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# A novel 0.7 V high sensitivity complementary differential MAGFET sensor for contactless mechatronic applications

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ABSTRACT

This paper discusses the design of a novel low-voltage complementary differential magnetic field effect transistor (CDMAGFET) with enhanced magnetic field sensing capability compared to previously reported NMOS only MAGFET or the single-ended cross-coupled MAGFET (CCMAGFET). It uses split-drain concave NMOS and PMOS devices which are cross-connected and operated differentially to provide an enhanced sense voltage. Simulations using the IBM 130 nm CMOS process technology indicate that it has almost double the sensed voltaic output ($V_{SENSE}$) for the same magnetic field intensity ($B_Z$) applied in quadrature to the MAGFET plane. Short channel devices are used for this design and comparison. The NMOS MAGFET had a sensing channel area of $2 \times 0.13\,\mu m \times 30\,\mu m$ while the PMOS MAGFET had a sensing channel area of $2 \times 0.13\,\mu m \times 150\,\mu m$. Depending on the operating bandwidth the sensing channel area can be linearly increased in order to increase the mTESLA vs. channel area sensitivity of the MAGFET (usually by using longer channel length). Careful CDMAGFET layout techniques are discussed to eliminate DC offsets in the presence of a DC magnetic field. Also, in order to minimize the transversal thermal noise current in an AC magnetic field a very low CDMAGFET bias current is used. Experimental verification of the nanometric CDMAGFET operation in the presence of orthogonal DC and AC magnetic field is also reported. The measured relative DC and AC voltaic sensitivity for the experimental CDMAGFET was, respectively, 0.564 and 1.65 mV/(V mTESLA) (the peak AC sensitivity @ 250 kHz).

## 1. Introduction

MAGFETs [1,2] are MOS magnetic field sensor elements which can be used for numerous applications in contact-less [3] mechatronic sensing (such as rotary encoders in speed/motion control [4–6]) and other electronic transducers [7] (such as magnetically controlled oscillator [1,8] and magnetic signal modulator [9]). The basic MAGFET devices published so far are usually split drain NMOSFETs whose current is steered between the two drains with changing magnetic flux density due to a magnetic field perpendicular to the channel of the NMOSFET. Compared to other available Hall effect magnetic field sensors [10], the MAGFET implementation along with its sensor readout pre-amplification can be easily integrated in today's standard digital CMOS process technology. Since the MAGFET does not steer the drain current between the two split drains in the absence of any magnetic field, it behaves as an ordinary MOSFET, and, can also be employed in any part of a mixed signal chip containing the MAGFET sensor by simply shorting the split drains. Another advantage is that SPICE simulations [2] can be seamlessly employed for evaluating MAGFET based sensor systems compared to other Hall effect magnetic sensors. In this paper a novel low-voltage MAGFET modification is presented consisting of the cross-coupling and differential operation of a NMOS and a PMOS MAGFET resulting in enhanced sensing of the magnetic field intensity orthogonal to the MAGFET plane. It is found that the magnetic field sensitivity can be increased significantly by using this modification compared to that using only a single-ended NMOS MAGFET or a single-ended cross-coupled MAGFET (CCMAGFET) [11] for the same geometry and process technology. Both simulation and experimental monolithic silicon implementation are discussed in this paper verifying the improvement in magnetic field sensing and the potential for practical contact-less mechatronic applications of the proposed modified MAGFET sensor in today's low-voltage nanometric CMOS.

## 2. MAGFET fundamentals and proposed complementary differential MAGFET

The operation of a MAGFET device is based on the well known Hall effect in semiconductor carrier transport behavior, whereby, a force $F_B$ (the Lorentz force) on an electrical charge $q$ traveling with

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velocity $v$ in a plane orthogonal to the plane containing a magnetic field of intensity $B_Z$ is given by,

$$F_B = q(v \times B_Z) = q\,E_H \tag{1}$$

where $E_H$ is the equivalent Hall electric field intensity normal to the direction of flow of the charge $q$, along which the force $F_B$ is exerted and the charge $q$ is steered away. The magnitude of $q$ is the charge of an electron (or a hole), so that the force $F_B$ has opposite directions for electron and hole. This relation between $F_B$, $v$ and $B_Z$ can be represented by the well-known LEFT-HAND-RULE in case of electron transport, and, by the RIGHT-HAND-RULE in case of hole transport. In a MAGFET constructed by splitting the drain of a regular MOSFET, the carriers are diverted from one drain to the other due to the presence of a magnetic field and hence acts as a magnetic field sensor. Fig. 1(a) shows the layout scheme of the proposed CDMAGFET where a PMOS and a NMOS device is used both with split drains. The magnetic field is coming out orthogonal to the MAGFET plane. The source of the PMAGFET is connected to VDD and that of the NMAGFET is connected to VSS(GND). The split drains of the PMAGFET and the NMAGFET are cross-connected, i.e., the drain 1 of the PMAGFET is connected to the drain 2 of the NMAGFET, and, the drain 2 of the PMAGFET is connected to the drain 1 of the NMAGFET. The magnetic field intensity causes both the holes and the electrons to deflect more towards the drain 1 of the respective devices with increasing magnetic field intensity because of the opposing direction of flow of the holes and the electrons. This causes the pull-up current to be higher at the drain 1 compared to the drain 2 of the PMAGFET. Similarly it causes the pull-down current to be higher for the drain 1 compared to the drain 2 of the NMAGFET. As a result with increasing magnetic field intensity,

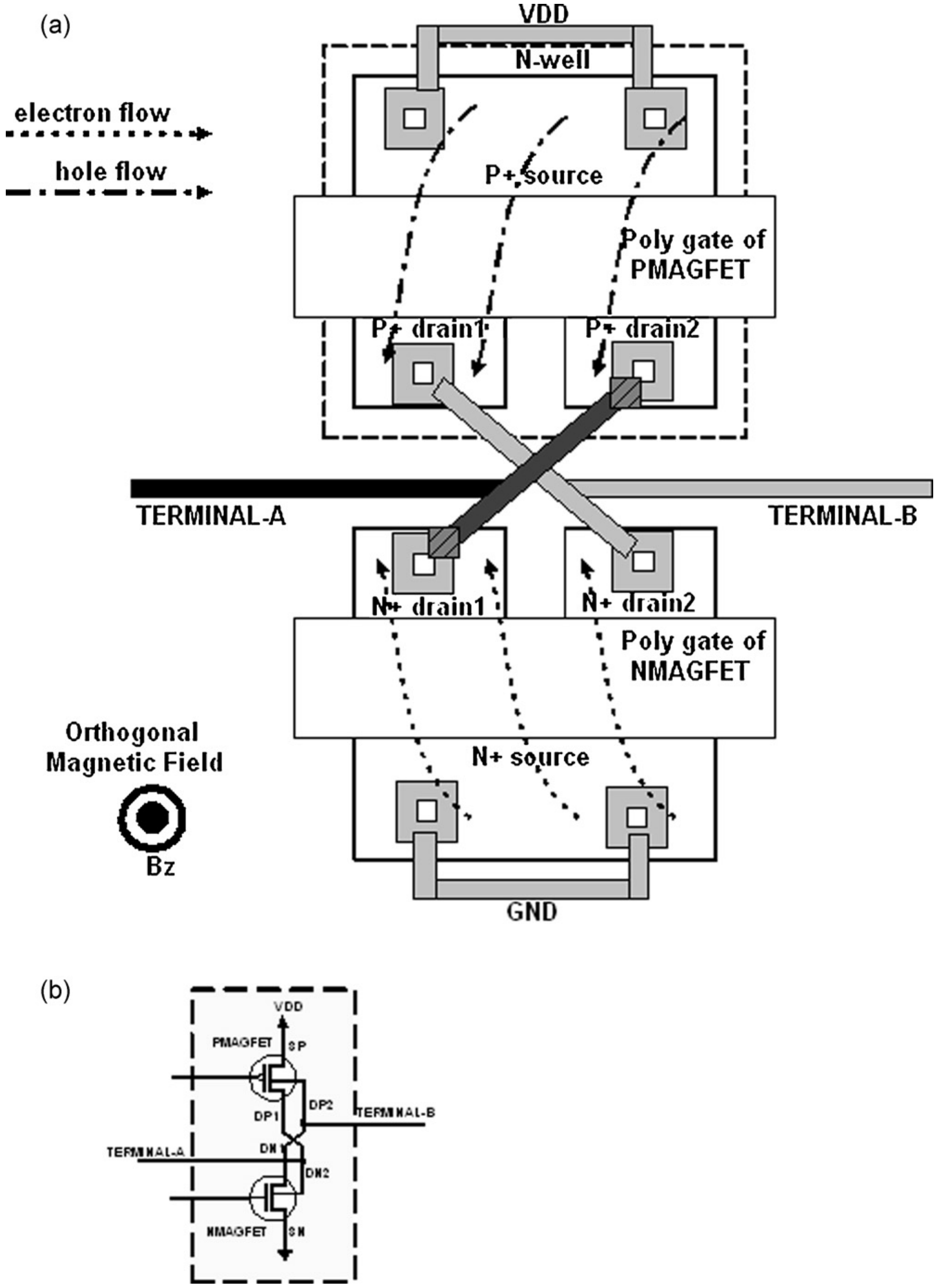

**Fig. 1.** (a) Layout scheme of the proposed novel low-voltage CDMAGFET sensor and (b) its circuit symbol.