THE FRAMELESS MEMBRANE: A NOVEL TECHNOLOGY FOR THz CIRCUITS

Jean Bruston, Suzanne Martin, Alain Maestrini, Erich Schlecht, Peter Smith[†] and Imran Mehdi

California Institute of Technology, Jet Propulsion Laboratory, Pasadena, CA
[†]Now at Cree Inc., Durham, NC

ABSTRACT

A novel GaAs based Schottky diode fabrication process has been developed that enables increased design flexibility and robust implementation of monolithic circuits well into the THz frequency range. The fabrication technique builds on the already demonstrated membrane technology for 2.5 THz mixers [1, 2]. Realizing that the small size of the active devices at these frequencies might not require extensive mechanical support, the thick GaAs frame around the device/circuit has been eliminated. Additionally, increased use of metal beam leads is made to provide not only DC connections, but also RF tuning elements, and handling/support structures. This technology allows designers to rethink their approach to high frequency circuits, by permitting many different types of circuit implementations, which were previously not possible with existing technology. We illustrate the flexibility and potential of this technology by presenting two multiplier circuit designs, a 1.2 THz tripler and a 2.4 THz doubler. Both circuits are based on balanced configuration and utilize split waveguide blocks. These circuits are currently under fabrication and once done will be used for the High Frequency (HIFI) instrument on the Far Infrared and Submillimeter-wave Telescope (FIRST).

1 INTRODUCTION

Millimeter and submillimeter heterodyne observations will improve our understanding of physical phenomena present in the universe, the solar system and Earth's atmosphere. To help these studies, several space missions will soon fly instruments with heterodyne receivers working at frequencies up to 2.7 THz (FIRST, EOS-MLS, ROSETTA). High frequency non-cryogenic mixers and local oscillators (LO) are critical to the successful implementation of these missions. The goal of the technology development presented here is to enable design, fabrication, and robust implementation of solid-state components into the THz range.

For years, Schottky mixers developed for the THz range have employed point contact single diodes with corner cube structures. These whisker contacted diodes have worked well for frequencies even above 2.4 THz [3] but the implementation of this technology, especially for space based missions, suffers from a number of disadvantages as pointed out in [1]. Similarly, current development of high frequency multiplier sources also relies on whisker contacted Schottky diodes. Though these whisker based circuits have worked at frequencies as high as 1395 GHz (about 17 μW of power with an input power of 7 mW from a carcinotron source [4]) they tend to suffer similar disadvantages, in that assembly tolerances are extremely tight and can substantially affect RF performance. Moreover, multiple diode configurations are extremely difficult to implement and reliability and bandwidth limitations continue to be a source of concern. To overcome these drawbacks, the monolithic membrane-diode (MOMED) process was developed, integrating Schottky diode mixers with RF filter circuitry on a 3-micron thick GaAs membrane suspended across a frame [1]. Mixer circuits based on this technology have shown excellent performance at terahertz frequencies [2]. The MOMED technology can be utilized for making multiplier circuits into the THz range but it was soon realized that the relatively thick GaAs frame limits the design flexibility especially when it comes to utilizing split-block housings. In order to adequately address this concern and further solidify planar technology for supra THz circuits it was clear that the MOMED technology must be further developed.

2 THE FRAMELESS MEMBRANE

In the MOMED approach, a thin (2-3 μm) insulating GaAs membrane bridge is left under the diode and RF filter regions, and a thicker support frame falls outside the active area. The membrane bridge can then be coupled to single-mode coaxial and waveguide circuits fabricated by more traditional machining techniques. A picture of a completed MOMED chip is shown in Figure 1. These circuits have proven to be robust and easy to handle with state-of-the-art performance [2]. However, one important draw back found during the design of high frequency multipliers using this architecture, is the necessity of having ports normal to the membrane. In other words, the RF waveguides have to be normal to the membrane, thus reducing the possible implementations. Furthermore, the huge frame (about $1x1mm^2$) takes up a large amount of real estate on the GaAs wafer, thus reducing the number of circuits that can be fabricated at one time.

To adequately address these limitations, the MOMED technology is being extended by:

- *Eliminating the thick GaAs support frame to increase design flexibility.*
- *Developing new beam lead structures to provide RF probes, tuning elements, mechanical support and DC bias contacts.*
- *Implementing multi-diode schemes to expand circuit possibilities.*
- *Shrinking overall circuit dimensions to increase devices per wafer.*
- *Maintaining or developing structures that can assist in circuit handling.*

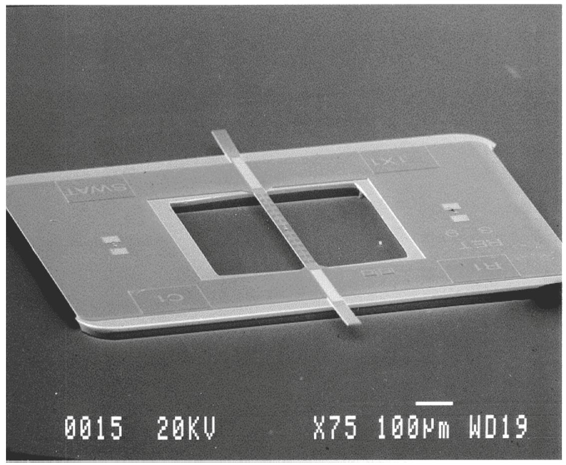

Figure 1 A 2.5 THz mixer [1,2] on a 3 µm thick GaAs membrane. The central strip is 30 µm wide and is supported by a large 50 µm thick frame, which lies outside the active region. Beam leads extend from the membrane and frame for DC contact and IF removal.

The resulting structures from this technology development will be based on GaAs membranes but will be frameless. This approach results in several significant advantages:

- First, it provides increased design flexibility: The elimination of the frame means that thick GaAs no longer lies in the plane of the membrane. It allows for the waveguides to launch in the same plane as the membrane, as in a split waveguide implementation.
- Second, because the membrane is not supported by a frame, the membrane size and shape can be dictated by the circuit needs rather than constrained by the surrounding frame.
- Third, the drastically reduced total size of the chips (one order of magnitude) means that more designs and variations can be laid out on a given wafer.

One important consideration is the handling, made difficult by the reduced size and the absence of a protective large structure. However, the use of a small "sacrificial frame", described below, may eliminate this concern. Moreover, at supra-THz frequencies, the very small dimensions of the chip implies a reasonable thickness to length aspect ratio providing for adequate strength. Preliminary tests of circuits that lack support frames (Figure 2) indicate that the 3µm thick GaAs membrane is strong enough to support diodes and some circuit elements and does survive mounting into a waveguide block [5].

A further improvement in the implementation scheme for these structures is achieved by the extensive use of beam leads. The advantages are a simplified assembly (no soldering, as chips are "dropped in" and support beam leads bonded to block), a simplified bias scheme requiring no wire bonds, the possible implementation of low loss, high bandwidth antennas/circuits using air as the dielectric. Again, one possible drawback is handling, as the beam leads may turn out to be rather sensitive to bending.

To protect the beam leads during handling and assembly, we are implementing a metalized membrane frame around the chip, connected by means of small metal tabs (Fig.3). This "sacrificial frame" provides a 'handle' during positioning of the chip in the waveguide block. Once the support and bias beam leads are tacked to the block, the frame is released by severing the small connecting tabs.

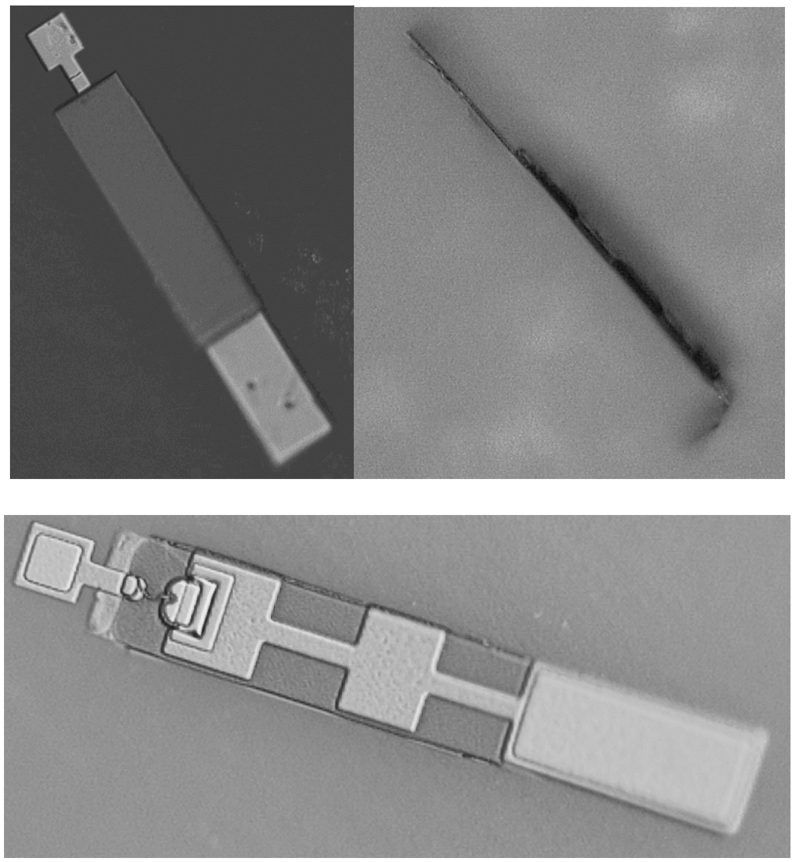

Figure 2 Three views (bottom, side and top) of a 2.5 THz mixer on a 3 μm thick GaAs frameless membrane (designed by RAL[5]). The membrane is 30 μm wide. Beam leads extend from the membrane for support and assembly, DC contact and IF removal.

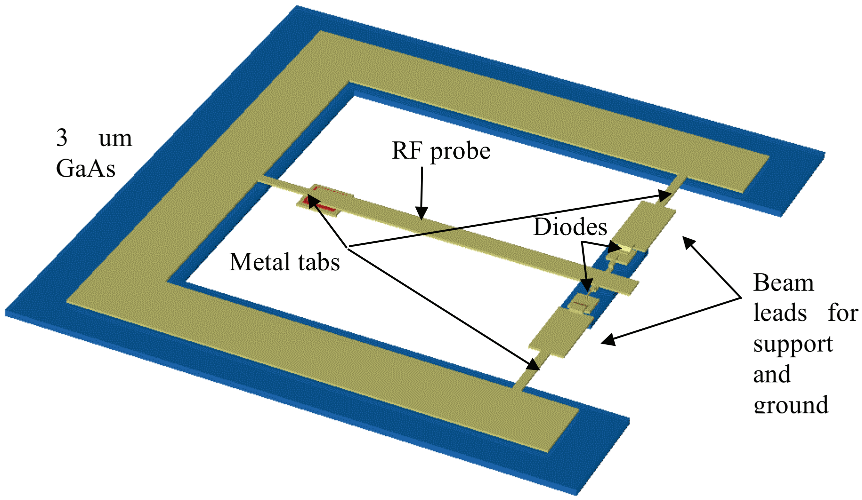

Figure 3 Example of a sacrificial frame supporting a 2.4 THz doubler chip (details of the design will be presented later). The frame is used for handling, and the metal tabs are cut after bonding of the beam leads to the block.

3 FABRICATION TECHNOLOGY

The fabrication of the membrane devices essentially follows the process outlined for the 2.5-Thz GaAs monolithic membrane-diode mixers reported earlier [1]. The epitaxial layers are MBE or MOCVD grown on semi-insulating GaAs. The diode structure consists of a 150nm of 5 x10^{17} /cm^3 n-type Schottky layer, a heavily doped (5x10^{18} /cm^3), one micron thick n+ layer for low-resistance ohmic contacts on a 50nm $Al_{0.5}Ga_{0.5}As$ etch-stop layer. Supporting these layers is a 3μm thick undoped GaAs membrane layer and a lower 400nm thick AlGaAs etch-stop layer. The ohmic contacts are an alloyed Au/Ge/Ni/Ag/Au metalization, recessed into the n+ GaAs layer. Device mesas are defined using a selective etch containing BCl_3, SF_6, and Ar in an electron cyclotron resonance (ECR) reactive ion-etch system (RIE), making use of the upper AlGaAs etch stop layer. Interconnect metal is then deposited to the height of the mesas. This is important for the anode definition, where the sample is covered with over 3 μm of PMMA, which is subsequently thinned using acetone spray, until the tops of the mesas and interconnect metal are just visible. This lower layer of PMMA forms a support for the PMMA/copolymer/PMMA tri-layer that is used for the electron-beam defined anodes. This resist structure allows the Ti/Pt/Au anode metal to bridge the gap between the interconnect metal and the actual Schottky contact area on the active mesa. Figure (4) shows the anode bridge of a 2.4 THz doubler circuit. At these frequencies Schottky contact dimensions are sub-micron, necessitating the use of e-beam lithography in their definition.

Following anode metalization and lift-off, silicon nitride is deposited using plasma enhanced chemical vapor deposition (PECVD). This acts as the dielectric for any required MIM capacitors in addition to passivating the diodes. A subsequent air-bridged metal step forms the top contact to the capacitors in addition to providing connections to the on-mesa ohmic metal areas.

The first membrane-related processing step lithographically defines the membrane areas of the circuits from the topside of the wafer. An RIE of CF_4/O_2 is used to remove the silicon nitride layer, followed by an ECR RIE of the 3μm GaAs membrane layer, again using $BCl_3/SF_6/Ar$, in order to stop on the lower AlGaAs etch stop layer. By defining the membrane during front-side processing of the sample rather than backside lithography, critical spacing between the circuit elements and the membrane edge can be maintained. However, the wafer topography following the membrane etch requires that the final front-side metalization, to define the circuit beam leads, be air-bridged from the top of the vertical-walled membrane layer to the field area, 3μm below. This 1-2μm thick metal layer will provide bias connections, mechanical support and RF tuning elements for the circuits.

The wafer is next mounted topside-down, using wax, onto a suitable carrier wafer, e.g. silicon, glass or sapphire. The GaAs substrate is thinned then removed by lapping, polishing and, finally, wet etching. A selective wet etch of H_2O_2 and NH_4OH is used that will stop on the AlGaAs layer below the membrane. A brief non-selective etch (phosphoric acid/hydrogen peroxide/water) is then used to remove the AlGaAs etch stop. At this point the circuits are separated and can be removed from the carrier wafer by dissolving the mounting wax in an appropriate solvent and collecting the chips on filter paper.

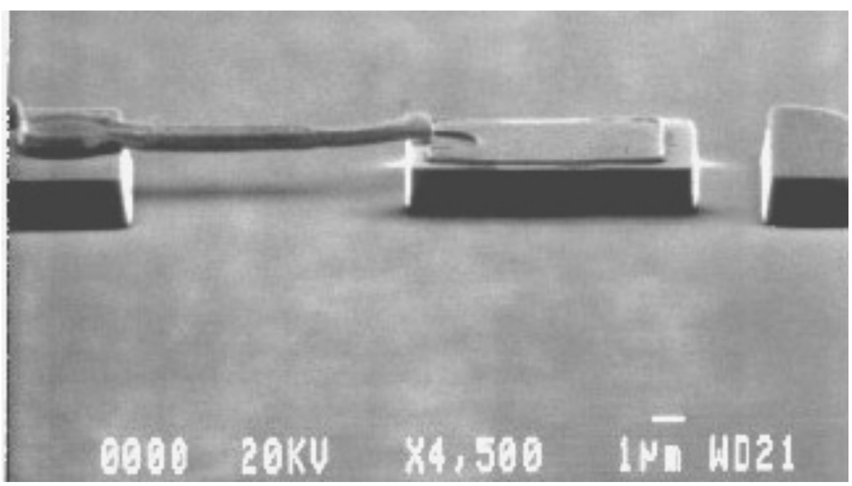

Figure 4. SEM image of one diode in the 2.4 THz doubler circuit. At the center is the device mesa mostly covered by the ohmic contact metalization. The anode finger bridges from the interconnect metal, at left, to the 0.14 μm by 0.6 μm Schottky contact on the GaAs mesa.

4 MULTIPLIER DESIGNS AND PERFORMANCE

The multiplier designs currently being developed at JPL are focused towards meeting the LO requirements for the High Frequency (HIFI) instrument on FIRST. Two of the multiplier designs that are made possible due to the development of this technology are discussed in this section.

4.1 Tripler to 1.2 THz

The tripler design to 1.2 THz uses a balanced configuration, where two diodes appear as anti-parallel for the odd harmonics (including the fundamental), and parallel for the even harmonics (Fig. 5). This configuration has the advantage of confining the second harmonic idler to the diode loop, reducing the design complexity. The input and output matching circuit need to consider only first and third harmonics, and the required idler tuning can be performed in the diode loop. Such a configuration had been tried previously [6] with limited success. However, the difficult idler tuning optimization is now greatly facilitated by the availability of 3-D electromagnetic simulators.

The circuit is implemented in coplanar waveguide which facilitates the biasing of the diodes, as they appear in series at DC. The idler tuning is accomplished by optimizing the length of the diode air-bridges. This approach has the advantage of making the circuit very simple, but has the drawback of reduced bandwidth. The extra inductance needed for tuning the second harmonic affects the third harmonic match, providing a highly inductive embedding impedance. The resulting matching circuit becomes fairly high Q, hence reducing the realizable bandwidth. However, in this specific case, we were able to compromise the efficiency slightly to achieve the desired bandwidth for FIRST(the predicted 3dB bandwidth is around 15 %). The input and output signals are coupled to the waveguides by means of E-field probes. The diodes are matched to the probes using a very simple high-low impedance matching circuit. On the output side, this is reduced to only one step. This is desirable to reduce loss, and increase the membrane mechanical stability. The membrane is held in the inter-waveguide channel with the help of beam leads, clamped between the two halves of the split waveguide block. The bias is provided via a pad and a line running on one of the beam leads, while the other beam lead is shorted, providing the DC ground.

Using a full simulation of the waveguide and circuit structures together with an harmonic balance simulation of the diodes [7], we find an efficiency better than 1% over the required bandwidth for FIRST, and up to 2% in the lower part of the band. This result is for 10 mW input power, yielding an approximate output power of 100 μW over 1104 to 1272 GHz. A very strong roll-off is found at the upper end of the band. It is due to the appearance of higher order evanescent modes in the output waveguide, coming from the interaction with the circuit channel. The next iteration will resolve this problem and a relatively flat response across the design range is expected.

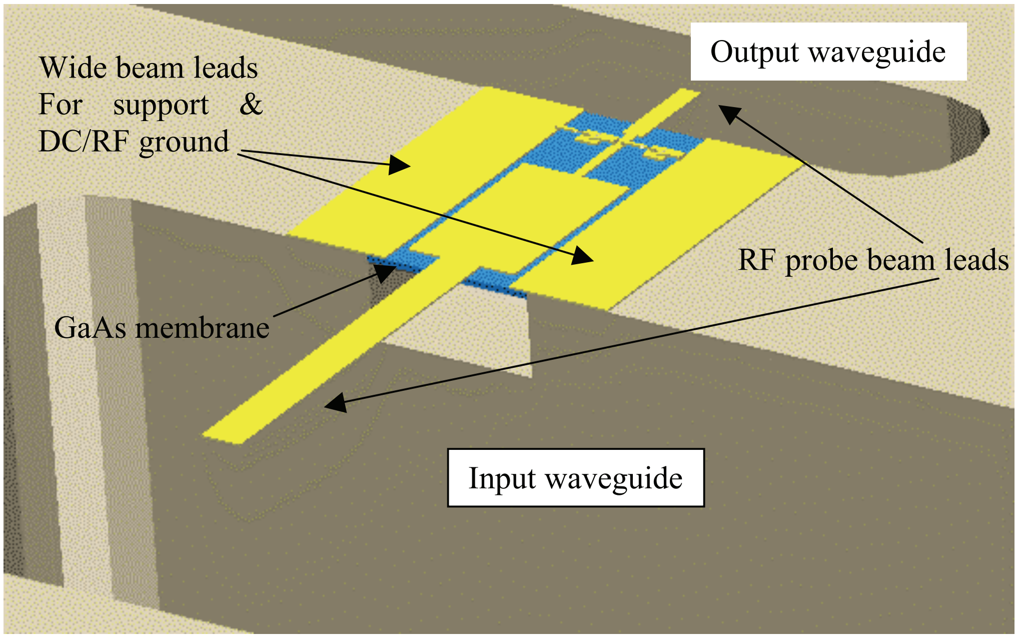

Figure 5 Sketch of the 1.2 THz tripler layout showing the E-plane probes in the input and output waveguides.

4.2 Doubler to 2.4 THz

The doubler from 1.2 THz to 2.4 THz is designed in a balanced doubler configuration, which provides isolation between the input and the output of the circuit. The general operating principle is the same as for lower frequency doublers, and is described in [8]. In this design, the input signal is coupled directly to the diodes, whereas the output is coupled to the output waveguide by means of an E-field probe. The input matching is done entirely using the waveguide structure. The output matching is realized using different slot dimensions for the inter-waveguide channel, which changes the impedance of the coaxial line. A small open stub is used on the input side of the diodes to tune out some of the varactor capacitance. As with the tripler, the membrane is held in the block by two metal beam leads formed monolithically with the circuit and diodes. Figure 6 shows the final design. Both the 1.2 THz tripler and the 2.4 THz doubler are currently in fabrication.

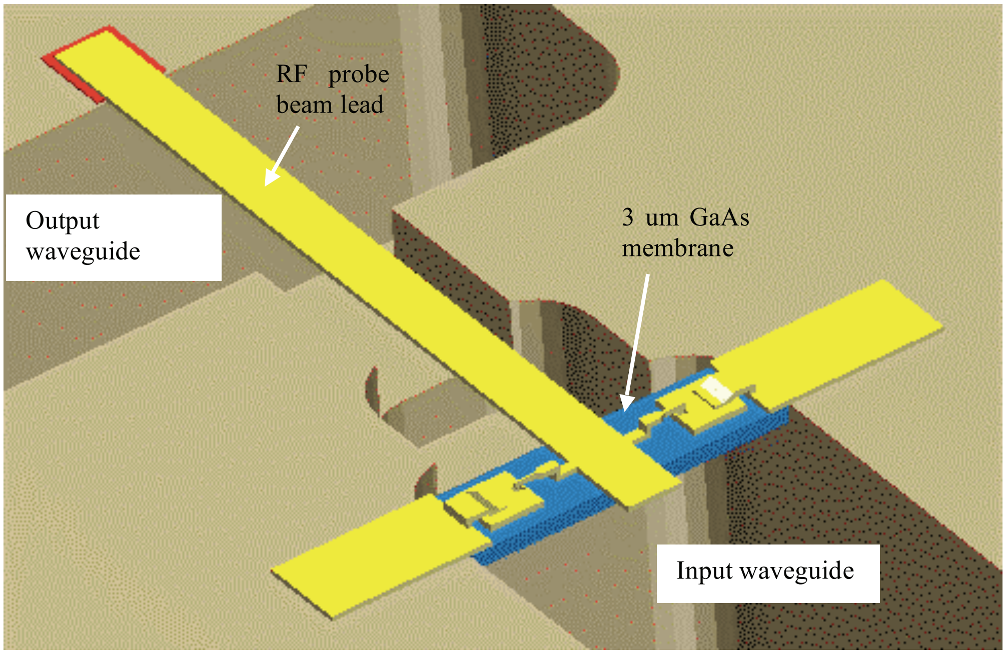

Figure 6 Sketch of the 2.4 THz doubler. The shorter beamleads provide a ground contact and mechanical support for the chip

5 CONCLUSIONS

An innovative and practical scheme of building Schottky diode based circuits for very high frequencies has been proposed which relies on the recent advances made in the fabrication of membrane based structures. The frameless membrane technology allows for the design of monolithic circuits with increased flexibility and lower loss. The enabling power of this technology is demonstrated by the two designs presented that are under fabrication and would be extremely difficult if not impossible to implement with presently available technologies.

ACKNOWLEDGEMENTS

We are highly appreciative of the numerous technical discussions that we have had with Neal Erickson (UMass), Peter Zimmermann (RPG), Chris Mann (RAL) and Tom Crowe (UVa). We also wish to acknowledge the technical help provided by Barbara Nakamura, Andy Fung, and Ray Tsang (all of JPL) for device fabrication and characterization. The research described in this publication was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration

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