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Planar Hall effect sensor with magnetostatic compensation layer

B.T. Dalslet [a], M. Donolato [a,b], M.F. Hansen [a,*]

[a] Department of Micro- and Nanotechnology, Technical University of Denmark, DTU Nanotech, Building 345 East, 2800 Kgs. Lyngby, Denmark
[b] L-NESS, Dipartimento di Fisica, Politecnico di Milano, Via Anzani 42, 22100 Como, Italy

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ABSTRACT

Demagnetization effects in cross-shaped planar Hall effect sensors cause inhomogeneous film magnetization and a hysteretic sensor response. Furthermore, when using sensors for detection of magnetic beads, the magnetostatic field from the sensor edges attracts and holds magnetic beads near the sensor edges causing inhomogeneous and non-specific binding of the beads. We show theoretically that adding a compensation magnetic stack beneath the sensor stack and exchange-biasing it antiparallel to the sensor stack, the magnetostatic field is minimized. We show experimentally that the compensation stack removes nonlinear effects from the sensor response, it strongly reduces hysteresis, and it increases the homogeneity of the bead distribution. Finally, it reduces the non-specific binding due to magnetostatic fields allowing us to completely remove beads from the compensated sensor using a water flow 60 times smaller than a flow that failed to remove beads from an uncompensated sensor.

1. Introduction

Magnetic microsensors have many applications [1] and the interest in their use in assays for magnetic detection of biomolecules is growing [2–5]. In some magnetic microsensors (planar Hall effect (PHE) sensors, spin valve sensors, magnetic tunneling junction sensors, etc.) a voltage signal varies as external fields rotate the magnetization of a thin film strip of a ferromagnetic material supporting an electric current. In small sensors or sensors made from magnetically soft materials the demagnetization field of the film can be comparably strong and important for determining the spin directions in the film. Some devices, e.g., spin-valve sensors, use the demagnetization field to define an easy magnetization axis of the sensor [3–5], but for other sensor types demagnetization effects are detrimental, introducing hysteresis and domain formation. Recently, we reported the size-induced effects in exchange-biased PHE sensor crosses and found that strong hysteresis was observed in crosses smaller than a critical dimension [6]. Hence, the miniaturization of some sensor types is prohibited by the demagnetizing effects.

Magnetic microsensors are used for biosensing due to their sensitivity to the magnetic field from magnetic beads present on [5] and near [7,8] the sensor. The direct influence of the magnetostatic field of the sensor on the signal from the beads can be reduced by using an alternating magnetic field for magnetizing the beads [9,10]. However, the magnetostatic field of the sensor also attracts beads to the sensor edges where magnetic charges are present [11]. To ensure reproducible detection, sedimentation and washing conditions and to avoid beads sticking to the sensor edges by magnetic forces rather than biological binding events, the magnetostatic field near the sensor must be minimized.

This study focuses on the $Ni_{80}Fe_{20}$ based PHE sensor crosses used in our group [12,13]. In these sensors an antiferromagnetic film is used to exchange bias the magnetically soft $Ni_{80}Fe_{20}$ film into a single domain with a well defined zero-field magnetization direction. This approach fails when the exchange field is small compared to the demagnetization field, i.e., when the in-plane sensor dimensions are small or when the $Ni_{80}Fe_{20}$ film is thick [6] resulting in hysteresis in the sensor response.

In this work, we demonstrate that both the hysteresis in the sensor response and the attraction of beads to the sensor edges can be strongly reduced when we include a magnetic compensation stack under the sensor stack. The compensation stack is identical to the sensor stack, except that it is exchange-biased in the antiparallel direction. The two stacks are separated by an electrically insulating spacer and when the total stack is structured to form the sensors the magnetizations of the two stacks form a closed magnetic flux loop that significantly reduces the magnetostatic field outside the sensors and the demagnetization field inside the sensors. The effect of the magnetic compensation stack is particularly pronounced for cross-shaped PHE sensors but the approach is also relevant for other sensor types where a large magnetostatic field outside the sensor is undesirable.

* Corresponding author. Tel.: +45 4525 6338.
E-mail address: Mikkel.Hansen@nanotech.dtu.dk (M.F. Hansen).

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2. Theory

2.1. Planar Hall effect sensors

The sensor geometry and the coordinate system and sensor variables are defined in Fig. 1(a). A planar Hall effect sensor consisting of a ferromagnetic $Ni_{80}Fe_{20}$ thin film of width w and thickness t_{FM} carrying a uniformly distributed current in the x-direction $I_x = J_x\, w\, t_{FM}$ will ideally develop the Hall voltage,

$$V_y = t_{FM}^{-1} I_x(\rho_\parallel - \rho_\perp)\cos\theta\sin\theta. \quad (1)$$

where $\rho_\parallel$ and $\rho_\perp$ are the resistivities parallel and perpendicular to the magnetization direction, respectively, and θ is the angle between the magnetization and the x-direction.

The sensors are exchange-biased in the positive x-direction ($\theta = 0$). The x-axis is also the easy axis of the crystal anisotropy. In [6] we have shown that the central part of a planar Hall effect sensor cross essentially remains a single domain when the cross dimension is reduced, but that the demagnetization effects favor magnetization orientations of the central part of the cross with $\theta = \pi/4 + n\pi/2, n = 1, 2, 3, 4$. The value of θ is estimated by minimizing the normalized energy density, u, given by

$$u = -H_{ex}\cos\theta - \frac{1}{2}H_K\cos^2\theta - \frac{1}{8}H_{ms}\cos^2(2\theta) - H_y\sin\theta \quad (2)$$

where H_y is an external magnetic field applied in the y-direction, H_{ex} is the exchange bias field, H_K is the anisotropy field and H_{ms} is a field representing the demagnetization effects [6].

Minimizing u in Eq. (2) to obtain θ and inserting the result in Eq. (1) yields V_y as function of H_y. For small values of H_y, V_y can be written

$$V_y = I_x S_0 \langle H_y \rangle \quad (3)$$

where $S_0 \approx (\rho_\parallel - \rho_\perp)/[t_{FM} \cdot (H_{ex} + H_K - H_{ms})]$ is the low-field sensitivity and $\langle H_y \rangle$ is the average y-component of the magnetic field acting on the active sensor area [6].

In this study V_y is recorded using lock-in detection using a sinusoidal current $I_x(t) = I_{x,0}\sin(\omega t)$. When measuring the sensor signal as function of a constant external field, we use the first harmonic in-phase component V_1', given by [10]

$$V_1' = 2^{-1/2} t_{FM}^{-1} I_{x,0}(\rho_\parallel - \rho_\perp)\cos\theta\sin\theta \quad (4)$$

When detecting beads we use the magnetic field caused by $I_x(t)$ (the self-field) to magnetize the beads. The field on the sensor from the beads can then be observed in the second harmonic out-of-phase component V_2'' of V_y given by

$$V_2'' = -2^{-3/2} I_{x,0}^2 S_0(\gamma_0 + \gamma_1) \quad (5)$$

where γ_0 is a geometry-dependent constant that accounts for the self-field on the sensor from current shunting in the antiferromagnetic layer, and γ_1 accounts for the contribution from the beads ($\gamma_1 = 0$ when no beads are present) [10,11].

2.2. Forces on a bead

In this section, we calculate the magnetic force on a bead due to the magnetostatic field from the sensors. This force is largest near the edges of the y-axis arms of the cross-shaped sensor. We get an upper estimate of the force by calculating it for an infinitely long strip along the y-axis of width w and thickness t_{FM}, which is uniformly magnetized in the x-direction with a magnetization $\mathbf{M} = M\hat{\mathbf{x}}$. Representing the magnetization as the bound surface currents with density $\mathbf{K}_b = \mathbf{M} \times \mathbf{n}$, where $\mathbf{n}$ is an outwards facing normal vector to the surface, we obtain $\mathbf{K}_b = \pm M\hat{\mathbf{y}}$ for the faces parallel to the xy-plane and $\mathbf{K}_b = \mathbf{0}$ elsewhere. The magnetic flux density at any point $\mathbf{r}$ can then be calculated from the Biot-Savart law as

$$\mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi}\int \frac{\mathbf{K}_b(\mathbf{r}') \times (\mathbf{r} - \mathbf{r}')}{(\mathbf{r} - \mathbf{r}')^{3/2}} da', \quad (6)$$

where μ_0 is the permeability of free space, $\mathbf{r}'$ is the position of the infinitesimal area da' and the integral is over the entire surface of the strip. Assuming that a magnetic bead has a magnetization proportional to the magnetic field in the absence of the bead, i.e., $\mathbf{M} = \chi\mu_0^{-1}\mathbf{B}$, where χ is the effective bead susceptibility, and that the magnetic force varies little over the size of the bead, we can calculate the magnetic force on the bead as [14]

$$\mathbf{F}_{mag} \simeq \frac{\pi D^3 \chi}{12\mu_0}\nabla\left(\mathbf{B}^2\right), \quad (7)$$

Here D is the diameter of the bead and $\mathbf{B}$ is given by Eq. (6).

Another force on the bead is the buoyancy force, $\mathbf{F}_{bouy}$ given by:

$$\mathbf{F}_{bouy} = -\hat{\mathbf{z}}g\frac{\pi}{6}D^3(\varrho_b - \varrho_f) \quad (8)$$

where $g = 9.82\ m/s^2$ is the magnitude of the gravitational acceleration and ϱ_b and ϱ_f are the densities of the bead and the fluid, respectively. For the beads used in this study with $\varrho_b = 2.5 \times 10^3\ kg/m^3$ and $D = 250$ nm, the buoyancy force in water is 0.12 fN.

To assess the importance of Brownian motion of the beads we follow the considerations of Friedman and Yellen [15]. When the thermal energy $k_B T$, where k_B is Boltzmann's constant, is low compared to the work $F_{ext}D$ performed by the external force F_{ext} to move the bead a single bead diameter, it is reasonable to use a deterministic description of the bead trajectories. In the other limit, the bead suspension is better described in terms of a statistical bead distribution function. The criterion $k_B T = F_{ext}D$ can be rewritten to define a 'Brownian force' $F_{Brown} = k_B T/D$. When $F_{ext} \ll F_{Brown}$ the trajectories of single beads will be strongly perturbed by Brownian motion and a distribution description is adequate and when $F_{ext} \gg F_{Brown}$ the influence of Brownian motion on the bead trajectory is negligible and a deterministic description can be used. For the beads used in the present study, we calculate $F_{Brown} = 16$ fN. Hence, we obtain $F_{Brown}/F_{bouy} = 136$ showing that a deterministic description of the sedimentation of these beads will be inadequate if no magnetic forces are affecting them. Including magnetic forces we require that $F_{mag}/F_{Brown} \gtrsim 1$, i.e., $F_{mag}/F_{buoy} \gtrsim 10^2$ for the beads to follow deterministic trajectories. It should be noted that this ratio depends strongly on the bead diameter as it scales with D^4.

Finally, it is relevant to consider the tension on a molecular tether attaching a bead to the top of the sensor surface when a fluid is flowing in the channel. The fluid velocity along the channel can be written $v_x(y_c, z_c)$, where (y_c, z_c) denotes the coordinate in the cross-section of the channel of width w_c and height h_c with its center at $(y_c, z_c) = (0, h_c/2)$. An exact analytical expression for $v_x(y_c, z_c)$ can, e.g., be found in [16]. The channel in the present study has $w_c = 0.4$ mm and $h_c = 1$ mm. For a fluid flow driven at the flow rate $Q = 1$ mL/h we find an average fluid flow velocity of $v_x = Q/(w_c h_c) = 0.69$ mm/s. Using the exact theoretical result for $v_x(y_c, z_c)$, we calculate the fluid shear rate, S, at the sensor at the same flow rate to $S = (\partial v_x/\partial z)_{(y_c,z_c)=(0,0)} = 10\ s^{-1}$. Values of these parameters for other fluid flow rates can be obtained by multiplying these numbers with the value of Q in mL/h. The drag force, F_D and torque, τ_D on a stationary spherical bead in contact with the floor of the fluid channel is [17]:

$$F_D = 8.01\eta S D^2, \qquad \tau_D = 0.185 D F_D, \quad (9)$$

where η is the viscosity (≈0.9 mPa s at $T = 298$ K). For $S = 10\ s^{-1}$ and $D = 250$ nm we get $F_D = 4.6$ fN and $\tau_D = 2.1 \times 10^{-22}$ N m. Using the method of Chang and Hammer [18] we calculate the tension T on