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Negative photomagnetoconductivity in thin semiconductor films

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Abstract. The conductivity of an extrinsic semiconductor sample subjected to a magnetic field can be reduced by illumination. This unusual situation occurs when the importance of the emerging mixed magnetoresistance balances the increase in free carriers. An analytical model is proposed together with a discussion of the optimum conditions to obtain a negative photomagnetoconductivity. The model is experimentally verified using n-type GaAs and InSb epitaxial films.

1. Introduction

Photoconductivity, Hall effect and magnetoresistance experiments are of great concern for the evaluation of semiconductor materials. It is well known that the resistivity is reduced by illuminating the sample and enhanced by applying a magnetic field. The aim of this paper is to demonstrate that the combination of these two effects can cause an unusual situation to occur: the electrical conductivity of a semiconductor submitted to a magnetic field can be reduced by illumination. This *negative* photomagnetoconductivity (PMC) is in fact due to the competitive implications of photo-injected carriers in extrinsic semiconductors; firstly, the conductivity is increased normally and, secondly, the material status is modified from monopolar to mixed conduction. As the magnetoresistance is much higher in nearly intrinsic semiconductors than in extrinsic ones (Lakeou *et al* 1977), the negative PMC will occur as soon as this additional magnetoresistance overtakes the excess photoconductivity.

2. Model

The quantitative analysis proceeds from the basic transport equations. We consider a homogeneous sample submitted to a transverse magnetic field B. The total magnetoconductivity σ_B in the dark is readily obtained by mixing the contributions of electrons and holes (Lakeou 1977, Cristoloveanu and Kang 1984):

$$\sigma_B = e(n_0\mu_n + p_0\mu_p)(1 + \mu_H^{*2}B^2) \tag{1}$$

with

$$\mu_H^* = (p_0\mu_p\mu_{Hp} - n_0\mu_n\mu_{Hn})(n_0\mu_n + p_0\mu_p)^{-1} \tag{2}$$

where n_0 and p_0 are equilibrium concentrations for electrons and holes, while μ_n, μ_p and μ_{Hn}, μ_{Hp} are their drift and Hall mobilities. These mobilities are functions of scattering mechanisms and magnetic field B:

$$\mu = \langle\mu(\varepsilon)/[1 + \mu^2(\varepsilon)B^2]\rangle \qquad \mu_H = \mu^{-1}\langle\mu^2(\varepsilon)/[1 + \mu^2(\varepsilon)B^2]\rangle \tag{3}$$

where $\mu(\varepsilon)$ is the microscopic mobility for electrons or holes and the angular brackets represent the usual averaging over energy (Cristoloveanu and Viktorovitch 1977, Kireev 1975).

Under homogeneous and intrinsic photogeneration, both carrier concentrations are increased, at each point along the sample, by $\Delta n = \Delta p$. Simple analysis of equation (2) shows that the ambipolar Hall mobility μ_H^* has a monotonous variation with Δn. In a p-type semiconductor, μ_H^* decreases from the extrinsic value μ_{Hp} to the intrinsic Hall mobility μ_{Hi}^*, given by equation (2) with $n_0 = p_0$. In a n-type semiconductor, μ_H^* is always negative and increases from $-\mu_{Hn}$ to μ_{Hi}^*, since $-\mu_{Hn} < \mu_{Hi}^* < 0 < \mu_{Hp}$. Note that, as the magnetic field increases, μ_{Hi}^* tends to zero or, in other words, the Hall field vanishes in the sample. In fact, μ_H^* and therefore the Hall effect is almost always reduced in magnitude under illumination. The only exception arises when light causes the sign of μ_H^* to change and this rare situation requires three simultaneous conditions:

(i) a p-type semiconductor,
(ii) a large photogeneration rate and
(iii) low magnetic fields.

The PMC value $\Delta\sigma_B$ is found by taking the difference between the magnetoconductivities under illumination and in darkness (equation (1)):

$$\begin{aligned}\Delta\sigma_B = {} & e\,\Delta n(\mu_n + \mu_p)(1 + \mu_{Hi}^{*2}B^2) \\ & - e\,\Delta n(p_0 - n_0)^2(\mu_{Hn} + \mu_{Hp})^2\mu_n^2\mu_p^2B^2/(n_0\mu_n + p_0\mu_p)^2(\mu_n + \mu_p) \\ & \times [1 + (\mu_n + \mu_p)\Delta n/(n_0\mu_n + p_0\mu_p)]^{-1}.\end{aligned} \tag{4}$$

The first term in equation (4) gives the pure photoconductivity of *injected carriers*, i.e. the conductivity of an imaginary intrinsic semiconductor having $\Delta n = \Delta p$ carriers. The second term illustrates the *coupling* between equilibrium and excess carriers. The negative sign results from the reduction of the Hall field by photogenerated carriers which in turn involves enhanced magnetoresistance. A negative PMC effect can be achieved if this term predominates. However, this coupling does not exist either for $B = 0$ or in *intrinsic* semiconductors where the Hall field cannot be varied by photoexcitation. It has indeed been proved for semi-insulating GaAs that the magnetoresistance is several times higher under illumination than in the dark (Cristoloveanu and Kang 1984). In that case, however, Δn greatly exceeds equilibrium concentrations, so that the first term in equation (4) is prevailing and no negative PMC is observed.

Better candidates for negative PMC are thin extrinsic films where carrier generation occurs across the whole thickness at low rates. For instance, in an n-type film ($p_0 \ll \Delta n \ll n_0$), equation (4) simplifies to

$$\Delta\sigma_B = e\langle\Delta n\rangle_B(\mu_n + \mu_p)(1 + \mu_{Hi}^{*2}B^2) - e\langle\Delta n\rangle_B\mu_p^2 B^2(\mu_{Hn} + \mu_{Hp})^2/(\mu_n + \mu_p) \quad (5)$$

where $\langle\Delta n\rangle_B$ is the average of the excess concentration across the film depth. Equation (5) includes, therefore, the case of inhomogeneous carrier distribution along the depth of the film due to the non-uniform light absorption, surface recombinations and deflection induced by the magnetic field (Kang and Cristoloveanu 1984). This profile depends on the diffusion length which is also a function of B. The normalisation of $\Delta\sigma_B$ by the excess photoconductivity $\Delta\sigma_0$ at $B = 0$ gives

$$\Delta\sigma_B/\Delta\sigma_0 = (\langle\Delta n\rangle_B/\langle\Delta n\rangle_0)[(\mu_n + \mu_p)/(\mu_{n0} + \mu_{p0})](1 + \mu_{Hi}^{*2}B^2) \times \{1 - [\mu_p^2 B^2/(1 + \mu_{Hi}^{*2}B^2)][(\mu_{Hn} + \mu_{Hp})^2/(\mu_n + \mu_p)^2]\}. \quad (6)$$

A further simplification is obtained by using in equation (3) the very reasonable approximation of monokinetic carriers: $\mu = \mu_0/(1 + \mu_0^2 B^2)$ and $\mu_H = \mu_0$ for electrons and holes, μ_0 being the carrier mobility for $B = 0$. In this case, the intrinsic Hall mobility becomes

$$\mu_{Hi}^* = (\mu_{p0} - \mu_{n0})/(1 + \mu_{n0}\mu_{p0}B^2) \quad (7)$$

and equation (6) may be rewritten as

$$\Delta\sigma_B/\Delta\sigma_0 = (\langle\Delta n\rangle_B/\langle\Delta n\rangle_0)[(1 - \mu_{n0}\mu_{p0}B^2)/(1 + \mu_{p0}^2 B^2)] \quad (8a)$$

for n-type semiconductors.

Figure 1(*a*) clearly shows the progressive decrease in $\Delta\sigma_B/\Delta\sigma_0$ with B in various n-type semiconductor films. The coupling term of equation (5) increases with increasing B and leads, finally, to a negative PMC value ($\Delta\sigma_B \leq 0$). The effect is accentuated for higher carrier mobilities and is strongly correlated with the increase in the magnetoresistance under illumination (figure 1(*b*)). These curves have been simulated using the monokinetic approximation and accurate carrier profile calculations (Kang and Cristoloveanu 1984). The film was assumed to be 1.5 μm thick and provided with low recombination velocities at both surfaces. Further calculations demonstrate that by increasing the surface recombination rates the number of minority carriers becomes insignificant in these thin films and the photomagnetoresistance decreases towards the dark value.

In figure 2 is presented the case of n-type semiconductors with higher carrier mobilities. A negative PMC effect can now be achieved with much lower magnetic fields (below 3 T).

Equations (5)–(8) can be immediately adapted for p-type semiconductors by changing the roles of μ_{n0} and μ_{p0}. Thus,

$$\Delta\sigma_B/\Delta\sigma_0 = (\langle\Delta n\rangle_B/\langle\Delta n\rangle_0)[(1 - \mu_{n0}\mu_{p0}B^2)/(1 + \mu_{n0}^2 B^2)]. \quad (8b)$$

Equation (8) suggests that, at high magnetic fields, if quantum effects are neglected, the PMC *saturates towards a negative value.* The difference between donor-doped and acceptor-doped semiconductors is illustrated in figure 3. In an n-type film the saturation value (about $-\mu_{n0}/\mu_{p0}$) appears at higher magnetic fields and is more negative than in p-type films (about $-\mu_{p0}/\mu_{n0}$). We conclude that n-type semiconductors have to be selected in order to make easier the observation of the negative PMC effect.

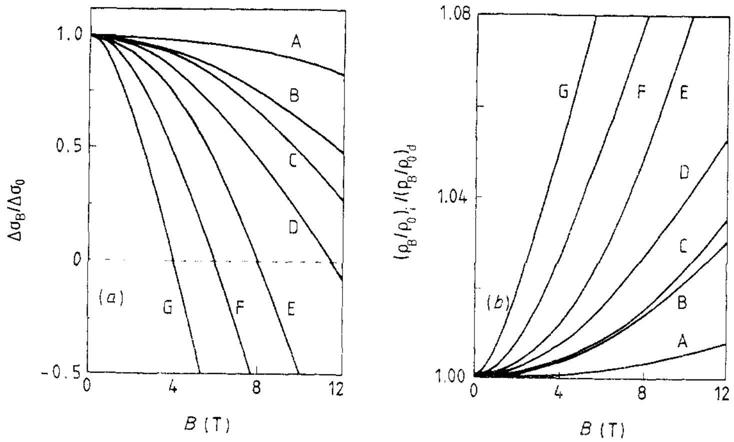

Figure 1. (*a*) Normalised PMC $\Delta\sigma_B/\Delta\sigma_0$ and (*b*) the ratio $(\rho_B/\rho_0)_i/(\rho_B/\rho_0)_d$ of the magnetoresistance under illumination to that in darkness against the magnetic field B, for semiconductors with relatively low carrier mobilities (curves A–C), silicon (curves D–F) and germanium (curves G) (T = 300 K; film thickness, 1.5 μm; photon flux, 10^{23} m^{-2} s^{-1}; absorption coefficient, 8×10^6 m^{-1}; lifetime, 10 ns; recombination velocities, 10 m s^{-1}): curves A, μ_{n0} = 0.1 m^2 V^{-1} s^{-1}, μ_{p0} = 0.01 m^2 V^{-1} s^{-1}; curves B, μ_{n0} = 0.1 m^2 V^{-1} s^{-1}, μ_{p0} = 0.03 m^2 V^{-1} s^{-1}; curves C, μ_{n0} = 0.5 m^2 V^{-1} s^{-1}, μ_{p0} = 0.01 m^2 V^{-1} s^{-1}; curves D, μ_{n0} = 0.15 m^2 V^{-1} s^{-1}, μ_{p0} = 0.05 m^2 V^{-1} s^{-1}; curves E, μ_{n0} = 0.5 m^2 V^{-1} s^{-1}, μ_{p0} = 0.03 m^2 V^{-1} s^{-1}; curves F, μ_{n0} = 0.3 m^2 V^{-1} s^{-1}, μ_{p0} = 0.1 m^2 V^{-1} s^{-1}; curves G, μ_{n0} = 0.38 m^2 V^{-1} s^{-1}, μ_{p0} = 0.18 m^2 V^{-1} s^{-1}.

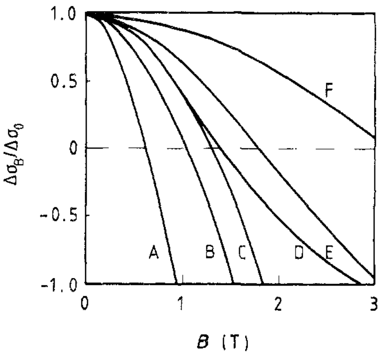

Figure 2. Normalised PMC $\Delta\sigma_B/\Delta\sigma_0$ against the magnetic field B for InSb (curve C) and other semiconductors with high carrier mobilities: curve A, μ_{n0} = 5 m^2 V^{-1} s^{-1}, μ_{p0} = 0.5 m^2 V^{-1} s^{-1}; curve B, μ_{n0} = 3 m^2 V^{-1} s^{-1}, μ_{p0} = 0.3 m^2 V^{-1} s^{-1}; curve C, μ_{n0} = 7.8 m^2 V^{-1} s^{-1}, μ_{p0} = 0.075 m^2 V^{-1} s^{-1}; curve D, μ_{n0} = 1 m^2 V^{-1} s^{-1}, μ_{p0} = 0.5 m^2 V^{-1} s^{-1}; curve E, μ_{n0} = 1 m^2 V^{-1} s^{-1}, μ_{p0} = 0.3 m^2 V^{-1} s^{-1}; curve F, μ_{n0} = 1 m^2 V^{-1} s^{-1}, μ_{p0} = 0.1 m^2 V^{-1} s^{-1}.

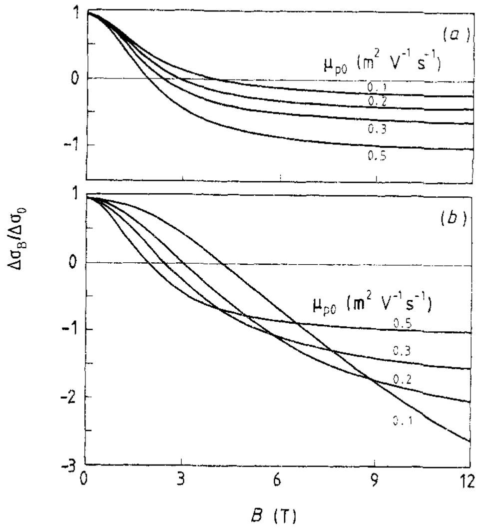

Figure 3. Saturation of the normalised PMC $\Delta\sigma_B/\Delta\sigma_0$ with magnetic field B in (*a*) p-type and (*b*) n-type semiconductor films. The simulation was conducted with an electron mobility μ_{n0} of 0.5 m^2 V^{-1} s^{-1} and the hole mobility μ_{p0} as a further parameter.

Not only do the reduced equations (8) give a very easy description of the effect but also they indicate that negative PMC can be expected above a critical magnetic field $B_c = (\mu_{n0}\mu_{p0})^{-0.5}$, which does not depend on the type of the film doping.

3. Experiment

The above model has been verified using tin-doped ($n_0 = 10^{16}$–10^{17} cm^{-3}) GaAs films 1.5 μm thick deposited epitaxially on semi-insulating GaAs. Bridge-type devices provided with diffused Ohmic contacts were isolated by mesa etching. Vertical photoexcitation was produced by an argon laser ($\lambda = 514.5$ nm) by controlling the power, thus limiting the excess photoconductivity ($\Delta\sigma_0/\sigma_d \leqslant 10\%$). Very small currents were used to avoid the field-assisted photomagneto-electric (PME) effect which consists of a significant modification of the vertical profile of photogenerated carriers when strong Lorentz forces are applied (Kang and Cristoloveanu 1984). The magnetic field was applied perpendicularly to both the current and the photon flux. The facility for high magnetic fields was provided by the Service National des Champs Intenses (Grenoble). The longitudinal voltages measured at $\pm B$ were averaged in order to eliminate the reminiscent PME effect due to the simple 'rotation' of diffusion currents by the Lorentz force (Aigrain and Bulliard 1953, Lile 1973). Further averaging was made by changing the current direction as well. The experiment was carried out at room temperature.

From an experimental point of view, it is more convenient to measure the normalised magnetoresistance $(\rho_B/\rho_0)_i$ under illumination and the normalised magnetoresistance $(\rho_B/\rho_0)_d$ in darkness:

$$[(\rho_B/\rho_0)_i/(\rho_B/\rho_0)_d] = [(\sigma_d + \Delta\sigma_0)/(\sigma_B + \Delta\sigma_B)](\sigma_B/\sigma_d)$$
$$= (1 + \Delta\sigma_0/\sigma_d)/(1 + \Delta\sigma_B/\sigma_B) \tag{9}$$

where $\sigma_d = en_0\mu_{n0}$ is the sample conductivity in darkness for $B = 0$. The value of the normalised PMC is, therefore, given by

$$\Delta\sigma_B/\Delta\sigma_0 = [1 + \Delta\sigma_0/\sigma_d - (\rho_B/\rho_0)_i/(\rho_B/\rho_0)_d][(\Delta\sigma_0/\sigma_d)(\rho_B/\rho_0)_i]^{-1}. \tag{10}$$

The experimental variation in $\Delta\sigma_B/\Delta\sigma_0$ against field is shown in figure 4(*a*) for two different samples. The higher the electron mobility, the more pronounced is the decrease in the excess photoconductivity with increasing B. Good agreement is found by simulation using the transport and recombination parameters deduced from Hall effect and field-assisted PME effect (Kang and Cristoloveanu 1984). The adjustable parameter was the hole mobility only.

As the carrier mobility in GaAs is still too low for a negative PMC to be observed, the experiment was repeated in two-terminal bars made on n-type ($n_0 \simeq 10^{17}$ cm^{-3}) InSb films 1 μm thick. As illustrated in figure 4(*b*), a rapid decrease in $\Delta\sigma_B/\Delta\sigma_0$ is now found owing to both the pre-factor in equation (6) and the coupling term. Taking into account the very low mobility of holes in InSb and neglecting the difference between $\langle\Delta n\rangle_B$ and $\langle\Delta n\rangle_0$, we have from equation (8*a*)

$$\Delta\sigma_B/\Delta\sigma_0 \simeq 1 - \mu_{n0}\mu_{p0}B^2. \tag{11}$$

Slight negative values are obtained above $B = 1.7$ T. In addition, the simplified equation (11) provides a reasonable fit for the experiment, from which the carrier mobilities are deduced ($\mu_{n0} \simeq 3$ m^2 V^{-1} s^{-1} and $\mu_{p0} \simeq 0.1$ m^2 V^{-1} s^{-1}).

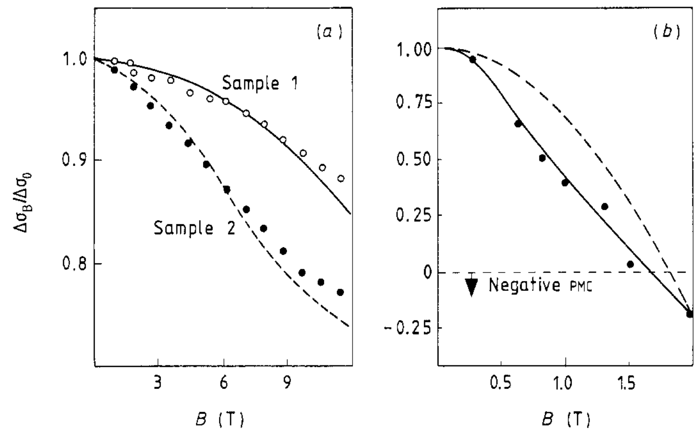

Figure 4. Experimental values of the normalised PMC $\Delta\sigma_B/\Delta\sigma_0$ against the magnetic field B in thin n-type (*a*) GaAs and (*b*) InSb films at room temperature. The simulated curves were calculated for GaAs using equation (6), experimental values of μ_{n0} (about 0.35 $m^2\,V^{-1}\,s^{-1}$ (Kang and Cristoloveanu 1984)), adjustable values of μ_{p0} (about 0.003 $m^2\,V^{-1}\,s^{-1}$) and the other parameters in figure 1. The simulation for InSb (---) was made using the simplified equations (11) and $\mu_{n0} = 3\ m^2\,V^{-1}\,s^{-1}$ and $\mu_{p0} = 0.1\ m^2\,V^{-1}\,s^{-1}$.

4. Conclusion

The major equations and the theoretical aspects related to the PMC have been derived. The PMC always decreases on increasing the magnetic field. We have demonstrated that a negative PMC value can be observed experimentally. This requires, however, a tight control of those parameters which limit the photoconductivity at $B = 0$ to a few per cent and simultaneously allow significant magnetoresistance. Small values of the excess photoconductivity are obtained using reduced illumination rates and selecting semiconductor materials with a low carrier lifetime or high surface recombination velocities. As semi-insulating or near-intrinsic semiconductors are not convenient candidates for negative PMC, we propose the use of semiconductor films which have to be thin, moderately doped and n type. In addition, high magnetoresistance requires either high carrier mobilities or the application of strong magnetic fields. From a practical point of view, the negative PMC effect offers the opportunity to determine both carrier mobilities in thin semiconductor films using only two-terminal bars, i.e. without any Hall effect measurement.

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