Trap saturation in InP:Fe by optical interband excitation

M. P. Petrov and V. V. Bryksin
Ioffe Physico-Technical Institute, Russian Academy of Sciences, St. Petersburg, 194021, Russia

B. Hilling,* M. Lemmer, and M. Imlau
Department of Physics, University of Osnabrück, 49069 Osnabrück, Germany

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Optically induced trap-recharging waves in InP:Fe at the condition of interband carrier excitation have been studied and the magnitudes of the effective trap concentration N_{eff} and the product of mobility and lifetime of the charge carriers $\mu\tau$ have been determined. It is shown that the results obtained can be interpreted in the framework of a monopolar model under the condition that interband illumination reduces dramatically the effective trap concentration as well as the carrier lifetime. Such a decrease results in a strong wave damping, so the waves under study are damped forced waves rather than eigenmodes of the material. A brief introduction into the theory describing a reduction in the effective trap concentration is presented.

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I. INTRODUCTION

Deep traps play an important role for the electrical and optical properties of semiconductors and semi-insulators. For instance, they provide efficient photoconductivity through photons with energies lower than the material band gap and even play a crucial role in holographic recording in photorefractive materials, such as sillenite crystals ($Bi_{12}TiO_{20}$, $Bi_{12}GeO_{20}$, and $Bi_{12}SiO_{20}$), $LiNbO_3$:Fe,[1,2] $KNbO_3$,[3] and others. Illumination of a photorefractive crystal with a periodical interference pattern results in an excitation of charge carriers (e.g., electrons) from donors and the buildup of a corresponding periodical charge grating by ionized donors. This periodical charge pattern forms a periodical variation in the refractive index, i.e., a phase holographic grating, via the linear electro-optic effect. In the "classical" high-resistive semiconductors, such as InP or GaAs doped with Fe or Cr, for instance, the presence of deep traps also results in the formation of a charge-carrier grating under illumination with an interference pattern. This can also be of interest though these materials are not efficient holographic media because of their rather poor electro-optic properties. At the same time, optical formation of charge gratings is of extreme importance for optical excitation and the study of space-charge waves (SCW) in these and other semiconductor materials.[4]

Let us remind the simplest, but most commonly used, monopolar model of charge grating formation (Fig. 1). It is assumed that there are donors with density N_D in the band gap of a material. A part of them are ionized donors with density N_{D+}, and the other part are nonionized donors with density N_{D0}, so $N_D=N_{D0}+N_{D+}$. There are also acceptors with density N_A. To fulfill the condition of electroneutrality, it is assumed that $N_{D+}=N_A$. Thermally excited electrons are neglected. It is assumed that acceptors are completely filled (negatively charged) and play only a passive role; i.e., they do not participate in any grating formation. Under illumination by an interference pattern electrons are excited from neutral donors in bright areas and move into dark ones due to diffusion or under an applied electric field. Here they recombine with ionized donors and a static grating occurs. The maximum possible grating amplitude is limited by the so-called effective trap concentration,

$$N_{\text{eff}} = \frac{N_{D0}N_A}{N_{D0}+N_A} = \frac{N_{D0}N_A}{N_D}. \tag{1}$$

This relationship shows that the maximal grating amplitude is limited by the lower value, N_{D0} or $N_A=N_{D+}$. For a grating with the definite period Λ the maximal amplitude of an electric field grating (E_q) is determined by N_{eff}. This amplitude is referred to as a saturation field.[5] It is equal to

$$E_q = \frac{eN_{\text{eff}}}{\epsilon\epsilon_0 K}. \tag{2}$$

Here, ϵ is the dielectric constant of a material (at zero frequency), ϵ_0 is the vacuum constant, $K=2\pi/\Lambda$ is the spatial frequency of the grating, and e is the electron charge.

It is a commonly accepted point of view that in the dark the effective trap concentration N_{eff} is an intrinsic characteristic of a material (especially for photorefractive crystals) and is typically taken to be a fixed value in holographic experiments. The possibility to control the effective trap density opens up a way of manipulating one of the important parameters of the material by using external factors, such as illumination of the sample. Such an opportunity is attractive for verification of various theoretical models of holographic recording and for space-charge wave investigations. Some characteristics of holographic recording and variations in N_{eff} under interband excitation have been considered in detail in

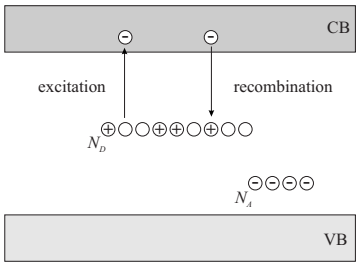

FIG. 1. Schematic diagram of electron excitation and recombination in the monopolar model when the photon energy of the illuminating light is less than the material band gap.

Ref. 3. However, interband carrier excitation can result not only in changes in N_{eff} but also in changes in the charge-carrier lifetime τ. This is more or less obvious because in this case a second efficient relaxation mechanism (namely, electron-hole interband recombination) exists, which reduces the carrier lifetime. Both parameters N_{eff} and τ (more precisely, the product $\mu\tau$, where μ is the carrier mobility) play a crucial role for a special kind of space-charge waves, i.e., trap-recharging waves (TRW),[6–8] because they determine the quality factor and dispersion law of SCW. The goal of the present paper is to study TRW and to establish the scale of variations in N_{eff} and τ in InP:Fe in the case of interband excitation of carriers.

II. EXPERIMENTAL CONDITIONS AND SETUP

The experiments described in this paper were performed with two samples of InP:Fe, designated as samples A and B in the following, obtained from different sources. The concentration of Fe in both samples was of the order of 10^{17} cm^{-3}. Sample A was cut out of the same wafer as the sample used in Refs. 9 and 10. Both samples have comparable darkconductivities, but at the same light intensity sample B possesses a much higher photoconductivity than sample A, which can indicate that the concentration of Fe in sample A was higher than that in sample B. Both samples had dimensions of $4\times7\times0.5$ mm^3 and their electrodes were made of gold with a spacing of $L=4$ mm. The experiments described in the present paper and those reported in Ref. 9 differ only in the wavelengths and intensities of light exposure. In Ref. 9 a laser source with $\lambda=1064$ nm ($\hbar\omega\approx1.17$ eV) was used, and the photon energy for this wavelength is lower than the InP band gap [$E_g=1.35$ eV (Ref. 11)]. So there was no interband carrier excitation, and only excitation from deep traps could provide photoconductivity and the recording of a charge grating. A laser source (an Ar$^+$ laser) with $\lambda=514$ nm ($\hbar\omega\approx2.4$ eV) has been used in the experiments reported here, so interband excitation could play an important role and results in very pronounced effects. In the experiments described in this paper and reported in Ref. 9, the TRW properties were studied. In Ref. 9 it was found that the experiment was in excellent agreement with the theory; i.e., the dispersion law for TRW was $\Omega_R\propto1/K$ and the wave amplitude was proportional to the product KE_0^2, where E_0 is the applied electric field and Ω_R is the TRW eigenfrequency. The quality factor of the waves was definitely more than unity. Such properties of TRW unambiguously indicated that no trap saturation effect was present (formally this means that $E_0\ll E_q$). It is not surprising because N_{eff} in the sample studied was comparable with the concentration of iron ions (of the order of 10^{17} cm^{-3}). However, the results obtained in the experiments described in the present paper are absolutely different.

The experimental setup is shown in Fig. 2. The principle of operation is the same as that described in Ref. 9. So we remind only the main points. The sample is connected to a power supply to provide an electric field and illumination is realized with two coherent laser beams with the total light intensity W, one of which is phase modulated with frequency

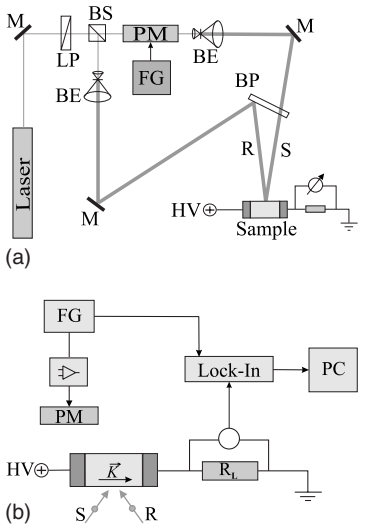

FIG. 2. (a) Scheme of the experimental setup: LP, combination of a half-wave plate and a polarizer; BS, beam splitter; R, reference beam; S, signal beam; PM, phase modulator; FG, function generator; BE, beam expander; BP, beam splitter plate; M, mirror; and HV, high-voltage source. An Ar$^+$ laser at $\lambda=488$ nm served as pump source. (b) Principle of electric detection of SCW in an external circuit; R_L, loading resistor.

Ω. This modulation provides oscillations of the interference pattern near the midpoint. As a result, three gratings are generated in the crystal due to charge carrier photoexcitation. One of them is a static grating with period $\Lambda=2\pi/K$. To reach the maximal amplitude of this grating, the condition $\Omega>1/\tau_M$ (where τ_M is the dielectric or Maxwell relaxation time) has to be met. The two other gratings are moving gratings that propagate in opposite directions. They feature the wave number K and frequency Ω. If we vary Ω, one of the moving charge gratings can coincide with one of the eigen-TRW in the crystal. In this case the photoexcited grating resonantly amplifies the eigen-TRW. Detection of the TRW can be accomplished through the so-called spatial TRW rectification[12,13] when a running grating interacts with the static one, thus giving rise to an alternating current in the outside circuit. When resonant TRW excitation occurs, the detected signal amplitude reaches its maximum. Below, the experimental dependences of the frequency position of the signal maximum (Ω_R) on K and E_0 and also the dependences of the maximum signal amplitude (i.e., at $\Omega=\Omega_R$) on K and E_0 are presented.

Figures 3–5 show the experimental data for sample A and Figs. 6–8 for sample B. The light intensity for sample A was about 50 mW/cm^2, whereas for sample B it was 5 mW/cm^2 to prevent a strong sample heating since sample B exhibited a higher photoconductivity. The curves are theoretical data in accordance with relationships (3)–(7) with fitting parameters $\mu\tau$, τ_M, and N_{eff} shown in Table I. In addition to the experimental data shown in Figs. 3–8, dependences of the resonance frequencies on the electric field were obtained. However, these data did not provide new information because they coincided within the experimental error with the theoretical data using the fitting parameters shown in Table I. The experimental data presented in Figs. 3–8 ex-

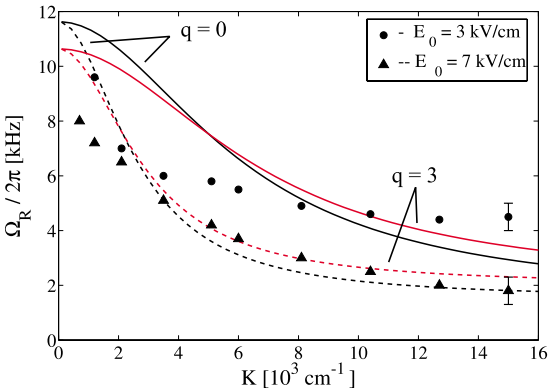

FIG. 3. (Color online) Frequency position of the signal maximum as a function of the wave number K for two electric fields for sample A.

hibit pronounced peculiarities as being compared with the data reported in Ref. 9. First of all, it can be seen that the resonance frequency as a function of K does not obey a simple law $\Omega_R \propto 1/K$. The second difference is that the dependences of the signal amplitudes on K are not monotonic but have maxima, whose positions depend on the strength of the applied field. The third difference is that the signal amplitude does not always obey the law $I_1 \propto E_0^2$. It either reaches some saturation value or even passes through a maximum. One more important peculiarity is a rather weak dependence of all the experimental results on the illuminating light intensity when the intensity varies in the range of $2-50$ mW/cm^2, i.e., in the most suitable range for the experiments performed. All these facts require a more general theoretical approach for their explanation.

III. THEORETICAL DESCRIPTION

A quite general theory of the current generated by space-charge waves for the monopolar model of optical charge excitation and taking into account the effect of trap saturation was published in Ref. 14. This theory will be used as a first step in our analysis. In accordance with Ref. 14 and neglecting diffusion processes, the alternating current amplitude in the outside circuit under the resonance condition (or at a maximum signal) is

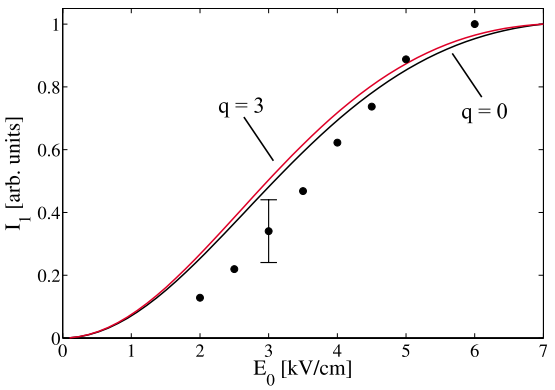

FIG. 4. (Color online) Maximum signal (at $\Omega=\Omega_R$) as a function of the electric field E_0 with $K=5.1\cdot10^3$ cm^{-1} for sample A.

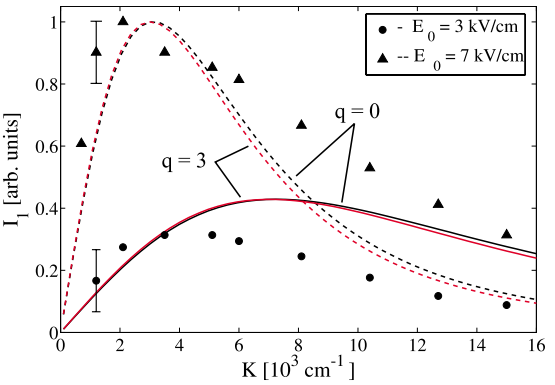

FIG. 5. (Color online) Maximum signal (at $\Omega=\Omega_R$) as a function of the wave number K for two electric fields for sample A.

$$I_1(\Omega_R) \approx \frac{\sigma E_{\text{int}} m^2 \theta d(|1-\beta|)}{4(1+\beta d^2)(1+\beta^2 d^2)}, \tag{3}$$

where σ is the photoconductivity, m is the contrast ratio of the interference pattern, θ is the phase modulation amplitude,

$$\beta = \frac{\epsilon\epsilon_0}{e\mu\tau N_{\text{eff}}}, \tag{4}$$

$$d = \mu\tau K E_{\text{int}}, \tag{5}$$

$$E_{\text{int}} = E_0/(q+1). \tag{6}$$

The parameter q takes screening effects into account and shows that the internal electric field E_{int} can be lower than the externally applied electric field $E_0=U/L$, where U is the applied voltage and L is the interelectrode distance. Note that it was found in Ref. 9 that $q\approx3$ for the sample used.

In this approximation the position of the signal maximum is described by Ω_R equal to

$$\Omega_R \approx \frac{\sqrt{1+(\beta d)^2}}{\tau_M\sqrt{1+d^2}}. \tag{7}$$

It is worth presenting the expression for the quality factor Q for TRW,

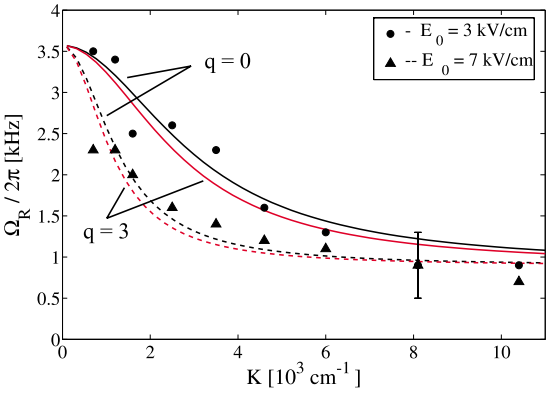

FIG. 6. (Color online) Frequency position of the signal maximum as a function of the wave number K for two electric fields for sample B.

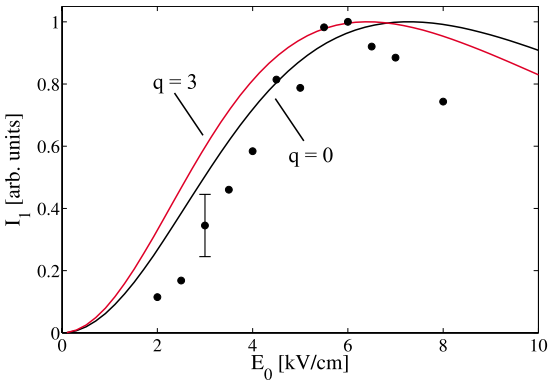

FIG. 7. (Color online) Maximum signal (at $\Omega=\Omega_R$) as a function of the electric field E_0 with $K=2.1\cdot10^3$ cm^{-1} for sample B.

$$Q \approx \frac{d|1-\beta|}{1+\beta d^2}. \tag{8}$$

In the case $Q>1$ one can say that resonant excitation of TRW eigenmodes occurs, and Ω_R is the resonance frequency. However, if $Q<1$, we deal with damped forced waves and Ω_R reflects the position of the signal maximum rather than the resonance condition. The experimental data given in Ref. 9 suggested that the $\mu\tau N_{\text{eff}}$ product was so high that $\beta\ll1$ and therefore it could be assumed that $\beta\approx0$. So expressions simpler than Eqs. (3)–(7) could be used to describe the signal intensity and resonance frequency. In the present paper, we have to keep β in the expressions because β can be of the order of unity, as it follows from comparison of experimental and theoretical data.

All the curves presented in Figs. 3–8 were calculated using Eqs. (3)–(7). So a monopolar model was used, and it turned out that it described all the experimental facts, at least it tends to describe the experimental facts. To fit the theory to the experiments, we have to take into account a much lower value of N_{eff}. Therefore the question arises how a decrease in the effective trap concentration can be connected with the optical interband excitation of carriers. A detailed theory of this process has been developed and will be published elsewhere. Here, we present only a brief introduction into the theory and the final formula for N_{eff} in the case when the

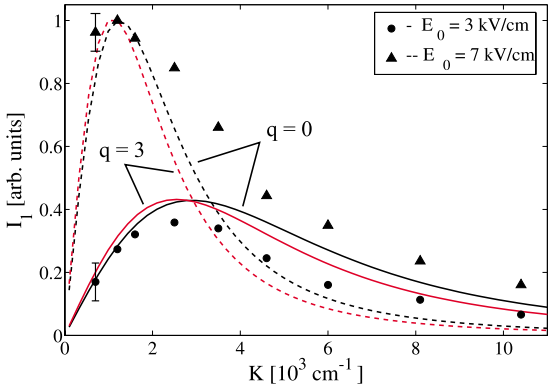

FIG. 8. (Color online) Maximum signal (at $\Omega=\Omega_R$) as a function of the wave number K for two electric fields for sample B.

TABLE I. Material parameters for InP:Fe samples A and B.

Sample A	$\mu\tau$ (10^{-7} cm^2/V)	τ_M (10^{-5} s)	N_{eff} (10^{14} cm^{-3})
$q=0$	0.55	4.3	3.5
$q=3$	2.0	4.7	0.8
Sample B			
$q=0$	1.1	14.0	1.4
$q=3$	5.0	14.0	0.3

interband excitation prevails over the excitation from traps. Note that there are numerous publications devoted to the problem of interband excitation in the case of holographic recording (see, e.g., Ref. 3 and the review paper[15]). There are also some publications devoted to the influence of interband excitation on the "photo-emf" effect (see, e.g., Ref. 16) and the effect of optical interband excitation on moving space-charge fields in semiconductors.[17] However, to our knowledge, no detailed analysis of space-charge waves at the condition of interband excitation has been performed so far.

We use the model of space-charge excitation in accordance with Fig. 9. The initial equations of this model are given in the Appendix. The rate of interband generation is described by the parameter G, which is proportional to the light intensity W. The rate of electron-hole interband recombination is described by $n_e n_p/\vartheta$, where n_e and n_p are the electron and hole concentrations in the conduction and the valence bands, respectively, and ϑ is the recombination parameter. Excitation of electrons and holes from traps is described by the products $g_e(N_D-\rho)$ and $g_p(N_A+\rho)$, where the parameters g_e and g_p are proportional to the light intensity. The quantity $e\rho$ is the charge arising at impurity levels due to photogeneration,

$$\rho = N_{D+} - N_{A-}. \tag{9}$$

Here, N_{D+} and N_{A-} are the concentrations of ionized donors and acceptors, respectively.

The electron-trap and hole-trap recombination rates are described by $n_e(N_A+\rho)/\vartheta_e$ and $n_p(N_D-\rho)/\vartheta_p$, where ϑ_e and ϑ_p are the parameters describing the recombination of electrons and holes with traps.

To simplify the mathematics, we ignore the processes of hole excitation and hole recombination associated with traps,

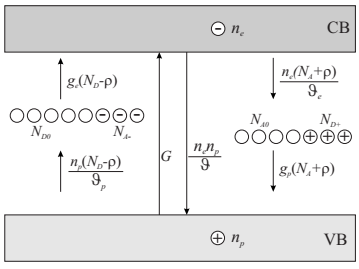

FIG. 9. Schematic diagram of excitation and relaxation processes including interband excitation and excitation of electrons and holes from traps.

$g_p=\vartheta_p^{-1}=0$, and assume that the hole mobility is low, $\mu_p=0$. We also neglect diffusion processes and take $D_{e,p}=0$ in Eq. (A3) (see the Appendix). Then it can be shown that the expression for N_{eff} under the steady-state conditions has the form

$$N_{\text{eff}}=\frac{(N_D-\rho^{(0)})(N_A+\rho^{(0)})}{N_D+N_A}. \tag{10}$$

Here and below, the upper index (0) corresponds to the conditions of uniform illumination, when $h=0$ [see Eq. (A5)] in Eqs. (A1) and (A2). Attention should be paid to the fact that without illumination, when $\rho^{(0)}=0$, Eq. (10) coincides with the monopolar model [Eq. (1)] after renormalization of the concentration of donor centers: $N_D \rightarrow N_D-N_A$. Such a renormalization is due to the fact that in a conventional monopolar model acceptor levels play a passive role of compensating centers.

Now two alternative situations can be considered. The first one is a weak illumination. In this case $\rho^{(0)} \ll N_D, N_A$, and the interband excitation results in only small corrections of N_{eff}. In the second case (a strong illumination) it is assumed that $n_p^{(0)}, n_e^{(0)} \gg \rho^{(0)}$, which means that $n_p^{(0)}, n_e^{(0)} \gg N_{D0}, N_A$ as well. Then the equilibrium values of electron $n_e^{(0)}$ and hole $n_p^{(0)}$ densities are

$$n_e^{(0)} \approx n_p^{(0)} \approx \sqrt{G\vartheta}, \tag{11}$$

and

$$\rho^{(0)} \cong \frac{g_e N_D \vartheta_e - n_e^{(0)} N_A}{g_e \vartheta_e + n_e^{(0)}}. \tag{12}$$

For a strong illumination, substitution of Eq. (12) into Eq. (10) gives

$$N_{\text{eff}} \approx \frac{N_D}{\left(\sqrt{\frac{g_e \vartheta_e}{\sqrt{G\vartheta}}}+\sqrt{\frac{\sqrt{G\vartheta}}{g_e \vartheta_e}}\right)^2}. \tag{13}$$

Note that Eq. (13) is identical to formula (11) obtained in Ref. 3 for the so-called model A. Because G and g_e are proportional to W, Eq. (13) describes the dependence of the effective trap concentration on the light intensity when the condition of a strong intensity is met. It follows from Eq. (13) that two various situations lead to the trap saturation effect. The first one is when

$$\frac{n_e^{(0)}}{g_e \vartheta_e} \ll 1. \tag{14}$$

Then, with Eq. (11),

$$N_{\text{eff}} \approx \frac{N_D n_e^{(0)}}{g_e \vartheta_e} = \frac{N_D \sqrt{G\vartheta}}{g_e \vartheta_e}. \tag{15}$$

It can be seen from Eq. (15) that the effective trap concentration reduces proportionally to the square root of the light intensity W (since $g_e \propto W$ and $G \propto W$) and it depends on the electron-trap recombination and electron-hole recombination. The physics of the trap saturation effect in the case of interband excitation under this condition is as follows: When the photon energy is higher than the band gap and the light intensity is high enough, there is a very efficient electron excitation into the conduction band. The excited electrons mostly recombine to the valence band, but partially recombine with ionized donors. Because the efficiency of electron excitation from traps is high due to the high light intensity and because the recombination of electrons with holes is also efficient, the rate of electron excitation from traps is higher than the rate of electron recombination on the traps [see Eq. (14)]. This leads to $(N_D-\rho)/(N_A+\rho) \ll 1$. As a result, the number of nonionized donors is exhausted and, therefore, N_{eff} is reduced. As it follows from Eq. (13), the situation opposite to that given by Eq. (14) can exist also.

In the case

$$\frac{n_e^{(0)}}{g_e \vartheta_e} \gg 1, \tag{16}$$

with Eq. (11) we can find

$$N_{\text{eff}} \approx \frac{N_D g_e \vartheta_e}{n_e^{(0)}} = \frac{N_D g_e \vartheta_e}{\sqrt{G\vartheta}}, \tag{17}$$

and the rate of electron excitation from traps is lower than the rate of electron recombination on the traps, which leads to $(N_A+\rho)/(N_D-\rho) \ll 1$. In this case ρ changes its sign. Unfortunately, we cannot estimate either ϑ or ϑ_e from the available experimental data, although it is reasonable to expect that $\vartheta_e \gg \vartheta$.

IV. DISCUSSION

In Table I two sets of parameters are presented, which are explained in the following: It is very well known (see, e.g., Refs. 18 and 19) that in many cases due to screening effects the real electric field E_{int} inside a sample is lower than the applied field E_0. In Ref. 9 we managed to estimate the screening effects in sample A and found that $E_0/E_{\text{int}}=q+1 \approx 4$.

In this work, we could not estimate the parameter q in the experiments with interband excitation because the overall rectification effect could not be detected with sufficient accuracy. In comparison to Ref. 9 a much weaker signal-to-noise ratio was found. So all the theoretical calculations were made for two values of q ($q=0$ and $q=3$) and two sets of fitting parameters were obtained. Their comparison has shown that screening effects can change the fitting parameters $\mu\tau$ and N_{eff} by approximately a factor of 4 ($\mu\tau$ increases but N_{eff} reduces with increasing q). However even with this uncertainty in the magnitudes of the fitting parameters there is an obvious difference between the data obtained in the present paper and Ref. 9. In the case of interband excitation the $\mu\tau$ product decreases approximately by 1 order of magnitude. The effective trap density N_{eff} reduces by more than 1 or even 2 orders of magnitude under the assumption that N_{eff} is higher than 10^{15} cm^{-3} in the absence of interband excitation[20] (this magnitude of N_{eff} also agrees with the fact that no trap saturation effects were observed in Ref. 9). The values of N_{eff} obtained in this study (Table I) correlate with the conductivities for samples A and B. As

mentioned above, it is expected that the trap concentration for sample B is lower than that for sample A. From the fitting parameters mentioned above we can estimate the quality parameter Q for the studied waves. In accordance with Eq. (8), $Q<1$ for both samples in all cases. So the trap-recharging waves studied are really forced damped waves rather than the material eigenwaves. A strong TRW damping is due to a reduction in N_{eff} and $\mu\tau$ at the condition of interband excitation. As far as variations in the $\mu\tau$ product are concerned, it is more probable that the interband excitation causes a reduction of the lifetime τ rather than of the carrier mobility. Since the electron mobility in InP:Fe is approximately 1470 $\text{cm}^2/\text{V s}$,[20] we can estimate τ to be of the order of $(10^{-10}-10^{-11})$ s.

Two more facts have to be discussed. The first one is a weak dependence of the experimental data on the light intensity, and the second fact is a relatively high value of τ_M compared with τ_M in Ref. 9. In our opinion, both facts can be explained taking a very strong inhomogeneity of the light intensity in the crystal into account. The absorption coefficient α in InP:Fe at $\lambda=514$ nm is of the order of 10^4 cm^{-1}. So the light intensity decreases sharply as a function of the penetration depth. In this situation, such parameters as τ_M and N_{eff} vary considerably along the light propagation direction. As a result, broadening of the space-charge wave spectrum arises, and the signal is observed only from a thin layer, where the signal is maximal and the spectrum is the most narrow. When the incident light intensity is varied, this layer simply shifts toward or from the front surface of the crystal without strong changes in the signal characteristics. A high τ_M indicates that this layer corresponds to a relatively low light intensity compared to the incident light intensity at the front surface.

The interpretation of the experimental data presented here has only a semiquantitative character because an accurate theoretical analysis includes a large number of parameters of electrons and holes that cannot be extracted from the experiments presented. Nevertheless, even a semiquantitative model explains the main TRW features at interband excitation.

V. CONCLUSIONS

Optically induced trap-recharging waves in InP:Fe at the condition of interband carrier excitation have been studied. Strong differences in the measured characteristics of trap-recharging wave spectra and those studied earlier,[9] when carrier excitation was provided by optical ionization of traps, have been revealed. The magnitudes of the effective trap concentration N_{eff} and the $\mu\tau$ product have been found from comparison of the experimental data with the monopolar model describing trap-recharging waves in semi-insulating materials. It is shown that the results obtained can be interpreted in the framework of the monopolar model under the condition that interband illumination reduces dramatically the effective trap concentration as well as the carrier lifetime. Such a decrease results in a strong wave damping, so the waves under study are damped forced waves rather than eigenmodes of the material. A brief introduction into the theory describing a reduction in the effective trap concentration is presented.

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APPENDIX

The balance equations corresponding to the optical transitions shown in Fig. 9 are

$$\frac{\partial n_e}{\partial t}+\frac{n_e n_p}{\vartheta}+\frac{n_e(N_A+\rho)}{\vartheta_e}-\frac{1}{e}\frac{\partial j_e}{\partial x}=[G+g_e(N_D-\rho)](1+h), \tag{A1}$$

and

$$\frac{\partial n_p}{\partial t}+\frac{n_e n_p}{\vartheta}+\frac{n_p(N_D-\rho)}{\vartheta_p}+\frac{1}{e}\frac{\partial j_p}{\partial x}=[G+g_p(N_A+\rho)](1+h), \tag{A2}$$

where $j_{e,p}$ are the electron and hole current components,

$$j_{e,p}=e\mu_{e,p}n_{e,p}E\pm eD_{e,p}\frac{\partial n_{e,p}}{\partial x}. \tag{A3}$$

The sample is illuminated with an interference pattern oscillating around the equilibrium position. The interference pattern intensity W depends on the coordinate x and the time t as

$$W(x,t)=W_0[1+h(x,t)], \tag{A4}$$

with

$$h(x,t)=m\cos(Kx+\Theta\cos\Omega t), \tag{A5}$$

where Θ is the amplitude of the interference patterns oscillations, K and Ω are the wave number of the grating and its oscillation frequency, and m is the interference patterns contrast ratio. The remaining designations are given in Sec. III.

The set of Eqs. (A1) and (A2) for the electron and hole concentrations $n_{e,p}$, trapped charge $e\rho$, and internal electric field should be supplemented by Poisson's equation,

$$\frac{\epsilon}{4\pi e}\frac{\partial E}{\partial x}=n_p-n_e+\rho, \tag{A6}$$

where ϵ is the samples dielectric permeability, and the equation for the full current I in the external circuit is

$$\frac{\epsilon\epsilon_0}{e}\frac{\partial E}{\partial t}+j_e+j_p=I. \tag{A7}$$

*buhillin@uos.de

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