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Investigation of the phenomenon of current transition $EuGa_2S_4$:Er^{3+} crystals

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The results of studying the static current-voltage characteristics of $EuGa_2S_4$:Er^{3+}crystals at room temperature are presented. The mechanism of current passage in them is revealed. The height of the potential barrier at the metal-semiconductor interface (0.9 eV), the relative permittivity of crystals (3.1), and the concentration of traps ($N \approx 7.14 \cdot 10^{16}\,\mathrm{cm}^{-3}$) were calculated, and the shape of the potential well for the electrons trapped in the traps was determined

Keywords: current-voltage, metal–semiconductor, crystals, potential barrier,erbium

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Europium tetrachalcogenides $EuGa_2S_4$ from group $AB_2^{III}C_4^{VI}$ (A — Eu, Yb, Dy; B — Ga, In; C — S, Se, Te) with an incomplete inner $4f$ shell, which are activated by rare-earth elements (specifically, erbium), have been studied extensively since the moment of their synthesis, and several intriguing physical properties have been revealed in the process. A considerable number of papers [1–6] focused on the photo-, electro-, and thermoluminescence properties of these crystals have already been published. The results of experiments performed in these studies provided an opportunity to determine certain key parameters of photoluminescence (red shift, Stokes shift, lifetime of Er^{3+} ions, etc.), electroluminescence, and thermoluminescence (frequency factor, activation energy, capture cross section, concentration of trap levels, etc.). Dependences of the photoluminescence intensity on the sample temperature and the excitation radiation power were determined, and it was demonstrated how erbium ions induce anti-Stokes luminescence and extend the retention time of electrons at traps, which specifies the fluorescence duration, in the indicated crystals.

The analysis of results of our studies revealed that $EuGa_2S_4$:Er crystals are novel anti-Stokes luminescent materials for fiber-optic communication lines, IR lasers, and night vision devices.

The present study is focused on the examination of current passage in $EuGa_2S_4$:Er^{3+} crystals and the determination of certain parameters.

$EuGa_2S_4$ crystals were synthesized in a solid-state reaction of binary compounds EuS and Ga_2S_3. A rare-earth element (erbium), which was introduced into the matrix in the form of erbium fluoride ErF_3, was used as an activator. Synthesis was performed at 1100°C for 5 h; the temperature was then reduced to 800°C, and the samples were annealed for 4 h [1].

Static current–voltage characteristics (CVCs) were examined using a setup that was described in [7]. A battery with an internal resistance of 1 MΩ served as a power source. The voltage across the sample was measured with a V7-16 digital voltmeter. An electrometric amplifier type U5-6, which allows one to measure currents ranging from $5 \cdot 10^{-15}$ to 10^{-6} A, was used to measure the current flow in the sample.

The studied sample had the shape of a narrow parallelepiped with secure indium contacts formed on its two opposite polished surfaces.

The working area of the obtained sandwich structure was $\sim 2\,\mathrm{mm}^2$, and the interelectrode distance (d) was ~ 1 mm. The crystals were n-type.

Figure 1, a presents the static CVC of the studied $EuGa_2S_4$:Er^{3+} crystal measured at room temperature. The following regions may be identified in this CVC: an Ohmic region, which extends up to a voltage of ~ 800 V; a nonlinear region in the 800–1150 V interval; and a region of steep current rise that ends with breakdown at ~ 1300 V. The passage of current in semiconductors in the nonlinear CVC region may be attributed to carrier injection from metal electrodes into a semiconductor in relatively weak electric fields and to field ionization of impurity trapping centers (or injection and field ionization acting simultaneously) in strong fields [8].

It follows from our analysis of a CVC in the nonlinear region that the variation of current with voltage is governed by exponential law $\exp U^{1/2}$ (Fig. 1, b), which is typical of both overbarrier Richardson–Schottky emission and Poole–Frenkel emission (a process [9] facilitated by the electric field of thermal excitation of electrons captured by traps into the conduction band of a semiconductor; see the formulae in [10], Fig. 2, processes *1* and *2*, respectively):

$$J_{Sch} = AT^2 \exp\left[\frac{-q(\varphi - \sqrt{qE/4\pi\varepsilon})}{kT}\right], \quad (1)$$

$$J_F = E \exp\left[\frac{-q(\varphi - \sqrt{qE/\pi\varepsilon})}{kT}\right], \quad (2)$$

where $k = 1.38 \cdot 10^{-23}$ J/K is the Boltzmann constant, ε is the material permittivity, T is absolute temperature, q is the electric charge, $A = 120\,\mathrm{A/(cm^2 \cdot K^2)}$ is the Richardson constant, $E = U/d$ is the electric-field intensity, and φ is the potential.

It follows from the comparison of these formulae that the expressions for traps with a Coulomb potential in them are almost the same.

However, the height of the potential barrier (a) at the metal–semiconductor interface (the very barrier that electrons moving from a metal to a semiconductor need to overcome) in Schottky emission is reduced by a factor of 2, which is attributable to the fixed space charge of a semiconductor (Fig. 2).

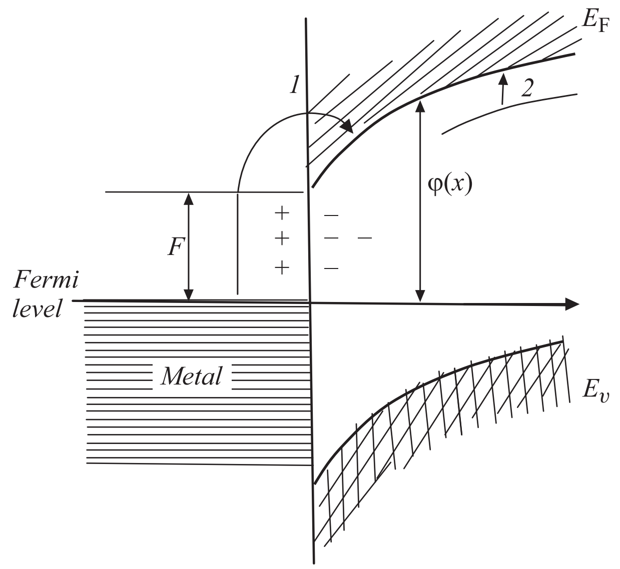

Figure 2. Energy diagram of a metal–semiconductor contact.

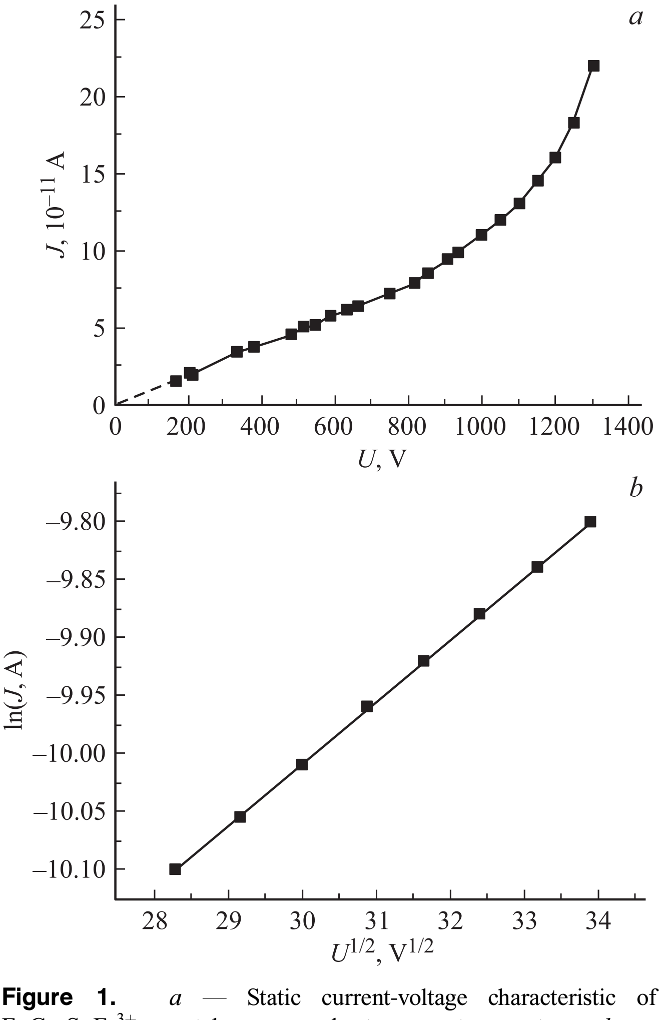

Figure 1. *a* — Static current-voltage characteristic of $EuGa_2S_4:Er^{3+}$ crystals measured at room temperature; *b* — dependence of $\ln J$ on $\sqrt{U}$ for samples at room temperature.

Applying the formula from [10]

$$\Phi = -\frac{kT}{0.43} \lg \frac{J}{SAT^2}, \quad (3)$$

where the values of $T = 293$ K, $S = 2\,\mathrm{mm}^2$, and cutoff current $J = 8 \cdot 10^{-11}$ A (the current at $U = 800$ V that corresponds to the onset of deviation from the Ohm's law; see Fig. 1, *a*) are known, we managed to find $\Phi = 0.91$ eV. This height is the same as the depth of the potential well for electrons captured by traps, the shape of which may be determined using the following expressions [11]:

$$\varphi(x) = -\frac{kT\beta}{2}\sqrt{U}, \quad (4)$$

$$x = \frac{kT\beta d}{2e}\frac{1}{\sqrt{U}}, \quad (5)$$

where $e = 1.6 \cdot 10^{-19}$ C is the electron charge, $\varphi(x)$ is the potential energy dependent on distance x to the trap measured along the electric field, and β is the slope of dependence $\lg J \sim \sqrt{U}$.

The data from Fig. 1, *b* were used to estimate $\beta \approx 0.0054\,\mathrm{V}^{-1/2}$. The shape of the potential well determined based on (4) and (5) is shown in Fig. 3.

Relation [10]

$$\beta = \frac{\sqrt{e^3}}{kT\sqrt{\pi\varepsilon\varepsilon_0 d}}$$

(where $\varepsilon_0 = 8.85 \cdot 10^{-12}$ F/m is the permittivity of vacuum) allows one to derive the expression for the relative permittivity of matter

$$\varepsilon = \frac{e^3}{\beta^2 k^2 T^2 \pi\varepsilon_0 d}, \quad (6)$$

which is needed to interpret the optical properties of materials ($\varepsilon = n^2$, where n is the refraction index of matter) and to determine the capacity of semiconductor converters.

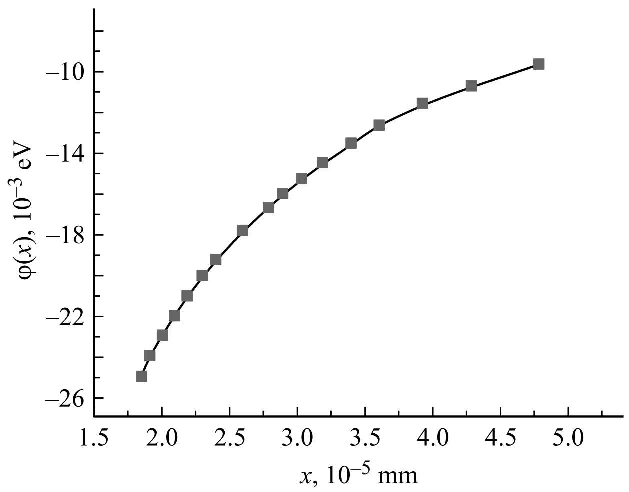

Figure 3. Shape of the potential well for trapped electrons.

The result of calculation by formula (6) was $\varepsilon = 3.1$, which is close to the value of $\varepsilon = 2.9$ reported in [5].

Since the examined compound has a significant amount of impurities (5%), traps (trapping centers) may exert a considerable influence on the passage of current (Fig. 2, process *2*). Their concentration may be determined in the following way [10]:

$$N = \left(\frac{2e}{kT\beta d}\sqrt{U}\right)^3. \quad (7)$$

It was thus determined that $N \approx 7.14 \cdot 10^{16}\,\text{cm}^{-3}$.

Thus, static CVCs in crystals $EuGa_2S_4:Er^{3+}$ were examined. The mechanism of current passage in them was established; the height of the potential barrier at the metal−semiconductor interface, the permittivity of the studied material, and the concentration of traps were determined; and the shape of the potential well for trapped electrons was identified.

Conflict of interest

The authors declare that they have no conflict of interest.

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