Electrically detected ferromagnetic resonance

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We study the magnetoresistance properties of thin ferromagnetic CrO_2 and Fe_3O_4 films under microwave irradiation. Both the sheet resistance ρ and the Hall voltage V_{Hall} characteristically change when a ferromagnetic resonance (FMR) occurs in the film. The electrically detected ferromagnetic resonance (EDFMR) signals closely match the conventional FMR, measured simultaneously, in both resonance fields and line shapes. The sign and the magnitude of the resonant changes $\Delta\rho/\rho$ and $\Delta V_{\mathrm{Hall}}/V_{\mathrm{Hall}}$ can be consistently described in terms of a Joule heating effect. Bolometric EDFMR thus is a powerful tool for the investigation of magnetic anisotropy and magnetoresistive phenomena in ferromagnetic micro- or nanostructures. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2722027]

The occurrence of ferromagnetic resonance (FMR) affects the quasistatic properties of a magnetic material, such as its magnetoresistance,[1–4] magnetoimpedance,[5] or caloric properties.[6] These effects can be used to detect FMR in magnetic micro- and nanostructures.[4,6] This is attractive, as FMR is one of the most sensitive methods for the investigation of magnetic anisotropy. However, to exploit the potential of such novel FMR detection methods, their full equivalence with the well established conventional cavity-based FMR must first be demonstrated. In semiconductors, the effect of paramagnetic resonance on transport processes is well known.[7–9] Here, we report on nonresonant and resonant changes of the magnetoresistance of thin ferromagnetic CrO_2 and Fe_3O_4 films upon microwave irradiation. We show that these electrically detected ferromagnetic resonance (EDFMR) signals are spectroscopically equivalent to conventional FMR measured simultaneously, and that the sign and the magnitude of the EDFMR signals can be quantitatively understood in terms of a Joule heating effect. This opens the way to selectively investigate particular transport processes in ferromagnets via magnetic resonance techniques.

The single-crystalline, 100 nm thick CrO_2 films studied were deposited on (100)-oriented TiO_2 substrates by chemical vapor deposition.[10] After patterning them into 80 μm wide and 600 μm long Hall bar structures using optical lithography and wet chemical etching, we fabricated Ohmic contacts by depositing Au *in situ* immediately after sputter cleaning the film surface in an Ar plasma.[11] The magnetite (Fe_3O_4) samples were grown on (100)-oriented MgO substrates by pulsed laser deposition.[12] Here, we study a 32 nm thick, coherently strained Fe_3O_4 film with Ohmic contacts in van der Pauw geometry, realized by wedge bonding Al wires.

The FMR spectra were measured in an *X*-band (9 GHz) electron spin resonance setup at room temperature as a function of a static magnetic field H, using magnetic field modulation at 100 kHz with an amplitude $\mu_0\Delta H=3.2$ mT. Simultaneously to the FMR, we recorded the longitudinal magnetoresistance or the Hall effect in the samples in four-point geometry, with ac current bias I at a frequency $\nu_I \leqslant 1.1$ kHz. The magnetization measurements were performed in a Quantum Design MPMS XL-7 superconducting quantum interference device (SQUID) magnetometer, and the resistivity as a function of temperature and the magnetotransport properties were recorded in a superconducting magnet cryostat.

Figure 1(a) shows how the longitudinal magnetoresistivity $\rho \propto V_{xx}$ of the CrO_2 Hall bar changes upon microwave irradiation, for H in the film plane. When the microwave source is "off," one observes the typical negative low-field magnetoresistance of CrO_2.[13,14] When the microwave source is turned "on" to an output power level of 200 mW, ρ increases by about 30% [see Fig. 1(a)], and a broad resonant structure appears around $\mu_0 H_{\mathrm{res}}=163$ mT.

This structure is the signature of FMR in the electrical resistance. Figure 1(b) shows the conventional FMR signal recorded simultaneously with the magnetoresistance. Because we use magnetic field modulation, the FMR signal $I_{\mathrm{FMR}} \propto (\partial\chi''/\partial H)\sqrt{P_{\mathrm{MW}}}$ scales with the first derivative of the imaginary part of the magnetic susceptibility χ'' and with the square root of the incident microwave power P_{MW}.[15] As indicated by the small arrows in Fig. 1(b), at least four different FMR modes can be resolved around $\mu_0 H_{\mathrm{res}} \approx 160$ mT. Rameev *et al.* reported similar observations in their FMR study of CrO_2 films and attributed the resonances to spin wave modes.[16,17] To allow for a direct comparison between the conventional FMR signal and the microwave-induced resistivity changes, we have plotted the resistivity data under microwave irradiation from Fig. 1(a) as the difference quotient $I_{\mathrm{EDFMR}}=\Delta\rho/\Delta H$ in Fig. 1(b). In this representation, the peaked structure around $\mu_0 H_{\mathrm{res}}=163$ mT in the magnetore-

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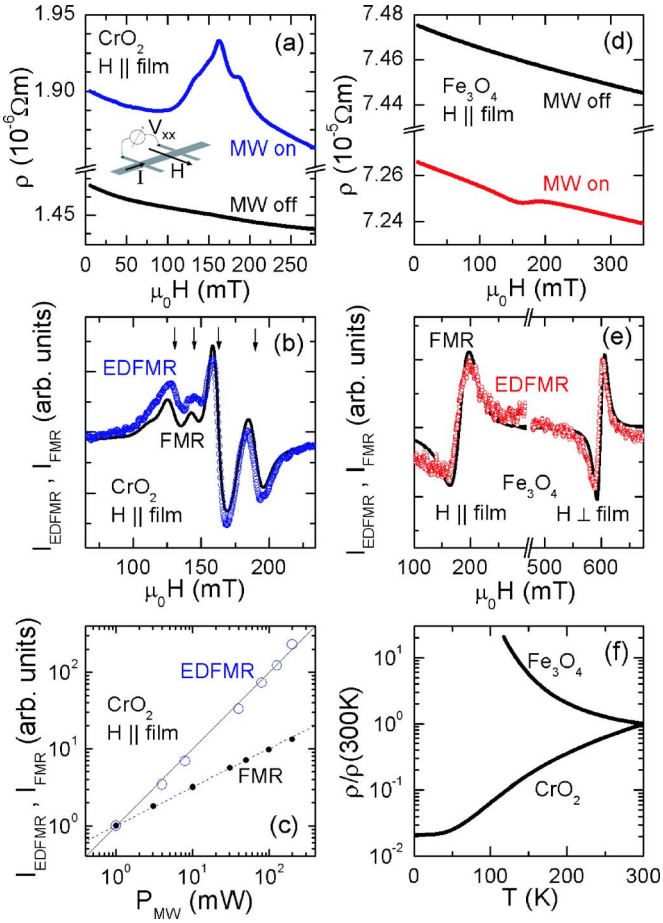

FIG. 1. (Color online) (a) The resistance ρ of a CrO_2 Hall bar at room temperature characteristically increases upon microwave irradiation, with additional peaks at the FMR resonance fields $\mu_0 H_{res} \approx 163$ mT. (b) The microwave-induced changes in ρ (electrically detected ferromagnetic resonance) $I_{EDFMR} = \Delta\rho/\Delta H$ (open circles) reproduce the conventional FMR signal (full line). (c) The EDFMR signal intensity in CrO_2 is proportional to the incident microwave power P_{MW}, while the FMR signal intensity scales with $\sqrt{P_{MW}}$. (d) In Fe_3O_4, ρ decreases upon microwave irradiation, with a dip at the FMR resonance field $\mu_0 H_{res} = 170$ mT. (e) The EDFMR signal (open circles) again reproduces the conventional FMR signal (full lines), for H both parallel and perpendicular to the Fe_3O_4 film plane. (f) The resistivities of CrO_2 and Fe_3O_4 show opposite temperature dependencies around 300 K, with ρ of CrO_2 increasing and ρ of Fe_3O_4 decreasing with increasing temperature.

sistance can be unambiguously identified as an EDFMR.[2–4] Note that all FMR modes in the conventional FMR signal are reproduced in the EDFMR trace with good fidelity. The slight discrepancies in signal shape and intensity between EDFMR and FMR are due to the bolometric nature of the EDFMR signal, as discussed below.

Upon microwave irradiation, the sample temperature T increases by ΔT, resulting in a corresponding change $\Delta\rho$ in resistivity. This bolometric effect can be written as[18]

$$\Delta\rho = \left(\frac{\partial\rho}{\partial T}\right)\Delta T = \left(\frac{\partial\rho}{\partial T}\right)\frac{P_{abs}\tau}{C}, \qquad (1)$$

with the microwave power $P_{abs} \propto P_{MW}$ absorbed by the sample, the thermal relaxation time constant τ between sample and environment, and the heat capacity C of the sample. A purely bolometric EDFMR signal should thus obey $I_{EDFMR} \propto \Delta\rho \propto (\partial_T \rho) P_{MW}$, with $\partial_T \rho = \partial\rho/\partial T$. Indeed, we show in Fig. 1(c) that the EDFMR signal intensity increases linearly with P_{MW} over more than two decades, as also observed by others.[3,4] Simultaneously, the FMR signal intensity increases as $\sqrt{P_{MW}}$ [Fig. 1(c)], as expected for conventional FMR below saturation. The linewidths of both the FMR and the EDFMR signals of the CrO_2 Hall bar sample are constant within experimental error for 1 mW $\leq P_{MW} \leq$ 200 mW.

To further test the validity of Eq. (1), we now consider the influence of $\partial_T \rho$ on the EDFMR signal. CrO_2 is a good metal,[13,14] with $\partial_T \rho > 0$ around room temperature [Fig. 1(f)]. A temperature increase $\Delta T > 0$ due to the absorption of microwave (in either a resonant or a nonresonant process) should thus lead to $\Delta\rho > 0$. Both the nonresonant and the resonant *increase* of ρ upon microwave irradiation of the CrO_2 sample shown in Fig. 1(a) are thus straightforwardly explained. In contrast to CrO_2, Fe_3O_4 has $\partial_T \rho < 0$ [Fig. 1(f)],[19] so that both nonresonant and resonant microwave absorption should result in a resistance *decrease*. This is indeed the case [Fig. 1(d)]: ρ decreases nonresonantly when the microwave source is switched on, with an additional dip-like decrease around a resonance field $\mu_0 H_{res} \approx 170$ mT for H in the film plane. The EDFMR and the conventional FMR signals closely match, as evident from Fig. 1(e) for the external magnetic field both parallel and perpendicular to the Fe_3O_4 film. The sign of the microwave-induced resistivity changes thus corresponds to $\partial_T \rho$, as expected for a bolometric effect. Currently, we can only speculate about the microscopic origin of the nonresonant Joule heating effect. However, Gui *et al.* invoke eddy currents as the origin.[4]

The time constant τ in Eq. (1) is of the order of several seconds. The agreement between FMR and EDFMR spectra shown in Figs. 1(b) and 1(e) is only obtained if the magnetic field is swept at a rate of 1 mT/s or slower, while the shape of the EDFMR signal is strongly distorted in faster sweeps. The nonresonant, microwave-induced changes in ρ also exhibit such a slow response. When the microwave power level is abruptly changed, ρ exponentially decays to the new resistance value, with time constants of several seconds. These observations suggest that in Eq. (1), C is the heat capacity of the sample, and $\tau = C/G$ is determined by the thermal conductance G between sample and heat sink. Note that our experiments were performed at room temperature. In this case, the heat capacitance is typically several orders of magnitude larger than at liquid He temperatures used, e.g., in Ref. 18, which leads to much longer time constants τ.

In addition to EDFMR in the longitudinal resistivity ρ, we also have observed EDFMR in the Hall signal or transverse voltage V_{trans} in CrO_2 (Fig. 2). In these experiments, the external magnetic field was applied perpendicular to the film plane. To exclude spurious longitudinal resistance contributions in the Hall signal, we measured V_{trans} for both magnetic field polarities and antisymmetrized the corresponding traces to obtain $V_{Hall}(H) = \{V_{trans}(H) - V_{trans}(-H)\}/2$. We again observe a clear nonresonant increase in V_{Hall} upon microwave irradiation (Fig. 2). Additionally, a peak appears around $\mu_0 H_{res} = 998$ mT, the field at which conventional FMR is observed in this sample for this magnetic field orientation.

To address the mechanism leading to this Hall-EDFMR signal, we recall that the Hall voltage $V_{Hall} = (R_0 \mu_0 H + R_A M_z) I/d$ in a ferromagnetic film of thickness d comprises both the ordinary and the anomalous Hall effects.[20] The ordinary Hall coefficient R_0 is inversely proportional to the carrier density. The anomalous Hall voltage $V_{AHE} = R_A M_z I/d$ depends on the magnetization component M_z per-

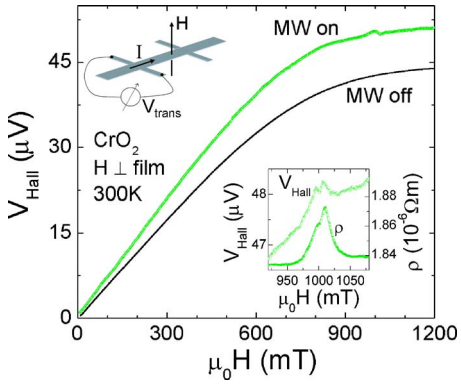

FIG. 2. (Color online) The Hall voltage $V_{\mathrm{Hall}}(H)$ of the CrO_2 Hall bar at room temperature increases upon microwave irradiation, with an additional resonant increase around the FMR at $\mu_0 H_{\mathrm{res}}=998$ mT. The upper inset depicts the measurement geometry. In the lower inset, the resonant microwave-induced changes in the longitudinal and the transverse (Hall) signals are shown in comparison, measured while sweeping the magnetic field very slowly.

pendicular to the sample, and the anomalous Hall coefficient $R_A=c\rho^{\alpha}$ usually scales with the resistivity,[20] with material-dependent constants c and α. In CrO_2, $R_A M_z \gg R_0\mu_0 H$ and $\alpha \lesssim 2$ for temperatures $T>100$ K.[13,21] This is confirmed by conventional magnetotransport experiments in our samples, which yield $1.4 \leqslant \alpha \leqslant 1.6$. Using $V_{\mathrm{Hall}} \approx c\rho^{\alpha} M_z I/d$, Eq. (1) gives

$$\frac{\Delta V_{\mathrm{Hall}}}{V_{\mathrm{Hall}}} = \frac{(\partial V_{\mathrm{Hall}}/\partial T)\Delta T}{V_{\mathrm{Hall}}} = \alpha\frac{\Delta\rho}{\rho} + \frac{\Delta M_z}{M_z}, \tag{2}$$

with $\Delta M_z=(\partial M_z/\partial T)\Delta T$. If the relative resonant change in magnetization $\Delta M_z/M_z$ is small, one has $\Delta V_{\mathrm{Hall}}/V_{\mathrm{Hall}} \approx \alpha\Delta\rho/\rho$, so that the value of α can be directly extracted from EDFMR measurements.

In CrO_2 at room temperature, however, $\Delta M_z/M_z$ cannot be neglected. SQUID magnetometry experiments on a larger piece of the same CrO_2 sample give $\partial_T M_z/M_z=(-4\pm2)\times10^{-3}$ K^{-1} in the relevant temperature and magnetic field range, while conventional resistance measurements yield $\partial_T\rho/\rho=(8\pm1)\times10^{-3}$ K^{-1}. With these values and $\alpha=1.5$, one expects $\partial_T V_{\mathrm{Hall}}/V_{\mathrm{Hall}}=(8\pm3)\times10^{-3}$ K^{-1} according to Eq. (2), closely matching $\partial_T V_{\mathrm{Hall}}/V_{\mathrm{Hall}}=(6\pm1)\times10^{-3}$ K^{-1} experimentally determined from the conventional magnetotransport data. The EDFMR measurements quantitatively corroborate this picture. The Hall-EDFMR trace shown in Fig. 2 corresponds to $\Delta V_{\mathrm{Hall}}/V_{\mathrm{Hall}} \approx 1.1\%$, while $\Delta\rho/\rho \approx 1.6\%$ for similar conditions (see the inset of Fig. 2). The ratio $(\Delta\rho/\rho)/(\Delta V_{\mathrm{Hall}}/V_{\mathrm{Hall}}) \approx 1.5$ thus determined from EDFMR agrees well with $(\partial_T\rho/\rho)/(\partial_T V_{\mathrm{Hall}}/V_{\mathrm{Hall}}) \approx 1.3$ obtained from conventional magnetotransport. These numbers also show that the temperature increase in resonance is a few Kelvin at most, warranting the use of Eqs. (1) and (2) *a posteriori*.

In conclusion, we have investigated the magnetoresistance properties of thin ferromagnetic CrO_2 and Fe_3O_4 films under microwave irradiation. Both the resistivity ρ and the Hall voltage V_{Hall} characteristically change when ferromagnetic resonance occurs in the film. The electrically detected ferromagnetic resonance spectra closely match the conventional FMR, measured simultaneously, in both resonance fields and line shapes. This demonstrates that EDFMR is spectroscopically equivalent to FMR. The sign and the magnitude of the EDFMR signals $\Delta\rho/\rho$ and $\Delta V_{\mathrm{Hall}}/V_{\mathrm{Hall}}$ can be consistently described as a Joule heating effect. Taken together, EDFMR thus is a powerful tool for the investigation of magnetic anisotropy and magnetoresistive phenomena in ferromagnetic thin films and could allow the detailed study of micro- and nanostructures too small to be investigated by conventional FMR.

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