Intensification of magnetostatic and spin waves by the drifting charge carriers in a magnetic semiconductor $HgCr_2Se_4$

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A decrease in the damping of magnetostatic and spin waves in an electric field was detected for the first time in a magnetic semiconductor $HgCr_2Se_4$. This behavior is attributed to the heating and buildup of spin waves by the drifting charge carriers.

The interaction of charge carriers with the magnetic waves is a topic of crucial interest in the physics of magnetic semiconductors. There are two principal interaction mechanisms: the Vonsovskiĭ *s-d* exchange interaction and the relativistic interaction of the electron current with the spin-wave field.[1,2] According to the theory, these interactions may lead to new phenomena, for example, to the intensification and heating of magnons by charge carriers.[3,4] The heating of magnons by hot charge carriers was detected and studied experimentally in magnetic semiconductors EuO, $CdCr_2Se_4$, and $HgCr_2Se_4$ (Refs. 5–7).

In the present letter we report a study of the effect of an electric field on the damping of spin waves which are excited by the method of transverse pumping[8] in a ferromagnetic semiconductor $HgCr_2Se_4$. Single crystal wafers with dimensions $\sim 1\times0.7\times0.2$ mm have a conductivity $\sigma = 1 - 10^{-3}$ s/cm and charge-carrier mobility $\mu = 10$–200 cm^2/(V·s) at a temperature $T = 77$ K. Under the conditions of the experimental study of the ferromagnetic resonance, at high microwave power levels ($P_{mw} \cong 10$ W), a single-crystal wafer, depending on the intensity of the static magnetic field H, exhibits an absorption line spectrum caused by the excitation of magnetostatic standing waves. The threshold microwave magnetic field h produced due to the excitation of the spin waves is determined from an extrapolation of the plot for the resonant ($H = H_{\text{res}}$) permeability, μ'', of the dominant mode of the magnetostatic waves, which corresponds to the ferromagnetic resonance in the wafer, as a function of h^{-1}. The values of μ'' and h were measured by the method of Ref. 9, in which the microwave power level at the output of a transmission microwave resonator was held constant by means of precision attenuators. The absorption line width, ΔH_0, was determined by the method of Ref. 10 at low values of h below the spin-wave excitation threshold. At resonance, a static electric field was applied to the sample along the field direction. To avoid heating, the measurements were carried out in a pulsed mode (the times of the electric and microwave pulses were ~ 1 μs) by gating. The experiments were carried out at a frequency of 9.4 GHz at $T = 77$ K.

Figure 1 is a typical plot of the functional dependence $\mu'' = f(h^{-1})$, measured for the dominant mode of the magnetostatic waves at various strengths of the electric field

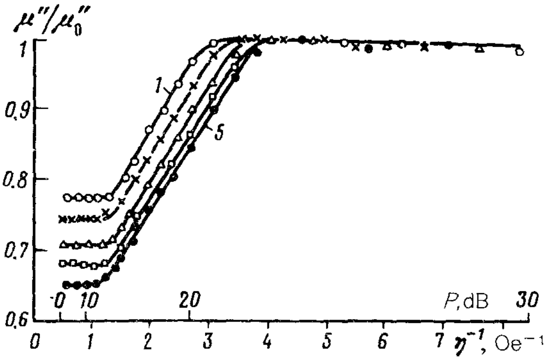

FIG. 1. Resonant permeability of sample 1 versus the strength of the microwave magnetic field. Curves 1–5 correspond to the following electric field strengths: $E = 0$, 0.7, 1.4, 2.1, and 2.8 kV/cm, respectively. For sample 1: $\sigma = 0.08$ S/cm and $\mu \cong 50$ $\text{cm}^2/(\text{V}\cdot\text{s})$.

E. According to the theory,[8] the observable decrease in μ'' as a function of h^{-1} is attributable to an unstable buildup of the spin waves with a pump frequency, which are directed along the magnetic field and which have the values of the wave vector, $k \cong \sqrt{4\pi M/D} \approx 10^6\ \text{cm}^{-1}$, for HgCr_2Se_4. Here M is the saturation magnetization, and D is the nonuniform-exchange constant. The variation of the damping constant of the spin waves, ΔH_k, as a function of the electric field strength can be estimated from the expression for the threshold field,[8] $h_{\text{thresh}} \sim \Delta H_0 \sqrt{\Delta H_k}$.

It can be seen from Fig. 2 that the width of the absorption line of the principal mode of the magnetostatic waves, plotted as a function of E, decreases by a factor of 1.1–1.2, and that ΔH_0 decreases to the largest extent at $E \lesssim 1.5$ kV/cm. It can also be seen that the E dependence of h_{thresh} for sample 1 differs from that for sample 2. For example, h_{thresh} versus E for sample 2 initially increases and then decreases by nearly a factor of 2. The variation of $h_{\text{thresh}} = f(E)$ which we see, cannot be explained solely by a decrease in ΔH_0. We can infer from the experimental results that in a field with

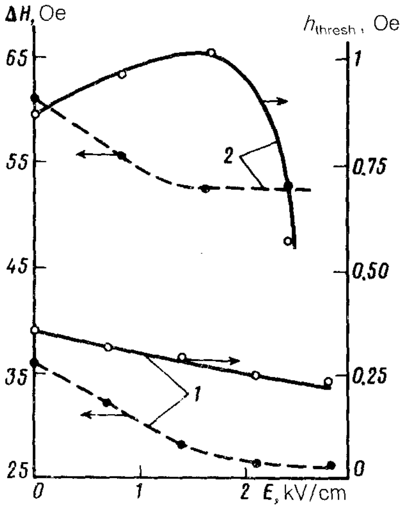

FIG. 2. Threshold field for the excitation of spin waves (solid curves) and the line widths of the dominant mode of the magnetostatic wave (dashed curves) versus the electric field strength for samples 1 and 2. For sample 2: $\sigma = 0.2$ S/cm and $\mu \cong 200$ $\text{cm}^2/(\text{V}\cdot\text{s})$.

$E = 3$ kV/cm, ΔH_k decreases by a factor of 1.2 for sample 1 and by a factor of 2.2 (~25–30 dB/cm) for sample 2. There was no evidence of the effect of the electric field on spin-wave damping in samples with a lower mobility and also in samples with σ differing by an order of magnitude from σ of samples 1 and 2.

The observable decrease in ΔH_0 of the magnetostatic waves can be explained in terms of heating of magnons by hot carriers if it is assumed that magnons with small k, which determine the value of ΔH_0, are heated by charge carriers to a greater extent than the entire magnon system. Evidence in favor of this model is the fact that the observable decrease in ΔH_0 versus E corresponds to an increase in the temperature by 20–30 K, as can be seen from the temperature dependence of ΔH_0. (We note that ordinary Joule heating of a sample is no greater than 1–1.5 K.) The magnetization determined from H_{res} in this case is virtually unaffected by E. The assumption that magnons with small k heat up more is consistent with the experiment on magnetic noise[11] in $HgCr_2Se_4$. It is evident from this experiment that at ferromagnetic resonance the magnetic radiation temperature is higher than that away from the resonance.

A decrease in the spin-wave damping in an electric field can be explained in terms of the Čerenkov generation of spin waves by the drifting charge carriers, since the drift velocity of the charge carriers ($\lesssim 5 \times 10^5$ cm/s) in this case is higher than the phase velocity of the spin waves that are excited ($\cong 5 \times 10^4$ cm/s). However, a decrease in ΔH_k estimated in Ref. 12 is, for our experimental conditions, well below the value observed experimentally. This discrepancy may stem from the fact that the hot electrons, magnons, and phonons in this case are in a nonequilibrium state.

It can also be assumed that this decrease of the magnetic losses is caused by a change in the differential conductivity of the magnetic semiconductor. This possibility was previously substantiated for a surface magnetostatic wave in a layered ferrite-semiconductor structure.[13] We accordingly found that the electrical conductivity of $HgCr_2Se_4$ decreases in a strong electric field and reaches a minimum at $E \cong 1.5$ kV/cm.

A change in the magnetization of $HgCr_2Se_4$, $f(E)$, in Ref. 14 is also attributed to an intensification of the spin waves by the charge carriers.

In summary, we have found that the damping of magnetostatic and spin waves decreases in a magnetic semiconductor in an electric field.

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