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GERMANIUM MICROWAVE SWITCHING TRANSISTOR

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Massachusetts Institute of Technology
Lexington, Massachusetts

20 September 1963

FINAL REPORT
ON
GERMANIUM MICROWAVE SWITCHING TRANSISTOR
TO
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LINCOLN LABORATORY

C-00949

September 20, 1963 03-63-38

TEXAS INSTRUMENTS INCORPORATED
SEMICONDUCTOR-COMPONENTS DIVISION
DALLAS, TEXAS

Final Report

on

GERMANIUM MICROWAVE SWITCHING TRANSISTOR

to

Massachusetts Institute of Technology

Lincoln Laboratory

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September 20, 1963

I. INTRODUCTION

Texas Instruments has completed a program under Lincoln Laboratory Order No. C-00949 to improve the germanium microwave switching transistor developed under previous contracts with Lincoln Laboratory. The principal objective was to materially reduce base resistance, r_b', while maintaining or slightly increasing the high cut-off frequency, f_T. Early stages of the work under this order were described in an Interim Report,[1] and this final report describes the total work and the results obtained.

Accepted for the Air Force
Franklin C. Hudson
Chief, Lincoln Laboratory Office

II. DESIGN APPROACH

The fundamental approach used in this work was to develop suitable three-stripe geometry (emitter in the center with two outside base stripes) thus reducing base resistance. This approach was outlined in detail in TI's proposal to Lincoln Laboratory dated 29 December 1962.

III. OBJECTIVE SPECIFICATIONS

Table I lists the objective specifications.

Table I

OBJECTIVE SPECIFICATIONS

PARAMETER	CONDITIONS	LIMITS
BV_{cbo}	100 μa	10 v min
BV_{ebo}	100 μa	1 v min
BV_{CEO}	15 ma	3 v min
h_{FE}	V_{CE} = 1 v, I_C = 10 ma	20 min
h_{FE}	V_{CE} = 1 v, I_C = 50 ma	20 min
I_{CBO}	3 v	5 μa min
τ_s	I_C = 30 ma,	
	$I_B \cong$ 3 ma	20 ns max
C_{TE}	V_{EB} = 0.5 v	1.5 pf max
C_{OB}	V_{CB} = 2.5 v	1.5 pf max
f_T	V_{CB} = 2.5 v	3 kmc min
	I_C = 10 ma and	
	I_C = 50 ma and	
	I_C = 80 ma	
r_b'	I_C = 10 ma	
	V_{CB} = 2.5 v	40 Ω max

IV. TECHNICAL DISCUSSION

The base resistance, r_b', of a switching transistor is important because this resistance increases the input signal voltage required to drive the transistor. Calculation of r_b' for the mesa transistor described in this report, with three-stripe geometry, can be approximated by:[2,3]

$$r_b' = \frac{\rho'_s S}{12 L} + \frac{\rho_s S_1}{2 L} = 31.7 \text{ ohms}$$

where

ρ_s' = sheet resistivity under emitter = 900 ohms/square

ρ_s = sheet resistivity outside the emitter = 40 ohms/square

S = emitter width = .5 mil

S_1 = space between contact stripes = .5 mil

L = length of contact stripe = 1.5 mils

This resistance, 31.7 ohms, can be compared to the values actually obtained in this program be referring to Fig. 1, a distribution chart for the state-of-the-art samples. The agreement between theory and practice is gratifying, considering that the sheet resistances ρ'_s and ρ_s are not known with good accuracy. The value assumed for ρ'_s, 900 ohms, is taken from a Gummel[4] measurement, and this type of measurement is now open to some question (although in this case no better method is known). The value for ρ_s, 40 ohms, was obtained by doubling the value measured just after vapor diffusion. It is assumed that the sheet resistance approximately doubles during subsequent etching. This has been verified to some extent in simple etch tests on diffused germanium slices, but is by no means certain.

In making a transistor to meet the r_b' and other requirements of this program, the geometry shown in Fig. 2 was used. This geometry is achieved by using a metal mask to evaporate pairs of interleaved emitter and base stripes as shown in Fig. 3. The extra emitter stripe is later removed during the mesa etch. Figure 3 also includes a photograph of a completed transistor. The process for making the transistor is shown in flow chart, Fig. 4.

The cut-off frequency, f_T, of a microwave switching transistor is of the utmost importance. The reason is that the circuit load resistances must be kept low at high frequencies and this limits the voltage gain. It is essential therefore to have current gain, and this requires a high f_T.

Calculations for f_T were given in the work under a previous MIT contract,[5] and need not be repeated here because the base layers were almost the same as in the current program. Subsequent increases in f_T which have been achieved were primarily due to improvements in epitaxial material and to reducing the collector resistivity. Alloy and diffusion temperatures have not been changed very significantly in this program. Predicted values of f_T obtained by calculation are higher by a factor of two than the values actually achieved, but even this agreement is better than could be obtained a few years earlier.

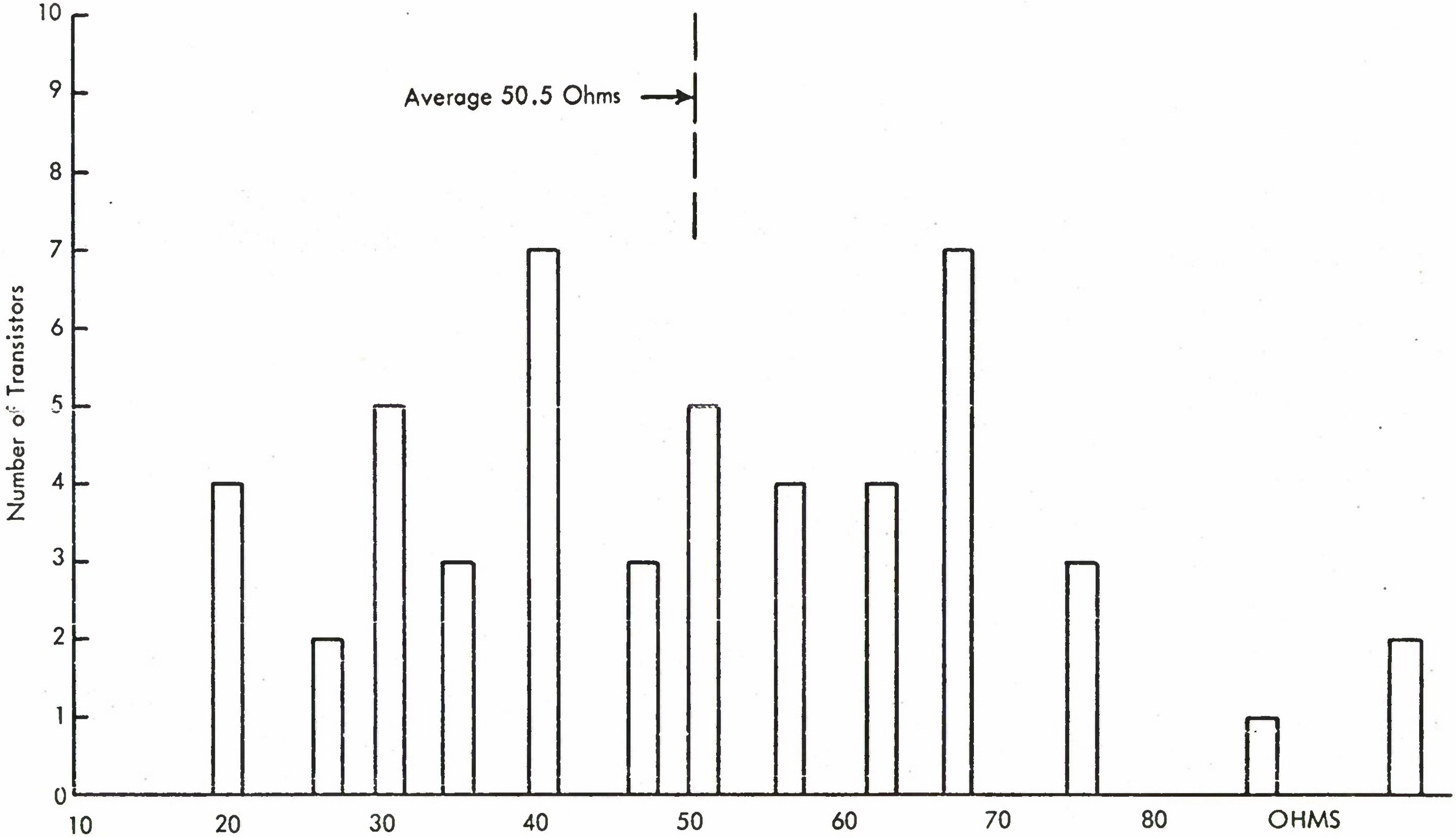
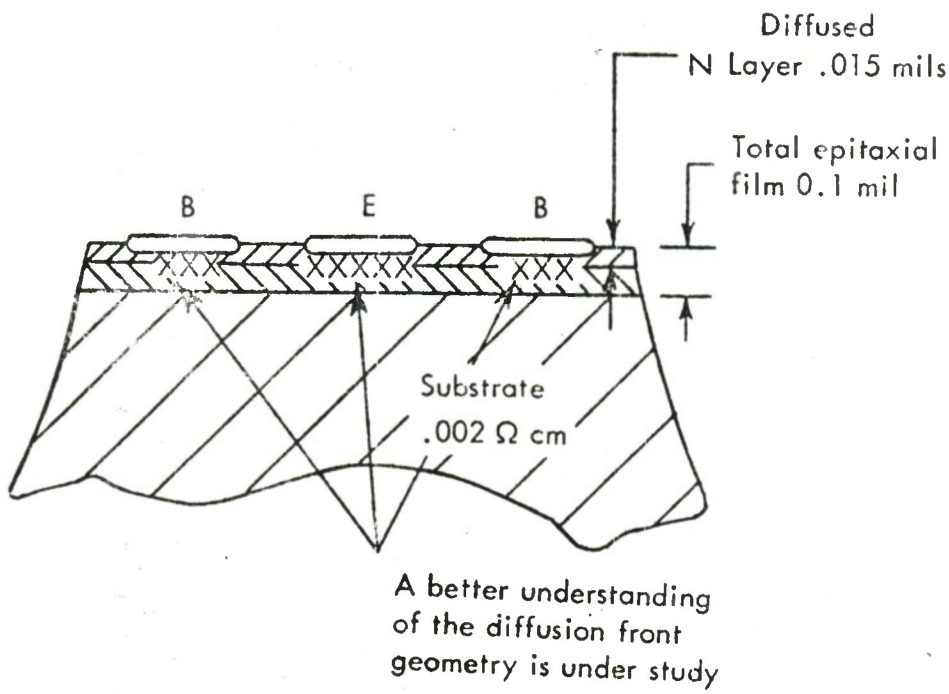


Fig. 1. Distribution of Base Resistance, $r b'_1$

Fig. 2
Geometry of Three-Stripe Transistor



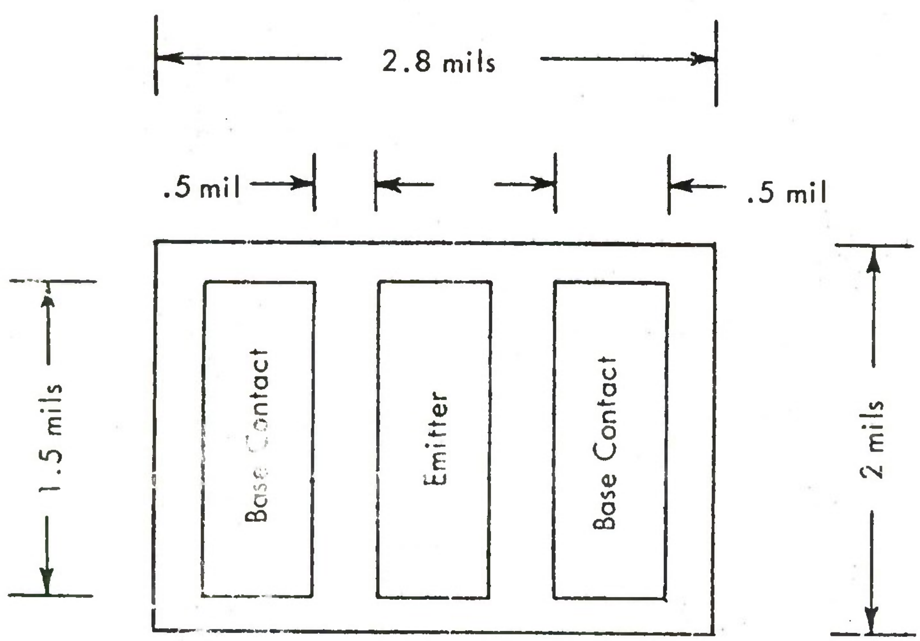
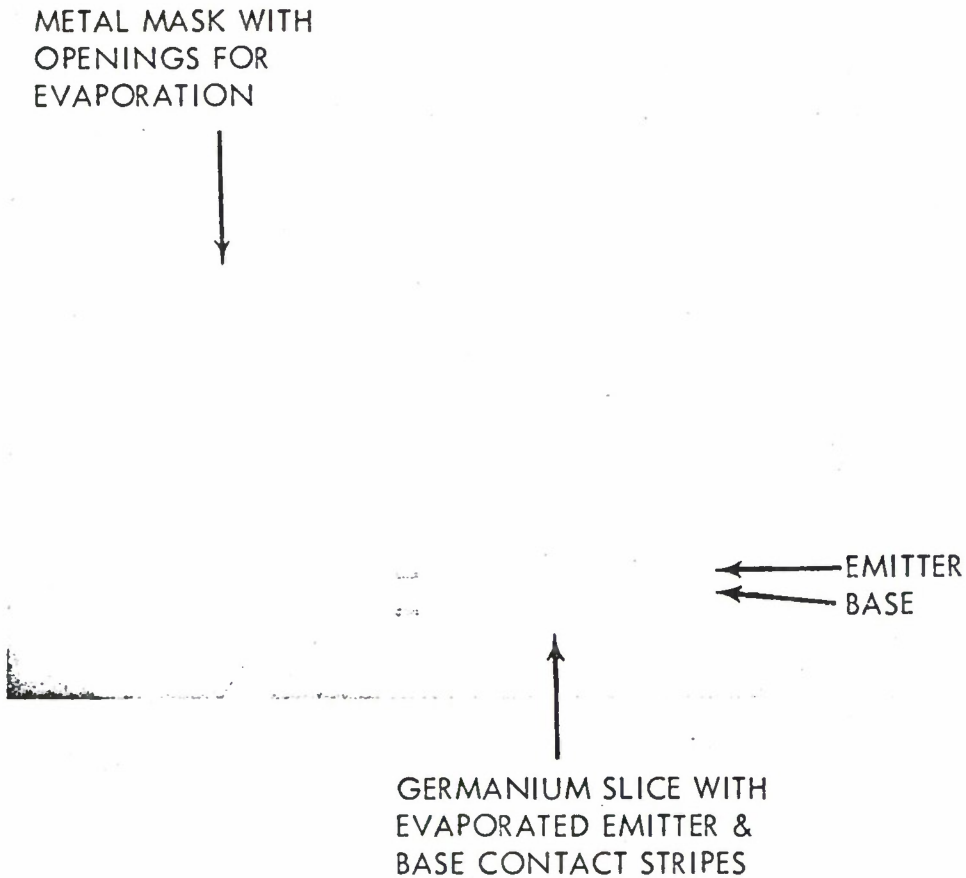


FIGURE 3



A. Composite photo of portion of metal evaporation mask and resulting 4-stripe pattern on germanium. (One emitter stripe is later removed in mesa etching)

B. Photograph of bonded 3-stripe transistor

Figure 4 FLOW CHART

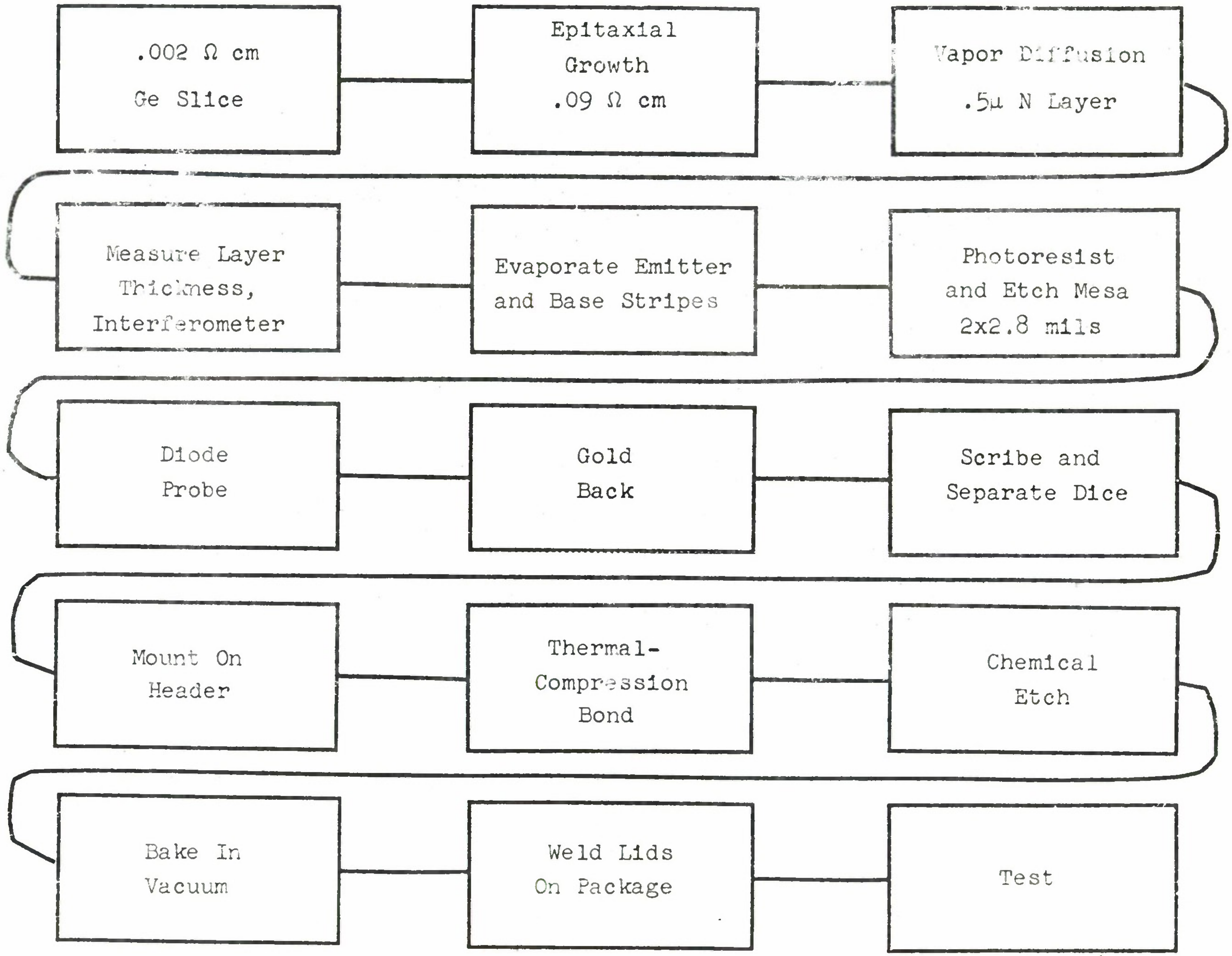


Figure 5 gives the f_T distribution for all the state-of-the-art samples submitted under the current program. Figure 6 is a plot of $1/f_T$ versus $1/I_E$ and gives the intrinsic f_T or f_{Ti} of one of these devices. For this particular transistor f_{Ti} is 3 gc.

In the area of technical problems, thermal compression bonding has been developed to the point of being usable, but it continues to limit repeatability and virtually prohibits further size reductions in the geometry. This bonding operation, using pressures on the order of 50,000 lbs/sq in often damages the half-micron base layers, causing shorts or leakage in the collector junctions as well as the emitter junctions. An approach for getting away from this problem has now been found and this will play an important part in our future plans for microwave transistors.

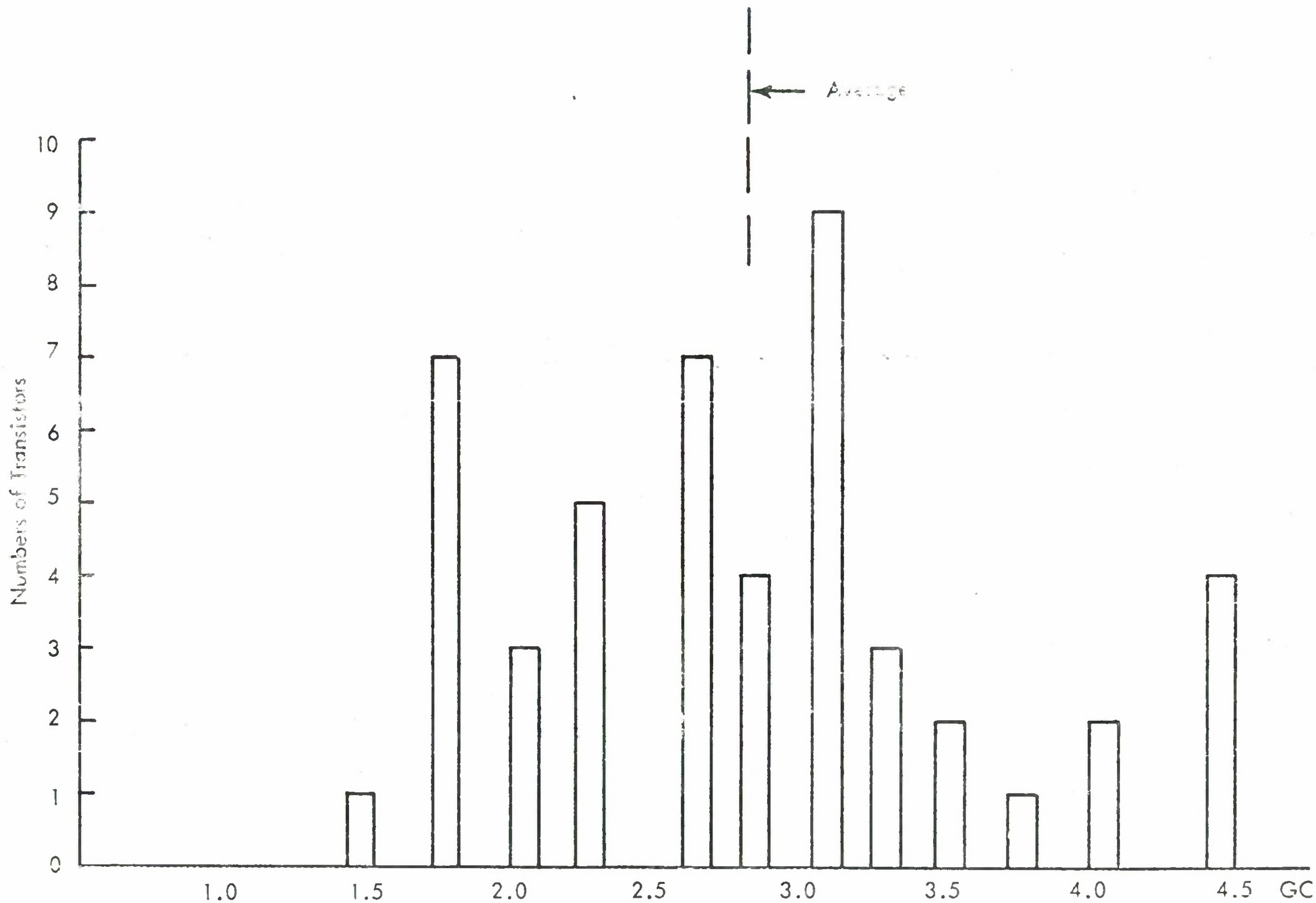
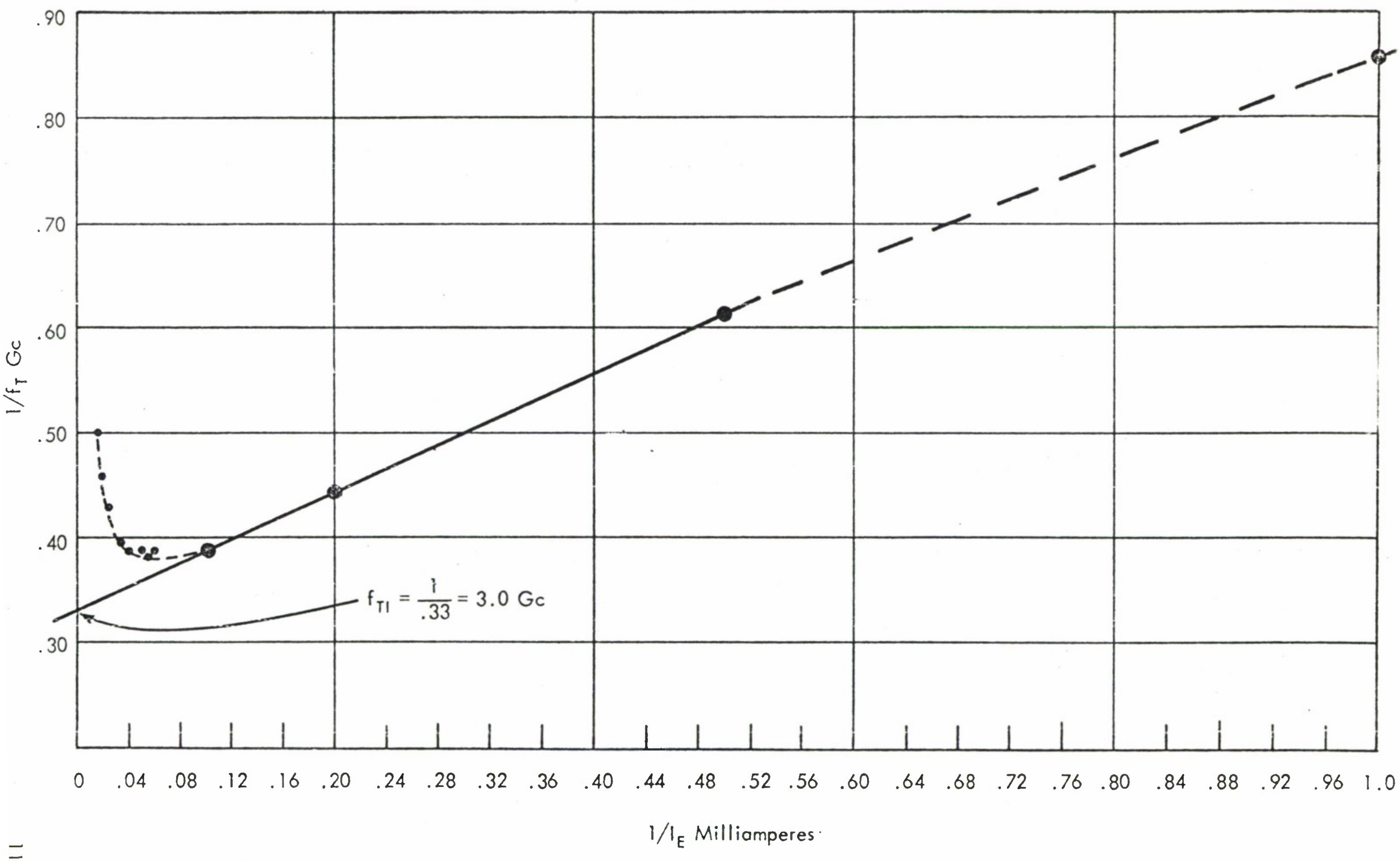


Fig. 5. Distribution of Cut Off Frequency, f_T (I_C = 10 MA, V_{CB} = 2.5V)

Fig. 6
GERMANIUM MICROWAVE SWITCHING TRANSISTOR
Intrinsic Cut-off Frequency f_{TI}



V. TRANSISTOR TEST RESULTS

Details of test results on the fifty transistors submitted to Lincoln Laboratory as state-of-the-art samples are shown in Tables 2 through 6. Results from the r_b' and f_T work have already been mentioned (Figs. 1 and 5).

Some special measurements have also been made in evaluating this new transistor.

Figure 7 is a circuit schematic of a 200 mc binary system using these transistors, indicative of the high frequency capability of the devices. Wave forms are also included in this figure.

Figure 8 shows a circuit schematic and a photograph of the jig used for amplifing extremely short pulses of 2 nanoseconds total length. Figure 9 is a photograph of the input and output pulse obtained in this 2 nsec application.

TABLE 2

Test Data on First Lot of State-of-the-art Samples

	2-679 B6P4	4-679 B6P4	9-680 A	9-679 A6	9-679 B6P4	11-679 A	12-679 B4	14-679 B4	15-679 B6P4	17-679 A
BV_{CBO}(100 μa) V	16.0	12.0	7.2	8.0	16.5	12.6	7.2	17.0	16.0	9.5
BV_{EBO}(100 μa) V	1.0	1.2	1.3	1.1	.99	.86	1.2	1.6	1.3	1.2
BV_{CEO}(15 ma) V	6.8	6.6	5.0	7.5	5.8	5.0	3.4	5.5	7.4	6.0
I_{CBO}(3 v) μa	.2	.1	5.0	2.0	.2	.1	.1	.1	.1	3.0
h_{FE}(1 v, 10 ma)	83.0	91.0	250	22	58.0	62.0	59.0	200.0	83.0	42.0
h_{FE}(1 v, 50 ma)	192.0	166.0	310	33.0	156.0	100.0	142.0	450.0	185.0	89.0
$V_{CE(sat)}$ I_C = 10ma, I_B = 1.0ma	.10	.09	.09	.11	.10	.13	.09	.09	.11	.14
$V_{CE(sat)}$ I_C = 50ma, I_B = 5.0ma	.17	.18	.19	.20	.19	.40	.17	.17	.18	.25
V_{BE} I_C = 10ma, I_B = 1.0ma	.46	.46	.46	.44	.48	.51	.47	.48	.47	.51
V_{BE} I_C = 50ma, I_B = 5.0ma	.56	.61	.61	.62	.66	.82	.64	.63	.57	.69
τ_s 30 ma, 3.0ma, Ns	22	30	30	19	36	28	32	30	21	18
C_{OB} 2.5 v	2.1	1.87	1.66	1.89	2.16	1.54	1.44	1.19	2.14	2.23
f_T 400 mc 2.5V, 10ma	1.48	1.76	3.14	2.22	1.78	3.36	2.04	2.0	1.72	1.76
f_T 400 mc 2.5 v, 50ma	1.28	1.41	2.24	1.57	1.30	2.35	1.44	1.65	1.46	1.46
NF 200 mc 2.5 v, 2 ma, db	2.2	3.2	3.5	3.8	3.6	4.3	4.5	5.0	2.9	3.5
h_{FE} 1 v, 2 ma	57.0	57.0	166.0	9.3	25.0	33.0	33.0	110.0	50.0	20.0
f_T 2.5 v, 2 ma	1.03	1.15	1.70	1.37	1.25	1.76	1.41	1.35	1.15	1.3
r_b', Calculated	18.0	38.0	50.0	30.0	39.0	58.0	61.0	87.0	30.0	34.0

TABLE 3

Test Data on Second Lot of State-of-the-art Samples

	1-734AA	2-734AB	7-727B	10-732BB	11-679B9
BV_{CBO} (100 μa) V	15.0	16.0	1.3	3.2	11.0
Avalanche Breakdown, Volts	14.5	16.0	17.0	16.2	15.0
BV_{EBO} (100 μA) V	.42	.72	.52	.80	1.6
BV_{CEO} (15 MA) V	5.8	6.0	4.5	5.5	5.6
i_{CBO} (3V) μA	.1	.1	250	9.0	.2
h_{FE} (1V, 10MA)	50	36.7	66.6	28.5	37
h_{FE} (1V, 50 MA)	120	122	166	71.5	1000
$V_{CE(SAT)}$ I_C = 10 MA, I_B = 1.0 MA	.08	.08	.07	.12	.07
$V_{CE(SAT)}$ I_C = 50 MA, I_B = 5.0 MA	.16	.15	.15	.20	.15
V_{BE} I_C = 10 MA, I_B = 1.0 MA	.58	.47	.45	.48	.46
V_{BE} I_C = 50 MA, I_B = 5.0 MA	.66	.61	.62	.67	.60
τ_s (30 MA, 3MA) Ns	33	38	28	23	35
C_{OB} (2.5 V) PF	1.04	.95	1.0	1.2	1.21
f_T (400 MC, 2.5V, 10 MA) Gc	2.3	2.58	4.45	2.72	2.07
f_T (400 MC, 2.5V, 50 MA) Gc	1.41	2.52	3.06	3.28	1.45

DATA FOR r_b'

NF (200 MC, 2.5V, 2 MA) DB	5.2	3.1	4.5	4.4	4.4
h_{FE} (1V, 2 MA)	20	10.5	28.6	11.1	400
f_T (2.5 V, 2 MA) Gc	1.23	1.46	2.38	1.44	1.53
r_b' (Calculated) OHMS	69	21	36	40	74

Table 4

MICROWAVE SWITCHING TRANSISTORS

Transistor #	2-749 AA1	3-748 AA	4-748 AA	6-748 AA1	6-748 AA1P2	8-748 AA1	8-748 AA1	9-738 AA	13-748 AB	20-734 AA2
BV_{CBO}(100 μa) V	13.0	12.4	18.0	8.8	15.5	15.8	16.8	7.0	9.0	15.5
BV_{EBO}(100 μa) V	1.5	1.3	1.4	1.3	1.2	1.1	1.4	.85	1.0	.75
BV_{CEO}(15 ma) V	4.7	4.0	7.0	6.5	4.2	6.4	4.5	4.5	4.8	6.5
I_{CBO}(3 V) μa	.5	.1	.1	15	.1	.1	.1	.2	1.0	.1
h_{FE}(1 V, 10 ma)	125	330	40	56	270	33	435	140	660	28
h_{FE}(1 V, 50 ma)	250	620	100	110	500	94	590	310	660	50
$V_{CE(SAT)}$ I_C = 10 ma, I_B = 1.0 ma	.12	.08	.10	.13	.07	.12	.08	.08	.09	.14
$V_{CE(SAT)}$ I_C = 50 ma, I_B = 5.0 ma	.21	.18	.16	.25	.20	.27	.17	.17	.17	.22
V_{BE} I_C = 10 ma, I_B = 1.0 ma	.51	.46	.46	.49	.47	.52	.48	.48	.51	.47
V_{BE} I_C = 50 ma, I_B = 5.0 ma	.67	.60	.60	.65	.65	.62	.67	.61	.67	.62
$_s$(30 ma, 3 ma) Ns	37	53	60	27	27	19	46	23	21	18
C_{OB}(2.5 V.) PF	1.2	.62	1.0	1.1	1.33	.57	1.22	1.2	1.0	.86
f_T(400 mc, 2.5 V, 10 ma) Gc	3.1	2.61	2.58	3.1	2.0	2.55	2.89	4.0	4.08	2.8
f_T(400 mc, 2.5 V, 50 ma) Gc	2.32	2.25	1.72	1.65	1.55	2.04	1.72	3.28	2.24	2.1
Data for r_b'										
NF(200 mc, 2.5 V, 2 ma) DB	4.2	4.1	4.5	3.8	4.6	5.8	3.7	5.4	5.0	2.8
h_{FE}(1 V, 2 ma)	160	220	12	25	220	10	200	80	400	12
f_T(2.5 V, 2 ma) Gc	2.27	1.89	1.76	2.22	1.3	1.68	2.07	2.2	2.64	2.0
r_b' (calculated) Ohms	67	66	44	43	76	67	57	97	95	22
g* parameter	.01	.01	.09	.051	.017	.1	.01	.018	.0064	.088

* g parameter $= \frac{I_{CBO}}{I_C} + \frac{1}{1 + h_{FE}} + \frac{f}{f}^{2}$

Table 5

MICROWAVE SWITCHING TRANSISTORS

Transistor #	2-737 BA	12-737 BA	10-732 AA	9-732 BA4	3-773 B	11-773 B	10-734 AB1P2	3-738 AA	4-738 AA	1-744 AA1
BV_{CBO}(100 μa) V	15.8	17.0	5.6	14.5	11.0	17.5	10.0	2.9	9.8	6.0
BV_{EBO}(100 μa) V	1.3	1.0	1.6	.75	.92	.45	.85	1.2	.92	.93
BV_{CEO}(15 ma) V	3.7	7.5	3.4	3.8	5.2	7.8	5.5	4.5	4.9	4.7
I_{CBO}(2.5 V) μa	.1	.1	18	.1	.2	.1	.1	60	21.0	7.0
h_{FE}(1 V, 10 ma)	270	32.2	250	250	500	45.5	50	83.5	69	62.5
h_{FE}(1 V, 50 ma)	625	59	417	385	832	100	125	185	156	143
$V_{CE(SAT)}$ I_C = 10 ma, I_B = 1.0 ma	.07	.09	.08	.07	.07	.09	.08	.09	.09	.10
$V_{CE(SAT)}$ I_C = 50 ma, I_B = 5.0 ma	.15	.18	.18	.14	.18	.2	.14	.17	.18	.19
V_{BE} I_C = 10 ma, I_B = 1.0 ma	.45	.44°	.45	.45	.45	.46	.46	.45	.46	.48
V_{BE} I_C = 50 ma, I_B = 5.0 ma	.60	.57	.61	.60	.59	.64	.58	.59	.62	.68
$_s$(30 ma, 3 ma)Ns	24	24	23	28	20	22	36	16	15	10
C_{OB} (2.5 V)PF	1.16	1.06	1.36	1.21	.763	.584	1.13	1.27	1.07	1.456
f_T(400 mc, 2.5 V, 10 ma)Gc	3.78	2.725	3.55	3.1	3.24	3.06	3.28	4.52	4.45	2.86
f_T(400 mc, 2.5 V, 50 ma)Gc	3.64	2.46	3.36	2.76	2.64	1.76	3.36	4.08	4.045	2.76
Data for r_b'										
NF(200 mc, 2.5 V, 2 ma)DB	4.9	3.2	4.4	3.1	3.9	4.45	2.7	3.9	4.7	4.2
h_{FE}(1 V, 2 ma)	125	18.2	166	143	286	18.2	25.0	40.0	40.0	33.3
f_T(2.5 V, 2 ma)Gc	2.045	1.608	2.0	1.745	2.320	1.865	1.72	2.27	2.40	1.78
r_b' (calculated) Ohms	77	30	68	42	63	52	25	41	63	55

Table 6

MICROWAVE SWITCHING TRANSISTORS

Transistor #	4-744 AA10	2-792 B20	4-744 AA22	8-744 AA22	5-737 BA7	4-792 B7	8-744 AA4	11-744 AA4	12-744 AA4	8-792 B	4-744 AA1	14-734 AB3P3	1-734 AB3P4	9-738 AA1P1	21-7 AB1
BV_{CBO}(100ua)V	13.0	16.2	7.0	11.0	17.0	7.9	8.5	13.9	15.0	17.0	12.0	7.0	15.5	5.6	3.9
BV_{EBO}(100ua)V	1.2	.64	1.1	1.2	1.4	.80	1.3	1.2	.95	.68	1.2	.82	.69	1.3	.87
BV_{CEO}(15ma)V	3.9	7.7	4.0	4.0	5.4	6.3	4.6	4.4	5.1	8.0	3.8	4.8	6.3	4.3	6.2
I_{CBO}(3V)ua	.1	.1	8.0	2.5	.1	3.0	3.0	.1	.1	.1	.1	7.0	.1	30.	70.
h_{FE}(1V.,10ma)	200	20	167	142	100	25	77	222	77	20	200	83	27	100	28
h_{FE}(1V.,50ma)	357	26	278	294	200	55	166	357	167	33	420	200	83	200	81
$V_{CE(SAT)}$ I_C=10ma I_B=1.0ma	.09	.16	.10	.09	.08	.14	.11	.09	.11	.15	.10	.13	.13	.12	.12
$V_{CE(SAT)}$ I_C=50ma I_B=5.0ma	.17	.25	.19	.18	.16	.22	.19	.15	.19	.22	.20	.20	.21	.24	.20
V_{BE} I_C=10ma I_B=1.0ma	.46	.50	.46	.47	.49	.51	.49	.48	.51	.52	.47	.51	.54	.48	.52
V_{BE} I_C=50ma I_B=5.0ma	.62	.66	.59	.62	.64	.66	.67	.64	.68	.67	.67	.67	.72	.61	.70
τ_s(30ma,3ma)Ns	21	12	15	22	43	15	20	50	27	14	18	25	30	15	23
C_{OB}(2.5V.)PF	1.36	1.07	1.38	1.38	1.15	1.34	1.29	1.31	1.21	.88	1.38	1.17	1.12	1.01	1.07
f_T(400mc,2.5V.,10ma)Gc	3.2	2.25	3.0	2.83	3.51	2.24	2.72	2.30	1.83	1.72	3.0	1.78	1.78	4.43	3.28
f_T(400mc,2.5V.,50ma)Gc	3.2	1.47	2.93	2.89	2.67	1.72	2.58	2.30	1.83	1.31	3.02	1.62	1.80	4.33	3.20
Data for r_b'															
NF(200mc,2.5V.,2ma)DB	3.8	3.2	3.5	3.6	3.7	3.8	4.8	2.7	4.1	3.9	4.3	3.4	5.6	4.5	5.3
h_{FE}(1V.,2ma)	118	7.4	100	74.	50.	12.5	33.	143.	36.4	8.0	125.	40.	7.4	67.	10.5
f_T(2.5V.,2ma)Gc	1.91	1.48	1.76	1.66	2.19	1.53	1.59	1.40	1.19	1.17	1.74	1.13	1.06	2.32	1.82
r_b' (calculated)Ohms	57	18	46	47	48	32	67	31	51	28	68	36	52	63	50

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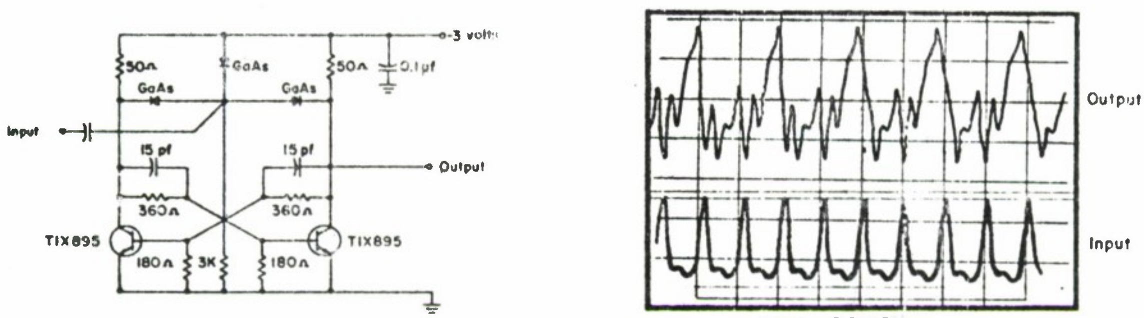
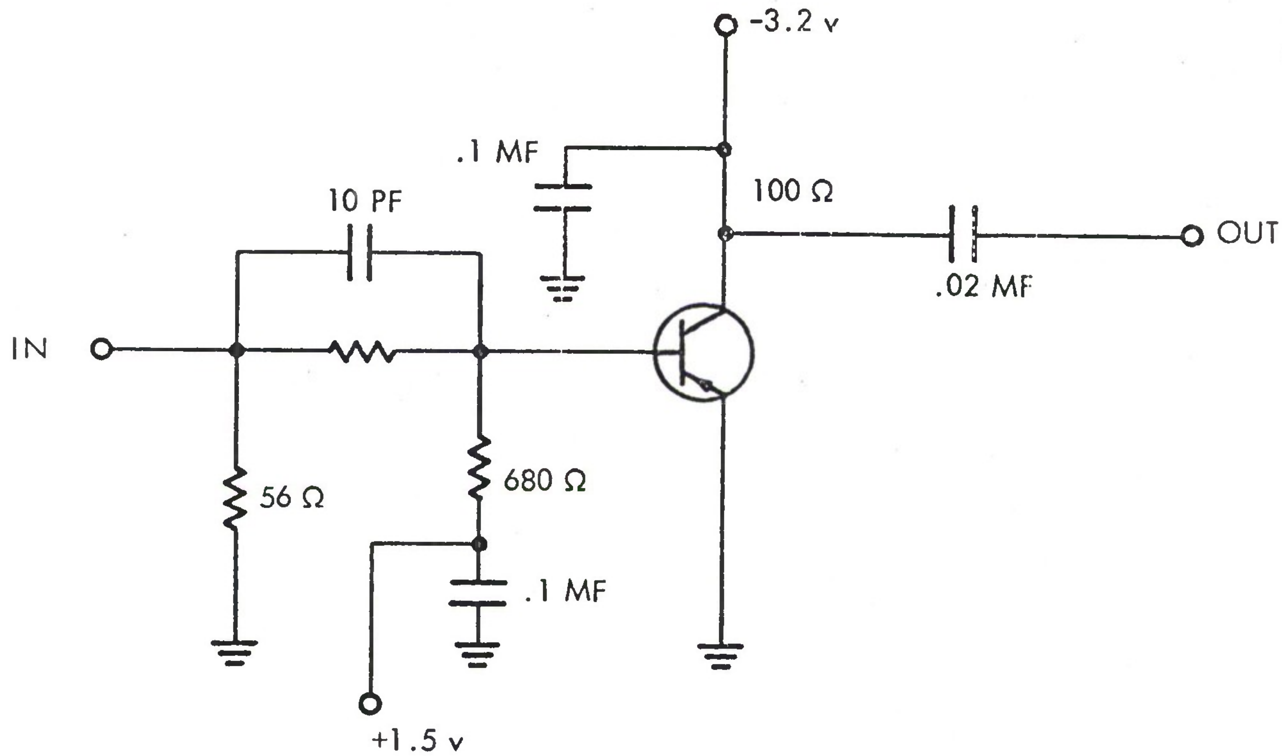
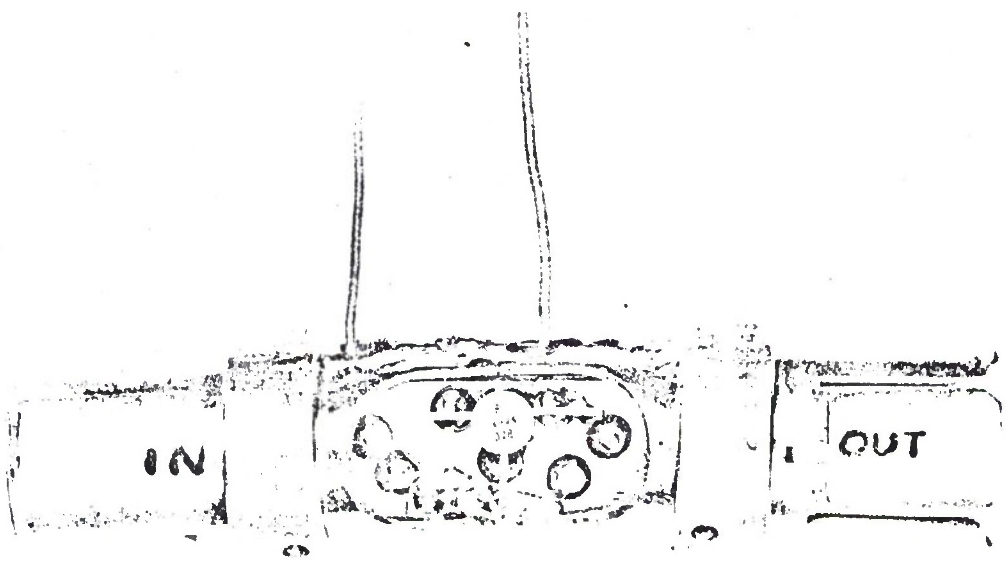


Upper 0.2V/CM
Lower 2.0V/CM
Time 5 NSEC/CM
Freq. 200 MC

Fig. 7
200 mc binary circuit and waveforms

FIGURE 8





Jig used to switch 2 nsec pulse with schematic

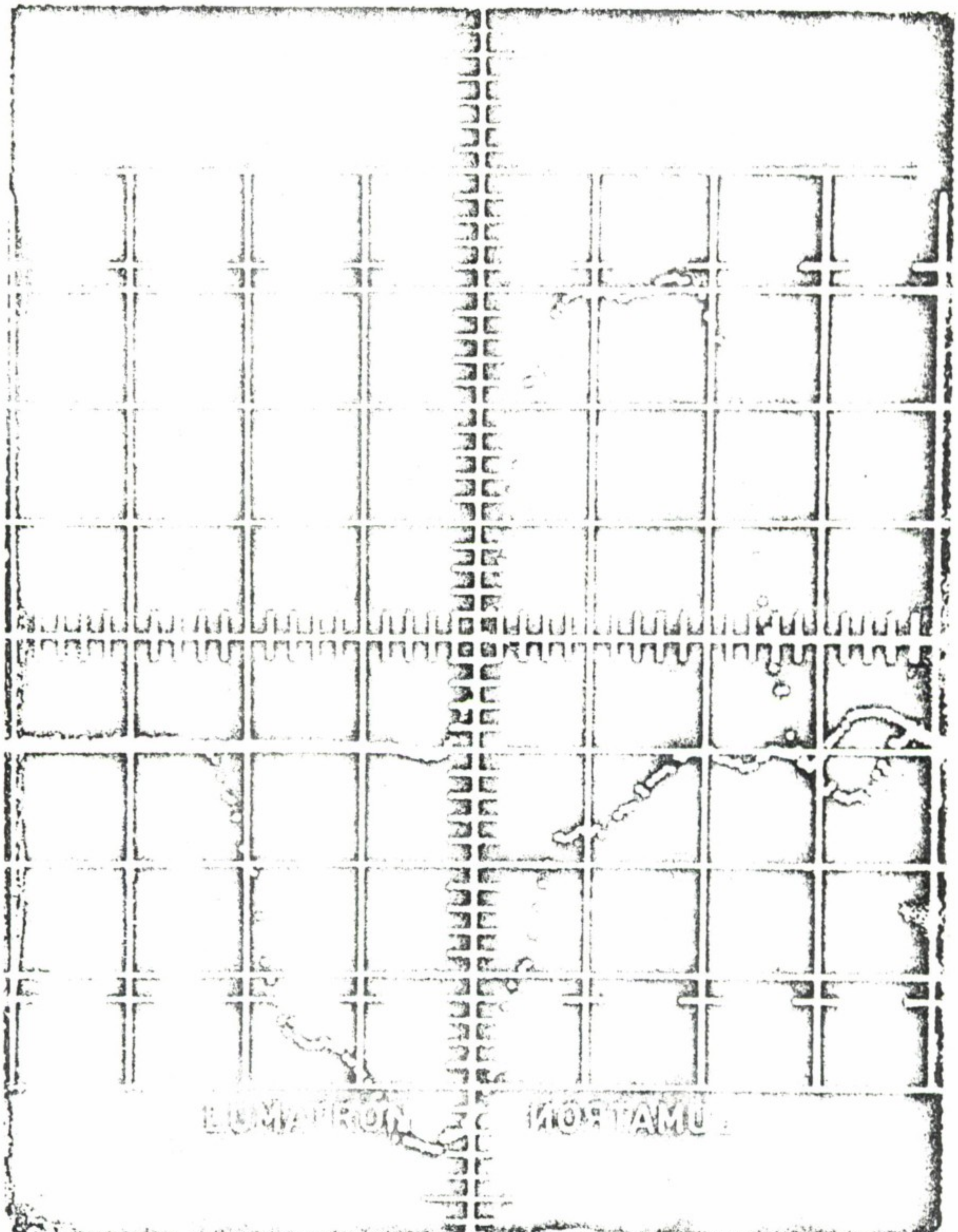


FIGURE 9
Photograph of input and output pulse in 2 ns application

VI. MICROSTRIP PACKAGE

A new package suitable for this and other microwave transistors has been designed with the following objectives:

1. Improved isolation between input and output.

2. Minimum series inductance (secured by holding rigidly to a characteristic impedance of 50 ohms).

3. Minimum high frequency loss (by careful matching).

4. Configuration suitable for use in microstrip transmission lines.

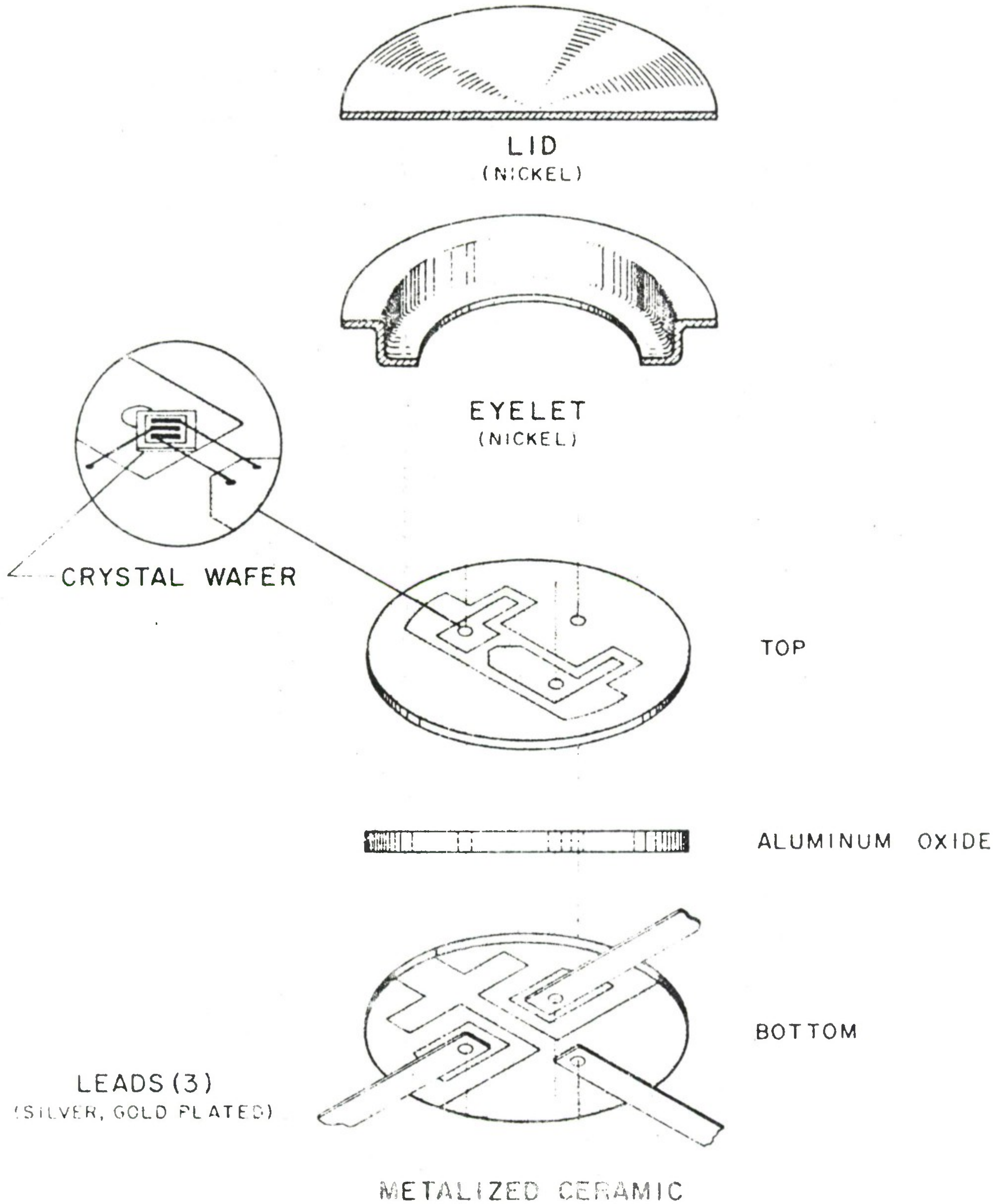
In the initial version of the package, the emitter is connected to the outside case in order to minimize emitter inductance, but this feature is not mandatory. Figure 10 shows the construction. The geometry is such that every portion of the internal circuit of the package has a nominal characteristic impedance of 50 ohms.

Evaluation of the new package has been started but is not yet complete. Characteristic impedance is being measured by a pulse technique shown in a block diagram, Fig. 11. Reflections that occur in the 50 ohm transmission line system are viewed on a calibrated sampling oscilloscope. The scope shows the magnitude of the impedance causing the reflection. It is calibrated by simply plugging in a known 75 ohm transmission line and adjusting the gain so that the 25 ohm impedance increment (above the 50 ohm system) produces 5 divisions of deflection or 5 ohms per division. Then the unknown microstrip line (containing the new transistor package) is inserted in place of the calibrating line, and the impedance of the unknown is observed directly.

Figure 12 is a photograph of the oscilloscope response obtained on the first engineering sample package. This shows that the moninal 50 ohm microstrip transmission line used for mounting the package had a characteristic impedance of 47 ohms, and the package sample had a characteristic impedance several ohms less than 47. This first package model had dimensional errors caused by an incorrect silk screen and these dimensional errors account for the low characteristic impedance. New silk screens have been obtained and new engineering samples have been built. These samples are now in process of evaluation. First indications are that the characteristic impedance of the new models is approaching closer to 50 ohms. Other measurements on the new package will include the high frequency losses.

FIGURE 10

50 OHM MICROSTRIP PACKAGE



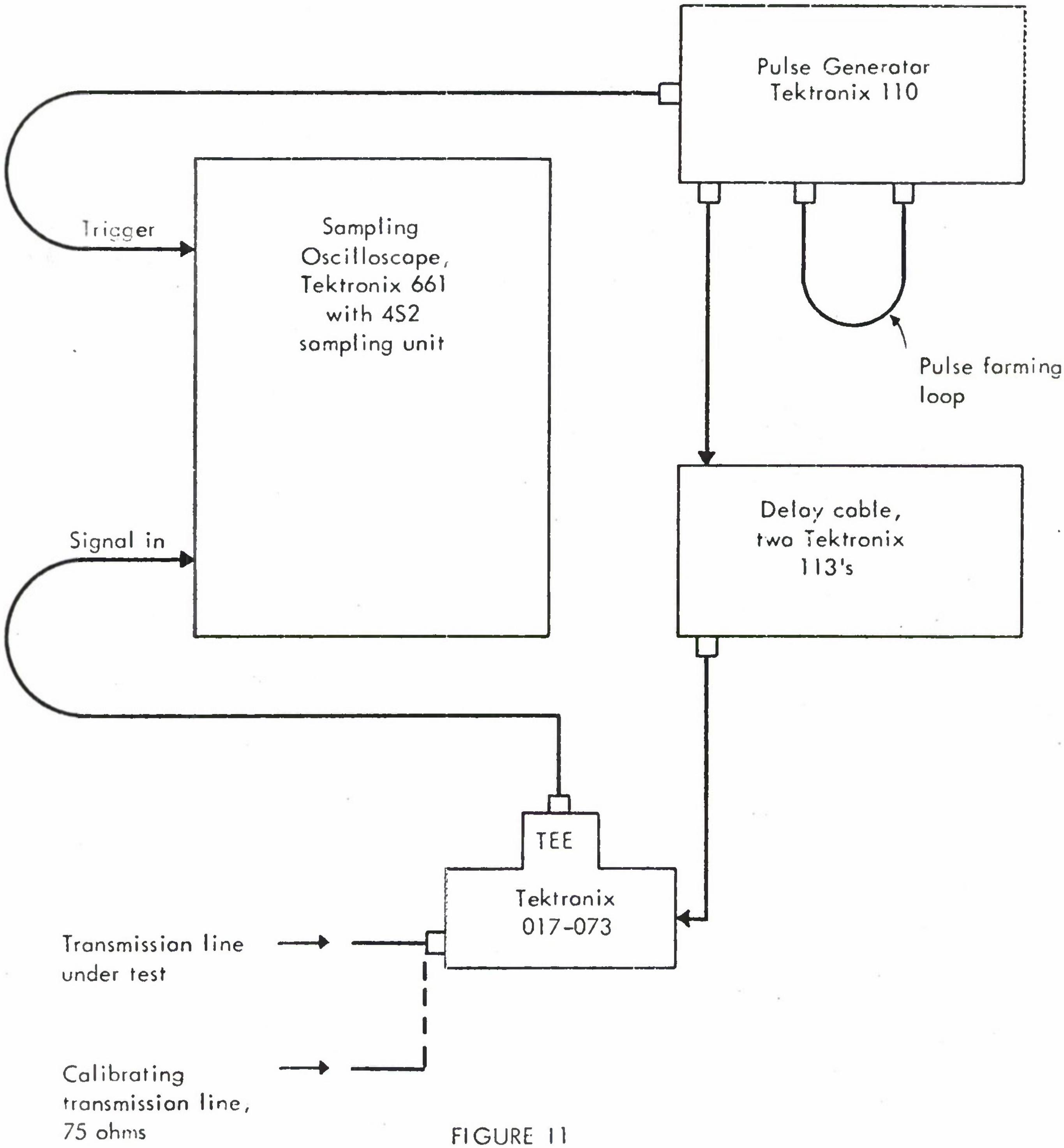


FIGURE 11

Pulse reflection technique for measuring characteristic impedance of microstrip line and microstrip package.

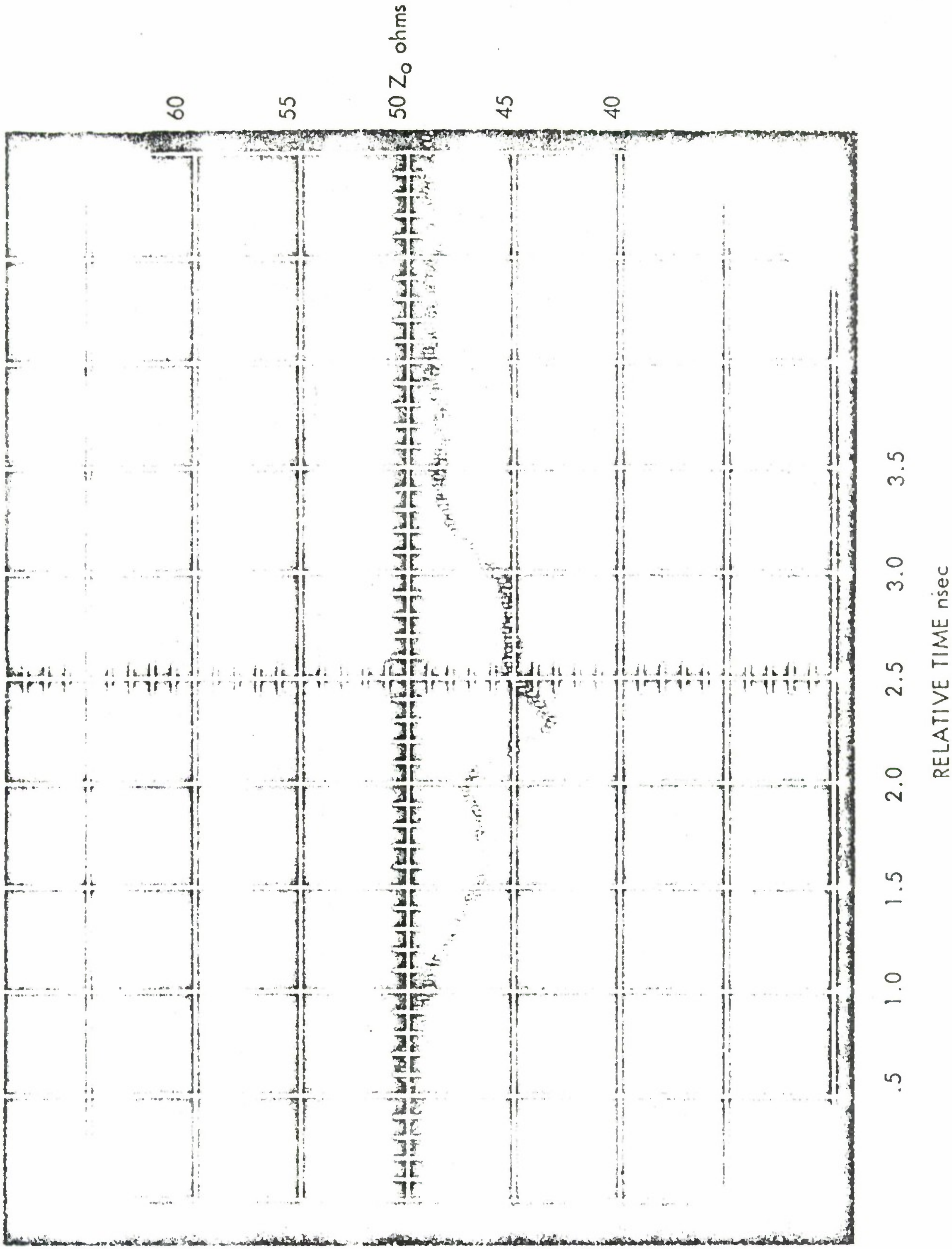


FIGURE 12
Characteristic impedance of 50 ohm microstrip package as measured by pulse technique

VII. FUTURE PLANS

A further improvement in this transistor which is now possible is to planarize it, including expanded contacts. This will improve repeatability by eliminating the damage to the crystals which is caused by thermal compression bonding. TI's proposal to Lincoln Laboratory dated 26 July 1963 describes an extensive but feasible program for planarizing the device. Planarizing also will give new design freedom in the geometry of germanium transistors. This will be a big step forward, leading probably to higher frequencies and lower base resistances.

VIII. SUMMARY

As the data indicates, the basic objectives of the germanium microwave switching transistor program under Lincoln Laboratory Order No. C-00949 have been achieved, obtaining an average base resistance of 51 ohms while retaining a high cut-off frequency f_T averaging 2.8 gc. A microstrip package has been designed, samples built, and evaluation has begun. Fifty transistors have been submitted to Lincoln Laboratory as state-of-the-art samples.

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13. ABSTRACT

Texas Instruments has completed a program under Lincoln Laboratory Order No. C-00949 to improve the germanium microwave switching transistor developed under previous contracts with Lincoln Laboratory. The principal objective was to materially reduce base resistance, r_b, while maintaining or slightly increasing the high cut-off frequency, f_T. Early stages of the work under this order were described in an Interim Report, and this final report describes the total work and the results obtained.

14. KEY WORDS

germanium
microwave switching transistor
bonding
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microstrip