ADVANCES IN SUBMILLIMETER SEMICONDUCTOR-BASED DEVICE DESIGNS AND PROCESSES

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Abstract

Planar submillimeter circuits arc slowly replacing wbiskcr-contacted devices at frequencies above 100 GHz, but in many cases the size constraints brought on by the short wavelengths associated with high frequency operation have not been adequately addressed. Also, reproducibility becomes more important as we make the transition from tunable, whisker-based circuits to more monolithic designs. We are continuing to develop new circuits and integration techniques to reduce parasitic losses and make monolithic circuits with more reproducible characteristics. Ncw photolithography techniques have been incorporated in our process in the last several months, and tbc use of better dry-etching equipment is enabling us to better control etching.

Wc will discuss second-generation designs of our quasi-optic and microstrip MMIC multipliers. Improvements have been made to our processing technology to make dimensions, and thus impedances, more accurate for both the active devices and the passive circuitry, Many of our alignment tolerances between layers need to be much less than a micron, and even passive structures incorporate extensive two micron-sized lines and spaces that must be accurately fabricated, The new designs and preliminary results will be discussed. In addition, a diode array produced about 9.2 mW approximately 20% efficiency at 262 GHz.

We arc also fabricating new 2.5 THz mixer diode circuits on membranes with 0.1 micron air-bridged anodes. We plan to have new results for the conference.

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2.5 *THz GaAs "Membrane-Diode Mixer"*

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Description of the Invention:

An extremely novel waveguide mixer concept employing an integrated GaAs membrane-diode for operation at 2.5 THz (wavelength of 118 microns) is described. The design has several innovations making it attractive for this and other RF applications in the millimeter and submillimeter wavelength bands. The "membrane-diode mixer" is an alternative to less robust, much more difficult to assemble whisker contact type corner-cube mixers ([1] for example) and recently introduced whisker contacted waveguide mixers [2]. The new membrane-diode mixer also demonstrates, for the first time, the fabrication and use of GaAs membrane structures combining both active devices and passive RF circuits at ultrahigh frequencies (above 1 THz). The 2.5 THz mixer incorporates a self supporting 3 micron thick x 40 micron wide x 600 micron long GaAs membrane [3] integrated into a robust frame and containing both a planar submicron-anode Schottky barrier diode and a suspended stripline RF filter/matching circuit required to perform the frequency down conversion. The membrane diode and associated RF circuit is held within a small electroformed copper button that also contains a 2.5 THz rectangular waveguide, a **rectangular-to-circular waveguide transition and an integrated dual-mode conical** feedhorn. This waveguide "button-mount" is pressed into a larger block which holds a fixed (but replaceable) waveguide tuner section, a separate intermediate frequency (IF) quartz suspended stripline impedance transformer and an SSMA connector to couple with external coaxial components such as an IF amplifier or splitter. The entire package is less than a cubic inch and represents a fully integrated, robust, planar-diode mixer design which can replace less reliable and much more costly whisker-contacted diode circuitry performing a similar function. The design can be scaled down or up in frequency to cover any millimeter or submillimeter wave band. The GaAs membrane concept has extensive RF applications outside the mixer area [3]. The simple waveguide block design can be applied directly to other circuits and devices, for example detectors and high-order multipliers or harmonic mixers. The concept has now been fully realized through the fabrication of a prototype 2,5 THz mixer mount and a membrane diode structure with working devices (as measured at DC). The first RF performance measurements are expected within the next two months.

Description and Novelty:

The new front-end downconverter consists of four separate components as described briefly in this section and which can be seen in the photographs: (1) a GaAs membrane structure formed delete by photolithography that includes a deep-submicron Schottky diode whose anode is fabricated with a unique, single-step electron-beam lithography procedure, (2) a mechanically machined electroformed waveguide “button mount” with integral feed horn and waveguide transformer, (3) a metallic waveguide tuner section, formed with a bobbing technique, that matches the diode to the RF waveguide, and (4) a machined brass split-block which holds the button mount and tuner and contains a 250-50 ohm intermediate frequency (IF) transformer composed of a quartz suspended stripline and a commercial stripline-to-coax connector.

There are several novel features of this design that deserve attention. The most interesting is the use of the all-GaAs membrane to form a low loss transmission line and RF coupling structure for an incorporated active two terminal device (Fig. 1). To our knowledge this has only been accomplished with much lower frequency (<200 GHz) GaAs MMIC circuits where selective etching has been used to define thinned GaAs areas astride passive or active circuit elements [4-6]. in contrast, silicon nitride membrane structures have been developed and utilized in high frequency RF applications for several years [7-8 for example]. However, in these structures the membrane serves only as a support for the active device and adjoining RF circuitry, and plays no role in the electrical performance. In our design, the active device is formed from the top surface of the membrane itself and is an integral part of the electronic circuit, as well as serving as the support substrate for the remaining RF elements. In addition, the width and thickness of the membrane can be altered readily to best match the frequency of operation or desired mechanical rigidity of the circuit structure. Membrane thicknesses of 1, 2 and 3 microns have been defined with widths of 20-75 microns. Careful adjustment of the membrane layer thickness to avoid mechanical stress (a concern in silicon nitride membrane configurations) does not appear to be necessary. In our tests a membrane thickness of 3 microns gave sufficient robustness to a 600 micron long, 40 micron wide beam, for withstanding fairly relaxed handling procedures. No stress related bowing was visible, even after device and metal deposition. Steps detailing the design and fabrication (as well as the additional novelty) of the membrane structure itself are described in a prior New Technology report [3] and will not be repeated here. One added feature of the membrane structure, not described in [3], is the incorporation of beam leads formed on the membrane layer and extending outwards from the membrane frame on the DC and IF sides of the filter circuitry. When the membrane under these beam leads is etched away, the remaining gold strip can be used to bond the membrane directly into the surrounding circuit. The DC side has the beam lead bonded directly to the metal waveguide block; the IF side has the beam lead bonded to an associated quartz IF filter circuit. The beam leads can be replaced by wire bonds if desired.

The diode is formed by a series of steps using PMMA and related resists. THz diodes are formed on very thin layers of GaAs, so it is imperative that processes do little or no damage or removal of the top layers of semiconductor. Our process is unique in that the anode and connecting air-bridge is formed by a single lithography step, and in that only mild solvents are used for developing and removing the resist.

First, a wafer is coated with a PMMA layer that is much thicker than the device topography. By sequentially flood-exposing the PMMA with deep UV radiation and then spin-developing in acetone, the PMMA can be smoothly removed to the mesa tops in a manner similar to planarization processes. The PMMA is not planar over large scales, but can be made sufficiently planar around small mesas for this purpose. Unlike all other known planarization processes, this approach causes no damage to the underlying GaAs, and the later removal of the PMMA occurs as a consequence of later processing that is required for metal lift-off.

After the quasi-planarization, additional, thinner layers consisting of PMMA, PMMA/PMAA, and more PMMA are spun onto the wafer. The anode and air-bridge are formed by exposing the resist layer to various doses of electron beam current and then developing the resist such that it is opened all the way to GaAs for the anode area (on top of a mesa, so there is none of the thick PMMA in the way), to the top of the first thin PMMA layer for the air-bridge (spanning from the anode, across the thick PMMA between mesas, onto a second mesa), and again through all of the thin layers of resist to a metal pad to serve as a connection to the anode.

After suitable surface preparation of the GaAs, metal is deposited through the resist, and the unwanted metal on top of the resist is lifted off in hot acetone, which dissolves all of the resist.

A second novel feature of the new 2.5 THz mixer design is the integration of the membrane circuit into a DC continuous single-mode waveguide "button mount" (Fig. 2). Past implementations for combining membrane structures (all have been silicon nitride based) with RF waveguide circuitry [9] have suffered from the limitation of having to interface a continuous membrane plane with a metallic housing that favors electrical contact through the membrane itself (not viable). In this design the membrane (and associated RF circuitry) forms a thin suspended line which bridges across it's frame allowing DC contacts to be made on both sides of the beam. In this way a single mode RF cavity is formed around the active device and input waveguide. This arrangement prevents RF power from leaking out of the waveguide.

A third unique feature of the design is the method employed to accurately align the membrane rim (and suspended 3 micron thick beam) vertically in a machined single mode cavity to form a low-loss suspended stripline circuit rather than the microstrip implemented in [9]. The vertical alignment of the membrane beam in the metallic stripline cavity is assured by using the membrane itself as a reference surface. This is accomplished by leaving a web of membrane protruding slightly on two sides of the support rim. This web is then supported by a ledge which has been preformed in the waveguide button mount (see below) by conventional machining techniques. The membrane web thickness is precisely determined during the wafer epitaxial growth process and allows the diode and RF filter to be positioned vertically within a few microns in the supplied cavity.

Finally, the design and fabrication of the "button mount" adds some novelty to the circuit implementation. The button mount holds the membrane and frame in position across the broad wall of an electroformed rectangular waveguide and also incorporates a rectangular-to-circular waveguide transition and integral Pickett-Potter feedhorn. The entire mount is formed from a single aluminum mandrel which is afterwards gold plated and copper electroformed to create the "button" only .175" in diameter and .075" thick (Fig. 2.). The membrane rim relief slots and vertical support ledge are machined into the button via conventional milling techniques. The support ledge is then positioned precisely (relative to the top of the button) by a few strokes on a hand lap. The suspended stripline cavity (which passes across the broad wall of the waveguide) is now machined into the finished button using a high speed semiconductor dicing saw with a cubic boron nitride wheel. Using the dicing saw, the depth and position of this slot, relative to the waveguide and surrounding support ledge, can be very precise. The width and finish of the cavity are determined by those of the dicing saw blade. After sawing, the suspended stripline cavity, the aluminum mandrel is etched out of the button, leaving the mounting structure seen in the figures. A separately fabricated fixed depth waveguide tuner section fits over the top of the button forming a seal for the stripline cavity and waveguide. The waveguide tuner section is made by bobbing a rectangular cavity into a copper shim and then lapping the shim to the appropriate thickness to achieve the desired tuner cavity depth. In this way no adjustable backshort is required and RF contact losses should be reduced substantially. At the edge of the membrane, when all RF propagation has been suppressed, the membrane rim crosses the incorporated RF filter and allows direct connection (using a wire bond or incorporated beam lead) to the metal block on the far **side of the diode and** to a separate quartz IF filter on the near side. The button is press fit into a larger brass block which contains the IF filter and commercial stripline-to-coax connector (Fig. 3). A top block seals the IF filter cavity and provides **a** flange mount for the SSMA connector.

To summarize the unique features of this concept we have: (1) the fabrication and incorporation of a planar GaAs Schottky diode and complete RF filter/coupling circuitry on a membrane structure formed totally lithographically, (2) utilization of a variable width GaAs membrane beam structure which allows the formation of a fully enclosed single mode RF circuit element, (3) use of a membrane web to precisely align the circuit vertically in a predefine channel, (4) inclusion of beam leads as part of the membrane structure to make the DC and IF contacts without the need to wire bond, (5) use of an electroformed "button-mount" which aligns the membrane diode to preformed RF waveguide and horn elements, (6) use of a bobbing technique to form a waveguide tuning section behind the diode.

Operation:

Theoperation of themixer is straightforward. A signal and local oscillator are combined in a frequency diplexer or interferometer. The RF and LO are then directed towards the feed horn in the mixer block. The two signals are combined at the planar diode and the beat frequency (IF) is removed via the membrane filter, quartz transformer and coaxial connector. There is no active tuning except via bias adjustment. The optimal backshort setting is obtained by trial and error (swapping out several metallic wafers with differing waveguide lengths). Performance is verified with thermal loads at the receiver input. An output IF amplifier is used to amplify the noise signal to detectable levels. Precise RF testing of the mixer requires a rather elaborate vacuum test setup due to the absorption by water vapor at these frequencies. Such tests will be conducted over the next several months. The DC performance of the membrane diodes has already been verified with standard probe techniques and a typical IV curve is shown in Fig. 4. The series resistance, a good tracer for diode behavior at RF is very low for the device areas that have been employed. The RF performance is expected to be competitive with existing mixer structures employing similar diodes in non-membrane circuits.

Spin-Offs:

Spin-offs for these techniques are numerous and include both mechanical and electronic applications. The ability to fabricate membranes which vary in thickness from 2 **to as** much as 5 microns via epitaxial growth has more flexibility than current silicon nitride membrane structures. The lack of problems encountered with material stress issues makes the GaAs membrane particularly easy to employ. The ability to open holes in or **around the membrane, combined with the fairly rugged structure and low mechanical** stress might make it suitable for use in many mechanical applications including ink jet sprayers, alignment holes etc. The RF circuits which become feasible with this process are numerous and include Schottky diode detectors, harmonic mixers and comb generators as well as multipliers, waveguide couplers, planar antennas with integrated devices, etc. Finally, the membrane technology presented here could be combined with more precise dry etching to form a whole class of novel RF structures from 100 GHz to 3 THz.

Summary:

A new membrane-diode waveguide mixer concept is described. The design has been prototype at 2.5 THz and will be RF tested over the next two months. The mixer has a significant advantage over existing designs in that it utilizes an all-planar integrated circuit architecture to form the RF filters and Schottky diode. The diode structure is fabricated monolithically and consists of a rigid GaAs support frame and a suspended GaAs membrane beam containing the filters and Schottky barrier. The design allows a single mode suspended stripline filter circuit to be realized at 2.5 THz, substantially reducing RF losses. The membrane diode is combined with an electroformed waveguide button mount, which incorporates a single mode rectangular waveguide, rectangular-to-circular waveguide transition and dual mode conical feedhorn. The button mount mates with a backshort tuning section and IF impedance transformer to complete the mixer mount. Assembly is extremely simple, involving gluing of the membrane frame in the button **mount and three** wire bonds. An additional simplification is incorporated into the membrane by forming beam leads, which protrude from the contact points at the IF and DC return positions. Both the membrane design and fabrication are extremely novel and lend themselves to many additional RF and mechanical applications. The diodes have been tested at DC and perform according to expectation. The mount has been completed and RF testing will begin shortly.

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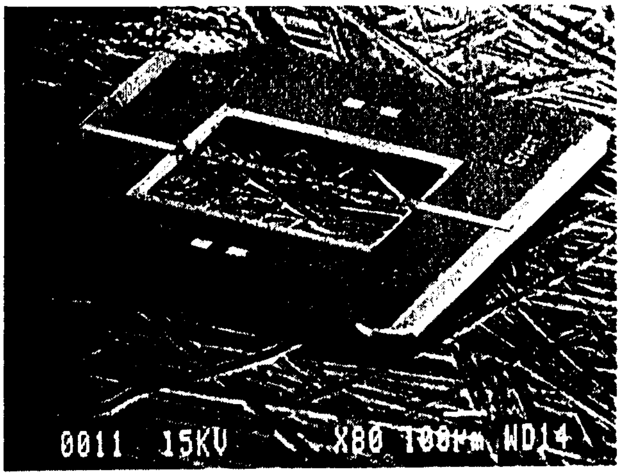

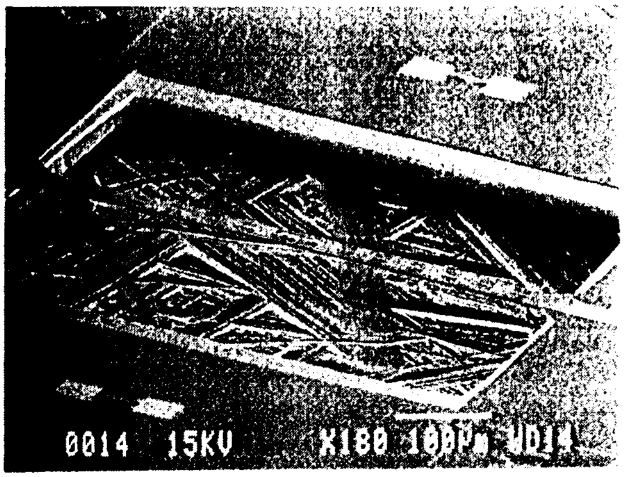

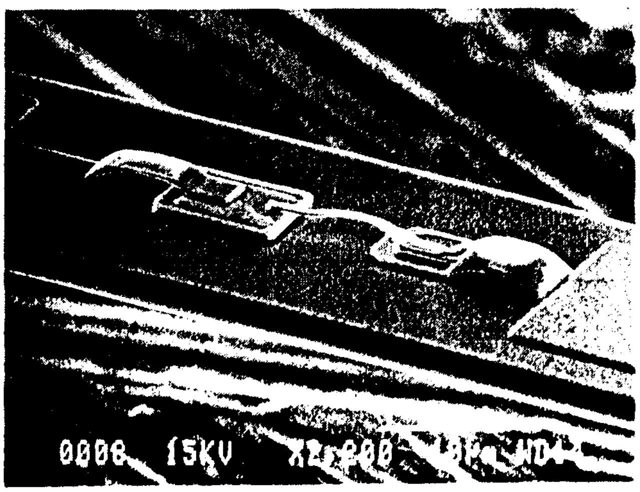

Figure 1. Photographs of the membrane diode mixer (diode, RF filter, membrane and membrane support rim).

A. View showing the full membrane rim and suspended membrane bridge. The diode is at the very center.

B. Closer view of the membrane with the **RF filter circuit and diode at the center.**

C. Close up showing the 2.5 THz Schottky diode on the 3 micron membrane with the airbridge contact finger and airbridge stress rellief bridges on either side. The Schottky anode is only 0.5x0. I microns.

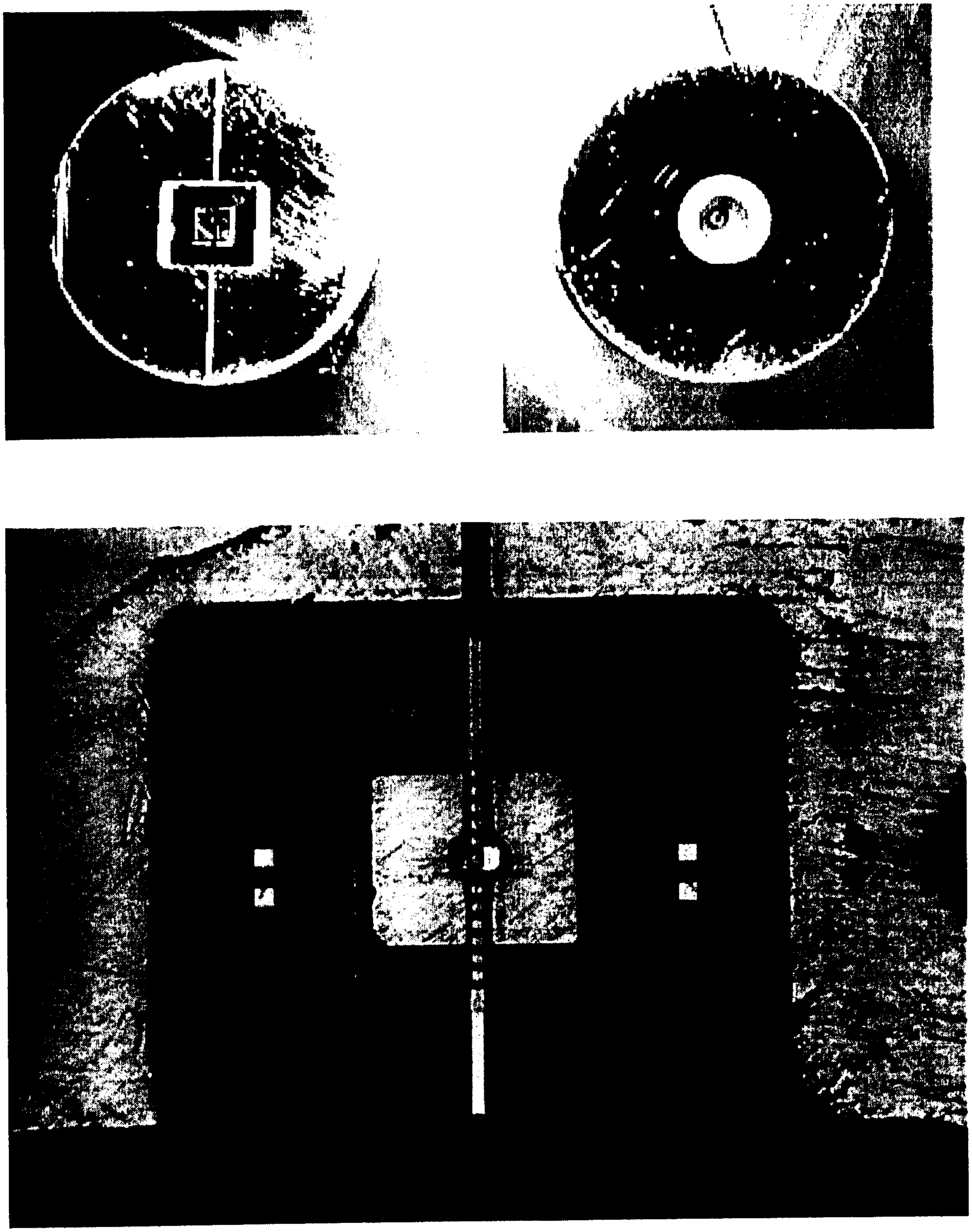

Figure 2. Photographs of **the 2.5** THz mixer **"button-mount" with incorporated membrane** diode and support rim. **Top Left: Top view of complete "button mount" showing membrane and** diode. **Top Right: Bottom view, showing integrated dual mode feed horn** Bottom: **Close up showing membrane** diode **and** RF filter **in** supplied **waveguide and** stripline **cavities**

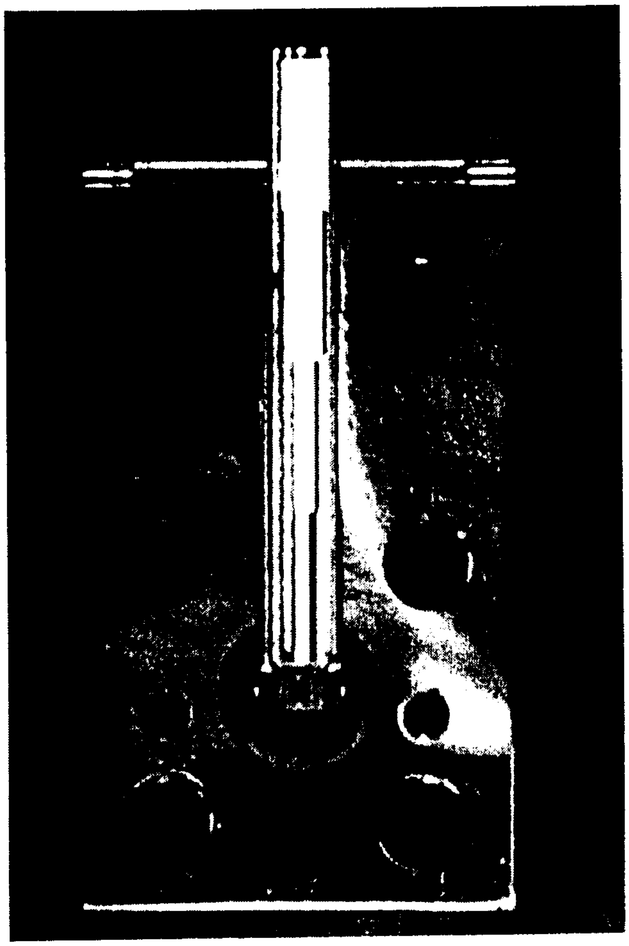

Figure 3. Photograph showing complete 2.5 THz mixer block (lower half) with button mount and IF transformer. When assembled the top half of the block forms a seal over the button mount and membrane, the RF waveguide and the IF transformer cavity. The backshort tuner section sits directly on top of the membrane and is aligned from the backside with special alignment holes in the button mount.

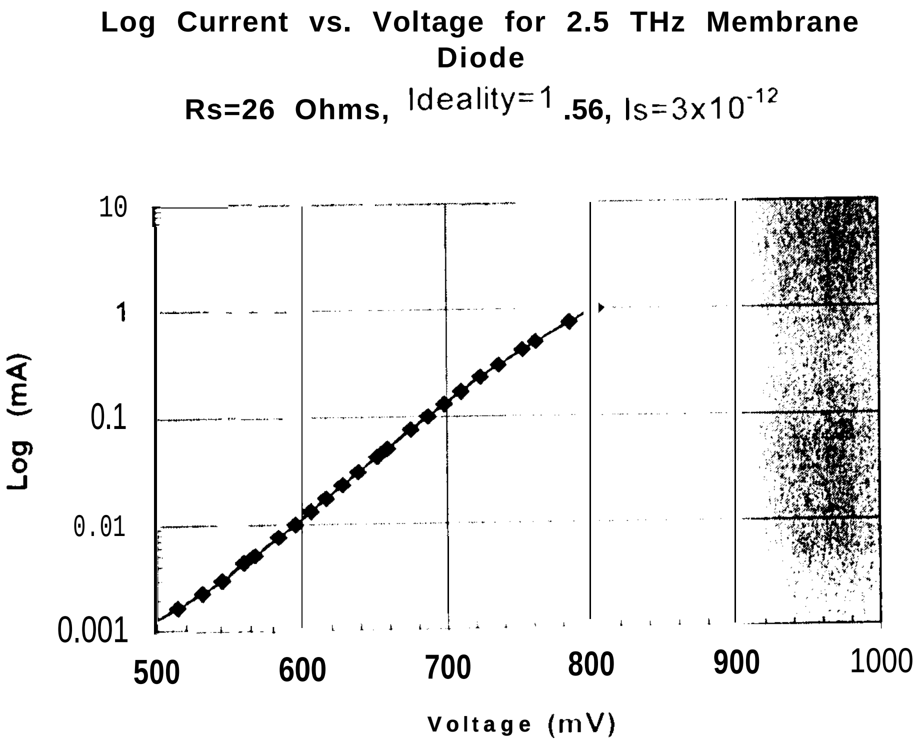

Figure 4. Measured IV curve for 2,5 THz Schottky diode and derived diode DC parameters. The series resistance and ideality factor are reasonable for this anode **area (0.05 square microns).**