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PROPERTIES OF MINIATURIZED TUNNEL DIODE CIRCUITS AT MICROWAVE FREQUENCIES

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ABSTRACT

The state of the art of semiconductor devices, especially tunnel diodes, is such that it is presently feasible to construct small, sensitive, low-power tuned RF microwave receivers up to and including K-band frequencies using only semiconductors as the active elements. Such a receiver might use tunnel diodes as the RF amplifier and detector and a transistor as the video amplifier. Receiver circuits of this type are shown to operate with a noise figure on the order of 5 db at frequencies at 10 Gc and above. Experiments indicate that tunnel diode operation at higher frequencies is possible, but the tunnel diodes should be physically integrated into the microwave structures for practical operation at 35 Gc. Tunnel diodes are very promising where low-level, broadband signals are needed.

FOREWORD

The work reported in this document, which was initiated at the Naval Ordnance Laboratory Corona in fiscal year 1962 under WepTask R360-FR-104/211-1/R011-01-001 (Foundational Research Program) and WepTask RM37-32-001/211-1/F009-01-017, was performed by personnel of the Electronics Division, Research Department. The objective of the project was to evolve microminiaturized solid-state microwave circuits and to explore their utility as guided missile components.

Studies of semiconductor devices and their potential applications in the microwave field have been continued in fiscal year 1963 under the Foundational Research Program.

C. J. HUMPHREYS
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INTRODUCTION

The initial NOLC investigation into the feasibility of microwave receiver components with microminiaturized configurations has mainly concentrated upon determining the properties of tunnel diodes in such configurations and to resolving allied circuit problems.

Several possible approaches to low-noise microwave amplification include masers, traveling-wave tubes, parametric devices, and tunnel diodes. To varying degrees, all but the tunnel diodes have disadvantages of narrow bandwidth, high cost, and complexity, plus handicaps in the size and weight of necessary auxiliary equipment (including, in certain cases, cryogenic gear). The major disadvantage of tunnel diodes is their maximum voltage limitation.

Tunnel diodes, however, have many advantages as microminiature microwave components. They function satisfactorily at room temperature in simple configurations, are by nature broad-band devices, and have been shown to operate in the higher microwave bands (X and K). Moreover, since the tunneling phenomena are dependent upon majority carriers (rather than upon minority carriers, as is the case with conventional semiconductor devices) and occur in the presence of very high impurity concentrations, the tunnel diodes are easy and cheap to manufacture, their tolerances are less critical, and they are more resistant to shock, vibration, and radiation damage. Such factors indicate that tunnel diodes are a logical choice for miniaturized microwave amplifiers whose ultimate application may be in airborne equipment, where space is at a premium, the environment severe, and cost and reliability of extreme importance.

As the end product of the investigation, it is desired to arrive at a combination of tunnel diode microwave circuits that will function as a microwave receiver with the following properties:

1. Noise figure of less than 5 db
2. Center frequency of 35 Gc
3. Bandwidth of 10 percent or more
4. Temperature range from -40 to +90°C

5. Video output of 10 to 100 mv/deg

6. Video bandpass of 1 cps to 10 kc

7. Minimum size and weight

Such a receiver would find many applications in research, radiometry, radio, astronomy, and military equipment.

This report shows the degree to which such an end product could be developed with presently available tunnel diodes. The above-described receiver requirements are considered, and the receiver design is described, along with the necessary preliminary measurements and experiments. A tunnel diode bibliography appears at the end of this report.

Anticipated output voltage excursions of 1 volt or more from the video amplifier precluded use of tunnel diodes at that point. Accordingly, two transistor video amplifiers were built. Since this is a report on tunnel diodes, the design, construction, and evaluation of the transistor components are relegated to the Appendix.

DESIGN APPROACH

Requirements for the receiver may seem modest, but there are several departures from normally desirable receiver characteristics. These departures include wide bandwidth, microminiaturization, elimination of the dc component from the detector output, low power requirements, and a center frequency of 35 Gc.

The desired 10 percent bandwidth led to selection of the tuned RF amplifier (TRF) as the most likely, if not the only, receiver technique that would give such widely separated limiting fequencies. On a basis of this, the block diagram shown in Figure 1 was developed for the planned

FIGURE 1. Block Diagram of Microminiaturized Receiver

receiver. Printed circuits, Microstrip,[1] and dot components were suggested as a suitable approach to minimizing size and weight. (See Figure 2.) The dc component of the detector output, which is undesirable because of considerations of ambient temperature and internal noise, should be removed for some applications. Removal of this dc component could be effected by capacitive coupling, but since it was planned to consider this problem last, no work has been done in this area. In fact, future system changes may obviate the need for this work.

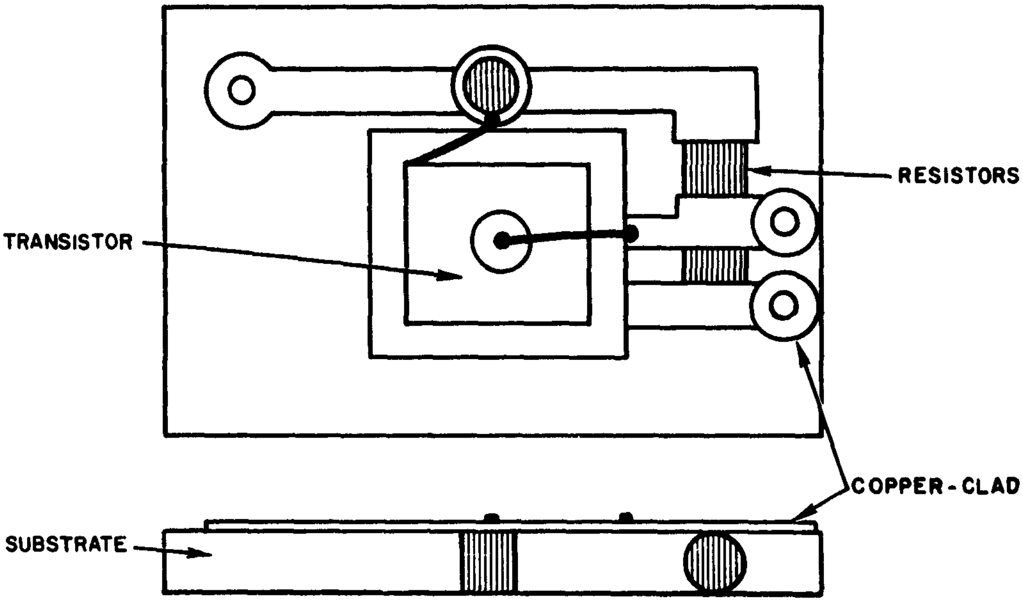

FIGURE 2. Dot Component Construction Technique

Their very low power requirements make use of tunnel diodes attractive wherever possible in the receiver under consideration. However, tunnel diodes have a maximum voltage swing of perhaps 0.500 volt or less, and this precludes their use in the video amplifier output stage, where a voltage excursion of 1 volt or more may occur. For this reason, a transistor output stage was chosen on a basis of power requirements, size, and simplicity. To meet temperature requirements, a silicon transistor was to be used in the video amplifier. In the interim before arrival of the uncased silicon transistors, a germanium transistor video amplifier was built for the experience it afforded in this type and size of construction. Thus, two video amplifiers, one of germanium and one of silicon, were built and tested, as described in the Appendix.

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[1] Trade name of a product of the International Telephone and Telegraph Corporation (ITT). Throughout this report, allusion to a manufacturer does not constitute an endorsement of the product of one manufacturer over a similar product of another.

To be broad-band at 35 Gc, the detector should be a diode. A tunnel diode was decided upon for this function, since it may also provide some gain at the low levels anticipated. As an alternative detector, a Unitunnel,[2] or backward diode, was considered. This diode has a very slight negative resistance in the forward direction and a very sharp low-level reverse conduction characteristic. It is capable of detecting signal levels approximately 2 orders of magnitude lower than would be possible with conventional diodes.

A tunnel diode RF amplifier was selected because of its small size, low power, and ruggedness, as well as for its wide range of operating temperatures. Tunnel diode microwave amplifiers have been constructed with gains up to 30 db, bandwidths of 20 percent, and noise figures as low as 3 db. To date, all these performance ratings have not been achieved simultaneously, but it seems possible to do so.

At the beginning of this task, the highest frequency available in a tunnel diode was 10 Gc, and diodes with this capability were in very limited supply. But as the work progressed, diodes with higher frequencies became available. However, none have yet been listed as having capabilities to 35 Gc. One supplier indicated, in a visit to this Laboratory, that his company could supply units capable of operation beyond 60 Gc, and one of these units is now on order for evaluation. The cost, however, would prohibit use of many of these units at present.

VIDEO AMPLIFIER

The first experimental module constructed was a transistor video amplifier (see Appendix). This device serves the dual purpose of increasing the output, as well as providing for the detector some isolation from the load. This output-stage-to-input-stage construction makes testing somewhat easier, especially in devices employing microminiature fabrication techniques.

It was at this time that the method of removing the dc component was postponed because it appeared that impending system changes would probably obviate the need for dc elimination. The effort was next directed toward the video detector.

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[2] Trade name of semiconductors manufactured by Hoffman Electronics Corporation.

VIDEO DETECTOR

Because of the low signal levels anticipated, a sensitive detector was needed, and the sensitivity requirement plus the bandwidth and frequency requirements dictated the use of a diode. Two silicon diode devices are capable of operation at signal levels far below the minimum signal level of silicon diodes usually used at microwave frequencies, the tunnel diode and the backward diode. At the time the first model was built, however, the available tunnel and backward diodes were unable to perform at these frequencies, so a conventional diode was used.

For the first unit, a 1N26 diode was removed from its coaxial package and mounted on the detector printed-circuit board. A 1/32-inch copper-clad board was used, and the etched circuit served as the RF bypass capacitor. Figure 3 shows the circuit of this unbiased detector.

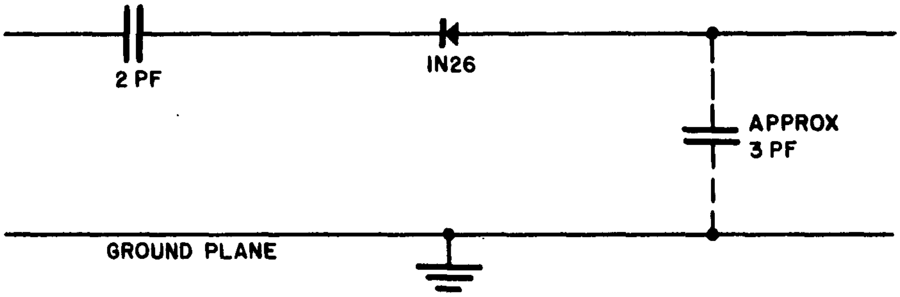

FIGURE 3. Unbiased Diode Video Detector

The minimum detectable signal was -28 dbm. The next circuit considered was that of a biased diode (Figure 4), which exhibited a minimum detectable sensitivity of -36 dbm. Manufacturers' data indicate that higher sensitivities, on the order of -44 to -50 dbm, can be obtained with biased silicon diode detectors. Part, if not all, of the insensitivity of the detector was due to losses associated with the physical configuration of the input circuit to the diode. Surface contamination of the silicon wafer soon rendered this unit unusable in spite of the protective wax coating.

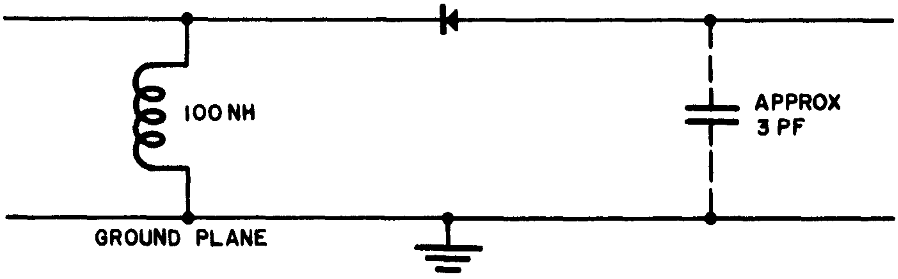

FIGURE 4. Biased Diode Video Detector

An uncased backward diode was then tested, using the same circuit (Figure 3) as for the first model. The case was removed to reduce the reactances (lead capacitance and inductance) and thus permit operation at higher frequencies. The bias had to be removed to keep from saturating the diode with direct current. The maximum sensitivity of this diode was -40 dbm. Again, the physical arrangement apparently reduced the sensitivity. The backward diode is heavily doped and is not so sensitive to surface contamination as the conventional diode. The circuit is the same as that shown for the unbiased diode in Figure 3.

An uncased germanium tunnel diode, which used the biased-diode circuit of Figure 4, was then tested. The top view of the diode is shown in Figure 5. The minimum detectable signal level with this unit was -55 dbm. Oscillations made it too unstable for reliable performance, and the mechanical structure led to a high VSWR. The results with this unit were not predictable, clearly indicating a need for better semiconductor element manipulation and techniques. It is also clear that package reactance must be reduced significantly if the frequency capability of tunnel and backward diodes is to be extended. The video amplifier-detector combination is shown in Figure 6.

RF AMPLIFIER

The final module of interest is the RF amplifier. Computations and available tunnel diode data indicate that presently there is no available packaged diode suitable for 35-Gc operation as a low-noise amplifier. Published information,[3] however, indicates very strongly that such devices may be fabricated directly into microwave structures with a high probability of attaining the desired performance.

Some computations of tunnel diode operational characteristics are the following: Let

$$R_T = R_g + R_L + R_s$$

where

R_T = total resistance
R_g = generator resistance

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[3] C. A. Burrus, "Gallium Arsenide Esaki Diodes for High Frequency Applications," Journal of Applied Physics, Vol. 52, No. 6, p. 1031, June 1961. See Bibliography for additional references.

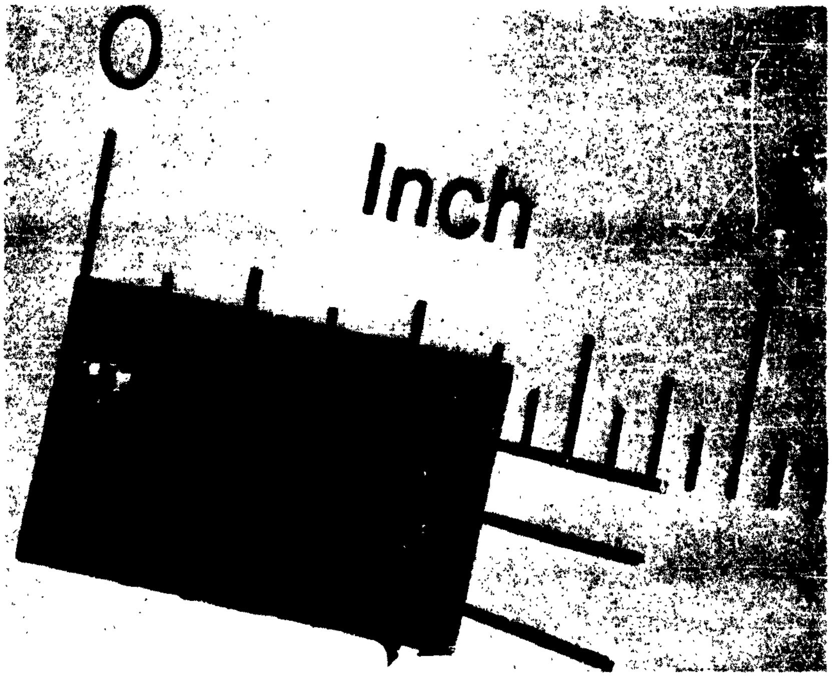

FIGURE 5. Video Detector, Top View

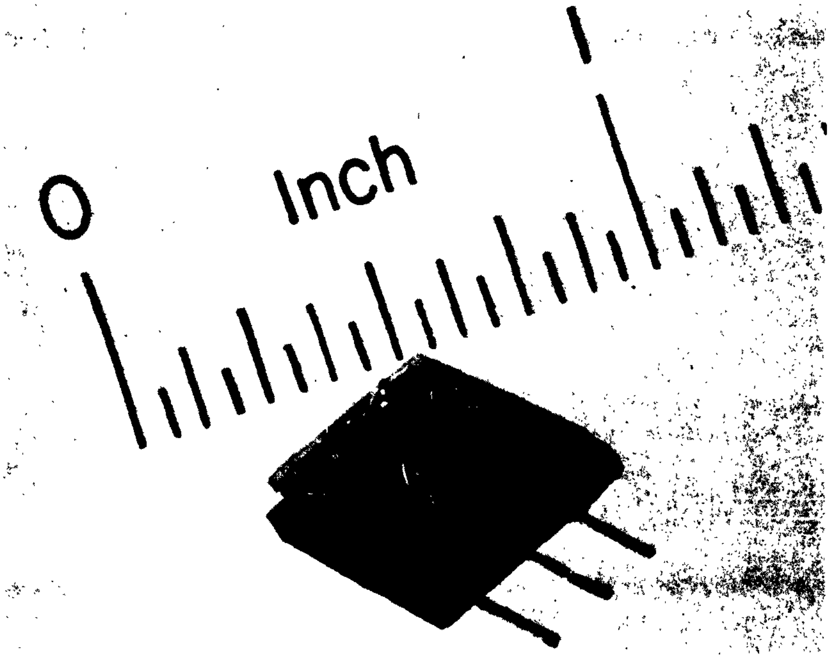

FIGURE 6. Video Amplifier-Detector Combination

R_L = load resistance

R_s = diode bulk resistance (series resistance)

and let

$$L = L_\ell + L_s$$

where

L = total inductance

L_ℓ = load inductance

L_s = sum of inherent lead inductance of diode (series inductance)

In order to be stable,

$$\frac{R_T}{L} - \frac{g}{c} > 0 \qquad (1)$$

and

$$1 - R_T g > 0 \qquad (2)$$

where

g = diode negative conductance

c = diode capacitance

R_T may also be expressed by

$$\frac{Lg}{c} < R_T < \frac{1}{g}$$

also

$$W_R = \frac{g}{c}\sqrt{\frac{1}{gR_T} - 1} \qquad (3)$$

where

W_R = frequency at which diode conductance goes to zero

R_T may then be written as

$$R_T = \frac{g}{g^2 + W_R^2 c^2}$$

At this point, with a given diode and its parameters, the value of R_T may be computed. In many instances, an external dc resistance must be added to make the external (generator and load) resistances (conductances) match those of the tunnel diode. With most tunnel diode packages, it is much easier in some instances to control inductance, rather than capacitance, while maintaining other characteristics. An example of a design using a tunnel diode with a cutoff frequency in the microwave region follows.

A 4-Gc amplifier is desired, using a tunnel diode active device. The diode to be used is a Sylvania D 4168D, which has the following characteristics (obtained from data enclosed with the diode):

I_p (peak current) = 2.9 ma

c (capacitance) = 0.9 pf

I_p/I_v (peak-to-valley ratio of current) = 7.8

R_s (series resistance) = 7.1 ohms

R_d (negative resistance) = 53.0 ohms

f_{osc} (frequency of oscillation) = 10.5 Gc

g (negative conductance) = -0.019 mho

L_s (typical series inductance) = 0.25 nh

To find the total resistance value,

$$R_T = \frac{g}{g^2 + W_R^2 c^2} \quad \text{or} \quad \frac{1}{g\left(1 + \frac{W_R^2 c^2}{g^2}\right)}$$

$$= \frac{1}{\left(19 \times 10^{-3}\right)\left[1 + \frac{\left(4 \times 10^{-9}\right)^2 \left(0.9 \times 10^{-12}\right)^2}{\left(19 \times 10^{-3}\right)^2}\right]}$$

$$= 51 \text{ ohms}$$

Thus, the diode should work in a low impedance line. Since $R_T = R_g + R_L + R_s$,

$$R_g + R_L = R_T - R_s$$

If

$$R_g = R_L$$

then

$$R_g = \frac{R_T - R_s}{2}$$

or

$$\frac{51 - 7.1}{2} = 22.95 \text{ ohms}$$

Thus, at this frequency, the diode should be operated in a 22-ohm line if the generator and load impedances are to be equal. If a lower line impedance is desired, sufficient resistance should be added in series with the diode to make up the difference. Impedance transformation for higher impedances may be employed.

From Equation (1), to be stable

$$\begin{aligned} L &= \frac{c}{g} R_T \\ &= \left(\frac{0.9 \times 10^{-12}}{19 \times 10^{-3}}\right) 51 \\ &= 2.4 \times 10^{-9} \text{ h} \qquad \text{or} \qquad 2.4 \text{ nh} \end{aligned}$$

Since typical series inductance is 0.25 nh,

$$2.4 - 0.25 = 2.15 \text{ nh to be added}$$

Thus, Figure 7 is the desired circuit for a 4-Gc amplifier, using the D 4168D.

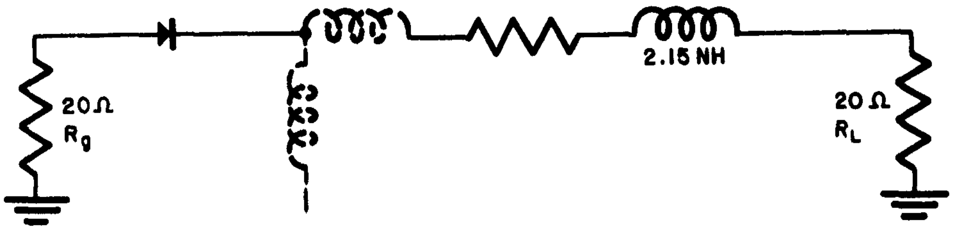

FIGURE 7. Circuit for an RF Amplifier (4 Gc), Using a Tunnel Diode Device

Power must be fed to the diode through an RF choke or inductance to reduce the amplifier loading for the signal (shown by dotted inductance in Figure 7).

The noise figure of microwave and other low-level amplifiers is of serious concern in many, if not most, cases. "Tunnel diode amplifiers are capable of a noise figure of 3 db or less."[4] In a low-loss system, it can be shown that the noise figure F_d of a germanium tunnel diode amplifier is

$$F_d = \frac{1 + \frac{G_e}{g}}{\left(1 - \frac{R_s}{R_d}\right)\left[1 - \left(\frac{f}{f_r}\right)^2\right]}$$

where

F_d = noise figure (db)

$G_e = \frac{2eI}{4KT}$ (the noise conductance)

$e = 1.6 \times 10^{-19}$ coulomb (electron charge)

I = diode current in amperes

$K = 1.38 \times 10^{-23}$ (Boltzman's constant)

T = absolute temperature (Kelvin) (290°K = room temperature)

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[4] E. G. Nielsen, "Noise Performance of Tunnel Diodes," IRE Proceedings (Correspondence), Vol. 48, pp. 1903-1904, November 1960.

g = diode negative conductance

R_s = series resistance

R_d = diode negative resistance

f = operating frequency

f_r = resistive cutoff frequency

In germanium tunnel diodes, G_e is approximately 20 I. For the amplifier under consideration, the best noise figure F_d would then be approximately (I = 1.4 ma):

$$F_d = \frac{1 + \frac{0.028}{0.019}}{\left(1 - \frac{7.1}{53}\right)\left[1 - \left(\frac{4 \times 10^9}{10 \times 10^9}\right)^2\right]} \text{ db}$$

$$= \frac{2.47}{0.87\ (0.84)} \approx 3.4 \text{ db}$$

Thus, this amplifier should have a good noise figure if advantage is taken of the diode's low-noise figure, since present techniques permit very low losses in the rest of the system.

At present, 30 Gc is the highest frequency attainable with available diodes. This is too low for 35-Gc applications. By fabricating diodes directly into microwave structures, reactances may be reduced significantly. For instance, the case of the D 4168 series has a typical capacitance of 0.3 pf, while the total capacitance (case and junction) is 0.9 pf. The total inductance is 0.25 nh, of which approximately 0.15 nh is attributable to the case itself.

To attain the high frequency performance required, it was decided at this time to consider fabricating active devices directly into the microwave structures, since tunnel diodes with a fundamental frequency of operation beyond 100 Gc have been constructed in this manner by Bell Telephone Laboratories. Current work is taking this direction. The equipment capable of accomplishing this task is approximately 90 percent complete.

Figure 8 shows the test setup used in this program.

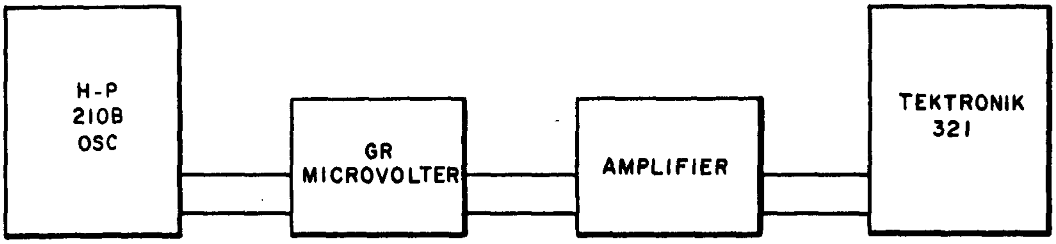

FIGURE 8. Test Setup

DISCUSSION

RADIOMETER CRITERIA

To be effective as a radiometer RF amplifier, an active device must have broad-band capability, a low noise figure, and a stable gain characteristic. There are several microwave amplifiers or devices available commercially; however, most of them will not meet some of the more critical requirements for radiometer performance. The maser and parametric amplifiers have the lowest noise figures, but both are very narrow-band devices, which makes them unsuitable for radiometer applications. Traveling-wave tubes and tunnel diodes are both capable of broad-band operation with low noise figures. One system is under construction, outside the Laboratory, using the traveling-wave tube RF amplifier.

TUNNEL DIODE CHARACTERISTICS

Small size, light weight, low noise, and low power consumption of the tunnel diode RF amplifier make it attractive. In order of increasing importance, three additional desirable characteristics are its relative immunity to nuclear radiation, wide operating temperature range, and reliability.

These advantages are due in part to the fact that tunnel diode conduction properties are determined by majority carrier movement, whereas conventional diodes and transistor properties are dependent upon minority carrier diffusion, which in turn is sensitive to temperature changes and/or nuclear radiation.

The major disadvantage of using tunnel diodes is their voltage swing limitations. The tunnel diode is capable of voltage swings from 0.26 to 0.35 volt, depending upon the material used in the manufacturing process.

For germanium tunnel diodes, the voltage limits of the negative resistance region are 0.06 and 0.35 volt, while the limits for silicon units are 0.065 and 0.420 volt for the peak current and valley current points, respectively. Gallium arsenide and other intermetallic compounds are somewhat variable over a narrow region, typical limit values for gallium arsenide being 0.1 and 0.45 volt. These voltages may be increased through impedance transformation, but the advantage of small size (as well as overall efficiency) is thereby compromised to some extent. For low-level RF and IF amplifiers, tunnel diodes may be used to their full advantage.

BASIC OPERATION OF THE TUNNEL DIODE

The tunnel diode negative resistance curve has been widely published and will not be repeated here. Basically, the tunnel diode is a single P-N junction, and it must meet two requirements in order to exhibit the negative resistance characteristic. First, the junction must be very narrow (on the order of 100 to 150 angstroms); i.e., the transition from P to N type must be abrupt. Second, the P and N regions must be degenerate; the Fermi level must be (1) within the conduction band on one side of the junction and (2) in or very near the valence band on the other side. After the tunnel diode has been made, its characteristics may be checked by existing methods.

SIGNIFICANT PARAMETERS OF THE TUNNEL DIODE

In the usual tunnel diode operation, signal levels are small, and small signal analysis may be used. For these very low signal levels, the negative resistance region may be considered as linear. The negative resistance appears across the junctions that have an associated capacitance +C. A small-signal equivalent-circuit may be considered as shown in Figure 9. Lead capacitance C_c is usually negligible. The resistance of the leads and of the semiconductor material is represented

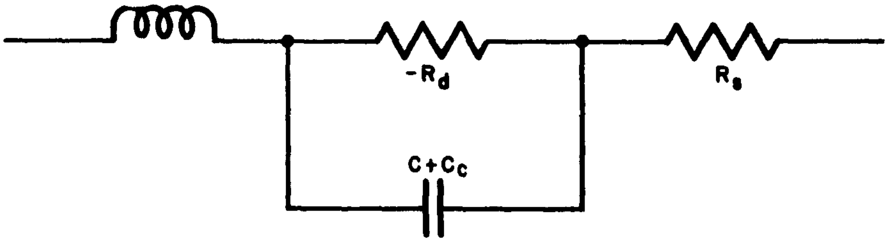

FIGURE 9. Small-Signal Equivalent-Circuit for a Tunnel Diode

by R_s, while the lead inductance is represented by L_s. The lead inductance and capacitance become more important as higher frequencies are considered; this is also true of the junction capacitance. As the junction area is reduced (hence junction capacitance is reduced), the parasitic rectances (case) become much more significant. Two important frequencies may be obtained from the equivalent circuit.

FREQUENCY LIMITATIONS OF THE TUNNEL DIODE

The self-resonant frequency is

$$f_s = \frac{1}{2\pi} \sqrt{\frac{1}{L_s C} - \left(\frac{g}{C}\right)^2}$$

and the resistive cutoff frequency is

$$f_r = \frac{|g|}{2C} \sqrt{\frac{1}{R_s |g|} - 1}$$

The resistive cutoff frequency is the frequency at which the real part of the diode impedance goes to zero. The diode cannot amplify with a real impedance of zero. As with all active devices, the external circuit plays an important role in the final values of parameters, and hence in determining maximum frequency.

Several parameters influence a tunnel diode amplier's performance:

1. A diode should have a relatively large negative resistance in order to match available line impedances.

2. The diode's resistive cutoff frequency should be well above the desired operating frequency.

3. To obtain high gain, the total circuit resistance should be just slightly below the negative resistance of the diode at the operating frequency.

Amplifiers using two-terminal negative-resistance devices may be either of the series or shunt type. That is, the device may be placed in series with the signal path, or it may be used to shunt the signal path. Both configurations provide gain. The series type is short-circuit stable and provides current gain at a constant voltage. The shunt connection is open-circuit stable and provides voltage gain at a constant current. It is also possible to use a compound, series and shunt, connection to provide voltage and current gain simultaneously. Most of the microwave amplifiers constructed with tunnel diodes have been of the shunt type to provide current gain. Of course, because of the absence of isolation in this configuration, an isolator must be used to prevent oscillation.

CONCLUSION

It is feasible to construct semiconductor microwave receivers up to and including K-band frequencies with low noise figures. Broad-band operation of tunnel diode amplifiers with high gain, low power consumption, and low noise figures also appears practicable. In view of its performance, the tunnel diode is perhaps one of the most promising of microwave devices where low-level, broad-band signals are concerned. While tunnel diode circuit operation above 30 Gc is not yet practicable with commercial components, it is felt that this will be achieved through the development of integrated circuit techniques, which will likewise reduce signal losses associated with the physical configuration of the input circuit to the diode.

A tunnel diode selected for the RF amplifier of such a receiver should have a cutoff frequency above the signal frequency, and it should have a negative resistance at the system's operating frequency.

Appendix

TRANSISTORIZED VIDEO AMPLIFIER FOR MICROMINIATURE CONFIGURATIONS

INTRODUCTION

As stated in the introduction of this report, anticipated output excursions of 1 volt or more from the video amplifier preclude the use of tunnel diodes at this point. Accordingly, two transistor video amplifiers have been built and tested. The first uses a germanium transistor with a low noise figure, and the second uses a silicon transistor with high operating-temperature capabilities.

VIDEO AMPLIFIER DESIGN

The bandpass requirements are extremely modest (0 to 10 kc); thus, no special effort is needed to improve the high frequency characteristics of the circuitry. The circuit shown in Figure 10 is that used in both amplifiers.

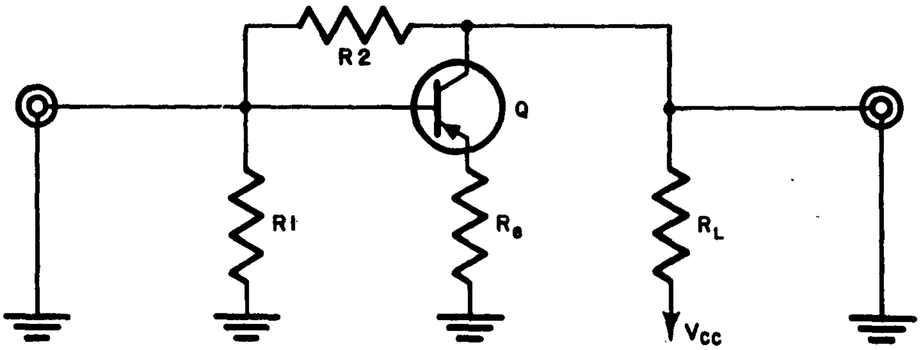

FIGURE 10. Circuit for Both Germanium and Silicon Video Amplifiers

GERMANIUM TRANSISTOR VIDEO AMPLIFIER

The first amplifier constructed used a cased 2N207B germanium transistor, which has a low noise figure. The 2N207B has the following typical characteristics at 25°C:

V_c (collector voltage) = 5 v

I_c (collector current) = 1 ma

h_{ib} (common base input impedance) = 33 ohms

h_{fe} (common emitter current gain) = 100

h_{ob} (common base output admittance) = 0.4 μmho

I_{cbo}(common emitter cutoff current with open base) = 3 μa

f_b (common base α cutoff) = 2 Mc

The h parameters are relatively insensitive to supply voltage V_{CC}, while collector current I_C is much more important in its effect on most parameters. The amplifier operates as class A. The first unit is not expected to be subjected to excessively high temperatures, so a very low stability factor is not required. A stability factor of 10 was chosen as a nominal figure of the first system. (This is a measure of the circuit's temperature stability.) For an output of 10 mv per degree and an anticipated temperature range of 40°C, a peak voltage of 400 mv would be adequate. A 6-volt supply would permit a peak voltage somewhat greater than 4 volts for a dynamic range somewhat greater than 20 db. Accordingly, if

V_{cc} (supply voltage) = 5 v

V_{ce} (dc voltage between collector and emitter) = 2.4 v

I_e (total emitter current) = 1 ma

R_e (emitter resistance) = 0.047 kilohm

$$\alpha \text{ (current amplification factor)} = \frac{h_{fe}}{1 + h_{fe}} = 0.99$$

I_{cbo} (common emitter cutoff current with open base) = 12 μa at 35°C (neglible)

V_{be} (approximate dc voltage between base and emitter) = 0.1 v

then the design may be

$$R_L = \frac{V_{cc} - \left(V_{ce} + I_e R_e\right)}{aI_e + I_{cbo}}$$

$$= \frac{5 - (2.4 + 0.047)}{0.99\ (1)}$$

$$\approx 2.5 \text{ kilohms}$$ (the nearest 1/10 watt EIA value available was 2.7 kilohms)

$$R_2 = \frac{R_1\left(V_{cc} - I_e R_e + V_{be}\right)}{I_e\left[R_e + (1 - a)R_1\right] + V_{be}}$$

$$= \frac{4.7(5 - 0.047 + 0.1)}{1[0.047 + (0.01)(0.047)] + 0.1}$$

$$= \frac{2.49}{0.194}$$

$$= 12 \text{ kilohms}$$

This amplifier was constructed on 1/16-inch double-clad, glass-epoxy laminate. Since the dot resistors had not yet arrived, regular resistors were used. After etching, the board was drilled and milled so the components could be embedded as much as possible in the laminate to reduce thickness. A special low-temperature solder was used to make all connections, since leads were cut shorter and connections soldered closer to the components than the manufacturers recommend. The transistor was mounted from the side opposite to the etched circuit and was allowed to protrude from the rear of the circuit board. No trouble developed as a result of this method of fabrication. The finished module is shown in Figures 11 and 12. The frequency response and nonlinearity of this amplifier are shown in Figures 13 and 14, respectively. Dependence of the signal output on the supply voltage is shown in Figure 15, while the current drain versus supply voltage is given in Figure 16. The lower end of Figure 14 is not shown because of limitations in the measuring method.

SILICON TRANSISTOR VIDEO AMPLIFIER

For the final video amplifier, a silicon transistor was chosen for its high operating-temperature capabilities. Uncased silicon transistors and dot resistors were procured to permit construction of a thinner final

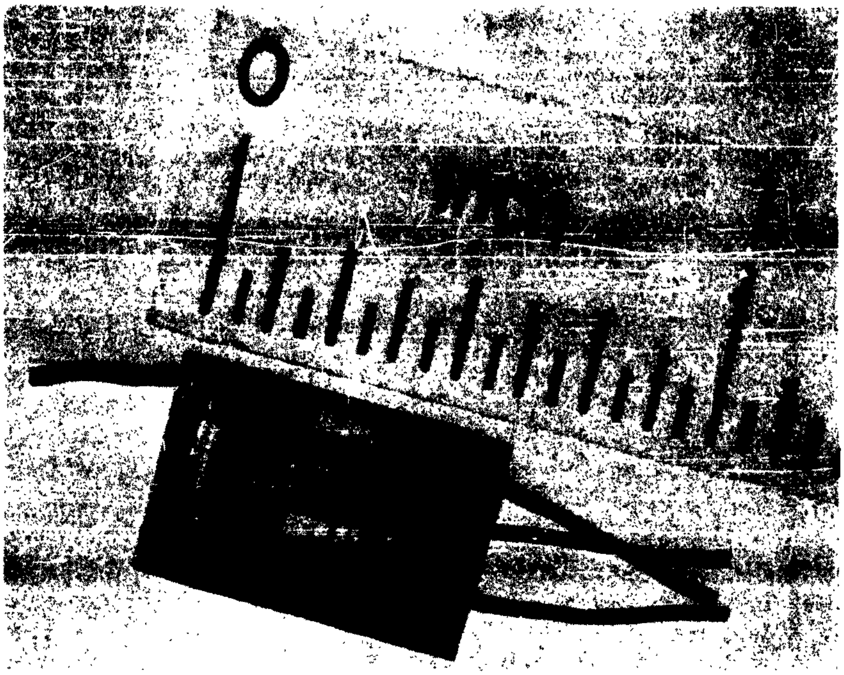

FIGURE 11. Germanium Video Amplifier: Finished Module, Top

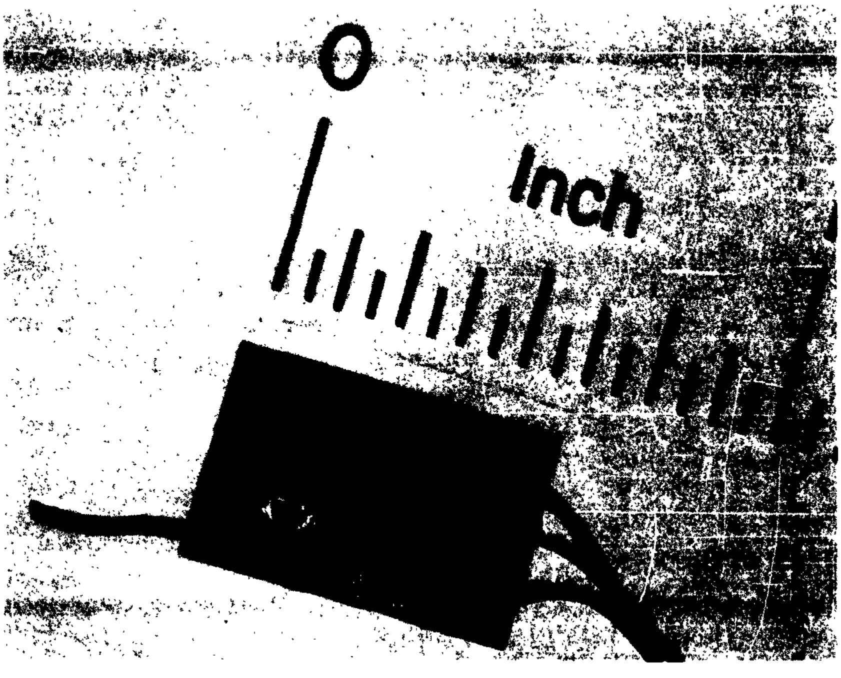

FIGURE 12. Germanium Video Amplifier: Finished Module, Bottom

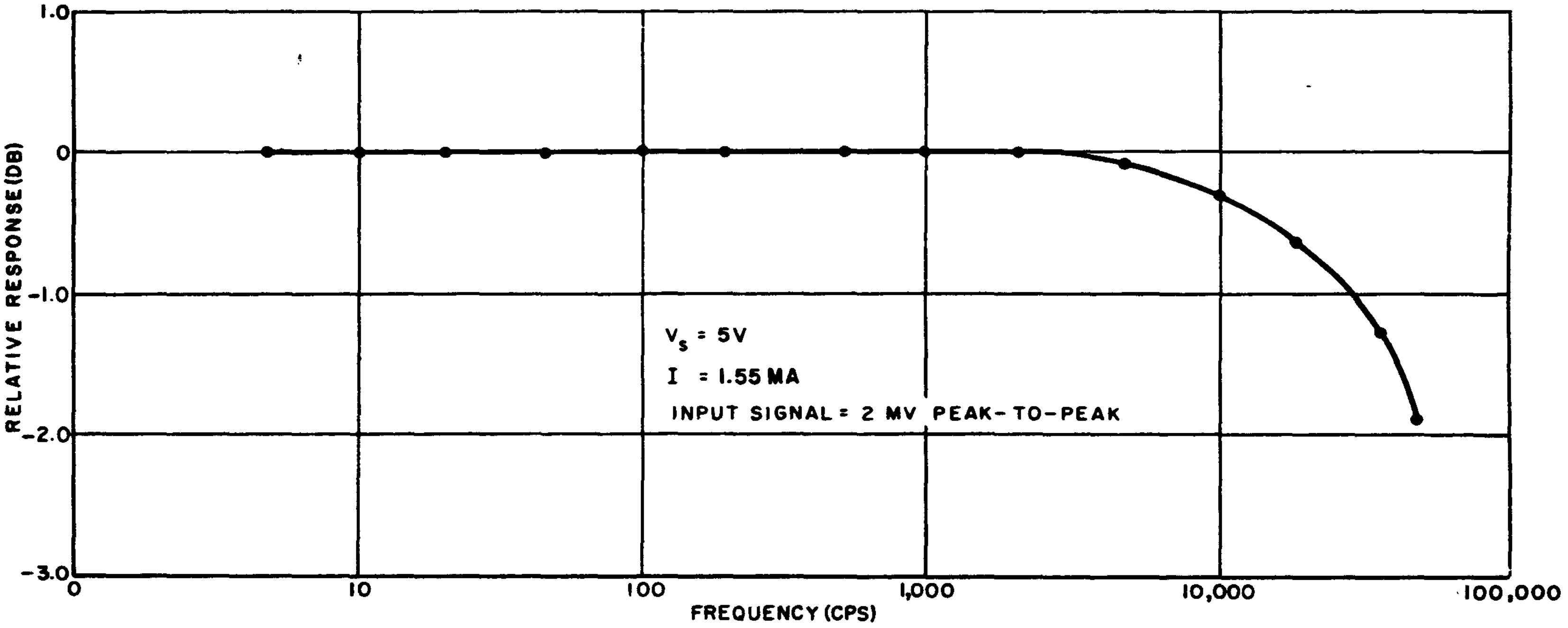

FIGURE 13. Germanium Video Amplifier Frequency Response

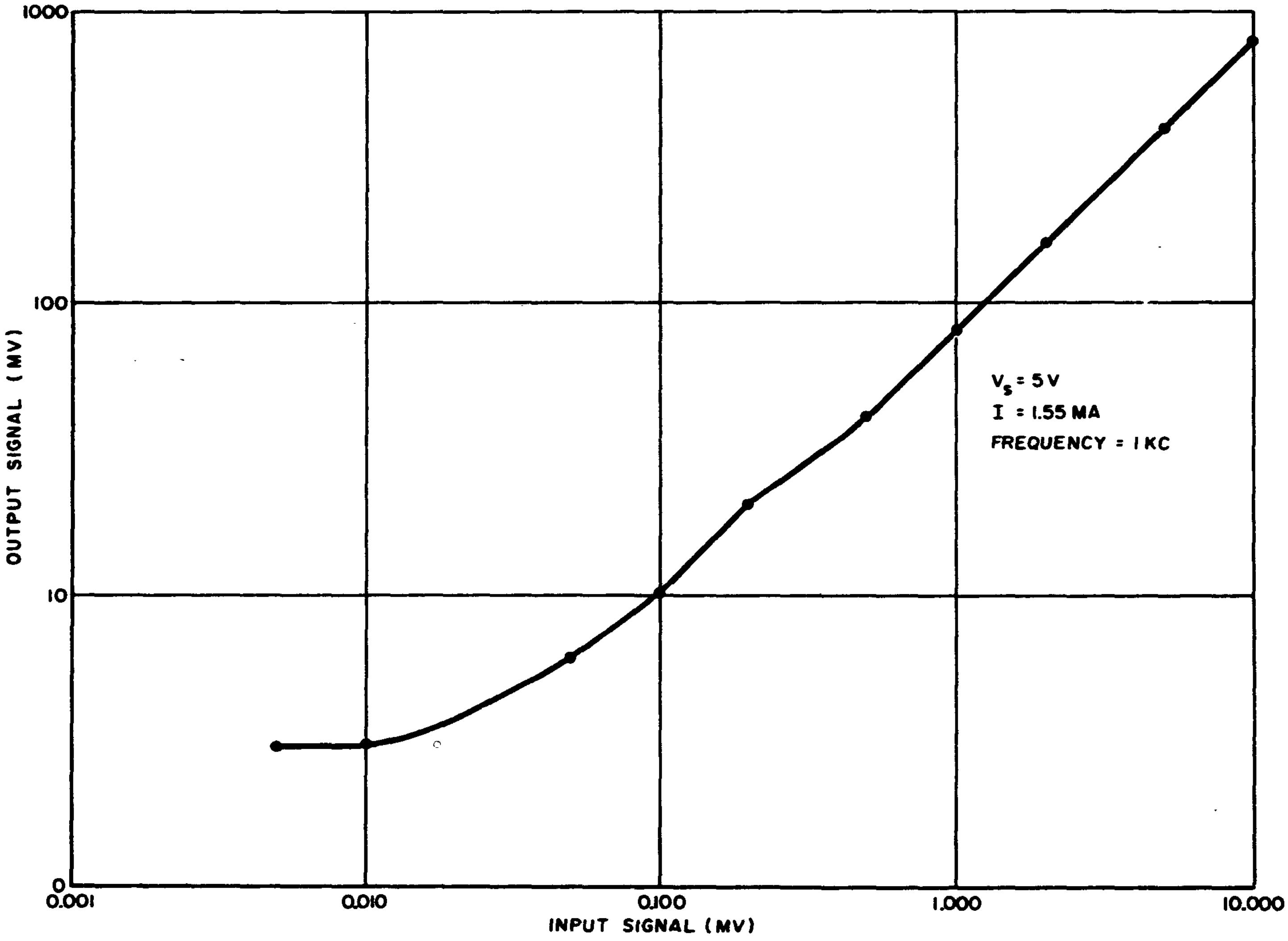

FIGURE 14. Germanium Video Amplifier Signal Gain

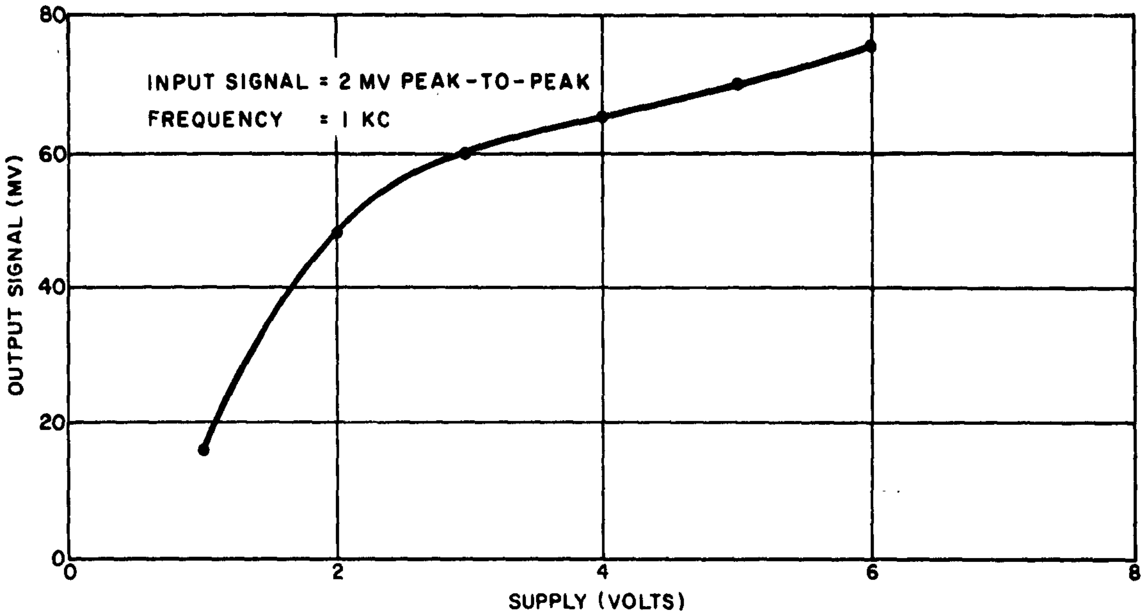

FIGURE 15. Germanium Video Amplifier Voltage Gain

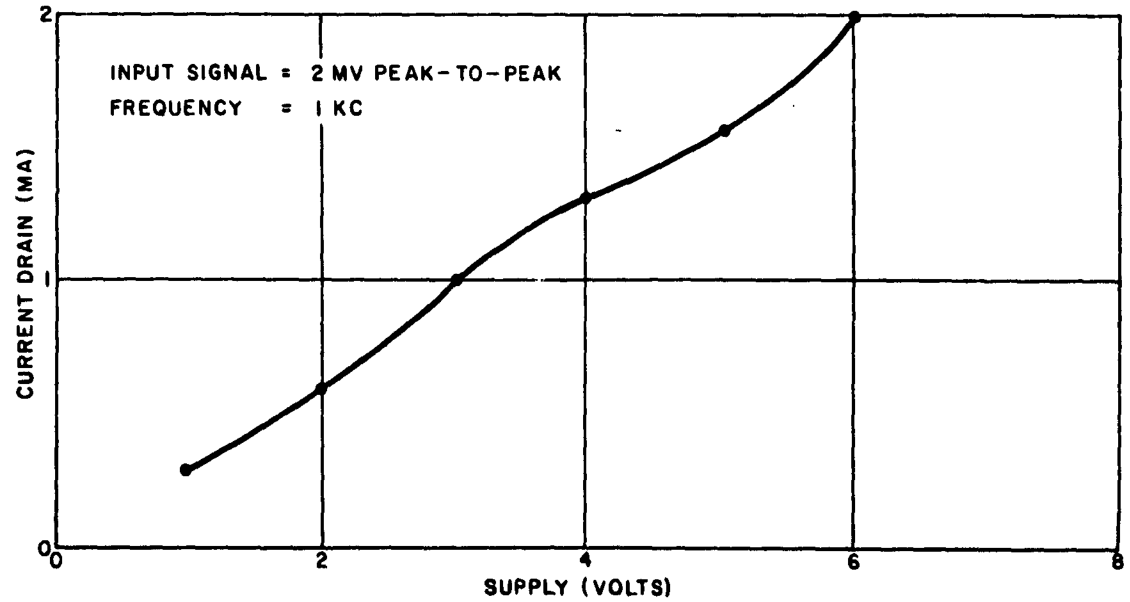

FIGURE 16. Germanium Video Amplifier Current Drain vs. Supply Voltage

module. This amplifier was designed around a 2N327A silicon alloy transistor. Typical characteristics at 25°C are:

$V_c = 6$ v

$I_c = 1$ ma

$h_{ib} = 130$ ohms

$h_{fe} = 24$

$h_{ob} = 1$ μmho

$I_{cbo} = 0.005$ μa

$f_b = 350$ kc

Some difficulty was experienced in removing the header from the transistor structure. Because the silicon transistor without its case is very light-sensitive, it had to be covered with an opaque cover after insertion in the board. This unit had an overall thickness of 1/16 inch. The bare transistor and dot resistors mounted in the board are shown in Figure 17. The complete unit is shown in Figure 18; performance characteristics of this amplifier are shown in Figures 19, 20, 21, and 22.

The base divider supply resistor of the silicon transistor amplifier was reduced to 3.3 kilohms (as compared to 6.8 kilohms for the germanium transistor amplifier) for two reasons. First, the higher V_{be} required for the silicon transistor dictated a lower value. Second, it was found that the peak h_{fe} occurred in the vicinity of 2 to 3 ma I_e for the 2N327A. The operating point was then shifted to 3 ma. Final values of this amplifier are:

V_{cc} (supply voltage) = 10 v

V_{ce} (voltage between collector and emitter) = 2.5 v

I_e (total emitter resistance) = 3 ma

R_e (emitter resistance) = 0.047 kilohm

I_{cbo} (common emitter cutoff current with open base and emitter) = 0.1 μa at 35°C

V_{be} (approximate dc voltage between base and emitter) = 0.6 v

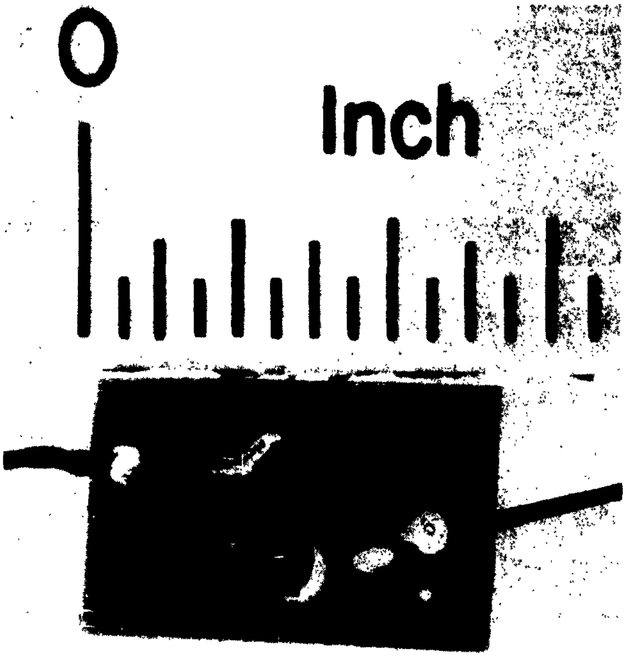

FIGURE 17. Silicon Video Amplifier: Bare Transistor and Dot Resistors in Board

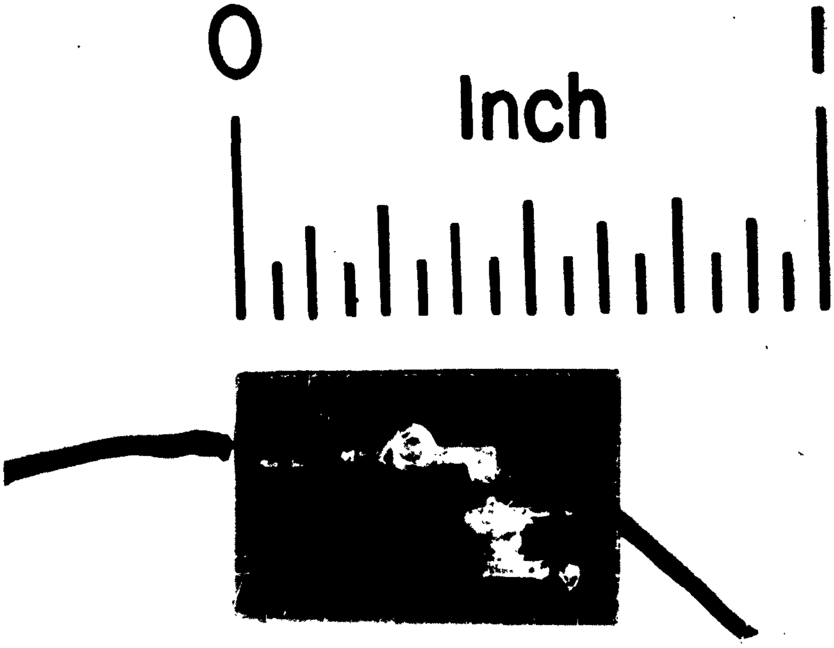

FIGURE 18. Silicon Video Amplifier: Finished Module

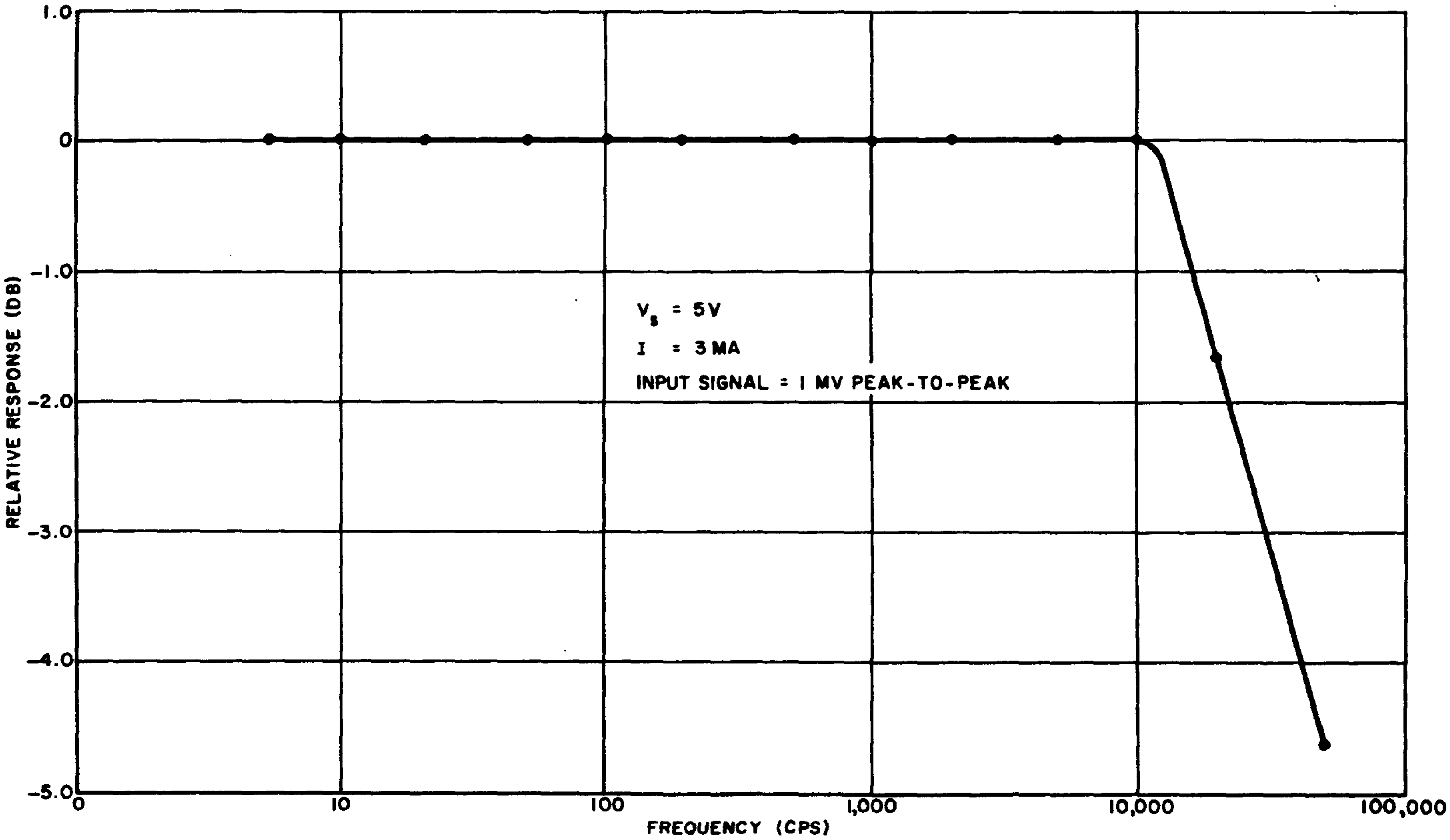

FIGURE 19. Silicon Video Amplifier Frequency Response

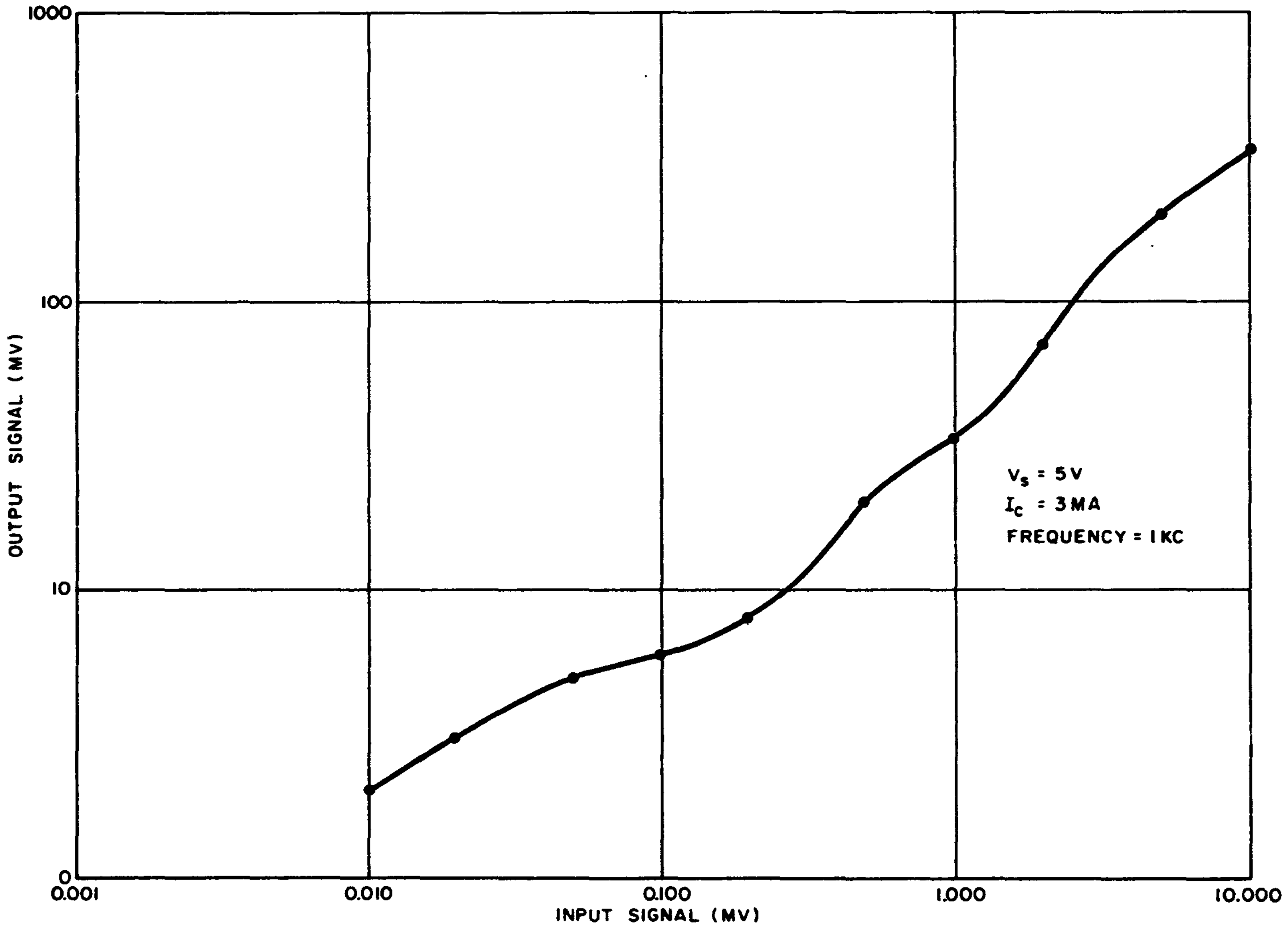

FIGURE 20. Silicon Video Amplifier Signal Gain

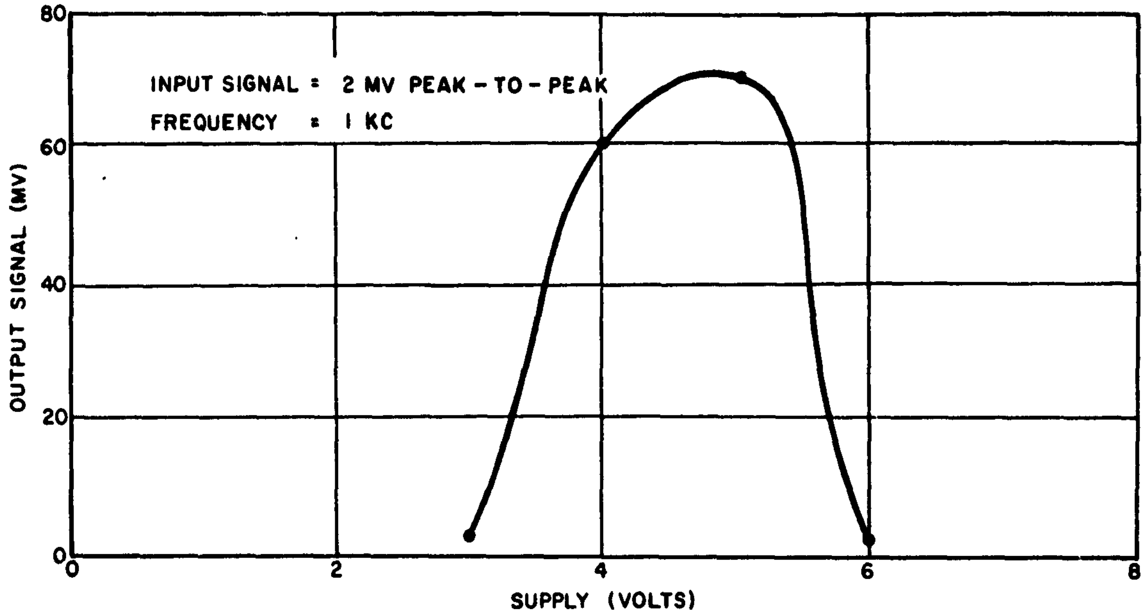

FIGURE 21. Silicon Video Amplifier Voltage Gain

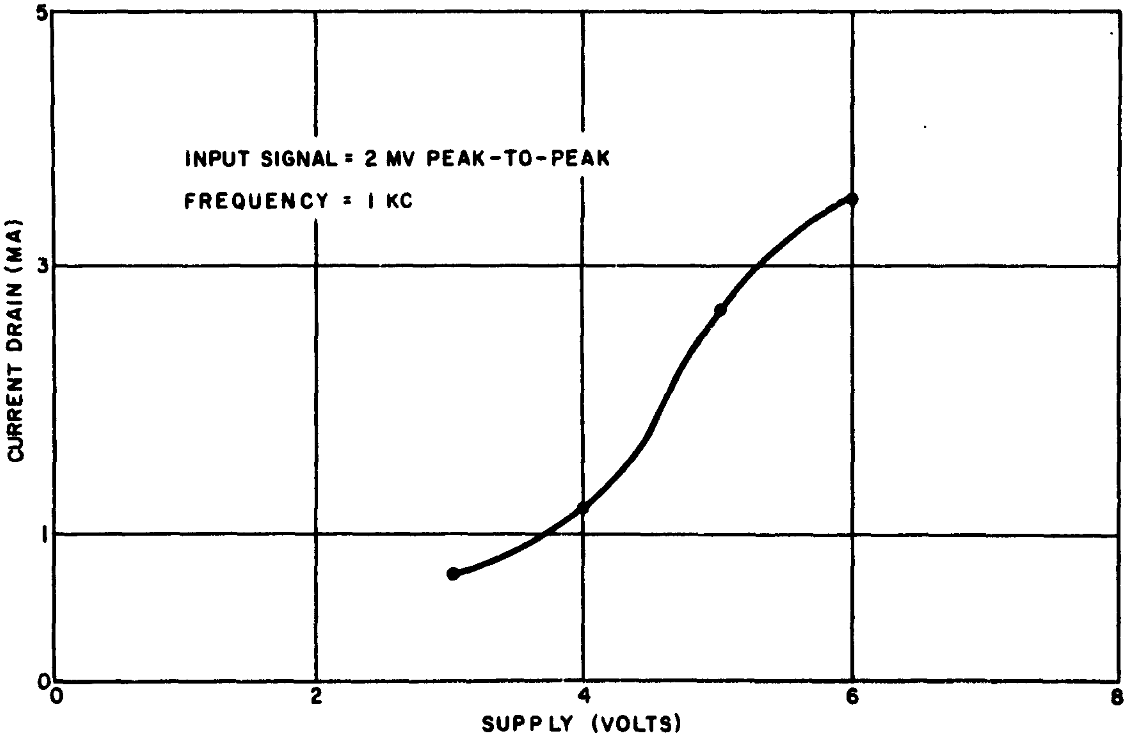

FIGURE 22. Silicon Video Amplifier Current Drain vs. Supply Voltage

R_L (total resistance) = 2.7 kilohms

R_1 = 3.3 kilohms

R_2 = 12 kilohms

DISCUSSION

Though the two amplifiers use the same collector load resistor and feed the same load, all their corresponding hybrid parameters are different. It is noteworthy that the response of the silicon amplifier is somewhat flatter than that of the unit employing the germanium transistor. The germanium transistor, however, has a higher cutoff frequency and better current gain ratings than the silicon transistor. Even though the germanium device has a lower bandwidth than does the silicon transistor amplifier, the germanium unit has a higher usable gain than the silicon unit beyond the frequency where the silicon transistor gain is down 3 db.

The silicon amplifier's great variation in gain with supply variation results from the greater change in bias point, since a larger portion of the bias power is dissipated in the bias network because of the higher V_{be} of 0.6 volt. The 47-ohm emitter resistor dictated this bias condition. If a larger value of emitter resistance had been used, substantial gain would have been lost as a result of the increased emitter degeneration.

For purposes of comparison, Table 1 gives the transistor parameters and Table 2 gives the operating parameters for the germanium and silicon transistor video amplifiers.

TABLE 1. Transistor Parameters

Transistor	V_c (volts)	I_c (ma)	h_{ib} (ohms)	h_{fe}	h_{ob} (μmho)	I_{cbo} (μa)	f_b
(Ge)(2N207B)	5	1	33	100	0.4	3.000	2 Mc
(Si)(2N327A)	6	1	130	24	1.0	0.005	350 kc

TABLE 2. Video Amplifier Operating Parameters

Transistor	V_{cc} (volts)	V_{ce} (volts)	I_e (ma)	R_e (kilohm)	I_{cbo} (μa at 35°C)	V_{be} (volt)	R_L (kilohms)	R_1 (kilohms)	R_2 (kilohms)
(Ge)(2N207B)	5	2.4	1	0.047	12.0	0.1	2.7	6.8	100
(si)(2N327A)	10	2.5	3	0.047	0.1	0.6	2.7	3.3	12

NOMENCLATURE

$+C$	Capacitance associated with tunnel diode's junction
C_c	Case capacitance of tunnel diode
F_d	Noise figure in db
G_e	$\frac{2eI}{4KT}$ = noise conductance
I	Diode current in amperes
I_c	Collector current
I_{cbo}	Collector current with open base
I_e	Total emitter current
I_p	Peak current
I_p/I_v	Peak-to-valley ratio of current
I_v	Valley current
K	Boltzman's constant = 1.38×10^{-23}
L	Inductance
L_ℓ	Load inductance
L_s	Lead inductance of tunnel diode (series inductance)
R_L	Load resistance
R_T	Total resistance
R_d	Negative resistance
R_e	Emitter resistance
R_g	Generator resistance

R_s	Series resistance (diode bulk resistance)
T	Absolute temperature (°Kelvin) (290°K = room temperature)
V_{be}	Voltage between base and emitter
V_c	Collector voltage
V_{cc}	Supply voltage
V_{ce}	Voltage between collector and emitter
W_R	Frequency at which diode conductance goes to zero
c	Capacitance
e	Electron charge
f	Operating frequency
f_b	Common base α cutoff
f_{osc}	Frequency of oscillation
f_r	Resistive cutoff frequency
f_s	Self-resonant frequency
g	Tunnel diode negative conductance
h_{fe}	Common current emitter gain
h_{ib}	Common base input impedance
h_{ob}	Common base output admittance
α	Current amplification factor $= \dfrac{h_{fe}}{1 + h_{fe}}$

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The state of the art of semiconductor devices, especially tunnel diodes, is such that it is presently feasible to construct small, sensitive, low-power tuned RF microwave receivers up to and including K-band frequencies using only semiconductors as the active elements. Such a receiver might use tunnel diodes as the RF amplifier and detector and a transistor as the video amplifier. Receiver circuits of this type are shown to operate with a noise figure on the order of 5 db at frequencies at 10 Gc and above. Experiments indicate that tunnel diode operation at higher frequencies is possible, but the tunnel diodes should be physically integrated into the microwave structures for practical operation at 35 Gc. Tunnel diodes are very promising where low-level, broad-band signals are needed.

1. Miniature electronic equipment—Design
2. Tunnel diodes—Properties

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