

## Electron interaction with domain walls in antiferromagnetically coupled multilayers

F. G. ALIEV<sup>1</sup>, R. SCHAD<sup>2</sup>, A. VOLODIN<sup>3</sup>, K. TEMST<sup>3</sup>, C. VAN HAESENDONCK<sup>3</sup>,  
Y. BRUYNSERAEDE<sup>3</sup>, I. VAVRA<sup>4</sup>, V. K. DUGAEV<sup>5</sup> and R. VILLAR<sup>1</sup>

<sup>1</sup> *Departamento de Física de la Materia Condensada, C-III  
Universidad Autónoma de Madrid - Madrid, Spain*

<sup>2</sup> *CMIT, University of Alabama - Tuscaloosa, AL 35487, USA*

<sup>3</sup> *Laboratorium voor vaste Stofffysica en Magnetisme, K.U. Leuven  
B-3001 Leuven, Belgium*

<sup>4</sup> *Institute of Electrical Engineering-SAS - 84239 Bratislava, Slovakia*

<sup>5</sup> *Max-Planck-Institut für Mikrostrukturphysik - Weinberg 2, 06120 Halle, Germany*

(received 2 May 2003; accepted 4 July 2003)

PACS. 75.60.-d – Domain effects, magnetization curves, and hysteresis.

PACS. 75.70.-i – Magnetic properties of thin films, surfaces, and interfaces.

PACS. 75.47.De – Giant magnetoresistance.

**Abstract.** – For antiferromagnetically coupled Fe/Cr multilayers the low-field contribution to the resistivity  $\rho_{\text{DW}}$ , which is caused by the domain walls, is strongly enhanced at low temperatures. The low-temperature resistivity  $\rho_{\text{DW}}$  varies according to a power law,  $\rho_{\text{DW}}(T) = \rho_{\text{DW}}(0) - A \cdot T^\alpha$  with the exponent  $\alpha \simeq 0.7$ –1. This behavior cannot be explained assuming ballistic electron transport through the domain walls. It is necessary to invoke the suppression of anti-localization effects (positive quantum correction to conductivity) by the non-uniform gauge fields caused by the domain walls.

Renewed interest in the domain wall (DW) contribution to the resistivity is stimulated by its relevance for fundamental physics [1–5] and possible applications. Indeed, domain walls may strongly influence the electrical noise and operation of magnetoelectronics devices [6]. Although the number of DWs was controlled and directly observed in Fe [5] and in Co [3] films at room temperature, where DW formation is relatively well understood, no clear picture has emerged allowing to explain the results. The anisotropic magnetoresistance (AMR) dominates the low-field magnetoresistance and complicates the extraction of the true DW contribution to the resistivity [7]. In order to minimize the AMR contribution, thin films with reduced magnetization and special DW configuration have been studied [8]. Apart from the ballistic contribution to the DW magnetoresistance [9], quantum interference also affects the electron transport through DWs [10,11].

Antiferromagnetically (AF) coupled magnetic multilayers (MMLs) are systems with reduced magnetization and, consequently, a strongly suppressed AMR. At high temperatures, weak pinning of the DWs in the MMLs is expected to suppress the DW magnetoresistance.

For fixed magnetic field the DW magnetoresistance should emerge at sufficiently low temperatures, where DWs become strongly pinned and their configuration is not affected by thermal fluctuations or by the applied electrical current.

Here, we report on our detailed study of the low-field electrical resistivity in AF coupled Fe/Cr MMLs. The well-known giant magnetoresistance (GMR) in this system is dominated by a realignment of the magnetization direction in adjacent magnetic layers [12]. The presence of DWs should result in an additional, small in-plane magnetoresistance [13]. While the GMR is known to saturate at low temperatures [14], the temperature dependence of DW magnetoresistance is still a matter of controversy. In order to separate the two contributions, we performed a systematic study of the temperature dependence of the resistivity in low magnetic fields. Our main findings are that i) the presence of DWs in an AF coupled MML does not affect the resistivity at room temperature, and ii) at low temperatures the DW contribution to the resistivity becomes positive and strongly temperature dependent. We explain these observations in terms of the suppression of positive quantum correction to conductivity (so-called “anti-localization” effect) by the domain walls.

Epitaxial [Fe/Cr]<sub>10</sub> multilayers with 10 bilayers are prepared in a molecular beam epitaxy system on MgO (100)-oriented substrates held at 50 °C and covered with an approximately 10 Å thick Cr layer. The thickness of the Fe layer was varied between 9 and 30 Å, while the Cr layer thickness (typically 12–13 Å) corresponds to the first antiferromagnetic peak in the interlayer exchange coupling for the Fe/Cr system [15] and produces a maximum GMR which is about 20% at 300 K and 100% at 4.2 K. A commercial cryogenic system (PPMS, Quantum Design) was used to measure magnetization, magnetic susceptibility, and electrical resistance with a standard four-probe ac method at a frequency of 321 Hz with currents ranging between 15 and 50 μA. The magnetic fields created by these currents are well below 0.1 Oe and do not affect the DWs. The magnetic-field dependence of the susceptibility along different crystallographic directions as well as the low residual resistivity (typically less than 13 μΩcm at a saturation field of 1 T) confirm the good epitaxial growth of our MMLs. Magnetization measurements at 4.2 K reveal that the antiferromagnetic fraction  $(1 - M_r/M_s)$ , with  $M_r$  and  $M_s$  the remanent and the saturation magnetization, respectively, exceeds 80%. This indicates that bilinear AF coupling dominates over biquadratic exchange coupling [16]. The existence of a small non-compensated magnetic moment may allow DW motion in our artificial antiferromagnet.

The inset in fig. 1a shows a typical magnetic image of an AF coupled Fe/Cr MML at  $T = 4.2$  K (image size is  $8 \times 8 \mu\text{m}^2$ ) using a home-built cryogenic magnetic-force microscope (MFM) [17]. The MFM picture, which “feels” magnetic contrast, reveals different irregularly shaped domain walls (which is a characteristic feature of strong AF coupling [12, 18]) with micrometer dimensions. While our MFM measurements reveal a similar domain structure at room temperature, the magnetoresistance curves, which are shown in fig. 1, are very different. The low-field magnetoresistance is strongly enhanced at low temperatures. The susceptibility data point towards a weak pinning of the DWs at room temperature and a strong pinning at low temperatures [19].

Figure 2a shows the temperature dependence of the electrical resistivity  $\rho$  for an [Fe(12 Å)/Cr]<sub>10</sub> MML for different magnetic fields ( $|H| \leq 300$  Oe). The magnetic field is applied in the plane of the film and is parallel to the current as well as to the longer side of the rectangular ( $5 \times 25 \mu\text{m}^2$ ) sample which is directed along the (110) axis. For  $|H| > 100$  Oe the  $\rho(T)$ -dependence reveals a metallic behavior, while for  $|H| \leq 100$  Oe there appears a shallow minimum in the  $\rho(T)$  curves. We note that in the  $\rho(T)$  curves measured after crossing zero field there appear aperiodic peaks when the applied current is smaller than 20 μA, which correspond to an intrinsic noise process in the sample. The peaks, which can be linked

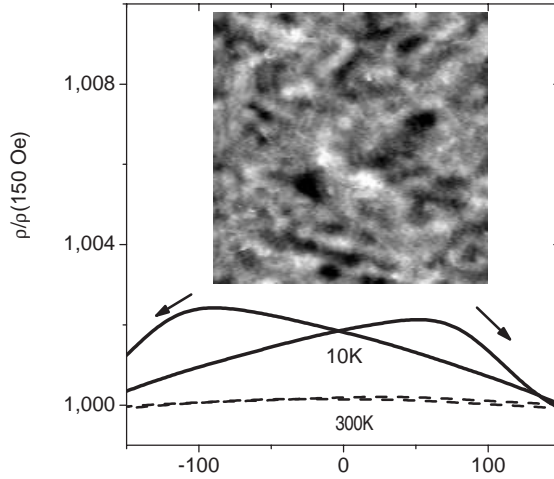


Fig. 1 – Room temperature and low-temperature normalized magnetoresistance  $\rho(H)/\rho(150 \text{ Oe})$  for an  $[\text{Fe}(12 \text{ \AA})/\text{Cr}]_{10}$  multilayer with the current  $I$  parallel to the field  $H$  and parallel to the (110) direction. The inset shows a typical MFM image ( $8 \times 8 \mu\text{m}^2$ ) of an AF coupled  $[\text{Fe}/\text{Cr}]_{10}$  multilayer at 4.2 K.

to Barkhausen noise, gradually disappear when doubling the electrical current or when the absolute value of the magnetic field exceeds 300 Oe [20].

A straightforward way to determine the magnetoresistivity of the DWs is to subtract the temperature dependences of the resistivity measured in the presence and in the absence of DWs, respectively. However, the magnetic field  $H_S^0$  which guarantees nearly uniform Néel vector along the external field (according to our magnetic susceptibility data  $300 \text{ Oe} < |H_S^0| < 1000 \text{ Oe}$ ), not only sweeps the DWs out of the sample, but may also change the angle of the magnetization between adjacent magnetic layers from the antiparallel alignment (GMR). In order to separate the magnetoresistivity induced by the GMR effect from the magnetoresistivity induced by the DWs, we define  $\rho_{\text{DW}} = \rho(T, H) - \rho(T, H_S)$  with  $|H_S| \leq 300 \text{ Oe}$ . Although this method may underestimate the magnetoresistivity of the DWs because not all domains will be removed by the applied field  $H_S$ , the method provides a possibility to determine the temperature dependence of the DW magnetoresistivity. In fig. 2b we show  $\rho_{\text{DW}}(T, H)$  between 1.9 and 100 K for different magnetic fields ranging between  $-200 \text{ Oe}$  and zero field for  $H_S = -300 \text{ Oe}$ . We find that, in contrast to the GMR, the DW magnetoresistivity is strongly temperature dependent with no sign of saturation at low temperatures.

Assuming that the magnetic field mainly changes the effective DW concentration  $n_{\text{DW}}$  [21], we expect  $\rho_{\text{DW}}$  to scale according to  $\Delta\rho_{\text{DW}} = \rho_{\text{DW}}(0) - \rho_{\text{DW}}(T) \propto n_{\text{DW}}(H) \cdot \rho_{\text{DW}}^0(T)$  with  $\rho_{\text{DW}}^0(T)$  a function describing the temperature-dependent electron interaction with DWs. Determined in this way  $\rho_{\text{DW}}^0(T)$  which is independent of the choice of  $H_S$  as long as  $|H_S| \leq 300 \text{ Oe}$ . Our data analysis reveals that the DW resistivity is roughly given by  $\Delta\rho_{\text{DW}} \sim n_{\text{DW}}(H) \cdot T^{0.7}$ ; fig. 3a illustrates the scaling  $\Delta\rho_{\text{DW}} \propto T^{0.7}$  for different magnetic fields  $|H| < H_S = -300 \text{ Oe}$  for temperatures between 1.9 K and 25 K. For comparison we also show the qualitatively different temperature scaling for the GMR (see dashed line in fig. 3a). The vertical bar in fig. 2b estimates the maximum influence of the GMR effect on our data. This estimation was obtained from the temperature dependence of the magnetoresistivity measured for two different magnetic fields sufficiently large to remove all DWs. In agreement with

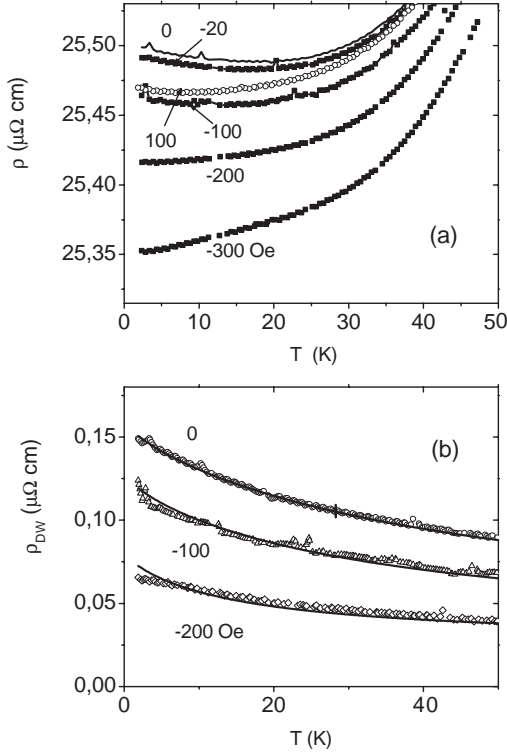


Fig. 2

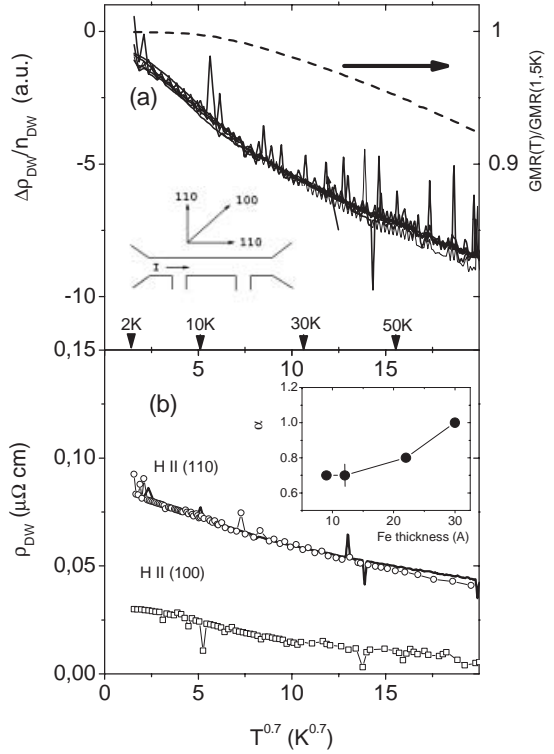


Fig. 3

Fig. 2 – (a) Temperature dependence of the resistivity for an  $[\text{Fe}(12 \text{ \AA})/\text{Cr}]_{10}$  multilayer in different magnetic fields. Both the field and the current are along the (110) axis. (b) Temperature dependence of the DW contribution to the resistivity.  $\rho_{\text{DW}} = \rho(T, H) - \rho(T, H_S)$  determined from the data shown in (a) for  $H_S = -300$  Oe. The solid lines correspond to the fits which are described in the text.

Fig. 3 – (a) Normalized temperature dependence of the DW contribution to the resistivity. The data have been obtained for magnetic fields: +100, +20, 0, -20, -100 and -200 Oe.  $n_{\text{DW}}(H)$  is the concentration of domain walls, and the DW resistivity has been determined for  $H_S = -300$  Oe. The dashed line corresponds to the GMR contribution which is obtained from the  $\Delta\rho_{\text{DW}}(T)$ -dependence for  $H = -500$  Oe with  $H_S = -1000$  Oe. The inset gives a schematic view of the sample geometry. (b) Temperature dependence of the DW contribution to the resistivity for an  $[\text{Fe}(12 \text{ \AA})/\text{Cr}]_{10}$  multilayer when  $H = 0$  and for  $H_S = -200$  Oe directed along the (110) direction. The circles correspond to the case where the field  $H$  is perpendicular to the current  $I$ , while the solid line corresponds to the case where  $H$  is parallel to  $I$ . The open squares give  $\rho_{\text{DW}}$  for  $H = 0$ , but with  $H_S = -200$  Oe directed along the (100). The inset illustrates the dependence of the scaling exponent  $\alpha$  on the Fe layer thickness.

previous results [14, 22], both saturation field and GMR are weakly temperature dependent below 50 K; GMR saturates as  $T^2$  and changes in less than 7%.

Next, we demonstrate that neither the AMR, which depends on the relative orientation of the magnetization and the current  $I$ , nor the ordinary magnetoresistivity (caused by the Lorentz force), which depends on the relative orientation of  $I$  and the magnetic induction  $B$ , contribute to  $\rho_{\text{DW}}$ . The upper curves in fig. 3b correspond to  $\Delta\rho_{\text{DW}}$  ( $H_S = -200$  Oe for the current parallel to (line) or perpendicular to (circles) the magnetic field  $H$  applied parallel to the (110) direction (see inset in fig. 3a)). If the AMR affects the low-field magnetoresistivity,

its contribution will be positive when the field is parallel to the current and negative when the field is perpendicular to the current [1]. It is, however, clear that  $\Delta\rho_{\text{DW}}$  is almost identical for both cases, indicating that the AMR effects can be neglected. The magnetic-field dependence of the DW resistivity is reduced when the field is applied along the (100) axis (see lower curve in fig. 3b). This probably reflects the presence of a crystal-lattice-induced anisotropy in the potential barrier which pins the DWs. We have obtained similar results with a slightly different scaling of the low-temperature DW magnetoresistivity for three other AF coupled Fe/Cr samples with an Fe layer thickness of 9, 22 and 30 Å, respectively. The inset in fig. 3b shows the dependence of the scaling exponent  $\alpha$  on the Fe thickness. This may reflect a change of the exponent  $p$  in the temperature dependence of the phase breaking time  $\tau_\varphi \propto T^{-p/2}$  which should occur between the “dirty” ( $p = 3/2$ ) and “clean” ( $p = 2$ ) limits [23].

A ballistic approach for the electron transport through DWs [9] requires that the mean free path  $\ell$  in our epitaxial layers exceeds the DW width  $D$  with  $20 < D < 200$  nm for Fe/Cr/Fe trilayers [24]. Therefore, the condition for ballistic transport may only be fulfilled at sufficiently low temperatures [25]. Although non-ballistic effects have not yet been incorporated into the theory [9], we believe that they cannot account for the strong variation of  $\rho_{\text{DW}}$  down to 1.9 K, because the mean free path is expected to saturate at low temperatures. Moreover, the strong pinning of DWs at low temperatures [19] implies that a distortion of the current lines by domain walls [1] or a change of the DW configuration cannot account for the *strongly temperature-dependent low-field contribution to the magnetoresistivity in antiferromagnetically coupled magnetic multilayers*.

In order to explain the strong variation of the DW magnetoresistivity at low temperatures, one has to go beyond the classical approach [9]. A possibility is to link the observed phenomena either to standard, disorder-related, weak-localization effects or to scattering by isolated spins. Our experimental results are in conflict with both scenarios since the resistivity correction with and without magnetic field is different when applying the magnetic field along the hard or along the easy axis (see fig. 3b). Moreover, we observe that  $\rho(T, H)$  is different when the magnetic field is changed at low temperature (4.2 K) or at high temperature ( $T > 150$  K). Finally, we observe some asymmetry in the  $\rho(T, H)$  data taken for fields with the same amplitude but applied along different directions (see data for  $H = 100$  Oe and  $H = -100$  Oe in fig. 2a).

Both [10] and [11] predict a destruction of weak electron localization by the domain walls, although the details of the destruction mechanism are different. *Direct application of these models results in a sign of the DW magnetoresistivity which is opposite to the sign of the experimentally observed magnetoresistance*. However, the sign of the localization correction may be reversed due to strong spin-orbit (SO) scattering (anti-localization) [26]. The suppression of the weak localization corrections by a DW, predicted in [10, 11], is related to the effective gauge potential created by the domain wall. In contrast to the electromagnetic vector potential, which can be linked to an external magnetic field, the gauge field depends on the spin, giving rise to a different influence of the domain wall on the different components of the so-called Cooperon [11]. Our measurements are consistent with an anti-localization effect in the absence of DWs ( $H > 300$  Oe) which is suppressed in the presence of DWs ( $H = 0$ ). The appearance of anti-localization is due to the SO scattering which suppresses the triplet Cooperons and does not affect the singlet Cooperon [23].

The SO interaction should be more pronounced in the case of multilayered structures than in single films. The potential steps at the interfaces in combination with the relativistic terms in the Hamiltonian may produce strong SO scattering. The corresponding theory for the interface SO interaction has been proposed by Bychkov and Rashba [27]. In the case of Fe/Cr multilayers, the potential steps are about 2.5 eV for the majority electrons, and one can expect a significant SO scattering from the interface. In case of strong SO scattering the

magnetoresistance is caused by the destruction of the singlet Cooperon by the gauge field of the DWs. The model [10] predicts a suppression of all components of the Cooperon, while the approach of Lyanda-Geller *et al.* [11] relies on the suppression of some of the components.

When  $\ell \ll D$ , we can characterize the system in terms of a local conductivity, which is defined as an average over distances larger than  $\ell$  but smaller than  $D$ . For the local conductivity inside a DW we can estimate the localization correction that is determined by smaller diffusive trajectories with size  $L < D$  as well as by large trajectories  $D < L < L_\varphi$ .  $L_\varphi$  is the phase relaxation length governing the destruction of the interference effects. The localization corrections associated with the small trajectories are suppressed by the gauge field since they are located within the DW. The contribution of large trajectories to localization is small, and for strong spin-orbit scattering the local conductivity within a DW is

$$\sigma_{\text{DW}} \simeq \sigma_0 + \frac{e^2}{4\pi^2\hbar} \left[ \frac{1}{\ell} - \left( \frac{1}{L_{\text{DW}}^2} + \frac{1}{L_\varphi^2} \right)^{1/2} \right], \quad (1)$$

where  $L_{\text{DW}}$  is the characteristic length which is determined by the influence of the gauge potential  $\mathbf{A}$ . Its magnitude can be estimated as  $A \sim 1/D$ , and consequently  $L_{\text{DW}} \sim D$ .

Since the anti-localization correction without DW is

$$\sigma \simeq \sigma_0 + \frac{e^2}{4\pi^2\hbar} \left( \frac{1}{\ell} - \frac{1}{L_\varphi} \right), \quad (2)$$

we are able to estimate the difference in magnetoresistivity due to the DWs as

$$\sigma_{\text{DW}} - \sigma \simeq -\frac{e^2}{4\pi^2\hbar} \left[ \left( \frac{1}{L_{\text{DW}}^2} + \frac{1}{L_\varphi^2} \right)^{1/2} - \frac{1}{L_\varphi} \right] \quad (3)$$

by taking into account that  $\sigma_{\text{DW}} - \sigma \simeq -\Delta\rho_{\text{DW}} * \sigma^2$ . The most important feature of our evaluation of the anti-localization effects is the fact that the correction to the local conductivity is determined by the gauge field inside the DW. If the current flow crosses the DWs, the corrections to the local conductivity, calculated for a narrow region inside a DW, show up in the sample resistance.

We can also estimate the influence of an external magnetic field of 300 Oe and of the internal magnetization on the localization corrections. These effects are small when the magnetic length  $l_H \equiv \sqrt{\hbar c / (eH)} \gg \ell$ . For  $H = 300$  Oe,  $l_H \simeq 1.4 \cdot 10^{-5}$  cm. Assuming the internal magnetic induction  $B = 2$  T (typical value for Fe), we obtain the corresponding length  $l_H \simeq 1.8 \cdot 10^{-6}$  cm. On the other hand, the mean free path  $\ell \simeq 10^{-7}$  cm. Thus, both the external magnetic field and the magnetization are unable to effectively suppress the anti-localization corrections.

We are able to fit our data to eq. (3) when we assume that  $L_{\text{DW}}$  is independent of temperature and that the phase-breaking length  $L_\varphi$  varies with temperature according to a power law  $L_\varphi \propto T^{-p/2}$  [23]. On the other hand, we have to introduce an additional (constant) shift of the data which takes into account the change of the resistance due to the variation of the angle between magnetic layers. It is important to note that the three different fits presented in fig. 2b correspond to the same fitting parameters (with  $p = 3/2$ ), except for the parameter which describes the magnetic contrast ( $L_{\text{DW}}$ ). We find that the effective DW width  $L_{\text{DW}}$  becomes about 2.5 times larger when the magnetic field is increased from 0 to 200 Oe.

\* \* \*

We thank A. P. LEVANUYK and V. V. MOSHCHALOV for discussions. The research was supported in parts by Spanish MCyT under project BFM2000-0016, by Comunidad de Madrid (07N/0050/2002) and by Polish Grant PBZ/KBN/044/P03/2001 (VD).

## REFERENCES

- [1] BERGER L., *J. Appl. Phys.*, **49** (1978) 2156.
- [2] HONG K. and GIORDANO N., *Phys. Rev. B*, **51** (1995) 9855.
- [3] GREGG J. F. *et al.*, *Phys. Rev. Lett.*, **77** (1996) 1580.
- [4] LEVY P. M. and ZHANG S., *Phys. Rev. Lett.*, **79** (1997) 5110.
- [5] RÜEDIGER U. *et al.*, *Phys. Rev. Lett.*, **80** (1998) 5639; KENT A. D. *et al.*, *IEEE Trans. Magn.*, **34** (1998) 900.
- [6] GIDER S. *et al.*, *Science*, **281** (1998) 797.
- [7] RÜEDIGER U. *et al.*, *Phys. Rev. B*, **59** (1999) 11914.
- [8] VIRET M. *et al.*, *Phys. Rev. Lett.*, **85** (2000) 3962.
- [9] VAN HOFF J. B. A. N. *et al.*, *Phys. Rev. B*, **59** (1999) 138.
- [10] TATARA G. and FUKUYAMA H., *Phys. Rev. Lett.*, **78** (1997) 3773.
- [11] LYANDA-GELLER Y. *et al.*, *Phys. Rev. Lett.*, **81** (1998) 3215.
- [12] FERT A. *et al.*, *J. Magn. & Magn. Mater.*, **140-144** (1995) 1.
- [13] ZHANG S. and LEVY P. M., *Phys. Rev. B*, **50** (1994) 6089.
- [14] MATTSON J. E. *et al.*, *Phys. Rev. B*, **44** (1991) 9378.
- [15] PARKIN S. S. P., *Phys. Rev. Lett.*, **71** (1993) 1641.
- [16] SLONCZEWSKI J. C., *Phys. Rev. Lett.*, **67** (1991) 3172.
- [17] VOLODIN A. *et al.*, *Appl. Phys. Lett.*, **73** (1998) 1134.
- [18] RÜHRIG M. *et al.*, *Phys. Status Solidi A*, **125** (1991) 635.
- [19] ALIEV F. G. *et al.*, *Phys. Rev. Lett.*, **88** (2002) 187201.
- [20] HARDNER H. T. *et al.*, *Appl. Phys. Lett.*, **67** (1995) 1938.
- [21] From the inset to fig. 1a it is clear that in our Fe/Cr samples the electron waves propagate in a strongly non-uniform magnetic field and the classical interpretation of domain walls may not be correct in this case. However, we continue to use the standard terminology. In our samples the scaling parameter  $n_{DW}$  (concentration of DWs) rather reflects the degree of non-uniformity of the local in-plane magnetic field inside the Fe layers.
- [22] ALIEV F. G. *et al.*, *Phys. Rev. Lett.*, **81** (1998) 5884.
- [23] LEE P. and RAMAKRISHNAN T. V., *Rev. Mod. Phys.*, **57** (1985) 287.
- [24] SCHMIDT C. M. *et al.*, *Phys. Rev. B*, **60** (1999) 4158.
- [25] SCHAD R. *et al.*, *J. Magn. & Magn. Mater.*, **192** (1998) 65.
- [26] KNAP W. *et al.*, *Phys. Rev. B*, **53** (1996) 3912.
- [27] BYCHKOV YU. A. and RASHBA E. I., *J. Phys. C*, **17** (1984) 6039.