PLANAR GaAs SCHOTTKY BARRIER DIODES

Steven M. Marazita, William L. Bishop, Thomas M. Cunningham,
Philip J. Koh, Thomas W. Crowe, and Robert M. Weikle, II

Applied Electrophysics Laboratories
Department of Electrical Engineering
University of Virginia
Charlottesville, VA 22901

Abstract

GaAs Schottky barrier diodes continue to be heavily used in millimeter and submillimeter wavelength heterodyne receiver applications where cryogenic cooling is not an acceptable option. This is because the diode technology is well known, reliable, and yields acceptable sensitivities at room temperature. Planar GaAs mixer diodes can now replace the older whisker contacted diodes to at least 600 GHz, and THz devices are easily within grasp.

This presentation will update the status of planar mixer diode technology at the University of Virginia. Recent developments include methods to reduce anode dimensions and parasitic shunt capacitance, fabrication of GaAs diodes on quartz substrates with integrated circuit elements, and fabrication of a diode pair with an integrated log-periodic antenna and separate diode biasing for subharmonic mixing. The paper will conclude with a summary of the status of mixer performance based on planar diodes and a discussion of the potential for THz mixers.

I. Introduction

Over the past several decades, there has been a surge of research in the detection of radiation in the submillimeter-wave portion of the electromagnetic spectrum (300 GHz to 3 THz). This research has been spurred in part by the desire of astrophysicists to map submillimeter-wave electromagnetic signatures in interstellar space. These signatures provide researchers with a better understanding of interstellar chemistry, star formation, and galactic structure. Research has also been driven by the need to observe radiation emitted from a number of molecules in the Earth's atmosphere. Detection of these emissions is critical to the study of the ozone layer and greenhouse warming. The detection of emissions from molecules involved in ozone depletion cycles such as O_3, ClO, and OH is particularly important.

The Microwave Limb Sounder (MLS) on the Earth Observing System (EOS), for example, will employ heterodyne radiometers operating from 240 GHz to 2.5 THz. These radiometers require mixers with sufficient spectral sensitivity, bandwidth, and low noise temperature. The mixers must also be highly robust to survive the launch and the lifetime of the satellite. The highest frequency receivers to date use quarter-micron diameter mixer diodes and have achieved record sensitivity at 2.5 THz [1][2]. However, these mixers are based on whisker-contacted diodes which are difficult to space qualify due to the fragility of the whisker contact. It is therefore essential that the new mixer diodes be fabricated using planar technology, thus eliminating the fragile whisker.

Several groups have developed planar Schottky diode technology with an integrated finger replacing the whisker [3][12][13]. These chips have been used in waveguide receivers and yielded excellent performance up to about 600 GHz [4]. These results are promising, but work must be done to optimize planar chips for operation in the THz range.

At UVA we have investigated several key issues which could pertain to successful THz device operation. These include fabrication of GaAs planar diodes on quartz substrates with integrated circuit elements, methods of reducing parasitic shunt capacitances and anode dimensions in the planar diode structure, and fabrication of an anti-parallel anode pair with an integrated log-periodic antenna incorporating separate diode biasing for subharmonic mixing. This paper presents the latest fabrication achievements in these areas and some preliminary RF results.

II. Quartz Substrate and Circuit Element Integration

As operating frequencies in a mixer are pushed to higher limits, minimizing the parasitic capacitances in the planar diode structure and the precise alignment of the diode to the RF circuit become increasingly important. One method of reducing the parasitic pad to pad capacitance is to remove the high dielectric GaAs substrate and replace it with a low dielectric material such as quartz, leaving only a small, thin GaAs active area around the device anodes. UVA successfully has integrated this technology into their planar diode process with the diode bonded face up on quartz [5]. NASA's Jet Propulsion Laboratory also has developed a quartz substrate integration technology, QUID, which has demonstrated promising results at 200 and 600 GHz [6-8]. This technology incorporates integrated RF circuitry fabricated along with the mixer diode, eliminating the alignment error associated with soldering a discrete device into an RF circuit. UVA and JPL are cooperatively developing this technology at 240 and 640 GHz for implementation on the MLS of EOS. The most recent results at 240 GHz use RF circuitry designed at JPL integrated with UVA planar diodes and QUID substrate replacement.

The fabrication process is similar to the standard planar diode process [3] with a few notable changes. Since the device is subharmonically pumped, it incorporates two anti-parallel diodes and hence two anodes and ohmic contact pads per device. The anode contact mask layer typically forms the finger and contact pads only. In this process, the RF/LO/IF mixer circuitry is integrated with the two anti-parallel fingers and anode contact pads of the device. Figure 1 shows an SEM of the device after the anode contact layer with integrated filters has been completed. Figure 2 shows the device after the surface channel etch has been performed. At this point, the frontside processing is complete.

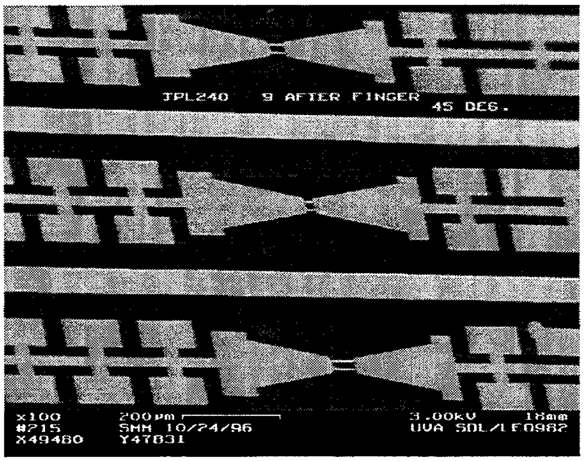

Figure 1: Devices after anode contact layer

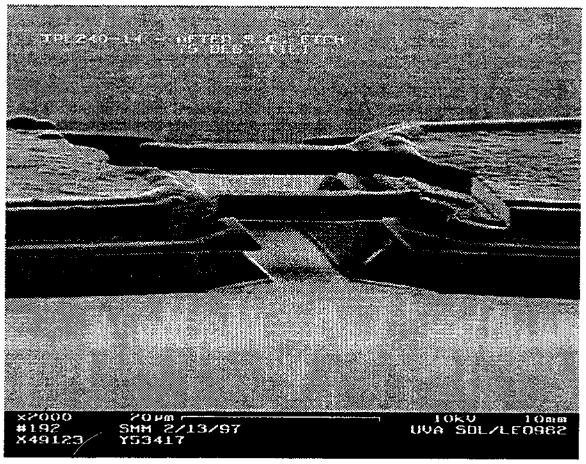

Figure 2: Device after surface channel etch

The backside processing of the devices begins with inverting the wafer and bonding it face down with epoxy to a 6 mil quartz substrate. The critical steps in this process are to ensure that the cured epoxy contains no air bubbles and that the epoxy is thin and of uniform thickness across the wafer. During the development of the wafer bonding and epoxy curing process, there were many problems with air bubble formation during the required 80°C curing cycle. By using a two day room temperature cure under vacuum, followed by post-curing at 80 and 120 °C, this problem has been solved. We use a homemade rubber membrane press under vacuum to minimize the cured epoxy thickness and consistently achieve thicknesses of 1-2 μm over the entire wafer. The GaAs substrate is removed using a selective wet etch composed of 96% H_2O_2:4% NH_4OH which etches GaAs approximately 60 times faster than AlGaAs. The GaAs material incorporates an AlGaAs etch stop layer between the n+ buffer layer and the substrate to provide a stopping point for the substrate removal etch from the backside. Figure 3 shows a wafer after the substrate has been removed. The dark area is epoxy and the lighter area is AlGaAs.

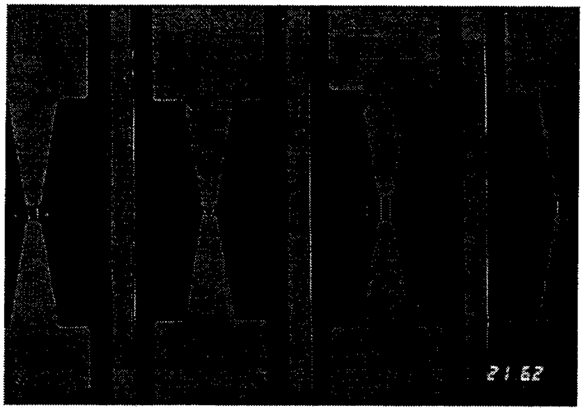

Figure 3: Backside of wafer after substrate removal

A photoresist pattern is applied to mask the active areas and ohmic contacts from the backside. Cl-RIE is used to remove the remaining AlGaAs and n+ GaAs buffer from outside the photoresist pattern. CF_4 RIE is utilized to etch the SiO_2 layer underneath the GaAs, and an Argon sputter etch removes the chrome adhesion layer on top of the filter circuitry to reveal the frontside gold filters from the backside of the wafer. Figure 4 shows the photoresist pattern on top of AlGaAs and epoxy, and Figure 5 shows the wafer after all dry etching is complete. In this figure the light areas are now gold. At first we were using a combination of wet etchants to perform the backside etching. The batch

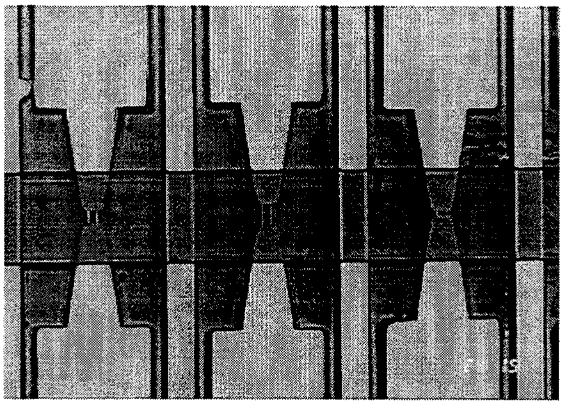

Figure 4: Photoresist pattern for backside etching

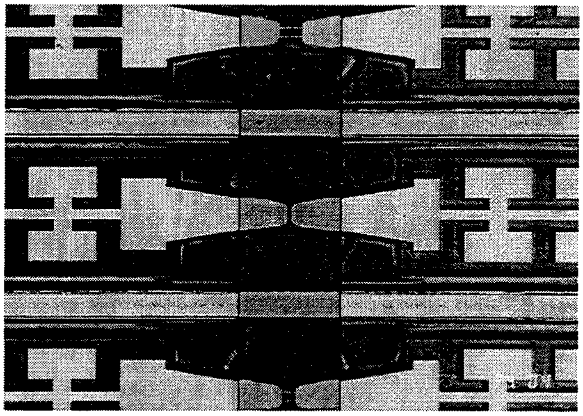

Figure 5: Devices after backside processing

yield was very low due to etchants leaking underneath the photoresist and epoxy, attacking the device's active areas. By switching to an entirely dry etch process, we improved the yield from approximately 7% to over 70%.

The last step in the process is to dice the wafer into individual mixers. The final chip dimensions are 8600 x 230 μm (340 x 9 mils). Figure 6 shows an SEM of a finished chip. The devices are fabricated on $2x10^{17}$ n-type GaAs epi and have anode diameters of approximately 1.3 μm. The I-V parameters are as follows: R_s=12-14 ohms,

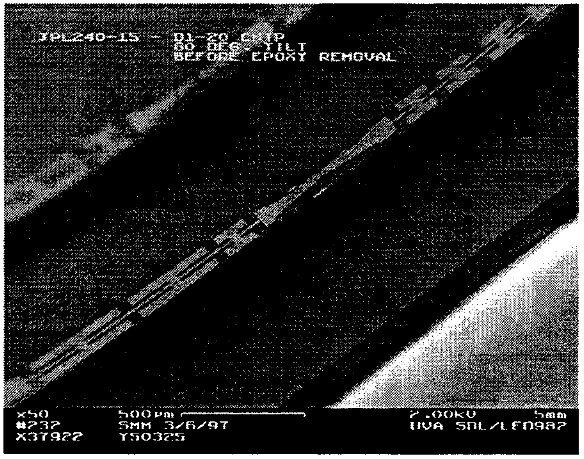

Figure 6: Complete 240 GHz mixer

$V_{knee}(1\mu A)=670$ mV, $\Delta V=73$-74 mV, $C_{j0}=2$ fF per anode, and $C_{total}=16$ fF with parasitics. This batch of mixers performed very well at 230 GHz: DSB $T_{mix}=716$ K, $P_{LO}=4.95$ mW, $L_{conv}=5.18$ dB, $Z_{IF}=139.8$ ohms, IF=1.5 GHz using JPL block 240A2. These numbers look very promising. Additionally, we have developed a technique at UVA to remove the epoxy from the surface channel to reveal an air channel once again. Figures 7 and 8 show before and after the epoxy was removed from a device. This procedure reduces its parasitic capacitance by over 20%. The RF performance seems to

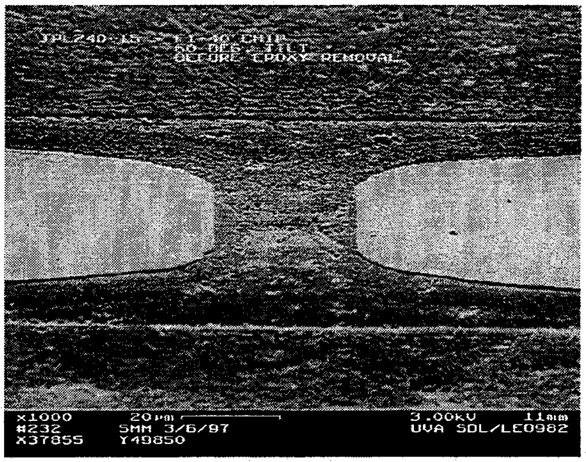

Figure 7: Before epoxy removal

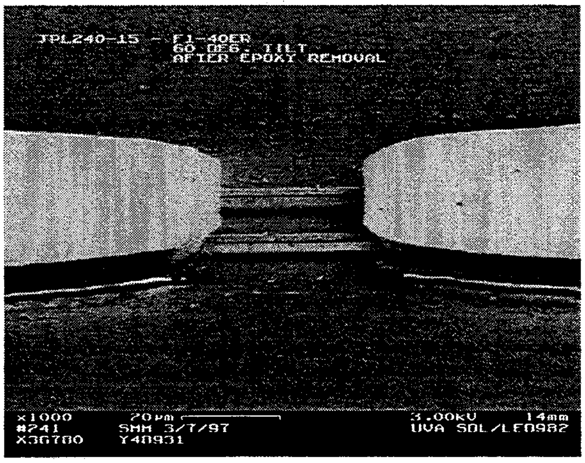

Figure 8: After epoxy removal

improve considerably after this step. JPL measured the RF performance for a different device which had the epoxy removed and was from the same wafer as quoted previously: at 235 GHz, DSB T_{mix}=537 K, P_{LO}=3.98 mW, L_{conv}=4.93 dB, Z_{IF}=176.1 ohms, IF=2.0 GHz. We believe that this is one of the best reported results at 235 GHz for a subharmonically-pumped integrated mixer. It shows a marked improvement over the device with epoxy in the surface channel. This is only one result, however, and more testing needs to be done to confirm this trend.

III. Finger Overlay Capacitance Reduction

Finger overlay capacitance arises due to the anode contact finger sitting on top of SiO_2 and GaAs around the device anode and to the wall of surface channel. We currently are applying an air bridge technology to planar varactor diodes with great success, reducing this capacitance to a negligible amount [9]. Figure 9 shows a recent planar varactor diode with the air bridge interconnect. This technique replaces a 0.5 μm layer

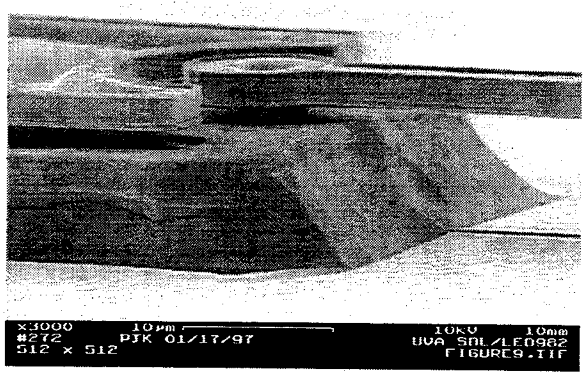

Figure 9: Planar varactor diode with air bridge interconnect to anode

of oxide of dielectric constant 6 with a 1 μm layer of dielectric constant 1 (air), yielding approximately a factor of 12 reduction in overlay capacitance. It also makes the position of the surface channel wall relative to the anode less critical. We feel that this technology can also be applied to mixer diodes if the small area anodes necessary for high frequency operation provide a robust contact. At THz frequencies any parasitic capacitance reduction techniques should improve device performance.

IV. Anode Dimension Reduction

Development is continuing at UVA on the Electroplate Window Shrink (EWS) process which uses conventional deep-ultraviolet lithography and an electroplated metal mask to define 0.25 μm and smaller Schottky contacts to GaAs for 2.5 THz whisker-contacted mixer diode development [10]. Figure 10 shows the most recent batch of 2.5 THz mixer diodes fabricated at UVA. The process has seen great improvements in anode uniformity, DC I-V characteristics, and minimization of C_{TOTAL}. Table 1 compares the

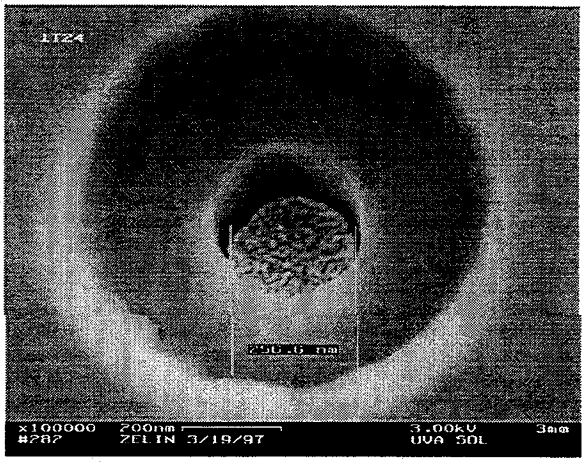

Figure 10: 0.25 μm Schottky contact to GaAs

I-V and capacitance data for the new batch 1T24 mixer diodes with the first generation batch 1T23:

Device	**V_{KNEE}@ 1 μA (mV)**	**ΔV @ 1-10 μA (mV)**	**V_{BR} @ -1 μA (V)**	**R_S @ 1 mA (Ω)**	**C_{TOTAL} (fF)**
1T23	680-700	89-92	2.1-2.4	25-36	0.5-0.65
1T24	720-730	85-86	3.4	26-38	0.32-0.5

Table 1: I-V and capacitance data comparing 1T23 and 1T24

The most notable changes in the above parameters are the reduction in ΔV, increase in V_{br}, and reduction in total capacitance. These factors should contribute to better RF performance for these devices. We are currently awaiting RF test data.

This technology is applicable to the next generation THz planar mixer diodes as anode dimensions will need to be scaled into the sub-0.5 μm regime to further reduce parasitic anode capacitance.

V. Separately Biasable Subharmonic Mixer Diodes with Integrated Antennas

Subharmonically pumped diodes seem very attractive for high frequency mixer applications since the LO frequency only needs to be one-half of the RF frequency. Since LO power is not abundant at THz frequencies, this is an attractive configuration for THz mixers. However, pumping the anti-parallel diodes into their turn-on regimes requires significantly more power than single-ended mixers if individual anode DC biasing is not provided. This work focuses on fabricating separately biasable anti-parallel planar diodes integrated with a log periodic receiving antenna. The antenna is designed to operate from 250 GHz to approximately 1.2 THz. Using chlorine RIE, a split was cut down the center of one side of the antenna so that each diode could be DC biased individually. Figure 11 is an SEM from a batch of mixers fabricated at UVA. The split is the dark band down the center of the log periodic structure on the left side of the figure. It penetrates into the semi-insulating GaAs substrate. The DC I-V characteristics are similar to other planar diodes from UVA with 0.75 μm anodes on 4×10^{17} cm^{-3} epitaxial layer doping. We are awaiting RF test results on the performance of these devices both as a receiving antenna and a mixer.

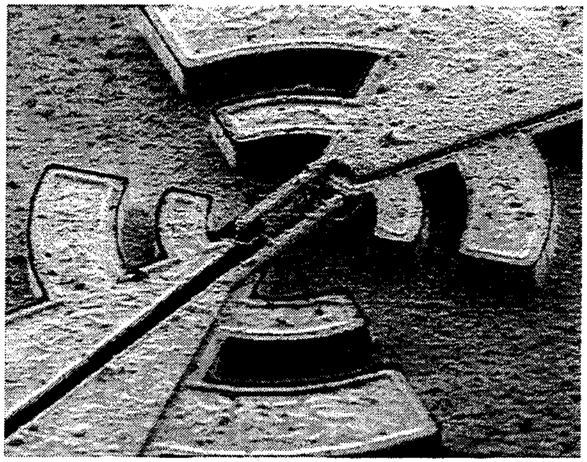

Figure 12: Subharmonically pumped separately biasable planar mixer diode with integrated log periodic antenna

VI. Summary and Conclusions

Several groups are actively developing millimeter and submillimeter wavelength mixers based on planar Schottky barrier diodes. Gencorp-Aerojet has a 200 GHz subharmonically pumped receiver operating from 150 to 300 GHz with a 6 to 18 GHz IF bandwidth. The best performance is DSB T_{rec}=496 K at 200 GHz with $P_{LO}<4$ mW [11]. NASA's Jet Propulsion Laboratory is investigating integrated subharmonic mixers at a variety of frequencies [6][7][8] and cooperatively with UVA [this work]. UVA is also actively researching fundamentally pumped planar mixers at 585 GHz and 690 GHz with DSB T_{rec}=2380 K and 3200 K, respectively [4].

GaAs Schottky diodes are presently the most promising technology for space based spectroscopy applications such as atmospheric limb sounding. These compact, all-solid-state systems require no complex cooling technology and are highly reliable. Furthermore, the rapid advance of planar Schottky diodes will reduce system costs and increase reliability. Planar Schottky mixers are now competitive to at least 700 GHz. Some of the key issues for planar devices as we push towards higher frequencies are:

1. Higher levels of integration - The alignment of the diode to the surrounding circuitry is too critical for discrete devices at THz frequencies.
2. Lower parasitics and shorter finger lengths (< 20 μm) for better bandwidth
3. Reduced chip dimensions to fit in higher frequency waveguide structures

As these issues and others are overcome in the near future, this technology should advance to the THz frequency range.

VII. Acknowledgements

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VIII. References

[1] H.-W. Hübers, W.C.B. Peatman, T.W. Crowe, G. Lundershausen and H.P. Röser, "Noise Temperature and Conversion Losses of Submicron GaAs Schottky-Barrier Diodes," Presented at the Fourth Intl. Symp. Space THz Tech., Los Angeles, CA, March 1993.

[2] P.A.D. Wood, D.W. Porterfield, William L. Bishop and T.W. Crowe, "GaAs Schottky Diodes for Atmospheric Measurements at 2.5 THz," Proc. Fifth Intl. Symp. Space THz Tech., Ann Arbor, pp.355-368, May 1994.

[3] W.L. Bishop, R.J. Mattauch, T.W. Crowe and L. Poli, "A Planar Schottky Diode for Submillimeter Wavelengths," 15th Int. Conf. on Infrared and Millimeter Waves, Orlando, FL, Dec. 1990.

[4] J.L. Hesler, W.R. Hall, T.W. Crowe, R.M. Weikle, II, B.S. Deaver, Jr., R.F. Bradley, and S.-K. Pan, "Fixed-Tuned Submillimeter Wavelength Waveguide Mixers Using Planar Schottky Barrier Diodes," To be published in the IEEE Trans. Microwave Theory Tech., May 1997.

[5] W.L. Bishop, T.W. Crowe, R.J. Mattauch, and P.H. Ostdiek, “Planar Schottky Barrier Mixer Diodes for Space Applications at Submillimeter Wavelengths,” Microwave and Optical Tech. Lett., Special Issue on Space THz Tech., Vol. 3, No. 1, pp. 44-49, Jan. 1991.

[6] I. Medhi, M. Mazed, R. Dengler, A. Pease, M. Natzic, and P.H. Siegel, “Planar GaAs Schottky diodes integrated with quartz substrate circuitry for waveguide subharmonic mixers at 215 GHz”, IEEE-International Microwave Symposium 1994 Digest, pp. 779-782.

[7] I. Medhi, S. Martin, R. Dengler, R.P. Smith, and P.H. Siegel, “Fabrication and performance of planar Schottky diodes with T-gate-like anodes in 200 GHz subharmonically pumped waveguide mixers,” IEEE Microwave and Guided Wave Letters, vol. 6, no. 1, January 1996.

[8] I. Medhi, T. Lee, D. Humphrey, S. Martin, R.J. Dengler, J.E. Oswald, A. Pease, R.P. Smith, and P.H. Siegel, “600 GHz Planar-Schottky-Diode Subharmonic Waveguide Mixers,” IEEE-MTT International Microwave Symposium, San Francisco, CA, June 17-21, 1996.

[9] Philip J. Koh, William C.B. Peatman, Thomas W. Crowe, and Neal R. Erickson, “Novel Planar Varactor Diodes”, Seventh International Symposium on Space Terahertz Technology, Charlottesville, VA, March 1996.

[10] William L. Bishop, Steven M. Marazita, Perry A.D. Wood, and Thomas W. Crowe, “A Novel Structure and Fabrication Process for Sub-Quarter-Micron THz diodes”, Seventh International Symposium on Space Terahertz Technology,

Charlottesville, VA, March 1996.

[11] I. Galin, "A Mixer up to 300 GHz with Whiskerless Schottky Diodes for Spaceborne Radiometers," 7th Intl. Symp. Space THz Tech., Charlottesville, VA, pp. 474-476, March 1996.

[12] 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.

[13] A. Simon, A. Grueb, V. Krozer, K. Beilenhoff, H.L. Hartnagel, "Planar THz Schottky Diode Based on a Quasi-Vertical Structure," 4th Intl. Symp. Space THz Tech., UCLA, pp. 392-403, March 1993.