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Micro-magnetometry for susceptibility measurement of superparamagnetic single bead

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ABSTRACT

We have fabricated a micro-planar Hall resistive (PHR) sensor consisting of a thin magnetic multilayer structure, and characterized the magnetic susceptibility of a single superparamagnetic bead (Dynabeads® M-280 of 2.8 μm). The sensor arm length with an active sensing junction of 3 μm × 3 μm was optimized using a finite element method (FEM) simulation to minimize its induced field effect over the junction area under an applied field, and the field sensitivity of the fabricated 7 μm arm length sensor was measured to be 0.075 μV/A m^{-1} (6.0 μV/Oe) in the low field region. An average voltage change of 7.6 μV with a standard deviation of 0.26 μV was observed in the sensor during the repeated bead droplet-washing procedure. The magnetic susceptibility of a single bead was calculated to be 0.65 (SI), which agreed with the measured susceptibility by a SQUID magnetometer. This novel approach provides an inexpensive micro-magnetometry method for measuring the magnetic susceptibility of magnetic micro-sized objects, which is applicable in widespread laboratories.

1. Introduction

Since the last decade, superparamagnetic beads have been playing an important role as labels of unknown biomolecules in magnetic based lab-on-a-chip bioassays for bio-detection [1–5], cell sorting and separation [6–10], and biomolecule translocation [11–14] in a liquid medium. The magnetic properties of individual single superparamagnetic beads, such as their magnetic susceptibility, field dependence, and saturation magnetization, are the crucial parameters in the performance of magnetic based bioassays, since the magnetic characteristics of individual bio-functionalized beads dominate the sensor's resolution and translocation capability [15]. Conventionally the magnetic properties of the superparamagnetic beads have been characterized by typical magnetic measurement instruments, i.e., the vibrating sample magnetometer (VSM) [16,17] and the superconducting quantum interference device (SQUID) [18]. In these instruments, an ensemble of bead clusters, typically a ∼100 μg sample, is required for evaluation of the magnetic properties, instead of a single bead in a liquid medium.

Usually, a bead is made of superparamagnetic nanoparticles, typically Fe_3O_4 or γ-Fe_2O_3 dispersed in a spherical polymer matrix, and produces a stray field over a range of a few micrometers under the applied magnetic field. Because a field is induced by a magnetic material under an applied field, such as a sensor element, the total effective field on a bead placed near the sensor element is the vector sum of the applied and induced fields. In previous reports, the analysis of the stray field effect on the voltage change of a sensor in terms of its size, bead diameter and magnetic susceptibility [19,20] was studied without considering the induced field effect by the sensor element.

The field dependent magnetic susceptibility of a single superparamagnetic bead of 1.2 μm in diameter has been evaluated by employing a micro-sized semiconductor Hall sensor, of which the sensor element does not produce an induced field [21]. The susceptibility of a single bead in the low field region has been formulated by the Langevin function, and its value was obtained by fitting a curve to the measured Hall voltage versus applied field, with the fitting parameters being the distribution median and the width of the constituent magnetic nanoparticles. This is a specific approach rather than a universal method for the evaluation of magnetic susceptibility because of the successive fitting approximation of the parameters.

In this study, we optimized the dimensions of a sensor element in order to minimize its induced field effect on a bead, and fabricated a micro-planar Hall resistive (PHR) sensor using a thin magnetic multilayer structure consisting of Ta (5 nm)/NiFe (6 nm)/Cu (3 nm)/NiFe (3 nm)/IrMn (10 nm)/Ta (5 nm). In the PHR sensor, a magnetic field is applied in the plane of the sensor surface, causing anisotropic scattering of the electrons carrying the

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current due to the magnetic moment of the lattice atoms, which is different from the Hall effect in the semiconductor caused by the Lorentz force interaction between electrons moving in a perpendicular magnetic field. The magnetic susceptibility of a single bead (Dynabeads® M-280 of 2.8 μm) was characterized by using the experimentally measured parameters of the fabricated sensor itself and compared with the value obtained by SQUID. The outcome of this investigation provides an inexpensive micro-magnetometry method for measuring the magnetic susceptibility of magnetic micro-sized objects.

2. Modeling of single bead susceptibility

The origin of the PHR effect in thin film magnetic materials is accounted for by the existence of spin–orbit and anisotropic scattering of s- and d-electrons [22]. But its phenomenological description relies on the magnetization being affected by the external magnetic field. Fig. 1 shows a schematic of the sensor's parameters with a typical active junction area of 3 μm × 3 μm (width $w_x = w_y = 3$ μm). The magnetization of the sensor element with the exchange coupling field is assumed to be a single domain in the y-direction, as shown in Fig. 1. With the magnetization deviated from the current due to the x-component of the applied field, the voltage due to the PHR effect is given as follows [23–25]:

$$V(H) = \frac{I(\rho_\parallel - \rho_\perp)l_y}{w_x \cdot t} \sin\phi \cdot \cos\phi = V_o \sin\phi \cdot \cos\phi \quad (1)$$

Here, I is the applied current in the y-direction, while $\rho_\parallel$ and $\rho_\perp$ are the resistivities of the current parallel and perpendicular to the magnetization, respectively. The sensor is sensitive to the x-axis field, however, the effect of the z-component is negligible due to the large demagnetizing effect in the z-direction. The parameters l_y, w_x, t are the length along the y-axis, width along the x-axis and the thickness of the sensor elements, respectively. Finally, ϕ is the angle between current and magnetization $\vec{M}$, and V_o is a constant including the material parameters of the sensor element and the current I.

When the applied field H is relatively smaller than the exchange coupling field H_{ex}, the relationship between the angle ϕ and the applied field in the x-direction is approximated by the sine function, and the voltage is written as follows:

$$V(H) = V_o h\sqrt{1-h^2}, \quad \text{for} \quad \sin\phi \cong \frac{H}{H_{ex}} \equiv h \quad (2)$$

It is noted that the PHR voltage is given as a function of the normalized applied field, h, which is the field applied in the x-direction divided by the exchange field, H_{ex}. The apparent field sensitivity,

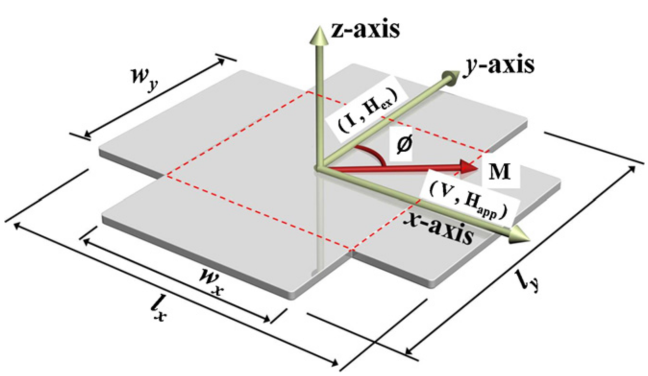

Fig. 1. A schematic diagram of the sensor's parameters with typical width $w_x = w_y = 3$ μm and arm length $l_x = l_y$.

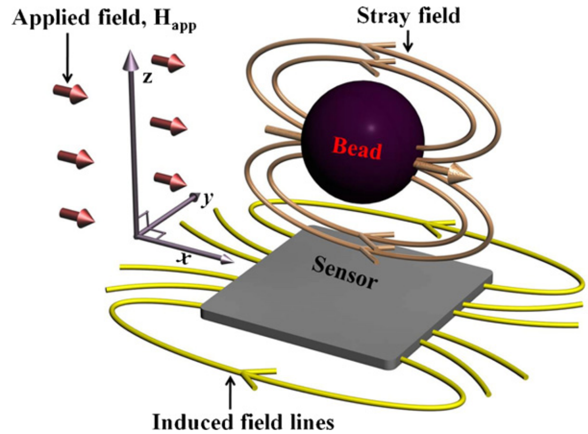

Fig. 2. A schematic illustration of the induced fields by sensor and stray fields by bead under an applied magnetic field.

S is given by the differential of the voltage by the applied field as follows:

$$S = \frac{dV}{dH} = V_o \frac{1-2h^2}{H_{ex}\sqrt{1-h^2}} \cong \frac{V_o}{H_{ex}}\left(1 - \frac{3}{2}h^2\right) \quad (3)$$

When a magnetic sensor element is exposed to the external field, the element is magnetized and in turn produces an "induced field" as depicted in Fig. 2. Then, the total effective field near the sensor element becomes the vector sum of the applied and induced fields. It is not easy to formulate the induced field from sensor element as it strongly depends on the size and shape of the element. Therefore, we have used an FEM simulation to estimate the total effective field.

While the superparamagnetic bead (or magnetic nanoparticle) is not subjected to an external magnetic field, there is no stray field because the spins are randomly oriented. With the applied field, a 3-dimensional stray field, ΔH_{stray}, is generated from the superparamagnetic bead due to the alignment of the spins through the applied field. However, the sensor is sensitive only to the in-plane field [26,27] in the opposite direction [19,28] to the applied field. The in-plane field in turn causes a voltage change in the magnetic sensor as follows [28]:

$$\Delta V = S \cdot \Delta H_{stray}, \quad \text{with } \Delta H_{stray} = -\frac{\chi_V V_{bead}}{4\pi z^3} H_{eff} \quad (4)$$

Here, χ_V is the susceptibility of a bead, V_{bead} is the volume of a bead and z is the distance between the sensor and bead in SI units. The effective field H_{eff} is equal to the applied field when there is no magnetic material near the bead.

The bead placed near the sensor element experiences the applied field as well as the induced field. Because the stray field due to the bead causes a voltage change, the bead susceptibility in SI units can be deduced from Eq. (4) as follows:

$$\chi_V = \frac{1}{S}\frac{\Delta V}{H_{eff}}\bigg|_{H_{app}} \frac{4\pi z^3}{V_{bead}} \quad (5)$$

Here, sensitivity, S, can be obtained from the voltage profile of a fabricated sensor. Moreover, the induced field should be taken into account for the estimation of the magnetic susceptibility of the bead, affecting the effective field. From the point of view of practical applications, however, it is desirable to optimize the sensor's element to minimize the sensor's induced field effect on the bead, i.e., so that it gives the same effective field value as the applied field.