The Gapless Design for High Sensitivity of Current Mode Dual Magnetodiode

Chalin Sutthinet\textsuperscript{1}, Sawatdipong Poonsawat\textsuperscript{1}, Toempong Phetchakul\textsuperscript{1} and Amporn Poyai\textsuperscript{2}

\textsuperscript{1} Electronics Department, Faculty of Engineering, King Mongkut’s Institute of Technology Ladkrabang, Bangkok, Thailand
\textsuperscript{2} Thai Microelectronics Center, National Electronics and Computer Technology Center, Chachoengsao, Thailand

Abstract. This paper presents the design for high sensitivity of magnetic detector device in current mode that uses Lorentz’s force deflects current depend on the magnetic density via the dual magnetodiode structure. The current mode devices have two symmetry regions for carrier current receiving that injected from another opposite region. This design has a gap between two carrier current receiving regions that causes some loss and reduce sensitivity. The proposed design has one carrier current receiving region or gapless design that has no loss from gap. The sensitivities of gap 5, 2.5 and 0 µm at 1 mA are 0.0010, 0.0028 and 0.0065 T\textsuperscript{-1} for split cathode structure and 0.00084, 0.0020 and 0.0051 T\textsuperscript{-1} for split anode structure, respectively. This design can be applied to all current mode magnetic device for high sensitivity.

1. Introduction
The magnetic sensors are the devices for detect magnetic field. There are various types and mechanisms [1], [2], [3], [4]. The Hall effect based devices are a group that detect magnetic field by this effect by ferromagnetic and non-ferromagnetic material (metal and semiconductor) [5]. There are two modes of operation that are voltage mode and current mode. The voltage mode use Hall voltage that is induced from magnetic field cross with current for balancing force between electric force \(qE_H\) and Lorentz’s force \(F_L = qv \times B\) where \(q\) is electric charge, \(E_H\) is Hall electric field, \(v\) is drift velocity of carrier and \(B\) is magnetic field density. The current mode use the Lorentz’s force \(F_L\) that greater than electrical force from Hall voltage deflect current or carrier. The structure of this mode device must have two separate regions for receiving the differential current which drain from another region. The output of current mode device is differential current \(\Delta I\) of the two regions. Magnetotransistors are the transistor that detects the magnetic field [6]. They are both in voltage and current mode of Hall effect. In current mode device, the collector must design in split collectors for receiving injected current passed base from emitter. The output is the differential collector current \(\Delta I_c\) which will have some value depend on the magnetic field density and direction.

The MAGFET (Magnetic Field Effect Transistor) [7] is one of the current mode Hall effect magnetic field detectors. The structure is split drain for receiving current from source. The output is the differential drain current \(\Delta I_D\). This device shows output \(\Delta I_D = 0\) when no applied magnetic field. When magnetic field is applied, \(\Delta I_D \neq 0\) depend on the density and direction.
Dual magnetodiode is the diode that detect magnetic field [8]. The structure has one anode and two separate cathodes. The current injected from anode to cathodes. The output is the differential current of cathodes $\Delta I$. When the magnetic field is applied, the output $\Delta I \neq 0$ and when no magnetic field is applied $\Delta I = 0$.

From the example that mention above, they use the Lorentz’s force deflect current from source of current to receiving regions, collectors, drains and cathodes. The structure of each device is designed for split regions that should have a gap between them. Even though, they are designed in very small scale technology as possible but the gap still exist in these structures. This design is used for very long time since the first device was created [9]. This paper will present the smarter design for higher sensitivity of these devices. The proposed design has no gap or gapless and independent of fabrication technology scaling.

2. Device structures and TCAD
The structures of dual magnetodiode studied here are shown in Fig. 1. The name dual diode [8] is from its structure that looks like two couple diodes that have one common anode and split cathode as shown in Fig. 1(a) or one common cathode and split anode as shown in Fig. 1(b).

![Figure 1. The structures of dual magnetodiode.](image)

The reason why it has to split cathode or anode is for magnetic field detection in current mode. The split cathodes one is start from n-type substrate, $10^{15}$ cm$^{-3}$, and diffuse acceptor atoms for p$+$ anode, $10^{20}$ cm$^{-3}$, on substrate and split anode one is start from p-type substrate, $10^{15}$ cm$^{-3}$ and diffuse donor atoms for n$+$ cathode, $5 \times 10^{19}$ cm$^{-3}$, on substrate. The ohmic contacts of substrate are formed by diffusion the same dopant atom as substrate in very high concentration. Each anodes and cathodes has a contact in the middle of region. The gap $W_g$ is the distance between split regions, the distance between anode and cathode is $L_D$ and the width of injection carrier cross section area of diode is $W_E$ which all of them are shown in Fig. 1. In this study, the $W_E$ is fixed constant at $8 \mu m$, $L_D$ is fixed at $10 \mu m$ but the gap $W_g$ are varied in three values of 5, 2.5 and 0 $\mu m$. In the case of $W_g= 0 \mu m$ is called gapless design which are also shown in Fig. 1.

TCAD sentaurus [10], [11], [12] is one of standard commercial programs for device and process simulation in micro/nano electronic industries.
It has magnetic models for magnetic response of device. The current density with magnetic field dependence model for this study is explain as

\[
\vec{J}_\alpha = \mu_\alpha \vec{g}_\alpha + \mu_\alpha \frac{1}{1 + (\mu_\alpha B)} \left[ \mu_\alpha^* \vec{B} \times \vec{g}_\alpha + \mu_\alpha^* \vec{B} \times (\mu_\alpha^* \vec{B} \times \vec{g}_\alpha) \right]
\]

(1)

where \( \alpha \) is n or p type of semiconductor material, \( \vec{J}_\alpha \) is carrier current density, \( \vec{g}_\alpha \) is current vector without mobility, \( \mu_\alpha \) is drift mobility, \( \mu_\alpha^* \) is the Hall mobility, \( \vec{B} \) is the magnetic induction vector and \( B \) is the magnitude of vector. This magnetic model with the conventional model of semiconductor material is used for dual magnetodiode in this work for studying the device design and mechanism for high sensitivity [13], [14].

**Figure 2.** Current density distribution of split cathode Dual Magnetodiode.
3. Experiment and Results

The magnetodiode split cathode and split anode structures as shown in Fig.1 are studied by TCAD simulation [15], [16]. These diodes are biased in forward direction by constant current source for keeping amount of carriers in order to avoid carrier modulation from magnetic field. The current density distribution are extracted out and shown as results. Then the magnetic field is applied in $-z$ and $+z$ direction and they show the variation of current density distribution with magnetic field. Dual magnetodiode is the current mode device that the output is differential diode current $\Delta I_D$ (differential cathode current for split cathode diode or differential anode current for split anode diode) which varied with magnetic field in amplitude and direction. Figure 2 shows current density distribution of split cathode dual magnetodiode with and without magnetic field. The results of cathode gap $W_g = 5$, 2.5 and 0 $\mu m$ are shown in Fig. 2 (a), (b, (c), respectively. The magnetic field in $-z$ direction is applied; the diode currents tilt to the left cathode.

On the other hand, when the magnetic field in $+z$ direction is applied; the diode currents tilt to the right. The cathodes current are equal when no applied magnetic field. Figure 4 (a) is the plot of $\Delta I_D$ versus magnetic field $B$ of split cathode diode. $\Delta I_D$ is $I_1 - I_2$ where $I_1$ is left cathode current and $I_2$ is right cathode current so the slope of graphs are positive. The relative sensitivities $S_R = \frac{1}{I_D} \frac{\Delta I_D}{\Delta B}$ at 1 mA of gaps 5, 2.5 and 0 $\mu m$ are 0.0010, 0.0028 and 0.0065 T$^{-1}$, respectively.

![Current density distribution of split anode Dual Magnetodiode.](image)

**Figure 3.** Current density distribution of split anode Dual Magnetodiode.
Figure 3 is the current density distribution of split anode diode structure. The same condition of forward biased, magnetic field and gaps parameters are applied. The conventional currents flow from split anodes to cathode. The plot of $\Delta I_D$ versus magnetic field $B$ of split anode is shown in Fig. 4(b). In this case $\Delta I_D$ is $I_1 - I_2$ where $I_1$ is left anode current and $I_2$ is right anode current. The positive slopes means that when magnetic field $+z$ direction is applied, the anode current $I_1$ is greater than $I_2$ and when magnetic field $-z$ is applied, the anode current $I_2$ is greater than $I_1$. The relative sensitivities $S_R = \frac{1}{I_D} \frac{\partial I_D}{\partial B}$ at 1 mA of gaps 5, 2.5 and 0 $\mu$m are 0.00084, 0.0020 and 0.0051 T$^{-1}$, respectively.

![Figure 4](image_url)

(a) Dual Magnetodiode split cathode. (b) Dual Magnetodiode split anode.

**Figure 4.** The magnetic field response of Dual Magnetodiode.

4. Discussion
Dual magnetodiode structure studied here is the normal diode that has one common anode and split cathode or common cathode and split anode. This special design is used for magnetic detection field rather than use as rectify. The current of dual magnetodiode is the same as p-n junction diode that can be written as

$$J = \left(\frac{qD_p n_{p0}}{L_p} + \frac{qD_n n_{n0}}{L_n}\right) \exp\left(\frac{qV_a}{kT} - 1\right)$$

where $q$ is electronic charge, $D_n$ and $D_p$ are minority carrier electron and minority carrier hole diffusion coefficient, $L_n$ and $L_p$ are minority carrier electron and hole diffusion length, $n_{n0}$ and $n_{p0}$ are thermal equilibrium minority carrier electron and minority carrier hole concentration, $k$ is Boltzmann’s constant, $T$ is temperature and $V_a$ applied voltage across junction. Equation 2 shows the amount of total current that calculate from the minority carrier diffusion current densities at the edge of space charge region. In the case of p’n or split cathode n-substrate, the term $n_{n0} < p_{n0}$ and can be neglected. The minority diffusion current is approximately hole injected across junction and become minority carrier which then diffuse from junction to split cathode terminals and recombine with majority carrier. The minority carrier diffusion current decay exponentially with distance for several time of minority diffusion length $L_p$ before completely recombine. In order to supply the majority electrons that are lost by recombination with the injected excess minority carrier hole and supply electrons that are being injected across the junction into p region, the electron drift into cathode create the majority electron drift current. The same discussion applies to the drift of holes majority carrier in p region in the case of pn’ or split anode p-substrate [17], [18].
Figure 5. Current deflection of split cathode when applied magnetic field in +z direction.

(a) Model of hole minority and electron majority carrier current density deflection.
(b) Conventional total current density deflection vector.

Figure 6. Current deflection of split anode when applied magnetic field in +z direction.

(a) Model of electron minority and hole.
(b) Conventional total current density deflection vector.

Figure 7. Comparison of total current density distribution of split cathode.

(a) Gap $W_g = 5 \, \mu m$.
(b) Gapless $W_g = 0 \, \mu m$.

Figure 5 shows current deflection in split cathode dual magnetodiode when magnetic field is applied in +z direction. As mention before, there are two carrier current components. The holes are injected from $p^+$ anode across junction to cathode and diffuse in n-substrate to cathodes. The Lorentz’s force is induced in $x$ direction causes the minority hole diffusion current density $J_h$ tilts in the right cathode. The hole minority diffusion current density $J_h$ of right cathode is greater than the left one. The electrons drift into cathode to supply the electron recombine with excess holes create majority electron drift current density $J_e$ from cathode to junction. The electron current density $J_e$ tilts in $x$ direction because of Lorentz’s force. The majority electron current density $J_e$ of left cathode is greater than the
right cathode. They are shown in Fig. 5(a). Figure 5(b) is the conventional total current density vector of carrier currents in Fig.5 (a) by TCAD simulation. The total currents are the sum of electron and hole currents. As the results $\Delta I = I_1 - I_2$ shown in Fig.4, $I_1$ is greater than $I_2$ in this case.

Figure 6 shows current deflection of split anode when applied magnetic field in $+z$ direction. In similarly, the model of carrier deflection and conventional total current density deflection vector are shown in Fig. 6 (a) and (b), respectively.

Figure 7 shows the total current density distribution selected from Fig.2. They are split cathode diodes with gap $W_g = 5 \mu m$ and gapless $W_g = 0 \mu m$ with the magnetic field $+z$ direction. The deflection current density with gap in Fig.7 (a) is not smooth and continuous. It is observed that there is low current density area in gap. The high current density deflection does not tilt continuous between cathodes. There is some loss of output differential current. The gapless in Fig. 7 (b) shows the smooth and continuous current density during deflection. There is no low current density area inserted in high current density area. The current density tilts smoothly and continuously. There is no loss and approach to the ideal.

5. Summary
Dual magnetodiode is a current mode device that can detect magnetic field. The dual magnetodiodes for this study are split cathode and split anode structure. It is current composed of two current components. One is minority diffusion current from injected holes from $p^+$ anode for split cathode and from injected electron from $n^+$ cathode for split anode across the junction, respectively. Another is majority electron drift current in cathode $n^-$ substrate for split cathode or majority hole drift current in anode $p^-$ substrate for split cathode. The induced Lorentz’s force acts upon both currents. The current mode device use Hall effect in current mode for current deflection. These devices have to be designed with split current receiving region to support current deflection from magnetic field. It must have a gap between split regions and has some loss in differential current $\Delta I$. The gapless design is proposed here for high sensitivity. It is not necessary to split receiving carrier current region anymore because the current deflection effect will be continue within this region until reach to the inner contacts. From this study, the sensitivity of gapless design is highest both in two structure. The relative sensitivity of gap 5, 2.5 $\mu m$ and gapless are 0.0010, 0.0028 and 0.0065 T$^{-1}$ for split cathode 0.00084, 0.0020 and 0.0051 T$^{-1}$ for split anode, respectively. The gapless design is the ideal for the high sensitivity current mode device.

6. References
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