Schottky Diode Technology at the Rutherford Appleton Laboratory

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ABSTRACT

Most parts of the electromagnetic spectrum are well understood and exploited, but the terahertz region between the microwave and infrared is still relatively under developed. Potential receiver applications are wide-ranging and cross-disciplinary, spanning the physical, biological, and medical sciences. In this spectral region, Schottky diode technology is uniquely important. InP MMIC amplifiers are generally limited to frequencies less than ~200 GHz, above which their noise performance rapidly deteriorates. Superconducting circuits, which require cooling, may not always be practical. Either as varistor diodes (heterodyne mixing), or varactor diodes (sub-millimetre power generation), Schottky technology underpins terahertz receiver development.

Two important developments have occurred in recent years. First, the underpinning technology base has demonstrably matured. Planar Schottky diode technology has been shown to be practical at frequencies as high as 2,500 GHz, and frequency multipliers have been shown to be capable of generating 100's of mW at frequencies around W-band. Secondly, circuit designs can now be optimised theoretically with CAD electromagnetic structure simulators and non-linear analysis programs. New high-speed computer controlled mills, improved lithographic capabilities and micro-machining techniques also offer exciting new options for cavity and circuit manufacture.

This paper describes the Schottky diode technology currently being developed at the Rutherford Appleton Laboratory. Discrete diode components are described as well as integrated diode/filter circuits. Mixer and multiplier diode structures are reported which include novel substrate transfer techniques to reduce the effects of dielectric loading and self-heating.

INTRODUCTION

The terahertz region of the electromagnetic spectrum is often described as the final unexplored area of the spectrum and is rich in potential for advancing scientific understanding and the development of commercial applications [1]. Until recently, the technology to explore this region has been limited to specific areas of astronomy and atmospheric remote sensing. In the case of astronomy, the desire to understand the chemical composition of cold gases, where higher order transitions that could be observed using available IR techniques are not excited, has driven hardware to be developed which is bespoke to a specific science instrument [2]. Molecular spectroscopy has been important in determining the spectral response of specific compounds where a comparison of retrieved data and ground based experiments has led to a better understanding of gas clouds in Earth's atmosphere and the wider universe [3, 4].

For terahertz passive imaging systems detectors arrays will be required that will preferably be operated at room temperature. Cooled detectors are feasible, both as bolometers or mixers, but are generally not be preferred due to increased system cost and complexity. Current room temperature technologies permit low noise amplifiers and Schottky mixers. Amplifiers are generally used at frequencies of the order 100 GHz and below, since the technology is readily available, may offer a lower cost solution and can easily included in arrays receivers. However, at higher frequencies, the only solution is to use a mixer followed by a lower frequency amplifier. The preferred non-linear technology for room temperature mixers is the Schottky diode. This device also operates well in harmonic multipliers and outperforms solid-state frequency sources above ~200 GHz.

SCHOTTKY RECEIVER TECHNOLOGY AT RAL

Schottky receiver technology at the Rutherford Appleton Laboratory (RAL) has traditionally been based on commercially available discrete diode technology [5]. A number of important Earth Observation instruments have been flown in space [6] and on high altitude aircraft [7]. The concern over future diode availability and the wish to design bespoke circuits has led RAL to establish a dedicated diode fabrication facility. This programme started in 2004 with the first mixer results reported in 2007 and frequency multiplier results published in 2009.

A stable GaAs Schottky diode process has been established to fabricate air-bridged diodes. A batch of diodes, consisting of 4 wafers of area 1 cm^2 with 800 diodes per wafer, can currently be processed within a period of 2 weeks with very high yields. The typical structure of a discrete air-bridged diode is shown in Fig. 1.

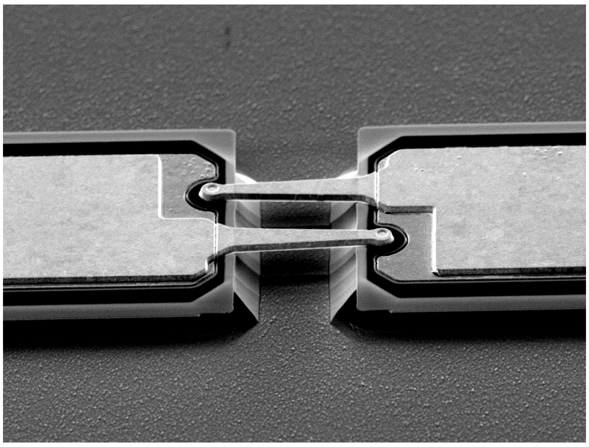

Fig.1. RAL Anti-parallel diode pair. The length of the air-bridges is 20 µm.

These Schottky diodes are fabricated as an array of devices of varying anode sizes and single/double diode combinations. A novel tagging system has been developed to identify the actual device geometry and anode size using a low power optical microscope [8]. An optical image of an array of diodes, on-wafer, with the tags at the end of the Ohmic pads is shown in Fig. 2. After fabrication the diodes can be diced to form discrete flip-chip structures, typically of overall dimensions 120 x 35 x 15 μm^3 (L x W x H).

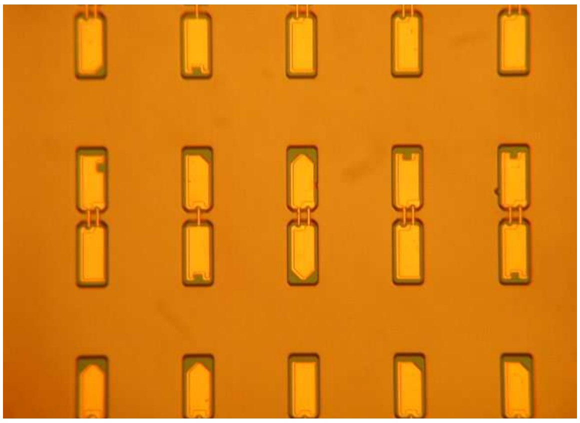

Fig. 2. An array of diodes shown on-wafer, i.e., before dicing. The patterning codes at the ends of the contact pads indicate the corresponding nominal anode diameter(s).

One of the most useful ways of characterizing a batch of Schottky diodes is to perform DC measurements and to extract the diode series resistance and ideality factor. A scatter plot of these parameters reveals the quality of the devices as well as the dispersion of their characteristics. A highly stable process, with low dispersion is essential in optimizing the diode fabrication process. Fig. 3 is a scatter plot of the diode series resistance and ideality for a batch of diodes fabricated on a single wafer. Four diode variations are shown with circular anodes of diameter 1.1, 1.4, 1.7 and 2.0 µm. The plot clearly shows four distinct regions of results representing the four anode variations. It is clear from this data that a stable process has been established. A series resistance of 1 Ω in the probe station has not been deducted from this data.

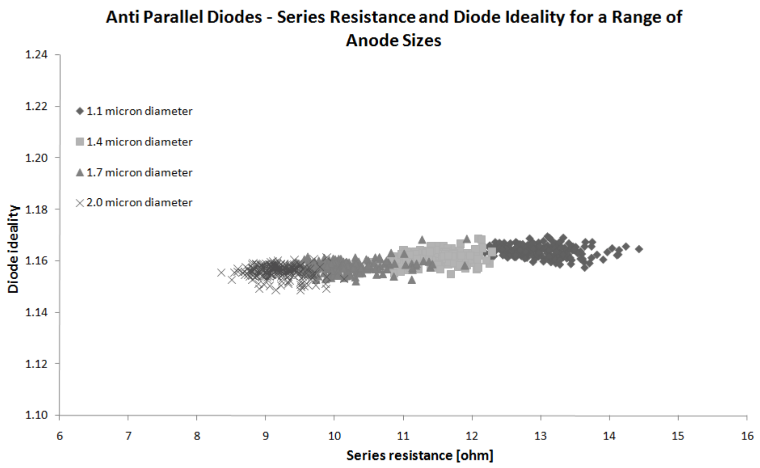

Fig. 3. Scatter plot of diode series resistance versus diode ideality for a range of anode sizes.

Discrete Schottky diodes from RAL have been tested in a range of mixers operating at frequencies from 160 to 380 GHz; measured mixer noise temperatures are presented in Fig. 4. The DSB mixer noise temperature of 500 K at a frequency of 183 GHz is at the state-of-the-art. The remainder of the results generally fit within the scatter of published data with noise temperatures quoted at specific frequencies. The result at 380 GHz was measured in a non-optimal fixed-tuned cavity at a high IF. A cavity is being designed specifically for these diodes at 380 GHz, but the results are not available at the time of writing, September 2009.

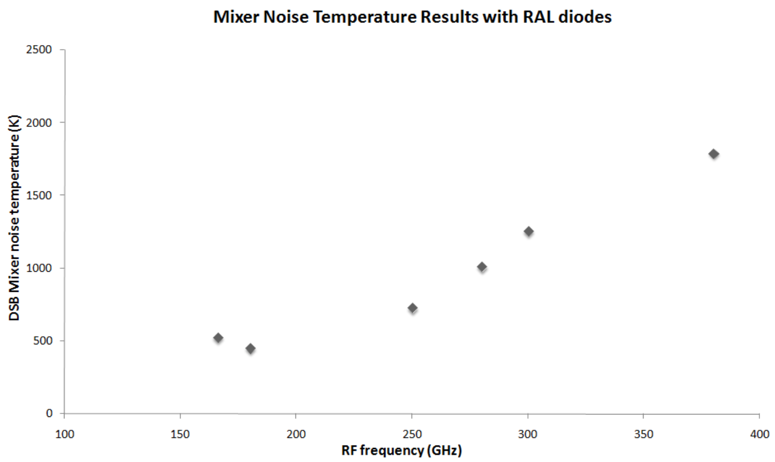

Fig. 4. Mixer performance results obtained with Schottky diodes fabricated at RAL

The move to higher frequencies and the demand for improved performance and more complicated structures is driving the transition from circuits fabricated as discrete diodes soldered to a separate filter, to integrated structures where the diodes are fabricated with their associated filter network. The integrated approach significantly reduces the effect of alignment tolerances and therefore facilitates operation at frequencies above that where errors of alignment significantly degrade circuit performance. At this point the extra effort and reduced number of devices fabricated per wafer become economical due to the enhanced performance.

One of the simplest approaches to integration is to fabricate the entire diode and filter network on thick GaAs and place the circuit in a microstrip or suspended stripline environment. Essentially this structure is simply a diode with a transition to a semi-insulating GaAs substrate, upon which the metallization for the filter structure is applied. An example of such a circuit is shown in Fig. 5. This has been fabricated to demonstrate an integrated 183 GHz sub-harmonic mixer. The entire circuit, including an IF filter, was fabricated on a 50 μm thick GaAs substrate. The overall circuit dimensions are 4.2 x 0.3 x 0.05 mm^3 (L x W x H). An image of an array of these structures is shown together with a magnified view of the air-bridged diodes. An image of this device in a mixer cavity is shown in Fig. 6; the results which are equivalent to state-of-the-art have been previously presented in Fig. 4.

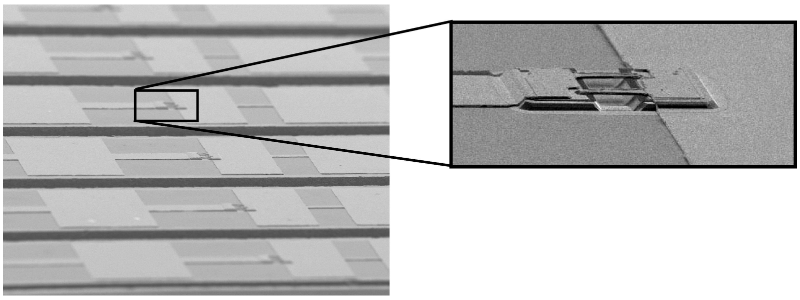

Fig.5: SEM images of integrated diode/filter structures for 183 GHz sub-harmonic mixers

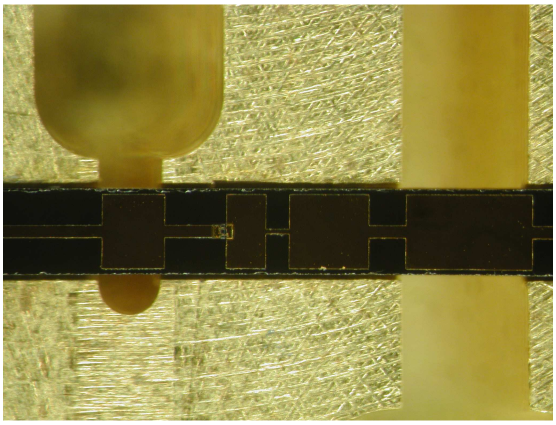

Fig. 6. Optical image of the integrated diode/filter structure in a 183GHz waveguide cavity.

The approach to integration discussed above is suitable for some applications but the thick GaAs substrate is not ideal and causes limitations due to dielectric loading. The high dielectric constant of GaAs increases the loss in the transmission lines and increases their dispersion characteristics, limiting the maximum operating frequency and bandwidth. The ideal case for the highest frequency circuits would be to completely remove all dielectric material and ensure the metal surfaces are highly conducting and smooth.

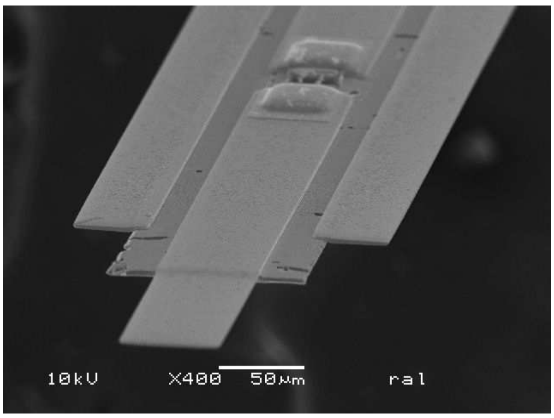

Fig. 7. Membrane diode structure with beam-leads

A close approximation to this condition is to place the circuit on a membrane of GaAs that is just 3 µm thick. This membrane can be suspended in a channel using beam-leads which can also be made to supply accurate grounding where required. An image of a 3 µm membrane of GaAs with gold beam-leads and air-bridged Schottky diodes is shown in Fig.7. The membrane circuit is for a 500 GHz sub-harmonic mixer that was designed and fabricated at RAL. The full circuit has approximate dimensions 2 x 0.25 x 0.003 mm^2 (L x W x H).

SCHOTTKY MULTIPLIER TECHNOLOGY AT RAL

The fabrication of Schottky varactor diodes is nominally identical to that of Schottky varistor diodes. However, for efficient harmonic generation, typically a different diode configuration is preferred. The diode structures reported here are in an anti-series configuration with a central contact pad and two anodes in series in each of two arms towards outer contact pads [9]. The devices have also been transferred to a 50 µm thick quartz substrate. The devices therefore exists as five islands of GaAs on a quartz substrate with gold bridges between them; a schematic of this is shown in Fig. 8. An SEM micrograph of the full chip is shown in Fig. 9. These discrete chips have dimensions 300 x 60 x 50 μm^3 (L x W x H) and they have been fabricated with values of junction capacitance between 32 and 52 fF, defined by alterations to the anode areas. Initial studies have shown that the transfer process does not degrade the diode characteristics and that they can be heated to at least 150 C for a short time typical of soldering without either degradation to the junction or the GaAs pads delaminating.

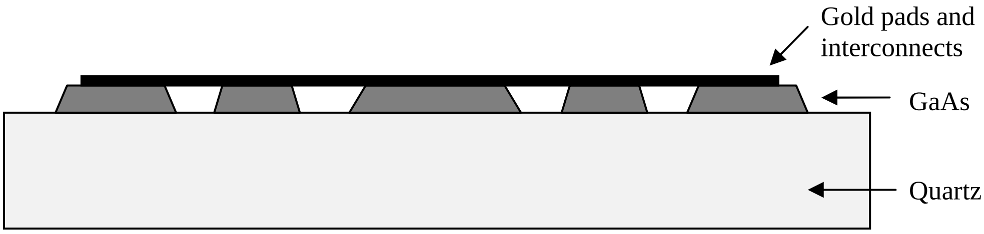

Fig. 8. Schematic diagram of the transferred diode chip

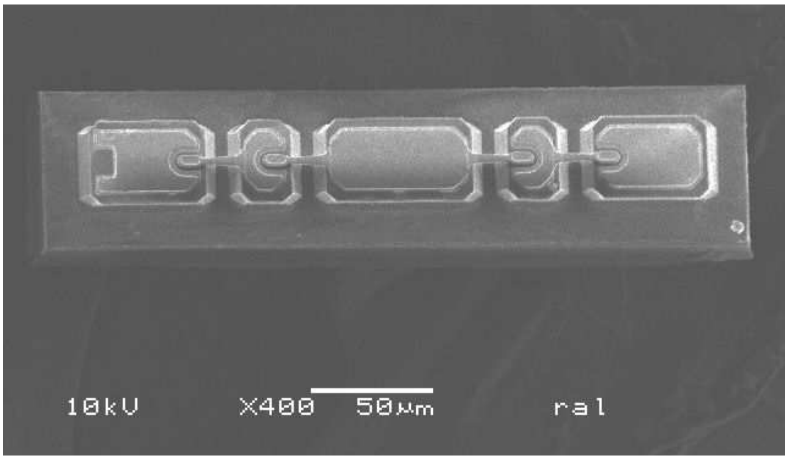

Fig. 9. SEM micrograph of the diode chip

FREQUENCY MULTIPLIER RESULTS

Discrete devices were soldered to a gold-on-quartz filter and placed in a 2-way split block. An image of the internal circuit structure is shown in Fig. 10a, with the complete block shown in Fig.10b. This circuit has been designed to make the input and output in-line, simplifying system level design and integration.

Typical RF results for these devices are presented in Fig. 11. The graphs show the flange-to-flange conversion efficiency and output power for a device pumped at a constant 50 mW input. The input power was supplied by a Calstrom Gunn oscillator and all power measurements were made with a PM3 from Erickson Instruments. A wideband isolator was placed after the oscillator.

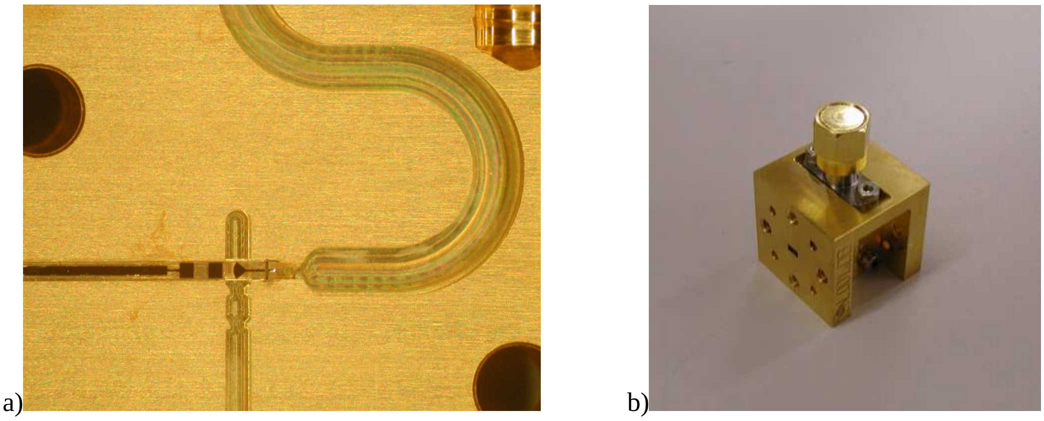

Fig. 10.a) Internal circuit of frequency doubler, b) multiplier block

A peak efficiency of 29.4% was measured at 168 GHz with an output power of 14.7 mW. The 3 dB bandwidth was 12%. The zero biased junction capacitance of these devices was calculated at 43 fF per anode. These tests were limited by available input power and therefore do not necessarily represent ultimate performance. However measurements from lower input powers show clear saturation effects so whilst more input power could be applied, the efficiency is not expected to increase significantly from the results presented here.

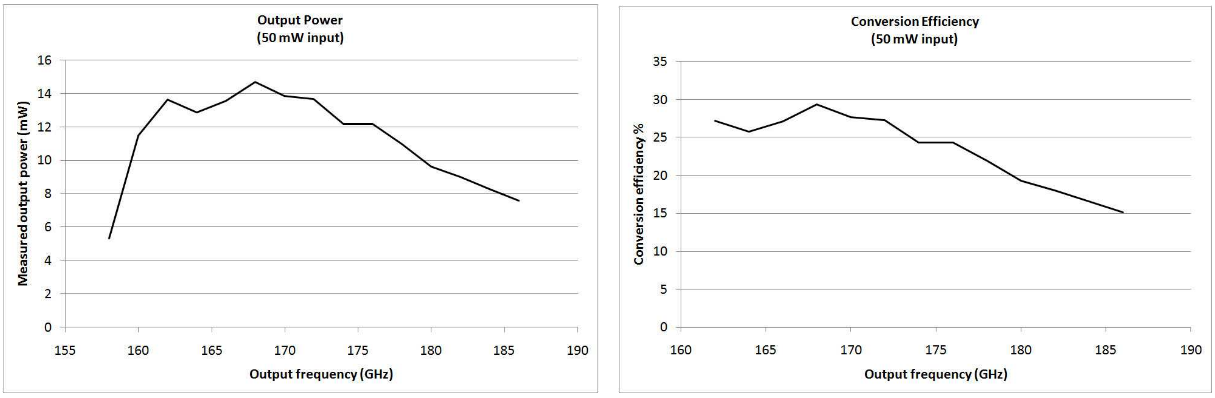

Fig. 11. Typical multiplier results

SUMMARY AND CONCLUSION

Advances in device fabrication, circuit design and mechanical machining have led to the development of fixed tuned Schottky receivers operating well into the terahertz region. Device technology has reached a level of maturity at which generic component technology is becoming available and potential scientific and commercial applications are being unlocked.

This paper has outlined the current state of Schottky diode technology at RAL. Discrete and integrated diode/filter structures have been presented which show good results to 400 GHz. A new generation of frequency multipliers has also been shown which are based on diodes transferred from GaAs to substrates with preferred dielectric and thermal properties.

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