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ADP011763

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Micromachining and Integration of Terahertz Components

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Abstract – **Two recent innovations at the University of Virginia have the potential to significantly reduce the cost of terahertz mixers and multipliers. These are the integration of high-quality and low-parasitic GaAs diodes on dielectric substrates and the fabrication of terahertz waveguide circuits by micromachining. This paper reviews the basic fabrication processes and presents the most recent results.**

I. Introduction

GaAs Schottky barrier mixer and multiplier diodes are used to extend the range of electronic receiver technology well into the terahertz frequency band. To date, frequency mixers have been realized to at least 5 THz and all-solid-state sources using frequency multipliers have reached slightly above 1 THz. However, these components rely on discrete diodes, often with whisker-contacts. This causes the components to be very difficult to assemble and virtually impossible to accurately model, even with the most advanced software packages. This is because the actual circuit cannot be assembled with the precision required to match the computer model. For these reasons the circuits are not particularly frequency agile and generally rely on mechanical tuners to achieve their optimum performance. Clearly, the solution to this problem is to develop integrated diode circuits that eliminate the need to handle and solder discrete devices while also ensuring that the Schottky anode is placed in the embedding circuit with micron precision. Our GaAs-on-dielectric integration process achieves this important goal.

A second major concern is the expense and delay of relying on traditionally machined waveguide housings. Although many groups in the terahertz field have developed extensive machining capabilities to fabricate terahertz waveguides and horns, this technology is simply not available to most terahertz engineers. For example, we have often been forced to wait six months or more to receive a single split-block housing from a commercial supplier or a national laboratory that was kind enough to fabricate our components. Needless to say, this delay has greatly hampered our research program. Several years ago we began to develop a process to fabricate high-quality waveguide housings on silicon wafers using standard semiconductor processing techniques. Using this process we have now fabricated state-of-the-art mixers at 585 GHz and prototype components to as high as 1.6 THz.

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II. GaAs-on-Dielectric Integration

Our integration process [1,2] begins with a GaAs epitaxial wafer consisting of a heavily doped substrate and the following layers in order of growth,

i) an AlGaAs etch stop layer,

ii) a heavily doped GaAs buffer layer, typically about five microns thick with $n \geq 5x10^{18}cm^{-3}$,

iii) a thin GaAs active layer designed to achieve the desired anode properties.

A SiO_2 passivation layer is deposited on the GaAs surface using atmospheric pressure chemical vapor deposition (APCVD). Circular anode wells of the appropriate diameter are then etched into the oxide to within about 50 nm of the GaAs surface by standard lithography and reactive ion etching (RIE). Next, the SnNi/Au ohmic contacts are formed, alloyed, and electroplated with additional Au to form a low resistance contact. The wafer is then mounted facedown in wax (Apiezon-W) on a silicon carrier and the bulk GaAs substrate and AlGaAs etch stop layer are removed by a wet chemical etch.

Simultaneously, a quartz wafer is similarly mounted to a second silicon wafer and thoroughly cleaned. A spin-on-dielectric (SOD) is applied to the quartz substrate and baked on a hotplate to yield a solid film about 0.5 microns thick. The GaAs and SOD/quartz surfaces are brought together and bonded under vacuum at elevated temperature. Although the temporary adhesive wax melts during this step, the wafers are held in place by pressure. After cooling, the Si carrier is removed from the front surface of the GaAs wafer by remelting the wax on a hotplate.

Processing then continues on the top surface of the GaAs epitaxial layers, which are now supported by the quartz substrate. The GaAs outside of the device areas is removed to reveal the SOD layer and the exposed SOD is plasma etched to reveal the surface of the quartz substrate. The thin SiO_2 layer protecting the GaAs anode surface is then etched in buffered oxide etchant and a thin layer of Ti/Au is electron beam evaporated over the entire wafer to form the Schottky anode contact. Photoresist is then applied to the wafer and the diode fingers and microstrip circuitry are defined and plated through the photoresist. After plating and photoresist removal, an RIE process followed by a brief wet etch removes the thin evaporated metals from areas outside of the fingers, contact pads and circuit lines. Fig. 1 shows an array of 585 GHz mixers. Note the filters are formed directly on quartz outside of the device mesa to form low loss microstrip lines. Also, excellent metal step coverage is achieved between the GaAs mesa and the quartz substrate. The surface channel etch step is then used to form a low parasitic air bridge under the fingers and a plasma etch removes the SOD from the surface channel area. A dicing saw is then used to separate the completed circuits from the wafer. In the final devices, shown in Fig. 2, the only remaining SOD is sandwiched between the quartz and the small GaAs mesas.

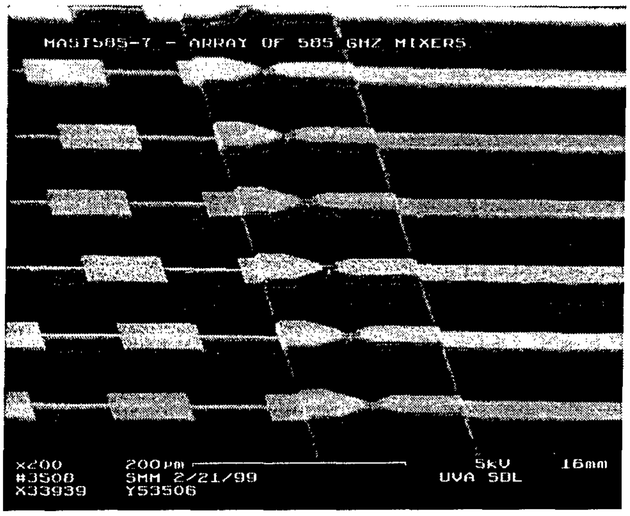

Fig. 1: An array of 585 GHz mixers. The metal circuitry is deposited directly on quartz.

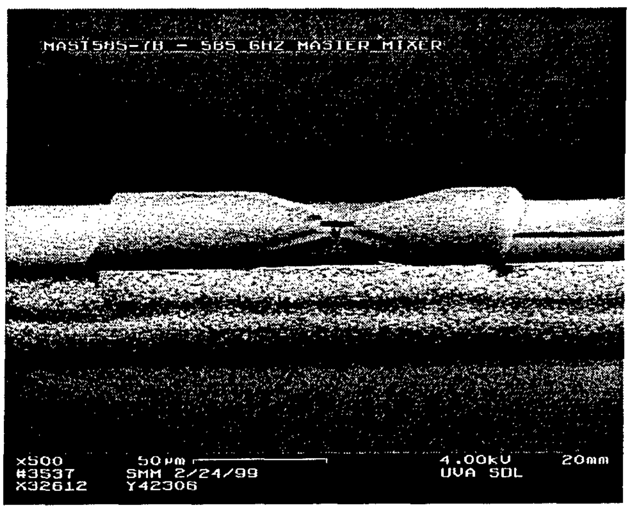

Fig. 2: An integrated GaAs-on-quartz mixer circuit after dicing. The only GaAs is the thin mesa below the metal pads in the center of the device.

The mixers were first tested in a standard metal waveguide housing as described in [3]. A molecular gas laser supplied the LO pump power and the hot/cold method was used to measure the receiver sensitivity. The results, summarized in Table I, are equivalent to the best ever reported in this frequency range at room temperature and 77 K. Also, it should be pointed out that this mixer had no mechanical tuners and the mixer assembly was simple and repeatable. These excellent results demonstrate the benefit of GaAs-on-dielectric integration over the use of discrete devices.

TABLE I
SUMMARY OF INTEGRATED MIXER PERFORMANCE AT 585 GHz

Ambient (K)	T_{sys} (K)	T_{mix} (K)	L_{mix} (dB)	P_{LO} (mW)
300	1631	1135	6.6	1.74
300	1799	1341	6.7	0.35
77	970	880	7.2	-

III. Micromachined Waveguide Circuits

The fabrication process presented here is a modified version of the process reported in several previous conference publications [4,5,6] and has been described more fully in a recent paper [7]. It 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. 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. For our 585 GHz mixer the cut had a depth of 150 μm (±5 μm) and width 205 μm (±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 [8]. 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. 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 ±2 μm and eliminates any problem with the planarity of the original SU-8 surface. For 585 GHz the width of the microstrip channel was 120 μm (±2 μm).

Alignment grooves are then diced into the wafer (200μm deep by 400μm 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 prepatterned in the SU-8 layer to facilitate proper alignment on the wafer. A three-inch process wafer yielded twelve complete waveguide pairs and required two weeks for a graduate student. As this process is refined we expect this time to be significantly reduced. The result is shown in Fig 3. Note that the features are very crisp and the fixed backshort is defined with lithographic precision.

To date, we have assembled several 585 GHz mixers using the micromachined waveguides and the integrated diodes described above. The results have been equivalent to those obtained with the traditionally machined metal waveguides. However, we have noted that the precision of the micromachined features is far superior to any of the metal housing we have obtained. More recently we have assembled and tested prototype mixers and a sideband generator at 1.6 THz.

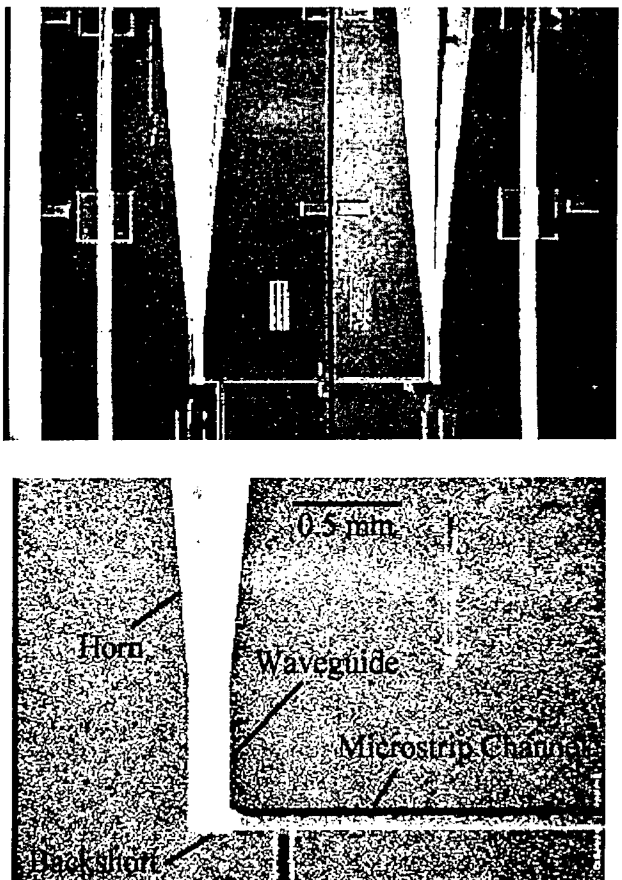

Fig. 3: Two views of the micromachined 585 GHz mixer, top: a split-block pair, and bottom: a closer view of the flared horn, waveguide and channel.

IV. Conclusion

GaAs Schottky diode technology continues to be a workhorse for many scientific applications in the terahertz frequency band. However, the complexity of using discrete diodes in traditionally machined waveguide circuits greatly increases the cost. This will prevent terahertz technology from ever being used in the broader array of potential military and commercial applications that are now being proposed. Through the use GaAs-on-dielectric integration and the micromachining of waveguide circuits we hope to greatly reduce these costs. Our results to date have demonstrated that integrated terahertz circuits and micromachined waveguides can be fabricated with high precision, low cost and excellent performance.

Acknowledgement

This work was supported by the U.S. Army National Group Intelligence Center (DAHC90-96-C-0010), the Army Research Office (D. Woolard) and NASA/JPL.

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