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Review

Exploiting magnetic sensing capabilities of Short Split-Drain MAGFETs

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ABSTRACT

The magnetic sensing capabilities of Split-Drain MAGFETs (SD-MAGFETs) with a channel that is a short Hall plate, herein called Short Split-Drain MAGFETs, are analyzed. In addition to the current-lines deflection effect, this paper shows that the magnetoresistance effect also contributes to establish the sensitivity of Short SD-MAGFETs. A relationship between the forces acting on the deflection direction and a model of the Hall angle are developed showing that these effects are favored notoriously when $L/W \leqslant 0.27$. Furthermore, the magnetoresistance effect improves the sensitivity when the channel length is reduced. This allows to design a high-sensitivity SD-MAGFET with a reduced active area. Using the proposed model of the Hall angle with a continuous model of the geometric correction factor, a continuous variation of the Hall angle along the channel for any L/W can be obtained, and a quantitative criterion to establish which range of the L/W values corresponds to a short Hall plate and which one to a long Hall plate can be established. In order to validate the proposed design criteria, a Short SD-MAGFET with $L/W = 0.2$ and $W/L = 10\ \mu m/2\ \mu m$ has been characterized. Sensing capabilities from 90 μT to 27 μT and sensitivities from 15.51% to 59.9% have been experimentally obtained at room temperature and in strong inversion.

Contents

1. Introduction

A Split-Drain MAGFET (SD-MAGFET) is a MOSFET structure able to convert a Magnetic Flux Density (MFD) to a drain current imbalance using galvanomagnetic effects [1,2]. SD-MAGFETs are attractive sensors due to their compatibility with standard CMOS processes and their good linearity with MFD [1,2]. SD-MAGFETs manufactured in standard CMOS processes even with non-rectangular structures [3–10] have achieved sensitivities <10% at room temperature. Analyses of SD-MAGFETs, until now, have considered just the current-lines deflection effect, nevertheless, being its channel a split-contact Hall plate, the current-lines deflection effect [5,11] and the magnetoresistance effect [12,13,11] establish the drain current imbalance and, thus, the sensitivity.

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The SD-MAGFET sensitivity depends on the channel geometry and the bias conditions [14,5–7]. Until now, reported SD-MAGFETs have been optimized considering the ratio between the channel length, L, and channel width, W, of $L/W \geqslant 1$, being L as large as possible [4–7,15–17,8,18]. On the other hand, most of SD-MAGFETs have been characterized with MFDs of units of mT or above [5–7,15,8,18], and some ones with MFDs from hundreds of μT and above [4,19–21].

SD-MAGFETs have been proposed for several applications such as controlling the volume in hearing aids [22], reading magnetically stored information directly [4], developing an IDDQ testing scheme [23,24], monitoring voltage drops in supply lines [25], or monitoring signal integrity [21]. In all these cases, it is desirable to have SD-MAGFETs with a reduced active area in order to be able to use several of these devices in a single chip.

This work investigates the feasibility of using Short SD-MAGFETs, with $L/W < 1$, fully compatible with standard CMOS technology, for sensing MFDs as small as 90 μT. The key to do this is to establish the geometric conditions to favor both the current-lines deflection and the magnetoresistance effects. These effects become more important when the Hall angle increases [1,2].

The rest of this paper is organized as follows: in Section 2, the parameters to characterize MAGFET performance are presented. In Section 3, analytical expressions are developed to establish those L/W ratios that favor the current-lines deflection effect and the magnetoresistance effect. Section 4 shows the design issues of the fabricated Short Split-Drain MAGFET. Section 5 shows the methodology to estimate the magnitude of the MFD experimentally applied. Section 6 shows the followed experimental methodology. In Section 7, the experimental results are presented and discussed. Finally, the conclusions are summarized in Section 8.

2. Performance of a Split-Drain MAGFET

The sensitivity, S, of a SD-MAGFET is defined by Eq. (1). I_{D2} and I_{D1} are the currents in each drain, $I_{D2} - I_{D1}$ is the drain current imbalance denoted as ΔI_D, $I_{D1} + I_{D2}$ is the total drain current and B_z is the intensity of the MFD normal to the channel plane.

$$S = \frac{|I_{D2} - I_{D1}|}{(I_{D1} + I_{D2})B_z} = \frac{|\Delta I_D|}{(I_{D1} + I_{D2})B_z} \tag{1}$$

The output signal of a SD-MAGFET is the drain current imbalance which has a good linearity with the MFD. In this work, both the sensitivity and the drain current imbalance are used to characterize the performance of the proposed Short SD-MAGFET.

Some SD-MAGFETs [3–5] have been characterized using a constant current source connected serially between source and V_{SS} to establish the total drain current. Under this scheme, for certain gate and drain voltages, different source voltages are produced for different W/L ratios. In this work, in order to eliminate the V_{GS} variation, the total drain current is established by the gate and drain voltages and the channel geometry. This scheme allows to compare the results for different geometry MAGFETs at the same bias conditions.

3. Improving sensing capability of a Split-Drain MAGFET

When a n-type Hall plate driving a current $\vec{I}$ is immersed in a magnetic flux density, $\vec{B}_z$, normal to its plane, a bias electric force, $\vec{F}_e$, a Hall electric force, $\vec{F}_{Hn}$, and the magnetic part of the Lorentz force, $\vec{F}_{Lm}$ (see Eq. (2)), act on each carrier with a charge $-q$ moving with a drift velocity $\vec{v}_{dn}$ (see Fig. 1). Where q is the elementary charge.

$$\vec{F}_{Lm} = -q\left[\vec{v}_{dn} \times \vec{B}_z\right] \tag{2}$$

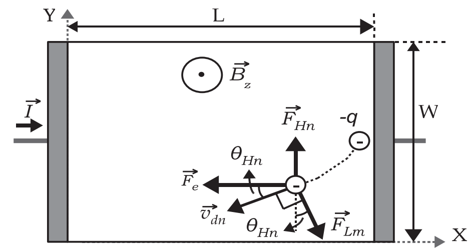

Fig. 1. Forces acting on a carrier and the Hall angle in n-type Hall plate.

Since $\vec{F}_{Lmy}$ is the component of $\vec{F}_{Lm}$ in the deflection direction, if the magnitude of the resulting force in the deflection direction, $\vec{F}_{Lmy} - \vec{F}_{Hn}$, increases, the Hall angle increases, and, thus, the current-lines deflection and the magnetoresistance effects are favored. Because of this, the geometric conditions to increase the Hall angle are analyzed.

3.1. Forces acting on the deflection direction

The geometry effect is introduced through the geometric correction factor, G, which varies along a Hall plate. G is defined as the ratio between the Hall voltage obtained by action of F_{Hn} in a real Hall plate, V_{Hn}, and one, $V_{H\infty}$, obtained in an ideal Hall plate where $F_{Hn} = F_{Lmy}$ along a Hall plate [2,5]. Then, if W is the width of the Hall plate, G can be expressed as:

$$G(x) = \frac{V_{Hn}(x)}{V_{H\infty}} = \frac{W \cdot F_{Hn}/(-q)}{W \cdot F_{Lmy}/(-q)} = \frac{F_{Hn}}{F_{Lmy}} \tag{3}$$

From Eq. (3), when the L/W ratio decreases, the F_{Hn}/F_{Lmy} ratio decreases [5], and, therefore, the magnitude of the resulting force in the deflection direction increases.

3.2. Continuous model of the Hall angle

The deflection angle of the current lines with respect to the longitudinal direction, the Hall angle, θ_{Hn}, is established by the forces acting on carriers (see Fig. 1). According to the reported expression for θ_{Hn} given in [1,2], $\theta_{Hn} < 3°$ for $B_z \leqslant 1$ T with $\mu_n \leqslant 500$ cm^2/V s. Therefore, the longitudinal component of $\vec{F}_{Lm}$ can be neglected. Then, using Eq. (3), the Hall angle can be defined as:

$$\tan\theta_{Hn} = \frac{F_{Lmy} - F_{Hn}}{F_e} = (1 - G(x))\frac{F_{Lmy}}{F_e} \tag{4}$$

Using Eq. (2) and Fig. 1, $F_{Lmy} = q\, v_{dn} B_z \cos\theta_{Hn}.\vec{F}_e$ is generated by the bias electric field, $\vec{E}_e, (\vec{F}_e = -q\vec{E}_e)$ that can be related to the x-component of the drift velocity as $\vec{E}_e = -\vec{v}_{dnx}/\mu_{Hn}$. Where $\mu_{Hn} = r_{Hn} \cdot \mu_n$ is the Hall mobility, r_{Hn} is the Hall scattering factor and μ_n is the carrier mobility. Then, according to Fig. 1 and using the previous definitions, F_e can be expressed as $F_e = q\, v_{dn} \cos\theta_{Hn}/\mu_{Hn}$. Replacing the previous expressions of F_e and F_{Lmy} in Eq. (4), the Hall angle is defined as:

$$\tan\theta_{Hn} = (1 - G(x))\mu_{Hn} B_z \tag{5}$$

Eq. (3) is coherent with Eq. (5). When the L/W ratio decreases, the F_{Hn}/F_{Lmy} ratio also decreases (see Eq. (3)) which means that the magnitude of the resulting force acting on each carrier in the deflection sense increases, and hence, the magnitude of θ_{Hn} increases (see Eq. (5)).

Using the continuous model of G reported in [5], Eq. (5) is a continuous model of the Hall angle at L/W and all along the channel length. This is a significant improvement with respect to the model reported in the literature [1,2] since the proposed model allows to analyze the impact of the channel geometry on the deflection