https://doi.org/10.1016/j.jmmm.2019.04.075

Photo-induced anomalous Hall effect in nickel thin films

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Abstract:

Anomalous Hall effect is commonly used as a simple technique to study the magnetization reversal of perpendicularly magnetized thin films. Yet, in most applications, the easy-magnetization direction is in the film-plane. We here propose photo-induced anomalous Hall effect as a new magneto-metric technique to reconstruct the in-plane magnetization loop of metallic thin films. Nickel thin films were deposited on intrinsic silicon to form a Schottky contact. Photo-induced Hall voltage was found hysteretic with the in-plane, magnetic field. The measured voltage-loop was found to mimic the magnetization loop as measured by a magnetometer.

Keywords: Anomalous Hall effect; Schottky contacts; Photo-diodes

Introduction

In a thin film, if a current I is made to flow in the film plane and a magnetic field H is applied perpendicular to the film (Fig. 1a), a Hall voltage (V_H) appears that is transverse to both I and H. This voltage is due to Lorentz forces (F) acting on the charge carriers q moving at a velocity v [1]. If the film is magnetic, an extraordinary contribution appears that is proportional to the component of the magnetization M along the z-direction, perpendicular to the film plane, through a constant coefficient R_{AHE} [2], [3]:

$$V_H/I = R_0 H + R_{AHE} M_z \tag{1}$$

where R_0 and R_{AHE} are the ordinary and anomalous (or extraordinary) Hall coefficients, respectively. As early experiments revealed that $R_{AHE} \neq R_0$, it became immediately clear that this extraordinary contribution could not be simply ascribed to additional Lorentz forces exerted by the 'internal' magnetic field M on the charge carriers [4], [5]. It is now fairly understood that the AHE is due to spin-dependent scattering of the charge carriers, which may arise from different scattering mechanisms in different materials [6], [7].

Regardless of the dominant mechanism, the AHE has become a tool for the study of the magnetization loop of magnetic thin films [8], [9]. In fact, the ordinary Hall contribution in Eq. (1) can easily be subtracted because it is linear. Moreover, in thick films, this contribution is negligible, because so is H with respect to M:

$$V_H/I \simeq R_{AHE} M_z \tag{2}$$

As a consequence, the measured voltage will closely follow the magnetization loop when an external field is applied perpendicular to the plane.

This technique is particularly useful for the study of the magnetization process in perpendicularly magnetized films [10]. Instead, if the film plane is the easy-plane of magnetization, the system will develop a strong out-of-plane demagnetization field that cannot be easily calculated and subtracted [11], [12]. Changing the direction of the current from in-plane to out-of-plane would require deposition of metallic electrodes that would short the Hall voltage.

The newly discovered photo-induced Hall effect in metals provides an original way to change the direction of the charge carriers from in-plane to out-of plane, without requiring metallic electrodes [13]. If a metallic film is deposited on a highly-resistive, intrinsic semiconductor to form a Schottky junction, photo-generated carriers can be injected into the metal at high velocity (Fig. 1a). If a magnetic field is applied in the film-plane, a Hall voltage appears that is proportional to the applied field.

Here we show that, if the metal is ferromagnetic, a photo-induced anomalous Hall contribution arises. When the external field is swept in the film-plane, the photo-induced Hall voltage is hysteretic and the loop mimics the magnetization loop as measured by using a standard magnetometer.

Experimental section

The experiment was carried out on three films of nickel (Ni) of thickness t = 10, 30 and 80 nm. The films were deposited by pulsed laser deposition on 1×1 cm2 intrinsic silicon substrates. The silicon was (100)-oriented and had a resistivity higher than 10^3 Ωm. The films were deposited in vacuum and at room temperature from a target of 99.99% pure nickel purchased from Kurt J. Lesker. For the ablation, a pulsed KrF excimer laser (λ = 248 nm) was used with an energy of 300 mJ, a pulse duration of 25 ns and a repetition rate of 10 Hz. The distance between the target and substrate was kept at 4 cm. Both of the target and substrate holder were rotated continuously to ensure uniform deposition of the film.

Electrical contacts to the sample were made by using an aluminum wire bonder. The resistivity of the films was measured to be $\rho_{Ni} = 2.1 \times 10^{-7}$ Ωm by using van der Pauw method. It was not found to be thickness-dependent in the range of thickness used in this work. The magnetic field was applied by using an electromagnet. The open-circuit voltage was measured by using a Keithley nanovoltmeter.

The light source was an optical fiber illuminator emitting non-polarized, white light with a wavelength spectrum ranging from λ = 450 nm (violet) to λ = 750 nm (red). The light was uniformly shed on the sample along the z-direction (see Fig. 1), with the magnetic field applied along the x-direction and the open-circuit voltage measured along y-direction.

Nickel was the material chosen in the experiment for the following reasons: (i) amongst the ferromagnetic metals, it is the one with the highest work function (ϕ_{Ni} = 5.3 eV) and, therefore, it can easily form Schottky contact to intrinsic silicon; (ii) it is well known to show a strong AHE, the strongest amongst the ferromagnetic metals [7]; (iii) it has a relatively high resistivity, which makes it highly transparent to light when deposited in thin films. In fact, light penetration depth in metals is given by:

$$\delta = \sqrt{\rho\lambda/\pi\mu c} \tag{3}$$

where ρ is the resistivity of the metal, c is the speed of light in vacuum and μ is the magnetic permeability, which, at optical frequencies and non-polarized light, can be assumed to be equal to the permeability of vacuum $\mu = \mu 0 = 4\pi \times 10^{-7}$ Hm^{-1}. For an as-measured resistivity $\rho_{Ni} = 2.1 \times 10^{-7}$ Ωm, Eq. (3) yields δ = 8.8 nm for λ = 450 nm nm and δ = 11.3 nm for λ = 750 nm nm.

Results and discussion

Fig. 2 shows the open-circuit voltage measured when a constant magnetic field of intensity $\mu 0H = \pm 100$ mT was applied and a light of intensity I = 4.8 W was shed on the sample. The voltage sign changes with the sign of the applied field, because so do Lorentz forces. The change of voltage is far too fast to be ascribed to slow thermal effects associated with light-induced, temperature gradient, such as spin-Seebeck effects and Nernst effects [14], [15], [16], [17].

The physical origin of the transverse Hall voltage measured in metal/intrinsic-semiconductor extended Schottky contacts has been extensively explained in Ref. [13]. Briefly, light reaching the interface is photo-converted in the semiconductor and electron–hole pairs are photo-generated (see inset Fig. 2). Like in a Schottky photo-diode, the holes cross the interface and, in open-circuit condition, will eventually recombine with the electrons in the metal. Unlike a Schottky photo-diode, the electrons cannot diffuse into the highly-resistive semiconductor and a transient arises in which photo-generated electrons are trapped at the interface. An image potential builds up, which has opposite sign as the Schottky built-in potential V_{bi} and decays with the inverse of the distance from the interface [18]. As a result, a significant rounding-off of the barrier arises with the contact turning from Schottky to ohmic (see light dependent current-voltage characteristics in Ref. [13]). Electrons can now be injected into the metal and replace those that recombined with the holes. At equilibrium, no net current flows along the z-direction (the current of electrons equals the current of holes). If a magnetic field is applied, the charge transfer is not uniform in the x-y plane. As both charge carriers are moving at a certain velocity across the interface, they are subject to Lorentz forces, from which a Hall-voltage arises.

The intensity of the measured voltage decreases more than linearly with the metallic film-thickness, because so does the light intensity at the interface, which decays as ~ $e^{-z/\delta}$ with δ being wavelength dependent (see Eq. (3)). Nevertheless, a voltage could still be elicited and measured for the sample of thickness t =80 nm, i.e. t =7δ at red-wavelengths, before reaching the interface. This proves that the magneto-metric technique we present in the following can work for film-thickness as large as ~ 100 nm if a light source with larger spectrum is employed. Of course, silicon has a band-gap Eg = 1.1 eV, therefore it is transparent to wavelengths $\lambda > 1127$ nm, after which, a larger spectrum will not result in an increase of sensitivity.

While this photo-induced Hall voltage has been proven to be linear with magnetic field for paramagnetic metals, such as platinum and gold [13], an anomalous contribution should arise from spin-dependent scattering in ferromagnetic metals. Therefore we measured the photo-induced voltage in sweeping magnetic field. Fig. 3 shows the normalized voltage for the three films, after subtracting the linear contribution. As expected, the voltage was found to be hysteretic. The coercive field was found to decrease with decreasing film thickness. The coercive field (H_C) of thin magnetic films is expected to decrease as $H_C = H_{C0}(1-t_c/t)^{3/2}$, where H_{C0} is the coercive field of the bulk material and t_c is a critical thickness [19]. For Nickel, t_c is known to be ~ 10 nm and dependent on microstucture and film texture [20], [21].

The relatively large thickness of our thickest sample allowed a direct comparison between the anomalous voltage loop and the magnetization loop measured by using a commercial vibrating sample magnetometer (VSM). The two loops were found to be in good agreement (see Fig. 4). We could not detect any in-plane, crystalline anisotropy by using either techniques. On the other hand, nickel films are known to show in-plane crystalline anisotropy only when grown on (011)-oriented substrates [21], [22].

Conclusion

In conclusion, we have demonstrated a new magneto-metric technique to reconstruct the magnetization loop of thin films with in-plane easy axis. The technique is based on photo-induced anomalous Hall effect, with the carriers being photo-generated in the semiconductor and transferred across the interface perpendicular to the applied field. Like any other magneto-optic technique, such as those based on Kerr effect, it does not allow quantitative measurement of the magnetic moment [23]. Yet, it does not require the use of collimated light, accurate alignment of optical polarizers or expensive light detectors.

Acknowledgement

This study was funded by the Science, Technology and Innovation Commission of Shenzhen Municipality (Project No. JCYJ20170307091130687).

Figures

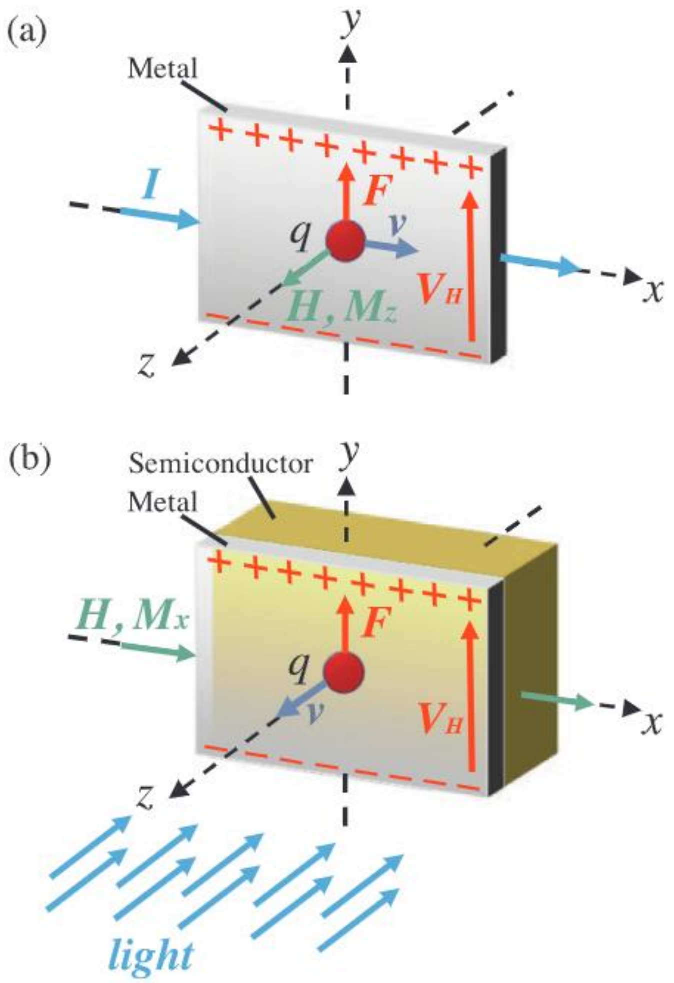

Fig. 1. (a) Hall effect in a thin film; (b) Photo-induced Hall effect in a Schottky photo-diode.

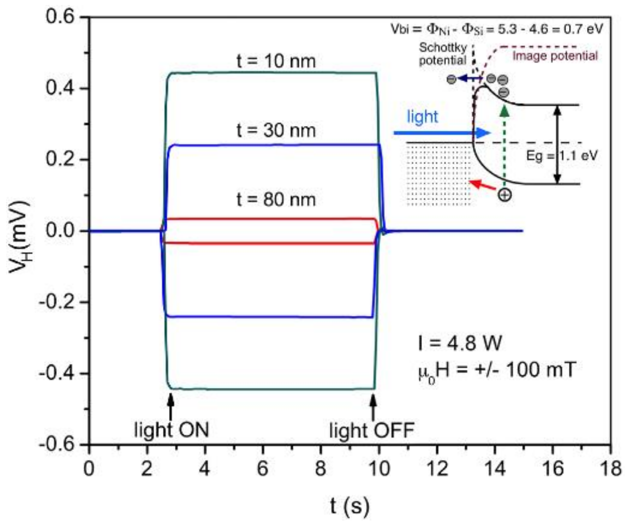

Fig. 2. Voltage *vs* time elicited when exposing the samples to light with intensity *I* = 4.8 W and μ0H = 0.1 T.

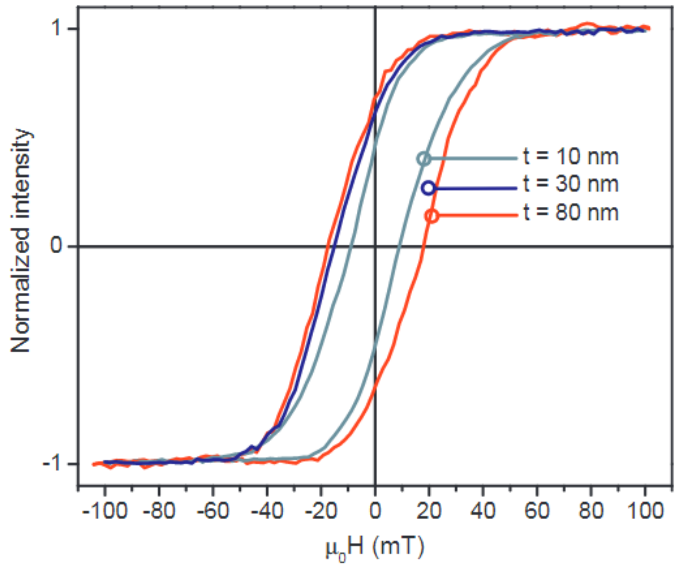

Fig. 3. Normalized, photo-induced anomalous Hall voltage as a function of the sweeping field.

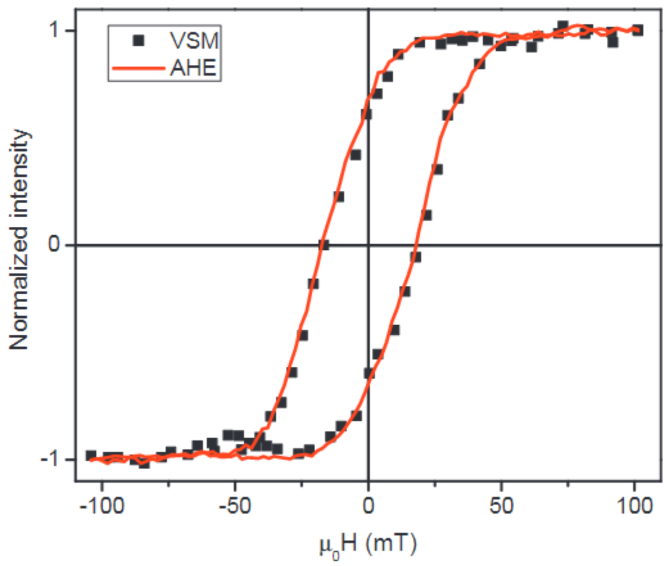

Fig. 4. Comparison between the photo-induced Hall voltage and the magnetization loop as measured by VSM. Both loops were normalized to the respective saturation values for the purpose of comparing the shapes.

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