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Rectification of space charge waves in the semiconductor InP:Fe

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The effects of overall and spatial rectification of space charge waves (SCWs) have been seen in a semiconductor material. A technique of optical excitation of SCWs has been applied to investigate InP:Fe. Excellent agreement with the predicted dispersion law was revealed. The concept of an effective quality factor of SCWs was introduced to describe a strong inhomogeneous broadening of the resonance. A reasonable agreement of the experimental data with the proposed model has been found.

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I. INTRODUCTION

The effects of space charge wave (SCW) rectification[1–4] have been discovered and studied in detail in photoconductive crystals of the sillenite family ($Bi_{12}MO_{20}$ where M = Si,Ge,Ti) which are in fact dielectrics in the dark. In this paper, we report on SCW rectification effects in a semiconductor material. The SCWs under consideration are associated with processes of trap recharging, and they are eigenmodes of charge carrier oscillations in the presence of an applied electric field.[5] These waves have an unusual dispersion law $\Omega_w \sim K_w^{-1}$, where Ω_w is the eigenfrequency and K_w is the wave number of the SCW.[5,6] Due to a second-order nonlinearity in the process of space charge formation, the effects of overall and spatial rectification arise. The effect of overall rectification[1–3] reminds one of rectification in nonlinear optics in which a static homogeneous polarization arises due to a second order nonlinearity of the crystals under illumination. In the case of overall rectification of SCWs an additional direct current arises in the crystals because the grating of the excited charges moves together with the resulting grating of the space charge field, and there is a phase shift between these gratings different from $\pi/2$. Spatial rectification of SCWs arises when there are both running and static gratings of the charges in the crystal. An electric field[4,7] and a current[8] occur, homogeneous in space but oscillating in time. All these effects show resonances because they are associated with a resonant excitation of SCWs.

SCWs exist only under an externally applied electric field. In the absence of an applied field, the well known effect of non-steady-state photoelectromotive force (photo-EMF) can generate either an alternating current if an oscillating interference pattern is used[9] or a direct current for a running pattern.[10] However, these effects are not associated with the excitation of eigenmodes of charge carrier oscillations so that no resonance phenomena connected with SCW excitation are found. Investigations of SCWs in semiconductors are of interest not only for scientific reasons but also for applications, e.g., improving the sensitivity of sensors for weak vibrations. Under resonance conditions of SCWs the detected signals are two or even three orders of magnitude higher than far from the resonance.

In this paper, we selected InP:Fe crystals because they satisfy all necessary conditions for optical excitation of SCWs. They have a relatively high dark resistivity ($10^6 - 10^8\ \Omega$ cm),[11–14] allowing the application of an electric field. Their band gap is equal to 1.35 eV,[15] providing high photoconductivity at available laser wavelengths. This material has been successfully employed for the detection of an ultrasonic motion of a scattering surface by using the technique of holographic two-wave mixing.[13] The data presented in Ref. 13 indicate a high probability for the excitation of SCWs.

II. THEORETICAL BACKGROUND

In the present work, we used the method of an oscillating interference pattern. The crystal was illuminated by two coherent laser beams, one of which is phase-modulated with the frequency Ω and the amplitude of phase modulation θ (Fig. 1).

Under the condition $\theta < 1$, the intensity pattern $W(x,t)$ is described by the expression

$$\begin{aligned} W(x,t) &= W_0[1 + m_I \cos(Kx + \theta \cos \Omega t)] \\ &\approx W_0 + W_0 m_I \cos Kx - \tfrac{1}{2} W_0 m_I \theta \sin(Kx + \Omega t) \\ &\quad - \tfrac{1}{2} W_0 m_I \theta \sin(Kx - \Omega t). \end{aligned} \tag{1}$$

Here, W_0 is the average light intensity, m_I is the contrast ratio of the light pattern and $K = 2\pi/\Lambda$ is the wave number of the grating with the grating spacing Λ.

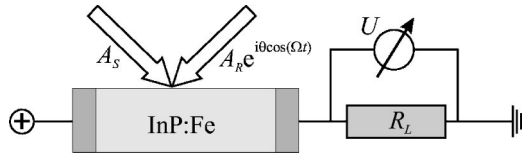

FIG. 1. Schematic diagram of the experimental setup. The waves A_S and $A_R \exp[i\theta \cos(\Omega t)]$ interfere inside the InP:Fe crystal. The voltage U across the loading resistor R_L was measured. A cw operating Nd:YAG laser ($\lambda = 1064$ nm) was used as a light source.

The incident light causes photogeneration of carriers and the formation of space charge gratings in the crystal. The static part $W_0 m_I \cos Kx$ of the intensity pattern leads to a standing space charge grating, and the dynamic part given by the last two terms in Eq. (1) leads to two running space charge gratings propagating in opposite directions. Resonant excitation of the SCW occurs when K and Ω of the running gratings coincide with K_w and Ω_w of an eigenmode of the SCW.

The effects of SCW rectification are associated with a second-order nonlinearity in the current. For one type of charge carriers and neglecting diffusion, the expression for the current density reads

$$J(x,t) = e\mu n(x,t)[E_0 + E(x,t)]. \tag{2}$$

Here, μ is the carrier mobility, $n(x,t)$ the density of carriers (including photoexcited carriers), E_0 the applied field and $E(x,t)$ the space charge field. It turns out that both terms $n(x,t)$ and $E(x,t)$ are proportional to phase factors of the type $\{\exp[i(Kx+\Omega t)]+\exp(iKx)$ +complex conjugated terms$\}$. As a result, the product $n(x,t)E(x,t)$ contains terms of the form $\{\exp[i(Kx+\Omega t)]\exp(-iKx)\}$ describing spatial rectification and of the form $\{\exp[i(Kx+\Omega t)]\exp[-i(Kx+\Omega t)]\}$ describing overall rectification.

A rather general treatment of SCW rectification is presented in Ref. 16. However, the effect of inhomogeneous broadening of the resonance of SCWs which can be caused by inhomogeneities of illumination and/or internal electric field was not considered, as in other theoretical papers (e.g., Refs. 3 and 17). To take into account this broadening, we modified the calculations of Ref. 16 by introducing an effective quality factor Q that contains an empirical parameter b. For the simplest case ($m \leqslant 1$, $\theta \leqslant 1$, one type of charge carriers) the overall rectification, i.e., the variation of the direct current due to SCW excitation is described as

$$J_0(\omega) = \frac{\sigma E_0}{(1+q)}\left\{1 - \frac{m^2}{2(1+q)} + \frac{m^2\theta^2}{8(1+q)}\left[2 - \frac{1}{(1-\omega d)^2 + (d\omega/Q)^2} - \frac{1}{(1+\omega d)^2 + (d\omega/Q)^2}\right]\right\}. \tag{3}$$

Here, σ is the average conductivity of the illuminated crystal; $E_0 = U_0/L$ with the applied voltage U_0 and the distance L between the electrodes; q characterizes a reduction of the applied field in the crystal (due to possible screening effects) compared to the expected applied field, so that $1+q = E_0/E_{\text{int}}$ with the real field inside the crystal E_{int}, $m = m_I(1-\sigma_d/\sigma)$, with the dark conductivity σ_d; $\omega = \Omega\tau_M$, with the Maxwell relaxation time τ_M; and $d = K\tau\mu E_0/(1+q)$, with the lifetime of carriers τ. The expression for Q has the form

$$Q^{-1} = \frac{1}{d} + \frac{E_D(1+q)}{E_0} + \frac{E_0}{(1+q)E_q} + b. \tag{4}$$

Here, $E_D = KD/\mu$ is the diffusion field with the diffusion coefficient D, and $E_q = eN_A/\epsilon\epsilon_0 K$ is the saturation field with the electron charge e, the trap concentration N_A, and the dielectric constant ϵ. The expression for Q in (4) differs from that in Ref. 17 by the presence of the parameters b and q. It follows from (3) that the relative variation of the direct current at the resonance (at the minimum of the direct current) is proportional to $m^2\theta^2Q^2$.

For spatial rectification, we also have taken into account the quality factor Q in the form given in (4). A calculation similar to that of Refs. 7 and 16 yields for the simplest case ($m \leqslant 1$, $\theta < 1$, one type of charge carriers) the amplitude $J_1(\omega)$ of the alternating current density, as

$$J_1(\omega) = \frac{\sigma\theta m^2 \omega d E_0 \sqrt{1+\omega^2/4}}{(1+q)\sqrt{(1+q)^2 + (q\omega)^2}} \times \frac{1}{\sqrt{[(1-\omega d)^2 + (d\omega/Q)^2][(1+\omega d)^2 + (d\omega/Q)^2]}}. \tag{5}$$

The resonance occurs at

$$f_{\text{res}} = \frac{\omega_{\text{res}}}{2\pi\tau_M} \approx \frac{1}{2\pi\tau_M d(1+Q^{-2})^{1/2}}, \tag{6}$$

and at the resonance, the amplitude of the alternating current is proportional to $\theta E_0 m^2 Q$.

III. EXPERIMENTAL RESULTS AND DISCUSSION

The direct and alternating currents were detected by measuring the voltage across the loading resistor R_L (Fig. 1). For direct current measurements, the technique of double-phase modulation[18] was used to exclude low-frequency fluctuations of the current in the circuit. The crystal used has a size of $2.5 \times 3.65 \times 0.4$ mm^3. Electrodes of thin Cr layers were deposited onto the crystal and then covered by thin Au layers. The spacing between the electrodes was 2.5 mm and the dark resistivity of the sample 6×10^7 Ω cm. The investigations have been performed with a Nd:YAG laser at $\lambda = 1064$ nm. Here, the crystals are relatively transparent with an absorption of 4.3 cm^{-1}. The total intensity was chosen as $W_0 = 77$ mW/cm^2, the contrast ratio as $m_I = 0.47$, and the amplitude of phase modulation as $\theta = 0.3\pi$.

Figure 2 shows the direct and alternating currents as a function of the frequency $f = \Omega/2\pi$.

There is a clear maximum of the alternating current and a minimum of the direct current, indicating that SCWs are excited and rectification effects are detected. For the direct current, the experimental data correspond to the ratio $[J_0(\theta = 0.3\pi) - J_0(\theta = 0)]/J_0(\theta = 0)$. The resonance frequency $f_{\text{res}} = \Omega_{\text{res}}/2\pi$ is determined from the experimental data of the alternating current. Figure 3 illustrates the dependence of f_{res} on K. The solid line represents the dispersion law for SCWs

$$\Omega_w = \frac{1}{GK_wE_0}, \tag{7}$$

with $G = (1+Q^{-2})^{1/2}\tau_M\tau\mu/(1+q)$.

Excellent agreement is obtained between the experimental data and the theoretical function describing the dispersion law. Figure 4 shows the resonance frequency f_{res} and the

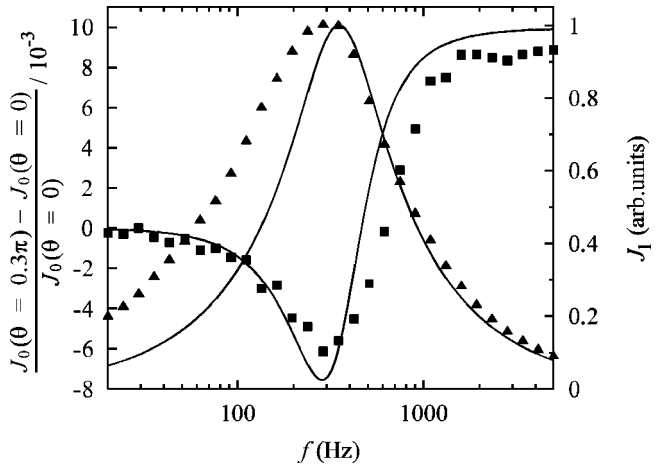

FIG. 2. Frequency dependence of the direct current $[J_0(\theta) - J_0(\theta=0)]/J_0(\theta=0)$ (squares) and the alternating current J_1 (triangles) at $E_0=7$ kV/cm, $W_0=77$ mW/cm^2, $K=2.07$ μm^{-1}, $m_l=0.47$, and $\theta=0.3\pi$. The solid curves are calculations according to Eqs. (3) and (5).

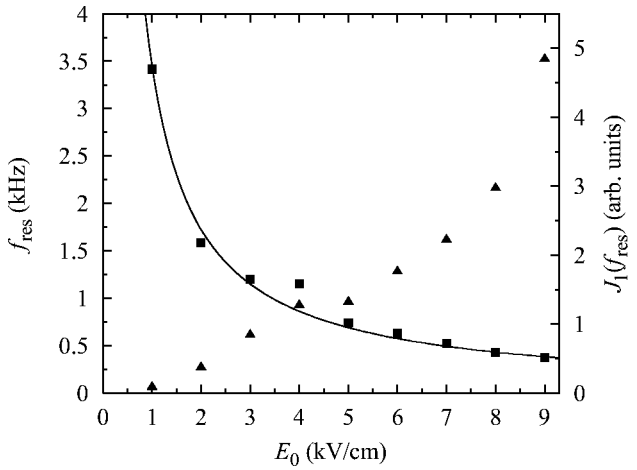

FIG. 4. The dependence of the resonance frequency f_{res} (squares) and of the amplitude of the alternating current at the resonance $J_1(f_{res})$ (triangles) on the applied electric field E_0 at $W_0=77$ mW/cm^2, $K=1$ μm^{-1}, $m_l=0.47$, and $\theta=0.3\pi$. The solid curve is a calculation according to Eq. (7).

amplitude of the alternating current at the resonance $J_1(f_{res})$ as a function of the applied electric field E_0.

The dependence of the resonance position on E_0 agrees very well with the dispersion law. With the discussion of the dependence of the amplitude $J_1(f_{res})$ on E_0, we have to take into account the heating of the sample for fields larger than 7 kV/cm. Omitting the experimental data taken at 8 and 9 kV/cm, the dependence points to a linear law.

The whole set of solid curves corresponds to calculations with $\tau_M=4\times10^{-6}$ s, $\sigma_d/\sigma=0.1$, and the fit parameters $Q=1.44$, $q=3.07$, and $\mu\tau=3.2\times10^{-6}$ cm^2/V. Here, τ_M was obtained from measurements without electric field using the photo-EMF analysis,[9] and σ_d/σ at $W_0=77$ mW/cm^2 was taken from direct measurements of the photoconductivity. These values of τ_M and $\mu\tau$ can be compared with the published data $\tau_M=10^{-4}$ s in the dark,[12] $\tau_M=3\times10^{-5}$ s under illumination of 1.14 W/cm^2 (Ref. 13) and $\mu\tau=(10^{-7}-6\times10^{-6})$ cm^2/V.[12,14] Using the obtained product $\mu\tau$, we can find the diffusion length $L_D\approx3$ μm and the drift length $L_0\approx60$ μm at $E_0=7$ kV/cm. Since the mobility of the electrons is known in similar InP:Fe crystals ($\mu=1470$ cm^2/V s), we can estimate the carrier lifetime as $\tau\approx2\times10^{-9}$ s. It follows from the experiments that Q is almost independent from K in a wide range. From this fact as well as from direct estimations of the parameters d, E_D, and E_q, it can be concluded that for $K<1$ μm^{-1} the factor b plays a dominating role for the effective quality factor Q and can be estimated as 0.4–0.5. Thus, it is an additive term describing the effect of inhomogeneous broadening that allows us to explain two main experimental facts: the weak dependence of Q in a wide range of K and the small value of Q. The main uncertainty in the numerical estimation of b is connected with the parameter q because it is very sensitive to the contrast ratio m. The maximum value of m is limited by the contrast ratio of the light interference pattern m_l, which may be reduced in the crystal by light scattering due to imperfections.[19] Thus, the obtained value of q can be considered as an upper limit.

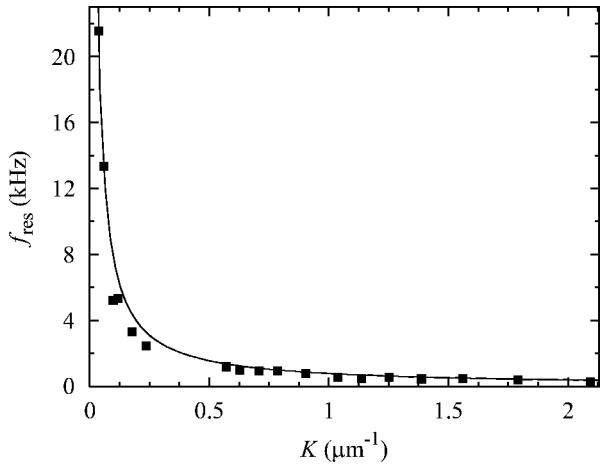

FIG. 3. Resonance frequency f_{res} as a function of K at $E_0=7$ kV/cm, $W_0=77$ mW/cm^2, $m_l=0.47$, and $\theta=0.3\pi$. The solid curve is a calculation according to Eq. (7).

The high value of the parameter b leads to a rather strong inhomogeneous broadening of the spectrum of the SCW. Two major mechanisms of broadening can be proposed. First, an inhomogeneity of the intensity of illumination leads to a variation of the conductivity and, as a consequence, to a variation of τ_M as well as to a variation of the internal electric field. We have estimated an inhomogeneity of illumination in our experiments (including the inhomogenity of illumination due to light absorption) smaller than 20%. Second, an inhomogeneity of the internal electric field results from non-ohmic contacts and the geometry of the contacts. It is well known from investigations of semi-insulating semiconductors such as GaAs:Cr that the internal field in the sample can vary strongly.[20,21] We therefore expect that the main contribution in b originates from an inhomogeneity of the electric field. In particular, the relatively high value of q indicates a strong screening effect in our sample.

IV. CONCLUSIONS

The presented data unambiguously prove strong effects of SCW rectification in the semiconductor material InP:Fe. The excellent agreement between experiments and theoretical predictions for the dispersion law of SCWs shows the validity of the general concept of SCWs in semiconductors. The strong inhomogeneous broadening of the SCW resonance originates from an inhomogeneity of the internal electric field. The data obtained from such experiments can be useful for the study of kinetic electronic properties of semiconductors, for material characterization, and for the optimization of various optical sensors and photo-receivers.[22] A large variety of semiconductors can be studied by the technique used. One of the most interesting materials can be CdTe:Ge, where parametric excitation of SCWs has already been found.[23]

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[1] M. P. Petrov, V. V. Bryksin, H. Vogt, F. Rahe, and E. Krätzig, Phys. Rev. B **66**, 085107 (2002).
[2] M. P. Petrov, V. V. Bryksin, S. Wevering, and E. Krätzig, Appl. Phys. B: Lasers Opt. **73**, 669 (2001).
[3] V. V. Bryksin and M. P. Petrov, Phys. Solid State **44**, 1869 (2002).
[4] M. P. Petrov, A. P. Paugurt, V. V. Bryksin, S. Wevering, and E. Krätzig, Phys. Rev. Lett. **84**, 5114 (2000).
[5] R. F. Kazarinov, R. A. Suris, and B. I. Fuks, Sov. Phys. Semicond. **6**, 500 (1972).
[6] M. P. Petrov, V. V. Bryksin, V. M. Petrov, S. Wevering, and E. Krätzig, Phys. Rev. A **60**, 2413 (1999).
[7] V. V. Bryksin and M. P. Petrov, Phys. Solid State **42**, 1854 (2000).
[8] S. Mansurova, S. Stepanov, N. Korneev, and C. Dibon, Opt. Commun. **152**, 207 (1998).
[9] M. P. Petrov, I. A. Sokolov, S. I. Stepanov, and G. S. Trofimov, J. Appl. Phys. **68**, 2216 (1990).
[10] U. Haken, M. Hundhausen, and L. Ley, Phys. Rev. B **51**, 10579 (1995).
[11] G. C. Valley, S. W. McCahon, and M. B. Klein, J. Appl. Phys. **64**, 6684 (1988).
[12] A. M. Glass, A. M. Jonson, D. H. Olson, W. Simpson, and A. A. Ballman, Appl. Phys. Lett. **44**, 948 (1984).
[13] P. Delaye, A. Blouin, D. Drolet, L. A. de Montmorilon, G. Roosen, and J. P. Monchalin, J. Opt. Soc. Am. B **14**, 1723 (1997).
[14] R. S. Rana, D. D. Nolte, R. Steldt, and E. M. Monberg, J. Opt. Soc. Am. B **9**, 1614 (1992).
[15] T. P. Pearsaal, *GaInAsP Alloy Semiconductors* (Wiley, New York, 1982), Appendix.
[16] V. V. Bryksin, P. Kleinert, and M. P. Petrov, Phys. Solid State **45**, 2044 (2003).
[17] B. I. Sturman, M. Mann, J. Otten, and K. Ringhofer, J. Opt. Soc. Am. B **10**, 1919 (1993).
[18] M. P. Petrov, V. V. Bryksin, F. Rahe, C. E. Rüter, and E. Krätzig, Opt. Commun. **227**, 183 (2003).
[19] U. van Stevendaal, K. Buse, H. Malz, H. Veenhuis, and E. Krätzig, J. Opt. Soc. Am. B **15**, 2868 (1998).
[20] B. Imbert, H. Rajbenbach, S. Mallick, J. P. Herrau, and J. P. Huignard, Opt. Lett. **13**, 327 (1988).
[21] M. B. Klein, S. W. McCahon, T. F. Boggess, and G. C. Valley, J. Opt. Soc. Am. B **5**, 2467 (1988).
[22] S. Stepanov, in *Handbook of Advanced Electronic and Photonic Materials and Devices*, edited by H. S. Nalwa (Academic, New York, 2001), p. 205.
[23] K. Shcherbin, Appl. Phys. B: Lasers Opt. **71**, 123 (2000).