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MAGNETIC ANISOTROPIES IN ULTRA-THIN IRON FILMS GROWN ON THE SURFACE-RECONSTRUCTED GaAs SUBSTRATE

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Magnetic anisotropies of epitaxial ultra-thin iron films grown on the surface reconstructed GaAs substrate have been studied. Ferromagnetic resonance (FMR) technique has been exploited to determine magnetic parameters of the films in the temperature range 4-300 K. The unusual angular dependence of FMR spectra allowed us to build precise model of the magnetic anisotropies of the studied systems. The presence of strong perpendicular anisotropy have been deduced. Switching of the principal anisotropy axes has been observed in the double ferromagnetic-layer sample. It has been attributed to drastic relaxation of the uniaxial component of anisotropy induced by the surface reconstruction of the substrate. The linear variation of magnetic anisotropy parameters with the temperature has been observed and discussed in terms of magneto-elastic anisotropies controlled by thermal expansion coefficients of the materials in a contact.

INTRODUCTION

The interest to ultra-thin magnetic multilayers has been steadily increasing. It is motivated by the fact that magnetic properties of this type of structures are the real technological issues in mass production of data storage devices and magnetic random access memories. A good grasp of the fundamental physics of the magnetization dynamics becomes of essential importance to sustain the exponential growth of device performance factors.

The magnetic anisotropy of the thin films is of crucial importance in applications. It is well known that ferromagnetic resonance (FMR) is the most sensitive and accurate technique to determine magnetic anisotropy fields of very thin magnetic films [1,2]. In this paper we study the magnetic anisotropies in single and double iron layer structures grown on the surface-reconstructed GaAs single-crystalline substrate and demonstrate how surface-induced anisotropy can be used to tailor overall magnetic properties of the studied system. In our experiments we observed unconventional triple-mode FMR spectra. They are interpreted and explained based on the model proposed in this study. Consistent fitting of angular and frequency behaviors of the FMR spectra in the temperature range 4-300 K allowed us to determine accurately the cubic, uniaxial and perpendicular components of the magnetic anisotropy, as well as establish directions of easy and hard axes for the magnetization in the layer(s). The origin and temperature dependence of the magnetic anisotropy fields are extensively discussed in terms of the surface-induced anisotropies and thermal expansion coefficients of the materials subject to a stress, induced by lattice mismatch.

EXPERIMENTAL RESULTS

The single and double iron-layer ultrathin film structures (Au/Fe/GaAs, Cr/Fe/GaAs, Au/Pd/Fe/GaAs, Au/Fe/Au/Fe/GaAs) were prepared by Molecular Beam Epitaxy (MBE) on (4×6) reconstructed GaAs(001) substrates. A brief description of the sample preparation procedure is as follows. The GaAs(001) single-crystalline wafers were subject to annealing and sputtering cycles and

monitored by means of reflection high energy electron diffraction (RHEED) until a well-ordered (4×6) reconstruction appeared [3]. Then GaAs substrates were heated to approximately 500 C in order to desorb contaminants. Residual oxides were removed using a low-energy Ar^+ bombardment (0.6 keV) under grazing incidence. Substrates were rotated around their normal during the sputtering. The (4×6) reconstruction consists of (1×6) and (4×2) domains with the (1×6) domain is As-rich, while the (4×2) domain is Ga-rich.

The Fe films were further deposited directly on the GaAs(001) substrates at room-temperature from a resistively heated piece of Fe at the base pressure of 1×10^{-10} Torr. The film thickness was monitored by a quartz crystal microbalance and by means of RHEED intensity oscillations. The deposition rate was adjusted at about one mono-layer (ML) per minute. The gold layer was evaporated at room temperature at the deposition rate of about one monolayer per minute. RHEED oscillations were visible for up to 30 atomic layers. Noble metals are known to have long spin-diffusion length that makes them suitable as a spacer-layer in the spin-valve magnetic field sensor applications. Films under study were covered by a 20 ML thick Au(001) or Cr cap layer for protection in ambient conditions. More details of the sample preparation are given in Ref. [3]. The sketch of the single-layer film, coordinate system and principal vector directions are shown in Fig. 1.

Main FMR measurements have been carried out using the commercial Bruker EMX X-band ESR spectrometer equipped by an electromagnet, which provides a DC magnetic field up to 22 kG in the horizontal plane.

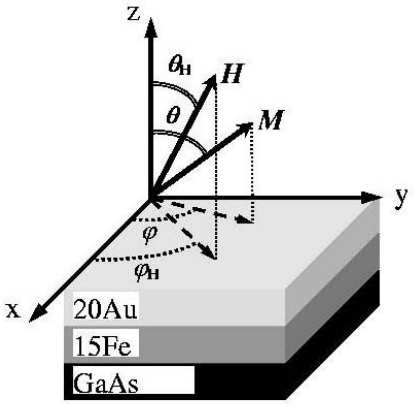

Fig.1. The sketch of the samples studied in the paper.

The small amplitude modulation of the field is employed to record field-derivative absorption signal at the temperature range 4-300 K. An Oxford Instruments continuous helium-gas flow cryostat was used to cool the sample down to the measurement temperatures, and the temperature was controlled by the commercial LakeShore 340 temperature-control system. A goniometer was used to rotate the sample around the rod-like sample holder in the cryostat tube. The sample-holder was always perpendicular to the DC magnetic field and parallel to the microwave magnetic field. The samples were placed on the sample-holder in two different geometries. For the in-plane angular studies the films were attached horizontally on the bottom edge of the sample holder. During rotation, normal to the film plane remained parallel to the microwave field, but the external DC magnetic field held different directions in the sample plane. This geometry is not conventional and gives quite asymmetric absorption curves but still at the same resonance field as in the conventional geometry for the in-plane measurements (both DC and microwave magnetic fields always lie in the film plane). Thus, we could be able to study at least the angular dependence of the resonance field and magnetic anisotropies using the FMR data taken from the unconventional in-plane geometry. We have also recorded some FMR data in the conventional, in-plane geometry for some specific crystallographic direction to check correctness of the data obtained in the unconventional geometry.

For the out-of-plane measurements the samples were attached to a flat platform precisionally cut at a cheek of the sample holder. Upon rotation of the sample the microwave component of the field remained always in the sample plane, whereas the DC field was rotated from the sample plane towards the film normal to get additional data for accurate determination of the anisotropy fields.

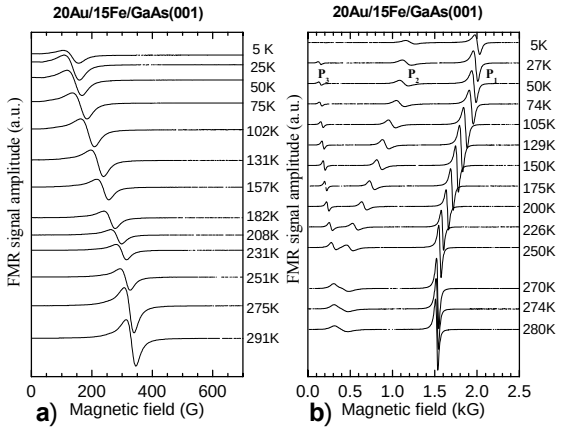

Fig.2. Temperature dependence of in-plane FMR spectra taken for **H**||**a** (a) and for **H**||**b** (b).

First we measured the in-plane FMR in the 20Au/15Fe/GaAs(001) sample. Figure 2a illustrates a temperature evolution of the in-plane FMR spectra taken in the direction of the DC magnetic field **H**||**a**, where **a** is the [110] direction of GaAs substrate or iron film (**a**||**x** in Fig. 1). The single, relatively narrow and intensive signal is observed at very low magnetic fields in the entire temperature range. As the temperature decreases starting from room temperature, the resonance field of FMR signal steadily shifts from 320 G for 300 K down to about 150 G at 5 K. The line width of the resonance increases with decreasing the temperature.

Contrary to the measurements along **a** axis, the in-plane FMR spectrum in the **b** direction (the [110] direction of the

GaAs substrate) unexpectedly consists of three signals (labeled by P_1, P_2 and P_3, Fig. 2b). As far as we know it is a unique observation of three FMR signals from a single, homogeneous ferromagnetic film. Usually, a single resonance peak (mode) is expected from such a very thin (15 monolayers) ferromagnetic layer, since the spin wave modes are expected to shift to negative fields due to very high excitation energies of the short-wavelength standing spin waves across the thickness of the ultrathin film. The temperature dependence of the FMR spectrum for **H**||**b** is shown in Fig. 2b. All three peaks are observable in the entire temperature range. The high-field signal has largest intensity at all temperatures. At room temperature the two low-field peaks overlap and almost merge into a common signal of distorted shape. As the temperature decreases, the low-field signal separates into two signals which shift one from the other in opposite directions. The intense high-field signal shifts monotonically to higher fields upon lowering the temperature. At lowest measurement temperatures (4-5 K) the overall splitting of the FMR spectra reaches 1700 G. It should be noted that the high-field mode for **H**||**b** shifts in the opposite direction to that for the **H**||**a** axis. This implies that the easy direction for magnetization in the sample plane is the **a** axis (and the **b** axis is the hard direction).

To study the in-plane anisotropy of the film, we rotated the DC magnetic field in the plane of the film (**ab**-plane). The room-temperature in-plane angular dependence of the FMR spectra is given in Fig. 3. As it can be seen from the figure the number of absorption peaks is varied with the in-plane rotation angle. The relative intensity of the signals is also angular-dependent. In fact, the FMR spectra show an overall periodicity of 180 degrees. This implies that the system must have at least uniaxial symmetry in the film plane. The unusual splitting of the spectra on the three components allows us to suppose that a considerable cubic anisotropy component is superimposed on the uniaxial anisotropy. We will see later from our simulations of the FMR spectra that it is actually the case.

In order to increase reliability of the FMR spectra interpretation we have also studied the frequency dependence of the in-plane FMR spectra between 9-36 GHz at room temperature using our high-frequency extension modules. Right-hand-side inset in Fig. 3 shows an angular variation of the in-plane resonance field measured at 24 GHz. Left-hand-side inset shows variation of the resonance fields with the microwave frequency. The parabolic dependence of experimental points on the frequency is clearly seen from the figure. This dependence is a general frequency behavior of the resonance field in systems with strong anisotropy (the anisotropy energy is comparable with the Zeeman energy at low-frequency region).

We have also made complementary out-of-plane FMR measurements when the DC magnetic field is rotated from the easy, **a**, or the hard, **b**, axes in the film plane towards the normal direction to the film plane. Figure 4 shows the evolution of the FMR field for resonance upon changing the polar angle in the **b-c** plane. Double-peak FMR spectra are observed for this geometry.

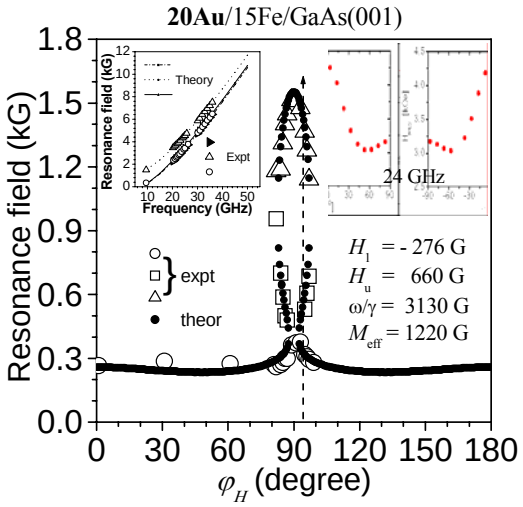

Fig.3. In-plane (**ab** plane) angular dependence of FMR spectra for the 20Au/15Fe/GaAs(001) sample at room temperature. Right-hand-side inset - the same angular dependence for 24 GHz, left-hand-side inset - the frequency dependence of the resonance field for the hard direction (upper) and easy (lower) directions.

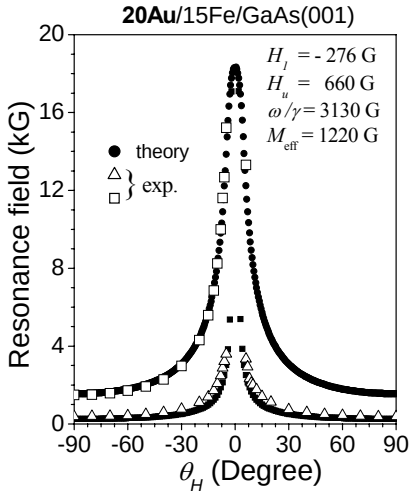

Fig.4. Out-of-plane angular dependence of resonance field for **H**||**b**.

The separation between modes steadily increases with approaching the film normal. As it will be clear later, the second mode does not belong to the higher-order spin-wave modes. However, the angular dependence of resonance field of the modes can be used to clarify the nature of magnetic anisotropy and to obtain accurately the anisotropy parameters from a computer fit.

We have studied also the sample where the gold cap-layer material had been replaced by chromium: 20Cr/15Fe/GaAs(001). In-plane geometry measurements

have shown drastic decrease of the uniaxial component in the in-plane anisotropy of the iron film as presented in Fig. 5a. The picture looks like the influence of the Cr cap-layer results in cancelling of the uniaxial anisotropy induced by the surface reconstruction of the GaAs substrate. At the same time, it is clearly visible that the principal axis of residual uniaxial anisotropy is tilted by about 23 degrees with respect to its original direction for the case of Au-capped sample. Another sample with a composite cap layer, 20Au/9Pd/16Fe/GaAs(001), revealed only minor influence of the palladium interlayer on the magnetic anisotropy of the iron film (see Fig. 5b). However, an additional FMR signal appeared in the main domain of the in-plane rotation angles, which we attribute to the magnetic response of the Pd interlayer (see discussion below).

After learning the FMR response from the single iron layer we have studied the spin-valve type, double-layer system.

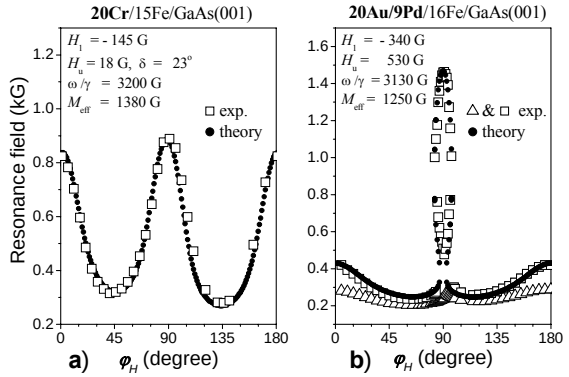

Fig.5. Influence of the cap layer - in-plane angular dependence of the resonance field: (a) chromium cap layer; (b) composite Pd/Au cap layer.

Figure 6 shows temperature evolution of the in-plane FMR spectra for the 20Au/40Fe/40Au/15Fe/GaAs(001) sample taken at two angles. We used data of our previous measurements on the single-layer sample, 20Au/15Fe/GaAs(001) as a reference, in which we have established easy and hard directions for the 15ML thick iron layer. The spectra at Figs. 6a and b have been recorded at the easy and hard axes for the first, 15ML thick iron layer.

Three FMR absorption peaks are clearly visible in the spectra recorded at the angle labelled "easy". As we do not expect any marked exchange or magnetostatic interaction through the 40ML-thick gold layer, the contribution of the first, 15 ML-thick, iron layer to the multi-component FMR signal can be easily attributed (see labelling in the Figure 6a) by comparison with the measurements on the single-layer sample, Fig. 2. The double-peak signal from the second, 40ML thick, iron layer gives a hint that easy and hard axes of the second iron layer are tilted with respect to the principal anisotropy axes of the first layer.

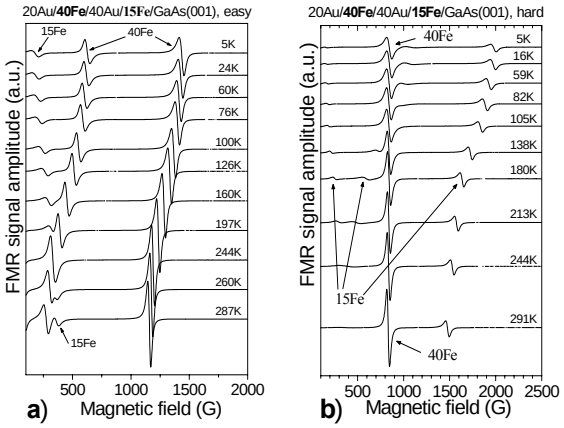

Fig.6. The in-plane FMR spectra of the double-layer sample for two orientations of magnetic field with respect to the crystallographic axes: (a) DC field is parallel to the hard axis of the first, 15LM-thick iron layer; (b) DC field is parallel to the easy axis of the first layer.

The FMR spectra recorded in the "hard" direction (Fig. 6b) show four-peak structure at certain range of temperatures, three of which are identified as a hard-axis spectra of the first, 15ML thick, iron layer. Then, the single-peak FMR spectrum of the 40ML-thick layer clearly indicates proximity to the easy direction for this layer.

Full angular dependence of the FMR spectra at room temperature is displayed in Fig. 7 (experimental points are given by empty symbols). From the figure it is evident that the hard axis (angle for maximal resonance field) of the second, 40ML thick, iron layer is switched on the 90 degrees apart of the hard axis of the first, 15ML thick, iron layer. Let us emphasize here the importance of the FMR measurements at different temperatures, Fig. 6, for identifications of the angular dependence of the resonance fields in Fig. 7.

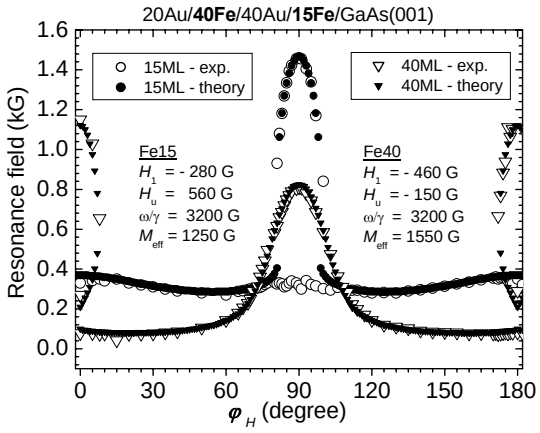

Fig. 7. The angular dependence of the in-plane resonance field for the double-layer sample at room temperature: open symbols - experimental data, solid symbols - results of the fitting.

MODEL AND COMPUTER SIMULATION OF THE FMR SPECTRA

The FMR data are analyzed using the model free energy expansion in the notations which is similar to that used in Ref. [4]:

$$E_T = -\mathbf{M}\cdot\mathbf{H} + \left(2\pi M_0^2 - K_p\right)\alpha_3^2 + K_1\left(\alpha_1^2\alpha_2^2 + \alpha_2^2\alpha_3^2 + \alpha_1^2\alpha_3^2\right) + K_u\alpha_1^2. \quad (1)$$

Here, the first term is the Zeeman energy in the external DC magnetic field, the second term is the demagnetization energy term including the effective perpendicular anisotropy as well, the third term is the cubic anisotropy energy characterized by the parameter K_1, and the last term is the uniaxial anisotropy energy. In this equation α_I's represent directional cosines [6] of the magnetization vector **M** with respect to the crystallographic axes ([100], [010] and [001]) of GaAs substrate (or iron film). M_0 is the saturation magnetization at the temperature of measurement. It should be remembered here that one of the crystallographic axes is always perpendicular to the sample plane, and the remaining two lie in the sample plane. That is why we could combine demagnetization and perpendicular anisotropy terms in a single term (second one) using only the α_3 directional cosine. The relative orientation of the reference axes, sample sketch and various vectors relevant in the problem are given in Fig. 1. The fields for resonance are obtained using the well known equation [5]:

$$\left(\frac{\omega_0}{\gamma}\right)^2 = \left(\frac{1}{M_0}\frac{\partial^2 E_T}{\partial\theta^2}\right)\left(\frac{1}{M_0\sin^2\theta}\frac{\partial^2 E_T}{\partial\phi^2}\right) - \left(\frac{1}{M_0\sin\theta}\frac{\partial^2 E_T}{\partial\theta\partial\phi}\right)^2 + \frac{1}{\gamma^2 T_2^2} \quad (2)$$

where $\omega_0 = 2\pi\nu$ is the circular frequency of the ESR spectrometer, γ is the gyro-magnetic ratio for the material of the magnetic film, θ and ϕ are usual polar and azimuthal angles of the magnetization vector ***M*** with respect to the reference system. We do not consider standing spin-wave excitations in the film because the film thickness is too small (20-40 Å).

The imaginary component of the dynamic magnetic susceptibility that corresponds to the absorbed microwave energy by the sample is given by [1,7]

$$\chi_2 = 4\pi\frac{m_\phi}{h_\phi} = 4\pi M_0\left(\frac{\partial^2 E_T}{\partial\theta^2}\right)\frac{2\omega}{\gamma^2 T_2}\left\{\left[\left(\frac{\omega_0}{\gamma}\right)^2 - \left(\frac{\omega}{\gamma}\right)^2\right]^2 + \frac{4\omega^2}{\gamma^4 T_2^2}\right\}^{-1} \quad (3)$$

Here $\omega_o/\gamma = g\mu_B H$ is the Larmour frequency of the magnetization in the external DC magnetic field,

To analyze the data for the in-plane geometry of measurements both polar angles in Eqs. (1) and (2), θ for magnetization, and θ_H for external DC magnetic field, are fixed at $\theta = \pi/2$, and the azimuthal angle of magnetization ϕ is obtained from the static equilibrium condition for the directions ϕ_H of the external field varied in the range from zero to π.

The results of computer solution for $H = H^{res}_{in\text{-}plane}$ of the above system for the 20Au/15Fe/GaAs(001) sample are plotted in Fig. 3 in solid circles. The best-fit parameters are given in the figure. The calculation procedure and Eq. (3) have also been used to simulate the experimental FMR spectra at different temperatures. The simulated spectra are plotted together with the experimental ones in Fig. 8a. There is quite good agreement between the calculated and the experimental angular dependence of the resonance field in Fig. 3 and the temperature evolution of the FMR spectrum in Fig. a. Notice here, that the in-plane angular dependence of the resonance field had been fitted simultaneously with the out-of-plane dependence, described below.

The computer simulations revealed that the angular dependence of the field for resonance shows unusual behavior. There is only single resonance line (Fig. 3) in the main domain of the angles. However, when direction of the DC magnetic field approaches the (hard) axis **b** (the angle ϕ varies ± 10º around 90º) double or even triple resonance absorption is observed (see Figs. 2b and a). This point can be made more clear if we follow the dash vertical line in the Figure 3. Moving along the line from zero magnetic field in the upward direction (just like spectrometer sweeps DC magnetic field when recording the FMR spectrum) we observe how the dash line intersects the figure of the angular dependence three times. In the close vicinity of 90º there are two intersections. Every intersection of the dash line with the figure of angular dependence gives FMR signal. For the triple-line FMR spectrum these intersections are marked as P_1, P_2 and P_3 in Figs. 2b and 8a.

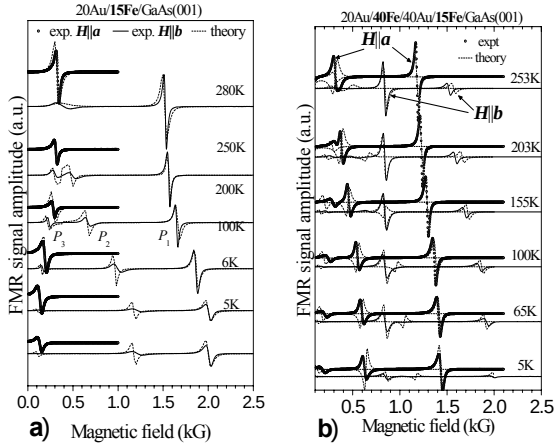

Fig. 8. Simulated FMR spectra taken as some selected temperatures for **H**||**b**: (a) for the single-layer sample; (b) for the double-layer sample.

In the case of double or triple FMR lines, the lower one(s) corresponds to the non-aligned situation, when the condition for resonance, Eq. (4), is satisfied at the direction of the magnetization, which is not parallel to the external magnetic field. The high-field signal may be called as an

aligned signal, when the magnetization and the external DC field are practically parallel. To our best knowledge, no observations of two non-aligned FMR resonances in a single ferromagnetic film had been reported in the literature. The double-peak FMR spectra in a single iron film have been observed previously (see, for example, Refs. [8,9,10,11]). We believe that a specific relation between cubic and uniaxial anisotropies is realized in the studied system, which gives rise the observed unusual behavior of the FMR spectra. However, if the measurement frequency is increased, the angular-dependence loop opens, and the single-line FMR spectrum is observed in the full domain of angles (right-hand-side inset of Fig. 3).

Fitting of the in-plane angular dependence for the Cr-capped sample (see solid symbols in Fig. 5a) revealed drastic suppression of the substrate-induced uniaxial anisotropy by the Cr overlayer. Contrary to this case, the Pd/Au-capped sample shows only minor influence of the palladium interlayer on the anisotropy of the iron layer (see Fig. 5b, solid symbols). However, an additional FMR line appears at low fields, which can not be reproduced within our model. We may speculate that this signal comes from the palladium layer magnetized by the proximity with the ferromagnetic iron layer. However, this question needs special investigation.

For the out-of-plane geometry of measurements the azimuthal angle ϕ_H is fixed either at $\phi_H = 0$ (hard axis, i.e. the DC magnetic field is rotated in the (110) plane), or $\phi_H = \pi/2$ (easy axis, i.e. the DC magnetic field is rotated in the (110) plane), while the polar angle θ_H is varied from $\pi/2$ to zero. The polar and azimuthal angles of magnetization for each direction of the external field have been obtained from static equilibrium condition corresponding to the minimum free energy of the system. Double-peak FMR spectra appeared also for the out-of-plane geometry when measured from the hard in-plane direction. The results of the computer solution of the system Eq. (5) obtained in the procedure of simultaneous fitting with the in-plane dependence from Fig. 3 for the 20Au/15Fe/GaAs(001) sample are plotted in Fig. 4 in solid symbols. The best-fit parameters are given in the figure. Thus, the calculations show fairly good agreement at all angles, in-plane and out-of-plane geometry, all temperatures and frequencies of the measurements. The deduced magnetic parameters used in the calculation of the simulated spectra are given in Fig.9a.

The comparison of the spectra from Fig. 2a with the spectra from Fig. 6a, recorded in the easy direction of the first, 15ML-thick iron layer, says us that the double-line FMR spectrum is observed for the second, 40ML-thick iron layer. And *vice-versa*, the spectra in Fig. 6b, recorded in the hard direction reveal the single-line FMR spectrum from the second iron layer. Being guided with the results of simulations for the single-layer sample we realize clearly that there is inclination angle between the easy and hard axes of the first and the second iron layers. The fitting of the full angular dependence of the second layer FMR spectra using the equation set (4) for the signal from each layer (Fig. 7) revealed that the hard axis of the uniaxial anisotropy term in the second, 40ML-thick iron layer, is switched 90 degrees with respect to the hard axis of that in the first, 15ML-thick iron layer. The fitting parameters shown in Figure 7 allow to conclude that origin of the observed switching is mainly drastic relaxation and change in sign of the uniaxial component of the magnetic anisotropy in the second layer (~-150 G as compared with ~660 G for the single 15ML-thick layer at room temperature). Comparison of the model calculations with the temperature evolution of the experimental spectra for both orientations is given on Fig. 8b. Except reversed phase for certain components of the FMR spectrum the agreement between the calculated and the experimental spectra is fairly good. This confirms validity of the proposed model of anisotropy Eq. (1). The deduced temperature dependence of the magnetic parameters is given in Fig.9b.

The cumulative data on the magnitudes and temperature variations of the magnetic parameters are given in Fig. 9. All the parameters are given in magnetic induction units (Gauss). It should be recalled that the effective magnetization, M_{eff}, includes perpendicular anisotropy (see Eq. (1)). That is why the values of M_{eff} are essentially reduced compared with the bulk magnetization (~17 kG [12]). This means that very strong, perpendicular to the film plane, surface anisotropy field (about 5 kG) is induced in the epitaxial ultra-thin film at room temperature. It is also a general feature that both the uniaxial (along the [110] axis of the GaAs substrate) and the cubic anisotropy fields are significantly large. That is why the anisotropy energy dominates the Zeeman energy and causes such unusual and surprising triple-line FMR spectra in the single ferromagnetic layer. To the authors knowledge, it is the first observation for three FMR lines, all of which correspond to the homogeneous (non-spin-wave) FMR response.

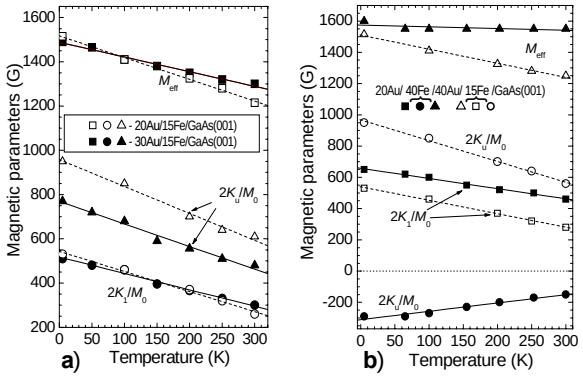

Fig. 9. Temperature dependence of the magnetic parameters: (a) for the single-layer sample; (b) for the double-layer sample.

It can be seen from Fig. 9 that all magnetic anisotropy parameters strongly depend on temperature. As the temperature decreases the effective magnetization increases. This is partly due to increase of the saturation magnetization of iron according to the Bloch law, and partly due to

decrease of the easy-axis perpendicular anisotropy. The ferromagnetic transition temperature of bulk iron is about 980 K, that is why even at room temperature the magnetic moment is almost fully saturated. Using the literature data on the temperature dependence of iron magnetic moment in the ferromagnetic phase [12] we estimate increase of the iron magnetization in the range from 300 K to 5 K as about 64 G. Obviously, the observed magnitude (~300 G) and almost linear temperature dependence of the effective magnetization do not follow the conventional temperature dependence of saturation magnetization described above. That is why we conclude that essential contribution to the temperature variation of the effective magnetization comes from the temperature dependence of the perpendicular anisotropy. As temperature decreases the perpendicular anisotropy relaxes.

The absolute values of the both, in-plane uniaxial and the cubic, anisotropies increase with decreasing the temperature. The sign of cubic anisotropy parameter is positive, making all of the three principal crystalline axes- [100], [010] and [001]- easy for magnetization. However the more strong uniaxial anisotropy, is positive making the **b =** [110] axis a hard direction for magnetization.

As can be noticed from Fig. 9 all of the magnetic anisotropy parameters depend on temperature almost linearly. This implies that there is a common physical reason behind this unified behavior. It is supposed that the strong uniaxial anisotropy in Fe films grown on GaAs is induced by hybridization of the interface electronic states in a ferromagnetic film and the valence electrons in the surface reconstructed GaAs substrate (see, for instance, [3], [13]). Therefore, it is possible that a contraction of interatomic distances, which changes a degree of the metal-substrate hybridization, may also contribute in the temperature dependence of the magnetic anisotropy parameters. However, one can notice from Fig. 9b that for the second iron layer, which is well separated from the substrate by two (first iron and Au) layers, only the perpendicular magnetic anisotropy reveals a change in the temperature behaviour with respect to the first Fe layer. On the other hand, taking into account appreciable differences between the lattice constants for bulk Fe and epitaxially prepared Fe film on the GaAs substrate one may attribute the temperature dependence of the anisotropy parameters to the linear magneto-elastic effect. It has been proposed that the strain contributes not only to the cubic and perpendicular anisotropies but also to the uniaxial anisotropy due to the anisotropic strain relaxation (see [4], and references therein). In this respect the change in the sign of uniaxial anisotropy for the second iron layer shows that even through the 40ML Au layer the strain-induced anisotropy does not relax to zero. Furthermore, both contributions to the uniaxial in-plane anisotropy mentioned above have to be taken into account to explain the observed behaviour, and the sign of the strain-induced anisotropy is opposite to that of the uniaxial anisotropy due to reconstructed GaAs surface. Therefore, these two contributions counteract each other in the first iron layer. This competition could be relevant for the non-linear behavior of the in-plane uniaxial anisotropy with the iron film thickness reported in the literature [4,3].

Actually, there is about –1.5% misfit between lattice parameters of Fe, Au and GaAs substrate. In a result, the Fe film is under a compressive strain. When temperature is lowered down to 4K from the room temperatures, this stress decreases by about 40 percent, as can be calculated by using the thermal expansion coefficient of Fe, Au and GaAs crystals, given in the Table. The lattice parameters vary linearly with the temperature, and, in the first approximation, we expect the anisotropy parameters vary linearly with temperature as a result of different thermal expansion coefficients of materials in the contact (see the Table) and the magneto-elastic coupling. In this case, the cubic anisotropy relaxes to the bulk iron value (about of 530 G) and the strain-induced contribution in the cubic anisotropy is negative in contrast to the bulk one, which is positive and dominating. However, in this picture an increase of absolute value of uniaxial component of anisotropy in the second 40ML iron layer for the 20Au/40Fe/40Au/15Fe/GaAs(001) sample is not clear. Possibly, the step-induced anisotropies in the top of the iron film also contributes in the total value of the uniaxial in-plane anisotropy [3,14]. A competition between various contributions in the in-plane anisotropies is especially indicative in the case of Cr-cap layer, where the iron layer is under the stretching influence due to larger lattice parameter of Cr compared to Fe. Since the misfit and interface interaction between chromium and iron is much larger compared to the case of contact with noble metals, the strain anisotropies, induced by the stretching influence of Cr cap layer, almost completely cancel the surface-induced uniaxial anisotropy due to the reconstructed GaAs and decrease the absolute value of cubic anisotropy as well.

CONCLUSION

We studied the magnetic anisotropies of epitaxial, ultra-thin iron films grown on the surface reconstructed GaAs substrate. The ferromagnetic resonance technique has been explored extensively to determine magnetic parameters of the films in the temperature range 4-300 K. The triple-peak behavior of FMR spectra was observed for the first time, which allowed accurate extraction of magnetic anisotropies from computer fitting of the model to the experimental data. Presence of the strong perpendicular anisotropy and the uniaxial in-plane anisotropy, induced by the surface reconstruction of the substrate and lattice mismatch with substrate/overlayer, have been deduced from the fitting of the FMR spectra. The switching of the principal anisotropy axes of the top iron layer with respect to the bottom (adjacent to the GaAs substrate) layer has been established in the double-layer sample. It was attributed to the competition of various contributions in the uniaxial anisotropy (surface anisotropy due to the surface reconstruction of the GaAs substrate and strain anisotropy). The surface- and interface-induced origin of the anisotropies has been demonstrated by extensive studies of temperature dependence of anisotropy fields, as well as influence of the cap layer material. The results on

temperature dependence have been discussed in terms of the magneto-elastic contribution to the magnetic anisotropies. It was shown that surface reconstruction of GaAs substrate as well as combination of materials in the stack can be used for the tailoring of the magnetic anisotropies in spin-valve-like, double ferromagnetic layer structure.

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