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Interactions of optically generated space-charge waves with magnetic fields in semi-insulating InP:Fe single crystals

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We report on the interaction of optically generated space-charge waves (SCWs) with magnetic fields with semiinsulating InP:Fe single crystals as an example. Variations of the SCW amplitude as a function of the applied magnetic field are revealed and uncover a quadratic dependence. The phenomenon strongly depends on the magnetic field direction. These results give strong evidence for a major contribution of the magnetoresistance to the discovered effect. Hence, SCW measurements in a magnetic field provide a precise tool for investigations of the magnetoresistance. Key advantages for purposes of material analysis are discussed.

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Investigations of space-charge waves (SCWs) in high resistive semiconductors are a powerful tool for the characterization of material properties and for general aspects of wave processes (both linear and nonlinear) in solids. SCW investigations are well known for photorefractive crystals with sillenite structure,[1,2] and there are only very few publications concerning "classical" semiconductors [see, for instance, Ref. 3 (InP:Fe) or Ref. 4 (CdTe:Ge)]. There are also few publications concerning investigations of hologram recording at the presence of a magnetic field (see, for instance, Ref. 5), or the interaction of nonsteady state photocurrents in photorefractive materials with a magnetic field.[6,7] The latter are related to the problem of the interaction of the current excited by the interference light pattern with a magnetic field. To our knowledge there are no publications devoted to investigations on the interaction of SCW with magnetic fields.

In this paper we present the results of SCW investigations in InP:Fe under magnetic fields. The specific type of SCW called trap recharging waves[8] has been studied. A distinct interaction of SCW with magnetic fields is discovered and the detected effects are unambiguously related to the magnetoresistance of the sample. Prospects of these results, particularly for investigations of the magnetoresistance and screening effects in semiconductors, are discussed.

The experimental setup and samples for our investigations are chosen as described in Ref. 3. Here, an electromagnet with a proper holder for the sample between the pole shoes of the magnet was added as shown in Fig. 1. The size of the InP:Fe sample was $4 \times 7 \times 0.5$ mm^3. Gold electrodes were deposited on the surface of the sample with a distance of $L = 4$ mm to apply an electric field.

Optical excitation of SCW was provided by illumination of the crystal with an oscillating interference pattern. Oscillation was realized by phase modulation of one of the illuminating laser beams (argon ion laser, $\lambda = 514$ nm) with frequency Ω and amplitude Θ. Signal detection was performed by measuring the ac current arising in the outside circuit due to SCW spatial rectification inside the sample. Resonant SCW excitation occurs when Ω is equal to the eigenfrequency of the corresponding SCW. The optical excitation and electrical detection of SCW are described in more detail in Refs. 1, 3, and 4.

Figure 2 shows the normalized alternating current (ac) amplitude $I(\Omega)$ as a function of the modulation frequency Ω without and with magnetic field ($B = 0.86$ T at the sample position), respectively. We note that the detected signal is proportional to the amplitude of the SCW. The signal maximum near $f = \Omega / 2\pi = 5$ kHz indicates that resonant excitation of SCW occurs. Obviously, a reduction in the signal amplitude at resonance occurs, if a magnetic field is applied. Although this reduction is less than 10%, this result is well reproducible because of the high signal-to-noise ratio at the resonance frequency. All measurements were made after short-circuiting the sample eliminating charge storage at the contact areas. In these experiments, magnetic and electric fields were chosen orthogonal to each other. An influence of the magnetic field on the SCW for a direction of B and E parallel to each other was not detected.

To verify the influence of the magnetic field on the SCW

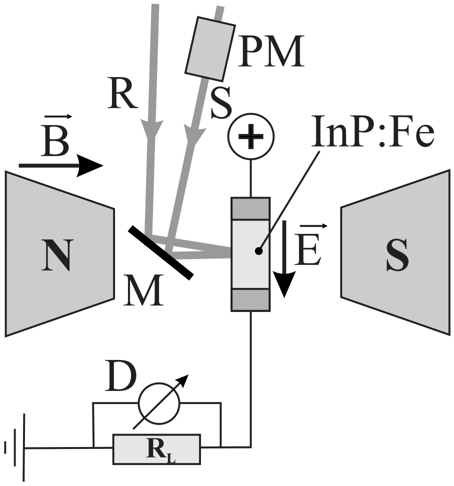

FIG. 1. Experimental setup (schematically); R: reference beam, S: signal beam modulated via the phase modulator PM, M: mirror, and R_L: loading resistor, D: detection system including lock-in amplifier.

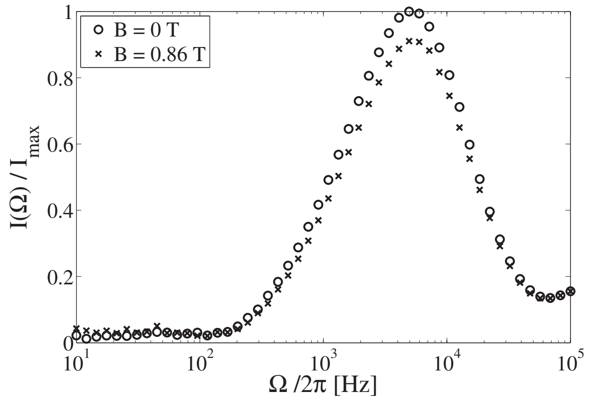

FIG. 2. Frequency dependence of the ac amplitude for a light intensity of $W_0=50$ mW/cm^2, $K=6.9\times10^3$ cm^{-1}, $E_0=4.0$ kV/cm without and with magnetic field ($B=0.86$ T at the sample position), respectively.

amplitude, the degree of signal reduction was investigated as a function of the magnetic field strength. Figure 3 shows that the relative change of the current amplitude $\Delta I^B/I^0$ increases as a function of the applied magnetic field. Here, $\Delta I^B=(I^B-I^0)$ and I^B and I^0 are the output signals at the resonance frequency with a magnetic field of magnitude B or $B=0$, respectively. The experimental values of ΔI^B are negative and the dependence of $\Delta I^B/I^0$ on B remarkably uncovers a quadratic character.

A second characteristic dependence was found by investigating $\Delta I^B/I^0$ as a function of the wave number K of the excited SCW at constant B. Here, $K=2\pi/\Lambda$ and Λ is the SCW spatial period. The value of $\Delta I^B/I^0$ diminishes approximately by a factor of two when K is varied from 1.5×10^3 to 15×10^3 cm^{-1} and $B=0.86$ T at the sample. We did not find a definite shift of the resonance frequency due to the magnetic field. It might be, that it is because the resonance profile is rather broad and we did not have a resolution which is high enough to detect a small frequency shift.

We will now discuss the origin of the discovered interaction of SCW with magnetic fields. Our basic idea is that the magnetoresistance is the major contribution to the variations of the SCW amplitude in the presence of a magnetic field. We first address to the dependence of SCW on the conductivity of the sample and, hence, on the mobility of the carriers. In the simplest model with only one kind of charge carriers, the mobility can be expressed via the conductivity as

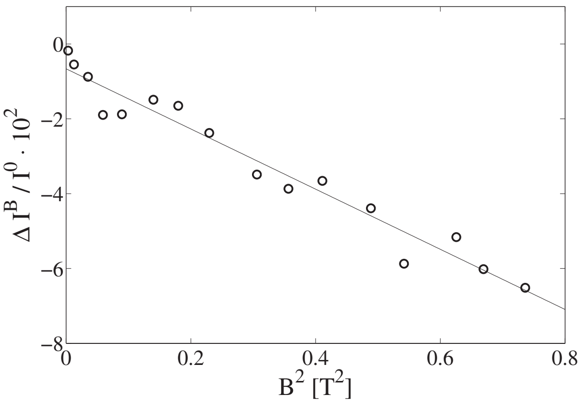

FIG. 3. Dependence of the relative change in the ac amplitude at resonance maximum (in %) on the magnetic field, for $K=5.1\times10^3$ cm^{-1} and $E_0=4$ kV/cm. The line is a guide to the eye.

$$\mu = \sigma/(en), \tag{1}$$

where n is the carrier density and e is the electron charge. As it is known (see, for instance, Ref. 3) the measured current in the outside circuit at the resonance condition is equal to

$$I^0 = I(\Omega_R) \approx \frac{\sigma E_0 \Theta m^2 Q}{4(q+1)}. \tag{2}$$

Here, E_0 is the applied electric field ($E_0=U/L$, where U is the applied voltage), m is the contrast ratio of the interference pattern, and Q is the quality factor of the excited SCW:

$$Q = \frac{eN\mu\tau K E_0 (q+1)^{-1}}{eN + \mu\tau K^2 E_0^2 \epsilon\epsilon_0 (q+1)^{-2}} \tag{3}$$

with the relaxation (recombination) time τ, the effective trap concentration N, and the dielectric permittivity of the material ϵ. The factor $(q+1)$ considers the reduction of the electric field inside the crystal due to various screening effects, i.e., the internal electric field is expressed by $E_{\rm int}=E_0/(q+1)$. Equation (3) is derived under the assumption of a negligible diffusion field and a number of free charge carriers less than the effective trap concentration.[1–3] Obviously, Q diminishes at high K values when $\mu\tau K^2 E_0^2 \epsilon\epsilon_0 (q+1)^{-2} > eN$.

Considering the model of magnetoresistance, the conductivity can be presented in the standard form as

$$\sigma \simeq \sigma_0(1-gB^2), \tag{4}$$

where σ_0 is the conductivity in the absence of a magnetic field and g is the phenomenological coefficient. It is assumed that $gB^2 \ll 1$ and a possible dependence of the carrier lifetime on the magnetic field is ignored. With approach (4), we can find relative variations in the maximum current at varying magnetic fields. In the case $Q\sim\mu$ (that corresponds to small values of K), they are

$$\frac{\Delta I^B}{I^0} = \frac{\sigma^2-\sigma_0^2}{\sigma_0^2} \approx -2gB^2. \tag{5}$$

However, if K is sufficiently large, Q is weakly depending on μ, the measured ac current is proportional to σ and

$$\frac{\Delta I^B}{I^0} \approx -gB^2. \tag{6}$$

Accordingly, one can expect that relative variations in the current can decrease with increasing K because of the reduction of the derivative $\partial Q/\partial\mu$ at high K.

All of our experimental data can be described quite satisfactorily by this set of equations: The relative variation in the current is proportional to B^2, has a negative sign (see Fig. 3) and tends to decrease with increasing K. The restriction of the magnetic field interaction of SCW to a geometry B orthogonal E, further underlines the validity of our model related to the magnetoresistance.

By comparing our data with measurements of the magnetoresistance in Ref. [9], where the parameter $S_{\mathrm{PMR}}=\Delta R/(RB^2)$ is used, we see that the parameter g is analog to S_{PMR}. The experimental magnitude of $\Delta I^B/(I^0B^2)$ depends on K in the interval (0.09–0.05) T^{-2}. We hence conclude that $g=(0.05\pm0.01)\ \mathrm{T}^{-2}$ if we use Eqs. (5) and (6). This value agrees quite well with the reported parameters $S_{\mathrm{PMR}}=0.06\ \mathrm{T}^{-2}$ (Ref. 9) and $S_{\mathrm{PMR}}=0.035\ \mathrm{T}^{-2}$,[10] that describe the magnetoresistance of InP:Fe. The positive sign of g means that the corresponding variation in ΔR is positive, which agrees with Refs. 9 and 10, too.

To verify the reproducibility of the obtained experimental data, we repeated the measurements mentioned above with another sample of InP:Fe, which was obtained from a different source. The second sample had less dark resistivity so that the measurements were performed at a lower light intensity (less than $10\ \mathrm{mW/cm^2}$) in order to prevent heating effects. The obtained experimental data agree quite well with those of the first sample. The difference does not exceed the experimental error although the magnitude of the g value reached almost 0.06. We additionally performed *direct* measurements of $\Delta R/R$ for our sample using the same electrodes as in the SCW measurements, i.e., the direct current appearing under an externally applied electric field was determined as a function of the magnetic field. We found $\Delta R/(RB^2)=(0.012\pm0.002)\ \mathrm{T}^{-2}$ under light illumination with intensities comparable to the SCW experiments. The determined value is more than four times less than g. The obvious reason for this is the existence of screening effects and a drop of the voltage at the contact areas as well as at the loading resistor. The drop of the voltage does not influence the relative magnitude of the ac current caused by SCW rectification. In contrary, the drop of the voltage due to screening effects and the presence of a loading resistor can strongly affect the performed direct measurements of magnetoresistance. The detected variations in the conductivity or in the current due to the magnetoresistance depend either on the total resistivity or on the effective—rather than the intrinsic—conductivity of the sample. So, the direct measurements of the magnetoresistance suffer from screening effects and result in an error in the calculation of the parameter $\Delta R/(RB^2)$. As it was found in Ref. 3, the upper limit of the parameter $q+1$ can reach 4.07 in the studied sample. This explains the difference between the estimation of the magnetoresistance with SCW and our direct current measurements. We hence stress that SCW measurements in a magnetic field provide a powerful tool for the determination of the magnetoresistance with quite high precision. At the same time, it allows to estimate the effect of field screening $(q+1)$ in semiconductors.

Concluding our results, the interaction of SCW with magnetic fields is discovered and the detected effects are unambiguously related to the magnetoresistance of the sample. Specific advantageous for the detection of the magnetoresistance become obvious by the technique of SCW excitation. They particularly reveal a sensitivity which can be two times higher compared with direct magnetoresistance measurements. They further are not influenced by screening effects. The comparison of the results from SCW and direct magnetoresistance measurements represents a tool to estimate the magnitude of the screening effect itself.

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