Spin wave excitation by carriers in the magnetic semiconductors EuO and $CdCr_2Se_4$

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The decrease of the magnetization and of the electric conductivity of the magnetic semiconductors EuO and $CdCr_2Se_4$ in a strong electric field, due to spin-wave excitation by the carriers, is investigated.

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The high mobility of the carriers and the small damping of the spin waves in EuO and $CdCr_2Se_4$ make these magnetic semiconductors favorable objects for investigations of electron-magnon interaction. This interaction can lead to new phenomena such as heating, enhancement or Cerenkov generation of spin waves by sufficiently fast carriers.[1,2] This should manifest itself macroscopically in a change of the physical properties of the magnetic semiconductors in a strong electric field.[3–5] In the present paper we investigate a direct consequence of spin-wave excitation by carriers, namely the decrease of the magnetization of EuO and $CdCr_2Se_4$ in a strong electric field.

The measurements were made at temperatures 20–300 K on single crystals of EuO($T\approx 70$ K) and $Cd_{1-x}Ag_xCr_2Se_4$($T\approx 130$ K) with sufficiently high electric conductivity ($\gtrsim 10^{-4}\Omega^{-1}\cdot cm^{-1}$ at the measurement temperature). To decrease the Joule heating, square-wave pulsed electric fields were used with durations 5–50 μsec and repetition frequencies 1–10 Hz. The decrease of the magnetization following application of an electric pulse to the sample was measured by an induction method with compensated coils (to decrease the outside interference). The magnetized sample produced a magnetic flux in the coil. When the magnetization M changed during the time of the applied electric pulse, a pulse proportional to dM/dt was induced in the coil. The change ΔM of the magnetization was determined by integrating dM/dt.

Typical measured values of dM/dt and $\Delta M/M_s$ (M_s is the saturation magnetization at 0 K) as functions of E are shown in Fig. 1 for EuO (sample 1) at 20°. At $E\gtrsim 3$ kV/cm the dM/dt pulses are no longer rectangular, thus indicating a decrease of the magnetization with time. At the same time a decrease of the electric conductivity during the time of action of the electric field also sets in at $E\gtrsim 3$ kV/cm—the current pulses are also no longer rectangular. The electric conductivity of a number of samples decreased by more than one order of magnitude during the time of action of the electric pulse, and the current-voltage characteristic (CVC) for the trailing edge of the current pulse was N-shaped. Owing to the long relaxation time of the magnetization after the electric pulse, the corresponding dM/dt signal was small, and this made measurement of this time difficult. However, the corresponding times of conductivity relaxation, which are obviously connected with the magnetization relaxations, amounted to 10^{-3}–10^{-4} sec. This result corresponds to large magnon-phonon relaxation times (in accord with the theory of Ref. 2) and is the consequence of the weak coupling of the magnon and phonon systems in ferromagnetic semiconductors having low Curie temperatures. A similar result for the dependence of $\Delta M/M_s$ on E was obtained for $CdCr_2Se_4$.

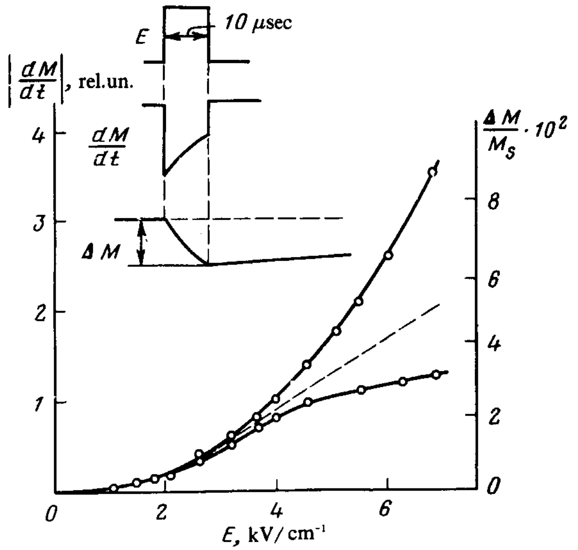

FIG. 1. Plot of dM/dt against E (solid lines) for EuO (sample 1). The upper and lower lines correspond to the leading and trailing edges of the dM/dt pulses. Dashed line–dependence of $\Delta M/M_s$ on E. In the upper left are shown schematically the E and dM/dt pulses and the variation of the magnetization with time.

Figures 2 and 3 show the temperature dependences of $\Delta M/M_s$ for EuO (sample 2) and $Cd_{1-x}Ag_xCr_2Se_4$ (sample 3), measured at fixed E. The value $\Delta M/M_s \approx 10^{-2}$ for EuO (sample 2) is less than for EuO (sample 1) because of the lower carrier density in sample 2. The temperature dependences of $\Delta M/M_s$ correlate with the temperature dependences of the carrier mobility for both magnetic semiconductors. The value of $\Delta M/M_s$ of EuO just as the mobility, decreases rapidly when the temperature is raised from 20 to 40 K, whereas for $Cd_{1-x}Ag_xCr_2Se_4$, on the contrary, it increases strongly from 77 K, as does the mobility, when the temperature is raised to the Curie point, and then vanishes rapidly. It can be stated that the magnetization of EuO and $CdCr_2Se_4$ decrease in a strong electric field only if the carriers have sufficiently high densities and mobilities.

The results presented for $\Delta M/M_s = f(E,T)$ cannot be attributed to Joule heating of the sample by an electric pulse. As a rule $\Delta M/M_s$ exceeded the value calculated from adiabatic heating with current. The nonthermal origin of $\Delta M/M_s$ can be regarded as confirmed by the comparison of the temperature dependences of $\Delta M/M_s$ and the resistivity of EuO (sample 2) (Fig. 2). In the 20–35 K region $\rho(T)$ is constant and therefore, at a constant pulse energy (E = const) Joule heating of the sample should cause $\Delta M/M_s$ to increase with rising temperature (since the slope $\Delta M/\Delta T$ increases

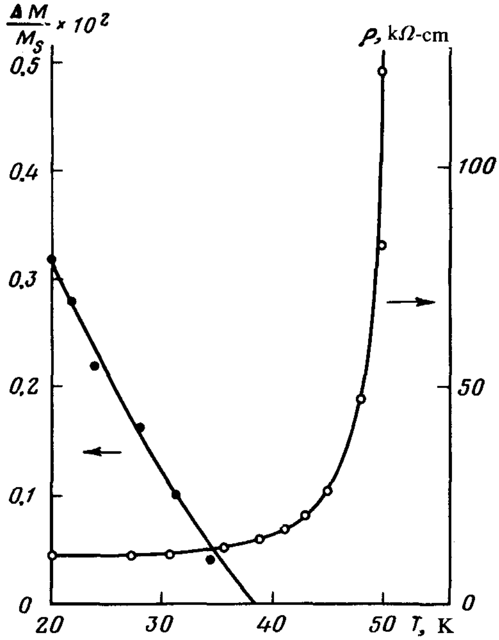

FIG. 2. Temperature dependences of $\Delta M/M_s$ and ρ for EuO (sample 2) at $E = 7$ kV/cm.

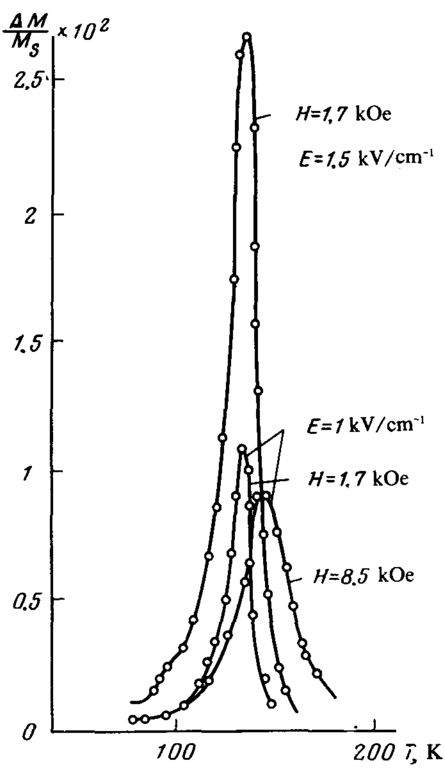

FIG. 3. Temperature dependences of $\Delta M/M_s$ for $CdCr_2Se_4$ (sample 3) at different intensities of the electric and magnetic field.

in this case), but $\Delta M/M_s$ decreases strongly, obviously because of the decrease of the mobility in this temperature region. It should be noted that in a number of cases the measured $\Delta M/M_s$ was several times smaller than the value calculated from the pulse energy for the adiabatic case. This situation can be attributed to the less favorable (for some samples) conditions of the heating of the magnon system by the carrier, because the latter have low mobility and (or) density. As noted above, the times of the magnon-phonon relaxations (up to 10^{-4}–10^{-3} sec) in the magnetic semiconductors EuO and $CdCr_2Se_4$ are large compared with the electric-field pulse durations ($\sim 10^{-5}$ sec). The magnons and phonons are therefore heated by the carriers independently and with different degrees of intensity, depending on the parameters of the magnetic semiconductor, say on the carrier mobility, the heat capacities of the subsystems and others. It is this which can cause the small value of $\Delta M/M_s$, observed for some samples, but not caused by Joule heating. In this case, after the end of the electric pulse, the lattice temperature may turn out to be higher than the spin-system temperature, and this is followed by establishment of thermal equilibrium between them in a time 10^{-3}–10^{-4} sec.

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