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Electric properties of $TlInS_2$ single crystals

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Abstract. Injection currents are studied in high-resistive layer of $TlInS_2$ single crystals and the following parameters were determined: equilibrium concentration of charge carriers in the allowed band $p_0 = 1.67 \cdot 10^{10}$ cm^{-3}; concentration of traps $N_t = 10^{12}$cm^{-3}; capture factor $\theta = 0.17$; mobility of charge carriers $\mu = 3.3 \cdot 10^{-3}$cm^2/V·s; the depth of trap level responsible for the injection current $E_t = 0.44$ eV.

Keywords: injection current, single crystal, charge transport, space charge, capture factor.

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1. Introduction

$TlInS_2$ single crystals are typical representatives of layered wide-gap semiconductors that are characterized by the low mobility of current carriers. Such materials are very perspective for creating solid state electron devices on their base.

Layered crystals usually contain structural defects, such as dislocations and vacancies. The presence of these defects results in a high density of localized states near the Fermi level.

Studying the charge transport processes in layer $TlInS_2$ single crystals at constant and an alternating current has shown that at low temperatures ($T < 200$ K) and frequencies $f = 10^5 \ldots 10^6$ Hz the hopping conductivity on localized near the Fermi level states takes place in them [1, 2].

In semiconductors with a high density of localized states in the vicinity of the Fermi level, the hopping conductivity in the forbidden band in a constant electric field and at low temperatures dominates over the conductivity caused by thermoactivated charge carriers in the allowed band. However, near the room temperature and above charge transport in semiconductors at a direct current basically occurs in the allowed band.

It was of interest to study non-ohmic conductivity in the allowed band of $TlInS_2$ single crystal and to establish the mechanism of charge transport, which was the purpose of this work.

2. Experimental results and discussion

Samples from $TlInS_2$ for measurements were obtained by spalling along C-axis of the natural spall from massive single crystal and had the thickness (200…280) μm. $TlInS_2$ samples formed flat capacitors whose plane was perpendicular to the crystalline C-axis. The capacitor plate area was $(4 \ldots 6) \cdot 10^{-2}$ cm^2. Ohmic contacts of samples were made using Ag paste.

In the figure, current-voltage characteristics (CVC) of Ag-$TlInS_2$-Ag sample are shown at the temperatures 293 (curve 1); 307 (2); 341 (3) and 381 K (4). CVCs at all the temperatures were characterized by enough long quadratic portion ($I \sim V^2$). At the temperatures 293, 307, and 341 K the square-law portion was preceded with short ohmic portion ($I \sim V$). And at 381 K for all the investigated electric voltages $I \sim V^2$. At 293 K, the CVC is characterized with super linear portion ($I \sim V^{6.5}$) after the quadratic portion.

The experimental results obtained in this study were interpreted within the Lampert theory for an electric current limited by the space charge (SCLC) [3].

In semiconductors, this theory allows to receive data on local levels in the forbidden band. Local levels render strong influence on the injection current caused by an external electric voltage. Thus, local states define not only change of a current, for example, reduction of an injection current owing to localization of charge carriers, but also the shape of CVC.

Within the limits of the SCLC theory in semiconductors with traps at times of flight of carriers through the semiconductor, exceeding times of capture for traps, up to a voltage of full filling of traps the current limited by space charge should flow, expression for which is as follows [3]:

$$I = \frac{9}{8} \varepsilon \varepsilon_0 \mu \theta \frac{V^2}{L^3}, \quad (1)$$

where ε_0 is the dielectric constant; ε is the dielectric permittivity of a crystal; θ is the capture factor; L is the thickness of a crystal; μ is the mobility of charge carriers; V is the applied electric voltage. At achievement of a voltage of full filling of traps (V_f) on the CVC of $TlInS_2$ sample, there is a portion of abrupt growth of the current (Figure, curve 1). In this case, determining from experiment V_f, we have calculated concentration of traps under the formula:

$$N_t = 1.1 \cdot 10^6 \frac{\varepsilon V_f}{L^2}, \quad (2)$$

$N_t = 10^{12}\,cm^{-3}$. We also determined the value of the equilibrium concentration of the basic charge carriers $p_0 = 1.67 \cdot 10^{10}\,cm^{-3}$ in $TlInS_2$ from the relation of the currents corresponding to two voltages V_f and $2V_f$ [3]:

$$p_0 = \frac{N_t I(V_f)}{I(2V_f)}. \quad (3)$$

For the sample of $TlInS_2$ single crystal at 293 K, we have determined also the factor of capture:

$$\theta = 1.8 \cdot 10^{-6} \frac{p_0 L^2}{\varepsilon V_x}, \quad (4)$$

which was equal to 0.17. In calculations for the dielectric permittivity of $TlInS_2$ single crystal, the value $\varepsilon = 10$ determined experimentally in [2] was taken. In the formula (4), V_x is such a voltage, at which the concentration of free injected charge carriers becomes comparable with the equilibrium concentration, in other words, it is a voltage of transition from an ohmic portion of CVC to the square-law one. Knowing the specific dark conductivity of $TlInS_2$ single crystal sample at 293 K $\sigma_0 = 10^{-11}\,Ohm^{-1}cm^{-1}$, under the formula

$$\sigma_0 = p_0 e \mu_0 \quad (5)$$

we have calculated the mobility of holes at the voltages corresponding to the ohmic portion of CVC: $\mu_0 = 3.7 \cdot 10^{-3}\,cm^2/V \cdot s$. Using experimental results under the formula (1), we have estimated the mobility of carriers at the voltages corresponding to the square-law portion of CVC for $TlInS_2$ single crystal: $\mu = 3.3 \cdot 10^{-3}\,cm^2/V \cdot s$. Apparently, both values of mobility, *i.e.* μ_0 and μ, practically coincide.

Knowing values of N_t and θ under the formula

$$E_t = kT \ln \frac{N_p}{2 \theta N_t}, \quad (6)$$

where N_p is the effective density of quantum states in the allowed band of a crystal ($\sim 10^{19}\,cm^{-3}$), we have estimated the depth of the local level responsible for an injection current: $E_t = 0.44$ eV. The level with the activation energy ~0.4 eV has been also revealed from the temperature dependence of the ohmic conductivity across layers of $TlInS_2$ single crystal [1] and from spectra of a photocurrent [4].

Absence an abrupt portion on CVC of Ag-$TlInS_2$-Ag sample at $T > 300$ K is connected with the fact that at these temperatures thermal emission of charge carriers began from a level 0.4 eV to the allowed band and full filling of traps did not manage to be achieved (Figure, curves 2-4).

An important feature of the current limited by the space charge is that the electric charge in this case cannot exceed the quantity $C_g V$, where C_g is the geometric capacitance of the sample and V is the voltage imposed across the sample. For the samples studied in this work, the geometric capacitance was estimated as $\sim 10^{-12}$ F.

The maximum voltage across the sample amounted to 150 V. This means that the electric charge of the system Ag-$TlInS_2$-Ag is equal to $1.5 \cdot 10^{-10}$ C. The charge per unit area Q_{max} allowed to be transported by the space charge limitations is $3.8 \cdot 10^{-9}\,C/cm^2$.

Illumination of $TlInS_2$ sample, in which the current of monopolar injection was supported by white light, leads to increase of SCLC (see Figure, curve 5).

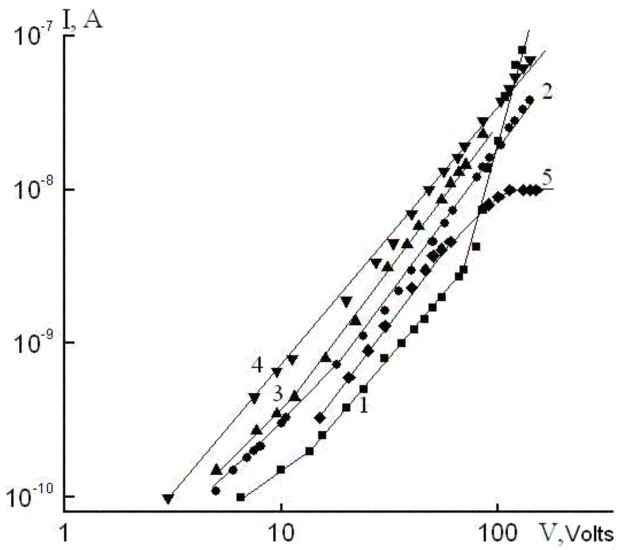

Figure. Current-voltage characteristics of dark (curves 1-4) and photocurrent (curve 5) of Ag-$TlInS_2$-Ag system. Curves 1 and 5 were measured at the temperatures 293 K; 2 – 304, 3 – 341, 4 – 381.

It testifies that the carriers injected from the contact and grasped on traps, absorb photons and are thrown out to the allowed band. *I.e.*, under influence of light the space charge is redistributed between states, on which there is a transport, and states, in which there are grasped carriers.

Thus, the full space charge in a crystal remains constant; it is determined by the applied voltage and geometry of the sample. It is seen from Figure that a photocurrent limited by space charge (curve 5), also as well as dark SCLC, changes as V^2, that is in the consent with SCLC theory.

Near to a voltage of full filling of traps, the dependence of a photocurrent on a voltage weakens, CVCs of dark and photocurrent (curves 1 and 5) are crossed, and then the photocurrent is saturated and ceases to depend on a voltage.

Saturation of a photocurrent with an electric field increase speaks about an exhaustion of the ohmic contact: in high electric fields the contact is not capable to provide any more sufficient number of electrons for establishment of SCLC in volume. *I.e.*, the centers of capture of charge carriers essentially influence on a photocurrent. In this connection, the effects connected with capture of charge carriers determine the sensitivity and operating speed of semiconductor devices.

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