Three types of 2-D lateral magnetoresistive sensors with p^+ -implant confinement

G.-M. Sung, J.-F. Wei and S.-I. Liu

Abstract: The paper presents three types of 2-D magnetic sensors fabricated by an industrial $0.8\text{ }\mu\text{m}$ CMOS process. They are designed to measure the horizontal magnetic component B_x and the vertical magnetic component B_y , simultaneously. The devices with p^+ -implant confinement have been investigated experimentally. According to experimental results, the magnitudes of the cross-coupling noises are proportional to the device size. Both the enlarged device size and the narrowed device conductive thickness with p^+ -implant confinement have higher sensitivity. The measured absolute voltage sensitivity S_A , the absolute current sensitivity S_I , and the supply-current-related sensitivity S_{RI} are 0.741 V/T , $493.7\text{ }\mu\text{A/T}$ and 439.4 V/AT , respectively.

1 Introduction

After Pearson in 1948 first presented a magnetic transducer made by a germanium plate [1], Corak in 1966 proposed that the MOS structure could be recognised as an attractive candidate [2]. He encouraged research on integrated semi-conductive sensors in the limelight of commercial Hall devices. Furthermore, the geometrical features of MOS-FET Hall devices can offer plenty of applications for a standard CMOS process [3].

Today, the research on future applications of magnetometers are focused on bulk Hall-effect devices, magnetoresistors, magnetotransistors, magnetodiodes, carrier-domain magnetometers, inductive coils and flux gates [4, 5]. Among these devices, magnetotransistors (MT) have higher sensitivity because their collector current is exponentially related to the magnetic field, while magnetoresistors (MR) have better linearity. The reason is that the induced Hall voltage V_H of the MR is approximately proportional to the sensor's bias current [6].

A typical n-channel Hall plate, with 20 mT offset equivalent field, 0.2 mT/K temperature coefficient and sensitivities 0.035 T^{-1} or 10^3 V/AT , has been developed [7]. It shows that offset equivalent field is still a serious problem. It limits the applicability of Hall devices. Fortunately, this effect may be mitigated by choosing proper geometry, doping density, surface conditions, contact resistance etc.. Hirata and Suzuki proved that the offset voltage could be reduced using a large device [8]. Apart from reducing the equivalent offset voltage, methods of enhancing sensitivity over conventional Hall devices are also important. Kahrizi combined the active confinement with post-process etching steps to achieve this goal [9]. He successfully reduced the cross-coupling noise due to unwanted diagonal carrier flow and considerably enhanced the sensitivity of devices.

Although the post-processing circuits and etching steps are now available, the possibility of sensor fabrication without additional processes excites everybody because of the tremendous cost reduction [10]. In this paper, the focus is on the standard CMOS process to design a differential lateral magnetoresistive sensor (DLMR). By enlarging the device's size and replacing the post-process etching confinement with p^+ -implant confinement, the ultimate goal of enhancing the absolute voltage sensitivity has been achieved. Magnetic sensors have been fabricated in a standard $0.8\text{ }\mu\text{m}$ CMOS process.

2 Sensor structures and readout circuit

2.1 Sensor structures

The sensor's structures are shown in Fig. 1. They are named as the two-dimensional (2-D) differential lateral magnetoresistor (DLMR). The DLMR is designed to detect the horizontal magnetic-field component B_x and the vertical magnetic-field component B_y , which are parallel to the chip's surface. The sensor's operation exploits the Lorentz force $\vec{F} = q\vec{v} \times \vec{B}$, where q is the electron charge, $\vec{v}$ is the electron velocity, and $\vec{B}$ is the magnetic induction.

Fig. 1 Three-dimensional view of the DLMR and its symbol

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Fig. 2 Type-I device: plan view

Three types of DLMR devices, shown in Figs. 2–4, are not only composed of five bias contacts, CC1 and CC2, and four sensing contacts, SC1 and SC2, but also implemented in the n-well and surrounded with p⁺-implant to inhibit cross-coupling noise and to enhance sensitivity. The bias contacts CC1 and CC2 are used as conductive pads. The bias current flows into the device via the contact CC1 and spills out from the contacts CC2. The sensing contacts SC1 and SC2 are positioned between the bias contacts CC1 and CC2 to detect the Hall current which is induced by the magnetic induction. The difference between the type-I device (Fig. 2) and the type-II device (Fig. 3) is the device's size. In Fig. 2, the device measures 50 μm × 30 μm, but it is 200 μm × 120 μm in Fig. 3. The difference between the type-I device and the type-III device (Fig. 4) is the absence of stabbed p⁺-implant confinement. In Fig. 4 the type-III device was implemented with stabbed p⁺-implant confinement to lessen the unwanted cross-coupling noise. In addition, the design of the differential-mode device is specially emphasised. In spite of the direction of the magnetic induction, the induced Hall voltage can be obtained correctly.

Fig. 3 Type-II device: plan view

Fig. 4 Type-III device: plan view

2.2 DLMR operation

The basic operation of the DLMR is similar to an ideal Hall plate. There are two limiting effects which are usually discussed. One is the Hall field effect; the other is the magnetoresistance. The detail descriptions are as follows.

According to the Boltzmann transport equation, the electron current density $\vec{J}_n(0)$ for zero magnetic induction $\vec{B}$ is given by [5, 11, 12]

$$\vec{J}_n(0) = \sigma_n \vec{E} + qD_n \nabla \bar{n} \quad (1)$$

where $\sigma_n = q\mu_n n$ denotes the electronic conductivity for $\vec{B} = 0$, $\vec{E}$ is the electric field, q is the elementary charge, μ_n is the electron drift mobility, n is the electron density and $qD_n \nabla \bar{n}$ is the diffusion current. For nonzero magnetic induction B , the electron current density $\vec{J}_n(\vec{B})$ can be expressed as

$$\begin{aligned} \vec{J}_n(\vec{B}) &= \vec{J}_n(0) - \mu_n^* \{ \vec{J}_n(\vec{B}) \times \vec{B} \} \\ &= \vec{J}_n(0) + \mu_n^* \{ \vec{B} \times \vec{J}_n(\vec{B}) \} \end{aligned} \quad (2)$$

where μ_n^* is the Hall mobility for electrons, $\mu_n^* = r_H \mu_n$, with the scattering factor r_H . Eqn. 2 can be solved with respect to $\vec{J}_n(\vec{B})$ by the mathematical equation $\vec{B} \times (\vec{A} \times \vec{C}) = (\vec{B} \cdot \vec{C})\vec{A} - (\vec{B} \cdot \vec{A})\vec{C}$, where $\vec{A}$, $\vec{B}$, and $\vec{C}$ are vectors, ' $\cdot$ ' is the inner product and ' $\times$ ' is the cross product; then

$$\begin{aligned} \vec{J}_n(\vec{B}) &= \left[\vec{J}_n(0) + \mu_n^* \{ \vec{B} \times \vec{J}_n(0) \} \right. \\ &\quad \left. + (\mu_n^*)^2 \{ \vec{B} \cdot \vec{J}_n(0) \} \vec{B} \right] \\ &\quad \left\{ 1 + (\mu_n^*)^2 (\vec{B} \cdot \vec{B}) \right\}^{-1} \end{aligned} \quad (3)$$

For magnetoresistive devices, the carrier-concentration gradients can be neglected, i.e. $\vec{J}_n(0) = \sigma_n \vec{E}$. Substituting the $\vec{J}_n(0)$ into eqn. 3, one can find that

$$\vec{J}_n(\vec{B}) = \sigma_{nB} \left\{ \vec{E} + \mu_n^* (\vec{B} \times \vec{E}) + (\mu_n^*)^2 (\vec{B} \cdot \vec{E}) \vec{B} \right\} \quad (4)$$

where $\sigma_{nB} = \sigma_n \{ 1 + (\mu_n^*)^2 (\vec{B} \cdot \vec{B}) \}^{-1}$. Since $\vec{B}$ is perpendicular to $\vec{E}$ and $\vec{B} \cdot \vec{E} = 0$, eqn. 4 can be reduced to

$$\begin{aligned} \vec{J}_n(\vec{B}) &= \sigma_{nB} \{ \vec{E} + \mu_n^* (\vec{B} \times \vec{E}) \} \\ &= \sigma_{nB} \{ \vec{E} - \mu_n^* (\vec{E} \times \vec{B}) \} \end{aligned} \quad (5)$$

There are two cases which are usually discussed for 2-D sensors. One is the operation of horizontal magnetic induction; the other is vertical magnetic induction.

(i) *Horizontal magnetic induction:* In terms of $\vec{B} = (B_x, 0, 0)$, $\vec{E} = (0, E_y, E_z)$ and $\vec{J}_n(\vec{B}) = (0, J_{ny}, J_{nz})$, eqn. 5 gives

$$J_{ny}(B_x) = \sigma_{nB} (E_y - \mu_n^* B_x E_z) \quad (6)$$

$$J_{nz}(B_x) = \sigma_{nB} (E_z + \mu_n^* B_x E_y) \quad (7)$$

There are two dominant effects which are distinguished.

(a) *Hall effect:* Assume that the current density only flows in the y -direction, i.e. $J_{nz} = 0$. The Hall electric field can be expressed as

$$E_z = -\mu_n^* E_y B_x = R_H \{ J_{ny}(B_x) \} (B_x) \quad (8)$$

where $R_H = (-\mu_n^* E_y) / \{\sigma_{nB}(E_y - \mu_n^* B_x E_z)\}$ denotes the Hall coefficient. $E_z = -v_y B_x = -\mu_p E_y B_x$ is the induced Hall electric-magnetic field for holes. For electrons, it can be expressed as

$$E_z = \mu_n E_y B_x \quad (9)$$

Substituting eqn. 9 into eqn. 8, the Hall coefficient can be given

$$R_H = -\mu_n^* / \sigma_{nB} \{1 - r_n (\mu_n)^2 (B_x)^2\} \quad (10)$$

The induced Hall current I_H is proportional to the Hall voltage V_H in the z -axis direction, where the Hall voltage V_H can be shown to be

$$V_H = R_H G B_y I_x / t \quad (11)$$

in which G is the geometrical correction factor, R_H denotes the Hall coefficient, t is the plate thickness, B_y represents the horizontal magnetic field along the y -direction and I_x is the bias current along the x -axis which is supplied via the bias contacts CC1 and CC2 [7, 10].

It is noticeable that R_H will be influenced by magnetic induction. If the magnetic induction B_x and the electric field E_y are considered, the higher Hall voltage V_H can be obtained and it will enhance the sensor's sensitivity as B_y is increased.

(b) Carrier deflection and magnetoresistance: First, assume that the electrical field in the z -direction E_z is zero. The carrier deflection can be expressed as

$$J_{ny}(B_x) = \sigma_{nB} E_y \quad (12)$$

$$J_{nz}(B_x) = \sigma_{nB} (\mu_n^* E_y B_x) = J_{ny} r_n \mu_n B_x \quad (13)$$

From eqn. 13, $J_{nz}(B_x)$ will be influenced by the production of B_x and E_y . It is the reason why the diagonal magnetic field will induce the cross-coupling noise. Secondly, the geometrical magnetoresistance will increase because of the longer carrier-drift paths. The electronic conductivity for the nonzero magnetic induction $\vec{B}$ is $\sigma_{nB} = \sigma_n \{1 + (\mu_n)^2 (\vec{B} \cdot \vec{B})\}^{-1}$. It can be rewritten with the magnetic induction B_x to be

$$(\varrho_{nB} - \varrho_n) / \varrho_n = (\mu_n^* B_x)^2 \quad (14)$$

where $\varrho_n = \sigma_n^{-1}$ denotes the resistivity for $B_x = 0$ and $\varrho_{nB} = \sigma_{nB}^{-1} = E_y / J_{ny}$ is the resistivity induced by the nonzero magnetic induction.

The effect of enhancing magnetoresistance is very small for silicon. Hence, the dominant effect of DLMR is focused on the Hall effect, which involves the geometrical correction factor G , the Hall coefficient R_H and the plate thickness t .

(ii) *Vertical magnetic induction:* In terms of $\vec{B} = (0, B_y, 0)$, $\vec{E} = (E_x, 0, E_z)$, $\vec{J}_n(\vec{B}) = (J_{nx}, 0, J_{nz})$, the deviation is the same as case (i). The induced Hall current I_H is proportional to the Hall voltage V_H in the z -axis direction, and the Hall voltage V_H is shown as

$$V_H = -R_H G B_x I_y / t \quad (15)$$

where R_H is the Hall coefficient, $R_H = -\mu_n^* / \sigma_{nB} \{1 - r_n (\mu_n)^2 (B_x)^2\}$.

The Hall effect on DLMR is shown in Fig. 5. While the bias current I_x flows from contact CC1 to contacts CC2, if the horizontal magnetic-field component B_y is parallel to the chip surface, the Lorentz force F_z will force holes and electrons to accumulate at SC1 (V_{H+}) and SC2 (V_{H-}), respectively, which will induce the differential Hall current between SC1 and SC2.

Fig. 5 Hall effect on the DLMR

The bias current I_x is injected into the contact CC1 and received from the contacts CC2. Assume that the horizontal magnetic-field component B_y is parallel to the chip surface; the Lorentz force F_z will force holes and electrons to induce the Hall current I_H

Fig. 6 Detailed structure of type-III device

It uses P^+ -implant confinement to narrow the effective conduction thickness t . This design is intended not only to increase the sensitivity, but also obviously to restrict the cross-coupling noise

The detailed structure of the type-III device is shown in Fig. 6. A staggered P^+ -implant confinement is implemented to enhance the sensitivity by narrowing conductive thickness t and leading the majority carrier to an isotropic direction. This design is intended not only to increase the sensitivity but also obviously to restrict the cross-coupling noise. Additionally, the layout of the P^+ -implant confinement must be connected with p -substrate to form the p - n -depletion layer.

2.3 Readout circuit design

The readout circuit shown in Fig. 7 includes a current-to-voltage converter, a filter and an instrumentation amplifier. The DLMR device is connected to the current-to-voltage converter. The filter is designed to inhibit power-line interference. The instrumentation amplifier is used to amplify the input voltage with a gain of 40dB. The OP177 is used to implement this circuit for its properties of low noise and low offset voltage [13].

If the bias current flows along the x -axis direction and the magnetic induction that is generated by ferromagnetic coil acts along the y -axis direction, the Lorentz force F_z compels the electrons to induce the Hall voltage V_{H+} and V_{H-} in the sensing contacts SC1 and SC2, respectively. Because the voltage at the negative side of OP is virtual ground, the induced Hall effect will produce currents I_1 and I_2 , respectively. By incorporating with the current-to-voltage converter, the currents I_1 and I_2 are converted into voltages, V_{o1} and V_{o2} , respectively [14]. They can be

Fig. 7 Readout circuit

The Lorentz force F_L compels the holes and electrons to induce the Hall currents I_1 and I_2 in the sensing contacts SC1 and SC2, respectively. By incorporating with current-to-voltage converter, filter and instrumentation amplifier, the difference between current I_1 and I_2 is converted into output voltage

R_1 and C_1 are the resistor and capacitor of filter; R_s is the resistor about the power supply of the device; R_v is the reference resistor for reference voltages V_+ and V_-

expressed as

$$V_{o1} = -I_1 \times R_f \quad (16)$$

$$V_{o2} = +I_2 \times R_f \quad (17)$$

where R_f is the feedback resistor of the OP in Fig. 7.

After eliminating power-line interference by the lowpass filter (LPF), the difference between V_{o1} and V_{o2} will be amplified by the instrumentation amplifier. Hence, the output voltage V_o can be given by

$$\begin{aligned} V_o &= - \left(1 + 2 \times \frac{R_a}{R_b} \right) \left(\frac{R_c}{R_b} \right) (V_{o1} - V_{o2}) \\ &= -A_v \times (V_{o1} - V_{o2}) \end{aligned} \quad (18)$$

where V_R , R_a , R_b and R_c are the resistors about the instrumentation amplifier. A_v is the gain of the instrumentation amplifier.

Sensitivity is the most significant characteristic for a magnetic sensor. The absolute voltage sensitivity S_A , the absolute current sensitivity S_I and the supply-current-related sensitivity S_{RI} of differential LMR are defined as

$$S_A = \left| \frac{\partial V_{II}}{\partial B} \right| = \left| \frac{V_{o1} - V_{o2}}{\Delta B} \right| = \left| \frac{V_o}{A_v \times \Delta B} \right| \quad (19)$$

$$S_I = \left| \frac{\partial I_{II}}{\partial B} \right| = \left| \frac{V_{o1} - V_{o2}}{R_f \times \Delta B} \right| = \left| \frac{V_o}{A_v \times \Delta B \times R_f} \right| \quad (20)$$

$$S_{RI} = \frac{S_A}{I} = \left| \frac{V_{o1} - V_{o2}}{\Delta B \times I} \right| = \left| \frac{V_o}{A_v \times \Delta B \times I} \right| \quad (21)$$

in which ΔB denotes the variation of magnetic induction. I is the bias current and V_o , V_{o1} , V_{o2} , R_f and A_v are defined as above.

3 Experimental results

First, the measuring system is calibrated by adapting each circuit properly with the absence of horizontal magnetic field B_x . The ultimate goal is to cancel the offset voltage and to confirm that the output voltage is zero; moreover, the peak-detection technique and averaging method are adopted to measure the Hall voltage and to keep it from vibrating noise. To find the effect of the cross-coupling noise, the measurement of the induced Hall voltage at the counter axis is also considered. The experimental steps are as follows. First, detect the output voltages V_o that appears on the x -axis direction and y -axis direction simultaneously to study the horizontal magnetic effect in the x -axis direction and the cross-coupling noise in the y -axis direction. Secondly, repeat it again but the device is rotated 90° . The results are shown in Figs. 8–16.

Fig. 8 Relative output voltage V_o as a function of magnetic field B for the type-I device: x -axis output voltages induced by the operation of horizontal magnetic field B_x
 Δ output voltage at ± 2.25 V
 $\blacksquare$ output voltage at ± 1.50 V
 $\blacklozenge$ output voltage at ± 0.75 V

In Figs. 8–10, the induced Hall voltages V_o as a function of the applied magnetic induction B are presented. All

DLMRs are biased with three different power voltages, $\pm 0.75\text{V}$, $\pm 1.5\text{V}$ and $\pm 2.25\text{V}$, respectively. The results show that the higher the power voltage, the better is the Hall voltage. Nevertheless, nonlinearity and breakdown phenomena are deserved to be discussed. The nonlinear characteristic is obvious at low bias voltage. This means that the Lorentz force is too small to induce a stable current at a low bias voltage. The breakdown phenomenon seriously destroys the linear characteristic when the Hall element is operated under the condition that the power supply voltage is $\pm 2.25\text{V}$ and the magnetic induction B is higher than 100mT . The reason is that the holes or electrons, generated by the bias-power-supply voltage, will be pushed to the sensing contacts SC1 and SC2 by the strong Lorentz force at high magnetic field. The resistance will be decreased tremendously between the bias contact CC1 and the sensing contacts SC1 and SC2. An extra amount of bias current will pass through the sensor contacts to bring about breakdown [15]. In addition, the cross-coupling noise is worthy of note in Fig. 10.

Fig. 9 Relative output voltage V_o as a function of magnetic field B for the type-I device: y-axis output voltages generated by the operation of horizontal magnetic field B_x
 Δ output voltage at $\pm 2.25\text{V}$
 $\blacksquare$ output voltage at $\pm 1.50\text{V}$
 $\blacklozenge$ output voltage at $\pm 0.75\text{V}$

Fig. 10 Relative output voltage V_o as a function of magnetic field B for the type-I device: cross-coupling noises of the x axis and y axis that are induced by the cross-sensitive effect of horizontal magnetic fields B_x and B_y , respectively
 Δ cross noise at $\pm 2.25\text{V}$ for x axis
 $\blacksquare$ cross noise at $\pm 1.50\text{V}$ for x axis
 $\blacklozenge$ cross noise at $\pm 0.75\text{V}$ for x axis
 $\bullet$ cross noise at $\pm 2.25\text{V}$ for y axis
 $*$ cross noise at $\pm 1.50\text{V}$ for y axis
 $\times$ cross noise at $\pm 0.75\text{V}$ for y axis

For the purpose of increasing the induced Hall voltage, the size of the Hall device is enlarged four times [8]. The experimental results, shown in Figs. 11–13, reveal that the breakdown phenomena are overcome and the induced Hall

voltages are obviously enlarged, which agrees with the prediction. However, the cross-coupling noise, as shown in Fig. 13, is too large to be acceptable. It is difficult to distinguish clearly the effects of the magnetic field from those of the cross-coupling noise. Hence the p^+ -implant confinement is proposed to reduce the unwanted cross-coupling noise.

Fig. 11 Relative output voltage V_o as a function of magnetic field B for the type-II device: x-axis output voltages induced by the operation of horizontal magnetic field B_x
 Δ output voltage at $\pm 2.25\text{V}$
 $\blacksquare$ output voltage at $\pm 1.50\text{V}$
 $\blacklozenge$ output voltage at $\pm 0.75\text{V}$

Fig. 12 Relative output voltage V_o as a function of magnetic field B for the type-II device: y-axis output voltages generated by the operation of horizontal magnetic field B_x
 Δ output voltage at $\pm 2.25\text{V}$
 $\blacksquare$ output voltage at $\pm 1.50\text{V}$
 $\blacklozenge$ output voltage at $\pm 0.75\text{V}$

Fig. 13 Relative output voltage V_o as a function of magnetic field B for the type-II device: cross-coupling noises of the x axis and y axis that are induced by the cross-sensitive effect of horizontal magnetic fields B_x and B_y , respectively
 Δ cross noise at $\pm 2.25\text{V}$ for x axis
 $\blacksquare$ cross noise at $\pm 1.50\text{V}$ for x axis
 $\blacklozenge$ cross noise at $\pm 0.75\text{V}$ for x axis
 $\bullet$ cross noise at $\pm 2.25\text{V}$ for y axis
 $*$ cross noise at $\pm 1.50\text{V}$ for y axis
 $\times$ cross noise at $\pm 0.75\text{V}$ for y axis

The p^+ -implant is stretched into the gap, between all of the contacts, to narrow the conductive-plate thickness t (as shown in Fig. 5) and to force the majority carrier in an isotropic direction. Eqn. 15 shows that the induced Hall

voltage can be increased. The results are given in Figs. 12–14. For the low power supply voltage, the absolute voltage sensitivity S_A is still low and the linear characteristic is also poor. Fortunately, sensitivity S_A can be increased tremendously at a higher power supply voltage. Eqn. 14 shows that the cross-coupling noise is reasonably small. Table 1 presents the summary of the absolute voltage sensitivity S_A , the absolute current sensitivity S_I and the supply-current-related sensitivity S_{RI} of the sensors.

Fig. 14 Relative output voltage V_o as a function of magnetic field B for the type-III device: x-axis output voltages induced by the operation of horizontal magnetic field B_x
 $\triangle$ output voltage at ± 2.25 V
 $\blacksquare$ output voltage at ± 1.50 V
 $\blacklozenge$ output voltage at ± 0.75 V

Fig. 15 Relative output voltage V_o as a function of magnetic field B for the type-III device: y-axis output voltages generated by the operation of horizontal magnetic field B_y
 $\triangle$ output voltage at ± 2.25 V
 $\blacksquare$ output voltage at ± 1.50 V
 $\blacklozenge$ output voltage at ± 0.75 V

Fig. 16 Relative output voltage V_o as a function of magnetic field B for the type-III device: cross-coupling noises of the x axis and y axis that are induced by the cross-sensitive effect of horizontal magnetic fields B_x and B_y , respectively
 $\triangle$ cross noise at ± 2.25 V for x axis
 $\blacksquare$ cross noise at ± 1.50 V for x axis
 $\blacklozenge$ cross noise at ± 0.75 V for x axis
 $\triangle$ cross noise at ± 2.25 V for y axis
 $\blacksquare$ cross noise at ± 1.50 V for y axis
 $\blacklozenge$ cross noise at ± 0.75 V for y axis

Table 1: Summary of the absolute voltage sensitivity S_A , the absolute current sensitivity S_I and the supply-current related sensitivity S_{RI} of differential LMRs

Category		x-axis effects			y-axis effects		
		± 0.75 V	± 1.50 V	± 2.25 V	± 0.75 V	± 1.50 V	± 2.25 V
Type I	S_A (V/T)	0.021	0.043	0.119	0.022	0.043	0.117
	S_I (μ A/T)	14.000	28.530	79.330	14.500	28.530	78.000
	S_{RI} (V/AT)	63.500	62.720	151.100	65.920	62.726	148.600
Type II	S_A (V/T)	0.133	0.162	0.259	0.136	0.162	0.259
	S_I (μ A/T)	88.900	108.000	172.400	90.800	108.030	172.400
	S_{RI} (V/AT)	264.000	204.200	236.600	270.000	204.200	236.600
Type III	S_A (V/T)	0.077	0.220	0.728	0.093	0.194	0.741
	S_I (μ A/T)	51.600	146.600	485.300	61.860	129.300	493.700
	S_{RI} (V/AT)	442.200	488.800	432.000	530.100	431.200	439.400

4 Discussion

The operation of the differential lateral magnetoresistor is based on a combination of the Hall effect and some other mechanisms. Table 1 shows that the optimum combination of the absolute voltage sensitivity S_A , the absolute current sensitivity S_I and the supply-current-related sensitivity S_{RI} are 0.741 V/T, 493.7 μ A/T and 439.4 V/AT, respectively. This is better than the results published by Kahrizi in 1996 [9] and their experimental value range between 80 V/AT [16] and 400 V/AT [17] produced by the integrated Hall devices. Because the sensors presented in this paper have excellent linearity, these sensors will have broad applications.

For the supply-current-related sensitivity S_{RI} of the type I and type II devices, there are two cases which are usually discussed:

(i) *Low power-supply voltage*: Although the conductive thickness t is enlarged four times, the experimental results in the type-II device at ± 0.75 V and ± 1.50 V are roughly four times those of the type-I device. According to eqn. 15, the Hall current induced by Hall voltage is proportional to the production of geometrical coefficient G and the Hall coefficient R_H . Because of low power-supply voltage, the magnetic field E_z in the z-axis direction is very low. Assume that the Hall coefficient R_H is constant in eqn. 15. The main effect is dominated by the geometrical coefficient G and it is proportional to the device's size.

(ii) *High power-supply voltage*: To know the effect of sensitivity S_{RI} at high power-supply voltage, the experimental process is reorganised and the experimental results are recorded. The data reveal that the breakdown phenomenon occurs at high magnetic induction. This means that the Lorentz force is very large in the z-axis direction. The E_z , induced by Lorentz force, may be enlarged tremendously. The Hall coefficient R_H will increase very quickly; then the effect of the geometrical coefficient G is reduced. In addition, the experimental results show that the maximum bias current is constricted within a limit value. This is why the sensitivity is constricted at high power-supply voltages.

Comparing type-I and type-III devices, the data for the type-III device are roughly seven times better than those in the type-I device at a low power-supply voltage. This results are also better than those for the type-II device. The key parameters to induce higher sensitivity include the effective conduction thickness, the p⁺-implant confinement, and the geometrical coefficient G . If the effective conduction thickness is reduced to a third, it will enhance the sensitivity three times. The p⁺-implant confinement is not only to eliminate the cross-coupling magnetic field E_z which will

Fig. 17 Type-I micrograph of differential lateral magnetoresistive sensor

Fig. 18 Type-III micrograph of differential lateral magnetoresistive sensor

Fig. 19 Type-III micrograph of differential lateral magnetoresistive sensor

influence the Hall coefficient R_H , but also to confine the majority carriers to an isotropic direction to enhance sensitivity by increasing the scattering factor r_n [11]. The geometrical coefficient G for the type-III device is not as large

as those for the type-I and type-II devices. The experimental results reveal that the Hall coefficient R_H may be the dominant role. Figs. 17–19 shows micrographs of the differential lateral magnetoresistive sensor.

5 Conclusions

Experimental comparison of three types of differential lateral magnetoresistor have been presented. The best choice is the type-III device that can be operated at $\pm 2.25V$. The optimum result based on the above choice is that S_A , S_I and S_{RI} are $0.741V/T$, $493.7\mu A/T$ and $439.4V/AT$, respectively. At low bias-power-supply voltage, both the enlarged device and the narrowed conductive thickness have higher sensitivity. The geometrical coefficient G may be the dominant effect in the enlarged device's size. At the high bias-power-supply voltage, the Hall coefficient R_H is the main effect in spite of the enlarged device's size or the p^+ -implant confinement. Combining the enlargement with confinement may be a good method to increase the device's sensitivity.

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