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IMPACT OF THE CARRIER HEATING KINETICS ON THE MULTIPLE PHOTOMAGNETOELECTRIC EFFECT PULSED PHOTORESPONSE FREQUENCY SPECTRA *

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Multiple photomagnetoelectric response has been investigated in strongly excited narrow gap semiconductors. The response frequency spectra dependence on experimental parameters determining the carrier heating kinetics has been studied. The discrete Fourier transform procedure has been applied to the photoresponse analysis. Possibility to guide the generation of the ultra high frequencies, including terahertz range at picosecond laser excitation of semiconductors, has been revealed.

Keywords: hot carriers, narrow gap semiconductors, laser photoexcitation, ultra high frequencies

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1. Introduction

Action of high power laser light corresponding to the fundamental semiconductor absorption area results in growth of free electron–hole plasma (EHP) density and EHP temperature. Effects caused by nonequilibrium EHP density and EHP heating often appear then [1]. Complex effects such as hot carrier luminescence, light absorption by hot carriers, "heating" of phonons, multiple photomagnetoelectric (PME) effect, and other phenomena are observed in this case. Multiple PME effect appearing due to gradients of EHP density and EHP temperature have been observed in the narrow gap semiconductors [2].

It was shown in previous report [3] that pulsed PME photoresponce frequency spectra contains ultra high frequency (UHF) bands at these conditions. The frequencies of these bands exceed those limited by the laser pulse envelope spectral range [5]. Variation of EHP density and EHP temperature kinetics depends on both semiconductor energy gap structure and carrier scattering, which are different in different semiconductors. These differences influence the kinetics of the pulsed PME photoresponse. Investigation of the influence of multiple PME pulsed photoresponse kinetics on the frequency spectra is performed in this work, to clarify the changes caused by EHP heating peculiarities in different semiconductors. The differences observed in pulsed photoresponse of the multiple PME effect in such semiconductors as InAs, InSb, and $Cd_xHg_{1-x}Te$ have been used as the experimental background of the investigations.

2. Multiple PME effect in InAs, InSb, and $Cd_xHg_{1-x}Te$ at the EHP heating

EHP density and EHP temperature gradients of the same direction are usually formed during the EHP heating by light in highly excited semiconductors. As it has been shown in [2] the total electromotive force (emf) is induced due to PME effect, when a magnetic field normal to the gradients direction is applied. Two effects make contribution to emf. Scilicet there are the diffuse Kikoin–Noskov (KN) effect caused by EHP density gradient and the electron analogue of thermomagnetic Nernst–Ettingshauzen (NE) effect induced by EHP temperature gradient. Short circuit current of the multiple PME effect consists, correspondingly, of two parts:

$$I_{\mathrm{PME}} = I_{\mathrm{KN}} + I_{\mathrm{NE}}\,. \qquad (1)$$

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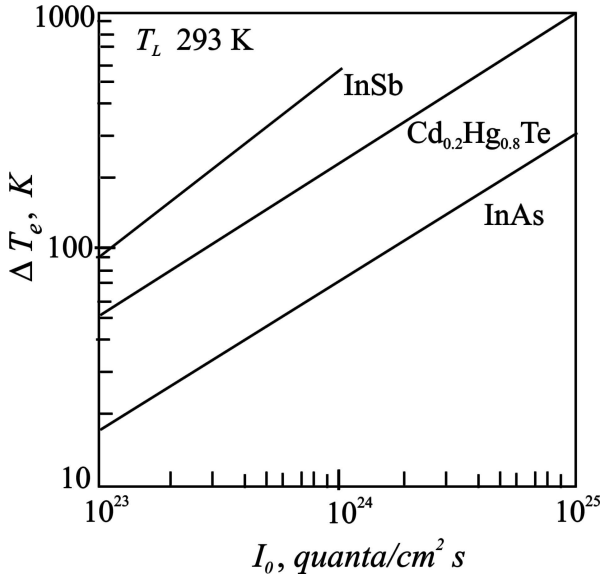

Fig. 1. Dependence of the excess electron temperature on the neodymium laser ($h\nu$ = 1.17 eV) exciting light flux.

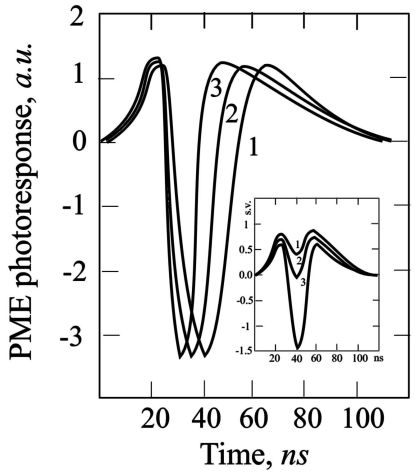

Fig. 2. Evolution of PME effect in ascending order of $\xi_{\rm e}$ parameter corresponding to numbering of pulses (correspondingly to the succession of semiconductors $Cd_{0.2}Hg_{0.8}Te$, InAs, and InSb). Inset shows the evolution of symmetrical PME signal by increase of the excitation intensity.

Here $I_{\rm KN}$ is the short circuit current of the diffuse Kikoin–Noskov effect, and $I_{\rm NE}$ is the short circuit current of the electron analogue of the thermomagnetic Nernst–Ettingshauzen effect [2]:

$$\begin{cases} I_{\rm KN} = ewB \int\limits_0^d (\mu_{\rm e} - \mu_{\rm h})\, D\, \dfrac{{\rm d}[\Delta n(x,t)]}{{\rm d}x}\, {\rm d}x\,, \\ I_{\rm NE} = ewB \int\limits_0^d (\mu_{\rm e} - \mu_{\rm h})\, n\, Q\, \dfrac{{\rm d}[\Delta T_{\rm e}(x,t)]}{{\rm d}x}\, {\rm d}x\,, \end{cases} \tag{2}$$

where e is electron charge, w, d are the sample dimensions, $\mu_{\rm e}$, $\mu_{\rm h}$ are carrier mobilities, B is magnetic field induction, D and Q are the coefficients of bipolar diffusion and Nernst–Ettingshauzen, correspondingly. $\Delta n(x,t)$ and $\Delta T(x,t)$ denote EHP density and excess temperature, correspondingly, depending on coordinate and time. EHP density $\Delta n(x,t)$ obeys the law $\Delta n(x,t) \sim J_0^{1/3}$ when intensity of exciting light J_0 is satisfying the range of 10^{22}–10^{25} photon/(cm^2 s) in semiconductors InAs, InSb, and $Cd_xHg_{1-x}Te$ [2]. The thermomagnetic component is markedly influencing PME photoresponse at fairly high EHP heating degree only, when exciting light flux reaches $J_0 > 10^{23}$ photon/(cm^2 s). Only the electron component of EHP is heated up when light flux J_0 is in the range of 10^{23}–10^{25} photon/(cm^2 s). In other words, $\Delta T(x,t) \cong \Delta T_{\rm e}(x,t)$ is the case, where subscript e denotes electron component of EHP. Moreover, the signal of the thermomagnetic PME component is opposite in sign to the diffusion component signal, due to unequal heating of the EHP components. As a consequence, the pulse of the multiple photoresponse changes its form when laser light intensity is augmented. Saturation of the signal amplitude is firstly observed during increase of excitation. Then the signal swoops in the middle of pulse and photoresponse undergoes double sign inversion further, when exceeding the critical excitation flux value $J_{\rm c}$ (see inset in Fig. 2). The spectra of electric signal broaden by an order of magnitude to super high frequencies (SHF) because of the complex form of photoresponse [4]. As follows from the second equation of the system (2), the change in the photoresponse form is determined by electron temperature $\Delta T_{\rm e}(x,t)$ increase kinetics, because the law $\Delta n(x,t) \sim J_0^{1/3}$ holds for the whole range of above-mentioned light intensities. The EHP heating up kinetics depends on laser light energy balance in excited EHP. It is described by the following system of the energy balance equations [3]:

$$gE_i^{\rm eff} + \sum_j \left(\frac{{\rm d}E_i}{{\rm d}t}\right)_j \Delta n = 0\,, \tag{3}$$

where $E_i^{\rm eff}$ denotes effective excess energy, $i \equiv {\rm e}, {\rm h}$ are EHP electron and hole component subscripts, $j \equiv {\rm r}$, ph, e-h are energy exchange channel subscripts (r – recombination, ph – phonon, e-h – electron–hole).

3. Parameters and results of investigations

Obtained experimental results proved by the theoretical calculations [3] show that EHP hole component temperature in investigated semiconductors is practically unchangeable up to light fluxes of $J_0 \sim 10^{25}$ photon/(cm^2 s). EHP electron component tem-

perature dependence in the semiconductors excited by neodymium laser irradiation is shown in Fig. 1. Excess of the electron temperature $\Delta T_{\rm e}(I_0)$ is well-approximated by power dependence:

$$\Delta T_{\rm e}(I_0) = A_{\rm e}\left(\frac{I_0}{10^{24}}\right)^{\xi_{\rm e}}. \qquad (4)$$

Values of $A_{\rm e}$ and $\xi_{\rm e}$ parameters for InAs, InSb, and $Cd_{0.2}Hg_{0.8}Te$ semiconductors are 80, 460, 250 and 0.62, 0.69, 0.60 correspondingly [3]. As it can be seen from (4) the kinetics of the multiple PME effect photoresponse is determined mainly by $\xi_{\rm e}$, value, which is different for different semiconductors. In the case of complete double sigh inversion the slowest signal rise time must be observed in cadmium-mercury telluride and the fastest one in indium stibide crystals. The normalized photoresponse signal for different semiconductors is presented in Fig. 2. The photoresponses *1*, *2*, and *3* correspond to $\xi_{\rm e}$ value variation in the sequence from $Cd_{0.2}Hg_{0.8}Te$ to InAs and InSb. As it is shown in Fig. 2 the photoresponse notably changes in shape due to the increase of $\xi_{\rm e}$. In turn, the changes in the signal shape cause the changes in signal frequency spectra.

The frequency spectra of the multiple pulse photoresponse have been found using the discrete Fourier transform (DFT) procedure of the signals [4]. Details of the applied procedure are described in [5]. The main task of the investigation is to distinguish spectral components weaker than the level of major component up to -30 dB. To increase the number of samples with increasing the harmonics number the linear interpolation of discrete photoresponse function $x[n]$ between nodes n has been introduced. The Hamming window was used for optimum relationship between the major lobe and side lobes. The most practically attractive case of the PME signal complete double sign inversion, that corresponds to excitation intensities $J_0 \gg J_{\rm c}$, was investigated in this work. Because the Fourier coefficient values are very sensitive to parameter $\xi_{\rm e}$, the estimation accuracy in this case must be higher than in [5]. To augment the calculation accuracy the signal averaging was added to the procedure used in this paper. Interpolation technique was applied to the averaged data samples. Evaluation of integrals, which define the Fourier coefficients, was realized by numerical integration methods of MathCad package. Spectral density distribution was obtained for up to 40 harmonics or respectively 1000 MHz in the case of nanosecond excitation. The first harmonic was found to be 25 MHz.

For the sake of easy comparison of the investigation results the positive amplitudes of PME pulses were

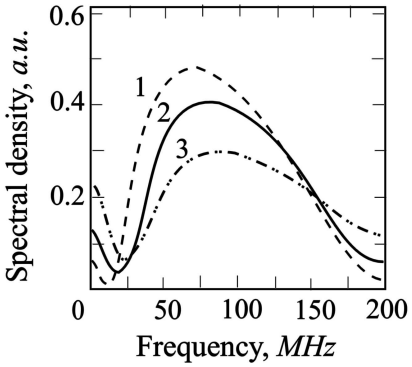

Fig. 3. Distribution of the spectral density of photoresponse signal in the range of low frequencies (spectral range of excited pulse envelope). Numbering of curves corresponds to the one in Fig. 2.

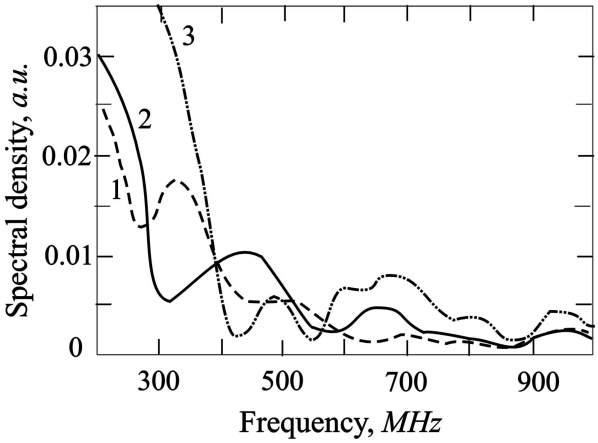

Fig. 4. Distribution of the spectral density of photoresponse signal in the range of high frequencies. Numbering of curves corresponds to the one in Fig. 2.

taken to be equal. Negative amplitudes of PME pulses are twice higher than positive ones. This relation corresponds to the real experimental results, which were obtained in InSb, and $Cd_{0.2}Hg_{0.8}Te$ illuminated by the nanosecond light pulses [3]. The results of frequency spectra obtained using DFT analysis are presented in Figs. 3 and 4. As it can be seen, the frequency band positions and amplitudes of spectral density distribution depend on the abruptness of the photoresponse double sigh inversion and also on the position of negative part of the pulse in regard to the start of excitation pulse. As it can be seen in Fig. 3 the main part of pulse power remains in the low frequency range of 50–100 MHz of nanosecond laser pulse envelope. Position of the band in frequency scale is changing insignificantly when the signal parameters are changed. Relative contribution of low frequencies decreases, however, when the negative pulse extremum is located nearer to the excitation start point, when the negative slope is shorter. In contrast to this, the contribution of

high frequencies markedly increases by increasing the speed of PME signal inversion, as it is shown in Fig. 4. Thus at frequency of 350 MHz, satisfying the condition $\nu_{\mathrm{AD}} \approx 10 \cdot (\Delta t_{\mathrm{imp}})^{-1}$ for duration of laser pulse Δt_{imp} = 40 ns, spectral density function value exceeds 1%. This value is noticeably greater than it was being obtained for symmetric pulse [5]. Furthermore, the bands of the greater frequencies appear at frequencies of 450 and 700 MHz. The position of those satisfies the relationship $\nu'_{\mathrm{AD}} \approx 50 \cdot (\Delta t_{\mathrm{imp}})^{-1}$. Thus one can deduce that there is the possibility to control UHF bands position by guiding EHP heating kinetics. It is expected that EHP heating kinetics remains unchangeable while using the picosecond exciting laser pulses. Then, extrapolating to the picosecond exciting laser pulses it is expected to obtain adequate high frequency bands beside 5–25 THz frequency range.

4. Conclusions

It was shown that the shape of the pulsed multiple PME signal is highly influenced by heating of nonequilibrium EHP in narrow gap semiconductors at strong laser light excitation. Thus the frequency spectra of the multiple PME pulse have been effectively controlled by EHP heating kinetics. The theoretical investigation has been performed of the pulsed PME signals using the improved DFT procedure in narrow gap semiconductors InAs, InSb, and $Cd_{0.2}Hg_{0.8}Te$. It was shown that the high frequency spectra part of the multiple PME signal highly exceeds the laser pulse envelope frequency spectra. The possibility to generate UHF and to control the high frequency band position has been revealed up to THz range using picosecond excitation of narrow gap semiconductors InAs, InSb, and $Cd_{0.2}Hg_{0.8}Te$.

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KRŪVININKŲ KAITIMO KINETIKOS ĮTAKA SUDĖTINIO FOTOMAGNETOELEKTRINIO REIŠKINIO IMPULSINIO FOTOATSAKO DAŽNIŲ SPEKTRUI

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Santrauka

Atlikti sudėtinio fotomagnetoelektrinio reiškinio, nulemto elektronų ir skylučių plazmos tankio ir temperatūros gradientų, impulsinio fotoatsako dažnių spektrinio tankio tyrimai siauratarpiuose puslaidininkiuose InAs, InSb ir $Cd_{0,2}Hg_{0,8}Te$. Parodyta, kad elektronų kaitimo kinetika efektyviai veikia impulsinio fotoatsako aukštadažnę spektro dalį. Daroma išvada, kad tai leidžia valdyti aukštųjų dažnių spinduliuotę iš spinduolio, veikiančio sudėtinio fotomagnetoelektrinio reiškinio pagrindu, keičiant žadinančio lazerio impulso trukmę ir naudojamą siauro draudžiamųjų energijų tarpo puslaidininkį. Nurodoma, kad, panaudojus pikosekundžių trukmės impulsus, generuojami aukšti dažniai siekia terahercų ruožą.