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An accurate compact model for CMOS cross-shaped Hall effect sensors

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The paper describes a new design-oriented compact model for horizontal Hall effect devices. This model is based on the physics of semi-conductor and is simplified according to some assumptions verified through experimental results and/or numerical simulations. Compared to existing models, it has the advantage to take most of the first-order effects into account while allowing fast simulations. A procedure to extract the parameters of the model is given and simulation results are compared to experimental data measured on a cross-shaped sensor designed in a standard 0.35 μm CMOS technology. The maximum error between simulation results and experimental data is less than 1%.

1. Introduction

The potential application range of CMOS integrated Hall effect magnetic sensors is large [1]. Such sensors provide low-cost solutions to measure a wide range of magnetic fields (from roughly 1 mT to 10 T) with a medium resolution (up to about 10 μT) [2]. They are, for instance, already widely used in the fields of medicine or automotive [3–8].

For those applications, the sensor is generally integrated, i.e. the sensing element (Hall device), the biasing electronics and the signal processing circuits are designed in a single chip [3]. However, the design of such a system remains a challenge when the sensing element is not included in the design-kit provided by the chip manufacturer. In order to reduce the design time as well as to improve the performances and the reliability of the whole system, the designer needs for a mathematical model suitable for circuit simulation.

To our knowledge, existing models of Hall effect sensor devices are either too complex [9] or too idealized [10]. For example, 2D or 3D physical models simulated thanks to FEM-like simulators need too long computation times to be coupled to a circuit simulator such as SPICE [9,11]. The simulation of the whole circuit at this level of abstraction would lead to huge computation times which is not acceptable in a design process. Nevertheless, such a modeling technique can be very useful to analyze the influence of the geometrical or technological parameters on the sensor behavior. Non-idealities and second order effects may be deeply investigated thanks to device simulators [9].

However, to achieve accurate simulations of Hall sensor based integrated systems, the electronic designer needs for an accurate while simple compact model similar to conventional electronic device compact models. Such a compact model must describe the behavior of the sensor thanks to a reduced equations set obtained through adequate assumptions and simplifications. Many different approaches have already been used to develop such Hall effect sensor compact models.

Jovanovic et al. used a purely mathematical approach consisting in extracting a set of mathematical equations that best fits the results obtained through device simulations under ISE-TCAD [9]. The result is a purely behavioral model made of resistors and current driven voltage sources [12]. Such a compact model does not rely on technological or geometrical parameters and is thus only valid for one particular device in a given integrated circuit technology.

Schweda and Riedling [13] used a similar approach but integrated more physics in the model to take the secondary effects (temperature, parasitic capacitances, biasing effects) into account. However, the model is built on the assumption that the resistance between each pair of contacts is always the same, which is not the case. This assumption may lead to simulation errors when the sensor is simulated with its biaising electronics. In addition, it is built for a given biasing direction, which limits its application range. For instance, such a model cannot be used to

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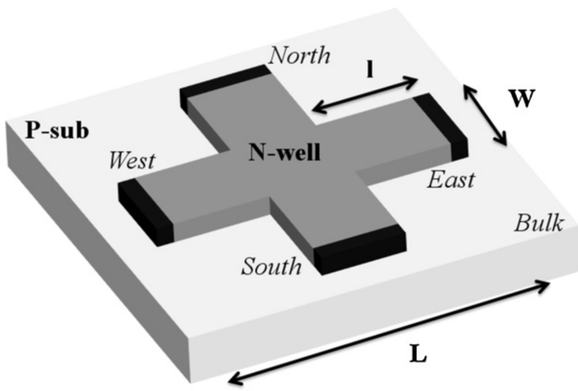

Fig. 1. A cross-shaped Hall effect sensor.

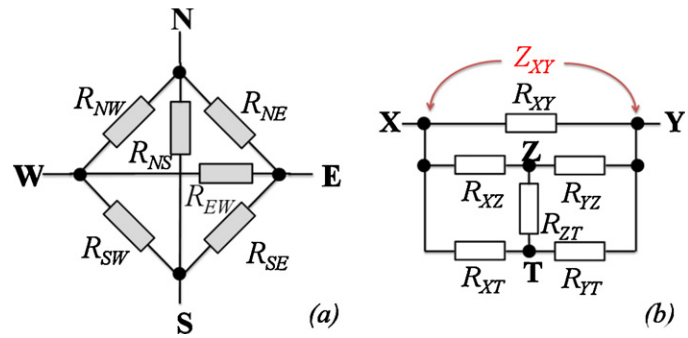

Fig. 2. (a) The 6-resistance bridge used to model the Hall sensor. (b) A resistance network equivalent to the 6-resistor bridge shown in (a). *X*, *Y*, *Z* and *T* corresponds to *N*, *S*, *E* and *W* whatever their order.

simulate a circuit using the widely used spinning-current technique [14,15].

Another approach proposed by Dimitropoulos et al., consists in mixing compact modeling and FEM approach to obtain a tradeoff between simplicity and accuracy [16]. The cross-shaped device is divided into square sub-devices, each sub-device being modeled through a set of resistors and current-driven current and voltage sources. Each elementary sub-devices is then connected with its four nearest neighbors leading to a mesh that defines the shape of the considered sensor. This approach allows to take into account many parasitic effects (channel depth modulation, current line deviations, short-circuit effects...) with only 9 physical parameters. Nevertheless, to obtain a good enough accuracy one must subdivide the sensor into a relatively large number of small elements. This leads to a complex circuit and, as a consequence, the simulation time becomes excessive.

In this paper, a physics based compact modeling approach is presented. The paper begins with a short reminder about Hall effect sensors and integrated Hall devices. Then, the structure of the model is presented in details and, in Section 4, we deal with its Verilog-A implementation. In Section 5, the method allowing to validate our assumptions and to extract the parameters of the model from experimental results is presented. Finally, the most important points are reminded in the conclusion with a discussion on some possible features which could be added in the model.

2. Basics on Hall effect

The principle of the Hall effect is well known since 1879: when a conductor, biased by a current I along x-direction, is immersed in a magnetic field B along the z-direction, an electrical field, called Hall field E_H, appears along the y-direction. The magnitude of the electrical field E_H is proportional to the product $B \cdot I$. The use of a semiconductor is a good way to build low-cost integrated magnetometers.

There are different kinds of integrated magnetic field sensors [17]. Among others, Horizontal Hall Devices (HHD) aim to measure the magnetic field which is perpendicular to the wafer. Different efficient shapes of HHD have been demonstrated [14] but the most popular one is the cross-shaped (Fig. 1). Such devices are symmetric by a $\pi/2$ rotation, which allows to implement the spinning current technique, a widely used offset and flicker noise reduction technique [14]. Our work focuses on such devices.

3. Cross-shaped HHD modeling

Our model aims to take into account all of second order effects that alter the ideal response of the sensor. One of the big issue in such devices is the output offset which strongly limits the DC resolution of the sensor. To take accurately the offset into account, it has been demonstrated that a network of six different resistors is required [12]. From a mathematical point of view, it corresponds to the necessity to adjust at least six parameters in order to fit the six possible inter-contact resistance measurements.

Our model is built upon the same principle (see on Fig. 2a). However, contrary to the existing models, the values of the resistances are not directly the parameters of the model but are derived from physical or semi-empirical parameters that can be easily extracted.

3.1. The six-resistor model

In the whole paper, the symbol Z_{xy} denotes the value of the resistance measured between the contacts x and y on the actual sensor whereas R_{xy} is the value of the resistance introduced between x and y in the six resistances model.

First, we consider the ideal case in which there is no technological mismatch, no mechanical stress on the device and the thickness of the conduction channel is constant along the device. Under those conditions, as the device is symmetric, there can be only two different inter-contact resistance measurements: Z_O for the resistance between two opposite contacts (i.e. N–S and W–E) and Z_A for the resistance between two adjacent contacts (i.e. N–E, S–E, N–W and S–W). As a consequence, the sensor can be modeled using only two different values for the resistances: $R_{NS} = R_{WE} = R_O$ and $R_{NE} = R_{NW} = R_{SE} = R_{SW} = R_A$. The relationships between Z_A, Z_O, R_A and R_O are obtained using serial-parallel association rules for resistors (Fig. 2b). It leads to a set of two equations, one for opposite contacts and the other for adjacent contacts:

$$\begin{aligned} Z_A &= \frac{R_A \cdot (R_A + 3 \cdot R_O)}{4 \cdot (R_A + R_O)} \\ Z_O &= \frac{R_O \cdot R_A}{(R_A + R_O)} \end{aligned} \tag{1}$$

In the following, we consider as a reference the resistance R of a L long W wide rectangular N-well resistor of the target technology. According to Fig. 1, the cross-shaped sensor can be seen as a reference resistor with two additional measurement contacts. Due to those contacts, the current lines widen out at the center of the device, which leads to a decrease of the resistance seen across the two biasing contacts. Numerical simulations, carried out with COMSOL®, show that the measured resistance Z_O is proportional to the reference resistance R. The proportionality coefficient $\alpha = (Z_O/R) < 1$ only depends on the geometry of the device. According to simulations (Fig. 3), the following fitting function has been established for α:

$$\alpha(\lambda) = 1 - 0.097 \cdot \lambda^{-0.662} \tag{2}$$