DEVELOPMENT OF A NOVEL 380GHZ MEMBRANE 'MMIC' SUBHARMONIC MIXER

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ABSTRACT

The basic concept of the transverse Schottky diode is discussed. Device simulations are presented for the discrete diodes and associated test structures (Silvaco TCAD). Independent Harmonic Balance calculations are compared with results from industry standard simulators. Diode integration into a mixer circuit on a GaAs membrane is described. Mixer noise temperature and conversion loss measurements are presented for the 380 GHz subharmonic membrane MMIC mixer. Conclusions are drawn.

INTRODUCTION

Receivers at THz frequencies are difficult and expensive to manufacture. Difficulties include mounting the very small planar Schottky diodes, usually configured as an antiparallel pair for subharmonic mixers, on to a substrate circuit with the diodes accurately positioned across the RF waveguide. Progress has been made by integrating the diode with the filter substrate but the standard high performance THz air-bridged planar diode can be fragile and easily damaged. Another challenge is that traditional manufacturing methods use metals such as gold plated brass for the waveguide (w/g) blocks, and require a high degree of precision to machine small dimension waveguides and channels, which effectively confines components to one-offs. Attempts have been made to overcome this and good progress has been achieved with micromachining techniques using a mix of polymer and silicon [1] or just silicon, however manufacture is complex with many process steps. The difficulties highlighted above make manufacturing THz receivers a costly and time-consuming business; whereas high performance but low cost production is required to enable THz applications. The aim of this work was to build a front end for a receiver demonstrating manufacturing techniques that with suitable development can fulfil the 'high performance but low cost' requirement for THz systems.

GaAs planar Schottky diodes have long been a mainstay for submillimeter mixer and multiplier applications. To reduce the parasitic capacitances the anode is usually contacted by an airbridge suspended over the substrate. The discrete devices are then flip-chipped into the waveguide circuitry. Disadvantages of this approach include: i.) To survive the bonding process the discrete devices need to be fabricated on thick substrates, ii.) There is a lower limit to the area of the footprint required to securely anchor the anode end of the bridge - this contributes to parasitic capacitance, iii.) The inevitable bump-bond parasitics. Varactor and varistor diodes have been fabricated using a novel design that overcomes these limitations and is used to integrate the diode into a membrane mixer circuit. Conventionally the Schottky contact is formed on a lower doped epilayer grown on the plane of the substrate. Our Schottky contact is made to a laterally grown sidewall epilayer (MOVPE) on a capped highly doped active GaAs layer grown on a semi-insulating substrate. With our transverse Schottky diode approach the anode finger remains in contact with the substrate along its length leading to robustness without a minimum junction footprint. In addition the junction area can now be controlled using the submicron accuracy of the grown n+ active layer thickness. The entire process is compatible with GaAs membrane technology so that the diodes, filters and matching circuitry finally remain monolithically on a thin membrane which directly mounts into the waveguide block. This approach is demonstrated by fabrication of a complete 380GHz subharmonic mixer on a thin GaAs membrane as a beamlead MMIC using the transverse contacted diode technology. This represents a potential development of the MOMED technique which has been used successfully at THz frequencies [2].

A further novel aspect of this work is a technique that has been developed aiming to reduce manufacturing costs of the mixer waveguide block by hot embossing a polymer with a stamp that represents the waveguide cavity design; the polymer block is then coated with metal. These developments demonstrate how manufacturing costs could be reduced for small scale volume production of sub-millimetre wave and THz components.

FABRICATION

Membrane Schottky MMIC

The diode structure consists of a mesa of n^+ GaAs fabricated on a semi-insulating GaAs substrate. A thin epilayer of n-type GaAs is grown on the vertical sidewall of this mesa by preferential lateral MOVPE growth for the Schottky contact. An ohmic contact and cathode pad is formed to the GaAs mesa; a thin section of SiO_2 is used to passivate this from the lateral grown epilayer. A Schottky contact is formed to the laterally grown sidewall, and anode finger and contact pad fabricated to this (Figs.1, 2). This structure has some major advantages over a conventional airbridged planar diode, such as a self-aligning anode/anode finger with no airbridge, which greatly simplifies fabrication and minimises parasitic capacitance. Also as no backside processing is required the transverse diode can take advantage of membrane technology by fabrication on GaAs membranes. Integration of the diode with other circuit structures on the membrane is therefore feasible. The doping levels and thicknesses of the sidewall epilayers can be controlled to produce varistors or varactors as desired (both, if opposing growths are used). Single mixer and anti-parallel pairs, and varactor diodes with a range of physical dimensions have been fabricated.

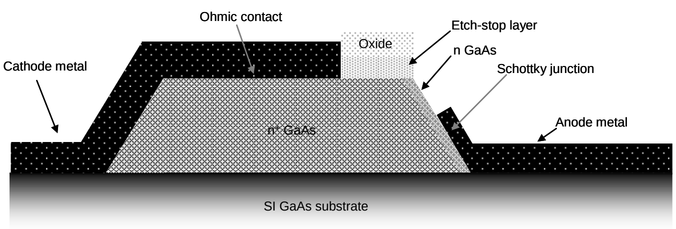

Fig.1. Schematic section of transverse Schottky diode showing Schottky contact

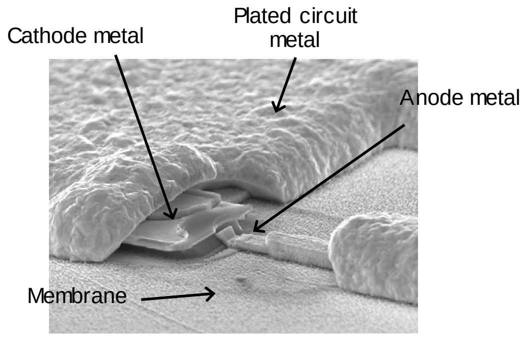

Fig.2. SEM image of transverse Schottky diode in membrane circuit

For this development of a 380GHz mixer as a Schottky MMIC, the diode fabrication was integrated with circuit elements on a GaAs membrane structure to realise the design of the mixer. The membrane consisted of 2.5um thick semi-insulating GaAs sandwiched between suitable etch-stop layers with metal beamleads being used for the IF connector and to suspend the membrane circuit in the cavity. The circuit metallisation and beamleads were fabricated using electroplated gold to 3um thickness (Fig.3).

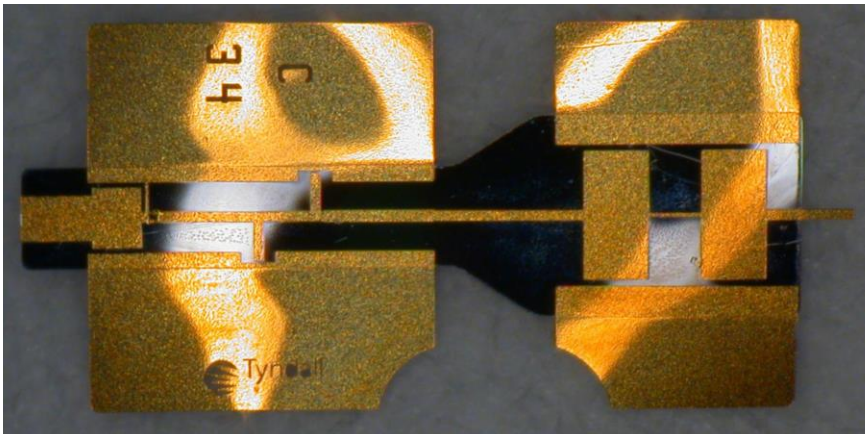

Fig.3. Image of 380GHz Schottky membrane mixer showing membrane, RF probe, gold beamleads and IF tab.

Polymer Waveguide Block

The hot embossing process involves heating a polymer to above its Tg (glass transition temperature) and then stamping a pattern into the softened polymer. The polymer selected for this work was an amorphous thermoplastic polyetherimide with high strength properties designed for injection moulding processing offering good dimensional stability. A glass fibre filled variant of the polymer with a lower thermal coefficient was also selected. Selection was made after embossing trials of several polymers had confirmed good feature reproducibility and low surface roughness.

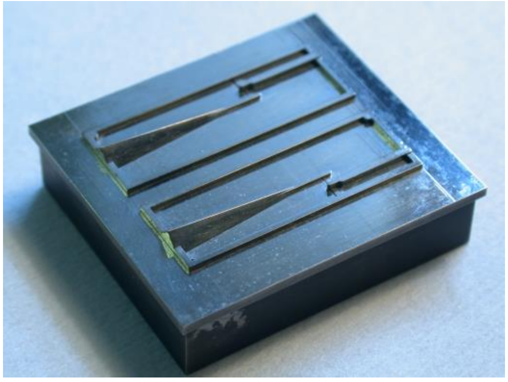

Fig.4. Image of mixer w/g block stamp

Fig.5. Image showing embossed gold coated polymer w/g block

The stamp for the mixer block was manufactured by electroforming in nickel from an aluminium mandrel as shown in Fig. 4. Many embossing cycles were performed with the stamp to optimise process conditions. A critical feature of the stamp was deformed during de-moulding in the early part of the optimisation rendering subsequent embossed parts unusable for RF measurements, however one part was selected before the deformation occurred for further processing. The embossing was not optimised at this stage and although the dimensions were not fully within the specification, useful information could be gained from completing the full manufacturing process. The embossed piece was therefore machined and fitted with alignment dowels to fit a carrier jig that would combine into the mixer block, and was then coated with gold. An image of the polymer split waveguide block coated with gold is shown in Fig. 5. Imperfections in this piece resulting from the non optimised embossing process precluded any RF measurements and further embossed parts could not be manufactured due to the damage incurred by the stamp. However the overall mean dimensional error of the embossed block was 0.01% of the stamp where a calibrated optical microscope was used for width measurements and a surface profiler used for depth measurements. Measured surface roughness was actually lower for the embossed samples than the stamp.

TEST STRUCTURES

As an aid to the technology development and characterisation of the transverse Schottky diodes we included on our mask sets: contact resistivity Transmission Line Measurement (TLM) structures, capacitance standards for low frequency LCR measurements, and RF de-embedding and diode measurement structures. The standard TLM method [3] was used to characterise and optimise the rapid thermally annealed ohmic AuGeNi cathode contact to the n+ active layer. These structures also proved useful in verifying the isolation between the mesas of the individual diodes. The contact resistance obtained was $R_c = 0.022\ \Omega$mm. Low value (5 fF) capacitance standards were included on the mask, these were used to verify our diode junction capacitance measurements [4]. RF test structures (Open , Short, Thru line) were included for one-port de-embedding of the diode S-parameters (to 110 GHz). The de-embedding strategies used are similar to those discussed by Cho and Burk [5] and Tiemeijer [6].

DEVICE SIMULATIONS AND CHARACTERISATION

The development process used for the Transverse Diode is shown schematically in Fig. 6. Ideally the three strands Diode Design, Diode Fabrication, RF Design and Mixer fabrication would occur separately and in that order. However in reality it was necessary for these themes to occur concurrently. To keep flexibility a range of diode structures and dimensions were fabricated. The parasitic (contact pad-contact pad) capacitances for the discrete diodes were modelled with ANSYS. The physical internal diodes were modelled using Silvaco™ TCAD tools. Atlas 3-D simulations were performed (Fig. 7). The resulting I-V and C-V curves were fitted to extract the expected diode model parameters (Rs, Is, n, CJ0, VJ, Gamma). Figs 8 and 9 show the Atlas/Blaze simulations of I-V, C-V for a fabricated n-GaAs mixer diode with parameters:

Epilayer thickness	110 nm
Epilayer doping	$2\ 10^{17}\ cm^{-3}$
Anode height	1.0 μm
Anode width	4.0 μm

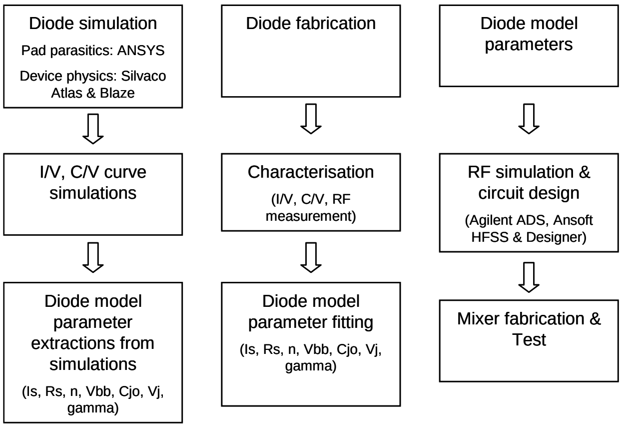

Fig. 6. Diode development schematic

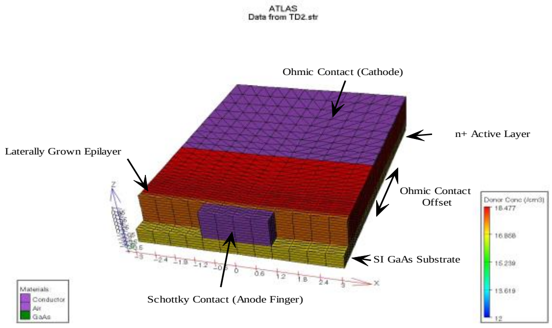

Fig. 7. Atlas 3-D structure for Transverse Diode simulation.

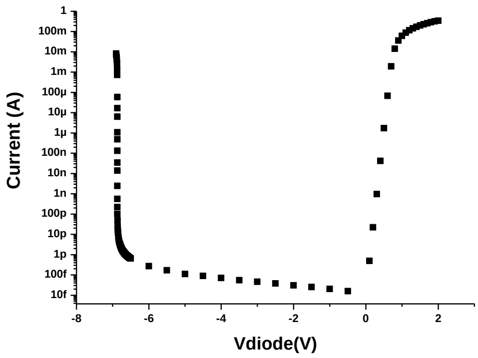

Fig. 8. I/V Characteristic Atlas/Blaze simulation

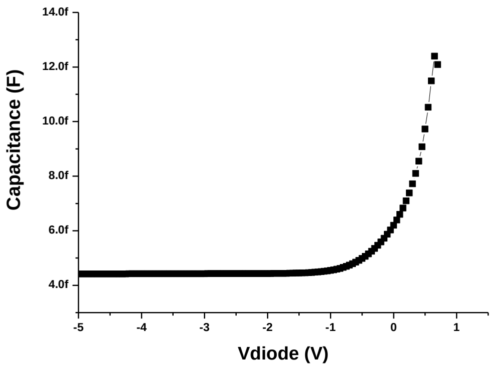

Fig. 9. Diode Junction Capacitance Atlas /Blaze simulation

The single and anti-parallel diode pairs were DC characterized at room temperature using a shielded Cascade probe station and an Agilent HP4156 parameter analyser. The SPICE parameters I_S, n, R_S, V_{bb} are then fitted. Fig. 10, shows a typical measurement and fitting for an antiparallel transverse diode pair, both diodes are closely matched. Capacitance measurements were performed on the transverse diodes using an Agilent 4284A LCR meter and the technique described by F. Sischa [7]. As an example, for varactor 8V10, the simulated junction capacitance gives a C_{JO} of approximately 22 fF, the parasitic pad capacitance from ANSYS is 11.3 fF and the agreement with measurements is excellent (Fig. 11). The diode parameters fitted to the Atlas simulations were in accord with those obtained from measurement.

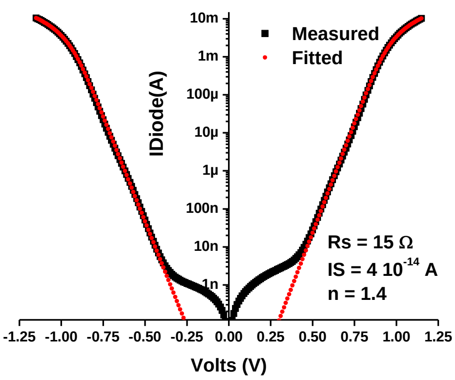

Fig. 10. I-V for anti-parallel pair (R10#4)

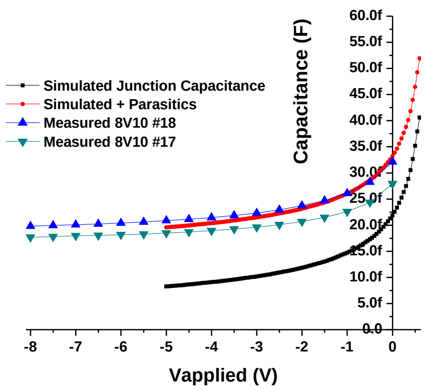

Fig. 11. Simulated and measured CV, for varactor (8V10)

HARMONIC BALANCE

The harmonic balance method is frequently used to determine the nonlinear device response to an applied large signal [8]. A Mathematica program has been written to implement Harmonic Balance for diode circuits. In Fig. 12, the Mathematica results for a single diode (with the parameters and excitation shown) are compared against those obtained from Silvaco SmartSpice and Ansoft Designer. In this case 20 harmonics have been calculated and the time domain response shown is then reconstructed. For ease of setting up in Designer and SmartSpice the embedding impedance is taken to be 50 Ω at the fundamental and all harmonic frequencies. For simple circuits the direct approach using Mathematica has several advantages, firstly all the embedding impedances can be exactly specified as complex numbers at each harmonic (no ideal filters are needed and for example Rs can be made frequency dependent). Also the exact steady-state initial condition can be applied (no time domain settling is needed). Flexible optimising of the embedding impedances should also be possible.

DESIGN

The 380 GHz subharmonic mixer (LO : 188 GHz, IF : 4 GHz) was designed as an MMIC module with an anti-parallel pair of transverse Schottky diodes being the non-linear element. This is fabricated together with the necessary matching and filtering on a common 3µm thick GaAs membrane, using gold beamleads to suspend the membrane in the cavity and for the IF tab. Fig.13, shows the structure with the component sections, the full beamleads are not shown in this drawing.

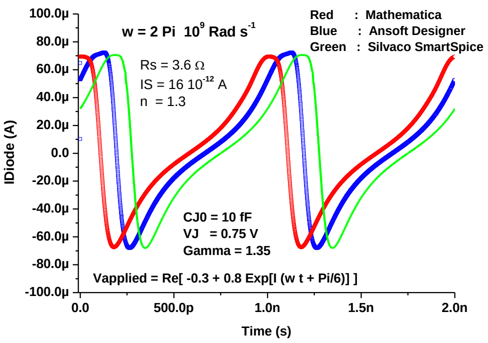

Fig. 12. Harmonic Balance Comparisons

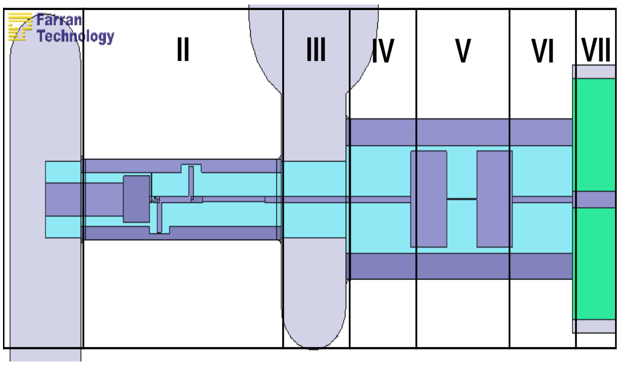

Fig. 13. Membrane structure with component sections.

These sections are as follows:

I. RF waveguide to microstrip probe.
II. Diodes, RF and LO matching section.
III. LO waveguide to microstrip probe.
IV. Line between the LO probe and the LO/IF filter. It provides together with the LO/IF filter an open circuit for the LO frequency.
V. LO/IF high-low impedance lowpass filter. Designed to block the LO and to pass the IF frequency.
VI. Line between the LO/IF filter and the quartz IF quarterwave transformer.
VII. Quartz quarterwave transformer for matching of the IF frequency

The waveguide design was accomplished with Ansoft HFSS. Using Harmonic Balance in Agilent ADS, the diode RF and LO frequency embedding impedances were optimised for conversion loss (the IF impedance being held fixed and frequencies above the RF terminated in 10 Ω (Hesler [9])). The DSB conversion loss estimated for the design was 6dB.

MIXER MEASUREMENTS

The mixer membrane was mounted in a machined metal waveguide block and tested using the hot and cold measurement technique to extract the noise temperature and the conversion losses of the mixer [10]. The “hot” load (295 deg K) is a piece of absorber at room temperature and the “cold” load (77 deg K) is an absorber piece that is cooled with liquid nitrogen. Fig. 14, shows the membrane mounted on the lower half block, slight bending of the membrane is visible in the image but this did not present any difficulties in mounting and assembly.

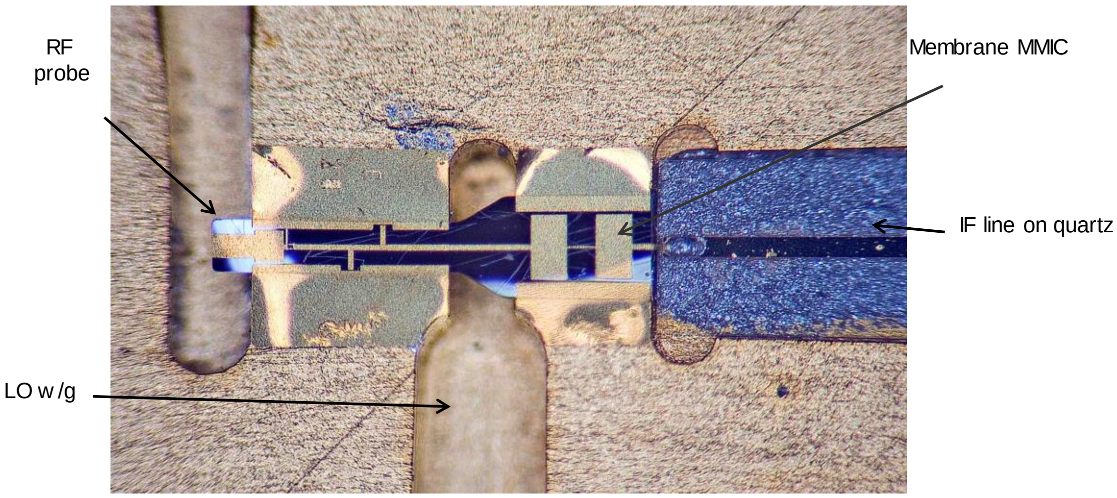

Fig. 14. 380GHz membrane mixer mounted in lower half waveguide block.

The LO source required for the measurement consisted of a chain made of:

- a BWO source providing 13 dBm at 95 GHz
- a power amplifier producing 23 dBm of output power at 94 GHz
- a 95-190 GHz Doubler

Approximately 7.2 mW of LO power were required to drive the diodes. The System Noise Temperature Vs IF Noise Temperature graph is shown Fig. 15. The slope of this curve as well as the Y intercept respectively corresponds to the conversion losses as well as the noise temperature of the mixer. These values were found to be 14 dB (DSB) and 11000 K respectively.

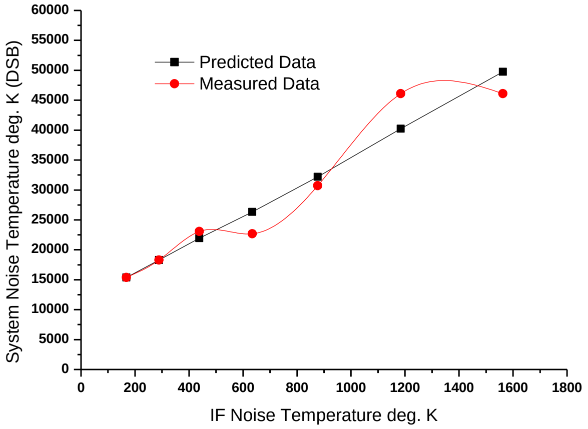

Fig. 15. System Noise Temperature vs IF Noise Temperature obtained using hot/cold method.

DISCUSSION

It is seen that the measured DSB conversion loss of 14 dB far exceeds the predicted loss of 6 dB. This may be attributable to two factors. Firstly, the diode parameters used during the design phase of the ADS model did not closely correspond to those of the diodes provided on the membrane mixer. Secondly it was found necessary in HFSS to use internal lumped ports at the active area rather than the preferred waveguide ports [10], this may lead to duplicating part of the junction capacitance when using the lumped diode model. The measured diode parameters of the membrane circuit used in the mixer which was device R13#1 C1, were as shown in Table 1 together with the values used for the design. Capacitance data is not available as the thinned membrane cannot be directly probed and these DC measurements were made before substrate thinning.

Table 1. Membrane mixer diode measured and design values

	Diode A				Diode B			
	Is1 (10^{-13}A)	N1	Rs1 (Ω)	Cjo (fF)	Is2 (10^{-13}A)	N2	Rs2 (Ω)	Cjo (fF)
Design	0.06	1.3	7.9	2.3	0.06	1.3	7.9	2.3
R13#1 C1	8.05	1.32	38.5	-	5.27	1.30	47.6	-
R13#4 C6	2.25	1.33	22.8	-	9.93	1.41	32.2	-

Simulations were implemented in HFSS to investigate the major discrepancy in the results, by first increasing the saturation current (Is) to 10×10^{-13} A, but no significant difference was obtained. Next increased series resistance values were simulated with both symmetric and asymmetric values which significantly increased the conversion loss but the measured value was still ~ 4dB higher. Finally the extra shunt capacitance from using lumped ports included in the original HFSS design was removed in the simulation resulting in a conversion loss some 3.5dB lower than the measured value. It is not known what is causing the excess conversion loss but another membrane circuit with lower series resistance, device R13#4 C6 in Table 1 is to be measured in the same mixer.

A major goal of this work was to develop and demonstrate possible routes to easier manufacturability of THz receivers. One part of this was to integrate the transverse Schottky diode into a GaAs membrane circuit with beamlead technology, and the other part was to explore hot embossing technology of polymers as a means of small scale volume production of THz waveguide blocks. The novel transverse diode that we have developed has some advantages over the standard planar airbridged Schottky diode from both a fabrication and parasitics viewpoint. The anode area of the transverse diode is defined by the width of the termination of the anode finger which is patterned by optical lithography, and the anode height which is controlled independently of the mesa height during fabrication. This makes small geometry anodes possible without resorting to E-beam lithography. The anode suffers less fringing parasitics as there is no overlap footprint of anode finger metallisation contact to the anode, and is self-aligning thereby simplifying fabrication. Parasitic capacitance is limited to pad to pad capacitance as the n+ GaAs layer only underlies the cathode and not the finger or anode pad. A further advantage is that the transverse structure is entirely compatible with beamlead membrane technology with no added fabrication complexity. This has been demonstrated in this work where a robust membrane Schottky MMIC was fabricated and assembled into a waveguide mixer using standard processing techniques.

Hot embossing technology could be a promising process for the small scale volume manufacture of polymer bodied THz waveguide blocks where shrinking waveguide dimensions are more difficult to produce using conventional machining. A suitable polymer has been selected and processed with space applications as a major selection criterion. Promising mixer blocks were manufactured in the polymer with good reproducibility of features and low surface roughness (as good as the stamp). Further development work was not possible after the stamp was deformed as manufacture of a replacement stamp was beyond the scope of this work. However this work has shown that hot embossing technology is a possible route to easier manufacturability of THz receivers, although RF testing has yet to be realised.

CONCLUSION

A novel transverse Schottky diode has been developed for both varactors and varistors. The diodes have been characterised by both simulation and measurement. A 380GHz Subharmonic mixer circuit with integrated diodes on a thin GaAs membrane has been designed and fabricated. The membrane circuit has been mounted in a mixer waveguide block and RF performance measured. A version of the mixer waveguide block has also been manufactured in polymer by hot embossing and coating with gold.

ACKNOWLEDGEMENT

The authors wish to thank Dr. Tapani Nahri of ESA ESTEC for his encouragement and support. This work was supported by the European Space Agency.

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