Current-Density Analysis of Three-Dimensional Planar Magnetic-Field Sensor

R. A. Silva
Department of Electrical Engineering,
Centro Universitário da FEI, S. B.
Campo, SP, Brazil
+55 (11) 98219-8751
msn_fra@hotmail.com

A.L. Perin
College of Exact Sciences and
Technology, Universidade Metodista
de São Paulo, S. B. Campo, SP,
Brazil
andre_perin@yahoo.com.br

R. C. Giacomini[a]
Department of Electrical Engineering,
Centro Universitário da FEI, S. B.
Campo, SP, Brazil
renato@fei.edu.br

ABSTRACT

This work analyses the magnetic field influence on the current density of nMOS transistors, in order to evaluate their susceptibility to these fields in different directions. The devices were manufactured by MOSIS Educational Program, using ON Semiconductors 0.35 technology and simulated using Atlas three-dimensional device simulator. The variation in current density caused by the vertical component of the magnetic field, which is orthogonal to the channel plane, causes a lateral asymmetry in current density (*Hall effect*), while the horizontal component, which is parallel to the surface of the channel and orthogonal to the direction of the current, pushes the carriers to the interface between the semiconductor and the gate dielectric, or into the bulk, depending on the signal of the field. This variation explains the change in drain current values under magnetic fields that were found.

1. INTRODUCTION

The evolution of integrated circuits technology driven by the MOSFET (metal-oxide-semiconductor field effect transistor) devices have become the basis for development of the electronics industry. These devices have shown continuous improvement in terms of cost and performance and are used in virtually all electronic devices nowadays [1].

A perpendicular magnetic field applied to a carrier produces a force (Lorentz force) that is proportional to this field (B) and also to the drift velocity of the carrier (v_d). This resultant force is perpendicular to both the directions of the magnetic field and of the electric current. This effect is known as the Hall effect, and the force as the Lorentz force (F_L). Some devices use it in order to integrate magnetic sensors into standard logic integrated circuits [2,3]. Although the Hall effect is the most relevant, the magnetic field also modifies the current path along the vertical direction. This secondary effect may also be used for sensing purposes.

1.1 Magnetic Effects

Since the planar devices have only one gate plane, these magnetic sensors are sensitive to magnetic fields in two directions

A) The magnetic field's component that is orthogonal to the channel plane produces a Lorentz force parallel to the channel and orthogonal to the direction of the current, which causes a lateral asymmetry in current density. For the construction of sensors, such asymmetry can be easily exploited by strategic placement of source and drain contacts.

B) The magnetic field's component which is parallel to the surface of the channel and orthogonal to the direction of the current, force carriers to a path far from the interface between the semiconductor and the gate dielectric, or force them against this interface, depending on the signal of the field and current. Therefore the effect of the magnetic field on a MOS transistor depends on the direction of the Lorentz force (F_L) and the current direction.

The objective of this work is to analyze quantitatively the influence of magnetic field on the current density of a conventional transistor built in planar technology and its use as a magnetic field sensor.

2. DEVICE STRUCTURE AND SIMULATIONS

The simulated device is a transistor of 0.35 µm technology manufactured in the MOSIS project by ON Semiconductors. Figure 1 shows the NMOS structure described in 3D Silvaco Atlas Simulator [4]. The contacts were defined to maximize this effect, respecting the project rules. The simulated device has the following characteristics: channel length of 21,0 µm, channel width of 12,6 µm, source and drain length of 7,0 µm, gate oxide thickness of 13.8 nm, p-type channel doping concentration of 6×10^{16} cm^{-3}, n-type source and drain doping concentration of 10^{20} cm^{-3}. The simulations were performed for a low drain voltage bias ($V_{DS} = 100\ mV$) and the gate voltage (V_{GS}) ranging from 0 to 5.0 V.

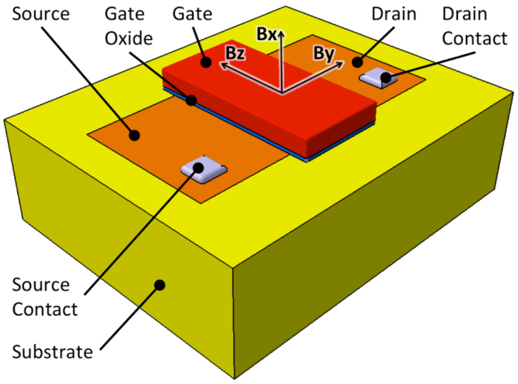

Figure 1. NMOS Transistor

The magnetic fields are applied in the directions *x*, *y* and *z*, positive and negative, with intensities of 100 mT, 200 mT and 500 mT.

3. RESULTS AND DISCUSSION

The intensity of the Lorentz force (F_L) is directly dependent on the angle φ between v_d and B, driven by the equation (1):

$$F_L = q.v_d.B.\sin\varphi \qquad (1)$$

Where:

q: is the electric charge;

v_d: is the speed of the electron density of an electric field from the gate;

B: is the module Magnetic Field;

$sin\varphi$: is the sine of the angle between v_d and B.

So, as expected, the magnetic field components in the direction of the current (y) do not influence the current path, neither the absolute current values, as shown in Figure 2.

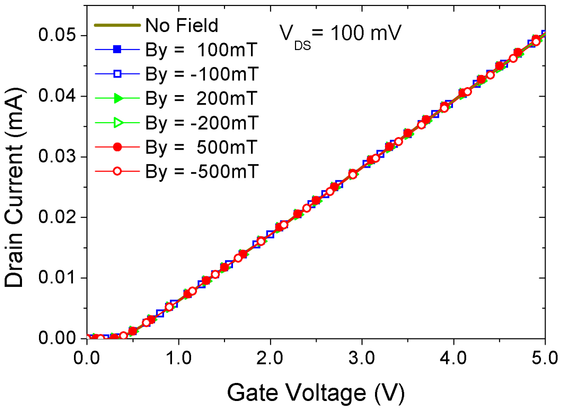

Figure 2. Drain current as a function of gate voltage for several values of magnetic field in y direction.

For magnetic field in x axis, the total current density at the center of silicon ($x = 1\ \mu m$), is presented in Figure 3, for three conditions: without magnetic field (Figure 3.a), with B = 500 mT in x direction (Figure 3.b) and with B = -500 mT in $-x$ direction (Figure 3.c). The x component of the magnetic field is orthogonal to the plane of the channel, and produces a Lorentz force parallel to the channel and orthogonal to the direction of the current, leading to a lateral asymmetry in the current density. In this case, a positive magnetic field raises the current density in the region closer to the drain and source contacts, what results in a drain current increase. In the case of a negative field, the opposite effect takes place, reducing the total current (Figure 3.c).

This variation in current density directly impacts the drain current and causes its modulation as shown in Figure 4, which shows the drain current as a function of the gate voltage for magnetic fields B = 100 mT, B = 200 mT, B = 500 mT in x direction compared to no magnetic field (B = 0).

The total current dependence on the magnetic field is higher for positive fields, due to the geometry, but this characteristic can be overcome by using differential circuits.

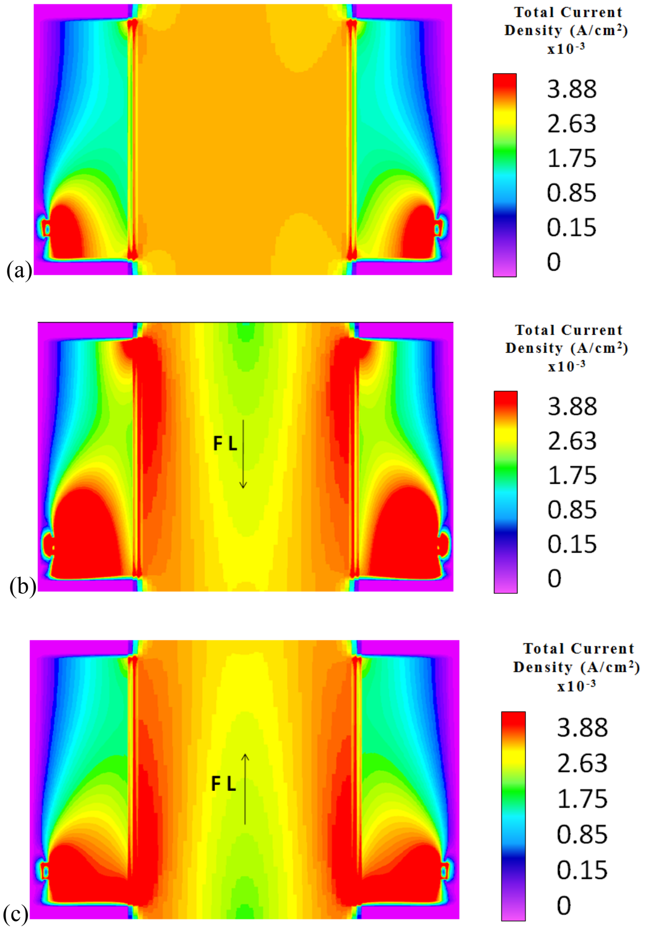

Figure 3. Total Current Density as a function of magnetic field in a horizontal cut plane at 1µm below the dielectric silicone interplace. (a) without magnetic field. (b) for B_x=500mT. (c) for B_x=-500mT.

Figure 5(a) shows the electron concentration without magnetic field in a vertical cut-plane. When the magnetic field is directed at $+B_z$, it is parallel to the surface of the channel and orthogonal to the electric field that drives the carriers movement, so it forces the carriers against the interface, then incrementing the current density in the surface. Figure 5(b) shows the same cut-plane for the magnetic field of 500 mT in $+z$ direction, and Figure 5(c) shows the effect for the opposite magnetic field.

The total drain current decreases when the carriers are forced against the interface, due to mobility degradation, which is highest near the surface, due to the highest transverse electric field, according to Shirahata´s mobility model [4]. Figure 6 shows the drain current as a function of the gate voltage for magnetic fields B = 100 mT, B = 200 mT, B = 500 mT in z direction and without magnetic field (B = 0).

For a drain-to-source voltage of 100 mV, the drain current in the absence of magnetic field grows linearly reaching 0.05 mA with V_{GS} = 5 V. Comparing the applied magnetic fields, we note that the magnetic field in the direction of y does not occur changes in current density due to the magnetic field is in the same direction of the drift velocity (Figure 3). The magnetic fields that most increase the drain current are the magnetic fields $+Bz$ and $+Bx$.

The magnetic field +*Bz* increases the drain current to approximately 2.85 mA (Figure 6), because exerts a Lorentz force that concentrates the carriers of electrons in +*x* direction in the channel region (Figure 5.b), and the magnetic field +*Bx* increases the drain current to about 0.13 mA (Figure 4), which exerts a Lorentz force leading to a lateral asymmetry in -*z* direction, closer to source and drain contacts (Figure 3.b). It was also observed that the magnetic fields which causes greater current reduction are the magnetic fields -*Bz* and –*Bx* (Figure 6).

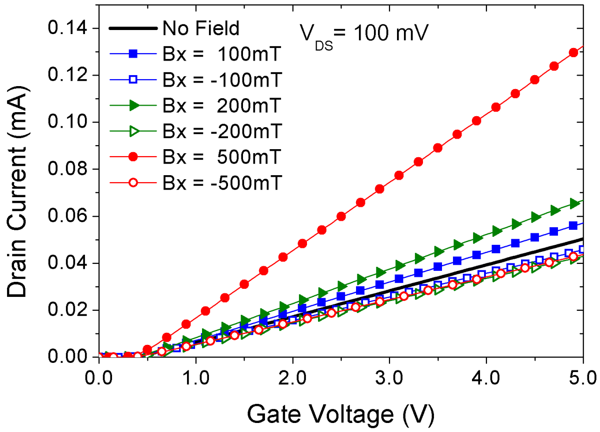

Figure 4. Drain current as a function of gate voltage for several values of the applied magnetic field in x direction.

4. CONCLUSION

The current density analysis allowed the observation of the lateral asymmetry of the device current, generated by the perpendicular magnetic field action. The magnetic field in +x direction increases the drain current to about 0.13 mA (VDS =5 V) and it decreases to about 0.045 mA when applied in -x direction. The magnetic field component which is parallel to the surface of the channel and orthogonal to the direction of the current pushes the carriers to the bulk, far from the gate dielectric/semiconductor interface, or against this surface, depending on the direction of the field and current. When applied in +z direction the magnetic field increases the drain current to approximately 2.85 mA and decreases the drain current close to 0 in the opposite direction. Besides that, a variation of the average length of the current path of carriers was noticed, which explains the change in drain current values, as well as its dependence on the signal and direction of the magnetic field.

5. ACKNOWLEDGEMENTS

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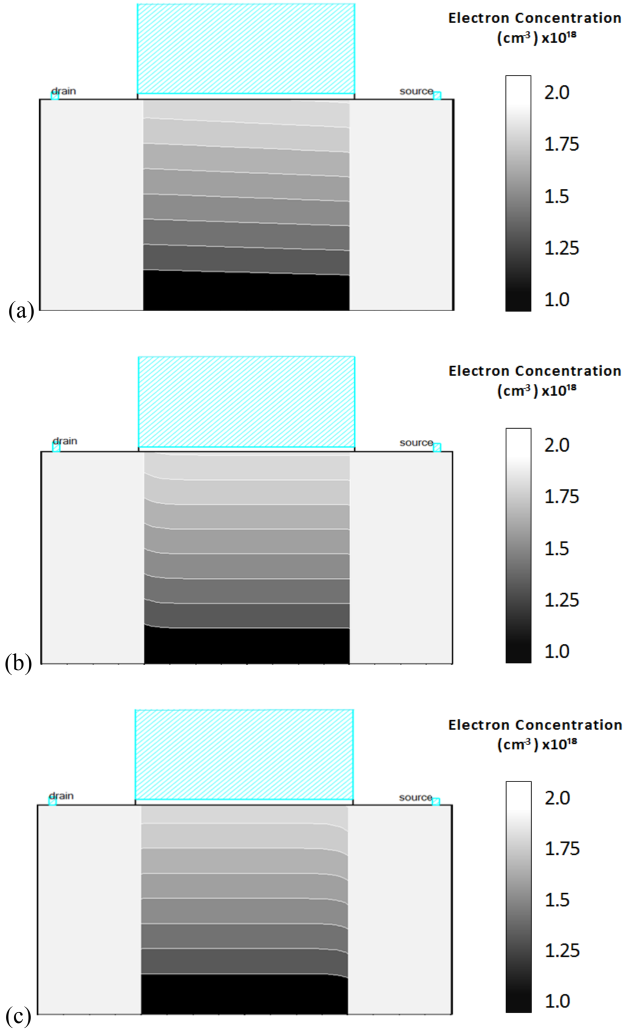

Figure 5. Electron Concentration in y direction for yz cut plane at aligned with source and drain. (a) without magnetic field. (b) for B_z = 500 mT. (c) for B_z = -500 mT.

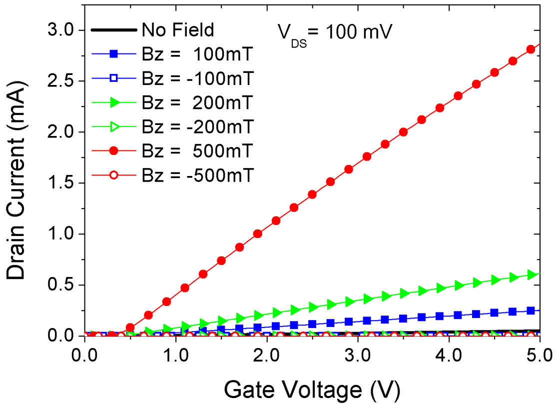

Figure 6. Drain current as a function of gate voltage for several values of the applied magnetic field in z direction.