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TECHNICAL REPORT ECOM-01758-5

GUNN EFFECT DEVICES

FIFTH QUARTERLY TECHNICAL REPORT

By

M.L. WRIGHT

MAY 1967

ECOM

UNITED STATES ARMY ELECTRONICS COMMAND • FORT MONMOUTH, N.J.

CONTRACT DA 28-043 AMC-01758(E) - ARPA Order No. 692
HEWLETT-PACKARD COMPANY
HEWLETT-PACKARD LABORATORIES
Palo Alto, California

The work prepared under this contract is a part of PROJECT DEFENDER and was made possible by the support of the Advanced Research Projects Agency under Order No. 692, through the U. S. Army Electronics Command.

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Technical Report ECOM-01758-5

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FIFTH QUARTERLY TECHNICAL REPORT
15 November 1966 to 15 March 1967

Report No. 5

Contract No. DA 28-043 AMC-01758(E)
ARPA Order No. 692
O/S Task No. 7900.21.243.38.00

Prepared by

M. L. Wright

HEWLETT-PACKARD COMPANY
Hewlett-Packard Laboratories
Palo Alto, California

for

U. S. Army Electronics Command, Fort Monmouth, New Jersey

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ABSTRACT

Additional devices have been made using GaAs material produced by Hewlett-Packard Laboratories. One series of these new devices (TE 65) has produced a noise level approaching that of a klystron signal generator. Low-frequency, low-field equivalent circuits have been experimentally determined for both the boat-grown and solution-grown materials.

A program to identify the noise mechanisms was begun and has eliminated the present pressure contacts as a noise source.

The computer circuit simulation program was run for resonant circuit loading conditions. A 10 mw power output at 1% efficiency was predicted at 4.45 Gc for our present circuit configuration.

PURPOSE

A development program is to be conducted aimed at the utilization of the Gunn effect for various types of microwave generating devices in the 1 to 50 GHz frequency range. Spectral line width should be less than 10kHz and operation should be in a single mode. Output power should be at least 25 mW in CW operation and 3W peak in pulsed operation with a conversion efficiency of at least 3%. CW operation should be obtained in ambient temperatures from -25°C to +50°C with a single device.

Application of these devices for amplification and modulation is to be investigated.

FOREWORD

The work reported on in this report has been authorized by the Contracting Officer, Mr. Edgar D. Fitzgerald, Electronic Components Laboratory, U. S. Army Electronics Command, Ft. Monmouth, New Jersey, under Contract No. DA 28-043 AMC-01758(E) and titled "Gunn Effect Devices". The Project Engineer at the U. S. Army Electronics Command is Mr. Maurice Druesne.

The work has been performed at Hewlett-Packard Laboratories under the supervision of M. L. Wright. The report has been prepared by M. L. Wright. Significant contributions during the report period have been made by J. Barrera, N. Mantena, G. W. Mathers, E. Gowen and B. Farrell. Discussions with M. M. Atalla and C. F. Quate were of great benefit.

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I. DEVICE FABRICATION AND MEASUREMENTS

I. 1 Introduction

During the last quarter the effort has centered on the HPL solution-grown material, because of the performance improvement over earlier boat-grown devices. One group of devices gave the best performance to date, and approached the noise level of klystron signal generators. Improved cavity designs have been made to take advantage of the improved devices.

I. 2 Solution-grown Epitaxial Device Evaluation

During the last quarter three more batches of HPL solution-grown epitaxial material have been processed and tested as oscillators. These completed devices have been given the designations TE 57, TE 65 and TE 79 samples. In addition a further evaluation of the first series of solution grown devices (TE 34) has been made.

a. Performance Summary

A summary and comparison of some of the more pertinent operating characteristics of these four groups of devices are given in the succeeding table and graphs.

TABLE I

Device Designation:	TE 34	TE 57	TE 65	TE 79 Si/79 SiH
Number of Samples Tested:	21	14	20	10
Resistivity (Ω cm)	0.65	1.5	0.9	0.45
Temperature Coefficient of Resistance	+	+	+	+
Thickness (microns)	25-30	25-30	20-25	20-25/30-35
Small Contact Diam. (microns)	75	75	75	94
Threshold Voltage (volts)	11-13	11-13	6.5-8.5	8-10/10-12
Threshold Current (m.a.)	100-120	50-60	70-90	190-220
Tuning Range in Coaxial Cavity (gHz)	3.5-6.5	4.5-7.0	4.5-8.5	4-7.5/3-6
Relative Noise Performance	Good	Fair	Very Good	Poor

In the TE 34 batch, the FM noise performance as well as the low frequency noise current below threshold was quite variable from unit to unit. Some of the units showed a steep rise in low frequency noise current versus D. C. device voltage from $\frac{Vth}{2}$ up to Vth. The low-frequency noise performance of representative devices is shown in Figures 1 and 2 and the microwave noise is shown in Figure 3.

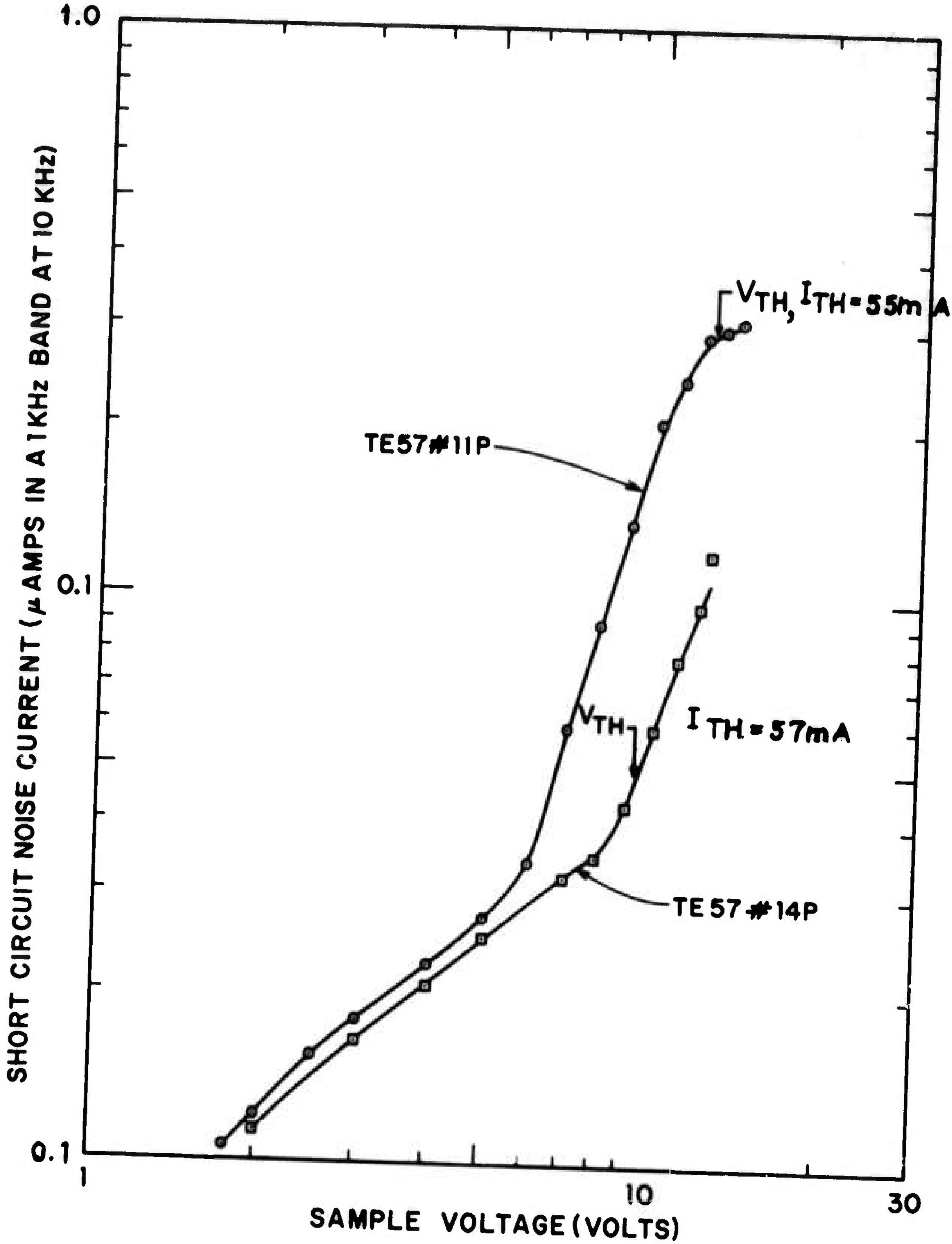


Fig. 1: Low-Frequency Noise Current vs. Voltage for Solution-Grown Devices

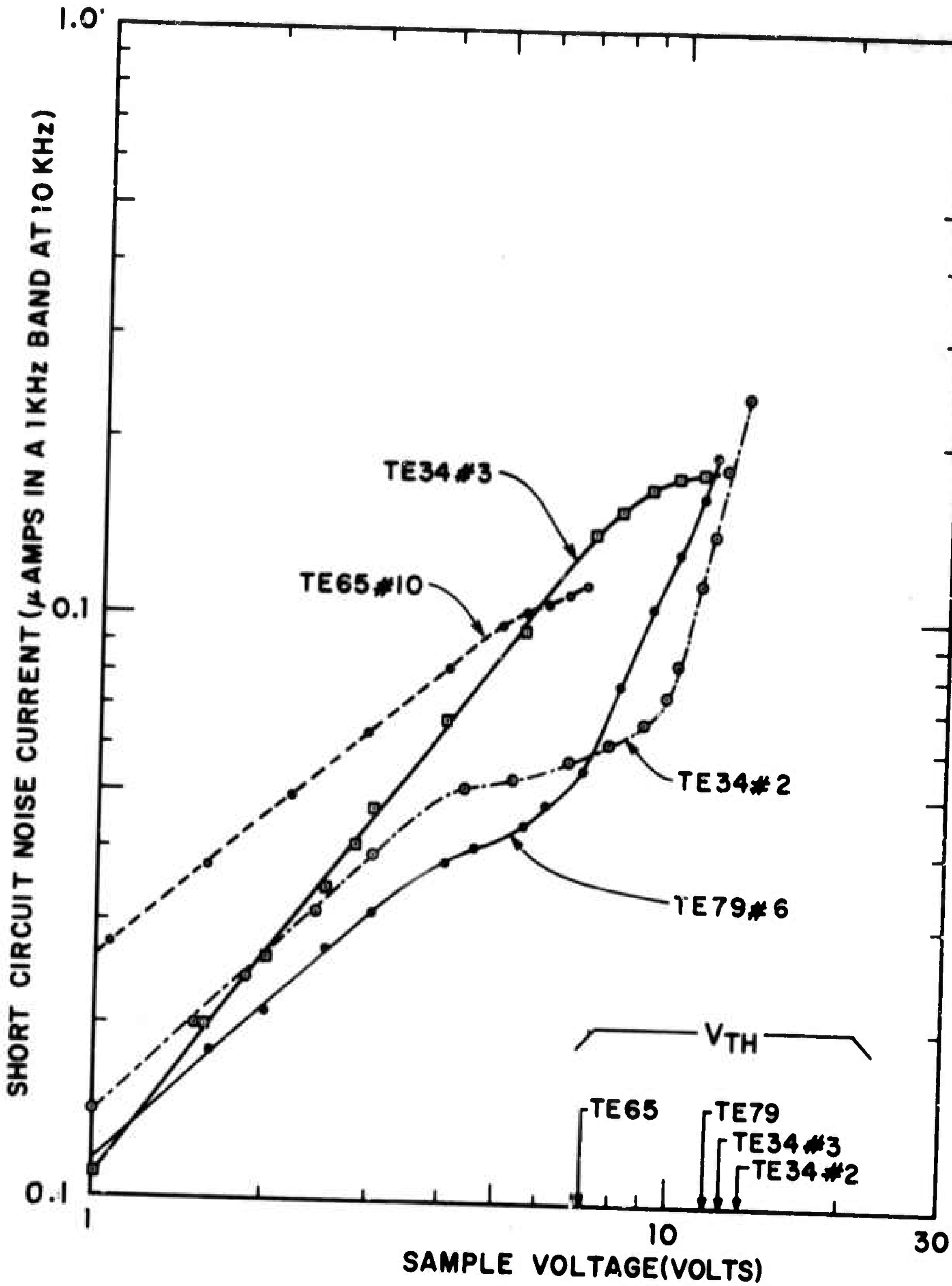


Fig. 2: Low-Frequency Noise Current vs. Voltage for Solution-Grown Devices

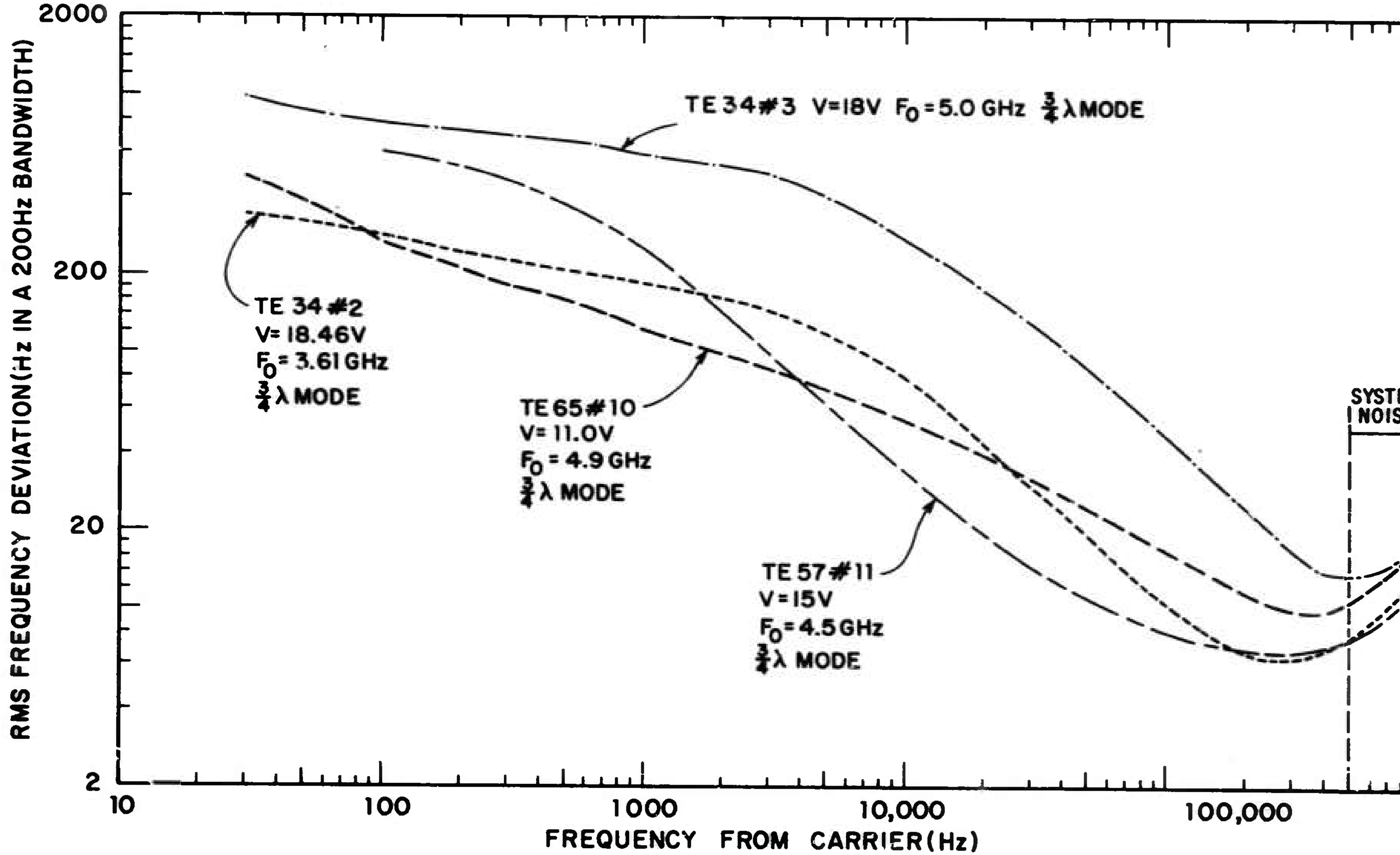


Fig. 3: Spectral Response of Detected Microwave Noise in Solution-Grown Devices

Quite a number of these devices shorted at operating voltages of from 16 to 20 volts under both pulsed and CW operation, although some devices would operate up to 25 volts CW without showing any appreciable change in characteristics. This effect was apparently not always due to overheating, since there is essentially no heating of the devices under pulsed operation.

The TE 65 batch represents the best devices that have been tested so far. The devices are quite consistent in their operating characteristics, and will operate CW up to 2 or 3 times the threshold voltage without showing any appreciable signs of deterioration. The noise performance of these devices is also very good -- some of the units under some operating conditions (frequency, voltage, cavity mode) approached the performance obtained with a fairly good klystron signal generator.

Three somewhat different processing procedures were used to make three series of devices from the TE 79 batch of material. These procedures and corresponding device designations were as follows:

(a) TE 79 - #___	Standard process as described previously.
(b) TE 79 - #___ Si	SiO_2 was evaporated over the entire top contact surface, after contact evaporation but before alloying. After alloying this

SiO_2 was completely removed. (This particular series of devices measured consistently thinner than the other two as indicated by the figures in the table.)

(c) TE 79 - #___SiH SiO_2 evaporated as described above, but after alloying the SiO_2 was removed only over the circular metal contact region.

No noticeable difference in the operating characteristics of any of these devices (a, b, c above) in a coaxial cavity was measurable.

Quite a number of the TE 79 devices also shorted at operating voltages of from 10 to 12 volts under both pulsed and CW operation. This behavior was somewhat similar to the TE 34 devices mentioned above, although the voltage range was lower. As shown in Figure 2, these units also showed a sharp rise in the low frequency noise current versus device voltage below threshold, and it is thought possible that these two effects might be related.

b. Low-Frequency Equivalent Circuits

An attempt has been made to find a relationship between the low frequency noise current measured below and above threshold and the FM noise measured on the RF carrier when the device is oscillating in a cavity. This has involved measuring the low frequency equivalent circuit of the device both above and below threshold,

$\frac{\Delta V}{\Delta I}$ and the FM modulation sensitivity of the device above threshold, and $\frac{\Delta F}{\Delta V}$ over a range of frequencies from 30 Hertz to 1 MHz. So far no consistent relationship has been found as there are still some missing links in our measurements. However, the demodulated FM noise and the low frequency noise current do vary similarly with frequency and in magnitude. The low frequency equivalent circuits as established to date for the two types of material is shown in Figure 4 and 5.

For both the boat-grown and solution-grown devices the following conditions are found to be true.

1. Above threshold, under <u>most</u> operating conditions and when the device is oscillating, the effective input resistance is negative: i. e.

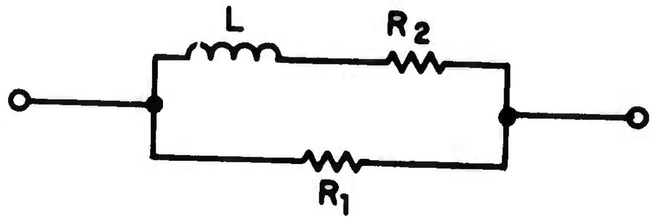
$$|Rn| > R_1' \quad \text{or} \quad \frac{R_1' \; R_2'}{R_1' + R_2'}$$

2. R_1 and R_2 approach infinity as the device voltage approaches $V_{threshold}$.

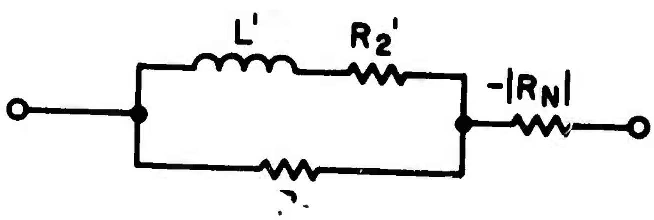
3. The time constants $\frac{L}{R_1}$, $\frac{L}{R_1+R_2}$, CR_2 and $C(R_1+R_2)$ are nearly independent of the applied d. c. voltage below threshold.

4. The inductance (L) and capacity (C) are apparently associated with the temperature sensitivity of the resistance and

a. BELOW THRESHOLD



b. ABOVE THRESHOLD



$R_1' \simeq R_1 = 40\Omega \longrightarrow \infty$ (AS CURRENT INCREASES)

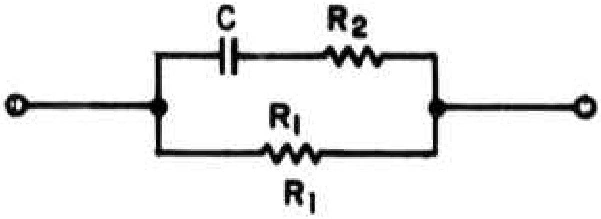
$R_2' \simeq R_2 = \infty \longrightarrow 20\Omega \longrightarrow \infty$ (AS CURRENT INCREASES)

$L' \simeq L = 800\,\mu H$

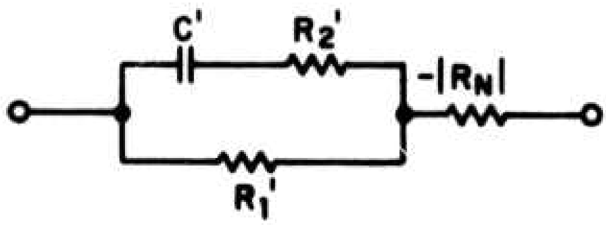
$R_N = -300 \longrightarrow -800\,\Omega$

Fig. 4: Low-Frequency Equivalent Circuits for Boat-Grown Devices

a. BELOW THRESHOLD



b. ABOVE THRESHOLD



$R_1' \simeq R_1 = 50\Omega \rightarrow \infty$ (AS CURRENT INCREASES)

$R_2' \simeq R_2 = \infty \rightarrow 1600\,\Omega \rightarrow \infty$ (AS CURRENT INCREASES)

$C' \simeq C \cong 1000$ pF

$R_N = -1000 \rightarrow -2500\Omega$

Fig. 5: Low-Frequency Equivalent Circuits for Solution-Grown Devices

the thermal time constant of the mounted device.

5. R_2 approaches infinity as the device voltage approaches zero.

As yet insufficient measurements have been made to enable us to quantitatively sort out the positive and negative parts of the resistance above threshold.

c. Improved Cavity Design

A small coaxial cavity, tunable from 4.0 to 8.0 gHz on the $\frac{\lambda}{4}$ mode with a non-contacting movable plunger has been designed and constructed. This design has incorporated in it the following features:

1. Either 1 or 2 devices can be mounted in the cavity and operated at the same time.

2. The location of the devices along the transmission line relative to the short circuit can be varied in desired steps. This affects a means of changing the effective resistance and reactance that the device sees.

3. The devices are mounted radially in the coaxial cavity on small radial posts of different diameters and lengths. This affords a second means of adjusting the effective impedance seen by the device.

Preliminary tests of some TE 65 devices operating in this cavity have shown the following results:

1. Tuning range from 3.5 to 6.5 GHz with either 1 or 2 devices under light loading. This frequency range is lower than the "unloaded" tuning range of the cavity because of the added capacitive loading produced by the device.

2. A power output of from 8.0 to 10.0 mw from one TE 65 device, and from 16.0 to 20.0 mw with 2 devices operating at 15V and 65 or 140 ma over the frequency range 4.5 to 6.0 GHz.

3. No significant deterioration in the spectrum was observed when the loading on the device was varied from very light up to nearly the maximum power output listed above.

Further tests with this cavity are planned in the future.

II. NOISE MEASUREMENTS

In an effort to obtain information on the controlling factors of Gunn oscillator noise a study was made of the possible low frequency noise sources. The sources can be separated into three categories 1) contact noise 2) bulk noise and 3) surface noise. Due to the magnitude and structure of the current noise previously reported (Fourth Quarterly Technical Report) it was initially supposed that the controlling noise source is connected with the device contacts including contact perimeter surface conditions, and possibly even the external pressure contacts. A program was planned for determining the various noise contributions and their relative importance to the total noise. In this report we present the first results of the program and can at this time arrive at some fairly important conclusions from the results.

The first phase of the program involved measurements on one large batch of solution-grown GaAs devices (TE 65) in order that a certain degree of control could be maintained. The devices were made with our standard evaporated contacts with 3.0 mil diameter dots on one side and completely covered areas on the other. The overall chip size was approximately 15 mil square and about 1 mil thick.

The first task was to establish what contribution, if any, the external pressure contacts make to the noise, and then determine if an intimate soldered or wire bonded external contact would reduce this noise. In general, pressure metal-to-metal contacts do <u>not</u> exhibit good noise behavior, especially for dissimilar metals. Several devices were mounted as usual on copper heat sinks and pressure contacted with a silver rod; others were mounted on TO-18 gold-plated headers with a gold wire soldered to the 3 mil dot, thereby making an intimate metal bond to the device. Low frequency current noise measurements were made on both types of mounted devices and a comparison between the two was made. In Figures 6 through 9 we show some typical results from the TE 65 devices. Figures 6 and 7 show a noise spectrum for both a pressure contacted and an intimate wire bonded device respectively. The noise plots show a $\frac{1}{f}$ behavior and the magnitudes are quite comparable. For these examples, the pressure contacted device even had a somewhat lower magnitude than the wire bonded device. Figures 8 and 9 show plots of current noise versus bias current for the same two devices -- both reaching a near square law dependence.

The conclusion is that the present external pressure contacting method does not contribute noticeably to the overall device noise. In the pressure contacted Gunn devices it was found that the samples showing the smallest low-frequency current noise also showed the lowest microwave FM noise. This continued correlation supports the previous hypothesis that the current noise and the FM noise are related.

Current noise measurements were also made with the dot contact biased both positively and negatively (the negative bias being the normal mode of operation) and the results showed very little or no difference for the two cases.

The next efforts will involve: 1) low temperature current noise measurement to check the supposed independency of $I/_f$ noise with temperature; 2) current noise measurements on samples with

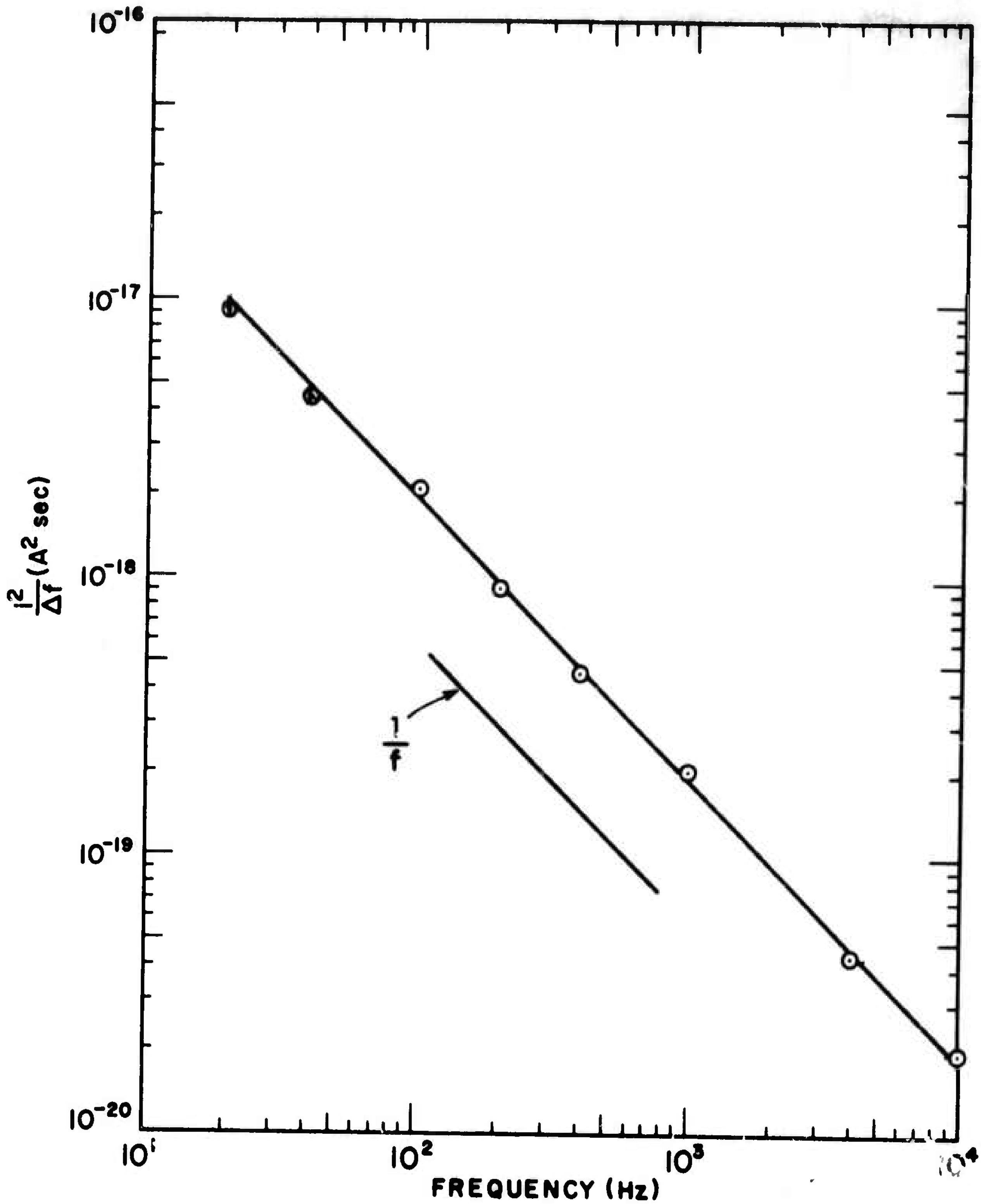


Fig. 6: Low-Frequency Noise Spectrum of Pressure-Contacted Device

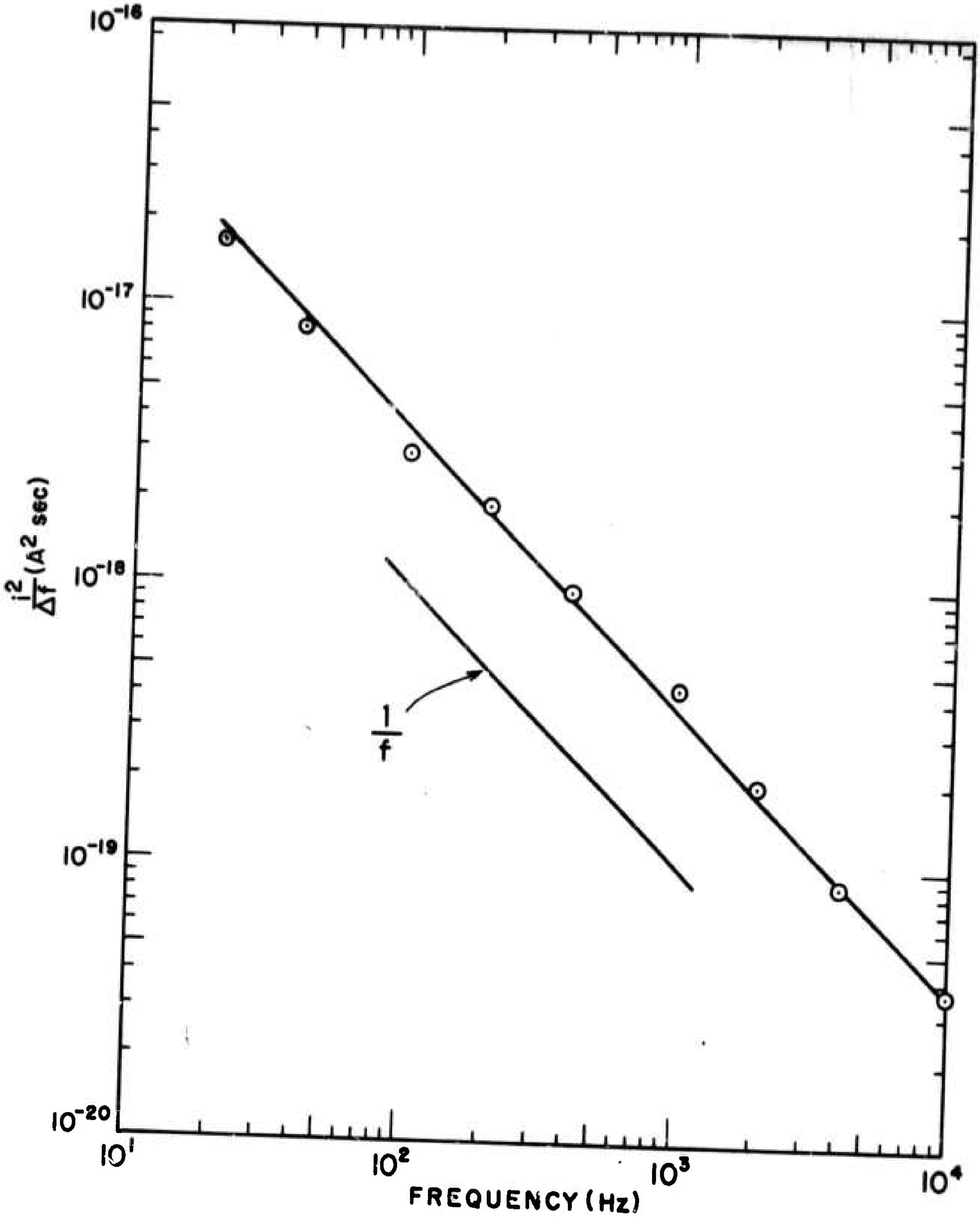


Fig. 7: Low-Frequency Noise Spec rum of Wire-Bonded Device

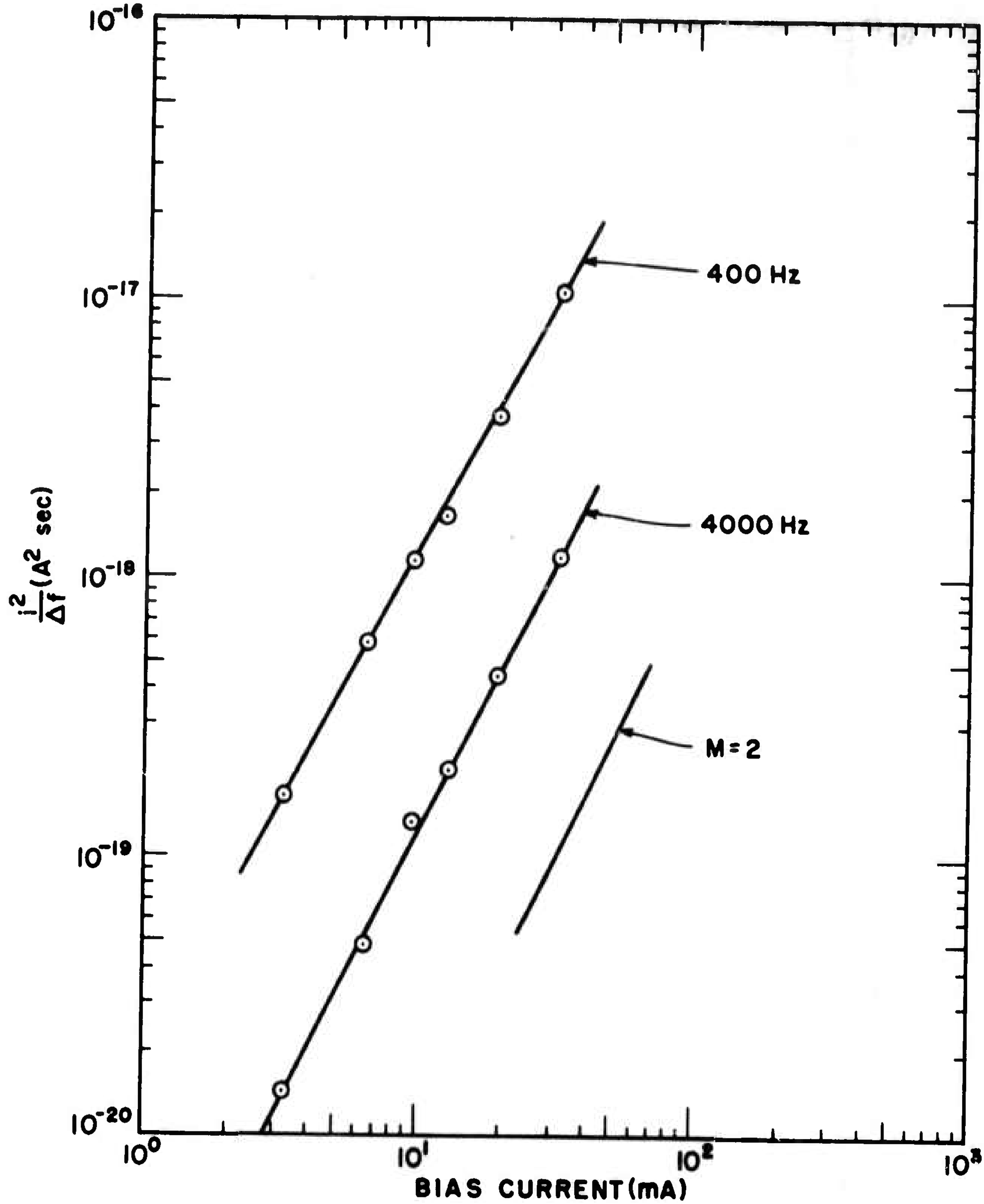


Fig. 8: Bias Current Dependence of Noise of Pressure-Contacted Device

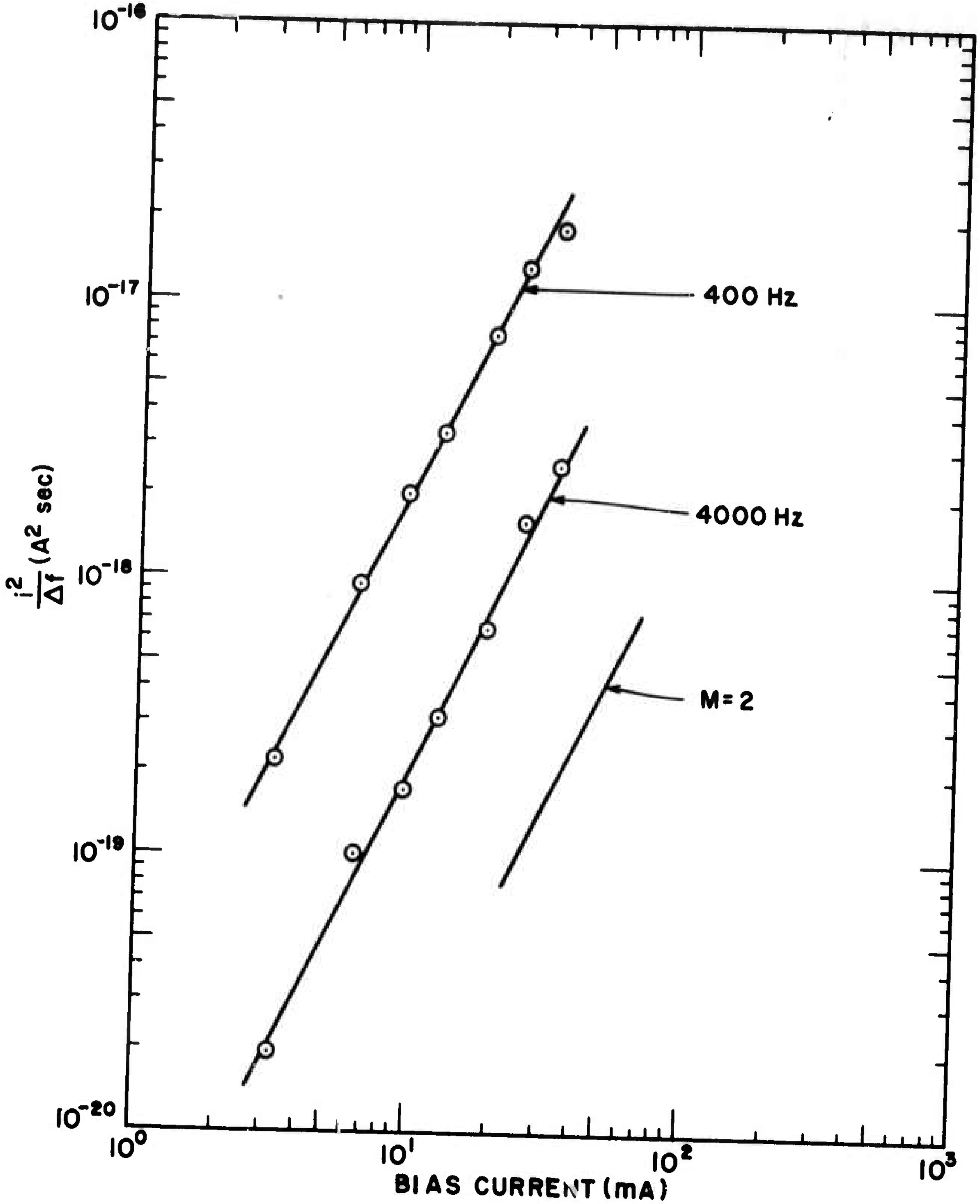


Fig. 9: Bias Current Dependence of Noise of Wire-Bonded Device

differing contact perimeter to area ratios; 3) current noise measurements on new devices made with η+ substrates; 4) current noise measurements on bar samples with non-current-carrying noise probes in order to separate out bulk and contact noise contributions.

III. COMPUTER CIRCUIT SIMULATION

The computer model of a high-field domain in a Gunn device has been described in the Fourth Quarterly Technical Report. Results obtained with pure resistive loads and a series combination of resistance and inductance were also discussed. In this quarter computer calculations have been made with parallel resonant circuits acting as loads. The device parameters are:

$$n_o = 10^{15}/cc$$

$$\mu_1 = 5000\ cm^2/V\ sec$$

$$A_d = 0.71 \times 10^{-4} (cm)^2$$

$$L_s = 20\ \mu m$$

$$W_d = 1\ micron$$

$$f_G = 5.5\ GHz$$

A new I-V curve for the domain resistance, shown in Fig. 10, is chosen for the present calculations since it is believed to be a closer representation of the actual domain resistance. A restriction placed on the

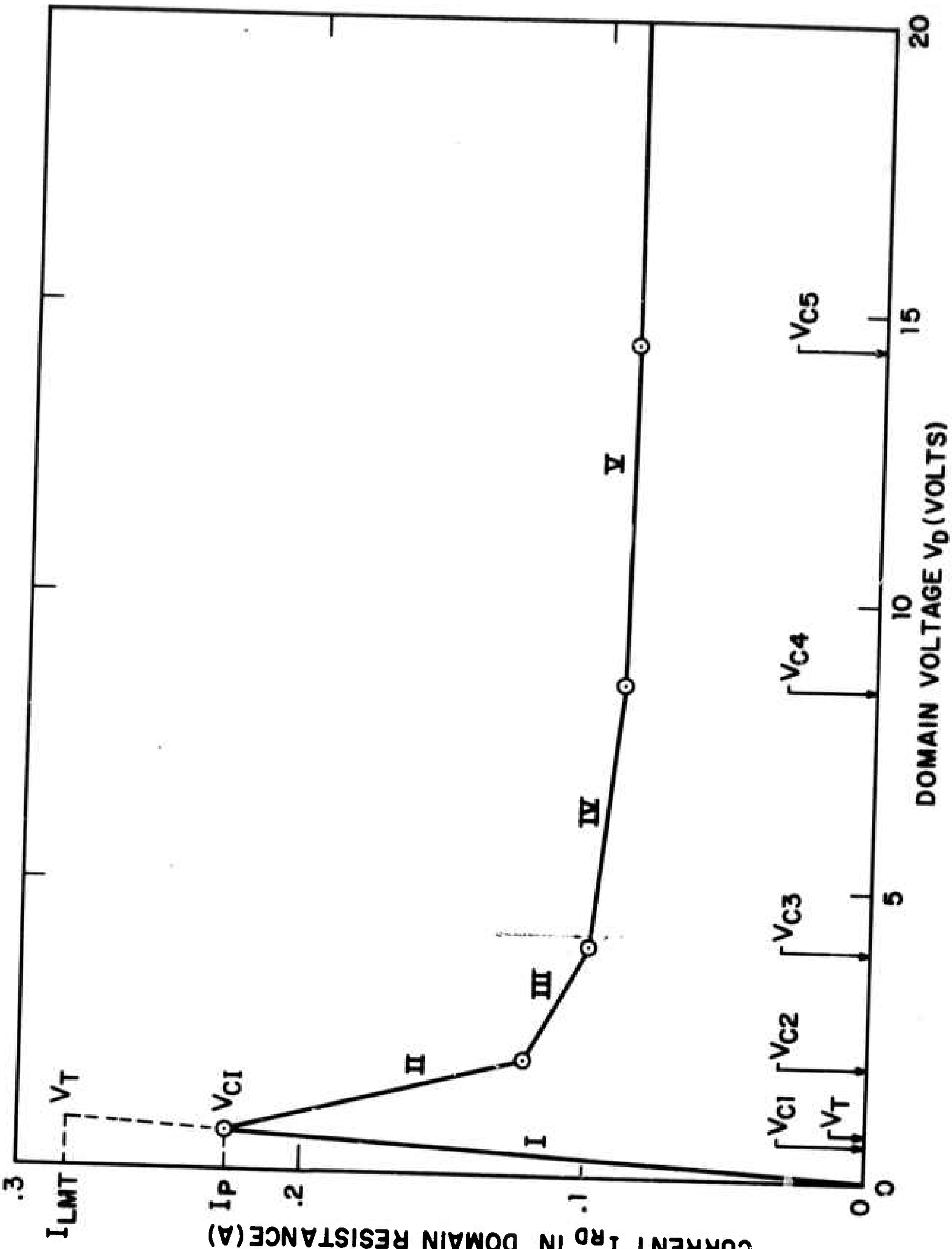


Fig. 10: Linearized Domain Voltage-Current Response

present computer model is that the bulk resistance always remains positive and the total bulk current is limited as described below.

A fully-formed domain may have a conductance G_d defined by any of the curve segments II - V in Figure 10. When the domain completes its passage through the sample or when it is shut down by the circuit voltage, G_d assumes the low-field conductance G_1 of Curve I although V_d may be very large compared to V_{c1}. In order to prevent a big spike in bulk current, G_1 is made nonlinear such that

$$G_1 = \text{Slope of Curve I for } V_{D1} \leq V_T$$

and $$G_1 = \frac{I_{LMT}}{V_D} \quad \text{for } V_{D1} > V_T$$

where V_T and I_{LMT} are arbirarily chosen as

$$V_T = 1.2\, V_{c1} \quad \text{and} \quad I_{LMT} = 1.2\, I_p.$$

This restriction limits the validity of the model to the pure Gunn mode in which the presence or the absence of a high-field domain determines whether the microwave oscillations can be sustained or not.

Microwave Circuit

For preliminary calculations, the microwave cavity - Gunn device system shown in Figure 11 is simulated on the computer. The cavity may be either a coaxial, a strip line or a waveguide type. However, most of the experiments with the Gunn device have been conducted with the coaxial cavity and we will obtain the equivalent parallel R, L, C circuit for this cavity

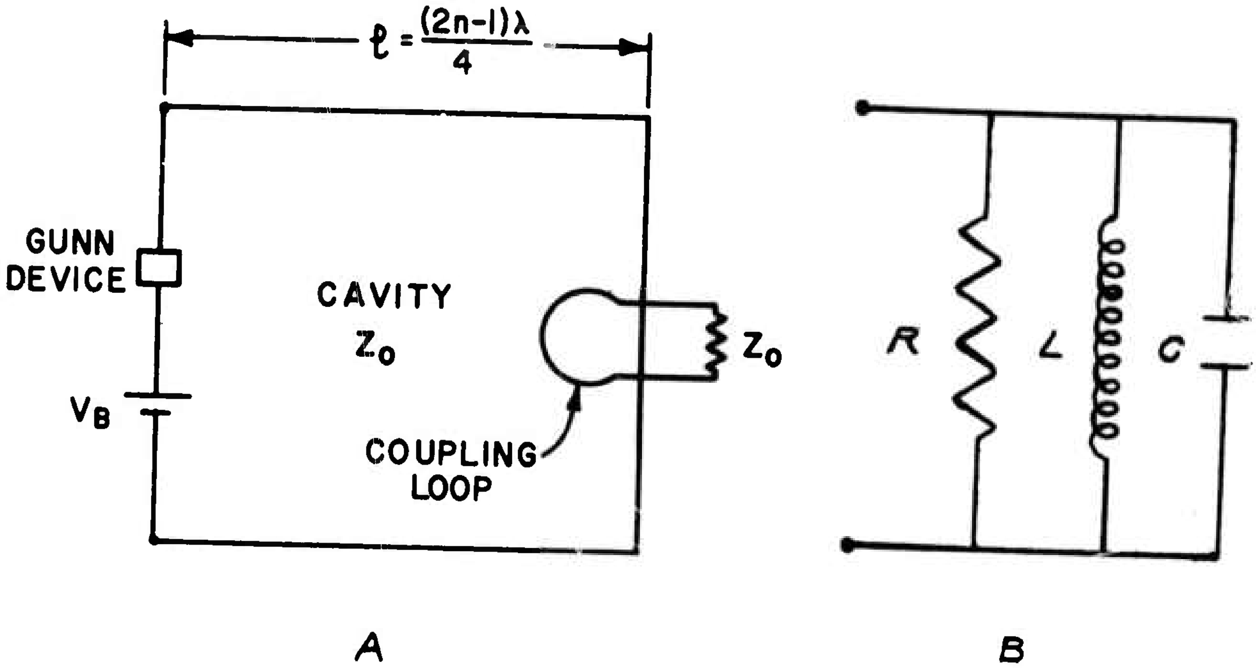


Fig. 11: A - Microwave Cavity - Gunn Device System
B - Lumped Equivalent Circuit of Cavity at Device Terminals

The equations which determine the equivalent R, L, C of the cavity at the device terminals are given by

$$B = Y_o \cot \beta l \tag{1}$$

$$\frac{Q}{R} = \frac{\omega_o}{2} \frac{dB}{d\omega} \tag{2}$$

For $\beta l = (2n-1)\frac{\lambda}{4}$, the equivalent parallel resonant circuit is specified by

$$R = \frac{2Q Z_o}{\beta l} \tag{3}$$

$$L = \frac{R}{\omega_o Q} \quad \text{and} \quad C = \frac{1}{\omega_o^2 L} \tag{4}$$

Where Q is the loaded Q of the cavity and ω_o is the resonant frequency of the cavity without the device. Therefore, by specifying the length l, Q and the characteristic impedance Z_o of the cavity, we can determine the equivalent R, L and C from equations 3 and 4 above The results obtained for $Q = 130$, $f_o = 5$ GHz and $V_b = 10.5$ volts are shown in Figures 12-16. Since the cavity frequency $f_o < f_G$, the free propagation of domains is unchanged. However, the formation of a new domain is delayed since the sample voltage controlled by the circuit is swinging below threshold at the time the old domain is disappearing into the drain electrode. A new domain begins to form only after $V_{ST} \geq V_{TH}$. This behavior, shown in Figs. 12 and 13, reflects in the sample current shown in Fig. 14. The top of these current pulses has the same wave shape as the sample voltage swing below threshold. The total microwave current which is the sum of sample current and the current through the stray capacitance across the sample is shown in Fig. 15. The V_{RS} across the bulk outside of the domain may be seen from Fig. 16 to be limited to values below its threshold value of 5.2 volts. The operating frequency, as determined from the period of V_{ST}, is about 4.45 GHz and hence the device looks capacitive to the cavity. The power output and the efficiency of the device at the operating frequency of 4.45 GHz is estimated to be 10 mw and 1%, respectively. Similar calculations can be carried out for $f_o > f_G$.

These computer calculations will be discontinued during the next quarter so that efforts may be concentrated on realizing a practical microwave source capable of producing a CW power output of 50 mw with a tuning range of 6 to 12 GHz.

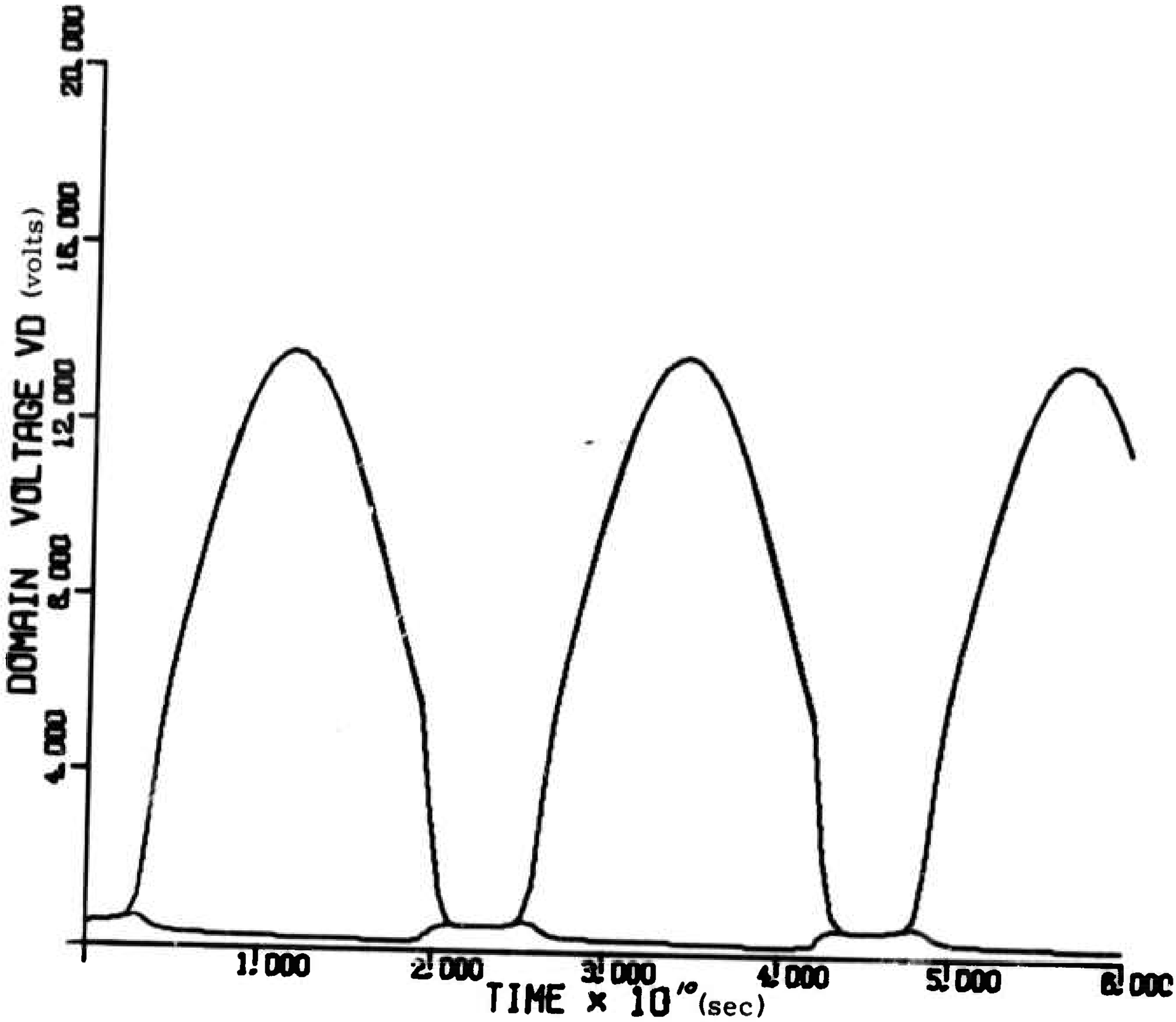


Fig. 12: Domain Voltage vs. Time (for resonant circuit at 5 Gc, Q = 130, fg = 5.5 Gc., bias voltage = 10.ₒ volts

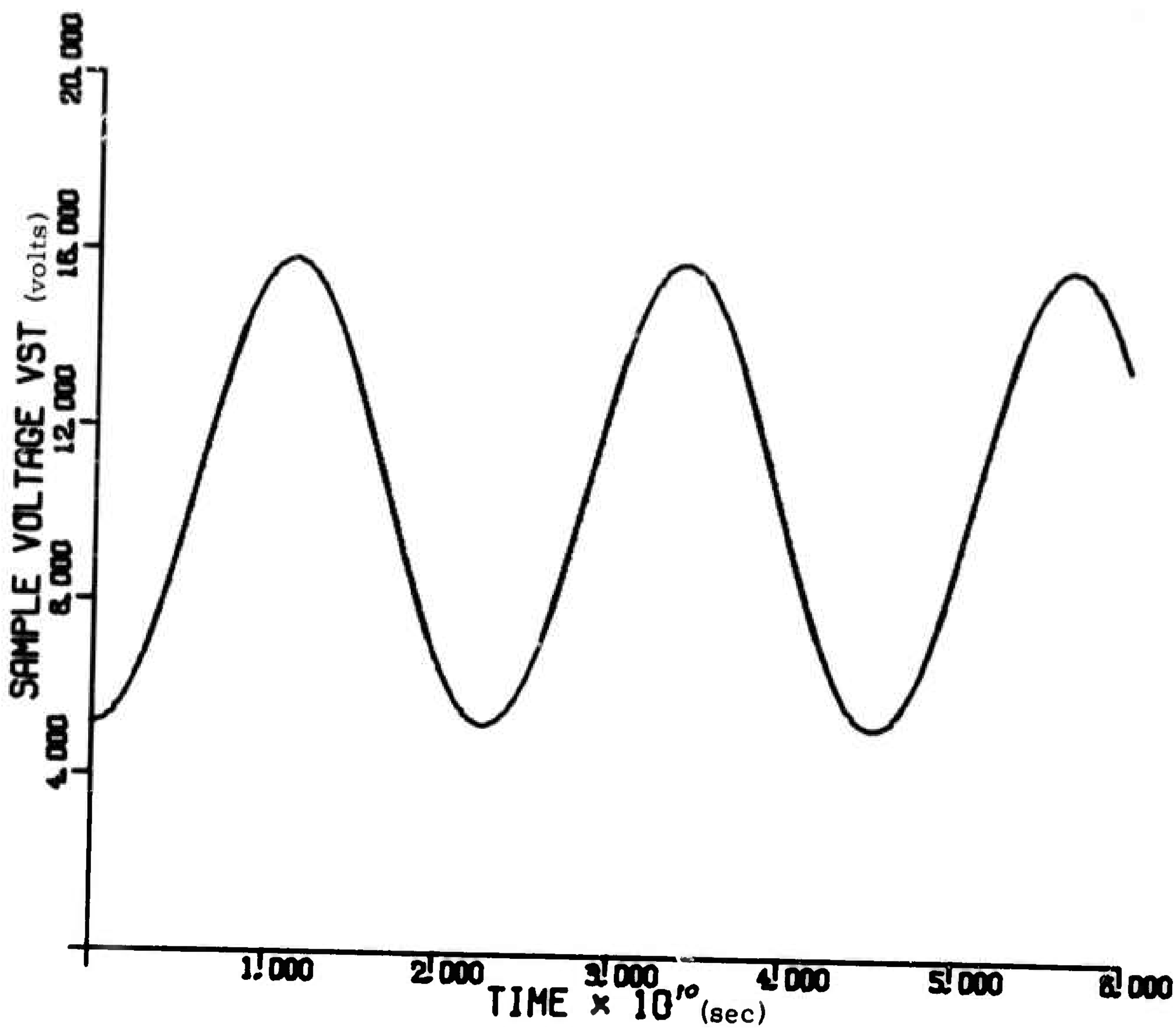


Fig. 13: Device Voltage vs. Time (for resonant circuit at 5 Gc, Q = 130, fg = 5. 5 Gc., bias voltage = 10. 5 volts

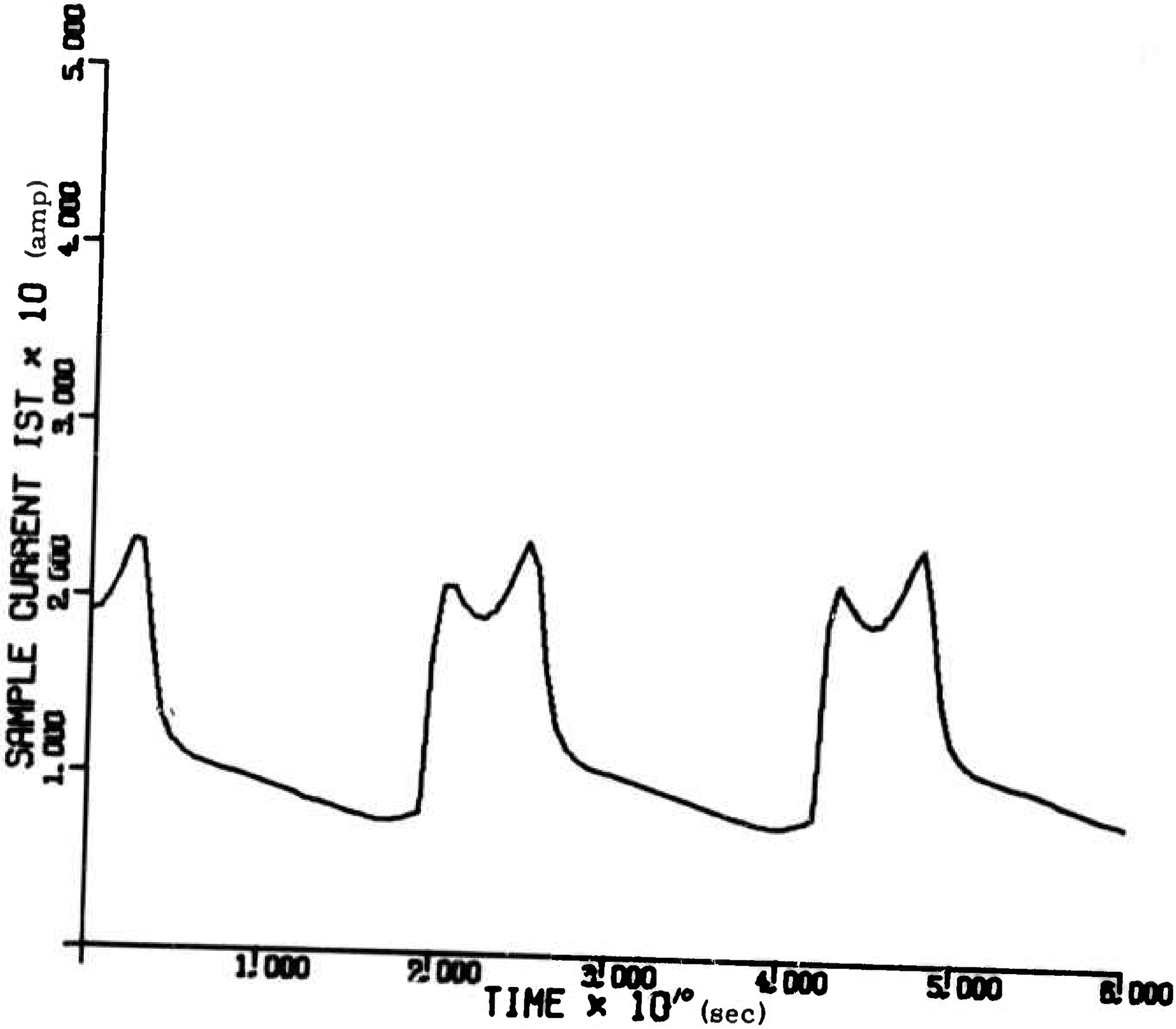


Fig. 14: Device Current vs. Time (for resonant circuit at 5 Gc, Q = 130, fg. = 5. 5 Gc., bias voltage = 10. 5 volts)

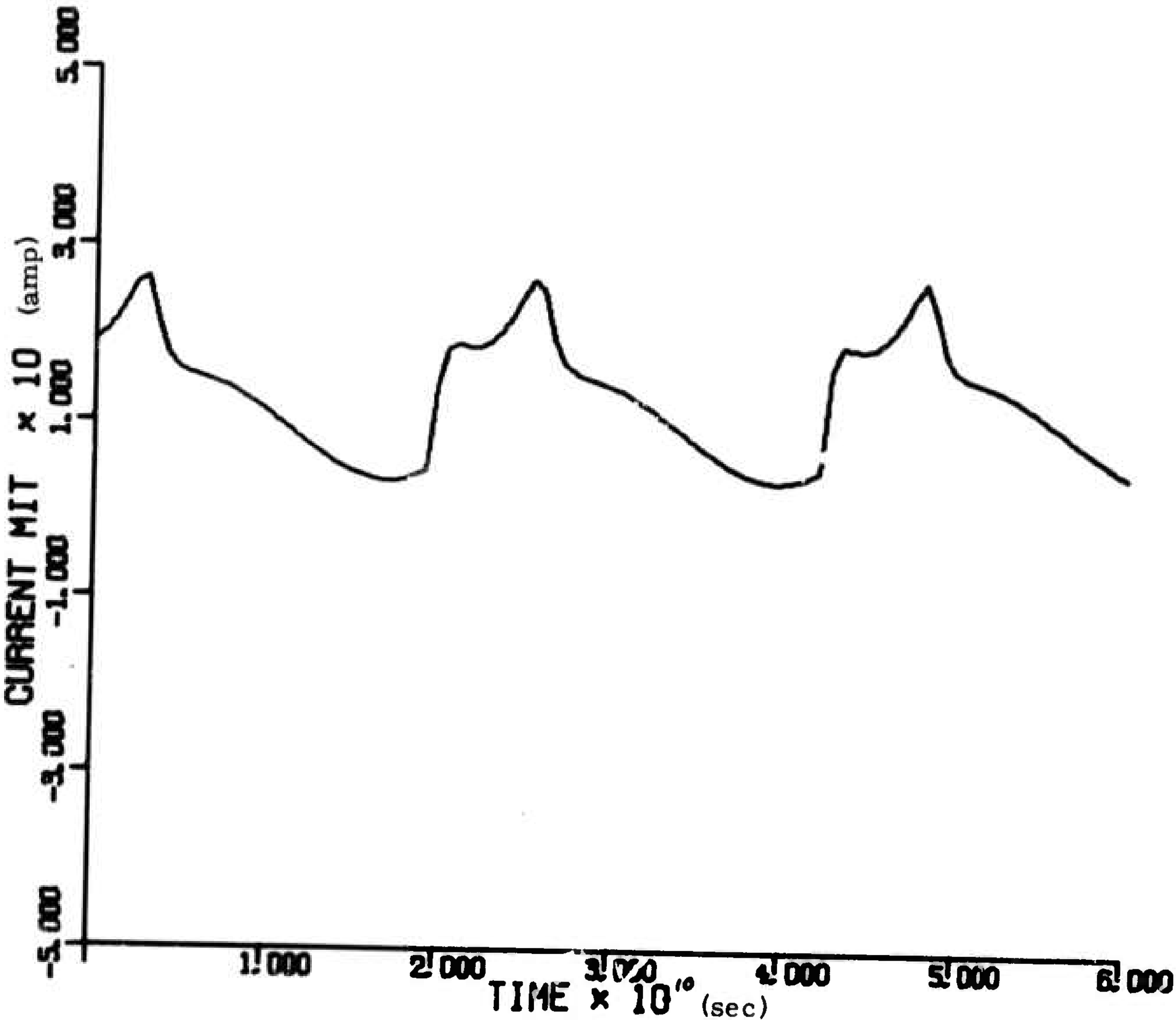


Fig. 15: Microwave Circuit Current vs. Time (for resonant circuit at 5 Gc, Q = 130, fg = 5. 5 Gc., bias voltage = 10. 5 volts)

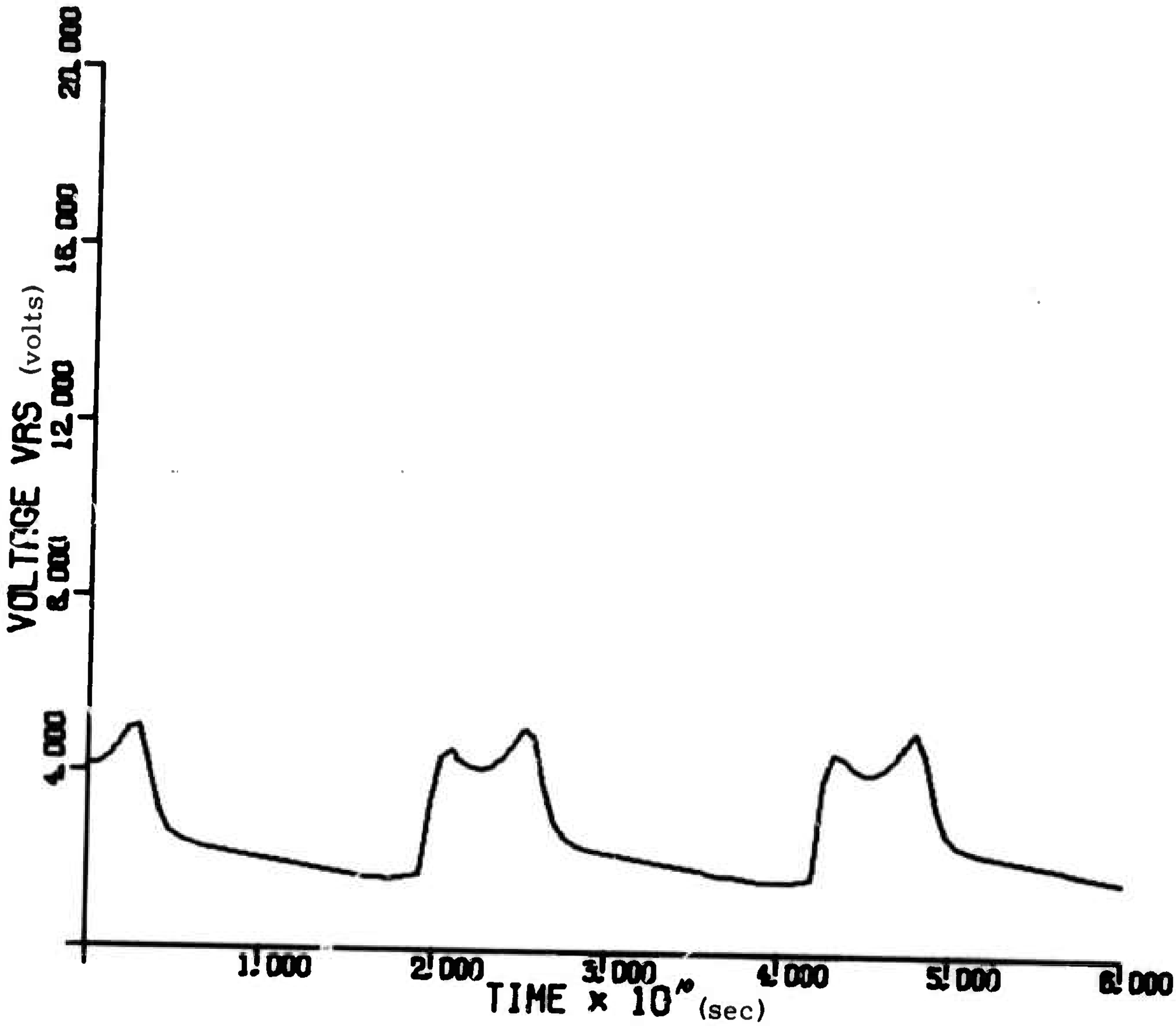


Fig. 16: Bulk Voltage vs. Time (for resonant circuit at 5 Gc, Q = 130, f_q = 5.5 Gc., bias voltage = 10.5 volts)

IV. CONCLUSIONS

The solution-grown material produced by Hewlett-Packard Laboratories provides better device performance than the boat-grown material used previously. The improved noise performance has still not been identified with the bulk or contacts, but the external pressure contact method appears to contribute a negligible noise.

Further batches of this solution-grown epitaxial material are being made and processed with the object of obtaining devices with consistent and repeatable RF characteristics, and hopefully with noise characteristics as good as, if not better, than the TE 65 devices. In addition further work will be done on modifying the device geometry and contacting procedure to find out what influence this has on the operating characteristics.

The circuit simulation describes the behavior of the device in the domain region. The region of primary interest, however, involves possible operation in the LSA or more likely a "hybrid" mode where the simplified LSA operation does not apply. The circuit characterization will be extended to include the effect of a bulk negative resistance effect.

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14. KEY WORDS	LINK A		LINK B		LINK C	
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Gunn Effect Devices						

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