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Magnetic properties of ultrathin Co/Pt multilayer Hall devices irradiated using focused ion beam

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Abstract. A ferromagnetic Co/Pt multilayer was lithographically patterned into 10-μm-wide Hall devices. The anisotropy of the fabricated devices was modified using focused ion beam (FIB). Extraordinary Hall effect (EHE) measurements reveal pronounced reduction in nucleation field of the perpendicular loops at room temperature. At low temperature of 4.2 K reduced remanent ratios in EHE loops were observed, indicating a tilting of easy magnetic axis. The canting magnetization can be explained by an increasing magnetic moment at low temperatures and a reduced anisotropy by irradiation. The aperture angles were estimated to be in the range of 20º- 32º at 4.2 K. The aperture angle of the easy cone of magnetization was found to increase with doses at low temperatures.

Keywords: Co/Pt multilayers, perpendicular magnetic anisotropy (PMA), Extraordinary Hall effect (EHE), Hall devices, ion irradiation.

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1. Introduction

Co/Pt multilayer system with ultrathin Co layer (~5 Å) has been attracting more interest for its good perpendicular magnetic anisotropy (PMA) from strong interfacial anisotropy [1-5]. The interfacial anisotropy is sufficiently strong to overcome the shape magnetic anisotropy to induce a perpendicular easy axis of magnetization, but is very sensitive to the sharpness of the interface [6]. Chappert *et al*. demonstrated a pioneering work using light He^+ ions irradiation through a pre-made resist mask to produce interfacial mixing and hence reduce the perpendicular anisotropy of the multilayer system [7]. Coercivity Hc and Curie temperature Tc of Co/Pt materials were shown to decrease with the dose due to reduced interfacial anisotropy from collision-induced intermixing of Co and Pt [8,9]. The magnetic properties of the Co/Pt films can be modified or controlled by ion irradiation [10]. It has been reported that heavy Ga^+ ion beam is more efficient than light He^+ ion beam to modify the magnetic properties of Co/Pt films [11-13]. Also, focused Ga+ ion beam can produce the patterning with a high resolution (~10 nm) [5,6].

In this work, focused Ga+ ion beam is used to partially irradiate the µm-sized Hall devices fabricated based on a Co/Pt multilayer. The magnetic properties of the irradiated micro-devices are investigated using EHE transport measurement. Different magnetic behaviour is found in the irradiated Hall devices at room temperature and low temperatures. The understanding on the changes in the magnetic properties of the irradiation of Co/Pt Hall devices will provide some useful information on potentially expanding the application of field or current-driven magnetic devices.

2. Experimental details

A Pt 47/(Co 5/Pt 27)$_2$/Co 5/Pt 22 Å multilayer was deposited on a (100) Si/SiO$_2$ substrate at room temperature using dc magnetron sputtering, as we described before [14]. The rms roughness of the deposited film was measured to be ~0.4 nm by atomic force microscopy (AFM). The perpendicular anisotropy of the Co/Pt multilayer was confirmed by magneto-optical Kerr effect (MOKE) measurements in polar geometry. The magnetic multilayer was then patterned into Hall bar structures, based on the intersection of 10-μm-wide wires, using optical lithography and Ar ion milling. The structures are extremely sensitive to the FIB, and an additional 8 nm SiO_2 film was sputtered on the top surface for protection.

Focused ion-beam irradiation is performed on the Co/Pt Hall devices with a commercial FIB (FEI Strata 201) at an incident Ga ion energy of 30 keV and a 1.5 pA current. The beam diameter was about 10 nm and the distance between neighbouring pixels was set to be 7.5 nm. Irradiation was performed at a magnification of 6 k× and half region in the middle of Hall crosses was dosed. An ion dose in the range of 0.004-0.02 pC/μm^2 is applied using variable pixel dwell times.

3. Results and discussion

As shown in Figure 1, MOKE measurement in polar geometry confirms a good perpendicular anisotropy in the sputtered Co/Pt multilayer. The coercivity of the film is determined to be ~250 Oe.

An optical micrograph of the patterned structure is presented in Fig. 2. The ac current flows (I = 1 μA, 310 Hz) along the patterned wire from the top to the bottom. The switching properties of perpendicularly magnetized dosed regions were investigated using EHE measured on each pair of left and right contacts.

Figure 3 shows the nucleation fields measured on the five 10-μm-wide Hall crosses with different doses. Here, the nucleation field H_N is the field at which the magnetization reversal starts. The coercivity of the device before dose determined by EHE is ~250 Oe, in good consistent with the value measured by the MOKE. The nucleation field is lower than the coercivity in the devices after irradiation. It shows a typical reversal characteristic of low-field nucleation and subsequent domain wall propagation, which is often observed in the magnetic reversal process in the irradiated Co/Pt multilayers [15, 16]. It is worth to mention that inverse domain nucleation can occur at a higher field than the coercivity in Co/Pt multilayers [17]. A clear reduction in the nucleation field with doses was observed in the irradiated Hall devices. The obvious falls of the nucleation field with doses can be attributed to a reduced perpendicular anisotropy of locally irradiated region. Inset shows in the loop measured on the device irradiated at the high dose of 0.02 pC/μm^2 a close-to-linear part at low fields appears before a jump of switching, implying an in-plane anisotropy may occur [18].

When the irradiated devices are cooled to 4.2 K, EHE loops with a remanent ratio less than one appear, as shown in Fig. 4a. The pronounced rounding in the EHE loops implies that nucleation events may become dominant in the magnetic reversal at low temperatures [19]. The coercivity of all the devices at the low temperature are measured to be ~600 Oe, suggesting the same reversal mechanism is dominant. As changes in EHE voltage are directly related to the out-of-plane component of the magnetization of the Hall cross region, the reduced remanence indicates magnetic reversal with a tilt of the easy axis. The canting magnetization might be attributed to an increase in magnetization at low temperature and reduced anisotropy by irradiation. The minor loops in Fig. 4b are measured in the way that, after negative saturation the applied field is increased to 400 Oe before it overcomes the coercivity of the devices and then reduced again to negative saturation. The initial part in the minor hysteresis loops along the increasing-field branch concides well with the corresponding part in the main loops in the irradiated devices. It suggests that the irradiated sites with reduced anisotropy, tend to align with the field direction. When the field reaches 400 Oe and then reduces back to negative saturation, the magnetization of the reversed sites will revert to the original state and the decreasing-field branch is formed in the minor hysteresis loops.

The change of remanent ratio with dose at low temperatures was plotted in Figure 5. A trend of gradual reduction in remanent ratio with dose can be clearly seen from the plots. The remanent ratio in the loops measured at 4.2 K reduces from 94% to 85% when the dose increases from 0.004 pC/μm^2 to 0.02 pC/μm^2.

From the measured ratio between remanent and saturation magnetization, an average tilt angle of magnetization away from the normal direction, i.e., the cone of easy magnetization with an aperture angle (defined by $\cos\theta = M_r/M_s$) can be deduced in the system with canted magnetization [20]. Using the remanent ratio from the plots, this average tilt angle with respect to the film normal is estimated to increase from 20° to 32° at this temperature with doses. At 50 K the remanent ratio in the loops reduces from 96% to 86%, which corresponds to an aperture angle of the cone of easy magnetization ranged from 16º to 31º.

4. Conclusions

In short, we investigate the magnetic properties of Co/Pt multilayer Hall devices irradiated by FIB. At room temperature perpendicular loops with pronounced reduction in nucleation field were exhibited, revealed by EHE measurements. At low temperatures reduced remanent ratios in EHE loops were observed. A tilt of easy magnetic axis in multilayer devices occurs at low temperatures, which can be attributed to an increasing magnetization at low temperature and a reduced anisotropy by irradiation. An aperture angle of the easy cone of magnetization was found to increase with doses.

Acknowledgements

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Captions

Fig. 1. MOKE loop of a continuous Pt 47/(Co 5/Pt 27)$_2$/Co 5/Pt 22 Å multilayer sample.

Fig. 2. Optical micrograph of lithographically patterned five Hall devices along a 10-μm-wide stripe.

Fig. 3. Plot of nucleation field against doses at room temperature. Insets show typical EHE loops measured on the Hall devices before and after doses, respectively.

Fig. 4. EHE measurements on the Hall devices at 4.2 K. a) EHE loops obtained from the dosed devices, b) minor loops (in red colour) obtained from the devices irradiated with doses of 0.011 and 0.02 pC/μm^2, respectively. (online colour)

Fig. 5. Remanent ratio in EHE loops against dose at low temperatures.

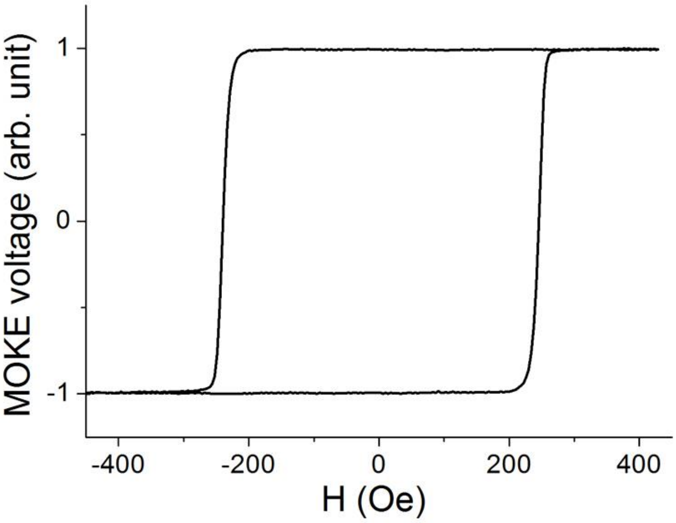

Fig. 1.

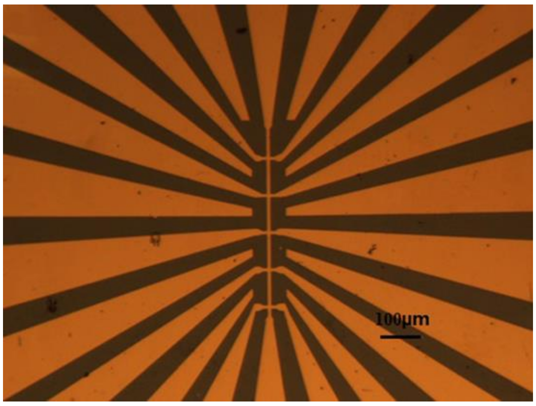

Fig. 2.

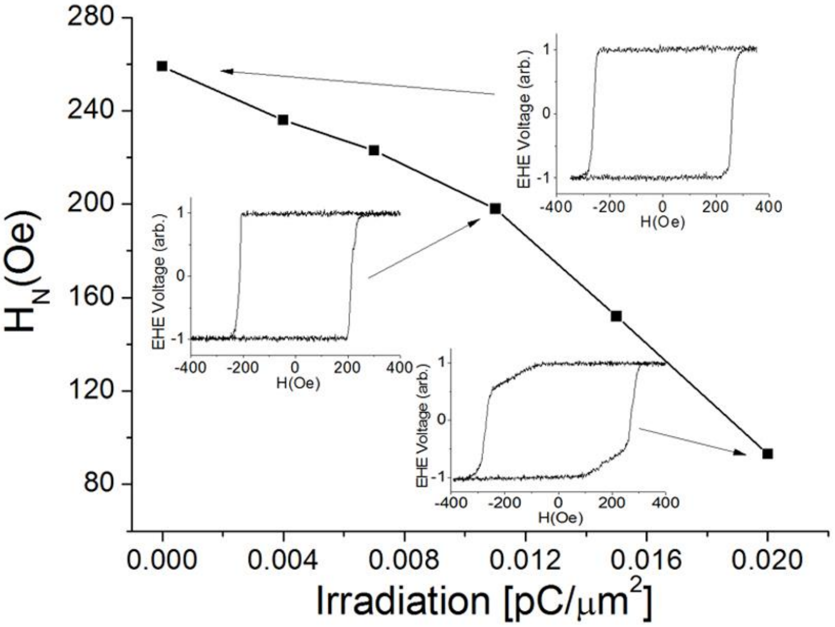
280
240
200
160
120
80
H_N(Oe)
0.000
0.004
0.008
0.012
0.016
0.020
Irradiation [pC/μm^2]
EHE Voltage (arb.)
1
0
-1
-400
-200
0
200
400
H(Oe)

Fig. 3.

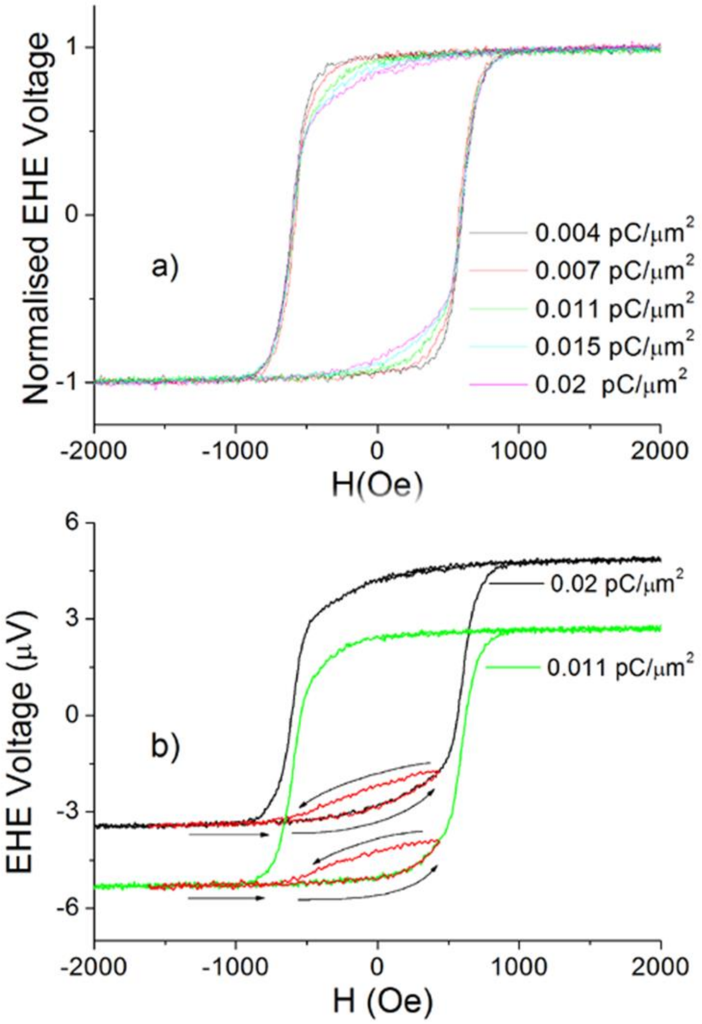
Normalised EHE Voltage
1
0
-1
a)
0.004 pC/μm^2
0.007 pC/μm^2
0.011 pC/μm^2
0.015 pC/μm^2
0.02 pC/μm^2
-2000
-1000
0
1000
2000
H(Oe)
EHE Voltage (μV)
6
3
0
-3
-6
b)
0.02 pC/μm^2
0.011 pC/μm^2
-2000
-1000
0
1000
2000
H (Oe)

Fig. 4.

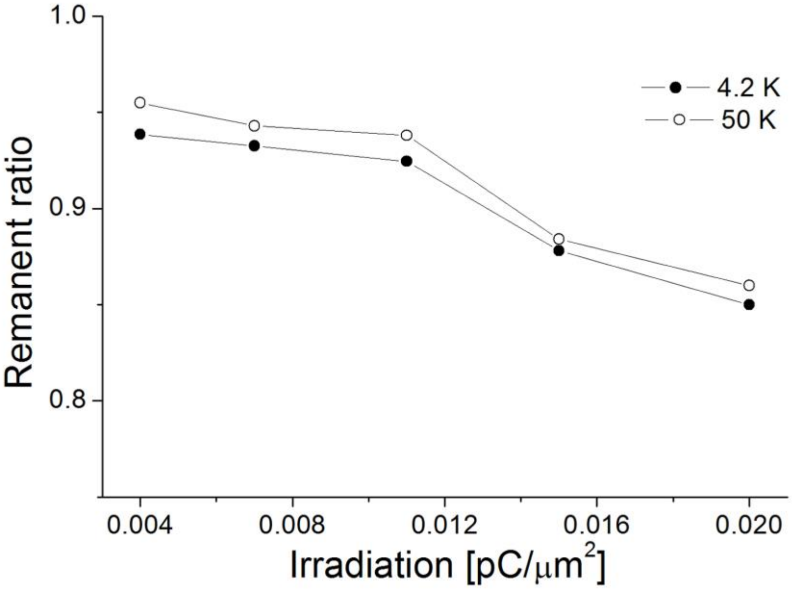
1.0
0.9
0.8
Remanent ratio
4.2 K
50 K
0.004
0.008
0.012
0.016
0.020
Irradiation [pC/μm2]

Fig. 5.