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MILLIMETER WAVE METAL-INSULATOR-METAL DETECTOR/MIXER DIODE

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20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

This report describes the fabrication of metal-insulator-metal
(MIM) structures for use as broadband detectors and mixers in
the microwave and mm region. Two types of structures have
been fabricated: a point contact diode based on a tungsten
whisker in contact with a nickel post through its natural oxide
layer (MOM), and a planar diode fabricated by deposition of dis-
continuous metal films on a glass substrate. Primary efforts were
directed at overcoming the known instability of the point contact

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diode and improving the low responsivity of the planar film diode.

The final MOM point contact diode acquired a controlled hooked whisker tip that demonstrated sufficient cushioning action against ambient vibrations, and provided a free end pointing slightly away from the junction area, thus introducing minimum degradation to diode performance. This enabled the diode to better accommodate thermal expansion under high power radiation with little degradation of performance. The nickel coated quartz post resolved the problem of significant variation in the metal-metal spacing due to ambient temperature fluctuations. Such a diode has shown stable X band detected output with less than 10% signal level fluctuations over three weeks under room temperature fluctuations from $50°F$ to $95°F$ and normal room vibrations.

The discontinuous nickel film on glass substrate has proven to be a feasible planar MIM diode in the X and V bands. IC chip fabrication techniques were used for the multi-chip diodes. Chips were connected in series or parallel configurations. The series array was used to control diode resistance and expand diode area for interception of incident radiation. Waveguide packaging and tuning of such a diode at X band brought diode detection to a level comparable to that of the MOM point contact diode.

Waveguide mounting of the point contact diode as opposed to the present open structure is contemplated. It is anticipated that such a diode package will give stable signal output matching that of commercial microwave diode packages. The X band planar diode can be scaled down to match V band dimensions, since chip resistance and performance were found to be essentially independent of chip size. However, better trimming techniques must be used for chip size control, especially for operation into V band and higher frequencies, where phase variation over diode surface may be critical.

FOREWORD

This report describes research performed under contract F33615-81-K-1418 to fabricate millimeter wave metal-insulator-metal detector/mixer diodes that are mechanically, electrical and thermally stable. The work was carried out in the Electrical Engineering Department of North Carolina A & T State University, Greensboro,North Carolina. The principal investigator was Chuno Yu, guiding graduate students: Matei Ndeti, A. Yekrangian, M. Hemmatian, S. Byers and several undergraduate students. The V band equipment was on loan from the Air Force Avionics Laboratory, and some of the film deposition was carried out at NASA Langley Research Center with the assitance of Mr. Alan Frizzell of the Microelectronics Development Unit.

The period in which this research was carried out was from May 1981 to July, 1983 and the final report was first submitted in October, 1983.

The Air Force program monitor was Mr. Theron J. Dersham, Project Engineer, Microwave Techniques and Applications Group, Microwave Technology Branch.

TABLE OF CONTENTS

LIST OF ILLUTRATIONS

LIST OF TABLES

1. INTRODUCTION AND BACKGROUND TECHNOLOGY

1.1 Status of MIM Point Contact and Planar Film Diodes

The well known ultrafast (References 1, 2) long whisker, metal-oxide-metal (MOM) point contact diode with majority carrier conduction and excellent antenna receiver properties has often been faulted for its inherent mechanical, thermal and electrical instabilities. These short-comings have hampered its practical system application, and prevented reliable analysis of its basic conduction mechanisms and their regimes of operation.

Attempts were made in this project to establish stability parameters essential to devising methods to remove or reduce the above instabilities. Each parameter was defined and optimized. This led to the mechanical modification of the whisker tip through the definition of the slender ratio and deliberate hooking with minimum damage to the tip, and the selection of post material other than nickel. Such a diode has been fabricated with long term stability and reasonable ruggedness. A systematic study of the various conduction mechanisms such as tunneling and thermally enhanced tunneling was performed.

This knowledge of a single junction has led to a better understanding of the performance parameters of more complex metal-insulator-metal (MIM) structures as candidates for possible replacements and improvements of the point contact configuration. The photolithographic film diode with apparent mechanical stability still possessed the sharp tip, hence its inherent instabilities (Reference 3, 4); the discontinuous metal film version with metal island vacuum deposited onto glass substrates possessed greater ease

1

of fabrication and removed most of the instabilities by eliminating the sharp tip. The loss of the long wire antenna was compensated by using IC and circuit interconnections.

In the point contact version using sharp tungsten whisker tip in contact with the naturally grown oxide layer of a nickel post, both the geometric shape of the tip and the nature and thickness of the oxide layer were scrutinized. Studies have led to the establishment of an undamaged or minimally damaged hooked tip with an optimum slender ratio defined as the ratio of whisker shaft length to tip diameter, and optimum penetration of the oxide layer by this tip. Excessive thermal expansion and contraction of the nickel post whether under irradiation or caused by ambient temperature fluctuations also called for the replacement of the nickel post by nickel coated kovar or quartz posts (Reference 5). In the discontinuous MIM films, metal and metal combinations, island spacing, and size were the key parameters in determining their performance and stability.

Thus, the performance and stability of both types of diodes are extremely dependent on the chemical, mechanical, electrical, and thermal properties of their constituent materials. The metals and their oxides determine the chemical stability of the oxide and optimum thickness; the geometric shape of the tungsten whisker tip in the point contact diode determines the extent of tip penetration into the oxide layer, thus the actual oxide thickness between the two metals, and the amount of hooking of the tip. These in turn determine the diode resistance, the spring or cushioning action of the hook, and the responsivity of the diode. In the MIM film diode, inter-island work functions, island size and spacing determine single chip resistance.

2. MATERIALS, PROCESSES AND STRUCTURES

2.1 MOM Point Contact Diode

2.1.1 Establishment of Stability Parameters

Chemical Stability Parameter

Tungsten is well known for its high melting point of 3410°C and its extremely strong atomic cohesion that accounts for its mechanical strength and small thermal expansion coefficient. It has thus been most widely adopted as the whisker in the point contact diode. Furthermore, tungsten is not oxidized to a significant degree in the atmosphere up to 550°C and remains so up to 1000°C, reached under normal laser irradiation. Even at higher temperatures, no considerable contribution comes from the inside oxide layer due to the metallic properties of W_4O_{11}, forming the outside layer (References 7, 8, 9).

The tungsten whisker is generally etched from polycrystalline wire, which is usually drawn with preferred grain orientations along the wire axis. Electrolytic etching of the wire produces tips much smaller than the grains so that the tip forms a single crystal, consisting of (111) faces with a common [110] axis along the whisker direction.

In the tungsten-on-nickel MOM diode, the insulating layer is thus mainly nickel oxide, which is one of the best insulators in nature with an electrical resistivity of 10^{15} ohm-cm. The oxide layer thickness is approximately 6-8 Å by electropolishing (Reference 10), and 9-12 Å by anodic oxidation (Reference 9). The oxide layer can also be obtained by mechanical polishing, followed by etching with phosphoric acid and then potassium dichromate to expose a clean surface. This is followed by baking at 450°C

with oxide layer thickness a function of baking time, varying from 5 Å
to 1000 Å. Dry air-formed oxide film at room temperature is normally
6-8 Å and is basically stoichiometric NiO (Reference 11).

It has been shown theoretically (Reference 12) and experimentally
(Reference 13) that diode responsivity increases with increasing insulator
thickness, reaching a maximum at 12 Å (Reference 13). Rectification
efficiency has also been shown (Reference 13) to be extremely sensitive to
work function differences between the two metals with superior performance
achieved in dissimilar metal diodes.

Chemically, oxide film thickness is the key factor, determining diode
performance. Since tunneling and Schottky emission are usually proposed as
the conduction mechanisms in MOM diodes, the former will render the diode
essentially temperature insensitive, while the latter is highly temperature
dependent. *Thus, tunneling MOM diodes with oxide layer less than 100 Å
thick will be temperature independent.*

Mechanical Stability Parameter

The nature of the oxide and its thickness constitute the chemical
parameter. The contact pressure between the whisker tip and the oxide
layer is the mechanical parameter for diode stability. A contacting scheme
was established to maintain steady contact pressure. Thus, a thick oxide
layer was grown such that the whisker tip was allowed to penetrate to an
optimum depth. In the process of penetration, the sharp tip was bent and
hooked. This elbow formed the contact area, which was considerably larger
than the tip diameter. The amount of hooking and the depth of penetration
were controlled by the geometrical shape of the tip defined as the slender
ratio (ratio of tapered shaft length to tip diameter).

The slender ratio was the single design parameter derived through careful and consistent definition of the physical state of the tip: damaged, blunted, hooked and undamaged. The shape of the tip controlled the stability of the diode with no significant degradation to diode responsivity.

The slender ratio was established by the systematic reexamination of the fabrication process. This process involved two steps: etching of the tip and contacting of the tip with the nickel post.

For a specified voltage between electrodes of a 3N KOH electrolytic solution, the single factor which determined the ultimate slender ratio after etching was the depth of immersion of the initial tungsten wire in the solution. The wire was being etched in the region around the miniscus and the submerged portion. The wire serving as one of the electrodes provided two conduction paths, with the submerged portion acting to prolong miniscus etching.

Etched tips with different slender ratios were used as whiskers in the point contact diode. Whiskers with optimum slender ratio would hook appropriately when they were brought into contact and made to penetrate the nickel oxide layers. An optimum hook was defined as one that produced a stable and reasonably strong detected signal.

This hooked or bent tip has often been encountered by workers in this field, but viewed negatively because of possible damage believed to have been suffered by the tip. Such hooking was judged to be detrimental to the performance of the resulting diode due to the non-reproducibility of such hooks and the increased contact area, and hence capacitance, resulting in reduced diode speed. However, it has often been argued that simultaneous

reduction of diode resistance should compensate the increase in capacitance so that the RC constant of the diode remains unchanged. The amount of hooking could be controlled and reproducible by strict maintenance of etching parameters.

Thermal Stability Parameter

Creation of a free end in the diode contact area was the most important feature of this stabilized diode, enabling it to avert heating instability due to incident radiation. Heating was especially severe under high power laser radiation focused on the contact area. Without hooking, the sharp tip expanded when heated, penetrating deeper into the oxide layer until it made contact with the nickel post. The latter then acted as the heat sink, cooling the tip, which then contracted and broke contact. If laser radiation was maintained, heating of the tip resumed and the cycle of heating and cooling repeated. A detected pulse train was observed, even though the incident laser radiation was unmodulated. This phenomenon was not observed with a hooked tip.

Nickel Post Modification

Since tungsten-nickel spacing must be maintained to within angstroms, the nickel post dimension changes with ambient temperature fluctuations could not be tolerated. Thus, the hooked tip stabilized the diode only against mechanical vibrations and tungsten tip dimension variations, but stability against dimension variations of the nickel post due to ambient temperature was impossible. A rather simple solution involved replacing

6

the nickel post by a kovar or quartz post coated with a one micron thick
layer of nickel. The quartz post was polished optically flat, nickel
coated and tested with extremely encouraging results. It was observed
that once short term stability was attained, long term stability was
assured with the nickel coated quartz post.

2.2 Planar Discontinuous MIM Films and Diodes

2.2.1 Film Selection and Deposition

In the initial phase of metal film deposition on a substrate, the
condensed film structure is discontinuous, consisting of a large number
of islands. These islands grow in size as metal atoms accumulate on the
substrate with time.
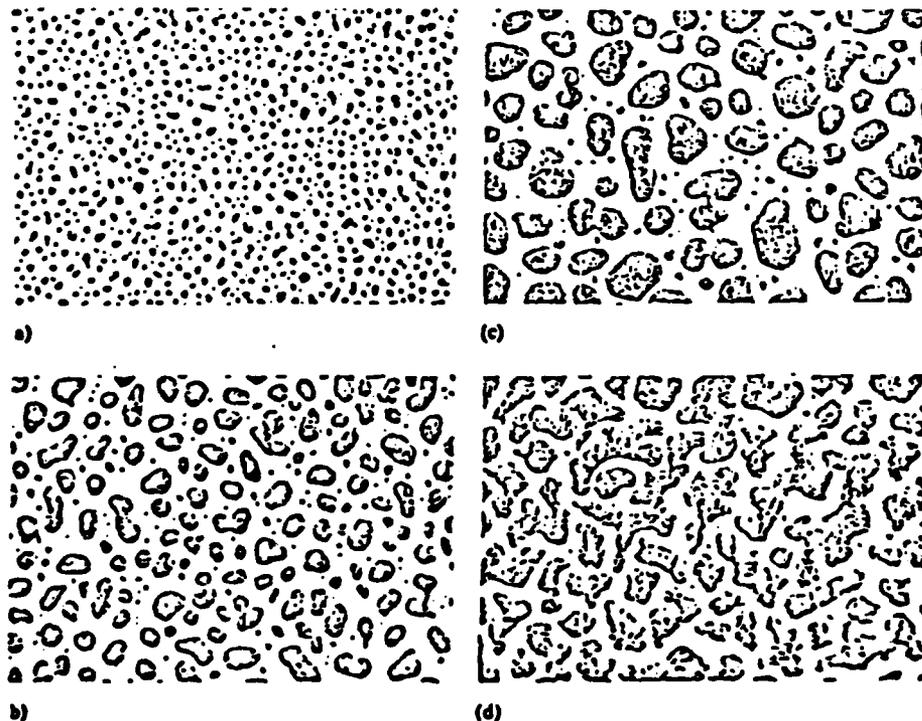
Figure 1. Electronmicrographs of ultrathin gold films: a) 1 nm, b) 4 nm,
c) 6 nm, d) 15 nm thick.

Typical sequence of film structure with increasing thickness or time
is shown in Figure 1. Nonuniform agglomeration is often observed. There
are basically four structural categories of small island-small gaps; small
island-large gaps; large island-small gaps and large island-large gaps.
Various conduction mechanisms have been proposed for these categories
(References 6, 15).
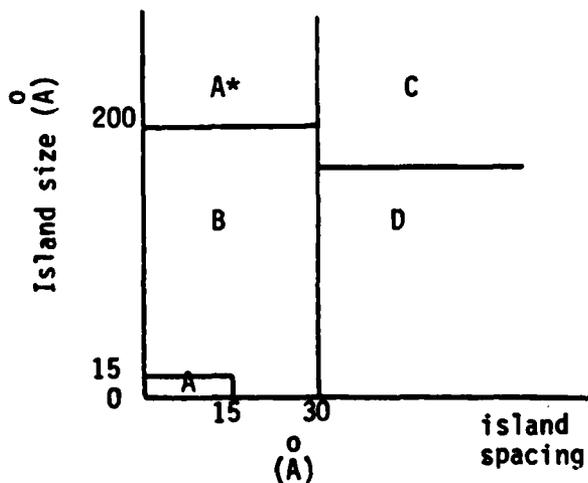
Figure 2.   Proposed conduction
            mechanisms.

A, A* -   direct tunneling

B   -   thermally enhanced tunneling

C   -   substrate assisted tunneling

D   -   thermal electron emission

Region A in Figure 2 corresponds to the small island-small gaps
category, where direct tunneling is the dominant conduction mechanism.
Island as oblate spheroids are well approximated as spheroids for small
islands. When an electric field is applied on the film, field line mapping
is as shown in Figure 3. The large number of MIM junctions are randomly
connected in series and parallel. Thus, the islands connected in series
will sum the detected signals, and these branches are automatically parallel
connected, with the branch of lowest resistance governing the output diode
resistance. The island pattern is thus crucial in determining diode resist-
ance and thus the detected signal that can be tapped.

8
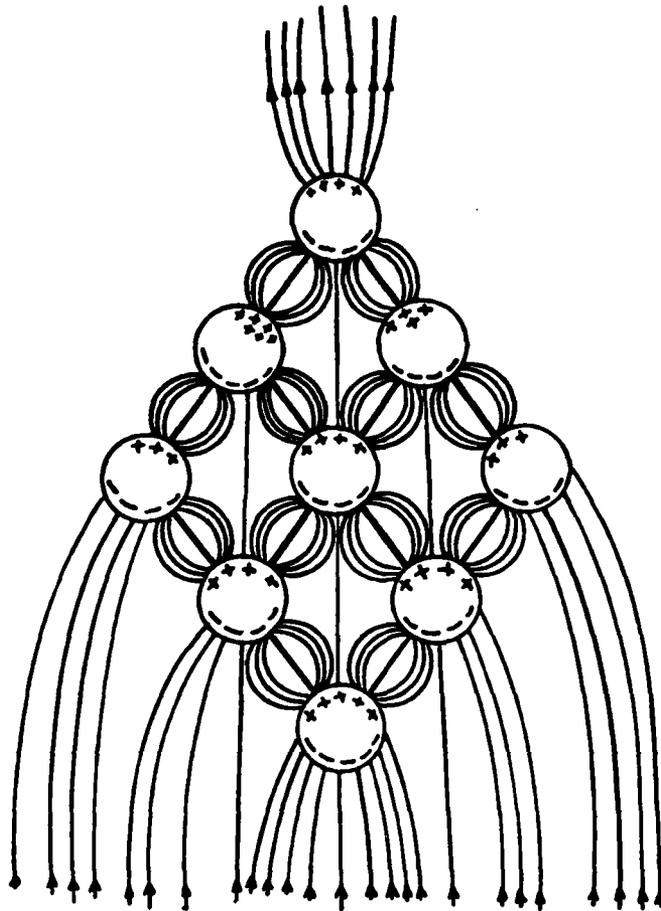
Figure 3. Electric field line mapping in metal island array.

Planar discontinuous MIM film diodes with low noise, wide bandwidth, high sensitivity and stability must therefore be operating in the direct tunneling region. It is known that palladium and palladium-on-platinum films deposited on glass plate provide stable islands of extremely small size. However, such films normally present high sheet resistance and low sensitivity. Multi-layer film structures have thus been suggested that

9

consisted of palladium-on-platinum film deposited on gold discontinuous film.

The relationship between film resistance and detection sensitivity (Reference 6) is shown in Figure 4. The lowering of sensitivity in the low resistance range is obviously due to the formation of a progressively continuous film, and that towards the high resistance range, due to increasing departure from the direct tunneling regime. There is also the circuit condition that it is difficult to tap signal from a diode with low resistance, while signal of a MIM diode of high resistance is very low due to reduced tunneling.
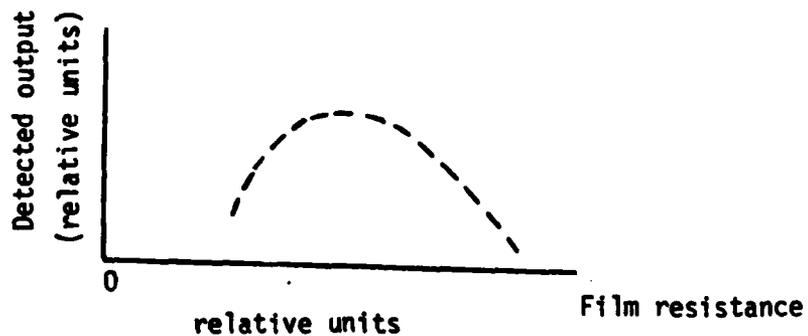
Figure 4. Film responsivity vs film resistance.

Procedure of Film Deposition

Microscope slides cleaned with Fisher biodegradable Sparkleen solution were used as the film substrate. Such slides were boiled in the solution and then both transferred into an ultrasonic cleaner and cleaned for 30 minutes. The slide was then rinsed in deionized water, which was boiled and subjected to another ultrasonic cleaning for 30 minutes. The slide was removed and blown dry with nitrogen gas. The dried slide was then mounted in the Model SEM-8620 sputtering unit manufactured by Material Research Corporation. The sample was placed on the J head; the target was made the cathode. The sputtering unit was then vacuum sealed and pumped down to a vacuum pressure of 10^{-6} Torr. The system was then backfilled with an inert gas (argon) to 5 microns as the sputtering plasma. The nickel target was pre-sputtered or degased to remove impurities. The sputtering power was then set and sputtering was performed over a prescribed period of time. The slide with the deposited film was then removed for film resistance check.
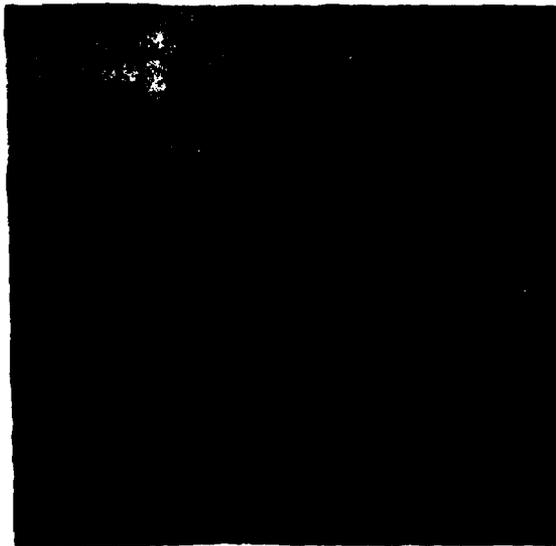
Figure 5. Picture of MRC model SEM-8620 sputtering unit.

2.2.2. Film channeling and chip Fabrication.

Since the films made were found to be highly nonuniform, and film performance was not dependent on the size of the film, "good" channels could be carved out of the film.

To select the best channel, a "chip" could be made , as shown in Figure 6a. The lead wires cemented to the multi-channel chip enabled us to select and tap channel. This process was repeated for every chip. The channel legs were of a width of 1 mm, while the channel backbone was tapered from 3-4 mm to less than 1 mm. Thus, the lead wires 11' tapped a channel that was expected to give the lowest resistance, and the 15' lead wire, the highest. This was found not always to be the case but some combination would give the optimum resistance of a few kiloohms.

2.2.3. Chip interconnections

A number of such chips were fabricated on the same substrate and electrically connected via wires or silver cement strips in series or parallel configurations (Figure 6b). The resulting multi-chip diode enabled us to further control the overall diode resistance in the series case or the multiplied detected output in the parallel case.

Such arrays should also make these diodes capable of withstanding high power incident microwave and mm wave radiation by spreading the incident radiation over a larger area, thus reducing incident power density on a single chip. The availability of multiple leads on each chip should also provide input ports for dc bias to the multi-chip diode.

12
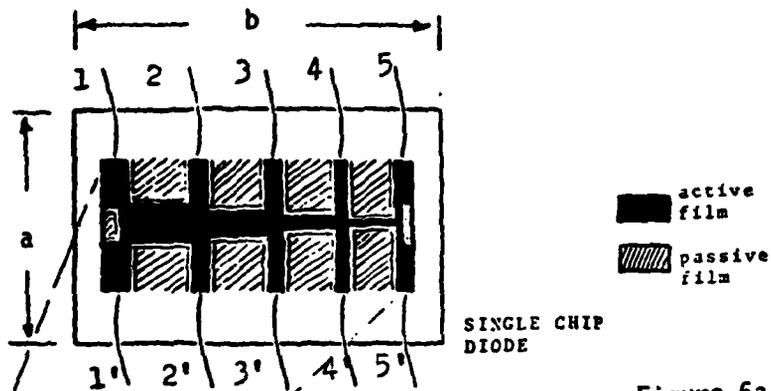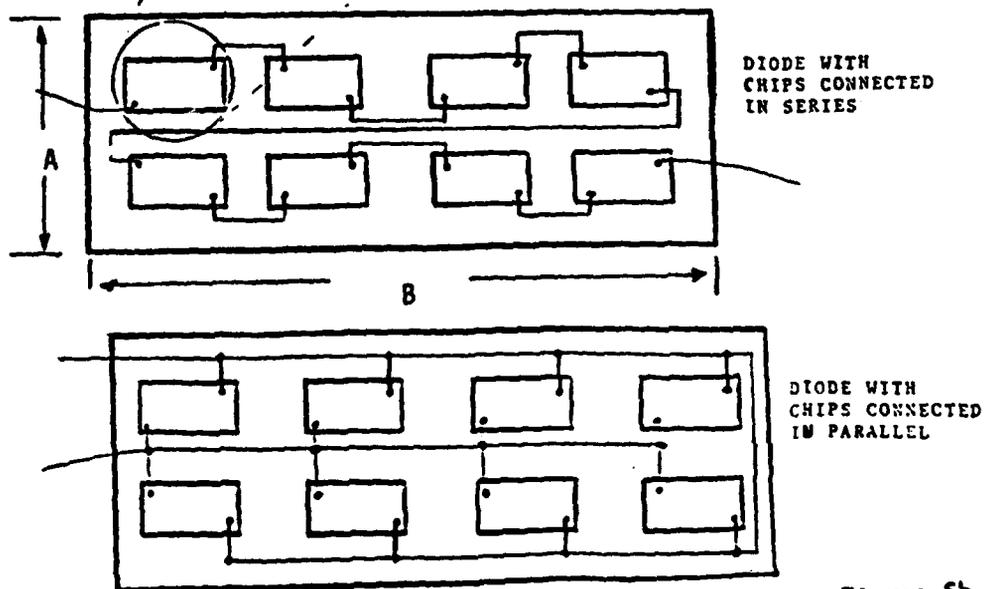
Figure 6a

Figure 6b

Figure 6a. Single chip with leads;

Figure 6b. Chip arrays in series and parallel.

A, B, dimensions conform to waveguide dimensions;

a, b dimensions typically in the range of a few millimeters.

Figure 6. Proposed single chip and chip arrays as MIM diode.

Two types of chip arrays were made, one with wire interconnections and the other with silver cement strips on the back surface of the glass substrate as shown in Figure 7. The wire-connected array was conceived with the sole purpose of incorporating some features of an antenna. These were the 25 μm diameters tungsten wire used as the catswhisker in the MOM point contact diode. These wires demonstrated the capacity of picking up the incident radiation in the X and V bands. However, such interchip wiring proved to be very cumbersome in mounting this diode in a waveguide. This scheme was then abandoned and a more compact scheme involving direct silver cementing the various chips together in series or parallel was adopted. The silver cement strips were located at the back surface of the diode substrate, thus not intercepting the incident radiation. On the other hand, it was discovered later, that this silver backing served as a partial short, and thus exerted a certain amount of stub tuning of the diode in the waveguide.
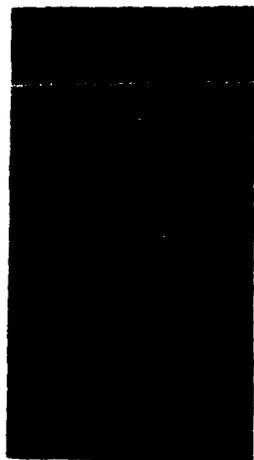
3 chips connected
by silver cement

3 chips connected
by wires

Figure 7. Multi-chip film diodes.

3. TESTING, RESULTS AND ANALYSIS

3.1. THE MOM point contact diode

After the whisker tip etching procedure was standardized, many whiskers were etched with various slender ratios, dependent on the immersion depth. Tips with small slender ratios or stout tips were difficult to hook. If hooks were formed, the tips were often damaged or blunted; the resulting hooks were stiff with little spring action. No stable signal was observed. Tips with large slender ratios were slender and hooked easily, producing hooks with a large radius of curvature. The tips were not damaged, but they were far from the junction area, and the hooks behaved as overly soft springs. Lack of penetration into the oxide layer also meant poor responsivity. Tips with optimum slender ratio penetrated sufficiently into the oxide layer, produced hooks of a curvature that did not divert the tip too far from the junction area and also rendered adequate spring action.

These optimum tips were then exposed to X and V band radiation. Only when a stable signal was achieved with less than 10% signal level variation over two weeks, would the diode be used in the mixing scheme. A schematic of the setup is shown in Figure 8. Direct detection at X or V band employed only a single oscillator, while in the mixing scheme, at least two oscillators were used at X band; for V band mixing, the beat from two V band oscillators was mixed again with the radiation from the tunable X band oscillator.

3.1.1. Bandwidth study

In the mixing scheme, the two V band oscillators were tuned to within approximately 10 GHz, which was within the tuning range of available X band sources. In the X band case, only two X band oscillators were used.

15

Approximately 10 GHz radiation from the two oscillators was fed to the diode. The oscillators were tuned such that a beat of less than 1 GHz was obtained and fed into the spectrum analyzer. The GHz beat was then fine tuned down to KHz or less so that the beat signal could be displayed on the ultrasensitive oscilloscope with the lowest scale of 0.1 mV/div . The beat frequency was further reduced using the scopes as monitors. The X band signal level deliberately set low, and its amplification by the beat of the V band oscillators at 8.25 GHz was clearly demonstrated in Figure 9. X band oscillator output at 10.9 GHz was very low and was undetected by the MOM point contact diode in the direct detection scheme. The signal was enhanced significantly when beat with the two V band oscillators. As is clear, the MOM point contact diode received radiation from both X and V bands and produced a beat tunable to the KHz and lower range; no commercial diode so far had this capability. The 10.9 GHz bandwidth was not the cutoff bandwidth of the point contact diode; it was the highest frequency the X band oscillator could generate. The MOM point contact diode bandwidth is theoretically much broader.

3.1.2. Stability Study

Once detection was achieved at X band, the diode was monitored for stability over a several-week period. During the stability tests, minimum measures were taken against ambient conditions, such as room temperature fluctuations, normal room vibrations and drafts. Hooking required some time to reach equilibrium. Once this was established, the optimum diode could withstand even rather severe impact shocks imparted on the optical table.

16
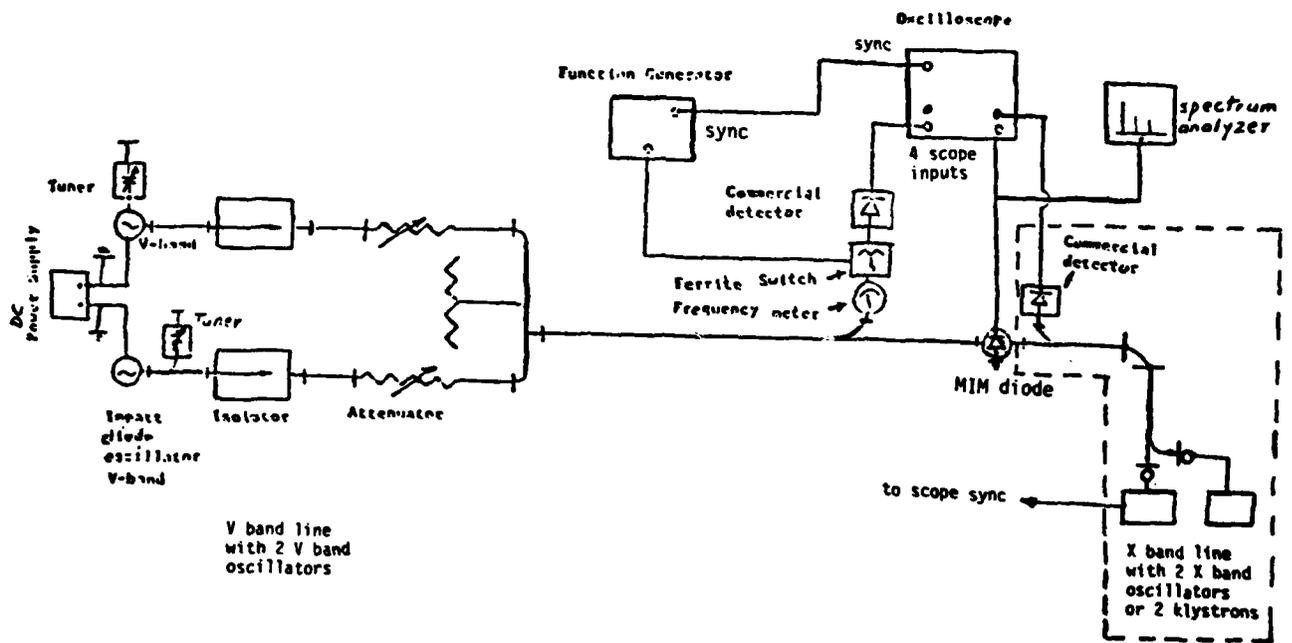
Figure 8. Schematic of setup for X and V band detection and mixing.

X band line

V band line

film diode in screen cage

Actual laboratory setup corresponding to above schematic.

2 mV/div.
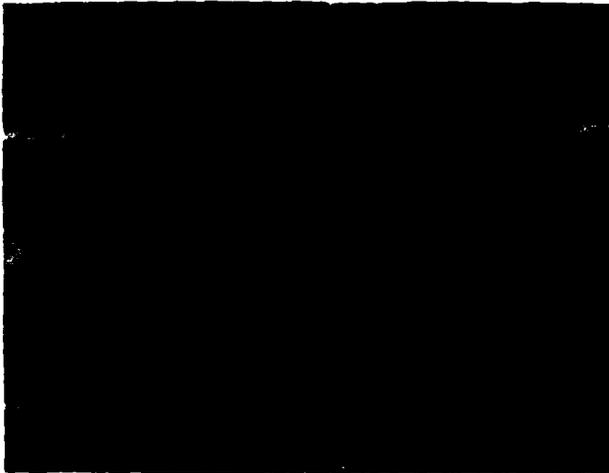
Weak X band signal amplified by the
beat of two V band oscillators.
X band signal is at 8.25 GHz.

directly detected weak X band signal

Time, 1 msec/div.

1 mV/div.

Extremely weak X band signal at 10.9 GHz
amplified by the V band beat,
otherwise undetected directly.

Time, 1 msec/div.

Figure 9. Weak X band signal directly detected and amplified by
V band beat signal on the MOM point contact diode.

The detected signal of a stabilized MOM point contact diode in the X and V bands over approximately three weeks is shown in Figure 10. Signal from the commercial X band detector was significantly higher than the MOM diode output. This was due to the fact that the latter was not packaged in a waveguide and properly tuned. A 3 db coupler was used in this case, so that both diodes were illuminated by the same amount of radiation. In V band detection, a 20 db coupler was used so that the main portion of the radiation was incident on the MOM diode situated at the open end of the waveguide. Signal levels from both diodes were comparable. Furthermore, the X band and V band oscillators were rated with output power in the hundred milliwatt range, so that the commercial detector output in the 10 V scale for the X band and 2 mV scale for the V band were good indication of the limits of the commercial detectors. On the other hand, MOM diode outputs were in the 2 mV range for both X and V bands, indicating consistent performance of the MOM point contact diode up to the V band.
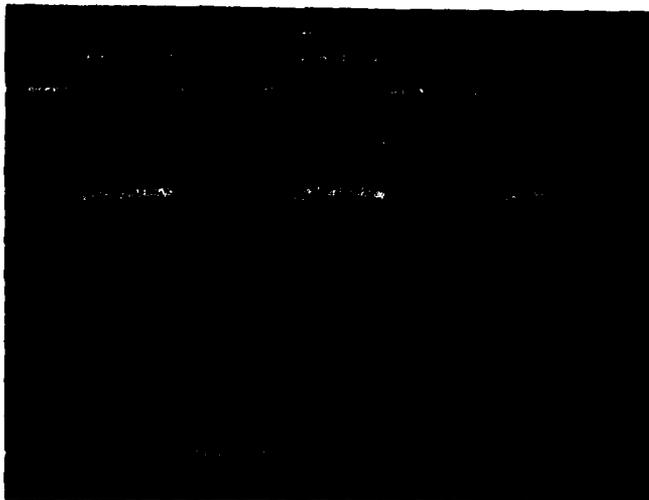
X band commercial diode detector
10 V/div.

MOM point contact diode detector
2 mV/div.
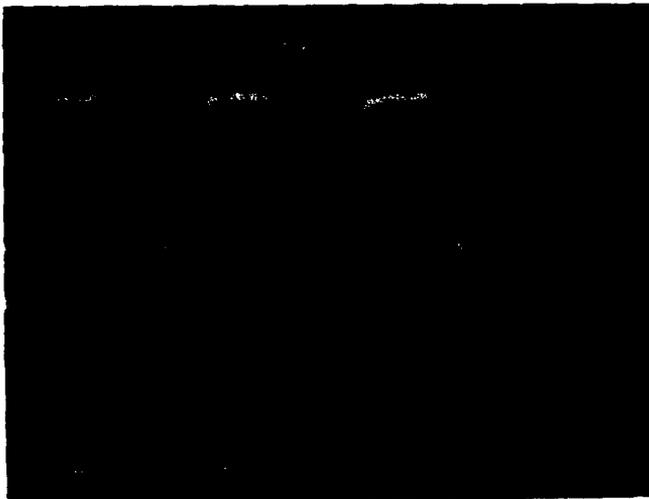
Time, 1 msec/div.

V band commercial diode detector
2 mV/div.

MOM point contact diode detector
2 mV/div.

Time, 1 msec/div.

Figure 10. MOM point contact diode responsivity in X and V bands, stable over three weeks.

3.2. Planar MIM discontinuous film diode

3.2.1 Discontinuous film study

The films tested were palladium, palladium -on- gold, palladium -on- platinum -on gold and nickel. Sheet resistance of these films of varying sizes was obtained by I-V curve characterization. This proved to be an adequate method of gauging the discontinuous nature of the films, and their performance in detection.

The first step in film characterization was film uniformity. These films were found to be highly nonuniform due to the very short sputtering time and low sputtering power (5-20 secs., 50 watt). Film spots of different sizes were probed by commercial sharp tip, blunt tip , gold-ball tips and silver cement contacts with leads.

Strips 1,2, 3 in Figure 11 were measured with sharp commercial tips with the size of strip 3 trimmed down progressively. The sheet resistance was randomly distributed, as evidenced by R_A to R_F in Figure 12. Nonlinearity in the I-V curves was due mainly to the sharp tip effect and proximity of the tips to each other, and was not a property of the films, as shown in strips 4 and 5. The I-V curves of the MOM point contact diode were included for comparison. Variation in the I-V curves of the latter demonstrated the stability of the diode.
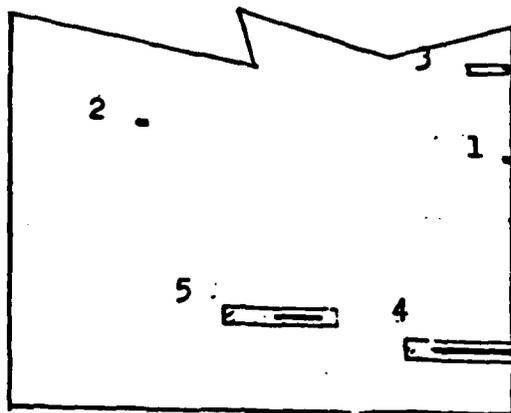
Randomly selected and isolated thin film strips
on glass substrate

STRIPS #	LENGTH L, mm	WIDTH W, mm
1	1.2	1.1
2	1.0	1.0
3 A	7.0	3.2
B	6.0	3.2
C	3.0	3.2
D	3.0	2.0
E	3.0	1.1
F	1.1	1.1

STRIPS #	LENGTH L, mm	WIDTH W, mm	COMMENTS
4 A	2.1	1.8	cement contacts
B	SAME		probes touching contacts
C	SAME		probes contacting thin film directly
5 A	2.2	2.8	cement contacts
B	SAME		probes touching thin film directly

Figure 11. Randomly selected film strips and specifications.
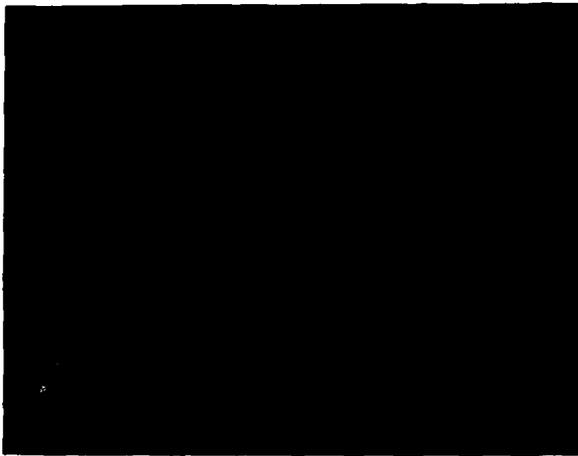
STRIP # 1

I : 0.2 mA/div; V: 0.5 V/div.

linearized resistance R = 1.6K Ω

Strip that gives the most
nonlinear result in the first try

STRIP #2

I : 0.2 mA/div; V: 1 V/div

R = 8.3K Ω

Slightly smaller than strip # 1
and at different location;
is significantly less nonlinear

Figure 12. I-V curves of film strips of varying sizes.

STRIP # 3

| A | B | C | | D | E | F |

A : I: 0.02 mA/div; V: 0.2 V/div R_A = 15 K Ω
B

C : I: 0.01 mA/div; V: 0.5 V/div R_B = 10 K Ω

D : I: 0.2 mA/div; V: 0.5 V/div R_C = 63 K Ω
E
                                           R_D = 2.9 K Ω

F : I: 0.2 mA/div; V; 0.5 V/div R_E = 2 K Ω
                                           R_F = 14 K Ω
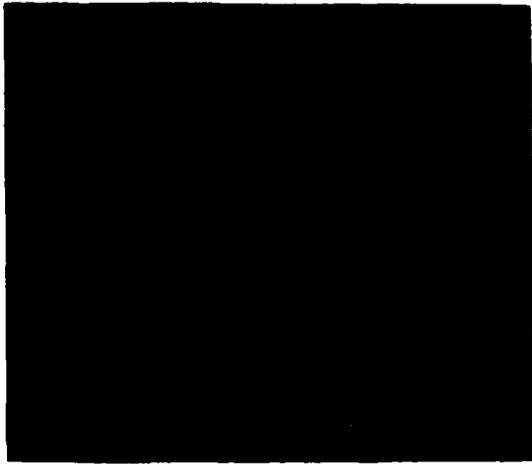
A   B   C

STRIP # 4

I: 0.1 mA/div; V: 1 V/div

R_A = 3.5KΩ; R_B = 4KΩ; R_C = 4.7KΩ
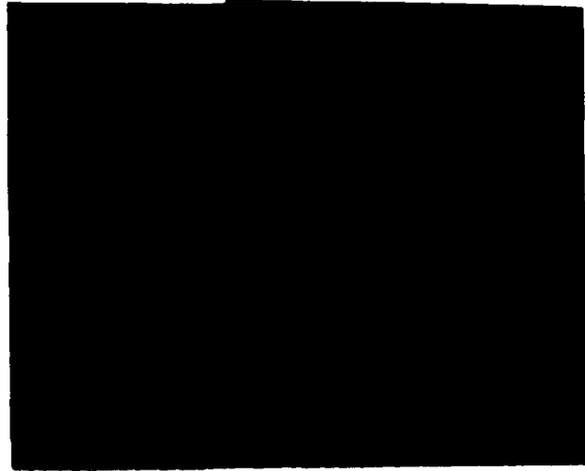
A   B

STRIP # 5

I: 0.1 mA/div;   V: 0.5 V/div

R_A = 2KΩ; R_B = 3.3KΩ
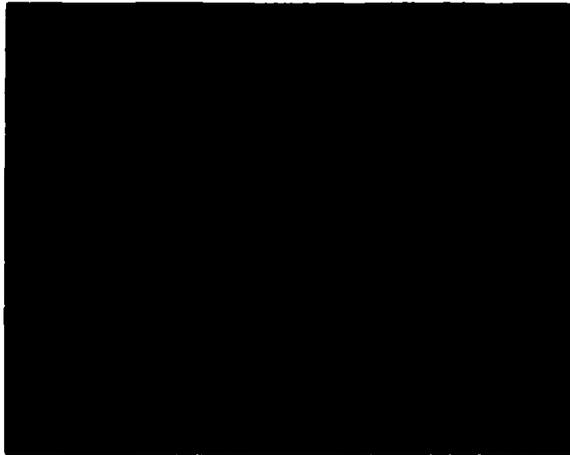
A   B   C

POINT CONTACT DIODE

I: 2 mA/div;   V = 0.5 V/div

R_A = 1.3KΩ; R_B = 3.6KΩ;

R_C = 1.8KΩ

Figure 12 continued

X and V band detection of MIM films

The same microwave setup was used to test the films in X and V band detection and mixing. In the first attempt, the films on glass plates were mounted on an open jig. This necessitated the use of a screen cage for shielding, as the detected signal was expected to be very low. The results are given in Table 1 and detected signals and I-V curves are shown in Figure 13.

Figure 13.1 was obtained with freshly deposited Pd-Au combination film. Only blunt tips and gold-ball commercial probes were used. The detected X band signal was stable over a short period, but was dependent on the contact pressure between the probe tips and the film. The signal was enhanced substantially by simply raising the contact resistance from 170 ohm to 1 K ohm (see Figure 13.2). Figure 13.3 gives results pertaining to Pd-only film. Although film resistance was higher, the detected output was lower as expected.

Detection stability was improved by substituting one blunt tip with a gold-ball tip. There was considerable reduction in the sensitivity of diode resistance to contact pressure between probe and film. X band mixing was achieved, as shown in Figure 13.4, but V band detection was not successful. V band detection was attempted with Pd-Au film and successfully demonstrated in Figure 13.5. The film resistance was extraordinarily high (100 K Ohm). There was still a significant amount of instability probably due to the extremely high sheet resistance. Part of this was due to the

25

probes, as is seen in Figure 13.6, where two gold-ball tips
were used. The detected signal was much lower, but stable.
These data seem to indicate that high density films with high
sheet resistance such as nickel would be ideal.

Figure #	Curve #	Diode type	Film type	Operation	Probes used	Voltage scale	Current scale	Film resistance
13.1	a'	commercial		x band detection		0.1v/div		
	a	MOM film 1	3:1 Pd:Au	"	2 blunt-tip probes	0.5mV		
13.1'		MOM film 1	"	I-V curve	"	0.05V	0.2 mA	170 Ω
13.2	a	"	"	x band detection	"	1 mV		
13.2'		"	"	I-V curve	"	0.05V	0.2 mA	1 KΩ
13.3	a	MOM film 2	Pd only	x band detection	"	0.1 mV		
	b	"	"	"	"	"		
13.3'	a	"	"	I-V curve	"	0.2 V	0.1 mA	2K Ω
	b	"	"	"	"	"	"	6K Ω
13.4	a	"	"	x band mixing	1 blunt tip & 1 gold ball tip	0.2 mV		
	b	"	"	x band detection	"	"		
13.5	a'	commercial		V band detection	2 blunt tip probes	1 mV		
	a	MOM film 1	Pd:Au 3:1	"	"	0.5 mV		
13.5'		"	"	I-V curve	"	0.05V	5 μA	100KΩ
13.6	a	MOM film 3	Pd strip (old film) 3mm x 2mm	x band detection	2 gold ball tips	0.1 mV		
	a'	commercial		x band detection		0.1 mV		
13.6'		MOM film 3	Pd strip	I-V curve	2 gold ball tips	0.1 V	5 μA	150KΩ

Table 1. Table of specifications for Figure 13.

Figure 13.1
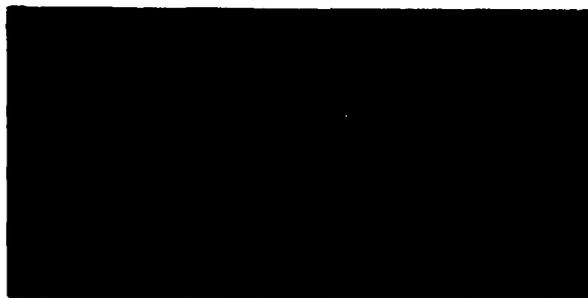
Figure 13.1′
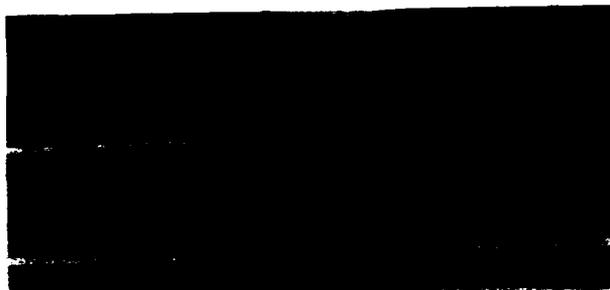
Figure 13.2

Figure 13.2′

Figure 13.3
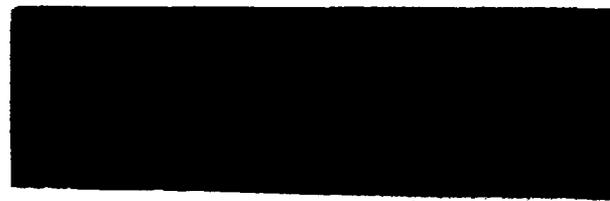
Figure 13.3′

Figure 13.4

27
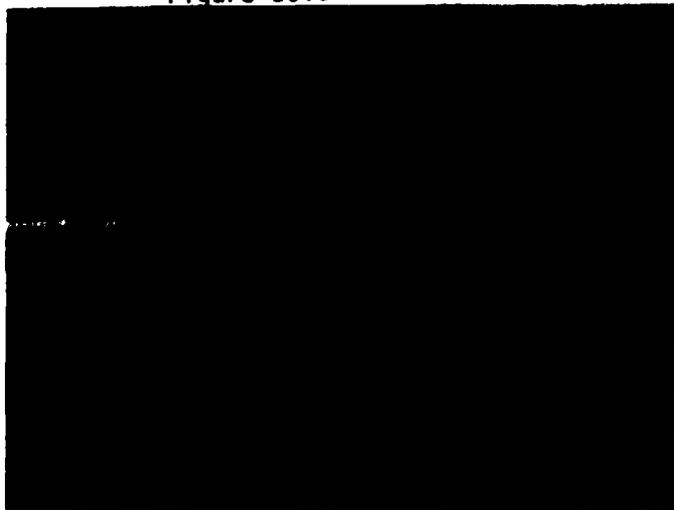
Figure 13.5

Figure 13.6

Figure 13.6'

Figure 13. Detected signal from different films using various types of commercial probes.

So far the results have indicated that the film to be adopted should be nickel and commercial probe tips cannot be used if stable MIM film diodes are desired. Silver cement was used as contacts, to which were attached wire leads. With this type of contacts, only nickel films produced a detected signal in the X band, and the signal was stable, as seen in Figure 14.

commercial detector
1 mV/div

nickel film diode
0.1 mV/div

Time   1 msec/div

20 μA/div

0.05V/div   film diode resistance
                   2.5 K ohm
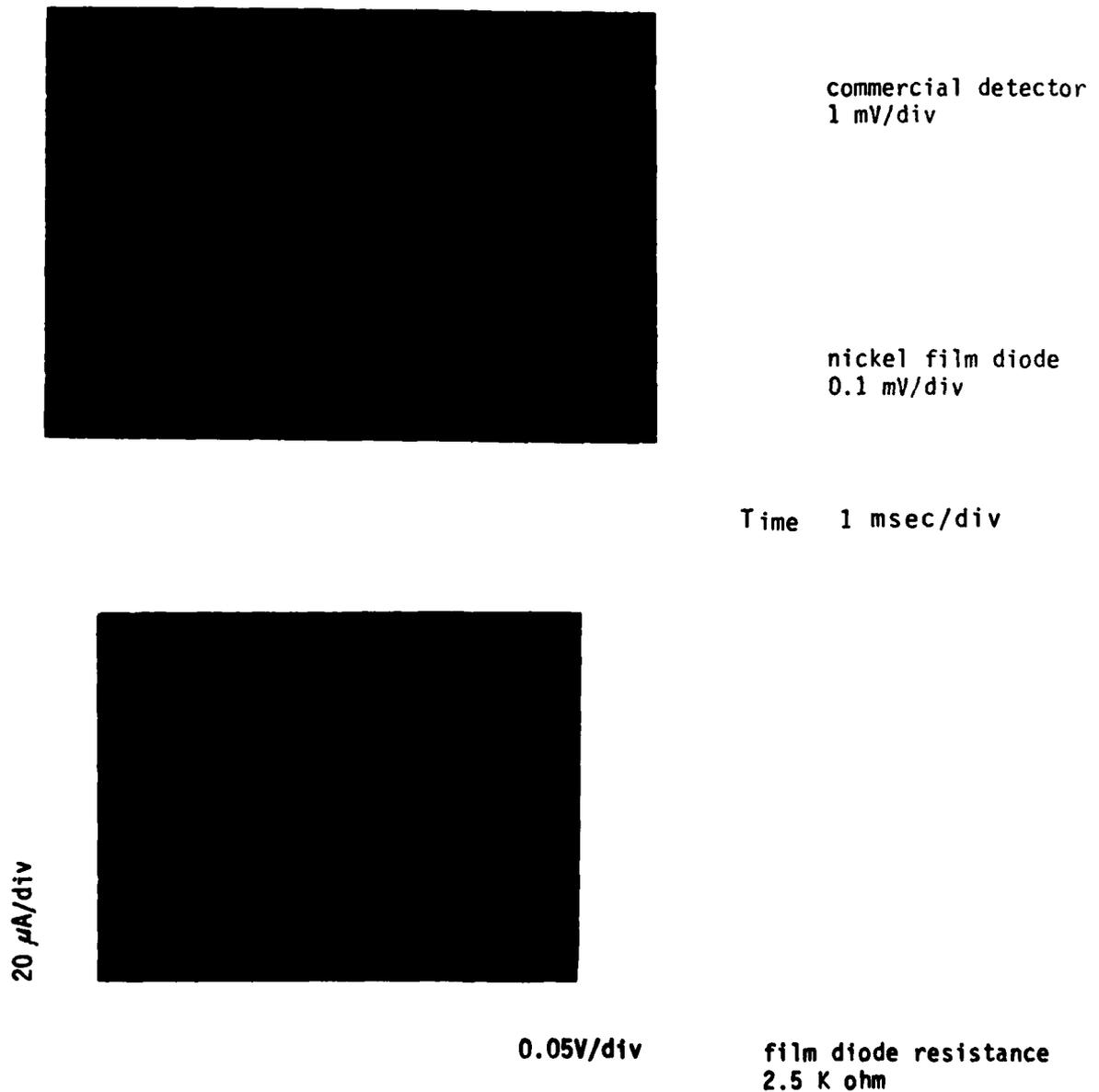
Figure 14. X band responsivity and I-V curve of nickel film using silver cement as contacts

29

3.2.2 Single chip and multi-chip diodes

Experimental data have so far confirmed that discontinuous MIM film diodes must be fashioned from chips and chip arrays due to the highly nonunifrom nature of the films. In view of the final packaging of the diode, a waveguide jig was made to replace the open jig used so far.

To verify the multi-chip concept, a single chip was prepared and tested at X band. An adjacent chip was added and the two connected in series. This two-chip diode was again tested at X band. This was the last diode tested on the open jig, and the results are shown in Figure 15. It is evident that the two-chip signal output is approximately twice that of the single chip, confirming the prediction that multi-chip series connection can raise overall diode resistance and signal output.
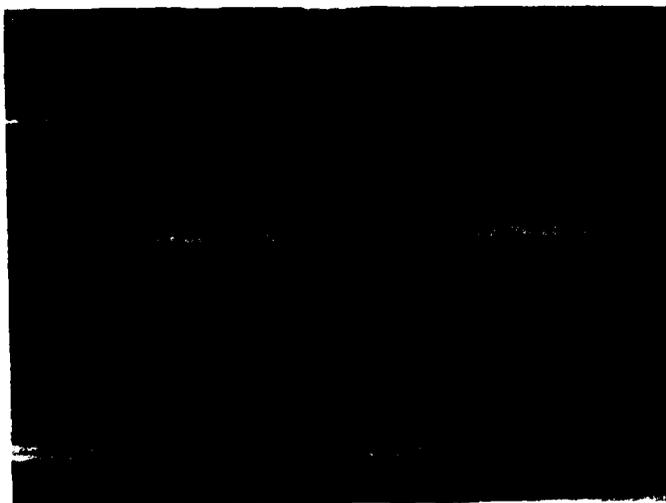
commercial detector

single strip Ni film
0.2 mV/div.

Time, 1 msec/div

commercial detector

two strips of Ni film in
series
0.5 mV/div.

Time, 1 msec/div

50 μA/div

R_1 = 1 K ohm

R_2 = 1.1 K ohm

$R_1 + R_2$ = 2.6 K ohm measured

0.05 V/div.

Figure 15. Comparison of detected X band signal of a single Ni film chip and two-chip diodes

31

3.2.3. Waveguide packaged MIM film diode

MIM discontinuous film diodes were tested only at X band due to the availability of tunable sources with adequate power. X band waveguide was used for the diode mount.

Two short section of waveguides were cut from X band waveguides. Section A was to serve as the BNC connector mount, while section B was to serve as the diode housing (see Figure 16). Section A was to be a lid sitting on top of section B. Thus, one face of the waveguide section was removed to create an open structure for the installation of the BNC panel receptacle on the remaining face. This served as the signal output port of the diode. The inner conductor inside this waveguide housing was used as the post to which the tungsten wire lead from one terminal of the chip array was attached using silver cement. This housing would remain open on three sides until all connections were made. The remaining side was then   sealed off and the entire structure soldered onto the top face of section B.

The waveguide section B was sliced into two halves as shown. This exposed the inside of the waveguide for ease of diode mounting. A plain glass plate of the inside dimensions of the waveguide was glued to the base of the lower half of section B. This would serve as the securing wall for the glass substrate with the chips and wire leads. The latter was glued to this wall and positioned for maximum interception of the radiation in the waveguide. During this test, the upper half of section B and the lower half were rejoined and temporarily clamped together to form a normal waveguide. A lead wire cemented to the other terminal of the chip array was shaped into a coil spring with the other end cemented to the base of the waveguide, which was the ground. The coiled long wire

connecting the chip diode and the inner conductor of the BNC panel receptacle provided freedom of opening up section B, and thus facilitated mounting and positioning of the chip substrate during packaging.

Once the optium position was established for the chip substrate in the waveguide, it was glued to the securing glass wall. The two halves of section B were soldered together with section A that was already soldered to the upper half of section B. The lateral side of section A was then put in place and soldered, thus forming a shield for the lead wire cemented to the inner conductor of the receptacle.


Section B

Section A
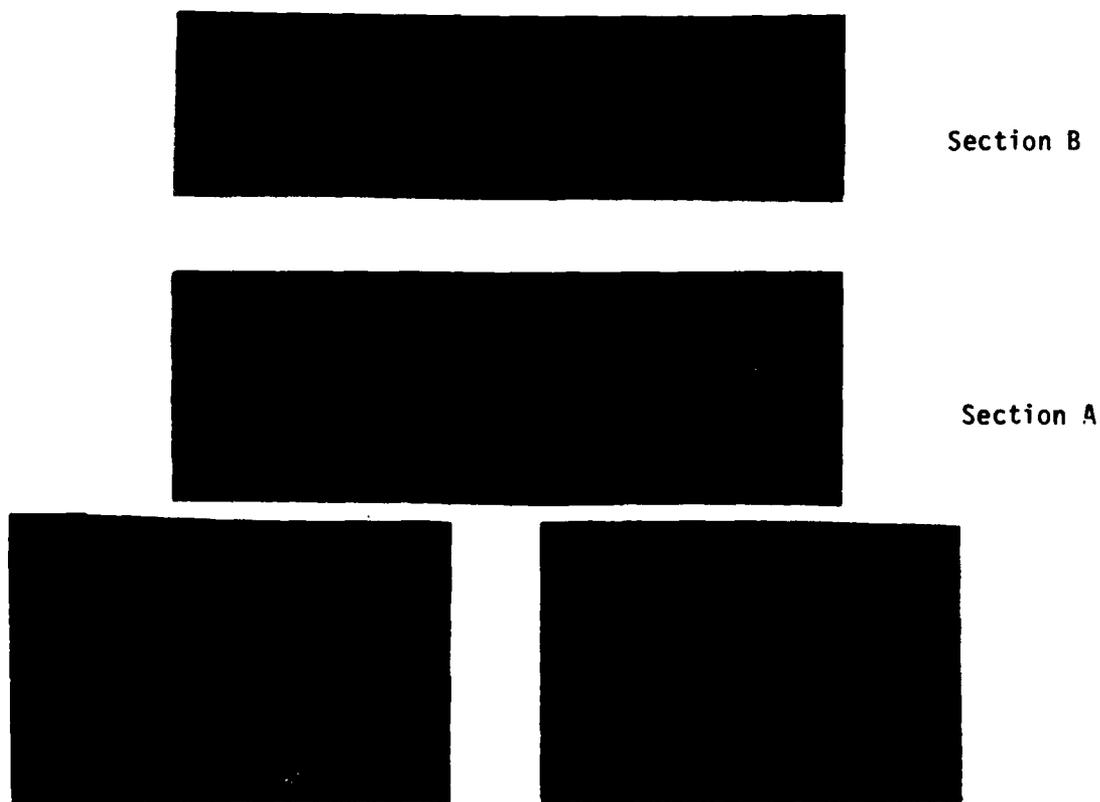
Figure 16. Waveguide mounting of multi-chip film diode in the X band.

Test results of the three diodes delivered

Three waveguide-packaged diodes were fabricated for delivery to the Air Force. They were all packaged in X band waveguide. Due to the nonuniformity of the films and their random nature, the three diodes were expected to perform differently. However, as proposed, these diodes should perform at a level comparable to the stabilized MOM point contact diode.

Hence, test conditions were set up such that both types of diodes would be exposed to similar level of radiation so as to duplicate their actual modes of operation. Thus, for the same klystron power level, the point contact structure intercepted significantly less radiation due to the slenderness of its whisker antenna and its position outside the open end of the waveguide.

It was found that under these radiation conditions, the waveguide packaged MIM discontinuous film diode demonstrated comparable performance to that of the MOM point contact diode in the X band with the aid of stub tuning using a well positioned shorting plate behind the chip substrate. The results are shown in Figure 17. Diode No. 3 had a significantly higher X band detected output as compared to the other two. This best diode had an output five times less than that from the MOM point contact diode, as seen in Figure 10. This is even more evident in the case of V band detection. The responsivity of the MOM point contact diode remained the same as that for X band, while the MIM film diode failed to pick up any signal in the V band. This could be due to the fact that X band power was three times V band power and the film diode was not mounted in V band waveguide.
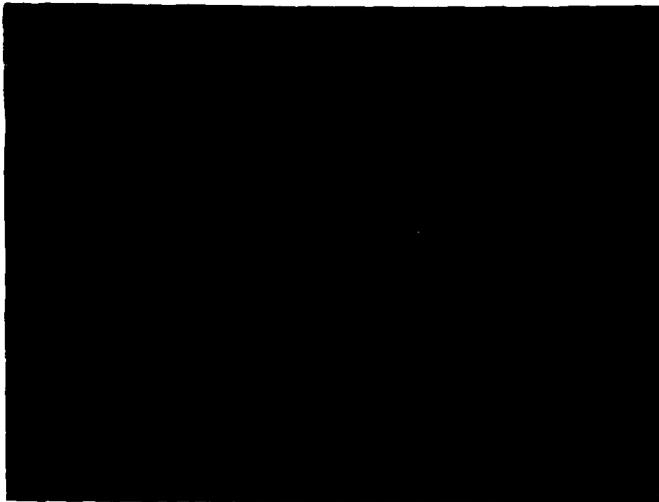
commercial detector
10 V/div

MIM film diode #1
0.1 mV/div

Time, 1 msec/div

commercial detector
10 V/div

MIM film diode # 2
0.1 mV/div

Time, 1 msec/div

commercial detector
10 V/div

MIM film diode # 3
0.5 mV/div

Time, 1 msec/div

Figure 17. X band detection of the three waveguide-packaged MIM film diodes delivered to the agency.

35

4. CONCLUSIONS

Our investigations on the stability of the MOM point contact and MIM discontinuous film diodes have demonstrated clearly the feasibility of long term stability without severe degradation in device performance. Such stabilized units will provide the opportunity of examining the basic conduction mechanisms in such devices and their optimization based on improved theoretical models and the incorporation of circuit considerations.

The hooked tip point contact diode with a nickel coated quartz post has demonstrated the capability of long term stability. The long wire with a hooked tip must then be analyzed theoretically using models distinct from the model adopted so far of a biconical antenna penetrating the oxide layer (Reference 14).

The discontinuous MIM film diode has been demonstrated under this program. Only one type of metal film, nickel, has been shown to be active in X band. Its performance was brought to within reach of the point contact version using chips and circuit interconnection schemes.

The MOM point contact diode is highly usable as a laboratory bench unit. Its field application still awaits further technological innovations such as encapsulation of the diode assembly, special vibration proof mounting in waveguides with multiple access ports and waveguide tuning.

The single chip of the MIM film diode must be further improved by selection of other metal films. Chip arrays

must be utilized to overcome single chip limitations. Chip fabrication must be improved for V band operation as the chips must be scaled down from the X band to match V band dimensions. This may necessitate the use of laser trimming techniques for finer chip size definition. This will lead to higher chip density.

Improvement of waveguide mounting of the MIM film diode is also being explored. Gluing the securing glass wall, and consequently, the glass substrate of the diode to the base of the X band waveguide section B does not render the diode mount immune to waveguide line vibrations. A scheme is under consideration, in which the entire glass securing wall and film substrate is to be suspended form the top face of section B, and isolated from the waveguide via springs.

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APPENDICES

2. Two conference digest papers attached, accepted for presentation at
   the 8th International Conference on Infrared and MM Waves, December,
   1983, Miami.

STABILITY PARAMETERS OF STABLE HOOKED-TIP
MOM POINT CONTACT DIODE AS MM WAVE AND INFRARED DETECTOR-MIXER

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ABSTRACT

A progress report is given on the hooked-tip MOM point contact diode with further stabilization based on control of oxide layer thickness, selection of the metal post material and waveguide packaging.

Introduction

The well known ultrafast [1] long whisker metal oxide-metal (MOM) point contact diode with majority carrier conduction and excellent antenna receiver properties has often been faulted for its inherent mechanical, thermal and electrical instabilities. These shortcomings have hampered its practical system application, and prevented reliable analysis of its basic conduction mechanisms and their regimes of operation.

Attempts were made in this work to establish stability parameters essential to deciding methods of stabilization. Each parameter was defined and optimized. This led to the mechanical modification of the whisker tip in terms of the slender ratio and deliberate hooking of the whisker tip, and the selection of other post material. Such a diode has been fabricated with long term stability and reasonable ruggedness. A systematic study of the various conduction mechanisms such as tunneling and thermally enhanced tunneling could then be performed.

This knowledge of a single junction has led to a better understanding of the performance parameters of more complex metal-insulator-metal (MIM) structures as candidates for possible replacements and improvements of the point contact version [2].

In the point contact version using sharp tungsten whisker tip in contact with the naturally grown oxide on a nickel post, both the geometric shape of the tip and nature and thickness of the oxide layer must be scrutinized. Studies have led to the establishment of an undamaged hooked tip with an optimum slender ratio between shaft length and tip diameter and optimum oxide thickness. Excessive thermal expansion and contraction of the nickel post have also led to the proposition of nickel coated quartz posts.

Thus, the performance and stability of the MOM point contact diode are extremely dependent on the chemical, mechanical, electrical and thermal properties of the materials that compose the diode: the metals and their oxides determine the chemical stability of the oxide layer, and the optimum thickness; the geometric shape of the whisker tip determines the amount of penetration of the tip into the oxide layer, and thus the ultimate oxide thickness between the metals, and the amount of hooking of the tip. These determine diode resistance and the amount of spring action of the hook, and also the responsivity of the diode.

Chemical stability parameter

Tungsten was adopted for the whisker tip due to its high melting point and strong atomic cohesion, and hence mechanical and thermal stability. Its resistance to oxidation even at elevated temperatures and the metallic property of W_4O_{11} also contribute to chemical stability. The tungsten whisker is generally etched from polycrystalline wire, which is usually drawn with preferred grain orientations along the wire axis. Electrolytic etching produces tips much smaller than the grains so that the tip forms a single crystal.

In the tungsten-on-nickel MOM diode, the insulating layer that forms the tunneling barrier is thus mainly the nickel oxide, which is one of the best insulator in nature. The oxide layer thickness is approximately 6-8Å by electropolishing [3], and 9-12Å by anodic oxidation [4], and much thicker at elevated temperatures. Dry air oxidation is also possible with thickness varying from 5 - 1500Å under baking [5].

It has been shown [6], that diode responsivity increases several order with increasing insulator thickness, reaching a peak at 12Å. Rectification efficiency has also been shown [7] to be extremely sensitive to work function differences between the two metals with superior performance achieved in dissimilar metal diodes.

Oxide film thickness thus has two main effects on diode performance: a thin oxide layer of less than 100Å allows only direct tunneling, while the highly temperature dependent Schottky emission dominates in thicker films. Hence, the tunneling MOM diode is temperature insensitive. On the other hand, a thinner oxide film means lower diode resistance, which prevents efficient tapping of the detected signal from the diode.

Mechanical stability parameter

It is thus clear that control of oxide film thickness and contact pressure of the whisker tip in the oxide layer is the key to diode stability and response. This was achieved by the growth of a thicker than optimum oxide layer. The whisker tip was then allowed to penetrate the layer, in the process of which the tip was the proper slender ratio hooked, creating a reasonably large contact area inside the oxide film. The key of the success of this scheme lied in the fabrication of a tip that would hook without significant tip damage. This was possible by careful control of the tip etching process to arive at an optimum slender ratio, defined as the shape parameter that would ensure hooking of the tip with minimum damage and tip diversion from the contact area. This called for careful definition of the physical state of the tip

3

damaged, blunted, hooked and undamaged. The slender ratio was established by systematic reexamination of the fabrication process of tip etching and contact pressure. An appropriate amount of pressure was defined as that which achieved diode stability and reasonable sensitivity.

Thermal stability parameters

Diversion of the sharp whisker tip away from the junction area is the single most important feature of this improved diode, enabling it to avert the major heating effect resulting from thermal expansion of the whisker tip under irradiation. Heating effect is definitely severe under laser irradiation.

Nickel post modifications

All the above improvements in the stability parameters were concerned with the establishment of an optimum spacing between the whisker tip and the nickel metal surface and the maintenance of that spacing under operating conditions to within dimensions of angstroms. Assuming thermal expansion of the tungsten whisker to be negligible, attention was directed at the thermal expansion of the nickel post in an ambient temperature range from 0-100°C. Such variation led to a long term instability of the diode as often encountered by us in the laboratory even with smaller ambient temperature fluctuations.

A rather simple and apparently successful solution involved replacing the nickel post by a quartz rod of similar dimensions polished at the ends. Kovar and other material can be used as long as they possess a very small thermal expansion coefficient. The quartz post was then coated with nickel by sputtering in a vacuum chamber or with inert gas fill. Nickel coating was to be sufficiently thicker than the optimum thickness.

A diode made of a nickel coated quartz post and a hooked tip with an optimum slender ratio was fabricated and tested at X and V bands. Diode response remained constant over weeks with no special precautions taken against normal ambient vibrations and temperature fluctuations.

Conclusions

The hooked-tip point contact diode with quartz post was demonstrated to possess long term stability with little loss of responsivity at X, V bands and in the mid-infrared. Wave guide packaging under study would render this device suitable for system application.

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X Band

10V/div commercial detector

2mV/div MOM detector

Time

V Band

2mV/div commercial detector

2mV/div MOM detector

Time
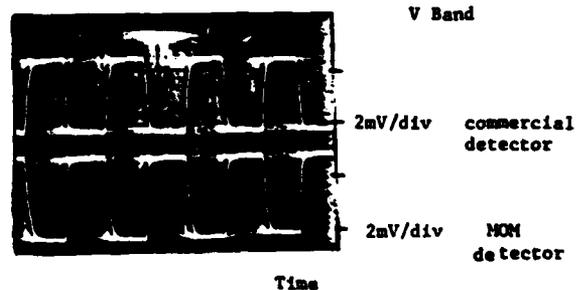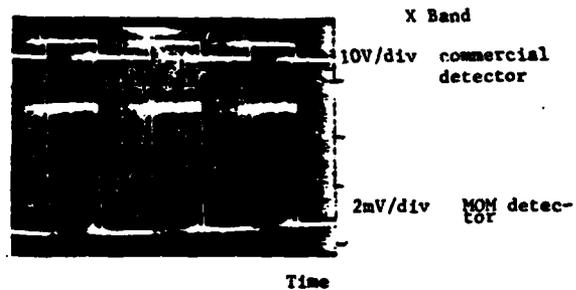
Detection stability over weeks

DISCONTINUOUS MIM FILM CHIP ARRAYS AS MM WAVE AND INFRARED DETECTOR-MIXER DIODES

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Abstract

Marked improvement is reported on the responsitivity and power handling capability of discontinuous MIM film diodes when deposited as IC chip arrays with microwave and infrared waveguide packaging and tuning.

Introduction

Planar metal-insulator-metal (MIM) structures [1] have been proposed as alternate structures to the metal-oxide-metal (MOM) point contact diode. The printed circuit version still retains the sharp tip structure and is thus inherently sensitive to thermal and electrical instabilities. These instabilities are absent in the discontinuous MIM film diode fabricated by vacuum sputtering of various types of metals onto a glass plate.

In the initial stage of continuous metal film deposition, the film structure is discontinuous, consisting of a large number of islands on the substrate and growing in size as metal atoms accumulate with time. In such high density films, electron transport between islands is via direct tunneling. However, as inter-island spacing and island size increase, the conduction process becomes complicated. Other conduction models proposed include conduction via impurity levels in the substrate material, thermal excitation of electrons in the islands and emission of electrons. Four regions of conduction have been proposed [2]. These are basically structural categories of a) small island, small gap, b) small island, large gap, c) large island, small gap, and d) large island, large gap. A discontinuous metal film corresponding to (region A), where direct tunneling is the dominant conduction mechanism, consists of a large number of MIM junctions connected in series and parallel totally randomly. The lowest resistance path determines the overall resistance of the film of any size. Since deposition conditions are initially highly irregular, the resulting film is also highly nonuniform. It was often found in our work that very small patches of film, say 1 mm x 1 mm, perform better as a diode as compared to much larger patches. Thus, selection of a group of islands with the proper resistance is the key in realizing practical thin film diodes. In theory, such an MIM structure is mechanically stable, and with further electrical improvements can be thermally and electrically stable even under high power irradiation.

In an attempt to construct MIM film diodes as high frequency detectors and mixers with low noise, high sensitivity and stability, it stands to reason to fabricate films in which direct tunneling is the dominant conduction mechanism (region A). Other regions involve conduction by thermally enhanced tunneling, substrate assisted tunneling and thermal electron emission.

Film selection and deposition

According to known results [3], palladium or platinum-palladium films form stable islands of extremely small size. However, such films normally present high sheet resistance in the meg-ohm-range and low sensitivity. Multi-layer films have thus been suggested with gold on Pt-Pd films. Test results indicated Pd-Au films were superior in performance in V band detection to Pd only film due possibly to the difference in the work functions of the dissimilar metals. However, film resistance was too low for extracting detectable signal from the film. This was the delimma facing such films, where an increase in island density for capturing increased incident radiation and thus larger rectified signal output was countered by the lowering of film resistance and thus increased difficulty in tapping such a signal.

The optimum condition of small islands at close separation with large work function between metals well satisfied by nickel film, whose natural oxide layer was very thin and of extremely high sheet resistance and durability, as learned from the MOM point contact diode [4]. Taking advantage of the nonuniformity of the discontinuous metal film, strips could be located with the desired combination of reasonably high sheet resistance and a sufficiently large number of islands.

Film channeling or chip making and interconnections

Channels of varying lengths and widths were carved out of the film as shown in Fig. 1. Multiple leads were cemented to the various fingers, tests were performed and the best pair of fingers chosen. A number of such "chips" were fabricated on the same substrate and electrically connected in series or parallel as shown. Such a multi-chip diode enabled us to further control the overall diode resistance in the series case or the multiplied detected output in the parallel case. Series interconnection was of greater interest. Thus, by selecting low resistance single chips, meaning the presence of high density of islands that ensured direct tunneling conduction and potential of higher signal output and stability, an optimum multi-chip diode could result by chip series connections that raised overall diode resistance. Thin wire chip interconnections could also serve as antennas as

3

that in the cat whisker MOM point contact diode.
Such arrays could also increase the power handling
capability of the diode by providing a larger cross
section to capture expanded incident radiation.
The availability of multiple leads on each chip in
the array also provided convenient input leads for
dc bias of the diode.

Diode packaging and testing

Three-chip, series connected diodes were
fabricated as shown in Fig. 2.   They were mounted
in a waveguide, stub tuned and tested at X band.
The aim of the test was to compare the MIM film
diode performance with that of the MOM point contact
diode. In line commercial detector output was used
as reference.   Results are presented in Fig. 3.

Conclusions

Comparable performance of the MIM film diode
to the MOM point contact version is convincing
evidence of its performance at V band and into the
mid infrared by proper scaling of the array dimen-
sions.   Single chip size was found to have no
effect on its performance.

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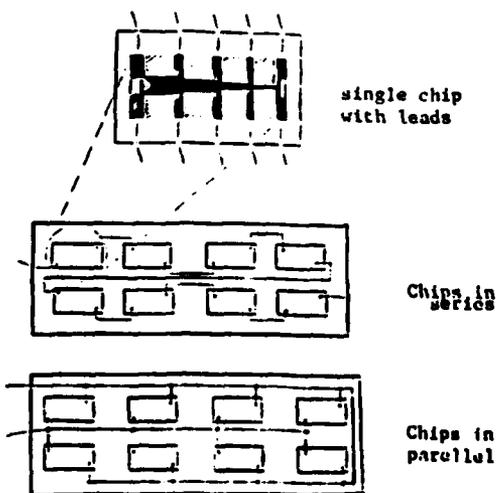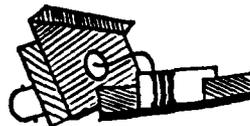
3-chip diode
mounted in X band
waveguide

Fig. 2.


10V/div   commercial
           detector

0.5 mV/div
           MIM film
           diode

Time

10V/div   commerc-
           ial
           detector

2mV/div   MOM point
           contact
           diode

Time

Fig. 3. V band detection

single chip
with leads

Chips in
series

Chips in
parallel

Fig. 1.

DAT
ILM