X International Voevodsky Conference "Physics and Chemistry of Elementary Chemical Processes" (VVV-2022)

Slow relaxation of anomalous Hall effect in GdFeCo/Ir/GdFeCo

Bakhmetiev Maxim V.,[1*] Morgunov Roman B.[1], Oksana Koplak V.[1],

Stéphane Mangin[2]

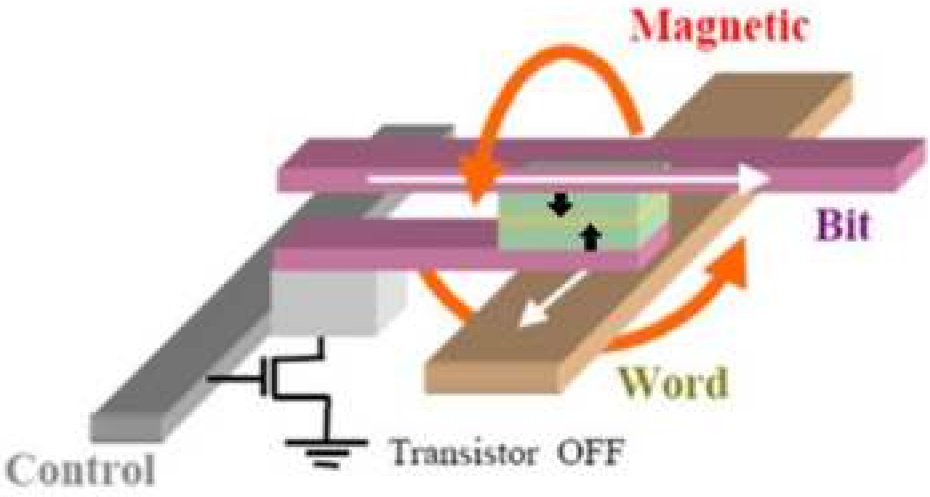
[1]*Center of Problems of Chemical Physics and Medicinal Chemistry Russian Academy Sciences, 142432, Chernogolovka, Russia*

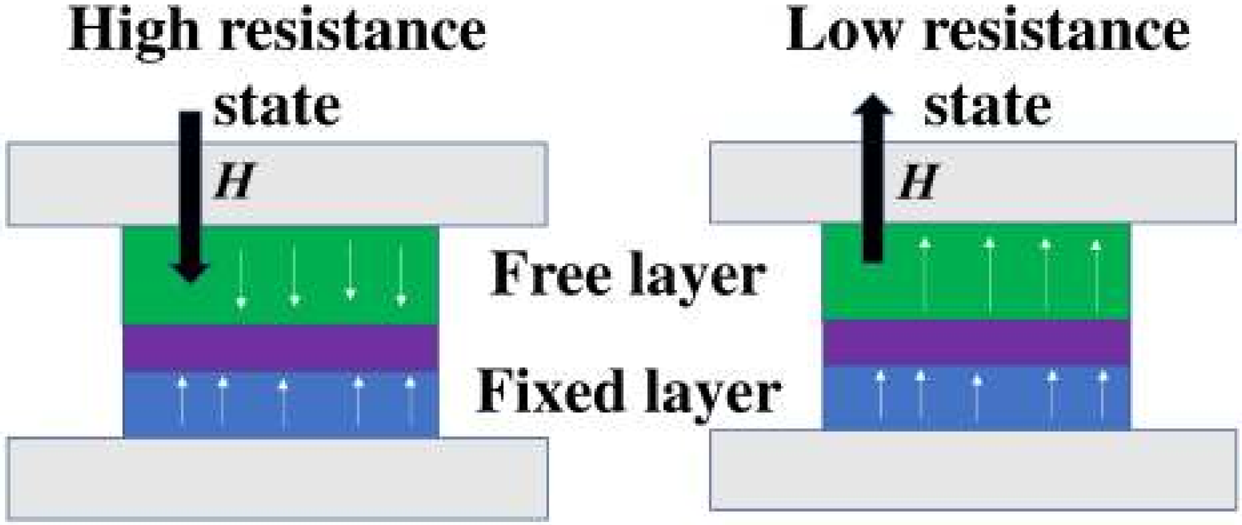
[2]*Institut Jean Lamour, UMR 7198 CNRS, Université de Lorraine, 54601, France*

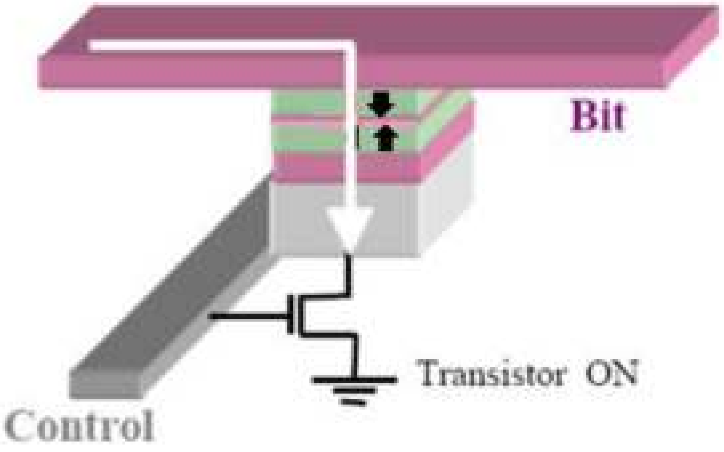
**E-mail:* bakhmetiev.maxim@gmail.com

Thin films switching

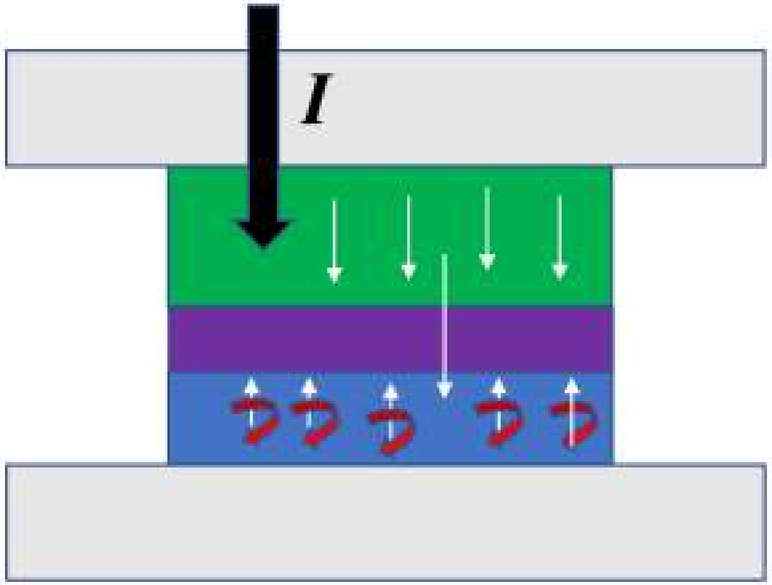
Field-induced magnetization switching





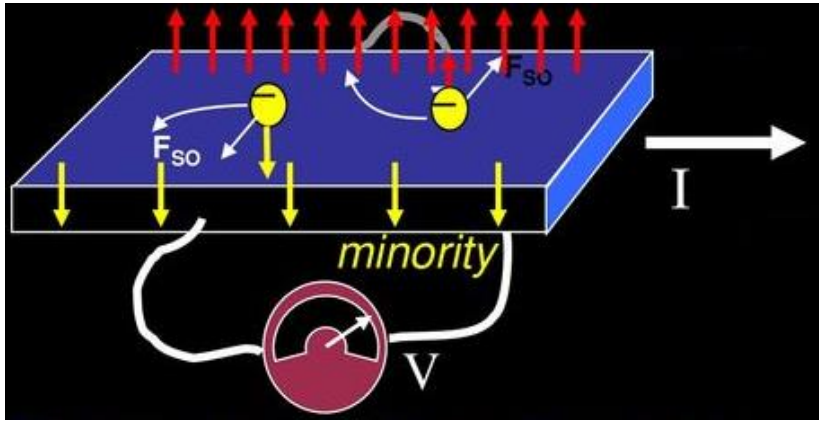


Current-induced switching

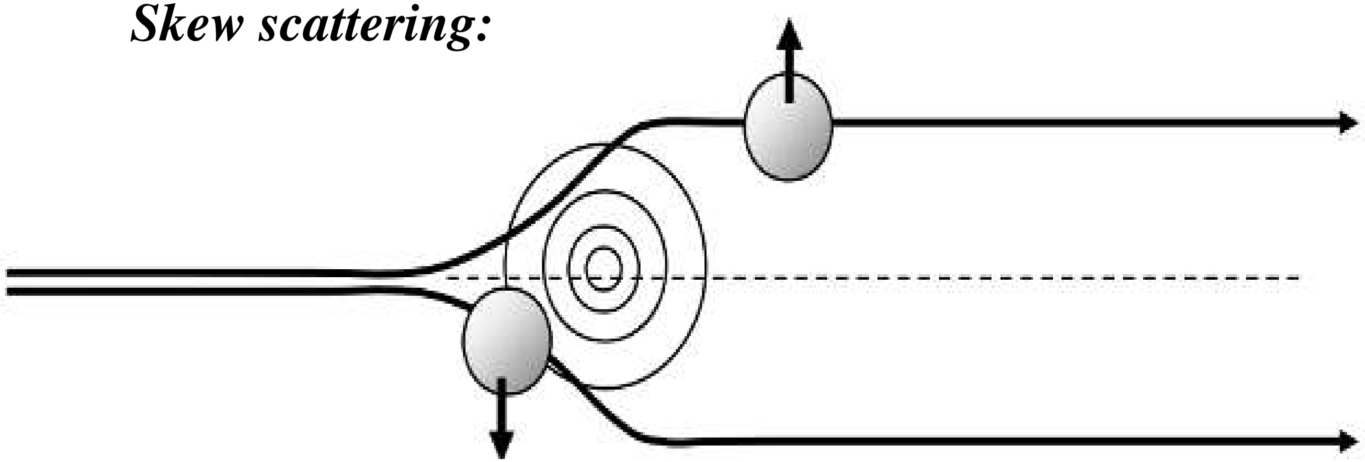


Anomalous Hall effect

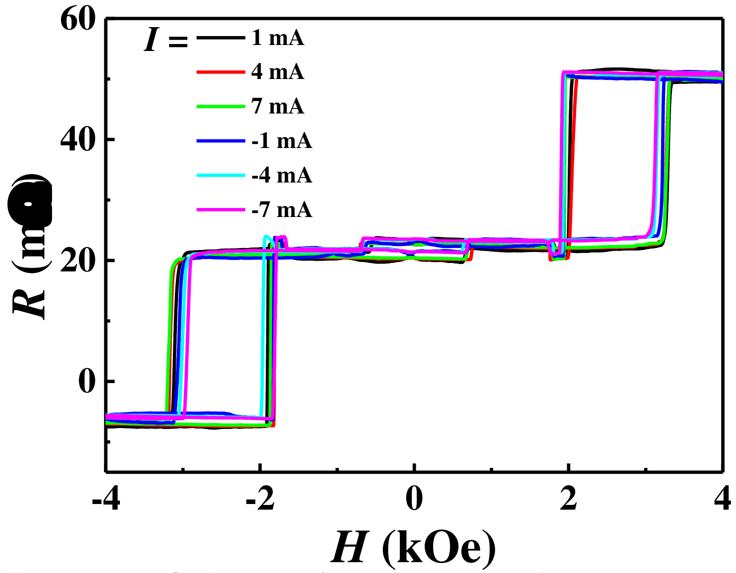
Spin-orbit coupling force deflects like-spin particles



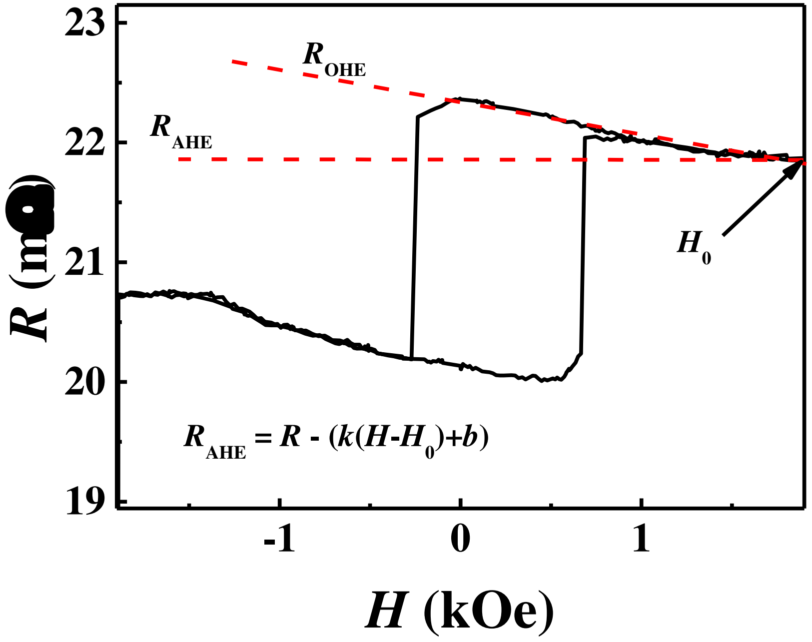
Skew scattering:



$$\rho_{xy} = R_0 B_z + 4\pi R_s M_z$$

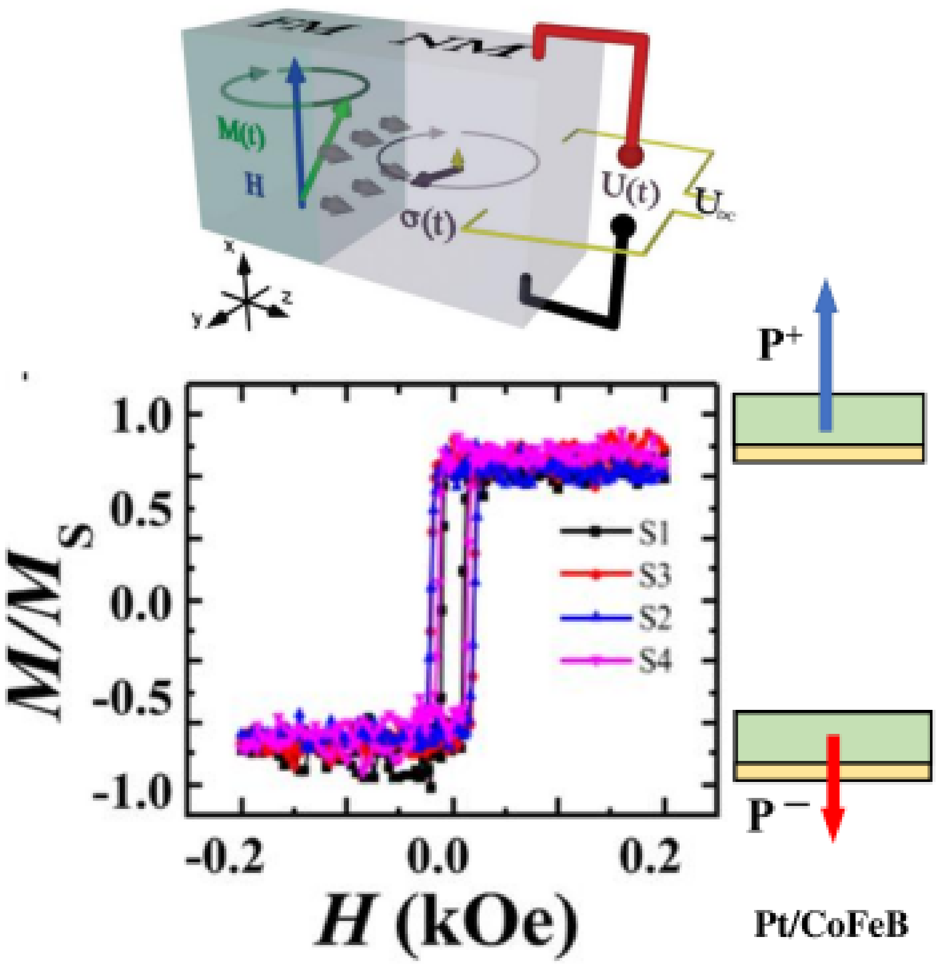


Dependences of the resistance on the external magnetic field at I = -7 - +7 mA.

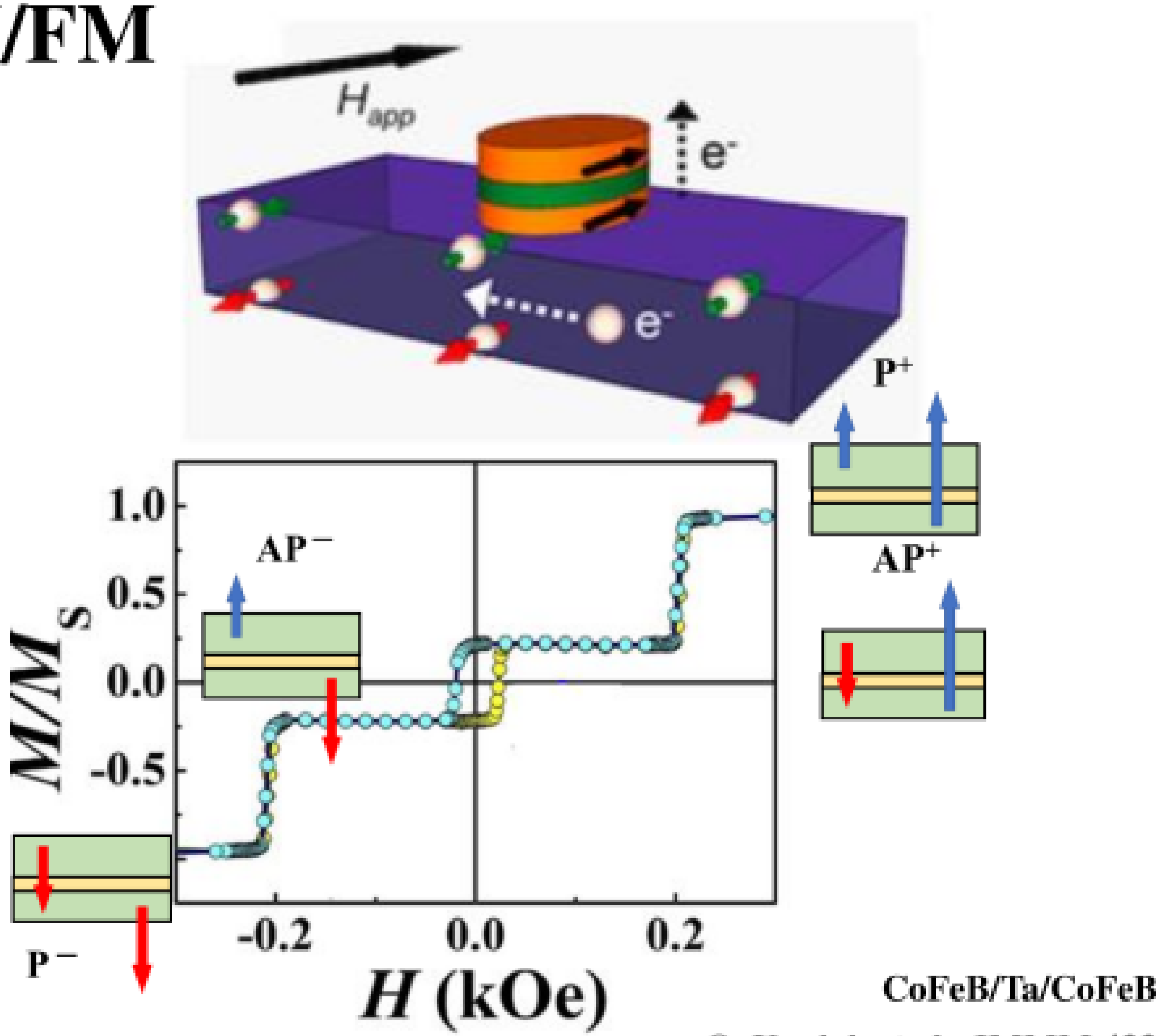


Extraction of ordinary Hall effect contribution from resistivity hysteresis loop

Thin films FM/NM and FM/NM/FM



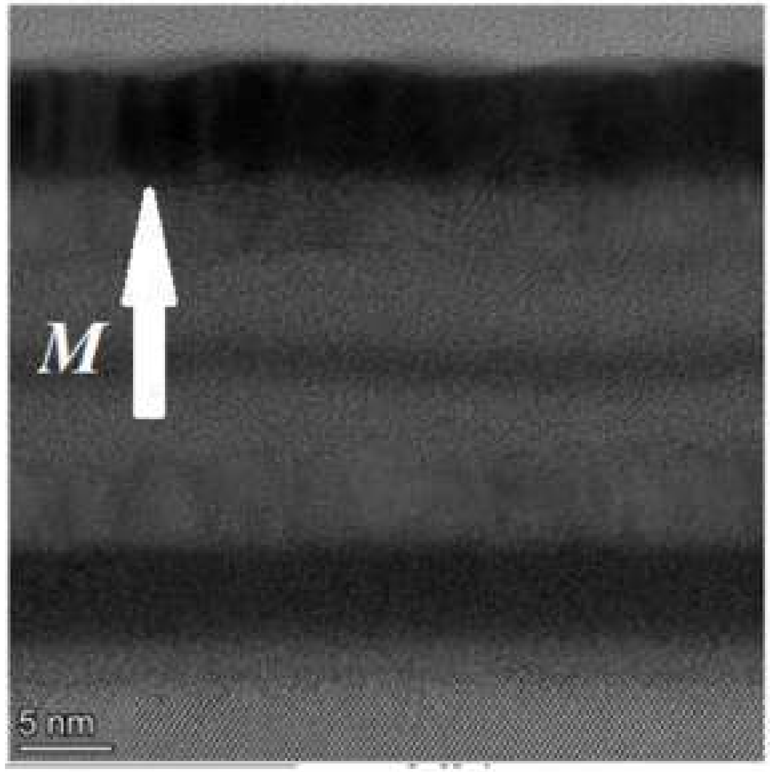
S. Kayal et al., JMMM 558, 169499 (2022)



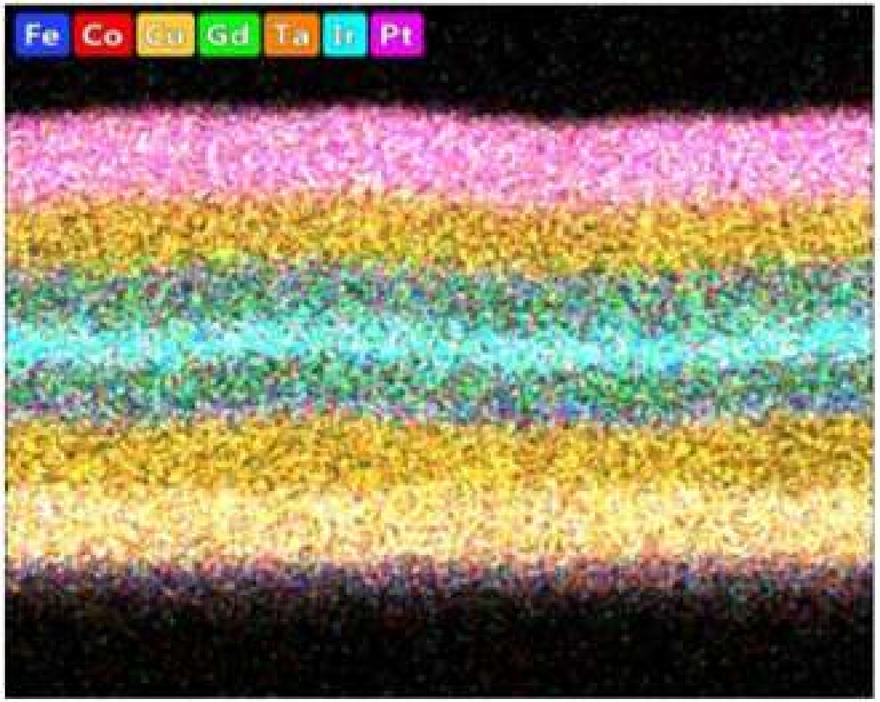
O. Koplak et al., JMMM 433, 97 (2017)

The aim of this work was to obtain the angular dependence of the anomalous Hall resistance and its analytical comparison with the angular dependence of the magnetization in two-layer synthetic $Gd_{25}[Fe_{90}Co_{10}]_{75}$ ferrimagnets with perpendicular magnetization. In addition, the aim of this work was to create experimental conditions for observing the slow magnetic relaxation of SOT caused by the rearrangement of the domain structure in the heterostructure upon a sharp change in the direction of the external magnetic field.

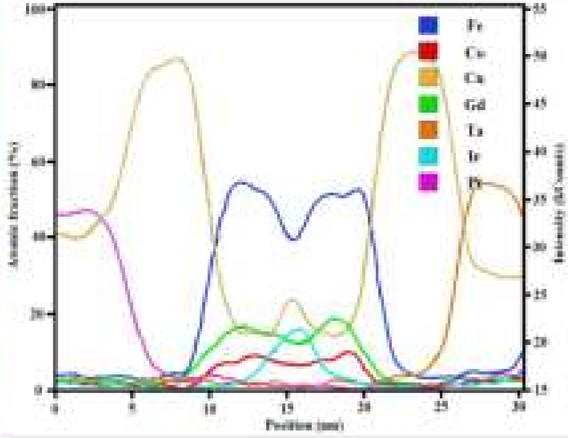
Heterostructure GdFeCo/Ir/GdFeCo



HRTEM image of the sample cross-section.

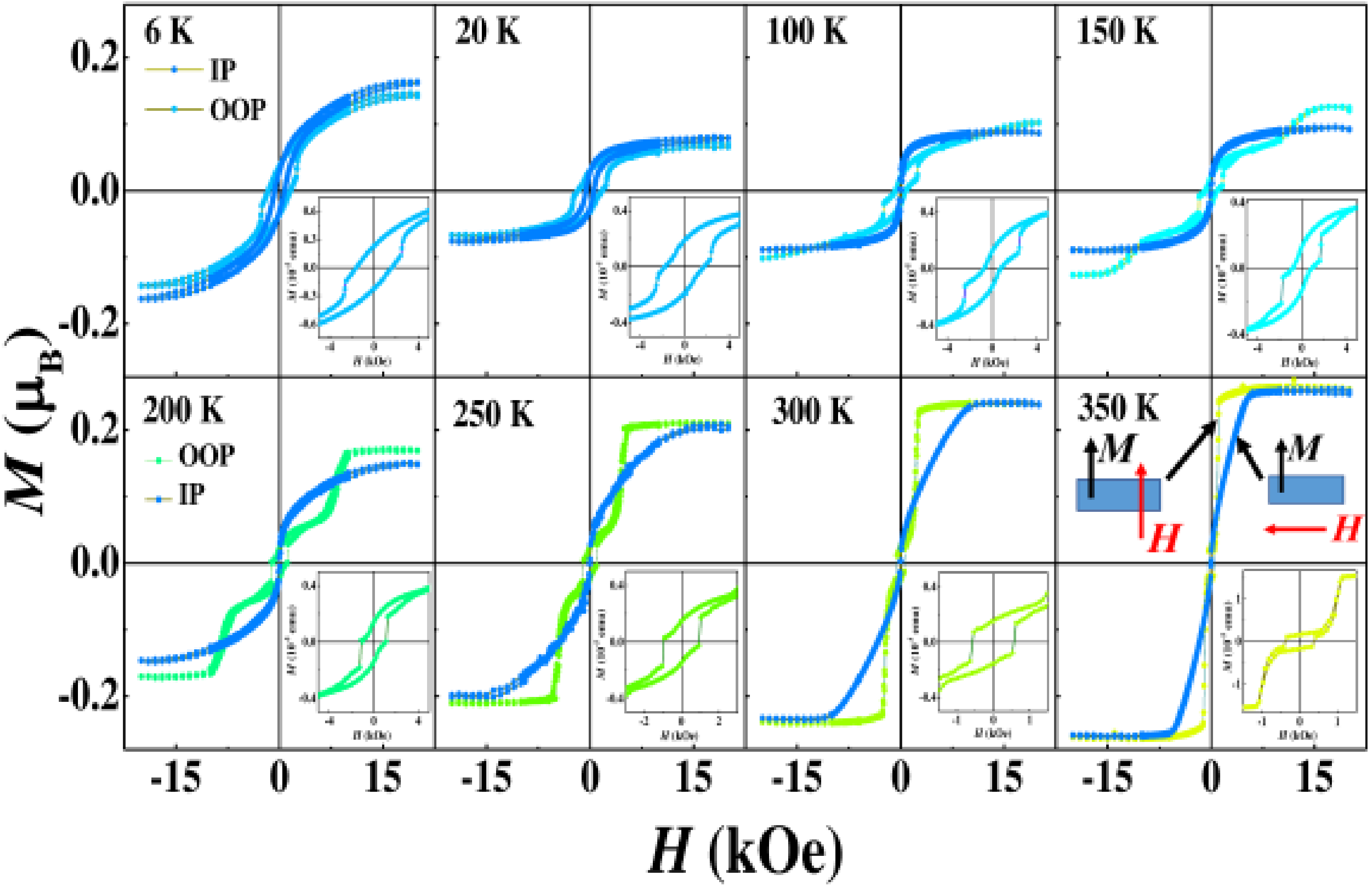


EDX images of chemical elements distribution in the sample cross-section.

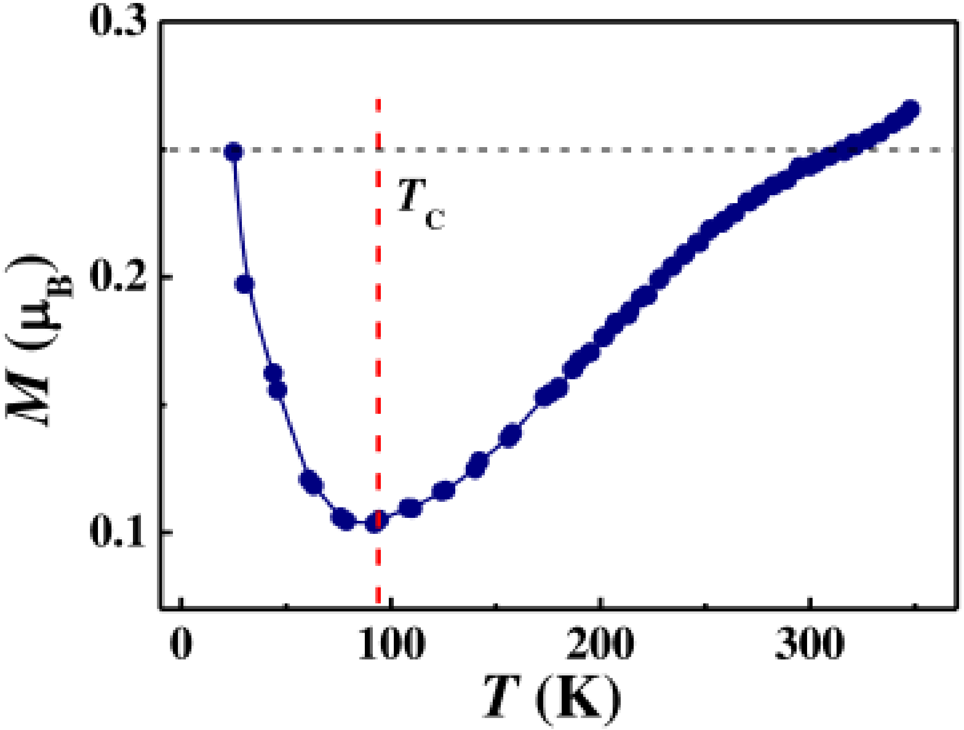


EDX distributions of chemical elements averaged for all sample area.

Integral magnetization of the sample by SQUID magnetometer

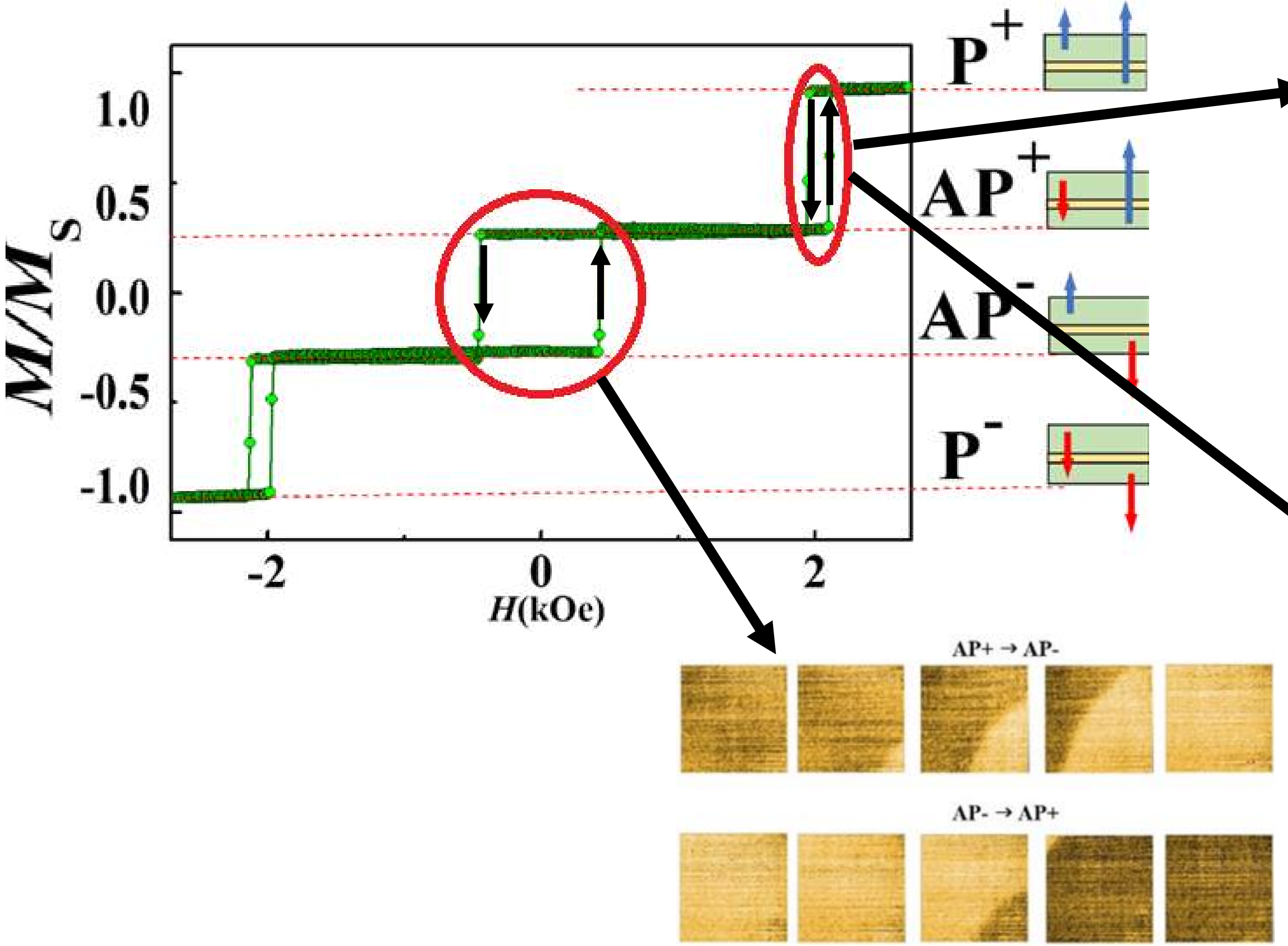


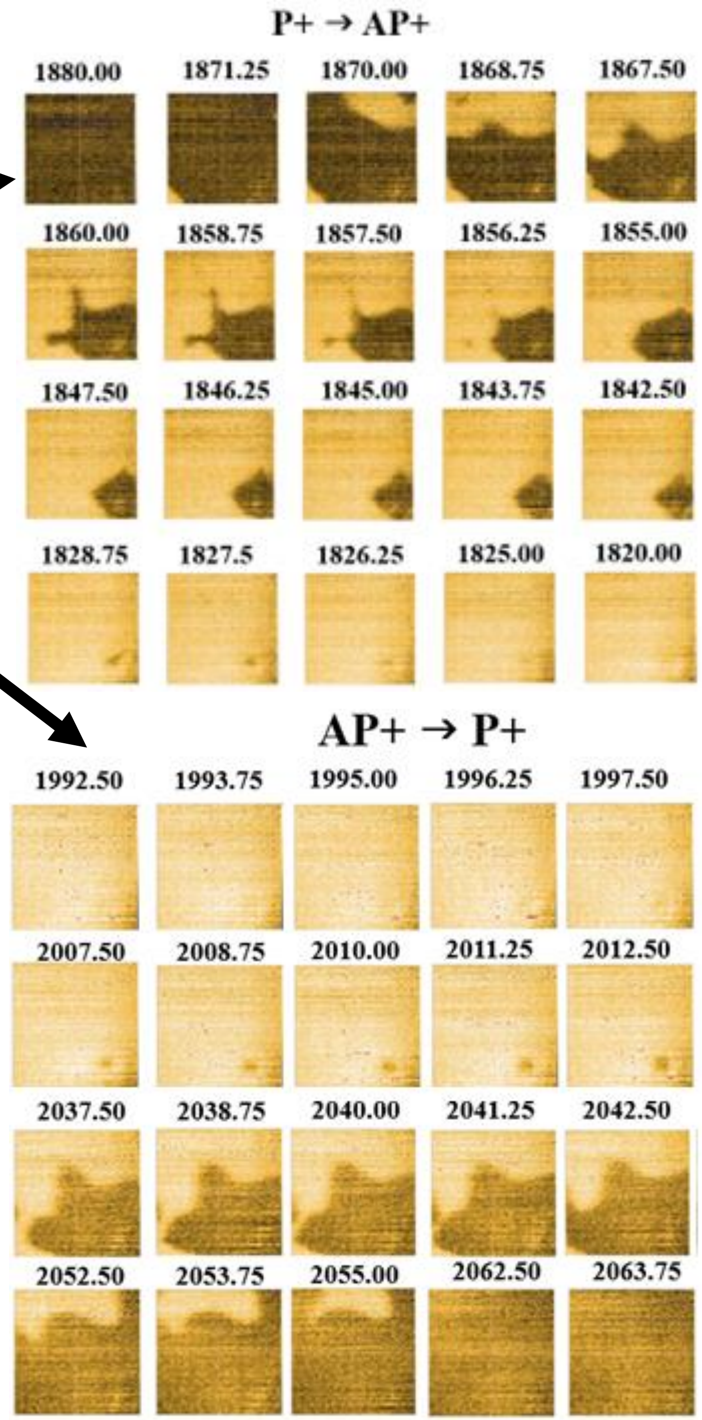
Hysteresis loops recorded in SQUID magnetometer in 6 - 350 K range. Magnetic moment M is normalized on Bohr magneton per formula unit $Gd_{0.25}[Fe_{0.9}Co_{0.1}]_{0.75}$. $M(H)$ loops recorded in in-plane (IP) and out-of-plane (OOP) orientations of magnetic field.



Temperature dependence of saturation magnetization normalized on Bohr magneton per formula unit $Gd_{0.25}[Fe_{0.9}Co_{0.1}]_{0.75}$. Dashed line shows calculated M_S value, determined with stoichiometry of our sample and individual ions values measured in by XMCD technique.

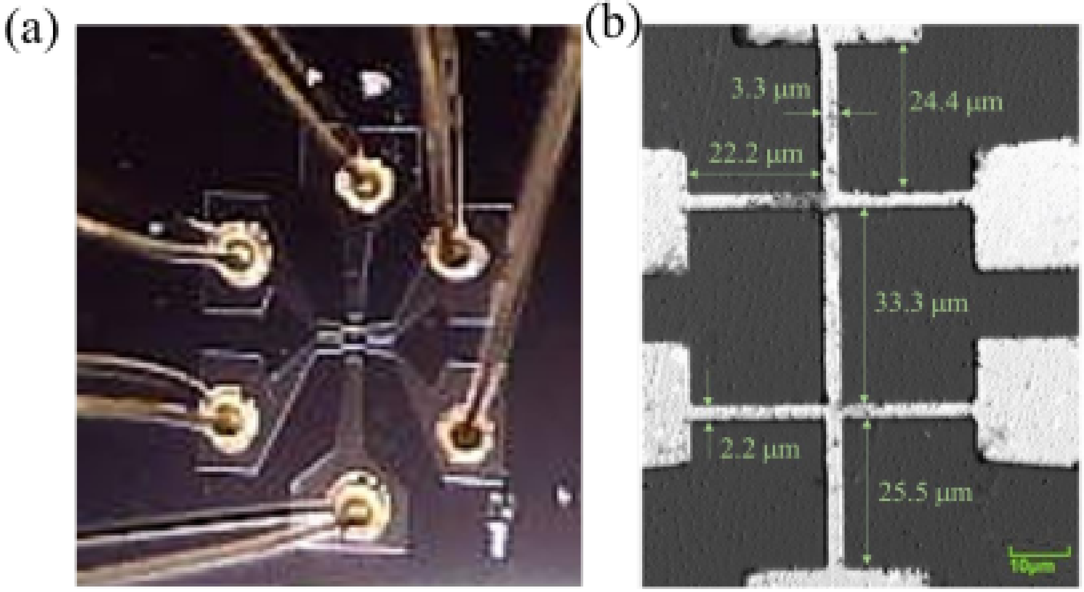
Local MOKE magnetization



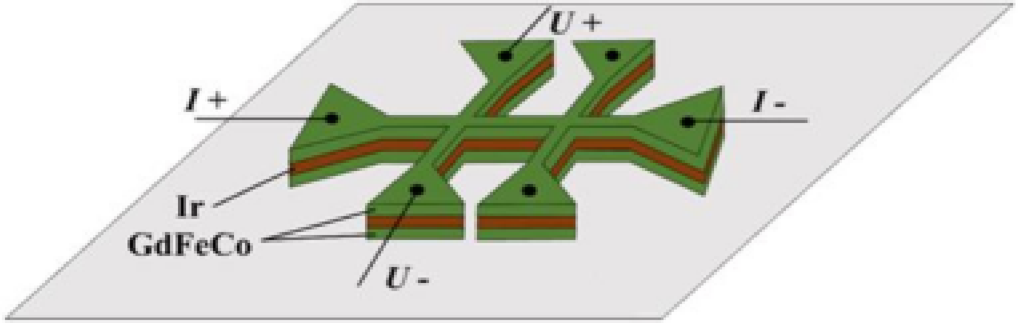


Hysteresis loop recorded in MOKE microscope at field sweeping rate 1080 Oe/s, 300 K temperature and magnetic field lying in-plane. Domain dynamics accompanying $P^+ \leftrightarrow AP^+$ and $P^- \leftrightarrow AP^-$ transitions.

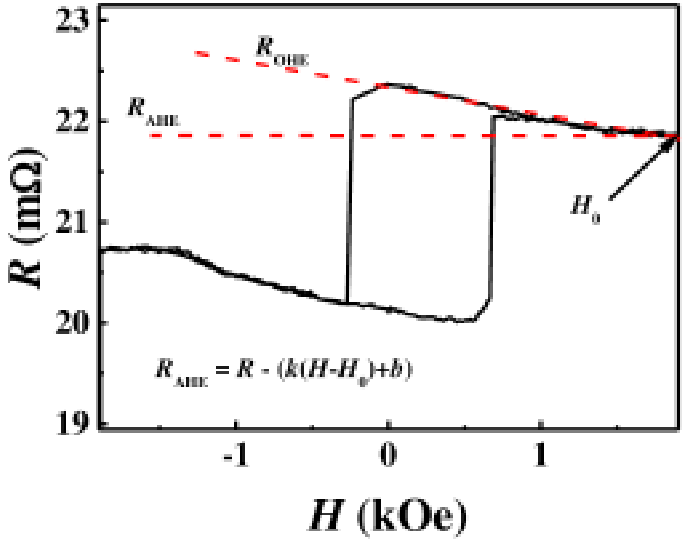
Anisotropy of switching fields detected by Hall voltage



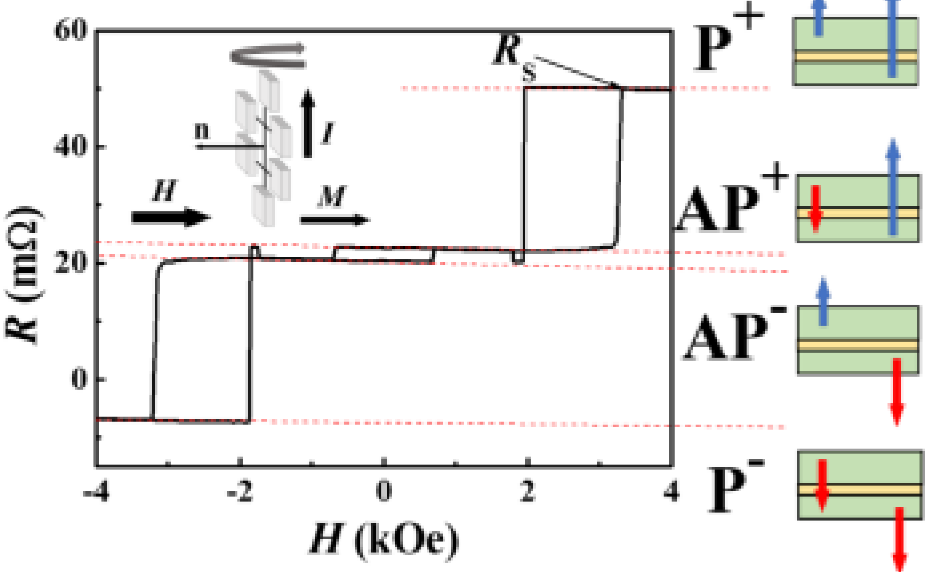
(a) Photo of the patterned samples with the gold contacts. (b) Photo of the Hall crosses.



Connection of contacts to heterostructure to measure current I and perpendicular Hall voltage U.

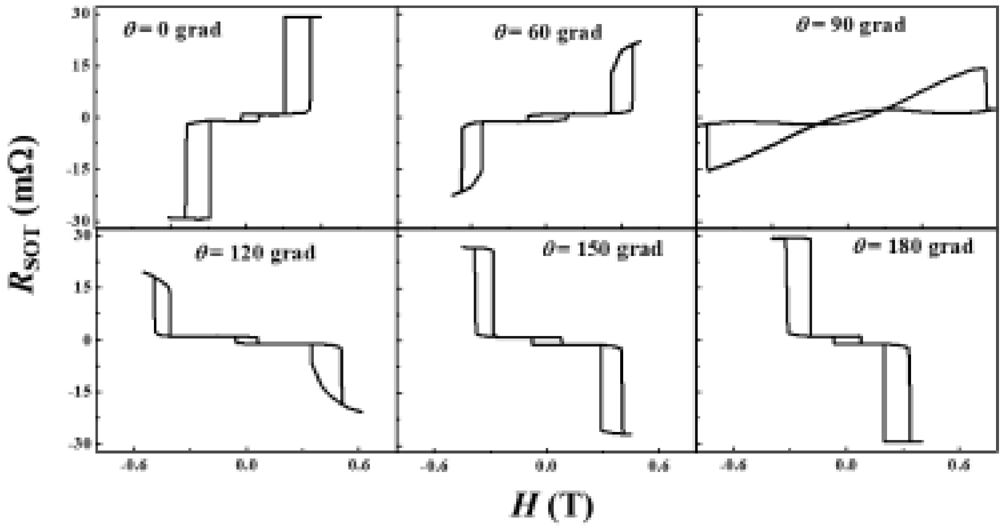


Extraction of ordinary Hall effect contribution from resistivity hysteresis loop



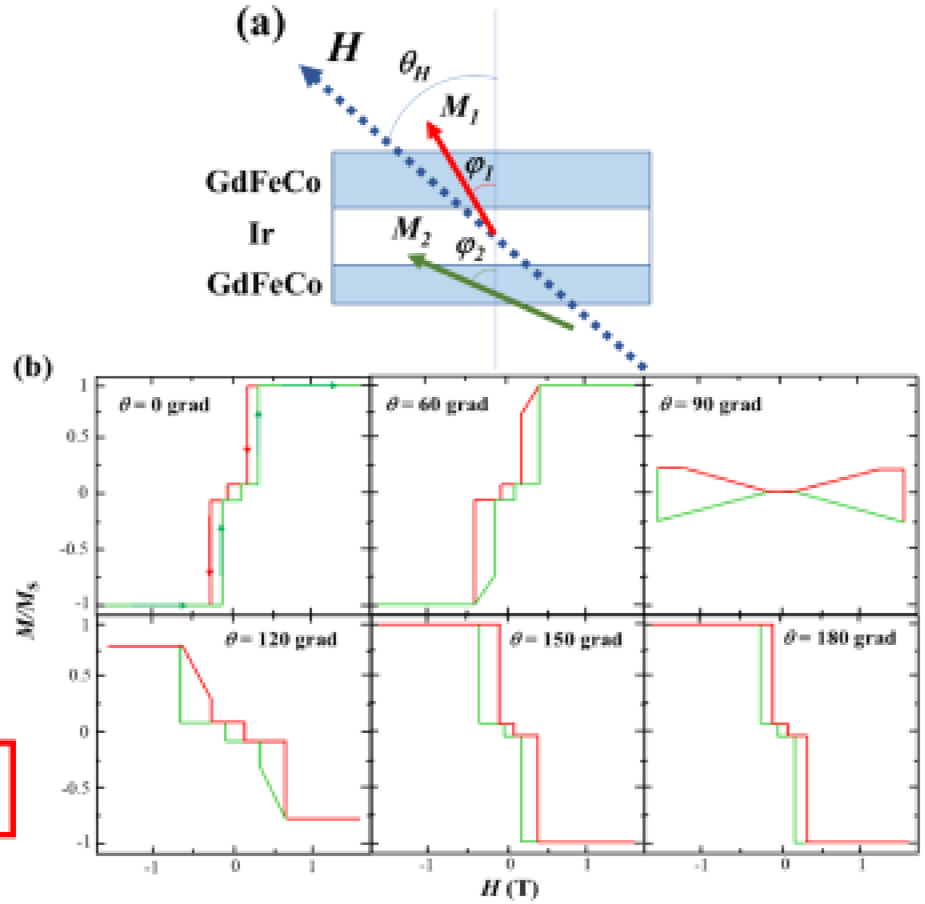
Dependences of Hall resistivity R on magnetic field at different current I = -7 – +7 mA. Field dependences of Hall resistivity at I = 1 mA.

Angular dependence



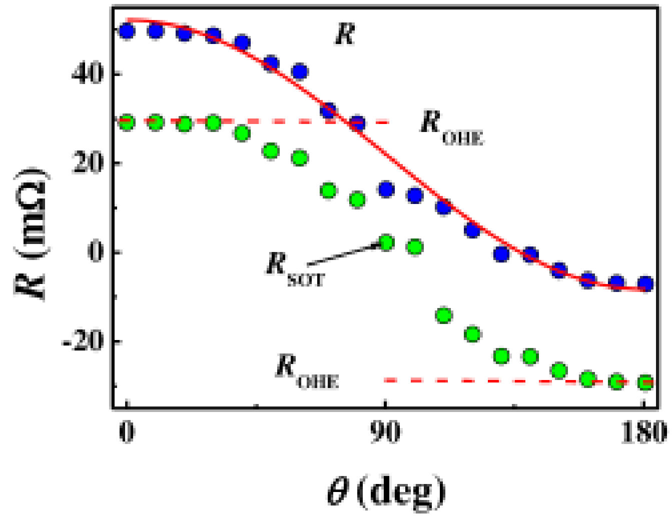
Field dependences of sample resistance recorded at different angles θ between sample normal and external magnetic field at 300 K.

$$R(I_{dc}) = R_{OHE}(I_{dc}) + R_{SOT} \cdot \cos\theta(I_{dc}) + R_{PHE} \cdot \sin^2\theta(I_{dc}) \cdot \sin 2\varphi(I_{dc})$$



(a) Scheme of the directions of the magnetizations ***M1*** and ***M2*** of the GdFeCo layers in the external magnetic field H and corresponding angles used for energy minimization.
(b) Calculated angular dependences of magnetization normalized on saturation magnetization.

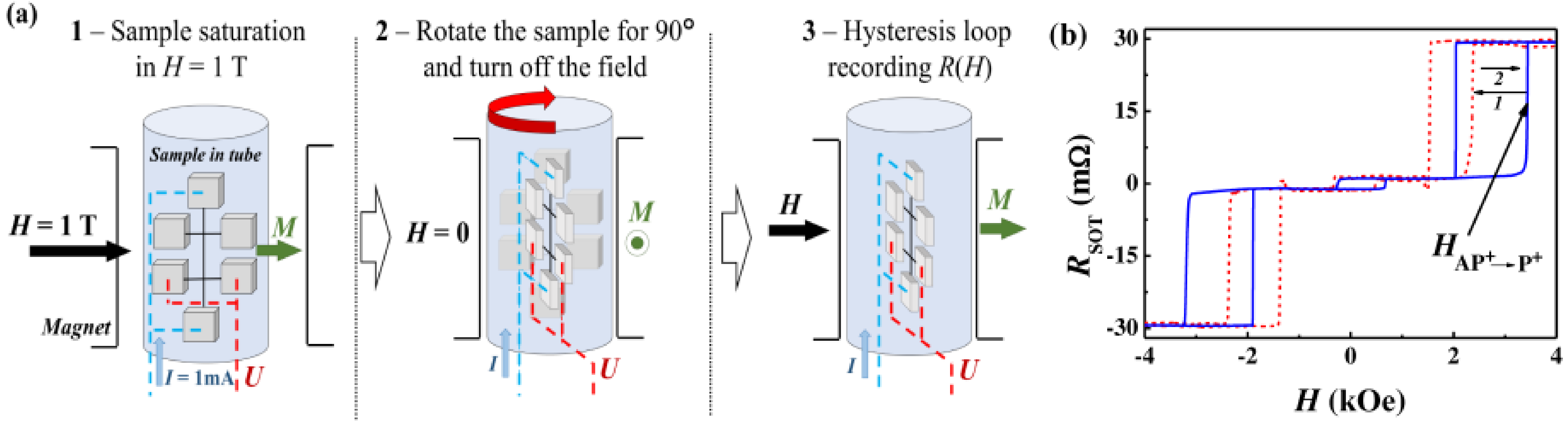
$$E_{tot} = -t_1 M_1 H_{ext}\cos(\theta-\varphi_1) - t_2 M_2 H_{ext}\cos(\theta-\varphi_2)$$
$$-K_{eff1}\cos^2\varphi_1 - K_{eff2}\cos^2\varphi_2 - J_{ex}\cos(\varphi_1-\varphi_2)$$

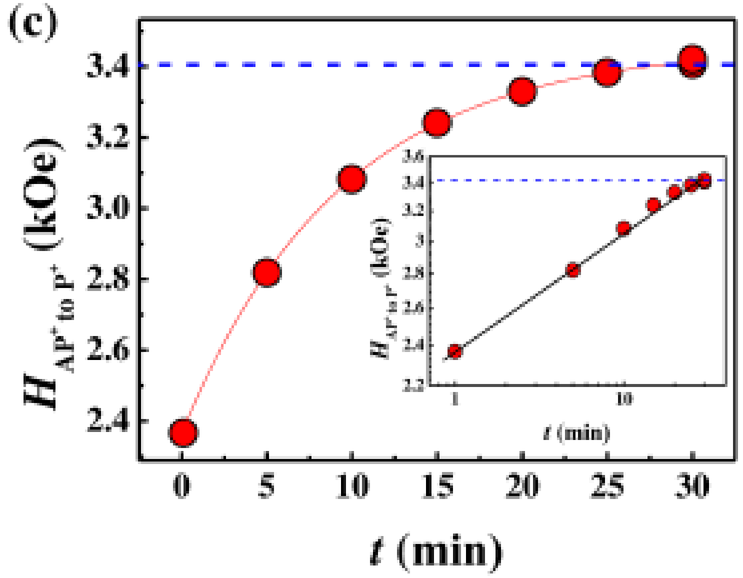


$$R_{OHE} = 22\ \text{m}\Omega,\ R_{SOT} = 30\ \text{m}\Omega$$

Angular dependence of the sample resistance I saturated state P$^+$ (blue symbols) and angular dependence of AHE extracted by approximation. Contribution of the ordinary Hall effect is shown by dashed line.

Relaxation of resistivity initiated by magnetic field reorientation





(a) Stages of the experiment detecting slow relaxation of Hall resistance. (b) Dependences of electric resistivity on magnetic field in the initially demagnetized sample (solid line) and in sample magnetized in parallel magnetic field 1 T. (c) time dependence of AP^+ to P^+ switching field in sample preliminary magnetized in field 1 T parallel to its plane. Solid line is exponential approximation to determine relaxation constant. Dashed line is switching field value equal to the resistance in non magnetized sample. 1 – First step (1 min), 2 - field movement to the original value.

Conclusions:

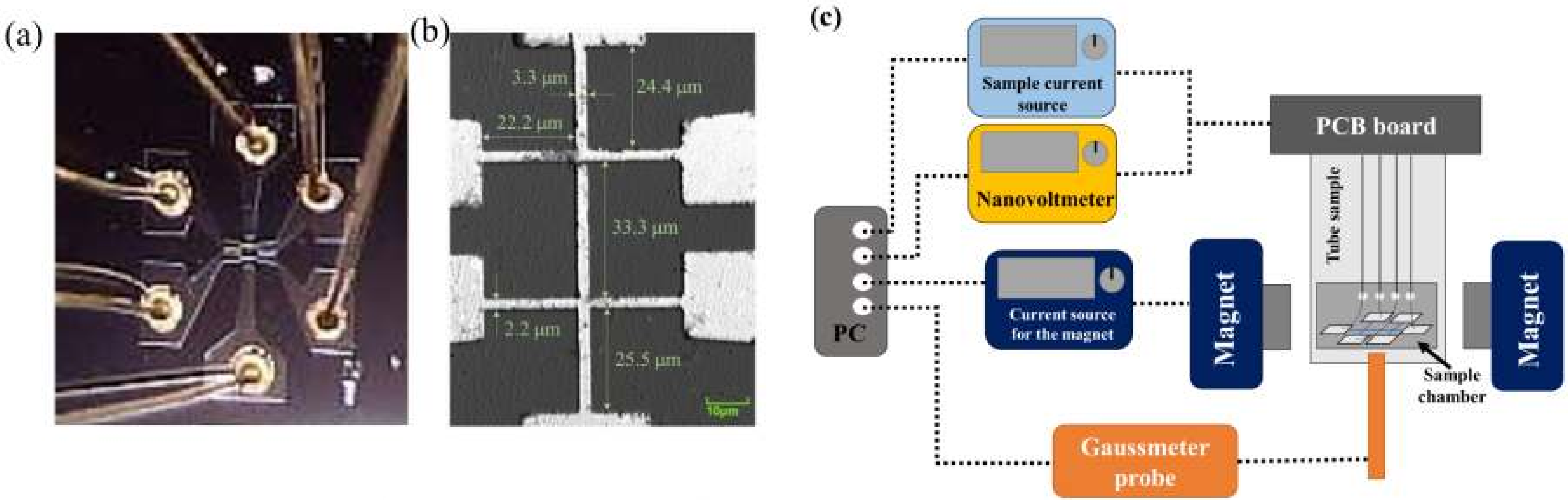
1. In GdFeCo/Ir/GdFeCo synthetic ferrimagnet, analysis of angular dependence of Hall effect allowed to extract contributions of classic and anomalous to the Hall resistance with their values at in-plane orientation R_{OHE} = 22 mΩ, R_{SOT} = 30 mΩ at room temperature exceeding compensation point ~ 100 K.

2. The shapes of experimentally determined hysteresis loops of anomalous Hall resistance are well described within a macrospin model for two antiferromagnetically coupled GdFeCo layers. Minimization of magnetic energy in this macro-spin system describes the experimentally observed angular behavior of the Hall resistance within full 180° range of the magnetic field angle.

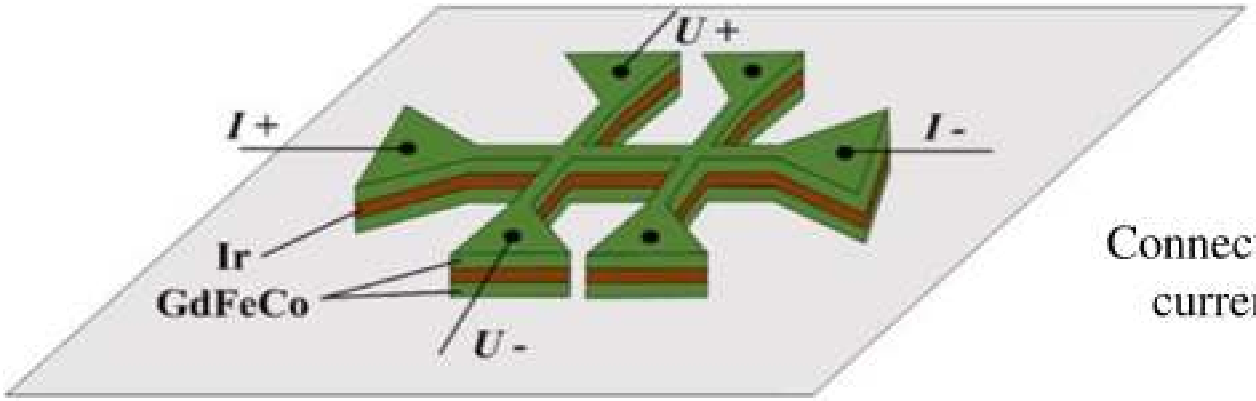
3. Exposure of the film in a saturating in-plane field leads to reduction of the out-of-plane exchange bias. The effect was found to be reversible and once the in-plane field is switched off, the out of-plane exchange bias slowly returns to its initial value with a characteristic relaxation time ~30 min. Comparability of the exchange bias relaxation time with the typical durations of magnetic domain propagation in the synthetic ferrimagnets paves a way for a new generation of antiferromagnetic spintronics devices, in which the magnetic relaxation times for antiferromagnetic and ferromagnetic subsystems are synchronized.

We acknowledge funding from the Ministry of Science and Higher Education of the Russian Federation (Grant No. 075-15-2020-779).

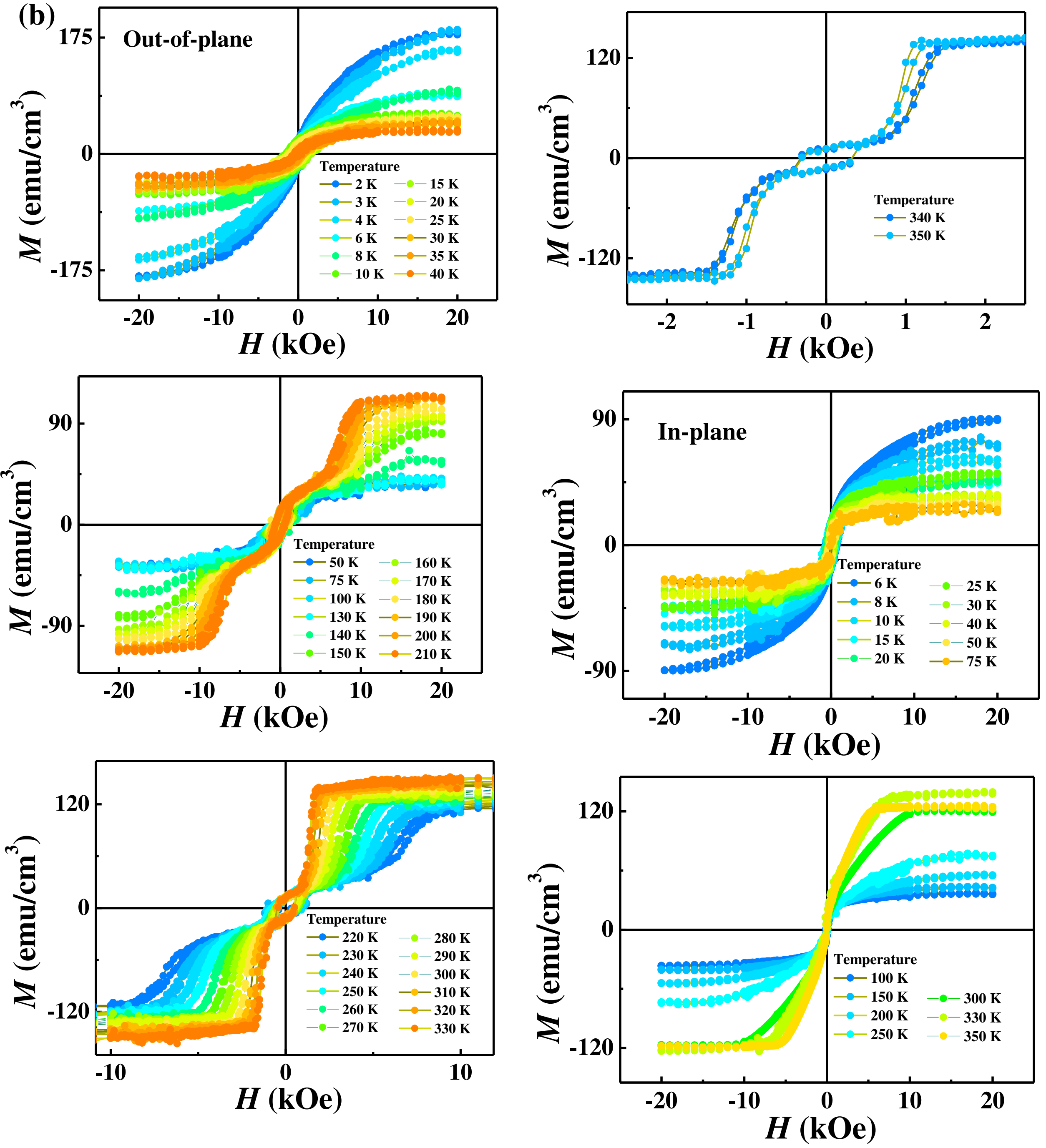
Supplemental Material



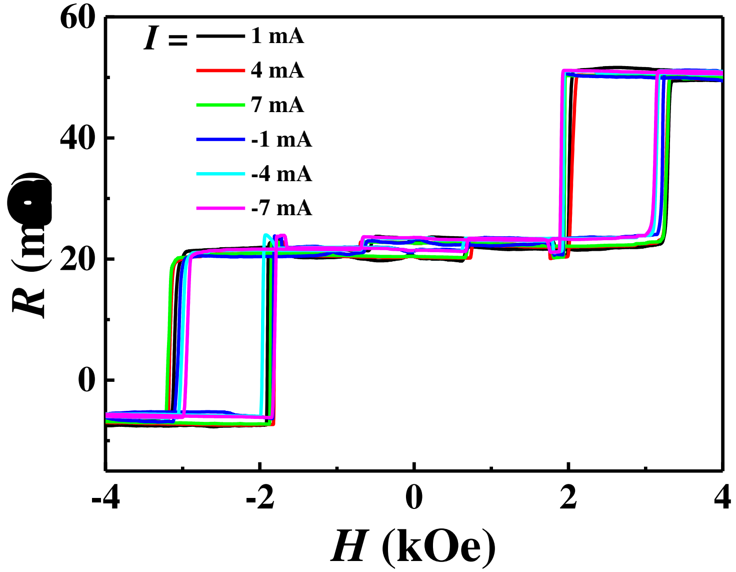
(a) Photo of the patterned samples with the gold contacts. (b) Photo of the Hall crosses. (c) Equipment for DC measurements of the Hall effect.



Connection of contacts to heterostructure to measure current I and perpendicular Hall voltage U.



Magnetic hysteresis recorded at different temperature for different temperatures in SQUID magnetiometer, which magnetic field is directed perpendicular to the sample plane. Upper panel (a) demonstrate magnetic moment *m*, down panel (b) demonstrates magnetization *M*.



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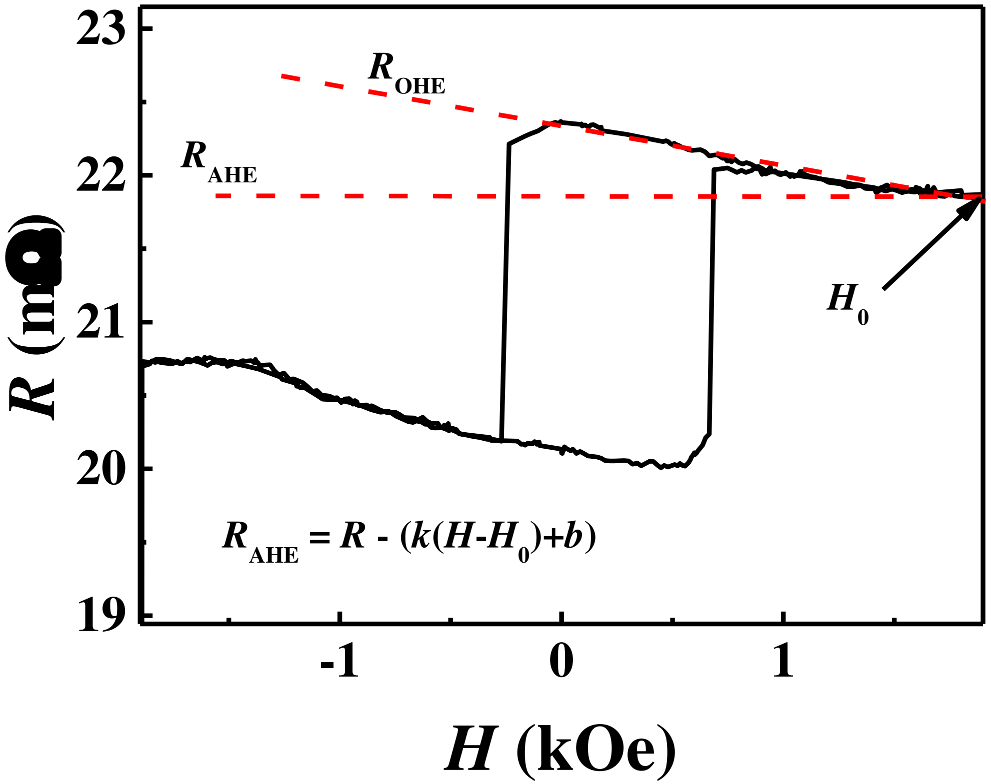

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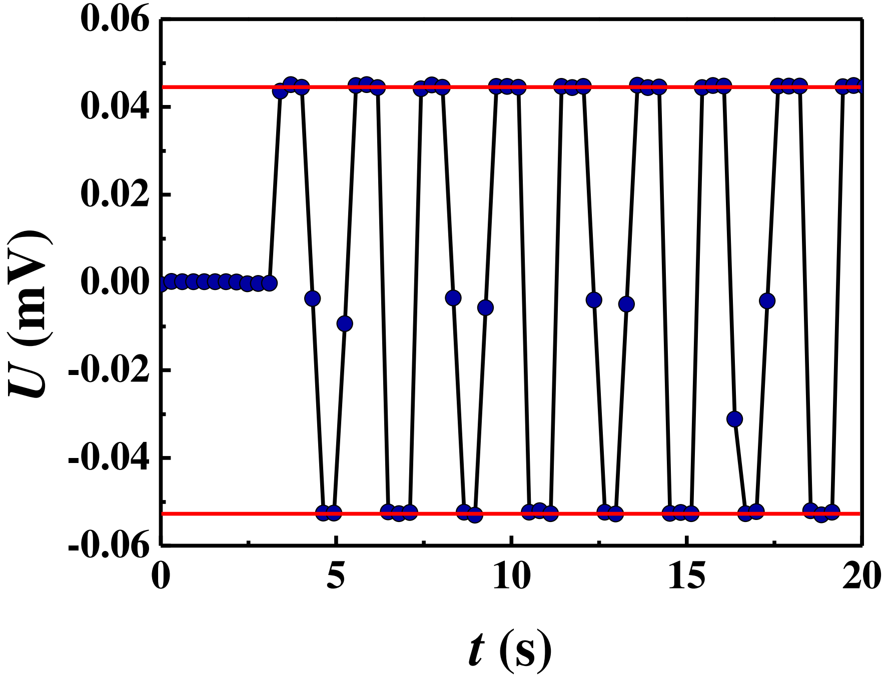
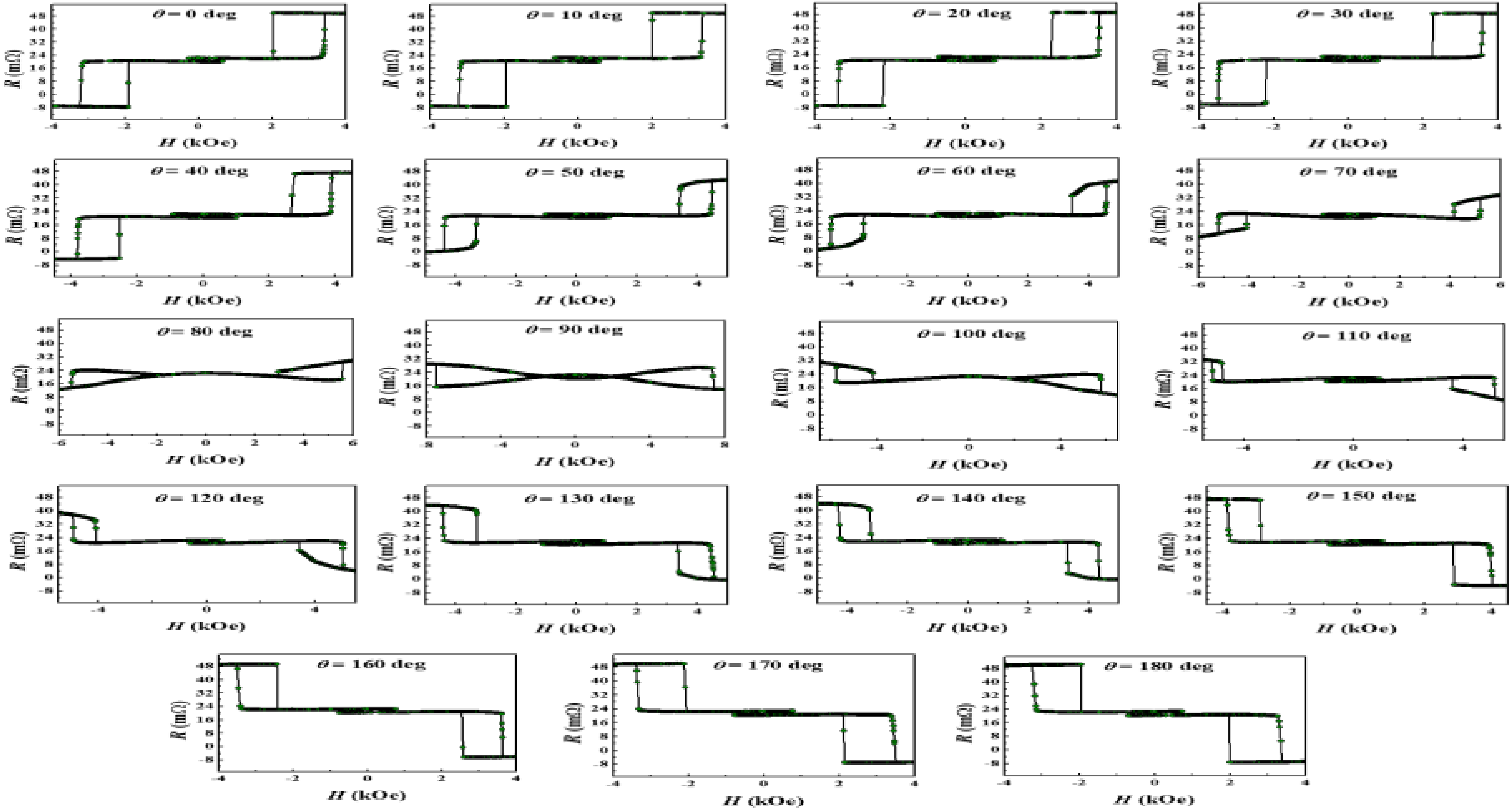
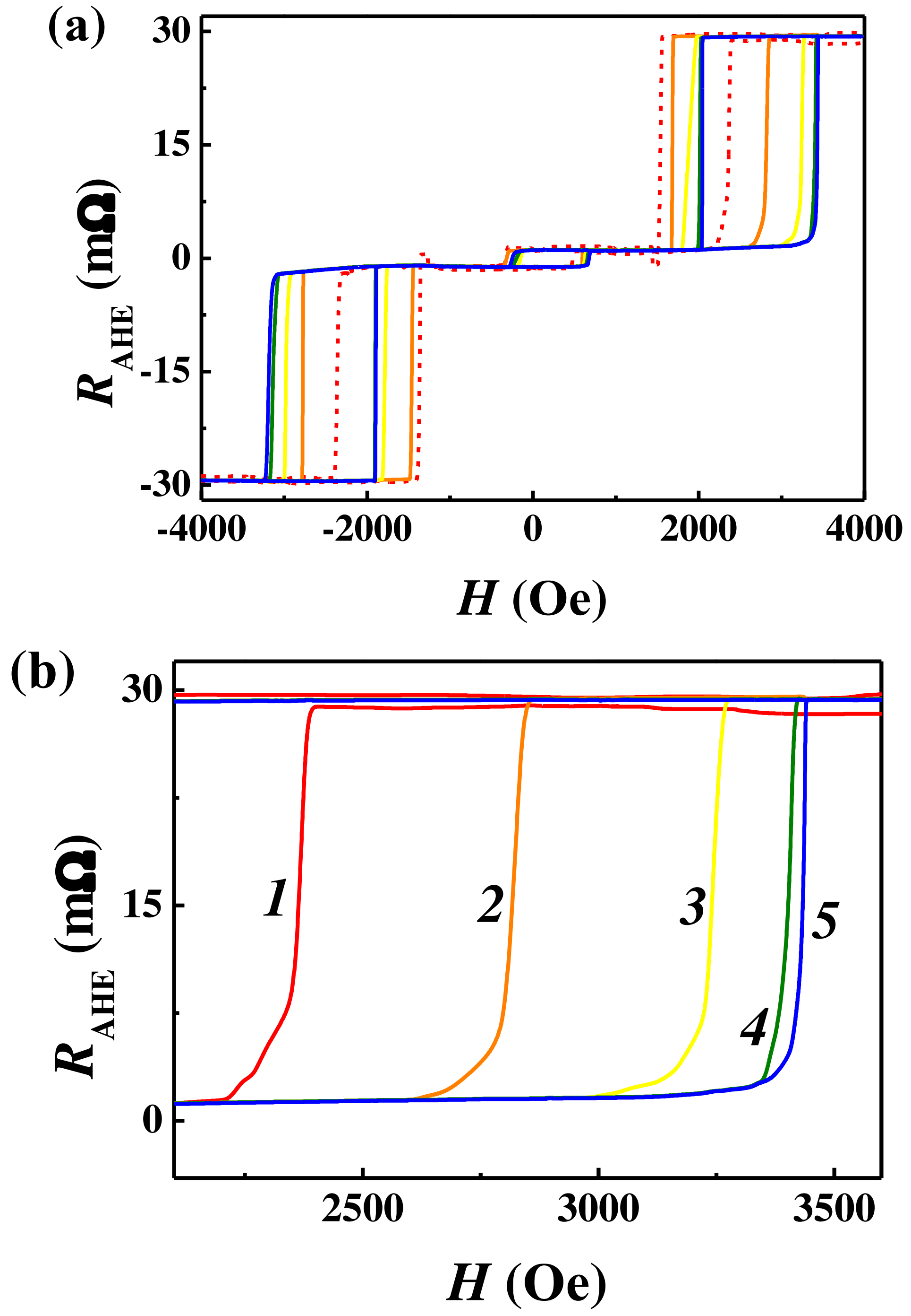


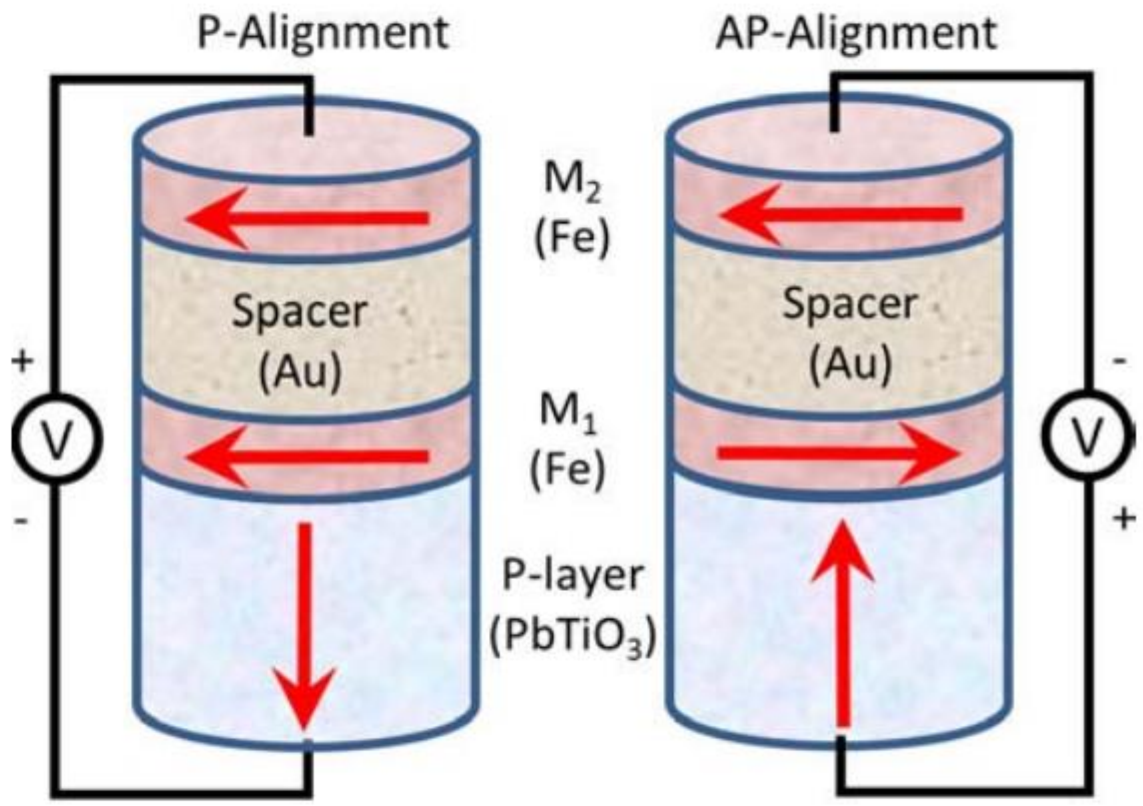
Time dependence of the Hall voltage during pulsed current switching between I = -1 mA and 1 mA. Pulse duration was 1 s.



Angular dependences of sample resistance recorded at different field orientation with the step $\theta = 10°$.



Dependences of the anomalous Hall effect on the magnetic field, recorded after 0 (1), 5 (2), 15 (3), and 30 min (4) after rotation of the sample (a). Switching fields enlarged (b). Line (5) corresponds to the dependence of the anomalous Hall effect on the magnetic field in the initial sample not subjected to saturation in parallel magnetic fields.


P-Alignment
AP-Alignment
M2
(Fe)
Spacer
(Au)
M1
(Fe)
P-layer
(PbTiO3)
Spacer
(Au)
V
V
+
-
-
+