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14. ABSTRACT

This report results from a contract tasking Tel Aviv University as follows: This project will attempt to develop a new type of magnetic memory devices based on the so-called Extraordinary Hall Effect (EHE) in which information is stored in nanometric magnetic units and detection of the stored data is performed by measurement of the Hall voltage across the current carrying memory unit. The objectives are: (1) development of films with room temperature out-of-plane magnetic anisotropy and enhanced extraordinary Hall effect coefficient;; (2) study of mechanisms responsible for the technically relevant parameters: coercive field, remanent magnetization, shape of the hysteresis loop, thermal coefficients and stability; (3) study of mechanisms and selection of tools to enhance the extraordinary Hall effect without compromising the magnetic properties of the chosen materials; and (4) fabrication and testing of memory devices with nanometric active elements. The work will includethe following tasks: (1) manufacture of FeTb and CoCr films of variable concentration, thickness and deposition conditions (Months 1 - 6); (2) characterization, magnetic and magnetotransport measurements of FeTb and CoCr films (Months 1 - 6); (3) manufacture of CoPd and CoPt bilayers and multilayers (Months 7 - 12); (4) characterization, magnetic and magnetotransport measurements of CoPd and CoPt bilayers and multilayers (Months 7 - 12); and (5) manufacture and testing of nanoscale memory units and arrays (Months 5 - 12).

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Hall Effect Spintronics

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Following the original work program we initiated the research devoted to manufacture, study and optimization of materials suitable for spintronics applications based on the extraordinary Hall effect (EHE). The major focus of the current work is manufacture of the prototype EHE magnetic memory units operating at room temperature. Materials needed for this application should possess an out-of –plane magnetic anisotropy and significant extraordinary Hall effect at room temperature. Materials selected for the study at this stage were FeTb alloy samples prepared by RF sputtering and Co/Pd multilayers deposited by the electron beam gun system. Three major tasks were accomplished during the first 12 months of the project:

1. **Development of a non-switching van der Pauw technique to improve the accuracy of the Hall effect measurements.**

2. Study of anomalous symmetry signals at the superconducting transition of conventional type II superconductors and at the magnetization reversal in ferromagnets with an out-of-plane magnetic anisotropy.

3. Preparation and study of Co/Pd multilayers for the Extraordinary Hall Effect based magnetic memory.

I. **Development of a non-switching van der Pauw technique to improve the accuracy of the Hall effect measurements.**

(The work is submitted for publication in Review of Scientific Instruments)

The Hall effect [1] is widely used both in academic research and in a variety of industrial applications. Under ideal conditions the Hall voltage is antisymmetric in external magnetic field and crosses zero at zero field. In real samples one usually finds a finite zero field offset voltage, which can be significantly larger than the Hall effect signal. This undesired offset can be a consequence of geometrical mismatch in voltage contacts, misalignment of the magnetic field and current directions, inhomogeneity of the sample, temperature gradients or piezoresistive effects [2-3]. As an additional complication, the offset voltage can change in time due to e.g. the sample's ageing or instability of temperature conditions. Several methods are used to eliminate or reduce the offset. These include either mathematical manipulations of the measured signals or design of special measurement setups or both. The offset caused by contacts mismatch can be modeled as a parasitic resistor. In homogeneous samples it can be estimated by the properly weighted magnetoresistance data and subtracted from the measured Hall voltage signal. Potentiometer can be incorporated in the measurement circuit to reduce the offset voltage in cases when changes of the longitudinal resistance under applied magnetic field are negligible. Following Onsager's relations [4] the longitudinal resistance and Hall resistance are symmetric and antisymmetric in magnetic field respectively. Hall effect data free of offset can be calculated by extracting the antisymmetric part of the data measured at both polarities of magnetic field. An additional technique is the use of two coupled Hall plates [5] positioned in opposite magnetic field polarities with orthogonal current directions. This setup can be free of offset up to an inevitable difference between the samples.

All these techniques fail when the sample is inhomogeneous and the offset changes during the measurement.

More sophisticated techniques were proposed to treat the offset on the local scale. Sample et al. [6] presented a reverse magnetic field reciprocity which applies to conducting specimens of arbitrary shapes in the presence of an applied magnetic field. Interchange of current and voltage contacts was shown to be equivalent to the reversal of magnetic field polarity, such that

$$R^{a}_{DBAC} = R^{b}_{ACDB} \quad (1)$$

where a and b stand for magnetic field pointing in and out of the sample plane, A, B, C and D are contacts, R_{DBAC} is defined as $V_{DB}/I_{AC,}$ and R_{ACDB} is defined as V_{AC}/I_{DB}. This idea is used in the so-called spinning current method of the Hall effect measurement [7]. Two Hall voltage measurements between two pairs of opposed contacts AC and BD are done at a given magnetic field by interchanging the current contacts between BD and AC respectively. If the offset is symmetric in magnetic field, the Hall voltage can be calculated as:

$$V_H = \frac{R^{a}_{DBAC} - R^{a}_{ACDB}}{2} I \quad (2)$$

immediately after two measurement cycles, which reduces significantly the time dependent changes. This technique requires a physical switching of the current and voltage contacts for each data point.

The continuous spinning current method was introduced [8] to address general cases of anisotropic sources of the offset voltage when the offset voltage is spatially periodic [7,9]. Effective current at a given angle can be achieved by supplying two weighted currents at opposite contacts of a Hall bar. The effective Hall voltage is calculated from the weighted averaging of the two measurements. The offset is reduced by averaging a set of measurements at different spatial angles. Accuracy of the reduction increases with the number of measured current orientations. The known implementation of the technique [8] uses dc currents with discrete measurements at selected effective current orientations. Time required to perform the entire set of measurements both in the spinning current and the continuous spinning current methods limits their accuracy in cases when the offset voltage is changing at a time scale comparable with the measurement cycle.

Kim et al. proposed a non-switching van der Pauw technique for resistivity measurements [10]. Two alternating current sources operating at different frequencies are connected to three adjacent contacts in the van der Pauw configuration [11]. Voltages are measured simultaneously by two lock-in amplifiers. We adopted and modified this technique for the Hall effect measurements.

The setup is presented in Fig. 1. An alternating current source operating at frequency f_1 is attached to contacts B and D with a respective lock-in amplifier monitoring the Hall signal between contacts A and C. The second current source operating at frequency f_2 is attached to contacts A and C with the corresponding lock-in amplifier measuring the Hall signal between B and D. The frequencies f_1 and f_2 have to be different enough so that the simultaneous measurements are independent and identical to the normal stand-alone operation. The Hall effect is calculated using Eq. 2. Differently from the van der Pauw resistance measurement, in which current sources can share a common ground, the Hall measurement requires electrically isolated current sources. It is possible to use a commercial floating ac current source (like Keithley 6221) or to build one from an alternating voltage source, a transformer that floats the signal and a transconductance amplifier. The input voltage of each lock-in amplifier is composed of two signals: the Hall voltage at the operating frequency and the resistance signal at the second frequency. The latter can be significantly larger than the Hall voltage. This resistance component can be reduced significantly by using a band pass filter in front of the lock-in amplifiers.

Fig.2 presents a standard room temperature measurement of the Hall effect in a 10 nm thick Fe film using one current source and one lock-in amplifier. Magnetic field was swept from zero to -1.5 T, then up to 1.5 T and back to zero field. The offset resistance in this case is two orders of magnitude higher then the Hall resistance at 1.5 T. The field dependent signal is irreproducible due to the temporal drift, typical for room temperature measurements of thin ferromagnetic films and related to aging effects in resistivity. Drift of the parasitic offset makes it impossible to analyze the data and extract physical quantities such as Hall coefficient and charge carrier density.

Feasibility of the proposed here non-switching van der Pauw technique was demonstrated by measuring the Hall effect of a similar 10 nm thick Fe film patterned as a Greek cross. The Hall voltage contacts were deposited with a deliberately large misalignment to produce a significant offset voltage. Currents with amplitude of 10 mA and frequencies of 77Hz and 87Hz were applied to the sample. Two sets of Hall signals measured simultaneously by two lock-in amplifiers at room temperature are presented in Fig. 3a. The data shown was collected during two sequential field sweeps between -1.5 T and +1.5 T. The offset resistance exceeds 200 Ω. The drift in the data is reflected in the Hall signal offset. Fig. 3b. presents the Hall voltage calculated by Eq.2. The resulting offset is reduced by four orders of magnitude and drift of the data is negligible. The extraordinary Hall coefficient extracted from the data presented in Fig. 3b is $2.4 \cdot 10^{-10}$ $\Omega \cdot cm \cdot G^{-1}$, two orders of magnitude higher then in bulk materials as expected in the case of thin ferromagnetic films with enhanced surface scattering [12].

To summarise, we presented a non-switching van der Pauw technique of the Hall effect measurement. The technique allows reducing dramatically the parasitic offset voltages. Application of the technique is particularly useful in cases when the offset voltage varies at a time scale comparable with the measurement cycle. In industrial applications this technique can be used as a relatively simple design for offset reduction over a long period of operation.

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Figure captions

Fig. 1. Measurement setup for the non-switching van der Pauw Hall technique. I_{AC} and I_{DB} are electrically isolated alternating current sources operating at frequencies f_1 and f_2 respectively. V_{AC} and V_{DB} are lock-in amplifiers set for the reference frequencies f_2 and f_1 respectively.

Fig. 2. Standard Hall resistance measurement of a 10 nm thick Fe film at room temperature using one current source and one lock-in amplifier. Arrows indicate the field sweep direction from zero to -1.5 T up to 1.5 T and back to zero. The offset resistance is two orders of magnitude higher then the Hall resistance at high magnetic fields. The drift in the data, typical for room temperature measurements of thin ferromagnetic films and related to aging effects in resistivity, is reflected in the Hall signal offset.

Fig. 3(a). Raw data of the Hall resistance measured simultaneously during several field sweeps by two lock-in amplifiers across a 10 nm thick Fe film at room temperature. The sample was patterned as a Greek cross. V_{DB} (●) was measured at frequency 77Hz and V_{AC} (○) was measured at frequency 87Hz. Arrow indicates the start of the measurement.

Fig. 3(b). The Hall voltage calculated from the two data sets by Eq. 2. The drift is eliminated and the offset is reduced by four orders of magnitude.

Figures.

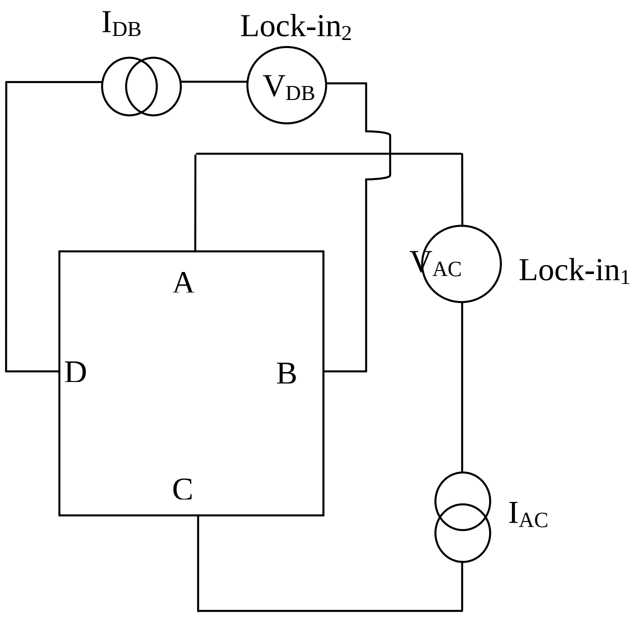

Fig. 1.

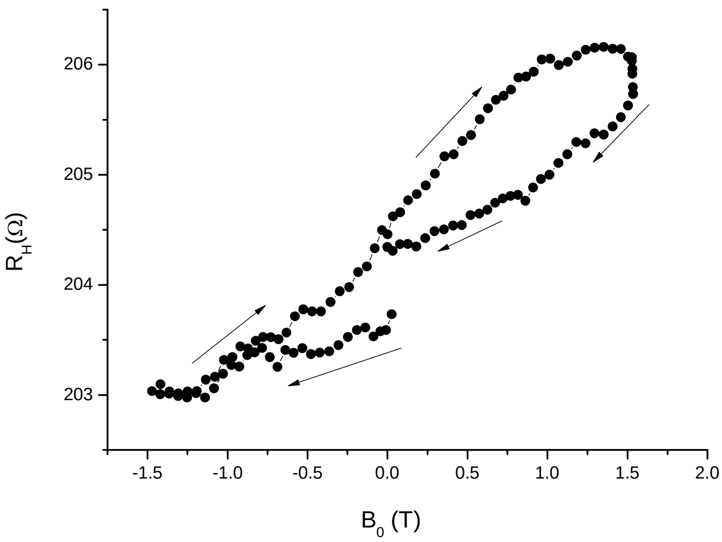
206
205
204
203
$R_H(\Omega)$
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
B_0 (T)

Fig. 2.

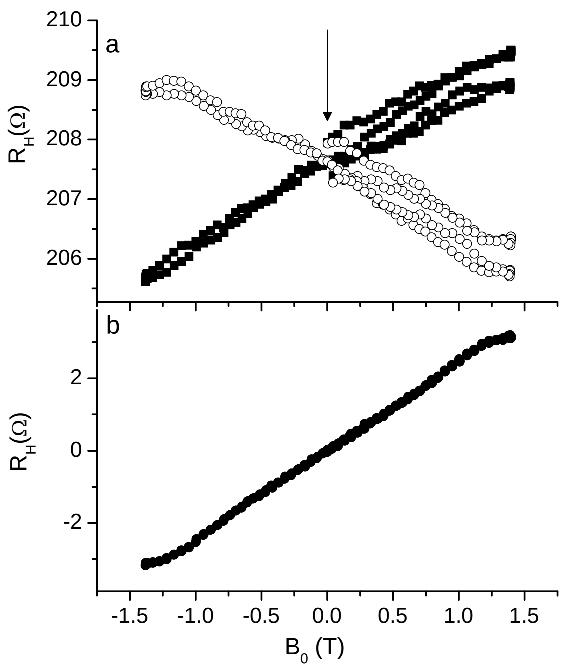
a
210
209
208
207
206
$R_H(\Omega)$
b
2
0
-2
$R_H(\Omega)$
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
B_0 (T)

Fig. 3.

II. Study of anomalous symmetry signals at the superconducting transition of conventional type II superconductors and at the magnetization reversal in ferromagnets with an out-of-plane magnetic anisotropy.

(The work is submitted for publication in Physical Review Letters)

Common understanding of magnetotransport properties is based on Onsager's reciprocity relations [1] that determine the symmetry of longitudinal and transverse resistivity with respect to polarity of applied fields. Longitudinal resistivity (measured along the electrical current) is expected to be an even function of magnetic induction B, whereas the transverse or Hall resistivity, measured normal to the current, is specified as an odd function of B when field is applied normal to the sample plane. There are several cases in which anomalous symmetry signals were detected either in longitudinal or in transverse resistivity measurements. The better known phenomenon is observation of the even in field transverse voltage at the superconductor to normal state transition. Vortices can generate an even transverse voltage if forced to move along tracks not-normal to the current direction. Such guided motion can be achieved by e.g. mechanical rolling [2-4] or lithographic patterning of the material [5,6]. Surprisingly, the phenomenon was also observed in a variety of untreated superconductors without any macroscopic pinning anisotropy [7-9]. Independently from the vortex dynamics, it was proposed that current redistribution due to the material's inhomogeneity can explain at least part of the resistivity and Hall effect anomalies [10,11]. Nevertheless, appearance of the even transverse voltage in superconductors is addressed almost unanimously to the flux motion.

Another puzzling phenomenon was recently found in ferromagnetic materials with perpendicular magnetic anisotropy: an odd in magnetic field signal was observed in longitudinal resistivity when magnetization reversed its polarity [12,13]. As argued by Cheng et al [12] the effect can appear when a domain wall, located between the voltage probes, runs perpendicular to both the magnetization and the current. Electric fields generated by the extraordinary Hall effect (EHE) have opposite polarities on both sides of the domain wall, which can produce a circulating current loop and a respective extra voltage contribution. The model successfully explained the odd in field longitudinal voltage peaks in a specially designed Co-Pt multilayer film with a single domain wall gradually propagating along the sample. However, the effect was also observed in other samples with multiple domains [12], and applicability of the "single wall" model in this general case is dubious.

In this Letter we report our study of the "anomalous symmetry" voltage in several superconducting and ferromagnetic materials. We found no evidence supporting the accepted interpretation of the phenomena – flux dynamics in superconductors and propagation of a single domain wall in ferromagnets. Instead, we show that both effects can be explained by a minor inhomogeneity of materials and described by a simple circuit model.

The primary mechanism responsible for depinning and motion of vortices in type II superconductors is the Lorentz force, given by $\vec{F}_L = \vec{J} \times \vec{B}$, where $\vec{F}_L$ is the force produced by the transport current $\vec{J}$ per unit volume of the vortex lattice. The force is largest when magnetic field is applied normal to electrical current and diminishes to zero when the field is aligned strictly along the current line. As such, any phenomenon related to flux motion is expected to depend strongly on orientation of applied field relative to electrical current. We tested the field orientation dependence of the "anomalous symmetry" signals in a number of conventional type II superconducting materials, including thin films of Pb and Pb-Ni.

Fig.1a presents the longitudinal (V_l) and transverse (V_t) voltages measured in 200 nm thick Pb film at 4.2 K as a function of field normal to the film plane. V_t data in this, and following figures, was obtained by subtracting the normal state mismatch voltage corresponding to an unavoidable misalignment of the transverse contacts pads. Anomalous even in field transverse voltage V_t is developed when the sample passes from the superconducting to normal state and vice versa. A similar measurement in the Lorentz force-free configuration with field applied in-plane parallel to the current contacts line is shown in Fig. 1b. Contrary to the Lorentz force mechanism, the magnitude of V_t peaks does not vary much when the field orientation relative to electrical current is changed from perpendicular to parallel (the maximum field orientation misalignment is 1-2°, as estimated from the Hall effect slopes in the normal state). Although not shown here, polarity of V_t is sample dependent and can even change its sign during the transition, as we found in Ni-Pb samples.

Fig.2 presents an anomalous transverse voltage that can also develop at the superconducting transition in the absence of any applied field (Earth field was unshielded). Similar effect was reported previously in a variety of superconductors [7-9].

Data shown above indicate that Lorentz force created by external field is not the source of the transverse voltage peaks. A somewhat different possibility is generation of V_t due to attraction among vortices and antivortices generated by the transport electrical current itself at two opposite edges of the film. Following Glazman [14] such interaction can contribute to vortex velocity, parallel or antiparallel to electrical current, and thus to the transverse voltage. When location and propagation paths of vortices are random, the overall V_t should average to zero. However, if for some reason the vortex motion is guided along tracks not normal to electrical current over distances comparable with sample's dimensions, this guided motion can generate a non-zero transverse voltage. To test the presence of an unintended preferable orientation for flux movement in our samples, we manufactured a circular shaped Pb film with 8 contacts along the perimeter. Current was passed between pairs of diametrically opposite contacts and voltage was measured across respective pairs of contacts perpendicular to current. Sinusoidal variation with a period of π would be expected in the angle dependence of V_t if a preferable track orientation is present in the sample [2-4]. No such sinusoidal signal was detected. Thus, we find no evidence connecting the even in field V_t to flux dynamics.

Vaglio et al [10] proposed a simple current redistribution model to explain the appearance of the excess voltage in zero field longitudinal resistivity across the superconductor-normal state transition. Here we adapt and extend their model to treat the transverse voltages. The sample is represented by a four resistors effective network, shown in Fig. 3a, where $R_{a\text{-}d}$ are resistors, and current I flows between I_{in} and I_{out} contacts. Each resistor represents a macroscopic portion of the sample and has a finite superconductor – normal transition width, similar to that of the whole sample. Longitudinal voltage V_l is measured between contacts F and B, and the transverse voltage V_t is measured between C and D. In the transition range where all four resistors have non-zero resistance, V_l and V_t are calculated by use of Kirchhoff's laws as:

$$V_l = I\frac{(R_a + R_c)(R_b + R_d)}{R_a + R_b + R_c + R_d} \qquad (1)$$

$$V_t = I\frac{R_a R_d - R_b R_c}{R_a + R_b + R_c + R_d} \qquad (2)$$

We assume the simplest case of inhomogeneity in which $R_a(T,H) = R_b(T,H) = R_c(T,H) \equiv R(T,H)$, and

$$R_d(T,H) = R(T+\Delta T, H+\Delta H) \approx R(T,H) + \Delta T\,\frac{\partial R(T,H)}{\partial T} + \Delta H\,\frac{\partial R(T,H)}{dH}$$

if expanded to the first order of ΔT and ΔH, where ΔT and ΔH are small deviations of the critical temperature and field respectively. In zero or constant magnetic field, V_t will develop at the superconducting transition according to:

$$V_t(T) = \frac{\Delta T}{4}\frac{\partial V_l(T,H)}{\partial T} \qquad (3)$$

Similarly, when magnetic field is varied at constant temperature the model predicts the transverse voltage given by:

$$V_t(H) = \frac{\Delta H}{4}\frac{\partial V_l(T,H)}{\partial H} \qquad (4)$$

ΔH changes sign for the negative field polarity, therefore the resulting V_t(H) is an even function of the magnetic field. The model predicts V_t(T,H) to be proportional to the temperature or/and field derivative of V_l(T,H). Solid lines in Figs.1 and 2 are fits to Eqs. 3 and 4 calculated using the measured longitudinal voltage and one fitting parameter ΔT or ΔH only. A perfect fit in Fig. 2 was obtained with $\Delta T = 2.8\cdot10^{-4}$K, which is more than two orders of magnitude smaller than the width of the superconducting transition $\delta T = 5\cdot10^{-2}$ K, the latter being defined as the temperature span over which resistivity changes between 10% and 90% of its normal value. Fits of V_t(H) drawn in Figs.1a and 1b were calculated with ΔH=230G and ΔH=170G for the perpendicular and parallel field orientations respectively. The transition widths in these orientations are by an order of magnitude larger: $\delta H_\perp$ = 2000G and $\delta H_{||}$ = 3000G. Experimental indication of macroscopic inhomogeneity can be found by measuring the longitudinal voltage between two pairs of contacts located at different sections of the sample or along two opposite edges of the film (see inset of Fig.1). A shift of about 100 G was found between two edges of the sample, which is in a fair agreement with the calculated ΔH.

Correlation between the transverse voltage and the temperature and field derivatives of the longitudinal resistivity (Eqs. 3,4) is a characteristic fingerprint of this inhomogeneity scenario that allows one to distinguish it from other mechanisms.

Notably, the correlation $V_t \propto dV_l / dT$ has been observed in MgB_2 [8] and in high T_c ceramics [9].

We turn now to another case, in which inhomogeneity can be the source of a seeming inconsistency with Onsager's reciprocity relations. Fig. 4a presents V_l measured in a Co/Pd multilayer sample as a function of magnetic field applied normal to the film. The sample has the six-contacts Hall bar geometry with inter-contacts separation of few millimeters. Sharp antisymmetric peaks, at about 0.5 T, are superimposed with a rather symmetric magnetoresistance signal, the latter typical for ferromagnets with an out-of plane magnetic anisotropy. The sign of the odd longitudinal voltage peaks is opposite if measured along the opposite edge of the film. A similar effect was found by us in FeTb films and was previously reported in Co/Pt multilayers [12] and (Ga,Mn)As epilayers [13] with perpendicular magnetic anisotropy.

Hall voltage in ferromagnets can be presented as [15]: $V_t = \frac{I}{t}(R_0 B + \mu_0 R_{EHE} M)$, where I is electrical current, t – thickness, R_0 and R_{EHE} are the ordinary and EHE coefficients, B - magnetic field induction, and M is magnetization. As argued by Cheng et al [12] the antisymmetric V_l can appear when a single domain wall separating two antiparallel magnetization domains is located between longitudinal voltage probes. Following this scenario, reversal of magnetization in the vicinity of the longitudinal voltage contacts is expected to take place at different fields H_{r1} and H_{r2}, and the odd voltage to appear at fields between H_{r1} and H_{r2}. Fig. 4b shows V_t measured between two pairs of contacts transversal to the current direction, while V_l shown in Fig. 4a is measured simultaneously between a pair of longitudinal contacts. The EHE term is much larger than the ordinary one and the curves in Fig. 4b are roughly proportional to magnetization. Magnetization reverses practically simultaneously at both pairs of transverse contacts (the difference in coercive fields is about 20 G, whereas the reversal width defined as the field span over which V_t varies between 10% and 90% is δH = 700G (Fig. 4b)). The antisymmetric longitudinal voltage peaks (Fig. 4a) appear at the reversal of magnetization. Width of the peaks is equal to width of the magnetization (Hall voltage) reversal. This result does not support the "single domain wall" picture. However, it agrees with a common expectation that in arbitrary macroscopic samples there are multiple nucleation centers and the reversal process can not be approximated by single domain wall propagation.

Following our earlier discussion we propose to model the sample by an effective circuit, shown in Fig. 3b. V_{AB} and V_{EF} represent V_t generated by the extraordinary and normal Hall effects at two cross-sections, while R represents two equal resistors with a usual magnetoresistance. We assume that due to the sample's inhomogeneity V_{AB} is not identical to V_{EF}. The origin of the difference can be variation of the coercive field or variation of the EHE coefficient due to e.g. non-uniform thickness [16]. For simplicity let's assume that $V_{AB}(H) = V_{EF}(H + \Delta H)$ where ΔH is the difference in coercive fields between cross-sections AB and EF. By use of Kirchhoff's laws and the first order expansion in ΔH we find:

$$V_{FB}(H) = \frac{1}{2}\left[IR(H) + \Delta H \frac{\partial V_{EF}(H)}{\partial H} \right] \quad (5)$$

The second term in Eq. 5 is antisymmetric with respect to field polarity, changes its sign if measured along AE edge instead of BF edge, and can be significant when V_t(H) varies sharply with field. We ascribe the anomalous peaks in V_l(H) to this term. The solid line in Fig. 4a presents the fit to the measured data calculated with ΔH = 24G which is in a very good agreement with the measured variation of the coercive field along the sample (see inset of Fig.4) and is more than an order of magnitude smaller than δH.

Thus far we discussed two separate cases in which either resistivity or Hall voltage vary sharply. One can imagine systems where both parameters are variables, as in measurements of the quantum Hall effect [17] or when Hall coefficient across the superconducting transition is the subject of interest [18]. Fig. 3c presents the generalization of the model. V_{AB} and V_{EF} present the transverse voltages at two cross-sections, while resistors R_{a-d} model the sample's longitudinal resistance. By compiling the two previous cases we obtain the longitudinal $V_{l(FB)}$ and transverse $V_{t(CD)}$ voltages given by:

$$V_l = IR + \frac{1}{2}\Delta H_t \frac{\partial V_t}{\partial H} + \frac{1}{4}\Delta H_l \frac{\partial V_l}{\partial H} \quad (6)$$

$$V_t = V_{EF} + \frac{1}{2}\Delta H_t \frac{\partial V_t}{\partial H} + \frac{1}{4}\Delta H_l \frac{\partial V_l}{\partial H} \quad (7)$$

where ΔH_t and ΔH_l are the effective transverse and longitudinal field deviations respectively. In addition to the expected signals, Eqs. 6,7 contain two terms: odd in field term proportional to the field derivative of the Hall voltage and even in field term proportional to the field derivative of resistivity. These extra “inhomogeneity” terms are pronounced when resistivity or Hall voltage vary sharply.

To summarize, we studied even in field transverse voltage and odd in field longitudinal voltage at the superconducting transition of type II superconductors and at the magnetization reversal in ferromagnets. No evidence supporting the flux flow origin of the effect in the studied superconductors and a single domain wall picture in macroscopic ferromagnets was found. We suggest that minor inhomogeneity of materials can be the major if not the only source of both phenomena. Our data can be consistently described by a simple circuit model that interconnects resistivity, Hall voltage and their derivatives in inhomogeneous materials. Important to mention that it is usual to define the longitudinal and Hall resistivity as the signals even and odd in applied field respectively. It follows, from the above discussion, that such practice can lead to erroneous conclusions. Our arguments might be relevant for many other cases in which resistivity or Hall effect vary significantly as a function of any external parameter, like pressure or electric field.

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Figure captions.

Figure 1: Transverse V_t (●) and longitudinal V_l (○) voltages measured in 200 nm thick Pb film as a function of magnetic field applied (a) normal to the film plane, (b) in-plane parallel to electric current. Solid lines are fits calculated according to Eq. 4. Inset: normalized resistance, measured along two opposite edges of the sample. T = 4.2 K.

Figure 2: Temperature dependence of the transverse V_t (●) and longitudinal V_l (○) voltages in Pb film at zero applied field. Solid line is a fit calculated according to Eq. 3.

Figure 3: (a) Model circuit representing a superconducting film, (b) model circuit representing a ferromagnetic film, (c) generalized circuit.

Figure 4: (a) Longitudinal magnetoresistance V_l (○) measured in a Co/Pd multilayer sample at 4.2 K with field normal to the film plane. Solid line is a fit according to Eq. 5. (b) Hall voltage V_t (● and ○) measured simultaneously between two different contact pairs perpendicular to the transport current. Inset: magnification of the marked area at magnetization reversal.

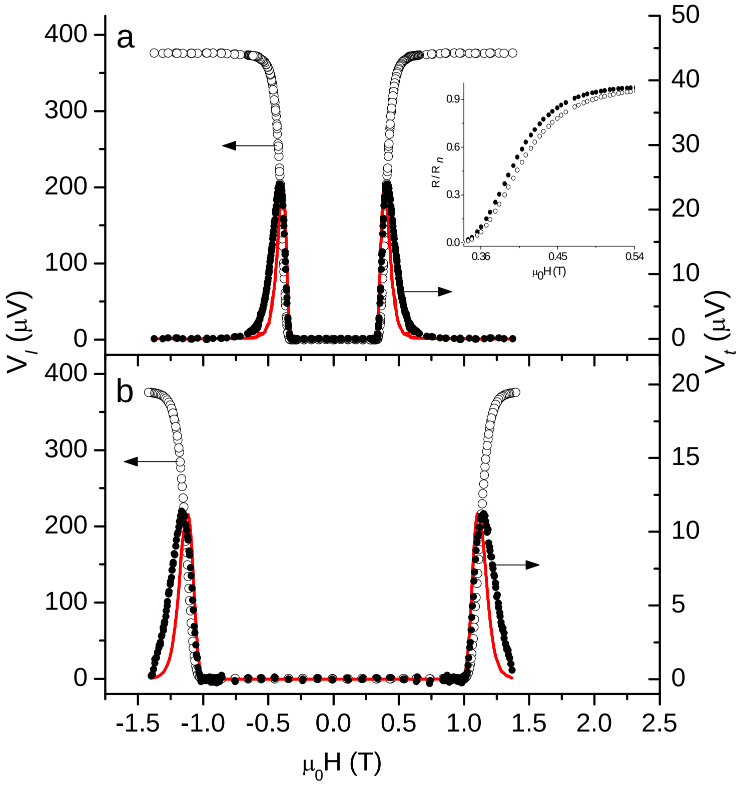
a
b
400
300
200
100
0
50
40
30
20
10
0
20
15
10
5
V_l (μV)
V_t (μV)
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
2.5
μ_0H (T)
R / R n
0.9
0.6
0.3
0.0
0.36
0.45
0.54

Fig.1

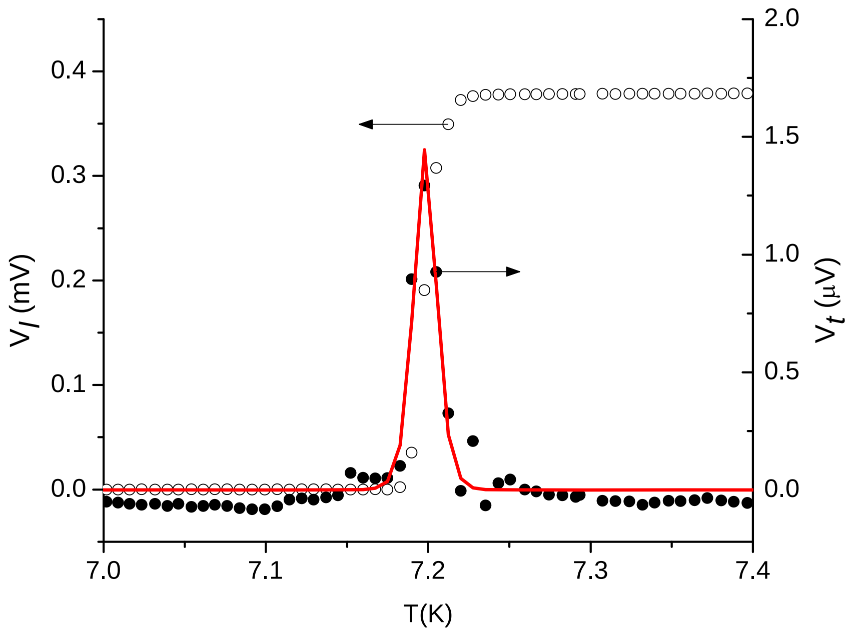
0.4
0.3
0.2
0.1
0.0
2.0
1.5
1.0
0.5
0.0
V_l (mV)
V_t (μV)
7.0
7.1
7.2
7.3
7.4
T(K)

Fig.2

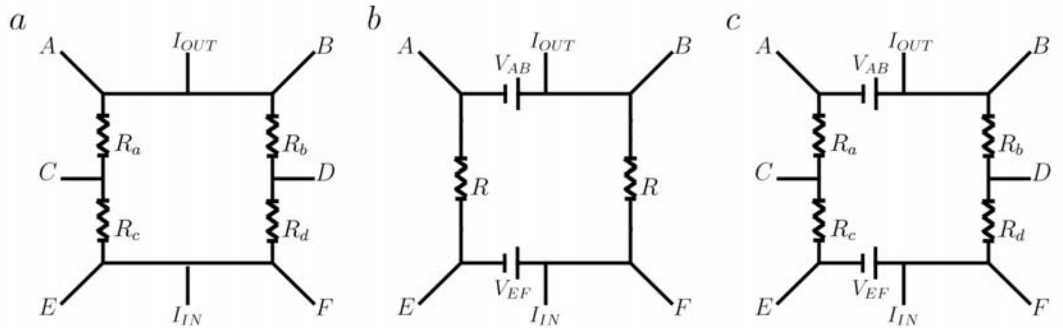
a
b
c
A
B
C
D
E
F
I_{OUT}
I_{IN}
R_a
R_b
R_c
R_d
R
V_{AB}
V_{EF}

Fig.3

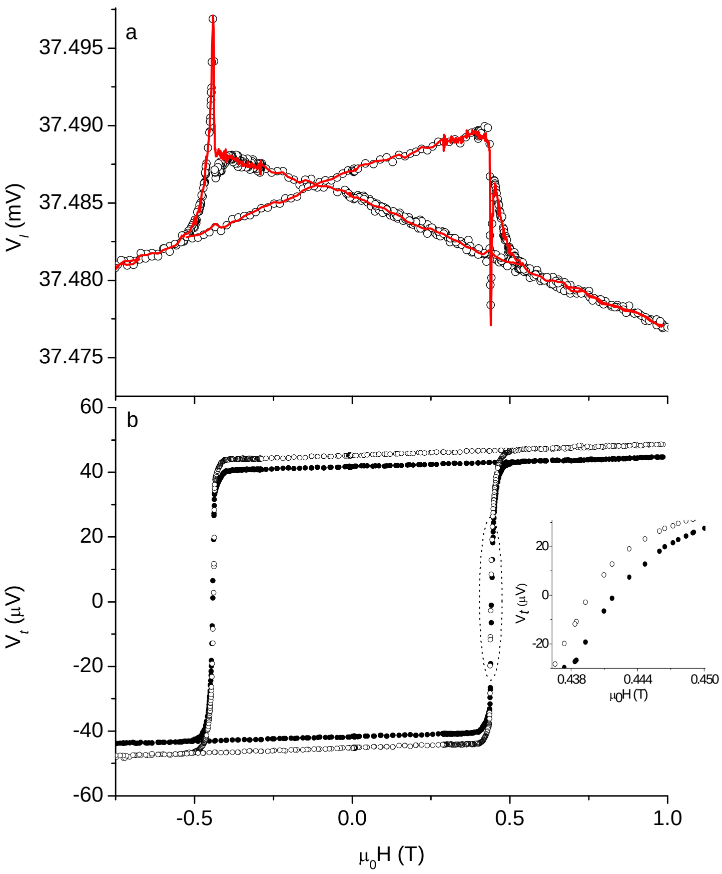
a
b
V_l (mV)
37.495
37.490
37.485
37.480
37.475
V_t (μV)
60
40
20
0
-20
-40
-60
-0.5
0.0
0.5
1.0
μ_0H (T)
0.438
0.444
0.450

Fig.4

III. Preparation and study of CoPd multilayers for the Extraordinary Hall Effect based magnetic memory.

(The work in progress)

Several series of Co/Pd multilayer samples were prepared by e-beam deposition on room temperature GaAs substrates. The thickness of Co and Pd layers was 2 and 9 Å respectively and the repetition of the bilayer structure varied from 4 to 13. No post-deposition annealing was done. Fig.1 presents the room temperature Hall effect resistance as a function of an applied field measured in the sample with 11 bilayers. Sharp and square hysteresis is a result of a significant out-of-plane anisotropy. The saturated peak-to-peak signal exceeds 0.2 Ω. Width of the hysteresis depends on the bilayers repetition number, as demonstrated in Fig.2. Here the room temperature coercive field is shown as a function of a number of Co/Pd bilayers. No hysteresis was observed in samples with less than 7 bilayers, whereas for thicker samples the coercive field increases linearly with a number of bilayers. The magnitude of the saturated extraordinary Hall effect resistance is presented in Fig.3 as a function the bilayers number. The surprising result is the reversal of the EHE polarity in samples with 7 and less bilayers. Positive EHE resistance of about 0.8 Ω is found in the 6 bilayers sample, while negative EHE resistance of about 0.1 Ω is observed in thick samples. The phenomenon is not understood and requires additional studies.

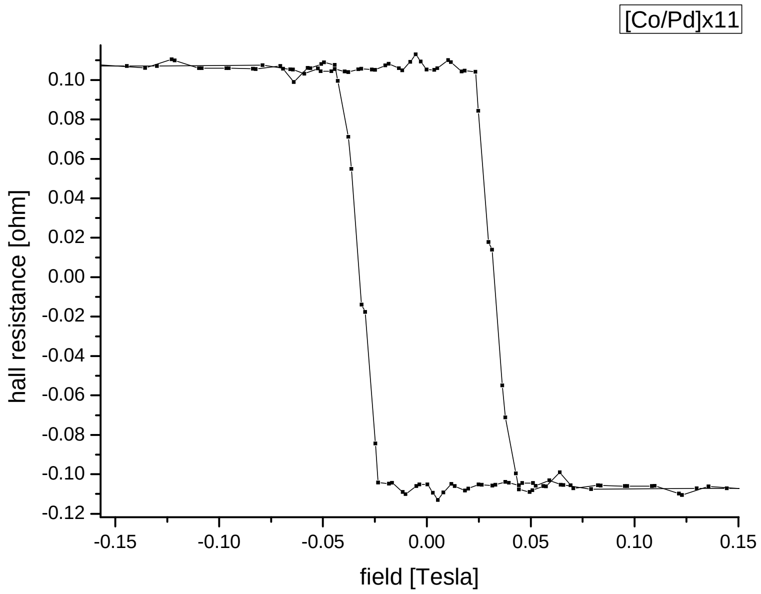

Fig.1. Room temperature Hall effect resistance as a function of an applied magnetic field measured in the Co/Pd sample with 11 bilayers.

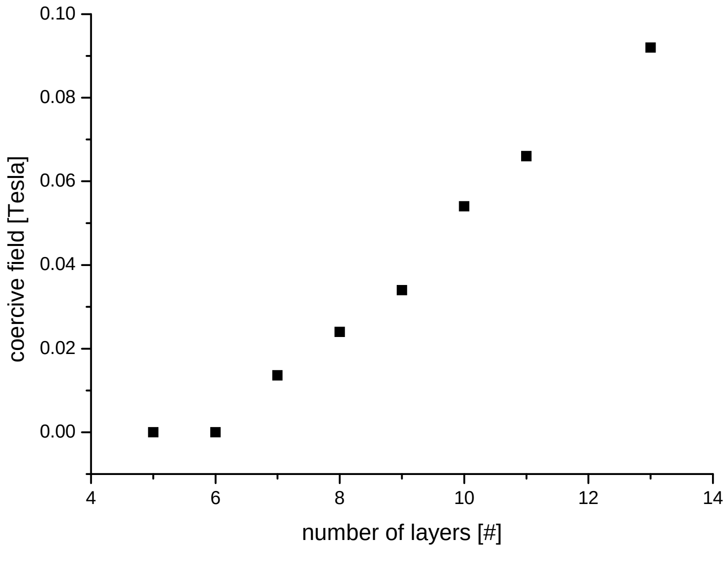

Fig.2. The room temperature coercive field as a function of a number of Co/Pd bilayers.

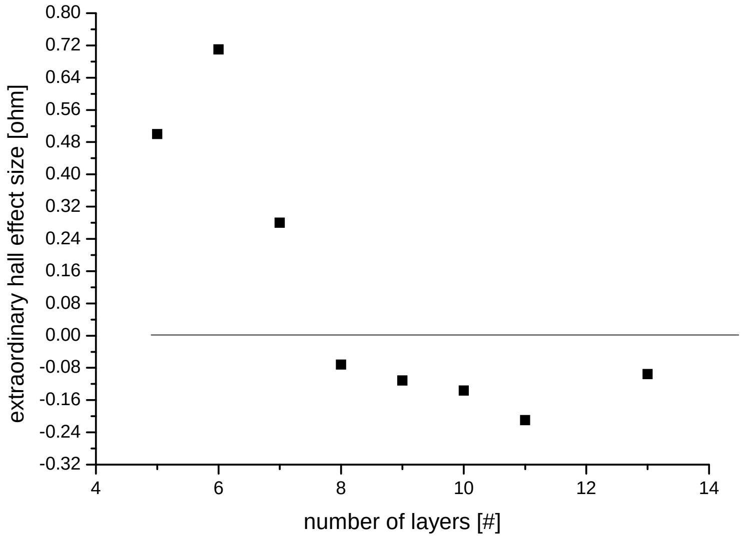

Fig.3. The magnitude of the saturated extraordinary Hall effect resistance as a function the bilayers number.