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Multi-analysis and modeling of asymmetry offset for Hall effect structures

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ABSTRACT

The topological (asymmetry) offset voltage of CMOS cross-like Hall cells is analyzed in this paper. In order to attain the stated objective, different approaches have been considered. Both circuit and three-dimensional models have been developed. Variation of the misalignment offset with the biasing current has been studied through physical and circuit models. The latter is a non-homogenous finite elements model, which relies on using parameterized resistances and current-controlled current sources, of CMOS Hall cells. The displacement offset for various asymmetries and the offset variation with the temperature were investigated through the circuit model developed. Various experimental results for the single and magnetic equivalent offset have also been provided.

1. Introduction

In the current industrial context, Hall effect sensors are still being used on a large scale due to their robustness, easy cointegration with the circuitry and ultimately low manufacturing cost. In the last decades, they have been employed to measure the currents, in DC motors and to serve different low-power applications [1,2]. More recently, they have been used in magnetic cameras [3].

In the automotive industry, this type of magnetic sensors is prevalent in a multitude of applications. They can be used both as linear and angle position sensors. The first ones are used for contactless sensing of both ferrous objects and magnets, and can be programmed to satisfy client needs [4]. For example, circular vertical Hall sensors are used as angular position sensors in transmission/clutch, braking, power steering, where the precise knowledge of the angle is very important [4].

A major drawback in the performance of the Hall effect sensors is their offset [5–8], which is obtained for no magnetic field acting upon the samples. To counteract this issue, electronic means are available in the employment of spinning current technique. However, device geometrical optimization is a very important tool in the hands of the designer, as it has been studied with great attention by the author in a previous paper [9]. Both SOI (Silicon on Insulator) [10–12] and regular bulk CMOS [13] technologies have been used in the development of Hall sensors.

The work in this paper is devoted to emphasize on different approaches, which have been used to characterize and model the offset (with the misalignment type at the forefront of this particular analysis), for cross-like Hall cells in a regular bulk CMOS technology. Three particular Hall cells have been considered, namely the Basic, L and XL Hall cells. Among the considered approaches, we can enumerate the use of three-dimensional physical models, as well as the implementation of a non-homogeneous finite element circuit model.

The paper is organized in six sections. The first section is the Introduction, while the second section is intended to present the modeling approaches for Hall cells, namely to speak about the physical and circuit models. In the third section, considerations on the offset modeling, including contacts misalignment, space charge region and piezoresistive effects are presented. The fourth section contains measurements results for both single phase offset and magnetic equivalent residual offset temperature dependence, for the three Hall cells considered.

In the fifth section, the paper presents the results obtained and discusses them. At this point, simulation results on the asymmetry offset dependence with the biasing current, for the three cross Hall cells considered are obtained, for certain misalignment asymmetries, through physical models.

Furthermore, circuit models are employed to numerically characterize the values of the displacement offset with the biasing current, for the XL Hall cells, for four asymmetries considered. In order to have a verification of the simulations results in terms of the offset, experimental results for single phase offset are also included, for the three studied cells. The temperature dependence of the offset for the XL Hall cell is obtained for two particular asymmetries, and a parabolic dependence is revealed at this point. Finally the paper concludes in the sixth section and proposes the direction for the future studies.

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Table 1
Geometrical parameters of Hall cells.

Hall cell	Basic	L	XL
Hall cell length, *L* (μm)	21.6	32.4	43.2
Hall cell width, *W* (μm)	9.5	14.25	19
Contacts length, *s* (μm)	8.8	13.55	18.3

2. Hall cells modeling approaches

This work will be focusing on the performance investigation and offset characterization of three specific Cross-like Hall cells. The protagonists of this comparative study are the basic, L and XL Hall cells. Their geometrical parameters (length, width, contacts dimensions) are included in Table 1.

In order to address the primary stated objective of this study to model and analyze the Hall cells offset, two types of models are provided. Both a physical and circuit model are used in order to reach the characterization.

2.1. Physical model of cross-like Hall cells

A useful investigation into the behaviour of the Hall cells is provided by three-dimensional physical models. In this sense, the Sentaurus software [14] from Synopsys® is used, which is able to solve the magnetic field influence on semiconductor structures. This software allows for both process and device simulation and solves the continuity equations (electrons and holes) and Poisson equation. More details on the equations used in the model could be found in [13]. For additional overview of the semiconductor physics, please consult [15,16].

Fig. 1 presents the three-dimensional model of the XL Hall cell. More specifically, these devices are modeled as a CMOS structure, with an n-well (red zone) in a p-substrate (blue zone), equipped with four electrical contacts (pink zones).

In the modeling stage of the Hall cells using three-dimensional physical simulator, the following numerical values have been used. More specifically, a p-substrate with a Boron concentration of 10^{+15} cm^{-3} and an active n-well region doped with Arsenic of peak concentration $1.5{\cdot}10^{+17}$ cm^{-3}, in the form of a Gaussian profile implantation were used. This doping profile allows an average mobility of 0.0630 $m^2V^{-1}s^{-1}$ at the surface of the devices. The thickness is 5 μm for the p-substrate and 1 μm for the implantation of the n-doped profile active region respectively.

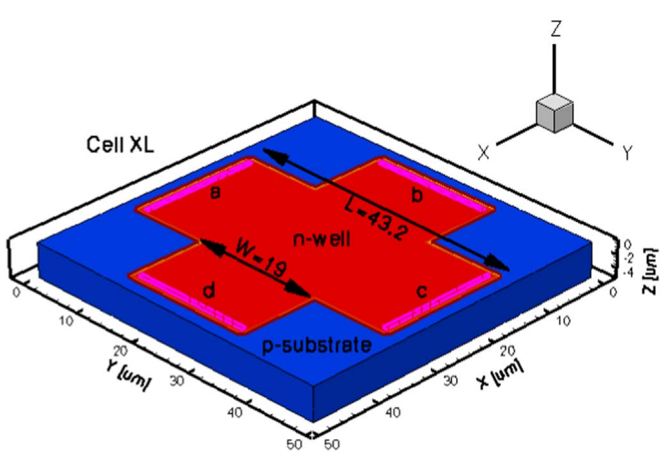

Fig. 1. Three-dimensional model of the XL Hall cell. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

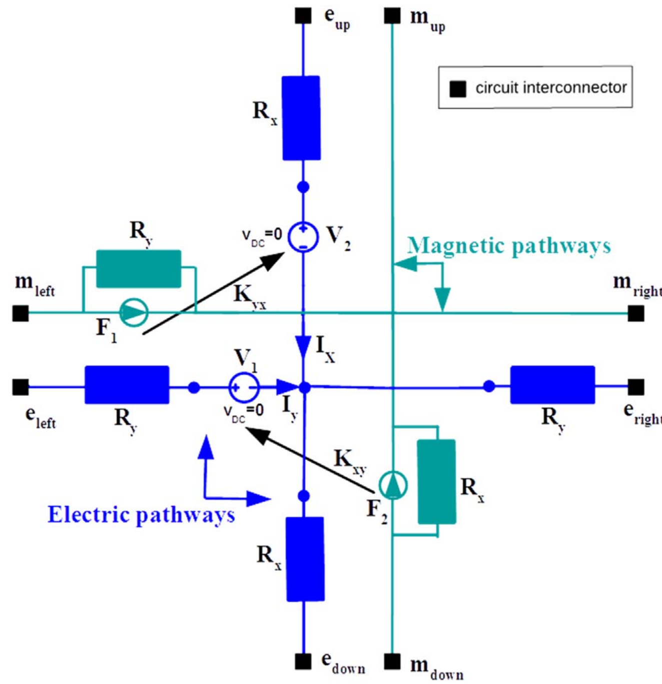

Fig. 2. The circuit model of the new elementary cell with the eight input/output pins.

2.2. Circuit model of cross-like Hall cells

The circuit model of Hall cells, developed in Cadence® and coded in Verilog-A has been presented in details by the author in her PhD thesis [13] and in a recent paper [17]. However, the present paper focuses on the adaptation of this model and its use for offset estimation.

Briefly speaking, the circuit model is a finite element model based on a particular elementary cell. To model Hall effect devices, a FEM lumped circuit model containing a new elementary cell, different from cell in [18], was developed and its circuit model is presented in Fig. 2. As we can see, the elementary cell is a collection of current-controlled current sources (F_1 and F_2) and parameterized resistances (R_X and R_Y). In order to sense the current flowing through each branch, DC sources with null voltage (V_1 and V_2) were introduced.

The parameterized resistances R_X, R_Y are described by the relations:

$$R_X = \frac{L}{tW\sigma}, \qquad R_Y = \frac{W}{tL\sigma} \tag{1}$$

where L and W are the Hall cells length and width respectively, t is the thickness of the n-well, σ is the conductivity [2].

The currents i_X and i_Y are defined as follows:

$$i_X = \frac{W}{L}\mu_H B i_Y, \qquad i_Y = \frac{L}{W}\mu_H B i_X \tag{2}$$

where μ_H is the Hall mobility and B is the magnetic field strength.

By consequence, from the equation above, we can observe that each current flowing through a branch can be defined by the current through the opposite (orthogonal) branch multiplied by certain gains, K_{YX} and K_{XY} respectively:

$$i_X = K_{XY} i_Y, \qquad i_Y = K_{YX} i_X \tag{3}$$

where the specific gains are introduced in the following way:

$$K_{XY} = \frac{W}{L}\mu_H B, \qquad K_{YX} = \frac{L}{W}\mu_H B \tag{4}$$

For a complete behavior characterization of the Hall cells, JFETs could also be used in the place of the parameterized resistances.

For subsequent inclusion in the finite element model and to establish multiple connections between identical cells, the elementary