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Compact Model of Dual-Drain MAGFETs Simulation

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Abstract—This work offers a study of new simple compact model of dual-drain Magnetic Field Effect Transistor (MAGFET) including geometrical effects and biasing dependency. An explanation of the sensitivity is investigated, involving carrier deflection as the dominant operating principle. Finally, model verification with simulation results is introduced to ensure that acceptable error of 2% is achieved.

Keywords—MAGFET, Modeling, Simulation, Split-drain.

I. Introduction

MAGNETIC field sensors are essential in modern life. Numerous applications of magnetic field sensors in different fields of engineering, science, and industry [1] rely on the performance and reliability of magnetic sensors. The list of magnetic sensor applications includes, but is not limited to, position-sensing, non-contact switching [2], vehicle detection [3], navigation [4], mineral prospecting [5], brain function mapping [6], contactless temperature measurement [7], wireless sensor network [8], earth magnetic field [9], etc. As an example, there can be as many as 40 magnetic field sensors in a modern automobile which are used for various purposes [10]. Depending on application, different types of magnetic field sensors are employed [11-13]. Designing such sensors is virtually impossible without device simulation tools which help to predict sensor behavior [14] before actual sensors are fabricated. Device simulation [15] has become very important, because, it is almost cheaper than performing experiments, and provides insight into the internal physical mechanisms associated with device operation for two-dimensional [16] and three-dimensional simulation. Moreover, finding compact model of the MAGFET is a good step in the circuit modeling and simulation areas. Recently, the MAGFET sensors have experienced an exponential growth, but the theoretical understanding of the electronic mechanisms underlying these devices has not kept up with this growth. Some efforts have been developed using numerical model such as finite element, Garlekin's residual method and finite difference scheme [17] that are accurate but unfortunately obscure to explain device operation. Other works propose a semi-analytic model [18-20] based on semiconductor physics and electromagnetic theory but it can not be linked with circuit simulation tools because it is implemented with MAPLE software by inverse Laplace. S. Liu and J. Wei [21] are introduced other approach that was SPICE macro model, where the magnetic control current source is used to model the current deviation caused by the external magnetic field. Hence, the drawback is the fact that sensitivity is included as an external model parameter and its dependence on the device operational point is usually included as polynomial approximation of measured data. Another study presents the influence of the gap between the two drains on the channel potential profile [22] through a combination of numerical simulation and analytical modeling using a symbolic computation tool. The work was reported to be accurate but it is complicated model. Another model based on empirical relation [23] dose not reflect the physical behavior and geometrical effects of the device. In all these works the authors found out that the experimental results are in good agreement with their model predictions. In this paper we propose a new simple model that includes geometrical effects and biasing dependency on the sensitivity. This paper is organized as; the modeling of the influence of the magnetic field on the current is described in section III and the feasibility of the proposed model and its working limits are compared with the simulation results in section IV.

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II. Split-Drain Magnetic Sensor Basics

A split-drain magnetic sensor device is a MOSFET with two or three adjacent drain regions replacing the conventional single-drain region. A split-drain MOSFET with two drains Drain1 and Drain2 with the same length D and separated by drain gap d is shown in Fig. 1 (Note: As usual the electron current flow is used not the conventional one). Both drains must have the same length, otherwise an undesirable offset will appear between both drain currents. In the absence of a magnetic field (balance condition), the drain currents are equal because of the device symmetry. The application of a magnetic field perpendicular on the chip surface will produce an imbalance in the two drain currents due to the deflection effect by Lorentz force, the current lines in the device skew, as shown in Fig. 2. Due to current deflection, Drain1 current increases but Drain2 current decreases.

III. Proposed Compact Model of Magnetic Effect

A model of the MAGFET can be developed based on the assumption that a magnetic flux density B, causes a linear displacement of the carriers in the channel. To obtain the magnetic response of the MAGFET we shall only consider

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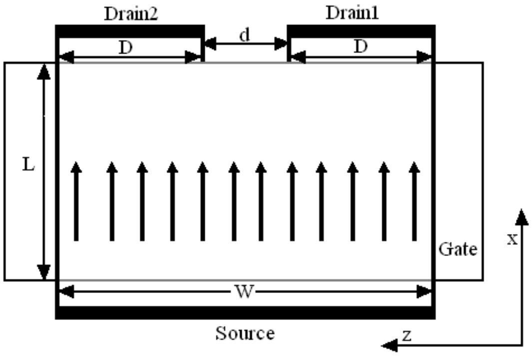

Fig. 1. Dual-drain MAGFET structure.

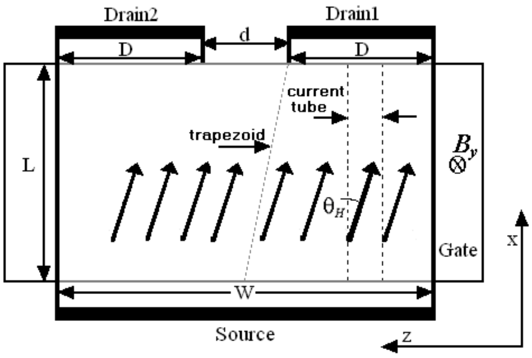

Fig. 2. The presence of magnetic field on Dual-drain MAGFET.

the action of the magnetic field on one half of the device as shown in Fig. 2. This half looks like a trapezoid because the length of Drain1 is not equal the length of the source. For simplicity a current tube, that has a flow of electrons from the source to the drain, which consists of constant cross-sectional area with a uniform current density [24 -26] as shown in Fig. 3-a.

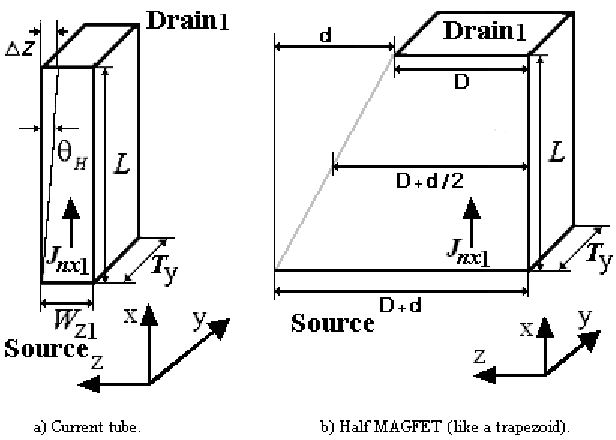

Fig. 3. The current tube approximation.

The current density within the tube is J_{nx1}, $W_{z1}$is the tube width, $T_y$is the channel thickness and L is the channel length. We assume that the drain gap d is << W. The current collected by Drain1 at zero magnetic field for the current tube can be expressed as:

$$I_{10} = J_{nx1}\ T_y\ W_{z1} \tag{1}$$

To obtain the current change ΔI_1due to a magnetic field B_y, the flow will be deflected through an angle θ_H, as [24]

$$tan(\theta_H) = \mu_H\ B_y = \frac{\Delta z}{L} \tag{2}$$

as shown in Fig. 3-a. Where μ_H, is the electron Hall mobility. The change in I_1 due to the deflection can be calculated by

$$\Delta I_1 = J_{nx1}\ T_y\ \Delta z \tag{3}$$

Using (2) and (3) we obtain

$$\Delta I_1 = J_{nx1}\ T_y\ \mu_H\ B_y\ L \tag{4}$$

Using (1) and (4) to express J_{nx1}, as a function of I_{10}, as

$$\Delta I_1 = I_{10}\ \mu_H\ B_y\ \frac{L}{W_{z1}} \tag{5}$$

extend (5) to cover the trapezoid with $W_{z1} = D + d/2$ as shown in Fig. 3-b to get the change due to B_y in the Drain1 current as

$$\Delta I_{d1} = I_{d10}\ K \tag{6}$$

where, K = $\mu_H\ B_y\ \frac{L}{D+\frac{d}{2}}$ and $I_{d10} = J_{nx1}\ T_y\ (D + \frac{d}{2})$
the drain currents including the change due to B_y are

$$I_{d1} = I_{d10}\ (1 + K) \tag{7}$$

$$I_{d2} = I_{d20}\ (1 - K) \tag{8}$$

at $B_y = 0, I_{d10} = I_{d20}$, so the total drain current is

$$I_{D0} = I_{d10} + I_{d20} = 2\ I_{d10} \tag{9}$$

the current difference ΔI_D due to B_y is

$$\Delta I_D = |I_{d1} - I_{d2}| = 2\ I_{d10}\ K \tag{10}$$

The relative sensitivity is defined as [27]

$$S = \frac{\Delta I_D}{I_{D0}\ B} = \frac{|I_{d1} - I_{d2}|}{(I_{d10} + I_{d20})\ B} \tag{11}$$

Substituting (9) and (10) into (11) to get the device sensitivity

$$S = \mu_H \frac{L}{D + \frac{d}{2}} \tag{12}$$

From (12), the relative sensitivity depends on the geometrical parameters and Hall mobility. So, in order to obtain high sensitivity the current deflection parameters must be maximized as possible. The maximized current deflection parameters are, increasing the channel length L, increasing the Hall mobility μ_H of the inversion layer of MAGFET channel, D and d should be made as small as possible. It should be noted that Rodrigo's model [14] assumed S = μ_H, which mean its geometry independent. Now we try to make our model fully implicit and stand alone. The only parameter depending on the MAGFET voltages is the mobility. This is due to the fact that the MAGFET behaves electrically like a MOSFET. Therefore its mobility is modeled like the MOSFET mobility. The MOSFET mobility decreases with increasing the gate voltage due to surface scattering and it decreases with increasing the drain voltage due to velocity saturation [28]. A good model for mobility which includes both effects is the level 6 model from HSPICE.

$$\mu_H = \frac{r\ \mu_n}{1 + \frac{V_g - V_{th}}{F_1 d_{ox}} + \frac{V_d}{F_3 L}} \tag{13}$$

where V_{th} is the threshold voltage, V_g is the gate voltage, V_d is the drain voltage d_{ox} is the oxide thickness, and r is the Hall factor. F_1 and F_3 are fitting parameters which depend on the technology by which the MAGFET has been processed.

IV. RESULTS AND DISCUSION

A. Verification of Simulation

The simulation is carried out using ATLAS device simulator [29]. We will check the simulation by two steps. First step, without magnetic field, Fig. 4. shows the electrical characteristics of the Dual-Drain MOSFET. The simulation results fit the published experimental data [15] of dual-drain MOSFET very well. In linear region the maximum relative error is equal 3.6% at gate voltage equal 3V and the minimum relative error is equal 0.58% at gate voltage equal 4.95V which are excellent errors. The relative error formula used is

$$Error = \frac{|Experimental - Simulation|}{Experimental} 100\% \tag{14}$$

The simulation data are N-channel MOS with substrate doping of 1×10^{15}cm^{-3}and 60 nm oxide thickness. The MAGFET width is 100 μm and the length is 125 μm. The separation between the two drain contacts is 10 μm and the drain voltage is 1V.

Second step, with applying magnetic field, ATLAS can model the effect of applied magnetic field on the behavior of a semiconductor device by including the Lorentz effect in a relaxation time transport equation [16] and making a low field approximation. Figure 5. shows the published experimental data [15] and the simulated differential current for dual-drain MAGFET. The drain voltage is 1V and the gate voltage is 4.95V and the magnetic field is changed from 5 m Tesla to 0.1 Tesla and the Hall factor is 1.1. Fig. 5. shows good linearity of the dual-drain MAGFET differential current because the dual-drain MAGFET is biased in the linear region. The maximum relative error is 0.9% for both 40 mT and 60 mT magnetic field and the minimum relative error is 0.8% for both 20 mT and 80 mT magnetic field.

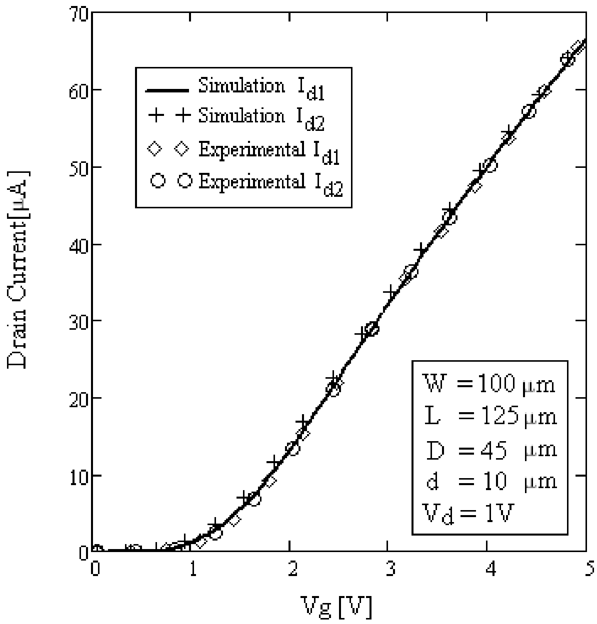

Fig. 4. currents as a function of the gate voltage.

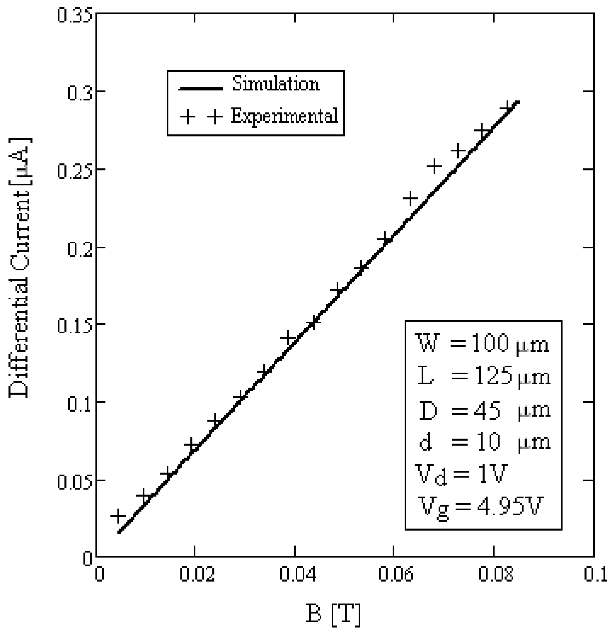

Fig. 5. Differential currents versus applied magnetic field (Dual-drain).

B. Comparing Differential Current

The differential current of the proposed model (10) is checked by using the simulation results. Fig. 6. shows the differential current against the gate voltage, which are good agreement between differential current model (10) and the simulation results in the linear region with the same device geometry and biasing voltage. The maximum relative error is

1.4% at 4.95V gate voltage.

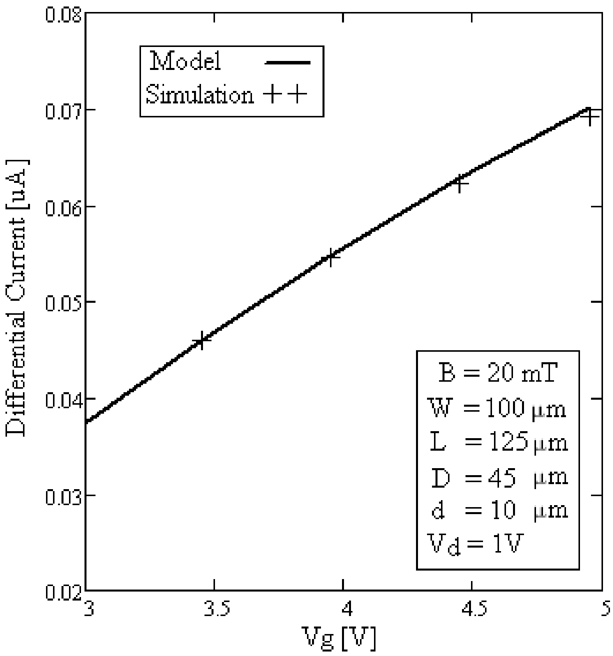

Fig. 6. Simulation and model for differential currents.

The proposed model (10) is checked against the magnetic field and compared with the simulation and experimental results as shown in Fig. 7. The maximum relative error is 5.47% at 20 mT, but the relative error is decreased to 0.42% as magnetic field increased to 80 mT. The relative error is decreased to less than 2% as increasing gate voltage to 4.95V because the MAGFET is operated in the linear region and our model is valid only in the linear region. The sensitivity is decreased at high gate voltages due to surface scattering. Reducing the gate voltage to achieve high sensitivity is pushing the MAGFET to operate in the none linear region. The minimum relative error of the proposed model is 0.6% at both gate voltage equal 4V and 3V.

C. Comparing Sensitivities

The sensitivity of the proposed model is checked by using the simulation results. Fig. 8. shows a good agreement between the proposed model (12) and the simulation results in the linear region with the same device geometry and biasing voltage.

To investigate the proposed compact model over wide range of device geometries the simulation is carried out over drain gaps from 1μm up to 20 μm with d/W ratio from 0.01 to 0.2 as shown in Fig. 9. The channel length is fixed at 125 μm with L/W ratio 1.25. Moreover, the biasing point is fixed at drain voltage equal 1V and gate voltage equal 4.95V. The maximum relative error of the proposed model is 7% at drain gap equal 15 μm and the minimum relative error is 0.36% at drain gap equal 1 μm. The validity of the proposed model is very good at small drain gaps smaller than 10 μm. At large drain gaps the proposed model is inaccurate, so, the geometrical formulation in (12) needs further attention.

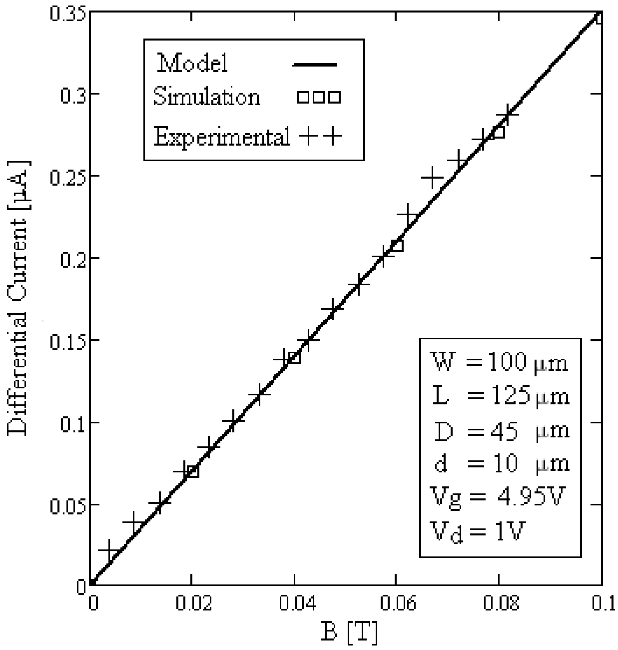

Fig. 7. Differential currents versus applied magnetic field.

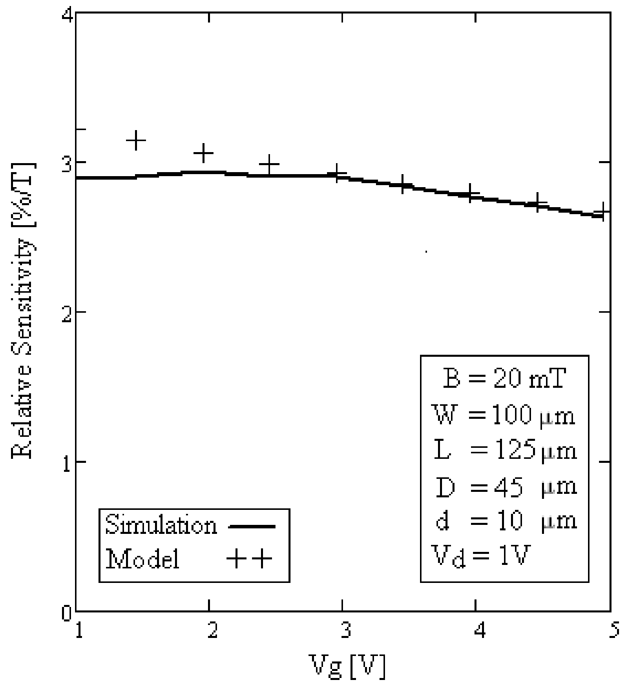

Fig. 8. Comparison between simulation and model sensitivities.

V. Conclusion

Compact model of sensitivity for the dual-drain MOS magnetic field sensor is described and has excellent error of 2% if biasing in linear region. Also the differential current model is proposed and has a maximum relative error less than 6% at 20 mT magnetic field. Our model shows that the imbalance of

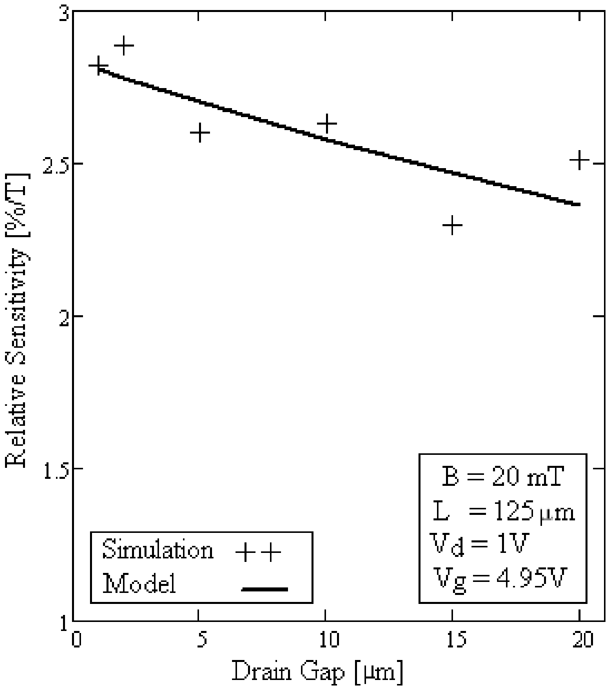

Fig. 9. Model and simulation for different drain gaps.

drain current is linear to magnetic field strength, and affected by the gap between the two drains. The models are compared with the simulation results to show excellent agreement.

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