A Final Progress Report
Grant No. NAG-5-712

April 15, 1989 - December 31, 1989

FABRICATION AND OPTIMIZATION OF A WHISKERLESS SCHOTTKY BARRIER DIODE FOR SUBMILLIMETER WAVE APPLICATIONS

Submitted to:

National Aeronautics and Space Administration
Goddard Space Flight Center
Instrument Division
Engineering Directorate
Greenbelt, MD 20771

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Attention:

Ms. Audrey J. Ewin, Code 724

Submitted by:

W. Bishop
Research Scientist

R. J. Mattauch
British Petroleum America Professor and Chairman

Report No. UVA/528247/EE90/101
March 1990

DEPARTMENT OF ELECTRICAL ENGINEERING

SCHOOL OF ENGINEERING & APPLIED SCIENCE

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Charlottesville, VA 22903

UNIVERSITY OF VIRGINIA
School of Engineering and Applied Science

The University of Virginia's School of Engineering and Applied Science has an undergraduate enrollment of approximately 1,500 students with a graduate enrollment of approximately 600. There are 160 faculty members, a majority of whom conduct research in addition to teaching.

Research is a vital part of the educational program and interests parallel academic specialties. These range from the classical engineering disciplines of Chemical, Civil, Electrical, and Mechanical and Aerospace to newer, more specialized fields of Applied Mechanics, Biomedical Engineering, Systems Engineering, Materials Science, Nuclear Engineering and Engineering Physics, Applied Mathematics and Computer Science. Within these disciplines there are well equipped laboratories for conducting highly specialized research. All departments offer the doctorate; Biomedical and Materials Science grant only graduate degrees. In addition, courses in the humanities are offered within the School.

The University of Virginia (which includes approximately 2,000 faculty and a total of full-time student enrollment of about 17,000), also offers professional degrees under the schools of Architecture, Law, Medicine, Nursing, Commerce, Business Administration, and Education. In addition, the College of Arts and Sciences houses departments of Mathematics, Physics, Chemistry and others relevant to the engineering research program. The School of Engineering and Applied Science is an integral part of this University community which provides opportunities for interdisciplinary work in pursuit of the basic goals of education, research, and public service.

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TABLE OF CONTENTS

Introduction

This is a final progress report for NASA Grant No. NASA-NAG-5-712, entitled "Fabrication And Optimization Of A Whiskerless Schottky Barrier Diode For Submillimeter Wave Applications". This work is a continuation of NASA sponsored planar diode research which was proposed in 1985 (UVa Proposal No. EE-NASA/GSFC-3186-86). This work was also supported and continues to be supported, in part, by the National Science Foundation (in cooperation with the U.S. Army at Fort Monmouth) and the Jet Propulsion Laboratory.

Background

Receivers which operate in the millimeter and submillimeter wavelength range (100 GHz to 3 THz) are of critical importance in numerous research applications, such as: radio astronomy, atmospheric physics, chemical spectroscopy, and plasma diagnostics. Such receivers are crucial to the following NASA programs: the proposed EOS-Microwave Limb Sounder, the Stratospheric Observatory for Infrared Astronomy (SOFIA), and the Large Deployable Reflector (LDR). Each of these programs, and several others, require receivers with the highest possible sensitivity and the lowest possible noise to detect very weak signals and to minimize observation time. Heterodyne techniques, which convert the high frequency signal to a much lower frequency, are used because of the unavailability of amplifying devices at the higher frequencies and their large instantaneous bandwidth and spectral resolution.

The small diameter, whisker-contacted Schottky barrier diode, shown in Fig. 1, has traditionally been the mixer element of choice because of its excellent nonlinear I-V characteristic and low shunt capacitance. Whisker contacted diodes produced by the University of Virginia Semiconductor Device Laboratory have posted world records in noise performance in the millimeter and submillimeter range [1].

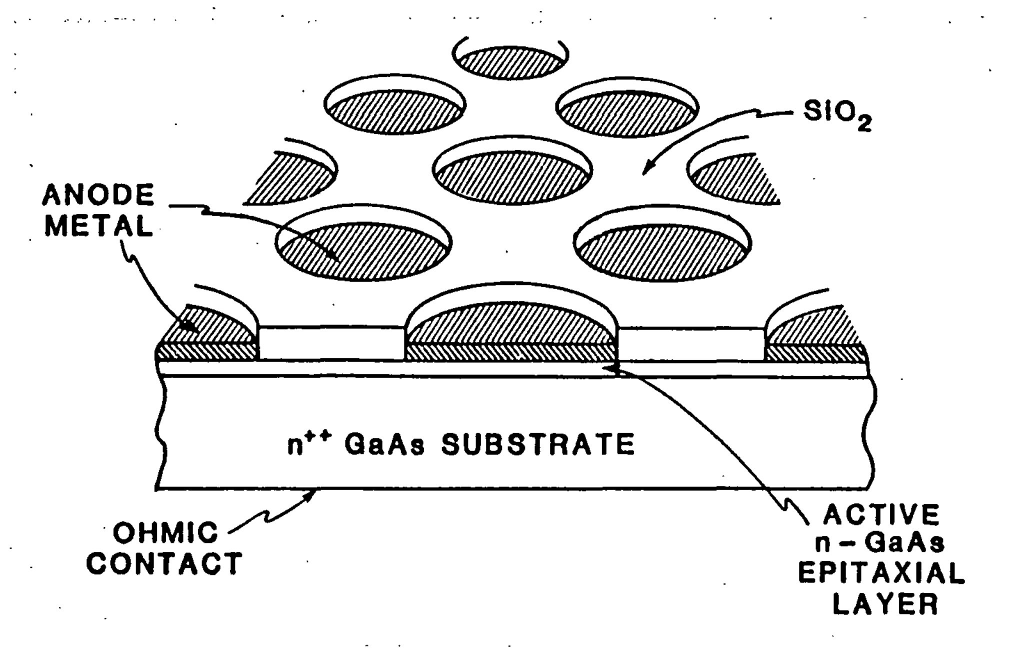

Figure 1. Whisker-Contacted Schottky Diode

However, the whisker contact method yields a device which: (1) is mechanically unstable in high vibration environments, such as a rocket launch, (2) is very difficult to incorporate into small hybrid circuits, such as planar antennas, (3) requires special mount design to facilitate operation at cryogenic temperatures because of thermal contraction, and (4) is incompatible with integrated circuits. The whiskering process is tedious and requires a high level of technical skill.

For these reasons, it is most desirable to use a monolitic, planar diode structure which replaces the whisker contact wire with integral contact pads and a contact "finger" as shown in Fig. 2.

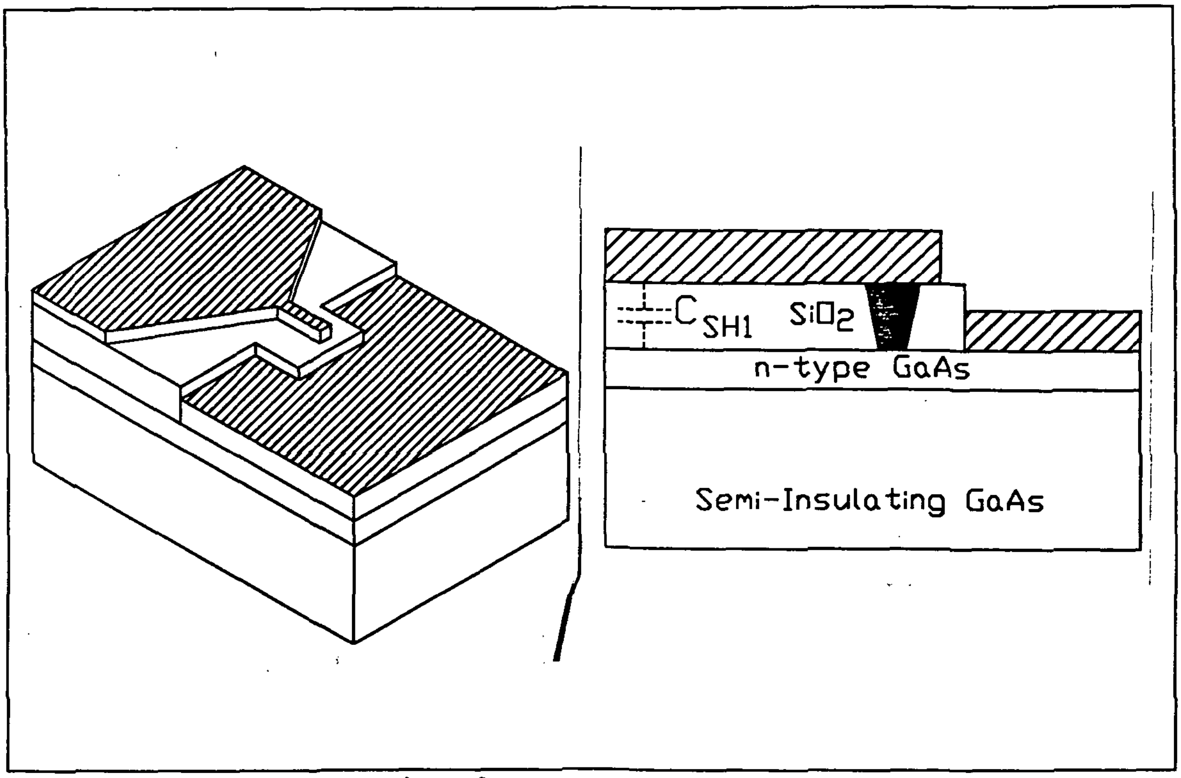

Figure 2. Generic Planar Diode Structure: Isometric and Cross Sectional Views

This device structure can overcome all of the problems associated with the whisker method. Planar diodes, however, suffer from inherently large shunt capacitance which arises primarily from the contact pads overlying the high dielectric constant substrate. Successful operation of planar diodes at the highest frequencies requires a design with minimal parasitic capacitance, inductance and resistance as well as excellent nonlinearity. While a number of research groups, including UVa, have developed planar diodes with excellent performance at 100 GHz, operation in the terahertz region of the spectrum awaits a planar diode with submicron anode diameter and theoretical minimum parasitics.

Research Goals

Planar diode research at UVA, funded in part by NASA, is focused on the development of mixer diodes with excellent performance in the millimeter and submillimeter wavelength range. Previous reports have discussed the development of the UVa planar diode structure. This work resulted in the development of a novel diode structure called the "surface channel" planar diode shown in Fig. 3.

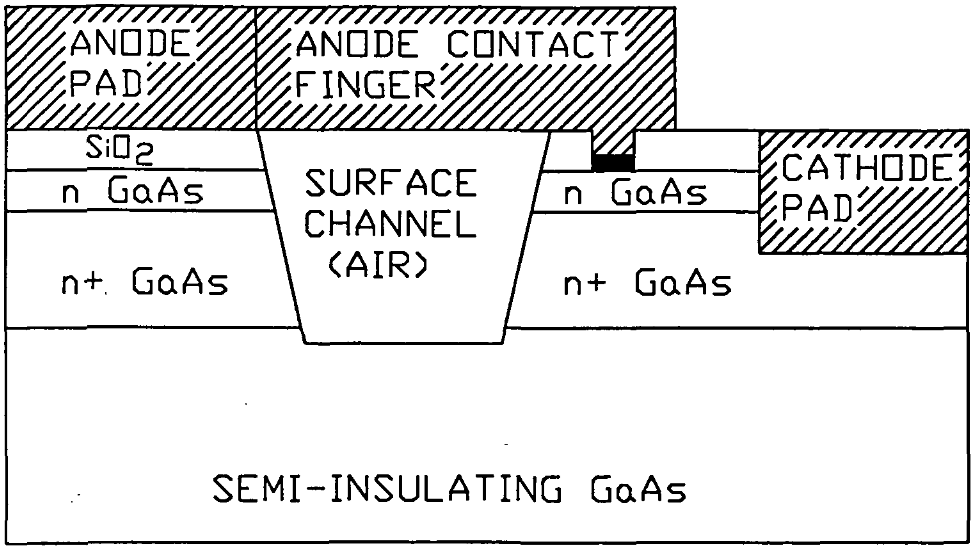

Figure 3. Surface Channel Planar Diode Structure

This structure reduces contact pad capacitance by means of an etched "surface channel" under the finger and completely across the width of the chip. The structure is relatively easy to fabricate compared to traditional mesa or proton isolated designs. Since the channel is formed at the end of the fabrication sequence, after the critical steps of anode and finger formation, the structure is very compatible with high resolution photolithography. The channel itself minimizes capacitance of the finger by virtue of the "air bridge" which it forms. A patent for this structure has been filed by NASA*. Three technical papers and one Master's thesis are a direct result of this effort and are included in Appendix 1. These references describe most of the advances made prior to the latest NASA grant. This work has recently been extended to include planar varactor diodes for use as local oscillator sources and dual, "balanced" configurations for subharmonically pumped mixers. Two Master's candidates and three Doctoral candidates are currently involved in research on the surface channel diode for mixer and varactor applications. A collaborative effort with Martin Marrietta Corporation is underway to produce a complete MMIC mixer for operation at 180 GHz.

Research goals in the latest NASA renewal proposal (August 1988) are as follows:

A. Fabrication of additional devices which are optimized for higher frequency operation (both cryogenic and room temperature),

B. DC and RF testing of these devices,

C. Modeling of parasitic elements to obtain information which is needed to understand and optimize such devices,

*NASA Case No. 130631CU

D. The incorporation of certain improvements such as (1) anodic thinning of the epilayer through the anode windows prior to anode formation for improved noise performance, (2) reactive ion etching for reduced shunt capacitance from the anode window metallization and, (3) attempts to produce a non-alloyed ohmic contact, and

E. Continuation of the lens-antenna work which was begun by Dr. Charles Bennett at NASA to include testing of the attenuation of the silicon lens and preliminary mixer testing at 1 THz.

Research Progress

A. Device Fabrication

A new batch of surface channel diodes was completed using the latest mask set. This mask set was produced in a joint NSF sponsored effort between UVa and the U.S. Army Electronic Technology and Devices Laboratory at Fort Monmouth, NJ. This design features tapered anode and ohmic contact pads for reduced shunt capacitance, variable feature dimensions for process and device optimization and a special marker level for improved alignment control. An SEM photograph of a chip from batch SC2R4 is shown in Figure 4.

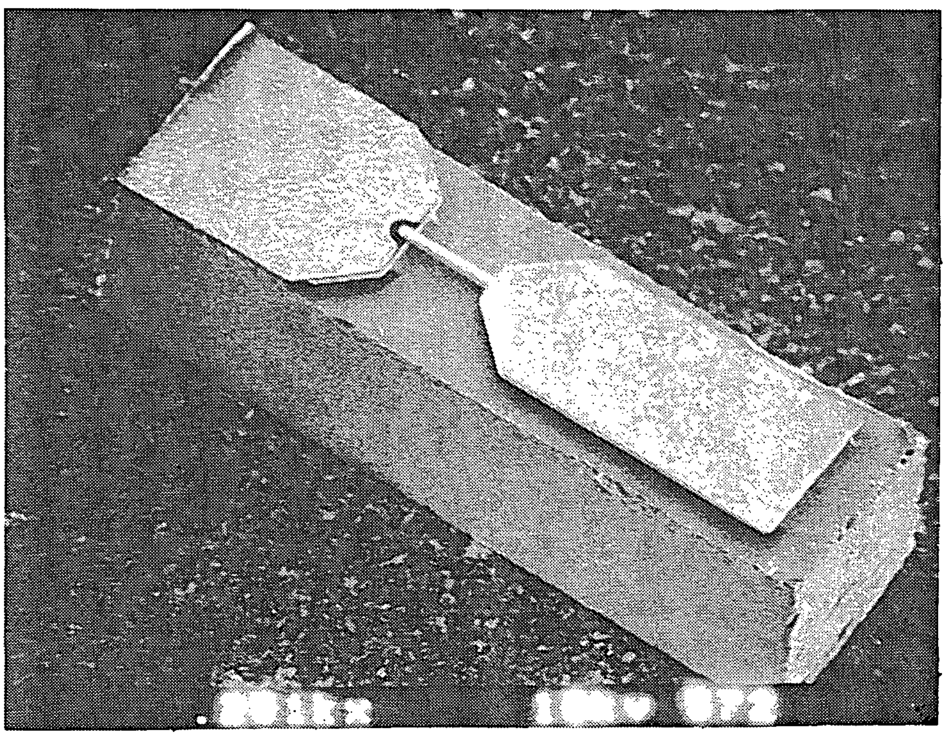

Figure 4. SEM Photograph of SC2R4 Surface Channel Diode Chip

A comparison of device I-V and capacitance for SC2R1 and SC2R4 diodes is given in Table I. The I-V characteristics of the two devices arevery similar while the total and shunt capacitance of the new chip is substantially lower. This is attributed to the tapered pads and reduced anode-to-surface channel spacing.

The SC2R4 devices also incorporate fabrication changes which improve process reliability and yield. In earlier attempts to reproduce previous batches, many of the resulting diodes had very low reverse breakdown voltage and, in some cases, low turn-on voltage and poor ideality factor. Test anodes on the wafers, which were identical with the exception of anode spacing , exhibited excellent I-V characteristics. The test devices were in a close-packed array for easy contact with a whisker while the actual device anodes were relatively far apart. Further investigation produced additional evidence to support the hypothesis that the widely spaced device anodes were damaged by the plating process while the closely spaced test array anodes were protected. The high energy pulse plating of platinum or the preplating GaAs etching process were suspected as the cause of this damage. In an effort to reduce the possibility of electrical pulse damage, the second silicon dioxide layer which normally isolates the ohmic contact from the plating current was eliminated. This allows the plating current to be spread over a large area and may prevent a large current spike from damaging the device anodes. The silicon dioxide layer over the ohmic contact was thought to be necessary to prevent a "thief" action from the nearby ohmic metallization and a resulting incomplete or poor quality anode plating. While this proved to be true in the case of pulse plating, it was found that direct current plating provides uniform anode metallization and excellent I-V characteristics, even without the oxide layer over the ohmic contact. Thus, the SC2R4 devices are fabricated with only one oxide layer which simplifies fabrication and the anodes are DC plated with platinum.

Table I. I-V and Capacitance Data Summary for Surface Channel Diode Batches

Batch No.	SC2R1	SC2R4
ΔV @10-100 μA (mV)	72	70
V_{knee} @ 10 μA (mV)	760	765
V_{rev} @ -1 μA (V)	5	6
R_s @ 10 mA (Ω)	5-6	5-6
C_{j0} (fF)	6	6
C_{total} (fF)	20	15

B. Device Testing

Diode chips from batches SC2R1 and SC2R2 have been RF tested at 94 GHZ in an optimized mixer mount [2]. A 2-micron diameter whisker contacted diode with comparable DC electrical characteristics was also measured in the same test setup for comparison. (This diode was from the same batch used in the Columbia-GISS 4 ft. radio telescope reported by Cong, Kerr and Mattauch which yielded the best reported receiver performance for a room temperature diode at this frequency [3].) The results of this work are summarized in Table II. The mixer noise temperature and conversion loss of the planar diodes is very nearly equal to that of the whisker contacted diode.

Table II. RF Mixer Noise Temperature and Conversion Loss for Surface Channel and Whisker Contacted Diodes at 94 GHz

Device	L_{MIXER}	T_{MIXER}
SC2R1	5.8	555
SC2R2	5.3	518
2D2*	5.3	560

* Whisker contacted