XIII. SEMICONDUCTOR NOISE

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RESEARCH OBJECTIVES

Our interest in the noise arising from semiconductor devices, its physical origins and circuit effects, has continued during the past year. It is expected that our studies of the following specific topics will extend into the immediate future:

1. Investigation of the physical origins of 1/f noise in semiconductor filaments, p-n junctions, and junction transistors. The role of surface conditions in this type of noise has been, and will probably continue to be, one of our major preoccupations.

2. Investigation of the statistics of 1/f noise, in particular its amplitude probability distribution. This topic is being pursued largely as a by-product of some general questions about the effect of band-limiting upon amplitude probability measurements on nongaussian noise (see the Quarterly Progress Report, July 15, 1954). Nevertheless, the usual temptation to construct models of 1/f noise based upon the superposition of many independent events would receive support if, indeed, the noise proved to be substantially gaussian in amplitude.

3. Determination of appropriate circuit representations for 1/f noise in diodes and transistors. The modulatory effects of resistance fluctuation are well known. If 1/f noise is, in fact, such a fluctuation, as much evidence now seems to indicate, the effect of the noise upon circuits involving nonlinear operation of diodes and/or transistors should be unique. Of special interest at the moment are oscillators and mixers. We eventually hope to face the problem of the point-contact microwave crystal mixer in this connection, but at present our general understanding of point contacts themselves is sufficiently poor to make our attempts to study their noise properties unsatisfactory. This problem may, therefore, have to wait until the work on semiconductor surfaces has progressed further.

The following sections of this report contain outlines of our present thinking about the physical origins of 1/f noise in semiconductor filaments. Two quite different models are proposed, both of which seemed to fit the (rather inadequate) data available a year ago. Our own work, as well as that of others, has since that time somewhat improved the status of the experimental background against which such theories must be judged. There is still a great deal to be done, however, before a positive choice can be made between these (or any other) models of 1/f noise. For the moment we plan to pursue independent experimental work aimed at testing as directly as possible the two theories outlined below. Here it should be mentioned that our earlier hopes of establishing a direct correspondence between 1/f noise and channel effect in p-n junctions (as reported in the Quarterly Progress Reports of Jan. 15, 1954 and July 15, 1954) proved to be unfounded. Careful experiments in this direction not only showed a weak correlation between these two phenomena, but exhibited sufficiently complicated behavior to warrant a "backward" step to homogeneous filaments. It was as a result of this step, and our previous detailed study of the channel effect (Quarterly Progress Report, July 15, 1954), that the theory and experiments described in section B were forthcoming. Soon we hope to return again to the p-n junction, with a better understanding of the homogeneous case.

Progress on topics 2 and 3 awaits the construction of special equipment now being designed. Also, for topic 3, some theoretical work on oscillator noise needs to be done before appropriate experiments can be designed for this phase of the "circuit effects" investigation.

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A. A THEORY OF 1/f NOISE IN SEMICONDUCTOR FILAMENTS

1. Introduction

Before presenting the theory, a general requirement for any 1/f noise mechanism will be pointed out.

It seems most probable that the 1/f spectrum in semiconductor noise can be accounted for by a process that consists of a large number of independent events. For a constant impressed voltage, the occurrence of each event will produce a small change in the flow of current, whose endurance will be the same as the lifetime of the event. In order to explain the observed 1/f shape of the spectrum, the events must have a very wide range of lifetimes, some of them as long as several hours. One test which must therefore be applied to any suggested noise-generating mechanism is its ability to produce single events capable of causing current changes of very long duration (of the order of hours). Two possible noise models which have been proposed in the past appear to fail this test.

The first is a simple trapping process such as that considered by Van der Ziel (1). Here a single mobile carrier (either hole or electron) is trapped, for a time dependent on the energy depth of the trap, and then released. A wide range of trapping times, T, is achieved by assuming a spectrum (or band) of energy depths. This type of mechanism cannot, however, give rise to a 1/f spectrum, since no single trapping event can cause a current change of long duration. This can be seen by referring to Figs. XIII-1 and XIII-2. Assuming that T is a very long time, one might suppose that this trapping does lead to the desired slow current fluctuation. This situation is illustrated in Fig. XIII-1. Actually, the current alteration caused by the trapping event will be that shown in Fig. XIII-2. The reason is that a mobile carrier can give rise to current only as long as it is free. Moreover, when a carrier is trapped for a time T, it can have only been in existence for a time τ (the lifetime of the carrier), before it was trapped, and live only a time τ after it has been released. Since in actual semiconductors $\tau \gg T$, the contribution to the current from the single carrier as a result of being trapped must be as shown in Fig. XIII-2. Thus there will, effectively, be two short pulses of duration τ instead of one long one of duration T. This type of current form cannot account

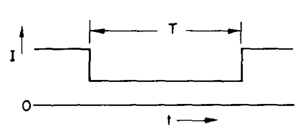

Fig. XIII-1
A long trapping event.

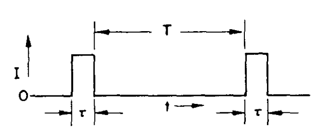

Fig. XIII-2
Effect of lifetime upon simple trapping.

for the shape of the low-frequency end of the 1/f spectrum, so it would seem that a simple trapping process cannot produce 1/f noise.

The second type of noise mechanism is a simple modulation of the generation or decay rate of either type of mobile carrier. If the quantities are averaged over a time long compared to τ, a relation that is always valid is

$$n = g\tau$$

where n is the mobile carrier volume density, g the generation rate per unit volume, and τ the lifetime. It is a known fact that in semiconductors near equilibrium (that is, with no external injection or photogeneration) the mean value of n is only a function of the doping and the temperature. Thus, with a sudden change of only the generation or decay rate (i.e., g or τ) there may be a time (of the order of τ) where the equation above is violated, but in a period long compared to τ, g and τ must adjust themselves so that n will return to its value before the change. This is because neither the doping (or Fermi level) nor the temperature has been assumed to change in the process described above, and the long-time average of n cannot change. Therefore it appears that no event in this noise mechanism can produce a long duration change in carrier concentration, or a long duration change in current at constant applied voltage. It follows that a simple modulation of the generation or decay rate alone cannot account for the observed spectrum shape of 1/f noise.

It was noted above that, when averaged over times long compared to τ, the carrier concentrations will depend upon the relative positions of the Fermi level and the band edges. A noise mechanism in which a single event can cause a slight relative shift of these levels can produce long-duration changes in carrier concentration, or current at constant voltage and thus will be able to produce 1/f noise. Qualitative noise models proposed by Shockley (2) and Montgomery (3) include this feature by means of the non-equilibrium action of trap pairs located in various regions of the semiconductor, most likely on the surface. The noise mechanism to be considered here is one in which the Fermi level in the whole sample is shifted by a single noise event.

In its most general terms, the model to be dealt with here will be constructed to satisfy three sets of empirical data: (a) the observed shape of the noise spectrum, which has nearly a 1/f behavior over at least eight decades; (b) the observed noise level; and (c) the connection, at least in part, between the noise and the surface conditions.

The model assumes that scattered at random over the surface of a germanium filament there are "emission centers" that can emit and absorb bulk impurity atoms. As long as they remain on the surface, these impurity atoms act as trapping centers for holes and electrons. A typical noise event is the emission of an impurity atom from an emissive center and diffusion along the surface in a sort of Brownian motion about the center. This event will go on until the impurity atom is either recaptured by its own emission center or captured by a neighboring center. During the time T that it was diffusing over the surface, the impurity atom, by virtue of its trapping action, was immobilizing nearly one hole or electron which otherwise would have been free to wander in the bulk. This action would cause a change in the sample conductance, and consequently would produce a change in the current through the sample for a constant impressed voltage. A random time sequence of these events produces 1/f noise.

It is apparent from this that there must be a wide distribution of trapping times T. In fact, the distribution function, g(T), of these times is what determines, essentially, the shape of the noise spectrum. With the particular model chosen, g(T) produces a spectrum with a $1/f^m$ behavior (where m can be nearly equal to, but is not necessarily exactly equal to, unity) over a very wide range of frequencies.

Detailed treatment of the spectrum shape is given in reference 4, which, however, described a somewhat different model. In making the connection between the two models, note that the "vacancies" of the model described in reference 4 play the role of the "emission centers" here. The two most important results derived from reference 4 are: (a) the spectral exponent m is determined by the atomic lattice spacing "a" and the capture length λc of an impurity atom by an emission center (the exact relation is $m = 2 - \lambda c/(\pi a)$); and (b) the frequency range of the 1/f behavior is determined by the surface density of emission centers, M_c. The exact relation between the upper radian frequency ω_h and the lower radian frequency ω_ℓ, beyond both of which the spectrum departs significantly from the f^{-m} form, is

$$\frac{\omega_h}{\omega_\ell} = \frac{1}{\pi(2-m)\, a^2 M_c}$$

To account for the observed spectrum behavior ($\omega_h/\omega_\ell \geqslant 10^8$), M_c cannot exceed $3 \times 10^6/\text{cm}^2$. On the other hand, it is found (see Sec. XIII-3) that to account for the observed noise level, the mean surface density M_T of trapping centers (that is, the mean number of impurity atoms wandering on a square centimeter of the surface) must be of the order of $2 \times 10^{11}/\text{cm}^2$. It will be shown that a specific model of the emission centers can reasonably lead to impurity emission rates and mean impurity lifetimes on the surface which are at least consistent with these figures.

The generalized model outlined above will now be described in terms of a more specific physical picture, which from all the available information seems to be exceedingly plausible. It should be noted, however, that the detailed picture treated here is only one of many possible ones that could fit the generalized model.

At this time, it seems very reasonable to assume that the emission centers described above are connected with some sort of edge-dislocation singularity line. These are quite common in metals and were first found in germanium by Bell Telephone Laboratories and subsequently discussed by S. A. Kulin and A. D. Kurtz (5). A crude and

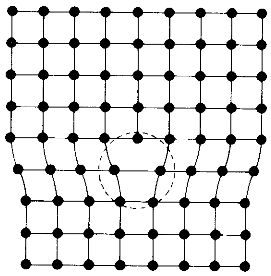

Fig. XIII-3
Schematic of a "pipe" dislocation.

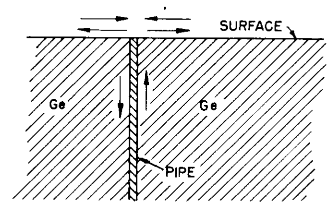

Fig. XIII-4
Alternate schematic of a "pipe" dislocation.

simplified pictorial representation of edge-dislocations has been attempted in Figs. XIII-3 and XIII-4. The way these dislocations arise is shown in Fig. XIII-3. A plane of atoms (represented by the black dots) will end abruptly and produce a region (within the dotted curve) where the atomic spacing is greater than in the rest of the crystal. This region has the form of a "pipe" or singularity line (here, perpendicular to the paper) which may extend the length of the whole crystal. A cross section of this "pipe" is shown in Fig. XIII-4 (represented by the heavily shaded region). One way to detect these "pipes" is by a surface etching treatment which will produce a pit at those points where the "pipes" come to the surface. Kulin and Kurtz measured the density of these pits in germanium, and found them to be of the order of $10^6/cm^2$. This also is the order of density value required of the emission centers in the noise model. Thus it will be assumed that an emission center occurs where the edge-dislocation singularity lines meet the surface.

2. Notation

These are the symbols used most often in the remainder of this discussion.

M_T = the surface density of trapping centers (that is, impurity atoms wandering on the surface).

M_c = the surface density of emission centers ("pipes").

D_s = the surface diffusion constant for impurity atoms.

D_ℓ = the diffusion constant of impurity atoms along a "pipe" dislocation.

L = the average length of a "pipe."

m = the spectral exponent (f^{-m}).

ω_h = the upper spectral "turnover" radian frequency.

ω_ℓ = the lower spectral turnover radian frequency.

a = the normal atomic lattice spacing.

$\bar{t}_s$ = the mean lifetime of an impurity atom on the surface. (Its exact definition is

$\bar{t}_s = \int_0^\infty g(s)\, s\, ds$ where $g(s)$ is the distribution of lifetimes defined in reference 4).

$\bar{t}_\ell$ = the mean lifetime of an impurity atom diffusing along a "pipe" dislocation.

g_ℓ = the average rate of emission of impurity atoms per emission center.

N_ℓ = the average number of atoms diffusing along a "pipe" (related to g_ℓ and $\bar{t}_\ell$ by $N_\ell = g_\ell \bar{t}_\ell$).

ρ_T = the state of occupancy of a trap at energy E_T (equal to $\left[1 + \exp(E_T - E_F)/kT\right]^{-1}$).

E_F = the Fermi level.

A = total surface area of a filament.

3. Noise Output Level

If M_T is known, it is possible to determine the noise output level. To do this the fluctuation (or variance) $\bar{\Delta}n$ in the number of trapping atoms from the mean value AM_T must be calculated. This can readily be obtained from simple probability theory if it is noted that at any time the probability that a given atom is on the surface is $\bar{t}_s/(\bar{t}_s + \bar{t}_\ell)$, while the probability that it is in a "pipe" dislocation is $\bar{t}_\ell/(\bar{t}_s + \bar{t}_\ell)$. Thus from the standard binominal distribution of probability theory

$$\bar{\Delta}n = \left[M_T\, A \frac{\bar{t}_\ell}{\bar{t}_s + \bar{t}_\ell}\right]^{1/2} \qquad (1)$$

Assuming that 1/f noise is due to a fluctuation of resistance caused by a fluctuation of surface traps, it follows that the noise in any filament is given by

$$\left[\frac{\langle \ell_N(t)\rangle^2}{V_o^2}\right]^{1/2} = \frac{\rho_T\, \bar{\Delta}n}{n_o} \qquad (2)$$

where $\ell_N(t)$ is the noise voltage, V_o is the dc bias impressed on the filament, and n_o is the total number of mobile carriers in the filament bulk. It will be assumed that, in general, $\rho_T \approx 1$ (see also Sec. XIII-4), and that $\bar{t}_\ell > \bar{t}_s$. Thus, with the aid of Eq. 1, Eq. 2 simplifies to

$$\left[\frac{\langle \ell_N(t)\rangle^2}{V_o^2}\right]^{1/2} = \left[\frac{M_T\, A}{n_o^2}\right]^{1/2} \qquad (3)$$

If δ_1 is the observed noise figure of $1/f^m$ noise at a frequency f_1, it can be shown that the rms noise voltage will be given by

$$\langle \ell_N(t) \rangle^2 = 4kTR(f_1 \delta_1)\left(\frac{m}{m-1}\right)\left[\left(\frac{\omega_h}{\omega_\ell}\right)^{m-1} - 1\right] \tag{4}$$

By using Montgomery's data (3), a typical n-type filament of 20 ohms cm resistivity can be expected to have a noise figure δ of about 10 at 1000 cps, with 10 volts/cm bias and dimensions of $0.05 \times 0.05 \times 0.7$ cm. Noting that the sample resistance R is about 6000 ohms, and $m \approx 1.2$, the rms noise voltage can be calculated from Eq. 4. It is found to be about 8×10^{-6} volt. A straightforward calculation will show that n_o of the filament is about 2×10^{11}.

Thus, by using the above values of $\langle \ell_N(t) \rangle$, n_o, and V_o in Eq. 3, it appears that M_T must be about $2 \times 10^{11}/\text{cm}^2$ to account for observed noise levels.

4. Detailed Description of Noise Generation

We can now describe the entire 1/f noise generation action. We shall assume an n-type sample, although an analogous argument holds for p-type. It was proposed by Kulin and Kurtz that the donor impurities tend to cluster about the "pipe" dislocations. It will be postulated here that, in addition, the impurity atoms will diffuse up and down the "pipe" dislocations with a diffusion constant D_ℓ. (This action is indicated in Fig. XIII-4 by the arrows going up and down on the "pipe.") Those impurity atoms going in the upward direction will emerge on the surface and diffuse out (with a diffusion constant D_s) in the manner described in reference 4. These atoms can be considered to be "emitted" from a center, as described previously. It is also possible for impurity atoms already present on the surface to migrate into the "pipe" dislocation and then diffuse downward into the bulk. This is equivalent to a surface diffusing atom being "captured" by a center. Thus, after a time, there must be an equilibrium condition where the average rate of atoms emitted from a "pipe" must equal the average rate captured. In this condition the following relationship will be valid

$$M_T = M_c \, g_\ell \, \bar{t}_s \tag{5}$$

The next question to be considered is just how the impurity atoms coming to the surface will affect the concentrations of mobile carriers. As shown in Section VIII-1 it seems plausible to assume that 1/f noise is caused by a shifting of the Fermi level. In this case, this means that the Fermi level must be changed slightly whenever an impurity atom (which will be assumed to be an ordinary donor atom) is moved from the bulk to the surface. There is good reason why this may be expected. The physical model of a donor will be assumed to be that given by Bethe. That is, a donor can trap an electron by keeping it in a hydrogen-like orbit whose ionization energy E_i is given by

$$E_i = \frac{2\pi^2 m \ell^4}{\epsilon^2 h^2} \tag{6}$$

where ϵ is the dielectric constant of the crystal. The donor energy level will be given by

$$E_D = E_C - E_i \tag{7}$$

where E_C is the edge of the conduction band. Now, it is apparent that, because of incomplete shielding, ϵ will be much less at the surface of the crystal than in the bulk. Thus E_i will be much greater when a donor is on the surface than in the bulk. The energy levels for E_D will then be as shown in Fig. XIII-5. The Fermi level in this case is determined only by the number of donors and their state of occupancy $\left(= \left[1 + \exp(E_D - E_F)/kT\right]^{-1}\right)$. As Fig. XIII-5 indicates, for donors within the bulk, $E_D - E_F \gg kT$ (E_F is the Fermi level), and their state occupancy is very nearly zero. For donor atoms on the surface, however, $E_{DS} - E_F \ll kT$, so that their state of occupancy will be nearly equal to unity. Thus, its state of occupancy increases when a donor goes from the bulk to the surface. This means that whenever a donor atom migrates from the bulk to the surface, the Fermi level will be lowered a given slight amount, and will be raised by the same amount as an atom goes from the surface to the bulk.

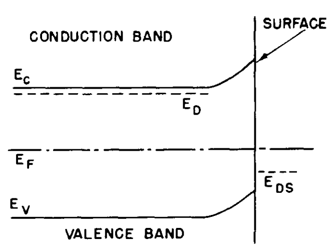

Fig. XIII-5
Energy bands of an n-type semiconductor.

This is equivalent to saying that each donor will be trapping $\left[1 + \exp(E_{DS} - E_F)/kT\right]^{-1}$ conduction electrons for the time that it is on the surface. The analysis of Section XIII-3 will then be valid for this kind of trapping effect. Incidentally, shifting the Fermi level affects both the electron concentration and the hole (minority carrier) concentration. This can be seen from the following relation:

$$n\,p = n_i^2 \tag{8a}$$

These quantities must be considered to be long-time averages, and the relationships are valid for all Fermi level shifts. Differentiating Eq. 8a, the following relationship results

$$\delta p = -\,(p/n)\,\delta n \tag{8b}$$

Thus, Eq. 8b shows that with every change of electron concentration, δn, there will be an opposite change in holes, δp, which will be smaller, since (p/n) is less than unity.

5. Variation of Noise with Temperature and Ambient

In this section, Eq. 1 will be studied in more detail. It can be shown that the quantities g_ℓ and $\bar{t}_s$ will have the following dependence on various physical parameters:

$$\bar{t}_s \approx \frac{a^2}{4D_s}\left(\frac{m}{m-1}\right)\left[\left(\frac{\omega_h}{\omega_\ell}\right)^{m-1} - 1\right] \tag{9}$$

$$g_\ell \approx \frac{2D_\ell}{a}\left(\frac{N_\ell}{L}\right) \tag{10}$$

From Eqs. 5, 9, and 10, the following explicit expression for M_T can be obtained:

$$M_T = \frac{M_c N_m}{1 + F \exp\left[(E_\ell - E_s)/kT\right]} \tag{11a}$$

where

$$F \equiv \left(\frac{2L}{a}\right)\left(\left(\frac{m}{m-1}\right)\left[\left(\frac{\omega_h}{\omega_\ell}\right)^{m-1} - 1\right]\right)^{-1} \tag{11b}$$

In deriving Eq. 11a, use was made of the relation $D_s/D_\ell \approx \exp\left[(E_\ell - E_s)/kT\right]$, where E_s is the activation energy for surface diffusion, and E_ℓ is the activation energy for diffusion along a "pipe" dislocation. N_m ($= g_\ell(\bar{t}_s + \bar{t}_\ell)$) is the average maximum of atoms clustering about a "pipe" dislocation. N_m is assumed to be a constant and has a value of the order of magnitude of (L/a).

From Eqs. 1, 2, and 11a, the rms noise voltage takes on the following form:

$$\langle \ell_N(t)^2 \rangle = \left(\frac{V_o}{n_o}\right)^2 (A\, N_m\, M_c)\left(\frac{M_T}{M_c N_m}\right)\left(1 - \frac{M_T}{M_c N_m}\right) \tag{12}$$

It is now possible from Eq. 12 to deduce, roughly, the behavior of $\langle \ell_N(t)^2 \rangle$ with temperature.

It will be assumed that the variation of V_o and n_o is small compared to the variation in M_T. Since the values of g_ℓ and ω_h are approximately known, estimates of E_ℓ and E_s can be made by means of Eqs. 9 and 10. When this is done, it is found that $E_\ell - E_s \approx -0.12$ ev. Typical values for the parameters F, N_m, and L will be assumed to be: $F \approx 3 \times 10^3$, $N_m \approx 3 \times 10^6$, and $L \approx 10^{-2}$ cm.

Using this set of values in Eqs. 11a and 12 rough plots were made (Fig. XIII-6) of M_T/M_c and $\langle \ell_N(t)^2 \rangle$ vs. temperature in the range from 100°K to 300°K. The dashed line illustrates the variation of M_T with temperature. At room temperature (300°K), M_T/M_c is about 10^5 and it increases to its maximum value N_m ($\approx 3 \times 10^6$) as T decreases to 100°K. This means that all of the impurity atoms associated with the "pipe" dislocations migrate to the surface as T decreases. This action may serve to explain certain anomalous behavior of the resistance of near-intrinsic germanium filaments with temperature. In going from 300°K to 100°K the resistance may increase by a factor up to 10^3. An intrinsic sample would have had a resistance increase of a factor of about 10^{10}. Up to now this behavior has been attributed to numerous deep-lying traps, since at 100°K all the bulk donors would still be ionized. An alternative explanation is that some of these donors migrate to the surface and become filled. This would increase the resistance by amounts roughly of the same order of magnitude as those observed.

The solid line in Fig. XIII-6 illustrates the behavior of the noise power with temperature, on the assumption that the length L of all of the "pipes" is constant. Actually, it seems reasonable to suppose that the L's for different "pipes" vary according to a distribution of lengths. It should be noted that for a given L the noise vs. temperature characteristic will be a maximum when $M_T = \frac{1}{2} M_c N_m$. The temperature at which this is so will depend on L. Thus, if the length of the "pipes" varied over a rather wide range, the variation of noise power with temperature would probably be that shown by the dotted line in Fig. XIII-6. Although the detailed shape of the characteristic would depend on the distribution function of the L's, the general effect of a variation in the "pipe" lengths is to reduce the variation of noise power with temperature in the low temperature region.

Moreover, it should be noted that in addition to the effect described above there is another effect that would keep the change of noise with temperature from being too great. It is probable that the value E_s will decrease with decreasing

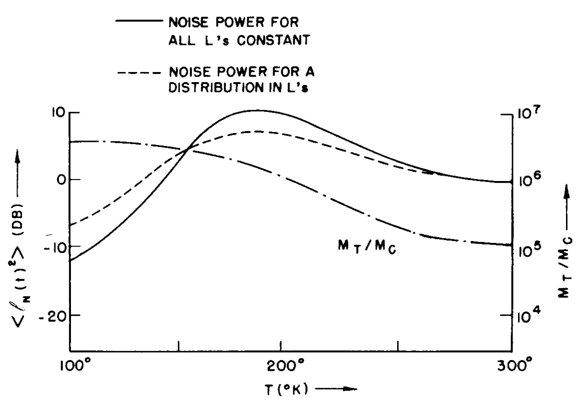

Fig. XIII-6

Theoretical temperature dependence of noise power and mean surface trap density for an n-type filament.

temperature. The reason is that E_s is a function of the concentration (6) of diffusing atoms, decreasing its value with increasing concentration. For concentrations of the order of $10^{13}/cm^2$, the decrease can be as much as 10 per cent. In this diffusion situation, the atom concentration will vary inversely with the distance to an emission center. The variation in concentration in going from a region immediately surrounding an emission center to a region in between centers will be of the order of 100 to 1. Thus, if the average concentration is of the order of $3 \times 10^{11}/cm^2$, the concentration right next to an emission center (where D_s is mostly determined) will be about $3 \times 10^{13}/cm^2$. As the temperature decreases, the concentration (determined from Eq. 11a) will tend to go up. This will tend to decrease E_s, opposing the increase in concentration, as an inspection of Eq. 11a will show.

The result of the preceding discussion is to show that, although an exact analysis of the variation of noise with temperature is very complicated, it is possible to make the following general comments. In the first place, the total variation of 1/f noise in the range of 100°K to 300°K need not be very great (certainly well within a range of 20 db). In the second place, the general shape of the characteristic curve will be that shown by the dotted line in Fig. XIII-6. These results would seem to be confirmed by Montgomery's data (3).

From Eqs. 5, 9, and 12 it can be seen that, all other parameters being constant, $\langle \ell_N(t)^2 \rangle$ will vary inversely with D_s at room temperatures (since $M_T \ll M_c N_m$). It seems reasonable to assume that immersing a filament in an inert liquid will decrease D_s (since the diffusion "jump" frequency should be lowered) without affecting any other parameter. This will therefore explain why an inert liquid ambient (like CCl_4) has been found to increase the noise level over its value in air.

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B. ROLE OF SURFACE OXIDE LAYERS IN 1/f NOISE

1. 1/f Noise and Impedance of an Aluminum Oxide Layer

Since most of the sources of 1/f noise involve current passing through potential barriers (1) and since 1/f noise is generally assumed to be a resistance fluctuation, it is natural to look for some process that could produce changes in the barrier height. One likely process is the trapping of free current carriers in, or adjacent to, the barrier, since the resulting localized charge would cause a large change in potential in the immediate vicinity of the trap. Also, it is well known from photoconductivity work that charges may remain trapped for hours and days, so that traps could easily give the long times necessary for 1/f noise (2).

In order to investigate this idea and also to get away from bulk semiconductor properties, a simple mercury-aluminum contact has been examined for 1/f noise. Since the mercury does not wet the aluminum, electrons must pass through the thin aluminum oxide, which is about 30A thick after oxidation at room temperature. An ohmic, low-resistance, noiseless contact was made to the aluminum with an ultrasonic soldering iron and to the mercury with a clean platinum wire. The dc current-voltage characteristics of several such contacts were linear from approximately -0.2 to +0.2 volt, with the resistance usually around 10K. Because of the extremely high fields produced across the oxide layer, higher voltages caused breakdown. The order of magnitude of the dc resistance checked very well with the assumption that the electrons tunneled through the oxide layer rather than being conducted by the oxide as a semiconductor. The calculations were based on formulas given by Holm (3) and barrier heights estimated by Cabrera (4). Furthermore, the ac characteristics were those of a simple parallel RC network, with the time constant agreeing with the product of the dc resistance and the capacitance calculated from the geometry. As would be expected from a tunneling process between two metals, neither the dc nor ac characteristics changed at dry ice or liquid nitrogen temperatures, the freezing of the mercury having no apparent effect. These results, incidentally, give very strong support to Mott's hypothesis that in the oxidation of aluminum, the adsorbed oxygen is easily ionized by electrons tunneling through the thin oxide (5).

To summarize the preceding discussion, it seems that as far as the average characteristics of the contact are concerned we are dealing with a simple potential barrier between two metals, through which electrons can pass by tunneling. As was hoped, however, the contact showed a very large voltage fluctuation when biased with small dc currents. The noise power obeyed quite accurately a 1/f law over the measured range of frequencies, 100 cps to 20 kc/sec, and increased with the square of the bias current from the minimum detectable signal to the highest which could be used without leaving the linear part of the characteristics, generally a range of two to three decades. There was usually no change in the noise level at dry-ice and liquid-nitrogen temperatures, but occasionally there was a drop of as much as 6-8 db. The polarity of the bias current had no effect on the noise.

Traps in the oxide layer could arise physically from impurities, deviations from stoichiometry, or other imperfections. If we postulate their existence, and a few will almost certainly be present, then it is quite plausible in view of the dc characteristics of the contact to assume that they communicate with the metals by tunneling. In fact, the temperature independence of the noise would lead to severe difficulties with any other assumption. In this case the effective capture cross section of a trap will vary exponentially with the product of the barrier width and the square root of the barrier height which are associated with it. Since each trap will produce a shot-noise type of spectrum, $\tau/\left[1 + (\omega\tau)^2\right]$, where τ is the trapping time, a large number of traps with a distribution function for τ proportional to $1/\tau$ would lead directly to the desired $1/f$ spectrum. Such a distribution function would be obtained if either the barrier widths or heights of the traps had approximately a uniform distribution over a sufficient range. In particular, if the traps are simply distributed homogeneously throughout the oxide layer, this result is obtained. With the strong exponential dependence of τ on the barrier dimensions, it is, of course, quite easy to get a very wide range of time constants, much more than enough to account for $1/f$ noise over the measured range. Quantitative calculations will be made shortly to see whether or not the number of traps necessary to account for the magnitude of the $1/f$ noise is a reasonable value.

2. Oxide Layers, Field Effect, and 1/f Noise for Germanium Filaments

Although no potential barriers are present to interfere with the current flow in single-crystal germanium filaments, the $1/f$ noise associated with it can still be produced by traps. Carriers trapped in the oxide layer would alter the number of free carriers in the germanium in the immediate neighborhood of the trap simply by the necessity of maintaining charge neutrality. This effect, which would persist for the duration of the trapping, modifies the conductivity and hence produces a change of voltage when a dc bias current is applied. Again a $1/\tau$ distribution is needed for the trapping times, and, again, this might arise by means of tunneling. For germanium we have the added possibility that if the traps arise from adsorbed ions, fluctuations of the oxide thickness over the surface would give the required variation of barrier width.

These speculations have received strong support by recent "field-effect" experiments on germanium filaments carried out in cooperation with R. H. Kingston at Lincoln Laboratory. The frequency response of the germanium conductivity to a sinusoidally varying electric field applied normally to the surface seems to require both the existence of surface traps and the $1/\tau$ distribution for an explanation. With the information obtained from the field-effect analysis, it has now been possible to make some quantitative calculations for the magnitude of the noise. Although a few details remain to be cleared up, preliminary results agree quite well with experiment. It is very probable that the theory can also account for the correlation effects observed by Montgomery (6). Hence there is every reason to hope that the same model will explain both 1/f noise and the field-effect experiment for germanium filaments. It should be mentioned that the calculations do not depend on how the $1/\tau$ distribution arises, but the tunneling hypothesis is favored by the lack of a strong temperature dependence of 1/f noise.

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References

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