Theory of the Germanium Diode Microwave Switch*

R. V. GARVER†, J. A. ROSADO†, AND E. F. TURNER‡

Summary—The application of a generally neglected theory of microwave detection to the poorly understood problem of metal-to-semiconductor junction behavior at microwave frequencies is discussed. Experimental results are disclosed which support the theory and appear to be the first experimental verification of it. It is shown how the theory predicts that germanium microwave diodes should exercise direct switching action upon microwaves while silicon microwave diodes should not, as had been observed in the past but with no explanation.

Introduction

FOR several years it has been known that germanium microwave diodes exercise direct switching action upon microwaves while silicon microwave diodes do not.[1] The gross difference in switching action between germanium and silicon implies some fundamental difference between the germanium and silicon metal-to-semiconductor junctions at microwave frequencies. No satisfactory explanation of this difference has hitherto been published. Little is known of the microwave frequency behavior of metal-to-semiconductor junctions. The popular assumption is that at a given reverse bias the junction equivalent circuit elements (a parallel capacitor and resistor) are unchanged from 10 mc to 10,000 mc. If this were true, the rectifying efficiency of diodes would decrease much more rapidly with frequency than is actually observed. Lawson[2] has formulated a theory based on majority carrier trapping which purports to explain microwave detection; however, Lawson's theory has never been verified experimentally and consequently it is seldom used. Designers of microwave diode devices to date[3,4,5] use empirical techniques in the absence of a complete precise theory.

New uses of junction diodes at microwave frequencies as switches, attenuators,[6] phase modulators, frequency translators,[7] and amplifying elements,[8] make it more important than ever to know the behavior of junctions at microwave frequencies.

The impedance of a diode junction is determined by the flow of currents across the junction. The junction current is made up of minority carriers and/or majority carriers. At higher frequencies the junction impedance is determined by the trapping of these minority and/or majority carriers. Shockley[9] presented several solutions for the junction impedance assuming minority carrier current. Penin and Skvortsova[10] have made measurements on point-contact junctions for forward currents at microwave frequencies, showing some correlation between minority carrier theory and their data. Lawson[2] presented a solution for the junction impedance assuming majority carrier current. Presented here is experimental verification of his theory. M. Cutler,[11] studying dc characteristics of point-contact diodes, considered the case in which current consists of both minority and majority carriers and demonstrated their coexistence. For forward currents, Penin and Skvortsova[10] found fair agreement with minority carrier theory if they could assume very short minority carrier lifetimes on the surface of the semiconductor. This indicates that a large portion of the forward current is due to minority carrier flow in the semiconductor. The data for germanium presented here for a small reverse bias more closely fits Lawson's theory for majority carrier current than Shockley's theory for minority carrier current, while no good correlation can be made between the silicon data and majority carrier theory. Thus, it is concluded that the current, flowing for a small reverse bias on the germanium

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† Diamond Ordnance Fuze Labs., Washington, D. C.
‡ Dept. of Physics, Washington and Lee University, Lexington, Va. Summers, Diamond Ordnance Fuze Labs., Washington, D. C.
[1] M. A. Armistead, E. G. Spencer, and R. D. Hatcher, "Microwave semiconductor switch," PROC. IRE, vol. 44, p. 1875; December, 1956.
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[6] 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.
[7] E. M. Rutz and J. E. Dye, "Frequency translation by phase modulation," 1957 IRE WESCON CONVENTION RECORD, vol. 1, pt. 1, p. 201.
[8] A. Uhlir, Jr., "The potential of semiconductor diodes in high-frequency communications," PROC. IRE, vol. 46, pp. 1099–1115; June, 1958.
[9] W. Shockley, "The theory of p-n junctions in semiconductor and p-n junction transistors," *Bell Sys. Tech. J.*, vol. 28, pp. 435–489; July, 1949.
[10] N. A. Penin and N. E. Skvortsova, "The impedance of the rectifying contact in germanium and silicon detectors at microwave frequencies," *Radiotekh. Elektron.*, vol. 3, pp. 267–275; February, 1958. (Complete translation from International Physical Index, Inc., New York 35, N. Y., Electronic Express No. Ex 1A13.)
[11] M. Cutler, "Point contact rectifier theory," IRE TRANS. ON ELECTRON DEVICES, vol. ED-4, pp. 201–206; July, 1957.

point-contact diodes studied here, is largely majority carrier current.

It is shown that a difference exists between germanium and silicon and that the germanium should work well as a switch in the standard microwave diode cartridge while silicon should not. This confirms earlier observations.

Data on Diodes

At a fixed reverse bias voltage, the impedance of point contacts on N-type germanium and P-type silicon were measured from 1 mc to 10 kmc. Measurements from 1 mc to 200 mc were made on the Boonton parallel RC bridge. Measurements at C and X-band were made in waveguide by the techniques reported by Garver and Rosado.[12]

The equivalent circuit for the diode junction at reverse bias is assumed to be a parallel resistance and capacitance. Figs. 1 and 2 respectively show the resistance and capacitance for germanium and silicon as functions of frequency. Special weight is assigned to 9.3-kmc data because it is the frequency at which the measurement technique was refined. The bridge measurements are considered to be those of typical diodes, independent of donor density in the range of 10^{16}–10^{18} donors per cm^3 for Ge (*e.g.*, 1N263) and 10^{19} acceptors per cm^3 for Si (*e.g.*, 1N23).

Very little will be said concerning the silicon diode data. The equivalent circuit assumed for the plots of Figs. 1 and 2 is not valid above 2 kmc for silicon because of high spreading resistance. The forward and reverse data plotted in Fig. 5 is similar to the observations of Penin and Skvortsova[10] which come fairly close to minority carrier theory. The germanium diode data however, plotted as Resistance vs Reactance for changing current, gives more of a straight line which implies that the depletion layer capacitance (from majority carrier current) is predominant over the diffusion capacitance (from minority carrier current).

Lawson's Theory[2]

Lawson's theory evolves from considerations of the probability per unit time for the ionization of a bound impurity atom. Of N impurity atoms n_0 are ionized at room temperature leaving $N-n_0$ bound majority carriers. The relaxation time constant τ for this ionization process is found to be

$$\tau = \frac{n_0}{(2N - n_0)B},$$

in which B is the ionization probability in unit time.

[12] R. V. Garver and J. A. Rosado, "Microwave diode cartridge impedance," this issue, pp. 104–107.

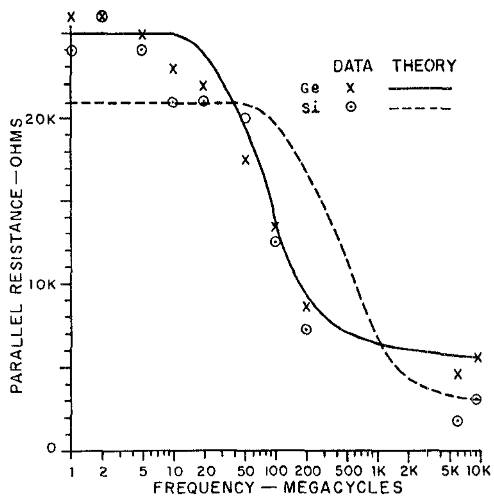

Fig. 1—Parallel resistance of a germanium and a silicon diode at a fixed reverse bias as a function of frequency.

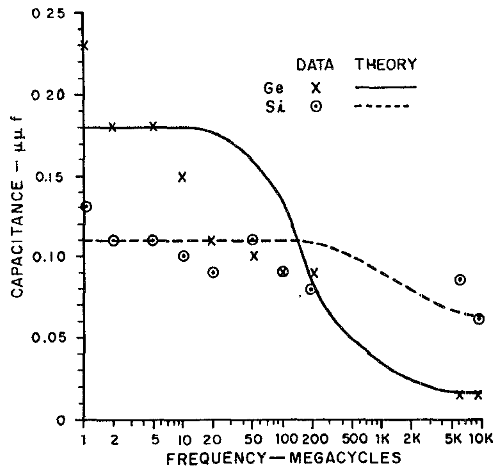

Fig. 2—Parallel capacitance of a germanium and a silicon diode at a fixed reverse bias as a function of frequency.

The portion of free-charge carriers with no field applied at room temperature is n_0/N, which should be about 1.00 for germanium. B may have any value from 10^6 seconds^{-1} to 10^{10} seconds^{-1}. Imperfections other than donors or acceptors in a material would change the value of an observed B because of the trapping of these additional impurities. The edge of a semicoductor, owing to the interruption of the lattice at an edge, contains impurities caused by irregularities in the lattice. The edge is also subject to absorption of gases which introduce impurities. And finally, the force exerted by a whisker and by heating in fabrication, can result in additional dislocation impurities and in possible diffused impurities that precede from the whisker into the semiconductor contact region or from the contact region further into the body of the semiconductor.

The parallel junction capacitances at zero frequency and infinite frequency are respectively C_0 and C_∞. The conductances are respectively G_0 and G_∞.

$$C_0 - C_\infty = \Delta_C \qquad G_\infty - G_0 = \Delta_G = G(\infty)$$

$$C(x) = C_0 - \Delta_C F_2$$

$$G(x) = G_0 + \Delta_G \frac{G(x)}{G(\infty)}$$

$$B = \frac{2}{3}\frac{\Delta_G}{\Delta_C} \qquad \frac{n_0}{N} = \frac{C_\infty}{C_0}$$

Fig. 3 shows F_2 and $G(x)/G(\infty)$ taken from Lawson[2]. It should be noted that the curves are incorrectly labeled in Torrey and Whitmer.[2]

According to minority carrier theory the conductance at infinite frequency becomes infinite. According to Lawson's theory the conductance at infinite frequency remains finite. For germanium the parallel resistance measured at lower frequencies (Fig. 1) would indicate essentially zero resistance at 10 kmc if minority carrier theory applied, but the data closely follow Lawson's majority carrier theory. In Fig. 2, the data for germanium deviate slightly from Lawson's theory. The discrepancy may be the result of B being multivalued or indiscrete. That is to say, more than one type of impurity may be dominant; for example, impurities frozen into the semiconductor lattice at different energy levels may give multiple discrete values of ionization energy or may even give a continuous range of ionization energies. Lawson's theory is based upon one discrete ionization energy.

To obtain the theoretical curves, it was assumed that

$$G_\infty = 1.82 \times 10^{-4} \text{ mhos}$$
$$G_0 = 0.4 \times 10^{-4} \text{ mhos}$$
$$C_0 = 0.18 \times 10^{-12} \text{ farad}$$
$$C_\infty = 0.012 \times 10^{-12} \text{ farad for germanium}$$

and

$$G_\infty = 3.76 \times 10^{-4} \text{ mhos}$$
$$G_0 = 0.476 \times 10^{-4} \text{ mhos}$$
$$C_0 = 0.11 \times 10^{-12} \text{ farad}$$
$$C_\infty = 0.057 \times 10^{-12} \text{ farad for silicon.}$$

This would indicate that 7 per cent of the carriers are free in germanium. This value for germanium is very low and would indicate that the energy level of the traps is much lower in the forbidden band than the donor impurity energy level. It might indicate that the depletion layer is receding only slightly into the neutral region, contributing only 7 per cent to the current, while the remainder of the current is coming from traps in the depletion region, ionized by the greater field caused by the ac test signal. The pulse reverse characteristic of germanium point-contact diodes is different from the dc reverse characteristic. This is also a result of trapping in the depletion region[13].

[13] G. Rupprecht, "Measurement of germanium surface states by pulsed channel effect," *Phys. Rev.*, vol. 111, pp. 75–81; July 1, 1958.

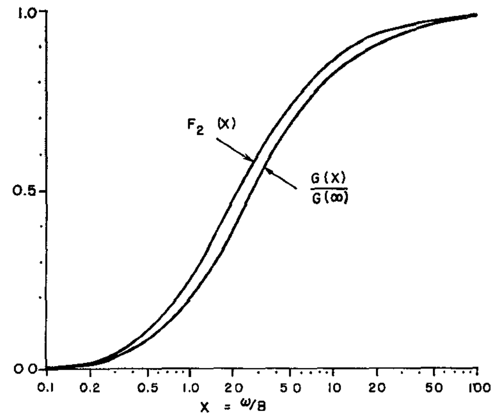

Fig. 3—Variable parameters of Lawson's Theory.[2] It is noted that the curves are incorrectly labeled there.

The values of B for germanium are 5.64×10^8 seconds^{-1}. These are of the anticipated order of magnitude. The lower melting point of germanium, and hence greater disturbance of its surface during fabrication, may account for the large amount of traps in the depletion region with energy gaps greater than those associated with the donor impurities.

To summarize, the current of point contacts on silicon and germanium at a fixed reverse bias may be either due to minority carriers, majority carriers, or both. The data reported here imply that the reverse current is mostly from majority carriers in germanium and from minority carriers in silicon.

Switching

If the diode is a reflecting discontinuity in a plane with a matched load behind it, then the attenuation of a diode switch is defined as the ratio in decibels of the microwave power getting past the diode, to the incident microwave power; and the impedance measured with reference to the exact plane of the diode, gives the attenuation according to $\text{db} = 10 \log (G/1 - \Gamma^2)$, in which G is the combined conductance of the diode and matched load, and Γ^2 is the power reflection coefficient (Fig. 4). Eliminating the effects of the matched load and cartridge impedance,[12] attenuation as a function of diode junction impedance is obtained (Figs. 5 and 6). Projecting the reverse impedances of Figs. 1 and 2 into Figs. 5 and 6, shows that germanium gives 20 db or higher isolation while silicon gives less than 3 db. The forward bias data points are also shown in Fig. 5. It is seen that the higher spreading resistance of silicon gives greater than 3 db insertion loss, while the low spreading resistance of germanium allows 1 db or less insertion loss.

Conclusion

The experimental results indicate that germanium closely follows the majority carrier theory of Lawson. This appears to be the first experimental verification of

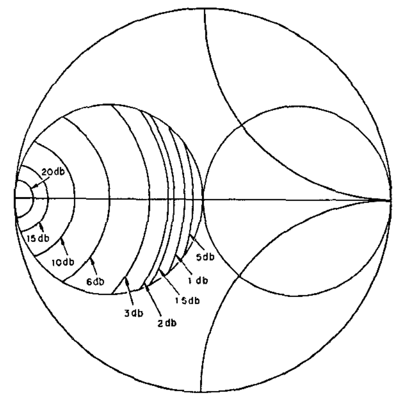

Fig. 4—Attenuation from a planar impedance in a transmission line.

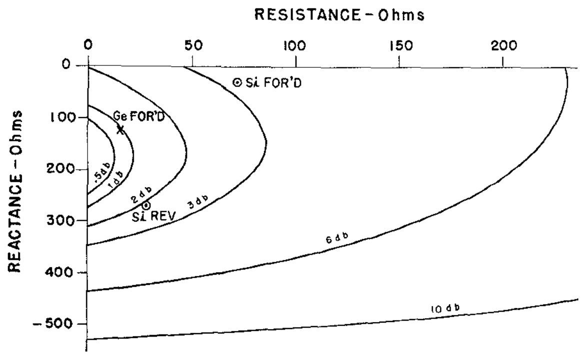

Fig. 5—Attenuation as a function of diode contact impedance for the 1N23 type cartridge at 9300 mc in full size standard X-band waveguide. The contact impedances of silicon and germanium are shown to demonstrate their switching behavior.

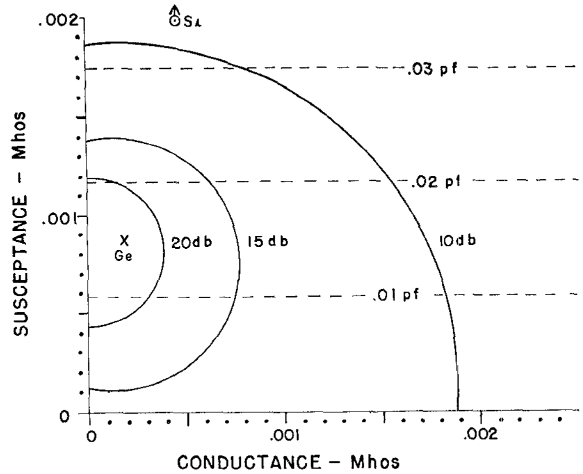

Fig. 6—Attenuation as a function of diode contact admittance for the 1N23 type cartridge at 9300 mc in full size standard X-band waveguide. The contact admittance of germanium at reverse bias is shown to demonstrate its good switching behavior.

Lawson's theory. Silicon, on the other hand, appears to follow the minority carrier theory of Shockley. Thus, the observed difference between the microwave switching capabilities of germanium and silicon is provided with a theoretical foundation.

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Improvement in the Square Law Operation of 1N23B Crystals From 2 to 11 kmc*

A. STANIFORTH† AND J. H. CRAVEN†

Summary—**Crystal rectifiers have been used for many years as video detectors in microwave measurements. In most of the applications the detection characteristic at low level is assumed to be square law. It is well known that, in general, this assumption is not justified, particularly if reasonable accuracy is desired. The conditions required to increase the dynamic range over which square law response may be achieved have been investigated experimentally. Results obtained in this laboratory have indicated that a forward bias current of 100 microamperes or more with a low video load resistance made the operation of the crystal closer to the ideal square law over a larger dynamic range.**

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† Radio and Elec. Engrg. Div., National Research Council, Ottawa, Can.

Introduction

Crystal diodes have been used for many years as low-level video detectors of radio-frequency energy both in microwave receivers and in laboratory measuring equipment. The superior low-level performance of the crystal as opposed to a bolometer, together with its small size and short-term stability, make it useful in such applications despite variations between crystals. The crystal rectifier is not limited to the measurement of average power or to low modulation frequencies as are bolometers and thermistors. In its square law region, the crystal is well suited to the comparative