There are at least two explanations which may describe the above phenomena. One explanation requires that the ac signal be large enough to swing into both forward conduction and dc breakdown. Rectification about the forward characteristic should be poor because of minority carrier storage, and thus breakdown current should counterbalance the forward current at bias levels closer to forward conduction. This effect would be aided by the asymmetry of the waveform of voltage across the diode, which is peaked in the negative direction because of the shape of the C-V curve.

The second explanation is that the voltage does not reach the dc breakdown value, but at high frequencies some new mechanism occurs causing reverse current to flow at a voltage less than the normal dc breakdown voltage. To determine which explanation is correct, we have measured the voltage across the diode under conditions when the anomalous behavior was observed. This was done by two methods. The first method involved determining the amplitude of the various frequency components of the voltage across the diode by the use of a slotted line and reconstructing the waveform under the most pessimistic assumptions about phase. If the relative phases were such that all the peaks added in the negative direction, the maximum reverse voltage would only be 6.6 volts. This is considerably less than the value of 10.5 volts at which dc breakdown occurs.

At this point, we must mention the difference between the voltage we measure at the diode terminals and that which exists at the junction. The diode lead inductance is resonant with the junction capacitance from 3 to 4 kmc depending on the bias. The fundamental frequency was made low enough (470 mc) so that even at the third harmonic the parasitic elements introduce a negligible discrepancy.

For a second independent measurement to determine whether the diode voltage reaches dc breakdown, a high-frequency peak reading voltmeter (HP410B) was mounted in 50-ohm line directly in front of the diode and its coaxial mount. The meter response was flat to the fourth harmonic of the 185-mc signal used here. By reversing the diode and bias polarities with respect to the meter, both forward and reverse peaks were measured. They were +1.4 volts and −7.3 volts respectively. Again we see that the reverse peak does not reach the breakdown level.

Additional enlightenment as to the nature of the reverse conduction process results from a plot of average diode current vs bias for a fixed value of ac drive. (See Fig. 2.) The curve shown is for 370 mc. Similar results were found at other frequencies. The current is seen to be continuous through zero, indicating both forward and reverse current even at small bias levels. After switching from negative to positive it returns to zero for a range of bias values midway between the forward and reverse portions of the dc characteristic. This indicates that the voltage swing is too small to enter either conduction region when biased midway. Therefore, the negative current at small bias levels is not due to a large signal entering dc breakdown, but seems to depend upon forward current being drawn during part of the cycle. A further increase in bias results in breakdown current at −5.8 volts, indicating an ac amplitude of 4.7 volts. When this is added to the bias (2.8v) for the first crossover through zero, negative current is seen to be generated when the instantaneous voltage reaches −7.5 volts.

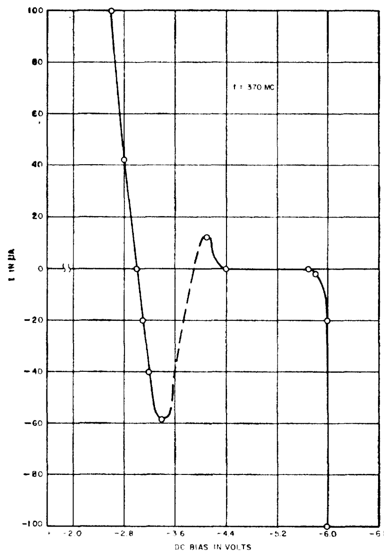

Fig. 2—Average diode current vs dc bias with ac drive (Si-43 No. 33).

The dashed portion of the curve denotes an unstable region, the operating point flipping from one extreme to the other. When biased in this region, a relaxation oscillation existed between these points at about 1 cps.

It should be noted that the circuits used have no structures tuned near the operating frequency, so that the variation of current with bias is not due to resonance effects involving the diode capacitance. The bias lead was suitably bypassed to ac.

Following the high-frequency experiments with the BTL Varactor diodes, the phenomenon was reproduced at low frequencies (15 mc) with a Hoffman 1N138 diode for which the lifetime was measured as about 1 μsec. The ratio of lifetime to RF period is seen to be of the same order of magnitude as in the high-frequency experiment. In addition, the breakdown mechanism is known to be of the avalanche type since this diode also exhibits the random pulse phenomenon described by McKay.[3] An oscilloscope verifies that the voltage is not required to reach dc breakdown, although the difference is not as great as in the high frequency case. A curve of average current vs diode bias similar to that of Fig. 2 was obtained, where the crossover through zero occurs at about −9 volts bias and the dc breakdown voltage is −27 volts.

It seems reasonable to conclude then that at RF periods which are short compared with the minority carrier lifetime, the carriers injected during the forward half cycle are multiplied through collision ionization on the reverse half cycle, resulting in a net reverse current. From the three high-frequency experiments presented, the maximum reverse voltage for anomalous current is about 7 volts. McKay has plotted the multiplication factor M vs V/V_b for a linearly graded silicon junction diode, where V_b is the breakdown voltage. For $V_b=10.5$, $V/V_b=0.7$, and the multiplication factor is about 2. Although this is not too much multiplication, the injected carriers represent a large increase in minority carrier density over the steady state level (of the order of 10^6). As a result, even a multiplication of two may yield considerable reverse current.

Conclusions have not yet been reached concerning the magnitude of the effects of this phenomenon on parametric amplifiers and harmonic generators, but it would seem to limit the voltage swing short of forward conduction under the penalty of an additional loss mechanism and some additional noise (even though the net dc current were zero, noise generated on the forward and reverse half cycles would degrade the noise figure of an amplifier). Operation in the nonconductive region between breakdown and forward conduction would avoid this effect, but considerable nonlinearity is probably lost by not driving into the forward region.

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[3] K. G. McKay, "Avalanche breakdown in silicon," *Phys. Rev.*, vol. 94, pp. 877–884; May, 1954.

Relativity and the Scientific Method*

The recent Proceedings article by J. R. Pierce[1] has triggered considerable adverse comment[2] on Einstein's Theory of Relativity. In the maze of detail which was discussed, one very important principle was all but forgotten, *i.e.*, the operation of the scientific method.

The objective of physical science is to provide a theoretical basis for interpretation of the observed behavior of nature. Observations are thus the final and conclusive arbiter of the "correctness" of any physical theory. It follows that a theory may never be "proved," since it is impossible to perform *all* experiments. Conversely, if such proof were possible, there would be no more

* Received by the IRE, October 22, 1959.
[1] J. R. Pierce, "Relativity and space travel," Proc. IRE, vol. 47, pp. 1053–1061; June, 1959.
[2] H. L. Armstrong, "Comment on relativity and space travel," Proc. IRE, vol. 47, p. 1778; October, 1959.

need for the theory itself since the purpose of any theory is to predict the outcome of new experiments. The success of a theory may thus be judged by the manner in which it fulfills this objective. In contrast, only one physical observation is required to disprove a theory. If it can be shown that a prediction of the theory is in clear contradiction to the behavior of nature as observed by a well-performed experiment, the theory must be discarded.

If we are to retain our present concepts of the scientific method, we should treat the Theory of Relativity as any other theory. No amount of belief or disbelief and no lengthy emotional expression of philosophy will substitute for a careful analysis of the observed physical facts in relation to the predictions of the theory. To date, a great number of results predicted by the Theory of Relativity have been experimentally verified. No case of clear contradiction has yet been found. Whether the theory in its present form will continue to enjoy such remarkable success indefinitely is not the subject under discussion here. Few scientists today would be willing to attest to the infallibility of any theory. However, until now the Theory of Relativity has stood the test of many critical experiments which any potential critic would do well to ponder, and until such an experiment demonstrates a clear contradiction, the critic should content himself with devising new experiments.

Irrespective of the eventual outcome of experimental work, the Theory of Relativity will remain the remarkable contribution of a remarkable man and a monument to the ability of the scientific method to bring understanding to an area where there was none.

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A Simple General Equation for Attenuation*

The familiar equations for the attenuation of various kinds of transmission media all involve two basic kinds of dependencies. One is the intrinsic electrical properties of the conductors and dielectric; the other is the geometric configuration and scale of the cross section. It may not be generally appreciated that the attenuation of most of the media in which the waves are guided by conductors can be expressed by a single simple equation in which the two kinds of dependencies just mentioned are represented by separate and distinct coefficients. Once the equation is written, its coefficients may be readily evaluated by comparison with the usual equations for those cases for which the wave equations have been solved, or by correlation with experimental data. We believe this concept of a general equation is interesting, and that the equation itself is of considerable engineering usefulness.

One of the writers, Szekely, has produced a mathematical proof, using perturbation techniques, that the equation presented is indeed general and applies to all transmission systems having conducting surfaces parallel to an axis of a general orthogonal curvilinear coordinate system, along which the waves are propagating and in which the wave equations are separable. The proof will not be given here. It is based, however, on the assumption of good conductors and good dielectric materials. The equation applies, for example, to the attenuation per unit length of wire pairs, of coaxial conductors, of all transmission modes of waveguides of any shape of cross section, of strip lines, etc. It even applies to such structures as conical horns if the attenuation is expressed in nepers or decibels per unit length, per unit solid angle.

The attenuation per unit length of any transmission medium in the class just defined is given by

$$\alpha = \frac{M \dfrac{\sqrt{f}}{a}\left[A + B\left(\dfrac{f_c}{f}\right)^2\right] + D}{\sqrt{1 - \left(\dfrac{f_c}{f}\right)^2}}, \quad (1)$$

where:

D = constant depending only on the intrinsic properties of the dielectric,

M = constant depending only on the intrinsic properties of the dielectric and of the conducting material,

A, B = constants depending on the configuration (but not the scale) of the cross section, and on the transmission mode,

a = a selected linear dimension of the cross section specifying its size or scale, all other dimensions having fixed ratios to a,

f = transmitted frequency, and

f_c = cutoff frequency of the particular transmission mode on the given medium.

The constant D accounts for that part of the attenuation that is due to dissipation in the dielectric. In many cases where the dielectric is air or some other gas, this may be neglected. The remainder of this equation, representing the attenuation due to dissipation in the conductors, can be written in a normalized form:

$$\alpha_m \cdot a^{3/2} = \frac{M\sqrt{af}\left[A + B\left(\dfrac{f_1}{af}\right)^2\right]}{\sqrt{1 - \left(\dfrac{f_1}{af}\right)^2}} \cdot \quad (2)$$

where $f_1 = af_c$.

A plot of $(\alpha_m \cdot a^{3/2})$ vs (af) gives one curve that is applicable to any scale of cross section, for a given medium of given shape of cross section and a given mode of transmission.

To apply (1) to a particular case, it is necessary to know the values of M, D, A, B and f_1. Since M and D depend only on the conducting and dielectric materials, they can be determined once for all transmission media employing particular materials, say copper and air. Their values are given by

$$D = \frac{\eta\sigma}{2} \quad (3)$$

$$M = \frac{1}{\eta}\sqrt{\frac{\pi\mu_m}{\sigma_m}} \cdot \quad (4)$$

In these,

$\eta = \sqrt{\mu/\epsilon}$ = intrinsic impedance of the dielectric, where μ and ϵ are the absolute permeability and dielectric constant of the dielectric,

μ_m = permeability of the conducting material,

σ = conductivity of the dielectric, and

σ_m = conductivity of the conducting material.

For a vacuum and substantially for gases, $\eta = 120\pi = 377$ ohms. For dielectrics having a different dielectric constant than that of a vacuum, $\eta = 377/\sqrt{\epsilon_r}$, where ϵ_r is the relative dielectric constant.

It shall be noted that at frequencies well above cutoff, the portion of the attenuation constant caused by a lossy dielectric is very nearly a frequency independent constant, $(\alpha_D \cong D = \frac{1}{2}\mu\sigma)$; this is true for any geometric configuration, scale of cross section, or mode of transmission, provided that the conductance of the dielectric is constant and small. (In some dielectrics such as paper in paper-insulated telephone cables, σ appears to be a function of frequency.)

If rationalized MKS units are used, the attenuation given by (1) will be in terms of nepers per meter. Obviously, the attenuation may be converted to other units by multiplying M and D by suitable factors. Table I gives some values of M for copper conductors ($\sigma_m = 58 \times 10^6$ mhos per meter) and air dielectric, corrected for several combinations of units.

TABLE I

Values of M for Copper Conductors and Gas Dielectric

α	a	f in cps.	f in KMC/sec.
Nepers /meter	cm	69.1×10^{-9}	2.19×10^{-3}
db/meter	cm	600×10^{-9}	19×10^{-3}
db/ft	inches	72.1×10^{-9}	2.28×10^{-3}
db/mile	inches	0.38×10^{-3}	12

The constants A, B, and f_1 are obtainable from the equations given in the literature for most cases of interest. For cases not yet explored mathematically, their determination requires the application of electromagnetic wave theory, a process often difficult and too lengthy to discuss here. However,

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