Two-Dimensional Magnetic Field Sensor Based on Silicon Magnetic Sensitive Transistors with Differential Structure

Xianghong Yang, Xiaofeng Zhao *, Yunjia Bai, Meiwei Lv and Dianzhong Wen

Key Laboratory of Electronics Engineering, College of Heilongjiang Province, Heilongjiang University, Harbin 150080, China; 2141220@s.hlju.edu.cn (X.Y.); 2161317@s.hlju.edu.cn (Y.B.); 2141200@s.hlju.edu.cn (M.L.); 2141207@s.hlju.edu.cn (D.W.)

* Correspondence: zhaoxiaofeng@hlju.edu.cn; Tel.: +86-451-8660-8413

Abstract: A two-dimensional (2D) magnetic field sensor consisting of four silicon magnetic sensitive transistors (SMSTs) with similar characteristics is presented in this paper. By use of micro-electromechanical systems (MEMS) and integrated packaging technology, this sensor fabricated by using the silicon wafer with a <100> orientation and high resistivity, was packaged on printed circuit boards (PCBs). In order to detect the magnetic fields in the x and y axes directions, two of the four SMSTs with opposite magnetic sensitive directions were located along the x and $-x$ axes directions, symmetrically, and the others were located along the y and $-y$ axes directions. The experimental results show that when the V_{CE} = 10.0 V and I_B = 6.0 mA, the magnetic sensitivities of the sensor in the x and y axes directions are 366.0 mV/T and 365.0 mV/T, respectively. It is possible to measure the 2D magnetic field and improve the magnetic sensitivity, significantly.

Keywords: two-dimensional (2D) magnetic field sensor; silicon magnetic sensitive transistor; differential structure; micro-electromechanical systems (MEMS) technology

1. Introduction

To the best of our knowledge, with the development of complementary metal-oxide-semiconductor (CMOS) and micro-electromechanical systems (MEMS) technology, magnetic field sensors have been applied in many different fields, such as in the detection of the Earth's magnetic field and angular position, etc. [1–3]. To date, the widely used magnetic sensitivity sensors include Hall sensor, giant magnetoresistance (GMR), magnetic sensitive transistor, and so on [4–6]. In 2003, the silicon magnetic sensitive transistor (SMST) with a cubic structure was fabricated by MEMS technology [7,8], achieving a maximum relative magnetic sensitivity of about 22.7%/kG. In 2013, the SMSTs with a differential structure were fabricated by MEMS technology and achieved an absolute magnetic sensitivity of 102.9 mV/kG [9]. In 2015, a two-dimensional (2D) magnetic field sensor based on the operating principle and characteristics of the magnetic sensitive diode (MSD) was proposed [10], exhibiting sensitivities of S_{xB} = 544 mV/T and S_{yB} = 498 mV/T in the x and y directions, respectively. In 2010, in order to improve the efficiency of the magnetic modulating system, a 2D Hall micro-sensor with lower noise and angular positioning function was proposed [11]. In 2013, based on peripheral processing electronics, a new type of 2D differential folded CMOS Hall device with higher accuracy was devised by integrating magneto-transistors in a single chip and connecting a p-substrate to the minimum power supply [12], so as to obviously reduce noise and cross-sensitivity.

In view of the operating principle and characteristics of the SMST, a 2D magnetic field sensor composed of two differential structures with four SMSTs is proposed in this paper. The sensor was

studied by using a magnetic field generator system. The detection of two-dimensional magnetic fields is significantly enhanced by using the differential structures and a referable uniform magnetic sensitivity is realized.

2. Basic Structure and Operation Principle

2.1. Basic Structure

Figure 1 shows the cubic structure of the SMST based on MEMS technology. It has a C-type silicon cup, an emitter (E), a base (B) and a collector (C); the C and B are on top of E. The thickness d of the C-type silicon cup diaphragm is 30 µm, and the width W and the length L of the base region of the SMST are 30 µm and 120 µm, respectively. The cross-section area of the chip is 2000 µm $\times$ 2000 µm. As shown in Figure 2, the 2D magnetic field sensor is made up of two differential structures consisting of the four SMSTs with opposite magnetic sensitive directions, where one of the differential structures is constructed by SMST1 and SMST3 located along the x and $-x$ axes, and another is composed of the SMST2 and SMST4 along the y and $-y$ axes. The sensor has a common emitter E, four collectors (C_1, C_2, C_3, C_4), and four bases (B_1, B_2, B_3, B_4).
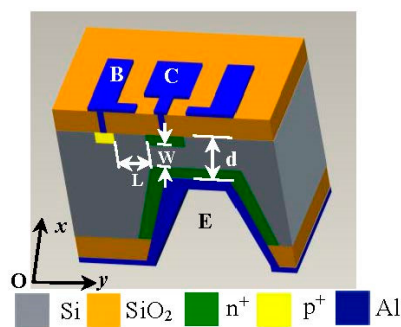

Figure 1. The cubic structure of the silicon magnetic sensitive transistor. E: emitter; B: base; and C: collector.

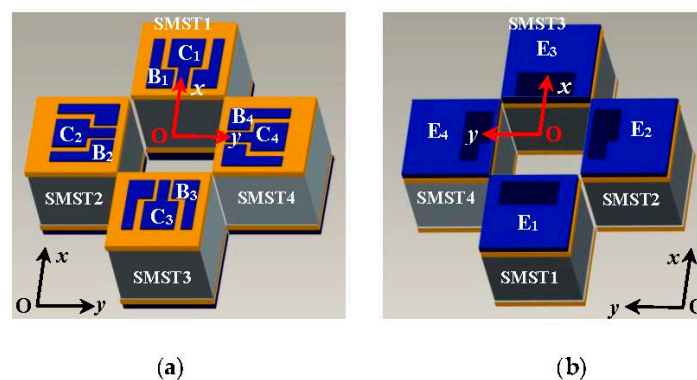

(**a**)   (**b**)

Figure 2. The basic structure of the two-dimensional (2D) magnetic field sensor: (**a**) top view; (**b**) bottom view.

2.2. Operation Principle

Figure 3a–c shows the cross-section views of the SMST1 and SMST3 along opposite magnetic sensitive directions; the operation principle for the 2D magnetic field sensor is discussed on the basis of the carriers deflected by different external magnetic fields. Figure 4 shows the test equivalent circuit of the 2D magnetic field sensor, where V_{x1}, V_{y2}, V_{x3} and V_{y4} are the collector voltages for the SMST1, SMST2, SMST3, and SMST4; R_{L1}, R_{L2}, R_{L3} and R_{L4} are the collector load resistances placed between the supply voltage V_{DD} and the collectors C_1, C_2, C_3 and C_4, respectively. R_{b1}, R_{b2}, R_{b3} and R_{b4} are the

base resistances placed between the supply voltage V_{DD} and the bases B_1, B_2, B_3 and B_4, respectively. The four integrated packaging SMSTs are given in the dashed square, as shown in Figure 4.
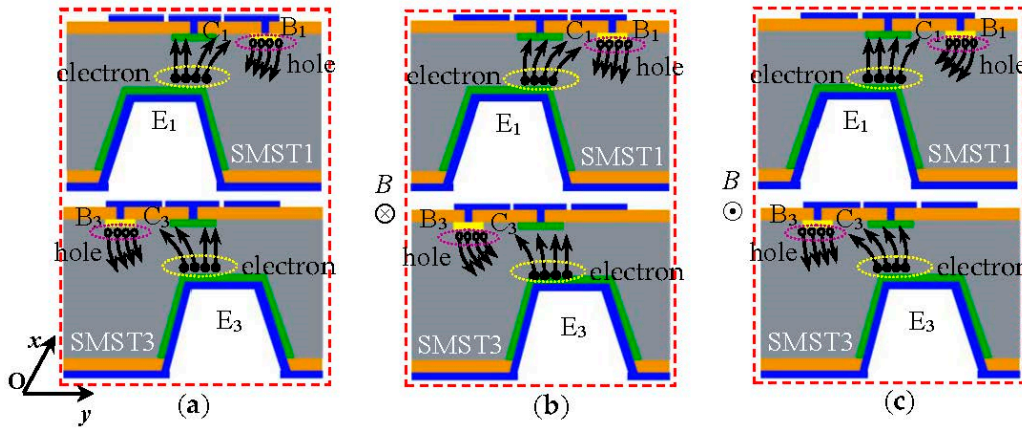

Figure 3. The operation principle of the silicon magnetic sensitive transistor (SMST) differential structure: (**a**) $B = 0$ T; (**b**) $B > 0$ T; (**c**) $B < 0$ T.
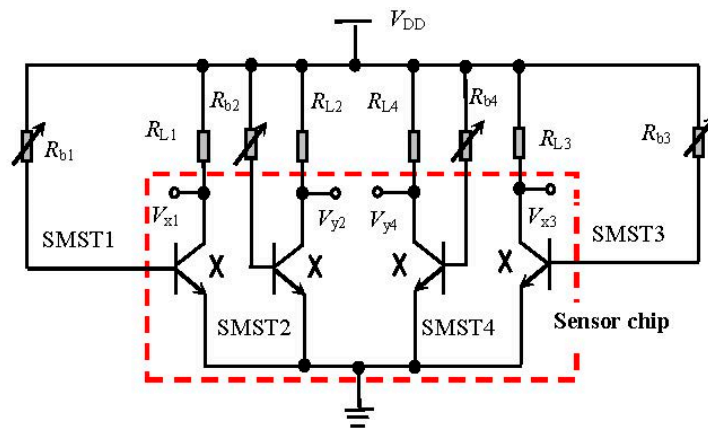

Figure 4. The equivalent circuit of the 2D magnetic field sensor.

In the ideal case, the two SMSTs along the *x* axis have the same characteristics, in which the deflection of carriers is the same under no external magnetic field, as shown in Figure 3a. The collector output voltage V_x along the *x* axis is:

$$V_x = V_{x1} - V_{x3} = I_{C03} \cdot R_{L3} - I_{C01} \cdot R_{L1} = 0 \tag{1}$$

where the collector current I_{C01} of the SMST1 is equal to the collector current I_{C03} of the SMST3.

In contrast, when exerting an external magnetic field *B* parallel to the chip that is along the *x* and $-x$ axes respectively, the carriers would be deflected by the Lorentz force as shown in Figure 3b,c. When the magnetic field direction in Figure 3b is defined as positive ($B > 0$ T); the carriers of SMST1 are deflected to a recombination region, as a sequence; I_{C1} is decreased and its decrement is ΔI_{C1}; the collector I_{C3} of the SMST3 is increased and its increment is ΔI_{C3}; the output voltage V_x can be obtained:

$$V_x = V_{x1} - V_{x3} = I_{C3} \cdot R_{L3} - I_{C1} \cdot R_{L1} = \Delta V_{x3} - \Delta V_{x1} \tag{2}$$

where the values of ΔV_{x1} and ΔV_{x3} are the variables of collector output voltages for the SMST1 and SMST3 under the external magnetic field, respectively.

Theoretical analysis dictates that if reversing the external magnetic field as negative ($B < 0$ T), as shown in Figure 3c, V_x can be given:

$$V_x = V_{x1} - V_{x3} = I_{C3} \cdot R_{L3} - I_{C1} \cdot R_{L1} = -(\Delta V_{x3} - \Delta V_{x1}) \tag{3}$$

Moreover, the absolute magnetic sensitivity S_x of the differential structure along the x axis can be expressed as:

$$S_x = \frac{|\Delta V|}{B} = \frac{|V_{x3} - V_{x1}|}{B} = S_{x1} + S_{x3} \tag{4}$$

where B is the external magnetic field, S_{x1} and S_{x3} are the absolute magnetic sensitivities for the SMST1 and SMST3, respectively. S_x is the sum of the sensitivities of the SMST1 and SMST3, so as to improve the magnetic sensitivity.

The same as above, when there is no external magnetic field along the y or $-y$ axes, the carriers of the SMST2 and SMST4 are also deflected, and the collector output voltage V_y along the y axis is

$$V_y = V_{y2} - V_{y4} = I_{C04} \cdot R_{L4} - I_{C02} \cdot R_{L2} = 0 \tag{5}$$

When an external magnetic field parallel to the chip is applied along the y axis direction, the magnetic field is defined as positive, and the carriers of the SMST4 are deflected to the recombination region, therefore I_{C4} is decreased and its decrement is ΔI_{C4}, while the collector I_{C2} of the SMST2 is increased and its increment is ΔI_{C2}, the output voltage V_y can be obtained as:

$$V_y = V_{y2} - V_{y4} = I_{C4} \cdot R_{L4} - I_{C2} \cdot R_{L2} = \Delta V_{y4} - \Delta V_{y2} \tag{6}$$

where the values of ΔV_{y2} and ΔV_{y4} are variables of the collector output voltages for the SMST2 and SMST4 under the external magnetic field, respectively.

Reversing the external magnetic field as negative, V_y can be given as:

$$V_y = V_{y2} - V_{y4} = I_{C4} \cdot R_{L4} - I_{C2} \cdot R_{L2} = -(\Delta V_{y4} - \Delta V_{y2}) \tag{7}$$

Moreover, the absolute magnetic sensitivity S_y of the differential structure can be expressed as:

$$S_y = \frac{|\Delta V|}{B} = \frac{|V_{y2} - V_{y4}|}{B} = S_{y2} + S_{y4} \tag{8}$$

The magnetic sensitivity S_y is also equal to the sum of the sensitivities of the SMST2 and SMST4, therefore the magnetic sensitivity can be improved as well.

3. Fabrication Technology

The main fabrication process of the SMSTs is shown in Figure 5, and the processing steps are as follows: (a) cleaning the p-type silicon wafer with a <100> orientation and high resistivity ($\rho = 1000$ $\Omega \cdot$cm); (b) growing the SiO_2 layer (450 nm) by using a thermal oxide method and depositing the Si_3N_4 layer (200 nm) by low-pressure chemical vapor deposition (LPCVD) on the double-side of the silicon wafer; (c) etching Si_3N_4 and SiO_2 to form a window of the emitter region by first photolithography, then etching a C-type silicon cup with the silicon diaphragm thickness of 30 μm (emitter regions) by the KOH anisotropic etching technique, fabricating the collector region by second photolithography and forming the collector and the emitter regions by diffusing dense phosphorus; (d) photo-etching the base region and etching the double-sided Si_3N_4 layers and the upper-sided SiO_2 layer after diffusing dense boron, and then depositing the single-side of the SiO_2 layer; (e) etching contacts of the collector and the base, and depositing an aluminum film on the upper surface by vacuum coating; after that, fabricating the aluminum electrodes of the collector and the base by photography, and then depositing an aluminum film on the bottom to form the aluminum electrode

of the emitter and metallizing at 420 °C for a half-hour to form better Ohmic contacts with the base, collector, and emitter. Then, the four chips which have similar characteristics and opposite magnetic sensitive directions are packaged. Figure 6 shows the packaging photograph of the 2D magnetic field sensor based on the SMSTs.
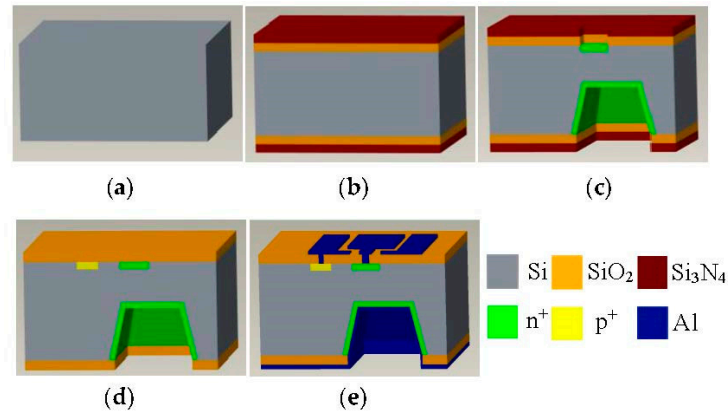

Figure 5. The fabrication technology of the silicon magnetic sensitive transistor. (**a**) Cleaning wafer; (**b**) growing the SiO_2 layer and depositing the Si_3N_4 layer; (**c**) making the collector and the emitter regions by photolithography; (**d**) fabricating the base region by photolithography; (**e**) fabricating the electrodes.
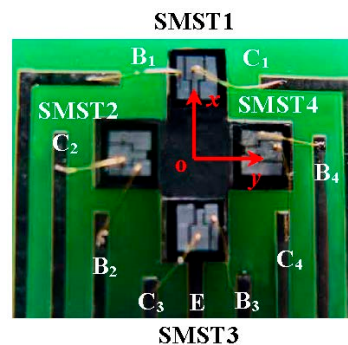

Figure 6. The packaging photograph of the 2D magnetic field sensor.

4. Results and Discussion

4.1. Magnetic Sensitive Characteristics of SMSTs

The magnetic sensitive characteristics of the SMSTs were studied by a semiconductor characterization system (4200, KEITHLEY, Cleveland, OH, USA) and a magnetic field generator (CH-100, Cuihaijiacheng Magnetic Technology, Beijing, China) at room temperature. The magnetic sensitive characteristics of the SMST1 and SMST3 were measured under a magnetic field along the *x*-axis direction, and those of the SMST2 and SMST4 were measured under a magnetic field along the *y*-axis direction. When the operating current I_B = 6.0 mA in a 2D magnetic field range of 0.1 mT–1.2 T, the *I–V* characteristic curves of the four SMSTs with a resolution of 1 Gs at $B = -0.6$ T, $B = 0$ T and $B = 0.6$ T are shown in Figure 7, respectively.

The experiment results show that, under a constant external supplied voltage, the measured I_{C1} decreases with the increasing magnetic field, and moves towards the positive direction, while I_{C3} increases under the same conditions. However, in the subsequent opposite magnetic field direction, the I_{C1} increases, and the I_{C3} decreases with the increasing magnetic field. Moreover, under the same conditions, the *I–V* characteristics of the SMST2 and SMST4 are similar to those of the SMST1 and SMST3, respectively. It indicates that all of the four SMSTs have positive and negative magnetic characteristics. Figure 8a,b

shows the relationship curves between the output current (I_{C1}, I_{C3}, I_{C2}, I_{C4}) and B, where the magnetic field ranges from -0.6 T to 0.6 T with a step of 0.1 T. It shows that the measured I_C increases not only with a constant operating current but also a constant external magnetic field. When the V_{CE} = 10.0 V and I_B = 6.0 mA, the sensitivities of the SMST1, SMST2, SMST3 and SMST4 are 1.08 mA/T, 1.03 mA/T, 1.89 mA/T and 1.92 mA/T, respectively.
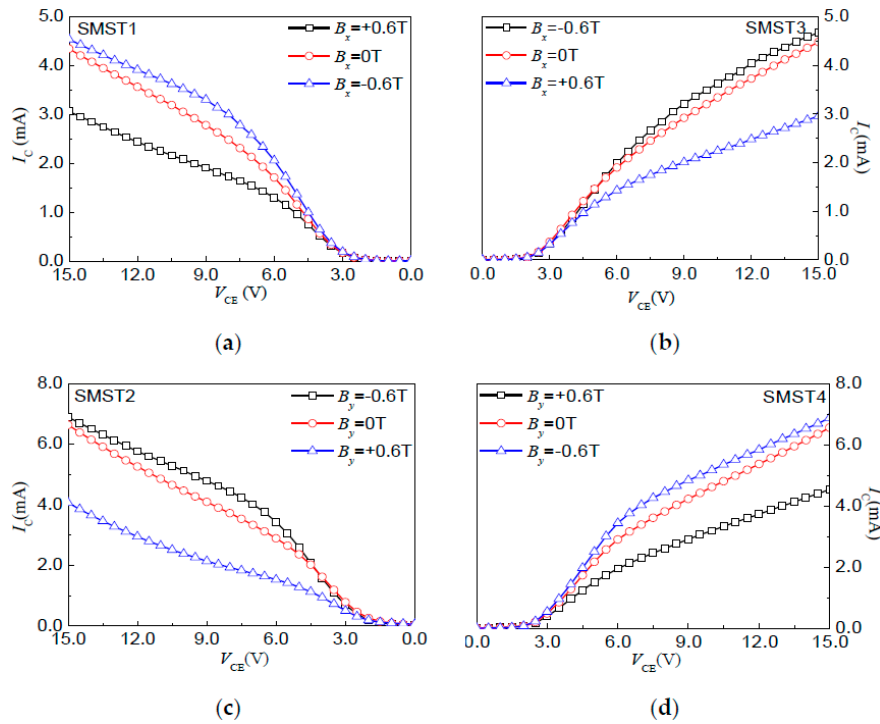

Figure 7. The *I–V* characteristic curves of the silicon magnetic sensitive transistor: (**a**) SMST1; (**b**) SMST3; (**c**) SMST2; (**d**) SMST4.
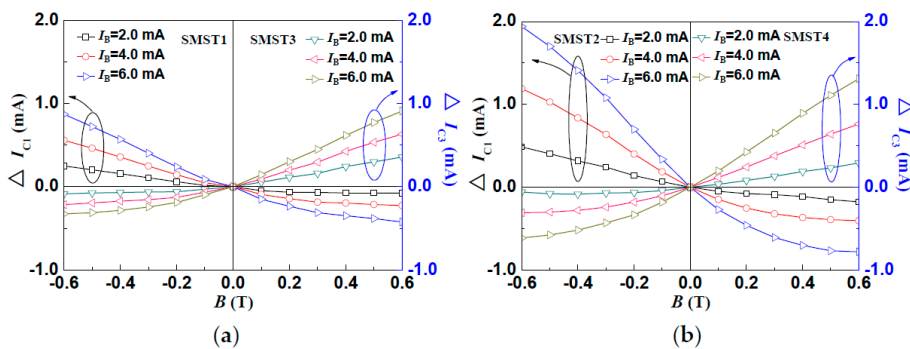

Figure 8. The ΔI_C–B characteristics of the silicon magnetic sensitive transistor: (**a**) SMST1 and SMST3; (**b**) SMST2 and SMST4.

4.2. 2D Magnetic Sensitive Characteristics

The 2D magnetic sensitive characteristics of the proposed sensor were studied by the rotation platform, magnetic field generator (CH-100), teslameter, multi-meter (Agilent 34401A, Agilent, Santa Clara, CA, USA), and power source (DP832A, RIGOL, Beijng, China), as shown in Figure 9, where the θ is the rotation angle of rotating platform. First, the sensor was fastened on the rotating platform, where the θ is defined as zero when the magnetic induction direction parallel to the sensor surface is along the *x* axis. At room temperature, the relationship of the sensitivities for the 2D magnetic

field sensor at about V_x–θ and V_y–θ was studied by every equivalent circuit respectively, as shown in Figure 4. During the test process, to achieve the same sensitivity of the sensors in the two directions, some external resistors were added between the collector and V_{DD}. When the supply voltage is 10.0 V and the current is 6.0 mA, the characteristic curves of output voltages (V_x and V_y) and θ for the sensor at B = 0.2 T are shown in Figure 10.
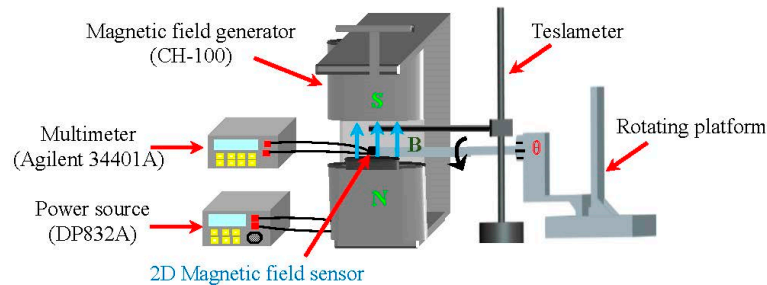

Figure 9. Testing system of the 2D magnetic field sensor.

The results indicate that under a constant external magnetic field B and operating voltage, θ = 0°, V_x is nearly the maximum and V_y is very small. With an increasing rotation angle θ, V_x is reduced and V_y is increased, gradually. When θ = 90°, V_x is nearly zero and V_y is close to the maximum. When θ = 180°, V_x is nearly the minimum and V_y is nearly zero. When θ = 270°, V_x is nearly zero and V_y is close to the minimum. When θ = 360°, V_x is nearly the maximum and V_y is close to zero. It shows that the output voltages V_x and V_y of the 2D magnetic field sensor regularly follow as the sinusoidal or cosine functions of the rotation angle θ, therefore the direction and the strength of the two-dimensional magnetic field can be measured by the sensor. When θ is a constant, the absolute values of output voltages (V_x and V_y) increase with the B. It indicates that when V_{DD} = 10.0 V and I_B = 6.0 mA, the magnetic sensitivities of the sensor in the x and y directions are 360.0 mV/T and 365.0 mV/T, respectively. Equation (9) is the average value expression of the output voltage in the whole period.

$$\overline{V}_{out} = \frac{1}{n}\sum_{i=1}^{n} V_{outi} = \frac{1}{n}\sum_{i=1}^{n} \sqrt{V_{outxi}^2 + V_{outyi}^2}(i = 1, 2, 3...37) \tag{9}$$

According to Equation (9), under the external magnetic field B, the relationship curves of the output voltage V_{out} and the rotation angle θ are shown in Figure 11. In the ideal situation, V_{out} is a constant and the curve is a circle with a radius of 73 mV. The experiment results show that the output voltage V_{out} changes with the rotation angle θ, attributable to the different characteristics of the four SMSTs in the x and y directions.
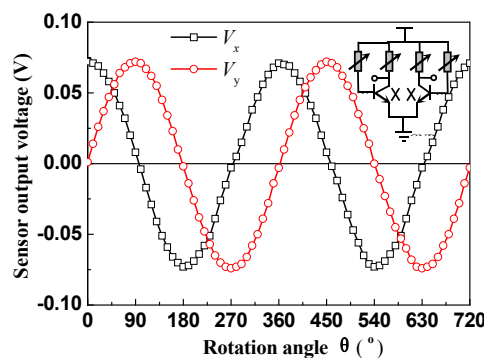

Figure 10. Characteristic curves of the 2D magnetic field sensor at B = 0.2 T.
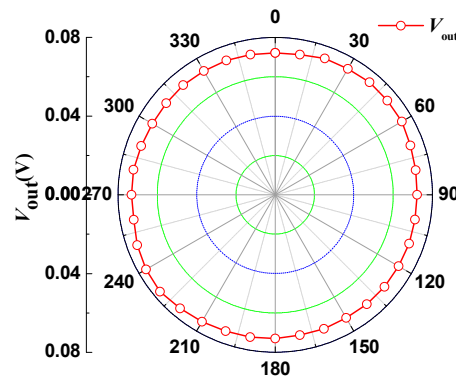
Figure 11. Relationship curves for the output voltage V_{out} and θ.

In terms of a synthetic analysis of journal articles and experimental results, some designs of 2D magnetic field sensors based on diodes, transistors, and Hall elements are summarized in Table 1. From Table 1, the study of the 2D magnetic field sensor includes Hall components, magnetic diodes and magnetic sensitive transistors, and so on. In this work, a novel 2D magnetic field sensor based on a magnetic sensitive transistor by MEMS technology is designed and fabricated; the magnetic sensitivities in the *x* and *y* directions could approach 366.0 mV/T and 365.0 mV/T, respectively. In particular, a referable uniform sensitivity can be measured along the *x*-axis and *y*-axis. The study on the novel 2D magnetic field sensor helps to provide a new guide for development in the monolithic integrated magnetic field sensor field.

Table 1. Two-dimensional (2D) magnetic field sensors based on magnetic diodes, transistors and Hall elements. SOS: silicon-on-sapphire; CMOS: complementary metal-oxide-semiconductor; IC: integrated circuit; MEMS: micro-electromechanical systems.

Structure	Technology	Sensitivity	Reference
Magneto-diode	SOS	0.46 μA/mT	[2]
Hall sensor	Simple planar	41 V/AT, 30 V/AT	[5]
Hall sensor	CMOS	19 V/AT, 19 V/AT	[6]
Diode	Bipolar	544 mV/T, 498 mV/T	[10]
Hall device	CMOS	9.564 mV/T	[12]
Transistor a Hall plate	CMOS	30%/T	[13]
Hall element	Bipolar IC	39 V/AT	[14]
Transistor	MEMS	366 mV/T, 365 mV/T	In this work

5. Conclusions

A new type of 2D magnetic field sensor based on the operating principle and characteristics of the silicon magnetic sensitive transistor (SMST) is proposed in this paper. The sensor was composed of two differential structures with four SMSTs. The experiment results show that when the V_{CE} = 10.0 V and I_B = 6.0 mA, the magnetic sensitivities of the sensor in the *x* and *y* directions reach 366.0 mV/T and 365.0 mV/T, respectively. Based on the differential structure of SMSTs, the 2D magnetic field sensor with a resolution of 1 Gs can measure a 2D magnetic field from 0.1 mT to 1.2 T, not only significantly improving the magnetic sensitivity but also exhibiting a referable uniformity along the *x*-axis and *y*-axis.

Author Contributions: Xianghong Yang, Yunjia Bai and Meiwei Lv coordinated the study; Xiaofeng Zhao and Dianzhong Wen designed the sensor device; Xianghong Yang, Yunjia Bai and Meiwei Lv performed the experiments; Xiaofeng Zhao and Xianghong Yang plotted and performed the initial analysis of the data; Xiaofeng Zhao and Xianghong Yang wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Almeida, M.J.; Götze, T.; Ueberschär, O.; Matthes, P.; Müller, M.; Ecke, R.; Exner, H.; Schulz, S.E. Monolithic integration of 2D spin valve magnetic field sensors for angular sensing. *Mater. Today Proc.* **2015**, *2*, 4206–4211. [CrossRef]
2. Roumenin, C.S. 2D magnetodiode sensors based on SOS technology. *Sens. Actuators A* **1996**, *54*, 584–588. [CrossRef]
3. Shapovalov, G.; Chektybayev, B.; Sadykov, A.; Skakov, M.; Kupishev, E. Experimental measurement of magnetic field null in the vacuum chamber of KTM tokamak based on matrix of 2D Hall sensors. *Fusion Eng. Des.* **2016**, *112*, 432–439. [CrossRef]
4. Zhao, X.F.; Li, B.Z.; Wen, D.Z. Fabrication technology and characteristics of a magnetic sensitive transistor with nc-Si:H/c-Si heterojunction. *Sensors* **2017**, *17*, 212. [CrossRef] [PubMed]
5. Roumenin, C.S.; Nikolov, D.; Ivanov, A. A novel parallel-field Hall sensor with low offset and temperature drift 2D integrated magnetometer. *Sens. Actuators A* **2004**, *115*, 303–307. [CrossRef]
6. Lozanova, S.A.; Roumenin, C.S. A novel magnetometer based on a parallel-field silicon Hall sensor. *Procedia Chem.* **2009**, *1*, 847–850. [CrossRef]
7. Zhao, X.F.; Wen, D.Z. Negative-resistance oscillations characteristics of a new type silicon magnetic sensitive transistor on MEMS. *J. Semicond.* **2005**, *6*, 1214–1217.
8. Zhao, X.F.; Wen, D.Z. Fabrication–technology research of new type silicon magnetic-sensitive transistor. *Rare Met. Mater. Eng.* **2006**, *12*, 492–494.
9. Zhao, X.F.; Wen, D.Z.; Pan, D.Y.; Guan, H.Y.; Lv, M.W.; Li, L. Differential structure and characteristics of new type silicon magnetic sensitivity transistor. *Chin. Phys. Lett.* **2013**, *30*, 088501. [CrossRef]
10. Zhao, X.F.; Yang, X.H.; Yu, Y.; Wu, T.; Wen, D. Characteristics of 2D magnetic field sensor based on magnetic sensitivity diodes. *Am. Inst. Phys. Adv.* **2015**, *5*, 041321. [CrossRef]
11. Lozanova, S.; Roumenin, C. Angular position device with 2D low-noise Hall microsensor. *Sens. Actuators A* **2010**, *162*, 167–171. [CrossRef]
12. Yu, C.P.; Sung, G.M. Two-dimensional folded CMOS Hall device with interacting lateral magnetotransistor and magnetoresistor. *Sens. Actuators A* **2012**, *182*, 6–15. [CrossRef]
13. Janković, N.; Pantić, D.; Batcup, S.; Igic, P. A lateral double-diffused magnetic sensitive metal-oxide-semiconductor field-effect transistor with integrated n-type Hall plate. *Appl. Phys. Lett.* **2012**, *100*, 263507. [CrossRef]
14. Lozanova, S.V.; Noykov, S.A.; Ivanov, A.J.; Roumenin, C.S. 2D in-plane Hall sensing based on a new microdevice couple concept. *Procedia Eng.* **2015**, *120*, 820–923. [CrossRef]