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Experimental studies of the non-collinear magnetic states in epitaxial FeAu multilayers

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Abstract

We have investigated the magnetic structure and coupling in epitaxial $[Fe_3/Au(0\,0\,1)_N/(Fe_1Au_1)_3/Au(0\,0\,1)_N]\times 2$ multilayers. Our system contains alternating $(Fe_1Au_1)_3$ monoatomic stacks with perpendicular magnetic anisotropy and 3 atomic layer (AL) thick Fe films (Fe_3) with an in-plane easy magnetization axis, separated by an Au(0 0 1) spacer layer. Giant magnetoresistance and magnetization measurements as a function of $N = 4, 5, \ldots, 24$ AL of the Au spacer revealed different non-collinear magnetic alignment of the sub-layer magnetization, dependent on the interlayer exchange coupling. © 2001 Published by Elsevier Science B.V.

Keywords: Perpendicular magnetic anisotropy; Indirect exchange coupling; FeAu magnetic multilayers; Non-collinear magnetic states

The interesting and spectacular phenomena displayed by magnetic multilayers have drawn considerable attention in recent years. In particular, perpendicular magnetic anisotropy, giant magnetoresistance and the interlayer exchange coupling have been the subject of the fundamental and also technological interest. Giant magnetoresistance (GMR) sensors are typically designed for maximum sensitivity to low magnetic fields. On the other hand, some applications, such as, for example, electric motors, magnetic levitating trains, position sensors or synchrotron insertion devices require sensing of much higher magnetic fields. Recently, stabilization of novel non-collinear magnetic states in systems combining thin magnetic layers of different materials, separated by non-magnetic spacers was theoretically predicted [1]. This new magnetic configuration can be observed if every second magnetic layer in the stack has magnetization direction pointing out-of-plane, whereas intermediate layers are in-plane magnetized. That kind of magnetic structure can be, depending on the composition, the sensor of extremely low magnetic field [1], as well as the highly linear device sensing high magnetic fields [2].

We report on observation of the non-collinear magnetic states in multilayers composed of Fe and Au (atomic) layers. The samples were grown by MBE in the UHV conditions (pressure during preparation below 10^{-9} mbar), at room temperature, on a 30 nm Au(0 0 1) buffer layer with the so-called *hex*-type surface reconstruction, deposited on polished MgO(0 0 1) substrates in a multistage process [3]. The thickness of the layers was controlled by a quartz microbalance with the accuracy of about 5%. The sample growth was monitored in situ by reflection high-energy electron diffraction (RHEED). All samples were covered by a 3 nm thick Au protective layer. Magnetization measurements were performed ex situ using a vibrating sample magnetometer (VSM). The CIP magnetoresistance was measured with conventional four-terminal method at temperatures between 5 K and RT.

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$[Fe_3/Au(001)_N/(Fe_1Au_1)_3/Au(001)_N] \times 2$ multilayers were obtained on the Au(0 0 1) buffer layer for different Au(0 0 1) spacer thickness measured in number N of atomic layers (AL). N value was varied between $N = 4$ and 24 with the monolayer step. $(Fe_1Au_1)_3$ monoatomic superlattices grown by alternate deposition of Fe and Au monolayers were chosen as having the perpendicular magnetic anisotropy [4], while 3 AL Fe films (Fe_3) had nominally in-plane magnetization direction [5]. Sharp diffraction stripes and low background characteristic for the RHEED patterns in all stages of the growth indicated a high degree of the structural order. The Au(0 0 1)-*hex* reconstruction was clearly seen for the buffer and capping layer surfaces. The reconstruction of the buffer layer, disappearing at the early stages of the Fe_3 sub-layers growth (at about 0.6 monolayer (ML)), was recovered after deposition of a few 2–3 ML of the Au spacer. Similarly, reconstruction of the Au spacer layer surface vanishes at the very beginning of the $(Fe_1Au_1)_3$ superlattices growth (during growth of the first Fe monolayer) and reappears again after deposition of 2–3 AL. The RHEED observations indicated that all Fe_3 as well as $(Fe_1Au_1)_3$ sub-layers were grown at very similar conditions as concerned with the substrate structure and morphology.

In Fig. 1, GMR curves measured at 10 K are shown for the magnetic field applied perpendicular (a) and parallel (b) to the plane of the $[Fe_3/Au(001)_9/(Fe_1Au_1)_3/Au(001)_9] \times 2$ multilayer. The magnetization loop measured at 10 K in the normal direction is also shown as inset in Fig. 1a. Following the perpendicular GMR (magnetization) curve from the positive saturation field towards the negative one, different configurations of the magnetic moments are deduced as indicated with arrows. At saturation, the magnetic moments of the Fe_3 and $(Fe_1Au_1)_3$ sub-layers are aligned along the field direction. With decreasing field, the angle Φ between them is gradually increasing, as the Fe_3 magnetic moments are rotating towards an in-plane direction. This behavior is uniformly manifested by the decrease of the VSM signal as well as the increase of the resistance. When the field increases from zero towards negative values, the magnetic moments of Fe_3 films are passing through the plane and then they rotate further, till the magnetic field reaches a value, for which the $(Fe_1Au_1)_3$ magnetization reverses to the orientation symmetric with respect to the plane. This can be seen in the GMR curve (Fig. 1a) as a gradual increase of the resistance followed by a rather abrupt decrease. Finally, Fe_3 magnetic moments rotate to the saturation along the negative magnetic field.

Without magnetic field, the angle Φ can be, depending on the interlayer exchange coupling, smaller, bigger or equal to 90°, for ferromagnetic, antiferromagnetic and 'no' coupling, respectively. The relative orientation of the magnetic moments in the absence of the magnetic field can be inferred from the resistance versus field dependence (Fig. 1b) with the magnetic field applied in the film plane. The most characteristic feature of this GMR curve is a dip centered at zero field. Such a behavior can be attributed to the presence of ferromagnetic interlayer coupling, which stabilizes sub-layers magnetic moments orientation with the angle Φ smaller than 90°. In the first approach, we assume that orientation of the $(Fe_1Au_1)_3$ magnetization is as it would be without coupling (normal) but, in principle, certain deviation from the normal cannot be excluded. Following the in-plane GMR curve from the remanent state towards saturation, first the inverse resistance change occurs resulting from an increase of the angle between sub-layer magnetizations. The Fe_3 magnetization rotates easier (according to its nominal in-plane anisotropy) than the one of $(Fe_1Au_1)_3$ with the perpendicular anisotropy. At the magnetic field H_m for which a maximum GMR value is observed, the Fe_3 magnetic moments reach the plane and then only slow rotation of $(Fe_1Au_1)_3$ magnetization occurs resulting in the decrease of the resistance to a saturation value. The shape of the in-plane GMR curve is very similar to

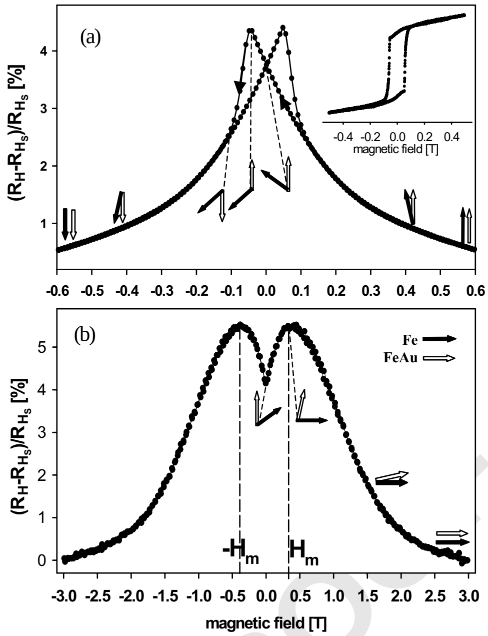

Fig. 1. GMR curves measured at 10 K for the $[Fe_3/Au(001)_9/(Fe_1Au_1)_3/Au(001)_9] \times 2$ multilayers with the magnetic field applied in the normal direction (a) and an in-plane direction (b). The inset shows the out-of-plane magnetization curve measured with VSM. The arrows indicate the orientation of the magnetization of Fe_3 (full symbols) and $(Fe_1Au_1)_3$ (empty symbols) sub-layers at the different values of the magnetic field. H_m (b) denotes magnetic field value related to maximal GMR effect.

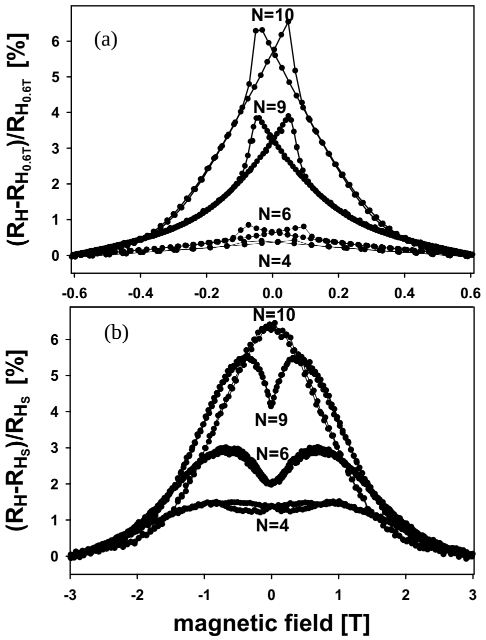

Fig. 2. GMR curves measured as a function of N for the $[Fe_3/Au(001)_N/(Fe_1Au_1)_3/Au(001)_N] \times 2$ multilayers at 10 K with the magnetic field applied in the normal direction (a) and an in-plane direction (b). The thickness of the Au spacer layer measured in the number N of Au(0 0 1) atomic layers is indicated.

that one reported by Renard et al. for Co/Au/Co system [6].

The GMR results for multilayers with $N = 4$, 6, 9, 10 AL of the Au spacer layer are summarized in Fig. 2. The in-plane GMR measurements (Fig. 2b) show formation of different non-collinear states for $N = 6, 9, 10$. This is indicated by gradual decrease of the GMR value with decreasing N. Since all curves are normalized to the saturation (parallel alignment) resistance value, the GMR effect at the given magnetic field provides information about the relative angle Φ between the magnetization vectors of the Fe_3 and $(Fe_1Au_1)_3$ sub-layers at this field value. The maximum GMR value roughly corresponds to a smallest field H_m sufficient to orient magnetization of Fe_3 sub-layers in the film plane. Since the maximum GMR value decreases with decreasing N, orientation of $(Fe_1Au_1)_3$ magnetization must be for H_m closer to the plane. This effect can be attributed to the increase of the strength of interlayer coupling with decreasing the Au spacer thickness. When the ferromagnetic coupling is strong, the simultaneous reversal of the sub-layer magnetic moments dominates the change of their relative orientation. Finally, for the thinnest spacer ($N = 4$), GMR effect becomes very small and only anisotropic-like contribution to the magnetoresistance remains. On the other hand, for the sample with $N = 10$, there is no initial increase of the resistance indicating in-plane orientation of Fe_3 moments. This behavior is accompanied by the highest GMR effect observed with the normal magnetic field (Fig. 2a) suggesting only weak (or none) interlayer coupling, which is not able to strongly alter the nominal orientation of the sub-layer magnetization. We attribute this behavior to an oscillatory character of interlayer coupling, which probably has a node for this spacer thickness. For the curves measured with perpendicular field (Fig. 2b), the remanent GMR value gradually decreases with the decreasing thickness of the Au spacer, which is related to the more collinear-like configuration and correlates with the GMR measurements with the field in-plane. Also, the maximum GMR value decreases with decreasing N.

In summary, it was shown that different non-collinear magnetic states could be stabilized in the Fe/Au/FeAu multilayers composed of sub-layers with the alternate in-plane and out-of-plane anisotropy. The effect, coming from a subtle competition between the magnetic anisotropy and the interlayer exchange coupling, can be tuned with the thickness of the non-magnetic spacer.

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