surface dA and oriented in the direction of the change in $\mathbf{\Omega}$ under the rotation $\boldsymbol{\varepsilon}d\alpha$,

$$\Delta\mathbf{\Omega}=-id\alpha(\boldsymbol{\varepsilon}\cdot\mathbf{M})\mathbf{\Omega}.$$

This yields the expression for the volume element $d\tau$,

$$d\tau=\Gamma^{-1}dA\,\Delta\Omega_l=\Gamma^{-1}dA\,d\alpha(-i\boldsymbol{\varepsilon}\cdot\mathbf{M}\Omega_l).$$

The probability passed through the surface due to all rotations of magnitude $\boldsymbol{\varepsilon}$ in the time Δt is then

$$p(\boldsymbol{\varepsilon},\Delta t)d^3\epsilon\int_0^1 d\alpha\,\Gamma^{-1}dA\,(-i\boldsymbol{\varepsilon}\cdot\mathbf{M}\Omega_l)\times\exp(i\alpha\boldsymbol{\varepsilon}\cdot\mathbf{M})P(\mathbf{\Omega},t).$$

This must be integrated over all possible values of $\boldsymbol{\varepsilon}$ to obtain the total probability passed through the surface. The result, to first order in Δt is

$$dA\,\Delta t\Gamma^{-1}(M_j\Omega_l)D_{jk}M_kP(\mathbf{\Omega},t).$$

This must be divided by dA and Δt to obtain the current density, J_l,

$$J_l=\Gamma^{-1}(M_j\Omega_l)D_{jk}M_kP(\mathbf{\Omega},t)\equiv\mathfrak{j}_lP(\mathbf{\Omega},t).$$

Thus

$$\mathfrak{j}_l=\Gamma^{-1}(M_j\Omega_l)D_{jk}M_k,$$

or

$$\mathfrak{j}_l=i\Gamma^{-1}\tfrac{1}{2}(\Gamma D_{lk}+\Omega_i\epsilon_{ijl}D_{jk})M_k.$$

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Surface-Dependent 1/f Noise in Germanium*

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The surface characteristics of $1/f$ noise have been investigated by using field effect techniques on 100 micron thick single crystal germanium filaments. The $1/f$ noise is independent of the surface potential when an accumulation layer is on the surface but increases rapidly as the surface conductivity gradually becomes inverted with respect to the bulk. No $1/f$ noise is observed due to charge transfer between the bulk and the slow surface states. An increase in the $1/f$ noise associated with the inversion layer occurs when the temperature of the germanium is decreased. The magnitude of the $1/f$ noise depends on the ambient, increasing as the slow state relaxation time decreases. An investigation of the relaxation processes associated with the charge transfer between the bulk and the slow surface states after the application of a dc electric field to the field effect electrode reveals a $1/f$ noise relaxation which is independent of the mode of the conductivity relaxation. The noise relaxes back to its original value with a logarithmic time dependence which is characteristic of a $1/\tau$ distribution in time constants and the conductance decays with a combination of exponential and logarithmic terms, depending on the surface conditions.

I. INTRODUCTION

Single crystal semiconductor filaments generally exhibit a noise power spectrum which varies inversely with frequency over a wide range of frequencies.[1] The $1/f$ law has been observed at frequencies as low as 6×10^{-5} cps[2] and as high as 12 Mc/sec.[3] The absence of an appreciable temperature dependence[1,4] of $1/f$ noise has introduced difficulties into the formulation of a satisfactory physical explanation of the origin of this particular type of fluctuation.

While the exact physical origin of the $1/f$ noise is presently open to conjecture, there is considerable evidence that the surface of the semiconductor may be the source of at least part of this noise. $1/f$ noise seems to be dependent on the samples' ambient[5,6] as well as its surface to volume ratio.[7] The most promising experimental evidence for assigning the origin of $1/f$ noise to the surface is the $1/\tau$ distribution in relaxation times of the slow surface states,[8] which are located on the oxide layer of a semiconductor. A $1/\tau$ distribution in relaxation times will lead to a $1/f$ noise spectrum if individual noise spectra of the generation-recombination type are added.[9] It has been pointed out, however, that the experimentally observed $1/\tau$ distribution does not cover the range in times necessary to explain the complete $1/f$ noise spectrum.[10]

Even though it is well known that the surface has a

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[1] H. C. Montgomery, Bell System Tech. J. **31**, 950 (1952).
[2] T. E. Firle and H. Winston, J. Appl. Phys. **26**, 716 (1955).
[3] F. J. Hyde, Proc. Phys. Soc. (London) **B69**, 231 (1956).
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[7] J. J. Brophy, J. Appl. Phys. **29**, 1377 (1958).
[8] A. L. McWhorter in *Semiconductor Surface Physics*, edited by R. H. Kingston (University of Pennsylvania Press, Philadelphia, Pennsylvania, 1957), p. 207.
[9] J. Bernamont, Proc. Phys. Soc. (London) **49**, (extra part), 138 (1937).
[10] H. C. Montgomery (personal communication).

profound influence on the magnitude of the $1/f$ noise, very little is known about the exact relation between the physical surface parameters and the $1/f$ noise. This investigation was undertaken in an attempt to correlate the $1/f$ noise in single crystal germanium filaments with various surface characteristics.[11] This was accomplished by making both noise and field effect[12] measurements on the same samples as a function of surface parameters.

II. EXPERIMENTAL PROCEDURE

This noise study was made on high bulk lifetime, 35 ohm-cm, *n* and *p*-type germanium single crystals grown in this laboratory and at the Western Electric facilities in Allentown, Pennsylvania. Some preliminary measurements were performed at 78°K with gold-doped germanium[13,14] crystals containing 10^{15} gold atoms per cm^3. Thin slices, having their ⟨111⟩ crystal axis perpendicular to the predominant surfaces were lapped and then etched to a thickness of from 50 to 100 microns. Prior to the etching, the germanium was sandblasted into the conventional bridge shaped samples used in noise measurements.[10] Typical dimensions for the straight central filament of the bridge were 2×0.6 cm. The side arms were so removed from the dc current carrying end electrodes, that spurious effects due to injection of charge carriers at the electrodes were eliminated.

Ohmic contacts were made to the *p*-type germanium with indium and to the *n*-type germanium with a 95% tin, 5% antimony alloy. The specimens were then placed in a demountable Dewar-type container which could be evacuated to a pressure of 10^{-7} mm Hg or filled with various gases. Provision was also made to cool the specimen to temperatures as low as 78°K.

A block diagram of the noise measuring circuit is shown in Fig. 1. The battery and load resistor provided a constant current source for the germanium filament. A modified Tektronix 122 low level preamplifier[15] or a transistorized Millivac AC voltmeter, type MV45A

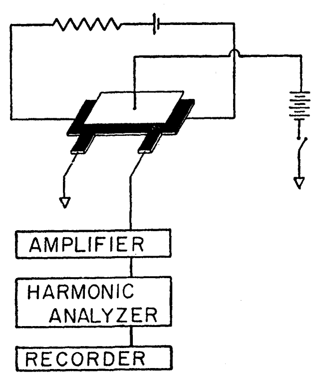

FIG. 1. Noise measuring circuit.

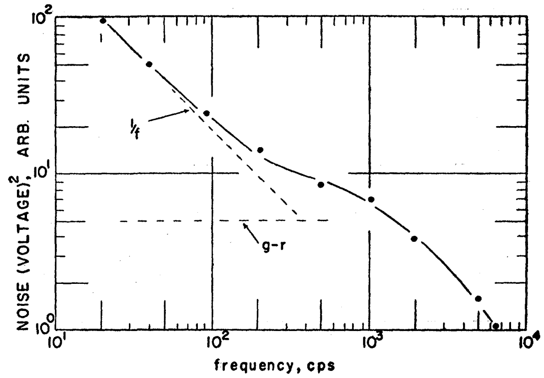

FIG. 2. Noise spectrum of *n*-type Ge:Au, Sb at 90°K.

was used to amplify the noise. This was followed by a General Radio 736A audio-frequency wave analyzer which consists of a tuneable 5-cps bandwidth filter. The noise output from the analyzer was recorded.

The surface properties of the germanium were monitored during the noise measurements with conventional ac and dc field effect apparatus.[16] A molybdenum plate, separated from the germanium filament by a few micron thick mica sheet, served as the field effect electrode. The capacitance of this arrangement was of the order of 50 to 100 $\mu\mu$f. The surface potential of the germanium was varied either by the Brattain-Bardeen cycle[17] in which different gases are allowed to interact with the material, or by the application of a dc voltage to the field effect electrode. This last mentioned method can be used only if the charge transfer between the bulk and slow surface states is sufficiently slow to permit a noise measurement. It is then possible to investigate the dependence of the $1/f$ noise on the surface potential. In addition, the noise relaxation process which occurs after the application of a dc voltage to the field effect electrode, may be measured. The required long relaxation time is obtained by maintaining the sample in vacuum or holding it at a reduced temperature.

III. NOISE SPECTRUM

The noise spectrum of the filaments was determined prior to any detailed measurements on $1/f$ noise. In general the spectrum in the audio frequency region consisted of two components, one due to generation recombination noise[18] and the other to $1/f$ noise. Typical spectra are shown in Figs. 2 and 3. The decrease in the noise in the vicinity of 1 kcps for the *n*-type gold-doped germanium indicates the presence of the frequency dependent, $(1+\omega^2\tau^2)^{-1}$ generation recombination noise term. At lower frequencies the spectrum is of the $1/f$ type. *p*-type gold-doped germanium has a noise spectrum at 77°K which is also composed of these

[11] R. H. Kingston, J. Appl. Phys. **27**, 101 (1056).
[12] W. Shockley and J. L. Pearson, Phys. Rev. **74**, 232 (1948).
[13] W. C. Dunlap, Jr., Phys. Rev. **97**, 614 (1955); **100**, 1629 (1955).
[14] M. L. Schultz and G. A. Morton, Proc. Inst. Radio Engrs. **43**, 1819 (1955).
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[16] *Semiconductor Surface Physics*, edited by R. H. Kingston (University of Pennsylvania Press, Philadelphia, Pennsylvania, 1957).
[17] J. Brattain and J. Bardeen, Bell System Tech. J. **32**, 1 (1953).
[18] K. M. van Vliet, Proc. Inst. Radio Engrs. **46**, 1004 (1958).

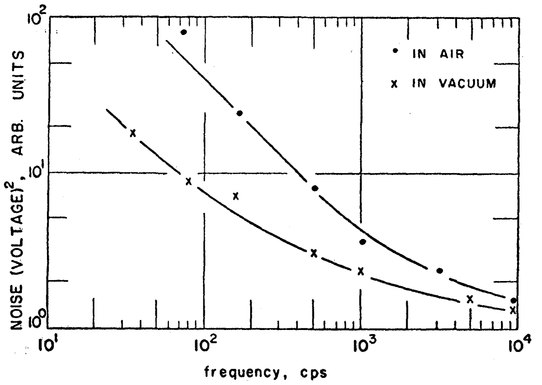

FIG. 3. Noise spectrum of 30 Ω-cm, p-type germanium at 300°K, 150 microns thick.

two types of noise but no decrease in the g-r noise is observable in the audio-frequency region due to the very low lifetime of the current carriers. Lifetimes calculated from the magnitude of the g-r noise are of the order of 10^{-7} sec. By making use of apparatus developed for the measurement of short lifetimes by the photoconductive decay method,[19] agreement has been obtained between the experimentally determined lifetime and the lifetimes as calculated from the magnitude of the g-r noise spectrum.[20]

When the p-type gold-doped germanium is cooled to a lower temperature, i.e., 65°K, the g-r noise due to thermal excitation of carriers by the lattice is no longer observed. At this temperature considerably more charge carriers are excited by the background radiation than by the lattice. The noise in the Ge:Au specimens is then due to fluctuations in the carrier generation rate which in turn is caused by fluctuations in the number of photons striking the crystal.[21] This noise is similar to g-r noise since there are fluctuations in both the carrier generation and recombination rates, but in this instance the fluctuation in the generation rate is due to fluctuations in the photon stream. A calculation of the noise expected in a photoconductor due to the photons is in agreement with the experimentally observed results.

The noise spectrum of nearly intrinsic germanium at room temperature as shown in Fig. 3, also is composed of both g-r and $1/f$ noise. The observed $1/f$ noise obeys a relationship $1/f^n$ where n varies between 1.0 and 1.2. No significant deviation from the $1/f$ law was observed in the frequency region investigated.

IV. FACTORS AFFECTING THE $1/f$ NOISE

1. Surface Potential[22]

The dependence of the $1/f$ noise on surface potential was investigated. The surface potential may be varied by two methods: by the application of a dc voltage perpendicular to the surface, or by allowing gases to interact with the surface. The latter technique was not used since the different gases can change the physical structure of the slow surface states. In addition, the field effect method permits low temperature measurements which must be performed in a vacuum.

Measurements on p-type bulk germanium show that the $1/f$ noise increases as the conductivity of the surface becomes increasingly n-type. No change in the $1/f$ noise was observed when the surface potential was changed such that the surface remained p-type. These results on p-type material indicate that the $1/f$ noise is associated with the inversion layer.[23] Typical results for p-type bulk material are shown in Fig. 4. In this instance,

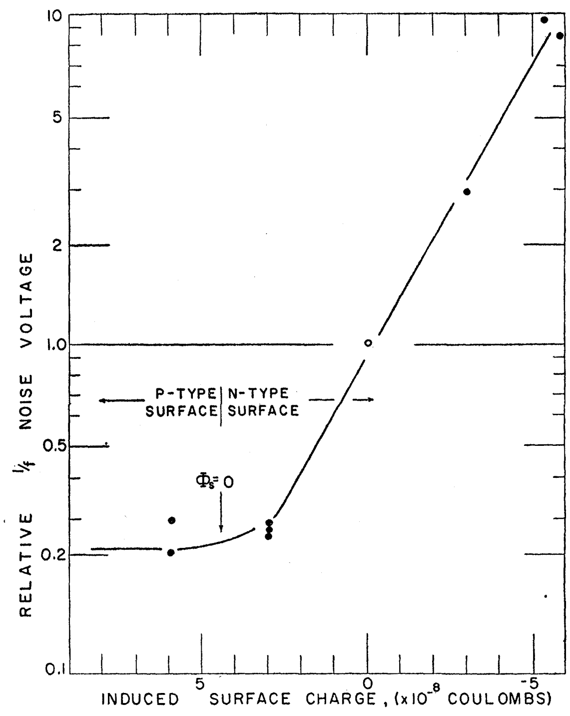

FIG. 4. The dependence of the $1/f$ noise on the induced surface charge for p-type bulk germanium.

as well as for other samples, it was possible to decrease the magnitude of the $1/f$ noise by eliminating the naturally occurring inversion layer on the sample. The relative decrease in $1/f$ noise voltage for different samples (a factor of five in Fig. 4) is dependent on the equilibrium value of the surface potential.

Similar results were obtained using n-type germanium. The $1/f$ noise in n-type germanium, as shown in Fig. 5, is also associated with the inversion layer.

It was very difficult to obtain a quantitative relation between $1/f$ noise and surface potential when there was an inversion layer on the surface. Figures 4 and 5 indi-

[19] M. Garbuny, T. P. Vogl, and J. R. Hansen, Rev. Sci. Instr. 28, 826 (1957).
[20] M. Garbuny, T. P. Vogl, and J. R. Hansen (personal communication).
[21] W. B. Lewis, Proc. Phys. Soc. (London) 59, 34 (1947).
[22] First reported at the Fluctuation in Solids Symposium, Chicago, 1957.
[23] A. MacRae and H. Levinstein, Bull. Am. Phys. Soc. 4, 179 (1959).

cate that this increase may possibly be exponential with the introduction of additional surface charge.

A typical example of the variation in the noise spectrum which occurred when the surface potential was changed is shown in Fig. 6. The noise spectrum for the sample whose surface conductivity is inverted with respect to the bulk conductivity follows a $1/f^n$ law where n is approximately 1.1. The spectrum associated with the intrinsic surface is characterized by the presence of both $1/f$ and g-r noise.

The invariance of the $1/f$ noise with surface potential (ϕ_s) for a surface accumulation layer and the large increase in the $1/f$ noise accompanying increases in $|\phi_s|$ for an inversion layer, indicate that the $1/f$ noise is not related to the field effect mobility.[8] It also appears that charge transfer between bulk and slow surface states is not the dominant physical process in determining $1/f$ noise.[8] If such a mechanism were responsible for the $1/f$ noise, an increase in the noise would be observed when an electric field is applied perpendicular to an accumulation layer surface, since a large charge transfer occurs in this instance (as evidenced by the decay of the surface conductivity).

2. Temperature Effects

The importance of the slow surface states in determining the $1/f$ noise has been questioned[24] since the

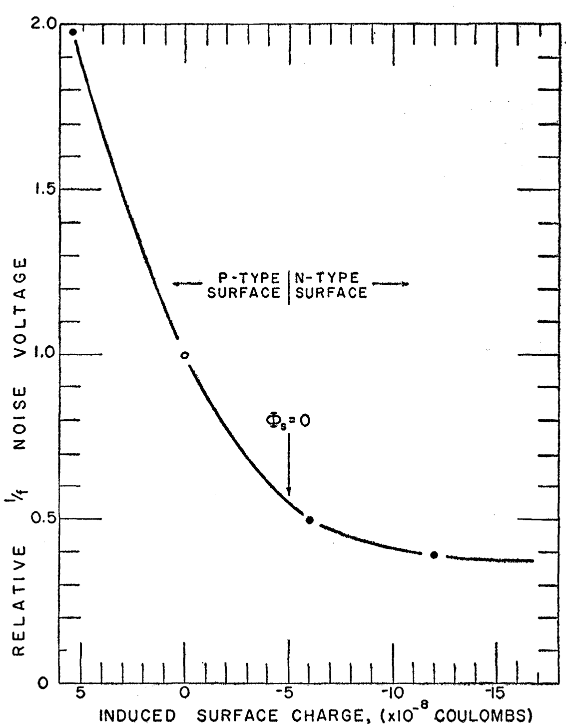

FIG. 5. The dependence of the $1/f$ noise on the induced surface charge for n-type bulk germanium.

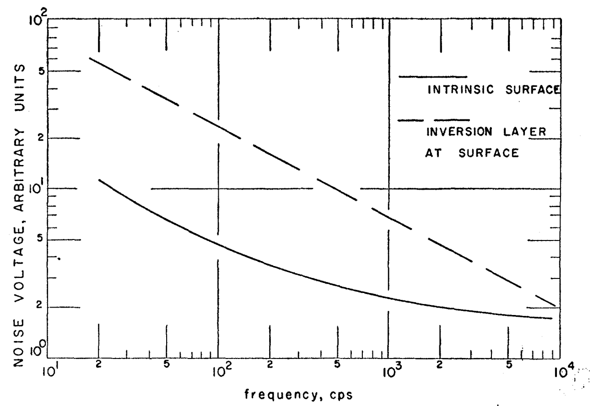

FIG. 6. The noise spectrum for p-type germanium whose surface conductivity is first intrinsic and then inverted. The inversion layer was formed by the application of an electric field perpendicular to the surface.

magnitude of the $1/f$ noise usually appears to be temperature independent while the slow state relaxation time is temperature dependent.[25] The $1/f$ noise associated with both inversion and accumulation layers was investigated as a function of temperature. The $1/f$ noise associated with an accumulation layer was found to be temperature independent while that associated with the inversion layer was found to be temperature dependent. The dependence on temperature when an inversion layer exists is shown in Fig. 7. It follows the relationship:

$$\langle \Delta v^2 \rangle = A \exp(-E/kT)$$

for both n and p-type material, with $E \cong 0.25$ ev for T between 300°K and 200°K. Since normally an accumulation layer is present at low temperatures, it was necessary to induce the inversion layer onto the surface by applying a dc electric field to the field effect electrode.

Usually the temperature dependence of the noise is investigated with samples whose surface potential is allowed to assume its own value. Dynamic ac field effect measurements as a function of temperature indicate that the surface of germanium tends to assume the same conductivity as that of the bulk below room temperature, even though an inversion layer may be present at room temperature. Thus ordinarily when the temperature dependence of the $1/f$ noise is investigated, it is the noise associated with the accumulation layer that is measured and found to be temperature independent.

3. Relaxation Effects

When excess charge is induced into the semiconductor space charge region by the continuous application of a dc field to the field effect electrode, an initial change occurs in the conductance of the sample. A change in the $1/f$ noise also occurs if an inversion layer exists at

[24] R. L. Petritz in *Semiconductor Surface Physics*, edited by R. H. Kingston (University of Pennsylvania Press, Philadelphia, Pennsylvania, 1957), p. 226.

[25] S. R. Morrison in *Semiconductor Surface Physics*, edited by R. H. Kingston (University of Pennsylvania Press, Philadelphia, Pennsylvania, 1957).

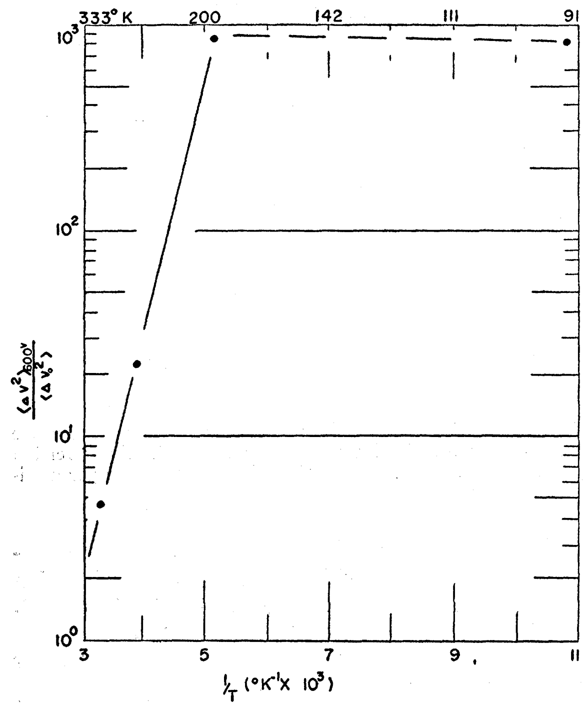

FIG. 7. Temperature dependence of the $1/f$ noise associated with an inversion layer on p-type bulk germanium.

the surface. After this initial change, both the conductance and the $1/f$ noise relax back to their original values. Charge transfer across the surface oxide into the slow surface states is responsible for this relaxation process. The length of this relaxation time is dependent on the temperature and the surface conditions. Ozone or wet air tend to produce a rapid decay. The decay in vacuum is fairly slow, of the order of several minutes at room temperature.

The mode of the $1/f$ noise decay is independent of the surface conditions and follows a logarithmic time dependence. Typical relaxation curves for this process are shown in Fig. 8 for two different values of the voltage applied to the field effect electrode. As is indicated in Figs. 4 and 5, the noise change, upon the application of the field, is not linear with the impressed voltage.

A logarithmic law characterizes the chemisorption of gases on metals[26] and has been explained in terms of an exponential rate law.[27] It is possible to synthesize such a time dependence from the sum of many exponential decays. If it is assumed that the surface is divided up into regions separated by a Debye length,[8] the conductance and presumably the noise of the different regions will vary independently upon the application of the electric field. The conductance and noise of each region will decay back to their original values with an exp $(-t/\tau_i)$ time dependence. The total decay will be the sum of all these individual processes. If there is a distribution in the τ's which is proportional to $1/f$, the decay will assume a logarithmic form. It is specifically this distribution in τ's which will account for the $1/f$ noise spectrum.[9]

A $1/\tau$ distribution in slow surface states has been proposed to explain the frequency response of the ac field effect over a restricted frequency range.[8] The frequency response of the ac field effect and the decay of the dc field are essentially Fourier transforms of one another. The time dependence of the conductance decay was investigated in an attempt to correlate the noise and conductance relaxation with the surface conditions. It was observed that the mode of the conductance decay is independent of the mode of the $1/f$ noise decay. While the noise always relaxes back to its original value with a logarithmic time dependence, the conductance decay varies between exponential and logarithmic, depending on the surface conditions. Typical such decay traces are shown in Fig. 9. A logarithmic decay occurs when the sample is in a vacuum of 10^{-6} mm Hg and an exponential decay in ammonia gas. This exponential decay would be characteristic of a single energy level introduced onto the surface by this gas. Usually the decay is a combination of the logarithmic and exponential processes. A decrease in the temperature causes a change in the mode of decay as well as an increase in the decay time. No decrease in the $1/f$ noise over a period of several hours was observed at

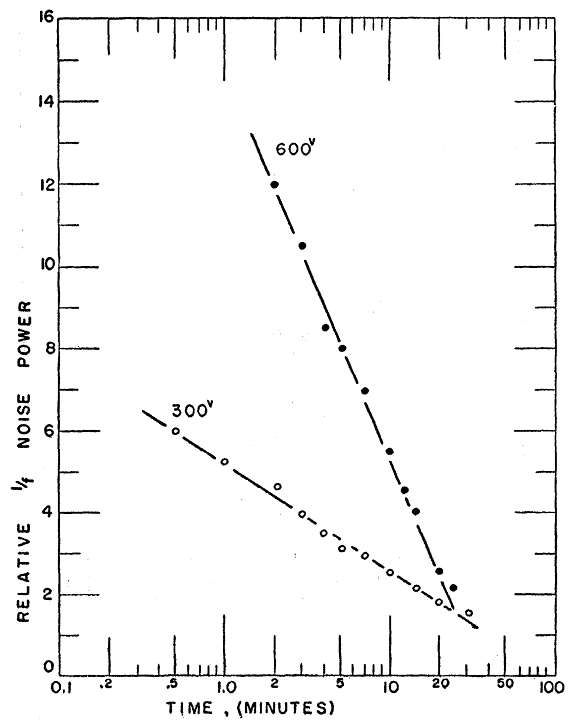

FIG. 8. $1/f$ noise relaxation after the application of an electric field perpendicular to the surface.

[26] P. T. Landsberg, J. Chem. Phys. 23, 1079 (1955).
[27] N. Cabrera and N. F. Mott, Repts. Progr. in Phys. 12, 163 (1949).

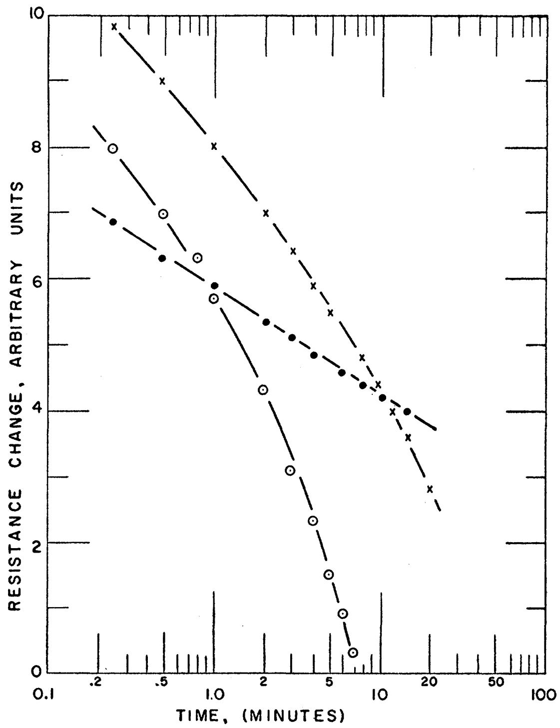

FIG. 9. Typical dc field effect relaxation: ×—× in room air; ⊙—⊙ after exposure to HN_3; ●—● in vacuum.

78°K. The presence of the combination of an exponential as well as a logarithmic decay suggest that discrete states are superimposed upon a continuous $1/\tau$ distribution. It is the $1/\tau$ distribution in the surface states, however, that effects the $1/f$ noise, as evidenced by the logarithmic noise decay. Even though the presence of discrete states is evident from conductivity decay measurements, the noise is not affected by these states. The presence of a distribution in surface states is not unique to the explanation of $1/f$ noise. It is necessary, for instance, to introduce an inhomogeneous surface to explain surface mobility results.[28]

4. Ambient Effects

It was noticed during the course of this investigation that the nature of the ambient has a marked effect on the magnitude of the $1/f$ noise. Such an influence on the noise spectrum is depicted in Fig. 3. The noise spectrum which is predominantly of the g-r type in vacuum becomes $1/f$ upon exposure to room air. Similar effects were noticed with all the samples.

This variation in the $1/f$ noise is due not only to a change in the surface potential but also to a change in the effective slow surface state density. The effect of the slow surface density on the $1/f$ noise was investigated at a nearly constant value of the surface potential for a sample whose surface conductivity was of the same type as the bulk. The slow state density was varied by changing the pressure of the ambient. In this way it was possible to measure the magnitude of the $1/f$ noise and to correlate it with the slow surface state relaxation time, which should be a measure of the slow surface state density. Since this decay does not follow a single exponential relaxation, it is difficult to assign a single time constant to this process. It was necessary to define arbitrarily a quantity which is a measure of the relaxation in order to investigate the dependence of the $1/f$ noise on the slow state density. The fractional decay between 0.1 and 1.0 minutes was used to describe the decay. In this manner, large fractional decay is proportional to a large slow surface density. The conductance decay for a particular sample in several different ambients is shown in Fig. 10. The ambient was changed in the order indicated by the Roman numerals. In general, the slowest decay occurred after the sample had been in a vacuum (10^{-6} mm Hg) for a few days and the most rapid decay when in room air. The $1/f$ noise associated with each of these decay curves is shown in Fig. 11. While this figure is qualitative in nature, it illustrates the dependence of the $1/f$ noise on the effective slow surface state density or the slow surface state relaxation time. The $1/f$ noise increases as the relaxation time decreases or the density of states increases. A similar decrease in the $1/f$ noise has been

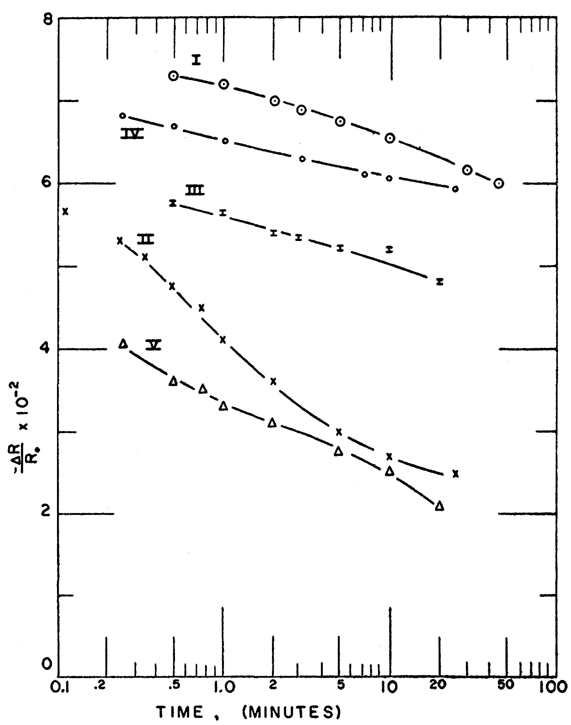

FIG. 10. The resistance decay for a sample which has undergone the cycle: I, in vacuum of 10^{-6} mm Hg for three days; II, in room air; III, immediately after evacuation; IV, in vacuum of 10^{-6} mm Hg for one day; V, in room air.

[28] D. H. Lindley and P. C. Banbury, Proc. Phys. Soc. (London) **74**, 395 (1959).

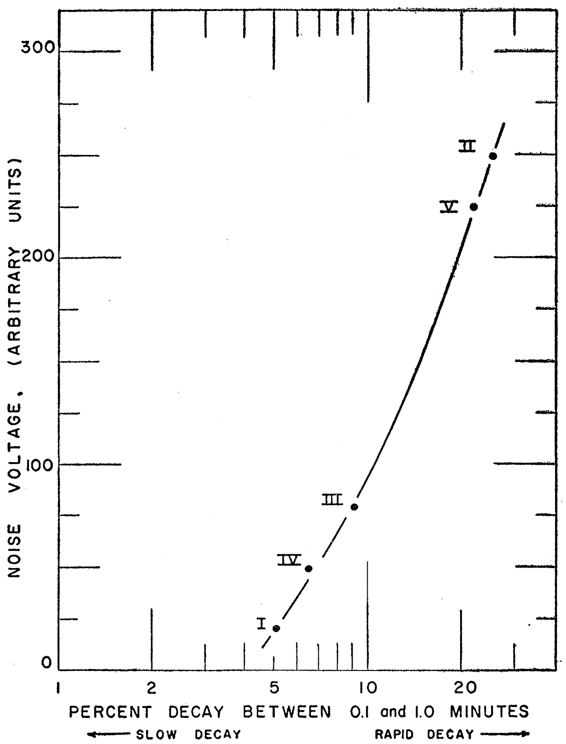

FIG. 11. Dependence of $1/f$ noise on the slow state relaxation time.

observed for silicon samples containing thick oxide layers.[29] This was attributed to the lack of charge transfer between the bulk and the slow surface states.

The effect of a thin metallic film on the $1/f$ noise was also investigated. Aluminum was evaporated onto the surface of a thin germanium filament through a No. 325 mesh screen. This produced 1.5×10^4 distinct high conductance regions of aluminum per cm^2. Even though the resistance of the sample was not changed, the $1/f$ noise voltage increased by a factor of 200. Removal of the thin film by etching restored the $1/f$ noise to its original value. The evaporation of an insulator, SiO, onto the surface by the same technique caused no increase in the $1/f$ noise.

5. Charge Carrier Density Effects

Montgomery has made the observation that the ratio of the $1/f$ to the Johnson noise at a constant bias voltage tends to be independent of the resistivity of the material.[1] Similar results were observed for the variation of the $1/f$ noise with the resistance of gold-doped germanium. A large variation of the resistance was obtained by varying the temperature of the material in the vicinity of 77°K. It was found that the $1/f$ noise could be expressed as:

$$\langle\Delta v^2\rangle=4A(E^2R/f) \qquad (1)$$

or the $1/f$ noise power as:

$$\langle\Delta v^2\rangle/4R=AE^2/f \qquad (2)$$

where R is the resistance of the sample, E is the electric field across the sample, and A is a constant. Aside from the frequency dependence, a similar result is valid for g-r noise. These results indicate that the $1/f$ noise power is independent of any change in the resistance or temperature of the germanium. No attempt was made to control the surface potential of these samples. Thus Eq. (2) is presumably true for the residual noise associated with the accumulation layer and not the inversion layer. It is possible that this $1/f$ noise is due to the electrical contacts to the germanium.

A further investigation of the temperature dependence of the $1/f$ noise associated with the accumulation layer revealed results which were apparently in contradiction to the above results. By varying the temperature of thin filaments of 35 ohm-cm n and p-type germanium from 300°K to 77°K, it was possible to obtain a dependence of the $1/f$ noise on the resistance of the sample. Even though there was only a small change in the resistance of these samples, it appears that the $1/f$ noise in this instance can be expressed as:

$$\langle\Delta v^2\rangle=4B(I^2R/f) \qquad (3)$$

where I is the current through the sample and B an experimentally determined constant. While these last mentioned results may be accidental due to the small range in resistance covered, it may be possible that the total $1/f$ noise associated with the accumulation layer is the sum of Eqs. (1) and (3): (1) being due to the contracts and (3) due to the surface. Both surface and contact effects must be taken into consideration to explain the $1/f$ noise in InSb photodiodes.[30]

V. DISCUSSION

While several physical mechanisms have recently been proposed to explain $1/f$ noise,[8,24,31] it appears that these mechanisms are not sufficiently inclusive to explain its many facets.

The one common characteristic of the probable sources of $1/f$ noise (contacts, dislocations,[32] and the surface), is the presence of a potential barrier. The mere presence of a barrier does not guarantee the existence of $1/f$ noise, however. This is evidenced by the absence of $1/f$ noise at some p-n junctions and at a surface accumulation layer. It may be possible that inhomogeneities in the width and height of the barriers may be the cause of $1/f$ noise. If there exist inhomogeneities in the surface barrier (as shown in Fig. 12), the different times necessary to produce this unique noise spectrum may arise from the tunneling of carriers through the

[29] M. M. Atalla, E. Tannenbaum, and E. J. Schreibner, Bell System Tech. J. 38, 749 (1959).

[30] W. Pagel and R. L. Petritz (personal communication) (to be published).

[31] L. Bess, Phys. Rev. 103, 72 (1956).

[32] J. J. Brophy, Phys. Rev. 115, 1122 (1959).

different thicknesses of the barriers. Another possible source of $1/f$ noise may be the region at the barrier where the conductivity changes from n to p-type. This region is characterized by a small number of carriers. Any fluctuation in the p-n product could be quite appreciable here. Such a fluctuation would cause a fluctuation in the Fermi level with respect to the band edges and would cause the trapping statistics to fluctuate in the vicinity of the barriers. These minority carrier inclusions may also be the centers referred to by Shockley in his model of $1/f$ noise.[33] He maintains that a center is the source of electron-hole pairs, whose ability to emit or absorb charged pairs is modulated by its charge. Since the minority carrier charge in the barrier of an inversion layer diminishes with increasing distance away from the surface, it may be possible to have the necessary variation in the charge of these sites, giving rise to the time distribution which is responsible for $1/f$ noise. The $1/\tau$ distribution in trapping times may then be a type of artifice which is the result of the distribution in the charge sites.

VI. SUMMARY

This investigation emphasizes the importance of the role of the surface in determining the properties of $1/f$ noise. The large increase in the $1/f$ noise as the surface conductance becomes inverted with respect to the bulk may provide an indication as to the source of this noise. A large temperature dependence of the $1/f$ noise caused by the creation of an inversion layer by the electric field was also observed. The absence of additional $1/f$ noise when an electric field is applied perpendicular to the surface containing an accumulation layer precludes the importance of charge transfer between the bulk and slow states as a source of noise. The possibility that a $1/\tau$ type of distribution in "times" may exist at the surface is indicated by the logarithmic time dependence of the noise relaxation upon the application of a perpendicular dc field. This relaxation is independent of the mode of relaxation assumed by the conductance under similar circumstances. Even though many characteristics of $1/f$ noise are now known, additional information is needed before a satisfactory physical explanation of this phenomena can be attained.

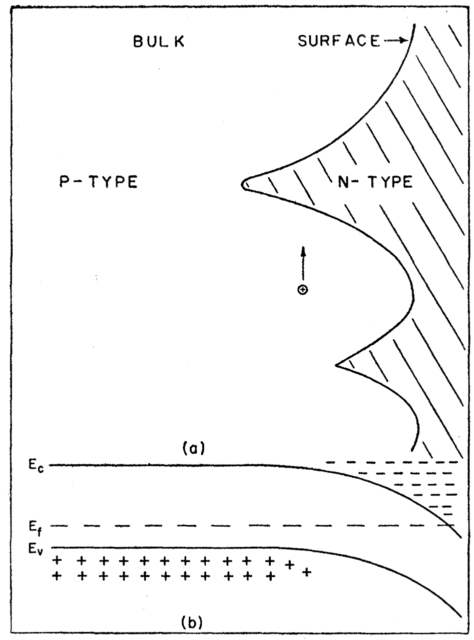

FIG. 12. An inversion layer on germanium: (a) inhomogeneous barrier distribution; (b) representative charge distribution.

[33] W. Shockley, *Electrons and Holes in Semiconductors* (D. van Nostrand Company, Inc., Princeton, New Jersey, 1950), p. 342.