High-Sensitivity Split-Contact Magnetoresistors on Lightly Doped Silicon Substrates

Gerard F. Santillan-Quiñonez
Smart Electronics Peru, Peru
Department of Research and Development
gerard.santillan@smart-elect.com / gsantil@ieee.org

Carlos Galup-Montoro
Federal University of Santa Catarina, Brazil
Integrated Cicuits Laboratory
carlos@eel.ufsc.br

***Abstract*—In this paper we show that silicon split-contact magnetoresistors with geometric dimensions of the order of the Debye length (L_D) can have much higher sensitivities than the usual devices with much larger length and width than L_D. Numerical simulations carried out with Comsol Multiphysics show that silicon n-type magnetoresistors with dimensions of the order of L_D can have magnetic sensitivity as high as $60\%/T$ which is ten times higher than usual sensitivities.**

I. Introduction

When a Hall plate is immersed in a magnetic field perpendicular to its plane, galvanomagnetic effects occur due to the Lorentz force acting on charge carriers [1]. The output signal can be a Hall voltage or a current imbalance. In the latter case, Split-Contact Magnetoresistors (SC-MR) [2]–[4] or split-contact magnetotransistors [1] are the usual devices.

Hall plates have been numerically modeled and experimentally characterized with many technologies and geometric shapes [5], [6]. However, the Hall plates usually studied have geometrical dimensions much larger than the Debye length (L_D). The reported experimental results show that the silicon SC-MR sensitivity is around $6\,\%$ of relative current imbalance /Tesla [2]–[4], [6], [7].

This work shows that it is possible to significantly increase the sensitivity of silicon SC-MRs using dimensions of the order of the Debye length. Numerical simulations carried out with COMSOL Multiphysics [8] enabled to confirm a simple analytical model of the sensitivity as a function of the ratio (geometric dimensions)/L_D.

This paper is organized as follows. Section II introduces the split-contact magnetoresistor and the definition of a current deflection quality parameter. Section III presents a simple analytical model of the current imbalance due to the magnetoresistance effect, Section IV summarizes the numerical simulation model, Section V discusses the simulation results, and finally, conclusions are given in Section VI.

II. Split-Contact Magnetoresistors

A standard rectangular SC-MR is a Hall plate with split contacts as shown in Fig, 1. Its active area is L in length and W in width, and the separation between contacts is dd. The sensitivity, S, of such devices is usually defined as

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

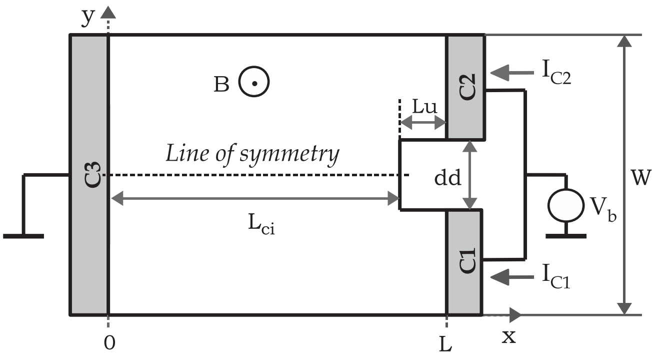

Figure 1. Schematic view of a standard rectangular split-contact magnetoresistor.

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

The importance of the current-line deflection effect in the performance of a SC-MR can be characterized using the normalized deflection-quality factor J_{DQn} defined as [9]:

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

where J_{By-ls} is the lateral current density on the line of symmentry, $\overline{J}_{Bx-L}$ is the average longitudinal current density on the contacts $C1$ and $C2$ (at $x = L$), and L_{ci} is the SC-MR length where the current imbalance due to the current-line deflection effect is generated.

III. Analytical Model

In an *n*-type SC-MR, the magnetic part of the Lorentz force $F_{Lm} = -q(v_d \times B)$, where v_d is the carrier drift velocity, concentrates charge carriers on a lateral side. Therefore, this side of the plate becomes negatively and the opposite positively charged, as Figure 2 shows [1]. The width of these charged regions are of the order of the Debye length L_D since it is the characteristic distance over which large departure from neutrality occurs in a uniformly doped material in equilibrium.

To obtain a simple analytical model, let us assume that the excess of electron density Δn and the defect of electron density $-\Delta n$ on each lateral side of the plate are constant over the lateral distance $m\,L_D$ (see Fig. 2), where m is a

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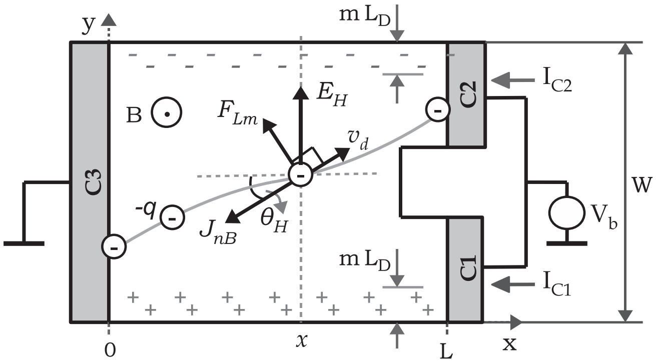


Figure 2. Current-lines deflection effect and variation of the carriers concentration on the lateral sides of a SC-MR in regions with extensions of the order of the Debye length L_D.

positive proportional factor. Applying the Gauss theorem, the Hall electric field E_H is

$$E_H = \frac{q\,\Delta n\, m\, L_D}{\epsilon_s} \tag{3}$$

where m is a positive number, q is the elementary charge and ϵ_s is the silicon permittivity.

The Hall electric field is $E_H = G\,\mu_{Hn} E_x B$, where G is the geometric correction factor [1], μ_{Hn} is the Hall mobility for electrons, $E_x = V_b/L$ is the longitudinal component of the electric field and V_b is the bias voltage (see Fig. 2). Applying these expressions in Equation 3, we obtain

$$\Delta n = \mu_{Hn} B \frac{\epsilon_s}{q} \frac{V_b}{L\, m\, L_D}\, G\,(L, W, L_D) \tag{4}$$

From the definition of $L_D = \sqrt{kT\,\epsilon_s/q^2/n}$, where k is the Boltzmann's constant and T is the absolute temperature, the electrons concentration is

$$n = \frac{k\,T}{q^2} \frac{\epsilon_s}{L_D^2} \tag{5}$$

Then, from Equations 4 and 5, we obtain

$$\frac{\Delta n}{n} = \mu_{Hn} B \frac{V_b}{\frac{kT}{q}} \frac{L_D}{m\,L}\, G\,(L, W, L_D) \tag{6}$$

On the other hand, the normalized current imbalance generated by the excess and defect of electrons in the lateral regions of width mL_D, is

$$\frac{\Delta I}{I} = 2 \frac{\Delta n}{n} \frac{m\,L_D}{W} \tag{7}$$

Then, from Equations 6 and 7, $\Delta I/I$ can be expressed as

$$\frac{\Delta I}{I} = 2\,\mu_{Hn} B \frac{V_b}{\frac{kT}{q}} \frac{L_D^2}{L\,W}\, G\,(L, W, L_D) \tag{8}$$

Equation 8 shows that the magnetoresistance effect is proportional to the ratio $L_D^2/(L\,W)$. Let us consider, as an example, a doping concentration of $N_D = 10^{15}\,cm^{-3}$ for which the Debye length is $L_D = 130\,nm$. For geometric dimensions as large as $100\,\mu m$, $L_D^2/(L\,W)$ is of the order of 10^{-6} while for dimensions of the order of L_D (such as $100\,nm$), $L_D^2/(L\,W)$ is of the order of the unity. The last case can be realized in advanced technologies such as FDSOI, where the doping concentration is $N_A = 10^{15}\,cm^{-3}$ [10]. Thus, the magnetoresistance effect in FDSOI can be 6 orders of magnitude higher than in conventional technologies.

IV. Numerical Simulation

In this work, n-type SC-MR were studied. Poisson´s equation and the continuity equation for electrons were solved in COMSOL Multiphysics $4.2a$ [8]

$$-\nabla \cdot (\epsilon \nabla \Psi) = q\,(p - n + N_D - N_A) \tag{9}$$

$$-\frac{1}{q} \nabla \cdot J_{nB} = -R_{SRH} \tag{10}$$

where Ψ is the electrostatic potential, p and n are the holes and electrons concentrations, respectively, N_D and N_A are the donors and acceptors concentrations, respectively, J_{nB} is the current density for electrons and R_{SRH} is the Shockley-Read-Hall generation-recombination ratio.

Considering an isothermal and stationary process with a magnetic field $B = 1\,T$ perpendicular to the magnetoresistor area, the total current density for electrons is

$$J_{nB} = (J_{n0} - \mu_{Hn}\,(J_{n0} \times B)) \left(1 + (\mu_{Hn} B)^2\right)^{-1} \tag{11}$$

where J_{n0} is the current density for electrons under a zero magnetic field. $J_{n0} = -q\,n\,\mu_n\,\nabla\Psi + qD_n \nabla n$ where μ_n is the electron mobility and D_n is the electron diffusion constant [1].

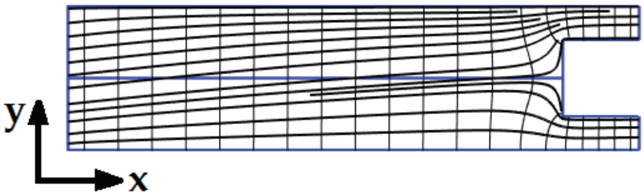
Dirichlet boundary conditions for the electrostatic potential, Ψ, and for electron density at ideal contacts ($C1$, $C2$ and $C3$) are considered (see Fig. 1). At the remaining boundaries, the normal components of electron current density and the field strength are assumed to be zero.

V. Results

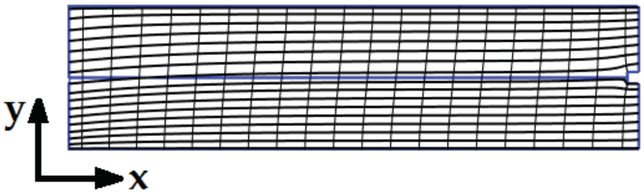
Applying a bias voltage $V_b = 5\,V$, SC-MRs with aspect ratio L/W from 0.5 to 4, electrons concentrations $N_D = 5E13\,cm^{-3}$ and $N_D = 5E17\,cm^{-3}$ and contacts split $dd = 0\,\mu m$ and $dd = 0.4\,\mu m$ immersed in a magnetic field of $1\,T$ were modeled in COMSOL Multiphysics [8]. A constant mobility $\mu_n = 1000\,cm^2/V/s$ was considered.

For $N_D = 5E13\,cm^{-3}$, the current and equipotential lines of SC-MRs with non-ideal split contacts $dd = 0.4\,\mu m$ and an aspect ratio $L/W = 4$ are shown in Figure 3. The Debye length L_D for this value of N_D is $\approx 0.574\,\mu m$. Figure 3(a) shows the case when $L = 3\,\mu m$ and $W = 0.75\,\mu m$, and Figure 3(b) shows the case when $L = 20\,\mu m$ and $W = 5\,\mu m$. In the first case, the current-lines deflection effect is more important than in the second one, due to the dimensions of the SC-MR are in the order of L_D. For the same reason, the variation of the electrons concentration n is more important in the first case than in the second one as Figure 4 shows.

According to [9], the sensitivity due to the current-lines deflection effect can be calculated by the average value of



(a) $L = 3\,\mu m$



(b) $L = 20\,\mu m$

Figure 3. Current and equipotential lines in split-contact magnetoresistors with non-ideal split contacts $dd = 0.4\,\mu m$ @ $N_D = 5E13\,cm^{-3}$, $L/W = 0.4$ and $B = 1\,T$.

the normalized deflection-quality factor J_{DQn}. Figure 5 shows the values of J_{DQn} for non-ideal split contacts $dd = 0.4\,\mu m$ with $N_D = 5E13\,cm^{-3}$ and $L/W = 4$. The average value of J_{DQn} for $L = 3\,\mu m$ and $L = 5\,\mu m$ is around $30\,\%/T$, but the sensitivity for these cases are $45\,\%/T$ and $48\,\%/T$, respectively. As a result, the current-lines deflection effect is not sufficient to characterize the sensitivity of SC-MR with dimensions of the order of the Debye length.

As Figure 4 shows, the variation of the electrons concentration on the lateral sides of a SC-MR is also important when its dimensions are of the order of L_D which also contributes to the current imbalance (see Equation 7).

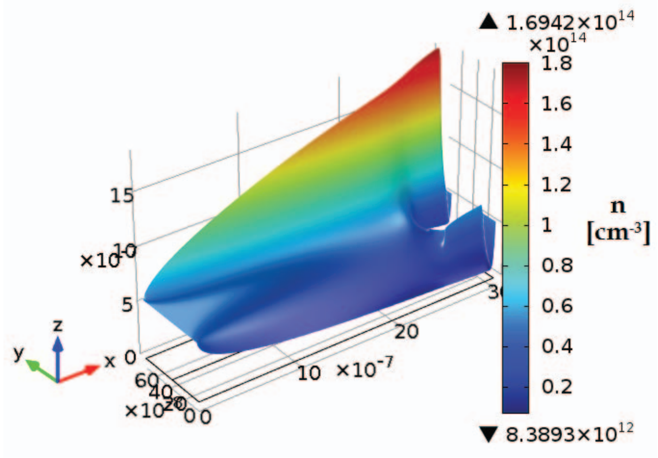
Figure 6 compares the cases of SC-MRs with ideally split and non-ideally split contacts. The sensitivity of a SC-MR decreases when its contacts are non-ideally split. In order to analyze the impact of the aspect ratio L/W on the sensitivity, SC-MRs with ideally split contacts were considered. The sensitivity of these SC-MRs decreases when the aspect ratio L/W decreases from 4 to 0.5 as Figure 7(a) shows.

Figure 7(b) compares the sensitivities of square devices with low ($N_D = 5E13cm^{-3}$) and high ($N_D = 5E17cm^{-3}$) doping. As it is clear from Figure 7(b), the sensitivity of a high doped device is the same as for a hundred times larger low doped device. Thus, the sensitivity is a function of L/L_D and W/L_D. Consequently, the function G in Equations 4, 6 and 8 has the form

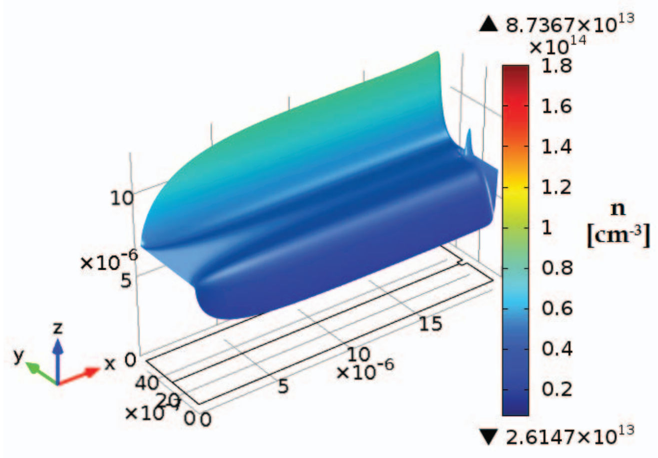
$$G = G\left(\frac{L}{L_D}, \frac{W}{L_D}\right) \tag{12}$$

VI. Conclusions

Simulation results show that the the sensitivity of Split-Contact Magnetoresistors (SC-MR) is a function of their geometric dimensions normalized to the Debye length (L_D). High-sensitivity SC-MRs are obtained when their width and length are of the order of L_D. For these devices, the carriers



(a) $L = 3\,\mu m$



(b) $L = 20\,\mu m$

Figure 4. Electrons concentration in split-contact magnetoresistors with non-ideal split contacts $dd = 0.4\,\mu m$ @ $N_D = 5E13\,cm^{-3}$, $L/W = 0.4$ and $B = 1\,T$.

concentration variation can produce a current imbalance more intense than the one produced by the current-lines deflection effect. Numerical simulation results show that sensitivities up to $60\,\%/T$ are obtained.

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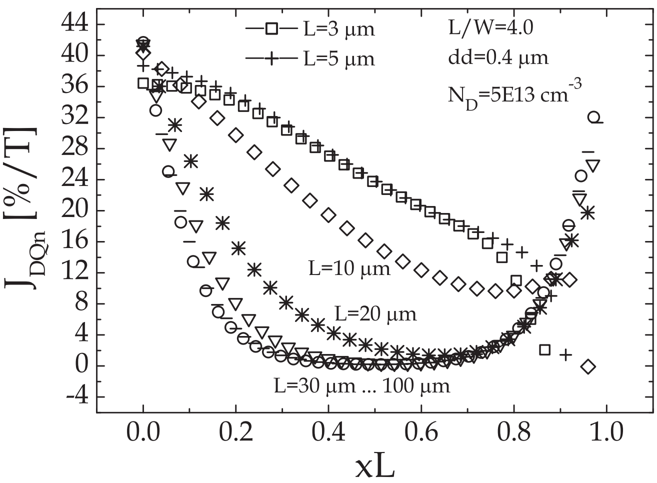

Figure 5. Normalized deflection-quality factor of split-contact magnetoresistors with non-ideal split contacts $dd = 0.4\,\mu m$ @ $N_D = 5E13\,cm^{-3}$, $L/W = 4$ and $B = 1\,T$.

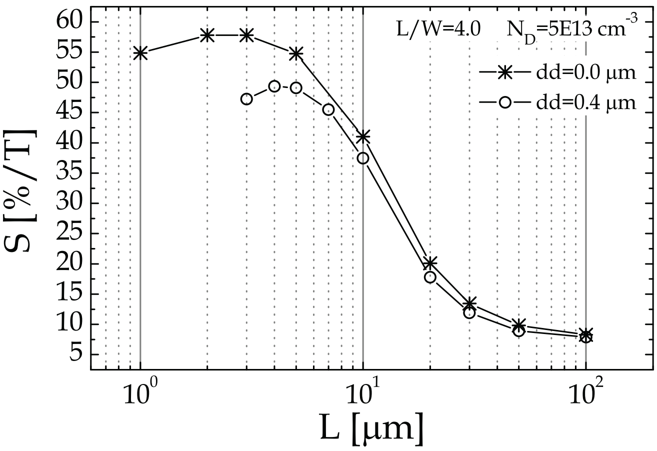

Figure 6. Sensitivity of split-contact magnetoresistors with ideal ($dd = 0\,\mu m$) and non-ideal ($dd = 0.4\,\mu m$) split contacts @ $L/W = 4$ and $B = 1\,T$.

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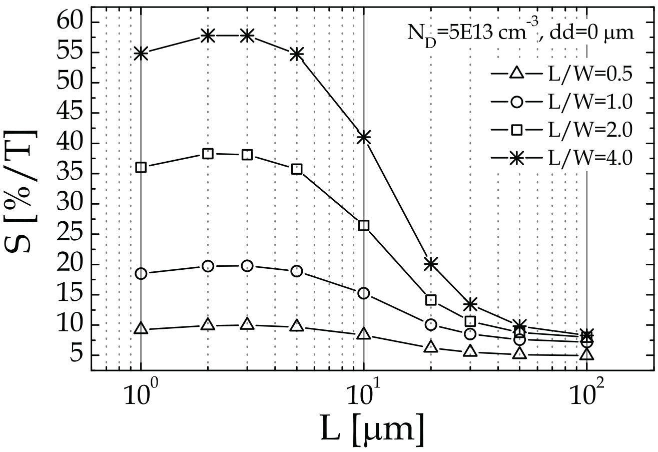
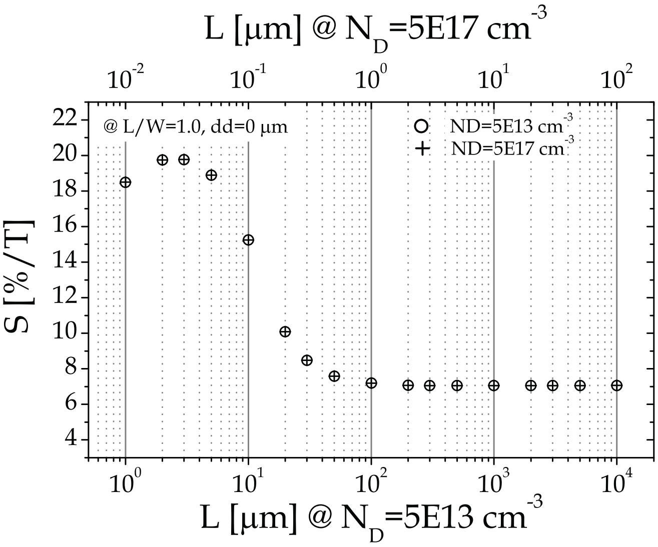


(a) For different aspect ratios L/W



(b) Sensitivity of magneto-resistors of square geometry ($L = W$). The dimensions of the devices with doping concentration of $5E17\,cm^{-3}$ ($5E13\,cm^{-3}$) are indicated on the top (bottom) horizontal scale.

Figure 7. Sensitivity of split-contact magnetoresistors with ideal split contacts $dd = 0\,\mu m$ @ $B = 1\,T$.