GaAs Schottky Barrier Diodes for Space Based Applications at Submillimeter Wavelengths †

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ABSTRACT

Recent technological advances have made possible the development of heterodyne receivers with high sensitivity and high spectral resolution for frequencies up to 3,000 GHz (3 THz). These receivers, which rely on GaAs Schottky barrier mixer diodes to translate the high-frequency signal to a lower frequency where amplification and signal processing are possible, have found a variety of important scientific applications. Recently there has been a great deal of interest in developing submillimeter wavelength receivers for space based applications involving both radio astronomy and remote sensing of the Earth's atmosphere. Such receivers must be much more compact, reliable and power efficient than those presently available. This will be achieved through the development of a new generation of planar Schottky diodes that will be driven by solid-state local oscillator sources and have parasitic capacitances as low as those of the best whisker contacted diodes. This paper reviews the status of submillimeter wavelength heterodyne receivers and the ongoing work at the University of Virginia which is focussed on the development of improved diode structures.

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I. INTRODUCTION

Technological advances have made possible the development of heterodyne receivers with high sensitivity and high spectral resolution for frequencies up to 3,000 GHz (3 THz) [1,2,3]. These receivers are opening a major region of the electromagnetic spectrum to spectroscopic investigation and are thus having an important impact on radio astronomy. They are also finding increasing applications in fields such as plasma diagnostics, chemical spectroscopy and remote sensing of the Earth's atmosphere. Recently there has been a great deal of interest in the development of receiver systems that are suitable for deployment in satellites. Such a space based system would clearly be an advantage for submillimeter wavelength radio astronomy and investigation of the Earth's upper atmosphere. This paper is an attempt to review briefly the current state-of-the-art of submillimeter wavelength Schottky diode receivers and consider the development that is needed for these receivers to be suitable for space based applications. The ongoing research at the University of Virginia is highlighted.

A simplified block diagram of a heterodyne receiver is shown in Fig. 1. The receiving antenna and optical components couple the signal and local oscillator (LO) power into the mixer structure. The mixer consists of a non-linear element that "mixes" these two frequencies to

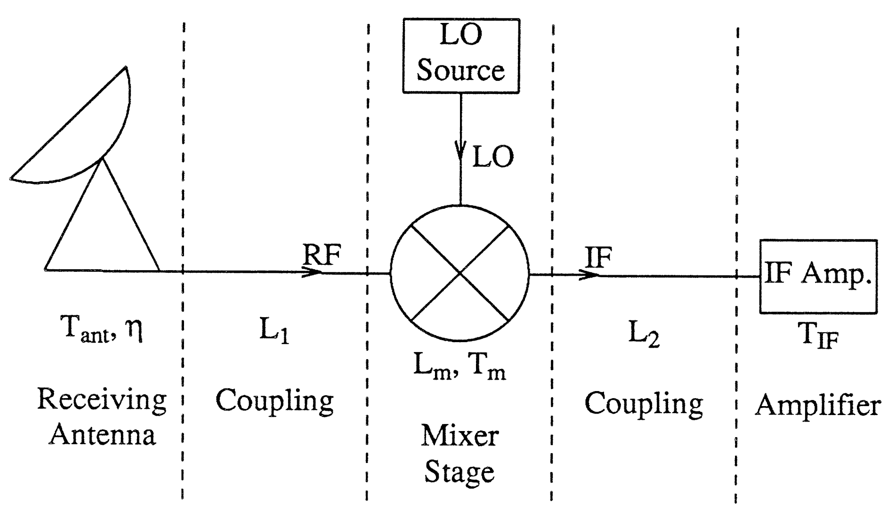

Fig. 1. A simplified block diagram of a typical heterodyne receiver.

generate the intermediate frequency, ν_{IF}, given by

$$\nu_{IF} = |\nu_{sig} - \nu_{LO}| . \quad (1)$$

If the LO source is spectrally pure, the resulting IF signal will have the same frequency spectrum as the original signal, except that it will be at a much lower center frequency that can now be amplified and analyzed by standard microwave techniques. The first stage of the IF amplifier is typically either a cooled GaAs FET or a high electron mobility transistor[4].

The most important figure-of-merit of the receiver is the system noise temperature, which can be approximated as

$$T_{sys} = T_{ant} + \frac{1}{\eta} L_1 T_{rec} \quad (2)$$

where T_{ant} and η are the noise temperature and efficiency of the receiving antenna, L_1 represents the loss between the receiving antenna and the mixer due to coupling losses and attenuation in the signal path, and T_{rec} is the noise temperature of all components from the mixer back. T_{rec} can be expressed as

$$T_{rec} = T_m + L_m L_2 T_{IF} \quad (3)$$

where T_m and L_m are the mixer noise temperature and conversion loss respectively, L_2 is the IF signal loss between the mixer and the amplifier due to coupling losses and attenuation, and T_{IF} is the noise temperature of the IF amplifier stage. Noise sources beyond the IF amplifier have only a marginal effect and are not considered here.

The two most important components for consideration in this paper are the mixer and the LO source. At millimeter wavelengths the LO source is typically a Gunn diode in combination with a solid-state multiplier. The output from the Gunn diode, which can be as high as 120 GHz, is coupled into the multiplier circuit where the non-linear capacitance of a Schottky varactor diode is used to generate harmonics. By proper design of the multiplier circuit the unwanted harmonics are suppressed and the desired frequency is coupled to the mixer input. This LO system is noted for its simplicity, compactness, reliability and low cost. However, as is discussed more generally in the next section, the power available from such systems drops drastically at submillimeter wavelengths, and is presently insufficient for many applications.

GaAs Schottky barrier diodes are used in the mixer for a wide variety of applications due to their excellent mixing properties and their relative ease of use and reliability. There are two main figures-of-merit for the diodes. The first is the figure-of-merit cut-off frequency, defined as

$$\nu_{co} = \frac{1}{2\pi R_s C_{jo}}, \tag{4}$$

where R_s and C_{jo} are the diode series resistance and zero-bias junction capacitance, respectively. For good receiver performance ν_{co} must be much greater than the signal frequency. The second figure-of-merit is the diode slope parameter, V_o, which is a function of the sharpness of the diode's I-V curve. The I-V curve is generally assumed to be exponential with a series resistance,

$$I = I_{sat} e^{(\Phi - V - IR_s)/V_o} \tag{5}$$

where I_{sat} is the diode saturation current and Φ is the barrier height. A lower value of V_o yields a sharper I-V curve and less diode noise. At frequencies above about 600 GHz the overall receiver performance is more dependent on the cut-off frequency than V_o so that it is most important to minimize the $R_s C_{jo}$ product. At lower frequencies the state-of-the-art diodes already have a high enough cut-off frequency so that the major emphasis is in the reduction of V_o [5]. To date Schottky diodes have been used in radio astronomy applications at frequencies as high as 3 THz, and it is quite reasonable to consider how these diodes need to be improved to make them available for space based applications.

II. THE STATE OF THE TECHNOLOGY

The development of Schottky diode receivers for heterodyne spectroscopy in the submillimeter wavelength region has been quite rapid. As of 1982 the highest reported operating frequency was roughly 700 GHz with a noise temperature of 8000K (SSB) [6]. Since then several newer versions of the original corner cube receiver [7] have improved the receiver sensitivity and the operating frequency [1,2,3]. A good example of this technology is the receiver developed at the Max Planck Institute for Radioastronomy in Bonn, West Germany [1]. This system was reported in 1986 having noise temperatures of only 4,850 K SSB at 693 GHz and 17,000 K SSB at 2,500 GHz. The increased sensitivity can be traced mostly to improvements in the coupling of the signal into the diode and to improvements in the diode itself. Also, there has been much development in the laser local oscillator systems. This has improved the coverage of the submillimeter wavelength region and the system reliability. In fact, several of these systems now meet airborne specifications and have been used very successfully on the Kuiper Airborne Observatory [1,2]. In the remaining part of this section the present status of the Schottky diodes for submillimeter wavelength applications is considered.

A. GaAs Schottky Barrier Mixer Diodes

A cross-sectional sketch of a typical high-frequency diode chip is shown in Fig. 2. These diodes are in essence quite similar to the original "honeycomb" diodes first produced by Young and Irvin in 1965[8]. However, with increased understanding of diode operation their basic structure has been greatly optimized. Also, the improvement in fabrication technology has made possible the development of high-quality devices with much smaller feature sizes for reduced capacitance. A comparison of the original diodes of Young and Irvin and several state-of-the-art

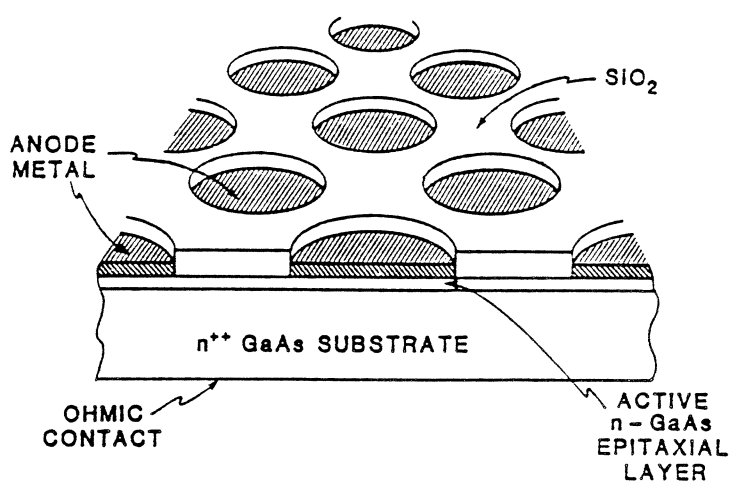

Fig. 2. A cross-sectional sketch of a typical high-frequency diode chip (not to scale).

devices is given in Table I. The new diodes have thinner epitaxial layers and reduced anode diameters. More importantly, the doping density of the epitaxial layers is now optimized for the specific frequency of operation. The result is greatly increased cut-off frequency and reduced diode noise. An SEM photograph of a diode chip with 0.5 μm diameter anodes is shown in Fig. 3.

In a typical mixer, an individual anode on the diode chip is contacted with a pointed metal wire, or whisker. Although the whisker contact technique is fraught with difficulties, it yields the lowest possible shunt capacitance (of order 1fF) and is thus necessary for the highest operating frequencies. For comparison several planar diodes are also included in Table I. These diodes have integrated anode contacts (i.e. they are whiskerless) and thus are much easier to install in the mixer and much more reliable. However, this comes at a cost in shunt capacitance, as is seen in the table. An SEM of a planar diode developed at the University of Virginia is shown in Fig. 4 [9]. The major component of the shunt capacitance is between the large anode and cathode pads. This shunt capacitance must be significantly reduced if this diode is to be used at submillimeter wavelengths.

Some recent high-frequency results are presented in Table II. These results have been compiled from a quick survey of several research teams and thus do not necessarily represent the best results obtained to date, but rather a cross-section of results that have been achieved. It is clear from this table that Schottky diodes are useful for scientific applications throughout all of the submillimeter wavelength region (0.3 - 3 THz), and perhaps to higher frequencies. It should also be noted that all of these results were obtained with whisker contacted Schottky diodes. Planar diode technology has not yet reached the submillimeter region. This is a problem that will be discussed in more detail later.

Throughout most of the submillimeter wavelength region the most common local oscillator source has been the submillimeter gas laser. A gas discharge CO_2 laser is used to pump the submillimeter wavelength laser, whose active medium is an organic molecule that is chosen to

Table I
Characteristics of GaAs Schottky Barrier Mixer Diodes

Diode	R_s (Ω)	C_{jo} (fF)		ν_{co} (GHz)	V_o@ 10–100μA (mV)	diameter (μm)
Original[8]	15	15-20		530-700	31	3
212-150	10	6.5		2,400	28	2
111	9	1.5		11,800	33.4	1
1T6	≈35	0.4		11,400	35.6	0.45
Planar Diodes	R_s (Ω)	C_{jo} (fF)	C_{shunt} (fF)	ν_{co} (GHz)	V_o@ 10–100μA (mV)	diameter (μm)
SC2R2	5.5	5.5	14	-	31.0	2.5
SC2R4	5-6	6.0	9-10	-	30.4	2.5

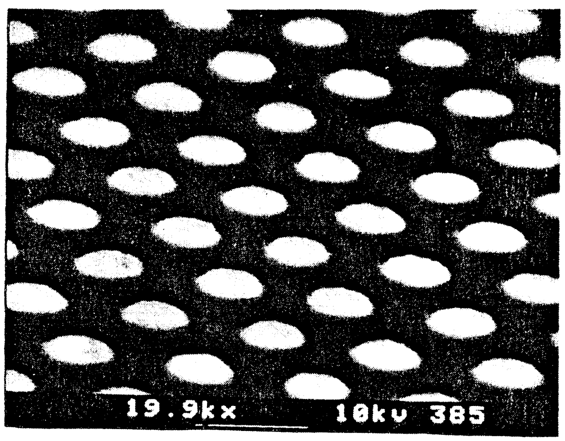

Fig. 3. *An SEM photograph of the surface of a 1T6 diode chip. The anode diameter is roughly 0.45 microns.*

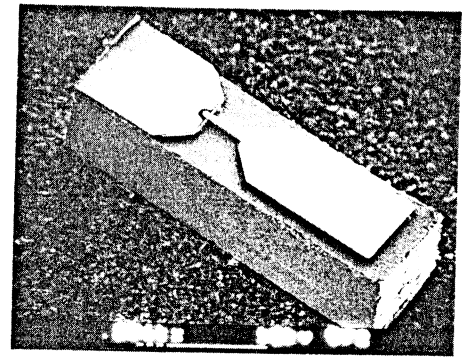

Fig. 4. *An SEM photograph of a planar Schottky barrier mixer diode developed at the University of Virginia. It has yielded excellent performance at 100 GHz [9].*

Table II
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
460-490	1740	1.45	0.3	20	Keen, 1986 [10]
693	4850	1.4	1	300	Röser, 1986 [1]
800	3150	6.4	1	77	Harris, 1989 [3]
1,963	21,000*	6.7	0.2	77	Boreiko, 1989 [11]
2,520	17,000	1.4	1	300	Röser, 1986 [1]

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

* *Measured on the Kuiper Airborne Observatory.*

have an emission line close to the desired signal frequency. These systems are large, heavy, consume lots of power and are quite difficult to maintain. In fact, the sole virtue of these systems is that they generate sufficient power to drive a Schottky receiver at essentially any frequency from 300 to over 3000 GHz. Although these systems are airborne qualified, it is doubtful that they will be space qualified at any time in the near future. (This would require months/years of continuous operation without manual adjustment.) This is the most significant obstacle to the development of space based receivers.

B. GaAs Schottky Barrier Varactor Diodes

As was mentioned in Section I, varactor diodes are used to multiply the output frequency of Gunn diodes to frequencies well into the submillimeter wavelength region. To date these devices have generated sufficient output power to drive Schottky mixer diodes at frequencies as high as 600 GHz. A comparison of the characteristics of several varactor diode batches is presented in Table III. The data in this table shows a very important trend that gives some indication of the difficulty involved in the fabrication of varactor diodes for THz applications. Specifically, as the cut-off frequency of the diodes is increased the reverse breakdown voltage, V_{bd}, is decreased, thus reducing the capacitance modulation. This means that diodes optimized for high-frequency operation will be less efficient multipliers and will not be able to handle large input powers. The most recent varactor diodes (2T2) have been used by Erickson at the University of Massachusetts

Table III
Characteristics of Several Schottky Barrier Varactor Diodes

Diode	N_{epi} (cm^{-3})	R_s (Ω)	C_{jo} (fF)	C_{min} (fF)	V_{bd} (V)	ν_{co} (GHz)	C_{max}/C_{min}
6P2	$3x10^{16}$	9.5	20.1	5.2	19.5	833	3.9
5P8	$5x10^{16}$	12	13	5	16	1,020	≈3.5
2T2	$1x10^{17}$	11.5	5.5	1.9	10.7	2,500	2.8

to generate as much as 0.7 mW of power at 500 GHz [12]. This is a very encouraging result, but much more development in this area is necessary.

III. TECHNOLOGY NEEDED FOR SPACE BASED APPLICATIONS

The requirements for a space based receiver system are quite easily stated. The receiver must be compact, light in weight, consume the smallest amount of power possible, be able to withstand high vibration (during launch for example) and, most importantly, it must be highly reliable without system maintenance. The current generation of submillimeter wavelength receivers fails to meet each one of these constraints. There are two main problems that must be overcome. The submillimeter wavelength laser must be replaced with a solid-state source and the whisker contacted diode must be replaced with a planar diode structure.

The elimination of the laser LO system can be achieved by increasing the output power of varactor diodes and/or decreasing the power required to drive Schottky diodes. As will be shown in the next section there has been significant progress in both of these areas. Another method to extend the frequency range of multipliers is to use subharmonically pumped mixers. This type of mixer uses an LO frequency that is roughly one-half of the signal frequency. There are two ways to do this. The first is to simply drive a standard diode with the LO and let the mixer diode itself generate upper harmonics that are then mixed with the signal. Although these devices do not, in general, achieve the sensitivity that is available from fundamental mixers, they are quite good and have been demonstrated up to about 600 GHz with solid-state sources [13]. The second type of subharmonically pumped mixer incorporates two Schottky barrier mixer diodes that are in anti-parallel configuration. The I-V of such a diode combination is symmetric. If the LO power is strong enough to turn on both of the diodes the conductivity will peak twice during each LO cycle. This will allow the signal to see an impedance that varies at a frequency of $2\nu_{LO}$, thereby generating an IF at $\nu_{sig} - 2\nu_{LO}$. Such a device can have sensitivity very close to that achieved in fundamental mixers, but they are quite difficult to build with whisker contacted diodes.

The second difficulty in putting today's receiver technology into space is the stability of the whisker contact. Although several satellites incorporating whisker contacted Schottky diodes have been successfully space qualified, the fabrication and qualification of these receivers is time consuming, labor intensive and quite expensive. (An example of an upcoming launch is the Microwave Limb Sounder on the Upper Atmosphere Research Satellite scheduled to be launched in 1991.) A better solution is the development of planar Schottky diodes for this frequency range. Planar Schottky diodes are being developed at a number of research laboratories and substantial progress has been made over the past several years [9,14]. Although these devices have given quite good results at 100 GHz, they are not yet competitive with whisker contacted diodes at submillimeter wavelengths. This is due to the large shunt capacitance that is inherent in the planar diode structure and the difficulty in fabricating sub-micron anodes. The planar diode research at the University of Virginia is outlined in the next section. It is the goal of this research to develop planar diodes that have the same performance as whisker contacted diodes throughout the submillimeter wavelength region.

IV. Recent Advances at the University of Virginia

Research at the University of Virginia Semiconductor Device Laboratory is focussed on the development of improved solid-state devices for high frequency applications. Recently, several important advances have been made which greatly improve the prospects for the development of solid-state heterodyne receivers for space based applications. These advances are in the areas of reduced LO power requirement for Schottky mixer diodes, increased cutoff frequency of Schottky barrier varactor diodes, and fabrication of planar Schottky devices with greatly reduced parasitic capacitance.

A. Reduced LO Power Require for Submillimeter Wavelength Schottky Barrier Mixer Diodes

In a mixer, the local oscillator power is used to drive the non-linear mixer element between its high and low impedance states. For good conversion efficiency, the ratio of these impedances must be as large as possible. If there is not sufficient LO power available to drive the element over its full impedance range, the conversion loss will be degraded. Thus, the non-linear device requires a certain amount of power in order to achieve an acceptably low conversion loss. Since solid-state LO sources generate very low power levels it is important to reduce the amount of power that the mixer element requires. There are two ways to do this, either increase the coupling efficiency between the source and the diode or reduce the power needed in the diode itself.

In an attempt to reduce the LO power requirement of the Schottky diodes we have tried to reduce the diode parasitic elements as much as possible. The series resistance dissipates much of the LO power before it reaches the non-linear junction impedance and the junction capacitance tends to short power around the junction. Also, it is important to make the junction capacitance as small as possible, even at the cost of a slight increase in series resistance. This is done in an attempt to increase the coupling efficiency between the diode's antenna structure and the diode itself. For example, at 1 THz a diode with 1 fF of capacitance has a maximum impedance magnitude of 160 Ω ($1/\omega C_{jo}$) and a minimum impedance equal to the diode's series resistance (roughly 10 - 30 Ω). The effective impedance of the diode at the LO frequency is bounded by these two values, and as a rule of thumb is assumed to be equal to their geometric mean, for this example 60 Ω †. Since the high-frequency impedance of the antenna is typically of the order of 100 - 200 Ω, it is expected that a large fraction of the LO power is reflected by the diode. A reduction of the junction capacitance while maintaining the series resistance - junction capacitance product constant should help to reduce this reflection.

We have fabricated Schottky diodes with half micron anodes to test this hypothesis. A comparison of receiver noise temperature as a function of LO power at 1,400 GHz for a standard

† *It is quite complicated to calculate the diode's actual high-frequency impedance when it is dc biased and LO power is applied. However, it is reasonable to assume that this impedance is between the maximum and minimum diode impedances and as a rule of thumb it is assumed to be near the geometric mean of these values. For the case described above* $Z_{geom} = \sqrt{160 \cdot 20} = 60\,\Omega$.

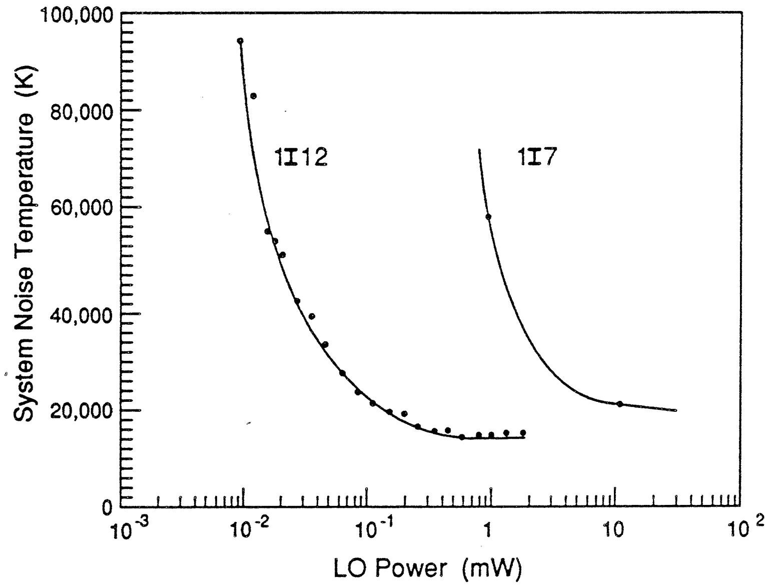

Fig. 5. A comparison of receiver noise temperature versus LO power for two diodes at 1,400 GHz. The newer 1I12 diode has one-half the capacitance of the 1I7 diode and requires an order of magnitude less LO power. The diodes were mounted in identical corner cubes and tested in the same receiver system.

Schottky diode (1I7, C_{jo}=1.0fF) and the half-micron diode (1I12, C_{jo}=0.5fF) is presented in Fig. 5 [15]. The new diode requires only about 0.1 mW of LO power to attain the same performance level that the old diode achieved at nearly 5 mW. This is a very substantial improvement. However, solid-state sources can not yet generate even this small amount of power at THz frequencies.

B. Increased Cut-off Frequency of Varactor Diodes

Until recently the maximum cut-off frequency of Schottky barrier varactor diodes was limited to values below 1 THz. This is substantially below the cut-off frequency of mixer diodes because the varactor's epilayer must be low doped and thick enough to yield a large reverse breakdown voltage. However several recent batches of devices have cut-off frequencies in the THz range. This has been achieved by judiciously increasing the epilayer doping density to reduce the R_sC_{jo} product and accepting a small decrease in reverse breakdown voltage. A summary of dc results was presented in Table III.

A novel doping structure for varactor diodes, called the Barrier-Intrinsic-N^+ (BIN) diode, is also quite encouraging. This work was pioneered at UCLA and the Jet Propulsion Laboratory [16]. These devices have extremely sharp capacitance-voltage (CV) characteristics, and may be very useful at high-frequencies where efficiency is much more important than power handling capability. This is provided that the new diodes can be fabricated with low enough series resistance and zero-bias junction capacitance. The result of a first attempt to fabricate a BIN-like diode is summarized in Fig. 6, which shows the capacitance modulation of the BIN-like diode compared to a standard varactor diode. The improved sharpness of the CV curve is clear. These devices may become very useful for harmonic multiplication into the THz range.

C. Planar Schottky Diodes with Reduced Parasitic Capacitance

The major problem with all planar Schottky barrier diodes is the excessive shunt capacitance caused by the large contact pads which overlay the high dielectric constant GaAs substrate ($\varepsilon_r = 13$). To improve this situation the substrate must be replaced with a low dielectric constant material or entirely removed. This is exactly what has been done [17]. Fig. 7 shows an SEM photograph of a planar diode that is fabricated on a quartz substrate. The only remaining GaAs is a thin layer below each of the contact pads and below the anode itself. The rest of the material is simply a quartz substrate that is adhered with a thin adhesive layer.

To achieve the minimum possible capacitance for this diode structure it would be desirable to remove even the quartz substrate. This is easily achieved provided that the adhesive is properly chosen so that it can be dissolved without damaging the diode itself. Fig. 8 is an SEM photograph of a chip that has been soldered to a quartz stripline and then had the substrate removed. All that remains is the metal contact pads and a thin layer of GaAs (a few microns thick). There is no GaAs near the anode finger itself. This structure has very low shunt capacitance and, in fact, the pad capacitance should be thought of as part of the stripline impedance and thus should not degrade high-frequency performance. Also, the pads can be used as part of a planar antenna

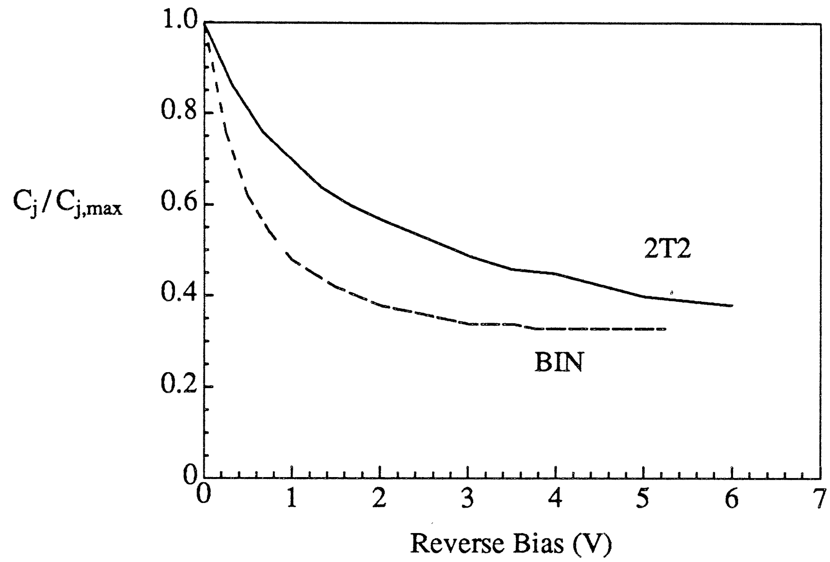

Fig. 6. *The capacitance-voltage characteristics of two varactor diodes of similar capacitance and series resistance. The 2T2 is a standard varactor diode with* $C_{jo}=5.5$ fF *and* $R_s=11.5\Omega$. *The BIN-like diode has* $C_{jo}=3.9$ fF *and* $R_s=18\ \Omega$. *The BIN-like diode has a much sharper CV curve and better overall capacitance modulation.*

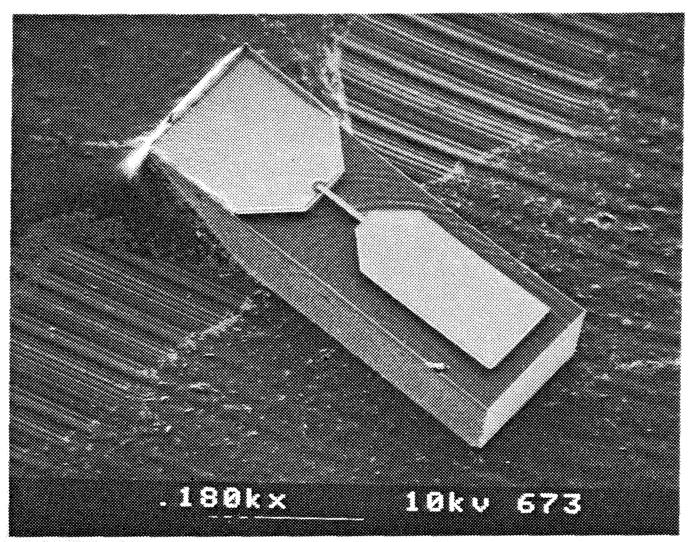

Fig. 7. *An SEM photograph of a planar GaAs Schottky barrier diode on a quartz substrate [17]. The only remaining GaAs is a thin layer below each contact pad and below the anode.*

structure for a quasi-optical coupling system. This type of planar diode structure will yield performance that is equivalent to the best whisker contacted devices, or perhaps better.

A planar diode chip with two anodes connected in anti-parallel is shown in Fig. 9. This prototype device has been designed for subharmonic mixing in the millimeter wave range and is now available for evaluation. The fabrication process has been designed so that the shape of the contact pads and the anode finger length and spacing can be easily changed. This chip will also be fabricated on a quartz substrate for high-frequency applications.

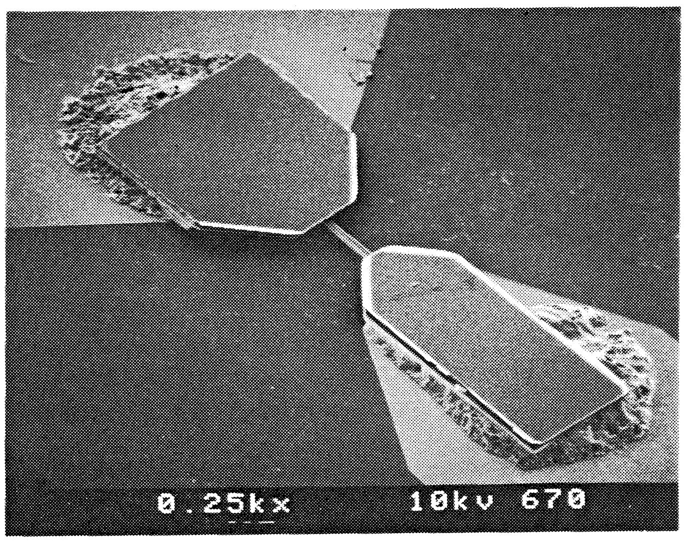

Fig. 8. An SEM photograph of a planar GaAs Schottky barrier diode without any substrate [17]. The chip was soldered to a quartz stripline before the substrate was removed.

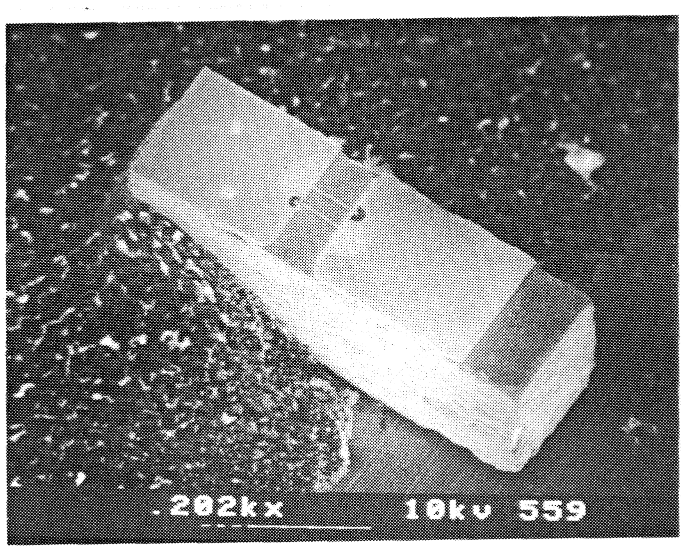

Fig. 9. An SEM photograph of a planar dual-diode structure. The diodes are in anti-parallel configuration for subharmonic pumping applications.

V. FUTURE RESEARCH AND CONCLUSION

GaAs Schottky barrier diodes are used in heterodyne receivers throughout the submillimeter wavelength region. Although receivers based on these devices have been highly successful, and have met airborne requirements, a great deal of work remains to be done before they can be routinely space qualified. First the laser local oscillator must be replaced by an solid-state source. This is already possible at frequencies up to about 600 GHz, but development of improved varactor diodes is necessary to increase this into the THz frequency range. Investigation of novel varactor diode structures, such as the BIN diodes and perhaps high electron mobility varactors, may yield the required improvement. Also, development of mixer diodes that require less LO power will help to lessen the burden on the varactor diodes. Further work in this area is necessary to determine if the significant improvements that have recently been achieved can be extended.

Although whisker contacted diodes can be space qualified, this is a costly, and to some extent risky, process. The development of planar Schottky diodes for THz frequencies is thus very important. New planar diodes with greatly reduced shunt capacitance are now becoming available. These devices will eventually yield better performance than the present whisker contacted diodes. However, a substantial amount of further research is necessary before this is achieved. The major problems to overcome are the reduction of the anode diameter to sub-micron dimensions and detailed optimization of the chip design to improve the coupling of the high-frequency signal into the diode. The new substrateless diode should be ideal for incorporation into waveguide or open structure mixer designs. This planar technology will greatly simplify the space-qualification process for submillimeter wavelength receivers, improve the receiver reliability and extend the maximum frequency of operation of space based receiver systems.

REFERENCES

[1] H.P. Röser, R. Wattenbach, E.J. Durwen, and G.V. Schultz, "A High Resolution Spectrometer for 100 μm to 1000 μm and Detection of CO (J=7-6), CO (J=6-5) and ^{13}CO (J=3-2)," Astron. Astrophys., 165, 287-299, (1986).

[2] J. Zmuidzinas, A.L. Betz, and R.T. Boreiko, "A Corner-Reflector Mixer Mount for Far Infrared Wavelengths," Infrared Phys., Vol. 29, No. 1, pp. 119-131, (1989)

[3] A.I. Harris, D.T. Jaffe, J. Stutzki, and R. Genzel, "The UCB/MPE Cassegrain Submillimeter Heterodyne Spectrometer," Int. J. IR and MM Waves, Vol. 8, No. 8, pp. 857-883, (1987).

[4] M.W. Pospieszalski, S. Weinreb, R.D. Norrod, and R. Harris, "FETs and HEMTs at Cryogenic Temperatures, Their Properties and Use in Low Noise Amps," IEEE Trans. Microwave Theory Tech., Vol. MTT-36, No. 3, pp. 552-560, (1988).

M.W. Pospieszalski, J.D. Gallego, W.J. Lackatosh, "Broadband, Low-Noise Amplifiers in the 1-50 GHz Range," To be presented at the 1990 IEEE MTT-S International Microwave Symposium, Dallas, TX, May 1990.

[5] T.W. Crowe and R.J. Mattauch, "Analysis and Optimization of Millimeter- and Submillimeter-Wavelength Mixer Diodes," IEEE Trans. Microwave Theory Tech., Vol. MTT-35, No. 2, pp. 159-168, (1987).

[6] P.L. Goldsmith, N.R. Erickson H.R. Fetterman, C.D. Parker, B.J. Clifton, D.D. Peck, P.E. Tannenwald, G.A. Koepf, D. Buhl, and N. McAvoy, "Detection of the $J=6 \rightarrow 5$ Transition of Carbon Monoxide," Ap. J. Lett., Vol. 243, pp. L79-L82, Jan. 1981.

[7] H. Kräutle, E. Sauter and G.V. Schultz, "Antenna Characteristics of Whisker Diodes Used as Submillimeter Receivers," Infrared Physics, Vol. 17, p. 477, (1977).

[8] D.T. Young and J.C. Irvin, "Millimeter Frequency Conversion Using Au-n-Type GaAs Schottky Barrier Epitaxial Diodes with a Novel Contacting Technique," Proceedings of the IEEE, pp. 2130-2131, (1965).

[9] W.L. Bishop, K. McKinney, R.J. Mattauch, T.W. Crowe, and G. Green, "A Novel Whiskerless Schottky Diode for Millimeter and Submillimeter Wave Applications," Proceedings of the 1987 IEEE MTT-S International Symposium, Las Vegas, Nev., 607-610, June 1987.

[10] N.J. Keen, K.-D. Mischerikow and G.A. Ediss, "Three Facility Low-Noise Receivers for Millimeter and Submillimeter Radio-Astronomy," 16th European Microwave Conf., Dublin, Sept. 1986.

[11] R.T. Boreiko and A.L. Betz, "Heterodyne Spectroscopy of the J=17-16 CO Line in Orion," Astrophys. J., Vol. 337, No. 1, pp. 332-341, Feb 1989.

[12] N.R. Erickson, "High Efficiency Submillimeter Frequency Multipliers," To be presented at the 1990 IEEE MTT-S International Microwave Symposium, Dallas, TX, May 1990.

[13] N.R. Erickson, "Low Noise 500- to 700-GHz Receivers Using Single-Diode Harmonic Mixers," First International Symposium on Space Terahertz Technology, Ann Arbor, MI, March 1990.

[14] J.W. Archer, R.A. Batchelor, and C.J. Smith, "Low-Parasitic, Planar Schottky Diodes for Millimeter-Wave Integrated Circuits," IEEE Trans. Microwave Theory Tech., Vol. MTT-38, No. 1, pp. 15-22, Jan. 1990.

[15] W.C.B. Peatman and T.W. Crowe, "Design and Fabrication of 0.5 Micron GaAs Schottky Barrier Diodes for Low-Noise Terahertz Receiver Applications," To appear in Int. J. Infrared and Millimeter Waves, 1990.

[16] R.J. Hwu, N.C. Luhmann, Jr., D.B. Rutledge, D. Streit, T. O'Neill, U. Lieneweg, "Monolithic Watt-Level Millimeter-Wave Barrier-Intrinsic-N^+ (BIN) Diode-Grid Frequency Tripler," Conference Digest: Thirteenth Int. Conf. Infrared and Millimeter Waves, pp. 328-329, Honolulu, HI, 1988.

[17] W.L. Bishop, E.R. Meiberg, R.J. Mattauch and T.W. Crowe, "A Micron Thickness, Planar Schottky Barrier Diode Chip for Terahertz Applications with Theoretical Minimum Parasitic Capacitance," To be presented at the 1990 IEEE MTT-S Int. Microwave Symp., Dallas, TX, May 1990.