4. Experimental Objectives

1) Understand different magnetoresistor effects and measure the magnetoresistance R_B of three different materials.
2) Plot R_B/R_0 with B and find the maximum value of resistance relative change $(R_B\text{-}R_0)/R_0$.
3) Calibrate magnetoresistor sensors and calculate sensitivity of magnetoresistor sensors.
4) Acquire the relationship of sensor output voltage vs current in a current-carrying wire for three magnetoresistor sensors (i.e. calibrate current sensors)
5) Plot the magnetic hysteresis loop of a spin-valve GMR.

5. Precautions

1) Be aware of the influence of the earth magnetic field on the experimental results.
2) When using a magnetic sensor, any magnetic materials such as ferromagnetic materials should not be placed near the sensor to avoid their effect on the sensor.
3) **To extend the lifetime of the apparatus, do not keep a large current to the current source for a long period of time. Set current to minimum when apparatus is idle.**
4) **Turn off the main power before changing sensor. Plug/unplug connectors carefully to avoid pin damage to the sensor**.
5) The sensitivity of an AMR sensor decreases in the presence of a strong magnetic field. Press the red reset button on the panel to resume its original sensitivity. The other two sensors do not require such an action.

6. Experimental Contents

Experiment 1

Understand the principle of multilayer GMR effect; measure the resistance R_B of a GMR under different magnetic field strength; plot graph of R_B/R_0 with B; and find the maximum value of relative resistance change $(R_B\text{-}R_0)/R_0$.

1) Mount the multilayer GMR sensor module onto the sample stage in the Helmholtz coil. Connect the electric unit (socket is on the back panel) and the coil unit using the 7-core cable. Connect the two Helmholtz coils **in series** with the blue wire and then connect to the coil power source (left side) of the controller unit using the two red and black wires (w/2.5 mm pin diameter). Press down "Coil" and "MR Ratio" buttons on the front panel.
2) Turn on power, set coil current to zero via the left "Adj." knob, then gradually increase coil current while observing the reading of the voltmeter. Set the coil current to zero.
3) Record the voltmeter reading V_0 when the coil current is zero. Gradually increase coil current by 0.05 A in step, while recording the voltage reading V at each current value.
4) Calculate magnetic resistance R_B under various magnetic field strengths, plot R_B/R_0 vs B, and find the maximum value of $(R_B - R_0)/R_0$.

Experiment 2

Learn how to calibrate a multilayer GMR sensor and calculate the sensitivity of a GMR sensor

1) Press down the "Coil" and "Sensor" buttons on the front panel of the electric unit.
2) Turn on the power, set coil current (shown on the current meter, using the left "Adj." knob) and sensor output (shown on the voltmeter, using the "Zero" knob) to zero, then gradually increase the coil current, while monitoring the reading increase of the voltmeter. Set both coil current and sensor output to zero again.

3) Gradually increase coil current from zero with a step of 0.05 A, while recording the voltage reading V at each current value.
4) Plot sensor output voltage V vs magnetic field B and acquire sensitivity K of the sensor.

Experiment 3

Acquire the relationship between output voltage and input current (in a current-carrying wire) for a multilayer GMR sensor

1) Use a pair of red and black wires (w/3.5 mm pin diameter) to connect the test "Output" terminals (i.e. test current) on the front panel (in the middle) of the electric unit with the corresponding terminals (w/ "Test +" and "Test –" labels) on the base of the coil unit. Press down the "Test" and "Sensor" buttons on the front panel of the electric unit.
2) Turn on the power, set test current (shown on the current meter, using the right "Adj." knob) and sensor output (voltmeter) to zero, and gradually increase test current from zero, while monitoring the reading increase of the voltmeter. Finally, set both test current and sensor output to zero again
3) Gradually increase test current from zero with a step of 0.5 A, while recording voltage reading V at each current value.
4) Plot sensor output voltage V vs test current I.

Experiment 4

Acquire the magnetic hysteresis loop of a spin-valve GMR

1) Replace the sample with the spin valve GMR sensor. Press down "Coil" and "Sensor" buttons on the front panel of the electric unit.
2) Turn on the power, set coil current (i.e. current meter) and sensor output (i.e. voltmeter) to zero, gradually increase the coil current from zero with a step of 0.1 A while recording sensor output voltage V at each current value until coil current reaches 1.2 A. Next, gradually reduce coil current to zero and then increase coil current step by step in a reverse direction (i.e. exchanging red/black wire connections of the coil "Output"), while recording sensor output voltage at each current value until coil current reaches -1.2 A. Then gradually decrease coil current to zero, change current direction again, and increase coil current step by step while recording sensor output voltage at each current value until coil current reaches 1.2 A.
3) Plot sensor output voltage V vs magnetic field B, and acquire the magnetic hysteresis loop of the spin valve GMR sensor.

Experiment 5

Experiments with spin valve GMR sensor and anisotropic MR sensor

1) Repeat experiments 1, 2 and 3 using the spin valve GMR sensor.
2) Replace the spin valve GMR sensor with the anisotropic MR sensor, repeat experiments 1, 2, and 3.

7. An example of data recording and processing

Note: following data are for reference purpose only, not the criteria for apparatus performance:

Experiment 1

Table 1 Relationship between R_B/R_0 and B of a multilayer GMR

Coil Current I (A)	Magnetic Field B (mT)	Sensor Output V (V)	R_B (kΩ)	R_B/R_0	Coil Current I (A)	Magnetic Field B (mT)	Sensor Output V (V)	R_B (kΩ)	R_B/R_0
0	0	1.5961	5.118	1.000	0.650	1.169	1.6835	4.728	0.924
0.050	0.090	1.6023	5.089	0.994	0.700	1.259	1.6901	4.700	0.918
0.100	0.180	1.6086	5.060	0.989	0.750	1.349	1.6967	4.673	0.913
0.150	0.270	1.6151	5.030	0.983	0.800	1.438	1.7026	4.648	0.908
0.200	0.360	1.6217	5.000	0.977	0.850	1.528	1.7079	4.626	0.904
0.250	0.450	1.6283	4.970	0.971	0.900	1.618	1.7119	4.610	0.901
0.300	0.539	1.6350	4.939	0.965	0.950	1.708	1.7147	4.598	0.898
0.350	0.629	1.6418	4.909	0.959	1.000	1.798	1.7163	4.592	0.897
0.400	0.719	1.6487	4.878	0.953	1.050	1.888	1.7172	4.588	0.896
0.450	0.809	1.6556	4.848	0.947	1.100	1.978	1.7177	4.586	0.896
0.500	0.899	1.6627	4.817	0.941	1.150	2.068	1.7179	4.585	0.896
0.550	0.989	1.6697	4.787	0.935	1.200	2.158	1.7180	4.585	0.896
0.600	1.079	1.6766	4.757	0.930					

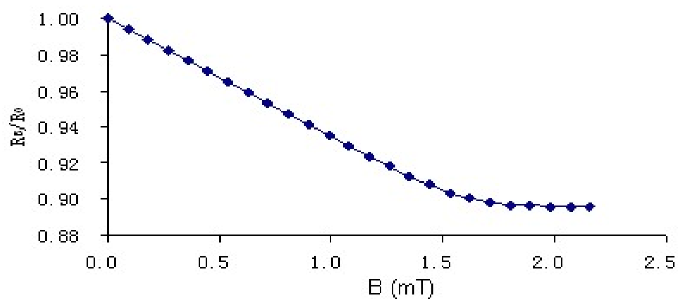

Figure 5 Relationship between R_B/R_0 and B of the multilayer GMR

Magnetic field strength B at the central area of the Helmholtz coil is calculated as

$$B = \frac{8\mu_0 \mathrm{NI}}{5^{3/2} R} = \frac{8 \times 4\pi \times 10^{-7} \times 200}{5^{3/2} \times 0.100} \times I = 17.98 \times 10^{-4} I \qquad (7)$$

where N is the turns of the Helmholtz coil, R is the radius of the Helmholtz coil, B is in unit of T (Tesla), and I is the current of the coil in unit of A (Ampere).

From Equation (6) by taking V_+ as 5.0 V and the data in Table 1, we get

$$\left(R_B - R_0\right)/R_0\big|_{\max} = 0.896\text{-}1 = -0.104 = -10.4\%$$

Experiment 2

Table 2 Relationship between V and B of a multilayer GMR sensor

Coil Current I (A)	Magnetic Field B (mT)	Sensor Output V (V)	Coil Current I (A)	Magnetic Field B (mT)	Sensor Output V (V)	Coil Current I (A)	Magnetic Field B (mT)	Sensor Output V (V)
0	0	0	0.450	0.809	0.1382	0.900	1.618	0.2646
0.050	0.090	0.0153	0.500	0.899	0.1538	0.950	1.708	0.2708
0.100	0.180	0.0303	0.550	0.989	0.1697	1.000	1.798	0.2745
0.150	0.270	0.0454	0.600	1.079	0.1854	1.050	1.888	0.2766
0.200	0.360	0.0604	0.650	1.169	0.2006	1.100	1.978	0.2777

0.250	0.450	0.0756	0.700	1.259	0.2158	1.150	2.068	0.2784
0.300	0.539	0.0912	0.750	1.349	0.2300	1.200	2.158	0.2789
0.350	0.629	0.1066	0.800	1.438	0.2436			
0.400	0.719	0.1222	0.850	1.528	0.2554			

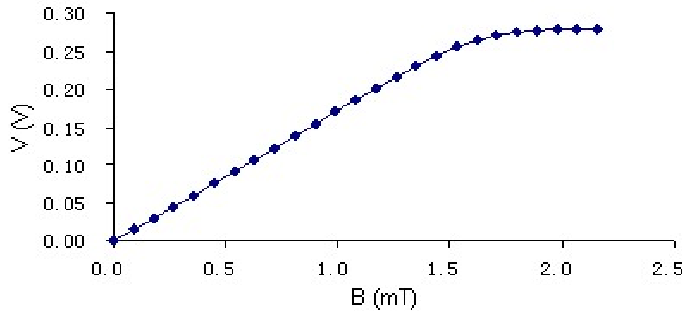

Figure 6 Relationship between *V* and *B* of the multilayer GMR sensor

From the given specifications of the multilayer GMR sensor, we know its linear range is from 0.15 mT to 1.05 mT. By taking the least-square fitting of the data in the linear range in Table 2, we get $V = 0.172B$ with a correlation coefficient of 0.999. Since sensor operating voltage $V_+ = 5$ V, we get sensor sensitivity of 34.4 mV/V/mT.

Experiment 3

Table 3 Relationship between *V* and *I* of a multilayer GMR sensor

Test Current *I* (A)	Sensor Output *V* (V)	Test Current *I* (A)	Sensor Output *V* (V)	Test Current *I* (A)	Sensor Output *V* (V)	Test Current *I* (A)	Sensor Output *V* (V)
0	0	1.50	0.0054	3.00	0.0110	4.50	0.0168
0.50	0.0017	2.00	0.0073	3.50	0.0130	5.00	0.0187
1.00	0.0035	2.50	0.0092	4.00	0.0149		

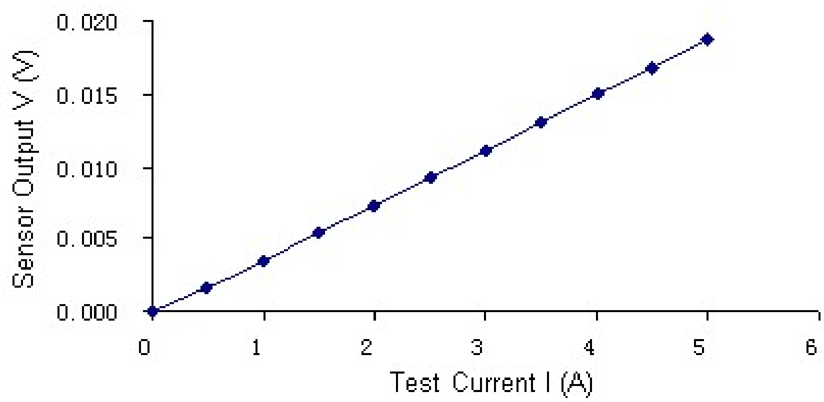

Figure 7 Relationship between *V* and *I* of the multilayer GMR sensor

By taking least-square fitting of the data in Table 3, we get $V=0.0038I$ with a correlation coefficient of 0.999, indicating a linear relationship between the output voltage of a multilayer GMR and the test current. Thus, a multilayer GMR sensor can be used to measure an unknown current.

Experiment 4

Table 4 Relationship between *V* and *B* of a spin valve GMR sensor

Coil Current *I* (A)	Magnetic Field *B* (mT)	Sensor Output *V* (V)	Coil Current *I* (A)	Magnetic Field *B* (mT)	Sensor Output *V* (V)	Coil Current *I* (A)	Magnetic Field *B* (mT)	Sensor Output *V* (V)
0	0	0	0.3	0.539	0.0414	-0.6	-1.079	-0.0798
0.1	0.180	0.0095	0.2	0.360	0.0308	-0.5	-0.899	-0.0718
0.2	0.360	0.0204	0.1	0.180	0.0195	-0.4	-0.719	-0.0614
0.3	0.539	0.0325	0	0.000	0.0081	-0.3	-0.539	-0.0469
0.4	0.719	0.0448	-0.1	-0.180	-0.0057	-0.2	-0.360	-0.0342
0.5	0.899	0.0576	-0.2	-0.360	-0.0211	-0.1	-0.180	-0.0215
0.6	1.079	0.0664	-0.3	-0.539	-0.0376	0	0.000	-0.0107
0.7	1.259	0.0711	-0.4	-0.719	-0.0514	0.1	0.180	0.0005
0.8	1.438	0.0742	-0.5	-0.899	-0.0651	0.2	0.360	0.0134
0.9	1.618	0.0762	-0.6	-1.079	-0.0771	0.3	0.539	0.0277
1.0	1.798	0.0779	-0.7	-1.259	-0.0841	0.4	0.719	0.0415
1.1	1.978	0.0791	-0.8	-1.438	-0.0883	0.5	0.899	0.0546
1.2	2.158	0.0802	-0.9	-1.618	-0.0912	0.6	1.079	0.0653
1.1	1.978	0.0791	-1.0	-1.798	-0.0934	0.7	1.259	0.0704
1.0	1.798	0.0779	-1.1	-1.978	-0.0949	0.8	1.438	0.0736
0.9	1.618	0.0763	-1.2	-2.158	-0.0961	0.9	1.618	0.0757
0.8	1.438	0.0743	-1.1	-1.978	-0.095	1.0	1.798	0.0775
0.7	1.259	0.0714	-1.0	-1.798	-0.0934	1.1	1.978	0.0787
0.6	1.079	0.0669	-0.9	-1.618	-0.0915	1.2	2.158	0.0797
0.5	0.899	0.0605	-0.8	-1.438	-0.0889			
0.4	0.719	0.0517	-0.7	-1.259	-0.0854			

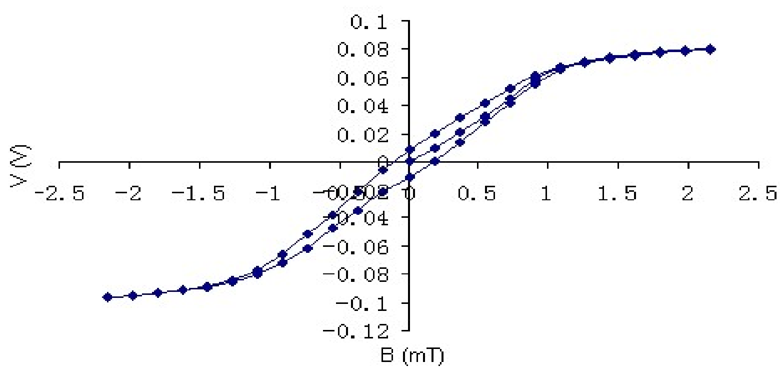

Figure 8 Relationship between *V* and *B* of the spin valve GMR sensor

From the given specifications of the spin valve GMR sensor, we know its linear range is from -0.81 mT to 0.87 mT. By taking least-square fitting of the data in the linear range, we get V= 0.07B with a correlation coefficient of 0.999. Since the sensor operating voltage V_+ =5 V, we get sensor sensitivity of 14.0 mV/V/mT.

Experiment 5

Table 5 Relationship between R_B/R_0 and B of the spin valve GMR sensor

Coil Current I (A)	Magnetic Field B (mT)	Sensor Output V (V)	R_B (kΩ)	R_B/R_0	Coil Current I (A)	Magnetic Field B (mT)	Sensor Output V (V)	R_B (kΩ)	R_B/R_0
0	0	1.6650	1.442	1.000	0.650	1.169	1.6853	1.416	0.982
0.050	0.090	1.6661	1.441	0.999	0.700	1.259	1.6860	1.415	0.981
0.100	0.180	1.6673	1.439	0.998	0.750	1.349	1.6865	1.415	0.981
0.150	0.270	1.6686	1.437	0.997	0.800	1.438	1.6868	1.414	0.981
0.200	0.360	1.6701	1.436	0.996	0.850	1.528	1.6872	1.414	0.980
0.250	0.450	1.6719	1.433	0.994	0.900	1.618	1.6876	1.413	0.980
0.300	0.539	1.6736	1.431	0.992	0.950	1.708	1.6879	1.413	0.980
0.350	0.629	1.6754	1.429	0.991	1.000	1.798	1.6882	1.412	0.980
0.400	0.719	1.6773	1.426	0.989	1.050	1.888	1.6884	1.412	0.979
0.450	0.809	1.6794	1.424	0.987	1.100	1.978	1.6885	1.412	0.979
0.500	0.899	1.6815	1.421	0.985	1.150	2.068	1.6887	1.412	0.979
0.550	0.989	1.6834	1.419	0.984	1.200	2.158	1.6888	1.412	0.979
0.600	1.079	1.6845	1.417	0.983					

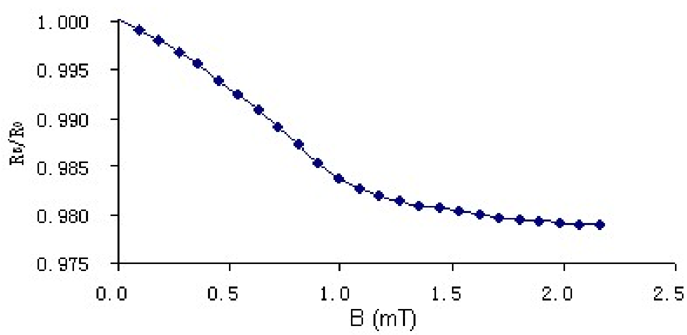

Figure 9 Relationship between R_B/R_0 and B of the spin valve GMR sensor.

From Equation (6) by taking V_+ as 5.0 V and the data in Table from Table 5, we get

$$\left(R_B - R_0\right)/R_0\Big|_{\max} = 0.979-1=-0.021=-2.1\%$$

Table 6 Relationship between V and I of the spin valve GMR sensor

Test Current I (A)	Sensor Output V (V)	Test Current I (A)	Sensor Output V (V)	Test Current I (A)	Sensor Output V (V)	Test Current I (A)	Sensor Output V (V)
0	0	1.50	0.0022	3.00	0.0044	4.50	0.0066
0.50	0.0008	2.00	0.0029	3.50	0.0051	5.00	0.0074
1.00	0.0015	2.50	0.0036	4.00	0.0059		

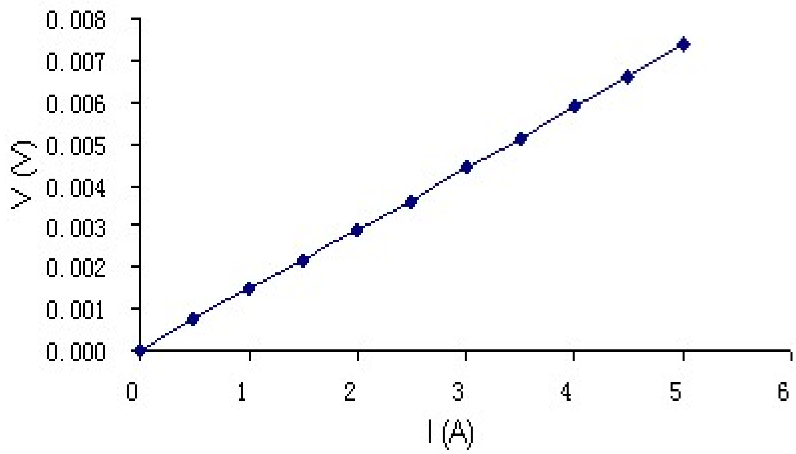

Figure 10 Relationship between V and I of the spin valve GMR sensor

By taking the least-square fitting of the data in Table 6, we get V=0.0015I with a correlation coefficient of 0.999, indicating a linear relationship between the output voltage of a spin valve GMR sensor and the test current. Thus, a spin valve GMR sensor can be used to measure an unknown current.

Table 7 Relationship between R_B/R_0 and B of an anisotropic MR sensor

Coil Current I (A)	Magnetic Field B (mT)	Sensor Output V (V)	R_B (kΩ)	R_B/R_0	Coil Current I (A)	Magnetic Field B (mT)	Sensor Output V (V)	R_B (kΩ)	R_B/R_0
0	0	1.7059	1.043	1.000	0.400	0.719	1.7142	1.035	0.992
0.050	0.090	1.7069	1.042	0.999	0.450	0.809	1.7152	1.034	0.992
0.100	0.180	1.7080	1.041	0.998	0.500	0.899	1.7162	1.033	0.991
0.150	0.270	1.7090	1.040	0.997	0.550	0.989	1.7171	1.032	0.990
0.200	0.360	1.7101	1.039	0.996	0.600	1.079	1.7180	1.032	0.989
0.250	0.450	1.7111	1.038	0.995	0.650	1.169	1.7187	1.031	0.988
0.300	0.539	1.7122	1.037	0.994	0.700	1.259	1.7192	1.030	0.988
0.350	0.629	1.7132	1.036	0.993	0.750	1.349	1.7170	1.033	0.990

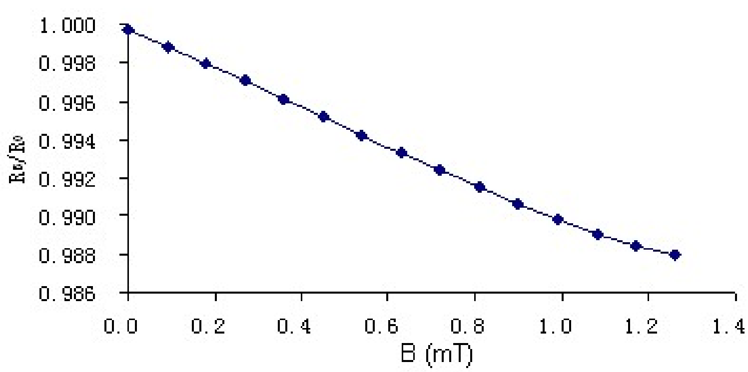

Figure 11 Relationship between R_B/R_0 and B of an anisotropic MR sensor

From Equation (6) by taking V_+ as 5.0 V and the data in Table 7, we get

$$\left(R_B - R_0\right)/\left.R_0\right|_{\max} = 0.988\text{-}1 = \text{-}0.012 = \text{-}1.2\%$$

Note: repetitive output of an AMR sensor will occur within the magnetic field range of ± 2 mT. Unlike other sensors, the output of an AMR sensor reaches the maximum at a certain magnetic field strength, and then it decreases when the magnetic field is continuously increased. Thus, no output saturation is encountered by an AMR sensor. For this reason, once the output of the AMR sensor reaches maximum, the experiment can be stopped as it is unnecessary to continue the experiment until the coil current reaches maximum.

Table 8 Relationship between V and B of the AMR sensor

Coil Current I (A)	Magnetic Field B (mT)	Sensor Output V (V)	Coil Current I (A)	Magnetic Field B (mT)	Sensor Output V (V)	Coil Current I (A)	Magnetic Field B (mT)	Sensor Output V (V)
-0.35	-0.6293	-0.0280	-0.10	-0.1798	-0.0084	0.15	0.2697	0.0125
-0.30	-0.5394	-0.0244	-0.05	-0.0899	-0.0043	0.20	0.3596	0.0165
-0.25	-0.4495	-0.0205	0	0	0	0.25	0.4495	0.0205
-0.20	-0.3596	-0.0166	0.05	0.0899	0.0043	0.30	0.5394	0.0243
-0.15	-0.2697	-0.0125	0.10	0.1798	0.0084	0.35	0.6293	0.0280

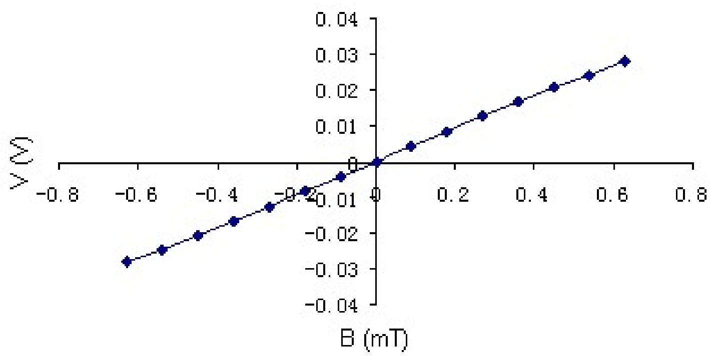

Figure 12 Relationship between V and B of the AMR sensor

From the given specifications of the AMR sensor, we know its linear range is from -0.6 mT to 0.6 mT. By taking least-square fitting of the data in the linear range, we get V=0.045B with a correlation coefficient of 0.999. As sensor operating voltage V_+=5 V, we get sensor sensitivity of 9.0 mV/V/mT.

Note: when an AMR sensor is affected by a strong magnetic field, the sensitivity of the sensor decreases. If necessary, press the red “Reset” button on the front panel of the electric unit to resume the original sensitivity of the AMR sensor. By contrast, the other two sensors do not require such operation.

Table 9 Relationship between V and I of the AMR sensor

Test Current I (A)	Sensor Output V (V)	Test Current I (A)	Sensor Output V (V)	Test Current I (A)	Sensor Output V (V)	Test Current I (A)	Sensor Output V (V)
0	0	1.50	0.0021	3.00	0.0043	4.50	0.0064
0.50	0.0008	2.00	0.0029	3.50	0.0050	5.00	0.0071
1.00	0.0015	2.50	0.0036	4.00	0.0057		

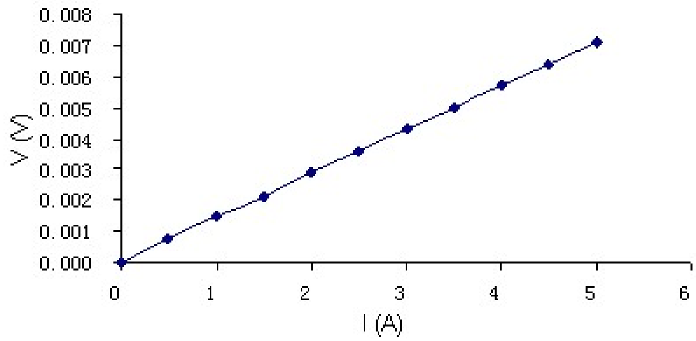

Figure 13 Relationship between V and I of the AMR sensor

By taking the least square fitting of the data, we get $V=0.0014I$ with a correlation coefficient of 0.999, indicating a linear relationship between the output voltage of an AMR sensor and the test current. Therefore, an AMR sensor can be used to measure an unknown current.