Unexpected Resonant Response in $[Fe(001)/Cr(001)]_{10}/MgO(001)$ Multilayers in a Magnetic Field

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(Received 22 February 2008; published 23 January 2009)

We observed unexpected resonant response in $[Fe/Cr]_{10}$ multilayers epitaxially grown on MgO(100) substrates which exists only when both ac current and dc magnetic field are simultaneously applied. The magnitude of the resonances is determined by the multilayer magnetization proving their intrinsic character. The reduction of interface epitaxy leads to nonlinear dependence of the magnitude of resonances on the alternating current density. We speculate that the existence of the interface transition zone could facilitate the subatomic vibrations in thin metallic films and multilayers grown on bulk insulating substrates.

DOI: 10.1103/PhysRevLett.102.035503 PACS numbers: 75.70.Cn, 46.40.−f, 62.25.−g, 77.65.−j

Two decades ago giant magnetoresistance (GMR) was discovered in Fe/Cr multilayers [1,2]. The GMR phenomenon was found with in-plane permanent (dc) electric current flowing through the multilayer (ML) structure in the presence of dc magnetic field. Recently, unusual dynamic properties of metallic multilayers such as current induced magnetization reversal [3], spin torque oscillations [4], anomalous magnetic losses at low temperatures [5] were observed. These investigations open new horizons in the development of new spintronic and thin film based devices.

The high density alternating current (ac) flowing through a conducting film situated in a dc magnetic field creates the longitudinal voltage drop U_{ac}. In addition, electromotive resonances U_{em} excited by a time dependent Lorentz force might be observed. These resonances down to kHz frequencies could be either due to time dependent current redistribution in semiconducting films [6] or mechanical vibrations in suspended films [7–9]. Our Letter reports on unexpected low frequency voltage response in $[Fe/Cr]_{10}$ multilayers epitaxially grown on single crystal MgO substrates which exist only with both ac current and dc magnetic field *simultaneously applied*. We observed qualitatively similar effects in other thin films and multilayers such as Nb(1000 Å)/Si(001), Al(30 Å)/Fe(150 Å)/MgO(001), and Cr(200 Å)/MgO(001). This proves that these features are common for different thin metallic films and multilayers grown on insulating bulk substrates. Here we report only findings for Fe/Cr multilayers. First, because these are multilayers where the GMR effect was discovered. Second, Fe/Cr MLs in the strong antiferromagnetic coupling regime provide unique possibilities to verify an intrinsic character of the effects by investigating the link between magnitude of the resonances and the sample magnetization. And, finally, because the epitaxial growth of [Fe/Cr]/MgO(100) multilayers is well established.

The epitaxial $[Fe(30\ Å)/Cr(12\ Å)]_{10}$ multilayers are prepared in a molecular beam epitaxy system on MgO (100) substrates with thickness of about 1.5 mm held (unless otherwise stated) at 50 °C [10]. The magnetic and electron transport characteristics [5,11] as well as TEM analysis both in conventional and in high resolution mode (HRTEM) with point resolution of 0.12 nm confirms good epitaxial growth of multilayers. The quantitative analysis of the lattice deformation between the substrate and the ML was carried out using the Geometrical Phase Analysis (GPA) to study the HRTEM micrographs [12,13].

To measure precisely the response, we employed either a five-probe scheme with in-plane magnetic field, with electric current injected through the central contact and split in two opposite directions or used a Hall scheme with the probes at the opposite sides and field being perpendicular to the film plane. The reduced U_{ac}, and therefore relatively small background voltage, achieved with these balanced schemes permits more clear detection of the U_{em}. Figure 1 compares the results obtained for ML1 with four and five-point schemes sketched in the insets to Figs. 1 and 2, correspondingly, and by using the same drive current and magnetic field. Only weak (about 10^{-3} of the background voltage U_{ac} as demonstrates the expanded scale) resonances have been observed with the conventional four-probe technique. Below we shall discuss only the measurements in the balanced (i.e., five-probe and Hall) geometries. Similar to the five-probe schemes [14,15] were applied for sensitive detection of the electromotive response in nanoelectromechanical systems (NEMS). In our experiments the generated ac voltage was recorded between few Hz and 60 kHz by using EGG-7265 lock-in amplifier [insets in Figs. 1 and 2(a)]

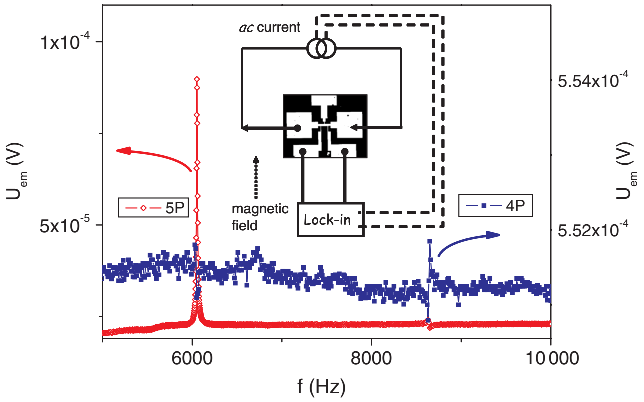

FIG. 1 (color online). Comparison of the frequency dependent response in the four and five-probe schemes for ML1 ($7.5 \times 30\ \mu\mathrm{m}^2$ active zone) measured at 10 K with in-plane field of 3 T perpendicular to the current of 25 μA. The inset explains the four-probe scheme.

while the magnetic field was created by a superconducting magnet.

In Fig. 2(a) we compare frequency dependence of the electromotive voltage measured by using a five-probe scheme in $[\mathrm{Fe/Cr}]_{10}$ multilayers ML2 and ML3 with different size of active (i.e. with maximum current density) zones. Both structures show the presence of few highly reproducible fundamental resonances and a number of less pronounced smaller resonances, all induced by the magnetic field. In the sample with the larger active zone we observed the appearance of new resonances at lower frequencies (below 1 kHz). The dominant resonances should correspond to those modes whose electric potential profiles, integrated between the voltage contacts, have maximum values. The in-plane field rotation at 45° for the ML2 (which does not change the resistance) strongly influences the resonances [see Figs. 2(a) and 2(b)]. This shows importance of the direction of in-plane magnetic field for the excited fundamental frequencies. The inset in the Fig. 2(b) demonstrates the evidence for quadratic dependence of the magnitude on the magnetic field in the low field regime ($0 < H < 1T$).

In order to prove further the intrinsic character of the observed resonances in Fig. 3(a)–3(c) we compare the ac and dc responses. Here we take advantage of the special feature of Fe/Cr MMLs, namely, the field induced transition from antiparallel to parallel Fe layers alignment [Fig. 3(c)]. Figure 3(a) presents the normalized by the field ac voltage response measured in the Hall configuration for ML2 at frequencies close to the main resonance. Increasing magnetic field broadens the resonances but weakly influences the resonant frequency [Fig. 3(a)]. Figs. 3(b) and 3(c) compare the dc characteristics (Hall effect, magnetoresistance and out-of plane magnetization) with magnitude of the resonant ac Hall response shown in Fig. 3(a). The dc Hall resistance in magnetic films is expected to be dependent on magnetization M as: $R_H = (R_0 H + R_A 4\pi M)$ where R_0 and R_A are the ordinary and anomalous Hall,

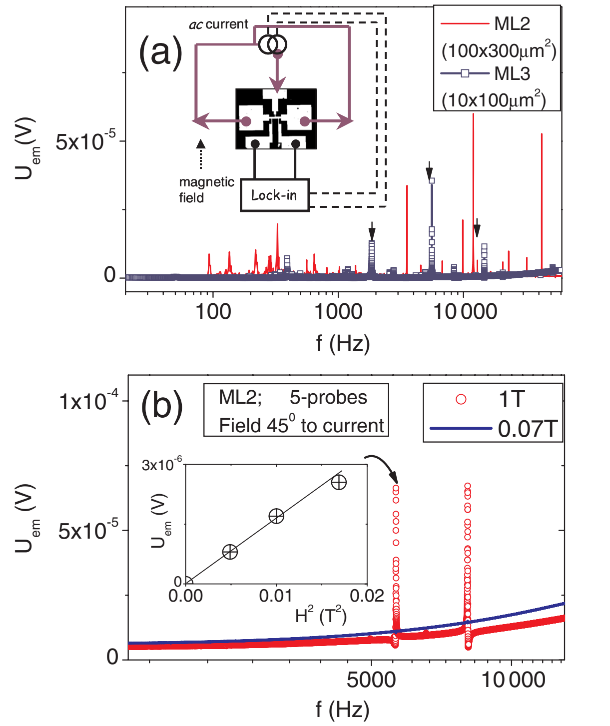

FIG. 2 (color online). (a) Frequency dependence of the U_{em} measured at 6 K for the in-plane field of 1 T for two $[\mathrm{Fe/Cr}]_{10}$ on MgO multilayers with different dimensions. Current of 100 μA (ML2) and of 10 μA (ML3) was used to provide the same current density of about $2.5 \times 10^3\ \mathrm{A/cm^2}$. The inset sketches the five-probe measurement scheme. Vertical arrows are described in the text. (b) Frequency dependence of the U_{em} measured for the ML2 in the same conditions as in the part (a) but with the in-plane fields of 1 T and of 0.07 T rotated at 45°. The inset plots dependence of the magnitude of one of resonances on the square of the magnetic field.

respectively. Figure 3(b) demonstrates that the dc and the resonant ac Hall responses are determined by the field dependence of the out-of plane magnetization [Fig. 3(c)]. The above experiments directly prove that we are not dealing with artifacts.

Even higher magnitude voltage resonances (for the similar conditions) have been observed in ML4 [Fig. 4(a)] with the same dimensions as ML2, but deposited at higher temperature (450 °C). The multilayer ML4 has enhanced interface disorder [10] which suppresses the antiferromagnetic coupling and reduces the GMR to below 20% at 10 K. In ML4 the main resonances have been found to exceed notably those measured in ML2 with similar current and magnetic field allowing observation of transition to the nonlinear resonant response. Figure 4(a) demonstrates an evidence of strong deviation from the Lorenzian shape of the resonance curves for the current densities exceeding $J = 0.6 \times 10^3\ \mathrm{A/cm^2}$.

The resonant excitations in $[\mathrm{Fe/Cr}]_{10}/\mathrm{MgO}(100)$ multilayers are observed up to 300 K. Figure 4(b) shows a typical temperature dependence of the position and the magnitude of one of fundamental resonances which reveals

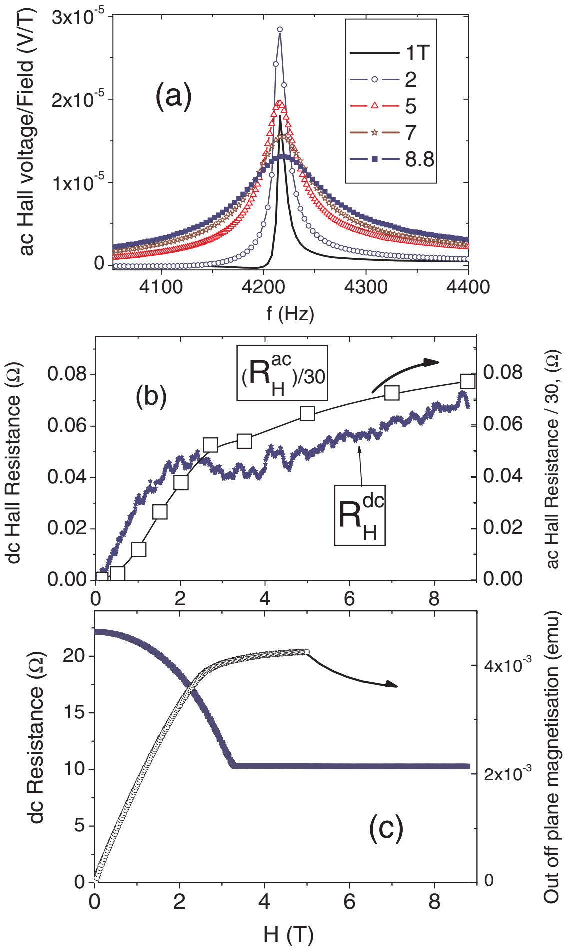

FIG. 3 (color online). (a) Magnitude of one of the dominant resonances normalized by the magnetic field and measured for ML2 at $T = 10$ K in the Hall geometry with 50 μA (current density of about 1.25×10^3 A/cm^2). (b) Comparison between field dependent dc Hall resistance and resonant ac Hall resistance ($f_r = 4210$ Hz, divided by 30) measured for $T = 10$ K. (c) Field dependence of the out-of-plane magnetoresistance and of the magnetization for MML2 measured at 10 K.

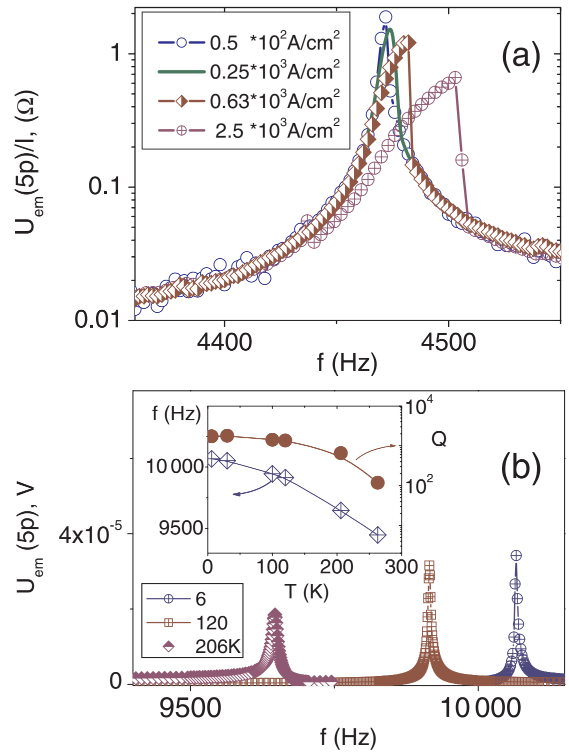

FIG. 4 (color online). (a) Normalized by the current of 2, 10, 25, and 100 μA electromotive response close to the dominant resonance in ML4 measured with $H = 1$ T and with the five-probe scheme, shown in Fig. 2(a). (b) Temperature dependence of one of the dominant resonances measured with the five-probe configuration for the ML2 with $H = 1$ T and with current of 100 μA (2.5×10^3 A/cm^2). The inset shows temperature dependence of the resonant frequency and of the corresponding Q factor.

a shift in the resonance to lower frequencies probably reflecting the thermal expansion of the multilayer-substrate system. For metallic multilayers under study conductance increases with decreasing temperature [11], therefore, the resonance broadening for the fixed fields with temperature contradicts to explanation in terms of Foucault current effect.

Our HRTEM experiments (Fig. 5) show that the growth is epitaxial and no amorphous layers close to interphase is observed. The bcc structure of Fe/Cr is rotated by 45° in the interface plane relative to MgO(001) substrate. The epitaxial relation is therefore Fe/Cr(001)[110]// MgO(001)[100] as expected for Fe/MgO(001) [10]. The relative deformation [Figs. 5(b) and 5(c)] between the planes perpendicular to the interface, i.e., the (110) planes of Fe/Cr and the (200) MgO ones is about 3.3%. This corresponds well to the misfit between the (002)-MgO (0.21 nm) plane and the (110)-Fe ones (0.203 nm) or (110)-Cr (0.204 nm). We did not measure any large change of the (110) Fe and Cr intereticular distance on the HREM images of the top surface of the Fe/Cr) which suggest that the relaxation of the metallic ML is constant. Electron microscopy therefore shows that we deal with high quality metallic films epitaxially grown on insulating substrates.

What could be physical explanation of these resonances? Scenarios involving different types of interface or bulk sound waves as well as magnetic domain wall excitations imply frequencies above MHz, substantially exceeding the experimentally observed. Purely electronic origin of resonances, similar to those previously reported for solid state plasma in the presence of large electric and magnetic fields [6] and attributed to current filaments instabilities, is inconsistent with linear variation of the resonance magnitude with the ac drive. Below we speculate that subatomic vibrations due to interface transition zone between substrate and multilayer might explain our experiments.

We suppose that ML is connected to MgO through interface transition zone (ITZ) [16] which has a different mechanical properties than the rest of layers. The ITZ is originated from the lost bonds and misfit dislocations.

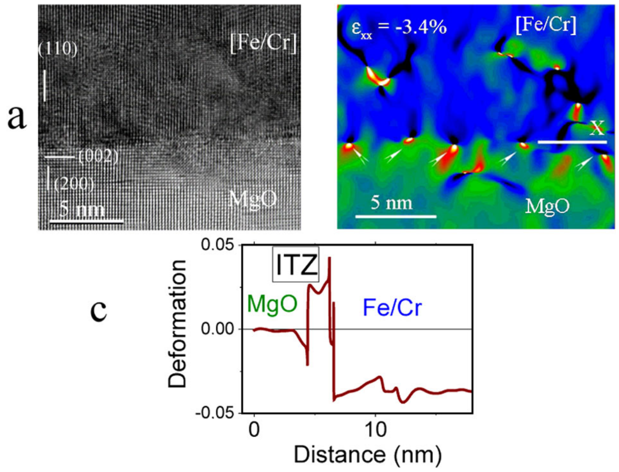

FIG. 5 (color online). (a) HRTEM micrograph of the MgO/[Fe/Cr] interface studied along the 100-MgO zone axis. (b) ε_{xx} deformation image calculated from (a) (with "x" being parallel to the interface). (c) Typical variation of the relative deformation across the interface between Fe/Cr multilayer and MgO substrate.

Indeed, Fig. 5(b) shows the presence of regularly distributed misfit dislocations (indicated by arrows) along the interface. The rough estimation for the width of the ITZ by evaluating spacial derivative of the stress in the direction perpendicularly to the interface [Fig. 5(c)] gives 2–4 nm. We believe that notable reduction of the Young's modulus for the ITZ [16] might allow the flexural or sliding subatomic vibrations. We note that recent studies reveal that tribology on nanoscale is very different from the one expected for bulk materials with sliding friction vanishing for weak transversal mechanical vibrations [17].

Our hypothesis is supported by the main experimental data including: (i) dependence of the resonance frequency and the magnitude on the temperature (if active zone mechanically vibrates, fundamental frequencies are expected to decrease with temperature due to thermal expansion); (ii) dependence on the resonance magnitude and the width on the magnetic field as well as their dependence on the ac current drive density which are similar to those predicted and observed for the NEMS [7–9,14,15]. Moreover, (iii) the nonlinear response at high current densities observed for the ML4 [Fig. 4(a)] with suppressed GMR due to the atom's interdiffusion [10] and the reduced (in comparison with multilayers ML1-ML3) epitaxy of the ITZ is also along with our hypothesis. Finally, (iv) the quality factors observed $Q \sim 10^3$–10^4 are close to those expected from the phenomenological Q vs volume scaling reported for Si-based NEMS [8].

Within the proposed model, the electromotive voltage depends on the modes excited and the contacts configuration. Assuming low damping [7], the voltage generated by flexural resonance is: $U_{\rm em} \approx \xi Q B^2 L^2 I / 2\pi m f$, where ξ is a constant of the order of unity which depends on the shape of resonant mode, m is the mass, L is the conductance length, and Q is the quality factor. For $Q \approx 10^3$; $B = 1$ T, $L = 100$ μm, $m = 10^{-12}$ kg, $f \approx 10^4$ Hz, and current $I = 10^{-4} A$ we get electromotive voltage $U_{\rm em} \approx 2.5 \times 10^{-4}$ V which exceeds in about one order the experimentally observed values. The above model also explains typical values of the observed resonance frequencies. By using Young's values $E \approx 10^{11}$ Pa reported for the metallic multilayers [18], mass density and geometrical factors of the actively vibrating zones ($L_0 = 300$–100 μm), we obtain the fundamental flexural frequencies $f_0 \sim 1.5$–15 kHz close to the experimentally measured. Arrows in Fig. 2(a) indicate relative (normalized to the lowest in frequency mode with largest amplitude for ML2) position of the three main resonances expected within the above model in the conditions when only flexural resonances are excited. Having in mind contacts attached, we find agreement with the model to be satisfactory.

In conclusion, we have observed unexpected intrinsic low frequency resonant response in Fe/Cr multilayers only presented with both ac current and dc magnetic field applied. Although the physical mechanism behind still remains to be fully clarified, the consistent experimental data and simple estimations support the possibility of the excitation of subatomic vibrations in metallic thin films epitaxially grown on bulk substrates.

The authors acknowledge R. Schad for samples preparation, T. Alieva, F. Guinea, and A. Levanuyk for fruitful discussions, Spanish MEC (MAT2006-07196, CSD2007-00010), European Union (026019 ESTEEM), and CAM (S-505/MAT0194) for support. This work, as a part of the ESF EUROCORES 05-FONE-FP-010-SPINTRA, was also supported by funds from the Spanish MEC (MAT2006-28183-E) and the EC Sixth Framework Programme, under Contract No. ERAS-CT-2003-980409.

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