XII. SEMICONDUCTOR NOISE

Prof. R. B. Adler
Prof. J. B. Wiesner
J. Gross
J. Hilibrand
J. G. Ingersoll
D. I. Kosowsky
R. E. Lull
A. L. McWhorter

A. INTRODUCTION

The problem of noise generated in semiconductors has two major facets, each of which could absorb considerable effort:

(a) nature of the physical processes responsible for the noise;

(b) effect of the noise upon device performance in circuit applications.

A detailed study of (a) necessarily involves considerations on an atomic scale and appears to require the investigation of noise from exceedingly simple structures over a wide range of materials, atmospheres, and temperatures. In addition, the spectral properties of the "excess (1/f) noise" at extremely low frequencies are bizarre enough to deserve special attention in any such project. While it is not our intention to emphasize these matters in our noise program, we do plan to continue cooperating with some of those members of Lincoln Laboratory who are engaged principally in these aspects of the semiconductor noise problem.

Our interest resides principally in the effect of noise upon device performance in circuit applications, mentioned in (b) above. Nevertheless, it is not possible to separate completely the issues involved in the two aspects of the noise problem. For example, the need for an equivalent-circuit representation of noisy materials or devices is evident in both parts of the problem. A direct approach to the formulation of a flexible equivalent circuit leads us to study noise manifestations in both the linear and nonlinear operation of semiconductor devices. We must also obtain a fairly complete statistical picture of the noise process, in order to take maximum advantage of its special characteristics in various applications. Yet to obtain this picture we have to undertake some study of the dependence of the noise from devices upon temperature, packaging, surface treatment, or atmospheric surroundings, if only to establish controlled conditions under which reliable and reproducible noise measurements may be made. Hopefully, of course, such work will collaterally yield information leading to the improvement of the noise characteristics of the devices themselves. Thus our program may fairly be called a circuit- and device-oriented study of semiconductor noise.

The following paragraphs contain brief descriptions of our current progress and more extended plans for those phases of the program that are already underway.

R. B. Adler, J. B. Wiesner

B. NOISE AND CHANNEL EFFECT IN P-N JUNCTIONS

In cooperation with R. H. Kingston, of Lincoln Laboratory, experiments are underway to establish the definite connection, if any, between the excess noise from a reversed-biased p-n junction and the presence of a water-vapor induced "channel" on the p-type material. The techniques used to control and measure the channel properties are essentially those described elsewhere by W. L. Brown (Phys. Rev. 91, 518, 1953) and R. H. Kingston (Quarterly Progress Report of Group 35, Transistors and Solid State, Lincoln Laboratory, Oct. 15, 1953, unclassified). To date only broadband noise measurements have been made, including all frequencies between 1 kc/sec and 5 kc/sec. Tentative results on one n-p-n crystal indicate that the noise current increases by a factor of about 10 when the channel is formed. Spectrum measurements will be made with the new noise analyzer when it is completed (see section E below), and the dependence of the noise and its spectrum upon the operating point and channel parameters will be obtained.

A. L. McWhorter

C. PROBLEMS IN THE MEASUREMENT OF NOISE AMPLITUDE PROBABILITIES

In merely contemplating the possibility of making measurements of the first (and possibly second) amplitude probability distributions of excess (1/f) noise from semiconductors, the problem of the bandwidth of the measurement occurs with serious implications. Since much of the excess noise power arises from the exceedingly low-frequency spectral components, the use of dc amplifiers appears unavoidable at first glance. Yet the long-time stability requirements for such a system would be difficult to meet experimentally. It would therefore be desirable to limit the frequency band at the low-frequency end. Unfortunately, only a little is known about the effect of band-limiting upon the amplitude probability distribution of nongaussian noise. Thus it is not clear how to estimate the errors that would be committed in attempting to find the amplitude probability distribution of semiconductor excess noise if we assume that it might not be gaussian and agree to avoid the exceedingly low-frequency end of the spectrum. At the moment, some preliminary study is being undertaken on the theoretical aspects of this general question. Future work may be either experimental or theoretical, depending upon the progress of the present study.

J. Hilibrand

D. MODULATION NOISE IN SEMICONDUCTOR DEVICES

In the Quarterly Progress Report of July 15, 1953, preliminary experiments were discussed that suggested the existence of amplitude-modulation noise from point-contact diodes. More refined experiments on this effect are now in progress. Specifically, a 1N34 point-contact diode is biased in the reverse direction by a dc source. An ac source of 10 kc/sec frequency is superimposed, and the voltage across the diode (actually the output of an ac, dc bridge circuit containing the diode) is recorded simultaneously through two channels. Channel 1 has a passband from 0 cps to approximately

1 cps. Channel 2 contains a bandpass amplifier centered at 10 kc/sec, followed by an AM detector and an RC filter. The RC filter has a passband similar to that of channel 1, and its output is recorded simultaneously with that of channel 1. The similarity between the two noise recordings suggests two possible circuit models for the noisy diode:

(a) The V-I characteristic of the diode fluctuates as a whole, giving rise to both the low-frequency and the AM noise via correlated fluctuations in the static and incremental resistances at the dc operating point. This model was discussed in greater detail in the Quarterly Progress Report of July 15, 1953.

(b) The low-frequency noise acts as a noisy voltage source in series (or a noisy current source in parallel) with the nonlinear diode. This source and the applied 10 kc/sec signal simply mix in the diode, giving rise to the modulation.

Measurements of the relative noise amplitudes and of the conversion efficiency of the diode are now being made to determine which of the two processes, described in (a) and (b) above, is predominant.

Plans for the future include a study of the noise from transistor oscillators, including both AM and FM noise. Such studies may have to be preceded by investigations of transistor noise in simpler nonlinear situations.

J. Gross

E. NOISE ANALYZER AND NOISE FROM MICROWAVE DEVICES

Plans are being completed for an improved recording noise analyzer to cover the frequency range from 10 cps to 60 kc/sec. Tentative specifications are as follows:

1. Analysis Bandwidth: either 10 cps or 100 cps
2. Sweep Rate:
   (a) 10 cycles swept per second for spectrum between 10 cps and 1 kc/sec;
   (b) 50 cycles swept per second for spectrum above 1 kc/sec.
3. Dynamic Range: 40 db without alteration of gain settings
4. Minimum Input Signal (in 10-cps bandwidth):
   (a) with special low-impedance input circuit (200 ohms): 0.01 μv
   (b) with slight changes of the input circuit for other low-impedance sources: 0.002 μv
   (c) with cathode-follower input circuit: 0.02 μv

(Note: Thermal noise at 300°K from a 200-ohm resistor, in a 10-cps bandwidth, is 0.00562 μv.)

Other features of the system are that: (a) it is linear and direct-reading on all scales; (b) the recording cycle is entirely automatic; (c) frequency markers are available to provide frequency-scale calibration; and (d) a thermal voltmeter is available for all bandwidths.

Present plans call for the incorporation of this analyzer into a rather broad microwave-system noise-study program. This program will consist of two major phases. First, the investigation of AM and FM noise spectra of microwave system components (such as magnetron and klystron oscillators, diode mixers, and i-f amplifiers), and study of the effect upon these spectra of the interconnection of components to form a system.

The second phase will be an independent investigation of microwave mixer diodes of the point-contact silicon and germanium types, with special attention given to the role (if any) in these applications of the so-called semiconductor excess noise. The possibility of improving mixer conversion loss and/or noise figure by the use of low ambient temperatures will be a special point of consideration. In this connection, since a great deal more theory is available for junction diodes than for point-contact types, some preliminary work will be done on semiconductor rectifying junctions even though they are not generally suitable for microwave conversion applications.

D. I. Kosowsky, J. G. Ingersoll, R. E. Lull

F. SPECTRUM OF EXCESS NOISE FROM GERMANIUM FILAMENTS

It has been suggested by H. C. Montgomery (Bell System Tech. J. 31, 950, 1952) that in single-crystal germanium filaments the excess noise observed in the presence of a dc bias current is the result of fluctuations in the concentration of the minority carriers. The resulting fluctuation in conductivity produces the excess noise voltage. Montgomery's hypothesis, substantiated quite well by experiment, is that this fluctuation is caused by random injection of minority carriers from sources generally distributed over the material (more likely over just the surface), and that the activity of these sources is being modified at a slow rate by some unspecified "local influence" in such a way as to give the observed (1/f) spectrum. It is assumed that there are a large number of such sources that may be taken to be statistically independent.

It is possible to relate quantitatively the statistical characteristics of the "local influence" to those of the measurable noise, by assuming a little more about the details of the injection process. We shall give the assumptions, and an outline of the solution, for one model of the injection process that appears to exhibit the correct major features.

We suppose that each source, if undisturbed, would emit minority carriers randomly, according to a Poisson law, but that the effect of the "local influence" is to modulate the short-term "average" rate of emission by a (slowly varying) random function of time. Specifically, the probability that a minority carrier will be emitted from a given source during the interval $(t, t + dt)$ is assumed to be $g(t)\,dt$, independent of previous emissions. The "local influence" $g(t)$ is taken to be a stationary random process, with the same statistics for each source. The assumption is also made that the (expected) minority-carrier lifetime τ of the emitted carriers is a constant, independent of the time of emission (especially if the dc field is strong enough to sweep the emitted carriers away from the source region), and independent of the sources (especially if the latter are located only on the surface). Under these assumptions, the spectrum of the noise voltage is proportional to the spectrum of the function which describes the number of emitted minority carriers, from any one source, that are still unrecombined at time t.

Note that the assumptions we have made are not equivalent to assuming that the noise produced by a given source is simply what it would be if the source were undisturbed, amplitude-modulated by an independent random function representing the effect of the "local influence." This model would give for the autocorrelation function of the total noise the product of those for the undisturbed source and the "local influence;" a result that would not yield the long-time correlations necessary for a (1/f) spectrum.

On the basis of our model, the spectral density of the number of unrecombined minority carriers can be expressed in terms of that of the random function g(t) which characterizes the "local influence." First, we obtain the autocorrelation function which results for any one sample function g(t). This answer is then averaged over the function space of the g's, and the power spectrum obtained by Fourier transformation.

If $P_n(t)$ is the probability of n carriers being unrecombined at time t, then for any particular g(t)[†]

$$P_n(t) = e^{-\lambda(t)} \frac{[\lambda(t)]^n}{n!} \tag{1}$$

where

$$\lambda(t) = \int_0^\infty g(t-\sigma)\, e^{-(\sigma/\tau)}\, d\sigma \tag{2}$$

If

$$M(t) = \sum_{n=1}^{\infty} n\, P_n(t)$$

is the expected number of carriers present at time t, then the conditional expectation $M_n(t+u)$ of the number present at time t + u, given n present at time t, is

$$M_n(t+u) = \int_0^u g(t+u-\sigma)\, e^{-(\sigma/\tau)}\, d\sigma + n\, e^{-(u/\tau)} \tag{3}$$

[†] The derivation essentially follows W. Feller, "An Introduction to Probability Theory," Vol. I, pp. 371-373 (cf. 386-391), John Wiley, New York, 1950.

Thus the autocorrelation function of the number of minority carriers present, given a particular g(t), is

$$R(t, t+u \mid g) \equiv \sum_n n\, M_n(t+u)\, P_n(t)$$

$$= \left[\int_0^\infty g(t+u-\sigma)\, e^{-(\sigma/\tau)}\, d\sigma\right]^2 + e^{-(u/\tau)} \int_0^\infty g(t-\sigma)\, e^{-(\sigma/\tau)}\, d\sigma \qquad (4)$$

We now average Eq. 4 over the function space[†] of the g's to get the desired autocorrelation function R(u):

$$R(u) \equiv E\left\{R(t, t+u \mid g)\right\} = \int_0^\infty e^{-(\sigma/\tau)}\, d\sigma \int_0^\infty R_g(u-\sigma+v)\, e^{-(v/\tau)}\, dv + \bar{g}\tau\, e^{-(u/\tau)} \qquad (5)$$

where

$$E\left\{g(t+u-\sigma)\, g(t-v)\right\} = R_g(u-\sigma+v) \qquad (6)$$

and

$$E\left\{g(t-\sigma)\right\} = \bar{g} \qquad (7)$$

Hence the spectral density is

$$G(\omega) = G_g(\omega)\, \frac{\tau^2}{1+(\omega\tau)^2} + \frac{2\bar{g}\,\tau^2}{1+(\omega\tau)^2} \qquad (8)$$

The second term of Eq. 8 represents one contribution of the unmodulated sources to the total noise, but it is not really distinct from the shot noise (which we have not considered here). The first term of Eq. 8 is identified at low frequencies with the so-called excess noise, usually found to have a (1/f) spectrum. We note that at frequencies low compared to $(1/\tau)$ the total noise is proportional to τ^2, and that a frequency dispersion occurs in the vicinity of $\omega = 1/\tau$. Both of these properties of the excess noise have been pointed out by Montgomery in connection with his magnetic field measurements. The most important fact for our purposes, however, is that the spectrum $G_g(\omega)$ of the "local influence" g(t) must be the same as that of the excess noise at low frequencies; that is, (1/f) in most cases.

A. L. McWhorter

[†] See J. L. Doob, "Stochastic Processes," pp. 62-63, John Wiley, New York, 1953, for the basis of the method and the justification of the required interchanges of limiting processes.