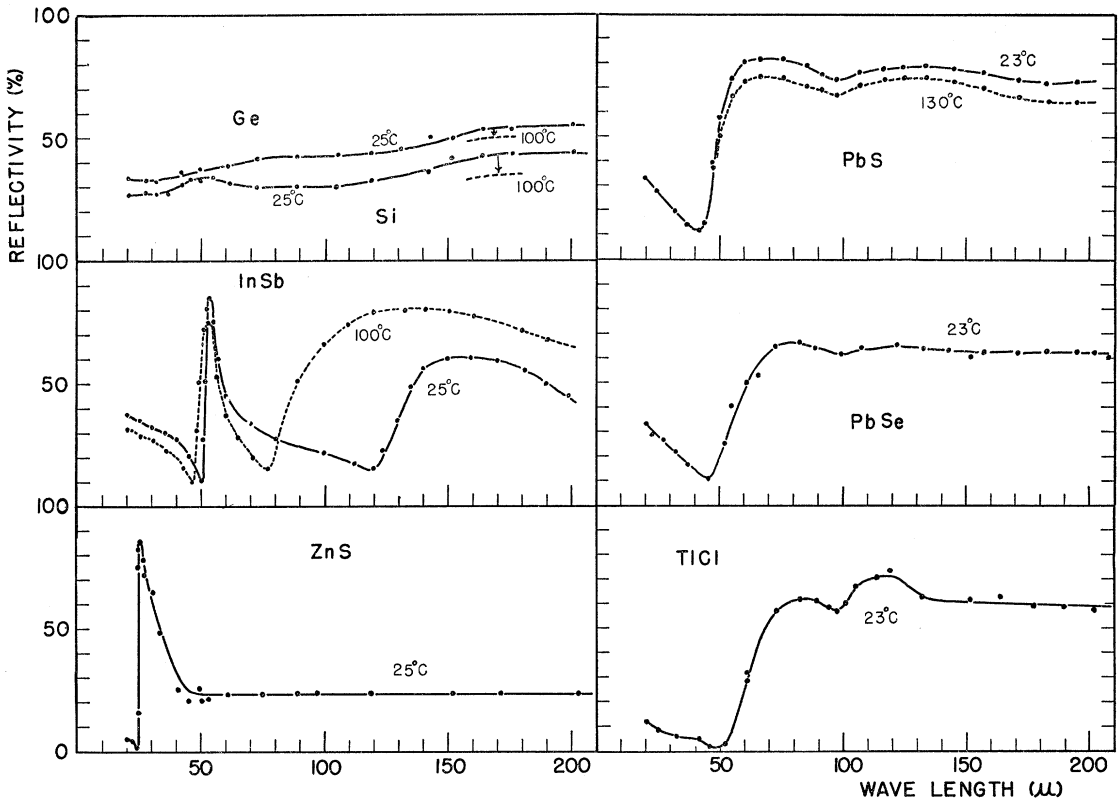

FIG. 1. Far infrared reflectivities of Ge, Si, InSb, ZnS, PbS, PbSe, and TlCl.

The reflectivities of Ge and Si are almost constant throughout the spectral region observed. For impure Ge, a peak in the 117-micron region has been reported,[2] but we were unable to find evidence of its existance with a fairly pure Ge crystal.

The reflectivity curves of InSb show a sharp maximum at 54.6 microns and a flat peak in the longer wave region. The maximum value of the peak at 54.6 microns decreases with increase of temperature, but the maximum value of the flat peak increases rapidly and the position of this peak shifts toward short wave lengths with increase of temperature. The reflectivity curve of ZnS has a sharp peak at 25.5 microns, but it is completely flat beyond 50 microns. InSb and ZnS have the same crystal form. The sharp peaks of reflectivity of InSb and ZnS appear to be due to lattice vibrations, and the flat peak of InSb may be attributed to free electrons. Details of these and other measurements on InSb are being published elsewhere.[3]

Far infrared reflectivities were previously reported by Strong[4] for PbS and by Sinton and Davis[5] for PbS and TlCl. PbS, PbSe, and TlCl have similar reflectivity characteristics, each having two flat reflectivity maxima. Measurements at 23° and 130°C show that the peak in the longer wave region does not depend on free electrons.

The author wishes to acknowledge help given by Robert A. Oetjen and Ely E. Bell. The PbSe crystal was made available by Richard Lord of the Massachusetts Institute of Technology, the InSb crystals by Leonard Eisner and T. Harman of Battelle Memorial Institute, and the ZnS crystal by Elias Burstein of the Naval Research Laboratory.

* Construction and maintenance of the far infrared spectrograph used in this investigation was supported in part by Wright Air Development Center through a contract with The Ohio State University Research Foundation.

[1] Oetjen, Haynie, Ward, Hansler, Schauwecker, and Bell, J. Opt. Soc. Am. **42**, 559 (1952).
[2] H. Y. Fan and M. Becker, *Semiconducting Materials* (Academic Press, Inc., New York, 1951).
[3] H. Yoshinaga and R. A. Oetjen, Phys. Rev. (to be published).
[4] J. Strong, Phys. Rev. **38**, 1818 (1931).
[5] W. M. Sinton and W. C. Davis, J. Opt. Soc. Am. **44**, 503 (1954).

Hall Effect Noise

JAMES J. BROPHY AND NORMAN ROSTOKER
Armour Research Foundation of Illinois Institute of Technology, Chicago, Illinois

(Received July 29, 1955)

EXCESS noise, characterized by a noise power density with a $1/f$ spectrum, is the major form of electrical noise in semiconductors, particularly at low frequencies. It may be present in single-crystal semi-

conductor samples with "noiseless" electrodes and no obvious external discontinuities.[1] It has been suggested that the effect is caused by conductivity modulation of the semiconductor due to fluctuations in carrier density. We have undertaken to examine variations in carrier density in semiconductors exhibiting excess noise, through the use of the Hall effect.

Specimens used for this study are n-type single-crystal germanium, of approximately 10 ohm-centimeter resistivity. They were sandblasted into "bridges" similar to those used by Montgomery.[1] This shape is known to be most suitable for noise investigations as it eliminates effects of metallic probe electrodes in the current path. To increase the noise level of some samples, they were plastically deformed by bending in air at 600°C.

The excess noise observed in these specimens is found to have the usual $1/f$ spectrum of excess noise in the frequency interval studied, 1 cps to 10 kc/sec.

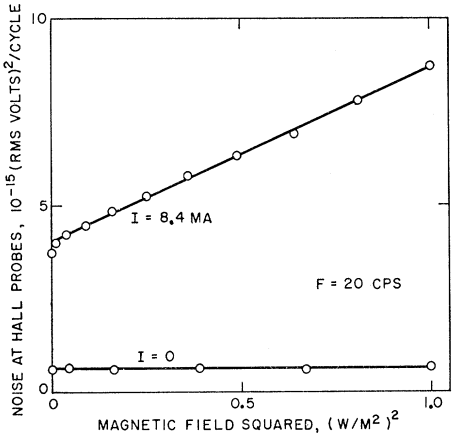

FIG. 1. Noise observed at the Hall probes as a function of magnetic field squared. The curve for $I=0$ represents amplifier noise. The intercept of the $I=8.4$ ma curve at $H=0$ is "unbalanced" noise. The linear variation of noise with H^2 should be noted.

A magnetic field of 1.0 weber/m^2 perpendicular to the plane of the sample and to the direction of current flow had a negligible effect on the magnitude and spectrum of the noise. It has been demonstrated experimentally that the noise was generated in the germanium and was not due to contacts.

To determine noise voltages at the Hall electrodes, the sample was placed between the pole pieces of an electromagnet supplied with current from a bank of storage cells. The noise voltages observed at a frequency of 20 cps are plotted in Fig. 1. The noise level for $I=0$ represents amplifier and thermal noise in the input circuit and illustrates that no noise is generated due to fluctuations in the magnetic field. With current passing through the sample, noise is observed at the probes at zero magnetic field. This is analogous to the usual "unbalance" voltage encountered in the Hall effect.

Additional noise is observed when the magnetic field is applied and the mean square noise voltage increases linearly with the square of the field, as shown in Fig. 1. This behavior is as expected in the Hall effect, and also shows that there is little correlation between the unbalance excess noise voltage and the Hall noise voltage, for if correlation existed the observed noise would have, in addition, a linear dependence upon field.

Residual current fluctuations may be expected also to contribute to noise at the Hall probes and this component would be difficult to distinguish from the Hall noise. We compute residual current fluctuations to be $\langle \Delta I^2 \rangle = 5\times10^{-21}$ amp^2/cycle under the conditions pertaining to Fig. 1. From the known Hall constant this contribution to noise at the Hall probes is of the order of 2×10^{-19} volt^2/cycle, much below the level observed. We conclude that the field-dependent noise voltage observed is truly Hall noise and may be interpreted in terms of carrier density fluctuations. The excess noise and the Hall noise may be represented by the following expressions in the frequency interval 1 cps to 10 kc/sec:

$$\langle \Delta V_I^2 \rangle = 7.3\times10^{-16} I^{2.2} f^{-1.0} \text{ volt}^2/\text{cycle},$$
$$\langle \Delta V_H^2 \rangle = 7.4\times10^{-16} I^{2.3} f^{-1.0} H^{2.0} \text{ volt}^2/\text{cycle},$$

where I is the sample current in milliamperes, f is the frequency, and H is the magnetic field in webers/m^2.

These noise voltages may be interpreted in terms of conductivity modulations caused by fluctuation in carrier density in the following manner. With zero magnetic field the potential is simply that due to the current, while the additional voltage with magnetic field is given by the usual Hall relation. The two potentials are thus:

$$V_I = RI \quad \text{and} \quad V_H = R_H IH/t, \tag{1}$$

where R is the sample resistance between probes, R_H is the Hall constant, and t is the sample thickness. If we ascribe fluctuations in these potentials to variations in

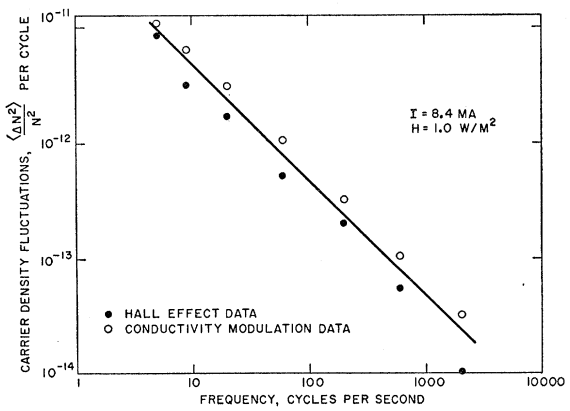

FIG. 2. Spectral density of carrier density fluctuations as a function of frequency as determined from excess noise measurements (open circles) and Hall noise (solid circles). The inverse frequency spectrum is clearly illustrated.

R and R_H caused by fluctuations in carrier density, n, it may be shown that on the basis of a simple, single-carrier model:

$$\langle \Delta V_I^2 \rangle = V_I^2(\langle \Delta n^2 \rangle / n^2) \quad \text{and} \quad \langle \Delta V_H^2 \rangle = V_H^2(\langle \Delta n^2 \rangle / n^2), \quad (2)$$

where V_I is the dc potential drop between the probes and V_H is the usual Hall voltage. It is convenient to treat the data in this manner, since all potentials are directly measurable and the results are independent of sample dimensions and calibration of the magnetic field. The quantities V_I and V_H were determined for the sample by standard techniques.

Carrier fluctuations calculated from Eqs. (2) are shown in Fig. 2. The agreement between the results is within the experimental errors of the present data. In particular, the carrier density fluctuations as directly measured by the Hall effect have the $1/f$ spectrum and the proper order of magnitude to account for excess noise. We believe that these results constitute the first proof that excess noise is a result of carrier density fluctuation.

[1] H. C. Montgomery, Bell System Tech. J. **31**, 950 (1952).

Scattering of Neutrons by Phonons in an Aluminum Single Crystal

B. N. Brockhouse and A. T. Stewart
Physics Division, Atomic Energy of Canada, Limited, Chalk River, Ontario, Canada
(Received August 29, 1955)

IT has long been realized[1] that the normal vibrational modes of a crystal could be determined from measurements of the energy distribution of coherently scattered neutrons. The basic theory of inelastic coherent scattering is largely due to Weinstock.[2] The neutron gains or loses energy corresponding to the annihilation or production of one or more phonons in the crystal. The zero-phonon process represents Bragg scattering. If this process is avoided by selecting the angular setting of the crystal, the one-phonon process can be dominant. The partial differential cross section for production of one phonon of the fth normal mode in a monoatomic crystal is[3]

$$G_1^f = \frac{\pi^2 \hbar \sigma_{\text{coh}}}{2MBN} \cdot \frac{[(\mathbf{k}-\mathbf{k}')\cdot\boldsymbol{\alpha}_f]^2}{\omega_f(1-x_f)} \frac{k'}{k} \times \exp(-2W_f^\tau) \cdot \delta(\mathbf{k}-\mathbf{k}'-2\pi\boldsymbol{\tau}+\mathbf{q}), \quad (1)$$

where $\mathbf{k}$ and $\mathbf{k}'$ are the initial and final neutron propagation vectors, ω_f is the phonon angular frequency, $\boldsymbol{\alpha}_f$ is the phonon unit polarization vector, $\boldsymbol{\tau}$ is a vector of the reciprocal lattice, $\mathbf{q}$ is the phonon wave vector, $x_f = \exp(-\hbar\omega_f/k_BT)$, N is the number of atoms in the crystal, B is the volume per atom, and M is the mass of the atom, and $\exp(-2W_f^\tau)$ is the Debye-Waller factor. The δ function in this expression represents the momentum conservation between neutron, phonon and crystal. In addition, the neutron-phonon system must conserve energy so that[4]

$$E' = \frac{\hbar^2 k'^2}{2m} = E - \hbar\omega_f = \frac{\hbar^2 k^2}{2m} - \hbar\omega_f. \quad (2)$$

When these energy and momentum conditions are simultaneously satisfied, neutrons are scattered with an intensity given by (1).

Since $\mathbf{q}$ is restricted to the zone around each reciprocal lattice point $\boldsymbol{\tau}$, this latter can be unambiguously

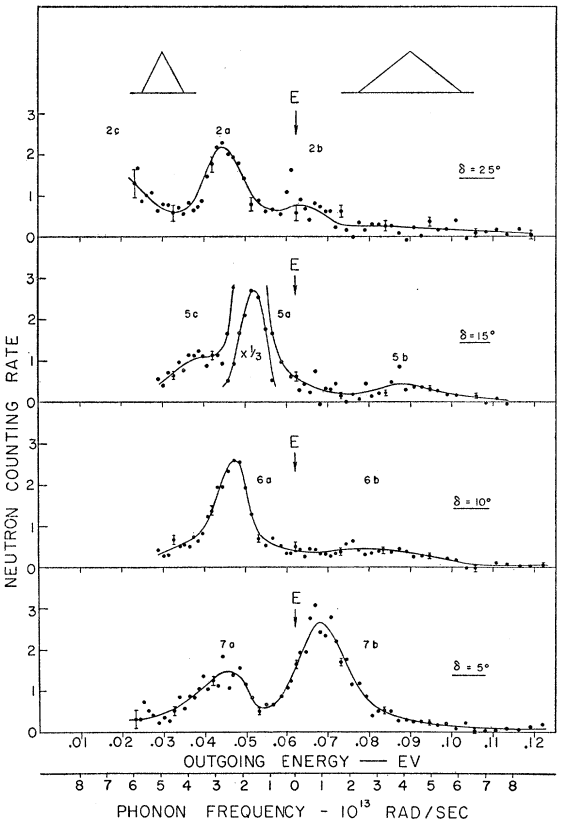

FIG. 1. Typical energy distributions of neutrons inelastically scattered by an aluminum single crystal and approximate resolution functions. The incident neutron energy E is indicated by the arrows.

assigned. Then the two conservation equations are sufficient to determine the angular frequency ω in terms of the phonon wave vector $\mathbf{q}$. For a monoatomic lattice $\omega(q)$ is expected to separate into three branches corresponding in the low-frequency limit to the longitudinal and two transverse polarizations of sound waves. In principle the directions of the polarization vectors, $\boldsymbol{\alpha}$, can be obtained by repeated observation of the same point in a zone of reciprocal space using different initial and final neutron momenta, and comparison of the intensities of the observed neutron groups with Eq. (1).