Spectral Distribution of the Photomagnetoelectric Effect in Ge: Experiment

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The photomagnetoelectric effect has been studied in germanium as a function of the wavelength of incident radiation in the region from 0.5 to 2.0 microns. The dependence of both photoconductivity and photomagnetoelectric (PME) response has been measured in various samples, using front and back surface recombination velocities and bulk recombination as parameters. It has been found that under certain conditions of bulk and surface recombination a reversal in sign for the PME response occurs over the frequency range studied. Sign reversals obtain at wavelength in the range from 1.55 to 1.85 microns, corresponding to partial optical transparency. The exact frequencies at which reversal occurs depend on the surface and bulk recombination rates, the condition being that the Dember field be zero corresponding to equal carrier concentrations on the front and back surfaces. Furthermore, the present observations are shown to be in good qualitative agreement with the theoretical work reported by Gärtner. Experimental procedures are described, and it is shown how this effect can be used to advantage in the study of surface recombination velocities in various environments.

1. INTRODUCTION

GÄRTNER[1] has recently developed a theory of the spectral distribution of the photomagnetoelectric (PME) effect and computed the PME short circuit current, the photoconductance, and the ratio PME short circuit current over photoconductance for germanium samples of various values of lifetime and surface recombination velocities. In particular, this theory describes falloff in response with increasing wavelength and predicts an actual sign reversal of the effect in a certain wavelength range if the front surface recombination is higher than the back surface recombination velocity. Previous workers have only superficially examined the frequency response of the PME effect, but have not observed the predicted sign reversal. The present work deals with the observation of this effect and related implications.

2. EXPERIMENTAL PROCEDURE

Light of a wavelength between 0.5 and 2.0 μ was obtained from an incandescent tungsten lamp with a Farrand double monochromator, calibrated for light intensity by a thermocouple and focused upon germanium samples of 0.7×2 cm^2 area and various thicknesses to the ends of which ohmic contacts were made by ultrasonic soldering.

Since the PME short circuit current I_x^{sc} rather than the open circuit voltage should be measured, a low impedance Perkin-Elmer breaker amplifier, synchronized at 7 cps to a rotating light chopper feeding into an amplifier, was used for current detection. In addition to the PME effect, the photoconductivity was also measured for the same surface recombination conditions by a modified Wheatstone Bridge using low bridge current. PME and photoconductivity measurements were made alternately in fast sequence by rapidly connecting the leads of the sample to the bridge circuit or to the current measuring apparatus by means of a thermo-free switch, eliminating errors by self-heating of the sample, thermo emf's at the metal contacts or changes in the ambient temperature.

The experimental samples were obtained from a single ingot of n-type 5.36 ohm-cm germanium, grown by the Czochralski method. In most cases, changes in surface recombination velocity were effected by starting with a surface freshly etched in CP-4 and abrading it slightly to increase the surface recombination just enough to be detectable in the spectral analysis. This treatment, however, did not affect the optical properties of the surface to any measurable extent. In all cases, the dark surface was etched for low surface recombination velocity. A variation of the bulk lifetime was simulated by normalizing the recombination factors, similar to Gärtner's relationships,[1] so that diffusion length and sample thickness occur as a ratio. Reducing the slab thickness then affects the PME response in the same manner as increasing the bulk lifetime.

All measurements were taken at fields of 2000 gauss; control measurements at lower fields confirmed that the effect did not deviate from a linear dependence on the magnetic field to a measurable extent in the range investigated.

3. EXPERIMENTAL RESULTS

The lifetime of the samples was previously determined to be 60 microseconds, leading to a diffusion length in this material of approximately 0.05 cm. Samples of three different thicknesses were investigated corresponding to approximately $10L$, $5L$, and L, where L is the diffusion length. Following the example of Gärtner, ΔG, I_x^{sc} and their ratio have been plotted versus the absorption coefficient rather than wavelength. The symbol, K, is represented by

$$K=kw,$$

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[1] Wolfgang W. Gärtner, Phys. Rev. 105, 823 (1957).

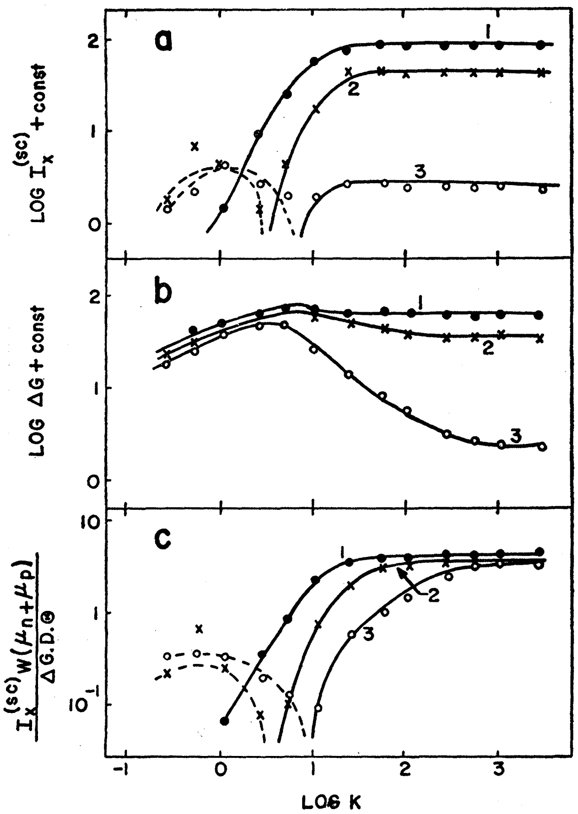

FIG. 1. Short-circuit PME current (a), photoconductance (b) (both normalized for light intensity), and their ratio, (c) as a function of normalized absorption coefficient for various values of surface recombination velocity (S) with (diffusion length $\ll$ sample thickness) $W\approx 10L$. If R=front surface S/dark surface S, we have for curve (1), $R=1$; curve (2), $R>1$; and curve (3), $R\gg 1$.

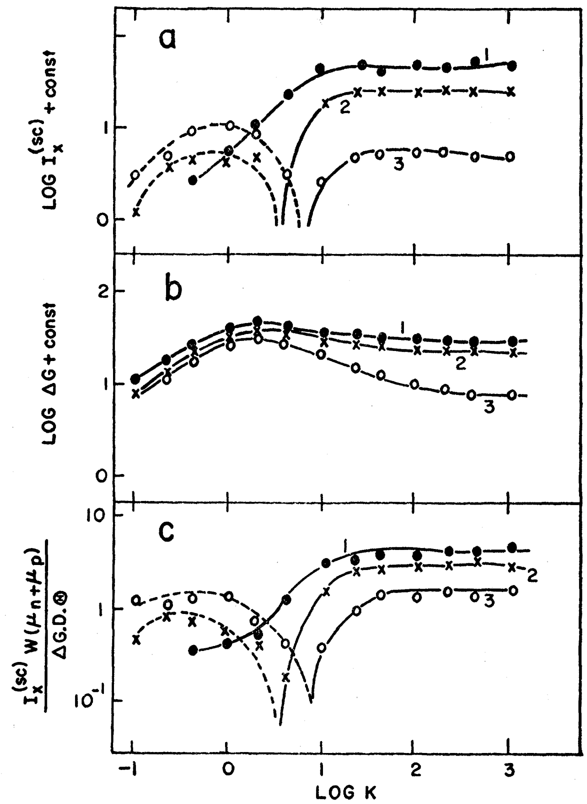

FIG. 2. Short-circuit PME current (a), photoconductance (b) (both normalized for light intensity) and their ratio, (c) as a function of normalized absorption coefficient for various values of surface recombination velocity with (diffusion length < sample thickness) $W\approx 4L$. If R=front surface S/dark surface S, we have for curve (1), $R=1$; curve (2), $R>1$; and curve (3), $R\gg 1$.

where k is the absorption coefficient[2] and w is the sample thickness. In terms of wavelength, for long $K=3$, $\lambda=1.5$ microns and for $K=1$, $\lambda=2$ microns.

In Fig. 1, we have plotted the results obtained on a sample whose thickness is 0.55 cm. Since lifetime for this material is about 60 microseconds, the ratio of sample thickness to diffusion length is 11. This implies that virtually all of the carriers generated at the front surface will recombine before they reach the dark surface. Three cases have been plotted. The curves labeled 1 correspond to a low surface recombination velocity (S) on both illuminated and dark surfaces. The second case represents a situation where the front surface recombination velocity is greater than the dark surface recombination velocity, and the third case corresponds to a much greater increase in front surface recombination velocity. Several interesting features are observed. The PME response undergoes an inversion in sign for cases 2 and 3 at some wavelength in the neighborhood of 1.8 microns. In these figures, the solid lines represent positive PME response and the dashed lines negative PME response. It is also noted that for increased front surface recombination velocity the sign reversal occurs at shorter wavelengths. In addition, the magnitude of both the PME response and the conductance change is decreased as the front surface recombination velocity is increased. Figure 1(c) indicates the ratio of the two effects multiplied by the factor $w[(\mu_n-\mu_p)/D]$ which was chosen to permit comparison with the equation for lifetime developed by van Roosbroeck[3] for thick samples

$$\tau=D[\theta\Delta G/(\mu_n+\mu_p)I_x^{sc}]^2,$$

where D is the diffusivity, θ is the sum of Hall angles, ΔG is the relative photoconductance change, I_x^{sc} is the PME short circuit current, and μ_n, μ_p are the electron, hole mobilities, respectively.

It will be noted that this factor is essentially a constant value for the case where the carrier generation is confined to the front surface which indicates the necessity of using light with wavelengths corresponding to high absorption for lifetime measurements.

In Fig. 2, we have plotted the same parameters under the condition that $w/L=4$. In this case, the bulk recom-

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[3] W. van Roosbroeck, Phys. Rev. 101, 1713 (1956). This article contains an excellent bibliography on the PME effect.

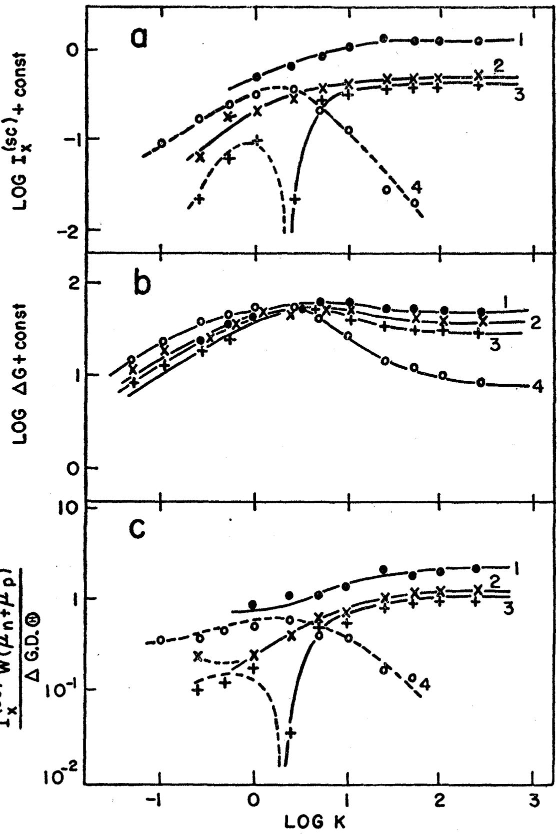

FIG. 3. Short-circuit PME current (a), photoconductance (b) (both normalized for light intensity), and their ratio, (c) as a function of normalized absorption coefficient for various values of surface recombination velocity with (diffusion length ≈ sample thickness) $W \approx L$. If R = front surface S/dark surface S, we have for curve (1), $R=1$; curve (2), $R>1$; curve (3), $R \gg 1$; and curve (4), R is very much greater than one.

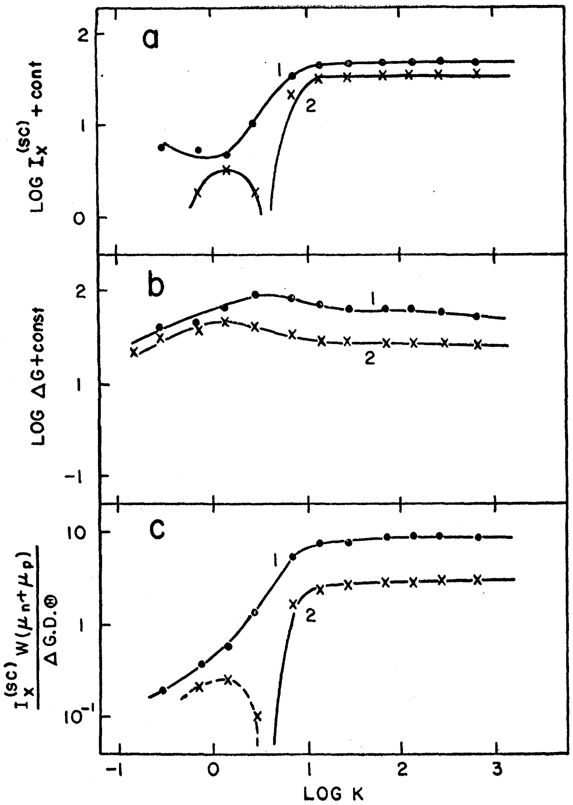

FIG. 4. Short-circuit PME current (a), photoconductance (b) (both normalized for light intensity), and their ratio, (c) as a function of normalized absorption coefficient to show effects of chemical treatment on the surface recombination velocities. Curve 1 illustrates conventional PME effect, Curve 2 results after front surface is exposed to HCl vapor.

bination, while still dominant for short wavelengths, is not as important as in the previous case. Again one notes the decrease in response as the front surface recombination velocity is increased, and the point of inversion shifts toward shorter wavelengths. In addition, the relative magnitudes of the PME response are reduced somewhat from the first case. This follows from the fact that the difference in excess carrier densities on the two surfaces (which determines the magnitude of the response) is reduced because more carriers reach the back surface than in the previous case. One also notes that compared to Fig. 1, the "lifetime factor" shows a deviation at short wavelengths for changes in front surface recombination velocity. This effect, of course, is related to the fact that the carriers generated at the front surface do not all recombine as they diffuse to the back surface and the expressions for photoconductance and PME short circuit can no longer be considered independent of the ratio of diffusion length to sample thickness.

Figure 3 illustrates the results for a "thin" sample where the ratio of diffusion length to sample thickness is almost unity. Again, the characteristic inversion is noted when the appropriate conditions of absorption coefficient and surface recombination velocities are satisfied. Curve 4 represents a case where the front surface recombination is so great that the response appears to remain negative over the entire spectrum. Actually, the inversion is shifted so far to the right that the positive response is never observed. It is also noted that the level of PME response is considerably lower than either of the two previous cases, again due to the fact that the excess carrier concentration on the front surface is only slightly different from that of the dark surface. On the other hand, one might have expected photoconductance to increase since this case corresponds to a long bulk lifetime. However, control of the surface recombination velocities to a degree sufficient to permit observation of this effect was not possible in these experiments. One, therefore, concludes that we have gone from one extreme to the other. In Fig. 1, the bulk lifetime is most important and the surface recombination velocity is secondary, except for curve 3 where S is making a major contribution. In Fig. 3, the situation is just the opposite; the bulk lifetime must now be

negligible compared to the surface recombination velocity but the relative response comparing Figs. 1 and 3 is the same. Fig. 2 represents an intermediate case. These findings are in good qualitative agreement with the theoretical predictions of Gärtner's theory.

In order to explore the possibility of utilizing the PME spectral dependence as a tool for investigating changes in surface recombination velocity, a specimen was freshly etched and measured. A stream of air, saturated with HCl vapor was allowed to impinge on the illuminated surface of the sample. The results are shown in Fig. 4. It is noted that after treatment (curve 2) an inversion typical of increased front surface recombination velocity occurs, which after rinsing with water reverts to the original condition (curve 1).

It seems reasonable to expect that this effect could be utilized to study the effects of different environments on surface recombination velocities. If experimental conditions are established so that the PME response is at a null point and an environment is introduced which alters the surface recombination velocity, the PME effect could register either a positive or negative signal depending on whether the environment increased or decreased the recombination effect.

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Galvanomagnetic and Thermomagnetic Potentials in Zinc at Liquid Helium Temperatures*

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The Hall effect, magnetoresistance, thermoelectric voltage, and transverse Ettingshausen-Nernst potential have been measured in a single crystal of zinc in the liquid helium temperature range. Oscillations as a function of magnetic field strength were observed in all of these potentials. The measured period in $1/H$ for the transverse oscillations was 6.2×10^{-5} gauss$^{-1}\pm0.5\%$, with the magnetic field parallel to the hexagonal axis. Both transverse effects possessed strong second harmonic oscillations. The oscillations in the longitudinal effects both exhibited a phase inversion in the neighborhood of 4.2 kgauss, the same field region for which the gross Hall field changed sign. In this same field region the period of the oscillations for the longitudinal effects was that of the second harmonic.

Empirical correlations between the reversal of sign of the Hall effect and: (1) the phase reversal of the magnetoresistance oscillations, (2) the strong second harmonic content of these oscillations in the region of the phase reversal, and (3) the quadratic shape of the envelope of the magnetoresistance oscillations in this region can be achieved by assuming the oscillatory component of σ_{21} to be much more significant than that of σ_{11}, where σ_{ik} is the conductivity tensor.

A further correlation between the oscillatory thermal effects can be achieved by assuming that the difference of the absolute thermoelectric power and the temperature derivative of the chemical potential is negligible.

I. INTRODUCTION

IN 1930 Schubnikow and de Haas[1] found that the transverse magnetoresistance of bismuth exhibited a magneto-oscillatory dependence at low temperatures. This led de Haas and van Alphen to their discovery of a similar behavior in the diamagnetic susceptibility of bismuth.[2] In recent years more attention has been given to the analogous oscillations in the galvanomagnetic and thermomagnetic effects in metals and semimetals such as Bi,[3–11] graphite,[12–15] Mg,[16] Sb,[17] Ga,[18] Sn.[19,20] Diamagnetic susceptibility oscillations in zinc were first observed by Marcus,[21] and later, the temperature dependence of the de Haas-van Alphen

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