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SOI Hall cells design selection using three-dimensional physical simulations

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ABSTRACT

The main characteristics of Hall Effect Sensors, based on "silicon-on-insulator" (SOI) structure in the ideal design features, are evaluated by performing three-dimensional physical simulations. A particular Hall shape reproducing an XFAB SOI XI10 integration process is analyzed in details. In order to assess the performance of the considered Hall cell, the Hall voltage, absolute sensitivity and input resistance were extracted through simulations. Electrostatic potential distribution and Hall mobility were also produced through simulations for the considered SOI Hall Basic cell. A comparison between the performance of the same Hall cell manufactured in regular bulk and SOI CMOS technology respectively is given.

1. Introduction

Over the years, Hall Effect sensors have been used in an array of practical applications, including contactless measurements of mechanical quantities such as position or angle, in DC motors, tachometers, etc. They have been also employed for direct magnetic field sensing, as in electronic compasses. Due to their cost-effective integration potential, reflected in low cost, robustness and versatility [1,2], silicon Hall sensors are often the candidates mostly sought for such applications.

In comparison to the bulk Hall sensors, the sensors fabricated in SOI (***S***ilicon ***O***n ***I***nsulator) technology have obvious benefits. Amongst these advantages of SOI Hall sensors, we can enumerate higher magnetic sensitivity, less noise production, no need for a high bias voltage, enhanced radiation resistance, smaller leakage current through the dielectric, etc. [3]. In [4], a high sensitivity Hall sensor fabricated on a SOI wafer using surface micromachining technique was presented.

As the depth of the active silicon layer in SOI integration process is much smaller than in a regular CMOS it immediately results in both increased sensitivity and increased input resistance. The latter consequence implies the use of a smaller biasing current and it ultimately results in smaller power consumption. Papers in literature investigated SOI Hall sensor based solid state meters for power and energy measurements [5,6]. SOI CMOS Hall effect sensor architecture was also used for high temperature applications [7].

The influence of the geometry on the Hall device performance is very important and was studied in [8–10]. Various designs for CMOS Hall devices were proposed and their behavior tested in [11–12]. Low magnetic-equivalent residual offset (less than 30 μT at room temperature) and offset temperature drift (less than $\pm$ 0.3 μT/$^{\circ}$C) values were obtained with specific Hall devices structures, such as the XL device [13].

The paper is intended to present the behavior investigation of a particular Hall sensor in SOI technology. In order to estimate the specific parameters of this Hall cell and evaluate its performance, three-dimensional physical simulations were performed. Section 2 is devoted to recall a few considerations on the three-dimensional physical simulations methodology, while Section 3 of this paper presents the basic equations governing Hall cells behavior. Further on, Section 4 is intended to present in details the three-dimensional model of the considered SOI basic Hall cell. Section 5 is summing up the simulation results and discusses them, by also making a comparison between the performance of the same Basic Hall cell studied in regular bulk and SOI CMOS technology respectively. Finally the paper concludes in Section 6.

2. Considerations on the three-dimensional physical simulations of Hall Effect cells

CMOS Hall cells design and integration as well as extensive investigation of geometry influence on the Hall cells performance

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have been performed by the first author in various recent papers [8–16]. CMOS Hall cells offset and temperature drift were analyzed in details in [13]. Three dimensional physical simulations of magnetic field influence on the semiconductors were performed by the first author in [14]. Circuit models including temperature effects for Hall cells in CMOS technology were developed in [15,16].

2.1. Governing equations for carrier transport in semiconductors

In semiconductor materials, the classical carrier transport model [17–19] is based on the continuity equations:

$$div\vec{J}_{nB} = q\left(R + \frac{dn}{dt}\right) \tag{1}$$

$$div\vec{J}_{pB} = -q\left(R + \frac{dp}{dt}\right) \tag{2}$$

where q is the elementary electronic charge, $\vec{J}_{nB}$, $\vec{J}_{pB}$ are magnetic field dependent current densities, R is the net recombination rate and n, p represent particle densities for electrons and holes, respectively. The particle densities expressions in terms of Fermi energy level $E_{F,n}$ and $E_{F,p}$ are as presented in the following relations:

$$n = n_i exp\left\{\frac{qV - E_{F,n}}{kT}\right\} \tag{3}$$

$$p = n_i exp\left\{\frac{E_{F,p} - qV}{kT}\right\} \tag{4}$$

where V denotes the electrostatic potential, n_i is the intrinsic carrier concentration, T is the absolute temperature and k is the Boltzmann constant.

The differential Eqs. (1) and (2) describe the conservation of electric charge and the carrier recombination rate can be a nonlinear function $R = R(V, n, p)$, in terms of V, n and p.

In particular, the transport models differ through the expressions used to define the current densities $\vec{J}_{nB}$ and $\vec{J}_{pB}$. For a complete description of semiconductor physical behavior, we also have to take into account the following equations:

$$div(\vec{D} + \vec{P}) = \rho - \rho_{trap} \tag{5}$$

$$\vec{E} = -gradV \tag{6}$$

In the penultimate equation, $\vec{D}$ is the electric field induction, $\vec{P}$ is the ferroelectric polarization, ρ is the space charge and ρ_{trap} is the charge density contributed by traps and fixed charges. Also, by definition, $\vec{D} = \varepsilon\vec{E}$, where $\vec{E}$ is the electric field and ε is the material electric permittivity. In the last equation V represents the electrostatic potential.

Replacing Eq. (6) in Eq. (5) and for a space charge ρ specified as $\rho = q(p - n + N)$ with $N = N_D - N_A$ denoting the fully ionized net impurity distribution, we get a partial differential equation of elliptic type:

$$div(\varepsilon gradV + \vec{P}) = -q(p - n + N_D - N_A) - \rho_{trap} \tag{7}$$

Here, N_D is the concentration of ionized donors, N_A is the concentration of ionized acceptors. Anew, n and respective p, are the electron and hole densities. Indubitably, the electrostatic potential V is the solution of the Poisson equation in (7).

It is to be mentioned that the magnetic induction effect only manifests in the mathematical relations which define the current density. Equivalently speaking, in the absence of the magnetic field, the continuity equations and the Poisson's Eq. (7) will remain the same. In fact, for gaining insight into the operating principles of the final artifact, the distributions of electrostatic potential and current density in the device are fundamental. This allows one to determine optimal parameters of an ideal semiconductor structure.

2.2. Simulation methodology

By using the Synopsys Sentaurus TCAD tool [20], which solves the Poisson equation, both electrons and holes continuity equations, three-dimensional simulations of Hall Effect sensors were performed. A 3D numerical modeling of carrier transport process in the magnetic field (electrostatic potential, current distributions) for semiconductor magnetic sensors with different geometries is used.

At each point of the grid, three unknowns will be considered, namely V, n, p. Further on, we would need three equations and the corresponding boundary conditions to solve the nonlinear system of partial differential equations. In order to have a correct solution, the discretization of the Poisson's equation, electron and holes continuity equations will be needed and a coupled method, which is a generalization of the Newton method, will be used to compute the initial proposed system by numerical iterative procedure.

The magnetic field acting on the semiconductor structure for Hall voltage generation was handled by the galvanic transport model, which is the model used for carrier transport in magnetic fields [20–22].

The analysis of magnetic field effects in semiconductor devices is done by solving the transport equation of electrons and holes inside the device. The usual drift-diffusion model of the carrier densities $\vec{J}_n$ and $\vec{J}_p$ should be rewritten by taking into account the magnetic field-dependent terms issued by the effect of Lorentz force on the carriers. Sentaurus includes the effect of magnetic field on semiconductors within the galvanic transport model. The following equation governs its behavior.

$$\vec{J}_\alpha = \mu_\alpha \vec{g}_\alpha + \mu_\alpha \frac{1}{1 + (\mu_\alpha^* B)^2}[\mu_\alpha^* \vec{B} \times \vec{g}_\alpha + \mu_\alpha^* \vec{B} \times (\mu_\alpha^* \vec{B} \times \vec{g}_\alpha)] \tag{8}$$

where $\alpha = n, p$, $\vec{g}_\alpha$ is the current vector without mobility and μ_α^* is the Hall mobility [17].

In order to simulate the influence of magnetic field onto semiconductor devices, Sentaurus simulator uses the galvanic transport model. However, as a first observation, one must note that the galvanic transport model cannot be combined with the hydrodynamic, impact ionization, piezoelectric models and quantum modeling. For simulation convergence, the value of the magnetic field constitutes a critical parameter. For doping-dependent mobility, the convergence is reliable up to 10 T. For more general mobility, the convergence has a limit of the magnetic field up to 1 T.

In the present work, the mobility was considered via doping dependence formula and recombination processes were taken into account via Shockley–Read–Hall and Auger model as considered in paper [23]. In this context, the ohmic contacts are assumed ideal and the contact regions support a sufficiently high dopant concentration. The constructed SOI Hall device, simulated through three-dimensional physical simulation and analyzed, will be presented in details in Section 4.

3. Definitions, units and equations involved in Hall devices performance analysis

Any Hall Effect device is characterized by the Hall voltage V_{HALL}, given as follows:

$$V_{HALL} = \frac{Gr_H}{nqt} I_{bias} B \tag{9}$$

where B is the magnetic field induction, G is the geometrical correction factor, I_{bias} is the biasing current, r_H is the Hall scattering