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A CLASS OF OPTICALLY CONTROLLED MILLIMETER WAVE DEVICES

PREPARED AND SUBMITTED
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ABSTRACT

This is the final report for the year starting February 1, 1985 and ending June 30, 1986. This is the second phase of research at Howard University entitled "A Class of Optically Controlled Millimeter Wave Devices". These devices are useful at millimeter wave frequencies as switches, mixers, phase shifters, etc.

Investigation during this period is mainly concentrated on three specific devices: the sheet resistance device, the Schottky-barrier diode and the PIN diode.

Several sheet resistance devices have been fabricated and tested. Based on the encouraging results from these devices, a mask is designed and sent to a vendor and is expected to be received very soon.

A set of masks for fabricating transparent cathode Schottky-barrier diodes has been designed. These masks are given to NASA Goddard Space Flight Center for fabrication of the diodes. These diodes may be available for testing by the end of July 1986.

A unique mask set is designed to fabricate PIN diodes with transparent electrodes. With slight

modifications, the same mask set also can be used to fabricate other devices, such as the MESFET and the IMPATT diode. We are in the process of adding these modifications.

I. INTRODUCTION

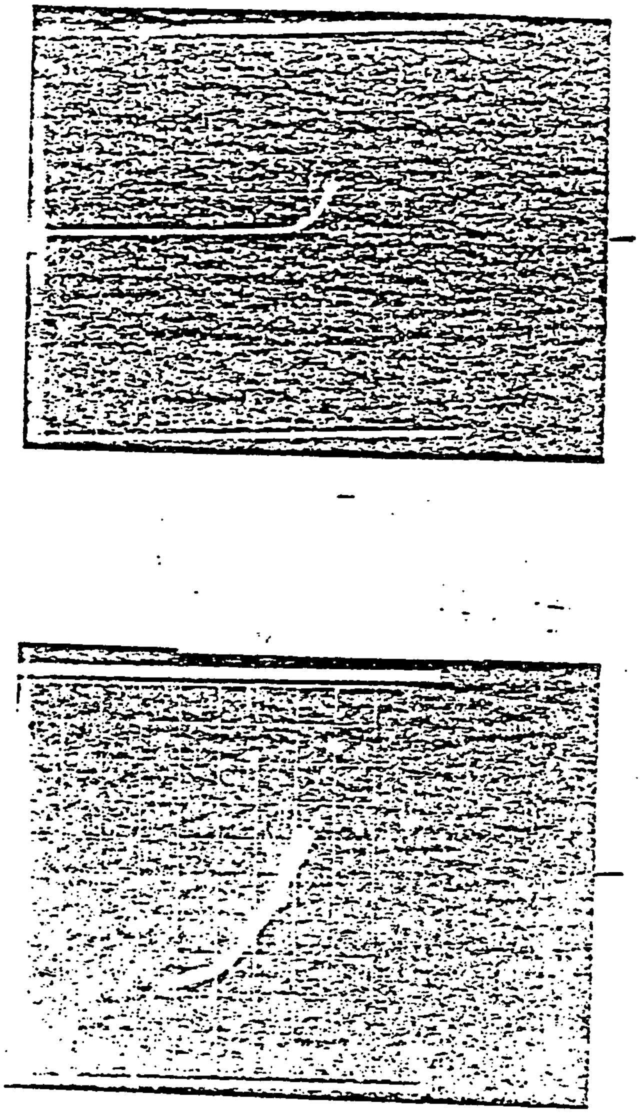
This is the continuing effort in establishing a class of optically controlled solid state devices that can be used in the millimeter wave circuits as switches, mixers, phase shifters, etc. Some of the results obtained in this effort are presented in this report.

Conceptually it is possible to fabricate devices that respond well to light illumination at millimeter wave frequency range. However, the question is how well can these devices perform under practical situations. If we can fabricate useful devices with transparent electrodes, then we will have created a new class of generic millimeter wave devices. As a result, we shall have established new techniques and technologies.

The optically controllable solid state devices may be simple photoconductors that may have light to dark resistance of 20 ohms to 10 megohms. They may also be junction, multi-layered, depletion layered and field effect semiconductor devices, whose light sensitive property is as depicted in Figure 1. Illustrated in this figure are the dark and light characteristics of a silicon PIN photo diode. When light hits the I-layer, the reverse current increases drastically. When the change in slope occurs, it is indicative that there is a change in microwave resistance. This property can be used in creating various useful devices, such as switches, modulators, phase shifters, limiters, etc.

In a junction device, if one of the electrodes is illuminated, it is conceivable that the illuminated electrode can have an extended conducting region that protrudes into the depletion region. If the device is a junction diode, it will behave like a light modulated varactor.

If the device is a MOSFET, an illuminated gate will convert the FET to allow its gain to be light controllable.



Dark-light V-I Characteristics of the PIN Photo Diode

Figure 1

II. PROGRESS MADE AT HOWARD UNIVERSITY

The progress made at Howard University and some of the results obtained during the period February 1, 1985 and June 30, 1986 are presented in this chapter. The presentation is given under the following headings:

A. The Test setup

B. The Sheet Resistance Device

C. The Schottky-Barrier Diode

D. The PIN Diode

A. The Test Setup

A microwave experimental test setup is established to test the devices. One can measure

i) the isolation and insertion losses and

ii) the return loss

using this setup.

i) The isolation and the insertion losses

The isolation loss and the insertion loss of a microstrip switch are measured using the setup shown in Figure 2. For example, Figure 3 shows a microstrip circuit to mount a Schottky-barrier diode type HP5082-2779. Actually, the diode acts as the switch. Different microstrip circuits must be designed for mounting different devices. This circuit, with the device mounted, is placed in a specially designed x-band waveguide and connected to the system as shown in Figure 2. The circulator diverts any reflected power from the microstrip switch to the dummy load, thus preventing the generator (BWO) from burning out due to the reflected power.

The microwave power is swept from 8 GHz to 12.4 GHz. In this setup, no tuner is used because, the tuner cannot be adjusted to match the microstrip switch as the frequency is swept.

The insertion loss is measured with the diode forward biased and the isolation loss is measured with the diode reverse biased. First the output power (in dB) is measured with no bias on the diode. This is the reference power level. Then a forward bias is applied to the device and the output power is measured. The difference, in dB, between these two readings is the insertion loss.

Next, a reverse bias is applied to the device and the output power is measured. The difference between this reading and the reference power gives the isolation loss.

The oscillograms of the insertion loss and the isolation loss are shown in Figure 4. From these oscillograms, the specific frequency at which maximum switching attenuation occurred is obtained as 11.5 GHz. Once this frequency is specified, the tuner is inserted between the circulator and the microstrip switch to obtain maximum power transfer. In this experiment, the attenuation is 10 dB.

This experimental setup will be used for testing our own transparent cathode Schottky-barrier diodes which are being fabricated at NASA, Goddard Space Flight Center. With these optically controlled diodes, there is no need for the external biasing; light from the He-Ne laser will be used to control the diode function.

ii) The return loss

The SWR of the diode circuit can be calculated by measuring the return loss. Figure 5 shows the

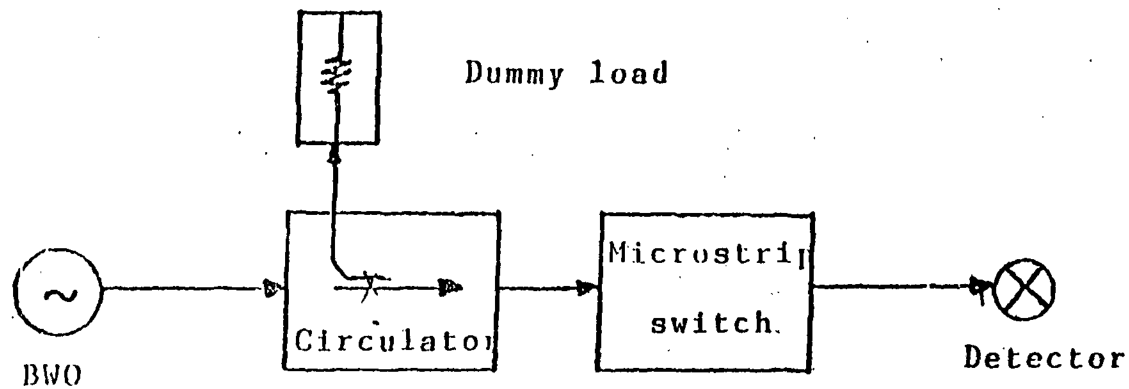
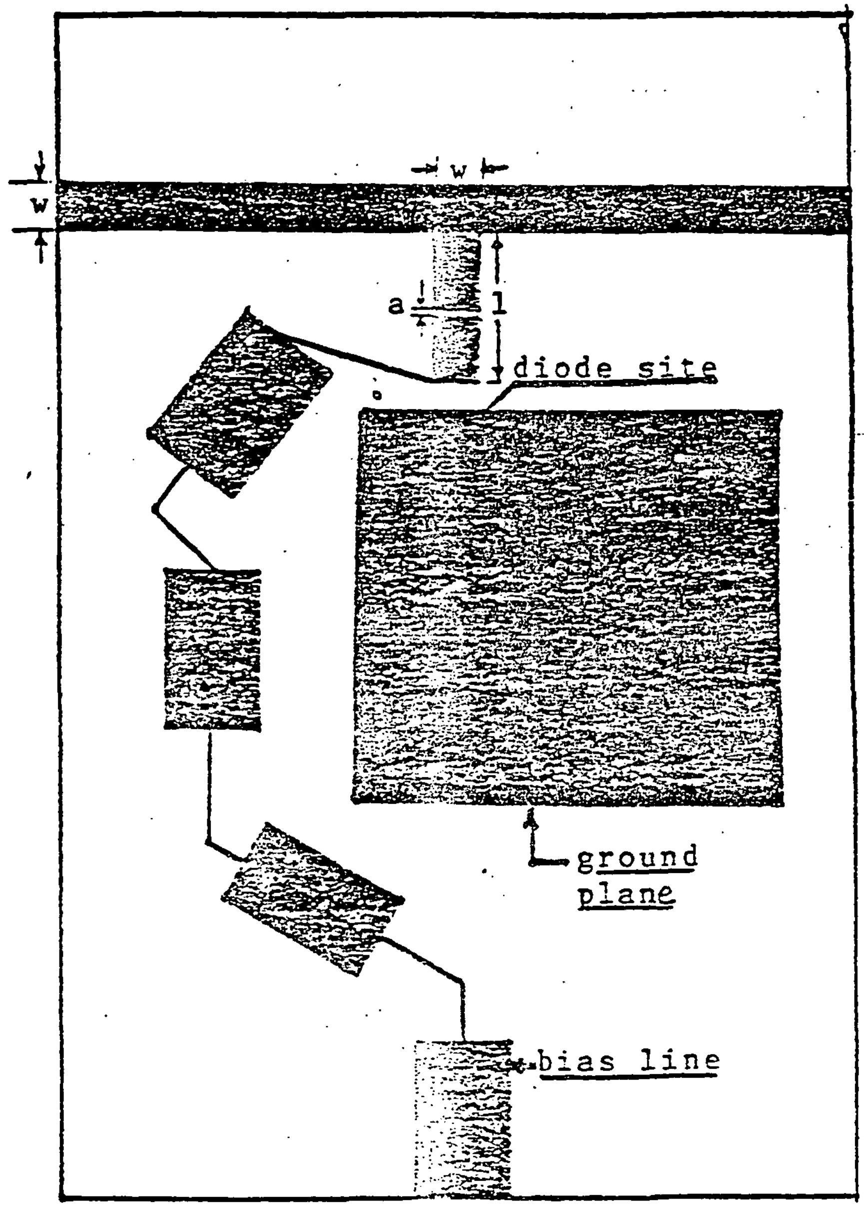


Figure 2

Isolation & Insertion loss measurement



Microstrip switch circuit (10 GHz)
Actual size w = .028 inch.
l = .0984 inch.
a < .001 inch.

Figure 3

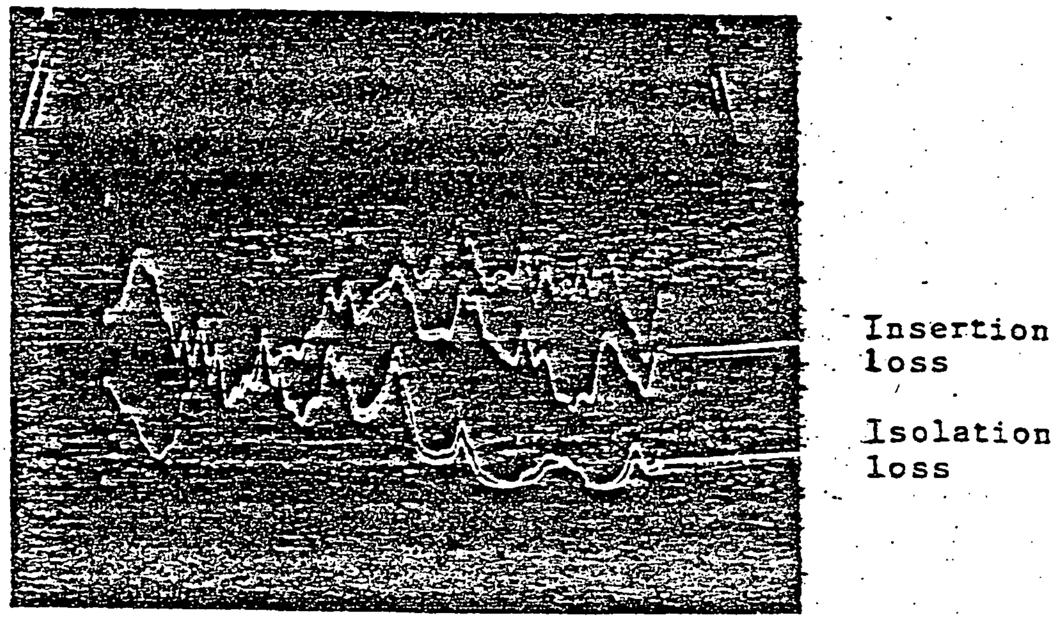
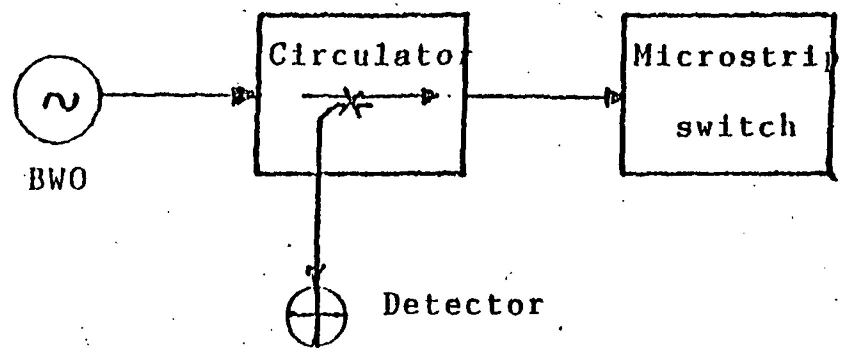


Figure 4

Isolation and insertion loss at frequencies 8-12.4 GHz



Return loss measurement

Figure 5

setup for this purpose. In this experiment, a set of standards is established by measuring the reflected powers of a set of known loads, such as a short, 50 ohms and a 12 dB attenuator. The short gives a measure of the total reflected power. With the 50 ohm load at the output end, the microswitch is connected in the circuit. The reflected power is measured. The difference between this reading and the reading with the short gives the return loss in dB. By using the Smith Chart, the return loss values can be changed into SWR values.

By repeating this process for different frequencies, the specific frequency at which minimum SWR occurs can be obtained. The minimum SWR in this experiment occurs at 11.9 GHz. Thus, the minimum SWR and maxiumum attenuation occurred at about the same frequency in this experiment; the actual frequencies being 11.9 and 11.5 GHz, respectively.

B. The Sheet Resistance Device

This device was called the bulk device in the past work. However, since the investigation is concerned with the flow of surface current, which is a function of the resistance of the device, the name 'sheet resistance device' seems to be more appropriate. This device is simply a piece of doped (or undoped) GaAs material of width W with two gold-germanium plated electrodes on either side. The width, W, can vary from a few millimeters to half a micrometer. This device is mounted on a piece of plain glass plate whose ends are metallized and bonded with aluminum foil. Gold wires are connected between the aluminum foil on glass and the gold-germanium electrodes on the device (Figure 6). The aluminum bonded ends of the glass plate act as external connectors for the device.

A set of four surface devices was tested in the microwave lab at Howard University. The widths of windows for these devices are 2.5 mm, 1.27 mm, 1.0 mm and 0.5 mm. The material is intrinsic GaAs. These window widths are very large for our purpose. However, the behavior of these experimental devices gave us an excellent indication of how the device responds to light as the width of the window is varied. As expected, it became more light sensitive as the window became smaller. Table 1 shows the experimental values of the four devices and Figure 7 gives their oscilloscope picture. Figure 8 is a plot of the average values taken from Table 1. This graph would have been more accurate if we had more points near the 'knee' of the curve. Nevertheless, the general trend of the response is very clear. One may conclude that with micron size windows, the light response will be excellent.

However, one word of caution. As the window becomes narrower, one may expect a capacitive effect in addition to the resistive effect. The resistance decreases while the capacitance increases. Thus, the device behaves as an RC circuit, where R is a function of the sheet resistance. At present, we do not have an idea of how the capacitance will come into play in the response. The final result will reveal this fact.

A mask is designed (Figure 9) to fabricate the surface devices with window sizes starting from 64 μm down to 0.5 μm. This is sent to a vendor for mask making. Fabrication of these devices is fairly easy. The mask may be received by the end of July, 1986.

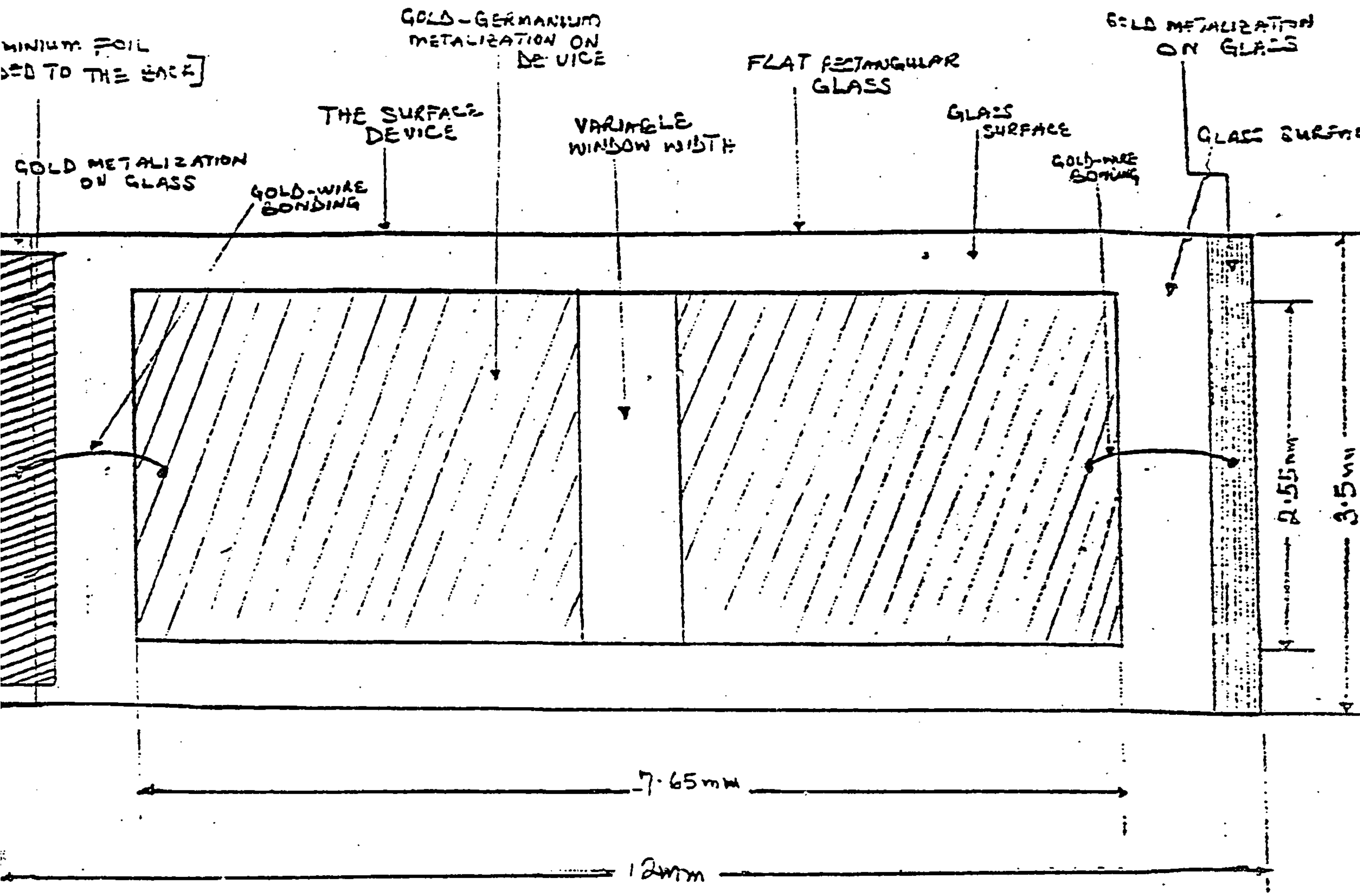
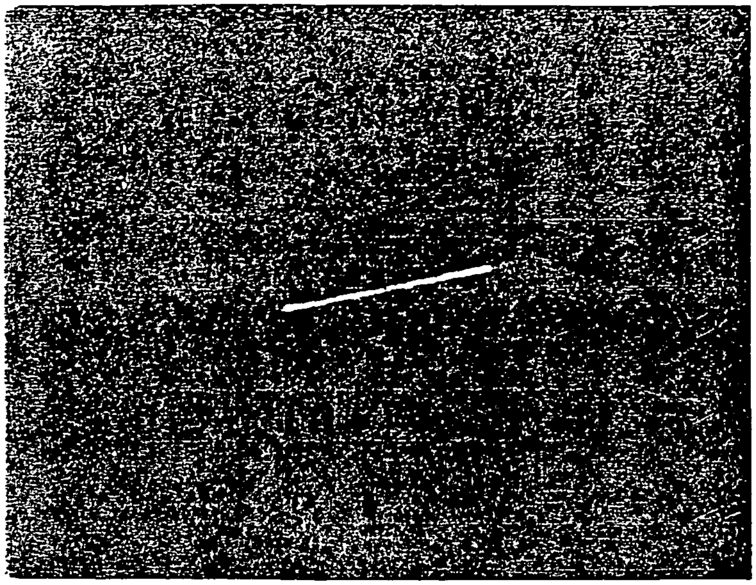
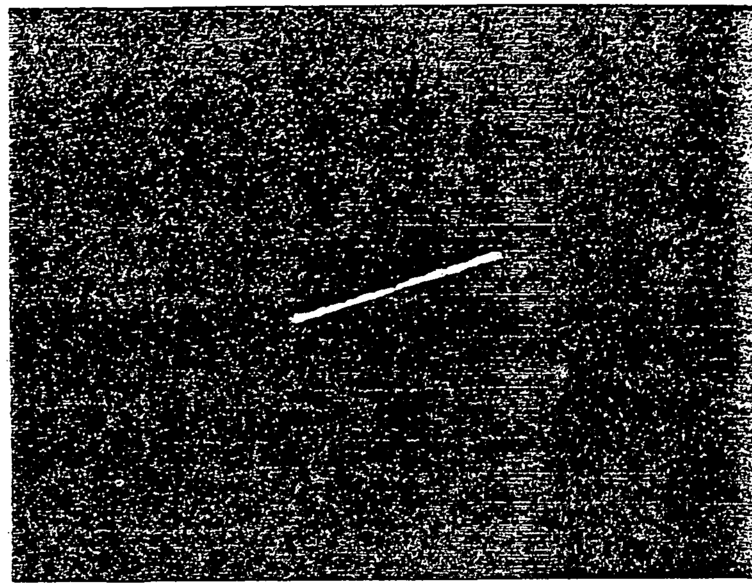


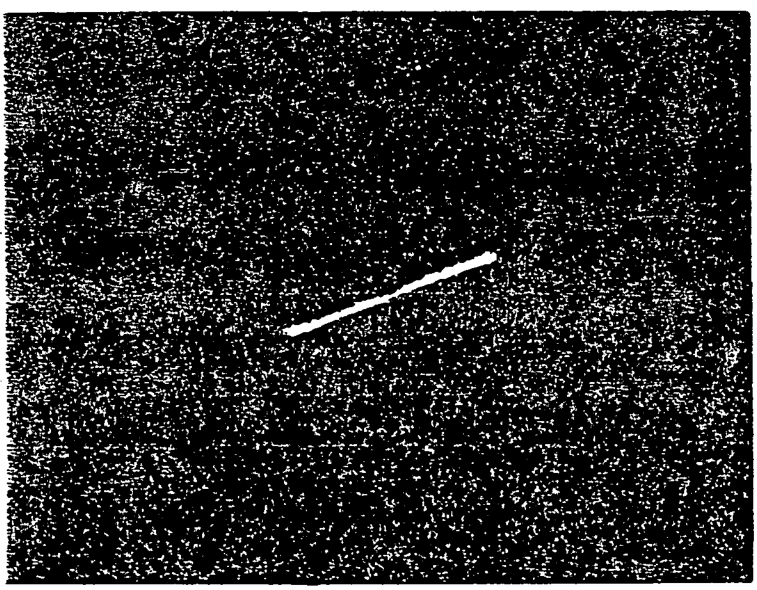
Fig. 6 Intrinsic GaAs Semiconductor Surface Device



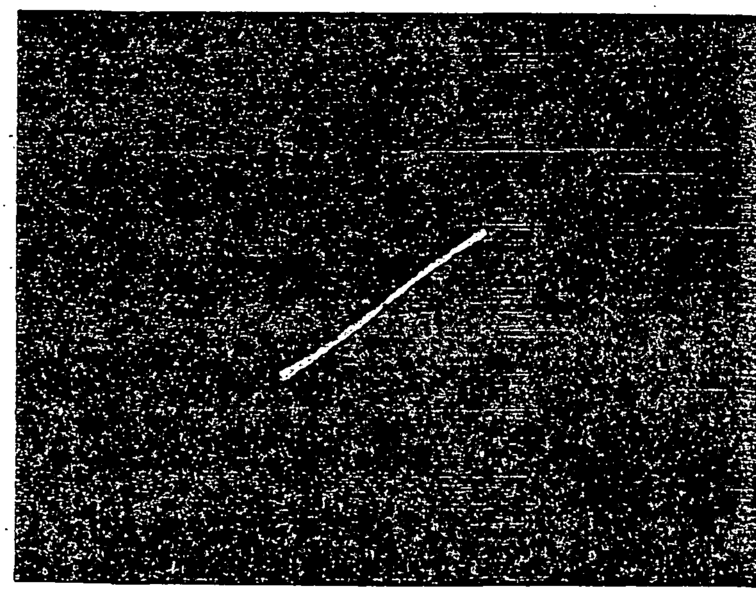
(a) window width 25mm



(b) window width 1.27mm



(c) window width 1mm



(d) window width 0.5mm

Vertical Scale 2V/div, Horizontal Scale 10 μA/div

Figure 7: Light sensitivity of the surface device

TABLE 1

6 Volts Bias

Window Width (mm)	Sample Number	Current (μA)	Average (μA)
2.5	1	18	17.8
	2	18	
	3	17	
1.27	1	28	26.3
	2	27	
	3	24	
1.0	1	30	28.7
	2	28	
	3	28	
0.5	1	36	35.67
	2	36	
	3	36	

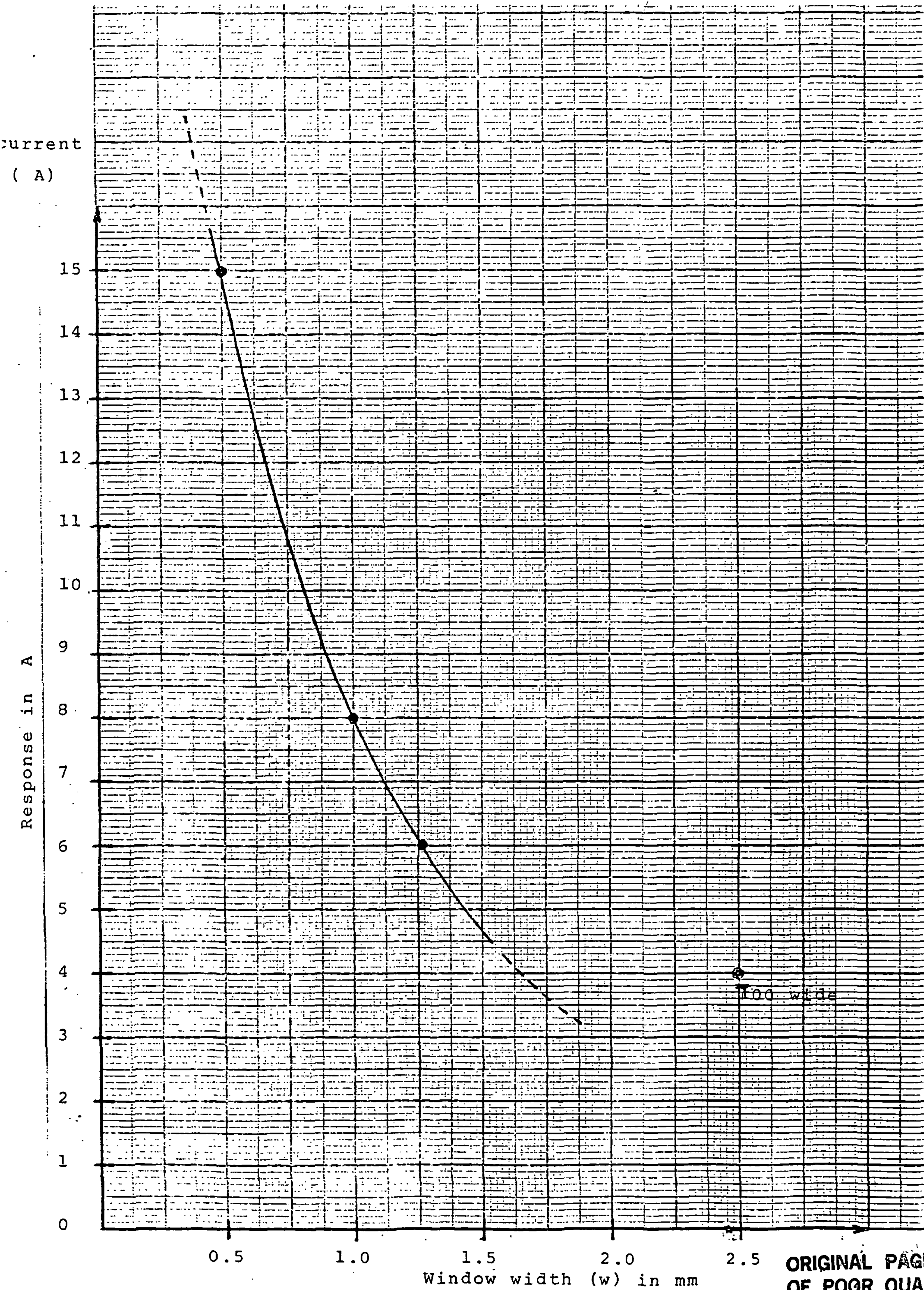


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Figure 8: Light response Vs. window width of the sheet resistance device

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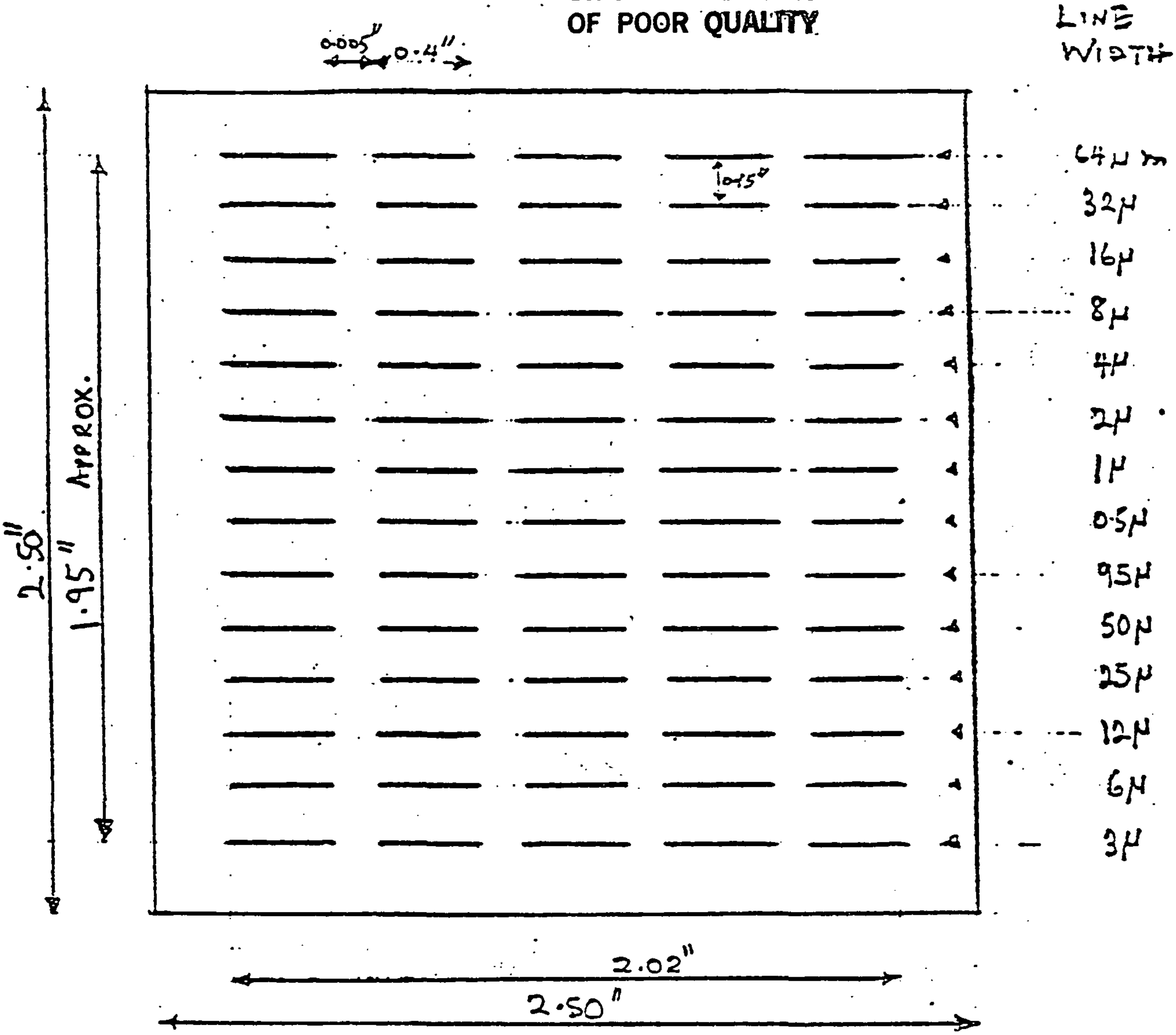

DIMENSION OF MASK: 2.5" x 2.5" PLATE. MICRON LINES ARE OPAQUE FOR POSITIVE MASK. FIVE 0.400" SEGMENTS WITH 5MIL. SPACING ON EACH HORIZONTAL LINE. LINE SPACING IS 0.150" LINE WIDTHS ARE SHOWN TO THE RIGHT OF DRAWING IN MICRONS STARTING FROM 64 MICRON THRU 0.5 MICRON AND 95 MICRON THRU 3 MICRON.

Fig. 9: Mask for the Surface Devices

C. The Schottky-Barrier Diode

A unique structure for the transparent cathode Schottky-barrier diode is designed. The Schottky-barrier metal consists of an ultra thin layer of a high-work function and high bulk resistivity metal such as nickel that acts as a glue covered by a second metal such as silver, copper or gold. A detailed description of the procedure in fabricating the GaAs Schottky-barrier diodes is given below. Figure 10 represents the various stages of this procedure.

Starting with a semi-insulating GaAs substrate (1) and using mask 1 combined with photolithography, etch a pocket (2) into the substrate. Deposit a highly doped n-layer (3) via liquid phase epitaxy until an excess layer of n^+ gallium arsenide is formed. Chemically polish the surface using sodium hydrochlorite until the n^+ layer is removed from the surface leaving behind a pocket of n^+ at the surface. Deposit a layer of n-type gallium arsenide (4) on top of the n^+ regions and the exposed semi-insulator to form an n-n^+ structure. Etch the n-layer until the stained n^+ regions of gold germanium eutectic alloy (5) is evaporated using an Ebeam vacuum system and etch to have the mesa coated with gold. The gold is remasked and the cathode opening (6), is made exposing the n-region (4). The gold germanium is then alloyed in and electroplated to two skin depths. Using the lift-off technique, the sandwich layer, using (7), is deposited on the n-layer (4) in the cathode opening (6). Again, using the lift-off with mask 6, the ohmic contact (8) is made to the transparent cathode (7). Mask 7 is applied and the ohmic contact (8) is electroplated to yield the final device shown in the flow diagram in Figure 10.

Silicon technology offers a simpler approach because oxide masking and diffusion are available. A layer of n-type silicon is grown on sapphire single crystal in the $\overline{100}$ orientation. Oxide is formed and holes opened up for n^+ packets forced by the diffusion of arsenic or antimony. These are used in the pocket because their diffusion rate is much slower than that of phosphorus. The oxide is removed and a layer of phosphorus doped silicon is grown over the pockets. The ohmic contact cathode and cathodic contact are again formed by the same technique. Separation of individual devices is done by a silicon etch, leaving behind a device on sapphire. Because of the lower electron mobility in silicon, these devices can be used at lower frequencies than the gallium arsenide devices.

In the case of indium antimonide, the technology used is the same as that for gallium arsenide, with one variation. Since indium antimonide is used primarily in the infrared region, the cathode material would be silicon, a metallic surface transparent to infrared light.

When the gallium arsenide Schottky-barrier diode is placed in a waveguide and biased in the reverse direction such that the space charge region is depleted of carriers, the microwaves pass through the diode because it is acting as an insulator. When illuminated by light via fiber optics, hole electron pairs are generated in the space charge region and the reverse current increases. Now, the microwaves see a short circuit and cannot pass through to the receiver. Thus, the time interval that is created by the light could be considered as a delay and a photo signal is essentially acting as a delay line. The light itself can be dropped or modulated so that it can act as a mathematical function on the microwaves.

The chips and the mask sets are given to Mr. Andre Burgess at Goddard Space Flight Center (GSFC) to fabricate the diodes. Mr. Harry Myers at GSFC kindly agreed to cut the final wafers into individual diodes. We thank these two gentlemen and Dr. George Alcorn for their valuable help in this matter.

The Schottky-barrier devices which are being fabricated at present may not be the optimum ones because this is our first attempt on these devices. These will be tested first on the microstrip circuit and then in a waveguide. This initial exploration will give us a good idea as to how the devices may be improved in future. Based on these results we will model and design mask sets for the improved devices.

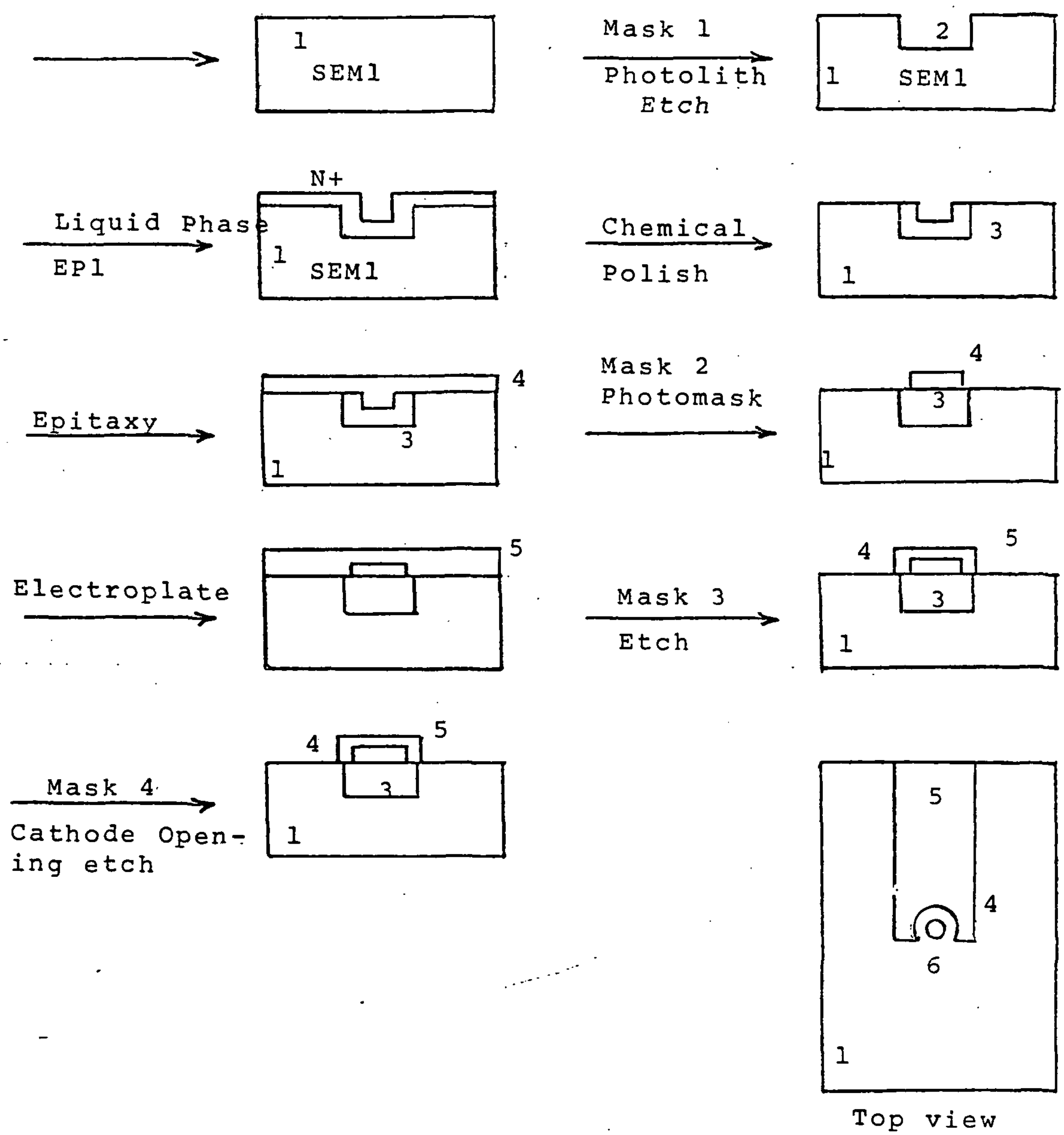

Figure 10: Flow diagram of GaAs Schottky-Barrier Diode Fabrication

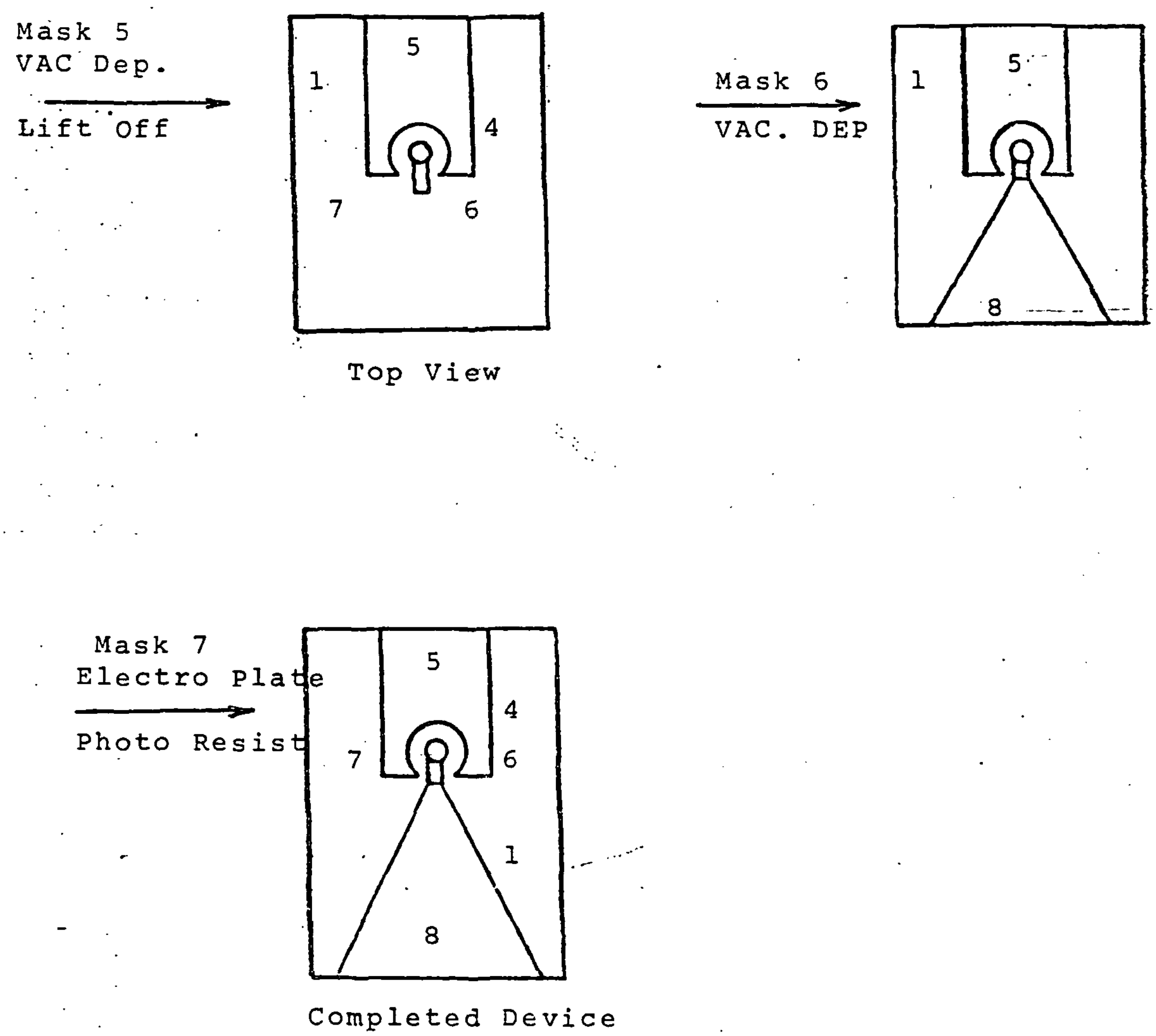

Figure 10 Continued

D. The PIN Diode

The interest in the PIN diode was created by the encouraging experimental results obtained with a commercial device (Ealing photo PIN 35-7194), which responded to light fairly well and performed a switching action at 13.9 GHZ. The experimental set up for this is shown in Figure 11. The diode is illuminated by reflected light from a He-Ne laser. The reflector is necessary so that the diode may not burn out due to the intensity of the direct laser light. The diode is mounted in a specially designed waveguide. The circulator allows both light and microwave signals to reach the same side of the diode. The tuner is used to maximize the microwave transmitted power.

The bias voltage is kept constant and the frequency is varied to determine the frequency at which maximum attenuation is obtained. This is determined to be 13.9 GHZ. Then, this frequency is kept constant and the bias voltage is varied. The dark current and the light current are measured and the attenuation in dB is calculated for each bias voltage. The results are shown in Table 2. The dark and light currents for the diode are shown in Figure 12. It is obvious from Table 2 that maximum attenuation is obtained near 0.5V forward bias. However, it is interesting to see from this table that a much larger attentuation (0.9dB) is obtained when the diode is not biased. We are investigating this process further to understand the physical principle involved. We have designed a unique mask to fabricate the PIN diodes with transparent electrodes. We affectionately call this the "Kidney Bean" because of its configuration. An examination of this Mask (Figure 13) demonstrates how the distance between the P^+ and n^+ layers can be varied and the exact distance for optimum performance at a given frequency can be obtained. The masks are designed to increase the I-layer width by a micron-by-micron stepping system, starting with one micron and going up to 50 microns. The calculated design parameters for the GaAs $P\pi N$ and $P\nu N$ are given in Table 3.

We believe that this same mask can be used to fabricate other devices, such as the MESFET and the IMPATT diodes. However, we will have to use additional masks for these devices. For example, we need an additional mask for the channel and the gate for the MESFET and the masks for the variation of concentration steps in IMPATT.

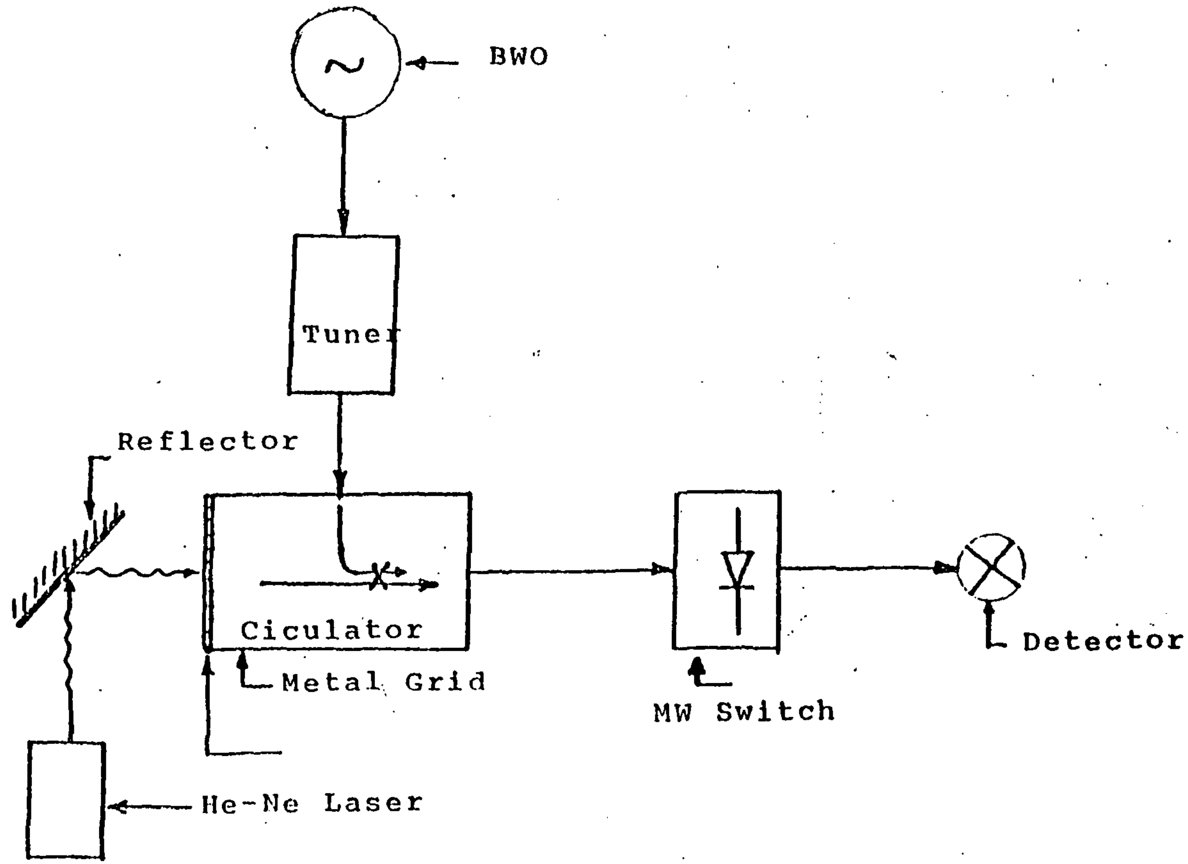
BWO
Tuner
Reflector
Ciculator
Metal Grid
MW Switch
Detector
He-Ne Laser

Figure 11

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TABLE 2

Bias Voltage (v)	Dark Current (mA)	Light Current (mA)	Attenuation (dB)
0.0	0.0	-1.53	0.025
0.1	0.0	-1.525	0.05
0.2	0.0	-1.43	0.175
0.3	0.005	-1.065	0.40
0.4	0.065	-0.610	0.575
0.5	0.320	-0.073	0.575
0.6	0.747	9,486	0.525
0.7	1.265	1.065	0.45
0.8	1.809	1.67	0.4
-1.0	0.0	-1.53	-
-5.0	0.0	-1.53	-
-10.0	0.0	-1.53	-
no bias	open circuit		0.9

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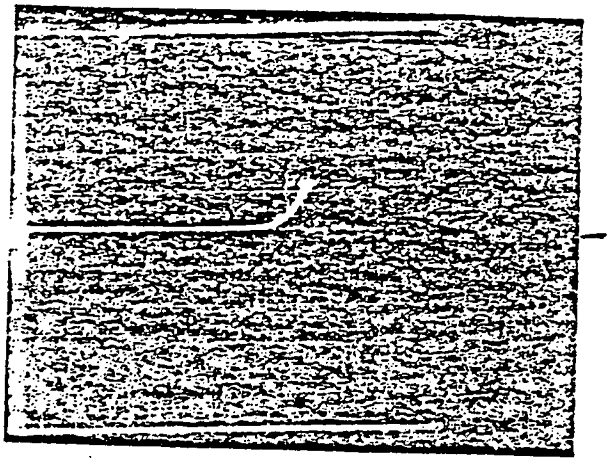

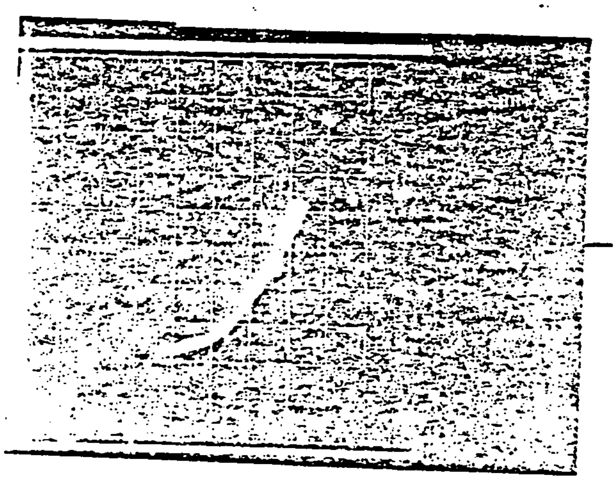

Figure 12 Dark-light V-I Characteristics of the
PIN Photo Diode

Figure 13

"The Kidney Bean" Mask

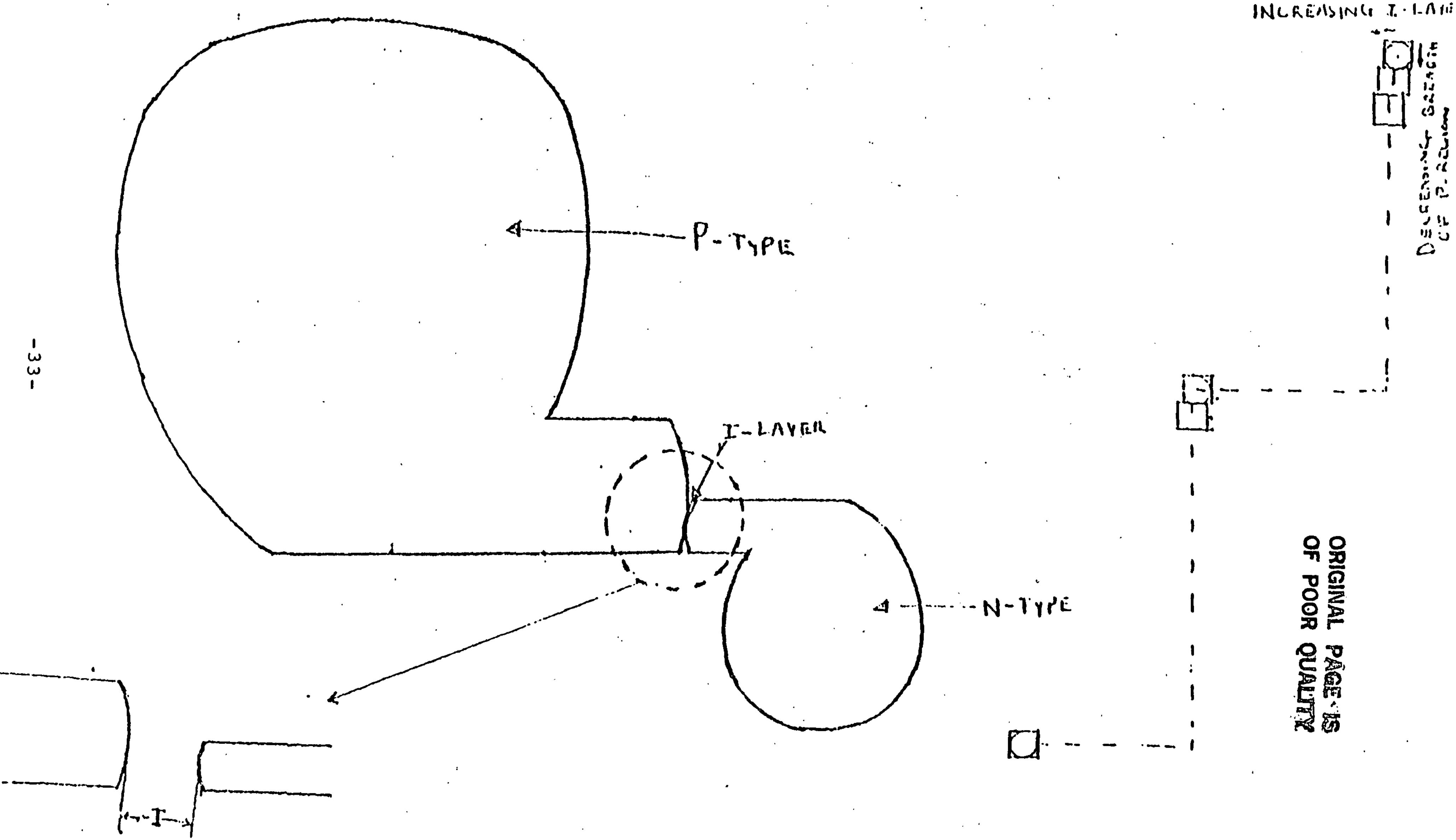

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Table 3

TYPES OF PIN DIODES

	$P\pi N$	$P\nu N$	$P\pi N$	$P\nu N$	$P\pi N$	$P\nu N$	$P\pi N$	$P\nu N$	$P\pi N$	$P\nu N$
Resistivity ohm-cm	100	100	200	200	300	300	1000	1000	$5X10^7$	$5X10^7$
Doping (cm^{-3}) N_a or N_d	$15.63X10^{13}$	$7.35X10^{13}$	$7.01X10^{13}$	$.37X10^{13}$	$5.21X10^{13}$	$.25X10^{13}$	$1.56X10^{13}$	$7.35X10^{11}$	$3.13X10^8$	$.15X10^8$
Depletion Width (ρ)micro-mm	9.004	41.0	12.73	58.70	15.60	71.89	28.47	131.25	6,367.0	29,349.0
Width of I-Layer (W micro-mm)	11.004	43.0	14.73	60.70	17.60	73.0	30.47	133.0	6,369.0	229,354.0
Area (10^{-6} mm^2)	6.065	23.67	8.12	33.0	9.67	40.13	16.75	73.10	3,500	16,140
Length μm	6.065	23.67	8.12	33.0	9.67	40.13	16.75	73.10	3,500	16,140
Depth μm	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Reversed bias Resistan. Prev. ohms)	996.50	255.67	373.19	91.56	208.2	50.36	36.08	8.26	3.45	0.02
Forward Bias Res. (R_f) milli-ohms	6.37	6.37	6.37	6.37	6.37	6.37	6.37	6.37	6.37	6.37
Transit Time T_t nano-sec	.11	.43	.147	.607	.176	.73	.305	1.33	63.69	293.54

Constants: Frequency = 30 GHZ
Doping for N or P = $20X10^{20}cm^{-3}$
Built-in potential (∅) = 0.5v
Reversed bias voltage = -10v
Reactance = 100,000 ohms