Crystalline Imperfections and $1/f$ Noise*

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The $1/f$ noise of single-crystal silicon and germanium has been examined as a function of naturally occurring imperfection densities, dislocations produced by plastic deformation, and imperfections resulting from fast-neutron irradiation. In all cases the noise power decreases with increasing crystalline imperfection. The results may be quantitatively explained by assuming that $1/f$ noise is proportional to the square of the minority carrier lifetime and accounting for the decrease in lifetime due to imperfections.

I. INTRODUCTION

THE $1/f$ noise levels of single-crystal semiconductors are observed to vary considerably from sample to sample for macroscopically identical specimens. Surface conditions[1] are known to be extremely important and it is conceivable that bulk properties, such as crystalline imperfections, could also contribute to this variation. It has been reported[2,3] that plastic deformation increases the noise level, and dislocations have been taken to play an important role in mechanisms leading to $1/f$ noise.[3,4]

A more complete examination of the effect of crystalline imperfections on $1/f$ noise has been carried out on silicon single crystals having a range of naturally occurring imperfection densities, germanium single crystals with imperfections produced by plastic deformation, and germanium crystals damaged by fast-neutron irradiation. In this work the $1/f$ noise power is found to decrease with increasing imperfection density.

II. SAMPLE PREPARATION

Three sets of silicon samples were cut from adjacent regions of three separate boules. Samples from crystal A ranged in resistivity from three to seventy ohm-cm (n-type) as shown in Table I. Crystals B and C were grown under conditions different from that of A and are similar except for conductivity type. Standard bridge-shaped specimens were fabricated by sandblasting such that the dimensions of the main sections were 7.6 mm×3.0 mm. Thicknesses ranged from 0.5 to 1.0 mm. Electrodes were attached by ultrasonic soldering and the surfaces were chemically etched.

TABLE I. Characteristics of silicon samples.

Crystal No. and conductivity	Sample No.	Resistivity (ohm-cm)	Dislocation density (10^7 cm^{-2})	Noise constant (10^{-14})
$A(n)$	$7L$	72	0.82	61
$A(n)$	$3R$	3.2	0.97	51
$A(n)$	$9R$	29	2.0	8.3
$A(n)$	$1R$	4.0	2.0	19
$A(n)$	$1L$	11	2.2	4.5
$B(n)$	$2N$	4.3	0.65	0.25
$B(n)$	$1N$	7.0	0.47	0.75
$B(n)$	$1NB$	6.2	1.9	0.17
$C(p)$	$3PB$	1.7	1.1	0.14
$C(p)$	$4PB$	1.5	0.63	0.4

Imperfection densities were determined by a modified x-ray diffraction Laue technique[5] using a microfocus x-ray tube. This method has the advantage of examining the sample in transmission and of being relatively rapid. X-ray line broadening determined in this way was used to compute dislocation densities from the expression[6]

$$N_D=\beta^2/9\lambda^2, \tag{1}$$

where β is the half-width of the x-ray reflection, and λ is a constant equal to 3.135×10^{-8} cm for this experiment. Equation (1) assumes that the imperfections contributing to the broadening are random edge dislocations. The range of dislocation densities found for these samples is shown in Table I.

The plastically deformed germanium crystals were all originally 3-ohm-cm n-type and were similarly fabricated into bridges 7 mm×2.2 mm×0.25 mm. They were plastically deformed by bending in air at about 600°C after a rigid surface cleansing. After deformation they were etched again and leads attached with tin solder. As shown in Table II the resistivity increased with increasing deformation. The dislocation density introduced by the bending was computed from the standard relation[7]

$$N_D=1/3.27\times10^{-8}R, \tag{2}$$

where R is the radius of bending.

The samples prepared for neutron irradiation were of 30-ohm-cm n-type germanium shaped into bridges 6.4 mm×3.2 mm×0.5 mm. The surfaces were etched and leads attached by tin soldering before irradiation. The minority carrier lifetime was determined by photoconductive decay for each crystal before irradiation, as shown in Table III.

The total neutron doses shown in the table were obtained by wrapping each sample in $\frac{1}{8}$-in. cadmium and

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[7] A. H. Cottrell, *Dislocations and Plastic Flow in Crystals* (Oxford University Press, London, 1953), p. 29.

inserting them into Armour Research Foundation's homogeneous reactor for varying irradiation times. Fast neutron flux at the sample position was $\sim 9.6\times 10^9$ neutrons/cm^2 sec, which was determined by foil activation measurements. The sample temperature during irradiation was 27°C. After irradiation, the 10^{14} and 10^{15} neutrons/cm^2 specimens were found to be somewhat activated due presumably to impurities in the tin solder and copper leads. The crystals were allowed to decay for a week to facilitate handling.

The resistivity and lifetime after irradiation are shown in the table. The more heavily irradiated specimens have converted to p-type material and have lifetimes too short to measure by photoconductive decay. The changes in resistivity and lifetime are in good quantitative agreement with previous work.[8,9]

III. NOISE MEASUREMENTS

The $1/f$ noise power density of single-crystal specimens is approximately proportional to the square of the dc current and also nearly inversely proportional to the frequency. In comparing the noise levels of similar specimens it is convenient to define a dimensionless constant, C, by the expression

$$\langle \Delta V^2 \rangle = CV^2/f, \tag{3}$$

where $\langle \Delta V^2 \rangle$ is the mean square $1/f$ noise voltage density at frequency f and V is the dc voltage across the noise probes. For ohmic samples this noise constant is equivalent to those quoted in current-dependent expressions and it may be related to current carrier fluctuations.[10]

The value of C for each of the samples was determined from Eq. (3) by standard noise measurements. In each case the noise at several frequencies was observed to verify the $1/f$ character and the variation with V checked to establish the approximate square law behavior. All samples were examined experimentally to be sure electrode effects were negligible.[10] The noise constants quoted in the tables are calculated from measurements made at 100 cps. The irradiated samples were measured both before and after bombardment except for the most heavily damaged crystals which had noise levels too low to determine conveniently.

TABLE II. Characteristics of plastically deformed germanium samples.

Bending radius (cm)	Resistivity after def. (ohm-cm)	Dislocation density (10^6 cm^{-2})	Noise constant (10^{-14})
∞	3.2	...	160
10	6.0	3.1	22
10	6.6	3.1	19
5	13	6.1	20
2.5	21	12	1.3
2.5	15	12	2.6

TABLE III. Characteristics of irradiated germanium samples.

Integrated flux, (neutrons/cm^2)	Resistivity, (ohm-cm) Initial	Final	Lifetime (μsec) τ_0	τ	Noise constant (10^{-16}) C_0	C
10^{11}	28	29	30	30	200	290
10^{11}	25	26	40	40	150	110
10^{12}	29	34	30	10	380	150
10^{12}	32	35	15	9	60	170
10^{13}	29	43	70	2	190	83
10^{13}	30	43	40	1.5	280	41
4×10^{13}	28	13	30	<1	150	45
10^{14}	26	6	70	...	350	4.6
10^{14}	25	5.5	30	...	240	Sample broken
10^{15}	28	0.7	30	...	120	<0.1
10^{15}	30	0.6	20	...	170	<0.1

IV. RESULTS

The data presented show that the noise constant decreases with increasing imperfection density. This behavior may be quantitatively explained by the following analysis. We may assume, as Montgomery has suggested,[11] that the $1/f$ noise voltage is proportional to the minority carrier lifetime, τ, so

$$C = C'\tau^2. \tag{4}$$

Now τ may be written

$$1/\tau = (1/\tau_0) + kN, \tag{5}$$

where τ_0 is the initial lifetime before introduction of imperfections and may be determined primarily by surface recombination, N is the dislocation density or

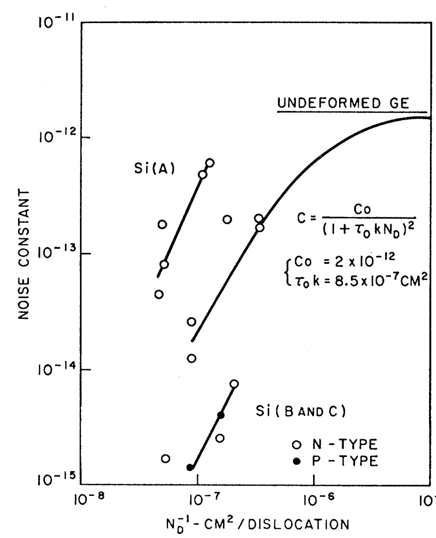

FIG. 1. Variation of the noise constant with dislocation density. The silicon crystals have naturally occurring dislocations while the germanium specimens were plastically deformed.

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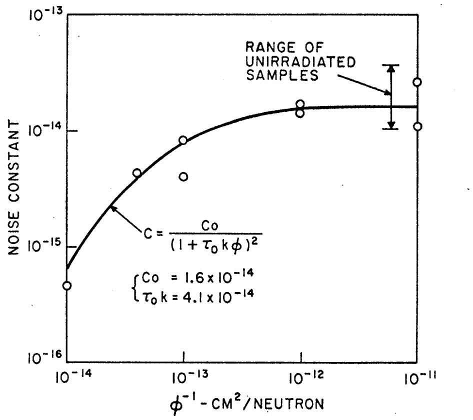

FIG. 2. Variation of the noise constant with fast-neutron irradiation of germanium crystals.

integrated fast-neutron flux, and k is a damage constant. The inverse proportionality between lifetime and dislocation density is well established,[12–14] as is the same behavior for fast-neutron irradiation.[8] Combining Eq. (4) and Eq. (5), the noise constant becomes

$$C=C_0/(1+\tau_0 kN)^2, \tag{6}$$

where $C_0=C'\tau_0^2$ and is a constant with respect to the change of imperfection density.

The variation of the noise constants with imperfection density for the three series of samples is plotted in Fig. 1 and 2. The data for the germanium samples are compared with Eq. (6) by adjusting the constants C_0 and $\tau_0 k$ to obtain the best fit. Satisfactory agreement between the behavior of Eq. (6) and the experimental data are obtained. The range of imperfection density for each group of silicon samples is not sufficient to make such a matching but here too the trend of the data is in agreement with Eq. (6). The reason for the large difference between crystal A compared to B and C it unknown. Since A was grown on different equipment, is is possible that other structural differences exist. The meager data available for crystals B and C seem to show no difference between p- and n-type conductivity.

From the value of $\tau_0 k$ thus determined for the plastically deformed samples and τ_0 measured for the undeformed sample (5 μsec) the damage constant, k, is calculated to be 0.2 cm^2/sec. This compares favorably with the value 0.4 cm^2/sec reported[14] from direct lifetime measurements. Similarly, a k of 2.1×10^{-9} cm^2/sec is calculated from the irradiated sample data, which is to be compared with 4.3×10^{-9} cm^2/sec determined[8] from lifetime studies of irradiated germanium.

As noted above, it has been reported that plastic deformation greatly increases $1/f$ noise in germanium.[2] The previous results were obtained on heavily deformed crystals ($\frac{1}{2}$- and 1-cm radii) and exhibited an anomalous I^4 dependence of the noise power on current. The noise power had a $1/f$ spectrum, however. One of the specimens of Table I bent to a 2.5-cm radius which showed traces of this behavior was studied in more detail and appears to offer evidence for a second noise mechanism in heavily deformed samples.

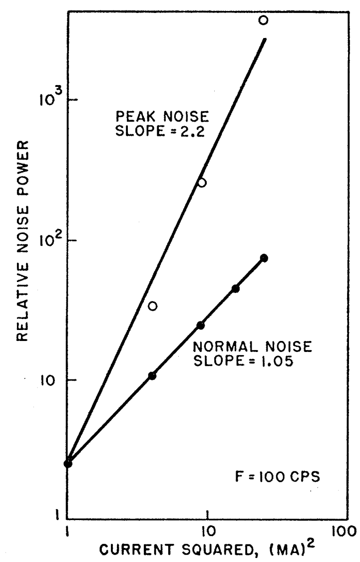

FIG. 4. Dependence of noise power on current for the two noise levels of the deformed sample of Fig. 3.

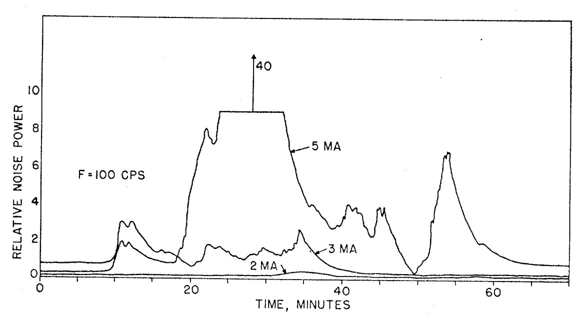

FIG. 3. Noise power as a function of time for a deformed sample. At higher currents, a higher noise level occurs for about 30 minutes.

This crystal exhibits short bursts of much higher noise level which are particularly evident at high bias currents. The bursts are sporadic and stop after about 30 min of current flow. In order to study this noise the output of the mean-square vacuum-tube voltmeter was connected to a chart recorder and the noise level plotted as a function of time for periods of several hours. An instrument time constant of 100 sec was used in order to smooth out irregularities caused by the bursts.

Tracings of several runs at different bias currents are shown in Fig. 3. The noise level is constant for several minutes after switching on the current and then increases as the bursting begins. After about 30 min the bursting stops and the original noise level is regained. The effect is progressively less evident at smaller currents. Having once gone through this cycle, the bursts

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do not reappear unless the sample is allowed to rest at zero current for several days. Current reversal will show the effect but here again after current has passed in each direction no further bursting is observed until the specimen recovers. The details of the noise level plot as a function of time are not reproducible but the incubation time, duration, and peak noise level are consistent from trial to trial at the same current.

The quiescent noise power varies as the current squared, as shown in Fig. 4. The peak noise, however, increases approximately as the fourth power. It appears that two noise mechanisms are acting and that this particular sample separates them clearly. The high noise behavior which occurs in very heavily deformed crystals is not time dependent. For the present work, the "normal" noise level showing the square law behavior was used to compute the noise constant.

V. DISCUSSION

The above results indicate that the effect of appreciable crystalline imperfection densities in germanium and silicon is to decrease the noise level through reduction in minority carrier lifetime. The good quantitative agreement is obtained even though the sample resistivity is appreciably altered by introduction of imperfections. This is so even in the case of the heavily irradiated specimens which convert from n-type to p-type. Probably the presence of these large imperfection densities overrides any resistivity effect.

The strong influence of minority carrier lifetime thus established appears to favor the importance of minority carriers over majority carriers in $1/f$ noise, as suggested by Montgomery.[11] However, as shown in Table III, the correlation between the noise constants and minority carrier lifetimes of the 11 supposedly identical samples before irradiation is only suggestive of this trend and is by no means a strong correlation.

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Electron Irradiation of Indium Antimonide*†

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The effects of 4.5-Mev electron bombardment on the electrical properties of n- and p-type InSb are studied. Isochronal annealing experiments carried out on samples bombarded at 80°K indicate three regions of rapid annealing, the first two between 80°K and 200°K and the third near room temperature. It is shown that the distribution of bombardment-produced energy levels is altered by heating a bombarded specimen to 200°K. The changes which occur as a result of this heat treatment suggest that energy levels are shifted as defects rearrange themselves into positions of greater stability. For samples bombarded at 200°K, the positions of energy levels and the rates at which they are generated are determined from careful studies of the rates at which they are generated are determined from careful studies of the temperature dependence of carrier concentration. Mobility changes are utilized to identify donor or acceptor behavior. The levels introduced into the forbidden band appear to be multiply ionized.

I. INTRODUCTION

THE effect of high-energy particle bombardment on the electrical properties of a semiconductor is usually interpreted in terms of the introduction of donor and acceptor sites.[1] According to a model by James and Lark-Horovitz,[2] interstitials are expected to be donors, and vacancies are expected to be acceptors, in the case of elementary semiconductors. This model has been confirmed in its qualitative aspects for germanium[3,4] and silicon,[5] and has been utilized in the interpretation of neutron-bombarded indium antimonide[6,7] and gallium antimonide.[8]

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