However, the upper frequency limitation is also set by the difficulties of getting magnetic fields greater than 25,000 oersteds. This sets the limit at wavelengths of about 3 mm. Because of the associated cavity size and beam requirements, it is unlikely that the proposed system will be extended below 5 mm. Certainly there would be much to be gained by working at 1.25 cm initially where the NH_3 maser can be used for a frequency reference.

For noise calculations, it would be difficult to improve upon the treatment given by Gordon and White[11] which applies to the NH_3 maser, and scarcely any modification is needed to extend the treatment to magnetic dipole transitions. There is good reason to believe that a noise temperature of a few degrees Kelvin is attainable.

It may be well to point out that a solid-state system presents certain advantages over the proposal outlined here.[12] The most important of these is a very much larger gain-bandwidth product. On the other hand, a continuously operating three-level solid-state maser requires a pump frequency higher than the operating frequency, and this is difficult to obtain at mm wavelengths. Also, a solid-state maser calls for very low temperatures in order to achieve long thermal relaxation times, while the gas beam maser has no such requirement.

ACKNOWLEDGMENT

It is a pleasure to thank H. B. Silsbee for an interesting discussion on molecular beams and for suggesting improvements in this manuscript. In addition, comments from C. H. Townes and S. Silver have proved profitable.

[11] J. P. Gordon and L. D. White, "Noise in maser amplifiers," Proc. IRE, vol. 46, pp. 1588–1594; September, 1958.

[12] Zacharias and A. Javan have been performing experiments related to the scheme proposed here. (Private communication from C. H. Townes.)

High-Speed Microwave Switching of Semiconductors—II*

ROBERT V. GARVER†

Summary—**A relationship between low-power isolation and small-signal, low-frequency diode resistance is reported. A study of ambient heating indicates that with increasing temperature the diode characteristics tend to approach the line characteristic of the above relationship. Observed switching speeds of 1.5 to 3.0 mμs are reported. A theory is presented which agrees with the switching time data and predicts microwave switching times as low as 0.2 to 0.3 mμs. High speed switching is discussed with reference to significant parameters, *e.g.*, hole storage, internal heating, and pulse reverse diode characteristics.**

Introduction

It has been shown in previous publications[1–3] that an n-type point contact germanium diode can be used to switch X-band microwaves. Placing the diode across the center of the waveguide and impressing a reverse or forward voltage upon it will cause the diode to reflect or transmit the microwave power. The ratio of the microwave power past the diode in the reflecting state, to the incident microwave power, defines the isolation in db. The same ratio in the transmitting state, defines the insertion loss. Isolations of 25 to 35 db with constant insertion losses of 1 db were reported[1] over a 1000 mc band-width at 1 milliwatt incident microwave power. Using a 1N263, the only commercially available microwave germanium diode, rapid deterioration of isolation occurred for incident microwave peak powers greater than 5 milliwatts. Ambient heating showed constant insertion loss and only slight deterioration of isolation from 20°C to 150°C. It was shown[2] that decreasing the donor density of the germanium allowed the diode to switch up to 1 watt of incident microwave peak power. It was demonstrated by observing two pulses at succeedingly closer intervals that there was essentially no dead time between switching events. The pulse time constants of the diode switch were found to be a function of germanium donor density and to be of the order of 3×10^{-9} to 10×10^{-9} seconds (3–10 mμsec). Devices

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[1] M. A. Armistead, E. G. Spencer, and R. D. Hatcher, "Microwave semiconductor switch," Proc. IRE, vol. 44, p. 1875; December, 1956.

[2] R. V. Garver, E. G. Spencer, and R. C. LeCraw, "High speed microwave switching of semiconductors," *J. Appl. Phys.*, vol. 28, pp. 1336–1338; November, 1957.

[3] R. V. Garver, E. G. Spencer, and M. A. Harper, "Microwave semiconductor switching techniques," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 378–383; October, 1958.

employing the principles of these diode switches are described.[3]

The crystal switch has proved useful in bench testing and has great potential uses in missiles and microwave computers. An understanding of the switching speed problem is of considerable importance, and was thus reinvestigated. The details of the investigation are given so that application engineers may obtain a good understanding of the switching speed problem from the text, and to reinforce the point that the detector diode contributes most to the observed switching time and is a limiting factor in any microwave switching speed study.

Fabrication of higher power switches has provided a less delicate switch, but these cannot yet be mass produced with 1 db insertion loss. Despite intensive efforts in this laboratory to analyze the diodes, they defy the accepted laws of transistor physics. If point contact junctions of germanium and silicon are made in identical cartridges whose equivalent circuit is known for X-band, and the junction impedances are measured at X-band by varying the diode bias, the intrinsic impedances of the two junctions are quite different and neither junction behaves according to high frequency semiconductor theory; however, at 10 mc both diodes behave according to the theory. Quite simply, the modifications of semiconductor theory which describe microwave behavior of point contacts on germanium and silicon have not yet been found. In the design of semiconductor microwave devices in the past, the empirical approach, in the absence of theory, has proved fruitful. Thus, the empirical approach is used here to provide a test that may allow diode switches to be mass produced with 1 db insertion loss. A relationship between microwave attenuation and 10 mc small-signal junction resistance[4] has been determined, and it has been found to be supported by temperature and pulsing measurements. This relationship at the same time provides an understanding of the heating effects and reverse pulsing effects.

Isolation

It was shown that for the isolation of the switch to be high for higher incident microwave peak powers, all parts of the microwave sine wave must cause little current to flow across the crystal junction.[2] This suggests the existence of a relationship between isolation and junction resistance. Measurements were made of 160 crystals, including some 1N263s, some pilot production high power models, and some hand made diode switches. The measurements consisted of 1) observing the maximum isolation and the minimum insertion loss of each switch for 1 milliwatt incident microwave peak power and 2) observing the junction resistance on a 10 mc bridge using the same applied voltages. Considerable scatter was observed but a consistent trend was evident. Fig. 1 shows the trend. For forward current through the

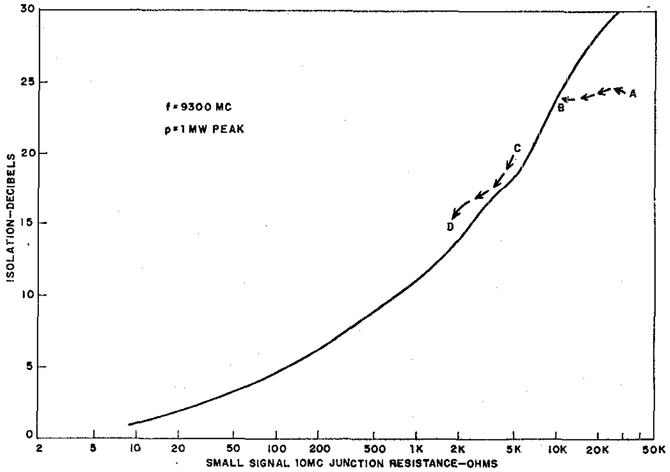

Fig. 1—Maximum small signal isolation as a function of small-signal 10-mc junction resistance for the same reverse bias. The arrow lines show two different effects observed in ambient heating. Lines either approach or lie within the proximity of the line characteristic of the function.

diode, a small signal resistance of 10 ohms gave about 1 db insertion loss. A reverse applied voltage giving 10^4 ohms small signal resistance gave about 24 db isolation. In many of the pilot production diodes the point contacts were near the edge of the germanium die and not near the crystal axis. These diodes were quite sensitive to rotation in the holder, giving radically different maximum isolations. This caused some of the scatter observed. Other contributing factors to the scatter may have been variation in area of contact, variation of hole injection characteristics, or some high frequency mechanism not yet known.

At different germanium donor densities the line above 20 db (Fig. 1) is not the same. The line characteristic of a diode having a high donor density ($10^{18}/cm^3$) is moved slightly to the left, while the line for a diode with low donor density ($10^{16}/cm^3$) is moved slightly to the right. Most of the data lie within ± 1 db of their characteristic line.

Fig. 1 is helpful in understanding the effect of ambient heating upon the isolation of the switch and may be useful in designing diode switches. This is explained in the following paragraph.

Ambient Heating

Earlier data[1] showed slight decrease in isolation with increase in ambient temperature. Later data on higher power diode switches revealed wide variations in change with ambient heating. Some few diodes improved with heating, while most others remained constant or showed the deterioration originally observed. The few diodes that improved showed some further improvement when returned to room temperature, and thereafter demonstrated the behavior of the others. These few diodes were probably welded during the thermal experiment to an improved characteristic. That is to say, they had not been welded enough in fabrication to have optimum characteristics.

[4] Junction resistance is defined as diode resistance at 10 mc.

Data from a higher power diode switch are shown in Fig. 2. At elevated ambient temperatures, the deterioration is greatest at higher powers, and deterioration exists at lower powers for this diode. A nondeteriorating diode gives the same line for higher ambient temperatures as for room temperature at low powers, while it drops off at higher powers for increasing temperature. Note that this diode, although deteriorating with temperature, gives greater than 20 db isolation for 50 milliwatt incident microwave peak power at a temperature greater than the melting point of the soft solder (180°C) used in making the diode. Upon returning this diode to room temperature, the isolation at low power returned to within $\frac{1}{2}$ db of that observed at the beginning of the test. The deterioration at 250°C caused little permanent damage. Other diodes were heated only to 150°C to avoid melting the solder.

The reverse dc characteristics of an *n*-type point contact germanium diode of 10^{16} donors/cm^3 are shown in Fig. 3. As ambient temperature is increased, the low voltage reverse resistance decreases, and breakdown occurs at lower reverse voltages. Referring to the solid line of Fig. 1, it should be expected that the isolation for lower power should decrease with increasing ambient temperature, and that due to the lowered voltage breakdown, higher power isolation should deteriorate rapidly. The question arises as to the behavior of the crystals that do not deteriorate at lower powers with increasing temperature. It is observed that those which do not deteriorate are represented by a horizontal progression on Fig. 1 as arrow line *AB*; and that they lie to the right of their characteristic curve. Arrow line *CD* represents a crystal that deteriorated at low power with increasing ambient temperature. Note that it lies to the left of the characteristic curve. Thus the data from both diodes tend to approach or lie within the proximity of the characteristic curve. The fact that diodes away from the characteristic curve approach it when heated gives added support to the validity of the relationship. If the relationship of Fig. 1 is valid, then production techniques can be established which will give low 10 mc forward resistance and high 10 mc reverse resistance without changing the mechanical dimensions of the cartridge or whisker; hence, a better switch can be made. It has also been shown that the crystal switch can function well in a very high temperature environment.

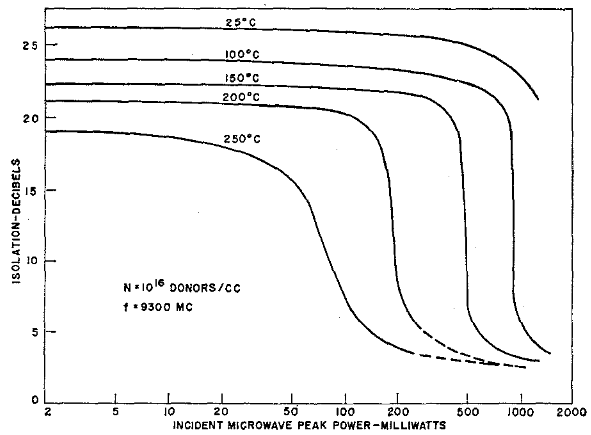

Fig. 2—Maximum isolation as a function of incident microwave peak power showing the effect of ambient heating. Upon cooling, the diodes returned to the curve characteristic of room temperature.

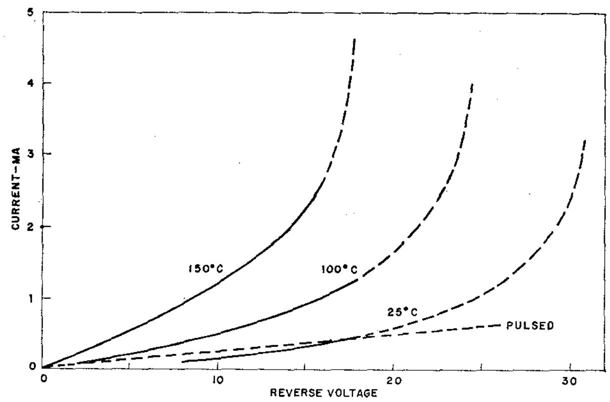

Fig. 3—Reverse characteristics of an *n*-type point-contact germanium diode. The curved lines are the dc reverse characteristics at various temperatures, while the straight line is characteristic of reverse pulsing from Bennett and Hunter.[7] The dashed lines are extrapolations.

Switching Speeds

Switching speeds of 3 to 10 mμsecs were reported,[2] and the mechanism causing those long response times was unknown. A different technique of pulsing has revealed observed switching speeds of 1.5 to 3.0 mμsecs. An equivalent circuit has been established whose pulse response agrees with the data.

In measuring the pulse time constants by biasing the switch "off" and pulsing it "on,"[2] pulses which are too large cause the decay time to increase, while pulses which are too small give insertion loss greater than that observed at dc.[5] With higher power switches these factors must be balanced against each other. Using higher voltage pulses from a mercury switch pulse source, the trailing edge below the 30 per cent voltage level decays so slowly that it is easily mistaken for the 0.0 per cent level. To date, increases of decay time due to large pulses can be attributed to the increased amplitude of the trailing edge of the switching pulse. If there is time required for hole return, it is overshadowed by the effect of the trailing edge. For higher power switches the low dc insertion loss is due partially to heating resulting from current in the forward direction. For very short pulses, time is insufficient to permit heating; therefore, a higher voltage pulse is required, which will lower the resistance by greater hole injection.

To eliminate the difficulties encountered in pulsing the semiconductor microwave switch "on," the technique of pulsing the switch "off" is employed. Then too small a switching pulse voltage will not give maximum isolation, and too large a switching pulse voltage will

[5] DC switching of microwaves is distinguished from pulsed switching since there is a difference for pulses shorter than 0.5 μseconds.

cause reverse current to flow with the occurrence of less than maximum isolation. The amplitude of the trailing edge is therefore kept to a minimum, and the optimum switching pulse amplitude is easily obtained. Fig. 4 shows the result of 200 milliwatts being pulsed "off" by a crystal switch of 10^{16} donors/cm^3.

The equivalent circuit for the switch pulsing network is shown in Fig. 5. To drive the crystal switch, a mercury switch pulser having output impedance of 50 ohms was employed. The 40-ohm and 10-ohm resistors are for matching the output impedance of the pulser. To bias the crystal "on" point B was connected to a dc voltage supply through a ferrite inductor. A 0.01 μf capacitor was connected between points A and B to prevent the bias voltage from entering the pulser. A 4000-ohm resistor was connected between point A and ground to provide a dc return path for the pulser. These components have little effect upon the pulse shape, and therefore they are omitted from the diagram. Lead lengths were kept to a minimum. C_2 is the capacitance of the detector crystal mount; C_1 is the capacitance of the switching crystal mount. C_1 is greater than C_2 because attempts to lower C_1 increased the insertion loss of the switch. L_1 is the inductance of the switching diode whisker. R_x is the nonlinear resistance of the crystal switch. The contact voltage i_xR_x imparts the voltage pulse, by the diode switching action, to the microwaves, which are in turn detected to give V_d. V_d is the detected voltage of the detector with no load. R_{id} is the internal resistance of the detector. R_{id} was computed from measurements on loading of the detector with 100 mw peak microwave power incident and load resistors varied above and below 120 ohms. R_{id} is nonlinear but not enough so to affect the computations. The inductive reactance of the detector whisker at the highest frequency involved here is only 0.07 R_{id}, and is therefore omitted. A traveling-wave oscilloscope having an input impedance of 120 ohms was used to view the pulses.

The inductance (L) of the whiskers was computed from $L=0.00508l\,(ln\ 4l/d-1)\times 10^{-6}$ henries,[6] where l and d are in inches. It was assumed that the inductances of these bent wires are equal to the inductances they would have if they were straight. For the 1N263, $L=3.6\times 10^{-9}$ henries. For the 1N23 type S-bend whisker, $L=5\times 10^{-9}$ henries. For the switching speed study, the detector and all of the higher power switches were fabricated in the 1N23 type cartridge.

Because the diode of 2×10^{18} donors/cm^3 can control only low power microwaves, the trace observed on the oscilloscope was too small from which to obtain accurate information. Data from the other crystals is shown in Table I. By inserting attenuation between the switch and detector as the power incident to the switch is increased, the power incident to the detector is not allowed to exceed 100 milliwatt peak. This limits the

[6] F. E. Terman, "Radio Engineer's Handbook," McGraw-Hill Book Co., Inc., New York, N. Y., p. 49; 1943.

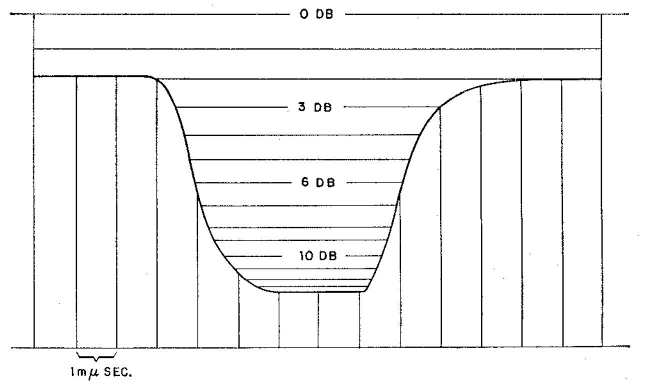

Fig. 4—Traveling wave scope display characteristic of pulsed "off" microwave switching using n-type germanium of 10^{16} donors/cm^3. 200 milliwatts of incident microwave peak power is being switched to 14 db isolation.

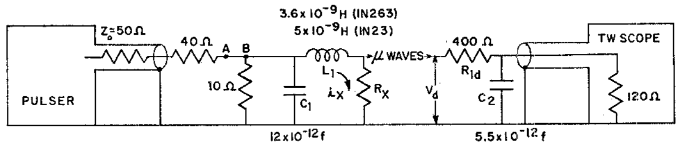

Fig. 5—Equivalent circuit for determining microwave pulsing time constants of the germanium diode switch with a silicon diode detector.

TABLE I

Experimental and Theoretical Values of Rise Time and Decay Time

Donors (no./cm^3)	Observed			Theoretical	
	3.5×10^{16}	1×10^{16}	3×10^{15}	Min.	Max.
Peak Power (watts)	0.05	0.20	1.50	—	—
Decay Time (mμs)	1.6	1.5	2.2	1.5	2.4
Rise Time (mμs)	1.8	1.9	3.0	1.4	3.4

cause of change in switching times to the switching diode. Pulse time constant is defined as the time elapsed between 10 per cent and 90 per cent of full pulse voltage amplitude. The minimum and maximum theoretical values shown in Table I were computed from the equivalent circuit of Fig. 4 on an analog computer. Taken into account in the computation were the nonlinearity of R_x, the nonlinear relationship between i_xR_x and V_d (Fig. 6), the real shape of the switching pulse from the pulse source, and the traveling wave oscilloscope's rise time of 0.5 mμsec. The minimum value corresponds to low power diodes and the maximum value corresponds to high power diodes. The observed data lie between these maximum and minimum limits. The real pulse shape was obtained on the analog computer by changing parameters of a function generating circuit until a function was generated which, when put through the traveling wave oscilloscope analog, corresponded to the traveling wave oscilloscope's picture of the pulse. The nonlinearity of R_x was easily measured for each diode. The nonlinear relationship between i_xR_x and V_d

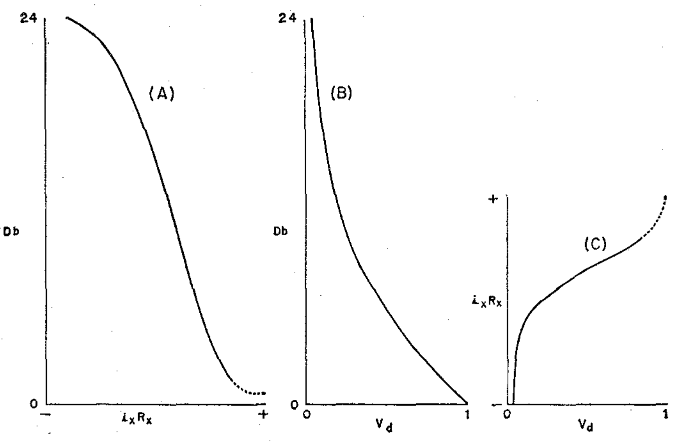

Fig. 6—Characteristics of the germanium diode switch and silicon diode detector for the purpose of determining their effect upon the pulsing time constant by limiting or heating.

may be obtained either as is shown in Fig. 6, or by direct measurement. Fig. 6 serves to show the difference between high- and low-power diodes as well as giving some meaning to microwave amplitudes at 10 per cent and 90 per cent voltage levels. Referring to Fig. 6, the solid line part of curve *A* is typical of higher power diode switches. Entering the dotted line region results in permanent damage to the crystal. However, for lower power diode switches the dotted line region is readily entered without damage. The lower insertion loss for the high-power diode switch is attained by lowering the diode resistance. This is accomplished by internally heating the junction with forward current. For lower power diode switches the resistivity of the germanium is low enough to give low forward diode resistance without generating internal heat. Curve *B* is characteristic of a 1N23B detector. Projecting curve *A* through curve *B* shows the limiting action of curve *C*.

It is observed in Fig. 4 that the pulsed isolation is only 14 db, while the dc isolation was 24 db. This lower pulsed isolation is typical of all germanium diode switches. It is suspected that this lowering of isolation is not caused by the return of stored injected holes, since their effect was not obvious in forward pulsing. The effect is probably due to the isothermal reverse characteristic differing from the dc characteristic. As was shown by Bennett and Hunter,[7] for pulses shorter than 500 mμs the reverse characteristic is nearly a straight line from the origin, with a greater slope than the dc characteristic and extending beyond twice the breakdown voltage (see Fig. 3). The lower small-signal resistance from the greater slope results in less isolation. It has also been observed that maximum pulsed isolation occurs at a much higher voltage than maximum dc isolation. This, too, is the result of the pulsing and dc characteristics being different.

From the analog computations it is predicted that, given a switching pulse voltage having 0 mμs pulse time constant, the semiconductor microwave switch will impart pulse time constants to the microwave of 0.2 to 0.3 mμs; and that, given a microwave pulse having 0 mμs pulse time constant, the display will have a rise time of 1.3 mμsec and a decay time of 1.5 mμsec, due to the detector crystal and traveling wave oscilloscope. That is to say, the detector diode contributes most to the observed switching times and is a limiting factor in any microwave switching speed study.

Conclusions

A consistent relationship has been observed between isolation and low-frequency small-signal junction resistance. The fact that diodes away from this characteristic line approach it when heated gives added support to the validity of the relationship. The establishment of this relationship should facilitate the fabrication of better diode switches.

Ambient heating results in little or no decrease in isolation at low powers and sudden rapid decrease in isolation at higher powers. This is explained in terms of the heating effect upon both the breakdown voltage and the slope of the dc reverse characteristics. It is concluded that the switch can function well in a very high-temperature environment.

Observations and calculations indicate the switch to be the highest speed microwave switch reported in the literature. The technique of pulsing the switch "on" results in increased decay time from the trailing edge of the switching voltage pulse, which obscures any evidence of the return of stored minority carriers. The technique of pulsing the switch "off" results in less than dc isolation due to the difference between dc reverse characteristics and short-pulse reverse characteristics. This investigation indicates that most of the observed switching time was due to the internal impedance of the diode detector and that it is a limiting factor in any switching speed study.

Acknowledgment

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[7] A. I. Bennett and L. P. Hunter, "Pulse measurement of the inverse voltage characteristics of germanium point contacts," *Phys. Rev.*, vol. 81, p. 152; January 1, 1951.