1,963	21,000*	6.7	0.2	77	Boreiko, 1989 [43]
2,520	17,000	1.4	1	300	Röser, 1986 [17]
2,528	31,000*	-	-	77	Betz, 1990 [32]

† *In order to express all of the data in a uniform manner it is assumed that* $T^{SSB} = 2T^{DSB}$ *when the values are quoted as DSB in the references.*

* *Measured on the Kuiper Airborne Observatory.*
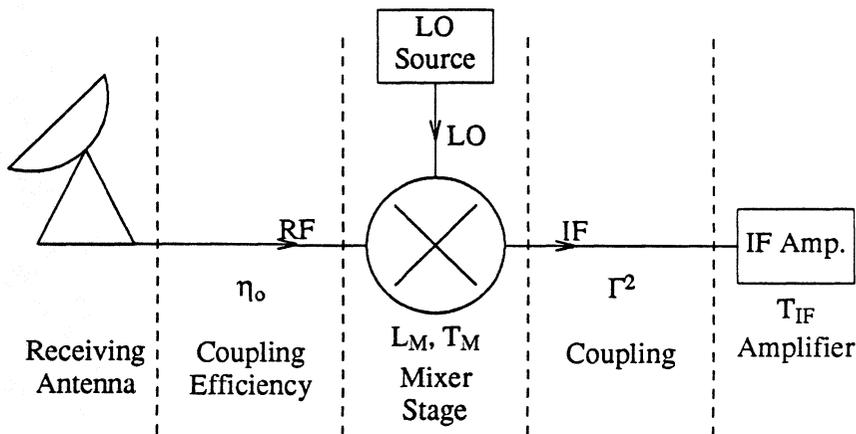
Fig. 2.   A simplified block diagram of a typical heterodyne receiver.

To determine the best method to optimize the receiver it is useful to consider the breakdown of receiver noise. A recent paper by Harris [24] has closely analyzed the noise of a Schottky heterodyne receiver at 800 GHz. They have achieved a receiver noise temperature of 6300 K single-sideband [t]. They express the receiver noise temperature in terms of an effective mixer temperature, T_m', and an effective mixer conversion loss, L_m',

$$T_{rec} = T_M' + L_M' T_{IF} \qquad (1)$$

where T_{IF} is the noise temperature of the IF amplifier. The effective mixer noise temperature and conversion loss are defined as

$$T_M' = L_M' \Gamma^2 T_{t,RJ} + \frac{L_o T_M}{\eta_o} \qquad (2)$$

$$L_M' = \frac{L_o L_M}{\eta_o (1 - \Gamma^2)} \qquad (3)$$

where

η_o is the RF coupling loss due to the corner-cube antenna efficiency, 0.5
L_o is the matched optical resistive loss factor, 0.86
Γ^2 is the mismatch reflection coefficient between the mixer and the IF amplifier, 0.25
$T_{t,RJ}$ is the effective Rayleigh-Jeans temperature of the isolator used
between the mixer and the IF amplifier, 58K

and L_M and T_M are the true mixer conversion loss and noise temperature. The mixer noise temperature is caused by the noise generated in the diode, but is also a function of the losses in the mixer [25],

$$T_M = (L_M - 2) T_{D,eff} \qquad (4)$$

where $T_{D,eff}$ is the effective diode noise temperature at the IF while the diode is dc biased and pumped by the LO. This is a function of both the shot and hot-electron noise in the diode. The calculated value of $T_{D,eff}$ for this case is 630K. At millimeter wavelengths, values as low as 50K have been reported [26]. However, it will be shown below that such a low value cannot be achieved at THz frequencies.

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[t] In this paper we will use single-sideband noise temperatures and conversion losses. All double-sideband values taken from the literature are converted to single-sideband by multiplying by two.

Table II shows how the receiver noise can be reduced by improving the various system parameters. We have tried to assume optimum values that do not violate any fundamental principles, but it is by no means clear that such values can actually be achieved. This table indicates that T_{IF} and Γ^2 have only a small effect, while the other terms are considerably more important. The mixer conversion loss is the product of two distinct terms which are not separable by this type of empirical analysis. These are the actual loss incurred in the mixing process, $L_{M,d}$, and the losses incurred due to the impedance mismatch between the diode and its antenna at the signal frequency, $L_{M,c}$. The assumed ideal value $(L_M=2)$ is the best that can be achieved with a real, resistive mixer with zero coupling loss [25].

III. OPTIMIZATION OF SCHOTTKY DIODES FOR THz FREQUENCIES

The three terms that contribute most to the receiver noise temperature are the efficiency of the corner-cube antenna, the mixer conversion loss, and the diode noise. In this section we will consider the possible reduction of each of these terms.

A. Diode Noise

To discuss the reduction of $T_{D,eff}$, we will consider two very successful diodes, whose parameters are shown in Table III. The 2P9 has achieved shot-noise-limited performance at millimeter wavelengths [26] and the 1E7 has been very successful at frequencies near 1 THz. The 1E7 is also the same diode used by Harris [24]. Fig. 3 shows the noise temperature of these diodes as a function of dc current at 1.4 GHz. At low currents, the junction impedance is much

Table II: Contribution to the Noise of a Schottky Receiver at 800 GHz					
Parameter	L_M^{SSB}	η_o	Γ^2	$T_{D,eff}(K)$	$T_{IF}(K)$
Estimated Value	7.1	0.5	0.25	630	36
Assumed ideal value	2	1	0	100	1
ΔT_{rec} (K)	-6090	-3150	-382	-4690	-584

Table III: Comparison of Two Schottky Diodes

Batch	Diameter (μm)	doping (cm^{-3})	R_s (Ω)	C_{jo} (fF)	ΔV (mV)	V_{co} (THz)
2P9	2.5	3×10^{16}	12	6.5	66	2
1E7	0.8	2×10^{17}	12	1.4	73	9
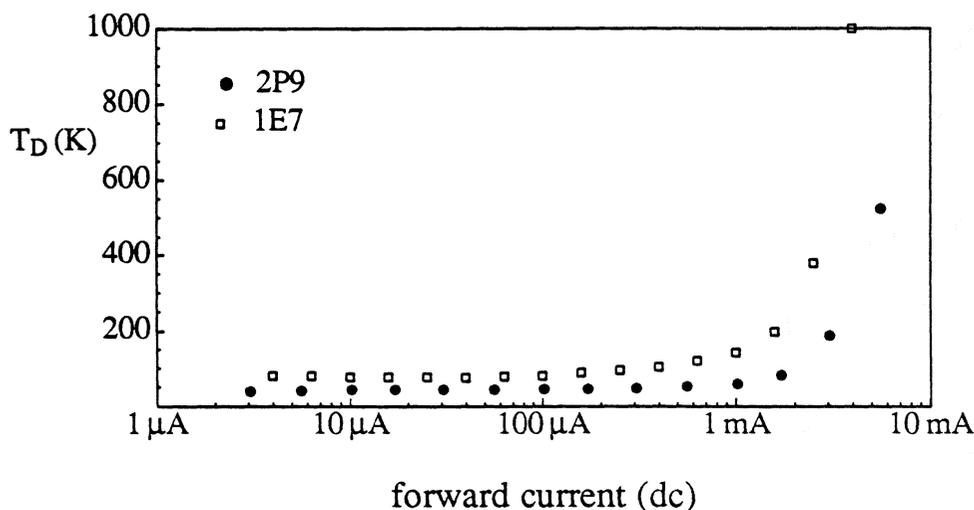
Fig. 3. *The equivalent noise temperature of two Schottky diodes as a function of dc current. The noise was measured at 1.4 GHz with a noise reflectometer*

larger than the series impedance of the diode and the junction shot-noise dominates, yielding a nearly constant noise temperature [5]. As the current is increased the junction resistance is decreased exponentially and the series resistance becomes significant. Also, the electron distribution in the series resistance becomes heated, causing a rapid increase in the diode noise temperature, the so called hot-electron noise [6]. Clearly, it would be beneficial for receiver performance if the diode could be used in such a manner that the current never approached the range where the hot-electron noise becomes significant. The 2P9 diode has achieved this goal at 100 GHz, and the result is shot-noise-limited performance with $T_{D,eff} = 50$ K [25].

If the 2P9 diode is used at significantly higher frequencies, the junction capacitance will short the junction resistance over a larger current range, forcing the higher current portion of the diode IV curve to be used for mixing. This will cause the hot-electron noise to have a greater

effect and $T_{D,eff}$ will increase. Although, we can make the diode area smaller, thereby reducing the junction capacitance, this will also increase the series resistance, making the hot-electron noise turn-on at a lower current level. The only way to achieve shot-noise-limited performance at higher frequencies is to increase the doping density in the epitaxial layer, thereby reducing the $R_s C_{jo}$ product [27]. Comparing the 1E7 diode to the 2P9, the epilayer doping density is increased by roughly an order of magnitude. This has reduced the $R_s C_{jo}$ product by a factor of about five, but has also increased the shot-noise, as seen in Fig. 3. This is directly attributed to increased tunneling current caused by the higher doping density [2]. However, since Harris reports $T_{D,eff}=630\,K$, the doping density of the 1E7 must be increased to an even higher level, if shot-noise-limited performance is to be achieved at 800 GHz. To summarize, as the frequency increases, the doping density must be increased to reduce the $R_s C_{jo}$ product. This causes the shot-noise to increase, so that even though shot-noise-limited performance is achieved, the receiver noise temperature increases with frequency.

Mixer Conversion Loss

From the above argument, it is clear that to increase the cut-off frequency the epilayer doping density must be increased. The choice of the anode diameter has only a secondary effect on the cut-off frequency, but a major impact on the coupling between the diode and its antenna. The impedance of the corner-cube antenna as seen by the diode is roughly 145 Ω [28]. As the frequency is increased, the effect of the junction capacitance becomes more pronounced and the total diode impedance is reduced, making coupling to the corner-cube more difficult. For example, we would like to bias the diode and adjust the LO power so that the small-signal junction resistance is nearly 145 Ω. However, at 1 THz a 2 fF junction capacitance would have an impedance of only j80, effectively shunting the junction resistance. Thus, the junction capacitance must be reduced.

The 1E7 diode has a much smaller anode than the 2P9, and therefore its capacitance is smaller. As can be seen from Fig. 3, this also causes the hot-electron noise to turn-on at a lower current. However, since the lower capacitance allows the diode to be used at lower voltages, this is not a problem and the increased small-signal junction impedance will improve coupling to the antenna. However, the capacitance of the 1E7 is still large enough to cause a substantial amount of signal power to be shorted around the junction, particularly when we acknowledge that the junction capacitance at forward bias is substantially larger than the zero-bias value. Therefore, it is expected that the diode conversion loss will be reduced by a further reduction in anode diameter.

For each frequency there is an optimum anode diameter - epitaxial layer doping pair. Typically, the determination of these values has been achieved empirically, although it is clear that the trends at higher frequency must be smaller anodes and higher doping. This optimization is particularly challenging at THz frequencies, where effects such as charge carrier inertia, dielectric relaxation, and the skin effect become significant, and diode design is limited by the fabrication technology. Although modern electron-beam lithography has been used by industry to fabricate tenth micron lines, high-quality Schottky diodes have only been fabricated with anode diameters as small as 0.4 microns [29].

Antenna Efficiency

The corner-cube mixer has only about 50% antenna efficiency, causing the receiver noise temperature to be about a factor of two higher than would be possible with ideal coupling. Although this is quite poor in comparison to waveguide mixers, it is still the best that is commonly achieved at THz frequencies. Since planar Schottky diodes are now available, it would seem that the integration of an optimized planar diode with a high efficiency planar antenna should lead to significant improvement. Also, such an integrated structure could easily evolve into an array technology that would significantly reduce observing time. Part of the reason that

this has not yet been achieved is a lack of close interaction between the device and RF researchers. Hopefully, this situation will be overcome in the near future.

Potential Receiver Performance at 800 GHz

If we assume the breakdown of noise contributions in the 800 GHz receiver described by Harris [24], it should be possible to design a diode that will significantly improve performance. The goal of this sub-section is to make reasonable assumptions about how the diode can be improved and predict a possible receiver noise temperature. The 1E7 diode has a shot-noise temperature of less than 100 K, but an effective noise temperature of 630 K, implying that the hot-electron noise is having a great impact. This can be alleviated by significantly increasing the epitaxial layer doping density. Although this will increase the shot-noise temperature, the elimination of the hot-electron noise will be more significant. If we assume the new diode has an ideality factor of 1.5 at room temperature (a reasonable guess for high doping density), the shot-noise temperature will be roughly 225K [5]. Assuming shot-noise-limited performance yields $T_{D,eff}=225$ K, which will reduce the receiver temperature to 2800 K (SSB).

The next improvement should come in the mixer conversion loss, which is estimated to be 7.1 (8.5 dB). The increase in doping, mentioned above, should increase the cutoff frequency, thereby improving $L_{M,d}$. Also, if the anode diameter is reduced sufficiently the coupling between the diode and the corner-cube antenna should also be improved, reducing $L_{M,c}$. Although it seems reasonable that L_M can be reduced, it is difficult to estimate how much. For the sake of this discussion, a value of $L_M=6$ is assumed. In combination with the reduction of $T_{D,eff}$, this yields a receiver temperature of 2,244 K (SSB).

The final significant improvement is in the antenna efficiency. It is doubtful that the corner-cube efficiency can be significantly improved. However, if we assume that a planar diode can be developed with an integrated planar antenna, it is possible that a large improvement may be possible [30]. If we assume an efficiency of 75%, the receiver temperature is reduced to 1500

K (SSB). This is a factor of four better than the present value and is roughly 40 hv/k. Although, a significant amount of work is necessary before this is achieved, none of the assumptions are unreasonable and we consider these proposed improvements to represent our design goals.

IV. RESEARCH AT THE UNIVERSITY OF VIRGINIA

The University of Virginia Semiconductor Device Laboratory is involved in the research of GaAs Schottky diodes for THz applications. This includes theoretical evaluation of device operation, design of optimized diodes for high-frequency applications, research of fabrication technologies for improved devices, and the fabrication and evaluation of prototype diodes. Presently, these prototype devices are in use around the world for a variety of applications, with radio astronomy being the most common. In this section several of the individual research projects are outlined.

Theoretical Analysis of THZ conduction in the GaAs Substrate

A computer program that determines the electromagnetic fields in the diode chip and performs a very accurate calculation of the diode series impedance has been developed [31]. This is the first such analysis that accurately incorporates all of the known phenomena at THz frequencies, including skin effect, charge carrier inertia, dielectric relaxation and the distributed nature of the series impedance. It is also the first analysis to accurately consider real diode structures that have nonideal ohmic contacts and epitaxial layers of lower doping than the substrate. This has led to proposed diode designs that are optimized for frequencies as high as 5 THz, shown in Table IV.

We have used a mixer analysis program [11,12] to evaluate mixer performance to frequencies as high as 1 THz. This was made possible by the extension of the diode noise model to include the correlated components of the diode's hot-electron noise [14]. We are presently working to improve the diode model to include the accurate analysis of the high-frequency series

Table IV. Optimized Schottky Diodes for THz Operation			
frequency	1 THz	3 THz	5 THz
anode diameter	0.50 μm	0.20 μm	0.15 μm
epilayer thickness	0.046 μm	0.033 μm	zero
epilayer doping	1.0×10^{18} cm^{-3}	2.0×10^{18} cm^{-3}	-
R_s	15.3 Ω	35.7 Ω	40.8 Ω
X_s	9.9 Ω	53.1 Ω	82.0 Ω
C_{jo}	0.74 fF	0.19 fF	0.16 fF
f_{co}	14 THz	23 THz	25 THz

resistance. This should extend the useful range of the mixer analysis program to at least 5 THz and should greatly facilitate diode optimization.

Fabrication of Whisker Contacted Diodes

We have performed extensive research on the fabrication of prototype diodes for experimental evaluation and use in scientific applications. We have fabricated diodes with anode diameters as small as 0.4 microns and figure-of-merit cut-off frequencies as high as 15 THz. A summary of the characteristics of several recent diode batches is given in Table V. These diodes have lead to consistently decreasing noise temperatures throughout the 1-3 THz range [32]. Also, these new diodes have had the added benefit of requiring less LO power than previous diodes[33]. The reduced LO power requirement is achieved because the smaller anode diameter improves the coupling of both the signal and the LO from the corner-cube antenna to the diode. This work is continuing with the goal of fabricating the diodes described in Table IV. We are also developing a fabrication technology for membrane diodes that will eliminate the skin effect component of the substrate resistance, significantly increasing the cut-off frequency.

Fabrication of Planar Diodes

The Semiconductor Device Laboratory is vigorously pursuing research of planar diode structures that are leading to the replacement of whisker contacted diodes [34,35,36,37].

Scanning electron micrographs of two recent diode chips are shown in Fig. 4 and characteristics of several recent batches are given in Table V. We have fabricated single anode diode chips that are competitive with whisker contacted diodes at millimeter wavelengths [35]. We have also recently developed a dual-diode chip structure which integrates an anti-parallel pair of anodes. This yields an anti-symmetric IV characteristic, which is ideal for subharmonically pumped mixing. This device has yielded excellent results at 183 GHz [37] and is being scaled to 640 GHz for use in a radiometer for the Eos Microwave Limb Sounder.

Investigation of Varactor Diodes

We have also begun to focus attention on varactor diodes. These diodes are used to multiply the output from a solid-state source, typically a Gunn diode, to a higher frequency. The goal is to achieve sufficient power for use as local oscillator sources through the submillimeter wavelength range, replacing the molecular gas laser with a reliable, light weight, and cost effective solid-state source. Standard varactors have been developed that have generated suitable amounts of power up to 600 GHz [38,39]. A novel δ-doped diode has been developed to increase the sharpness of the diode capacitance-voltage characteristic [40]. This will increase the efficiency of high-frequency multipliers when the available input power is small. Our first planar varactor diodes have also been fabricated. These have generated milliwatt power in a tripler to 275 GHz with encouraging efficiency [41]. This work will be expanded in the near future to consider series arrays of varactors to increase power handling ability and novel varactor structures.

V. SUMMARY AND FUTURE WORK

A great deal of work by many researchers has led to the development of heterodyne receivers based on GaAs Schottky diodes that are suitable for use throughout the submillimeter wavelength range. Although Schottky receivers will not approach the quantum noise limit, this is the most sensitive technology throughout most of this frequency range. Thus, it is important to consider methods to improve the performance of these receivers.

Table V: Recent Diode Batches							
Whisker Contacted Diodes for THz Frequencies							
Batch	Diameter (μm)	doping (cm^{-3})	R_s (Ω)	C_{jo} (fF)	ΔV (mV)	V_{br} (V)	ν_{co} (THz)
1T9	0.9	2×10^{17}	11-12	1.4	71-72	>5.5	10
1T11	0.4	4×10^{17}	25 ± 5	0.4-0.5	80 ± 1	>4	14
1T12	0.5	4×10^{17}	25 ± 5	0.45-0.55	79 ± 1	>4.5	13
Recent Planar Diode Batches							
Batch	Diameter (μm)	doping (cm^{-3})	R_s (Ω)	C_{jo} (fF)	ΔV (mV)	V_{br} (V)	C_T (fF)
SC2R4	2.5	2×10^{17}	5.5	6	70	5-6	10
SQ2S1	2.5	3×10^{17}	3	8	72	5-6	5
SC2T1	1.5	2×10^{17}	10	3	72	6	10
SD2T3	1.5	2×10^{17}	7.4	4.5	72	6	19
SR2T1	1.2	2×10^{17}	6.3	3.0	72	4	9.5
SD1T1*	<1.2	2×10^{17}	11	-	73	6.5	-
SD1T2*	<1.2	2×10^{17}	12.5	-	73	-	-
Denotes preliminary data.							
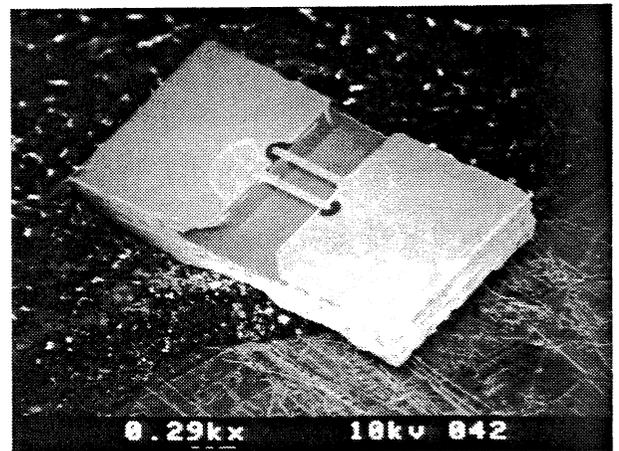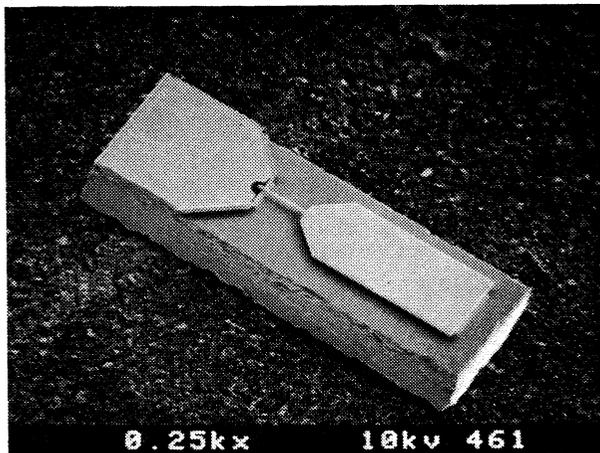
Fig. 4.   *Scanning electron micrographs of a planar diode (SC2T1) with junction capacitance of only 3 fF and total capacitance of 13 fF (left) and a dual-anode diode chip (SD2T3) for subharmonic mixing (right).*

Our research goals for the continued improvement of Schottky diodes at THz frequencies are as follows:

1) Fabricate diodes following the design rules given in Table IV for 1-5 THz. This requires anode diameters as small as 0.15 micron.

2) Fabricate diodes that are shot-noise-limited to as high a frequency as possible. This will be achieved first in the 600 - 800 GHz range, and then at higher frequencies.

3) Continue to investigate the RF coupling between the diode and the corner-cube antenna and develop methods to improve the coupling where possible. This can be achieved either by increasing the impedance of the diode or reducing the impedance of the antenna.

4) Develop planar diodes for THz applications. This will involve research of novel fabrication technologies and integrated antennas.

Through work in these four areas we will continue to increase the sensitivity of heterodyne receivers. A proposed set of goals should result in a single-sideband receiver temperature of 1500 K at 800 GHz (approximately 40 hv/k). Similar improvements should be expected at higher frequencies, provided suitable fabrication technology can be developed.

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