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Co/Pt Hall sensors for low field detection

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Abstract

We have investigated the use of CoPt ultrathin multilayers as an alternative material for a high sensitivity Hall sensor, capable of detecting very low fields at room temperature. We present measurements of a Pt(25Å)/[Co(6Å)/Pt(12Å)]\times2 (6 nm thick) sample with a Hall cross area of 5×2.5 µm\(^2\) and a coercive field of 170 Oe, both for the continuous film and the patterned device. This sensor has a field sensitivity \(S_I = 3960 \, \Omega/T\) and is capable of detecting a minimum field change \(B_{min} = 2.6 \, \text{nT}/\text{Hz}^{1/2}\), better than similarly sized semiconductor Hall sensors working at room temperature.

Keywords: CoPt; magnetic Hall sensors; Extraordinary Hall Effect; bead detection; biosensors.

1. Introduction

The Extraordinary Hall Effect (EHE) in magnetic thin films with out-of-plane anisotropy has been recently investigated for their potential compatibility with the CMOS technology\textsuperscript{1}. Previously, the EHE in Fe/Pt and Co0.9Fe0.1 /Pt multilayers with adjustable anisotropy and in plane magnetization has also been studied showing sensitivities up to 1200 V/AT while keeping a large dynamic field range\textsuperscript{2}. In this article we show that even higher sensitivities at room temperature can be achieved using ultrathin Co/Pt bilayers.

2. Experimental

We have used e-beam lithography to define a current line 80 µm long and 5µm wide, with three crosses 2.5 µm wide, on top of which contact pads have been aligned by means of UV-lithography, see Fig 1. The CoPt multilayer deposition was done by dc magnetron sputtering in a custom UHV chamber with base pressure \(\sim 2\times10^{-9}\) Torr; the growth rate was \(\sim 2 \, \text{Å/s}\) with an Ar working pressure \(\sim 2.5\) mTorr.

Using polar Magneto Optical Kerr Effect (MOKE) measurements on continuous films, we have optimized the Co:Pt layer thickness ratio and the layer repetition number in order to get a sharp magnetization reversal. Because of

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the correlation between the Extraordinary Hall Effect and the resistivity\(^3\), we have chosen the thinnest CoPt multilayer, for which the enhanced surface scattering should increase the Hall voltage\(^4\). Whilst keeping the 1:2 Co-Pt ratio, we have chosen a 3.6 nm thick bilayer grown, on a 2.5 nm Pt buffer - Pt(25Å)/[Co(6Å)/Pt(12Å)]\(\times\)2 with optimized electric and magnetic properties.

Fig. 1. Kerr microscope image of a Co/Pt device with 3 Hall crosses; the current line is 5 µm wide, and is attached to a large nucleation pad (top); the voltage lines are 2.5 µm wide; the magnetic structure has Au conduction leads (bright in the image), aligned on the top using alignment marks (right). A nucleated reverse domain structure (darker regions) can be observed on the nucleation pad and also on the first and second Hall crosses for \(H_C\sim170\) Oe.

The hysteresis curve of the CoPt thin film grown next to the device measured by polar MOKE is shown in Figure 2. The magnetization reversal is very similar with the EHE measurement of the patterned sample, with a coercive field \(H_C=170\) Oe. This confirms that, for the chosen sizes, there is little influence of the shape anisotropy, and the switching is sharp on a scale of only a few Oersteds. The two-point resistance of the current line was 1.6 kΩ and allowed a current of up to 0.5 mA before any thermal drift was noticeable.

Fig. 2. Hysteresis curve of the CoPt continuous film (blue points, left axis) and Hall Voltage on a patterned cross (red points, right axis) showing similar magnetization reversal and coercive fields (170 Oe).
3. Results and discussion

In Fig. 3(a) we present the variation of the Hall voltage $V_{\text{Hall}}$ when the field is swept perpendicular-to-the-plane from -2 T to +2 T, along the easy axis of the magnetization. Defining $b$ as the slope of the fitted curve, $S_I = b/I$ is the current sensitivity, and $B_{\text{min}} = \delta V/S_I I$ is the field resolution (the minimum detectable change in the magnetic field). Due to the square hysteresis curve, characteristic for switching along an easy axis, the Hall Voltage showed a sharp transition giving a sensitivity $S_I = 3960 \, \Omega/T$ and field resolution $B_{\text{min}} = 2.6 \, \text{nT/Hz}^{1/2}$ at 10 Hz, see Fig 3(b), limited at higher frequencies by the Johnson noise to $2.6 \, \text{nT/Hz}^{1/2}$. The corresponding minimum detectable change in the magnetic flux resolution is $\Phi_{\text{min}} = 2 \times 10^{-5} \Phi_0$ and the Hall coefficient of the CoPt multilayer is $R_H = 24 \times 10^{-6} \, \Omega \cdot \text{m/T}$.

![Figure 3](image1.png)

Fig. 3. Hall Voltage when the field is perpendicular to plane (a) and associated noise spectrum and magnetic field resolution (b).

The remarkably high value of the current sensitivity $S_I$ is due to the very sharp switching of the magnetization, so, as a draw-back, the working field range of the sensor $\Delta H_{\text{EHE}}$ is limited to less then 1 mT (16mT to 17 mT). We noticed the following empirical dependences: $S_I \sim 1/\Delta H_{\text{EHE}}$ and $B_{\text{min}} \sim \Delta H_{\text{EHE}}$. This can be checked by measuring the Hall Voltage when the field is swept in plane, along the hard axis, as shown in Fig. 4. Because the Hall voltage in Fig. 4(a) is higher than the Planar Hall anisotropy in Fig 4(b), the magnetization is also switching out-of-plane, and has three linear regions. So, if properly biased with an in plane field, one can extend the working field of this sensor between 105-155 mT, while still benefitting from a very good field resolution of $B_{\text{min}} = 219 \, \text{nT/Hz}^{1/2}$.

![Figure 4](image2.png)

Fig. 4. Hall Voltage when the field is swept along the current line in plane (a) and angular dependence of the Planar Hall Voltage when a 2T field is rotated in plane (b); the Hall Voltage is shifted by 45º with respect to the Anisotropic Magneto Resistance (blue points, right axis).
The performance of these sensors could be improved if a higher current could be pushed through the device. Reducing the length of the current line by two orders of magnitude would then decrease the magnetic field resolution to a few pT, comparable to the best MR sensors. Moreover, the active area of this device could be decreased as low as 500×250 nm², provided the shape anisotropy would not change too much the magnetization reversal, which is not to be expected on the basis of the data shown in Fig. 1. This would then result in a minimum detectable flux change at room temperature $\Phi \sim 10^{-9} \Phi_0$, better than most of the Hall sensors available. The smallest possible active area is essential when detecting very inhomogeneous fields, such as those produced by single paramagnetic beads, with a field profile at a distance $z$ above the sensor scaling with their diameter.

4. Conclusions

We have investigated the use of ultrathin CoPt multilayers as an alternative material for a high sensitivity Hall sensor, capable of detecting very low fields at room temperature. We present measurements of a Pt(25Å)/[Co(6Å)/Pt(12Å)]×2 (6 nm thick) sample with cross area 5×2.5 µm², showing a field sensitivity $S_i \sim 4000 \Omega/T$ and capable of detecting a minimum field change $B_{\text{min}} < 3 \text{nT/Hz}^{1/2}$, better than similar size semiconductor Hall sensors working at room temperature. The coercive fields of the continuous film and of the patterned device are similar, around 170 Oe, so the sensor needs to be biased by an external magnetic field provided either by on-chip current lines or proximity permanent magnets, in order to get a linear response at zero applied field. Alternatively, one can get a linear response by increasing the shape anisotropy and tilting the easy axis in-plane.

Given the limited field range in which the transition takes place, this device is best suited to be used as an On-Off sensor, either for detecting magnetic beads used as labels in biology, or as a read head in the magnetic storage industry. Smaller size sensors will detect lower fluxes and can be engineered to have a tilted magnetization resulting in a higher linear field range and true linear sensing in zero field, because of the magnetization reversal along the hard axis (Fig. 4a).

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