A Silicon Magnetic-Field Sensor: Low-Temperature Performance Evaluation

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ABSTRACT

A Si magnetic field-sensitive split-drain MOSFET has been used to study and analyze the effects of a magnetic field on the charge carrier conduction at liquid-nitrogen temperature. In magnetic field sensors (MFS), a key parameter is the Hall angle, which indicates the current line deviation due to the Lorentz force acting on the charge carriers. If temperature is lowered, the carrier mobility increases, therefore, an increase in carrier deflection is expected. To understand the internal deflection of carriers, and optimize the design of a magnetic field sensor, a semi-analytic model has been developed. Using such a model, a MFS has been fabricated and tested. The fi rst experimental results are presented in this work.

KEYWORDS: Transducers, magnetic field sensors, MOS technology, integrated circuits

1. INTRODUCTION

Semiconductor Magnetic Field Sensors exploit the galvanomagnetic effects, which are due to the action of the Lorentz force on the charge carriers [1]. In a phosphorous doped semiconductor material, the product of the electron mobility and the magnetic induction causes the sensitivity to magnetic fields [2]. Hence high charge carrier mobility is crucial for achieving high sensitivity. In contrast, let us consider as an additional option the III-V compound semiconductors. They are characterized by high carrier mobility; however, from the cost point of view, silicon is less expensive and offers the unique advantage of MFS compatibility to CMOS technology [3]. Recently, the MFS have experienced a tremendous growth [4]-[6], but the theoretical understanding of the electronic mechanisms underlying these devices has not kept up with this growth. There are several reasons by which the modeling of semiconductor devices in the presence of magnetic fields is required:

- In the bulk, the magnetic field determines a series of effects: changes in the motion of the carrier, the carrier distributions, and the electrostatic potential.
- The magnetic field originates asymmetries into the current equations. In contrast, the boundary conditions retain any zero-field conditions.

Due to the physical structure of a pure crystal, the most fundamental process by which a carrier is scattered is its interaction with the thermally generated vibrations of crystal atoms. At 77K, for instance, the electrical characteristics of the MFS-based MOSFET improve due to the increase in carrier mobility [7]-[11]. As the magnetic sensitivity is proportional to carrier mobility, the magnetic sensor structure may be able to detect magnetic fields below 1mT at 77K and, by optimizing its design, it would operate with low power consumption (μW).

This paper presents the performance evaluation of a silicon magnetic sensor taken into account the design of a split-drain MOSFET for low-temperature applications. In that sense, basics for the split-drain MOSFET is given in section 2. Experimental results are described in section 3. Finally, in section 4 the conclusion and future work are presented.

2. BASICS ON SPLIT-DRAIN MOSFET

When a magnetic field is applied to a flow of charge carriers (for instance, electrons) moving through a quasi-straight path, they tend to move according to a non-linear trajectory (see Fig. 1) [12]. The deflection of electrons under due to the Lorentz force can be calculated by solving the following equation B_B_

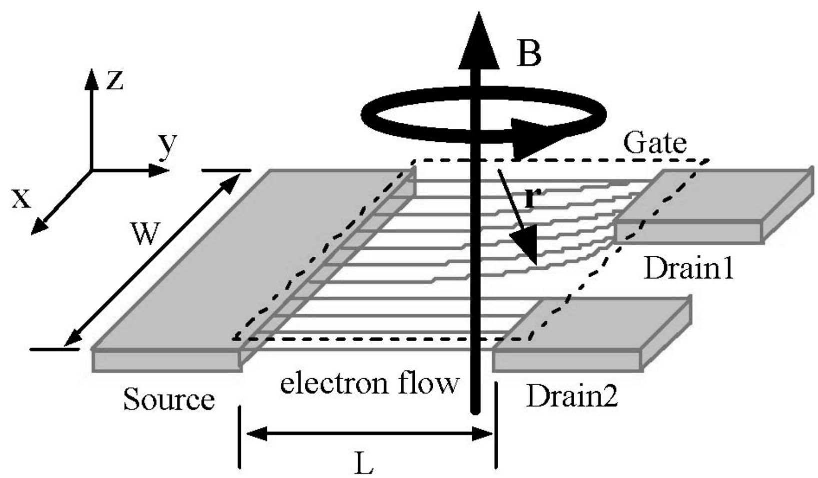

*Figure 1. Deflection of electrons under the influence of a magnetic field. Here **W** and **L** are the width and length of the MOSFET inversion layer, respectively. The electron deflection density is measured as a current difference given by (I_{DS1}-I_{DS2}).*

$$F_M = q\left(\upsilon_{drift} \times \vec{B}\right) \quad (1)$$

As we can see, the higher the drift velocity the higher the magnetic force that translates to a larger deflection. In practice, the distance that electrons deflect from the quasi-straight path is also related to the cyclotron radius

$$r_c = \frac{\upsilon_{drift} m_n^*}{q\left|\vec{B}\right|} \quad (2)$$

where $\mathbf{m}_n^*$ is the effective mass of electrons, **q** is the magnitude of electronic charge and $\upsilon_{\mathbf{drift\ t}}$ is the drift velocity.

It is known that the carrier deflection has been quantified using, as a measurement tool, the Hall effect. This procedure has been used since the end of the XIV century to measure the carrier deflection in extremely thin metallic plates. The last one is commonly named *Hall element*. In contrast, when the Hall effect is measured in a monolithic Hall element, a low mobility is detected because of the scattering process. On the other hand, the inversion layer of a MOS transistor can be used as a very thin hall element. However, to obtain a uniform structure, the inversion layer must be the channel of a MOSFET operating in the linear region ($V_D \ll V_G - V_T$) [1]. The effective mass of electrons is related to the channel mobility μ_s as

$$m_n^* = \frac{q}{s}\tau \tag{3}$$

where τ is the relaxation time. Substituting (3) in (2), we obtain

$$r_c = \frac{\upsilon_{drift}\,\tau}{\mu_s \vec{B}} = \frac{\upsilon_{drift}\,\tau}{\tan\Theta_H} \tag{4}$$

The previous relations, where Θ_H is the Hall angle, show that the current line deflection is strongly related to the charge carrier mobility. Hence, the higher the carrier mobility the shorter the curvature radius. For silicon, the charge carrier mobility increases as temperature is lowered; therefore, one expects a larger deflection at cryogenic temperatures. Since the carrier deflection is enhanced at low temperatures, we have designed a Split-Drain MOSFET, where the carrier deflection is measured as a drain current difference ΔI_{DS} (see Fig. 1).

In a MOSFET, when a magnetic induction vector perpendicular is applied to the inversion layer, it produces current imbalance $\Delta=(I_{D1}-I_{D2})$ between drains. In this work, the magnetic sensitivity is defined in terms of the relative drain current difference per magnetic induction [13], this is

$$S_R = \left|\frac{\Delta I_{DS}}{I_{DS}\,\vec{B}}\right| \tag{5}$$

where I_{DS} is the current supplied by the source region. To describe how the MOSFET works, we propose a semi-analytic model based on semiconductor physics and electromagnetic theory. Some considerations were taken into account [18]-[19]:

- A uniform magnetic-field induction is applied perpendicularly to the gate plane only, and
- the velocity of the ensemble of carriers along the channel is considered to have an average value $\upsilon_{drift\ t}$.

Additionally, the electric fields are labeled $\mathbf{E}_y$ and $\mathbf{E}_z$, where the first/second component is the longitudinal/perpendicular one. To quantify the electric field effect, we propose a model based upon Lorentz Force $\mathbf{F}=q(\mathbf{E}+\upsilon \times \mathbf{B})$ and Newton's second law. Starting by Lorentz force analysis, we obtain the force components as follows

$$m^* \frac{d^2x}{dt^2} = q\vec{B}_z \frac{dy}{dt} \tag{6a}$$

$$m^* \frac{d^2y}{dt^2} = -q\vec{B}_z \frac{dx}{dt} + q\vec{E}_y \tag{6b}$$

$$m^* \frac{d^2z}{dt^2} = q\vec{E}_z \tag{6c}$$

$$\vec{E}_y = \frac{V_{ds}}{L} \tag{6d}$$

$$\vec{E}_z = \frac{\sqrt{2}KT}{qL_D}\left\{e^{-\frac{\psi_s}{V_t}} + \frac{\psi_s}{V_t} - 1 + \frac{n_{p_o}}{N_b}\sqrt{e^{\frac{\psi_s}{V_t}} - \frac{\psi_s}{V_t} - 1}\right\} \tag{6e}$$

where ψ_s is the surface potential, $\mathbf{V_t}$ the thermal voltage, $\mathbf{k}$ the Boltzmann constant, $\mathbf{L_D}$ the Debye length, $\mathbf{N_b}$ the bulk doping concentration, $\mathbf{n_{po}}$ the concentration of electrons in thermal equilibrium in p-type semiconductor, and $\mathbf{T}$ is the absolute temperature. The set of equations (6) can be reduced to

$$m^* \frac{d^2 y}{dt^2} = -q\vec{B}_z \frac{dx}{dt} + q\frac{V_{ds}}{L} \tag{7b}$$

$$m^* \frac{d^2 z}{dt^2} = \frac{q\sqrt{2}KT}{qL_D}\left\{e^{-\frac{\psi_s}{V_t}} + \frac{\psi_s}{V_t} - 1 + \frac{n_{p_o}}{N_b}\left[e^{\frac{\psi_s}{V_t}} - \frac{\psi_s}{V_t} - 1\right]\right\} \tag{7c}$$

The trajectories of the carrier are obtained by solving (7) with the inverse Laplace transform method [20]-[21], with the following initial conditions:

$$x(0) = 0 \quad ; \quad \left.\frac{\partial x}{\partial t}\right|_{t=0} = 0 \tag{8a}$$

$$y(0) = 0 \quad ; \quad \left.\frac{\partial y}{\partial t}\right|_{t=0} = \upsilon_{drift} = \mu_s \frac{V_{ds}}{L} \tag{8b}$$

$$z(0) = 0 \quad ; \quad \left.\frac{\partial z}{\partial t}\right|_{t=0} = 0 \tag{8c}$$

Once the trajectories of the carrier have been obtained, the following step is to evaluate the time that electrons spend along the channel:

$$y(t_{final}) - L = 0 \tag{9}$$

Knowing that time, it is possible to find the carrier deflection under the influence of a magnetic field along the width of the MOSFET.

3. EXPERIMENTAL RESULTS

The MFS-based MOSFETs were fabricated on a P-type, (100) 3-in silicon wafers. All Split-Drain MOSFETs were fabricated in the 10µm CMOS MicroElectronics Laboratory of INAOE, at Tonantzintla, Puebla (Mexico). The measured threshold voltage at 300K was V_{TVN}=0.96V. For low-temperature testing, the device as well as an electromagnet were immersed in a liquid nitrogen vessel. All data were measured with the HP4156A Semiconductor Parameter Analyzer.

The carrier mobility *μ* and magnetic sensitivity S_r were estimated from our model and compared to extracted experimental results (see Fig. 2).

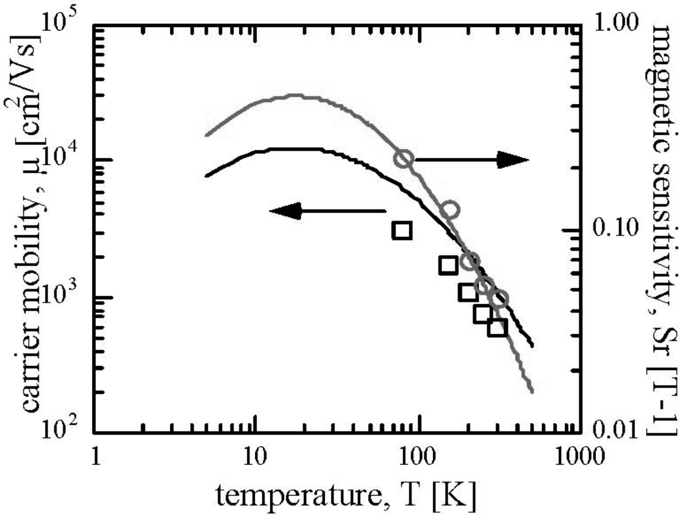

Figure 2. Measured (symbols) and calculated (lines) carrier mobility μ (squares) and magnetic sensitivity S_r (circles).

The increment in the deflection of current lines is confirmed by the augment in carrier mobility and magnetic sensitivity. The deflection of lines (cd) are calculated, and the differential current ΔI_D ($|I_{D1}-I_{D2}|$), is also measured at B=50mT as a function of temperature (see Fig. 3). As the deflection of current lines increases, due to the increment in carrier mobility, the differential current ΔI_D does too.

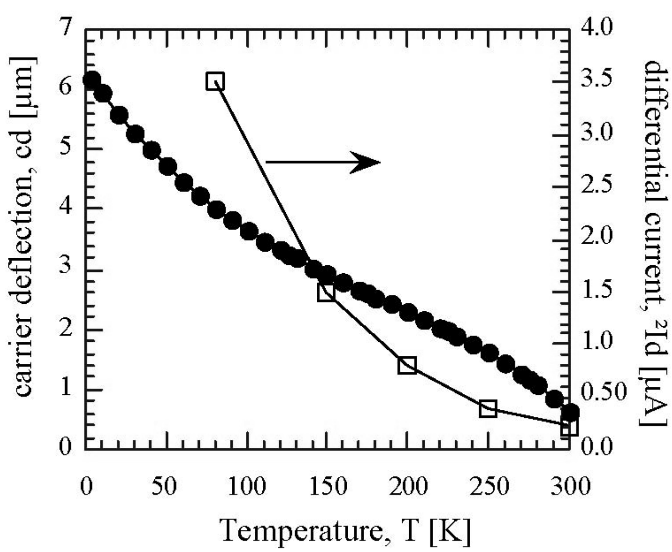

Figure 3. Calculated carrier deflection cd and measured differential current ∆Id at B=50 mT.

The differential current, which is result of the carrier mobility and the intensity of the magnetic field, is linearly dependent on the magnetic field itself. This is experimentally shown in Fig. 4. From the latest result, we also confirm the augment in magnetic sensitivity as temperature is lowered. Finally, the power consumption of this magnetic sensor is of about (5 V)(30 μA)=150 μW at 77K with a relative sensitivity S_r=0.23 T^{-1}, while at room temperature the power consumption is about 110 110 μW and S_r=0.045 T^{-1}. The magnetic sensitivity increases by a factor of 5.1 times when cooled down from room temperature to 77K. This implies that the minimum magnetic field B_{min} that can be sensed could be reduced down to the range of microTeslas (μT).

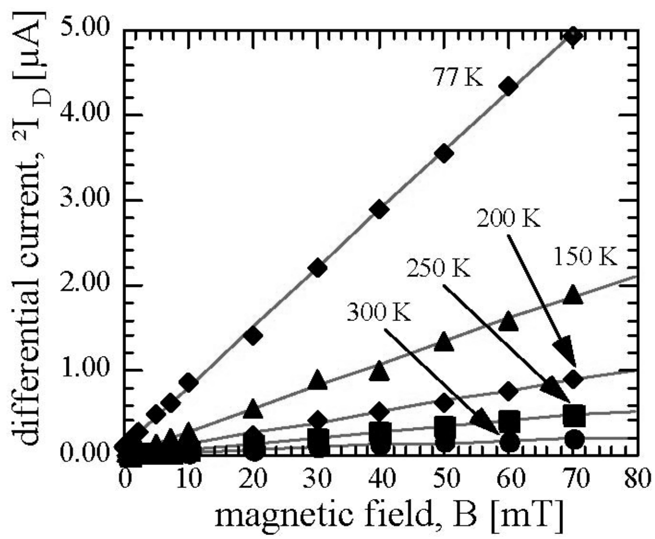

Figure 4. Measured ΔI_D current versus B for different temperatures. In this research the size of the split-drain transistor was W/L=100µm/400µm.

4. CONCLUSIONS

To study carrier deflection in Si under the influence of a magnetic field, a semi-analytical model, based on semiconductor physics has been developed. The model has been implemented with the MAPLE® software under a PC-based platform. The program allows us to solve the mentioned coupled equation system and give us a quick estimation on the carrier deflection. As a consequence, the carrier deflection is used to determine how many current lines deviate from one drain electrode to the other one. From this estimation, the differential current as well as the magnetic sensitivity can be calculated. This estimation, as a first approximation, is very useful to optimize the design of the MFS-based MOSFET.

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