A New Semiconductor Microwave Modulator*

H. JACOBS†, MEMBER, IRE, F. A. BRAND†, MEMBER, IRE, M. BENANTI†, MEMBER, IRE, R. BENJAMIN‡ AND J. MEINDL†, MEMBER, IRE

Summary—**A new semiconductor device is proposed for use as an amplitude modulator for microwave transmission. The principle of action depends upon the increase of absorption with an increase of conductivity caused by the injection of excess minority carriers. Experiments conducted at 9600 Mc indicate little or no phase and frequency modulation. The mechanism of the modulation action and the device design are discussed here.**

Introduction

There has been an increased interest recently in the possibility of designing semiconductor devices for microwave applications. In some of the proposed schemes, a block of germanium is inserted in a waveguide, and, by modulating the conductivity of the semiconductor crystal, a change in microwave energy transmitted through the system is attained. In one suggestion,[1] a semiconductor slab is inserted through slits in a waveguide and oriented in a direction parallel to the electric vector in the $TE_{0,1}$ mode. By application of high pulse fields across the semiconductor, a decrease in mobility of the majority carriers occurs with a concurrent decrease in conductivity. This results in more power being transmitted through the waveguide. Here we have a possible microwave modulator device. In still another case, the modulation by light of the conductivity of a semiconductor inserted in a waveguide, together with the measurement of changes in microwave power absorption as a function of time, has resulted in a new method of measuring the lifetime of semiconductors with an electrodeless technique.[2] That one could expect absorption of electromagnetic radiation by increasing the conductivity of the semiconductor, can be seen by examining the classical equations derived from Maxwell's field theory.

For a plane wave traveling in unbounded dielectric,

$$\gamma = \sqrt{j\omega\mu(\sigma + j\omega\epsilon)} = \alpha + j\beta, \tag{1}$$

where $\epsilon = 1.41664 \times 10^{-10}$, $\mu = 1.257 \times 10^{-6}$, $\omega = 2\pi 10^{10}$, σ is the conductivity, α the attenuation constant, and β the phase constant. For low loss dielectric,

$$\sigma < \omega\epsilon$$

and (1) reduces to

$$\gamma = \frac{\pi}{\lambda}\left[\frac{\sigma}{\omega\epsilon}\right] + j\omega\sqrt{\mu\epsilon} = \alpha + j\beta. \tag{2}$$

Hence, the attenuation constant is

$$\sigma = \frac{\pi}{\lambda}\left[\frac{\sigma}{\omega\epsilon}\right] = \eta\sigma/2, \tag{3}$$

where η is the intrinsic impedance of the medium. The attenuation factor increases linearly with conductivity in the region where $\sigma \ll \omega\epsilon$. In Figs. 1 and 2, we see the results of calculating α and β for germanium as a function of conductivity and frequency. These preliminary experiments and calculations form the basis of a new class of devices in which electromagnetic energy can be modulated. In particular, it now appears feasible to design an amplitude modulator with little or no frequency modulation or phase modulation. Such a device would be applicable to microwave communication systems, where it is desirable to maintain very narrow band transmission in order to communicate the maximum intelligence over a given portion of the electromagnetic spectrum.

To demonstrate modulation effects, experimental equipment was constructed in the following manner. In Fig. 3, we see the arrangment for mounting the semiconductor rod in the waveguide and the manner in which a probe, perpendicular to the electric field in the waveguide, can be used to inject additional minority carriers in the semiconductor. The microwave power at a frequency of 9600 Mc was transmitted through the waveguide and sample to the tuned diode. A semiconductor rod of germanium with dimensions of approximately $0.3 \times 0.3 \times 3.5$ ohms was inserted through the waveguide. A small hole was cut in the side of the waveguide, through which a tungsten probe could be inserted. With this arrangement, considerable flexibility of the sample position was allowed. In addition, the sample could be tested as a point contact diode, or if a junction were made on the side of the sample, the tungsten could be located on the alloyed dot and injection characteristics could be measured. In Fig. 4, we find the over-all microwave system schematic diagram. In this arrangement, the klystron operated without modulation and supplied electromagnetic radiation which was transmitted through the germanium rod. Under these conditions, the oscilloscope displayed no variations in amplitude because of the input on the A channel. Next, if the pulse generator were turned on to

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† U. S. Army Signal Res. and Dev. Lab., Fort Monmouth, N. J.
‡ Monmouth College, West Long Branch, N. J.

[1] A. F. Gibson, "Progress in Semiconductors," John Wiley and Sons, Inc., New York, N. Y., vol. 2, p. 229; 1957.

[2] A. P. Ramsa, H. Jacobs, and F. A. Brand, "Techniques in measurement of lifetime in germanium," 1959 IRE National Convention Record, pt. 3, pp. 159–169. Also, *J. Appl. Phys.*, vol. 30, pp. 1054–1060; 1959.

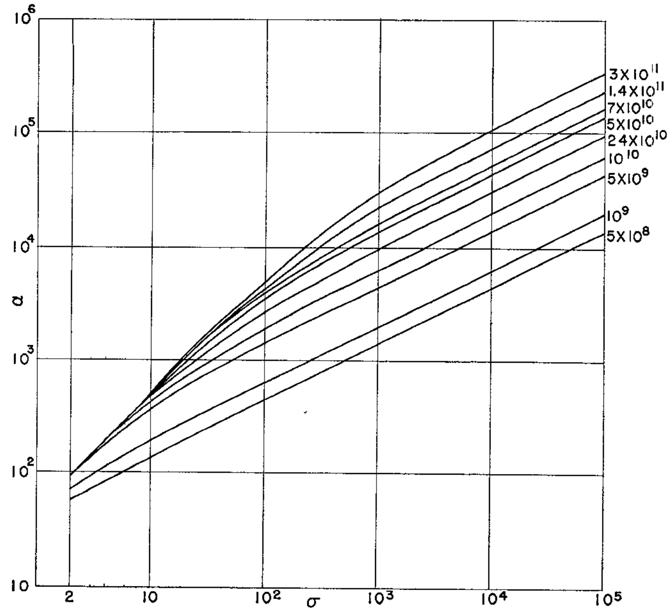

Fig. 1—Attenuation factor (nepers/meter) as a function of conductivity (mhos/meter) and frequency (cycles/second).

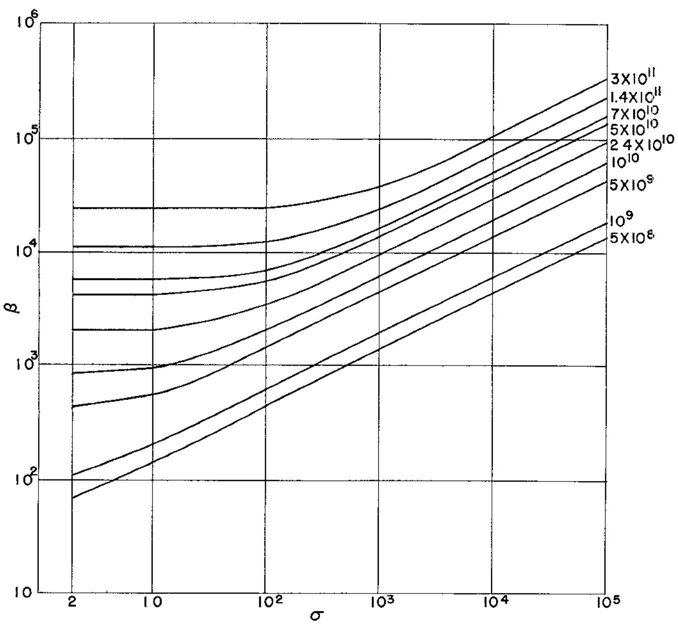

Fig. 2—Phase constant (radians/meter) as a function of conductivity (mhos/meter) and frequency (cycles/second).

give one to ten microsecond pulses to the probe in the forward direction, variations in the output of the detector diode could be readily observed. The voltage or current supplied to the probe could be monitored by the B channel. In this arrangement, an increase in the semiconductor conductivity could be displayed as a decrease in power on the A channel of the oscilloscope. At the cessation of the pulse, an exponential form of recovery was noted as the current from the detector diode increased back to equilibrium. It has been shown that this exponential characteristic is related to the "lifetime" of additional minority carriers.

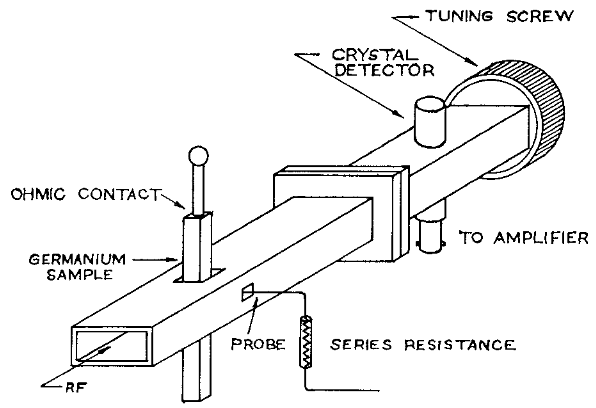

Fig. 3—Arrangement for location of sample in microwave power attenuation measurements.

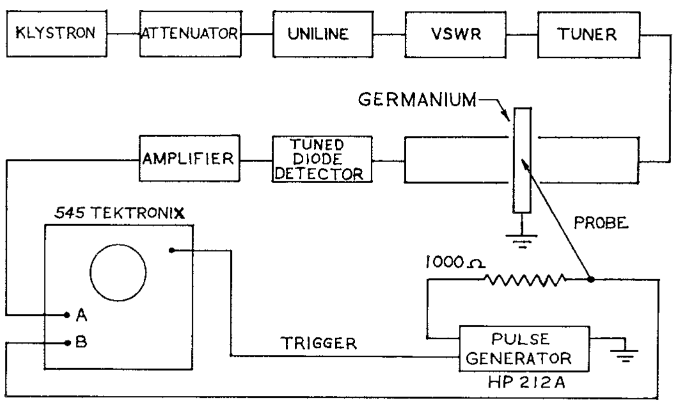

Fig. 4—Circuit diagram for microwave modulation.

During the remainder of this paper, we shall refer to the tuned diode feeding into the amplifier as the detector diode. It is also true that the probe making contact to the germanium rod which was under study makes another diode. This we shall refer to as the sample diode. In Fig. 5, we see a typical display of the oscilloscope presentation. Let us consider the sample diode now in more detail. In what follows, an alloyed dot was often made on the side of the semiconductor. The arrangement here is shown in Fig. 6. It is to be noted that the other contact of the sample, the ohmic contact, was not enclosed in the waveguide and, in fact, was more than two centimeters from the waveguide wall. This large distance was used to help prevent possible injection of minority carriers into the microwave field from the ohmic contact. In this manner only, one junction (the sample diode) could be studied without possible interference from the behavior of the ohmic contact.

Still another circuit arrangement was utilized. This we shall refer to as the *low-frequency amplitude modulation test.* Here, instead of using pulse voltages on the sample diode, 60-cycle ac voltage was applied to the probe. The circuit is shown in Fig. 7. In this arrangement, when 60-cycle ac voltage was applied to the probe the sample diode often rectified the current. The

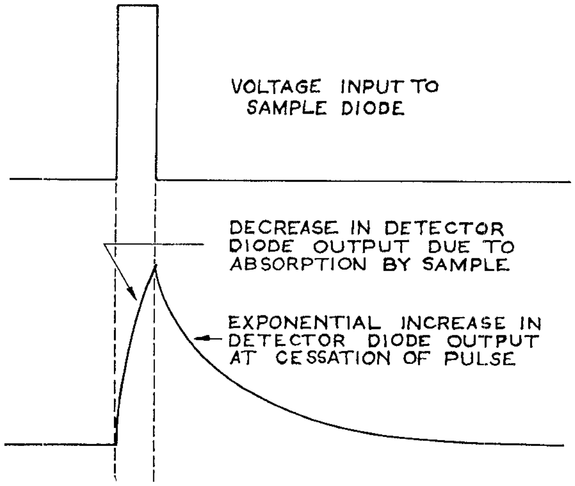

Fig. 5—Response of detector diode output to changes in power absorption. The polarity is such that an increase in oscilloscope voltage indicates an increase in absorption.

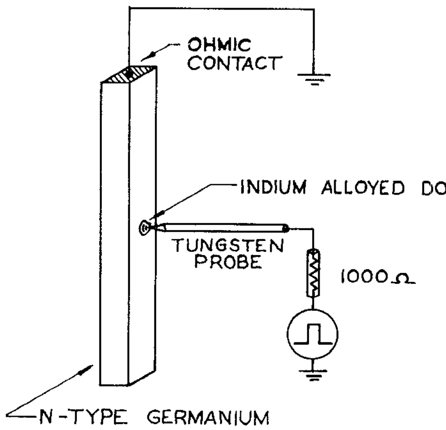

Fig. 6—Arrangement for study of alloy type of injection mechanisms.

output of the detector diode also showed a rectified sine wave characteristic.

In summary, the device to be considered is a germanium rod, the conductivity of which can be modulated by injected current carriers. An increase in conductivity will, in turn, cause a decrease of microwave power transmitted through the guide. In what follows, we shall describe the semiconductor preparation, some interesting physical effects observed during the testing, electrical characteristics and the design of the device.

Semiconductor Preparation

Rods were cut to the approximate desired dimensions, then polished with 600 mesh carborundum and etched in CP-4 solution to a bright finish. The ends of the rod were then abraded to reduce the possibility of injected minority carriers and plated with nickel. Soldered contacts were made to both ends and the resistivity of the material was determined. The type was then checked using two methods: the hot point probe, and the rectification point contact characteristics. Some samples were deliberately doped with copper impurity, by diffusion or by introducing copper in the melt.

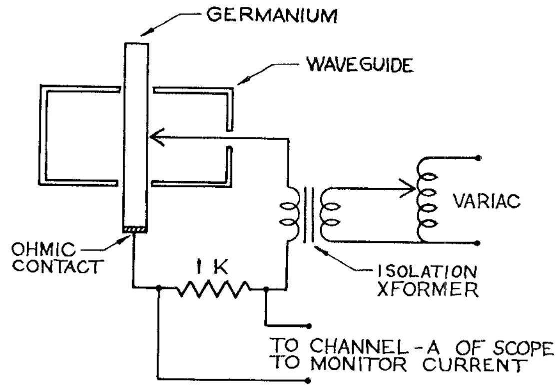

Fig. 7—Low-frequency modulation of germanium conductivity.

In relation to alloyed contacts for the sample diode, indium dots were fired on an N-type germanium crystal in an argon atmosphere, and for P-type material, alloyed dots were made with gold antimony. In general, the dots were about 1 mm in diameter. The samples were etched in CP-4 for 20–30 seconds, distilled-water washed, and then dried in air. Immediately after the etching, washing and drying steps, the samples were tested for diode characteristics. When the sample was placed in the waveguide, still another materials control was introduced. By injecting current into the sample with a 1–10 second pulse in the forward direction, one could observe the excess minority current carrier decay and from this deduce the lifetime. It has been shown in previous work[3] that the lifetime obtained in this manner is approximately the same as that obtained by more conventional photoconductive decay methods[4] or the microwave electrodeless techniques.

In Table I, there is a summary of samples tested in these experiments. It should be noted that some of the samples tested indicate a single lifetime. Others indicate more than one—a short lifetime and then a break in the recombination curve, followed by a longer lifetime. This longer lifetime was interpreted as being caused by deep traps of an unknown origin. This could be further checked by flooding the samples with light. Here the longer lifetime values changed considerably with variations in ambient light.

The deep trap samples could not be used for conventional design calculations of L_p, the diffusion length, D_p, the diffusion constant or τ_p, the bulk lifetime. However, the sensitivity of these samples to light and particularly infrared light, when tested in the waveguide holder, indicates that they may find considerable use in device applications.

[3] A. P. Ramsa, H. Jacobs, and F. A. Brand, "Techniques in measurement of lifetime in germanium," 1959 IRE National Convention Record, pt. 3, pp. 159–169. Also, *J. Appl. Phys.*, vol. 30, pp. 1054–1060; 1959.

[4] D. T. Stevenson and R. J. Keyes, "Measurement of carrier lifetimes in Germanium and Silicon," *J. Appl. Phys.*, vol. 26, p. 190; February, 1955.

G. Bemski, "Lifetime of electrons in p-type Silicon," *Phys. Rev.*, vol. 100, p. 523; October, 1955.

J. S. Blackmore, "Lifetime in p-type Silicon," *Phys. Rev.*, vol. 110, p. 1301; January, 1958.

TABLE I

Physical Properties of Samples

Number	Size in cm	Type	Resistivity ohm-cm	Lifetime in Microseconds	Comments
A	0.41×0.51×3.7	N	10.13	120−130	Single lifetime.
2	0.297×0.507×3.42	N	3.26	10	Single lifetime.
3	0.357×0.471×4.0	N	19.7	Two lifetimes noted. Longer lifetime 484 in room light.	Indication of deep traps.
4	0.302×0.325×3.45	N	33.6	Two lifetimes. Longer lifetime, roughly 1000 in room light.	Indication of deep traps.
5 90AE	0.338×0.386×3.60	N	35.2	1540	Single lifetime.
6	0.216×0.528×3.75	N	9.75	80	Single lifetime.
7 Same rod as sample No. 5	0.338×0.386×3.60	N	35.2	1540	Single lifetime.
C Same as A but copper doped at 700°C in argon.	0.330×0.412×3.62	P	1.43	0.2 to 1.5	Single lifetime.

Physical Effects in Semiconductors

At this point, it would be best to describe the observation of physical effects. We do this for two reasons. First, in the experiments to be described, we have a novel method of observing semiconductor phenomena related to variations in carrier concentration, such as injection, extraction, lifetime, trapping levels, etc. Second, in order to understand the mechanism of the modulator device and to foresee new arrangements and modifications, we must understand the physical effects. The physical phenomena of interest can be listed as follows: 1) Correlation of lifetime and modulation, 2) notes on injection, 3) observation of extraction, 4) further lifetime effects. Let us consider first the correlation in lifetime and modulation efficiency. Referring again to Fig. 4, we see that the tests were run as a modification of this arrangement. First, the lifetime was measured by a dual trace technique, whereby the pulse generator voltage was fed into an RC network and from here to the B channel on the oscilloscope. This allowed a comparison of the RC time constant with the lifetime characteristic obtained from the sample. Second, low-frequency amplitude modulation was measured by using the arrangement shown in Fig. 7 on the sample. The dc power level, P, reaching the detector diode was measured and then the peak decrease in power, ΔP, was determined for a given injection current (15 ma) into the sample. Power levels were measured using the output current of the detector diode through a 1000-ohm load resistor. This output of the detector diode was calibrated with a bolometer.

Now, consider the effects of injection in the forward direction. Assuming a low drift field, the minority carrier concentration will be given by

$$p_0 - p_n = p_n(e^{qv_{e0}/kT} - 1)e^{(X_n - X)/L_p}, \tag{4}$$

where

$$L_p = (D_p \tau_p)^{1/2} \tag{5}$$

and $p_0 = p_n$ is the excess minority carrier concentration, p_n the equilibrium minority carrier concentration, v_{e0} the applied voltage, X_n the boundary of the junction and X the distance inward. Thus, the longer the diffusion length, or τ_p, the greater the penetration of increased carrier concentration in the semiconductor rod. We should expect that, for long-lifetime samples, a longer time would be required for equilibrium to be established upon the advent of a forward bias voltage, and for a decrease in conductivity upon the cessation of the forward bias condition. In the low-frequency amplitude modulation test, the frequency was found to be low enough for equilibrium to be reached and the results were almost identical with dc effects of injection current upon transmitted power. In Table II, we find the data taken for the various samples studied. All numbers here refer to a point contact sample diode with 60-cycle voltage applied and providing 15 ma peak current through the sample.

TABLE II

Comparison of Lifetime and Power Modulation

Sample	ΔP (Relative Units)	P (Relative Units)	τ Microseconds
A	0.12	1.55	120–130
2	0.02	0.85	10
3	0.25	1.6	Double lifetime. Longer lifetime 400.
4	1.15	2.9	Double lifetime. Longer lifetime >1000.
5	1.25	2.9	1540
6	0.23	2.3	80
C	0.01	0.85	0.2 to 1.5

By (4) and (5) we might expect an empirical relationship between τ_p and $\Delta P/P$. A theoretical analysis is difficult because there are many other factors to consider. For instance, we must assume that the point contact at the sample has reasonable uniformity of efficiency of injection for all samples. In addition, the samples should be fairly uniform in geometry. Moreover, theoretical considerations[2] indicate that the lifetime measurement technique is more applicable to high-resistivity long-lifetime samples. The longer lifetimes resulting from the deep traps precluded the use of these particular samples in assembling the data in Fig. 8. We further assume that the quantity $\Delta P/P$ is constant for a given sample. Nevertheless, making these assumptions and choosing single lifetime samples A, 2, 5, 6, and C, we plotted the log $\Delta P/P$ vs log τ. The results indicate that a correlation exists in $\Delta P/P$ with τ. It may be suggested that this would provide a new technique in determining, by extrapolation, the lifetime for short-lifetime materials where measurements have been found difficult. In relating this to the design of the amplitude modulator, we should expect greater modulation efficiency with longer-lifetime semiconductors, provided the geometry is relatively constant. The situation for high drift fields will be discussed in a later section.

This technique of microwave absorption offers a novel method of inspecting injection phenomena which may be used to supplement more standard types of diode testing. For instance, double injection, with carriers being injected by a probe with either positive or negative polarities, can readily be observed by utilization of the microwave system. In the case of sample C (copper doped by diffusion at 700°C firing temperature), the sample was tested as a point contact diode with the standard circuit consisting of measuring current through a resistor. In this diode test, no rectification in the sample diode was demonstrated. One might conclude that the point contact formed an ohmic contact or that some other combination of circumstances prevented rectification. However, when the semiconductor block was inserted in the waveguide, one could observe the injection of carriers of both types and even get estimates of comparative injection efficiencies.

Referring to Fig. 9, we obtain the following data and interpretation. The upper line shows the oscilloscope trace representing current through the sample diode. No rectification was apparent and the peak current was set at 15 ma. In the second line, we see the result of double injection on the power absorption. The cusp points refer to the condition of no voltage and no injection, the downward path indicates absorption of microwave power due to injection. The larger absorption is due to injection of electrons, the smaller due to holes.[5] In this manner, comparative injection efficiencies can be demonstrated.

Another item of interest is that the microwave system allows a visual observation of extraction. This sometimes appears in the sample diode being reversed biased, with an increase in power transmitted.

Next, the effects of alloying on the lifetime of the sample were sought. A new indium alloyed dot was formed on the side of germanium rod No. 4. The sample was then placed in the waveguide and contact was made to the indium. The apparent lifetime was measured and found to be 350 μsec. This was the value of the longer lifetime resulting from the presence of traps. Then the probe was removed and a point contact was made to the germanium surface. The longer lifetime here was about 1000 μsec. This indicates that the presence of the indium alloy shortened the lifetime related to deep traps by a factor of three. It was concluded from further experiments with samples No. 6 and No. 7 that alloying does usually shorten the lifetime under the alloyed dot by a factor of $\frac{1}{3}$ to $\frac{1}{4}$, for germanium with the resistivity and lifetime in the ranges described above.[6]

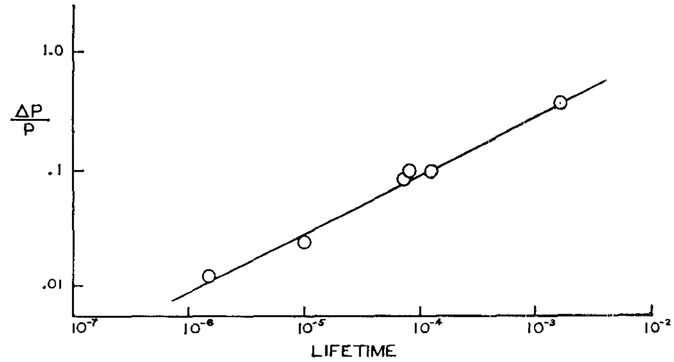

Fig. 8—The ratio of power absorbed by the semiconductor to the total power transmitted as a function of the bulk lifetime in seconds of the germanium specimen.

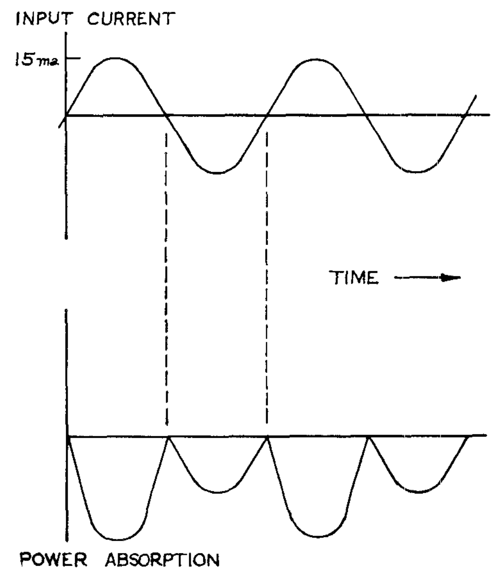

Fig. 9—Power absorption resulting from injection of carriers with alternating voltages on the probe.

[5] For reports on double injection, see W. G. Matthei and F. A. Brand, "On the injection of carriers into a depletion layer," *J. Appl. Phys.*, vol. 28, p. 513, April, 1957; and N. J. Harrick, "Metal to semiconductor contacts: injection or extraction for either direction of current flow," *Phys. Rev.*, vol. 115, p. 876, August, 1959.

[6] With the microwave absorption technique of lifetime measurement, it is shown by Ramsa, *et al.* ("Techniques in measurement of lifetime in germanium," *op. cit.*), that if the lifetime vs current curves are extrapolated to small current values, good agreement is found with the more conventional photoconductive decay methods. Experimental tests were run to confirm this conclusion, and the lower current values in Tables III and IV can be considered to provide the bulk lifetime values.

Electrical Characterization

The electrical properties of the semiconductor rod running parallel to the E field in the $TE_{0,1}$ mode were considered next. The microwave circuit was based on the arrangement of Fig. 4, with the following modifications. An EH tuner was used in place of the slide screw tuner and a bolometer was used in place of the detector diode. The sample diode current was supplied by a dc source consisting of a battery arrangement. In the following, the indium dot was used for injection.

For sample No. 6, the decrease in power, ΔP, reaching the bolometer for various forward currents in the sample diode, is shown in Table III. These data have been normalized by our calculating the $\Delta P/P$ ratio at different power levels. The data indicate that $\Delta P/P$ is relatively constant for constant forward currents, with the power levels changing by a factor of ten. The VSWR during these measurements was in the order of 1.10.

In the same microwave system, the EH tuner was removed; in order to examine the electrical effects of the semiconductor alone inserted in the waveguide, with the transmitted power going to a matched load. The wavelength in the guide was found to be 4.32 cm., and the standing wave ratio showed very slight variations with current. By means of Smith chart analysis, the normalized impedance and VSWR were demonstrated as a function of input current to the sample diode. Results are shown in Table IV.

We next consider sample No. 7 with resistivity at 35.2 ohm cm. The microwave system was matched by means of the EH tuner with the sample inserted. Results indicated that for this sample 43 per cent of the power was removed as insertion loss. This sample was tested for power transmitted as a function of sample diode current. The results are shown in Table V.

Next, for sample No. 7 without the EH tuner, the sample diode current was found as a function of VSWR, normalized impedance and $\Delta P/P$. The data are indicated in Table V.

Samples were tested for frequency modulation by means of a resonant cavity inserted in the line. In addition, a microwave bridge was assembled with calibrated attenuators and phase shifter. With the sample current injected to reduce the power transmitted to less than fifty per cent of its initial value, a phase shift of less than five degrees was noted.

TABLE III

Normalized Decrease in Power Transmitted as a Function of Various DC Currents (Sample No. 6)

DC Current in Sample Diode (ma)	Normalized Decrease in Power Transmitted $\Delta P/P$				
	P=0.3 mw Level	0.49 mw Level	1.0 mw level	2.0 mw Level	3.0 mw Level
0	0.0	0.0	0.0	0.0	0.0
5.5	0.0834	0.0633	0.078	0.080	0.084
12.0	0.133	0.122	0.130	0.130	0.130
19.5	0.166	9.153	0.140	0.155	0.163
27.5	0.173	0.1838	0.180	0.185	9.190
36.0	0.190	0.202	0.195	0.200	0.206
46.0	0.200	0.220	0.210	0.210	0.220

TABLE IV

Normalized Impedance vs DC Sample Diode Current (Sample No. 6)

Current in Milliamperes	VSWR	Normalized Impedance
0	3.59	$0.290+j.140$
5.8	3.60	$0.283+j.165$
12.5	3.68	$0.280+j.180$
19.5	3.75	$0.275+j.155$
27.5	3.80	$0.266+j.154$
45.5	3.90	$0.261+j.168$
(Drift noted due to temperature rise)		

TABLE V

Sample Diode Current vs VSWR and Normalized Impedance (Sample No. 7)

Current Bias (ma)	VSWR	Normalized Impedance	$\Delta P/P$
0	4.90	$0.21 -j.158$	0
2 ma	4.70	$0.008-j.140$	0.12
4 ma	4.60	$0.208-j.140$	0.2
7.5 ma	4.50	$0.205-j.100$	0.2
10.0 ma	4.50	$0.202-j.070$	0.36
15.0 ma	4.50	$0.202-j.070$	0.43
20.2 ma	4.50	$0.202-j.070$	0.48
25.0 ma	4.60	$0.202-j.070$	0.51
30.0 ma	4.70	$0.202-j.070$	0.54
(Drift starting due to temperature rise)			

Design of Modulator

In the design of the modulator, so far we have considered only the diffusion mechanism of injected minority carriers with relatively low drift fields. In fact, the samples were made deliberately long so that the ohmic contact to the germanium could be placed a considerable distance out of the waveguide. This was necessary in order to examine the physical effects of absorption, reflection, etc., related to the sample diode alone. If one is not too concerned with the isolation of the sample diode and could insert a PIN diode in the waveguide, one might take advantage of high drift fields in the semiconductor to enhance the modulation effects.

For calculation of the properties of the PIN modulator, the lifetime, resistivity and distance become the key factors. Assume that the region from the sample diode to the ohmic contact of the specimen can be treated as a filament structure with a high enough field to neglect diffusion.

Following Shockley, the hole density varies as e^{-ax}, where a is the hole density attenuation factor.[7] The

[7] W. Shockley, "Electrons and Holes in Semiconductors," D. Van Nostrand, Inc., Princeton, N. J., p. 319; 1952.

term $1/a$ is now the distance at which the density is e^{-1} of its initial value, assuming constant injection current, and

$$1/a = \tau_p \mu_p E. \tag{6}$$

Next consider the total number of minority carriers in the filament N'. Here we have

$$N' = \int_0^D N dx = \int_0^D K e^{-ax} dx, \tag{7}$$

where D is the distance, K a constant representing the density of injected minority carriers at the junction boundary, and N' the total number of carriers. If N' is in the waveguide and $\sigma \alpha \omega \epsilon$, we have seen that α is linearly increased with σ. By (7),

$$N' = \frac{K}{a} [1 - e^{-aD}], \tag{8}$$

and as D becomes large compared to $1/a$,

$$N' = \frac{K}{a} = K \tau_p \mu_p E. \tag{9}$$

Eq. (9) reveals that an increase of D and E increase N' and, hence, the attenuation α of the semiconductor. However, there are practical limits. The limit on E is due to heating of the sample. This can be helped by the arrangement in Fig. 10, allowing more heat conduction. The other factor to be varied is the thickness of the sample D. This, however, can have the disadvantage of providing too high an insertion loss. It is desirable for $D > 1/a$, but not so much so that insertion losses at zero current bias conditions are impracticable.

The sample dimensions used in these tests are a compromise of temperature, insertion loss, lifetime and $1/a$ considerations, with respect to physical measurements and device design. A proposed arrangement sim-

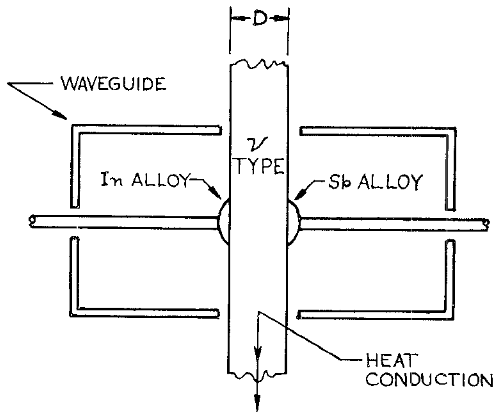

Fig. 10—Proposed method for enhancing the modulation efficiencies.

ilar to that of Fig. 10 should give improved device performance. In preliminary tests, $\Delta P/P$ ratios of 70 per cent have been obtained, as compared with 50 per cent using samples arranged as shown in Fig. 6. Other preliminary tests, using differently oriented samples of various sizes entirely enclosed within the walls of the waveguide, indicated that an optimum amplitude modulator configuration is determinable.

The possibility of designing a device specifically for enhanced phase modulation, using the present techniques, is also being investigated. In addition, multiple alloy dot arrangements would be worth studying, since N' will increase linearly with area.

Acknowledgment

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