3D FEM modelling of a new magnetic field sensor: the CHOPFET

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Abstract

A 3D model dedicated to MAGFET-type magnetic sensors is presented. It is applied to a new device design, the CHOPFET and dedicated to accelerating the conception of CHOPFET-based instrumentation systems. COMSOL Multiphysics capability is used to model the semiconductor equations coupled to the magnetic field effect related equations. Second order effects such as carrier velocity saturation are also taken into account. The sensitivity shows significant dependence on the geometric and biasing parameters. The model allows optimization in order to achieve maximum sensitivity.

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1. Introduction

MAGFET devices are an attractive alternative to the Hall effect sensors because they can achieve higher sensitivity. Unfortunately they suffer from serious offset as well as from noise issues, particularly at low frequencies, where 1/f noise prevails, and thus have poor resolution performances [1]. A new MAGFET-type sensor, called CHOPFET was proposed by Frick [2]. This new structure complies with the SCT, commonly applied to the conventional Hall effect transducers to dynamically cancel the offset and 1/f noise. The SCT principle applied to the CHOPFET has been validated and a first prototype achieves 40 μT resolution over 1.6 kHz bandwidth [2].

The CHOPFET needs to be modelled in order to optimize its dimensioning for submicrotesla performance. The physical model should also lead to a compact electrical model of the device for integration in the conception flow.

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when designing sensor systems with standard CAD tools. We have already developed a 2D FEM COMSOL® model including the carrier saturation velocity and the Hall effect [3]. It showed that, in first approximation, the electrical behavior is accurately modelled for a given gate to source voltage $V_{gs}$ in linear mode. Yet, some experimental results remained unexplained. Hence, for further CHOPFET understanding and optimization, we developed a 3D FEM model, which is presented in the following sections.

Section 2 is dedicated to a presentation of the CHOPFET’s structure. Section 3 focuses on the FEM model. Simulation results are presented and discussed in section 4, before concluding in section 5.

**Nomenclature**

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>MAGFET</td>
<td>Magnetic Field Effect Transistor</td>
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<td>SCT</td>
<td>Spinning Current Technique</td>
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<td>CHOPFET</td>
<td>Chopper and SCT compliant MAGFET</td>
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<tr>
<td>CAD</td>
<td>Computer Aided Design</td>
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<tr>
<td>FEM</td>
<td>Finite Element Method</td>
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</table>

### 2. Structure and operating principle

The structure of the CHOPFET consists of a symmetrical square ($W = L$) MOS transistor structure featuring 4 contacts, one at each angle (Fig. 1a). By connecting two contacts together, for instance C and D, and leaving the two others independent, one forms a MAGFET structure [4-5], where contacts A and B form the sub-drains while C and D act as the source. The biasing is usually performed by a current generator $I_S$ connected to the source of the transistor. The drain currents, $I_{D1}$ and $I_{D2}$, always verify the following relation: $I_S = I_{D1} + I_{D2}$. When the sub-drains are identical and there is no magnetic field component applied upon the transducer, the sub-drain currents verify: $I_{D1} = I_{D2} = I_S/2$.

The transduction principle is based on the current deflection due to the $B_z$ component perpendicular to the surface of the transistor (Fig. 1b), when a magnetic field $B$ is applied. This creates an imbalance $\Delta I$ in the sub-drain currents, which is directly proportional to the magnitude of $B_z$. The consequence of the CHOPFET’s structure on the sensing performance is important since it complies with the well-known SCT thus allowing dramatic improvement of the resolution by cancelling the $1/f$ noise and offset.

Previous works have shown that the sensitivity of MAGFET devices depends on their geometric parameters ($W$, $L$, $d$, $H_0$) and its operating mode [4]. The difference of the CHOPFET compared to the MAGFET is its dependence between the various geometrical parameters. Indeed, in the CHOPFET the parameters, $d$ and $H_0$, of the notch that separates the drains has an impact on the effective width and length of the transistor. This has an impact on the transducer’s behavior and thus requires specific modelling, as discussed below.

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**Fig. 1.** (a) N-type CHOPFET structure with dimensioning and biasing example, (b) 3D view with magnetic field and current deflection.
3. FEM modelling

3.1. Electrical model

By combining Gauss’s law to the continuity equations for electrons and holes [6]:

\[-\nabla J_n = -q \cdot R_{SRH}\]
\[-\nabla J_p = q \cdot R_{SRH}\]

(1)

the expressions of the respective current densities, \( J_n \) and \( J_p \), take both the convection and the diffusion into account:

\[ J_n = -q \cdot n \cdot \mu_n \cdot \nabla \psi + q \left( k \cdot T / q \right) \cdot \mu_n \cdot \nabla n \]
\[ J_p = -q \cdot p \cdot \mu_p \cdot \nabla \psi - q \left( k \cdot T / q \right) \cdot \mu_p \cdot \nabla p \]

(2)

In these equations, \( R_{SRH} \) is the Shockley-Read-Hall recombination model [7], \( \psi \) the electrostatic potential, \( \mu_n \) and \( \mu_p \) the mobility of electrons and holes respectively, \( n \) and \( p \) their respective doping concentration, \( q \) the elementary charge, \( k \) the Boltzmann constant, and \( T \) the temperature.

Note that, due to its small (micron or submicron) size and the proximity of the contacts, the electric fields within the CHOPFET can be high. Therefore, for both the electrons and the holes, it is important to take the carrier velocity saturation into account in the expression of their mobility [7].

3.2. Magnetic model

In order to predict the CHOPFET’s sensitivity, the magnetic field effect has been added to the model. Therefore, the constant carrier mobility is replaced by an anisotropic mobility tensor depending on the magnetic field. Supposing the \( B_z \) component of the magnetic field is low enough to assume the magneto-resistive (quadratic) effect negligible (i.e. below 8 T), the mobility of electrons and holes \( \mu_n \) becomes:

\[ \mu_n = \begin{pmatrix} \mu_{nx1}(B) & \mu_{nx2}(B) & \mu_{nx3}(B) \\ \mu_{ny1}(B) & \mu_{ny2}(B) & \mu_{ny3}(B) \\ \mu_{nz1}(B) & \mu_{nz2}(B) & \mu_{nz3}(B) \end{pmatrix} \quad \text{and} \quad \mu_p = \begin{pmatrix} \mu_{px1}(B) & \mu_{px2}(B) & \mu_{px3}(B) \\ \mu_{py1}(B) & \mu_{py2}(B) & \mu_{py3}(B) \\ \mu_{pz1}(B) & \mu_{pz2}(B) & \mu_{pz3}(B) \end{pmatrix} \]

(3)

Note that, considering an N-type CHOPFET, we can neglect the effect of B on it.

4. Simulation results

The transducer’s 3D model is thoroughly parametric in order to allow extensive geometry and biasing parametric simulation. Fig. 2 shows the electrical model validation results obtained with this methodology. The MOS transistor effect is accurately reproduced in its various operating regimes. Fig. 3 shows the full validation of the model including the magnetic effect on the transistor’s behavior. This imbalance is deduced by evaluating the sub-drains currents \( I_{D1} \) and \( I_{D2} \). When \( B_z = 0 \), \( I_{D1} = I_{D2} = I_{S/2} \) whereas when \( B_z = 10 \) mT, the carriers’ deflection clearly appears, inducing sub-drains currents imbalance.

It is interesting to note that for a fixed biasing current value \( I_s \), the imbalance, and thus the sensitivity, significantly increases with the drain to source voltage \( V_{ds} \), which makes the CHOPFET very interesting for low-power applications.
Fig. 2. Simulated electron density with drain to source voltage V_{ds} = 1V and gate to source voltage V_{gs} = 1V, (a) depth 0 nm, (b) 1 nm, (c) 2 nm, (d) 3 nm, and simulated electric potential map with (e) V_{ds} = 0V and (f) V_{ds} = 1V.

Fig. 3. (a) Effect of B_{z} on the carriers concentration, (b) Current/voltage characteristic with and without magnetic field, and (c) Current imbalance (B = 10 mT) as a function of V_{ds}.

Conclusion

A 3D FEM model of a new magnetic transducer has been developed. This model is based on multiphysics coupling that allows combination of the equations of semi-conductor devices with magnetic equations. The carriers’ velocity saturation effect has also been inserted in the model in order to obtain more realistic results with respect to small size devices. The simulations show promising results that make the CHOPFET a serious candidate for Hall devices replacement, especially in low-power applications.

References