Proceedings of the XXXVIII International School and Conference on the Physics of Semiconductors "Jaszowiec" 2009

Dispersion Law with a Low-Energy Non-Parabolicity for the Charge Carriers in the In_4Se_3 Crystal and Related Effects

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The influence of parameters of the dispersion law exhibiting a low-energy non-parabolicity for the In_4Se_3 crystal on the plasma-electric effect occurring in the non-equilibrium plasma of this semiconductor was investigated under the circumstances that a longitudinal plasma wave propagates in its non-equilibrium plasma.

PACS numbers: 71.15.Mb, 71.20.−b, 72.30.+q

1. Introduction

Peculiarities of the dispersion laws for charge carriers are well noticeable in strong electric fields [1]. Such peculiarities can be expected for low-symmetry semiconductors with a great number of atoms in the unit cell. In particular, a new type of the dispersion law with a low-energy non-parabolicity has been obtained for a layered In_4Se_3 crystal (D_{2h}^{12}, $Pnnm$) [2–5], based upon band structure calculations

$$E\,(k_i) = A + B_i k_i^2 + C_i k_i^4, \quad i = x, y, z, \tag{1}$$

where $|C_i| \gg |B_i|$ and they have opposite sign. It was shown that one can influence their values by applying an external pressure and by doping [4, 6]. The dispersion law (1) is not in contradiction with the symmetry principles of its formation for the one-dimensional representation that describes the upper state of the valence band in the Γ point. Due to the presence of the symmetry center in this crystal, taking into account the spin and spin–orbit interaction cannot change the functional dependence of this dispersion law. It was used for an explanation of some peculiarities of the kinetic properties in this crystal [7]. The existence of the condenson states owing to the electron–phonon interaction [3, 5] is also related to this dispersion law. Experimental investigations of the photoemission spectrum of the In_4Se_3 crystal [8] have confirmed the unusual dispersion law present for its charge carriers.

2. Plasma-electric effect in In_4Se_3

We discuss in this paper the plasma-electric effect at the presence of a strong electric field applied to the In_4Se_3 crystal. We will show that this effect is analogous to that of Te crystal whose dispersion law for holes $E(\boldsymbol{k}) = Ak^2 + B_z k_z^2 \pm \sqrt{S^2 k_z^2 + \Delta^2}$ [9, 10] is due to spin–orbit interaction and whose shape of the two shifted minima is similar to (1). As is known [11], electrons and holes in a semiconductor create a non-equilibrium plasma when the semiconductor is in a strong (heating) electric field. The plasma vibrations arise in this non-equilibrium plasma. When a travelling wave (sound, electromagnetic) propagates in plasma it drags charge carriers which leads to the additional constant electric current. This phenomenon is called the plasma-electric effect [12]. The amplitude and frequency of plasma vibrations depend essentially on the dispersion law of charge carriers and they influence the electric current caused by the plasma-electric effect, as was shown for the Te crystal [13, 14]. Let the longitudinal electromagnetic wave $\boldsymbol{E}(\boldsymbol{r}, t) = \boldsymbol{E}_0 \cos(\omega_0 t - \boldsymbol{k}_0 \boldsymbol{r})$, characteristic for plasma, propagates through a non-equilibrium plasma of the layered In_4Se_3 crystal. The state of plasma is described by the non-equilibrium distribution function

$$f\,(\boldsymbol{p}, \boldsymbol{r}, t) = f\,(\boldsymbol{p}) + \varphi_1\,(\boldsymbol{p}, \boldsymbol{r}, t) + \varphi_2\,(\boldsymbol{p}, \boldsymbol{r}, t)\,, \tag{2}$$

where $f(\boldsymbol{p}) = f_0^{\rm e}(\boldsymbol{p}) + f_1(\boldsymbol{p}), f_0^{\rm e}(\boldsymbol{p})$ is the Boltzmann distribution function that defines the equilibrium state of the non-equilibrium plasma of the electron temperature $T_{\rm e}$, $f_1(\boldsymbol{p})$ is a non-equilibrium correction, connected with the presence of the external electric field and which is expressed by the equilibrium Boltzmann distribution function at the temperature T_l of the crystal lattice: $f_1(\boldsymbol{p}) = f_0^l(\boldsymbol{p})\Phi(\boldsymbol{p})$. $\Phi(\boldsymbol{p})$, in turn, can be presented as a series with respect to a small parameter ε, $\Phi(\boldsymbol{p}) = \sum_{n,\alpha} c_n^{(\alpha)} p_\alpha \varepsilon^n$, $\alpha = x, y, z$, taking into account first terms $n = 0$, 1. $c_n^{(\alpha)}$ are variational parameters that depend on the intensity $\boldsymbol{F}$ of the external field [13, 14]. In the case of the dispersion law (1), a small parameter ε expresses a deviation of this law from the biquadratic dependence with respect to wave vector components, at small values of $\boldsymbol{k}$. $\varphi_1(\boldsymbol{p}, \boldsymbol{r}, t)$ and $\varphi_2(\boldsymbol{p}, \boldsymbol{r}, t)$ in Eq. (2)

are two corrections of the first and second order, respectively. The function (2) satisfies the Boltzmann kinetic equation

$$\left[\frac{\partial}{\partial t}+\boldsymbol{v}\frac{\partial}{\partial \boldsymbol{r}}+e_0\boldsymbol{F}\frac{\partial}{\partial \boldsymbol{p}}+e_0\boldsymbol{E}(\boldsymbol{r},t)\frac{\partial}{\partial \boldsymbol{p}}-\hat{\nu}(\boldsymbol{p})\right] \times f(\boldsymbol{p},\boldsymbol{r},t)=0, \quad (3)$$

where $\hat{\nu}(\boldsymbol{p})$ is a collision operator. Fourier components of the current related to the function $\varphi_2(\boldsymbol{p},\boldsymbol{r},t)$ are given by the relation

$$I_\alpha(\boldsymbol{k},\omega)=e_0\int\frac{\partial\varepsilon}{\partial p_\alpha}\varphi_2(\boldsymbol{p},\boldsymbol{k},\omega)\,\mathrm{d}\boldsymbol{p}. \quad (4)$$

Applying the subsequent approximation procedure [13, 14] we express $\varphi_1(\boldsymbol{p},\boldsymbol{r},t)$ and $\varphi_2(\boldsymbol{p},\boldsymbol{r},t)$ corrections by $f(\boldsymbol{p})$. Based upon Eq. (4) the following expression for the Fourier current component is obtained:

$$\overline{I_\alpha(\boldsymbol{k},\omega)} = \frac{e_0^3}{2\omega_0^2}\int\frac{\partial\varepsilon}{\partial p_\alpha}\left\{\left[\left(\boldsymbol{E}_0\frac{\partial}{\partial\boldsymbol{p}}\right)+\frac{1}{\nu(\boldsymbol{p})}\left(\boldsymbol{E}_0\frac{\partial\nu(\boldsymbol{p})}{\partial\boldsymbol{p}}\right)\right] \times\left[\left(1+\frac{2\boldsymbol{k}_0\boldsymbol{v}}{\omega_0}\right)\left(\boldsymbol{E}_0\frac{\partial}{\partial\boldsymbol{p}}\right)\right]\right\}f(\boldsymbol{p})\,\mathrm{d}\boldsymbol{p} \quad (5)$$

under conditions that $e_0\boldsymbol{F}/\bar{p}\nu<1$ ($\bar{p}$ is the average momentum, $\nu(\boldsymbol{p})$ is the effective collision frequency), $\frac{k_0\bar{v}}{\omega_0}<1$ ($\bar{v}$ is the average thermal velocity of carriers) which testifies to a small spatial dispersion, and under condition that a longitudinal wave exists $\nu/\omega_0<1$, where ν is a collision frequency [15]. Substituting into (5) the dispersion law (1) with the coefficients for the In_4Se_3 crystal presented in [4] as well as the distribution function $f(\boldsymbol{p})$, one obtains after integration (in the case $\nu(\boldsymbol{p})=\mathrm{const}$) the following expression for the x-th component of the current:

$$I_x=I_{x_1}+I_{x_2},$$

$$I_{x_1}=\frac{12ne_0^3E_{0x}^2C_xT_l}{\omega_0^2\hbar^2B_x}\frac{Q_1}{Q_0}\left[c_0^x+c_1^xT_l\left(1-\frac{Q_2}{Q_1}\right)\right],$$

$$I_{x_2}=\frac{12ne_0^3k_{0x}E_{0x}^2B_x^2}{\omega_0^3\hbar^4}\times\left(1-\frac{24C_xT_\mathrm{e}}{B_x^2}\frac{Q_1}{Q_0}+\frac{60C_x^2T_\mathrm{e}^2}{B_x^4}\frac{Q_2}{Q_0}\right), \quad (6)$$

where $Q_0=\int_0^\infty \mathrm{e}^{x^2-ax^4}\,\mathrm{d}x$, $Q_1=\int_0^\infty \mathrm{e}^{x^2-ax^4}x^2\,\mathrm{d}x$, $Q_2=\int_0^\infty \mathrm{e}^{x^2-ax^4}x^4\,\mathrm{d}x$, $a=\frac{C_xT_\mathrm{e}}{B_x^2}$, $c_0^x\approx c_1^xT_l\approx 2e_0nF_x\frac{Q_1}{Q_0}(-1+2\frac{C_xT_l}{B_x^2}\frac{Q_2}{Q_1})$. In the case of quadratic dispersion law ($C_x=0$) $I_{x_1}=0$. I_{x_2} describes exclusively the plasma-electric current resulting from a small spatial dispersion and it differs essentially from the corresponding one in the case of the quadratic dispersion law. It should be noted that to obtain Eq. (6) a model of the dispersion law was used that takes into account non--parabolicity in the direction k_x which corresponds to the experimentally confirmed dispersion law of holes in the In_4Se_3 crystal [8]. The modeling of the temperature dependence of the components I_{x_1} and I_{x_2} shows that at low temperatures both of them considerably increase and then I_{x_1} drops while I_{x_2} still increases but the speed of its growth continuously slows down. The plasma-electric effect depends essentially on values of the parameters of the dispersion law (1) and it is more pronounced when the non-parabolic term is dominant already at small k_x values. When only the non-parabolic term in (1) is taken into account, as it takes place for the dispersion law of holes in a non-deformed InSe crystal [4], the intensity of the current increases linearly with C_x and T_e. The investigated plasma-electric effect in the In_4Se_3 crystal in comparison with that of Te is more enhanced, the temperature coefficient $\frac{\mathrm{d}I_{x2}}{\mathrm{d}T_\mathrm{e}}$ is greater in the low temperature range and, having positive sign, decreases slowly at higher temperatures, while for the Te crystal it tends to zero.

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