# Enhanced Sensitivity Magnetoresistor with a Venturi-Tube Shape


Gerard F. Santillan-Quiñonez and Carlos Galup-Montoro
Federal University of Santa Catarina, Brazil
Email: gsantil@ieee.org, carlos@eel.ufsc.br



***Abstract*—Split-contact magnetoresistors (SCMs) are Hall effect sensors based on the current deflection effect of the magnetic field. We developed a simulation model of Hall sensors, including SCM, in COMSOL Multiphysics considering the transport mechanisms of diffusion and drift. We can simulate devices with a quite arbitrary shape. We use the magnitude of the current density in the deflection direction (on the longitudinal line of symmetry of the device) as a useful guide for the study of the effects of the geometry on the sensitivity to the magnetic field. Other than rectangular shapes, we propose a device with a Venturi-tube shape to increase the sensitivity of magnetoresistors.**


## I. Introduction

The output of a Hall magnetic sensor can be either a voltage or a current. The first type of sensor [1], [2] enhances the Hall voltage and is the most commonly used. In the second class of sensors [3]–[10] the current-lines deflection effect is enhanced and the resulting output current imbalance is measured on split-contacts. Magnetoresistors [3]–[5] and magnetotransistors [6]–[10] are the main current output sensors and their maximum reported sensitivity is similar, around $8\,\%$ of relative current imbalance /Tesla. This work focuses on magnetoresistors.

The influence of the geometry on the performance of Hall sensors was studied through experimental work [1], [3]–[5] and also by means of numerical simulations [2], [6]. Split-contact magnetoresistors and magnetotransistors with non rectangular shapes were reported [1], [4]–[9], but without a significant improvement in their magnetic sensitivity.

Since three-dimensional numerical simulation of devices is very computer demanding and often requires very long run time, we developed a bi-dimensional simulation model of Hall sensors in COMSOL Multiphysics [11]. We can simulate devices with a quite arbitrary shape, including Split-Contact Magnetoresistors (SCM), in short run times. The simulation model considers the transport mechanisms of diffusion and drift under a perpendicular magnetic field. We have found out that the magnitude of the current density in the deflection direction (on the longitudinal line of symmetry of the device) is a useful guide for the study of the effects of the geometry on the sensitivity to the magnetic field. Other than rectangular shapes, we studied a device with a Venturi-tube shape which shows a promising high magnetic sensitivity.

This paper is organized as follows. Section II introduces the split-contact magnetotransistor and the definition of a current deflection quality parameter. Section III describes a magnetoresistor with a Venturi-Tube shape, Section IV summarizes the numerical simulation model, Section IV presents the simulation results, and finally, conclusions are given in Section VI.

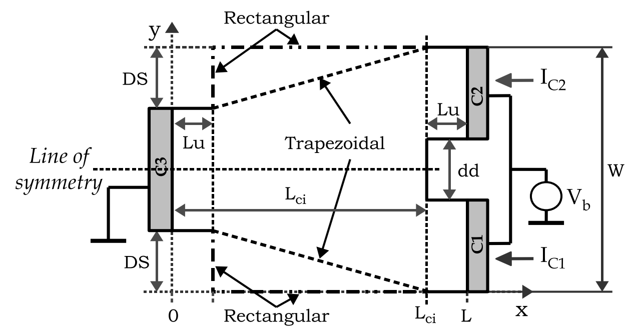



Figure 1. Schematic view of split-contact magnetoresistors.

## II. Split-Contact Magnetoresistors

A magnetoresistor is a Hall plate with split drain contacts as shown in Fig. 1. The ideal case is when $DS = dd = Lu = 0\,\mu m$. The sensitivity, $S$, of such devices is usually defined as

$$S = \frac{|I_{C2} - I_{C1}|}{(I_{C1} + I_{C2})\,B}\,100\,\% \qquad (1)$$

where $I_{C2} - I_{C1}$ is the current imbalance, $I_{C1} + I_{C2}$ is the total current, and $B$ is the intensity of the magnetic field perpendicular to the magnetoresistor active area.

In order to facilitate the analysis of the influence of the shape and dimensions on the performance of magnetoresistors we defined the normalized deflection-quality factor $J_{DQn}$ as:

$$J_{DQn}\,(x) = \frac{L_{ci}}{(W - dd)\left|\overline{J}_{Bx-L}\right|\,B}\,|J_{By-ls}|\;100\% \qquad (2)$$

where $J_{By-ls}$ is the lateral current density on the line of symmentry, and $\overline{J}_{Bx-L}$ as the average longitudinal current density on the contacts $C1$ and $C2$ (at $x = L$).

The normalized deflection-quality factor $J_{DQn}$ gives the transversal current density as a percentage of the longitudinal current density over the split contacts per Tesla. The average value of $J_{DQn}$ along the line of symmetry (from $x = 0$ to $x = L_{ci}$, see Fig. 1) gives the sensitivity, $S$. We will show that the effect of geometric parameters such as $DS$ and $dd$ can be easily understood with the plot of $J_{DQn}$ along a magnetoresistor.

978-1-4673-0859-5/12/$31.00 ©2012 IEEE

## III. Magnetoresistor with a Venturi-Tube Shape

The current deflection varies from source to drain in a SCM. On the source and drain contacts the transversal current component is maximum due to the short circuit effect of the contacts. On the other hand, in the central part of the device the Hall voltage is at its maximum value reducing the deflection of the current lines. The output current imbalance increases if the Hall voltage is reduced, and, consequently, the transversal current density is increased in the central part of the device. We will show that the Venturi-tube shape shown in Fig. 2 has this property. This device can be fabricated in a standard CMOS technology using the well layer.

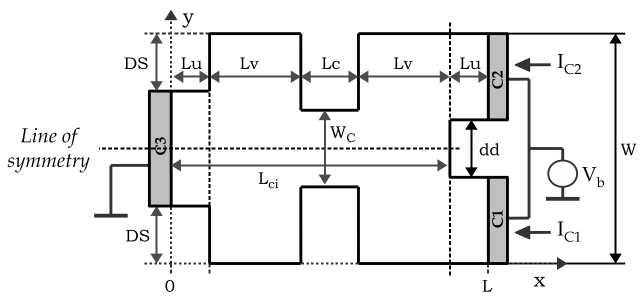



Figure 2. Magnetoresistor with a Venturi-tube shape.

## IV. Numerical Simulation

The Poisson's equation for the electrostatic potential $\Psi$ and the continuity equation for holes and electrons are solved considering Shockley-Read-Hall recombination, $R_{SRH}$ (see Equations 3, 4 and 5). We consider an isothermal and stationary process with a magnetic field $B = 1\,T$ perpendicular to the magnetoresistor area. The holes ($p$) and electrons ($n$) concentrations are assumed to obey Maxwell-Boltzman statistics. $q$ is the elementary charge. This elliptic equations system is solved in COMSOL Multiphysics $4.2a$ [11].

$$-\nabla \cdot (\epsilon \nabla \Psi) = q\,(p - n + N_D - N_A) \tag{3}$$

$$\frac{1}{q} \nabla \cdot J_{pB} = -R_{SRH} \tag{4}$$

$$-\frac{1}{q} \nabla \cdot J_{nB} = -R_{SRH} \tag{5}$$

The total current density is $J_B = J_{pB} + J_{nB}$. Defining $J_{p0}$ and $J_{n0}$ as the current densities for holes and electrons, respectively, under a zero magnetic field, $J_{pB}$ and $J_{nB}$ are given by :

$$J_{pB} = (J_{p0} + \mu_{Hp}\,(J_{p0} \times B))\left(1 + (\mu_{Hp} B)^2\right)^{-1} \tag{6}$$

$$J_{nB} = (J_{n0} - \mu_{Hn}\,(J_{n0} \times B))\left(1 + (\mu_{Hn} B)^2\right)^{-1} \tag{7}$$

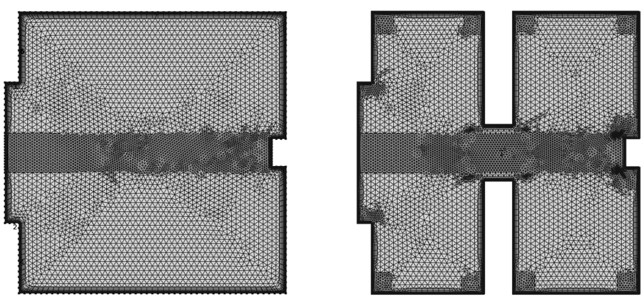
where $\mu_{Hp}$ and $\mu_{Hn}$ are the Hall mobility for holes and electrons, respectively, and $J_{p0} = -q\,p\,\mu_p\,\nabla\phi_{fp}$ and $J_{n0} = -q\,n\,\mu_n\,\nabla\phi_{fn}$, where $\phi_{fp}$ and $\phi_{fn}$ are the quasi-Fermi potentials for holes and electrons, respectively.

Dirichlet boundary conditions for the electrostatic potential, $\Psi$, and for both carrier density at ideal contacts ($C1$, $C2$ and $C3$, see Figs. 1 and 2) are considered. At the remaining boundaries, the normal components of electron and hole current densities and the field strength are assumed to be zero.

## V. Results

Magnetoresistors with different shapes (rectangular, trapezoidal and Venturi-Tube shape) were simulated in COMSOL Multiphysics 4.2a. The fixed simulation parameters were: bias voltage $V_b = 5\,V$, hole mobility $\mu_p = 500\,cm^2/V/s$, electron mobility $\mu_n = 1000\,cm^2/V/s$, magnetic field $B = 1\,T$ normal to the magnetoresistor plane and absolute temperature $T = 300\,K$. The geometric parameters were: $W = 10\,\mu m$, $dd = 1\,\mu m$, $DS = 2.5\,\mu m$ and $Lu = 0.5\,\mu m$ (see Figs. 1 and 2). The magnetoresistor length, $L$, was varied from $2\,\mu m$ to $40\,\mu m$ allowing to analyze $L/W$ ratios from $0.2$ to $4.0$. The doping concentration was varied from $N_D = 5\text{E}13 cm^{-3}$ to $N_D = 5\text{E}17\,cm^{-3}$.

The simulation mesh was refined around the line of symmetry, on the edges and in regions where the numerical convergence could be harder, as shown in Fig. 3.

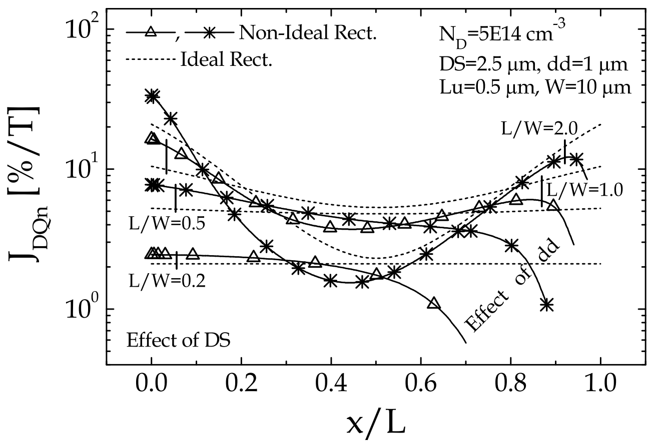


(a) Rectangular (b) Venturi-tube shape

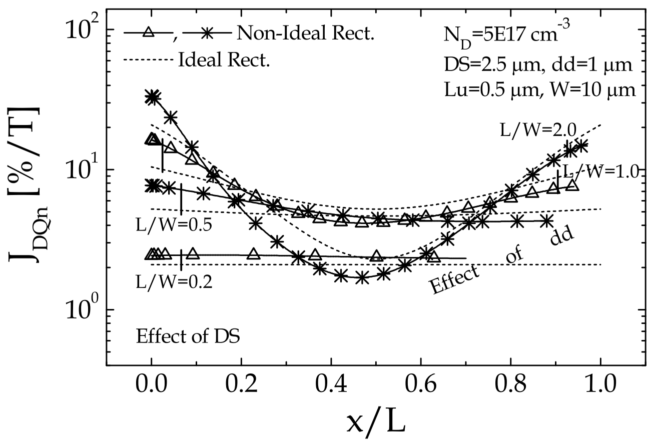
Figure 3. Simulation mesh for split-contact magnetoresistors.

The impact of $DS$, $dd$ and $W_C$ (see Figs. 1 and 2) on the performance of a SCM is analyzed using the normalized deflection-quality factor, $J_{DQn}$, defined by Equation 2. Fig. 4 shows the variation of $J_{DQn}$ along SCMs for ideal and non ideal rectangular devices having the same equivalent geometric ratio. The values of $J_{DQn}$ for trapezoidal SCMs are similar to the ones for rectangular SCMs. Figs. 4 show that $J_{DQn}$ increases due to $DS$, but it decreases in the central part and at the end of rectangular SCMs due to $dd$. As a result, the sensitivity $S$, that is the average value of $J_{DQn}$, increases due to $DS$ and decreases due to the central part and $dd$.

Magnetoresistors with Venturi-Tube shape were simulated. The geometric parameters were $W = L = 10\,\mu m$, $L_C = 1\,\mu m$ and $W_C$ from $2\,\mu m$ to $6\,\mu m$. For $N_D = 5\text{E}17\,cm^{-3}$ and $N_D = 5\text{E}15\,cm^{-3}$ the impact of the Venturi-tube shape on $J_{DQn}$ is not relevant (see Fig. 5(a)). In contrast, for $W_C = 2\,\mu m$ and $N_D = 5\text{E}14\,cm^{-3}$ and $N_D = 5\text{E}13\,cm^{-3}$, $J_{DQn}$ increases significantly due to the Venturi-tube shape as shown in Figs. 5(b) and 5(c).

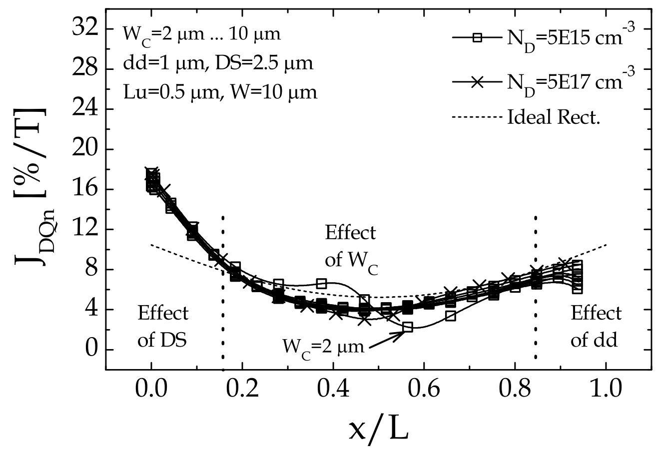



(a) For $N_D = 5\text{E}14\, cm^{-3}$

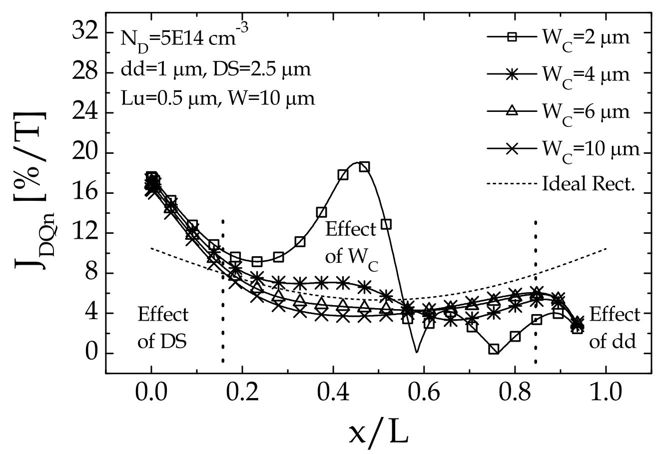



(b) For $N_D = 5\text{E}17\, cm^{-3}$

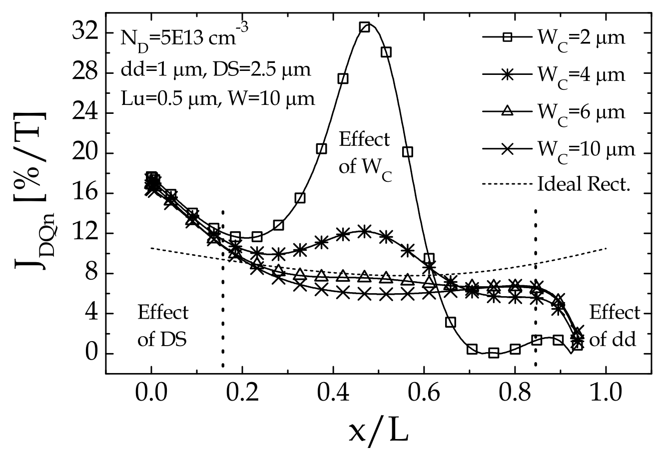
Figure 4. Normalized deflection-quality factor for the rectangular split-contact magnetoresistors




(a) For $N_D = 5\text{E}15\, cm^{-3}$ and $N_D = 5\text{E}17\, cm^{-3}$




(b) For $N_D = 5\text{E}14\, cm^{-3}$



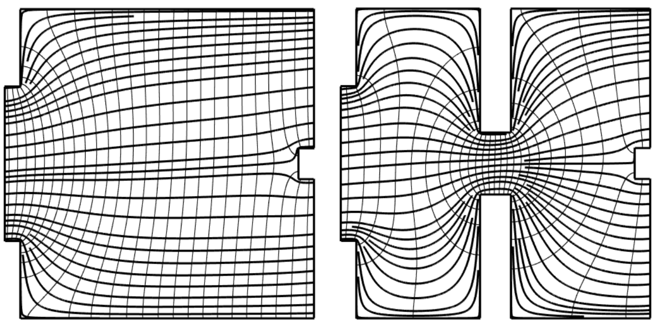

(c) For $N_D = 5\text{E}13\, cm^{-3}$

Figure 5. Normalized deflection-quality factor for the split-contact magnetoresistors with Venturi-tube shape.

The convergences of the numerical simulations were satisfactory. The calculated current and equipotential lines obtained for SCMs with a non-ideal rectangular and a Venturi-tube shapes for $N_D = 5\text{E}13\, cm^{-3}$ are shown in Fig. 6. It is possible to observe that around the line of symmetry, the current lines are more deflected in the SCM with a Venturi-tube shape than in the one with the rectangular shape. Furthermore, in the region where the Hall plate width is reduced, the equipotential lines keep better the transversal direction that in the rectangular geometry (see Fig. 6(b)). Thus, in the pinch-off region the Hall voltage is significantly reduced in favor of the current-line deflection effect [1]. Furthermore, the longitudinal carrier velocity is substantially increased in this region (see Fig. 7), producing a large increment of the magnitude of the magnetic part of the Lorentz force [1]. This explains the large increment of $J_{DQn}$ for $W_C = 2\, \mu m$ with $N_D = 5\text{E}14\, cm^{-3}$ and $N_D = 5\text{E}13\, cm^{-3}$ in Fig. 5(c).

The sensitivity, $S$, was calculated using Equation 1 and the contact currents were calculated integrating the longitudinal current density on contact bridges $C1$ and $C2$. The sensitivity tends to be reduced in a non-ideal rectangular and non-ideal trapezoidal cases with respect to the ideal case, due to $dd \neq 0\, \mu m$, as Fig. 8 shows. For non-ideal cases, $S < 8\,\%/T$ for the considered values of $L/W$.

The sensitivity of the proposed SCM with a Venturi-tube shape does not vary significantly with respect its equivalent non-ideal rectangular case ($W_C = 10\, \mu m$) using donor doping $N_D = 5\text{E}17\, cm^{-3}$ or $N_D = 5\text{E}15\, cm^{-3}$. In coherence



(a) Non-ideal rectangular shape (b) Venturi-Tube shape@ $W_C = 2\,\mu m$

Figure 6. Current and equipotential lines for split-contact magnetoresistors @ $L = W = 10\,\mu m$, $N_D = 5\text{E}13\,cm^{-3}$ and $B = 1\,T$.

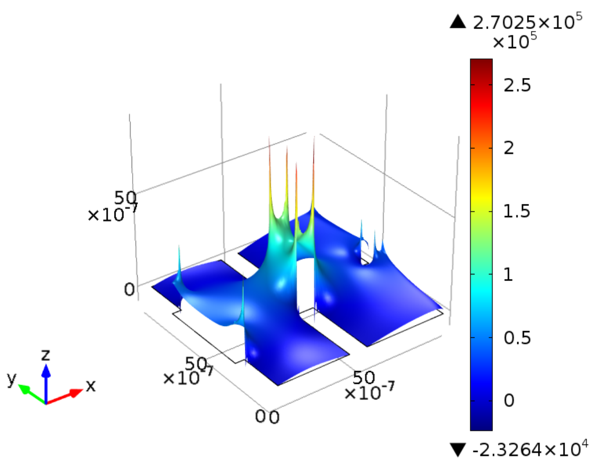



Figure 7. Magnitude of the longitudinal electron velocity in $[m/s]$ for the magnetoresistor with a Venturi-tube shape @ $W_C = 2\,\mu m$, $N_D = 5\text{E}13\,cm^{-3}$ and $B = 1\,T$.

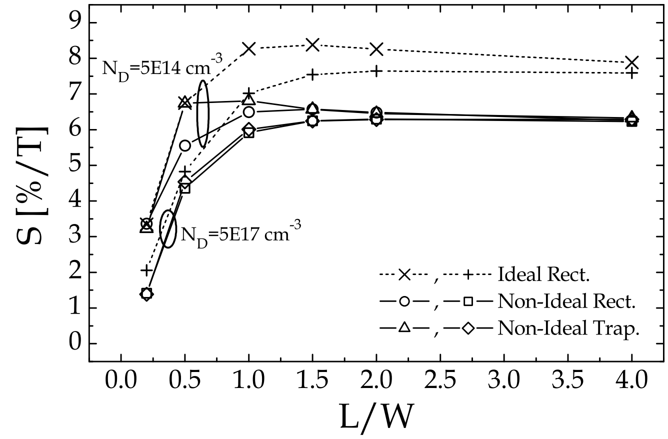



Figure 8. Sensitivity of rectangular and trapezoidal split-contact magnetoresistors for two different doping concentrations.

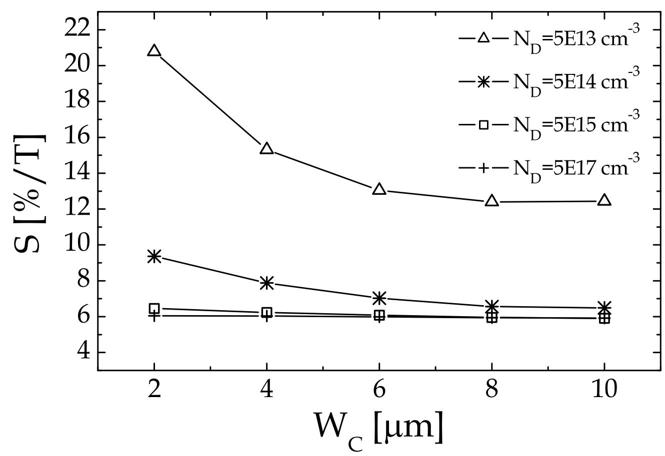



Figure 9. Sensitivity of split-contact magnetoresistors with Venturi-tube shape for different doping concentrations.

with results shown in Fig. 5, the sensitivity of the proposed SCM with a Venturi-tube shape increases from $6.5\,\%/T$ to $9.37\,\%/T$ for $N_D = 5\text{E}14\,cm^{-3}$ and from $12.43\,\%/T$ to $20.77\,\%/T$ for $N_D = 5\text{E}13\,cm^{-3}$ when $W_C = 2\,\mu m$ is used.

## VI. Conclusions

We have studied split-contact magnetoresistors by means of a bi-dimensional simulation model implemented in COMSOL Multiphysics. We have simulated Venturi-tube shape magnetoresistors with sensitivities as high as $20\,\%/T$. The new geometry can also be applied to magnetotransistors that can be fabricated in any standard CMOS technology.


## Acknowledgment

The authors acknowledge CNPp of Brazil for the Post-Doctoral Junior scholarship (Project $152257/2010-1$).


## References


[1] R. S. Popović, *Hall effect devices*, 2nd ed. Institute of Physics Publishing, Bristol and Philadelphia, 2004.

[2] M.-A. Paun, J.-M. Sallese, and M. Kayal, “Hall effect sensors performance investigation using three-dimensional simulations,” in *Proc. 18th International Conference Mixed Design of Integrated Circuits and Systems, MIXDES 2011*, 16-18 June 2011, pp. 450–455.

[3] Y. Sugiyama, H. Soga, M. Tacano, and H. Baltes, “Highly sensitive split-contact magnetoresistor with AlAs/GaAs superlattice structures,” *IEEE Trans. Electron Devices*, vol. 36, no. 9, pp. 1639–1643, Sep. 1989.

[4] J. W. A. von Kluge, “Analysis of split-current magnetic field sensitive resistors,” *Sensors and Actuators A: Physical*, vol. 93, no. 2, pp. 103–108, 2001.

[5] J. W. A. von Kluge, H. Acker, F. Umbach, and W. A. Langheinrich, “The sheer-contact MAGRES – a magnetic field sensor with minimal manufacturing complexity,” *Sensors and Actuators A: Physical*, vol. 100, no. 2-3, pp. 199–205, 2002.

[6] R. Rodríguez-Torres, E. Gutiérrez-Domínguez, R. Klima, and S. Selberherr, “Analysis of split-drain MAGFETs,” *IEEE Trans. Electron Devices*, vol. 51, no. 12, pp. 2237–2245, Dec. 2004.

[7] K. Nakano, T. Takahashi, and S. Kawahito, “A CMOS rotary encoder using magnetic sensor arrays,” *IEEE Sensors J.*, vol. 5, no. 5, pp. 889–894, Oct. 2005.

[8] G. Qing, Z. Dazhong, and Y. Yunruo, “CMOS magnetic sensor integrated circuit with sectorial MAGFET,” *Sensors and Actuators A: Physical*, vol. 126, no. 1, pp. 154–158, 2006.

[9] M. Daricek, M. Donoval, and A. Satka, “Behavior of various geometry MagFET structures,” in *European Conference on Circuit Theory and Design, ECCTD 2009*, Aug. 2009, pp. 17–20.

[10] G. F. Santillan-Quiñonez, V. Champac, and R. S. Murphy, “Exploiting magnetic sensing capabilities of short split-drain MAGFETs,” *Solid-State Electronics*, vol. 54, no. 11, pp. 1239–1245, Nov. 2010.

[11] COMSOL, *COMSOL Multiphysics: User Guide*. COMSOL AB, 2010.