A Novel Structure And Fabrication Process For Sub-Quarter-Micron THz Diodes

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Abstract

At frequencies greater than 1 THz, whisker-contacted GaAs Schottky barrier diodes are the most commonly used mixer element. This is primarily due to their ability to yield good noise performance even at room temperature and the relative ease of fabricating corner cube mixers. However, at 2.5 THz the best Schottky mixer diodes have anode diameters of only one-quarter micron. The need for such small dimensions causes two problems; the added expense and complexity of using direct-write electron beam lithography and the decreased reliability of the whisker contact. In this paper we describe a new diode structure with a stepped oxide profile for increased "whiskerability" and reliability. These new diodes are fabricated with an electroplated metal mask process (Electroplate Window Shrink) which eliminates the need for electron beam lithography. This new structure and process has yielded sub-quarter-micron anodes with the best noise performance that we have measured at 2.5 THz.

1. Introduction

GaAs Schottky diodes have been used in heterodyne receivers throughout the millimeter and submillimeter wavelength ranges. Despite the development of low-noise SIS mixers and, more recently, hot electron bolometric mixers with GHz bandwidth, Schottky technology still has several important advantages. Among these are the long history of successful usage, the lack of any hard limitation to either the maximum signal frequency or the intermediate frequency bandwidth, and, most importantly, their ability to operate at room temperature.

To frequencies as high as about 600 GHz planar Schottky diodes are now available which yield virtually the same performance as the less reliable whiskered diodes.[1] This is a tribute to both the development of advanced diode fabrication technologies which have greatly reduced the parasitic shunt capacitance inherent in most planar diode designs[2] and the development of high frequency design tools which allow the circuit designer to minimize the effects of the remaining parasitic capacitance. It is expected that in the near future these planar diodes will be extended into terahertz frequencies. However, for frequencies much above 1 THz, planar diodes may not be available for several years. Thus, only whisker-contacted Schottky diodes are presently available for room temperature mixers in this important frequency range.

The best mixer diodes for frequencies much above 1 THz have been from the batch UVA-1T15. These diodes have an anode diameter of roughly one quarter micron and an epitaxial layer doping density of 1×10^{18} cm^{-3}. The 1T15 diodes have been extensively tested in corner cube receivers by several groups.[3-6] In our laboratory, we have measured an uncorrected receiver noise temperature of about 14,000 K (DSB) by the Y-factor method with liquid nitrogen and room temperature hot/cold loads. For this measurement a laser local oscillator was used (2-5 mW required) and the IF noise temperature was 103 K. The total system loss was about 14 dB and we expect that about 1 dB was from atmospheric losses between the cold load and the diode.

Although the 1T15 diode has been extremely successful, it has several drawbacks. The most obvious is the difficulty of achieving and maintaining a solid contact between the whisker and the anode. Although these diodes have been used in airborne observations, the reliability of the whisker is a cause for serious concern and it is often necessary to use a contact with less than optimal performance on the actual flight. The second important drawback is the difficulty of fabricating the diodes. To achieve such small dimensions, direct-write electron beam lithography is normally required. This significantly increases the complexity and cost of diode fabrication. Furthermore, this technology is not available in most university laboratories (including our own) and the systems made available through visitor programs are not optimized to form small *circular* structures and are available only for short periods of time at intervals of several months.

To solve these problems, we have developed a new fabrication process which uses only ultraviolet lithography and creates an oxide structure around the anode which is much larger than the anode, thereby making whisker contacting both easier and more reliable. In the following sections, this procedure is described and preliminary RF measurements with the new diodes are presented.

2. Whisker Contacted Diode Structure

The layout of a traditional whisker-contacted diode for THz operation is a close-packed (honeycomb) array of circular metal anodes on GaAs. A thin layer of silicon dioxide is used to: (1) define and limit the area of metal deposition, (2) provide a "well" to guide and constrain the tip of the whisker and (3) passivate and insulate the GaAs between the anodes. This configuration is illustrated in Fig.1.

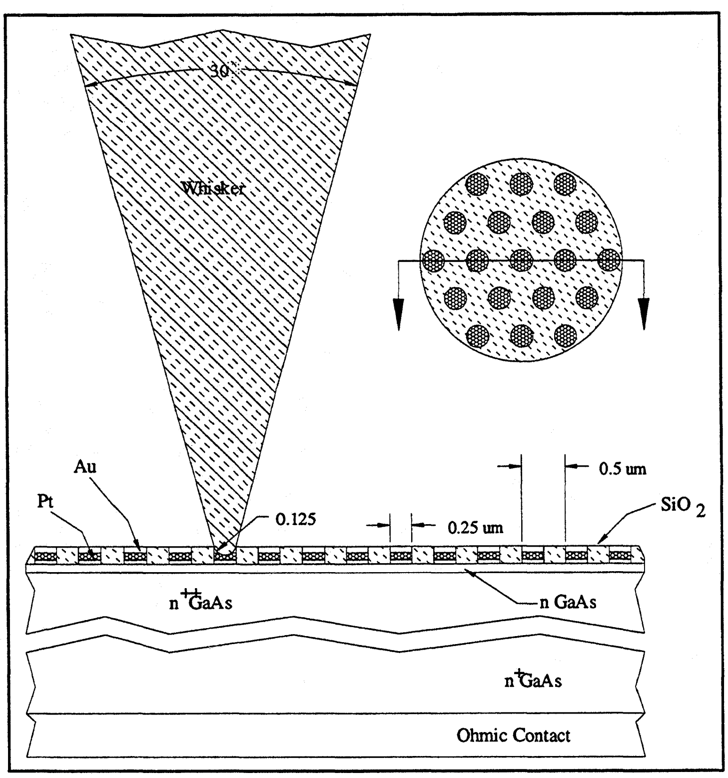

Fig. 1. Traditional Whiskered-Contacted Diode For THz Operation

The geometrical design parameters include the oxide thickness, metal thickness(s), anode diameter and center-to-center spacing. The choice of anode diameter is dictated by the operating frequency and doping. The other parameters also are not arbitrary, since they affect series resistance, shunt capacitance, fabrication complexity, the ease of contacting anodes, and contact stability. For example, deep oxide wells improve contact stability but increase shunt capacitance at the whisker tip. Extremely small anode-to-anode spacing increases the probability of achieving a contact but at the same time increase the likelihood of multiple contacts.

The whisker tip radius must be very small (about 1/8 μm) to properly fit into the oxide well. These very fragile whisker tips are easily deformed and compressed. This can result not only in a complete failure of the contact (i.e, open or multiple contact) but also in performance variation from one contact to another as whisker shunt capacitance varies. A whisker with a much larger tip radius can contact these small anodes by extrusion into the oxide well. This results in increased shunt capacitance from the whisker metal which now is forced to overlay the top surface of the oxide which surrounds the anode metal.

Expensive direct wafer electron-beam lithography is generally required for the fabrication of sub-half-micron anodes. While e-beam patterning can in principle provide excellent control of diameter, it is by no means a trivial matter to consistently and uniformly produce quarter-micron geometries, especially for circles. Also, conventional electron beam photoresist (PMMA) is a notoriously poor plasma etch mask which limits the maximum oxide thickness.

A new whisker-contacted diode geometry has been developed to overcome the problems associated with the simple thin-oxide honeycomb array. In this structure, shown in Fig. 2, the silicon dioxide thickness is several times greater than that of the traditional structure. Also, the anode well is composed of an inner portion with a quarter-micron or smaller diameter at the bottom. This inner well has vertical or slightly tapered sidewalls and abruptly expands to a much larger diameter (0.8-1.0 micron). A refractory metal (Pt) is deposited onto the GaAs at the bottom of the inner well. Gold is then deposited by electroplating to completely fill and just overflow the inner well. This stepped configuration provides an ultra- small junction diameter and a relatively large cavity to hold the whisker in place.

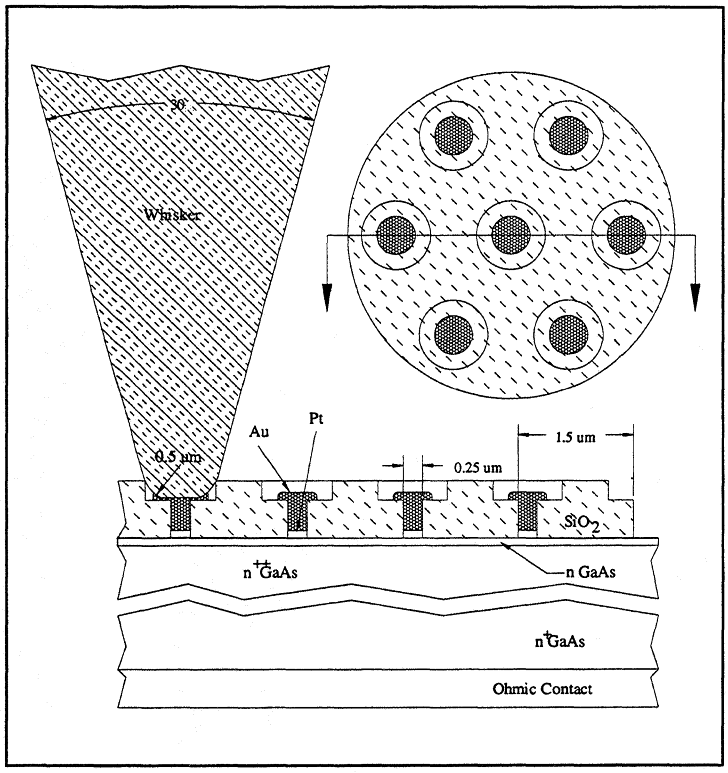

Fig. 2. Whisker-Contacted Diode For THz Operation With Stepped-Oxide Profile

The shunt capacitance of the stepped-oxide structure, excluding the whisker, is expected to be somewhat greater than that of the simple thin oxide diode. This is due to the fringing electric field lines from the outer walls of the now thicker gold plating through the silicon dioxide. Since our zero-bias capacitance measurement technique nulls the contribution of the whisker, the *measured* capacitance of the new devices is indeed higher. However, some reduction in shunt capacitance from the whisker is expected since the new design holds the whisker farther from the conductive GaAs surface. Also the new structure reduces the possibility of whisker tip deformation. Thus, when the whisker is taken into account, the total shunt capacitance of the new device is comparable to or less than that of the traditional structure. A numerical or scale model and/or improved experimental methods will provide a more accurate measurement of the total shunt capacitance for both structures.

3. Fabrication

The stepped-oxide structure could be fabricated by several means. One possibility is a two-level direct-write electron beam pattern. Another approach is to utilize the naturally occurring diffraction pattern produced by micron-sized circular apertures.[7, 8] In this work, however, the structure has been fabricated with a novel procedure which incorporates a two-layer metal mask structure combined with electroplating. This Electroplate Window Shrink

(EWS) technology is shown schematically in Fig 3.[9]

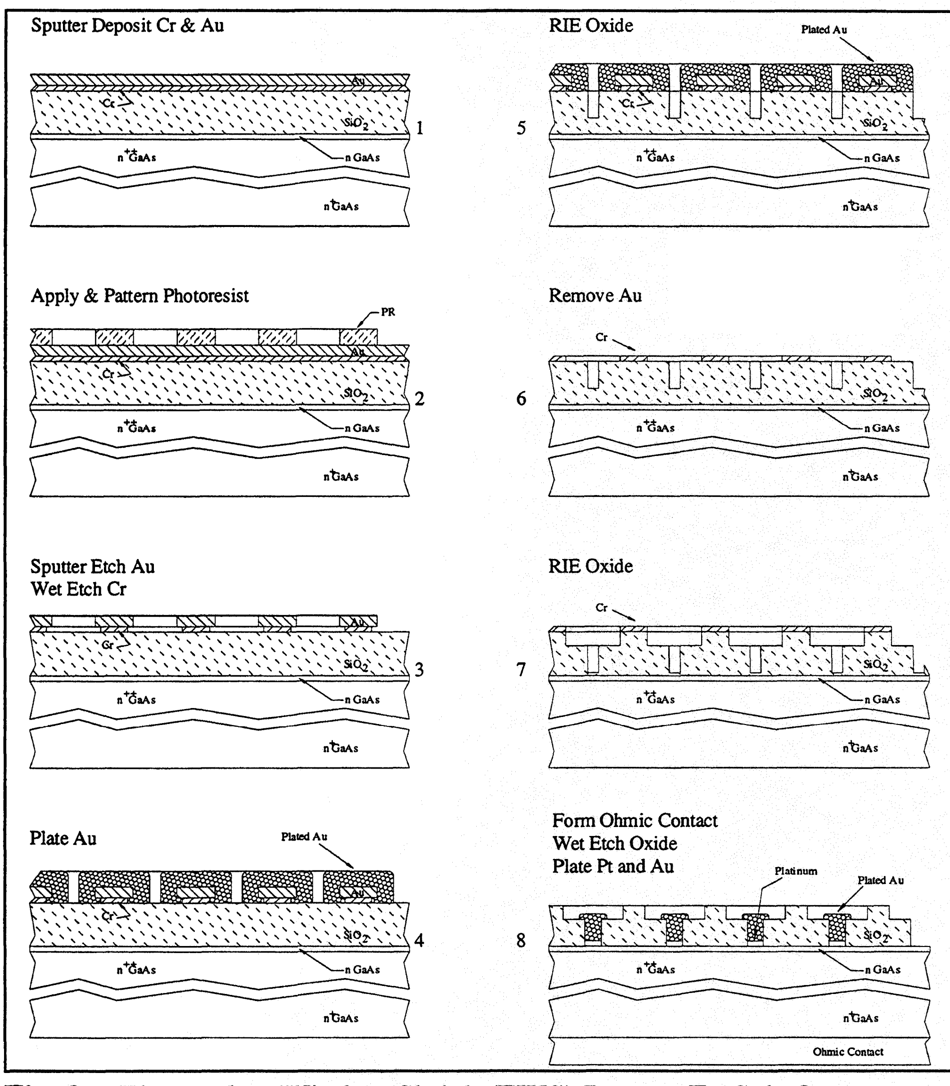

Fig. 3. Electroplate Window Shrink (EWS) Process ForSub-Quarter - Micron Anode Formation

Referring to Fig. 3:

1. A thin layer of chromium and gold are deposited on top of a relatively thick layer of silicon dioxide. This oxide is identical to that used for our standard diodes but is much thicker (8000 Å vs 2000 Å).

2. A thin layer of positive working photoresist is applied and patterned with a darkfield mask to form an array of circular openings. The diameter of these openings can be in the 0.5 to 1.0 micron range, easily accomplished with optical lithography.
3. The gold and chromium are etched away using argon sputter etching and wet chemical etching. Any remaining photoresist is removed with oxygen plasma and chemical stripping.
4. Gold is electroplated onto the patterned gold surface. Since the plating also proceeds laterally as well as vertically, the diameter of the circular openings in the metal film decreases as the metal thickness increases.
5. The reduced diameter pattern is transferred to the silicon dioxide with fluorine RIE at low pressure (5 mT) to minimize backsputtering of the gold onto the SiO_2. A significant amount of oxide is left.
6 The gold (electroplated and sputter deposited) is chemically stripped leaving the larger diameter chromium window in place.
7. The chromium pattern is transferred to the silicon dioxide with fluorine RIE. This etch is timed to leave a very thin layer of SiO_2 in the bottom of the wells to protect the GaAs from the RIE and the subsequent chromium etchant. (This step can be omitted to yield a straight oxide profile).
8. The chromium layer is chemically stripped. After wafer thinning and ohmic contact formation, the wafer is diced into chips (250 x 250 microns). Individual chips are mounted on pins and inspected with the SEM. A final wet etch in buffered HF removes the remaining SiO_2 and platinum followed by gold are electroplated into the anode wells.

4. Fabrication Results

Scanning electron micrographs of our first wafer and chips are shown in various stages of the process in Fig. 4 through 9.

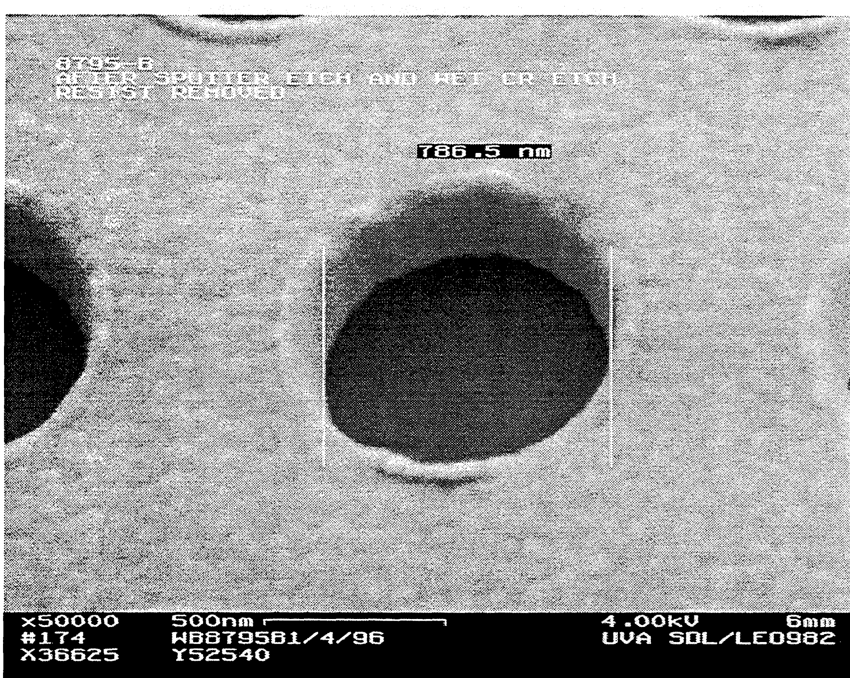

Fig. 4. Anode pattern in metal after argon sputter etch of gold and wet chemical removal of chromium

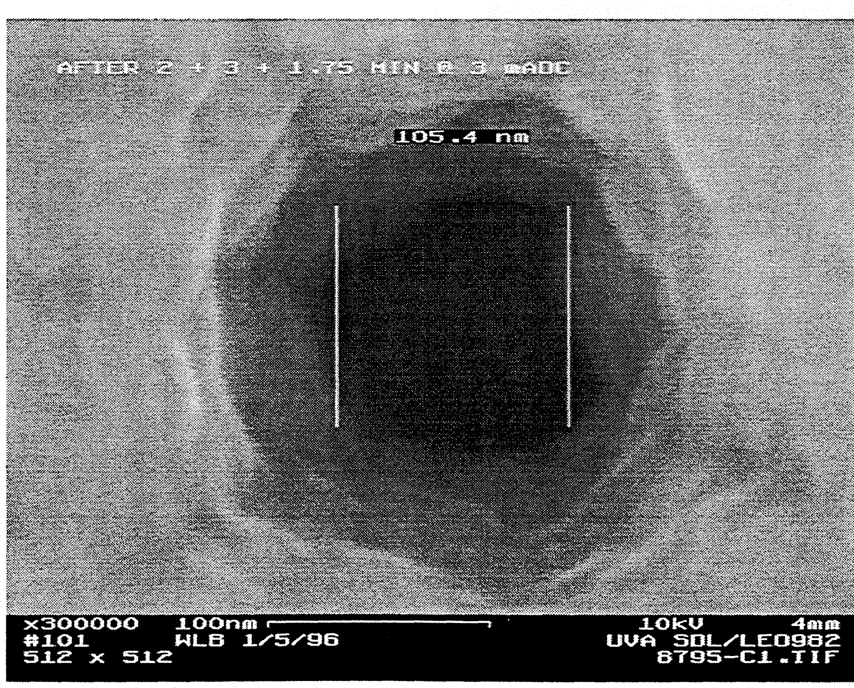

Fig. 5. Anode pattern after electroplate window shrink (EWS)

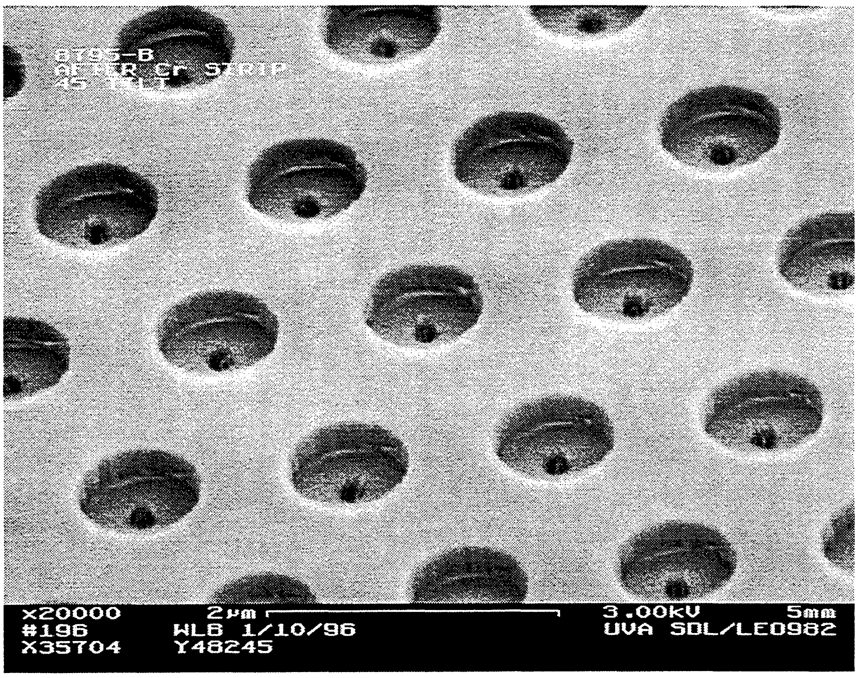

Fig. 6. Anode Pattern After Stripping Gold And Chromium

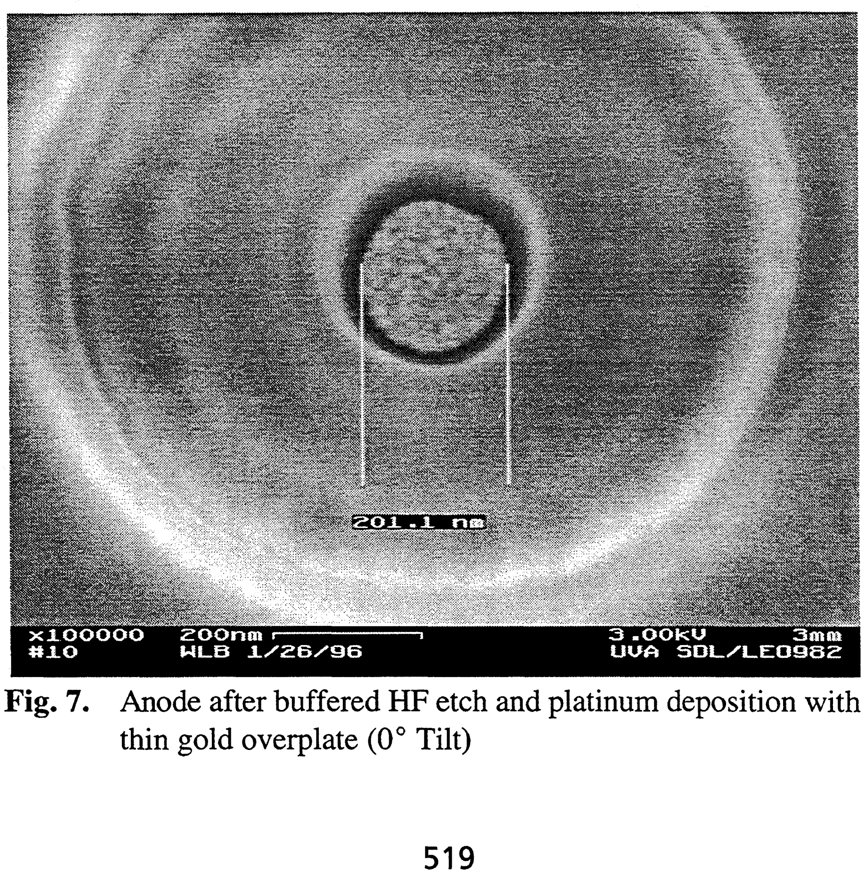

Fig. 7. Anode after buffered HF etch and platinum deposition with thin gold overplate (0° Tilt)

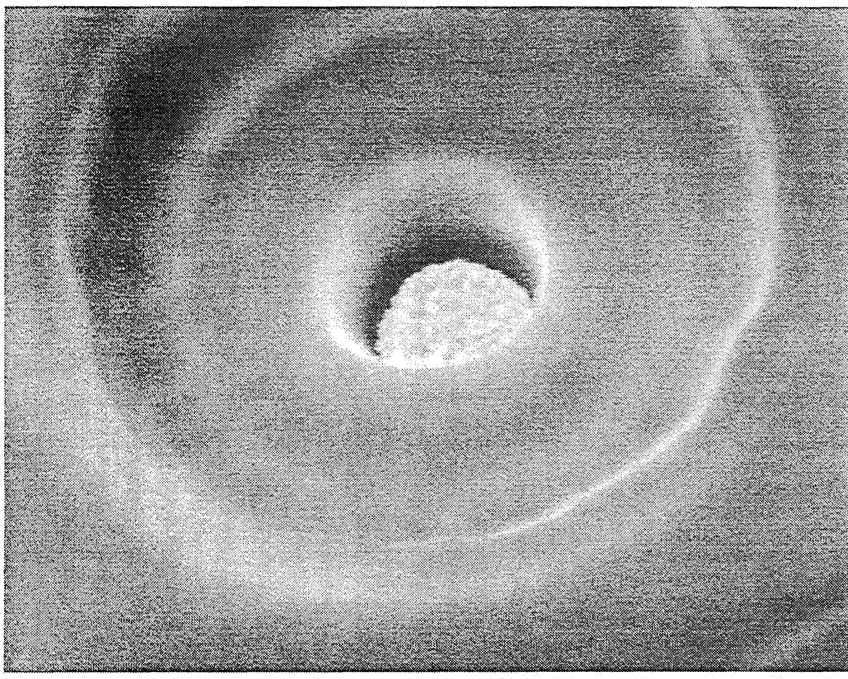

Fig. 8. Anode after buffered HF etch and platinum deposition with thin gold overplate (15° Tilt)

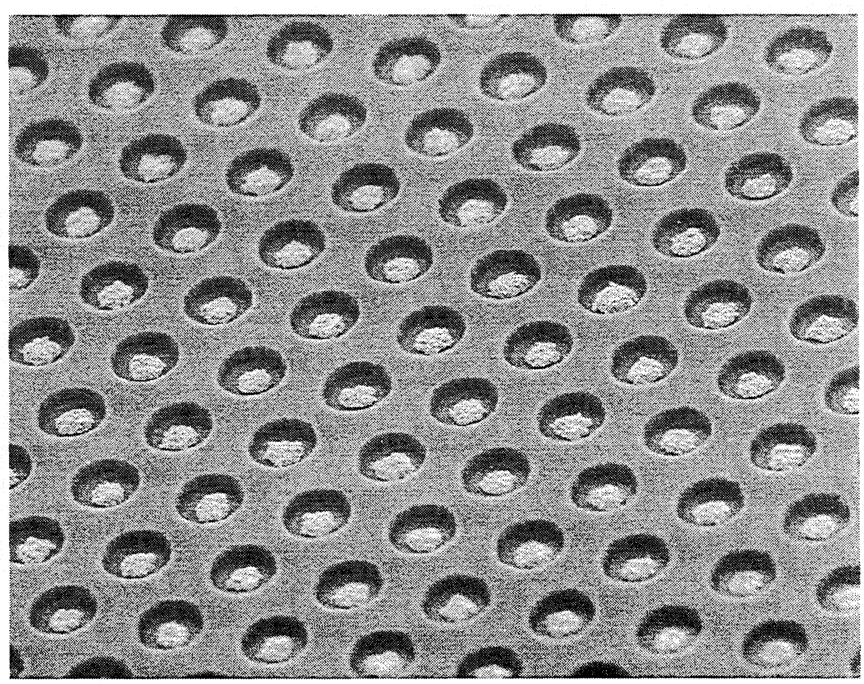

Fig. 9. Anodes after electroplated gold fill of inner oxide well

The SEM photograph in Fig. 10 shows a contacted 1T23 (stepped oxide) diode chip in a working corner cube assembly. Although the *anode* diameter is less than one-quarter micron, the whisker "well" diameter is about 0.9 microns and the whisker is securely held in position by the larger oxide cavity.

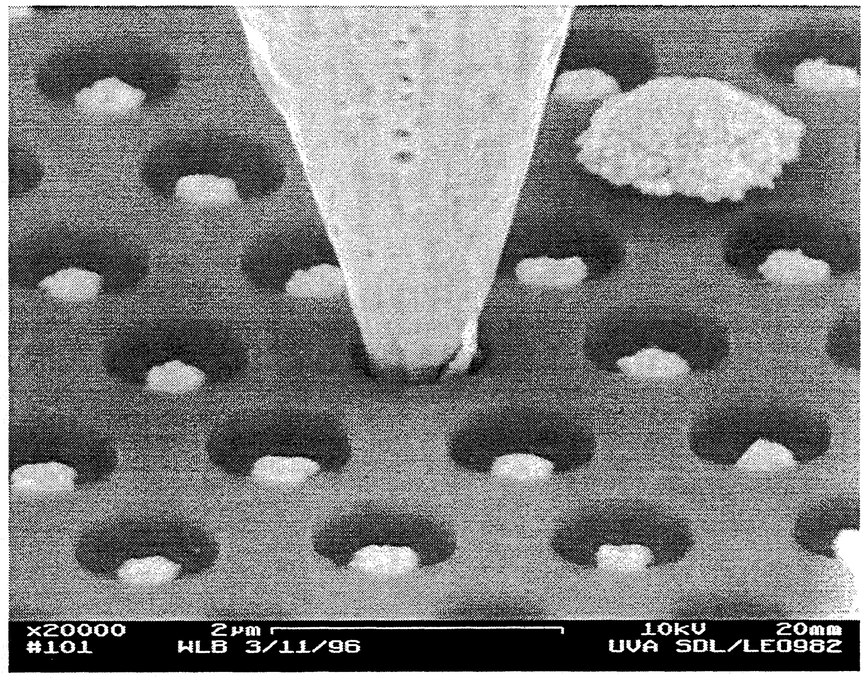

Fig. 10. Whisker-contacted 1T23 diode chip in a corner cube mixer mount

5. DC Characteristics

The DC I(V) characteristics of the new diode batch 1T23 made with the EWS process are given in Table 1.

Table 1. DC I(V) Characteristics

Batch	**ΔV @ 1-10 μA (mV)**	**η**	**V_{knee} @ 1 μA (mV)**	**R_S @ 1 mA (Ω)**	**V_R @ -1 μA (V)**	**C_T (fF)**
1T23	91-94	1.53-1.56	680-710	20-27	2.0-2.4	0.45-0.65

Note: $C_T = (C_{j0} + C_{\text{anode parasitic}})$

6. RF Results

Preliminary receiver noise temperature tests have been performed with the 1T23 diode in a corner cube mixer at 2.5 THz. The results are shown in Fig. 12.

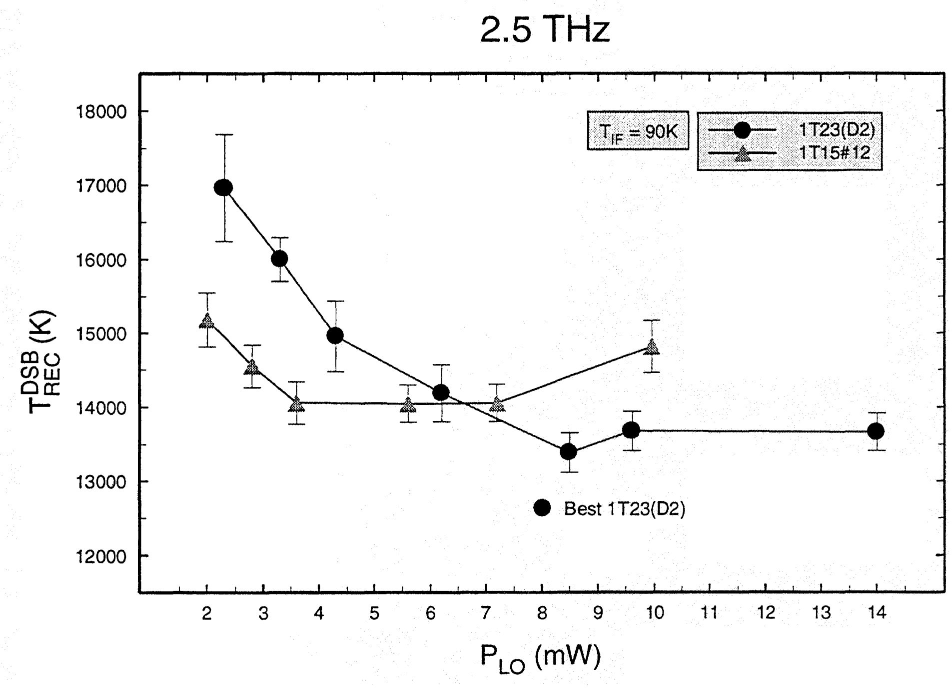

Fig. 12. Receiver noise temperature versus local oscillator power for 1T15 and 1T23 diodes

The 1T15 results are the *best* results that we have ever measured in our laboratory at 2.5 THz, and were only achieved with our best 1T15 chip. The 1T23 results are those measured with the *first* chip that we tested. The single point labeled "best 1T23(D2)" was obtained with this chip after the measurements on the plotted curve were completed and some additional tuning. It is expected that all of the corresponding noise levels will be proportionally reduced in future testing. These results show that RF performance of the new 1T23 diode is superior to the traditional whisker-contacted structure.

7. Conclusions

A new whisker-contacted diode structure with a stepped-oxide profile has been developed which is much easier to contact than the traditional (1T15 type) device. This structure improves the mechanical stability of the whisker contact and provides a less variable shunt capacitance.

A novel fabrication process (Electroplate Window Shrink) has also been developed which inherently produces a stepped-oxide profile. The key to the process is the lateral closure of a metal mask when it is electroplated. Sub-quarter-micron anode features can be produced with contact-mode UV lithography (i.e., no direct wafer electron beam lithography is required). Additional benefits include easy SEM imaging for diameter control and good plasma etch resistance for thick oxide patterns. The EWS process may useful in other applications which require an ultra-small aperture.

A new diode batch has been fabricated using this technology with anode diameters in the quarter-micron range. Preliminary DC and RF testing indicate that these devices are a major improvement over the traditional (1T15 type) device. Process improvements are expected to yield further gains in performance.

Acknowledgement:

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