A Micromachined 585 GHz Schottky Mixer

K. Hui, *Member, IEEE*, Jeffrey L. Hesler, *Member, IEEE*, David S. Kurtz, William L. Bishop, *Member, IEEE*, and Thomas W. Crowe, *Senior Member, IEEE*

***Abstract*—Standard semiconductor fabrication processes have been used to form waveguide components for the submillimeter wavelength range. A 585 GHz fundamentally pumped Schottky mixer with record performance demonstrates this technology. It consists of an etched silicon horn, a diced waveguide, and a lithographically formed microstrip channel for the diode circuit. The block dimensions are precisely controlled and extremely sharp. The measured mixer noise temperature is 1200K (DSB), which is equivalent to the best result obtained with standard metal machining.**

***Index Terms*—Micromachining, submillimeter-wave circuits.**

I. Introduction

SUBMILLIMETER-WAVE mixers and multipliers have long been available for scientific applications such as radio astronomy, atmospheric studies, and chemical spectroscopy. However, there is growing interest in the use of submillimeter-wave heterodyne receivers for more broad applications such as compact range radars, ultra-wide band and secure communications, medical diagnostics, weapons and explosives detection, and biological and chemical toxin detection. Traditional technology has used whisker-contacted and discrete planar diodes that yield suitable noise temperatures but tend to be narrow band and very expensive. Recently, two groups have developed GaAs on quartz integration technologies that promise better sensitivity and wider fix-tuned bandwidth, as well as reduced costs [1]–[3]. However, the difficulty and expense of forming the split-block waveguide housings for these terahertz circuits continues to limit the application of this technology.

This letter describes the fabrication and testing of a split-block 585 GHz mixer housing by standard semiconductor fabrication processes. The essential mixer design has been described previously [4], [1]. The micromachining process yields exceptional control of the critical block dimensions and extremely sharp features. The resulting mixer performance is equivalent to the best 585 GHz Schottky mixers. Also, the assembly survives immersion in liquid nitrogen and this process is readily scaled to well above 1 THz.

II. Overview of the Fabrication Process

The block fabrication process presented here is a modified version of the process reported in several previous conference publications [5]–[7]. As in the previous work, our new process begins with the formation of a modified diagonal horn by selective crystal etching of a silicon wafer through a silicon dioxide masking layer. This etch creates a very suitable horn structure with easily controlled flare angle and aperture [8]. Next, a thin layer of photoresist is spun onto the wafer and exposed to mark the precise position of the waveguide. An automatic dicing saw is then used to slit-cut the waveguide with depth of 150 μm ($\pm$5 μm) and width 205 μm ($\pm$2 μm) for each half of the block. The photoresist and oxide layers are then removed.

The next step is to form the microstrip circuit channel that runs perpendicular to the waveguide. This is achieved with an ultra-thick photoresist known as SU-8 [9]. This resist can be exposed by standard UV lithography to depths of up to 1 mm. First, the horn structure is filled with SU-8 resist. Next, a layer of SU-8 is spun on the wafer that is significantly thicker than our desired channel depth of 60 μm. This resist is then exposed through a mask that protects the horn, waveguide and channel areas. Both pre- and post-exposure bakes are used. After the exposure, the wafer is developed to remove the unexposed resist and hard-baked to cure the remaining SU-8 into a plastic layer that remains as a permanent part of our mixer. This plastic is then lapped to the desired thickness on a commercial wafer lapping system. Lapping allows control of the depth of the channel to within$\pm$2 μm and eliminates any problem with the planarity of the original SU-8 surface. The width of the microstrip channel was 120 μm ($\pm$2 μm).

Alignment grooves are then diced into the wafer (200 μm deep by 400 μm wide), the sample is coated with metal by a combination of sputtering and electroplating and the individual components are diced. Both the dicing and alignment grooves are patterned in the SU-8 layer to facilitate proper alignment on the wafer. The processing of one 3-in wafer took approximately two weeks of graduate student effort and yielded twelve complete waveguide pairs. The result is shown in Fig. 1. Note that the features are much sharper than is possible with traditional machining and the fixed backshort is defined with lithographic precision.

III. Mixer Assembly and Testing

To assemble the mixer a quartz microstrip circuit with an IF filter, a waveguide probe and an integrated GaAs diode is placed in the microstrip channel [1]. The diodes have a nominal anode diameter of 0.9 μm and an epitaxial layer doping of $4 \cdot 10^{17}$ cm^{-3}. The measured dc parameters for this diode were an ideality factor $\eta = 1.32$, a saturation current $I_{\text{SAT}} = 3 \cdot 10^{-13}$ A, and a series resistance $R_s = 11\ \Omega$. The zero bias junction capacitance was calculated to be 1.5 fF per anode based on the anode diameter and the epitaxial layer doping. Bond wires attached to

Manuscript received March 28, 2000; revised July 21, 2000. This work was supported by The U.S. Army National Ground Intelligence Center (DAHC90-96-C-0010) and the Army Research Laboratory (ARL/UMD-Z847301).

The authors are with the Department of Electrical Engineering, University of Virginia, Charlottesville, VA 22904-4743 USA(e-mail: twc8u@virginia.edu).

Publisher Item Identifier S 1051-8207(00)08447-6.

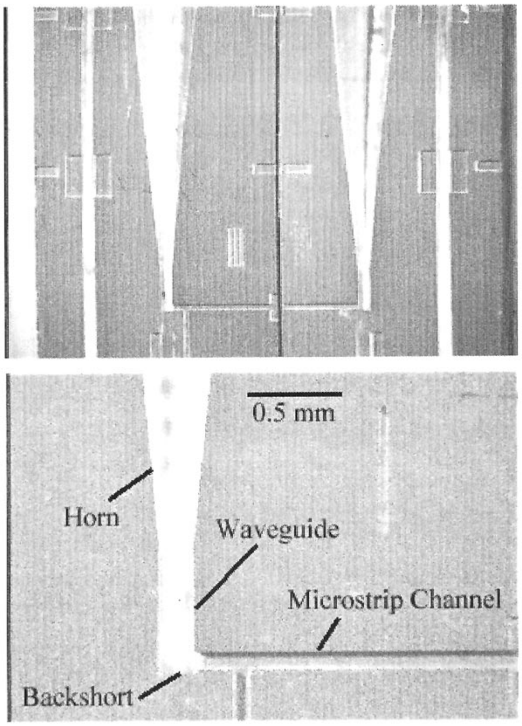

Fig. 1. Two views of the 585 GHz split-block mixer, showing the flared horn, waveguide, and microstrip channel. Note the extremely sharp features.

the circuit are then attached to the block for the IF return and to the center pin of the coaxial IF connection. Metal shims are placed in the alignment grooves and these shims guide the two halves precisely into place. This yields excellent alignment and the flat SU-8 surfaces formed by lapping yield no visible gap between the halves.

The mixer is then tested by the same method as has been described previously [4]. A molecular gas laser provides an LO source at 585 GHz and a hot/cold load source is used as a calibrated signal. The LO and signal are spatially combined in a diplexer and coupled to the horn through an off-axis parabolic mirror. The lowest system noise temperature measured was 1700K and a graph of the system noise temperature versus the input noise temperature of the IF amplifier indicated a mixer noise temperature of 1200K and conversion loss of 8 dB (all DSB). The system noise temperature is plotted versus LO power in Fig. 2. The mixer requires about 1 mW of LO power for optimum performance and the performance is still quite good down to 0.2 mW. These are essentially the same values obtained when a similar integrated mixer circuit was tested in a traditionally machined metal block [1]. The antenna pattern of the micromachined horn is shown in Fig. 3. There is a slight asymmetry in the beam but this can be corrected by adjusting the depth of the horn etch.

IV. Conclusions

We have fabricated split block mixer housings for 585 GHz through standard semiconductor processing techniques including crystallographic silicon etching, ultra-thick photoresist, automatic dicing and wafer lapping. The results indicate better dimensional control and sharper features than have been demonstrated with traditional machining. The mixers have been RF tested and yield essentially the same performance as the traditional blocks with a diagonal horn antenna. This is the first demonstration of a micromachined submillimeter-wave mixer with such exceptional performance. This process is readily scaled to frequencies above 1 THz and is suitable for large-scale manufacturing. For example, a single eight inch silicon wafer would yield over 80 600–GHz mixer housings. Finally, since the blocks have survived rapid immersion in liquid nitrogen with no degradation this technology can potentially be used for superconducting (SIS and HEB) mixers. Thus, this new micromachining process makes possible the rapid prototyping of waveguide circuits throughout the terahertz band while also greatly reducing costs for mass production.

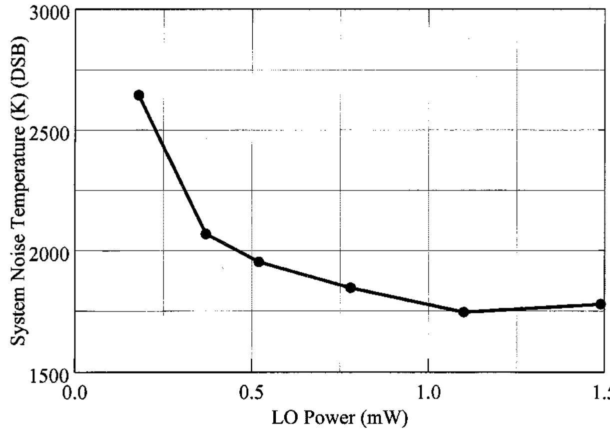

Fig. 2. System noise temperature versus LO power. The best measured result was 1700K (DSB).

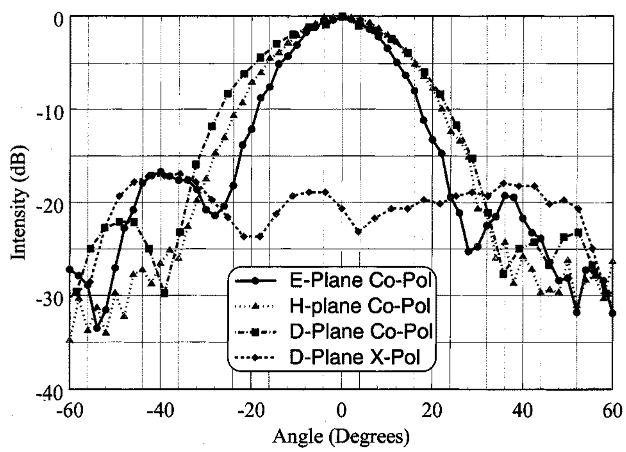

Fig. 3. Measured antenna pattern of the 585 GHz mixer. The slight asymmetry can be removed with a better selection of the silicon etch depth.

References

[1] S. M. Marazita, W. L. Bishop, J. L. Hesler, K. Hui, W. E. Bowen, and T. W. Crowe, "Integrated GaAs Schottky mixers by spin-on-dielectric wafer bonding," *IEEE Trans. Electron Devices*, vol. 47, pp. 1152–1157, June 2000.

[2] I. Mehdi, 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," in *IEEE Int. Microwave Symp. 1994 Dig.*, San Diego, CA, May 1994, pp. 779–782.

[3] P. H. Siegel, I. Mehdi, R. J. Dengler, T. H. Lee, D. A. Humphrey, A. Pease, R. Zimmermann, and P. Zimmermann, "A 640 GHz planar-diode fundamental mixer/receiver," in *1998 IEEE MTT-S Int. Microwave Symp. Dig.*, June 1998, pp. 407–410.

[4] J. L. Hesler, W. R. Hall, T. W. Crowe, R. M. Weikle, B. S. Deaver, R. F. Bradley, and S.-K. Pan, "Fixed tuned submillimeter wavelength mixers using planar Schottky barrier diodes," *IEEE Trans. Microwave Theory Tech.*, vol. 45, pp. 653–658, May 1997.

[5] C. M. Mann, D. N. Matheson, M. L. Oldfield, P. J. Koh, T. W. Crowe, W. L. Bishop, R. M. Weikle, and J. L. Hesler, "A simple micromachining technique for millimeter, submillimeter and terahertz waveguide cavities," in *Proc. 2nd ESA Workshop Millimeter Wave Technology and Applications*, Helsinki, Finland, May 1998, pp. 144–149.

[6] C. M. Mann, J. L. Hesler, P. J. Koh, T. W. Crowe, W. L. Bishop, R. M. Weikle, and D. N. Matheson, "A versatile micromachined horn antenna," in *20th ESTEC Antenna Workshop Millimeter Wave Antenna Technology and Antenna Measurements*, Noordwijk, NL, June 1997.

[7] T. W. Crowe, P. J. Koh, W. L. Bishop, C. M. Mann, J. L. Hesler, R. M. Weikle, P. A. D. Wood, and D. Matheson, "Inexpensive receiver components for millimeter and submillimeter wavelengths," in *Proc. 8th Int. Symp. Space THz Tech.*, Cambridge, MA, Mar. 25–27, 1997.

[8] J. L. Hesler, K. Hui, R. K. Dahlstrom, R. M. Weikle, T. W. Crowe, C. M. Mann, and H. B. Wallace, "Analysis of an octagonal micromachined horn antenna for submillimeter-wave applications," *IEEE Trans. Antennas Propagat.*, to be published.

[9] K. Y. Lee, N. LaBianca, S. A. Rishton, S. Zolgharnain, J. D. Gelorme, J. Shaw, and T. H.-P. Chang, "Micromachining applications of a high resolution ultrathick photoresist," *J. Vac. Sci. Technol. B*, vol. 13, no. 6, pp. 3012–3016, Nov./Dec. 1995.