Trap recharging wave mode with a linear dispersion law for space-charge waves in CdTe:Ge

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ac and dc currents arising in CdTe:Ge during optical excitation of space-charge waves (SCW) have been investigated. The experiments have been performed at a wavelength of $\lambda=1064$ nm using the technique of an oscillating interference pattern. Our investigations have shown that the SCWs studied can be attributed unambiguously to trap recharging waves (TRWs). Remarkably, we have found a linear dispersion law ($\Omega_K \propto K$) for these waves although an inverse law is usually expected. A corresponding theoretical model has been developed and shows that the theoretical data are in reasonable agreement with the experiments if the following fitting parameters are used: An effective trap concentration of $N_{\mathrm{eff}}=(2.5\pm0.3)\times10^{12}$ cm^{-3}, a mobility-lifetime product of $\mu\tau=(0.65\pm0.05)\times10^{-7}$ cm^2/V, and a Maxwell relaxation time of $\tau_M=(5.5\pm0.2)\times10^{-3}$ s. The appearance of an additional low-frequency ac resonance is discussed in the frame of a bipolar conductivity.

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INTRODUCTION

It is known that two modes of space-charge waves (SCW) can exist in semi-insulating crystals in the presence of an externally applied electric field. These are drift waves (DW) and trap recharging waves (TRW). Drift waves[1–3] exhibit an ordinary (linear) dispersion law where the eigenfrequency Ω_K is proportional to the wave number K. The dispersion law of earlier reported trap recharging waves[2–5] shows a very specific form. In particular, under definite conditions, such as a high trap concentration, a relatively high product of the carrier mobility μ and carrier lifetime τ, the eigenfrequency of the TRW is inversely proportional to its wave number: $\Omega_K \propto K^{-1}$. This results in opposite directions of phase and group velocities, which is typical for so-called backward waves. The eigenfrequencies of DW are proportional to the carrier mobility and are typically in the range of 10^5-10^{10} Hz,[6–8] whereas the eigenfrequencies of TRW are typically of the order of $2\pi/\tau_M$, where τ_M is the Maxwell (dielectric) relaxation time. A usual range of these frequencies in the materials studied [mostly photorefractive crystals of the sillenite family[8–10] and some semiconductors, such as InP:Fe (Ref. 11) or SiC (Ref. 12)] is 10–1000 Hz. However, it was shown before[13] that for a low $\mu\tau$ product, a low trap density, and a specific combination of parameters (the applied field E_0 is higher than the so-called saturation field E_q and the carrier drift length is much less than the TRW period), the dispersion law of TRW is modified. As a consequence, the TRW eigenfrequencies become proportional to their wave numbers, so that the dispersion law is similar to the dispersion law of DW. This mode of TRW was analyzed theoretically in Ref. 13 for ferroelectrics (especially those exhibiting very low carrier mobilities, i.e., for the crystals that are really dielectrics). No such mode was known in photorefractive sillenites, where TRW have been studied in detail, and this mode was not expected for semiconductors as the required set of parameters is not typical for semiconductors. The goal of the present paper is to show that this very unusual kind of TRW with a linear dispersion law can exist in semiconductors as well. Here, we describe the first experimental investigation of TRW with a linear dispersion law in CdTe:Ge and present some results of the theoretical calculations describing these particular experiments. A more general theoretical analysis of such TRW is published elsewhere.[14]

CdTe is a semiconductor material[15,16] with a band gap of $E_g=1.49$ eV, a high electron mobility of $\mu_e \approx 1000$ cm^2 V/s, and a dark resistivity that can be as high as 10^8 Ω cm.[17] The material belongs to the point group 43m. The relative dielectric constant is $\varepsilon=10.4$, and the refractive index is 2.82. Single crystals are transparent at $\lambda=1064$ nm with an absorption coefficient of $\alpha=3$ cm^{-1} (in our sample $\alpha \approx 0.7$ cm^{-1}).

When CdTe is doped with V, Ge, or some other ions, it becomes less conductive, with the resistivity reaching 3×10^9 Ω cm (Ref. 18) or even 2×10^{10} Ω cm (Ref. 19) (the $\mu\tau$ product was estimated to be 5.7×10^{-5} cm^2/V for holes).[19] Since doped crystals exhibit a rather high photorefractive effect, they were used in two- and four-wave mixing experiments (CdTe:V,Ge).[17,20,21] CdTe:V was also used for investigation of the photo-emf effect and for the detection of laser-induced ultrasonic surface displacements.[22] In accordance with Ref. 23, CdTe doped with Ge exhibits a hole dark conductivity with a hole mobility of 50 cm^2/V s at room temperature. However, the sign of the photogenerated carriers can vary with the quantum energy of the incident light. The doping of CdTe with Ge leads to the formation of levels at 0.73 eV above the valence band in addition to other levels (0.3 eV, 0.4 eV above the valence band, and 0.23 eV below the conductivity band) existing in undoped materials.[23] The subharmonic generation of holographic gratings was discovered and studied in CdTe:Ge, and the approximate value of

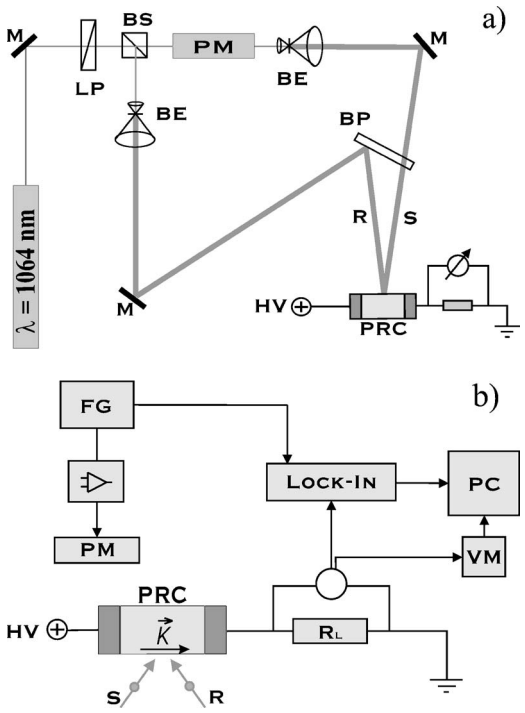

FIG. 1. (a) Experimental setup (schematically). LP, combination of a half-wave plate and a polarizer; BS, beam splitter; BP, beam splitting plate; PM, phase modulator; BE, beam expander; M, mirror; PRC, the studied crystal. A YAG:Nd laser at $\lambda=1064$ nm was used. (b) Diagram demonstrating the electronic detection of SCW. HV, high-voltage source; RL, loading resistor; FG, function generator; VM, voltmeter for dc measurements.

$\mu\tau$ was estimated to be 10^{-6} cm^2/V.[24,25] In Ref. 21, the dynamics of free carrier grating decay was studied in CdTe:Ge, and it was found that free carrier gratings have a very fast decay of 60–210 ps, and the electron recombination rate is of the order of 2 ns.

As can be seen from the data mentioned above, there are numerous investigations of various properties of CdTe:Ge, however, no detailed investigations of SCW in CdTe were reported and the nature of these waves in this material still remains unknown. Investigations of SCW in semiconductors are of great interest from both fundamental and practical points of view as they allow us to study in more detail fundamental properties of semiconductors and to optimize a broad variety of optical sensors.[7,26]

DESCRIPTION OF EXPERIMENTAL CONDITIONS AND SETUP

In this paper we present the investigations of SCW in CdTe:Ge using the technique of SCW excitation by an oscillating interference pattern. The SCW were detected by the effects of SCW spatial and overall rectification.[8] The experimental setup is shown schematically in Fig. 1. The sample is illuminated by two coherent laser beams, one of which is phase modulated with the phase-modulation amplitude Θ and the modulation frequency Ω. For the experiments, we used a YAG:Nd laser ($\lambda=1064$ nm). The total light intensity on the crystal input face is in the range of 10–100 mW/cm^2. The contrast ratio m of the interference pattern was estimated to $m=0.6$, in accordance with the ratio between the beam intensities illuminating the crystal. The experiments were performed with $\Theta\approx0.33$ and 0.94 rad. The major part of the experimental data presented in this paper is for $\Theta\approx0.94$ rad since this phase-modulation magnitude provided a better signal-to-noise ratio. No other important differences between the measurements of $\Theta\approx0.33$ and 0.94 rad were found. The detection of the output signal was accomplished by measuring the ac and dc voltages via a loading resistor. The measurements were performed with the same sample that was used in Ref. 24. The dc voltage was applied along the [112] axis. The distance between the electrodes was 4 mm. The measurements were performed in the interval of the externally applied electric fields of $E_0=0-3$ kV/cm (in several cases up to 5 kV/cm), with K varying from 0.2×10^3 cm^{-1} up to 1.9×10^4 cm^{-1} and for the frequencies $f=\Omega/2\pi$ between 1 and 10^5 Hz. The interval of the applied fields was adjusted to avoid self-excitation of spatial subharmonics[24] and to prevent sample overheating.

If the sample is illuminated in accordance with Fig. 1, the light intensity can be described as

$$W(x,t) = W_0[1 + m\cos(Kx + \Theta\cos(\Omega t))] \approx W_0 + W_0 m\cos(Kx) - \frac{1}{2}W_0 m\Theta\sin(Kx-\Omega t) - \frac{1}{2}W_0 m\Theta\sin(Kx+\Omega t). \quad (1)$$

Here, W_0 is the average intensity, m is the contrast ratio, $K=2\pi/\Lambda$, where Λ is the interference pattern period, and it is assumed that $\Theta\ll1$. The interference pattern described by Eq. (1) excites the charge density $n(x,t)$ proportional to $W(x,t)$ into the conduction band. Finally, under light illumination, three volume charge gratings are formed. One of them is a static charge grating with the period Λ, and the other two gratings are charge carrier gratings running in opposite directions, whose parameters of propagation are described by $\sin(Kx-\Omega t)$ and $\sin(Kx+\Omega t)$, respectively. If the period and speed of propagation of one of the running gratings coincides with the period and speed of propagation of one of the SCW eigenmodes, resonance excitation of this eigenmode occurs. If a SCW propagates along the static grating of the space-charge field (having the same grating spacing as the grating spacing of the moving grating), the effect of spatial SCW rectification arises.[27,28] Then, a homogeneous current arises that oscillates in time and can easily be detected in the outside circuit. At the same time, variations in the dc current can be detected because of the effect of overall SCW rectification, i.e., the effect arising from the interaction of two SCWs.[29] The overall SCW rectification formally reminds one of optical rectification in nonlinear optics.[30]

In the experiments, two resonant oscillating signals were detected at low K (Fig. 2). The position of the low-frequency maximum slowly shifted towards higher frequencies with increasing K and exhibited a weak dependence on the applied field. Its amplitude grew strongly with E (approximately

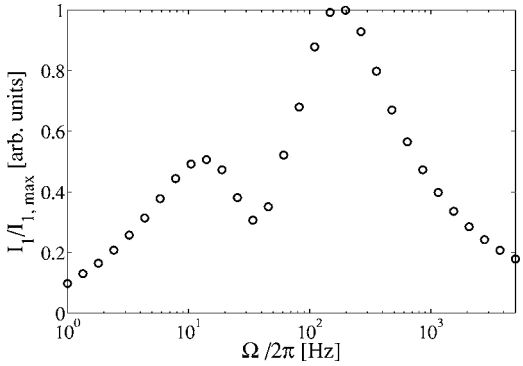

FIG. 2. Frequency dependence of the output ac signal for $W_0 = 100$ mW/cm^2, $E_0 = 1.5$ kV/cm, $K = 0.1 \times 10^4$ cm^{-1}, $m = 0.6$, and $\Theta = 0.3\pi$.

$\propto E_0^{2-3}$) in the interval of K of $0.2-0.5 \times 10^3$ cm^{-1}. At higher K, the signal amplitude became low and almost independent of E_0. Since this signal could be detected only in a rather limited range of the parameters (K, E_0, Θ), we did not study this low-frequency peak in detail and our attention was focused to the high-frequency resonance. The high-frequency maximum (or resonance) position exhibited quite strong dependences on the wave number K, the applied voltage, and the total light intensity illuminating the crystal. Moreover, the resonance of the alternating current was accompanied by variations in the dc current flowing through the crystal. Figure 3 shows the resonance dependence of the alternating current on the frequency of the phase modulation and an example of the dc variations under the conditions when these

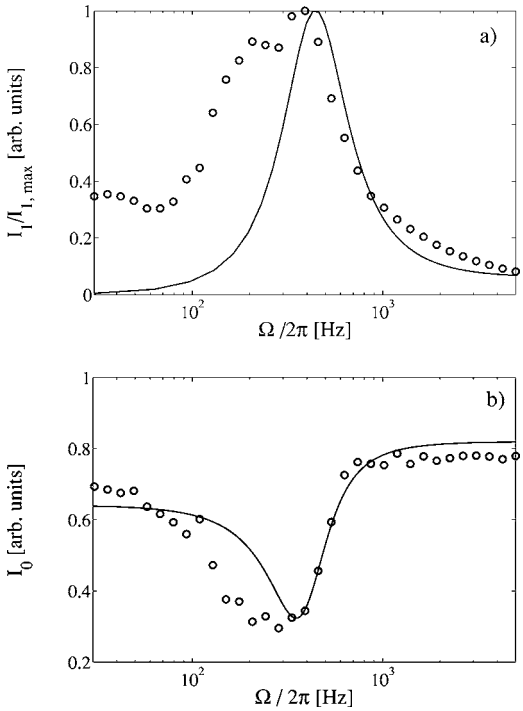

FIG. 3. (a) Frequency dependence of the ac output signal. (b) Frequency dependence of the dc output signal for $W_0 = 100$ mW/cm^2, $E_0 = 2.0$ kV/cm, $K = 0.31 \times 10^4$ cm^{-1}, $m = 0.6$, and $\Theta = 0.3\pi$. The lines are calculations in accordance with Eqs. (5)–(7).

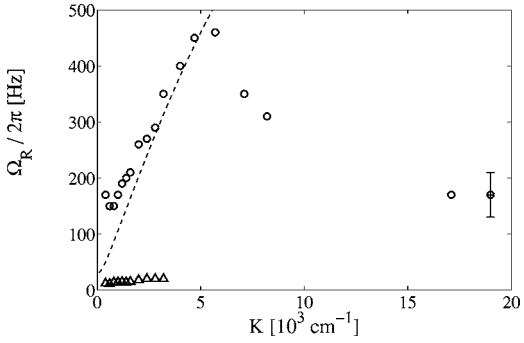

FIG. 4. Position of the resonance peak for the high- and low-frequency resonance as a function of the wave number K for $W_0 = 100$ mW/cm^2, $E_0 = 1.5$ kV/cm, $m = 0.6$, and $\Theta = 0.3\pi$. The line is a calculation in accordance with Eq. (4).

variations are maximal. The curves are calculations in accordance with relationships (5)–(7) and the fitting parameters mentioned below. Figure 4 shows the positions of the high- and low-frequency resonances versus K. The amplitude of the high-frequency signal has a strong dependence on K. The signal is almost undetectable at $K < 0.4 \times 10^3$ cm^{-1}, but it grows with increasing K (up to $K = 4 \times 10^3$ cm^{-1}) and then drops rapidly. At $K > 6 \times 10^3$ cm^{-1} the signal has a poor signal-to-noise ratio and its intensity is nearly independent of K. The solid curve in Fig. 4 is the theoretical calculation using Eq. (4) with the fitting parameters that are the same for comparison of all experiments with the theory.

We found that the amplitude of the alternating current at the resonance is a linear function of Θ if $\Theta < 1$ rad, and that the amplitude is approximately proportional to m^2 at high light intensities when the dark conductivity can be neglected. The dark resistivity of the crystal is about $\rho_d \approx 1.5 \times 10^8$ Ω cm, but at the light intensity used in our experiments the resistivity was approximately one order of magnitude lower. Figure 5 shows variations in the position of the high-frequency resonance as a function of the applied field. The curve is calculated using Eq. (4). Figure 6 shows the dependence of the resonance position on the light intensity.

The data presented in Figs. 2–6 were obtained with a sufficient signal-to-noise ratio. At a certain combination of

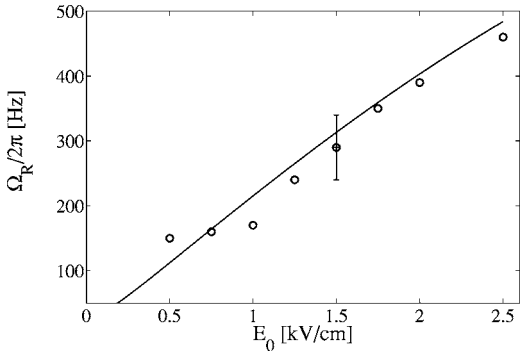

FIG. 5. Position of the resonance peak for the high-frequency resonance as a function of the applied electric field E_0 for $W_0 = 100$ mW/cm^2, $m = 0.6$, $\Theta = 0.3\pi$, and $K = 0.32 \times 10^4$ cm^{-1}. The line is a calculation in accordance with Eq. (4).

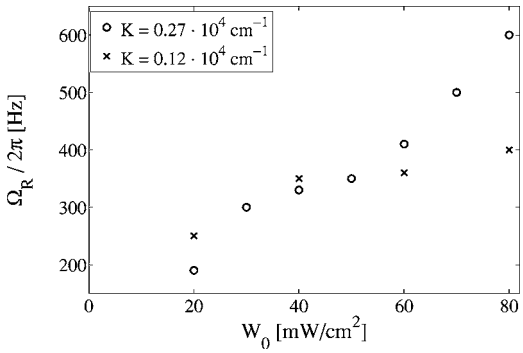

FIG. 6. Position of the resonance peak for the high-frequency resonance as a function of average light intensity for $E_0=3.0$ kV/cm, $m=0.6$, and $\Theta=0.1\pi$, and two different values of K.

parameters ($E_0>3$ kV/cm, $K>10^4$ cm^{-1}, $W_0\approx 100$ mW/cm^2), a chaotic behavior of the alternating current was observed, which can be associated with the generation of photorefractive subharmonics in the crystal.[24] Most of the experiments were performed at $E_0\leq 3$ kV/cm and $W_0\leq 100$ mW/cm^2, as a strong sample heating occurred at higher fields and light powers.

These experimental data unambiguously show that we are dealing with trap recharging waves since the resonance frequencies are in a frequency region that is typical for TRW, the ac resonance signal is accompanied by a variation of the dc current, and the resonance frequency grows with increasing light intensity due to the increasing conductivity. However, the dependence of the resonance frequency on the wave number and on the applied field proves a linear dispersion law for the SCW studied that is in clear contradiction with the known investigations of TRW in sillenites or semiconductors. Thus a new theoretical approach has to be developed for the interpretation of these experimental results.

THEORETICAL BACKGROUND

The interpretation of the experimental data obtained can be performed on the basis of the linear dispersion law of TRW and by taking into account the specific applied methods of SCW excitation and detection. In accordance with Refs. 13 and 14, the dispersion law, i.e., the relationship between the eigenfrequency and the K number, for TRW is in the simplest case of only one type of carriers contributing to the conductivity determined by

$$\Omega_K=\frac{1+\dfrac{E_D}{E_q}-i\dfrac{E_0}{E_q}}{\tau_M d(1+i\gamma)},\quad \gamma=\frac{1+d\dfrac{E_D}{E_0}}{d}. \tag{2}$$

Here $d=\mu\tau KE_0$, E_q is the so-called saturation field ($E_q=eN_{\text{eff}}/\varepsilon\varepsilon_0 K$), τ is the lifetime (recombination time) of the carriers, e is the electron charge, N_{eff} is the effective trap concentration, τ_M is the characteristic time that coincides with the Maxwell (dielectric) relaxation time if only one type of carrier is taken into account, $E_D=Kk_BT/e$ is the diffusion field, k_B is the Boltzmann constant, and T is the temperature.

The necessary condition for the existence of weakly damped waves is a high-quality factor $Q=|\text{Re}(\Omega_k)/\text{Im}(\Omega_k)|>1$. Neglecting diffusion, this requirement can be satisfied under the conditions $E_0/E_q\ll 1$ and $d\gg 1$ or $E_0/E_q\gg 1$ and $d\ll 1$. The first conditions ($E_0/E_q\ll 1$ and $d\gg 1$) correspond to the approximation considered in Refs. 2–4. This situation was met in sillenites for which TRW have been thoroughly studied in many papers. The second situation was theoretically analyzed in Ref. 13 and in more detail in Ref. 14, and was experimentally encountered so far only in ferroelectrics. It was not studied in semiconductors.

For this situation, i.e., $E_0\gg E_q$ but $E_0\ll(\mu\tau K)^{-1}$,

$$\text{Re}(\Omega_k)\approx E_0/(\tau_M E_q), \tag{3}$$

where $\tau_M=\epsilon\epsilon_0/\sigma$ and σ is the sample's photoconductivity (the dark conductivity is neglected). In this case the quality factor $Q\approx E_0/(E_q+dE_0)$ and the relationships (2) and (3) describe the properties of the SCW eigenmode. Experimentally, we observe a peak of alternating current (at frequency Ω_R) that is associated with the excitation of not only an eigenmode but also of a nonresonant grating (the grating moving in the opposite direction). The contribution of the nonresonant grating is negligible at high Q, and in this case the position of the peak (Ω_R) coincides with the frequency $\text{Re}(\Omega_k)$. At low Q ($Q\approx 1$), the position of the current peak can differ from $\text{Re}(\Omega_k)$ because of the contribution of the nonresonant moving grating.

The detailed calculations[14] yield the following expression for the peak position Ω_R for the case when the diffusion field is ignored (i.e., for relatively low K when $E_D\ll E_0$),

$$\Omega_R=\frac{\sqrt{1+\left(\dfrac{E_0}{E_q}\right)^2}}{\tau_M\sqrt{1+d^2}}. \tag{4}$$

It can be seen that (4) coincides with (3) if $E_0/E_q\gg 1$ and $d\ll 1$. Relationship (4) predicts a growth of Ω_R with increasing K and E_0 as well as with increasing light intensity W_0 as $\Omega_R\propto(\tau_M)^{-1}=\sigma/\varepsilon\varepsilon_0$ and $\sigma=\alpha\mu\tau\xi W_0/\hbar\omega_L$. Here, α is the light absorption coefficient, ξ is the quantum efficiency, and $\hbar\omega_L$ is the photon energy.

It can be shown[14] that variations in the dc current at TRW excitation can be described as a function of the phase modulation frequency,

$$I_0(\Omega)=E_0\sigma\left\{1-m^2\left[\frac{A(0)(1-\Theta^2/2)}{2(\beta^2d^2+1)}+\frac{A(\Omega)\Theta^2/8}{(\Omega\tau_M d-1)^2+(\Omega\tau_M+\beta d)^2}+\frac{A(-\Omega)\Theta^2/8}{(\Omega\tau_M d+1)^2+(\Omega\tau_M-\beta d)^2}\right]\right\}, \tag{5}$$

where $\beta=E_0d/E_q$,

$$A(\Omega)=1+2\frac{N_A}{N_D}\left(\frac{E_0}{E_q}\right)^2+2\frac{N_D-N_A}{N_D}\frac{E_0}{E_D}\Omega\tau_M.$$

Here, N_D is the density of donors and N_A is the density of acceptors in the crystal when the standard band-transport model is used.[31]

It follows from (5) that a negative contribution to the dc current caused by the TRW excitation in the case of a linear dispersion law can exist only if $(N_D-N_A)/N_D \ll 1$. In this case

$$A(\Omega) = A(-\Omega) = A(0) \approx 1 + 2\left(\frac{E_0}{E_q}\right)^2, \tag{6}$$

and $N_{\text{eff}} \approx N_D - N_A$.

The theoretical curve in Fig. 3 was obtained by applying this approximation. In all the cases where the theory is compared with the experiments in this paper, the following fitting parameters were used: $\tau_M = (5.5 \pm 0.2) \times 10^{-3}$ s, $N_{\text{eff}} = (2.5 \pm 0.3) \times 10^{12}$ cm^{-3}, and $\mu\tau = (0.65 \pm 0.05) \times 10^{-7}$ cm^2/V. In Ref. 14, the very general expression for the frequency dependence of the alternating current has also been obtained. However, this expression is very cumbersome, so here we shall use a simplified version of the expression for the ac signal that describes the current in the vicinity of the resonance, and with the conditions when diffusion is ignored, the number of excited carriers is much less than N_{eff}, the magnitude of $d \ll 1$, $E_0/E_q \gg 1$, and $(N_D - N_A) \ll N_D$. In this case the amplitude of the alternating current as a function of the frequency is

$$I_1(\Omega) \approx \frac{\sigma m^2 \Theta E_0^2}{8E_q\left[\left(\Omega\tau_M - \frac{E_0}{E_q}\right)^2 + C^2\right]^{1/2}}, \tag{7}$$

where $C = 1 + E_0 d/E_q$ and $D = (E_0/E_q)^2$.

Expression (7) has been used for calculation of the theoretical curve in Fig. 3(a). It follows from (7) that at low K, when $E_q > E_0 d$, the current peak, i.e., the value of the signal at $\Omega = \Omega_R$, is proportional to $E_0^2 K$. Accordingly, at high K, when $E_q < E_0 d$ (but $d \ll 1$), the peak is proportional to K^{-1}. Thus the dependence of the peak amplitude on K exhibits a maximum that is in agreement with our experiments.

DISCUSSION

The data presented in Figs. 4 and 5 unambiguously point to the existence of a region of parameters where the resonance (if $Q > 1$) or a peak frequency is growing with K and E_0. Two models can be used for explanation. The first is the excitation of drift waves and the second is the excitation of trap recharging waves with a linear dispersion law. However, the experimental data obtained cannot be explained by drift wave excitation. There are several reasons for this. First, the frequencies of the detected resonances are rather low, so that the carrier mobility in the case of DW has to be low. An estimate shows that it is not very realistic as it is less than 10^{-3} cm^2/V s if we use the expression $\Omega_D = \mu K E$, where Ω_D is the frequency of drift wave. Also, the carrier lifetime has to be too long (more than 10^{-3} s). Second, the resonance frequencies depend on the light intensity, which is typical of TRWs, whereas no theory and experiments are known where such a dependence has been found for DW, although, in principle, we cannot exclude that such a dependence can exist for DW in some very specific cases. Third, the resonance peak of the alternating current is accompanied by resonance variations in the dc current, which is unusual for DW as the overall rectification is nearly nondetectable for DW (Ref. 8)—instead it is usual for TRW. Fourth, the dependence of the signal amplitude at the resonance frequency on the external applied electric field does not contradict the quadratic law predicted by Eq. (7), and so this is consistent with our conclusion that we are dealing with TRW. This strongly suggests that we are dealing with trap recharging waves. However, such TRWs, which obey a linear dispersion law, were never detected or predicted for semiconductors. Nevertheless, in our case this unexpected mode was verified in CdTe:Ge. The theoretical model developed agrees (at least qualitatively) with all experimental data: the resonance frequency grows with increasing wave number K, applied electric field, and light intensity. The model agrees further with the existence of the dc minimum under the resonance condition. The existence of the maximal value of the current peak as a function of K predicted by (7) is also in agreement with the experiment as we observed the maximal signal at $K \approx (2.5-4) \times 10^3$ cm^{-1}. The fitting parameters are of the same order of value as the reported data, for instance, a deep trap concentration in CdTe:In is estimated to be 8.5×10^{12} cm^{-3}.[32] So the majority of the experimental facts support the proposed TRW model.

There are two facts that require additional comments. The first one is the maximum in the experimental dependence of Ω_R (for the high-frequency resonance) on K in the region $K \approx 6 \times 10^3$ cm^{-1}. The relationship (4) does not predict any maximum, but it can be used for comparison with our experiments for the condition $Q > 1$, i.e., at the condition of eigenmode excitation. At $K \approx 6 \times 10^3$ cm^{-1}, where the maximum of the frequency dependence is observed, the value $d \approx 1$ and so $Q < 1$, formula (4) cannot be used for comparison with the experiment. In principle, $\text{Re}(\Omega_K)$ can show a maximum with sufficient large K where the diffusion process becomes important. However, under this condition, forced damped waves of low intensity are excited rather than eigenmodes. This situation is beyond our consideration. The second fact is the second (low-frequency) resonance. The existence of the low-frequency resonance can be associated with the presence of a bipolar conductivity, a situation that is considered in Ref. 14. In this case the carriers have different parameters such as different relaxation dielectric time, $\mu\tau$ product, and an effective trap concentration yielding two different resonances. The behavior of these resonances depends on the frequency difference between them. For instance, they can repulse each other if the resonance frequencies are almost equal. Our experimental data do not contradict with such a model. Moreover, we definitely can explain the low-frequency resonance by the presence of a second type of carrier with the following set of parameters: $\tau_M' \approx 1.6 \times 10^{-2}$ s, $N_{\text{eff}}' \approx 1.5 \times 10^{13}$ cm^{-3}, $(\mu\tau)' \approx 10^{-7}$ cm^2/V. Using the formula set of equations (4)–(7), we can explain the dependence of the frequency position and of the intensity of the resonance peak on K and on the applied field at least qualitatively. Unfortunately, we do not have enough information to make definite conclusions about the nature of the two carrier types that are responsible for the high- and low-frequency resonance. Nevertheless, we underline the possibility to gain a comprehensive insight into the bipolar con-

ductivity by further analysis of both peak frequencies.

For the high-frequency resonance the fitting parameters obtained are determined with quite good accuracy. They have been found under the assumption that the internal electric field is equal to the so-called calculated field $E_0=U/L$, where U is the applied voltage and L is the distance between the electrodes. In other words, screening effects were not taken into account when we determined the fitting parameters. These effects reduce the internal electric field in the material bulk accompanied by a corresponding increase in the field near the electrodes. As a result, the electric field acting on the carriers can differ from the calculated applied field. The screening effects are well known in sillenites[8] where the internal field is lower by a factor of 2–3 than the calculated field. In CdTe, the screening effects are also very well known. For instance, in Ref. 32 it was shown that, in the CdTe:In, the electric field in the sample bulk is lower by more than one order of magnitude than the calculated field when the crystal is illuminated by the light with the wavelength in the region of 850–920 nm. It was also shown that the screening effects become weaker with increasing wavelength. In our work, we did not notice any direct indication for the presence of screening effects and so we did not pay attention to them. However, we cannot exclude completely the role of these effects, which in principle can modify the fitting parameters obtained in this paper.

We finally like to comment on the relatively low effective trap concentration ($N_{\text{eff}}=2.5\times10^{12}$ cm^{-3}) obtained from the comparison of the theoretical concept with our experimental results. This value is found to be three or four orders of magnitude lower than the trap density of other materials (for instance, of sillenites) where ordinary TRW were studied. In accordance with the definition given in Refs. 13, 14, and 31, the effective trap density is given by $N_{\text{eff}}\approx N_A(N_D-N_A)/N_D$ assuming one species of traps for the photoinduced charge grating formation. Here, N_D is the total density of the donors, N_A is the density of deeply located negatively charged acceptors (N_A is equal to density of positively ionized donors at the darkness), and (N_D-N_A) is the number of the filled (nonionized) donors. In order to adjust theory and experiment we have to assume that $(N_D-N_A)\ll N_D$, so that $N_{\text{eff}}\approx N_D-N_A$. Obviously, this value can be much less—even several orders of magnitude less—than the total trap concentration N_D. For ordinary TRWs it is mostly assumed that N_D-N_A is of the order of N_D, so that $N_{\text{eff}}\approx N_A$. From this it follows that in our case N_{eff} characterizes only the density of the nonionized donors rather than the total trap density. That is why this value can be rather low even at a high total trap density. In this model the deep acceptors play only a passive role to provide electron neutrality of the sample and they do not participate in the grating formation. With respect to the sign of the charge carriers, we note that SCW excitation was performed with an oscillating interference pattern. This results in two counterpropagating waves interacting with the static grating. In this case and because the measurements were performed under an applied field, the sign of the carriers cannot be determined unambiguously from the detected signal, and hence we cannot make a definite conclusion about the specific charge carrier type, i.e., electrons or holes. It is necessary to add that it is quite probable that assuming only one species of traps is too simplified for CdTe:Ge because of the complicated energy level structure in this material. In principle, we can expect that in different experiments, for instance, holographic experiments, different sets of traps and carriers will participate. It is especially important if different optical wavelengths are used or when high light intensities or high electric fields may cause a strong heating of the sample.

CONCLUSIONS

Trap recharging waves with a linear dispersion law have been discovered in a semiconductor. The experiments have been performed in the single-crystal CdTe:Ge by using the technique of optical SCW excitation with an oscillating interference pattern. The effects of spatial and overall SCW rectification have been used for the detection of the SCW. For the first time a theoretical model was developed that describes the generation of ac and variations of dc due to the excitation of TRW with a linear dispersion law. The model is in reasonable agreement with the experimental data at selected fitting parameters: the effective trap concentration, the $\mu\tau$ product, and the Maxwell relaxation time. The important role of the bipolar conductivity resulting in additional SCW resonance is discussed.

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