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Optimization of magnetoresistive sensor current for on-chip magnetic bead detection using the sensor self-field

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ABSTRACT

We investigate the self-heating of magnetoresistive sensors used for measurements on magnetic beads in magnetic biosensors. The signal from magnetic beads magnetized by the field due to the sensor bias current is proportional to the bias current squared. Therefore, we aim to maximize the bias current while limiting the sensor self-heating. We systematically characterize and model the Joule heating of magnetoresistive sensors with different sensor geometries and stack compositions. The sensor heating is determined using the increase of the sensor resistance as function of the bias current. The measured temperature increase is in good agreement with a finite element model and a simple analytical thermal model. The heat conductance of our system is limited by the 1 μm thick electrically insulating silicon dioxide layer between the sensor stack and the underlying silicon wafer, thus the heat conductance is proportional to the sensor area and inversely proportional to the oxide thickness. This simple heat conductance determines the relationship between bias current and sensor temperature, and we show that 25 μm wide sensor on a 1 μm oxide can sustain a bias current of 30 mA for an allowed temperature increase of 5 °C. The method and models used are generally applicable for thin film sensor systems. Further, the consequences for biosensor applications of the present sensor designs and the impact on future sensor designs are discussed.

1. Introduction

In recent years magnetic beads have become a viable alternative to fluorescent labels for both diagnostics and research purposes [1]. Magnetic beads are most often used in a sandwich assay, replacing fluorescent tags, such that the presence of the biological analyte can be detected indirectly via the magnetic field from the magnetic beads attached to the sensor surface. This magnetic field can be detected by magnetoresistive (MR) sensors [2–5]. We have previously demonstrated the use of planar Hall effect bridge (PHEB) sensors in a magnetic bead-based readout for on-chip DNA detection using both volume- and surface-based detection schemes [6–8]. In these studies, the magnetic beads were magnetized by the field arising from the sensor bias current. This eliminates the need for external electromagnets and ensures that the signal from a magnetic bead is positive for all bead positions with respect to the sensor [9].

For both surface- and volume-based detection the signal is proportional to the current squared. Therefore, a higher current means a higher signal and thereby a higher sensitivity assuming that the signal-to-noise ratio is limited by the noise of the readout electronics. However, high currents can cause a breakdown of the sensors due to failure of the sensor coating and will lead to increased Joule heating. Thus, it is of general interest to known the maximum current that can be used without affecting the experiment.

In this paper, we present a systematic study of the self-heating of PHEB magnetoresistive sensors in order to maximize the signal from magnetic beads. We first characterize the temperature dependence of the sensor bridge resistance. This knowledge is used to determine the sensor temperature increase due to Joule heating as function of the sensor bias current. The relation between sensor temperature and bias current is compared to two simplified analytical models as well as a finite element model of the heat transport through the underlying silicon wafer. The simple models are found to be in good agreement with the data and consequences for applications and future designs are discussed. As the models are generally applicable, they can be used to give an estimate of the expected heating from any current and any sensor geometry. These results are relevant for the application of magnetoresistive sensors for characterization of magnetic beads as well as for biodetection applications.

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2. Theory

2.1. Planar Hall effect bridge sensors

The sensors are based on the anisotropic magnetoresistance of permalloy ($Ni_{80}Fe_{20}$) and are designed in a Wheatstone bridge geometry with four sensor stripes, each having a width w and length l as illustrated in Fig. 1. The sensor stack, also given in Fig. 1, is exchange-pinned along the x-direction using $Mn_{80}Ir_{20}$ to define a unique magnetization orientation in zero applied magnetic field. The sensor bridge is biased using a current I_x applied along the x-direction. The bridge resistance R is obtained from the voltage drop V_x measured along the x-direction as $R = V_x/I_x$. When used for sensing of magnetic fields, the planar Hall effect signal V_y can be written as [10]

$$V_y = S_0 I_x H_y, \tag{1}$$

where S_0 is the low-field sensitivity and H_y is the average magnetic field experienced by the sensor in the y-direction. In the presence of magnetic beads that show a linear magnetic field response and in zero externally applied magnetic field, this field can be written as $H_y = \gamma I_x$, where γ depends on the sensor stack and geometry, the amount and distribution of magnetic beads near the sensor surface and the magnetic bead properties [6,9]. Thus, the sensor signal due to magnetic beads can be written as

$$V_y = S_0 \gamma I_x^2, \tag{2}$$

where it is noted that this signal is proportional to $I_x{}^2$.

2.2. Sensor self-heating

For a moderate temperature change, the bridge resistance depends linearly on the temperature T:

$$R(T) = R_0(1 + \alpha(T - T_0)) \tag{3}$$

where R_0 is the resistance at $T = T_0$ and α is the temperature coefficient.

The Joule heating in the PHEB sensor due to the applied sensor current is

$$P_{heating} = R(I_x) I_x^2 \tag{4}$$

where we have explicitly written the bias current dependence of the bridge resistance.

The heat transportation through a material due to a temperature difference $\Delta T = T - T_0$ with respect to the surroundings is

$$P_{dissipation} = G_{eff}\Delta T \tag{5}$$

where G_{eff} is the effective thermal conductance. In equilibrium, the dissipated power must equal the Joule heating and thus the resistance and temperature difference are given by

$$R(I_x) = \frac{R_0}{1 - \alpha R_0 I_x^2 / G_{eff}} \tag{6}$$

$$\Delta T = \frac{1}{\frac{G_{eff}}{R_0 I_x^2} - \alpha}. \tag{7}$$

For the sensor stack in Fig. 1, we expect that heat dissipation through the silicon dioxide beneath the sensor stack will be the dominating pathway for heat dissipation as the oxide is thin and silicon is a good thermal conductor. Because the thickness of the SiO_2 layer is much smaller than the sensor width, we expect the heat-flow to be approximately vertical through the SiO_2 under the sensor. In this case the heat conductance is given by

$$G_{SiO_2} = \kappa_{SiO_2}(4wl)/t_{SiO_2}. \tag{8}$$

where κ_{SiO_2} is the thermal conductivity (bulk value $\kappa_{SiO_2} = 1.4\ \mathrm{W/(m\ ^\circ C)}$) and t_{SiO_2} is the thickness of the silicon dioxide.

We further expand the model to also include the silicon wafer in the heat network. The width of the resistor elements is small compared to the wafer thickness, and we can therefore approximate them in a thermal calculation on the wafer cross-section as a point source. Moreover, we assume heat to flow radially away from the sensor resistor into the wafer. This radial heat flow can be approximated as heat conductance through a cylinder shell running along the resistor with inner radius $r_{inner} = w/2$ and outer radius $r_{outer} = t_{wafer}$, see Fig. 3 for an illustration. Including this approximation, the combined heat conductance is

$$G_{Si+SiO_2}^{-1} = \frac{t_{SiO_2}}{\kappa_{SiO_2}(4wl)} + \frac{\ln(2t_{wafer}/w)}{\kappa_{Si}\pi 4l}, \tag{9}$$

where κ_{Si} is the thermal conductivity of silicon (bulk value $\kappa_{Si} = 149\ \mathrm{W/(m\ ^\circ C)}$).

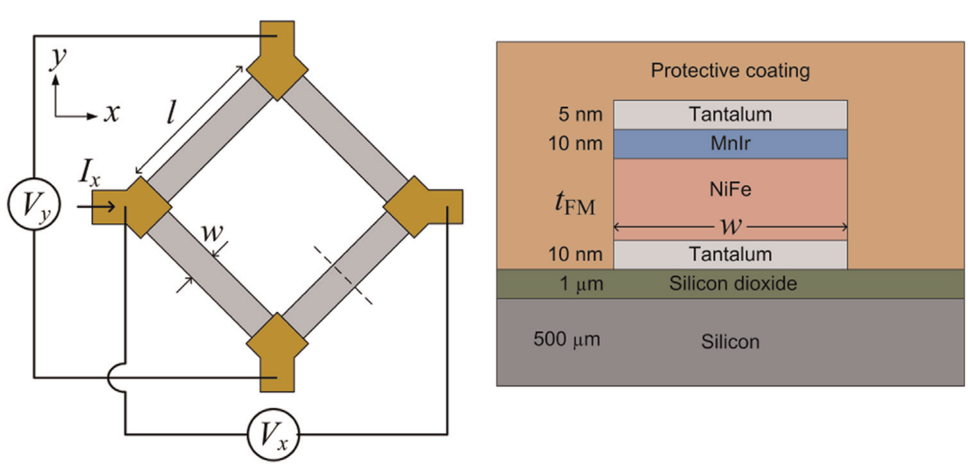

Fig. 1. Illustration of the sensor geometry and the sensor stack with definitions of geometrical and electrical parameters. The right panel shows a cross-section of a sensor arm (shown by the dashed line in the left panel). In the present study, we have used t_{FM} = 10, 20 or 30 nm.