# Integrated Schottky Structures for Applications Above 100 GHz

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***Abstract*— Recent developments in the fabrication of GaAs integrated Schottky structures for applications above 100 GHz are presented. Two approaches are discussed; the fabrication of integrated circuits using a GaAs foundry service, coupled with the research based post-processing of these structures, and the fabrication of discrete and integrated Schottky structures using a bespoke research laboratory.**

## I. Introduction

Low capacitance GaAs Schottky diode technology is required for millimetre and sub-millimetre wave heterodyne receivers. Schottky diodes operate at both ambient and cryogenic temperatures and are uniquely able to cover the frequency range from DC to above 1 THz. Schottky diode technology has been evolving for many years and has traditionally been driven by the demands of radio astronomy and remote sensing of the atmosphere. Ground based applications, e.g. security imaging, are now increasing in importance. For these applications, Schottky based technology offers an attractive alternative to detectors and sources that require cryogenic cooling [1].

Despite the growing demand for Schottky devices operating above 100 GHz, there remains limited availability within Europe and there is currently no space-qualified process available. The European Space Agency (ESA) has initiated a programme to investigate the use of the GaAs foundry service from United Monolithic Semiconductors (UMS) to fill the current gap between demand and availability (ESA AO/1-5084/06/NL/GLC). This programme aims to investigate the performance limitations of this GaAs foundry service and to explore ways of post-processing GaAs wafers to enhance device performance, for example, to reduce the dielectric loading around the anode to reduce the parasitic capacitance and the effect of dielectric loading. Using this approach, integrated Schottky structures have been designed for operation at frequencies upto 380 GHz.

Schottky diode fabrication is a relatively simple process which can be established in a research environment using optical lithography with simple manual alignment, deposition and etching tools. Structures in which the Schottky contact is integrated with an embedding network can also be fabricated in such an environment. In fact, a small research laboratory, with its inherent flexibility, can be very effective in optimising Schottky structures. Whereas a GaAs foundry can be considered as a fixed process with a small number of wafers procured with a single reticule design repeated across a wafer, in a research environment it is often the case that relatively small samples are processed using contact lithography, rather than a stepper, and that each sample iterates to an optimum set of process conditions. A foundry therefore offers a stable and reliable fabrication process whereas a research laboratory offers the ability to develop novel structures.

As operating wavelengths of Schottky structures move into the sub-millimetre wave range, novel integration and substrate transfer or removal techniques are required [2]. Here we report on the design, fabrication and test of devices fabricated at a GaAs foundry to which additional post-processing has been applied in order to improve their performance at higher frequencies. We also report on the fabrication and test of discrete and integrated Schottky structures designed and fabricated in a bespoke research laboratory which are being developed specifically to operate in the sub-millimetre wave range. In both cases, technology demonstrators are being targeted at the 200 to 400 GHz range.

## II. GaAs Foundry Devices

The use of a GaAs foundry service to fabricate high frequency Schottky structures has the potential to supply a large number of identical devices without the effort of developing the fabrication technology, which is often very expensive and time consuming. However, circuits operating above 100 GHz often require non-standard processing to reduce the parasitic capacitance and dielectric loading of waveguide cavities. These techniques are expensive to develop and there is little incentive for them to be available within a foundry service, given the current level of demand. For these reasons we have investigated the electromagnetic advantages and corresponding effort of post-processing foundry devices. Our results indicate that provided the quality of the Schottky contact can be retained for anodes that are smaller than is defined by typical design rules, the structure of the circuit metallisation can be designed to be suitable to at least 380 GHz for discrete diodes. Furthermore, provided that appropriate post-processing can be performed, integrated structures could operate over the same frequency range.

### A. Circuit Designs

A range of integrated Schottky circuits have been designed using a combination of 3D finite element analysis (HFSS) and non-linear circuit simulators (ADS). These circuits include:

- Sub-harmonic mixer at 183 GHz
- Sub-harmonic mixer at 380 GHz
- Frequency doubler at 190 GHz
- Frequency tripler at 90 GHz

These designs have been made with the assumption that certain post-processing will be performed on the GaAs wafer delivered by the foundry. For example, the sub-harmonic mixer at 380 GHz has been designed as a membrane structure; that is, the substrate of the circuit will be entirely removed leaving an epi-layer of thickness 4 µm. This ultra-thin circuit will be placed in a waveguide cavity, supported only by beam-leads, thin gold foils that extend beyond the edge of the circuit.

The design of the frequency doubler at 190 GHz was made assuming a substrate transfer technique. This approach is similar to the membrane process but instead of leaving the epi-structure suspended in air, the GaAs substrate is removed and replaced by quartz. This transferred substrate offers a lower dielectric constant and improved thermal conductivity, as compared to GaAs.

### B. Post-processing

Epi-structures, with diodes and passive matching elements have been successfully transferred from a GaAs substrate to quartz. The process to do this involves an epitaxial lift-off followed by transfer to quartz with an epoxy adhesion layer. The thickness of the epoxy layer was approximately 1 µm and the quartz was 50 µm thick. Fig. 1 shows an optical image of this circuit. The total length of the circuit is 1.8 mm. The diodes are situated in a vertical line towards the right hand side of this image and are in an anti-series configuration. Fig. 2 is an SEM micrograph of this structure, with the quartz substrate visible towards the bottom of the image.

Fig. 1 Optical image of a 190 GHz doubler circuit (total length 1.8 mm).

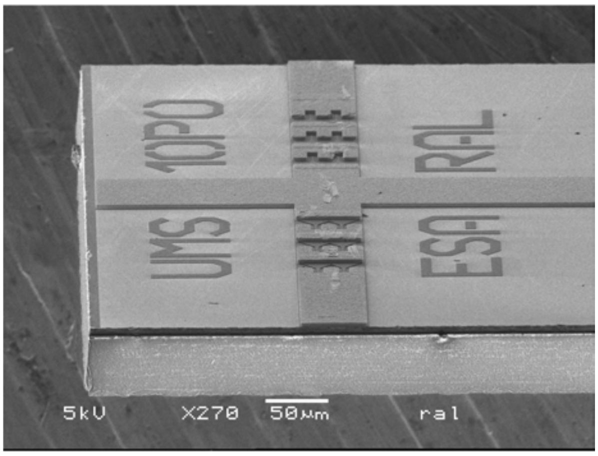


Fig. 2 SEM micrograph of a doubler circuit that has been transferred to a quartz substrate.

### C. Results

RF results have been demonstrated on the 190 GHz frequency doubler with a transferred quartz substrate. The results presented in Fig. 3 match simulated performance in both bandwidth and expected output power. The multiplication efficiency is recorded to be of the order 6%. This is quite low for a traditional frequency doubler in this range, however, this has been achieved with an epi-structures which is optimised for mixer applications [3].

Significant RF results are yet to be reported for the mixer and frequency tripler demonstrators.

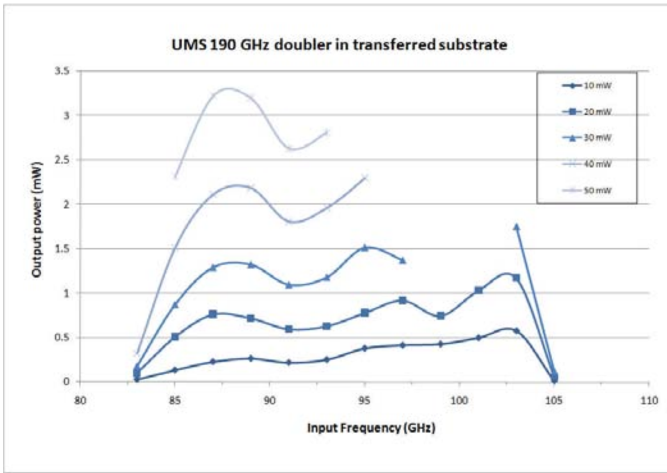


Fig. 3 RF results of a 190 GHz doubler using a transferred substrate process.

## III. Bespoke Device Fabrication

The ability to have full control over the design and fabrication of integrated Schottky structures offers significant advantages to the design of Schottky circuits operating above 100 GHz. The ability to fabricate air-bridged structures, significantly reduces the parasitic capacitance presented in parallel to the Schottky junction, improving bandwidth and performance. Techniques can be developed to fabricate very small anodes, typically sub-micron, and to ensure that where a pair of diodes are required, for example in the standard anti-parallel configuration of a sub-harmonic mixer, that these anodes have identical electrical performance. Furthermore, with full control of the process, it is possible to start investigating the use of substrate transfer or membrane techniques to gain control of the ways in which the substrate operates in the circuit, i.e., the ability to replace the GaAs of the substrate with a material with a high thermal conductivity, low dielectric constant, or to remove the substrate entirely.

### *A. The Development of a Stable Schottky Process*

The mechanical and electrical yield of these devices is excellent given the limitations of contact lithography used. Extraction of key DC parameters, namely the series resistance and ideality, provides a good indication of the quality of Schottky diodes. Results presented in Table I give the averaged measured values of these parameters for series of 100 diodes of circular anodes of diameters from 1.1 to 2 µm. Associated standard deviations are given in parenthesis following the mean values. The ideality factors were calculated from measurements at currents of 10 and 100 µA, whereas the series resistance was extracted at a forward current of 1 mA. The anode diameters are quoted to an accuracy of 7% and were measured immediately prior to the deposition which forms the Schottky diode [4].

TABLE I
EXTRACTED DIODE PARAMETERS: AVERAGE AND STANDARD DEVIATIONS

| Anode diameter (µm) | Series Resistance (Ω) | Diode Ideality |
|---|---|---|
| 1.1 | 12.98 (0.45) | 1.164 (0.002) |
| 1.4 | 11.46 (0.38) | 1.161 (0.002) |
| 1.7 | 10.13 (0.48) | 1.158 (0.002) |
| 2.0 | 9.16 (0.29) | 1.156 (0.002) |

### *B. Discrete Flip-Chip Devices*

The technique of flip-chip soldering discrete diodes to a circuit, typically gold-on-quartz, is commonly applied to millimetre wave circuits operating to approximately 400 GHz. Fig. 4 shows a schematic of a typical flip-chip device which has dimensions 120 x 40 x 15 µm$^3$, (length x width x thickness). An SEM micrograph of the air-bridge detail of one of these structures is shown in Fig. 5. In this image, the length of the air-bridge is 20 µm and the channel over which this passes is 4 µm.

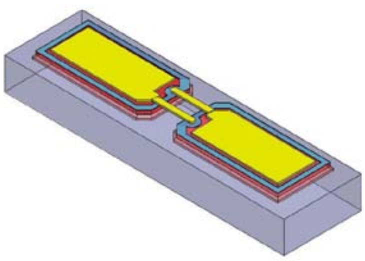

Fig. 4 A schematic of a flip-chip anti-parallel pair of Schottky diodes.

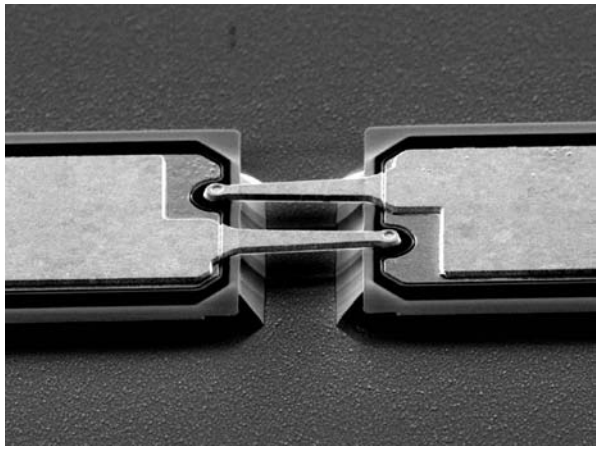

Fig. 5 An anti-parallel pair of air-bridged Schottky diodes.

Discrete flip-chip diodes from RAL have been measured in a range of fixed-tuned sub-harmonic mixers from 160 to 380 GHz. Only at 183 GHz have the circuits been specifically designed for these devices, where a double side band (DSB) mixer noise temperature below 500 K was recorded. A summary of these results is shown in Fig. 6.

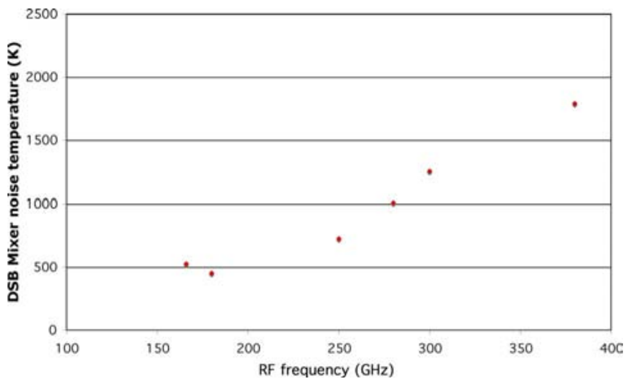


Fig. 6 A summary of mixer results using discrete diodes from RAL.

### *C. Integrated Structures*

Beyond the frequency at which flip-chip diodes can be accurately placed without degrading the circuit performance, integrated Schottky structures are required. In the work presented here, initial demonstration is given of the circuit of a sub-harmonic mixer designed for 183 GHz. The approach taken in this demonstrator was to fabricate the entire circuit on 50 µm thick GaAs substrate. Alternative techniques are required at higher frequencies but this remains an important stepping-stone to higher frequency demonstrators. Fig. 6 shows an optical image of this integrated structure, housed in a waveguide cavity, with an SEM micrograph of an array of these devices shown in Fig. 7, together with a detailed view of the air-bridge structure.

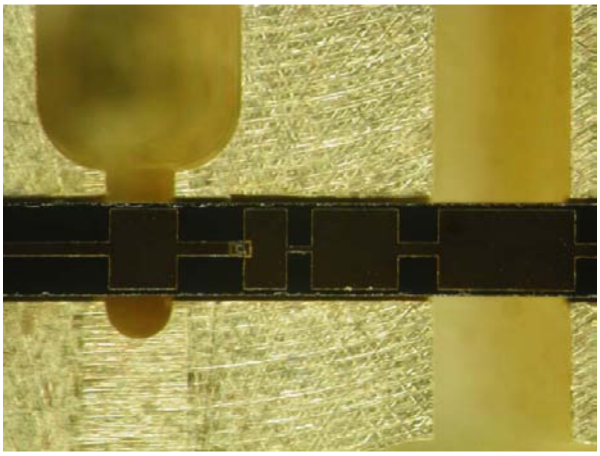

Fig. 6 An optical image of a diode/filter structure in a waveguide cavity.

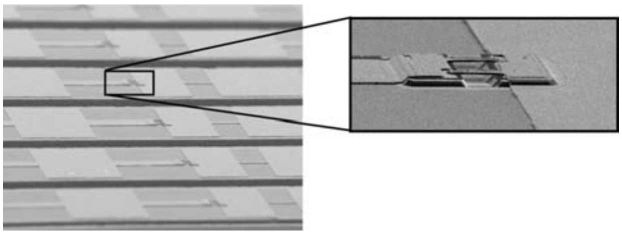

Fig. 7 An SEM micrograph of an integrated diode/filter structure of a 183 GHz sub-harmonic mixer.

Best performance for this device has realised a DSB mixer noise temperature of 550 K at 168 GHz. The offset in frequency from the design target of 183 GHz is due to the doping density of the GaAs being double that for which it was designed. A new structure on the intended epi-material is currently being processed.

## IV. Conclusions

Integrated Schottky structures have been fabricated using both a modified foundry process from UMS and a bespoke research fabrication laboratory at the Rutherford Appleton Laboratory, UK. Both approaches have been shown to be suitable for the fabrication of integrated Schottky structures at frequencies near 200 GHz. Furthermore, simulations have indicated that with a combination of foundry based processing and additional post-processing in a research environment, integrated structures can be fabricated that are suitable for applications to 380 GHz.


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