Modeling the effect of strong magnetic field on n-type MOSFET in strong inversion

D.-V. Nguyen, L. Werling, C. Po, N. Dumas, M. Madec, W. Uhring, L. Hébrard
ICube – Université de Strasbourg / CNRS
23, rue du Lœss – Strasbourg, France
duc-vinh.nguyen@etu.unistra.fr

L. Fakri-Bouchet¹, J. Pascal², Y. Wadghiri³
¹ISA – Université Claude Bernard Lyon 1 / CNRS
5 rue de la Doua, Villeurbanne, France
²University of Applied Sciences and Arts Northwestern
Switzerland FHNW, Muttens, Switzerland
³NYU School of Medicine, 660 1st Ave, New-York, NY
10016 (USA)

Abstract—This paper presents an approach to model the effect of magnetic field on the electrical behavior of MOS transistor. It is shown that an out-of-plane magnetic field B induces a reduction of the channel conductivity, and that this reduction is proportional to the square of B and the square of the carrier mobility. Providing an accurate model of the mobility versus the gate to source and drain to source voltages in all working conditions of the transistor, the effect of B on the MOS transistor can be accurately modeled. Experimental data in strong inversion and linear regime are in very good agreement with the proposed model.

Keywords—MOS transistors, strong magnetic field, modeling

I. INTRODUCTION

Nuclear Magnetic Resonance (NMR) is widely used in analytical chemistry, and its application to Magnetic Resonance Imaging (MRI) for medical diagnostic is now of routine use. Due to the inherent low sensitivity of NMR, engineers target the development of NMR/MRI systems at very high magnetic field. Indeed, the Signal-to-Noise Ratio (SNR) of NMR experiments scales with the static magnetic field B_0 used to magnetize the sample. This SNR scaling ranges from B_0 to $B_0^{7/4}$, depending on the sample properties (conducting or not) and on the loss in the antenna used to pick-up the Free Induction Decay (FID) signal [1]. Another way to increase the FID signal is to use an antenna with a filling factor close to 100%, i.e. whose sensing volume is the same as the sample volume [2]. This condition is ideally obtained with micro-coils [3], which in addition helps in having a good homogeneity of B_0 , leading to high resolution NMR spectrum [4]. The last source of loss is the preamplifying electronics which is generally deported, the antenna being connected to the preamplifier through a transmission line [5]. So, in order to get the best sensitivity, it is of primary importance to have a very high B_0 field, and to use a micro-antenna with a co-integrated electronics, or with a preamplifier placed very close to the antenna. The electronics has thus to withstand this strong B_0 field. In analytical NMR, field up to 28.2T are in use [1]. Although the most widespread magnets for biomedical and preclinical MRI and MRS (MR-Spectroscopy) on animal models are 7T and 14.1T, magnets up to 21.1T are used in research [1]. Finally human-body MRI scanner are only approved for 1.5T and 3T, however in brain research, static fields up to 10.5T are in use [1].

Twenty years ago, a few publications have reported parasitic effects on the electrical characteristics of Field Effect Transistors [6] [7]. However no research has been performed on the topic, certainly because the applications of such very high fields are limited. With the advent of ultra-high field NMR/MRI systems [1], and the trend to place the electronics inside the field, close to the sample, studying the effect of strong field on the electrical characteristics of MOS transistors becomes relevant. We have recently published a paper showing that under an out-of-plane magnetic field of $B = 7\text{T}$, i.e. a 7T field perpendicular to the plane of the chip, the current and the transconductance of NMOS transistors exhibiting a high W/L ratio may be reduced by up to 7% [8]. In addition, this current and transconductance reduction is proportional to $\tan(\mu_n^2 \cdot B^2)$, where μ_n is the mobility of electrons in the MOS channel. In silicon, where μ_n is low (typically between 300 and 400 $\text{cm}^2/\text{V}\cdot\text{s}$), for field below 15 T, $\tan(\mu_n^2 \cdot B^2) \approx \mu_n^2 \cdot B^2$. As a consequence a 28% reduction of the MOS transconductance is expected under 14 T, which may be very challenging in terms of circuit design. We have also shown that for transistors with a high W/L (small L/W), which is common in circuit design, the current reduction comes from the deflection of the current lines inside the channel due to the Lorentz force ($-q \cdot v \times B$) acting on the carriers [8]. Here q is the elementary electric charge, v is the drift velocity of electrons, and the symbol $\times$ denotes the vector cross product. Although our first experimental setup was very basic, we were able to show in [8] that the current reduction only depends on the out-of-plane component of the magnetic field, and that, as expected, the tilt angle $\mu_n^2 \cdot B^2$ depends on the gate to source voltage through the electron mobility reduction with V_{GS} , i.e. with the transverse electric field. A very simple model was also proposed where the length of the transistor is changed as $L \cdot \cos(\mu_n^2 \cdot B^2)$ in order to take the current line tilt into account. However, as shown below, this model is too much simplified. In this paper we push forward our study with an improved experimental setup, and we pave the way towards the development of a transistor model able to help the designer in taking into account the effect of strong magnetic fields on integrated circuits. Focus is put on transistors with a high W/L ratio since they are the most affected by magnetic field. A brief discussion on long transistors, i.e. with a small W/L is also given.

Section II settles the theoretical background necessary to guide the experiment and to develop the model. Section III describes the improvement in the experimental setup and the

measurement results. Section IV discusses these results and the limitation of the model. It is followed by a conclusion.

II. THEORETICAL BACKGROUND

A. Geometrical magnetoresistance

At least in linear regime, the MOS channel can be seen as a conventional linear resistance, where the density of carriers n is roughly constant (for a given V_{GS}), as well as the longitudinal electric field E_l , that is given by V_{DS}/L where V_{DS} is the drain to source voltage. When a magnetic field B is applied, the moving electrons feels the Laplace force:

$$F_L = -q \cdot E_l - q \cdot v \times B$$

The energy they acquire with F_L is lost in the silicon lattice through scattering, and the resulting equilibrium leads to an average electron velocity proportional to F_L :

$$v = \frac{\mu_n}{q} \cdot F_L = -\mu_n \cdot E_l - \mu_n \cdot v \times B$$

where μ_n is the above mentioned electron mobility. The current density is thus:

$$j = n \cdot q \cdot v = n \cdot q \cdot \mu_n \cdot E_l - \mu_n \cdot j \times B \quad (1)$$

Using the relation $(U \times V) \cdot W = (U \cdot V) \cdot W - (V \cdot W) \cdot U$, where $\cdot$ stands for the scalar product, and U , V , and W are three vectors, expression (1) can be solved under perpendicular magnetic field, i.e. $E_l \cdot B = 0$, leading to:

$$j = \frac{\sigma_n \cdot E_l + \mu_n \cdot \sigma_n \cdot (E_l \times B)}{1 + \mu_n^2 \cdot B^2} \quad (2)$$

where $\sigma_n = n \cdot q \cdot \mu_n$ is the silicon conductivity.

Fig.1. a) short transistor, b) long transistor, under B .

As seen in figure 1-a, for a short channel, i.e. a transistor with a small L/W ratio, the drift electric field in the channel, E_l , remains along the x axis, i.e. perpendicular to the equipotential lines formed by the source and drain that are assumed as ohmic contacts (see figure 1-a for axis definition). Expression (2) shows that the drift current is no longer along E_l . It is tilt by the angle θ , where $\tan(\theta) = \mu_n \cdot B$ and can be decomposed as a longitudinal component, j_x , and a perpendicular component, j_y :

$$j_x = \frac{\sigma_n \cdot E_l}{1 + \mu_n^2 \cdot B^2} \quad \text{and} \quad j_y = \frac{\mu_n \cdot \sigma_n \cdot (E_l \times B)}{1 + \mu_n^2 \cdot B^2} \quad (3)$$

For a short channel the electrons which tend to accumulate on the lateral side, due to j_y , flow immediately back through the source and drain ohmic contacts. On the contrary for long transistors, i.e. when L/W is high, in the center of the channel the resistive path for the electrons to flow back through the source and drain is too high, and electrons accumulate on one side of the channel where a negative surface charge appears, while the other side exhibits a deficit of electrons, i.e. a positive surface charge. This brings an electric field along y , the Hall field, and an electric force opposite to the Lorentz force. Finally, both forces are balanced, and the current lines remain along x in the center of the channel (see figure 1-b) while the electric field E_l is no longer aligned with x . A Hall voltage appears between the lateral sides of the MOS channel [9].

The only current density component leading to a drain-source current I_{DS} is j_x . So, for a small L/W transistor, the expression of j_x in equation (3) shows that under a magnetic field, the channel conductivity, respectively the carrier mobility, is reduced to an effective conductivity $\sigma_n(B)$, respectively an effective mobility $\mu_n(B)$, given by:

$$\sigma_n(B) = \frac{\sigma_n}{1 + \mu_n^2 \cdot B^2} \quad \text{and} \quad \mu_n(B) = \frac{\mu_n}{1 + \mu_n^2 \cdot B^2}$$

As a consequence, for a small L/W transistor, the transconductance parameter $KP_n = \mu_n \cdot C_{ox}$ has to be changed in:

$$KP_n(B) = \frac{\mu_n}{1 + \mu_n^2 \cdot B^2} \cdot C_{ox} = \mu_n(B) \cdot C_{ox}$$

in the expression of the I_{DS} current, where the parameter C_{ox} is the gate capacitance per unit area.

For long transistors, i.e. with a high L/W , rewriting equation (1) as:

$$E_l = \frac{j}{\sigma_n} + \frac{\mu_n}{\sigma_n} \cdot j \times B$$

shows that in the center of the channel, where j is aligned along x , the electric field is now the sum of a x -component given by $E_x = j/\sigma_n$ and a y -component given by $E_y = (\mu_n/\sigma_n) \cdot j \times B$. As a consequence, in the center, the channel conductivity is unaffected by the magnetic field and remains equal to σ_n . Of course, close to the drain and the source, this is no longer valid since the current lines are deflected (see figure 1-b).

To summarize, the deflection of the current lines leads to an effective mobility of the carriers in the calculation of I_{DS} given by $\mu_n/(1 + \tan^2 \theta)$ where θ is the deflection angle. For small L/W transistors, θ remains constant, equal to $\mu_n \cdot B$ (we assume $B < 15T$), and I_{DS} is simply reduced by the reduction factor (RF):

$$RF = 1/(1 + \mu_n^2 \cdot B^2) \approx 1 - \mu_n^2 \cdot B^2$$

For high L/W transistor, θ varies along the channel and the computation of I_{DS} is more complex. It will not be addressed in this paper.

It is worth to notice that our first model [8], where we just modified the length of the transistor, i.e. L changed in $L \cdot \cos \theta$, is too much approximate since it leads to a current reduction factor of $1 - \mu_n^2 \cdot B^2/2$.

However, whatever the model, the Relative Reduction Factor, RRF , is proportional to $\mu_n^2 \cdot B^2$:

$$RRF = \frac{I_{DS}(B) - I_{DS}}{I_{DS}} \approx -\mu_n^2 \cdot B^2$$

It thus depends on the carrier mobility which is well known to depend on V_{GS} and V_{DS} . The effect of magnetic field on MOS transistors is thus depending on the transistor biasing, and in order to derive a compact model of the transistor behavior, we have to consider the mobility dependence on V_{GS} and V_{DS} .

B. Electron mobility

In a MOS channel, electron mobility is known to depend on the longitudinal electric field, i.e. on V_{DS} , and on the transverse electric field, i.e. on V_{GS} .

- Mobility dependence on V_{DS}

The longitudinal electric field E_l leads to the electron drift from source to drain. Under high field, the electron drift velocity, $v = \mu_n \cdot E_l$ saturates, and the mobility is reduced. In silicon, a good model for the dependence of μ_n on E_l is given by [10]:

$$\mu_n(E_l) = \frac{\mu_0}{(1 + (\mu_0 \cdot E_l / v_{SAT})^\beta)^{1/\beta}} \quad (4)$$

where μ_0 is the mobility at low field (from 300 to 400 cm²/V·s), v_{SAT} is the saturation velocity, and β a fitting parameter. Typical values for β and v_{SAT} in a n-type channel are [11]:

$$\beta = 2 \quad \text{and} \quad 4 \cdot 10^6 \text{ cm/s} < v_{SAT} < 8.5 \cdot 10^6 \text{ cm/s}$$

For short transistors, i.e. with a low L/W , E_l can be approximated by $E_l = V_{DS}/L$. So, in our model, we will use the following expression for $\mu_n(V_{DS})$:

$$\mu_n(V_{DS}) = \frac{\mu_0}{\sqrt{1 + (\mu_0 \cdot V_{DS} / (v_{SAT} \cdot L))^2}} \quad (5)$$

where μ_0 and v_{SAT} will be determined from the experimental measurements.

- Mobility dependence on V_{GS}

The transverse electric field E_t , leading to the creation of the electron channel, pushes the electrons towards the SiO₂/Si interface where the carriers feel enhanced scattering effects due to interface states and surface roughness [11]. As a consequence, their mobility is reduced when V_{GS} increases.

E_t can be expressed as [11]:

$$E_t = \frac{Q_B(V_\sigma)}{\epsilon_{Si}} \cdot \left(1 + \frac{V_{GS} - V_{TH}}{V_{ov}}\right) \quad \text{with} \quad V_{ov} = 2 \cdot Q_B(V_\sigma) / C_{ox}$$

where V_{TH} is the threshold voltage of the transistor, and V_{ov} stands for the overdrive voltage above which the degradation of the mobility by the transverse field dominates. The depletion charge Q_B below the channel depends on the surface voltage V_σ at the SiO₂/Si interface. However when the transistor is in linear regime, V_σ is roughly constant, and thus V_{ov} . Under strong transverse field, many experiments show that $\log(\mu_n)$ decreases linearly with $\log(V_{GS} - V_{TH})$. It means a mobility dependence on $V_{GS} - V_{TH}$ proportional to $1/((V_{GS} - V_{TH})/V_{ov})^\delta$ where δ is

a fitting parameter that depends on the interface states density and substrate doping [11]. However, when $V_{GS} - V_{TH}$ is low, typically below 1V from our own measurements, this simple dependence on V_{GS} cannot fit the measurements since at small $V_{GS} - V_{TH}$ the mobility becomes roughly constant. We thus propose to use an equation similar to equation (4) to model the mobility dependence on V_{GS} :

$$\mu_n(V_{GS}) = \frac{\mu_0}{(1 + ((V_{GS} - V_{TH})/V_{ov})^a)^b} \quad (6)$$

where μ_0 , V_{ov} , a , and b are determined from the experiments.

III. EXPERIMENTS

A. Experimental setup

As for our first measurements, the chip was placed in a 7T Bruker BioSpec 70/30 MRI scanner [8]. However, the setup was drastically improved. First the chip was no longer encapsulated in a package but directly bonded on a small PCB, and no BNC connector, nor coaxial cable were used. This choice minimizes the influence of the setup on the direction of the magnetic field seen by the chip. In addition a plexiglass holder was etched by laser cutting to be able to precisely place the chip inside the MRI bore (see figure 2). The remaining measurement procedure is the same and all details may be found in [8].

Fig. 2. The chip is placed in its plexiglass holder and tilt by $\beta = 30^\circ$ with respect to the $B_0 = 7T$ field direction.

B. Measurements

For sake of space, the results presented here are focused on a two-finger NMOS transistor whose L/W is 0.7/20, i.e. each finger sizes 0.7/10 and features a small L/W . As in [8], $I_{DS}-V_{GS}$ characteristics were recorded for a varying V_{DS} , from 10mV to 500mV by step of 20mV. The transconductance dI_{DS}/dV_{GS} was computed versus V_{GS} , and the slope $\alpha = \mu_n \cdot C_{ox} \cdot W/L \cdot V_{DS}$ was determined at V_{GS0} for which the transconductance is maximum. The threshold voltage was also determined [8]. Finally, the slope α was computed for $V_{GS} - V_{TH}$ varying from 150mV to 1.1V, i.e. under strong inversion condition, by step of 20mV. Then the RRF was calculated as:

$$RRF = \frac{\alpha(B) - \alpha}{\alpha} \quad \text{i.e.} \quad RFF = \frac{\mu_n(B) - \mu_n}{\mu_n} \approx -\mu_n^2 \cdot B^2$$

Figure 3 shows RRF at V_{GS0} , i.e. at maximum transconductance, versus V_{DS} for three orientations of the chip, $\beta = 90^\circ$, 60° , and 30° where β is defined in figure 2. Using equation (4), a fitting of the data at $\beta = 90^\circ$ leads to the parameters $\mu_0 = 371 \text{ cm}^2/\text{V} \cdot \text{s}$ and $v_{SAT} = 4.9 \cdot 10^6 \text{ cm/s}$, in good accordance with [11]. Then the same parameters were used

to compute the expression $-\mu_n^2 \cdot B^2 \cdot \sin^2(B)$ that should fit the data recorded when the chip is placed at $\beta = 60^\circ$ and 30° . As seen in figure 3, the model is in very good agreement with the experiments, confirming that the transistor is only sensitive to the magnetic field component perpendicular to the chip plane.

Fig. 3. RRF at maximum transconductance versus V_{DS} for three β angles.

Figure 4 shows RRF for the chip at $\beta = 90^\circ$ computed versus $V_{GS} - V_{TH}$ at $V_{DS} = 10\text{mV}$, as well as its fitting by the analytical expression $-\mu_n^2 \cdot B^2$ where equation (6) is used for $\mu_n(V_{GS})$. Here again, the model is in very good agreement with the experimental data.

Fig. 4. RRF versus $V_{GS} - V_{TH}$ at $V_{DS} = 10\text{ mV}$

IV. DISCUSSION AND MODEL LIMITATION

This study shows that under a magnetic field B perpendicular to the chip, the main parameters of the circuit designers, i.e. the biasing current I_{DS} and the transconductance g_m feature a relative reduction equal to $-\mu_n^2 \cdot B^2$. It is also shown that the dependence of μ_n on V_{GS} and V_{DS} has to be taken into account to accurately model the magnetic field effect. As long as the transistor remains in linear regime and strong inversion, the proposed model, where μ_n is given by the product of equation (5) and (6) allows an accurate prediction of the magnetic field effect for short transistors.

In saturation, expression (5) may be used provided that the saturation voltage $V_{DSSat} \approx V_{GS} - V_{TH}$ is substituted for V_{DS} . However expression (6) is no longer valid since the surface voltage V_σ is no longer constant along the channel, and V_{ov} depends on V_{DSSat} . Finally, for long transistor, i.e. exhibiting a high L/W , RRF is reduced and a correction factor has to be introduced in order the model the current line deflection which varies along the channel.

V. CONCLUSION

This paper has presented our first step towards the modeling of the effect of strong magnetic field on the electrical behavior of MOS transistors. It is shown that for short transistors, the biasing current and the transconductance are reduced by a factor of $-\mu_n^2 \cdot B^2$. Although only valid when the transistor is in linear regime and in strong inversion, the proposed approach may be used to model the transistor behavior in saturation and/or in moderate and weak inversion, as soon as an appropriate model for the mobility is used. For long transistors, a geometrical factor depending on L/W has to be introduced. These developments will be the subject of future work.

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