NONEQUILIBRIUM PHASE TRANSITIONS IN FERROMAGNETIC SEMICONDUCTORS (EuO$_{1-d}$)

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The features of metal–semiconductor kinetic phase transformation in ferromagnetic semiconductors are studied. It is shown that heat release caused by current results in a positive feedback between the current density and the sample temperature, magnetization, and thermal-spin fluctuation amplitude. The Joule heating of the sample leads to disappearance of magnetization and, as a result, to restoration of the forbidden band between the conduction and valence bands. However, the energy gap width continues to change due to an increase in the fluctuations of internal exchange fields splitting the electron states. Within the framework of the developed model, an S-shaped volt-ampere characteristic is obtained for a EuO$_{1-d}$ ferromagnetic semiconductor. The lower branch of the characteristic corresponds to a ferromagnetic metal state (a “cold” phase) and the upper one is due to a semiconductor paramagnetic state (a “hot” phase).

Keywords: metal–semiconductor kinetic phase transformation, ferromagnetic semiconductor, spin fluctuations.

1. It is known that passing current through a nonmagnetic semiconductor whose electric resistance fairly quickly decreases with increase in temperature is accompanied by self-heating. As a result, the internal temperature of the sample differs from the temperature on the sample surface. In a stationary state, it is determined by the thermal equilibrium condition

$$jU = \frac{2}{h} \lambda (T' - T),$$

where $T'$ is the internal temperature of the sample determined by the dynamic equilibrium condition and depending on the current density $j$ and applied voltage $U$, $\lambda$ is the semiconductor thermal conductivity coefficient, which is constant across the sample thickness, $T$ is the sample surface temperature equal to the environment (substrate) temperature. In so doing, the volt-ampere characteristic of the sample assumes an S-shaped character. This points to the formation of bistable states of the electron subsystem and can be interpreted as formation of “cold” and “hot” semiconductor phases between which a kinetic electron transition can take place [1–3].

A special situation poorly understood to time can occur in ferromagnetic semiconductors, where an electron transition from the metal state to the semiconductor one takes place as the temperature increases (for example, EuO$_{1-d}$, La$_{1-x}$Ca$_x$MnO$_3$ [4, 5]). In the equilibrium conditions (in the absence of external magnetic field), the conductivity and other electrical properties of these semiconductors change sharply and nonmonotonously with temperature. In so doing, the electric resistance drastically increases at a temperature somewhat higher than the magnetic phase transition temperature. In addition, in the energy intervals near the forbidden bands of these semiconductors, there are the regions of localized electron states or sharp peaks of electron state density filled by electrons with high effective masses (with low mobility) [6].
An equilibrium metal–insulator electron transition in these semiconductors was studied in [7, 8] as a function of temperature. In so doing, the phase transition was caused by a sharp temperature decrease of magnetization and energy spin splitting of electron terms accompanied by an increase in the spin density fluctuations. The results obtained allowed the authors to describe the temperature variations of electronic properties of ferromagnetic semiconductors (in particular, the energy gap width variations) both for a magnetically ordered phase [7, 8] and a paramagnetic one [8].

However, neither work considers the possibility of electron phase transformations caused by the Joule heating of the sample under the action of electric field as well as the possible effect of this field on the magnetic characteristics of ferromagnetic semiconductors. The latter is of special importance due to strong correlation between the electrical and magnetic properties of these semiconductors found experimentally and in the light of possibilities to control technically important characteristics of magnetic semiconductors.

2. To study the effect of electric field on the electron and magnetic subsystems of ferromagnetic semiconductors based on rare-earth metals, use is made of an $f$–$d$-model with allowance for the electric energy shift. For this model, the Hamiltonian is written in the following form:

$$H = H_f + H_{dd} + H_{fd}.$$  \hspace{1cm} (2)

Here $H_{fd} = \sum_{q,k} Q^{(l,f)}_q \cdot S^{(l)}_q \cdot S^{(l)}_{-q}$ is the Hamiltonian of the interstitial exchange interaction between $f$- and $d$-electrons, $H_f$ and $H_{dd}$ are the Hamiltonians of the $f$- and $d$-electron systems having similar electron structures and including the Hamiltonian $H_0^{(l)} = \sum_{k,k',\sigma} e_{i,k} a_{i,k,\sigma}^\dagger a_{i,k',\sigma}$ of noninteracting electrons ($f$ ($l = 1$) or $d$ ($l = 2$)) in the external electric field $E$, $\epsilon^{(l)}_{i,k} + \left( eEv(\epsilon_{i,k}) \tau(\epsilon_{i,k}) \right)$ is the one-electron energy including the electrical shift caused by electron motion in the external electric field, $v(\epsilon_{i,k}), \tau(\epsilon_{i,k})$ are the velocity vector and the mean free time of an electron with the energy $\epsilon_{i,k}$, respectively, $H_{exc}^{(l)} = \sum_q Q^{(l,f)}_q \cdot S^{(l)}_q \cdot S^{(l)}_{-q}$ is the Hamiltonian of the interstitial exchange interaction between these electrons, $H_U^{(l)} = U_i \sum_q \left| S^{(l)}_q \cdot e^{(l)}_{q,i} \right|^2 - U_i \sum_q \left| N_{q,i} \right|^2$ is the Hamiltonian of their intra-atomic Hubbard repulsion at a site written using the Fourier transforms of the charge- and spin-density operators (see for example, [9]), $e_{i,k}$ are the one-electron band energies, $a_{i,k,\sigma}^\dagger a_{i,k,\sigma}$ is the operator of generation (annihilation) of $f$- ($l = 1$) and $d$- ($l = 2$) electrons with the quasi-momentum $k$ and spin quantum number $\sigma = (\pm 1)$. $Q^{(l,f)}_q$ is the Fourier transform of the interstitial exchange electron interaction parameter, $U_i$ is the parameter of the intraatomic Coulomb electron repulsion, $N_{q,i} = \sum_{\sigma} N_{q,i,\sigma}$, where $N_{q,i,\sigma} = \sum_k a_{i,k,\sigma}^\dagger a_{i,k+q,\sigma}$ is the Fourier transform of the density operator of the number of electrons with the spin $\sigma$ at the site, $q$ is the quasimomentum, $S^{(l)}_{q,i}$ is the Fourier transform of the operator of electron spin density vector, $e^{(l)}_{q,i}$ is the unit complex vector along the quantization axis of the Fourier transform of electron spin density operator. Further, we perform averaging over the directions of this vector.

Using the spin-fluctuation approach developed in [8] for a two-band model, we calculate the magnetization, spin fluctuation amplitudes, and spin splitting of the $d$-electron spectrum. For nonequilibrium conditions, an equation for the electron state density similar to that derived in [8] can be written, taking into account Eq. (1) and within the approximation of large correlation radius of spin fluctuations (much larger than the electron mean free path)

$$g_{\alpha\beta}(\epsilon) = \sum_{\alpha} \left( 1 + \frac{\alpha \sigma M_{\alpha\beta}}{m_i} \right) g_{\alpha\beta}(\epsilon + \left( eEv(\epsilon) \tau(\epsilon) \right) + \frac{U_i m_i}{2} + \alpha \xi_{\alpha\beta}),$$  \hspace{1cm} (3)

where (see [8] for details)