Heating of the spin system by current carriers and energy transfer between the magnon and phonon systems in $CdCr_2Se_4$ and EuO magnetic semiconductors

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Using the time dependence of high-frequency permeability in strong pulsed electric fields, we investigated the heating of a spin system by drifting current carriers in $CdCr_2Se_4$ and EuO. Both overheating and underheating of the spin system with respect to the lattice were observed.

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The presence of mobile current carriers, a relatively small spin-spin relaxation and anomalously small spin-lattice[2] relaxation in magnetic $CdCr_2Se_4$ and EuO semiconductors are a favorable combination for studying electron-magnon interaction (EMI) in strong electric fields. This interaction may produce new effects—Cerenkov generation and amplification and heating of spin waves (magnons) by drifting current carriers.[1,2] Macroscopically, the EMI manifests itself in the form of nonlinear volt-ampere characteristics[3] and a decrease of magnetization[4] in strong, pulsed electric fields. The technique used in Ref. 4, however, did not allow the recording of the magnetization relaxations associated with the establishment of thermal equilibrium between the spin system and the lattice after an electric-field pulse. Moreover, a study of such relaxations is of interest for two reasons. First, the magnetization relaxation time is a quantity that characterizes the spin-lattice relaxation. Second, a direct observation of the relaxation makes it possible to properly separate the heating of the spin system from Joule heating of the whole crystal.

To study the heating processes of the spin system produced by current carriers and subsequent establishment of the thermal balance between the spin and the phonon systems, we measured the time variations of the high-frequency permeability in strong pulsed electric fields of EuO ($\sigma_{20\,\mathrm{K}} = 2\times 10^{-2}\,\Omega^{-1}\cdot\mathrm{cm}^{-1}$) and $Cd_{0\cdot 98}Ag_{0\cdot 02}Cr_2Se_4$ ($\sigma_{77\,\mathrm{K}} = 10^{-1} - 2\times 10^{-2}\,\Omega^{-1}\cdot\mathrm{cm}^{-1}$) single crystals. During the measurements the parallelepiped- or octahedral-shaped sample was placed between coaxial receiving and transmitting coils. The external magnetic field was directed along the axes of the coils and the electric field was oriented perpendicular to them. The measurements were performed at a frequency of 7 MHz using an amplitude-stabilized quartz generator. The temperature dependences of the permeability are monotonically decreasing functions of the temperature of the sample or of the spin system in the 0.4- to 4-kG magnetic field range and are almost linearly decreasing functions of temperature for some fields in this range, depending on the shape of the measured sample. Thus, the time dependence of the temperature of the spin system can be judged by observing the time dependence of the permeability.

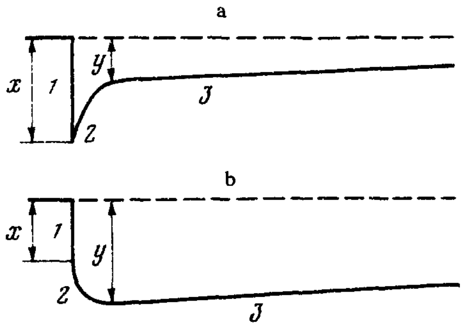

FIG. 1. Shape of the time variations of the permeability in $CdCr_2Se_4$ due to the action of the electric-field pulse.

Typical time variations of the permeability in $CdCr_2Se_4$ as a result of the action of the electric-field pulses ($\tau_p \sim 10^{-4}$ sec) are shown in Fig. 1. During the pulse the permeability decreases linearly with time (sections 1 in Fig. 1), then it decreases further or increases exponentially (depending on the sample, the magnitude of the electric field and the measurement temperature) in sections 2 with time $\tau_2 = 1 - 10$ msec and then the permeability relaxes to its original value during the time $\tau_3 \sim 5 \times 10^{-1}$ sec. As a result of variation of the measurement temperature, a transition from an increase in sections 2 (Fig. 1a) to a decrease (Fig. 1b) is sometimes observed. The shape of the time variations of the permeability also depended on the electric field. The time τ_2 decreased by a factor of 5–10 by changing the temperature from 77 to 130 K, whereas the time τ_3 remained almost the same. The variation of the susceptibility was $\sim 1\%$ or less.

The results obtained can be explained by using the model of independent heating of the spin and phonon system proposed in Ref. 4. When the electric-field pulses are shorter in duration than the time of the magnon-phonon relaxation but longer than the time for the establishment of thermal equilibrium in the magnon system, the spin and phonon systems are heated independently by drifting current carriers in the strong electric field and with a different intensity that depends on the parameters of the crystal (for example, on the mobility of the current carriers and specific heat of the systems). Consequently, the sections 1 of variations of permeability or temperature of

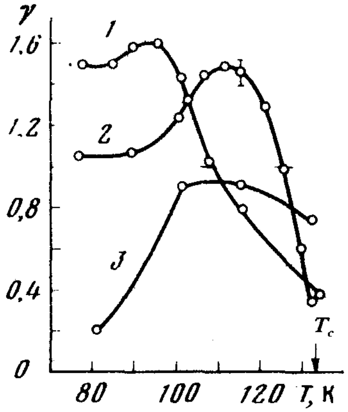

FIG. 2. Dependence of γ on temperature for several $CdCr_2Se_4$ samples at $E = 1$ kV·cm^{-1}.

the spin system can be explained by the heating of magnons by current carriers. Sections 2 correspond to establishment of thermal equilibrium between the magnon and the phonon systems—cooling of magnons on phonons (Fig. 1a) or preheating of magnons by phonons (Fig. 1b). In the latter case, the energy from the phonons is transmitted to the magnons. After thermal equilibrium between the systems is established, the sample, as a whole, cools in the cryostat during a time $\tau_3 \sim 5 \times 10^{-1}$ sec. We can introduce the parameter $\gamma = X/Y$ (Fig. 1). Since the lattice component of the specific heat in $CdCr_2Se_4$ is much larger than the magnetic component,[5] $\gamma \approx \Delta T_s / \Delta T_l$, i.e., it is a difference ratio of the temperature of the spin system and the lattice after the electric-field pulse. Figure 2 shows the $\gamma = f(T)$ dependences for several $CdCr_2Se_4$ samples. In samples 1 and 2 there is overheating of the spin system with respect to the lattice ($1 < \gamma < 1.6$), which is followed by its underheating ($\gamma < 1$) as the Curie temperature is approached at $T = 134$ K. In sample 3 taken from a different stock $\gamma < 1$ in the entire range of investigated temperatures. In all cases γ increases with increasing temperature from 77 K and then begins to decrease on approaching the Curie point. An increase of γ may be due to the increase of the mobility in this temperature interval.[6] A further decrease indicates a decrease of energy transfer to the spin system as compared to the lattice and shows that the efficiency of the mechanism of two-magnon heating of the spin system by the current carriers decreases on approaching the Curie temperature.[2] For the EuO sample we obtained $\gamma = 3$ at 20 K.

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