CHARGE ACCUMULATION IN M – TlGaSe$_2$ – M SYSTEMS

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ABSTRACT

It is shown that the falling dark-current relaxation, hysteresis in the current-voltage characteristic, and charge accumulation in M – TlGaSe$_2$ – M systems are caused by the passage of an injection current via localized states in the band gap of semiconductor single crystals. The contact capacitance and charge accumulation region in a TlGaSe$_2$ single crystal, the maximum density of accumulated charge, and the concentration of traps responsible for charge accumulation in M – TlGaSe$_2$ – M systems are found to be   C$_c$= 600 pF,   d$_c$ = 1.56×10^{-4}cm, Q$_{max}$ = 2.4×10^{-7} C/cm^2, μ_f = 3.75×10^{-4}cm^2/(V·s), and N = 10^{16} cm^{-3}.

Keywords: charge transport, current relaxation, contact capacitance, charge accumulation.

I. INTRODUCTION

Results of our previous studies [1, 2] have shown that in layered single crystals of TlGaSe$_2$, a hopping mechanism of charge transport over states localized near the Fermi level takes place both in a constant and in a variable current. These states are caused by the presence in TlGaSe$_2$ single crystals of structural defects such as vacancies, implantation impurities, and dislocations. The density of localized states at the Fermi level in TlGaSe$_2$ single crystals, calculated by us from the experimental results of the above-indicated studies, lies in the range $10^{18} \div 10^{19}$eV^{-1}cm^{-3} for different samples. It should be noted that our results [1, 2] pertain to the case in which the amplitude of the electric field applied to the TlGaSe$_2$ sample, whether constant or variable, corresponds to the ohmic region of the current-voltage

characteristic. It is of interest to examine the processes of charge transport in TlGaSe$_2$ single crystals in the regime of carrier injection from a contact. Transport of charge injected from the contact into the bulk of a semiconductor can be effected both through the allowed band [3] and with the help of local mobile centers that possess comparatively deep levels of free charge-carrier trapping [4].

II. EXPERIMENTAL RESULTS AND DISCUSSION

The single crystals of TlGaSe$_2$ investigated in the present study has a high electrical resistivity and a low concentration of free charge carriers. In addition, the TlGaSe$_2$ crystals are characterized by an abundance of localized states in the band gap with energies 0.54 eV and 0.8 –1.1 eV [1, 5, 6], over which the hopping conductivity takes place. It is precisely under these conditions that the mechanism for passage of an injection current via the band gap of a semiconductor can be manifested [4].

TlGaSe$_2$ crystals were grown by the Bridgman method of guided crystallization from a melt at the rate of 0.5 mm/h. The crystals were cooled to room temperature at a rate of 5 – 10 K/min.

Samples of the TlGaSe$_2$ single crystals were prepared in the sandwich form so that the electric field was applied to them along the C axis, i.e., transverse to the natural layers of the single crystals. To prepare the metal – TlGaSe$_2$ – metal systems, we used In – Ga eutectic for the injecting contacts. The thickness of the single crystals of TlGaSe$_2$ ranged from 150 to 200 μm, and the subcontact area was ~5 ×10^{-2}cm^2. The dark resistivity of the TlGaSe$_2$ samples ranged from 5 ×10^6 to 10^7 Ω·cm at T = 300 K.

In the course of our examination of charge transport processes in TlGaSe$_2$, we found that when we applied a constant voltage to the M – TlGaSe$_2$ – M sample, the dark current flowing in it varied with time. The nature of this variation depends on the magnitude of the applied voltage. At low enough voltages a falling relaxation of the current is observed and after roughly 1.5 min steady-state is reached. With increase of the voltage, after an insignificant drop in the time dependence a growing branch appears; the current then reaches saturation.

Since the magnitude of the current depends on the length of time the voltage is applied, the current-voltage characteristics of the TlGaSe$_2$ test samples revealed the presence of hysteresis; i.e., the forward and reserve branches of the current-voltage characteristics do not coincide; the forward branch was measured when the voltage was increased, and the reverse branch was measured with decreasing voltage. Charge accumulation took place in the M – TlGaSe$_2$ – M samples.

The enumerated peculiarities of current flow in TlGaSe$_2$ single crystals can be explained on the basis of the mechanism of charge transport proposed in Ref. [4]. According to this mechanism, in the M – TlGaSe$_2$ – M samples the charge injected from one contact is transported mainly by way of the band gap of the semiconductor with the help of local centers to the opposite contact. In this case, transfer of the charge carriers from the semiconductor to the metal is hindered by a potential barrier at the interface, which causes the charge to accumulate near this contact. The accumulation of this charge leads to a redistribution of the voltage applied to the crystal. Concentration of the field near the contact can lead to double injection of charge carriers into the crystal. As a result, the current may increase with time (the leakage current J$_1$). According to the indicated mechanism, the time dependence of the current for J$_1$ << J has the form

$$J = VC_c \frac{\tau}{(\tau + t)^2}, \qquad (1)$$

$$\tau = L^3 / \mu_f d_c V, \qquad (2)$$

where V is the applied external voltage, C$_c$ is the electrical capacitance of the contact, τ is the charging time of the contact, L is the thickness of the crystal, μ_f is the mobility associated with charge transport aided by the local centers, and d$_c$ is the linear region of charge buildup in the crystal.

For short voltage application times

$$J = \mu_f \varepsilon_0 \varepsilon S V^2 / L^3, \qquad (3)$$

where ε is the dielectric constant of the crystal, ε_0 is the dielectric constant in vacuum, and S is the subcontact area.

In this case the voltage dependence of the current in the system M – TlGaSe$_2$ – M for short voltage application time obeys a quadratic law as in the case of charge carrier transport via the band gap [3]. But in Eq. (3) instead of $\mu\theta$ (μ is the mobility of the carriers in the band gap and θ is the trapping factor) we find the mobility which is associated with the charge transport by way of the states localized in the band gap.

Such a dependence of the current on the voltage was experimentally confirmed by our investigations. The current-voltage characteristic of M – TlGaSe$_2$ – M sample consists of a quadratic segment J ~ V^2, which yields place to a segment with abrupt growth J ~ V^5. On the I–V characteristic the quadratic segment is observed for those voltages at which the falling relaxation takes place. The segment with abrupt growth takes place at those voltages for which the current grows with time.

From the experimental dependences J(t) we determined the charging time of the contact, $\tau = 10$ s, and

from Eq. (2) we estimated the charge-carrier mobility in the band gap of TlGaSe$_2$: $\mu_f = 3.75\times10^{-4}$cm^2/(V·s).

As was already mentioned, with falling relaxation of the current, the charge in the M – TlGaSe$_2$ – M samples is accumulated. Figure shows the dependence of accumulated charge on polarization time for M – TlGaSe$_2$ – M system. This Q(t)-dependence corresponds to theoretical formula

$$Q = VC_c \frac{t}{t + \tau}, \qquad (4)$$

obtained in [4]. If the M – TlGaSe$_2$ – M samples have identical resistances before polarization in both polarities of the external electric field, then after a special polarization the samples in one polarity have a resistance of 200 MΩ and in the other polarity they have a resistance of 3 MΩ. The electrical capacitance of the samples, measured after polarization, was 600 pF at 1000 Hz. The geometrical capacitance of the TlGaSe$_2$ samples (C = $\varepsilon\varepsilon_0$S/L) was 5 pF. In other words, the amount of charge accumulated in the TlGaSe$_2$ samples during falling relaxation was significantly greater (by more than two orders of magnitude) than the charge due to the geometrical capacitance. It can thus be concluded that charge accumulation takes place in a narrow region of the TlGaSe$_2$ single crystal. Associated with this charge is a reverse emf, which also causes the current that is flowing through the TlGaSe$_2$ single crystal to drop. The region of current buildup, calculated from the formula d$_c$ = $\varepsilon\varepsilon_0$S/C$_c$ (where C$_c$ = 600 pF is the capacitance of the contact), was 1.55$\times10^{-4}$cm. The maximum charge accumulated in the M – TlGaSe$_2$ – M sample was 1.2$\times10^{-8}$ C, which corresponds to a maximum charge density Q$_{max}$ = 2.4$\times10^{-7}$ C/cm^2. Determining the geometric dimensions of the region of charge buildup and the charge density in this region from the formula

$$N = \frac{Q_{max}}{e d_c S}, \qquad (5)$$

(where e is the charge of the electron), we estimated the concentration of the traps responsible for the charge accumulation in the samples of the single crystal TlGaSe$_2$: N = 10^{16} cm^{-3}.
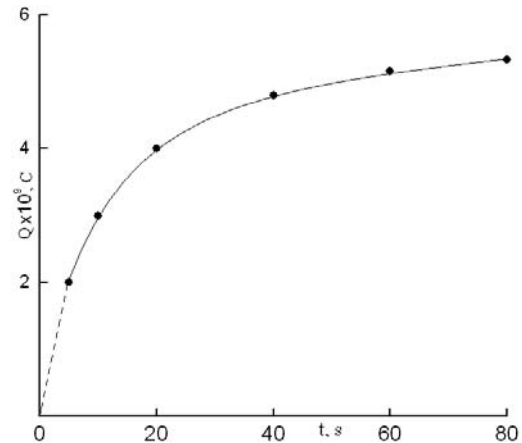
Figure. Time dependence of accumulated in M – TlGaSe$_2$ – M system charge at polarization voltage V$_{pol}$ = 10 V.

III. CONCLUSION

The accumulated charge is removed by heating the M – TlGaSe$_2$ – M sample while shorted out and also by irradiating it with light in the photosensitivity region of the crystal. Leakage of the accumulated charge takes place at voltages corresponding to the segment of abrupt current growth (J ~ V^5) in the current-voltage characteristic of the sample.

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