Angular and Temperature-related Specific Features of the Interaction between Light and Heavy Holes in Weakly Doped p-Ge:Ga at Low Temperatures

A.I. Veinger, A.G. Zabrodskii, T.V. Tisnek, and S.I. Goloshchapov

Ioffe Physico-Technical Institute of the Russian Academy of Sciences, Politekhnicheskaya 26, St.Petersburg, 194021, Russia

The microwave low temperature magnetoresistivity of the low doped (nondegenerated) p-Ge was investigated with the use of the electron spin resonance technique. This technique permits to detect the derivative of the microwave absorption with respect to magnetic field and its change with this field. In our case, this change is proportional to the magnetoconductivity of the sample under investigation. Because of the averaging time of the effective masses of the light and heavy holes is much more then microwave frequency (10 GHz), this method permits to investigate the reaction of the each kind of the holes on the magnetic field separately. The experimental results are compared with the theory of the classical magnetoresistivity effect.

Keywords: Doped semiconductors, magnetoresistance, hole effective masses, low temperatures, electron spin resonance.

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INTRODUCTION

The magnetoresistive effect belongs to classical kinetic effects and has been rather long studied [1, 2]. However, it is still difficult to distinguish between the contributions of each kind of carriers to the observed effect in materials with degenerate bands and, in particular, p-Ge. Changes in the mobility of each kind of holes in a magnetic field can be separately studied by using microwave frequencies [3–6]. As shown in these studies, the averaging of the hole effective mass in weakly doped p-Ge at low temperatures occurs during a time longer than $10^{-10}$ s, i.e., during the characteristic energy dissipation time. Thus, measuring the microwave magnetoabsorption (MMA) at a frequency of 10 GHz by using the technique of electronic spin resonance (ESR) in p-Ge makes it possible to separate the responses of light and heavy holes to a magnetic field.

The ESR technique records the derivative of the MMA with respect to the magnetic field (dP/dH) and, according to the properties of the effect, the dependence of this derivative on the magnetic field H must show a minimum when the following relation between the field and the mobility $\mu$ is observed:

$$\mu H \approx 1.$$  (1)
Because of the presence of two kinds of holes in a p-Ge sample, the field dependence of the MMA must show two minima corresponding to the different mobilities of light and heavy holes [5]. Using relation (1), we can find, by analyzing the positions of these minima, the angular and temperature dependences of the mobilities of both light and heavy holes in p-Ge. In this communication, we present results of a study of this kind, carried out with weakly doped p-Ge samples rotated in two mutually perpendicular planes, (1 1 0) and (1 1 2). These results are compared with the existing classical theory of the magnetoresistive effect [2].

**EXPERIMENTAL RESULTS**

Microwave measurements were made on oriented p-Ge samples having the form of parallelepipeds with characteristic dimensions of 4×1×0.3 mm³, with a resistivity of about 10 Ω cm (ρ ≈ 3×10¹⁴ cm⁻³). The effect was observed at temperatures higher than 10 K, when strong thermal ionization of shallow Ga acceptors begins in Ge.

Figure 1 and 2 show experimental dependences of the derivative of MMA, (dP/dH), with respect to the magnetic field at several temperatures in relation to the angle φ between the magnetic field direction and the crystallographic axes. The angle φ was assumed to be zero when the second (strong-field) minimum related to heavy holes was found to be at the weakest field. It can be seen in the figures that the minima corresponding to light and heavy holes are, indeed, observed separately in the temperature range under study, as shown previously in [5]. In addition, it was found that the field dependences of the MMA are different when the samples are rotated in the (1 1 0) and (1 1 0) planes.

Upon a rotation by 90° in the (1 1 0) plane (Fig. 1), both the amplitude of the derivative of MMA and the position of the strong-field minimum of the derivative markedly change. At the same time, the position of the weak-field minimum remains nearly unchanged. It can be seen that, at high temperatures, the amplitude of the strong-field minimum decreases, whereas that of the weak-field minimum grows.

**FIGURE 1.** Field dependences of the magnetoabsorption at various angles between the magnetic field and the [110] direction in rotation in the (1 1 0) plane: (1) 0°, (2) 20°, (3) 40°, (4) 60°, and (5) 80°. Temperature T, K: (a) 20 and (b) 80.
Figure 2 shows the same dependences for a sample rotated in the \( (1\bar{1}2) \) plane at various temperatures. Comparison of Figs. 1 and 2 reveals the difference between the effects in the case of rotation in different planes. These are the substantially more pronounced changes in the position of the strong-field minimum corresponding to heavy holes upon rotation in the \( (1\bar{1}0) \) plane, compared with that in the \( (11\bar{2}) \) plane. It should also be noted that, in the case of rotation in the \( (1\bar{1}0) \) plane, the amplitude of the minimum related to heavy holes markedly decreases, whereas in rotation in the \( (11\bar{2}) \) plane, the decrease is on the order of 10%.

The difference between the field dependences of MMA in rotation in various planes is more visually illustrated by Fig. 3, which shows how the position of the minimum for heavy holes depends on the angle \( \phi \). The field at which the derivative of MMA is at a minimum depends not only on the rotation plane and angle \( \phi \), but also on temperature. At low temperatures, the fields of the minima become close at \( \phi = 90^\circ \), whereas at high temperatures at angles \( \phi \approx 90^\circ \) in rotation in the \( (1\bar{1}0) \) plane, the field of minimum in the derivative of MMA is always substantially lower than that for rotation in the \( (11\bar{2}) \) plane.

FIGURE 2. Field dependences of the MMA at various angles between the magnetic field and the [111] direction: (1) 0°, (2) 90° in rotation in the \((11\bar{2})\) plane. Temperature T, K: (a) 20 and (b) 80.

FIGURE 3. Dependence of the field of minimum in the derivative of MMA for heavy holes on the angle between the current flow direction and the [111] axis in the case of rotation in the \((11\bar{2})\) plane and between the current flow direction and the [001] axis in rotation in the \((1\bar{1}0)\) plane at various temperatures T, K: (a) 20, (b) 40, and (c) 60.
It should be noted here that, in rotation about the [1\bar{1}0] and [11\bar{2}] axes, the extreme values of fields of minima in the derivative of MMA correspond to different directions in the sample. In the (\bar{1}00) plane, the minimum value of this field corresponds to the [001] direction, and the maximum value, to the [110] direction; in the (11\bar{2}) plane, the minimum and maximum fields correspond to the [1\bar{1}0] and [111] directions, respectively. It follows from Figs. 1 and 2 that the position of the minimum related to light holes remains unchanged when the sample is rotated.

Thus, the angular and temperature dependences of MMA, related to light and heavy holes, are found to be rather complex.

**DISCUSSION**

The theory of the anisotropic magnetoresistive effect, which relates the effect to the anisotropy of hole effective masses, can be found in the monograph [2]. The effective mass is largest when the current is directed along one of the [001] axes. Along the [110] and [112] axes, the same intermediate value coinciding.

Let us consider how a change in the effective mass affects the measured MMA effect. The MMA is mostly affected by the transverse magnetoresistive effect. Therefore, if a sample is rotated in the (1\bar{1}0) plane, the lowest value of the field of minimum must be observed when the field is directed along the [110] axis. In this case, the current making the largest contribution to the MMA flows along the [001] axis, in which direction the effective mass is the smallest. Upon a rotation by 90°, the [110] axis with a large effective mass becomes perpendicular to the field direction. Accordingly, the field at which the derivative is at a minimum shifts to stronger fields. This behavior can be seen in Figs. 1 and 3. However, the maximum field of minimum must be observed when the field is perpendicular to [111], the direction constituting an angle of about 55° with the [001] axis and an angle of about 35° with the [110] axis. The absence of a maximum of this kind indicates that the scattering anisotropy makes a significant contribution to the anisotropy of MMA.

When the sample is rotated in the (11\bar{2}) plane, the effective mass of heavy holes must change from values corresponding to the [1\bar{1}0] current flow direction to those corresponding to the [111] current direction. In this case, the effective mass varies within a narrow range around its largest value. And just this behavior is observed in Figs. 2 and 3, in which the field of minimum remains high at any direction of the current in this plane. Thus, in the case of rotation about the mutually perpendicular [1\bar{1}0] and [11\bar{2}] axes, the extreme values of the minima in the derivative of MMA are observed at different directions in the sample.

The complex nature of the momentum scattering and the angular dependence of the effective mass at low temperatures hinder an exact analytical description of the behavior of the derivative of MMA. However, the experimental angular dependences make it possible to obtain, by means of fitting, rather adequate curves describing the low-temperature dependence of the minimum of the derivative of MMA in rotation in the (1\bar{1}0) plane. It can be seen in Fig. 3 that the dependence must be sinusoidal with a
period of 180°. With the designations $H_{[110]} = H_{\text{min}}$ and $H_{[001]} = H_{\text{max}}$, we, by analogy with [2], represent the angular dependence of the field of minimum, $H_{\text{min}}(\phi)$, as

$$H_{\text{min}}(\phi) = H_{\text{min}} + (H_{\text{max}} - H_{\text{min}}) \sin^n \phi,$$

where the exponent $n$ is the fitting parameter.

The calculated values of such dependences of the field for temperatures of 20 and 40 K are represented by the curves in Figs. 3a and 3b, respectively. It can be seen that these curves are in satisfactory agreement with the experimental points at an exponent $n = 4$ for $T = 20$ K and $n = 8$ for $T = 40$ K. The decrease in the exponent on lowering the temperature is in qualitative agreement with the fact that the time of momentum scattering is more strongly affected by the scattering on ionized impurities.

Let us consider the temperature dependences of the positions of minima in the derivative of MMA in the $(\bar{1} 1 0)$ and $(1 1 2)$ planes. The dependences are shown in Fig. 4 in the log–log scale. It can be seen that, in accordance with the power-law temperature dependences of the mobility, the temperature dependences of the minimum in the derivative of MMA, indeed, have the form of straight line portions. There are, however, a number of specific features that make it possible to judge about interaction modification of light and heavy holes with temperature.

It should be noted in the first place that, for heavy holes and the current flowing in the $(\bar{1} 1 0)$ plane in the [110] direction (magnetic field is directed at an angle of 90° to the [110] axis), the dependence differs from that of a power-law type. In this case, the position of the minimum strongly depends on temperature. This indicates that, for the current flowing in this direction, the scattering mechanisms at low and high temperatures are different.

The rest of the dependences (for light and heavy holes in other directions and planes) are, as noted above, of the power-law type. At temperatures lower than 30 K, they are proportional to $T^{1/2}$, which points to the prevalent scattering on acoustic phonons. In this temperature range, intersubband transitions little affect the mobility of heavy and light holes, and the temperature dependences in Fig. 4 are nearly parallel.
However, at temperatures higher than 30 K, the curves for light and heavy holes start to gradually become closer, which reflects the enhancement of scattering between the subbands of light and heavy holes.

In other words, there occurs stronger mixing of light and heavy holes. As a result, the average mass of light holes increases and that of heavy holes decreases. At high temperatures the field of minimum in the derivative of MMA even decreases. The strong-field minimum approaches the weak-field minimum because the effective masses of heavy and light holes are averaged during a time that is substantially shorter than $10^{-10}$ s, the period of the microwave oscillations we used. This corresponds to the well-known fact: at high temperatures the mobility in the hole system of p-Ge, manifested in the magnetoresistive effect is close to that of light holes.

**CONCLUSIONS**

A study of the angular and temperature dependences of the microwave magnetic-field-dependent absorption in lightly doped p-Ge revealed a number of interesting specific features associated with the band degeneracy.

1. The anisotropy of the MMA by holes in a magnetic field is determined by the anisotropy of their mobility.
2. The anisotropy of heavy holes mobility at low temperatures ($10 K \leq T \leq 30 K$) is determined both by the anisotropy of the effective mass and by the anisotropy of momentum scattering.
3. The averaging time of the effective masses of light and heavy holes in the temperature range $10 K \leq T \leq 30 K$ substantially exceeds $10^{-10}$ s. Therefore, it is not manifested in the field and temperature dependences of the MMA.
4. The interparticle interaction becomes more pronounced with increasing temperature. The effect of the interaction between holes gradually becomes noticeable at temperatures higher than 30 K.

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