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ACTIVE MICROMACHINED INTEGRATED TERAHERTZ CIRCUITS

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Abstract

Schottky barrier diodes have been integrated into on-chip rectangular waveguides. Two novel techniques have been developed to fabricate diodes with posts suitable for integration into waveguides. One technique produces diodes with anode diameters of the order of microns with post heights from 90 to 125 microns and the second technique produces sub-micron anodes with post heights around 20 microns. A method has been developed to incorporate these structures into a rectangular waveguide and provide a top contact onto the anode which could be used as an I.F. output in a mixer circuit. Devices have been fabricated and D.C. characterised.

Key words: Schottky barrier diode, Micromachining, Terahertz circuits, Rectangular waveguide, Platinum Plating, Photolithography.

Introduction

In recent years, applications requiring the development of terahertz technology have attracted considerable attention within the research community [1]. Such applications include astronomical spectroscopy, atmospheric remote sensing, plasma diagnostics, high speed inter-satellite communications and covert terrestrial communications. Many innovative ideas for the design, fabrication and measurement of terahertz systems have been proposed. As the wavelength decreases, the dimensions of both the device and its associated transmission media must be reduced. Schottky barrier diodes having non-linear current-voltage characteristics and well characterised behaviour are commonly used as mixers and detectors at millimetre and submillimetre wavelengths. At terahertz frequencies, these devices require sub-micron sized dimensions to limit the effect of parasitic losses. In addition, a low loss transmission medium such as rectangular

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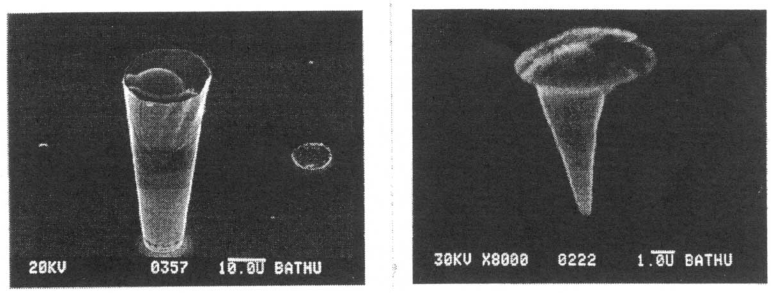
waveguide becomes increasingly difficult to machine due to its small size. As a consequence of these challenges, the integration of active devices with on-chip rectangular waveguides has been suggested [1] allowing the formation of integrated terahertz systems. The use of photolithography and the advent of new materials have made it possible to fabricate micromachined waveguides with successful repeatability [2]. The work described here demonstrates for the first time the integration of active devices within micromachined, on-chip rectangular waveguides. This has been demonstrated with devices scaled for operation at frequencies ranging from 200GHz to 1.6THz.

Devices

The Schottky barrier diodes were fabricated on epitaxial GaAs wafers. The epitaxial layers were grown using the molecular beam epitaxy technique and consisted of: GaAs semi-insulating substrate-AlGaAs undoped (1μm)-GaAs n^{++}doped 2×10^{18} cm^{-3} (5μm) followed by the Schottky layer of GaAs n^{+}doped 2×10^{17} cm^{-3} (0.12μm). The substrates were first prepared by performing a lift off procedure to leave ohmic pads on the n^{++} doped layer close to the side of a $1cm^2$ substrate. An ohmic ring of 50μm inner diameter was formed on the substrate encircling the device to minimise the series resistance. Following the formation of the ohmic ring, a gold seed layer was evaporated covering the entire surface of the GaAs except for the inside of the ohmic ring where the Schottky diode would be placed. This metal layer provides the bottom wall of the waveguide.

The Schottky diodes for this work have been fabricated by two different methods depending upon the frequency of operation. The first method uses UV photolithography and is applicable to photoresist layers of 90-125μm in thickness where the anode diameter is of the order of microns. The sample is coated with a positive AZ4533 Hoechst photoresist and baked in a temperature controlled oven. The temperature is gradually increased at a rate of 10°C/hour from room temperature to a ceiling temperature of 90°C, where its maintained for 2.5 hours before decreasing at a rate of 15°C/hour. The reason for the gradual increase and decrease is to ensure that the thick photoresist is baked gradually at the start and to reduce the thermal stress on the baked photoresist at the end respectively. Following the ramp bake the samples are exposed using a dark field mask with an appropriate hole size which ultimately defines the area of the diode. The exposure time can be varied according to the thickness of the photoresist. For a 90-125μm thick photoresist, 25 minutes UV exposure is performed at a power of 14 mW/cm^2. The development was carried out in diluted 4:1 H_2O:AZ400K for an average duration of 30 minutes in order to achieve the maximum contrast of the image. Once the sample is developed, a tapered hole is formed through the photoresist, exposing the GaAs epitaxial layer where the device is to be electroplated. A drop of platinum plating solution is then placed on the photoresist covering the hole. A platinum wire and the ohmic pad on the sample provide the anode and the cathode respectively. A constant current of 5nA is passed through the electrolyte, electroplating the device and building up the structure through the exposed hole in the photoresist former.



(a) (b)

Figure 1

(a) a micromachined platinum electroplated pin structure used for integrated mixers
(b) whisker platinum pin with a sub-micron device dimension

The current is increased after 2 hours to 100nA by which time the diode is formed. Electroplating is continued to build the pin to the required height. The electroplated platinum reaches the top of a hole of depth 95-125 μm after typically 12 hours. The solution is then rinsed in de-ionised water and dried gently with nitrogen gas leaving behind an electroplated Schottky diode structure of 90-125μm in height. Figure 1(a) illustrates a free-standing post formed by the above process after the photoresist was removed.

The second method of device fabrication is a whisker pin method developed at the University of Bath which is used predominantly for sub-micron device sizes [3]. Essentially a 20μm layer of AZ4562 positive photoresist is spun at 2000 rpm on the GaAs sample and with the use of a copper-beryllium whisker wire, an impression is made on the unbaked resist. The whisker has a sub-micron tip following an electrochemical etch in sodium hydroxide solution. It is pushed through the photoresist and aligned to a specific location on the sample by means of micropositioners. A curve tracer is employed to pass a nominal current of 2.5μA through the whisker and the substrate. Once the whisker tip pushes through the surface of the photoresist and touches the GaAs surface, a contact is made as monitored on the curve tracer. The resist is then left to dry for 3 hours after which a drop of platinum plating solution is placed on top of the sample and the whisker is pulled out to leave a hole of sub-micron dimension at the tip in the photoresist. The electroplating is then performed as described above except that a digital pulse of 10nA at 10ms intervals is used for the first hour and thereafter a constant current of 10nA for a 2 hour period. The resulting electroplated structure is shown in Figure 1(b) where the photoresist has been removed and a sub-micron whisker pin is revealed.

Fabrication of Active Terahertz Structures

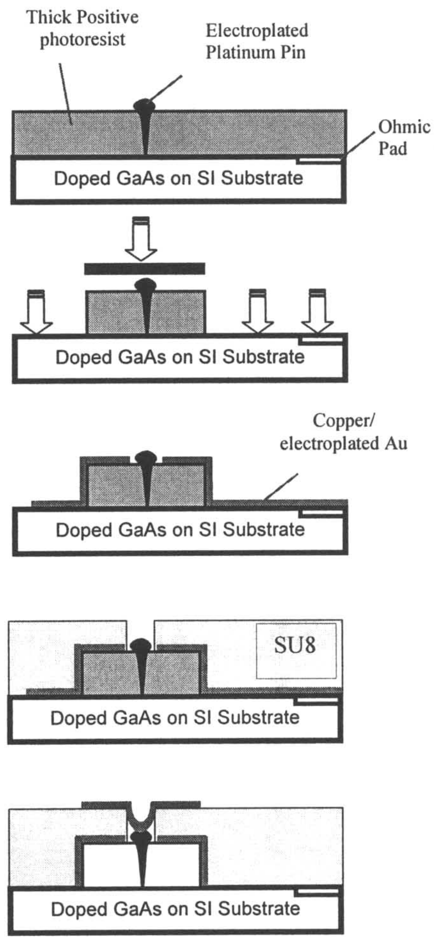
The work described in this paper has been the result of the terahertz integrated technology initiative (TINTIN) project which aimed to develop a range of active and passive terahertz components. This project was a collaboration between four British Universities (Bath, Leeds, Nottingham and Reading). The work undertaken at Bath University was to develop integrated Schottky diodes for use at 200GHz, 600GHz and 1.6THz. This has been achieved by integration of Schottky devices fabricated as described above into micromachined rectangular waveguides. The rectangular waveguides dimensions required for fundamental mode waveguide at the design frequencies are given in Table I, where broad and narrow wall heights are given by "a" and "b" respectively.

Design Frequency	a (μm)	b (μm) Full Height	b (μm) Half-Height	b (μm) Quarter-Height
200 GHz	1125	562.5	281	140
600 GHz	410	205	102.5	51.25
1.6 THz	140	70	35	17.5

Table I The dimensions of rectangular waveguides at the design frequencies

Figure 2 summarises the process used to incorporate the diodes into rectangular waveguide. As described above, the samples are covered with photoresist and ramp baked prior to electroplating the pin structure. Following the formation of the devices the rectangular waveguide pattern is re-exposed on the sample and developed to leave a photoresist former containing the pin structure. The duration of UV exposure is 25 through a layer thickness of 90-125μm and the development time is 30 minutes in a diluted 4:1 solution of AZ400K. At this stage the waveguide shape is defined with the top of the platinum pin exposed on the photoresist former. Before the metallisation of the waveguide takes place, the pin is covered using a 100μm diameter gold disc, positioned carefully with the aid of micropositioners on the top of the pin. This aids the isolation of the device from the rest of the waveguide in the next stage. The end of the waveguide is also covered to allow the coupling of power into and out of the integrated metal waveguide. The gold layer is then evaporated onto the waveguide former at various angles to cover all the sides of the waveguide as shown in Figure 2 where the fabrication process is illustrated schematically.

The gold disc is then released by rinsing the sample in de-ionised water leaving the pin structure isolated from the rest of the waveguide. To add mechanical support to the metallised waveguide, a 7 to 10μm thick layer of copper is electroplated using an acid copper sulphate solution [4]. To form the top contact of the structure, Epon SU8 negative photoresist is used to embed the waveguide leaving the top of the diode whisker exposed. This also provides mechanical support for the entire structure. The negative photoresist is set hard by a blanket exposure of the sample to UV for a duration of 3 minutes. A 300 nm layer of gold, evaporated through a shadow mask, makes a top contact to the diode pin. To improve contact reliability, the gold is subsequently



The positive photoresist is ramp baked, exposed and developed. A platinum pin is electroplated to form the Schottky diode.

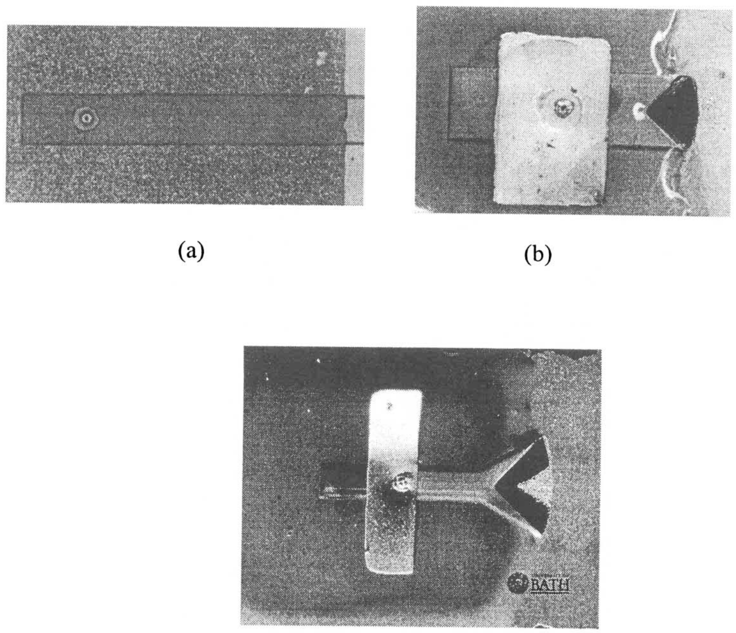
A waveguide mask is used to expose and develop the thick photoresist in a shape of the required waveguide.

The platinum pin is isolated and Au is evaporated to form the inside wall of the waveguide, followed by copper electroplating.

Epon SU8 negative photoresist is used to
embed the structure and isolate the waveguide from the top contact.

Evaporated Au/copper electroplating forms the top contact to the structure after which the waveguide is emptied.

Figure 2 Schematic illustration of the fabrication process of micromachined integrated rectangular waveguide circuits.



(a) (b)

(c)

Figure 3 Photographs of the Micromachined integrated terahertz structures fabricated at
(a) 1.6THz (a=140μm, b=25μm), (b) 200GHz (a=1125μm, b=90μm), (c) 600GHz (a=410μm, b=125μm).

electroplated with a 5 micron thick layer of copper. This top contact is supported by the layer of negative resist and could be patterned, for example, in the shape of an IF filter structure. The sample is then soaked in acetone in order to remove the positive photoresist within the metal waveguide, resulting in an air-filled, micromachined terahertz rectangular waveguide integrated with a Schottky diode.

Figure 3 shows several photographs of the integrated terahertz structures at 200, 600GHz and 1.6THz fabricated on GaAs semi-insulating substrates. Both methods of Schottky device fabrication were successfully implemented, achieving 5-7μm device diameters using the photolithographic technique and sub-micron diameters using the whisker method. In an attempt to integrate an antenna, a slotted H-plane horn was incorporated into the design of the mask used to produce the waveguide. This can be seen in the photographs shown in Figure 3. The antenna itself was developed at Reading

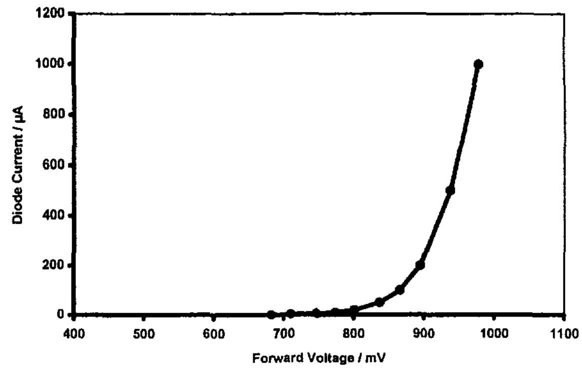


Figure 4 Current-voltage measurements of a micromachined integrated 600GHz circuit.

University [5] with early antenna beam measurements indicating that it does couple to the waveguide albeit with a rather poor radiation pattern. Work is currently in progress to develop methods by which the waveguide can be tapered or stepped from the diode to reach full height at the antenna. This will greatly ease the antenna problem and should lead to improved beam patterns.

The DC characteristics of the integrated diodes where measured following the assembly of the structures on brass fixtures. Figure 4 shows the DC current-voltage characteristic of a sub-micron diameter Schottky diode, integrated into a half-height 600GHz waveguide. The characteristic is typical of a number of such measurements, taken from a variety of fabricated circuits throughout the terahertz frequency range. It has a series resistance, R_s, of less than 23 ohms and ideality , n, of 1.54.

Work is currently in progress to improve the quality of the Schottky interface. The refinements to the fabrication process have mainly concentrated on improving the surface preparation prior to the platinum electroplating. This will be accompanied by the reduction of any associated contact resistance to the top of the platinum pin.

Discussion and Conclusions

Innovative photolithographic procedures and novel micromachining techniques have been employed to fabricate integrated rectangular waveguide/Schottky diodes on GaAs substrates. These structures have been fabricated in waveguide scaled for operation at 200GHz, 600GHz and 1.6THz. The authors believe that this is the first demonstration of the integration of Schottky devices in rectangular waveguide directly fabricated on a GaAs substrate. Two methods of fabricating Schottky diodes with integrated posts suitable for incorporation into integrated waveguide have been demonstrated. One of these methods should be suitable for anodes having diameters of the order of a micron or two and the other is suitable for sub-micron anodes. With improved device characteristics we believe that these structures are capable of rivalling the performance of conventional whisker contacted Schottky barrier diodes throughout the terahertz frequency range.

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