A VERY ACCURATE LOW CURRENT HALL EFFECT MEASUREMENTS

Y. Sharon[1], D. Cheskis[1]

[1]*Department of Physics, Faculty of Exact Sciences,*

Ariel University, Israel

ABSTRACT

Measurements of electron transport parameters play an important role in understanding the electronic behavior of new thin films. The development of new devices using thin films demands very precise measurements of these small signals. Many modern electronic devices utilize linear Hall sensors to measure current and the magnetic field, as well as to perform switching and latching operations. Smartphones, laptops, and e-readers all work with very low (sub-milliampere) currents. To perform a switching function in low-power devices, however, Hall sensors must work in the microampere regime. This paper demonstrates, for the first time, the ability of a standard Hall detector to work linearly in the microampere regime between 0 and 0.7 Tesla. To do so, we developed a current source with RMS noise on the order of
10-100 pA/sqrt(Hz). An optimized electronic circuit with minimal connections feeds current to the Hall sensor, and the Hall voltage is measured with an industrial nanovoltmeter. After cooling this system down to temperatures as low as 77 K, we found mostly 1/f noise. In this regime, the thermal noise was negligible. We demonstrate the capabilities of this system by precisely measuring the slope of the Hall effect with a four-point probe at current intensities of 100, 10, and 1 µA. We expect that our system can work as a microampere Hall sensor using external voltage detectors

INTRODUCTION

The technology of electronic transport makes it possible to study bulk electrical properties such as conductivity, resistance, mobility, and the populations of electrical levels, and model their dependence on the temperature, current, and magnetic field. In recent decades, these techniques have been successfully applied to the development of new materials for thin films, which support many modern technologies.

In particular, modern electronic devices need to achieve high speeds, which remaining small in size and consuming little power. Research in this area is pointing towards the magnetic field as a way of tuning the electronic properties of thin films. For example, the electric current passing through a film can be modified by changing the direction of the spins or the strength of an external magnetic field[1–4]. However, to take advantage of these properties in technology, we need highly accurate measurements of all electronic transport parameters.

Electronic transport measuring systems use either direct current or modulated alternating current. In the latter case, modulation has the effect of reducing noise from sources with frequencies different from the modulation frequency. This is commonly done using a lock-in amplifier. It is especially effective when the parameter changed during measurement is the modulation frequency. However, this setup is less useful in experiments where the magnetic field changes.

The alternative is to use direct current. However, conventional sources of direct current suffer greatly from low-frequency noise. In order for a direct current measurement to give results comparable to the current modulation system, it is necessary to identify and significantly reduce the sources of noise. Generally, the main causes of noise are the external electrical network and/or the industrial power source, which introduces a large number of electrical components at intermediate stages of the circuit. These components are required to operate an industrial power source over a wide range of currents.

We offer a direct current system which removes both sources of noise, and is suitable for studies of electrical transport at low current in thin films. First, our current source runs on a commercial 9-volt battery, not by plugging into the external electrical network. Secondly, we create a circuit that generates a single intensity of current. This setup significantly reduces the noise in our circuit.

The essence of this article is to describe our experimental setup. After explaining the apparatus, we demonstrate its sensitivity by measuring the Hall effect on an industrial magnetic field sensor.

Experimental Setup

Our setup for making magnetoresistance[2,3,5,6] and Hall effect measurements is shown in Fig. 1. This system consists of a DC current source, a very accurate nanovoltmeter, Helmholtz magnetic coils and a liquid nitrogen cryostat.

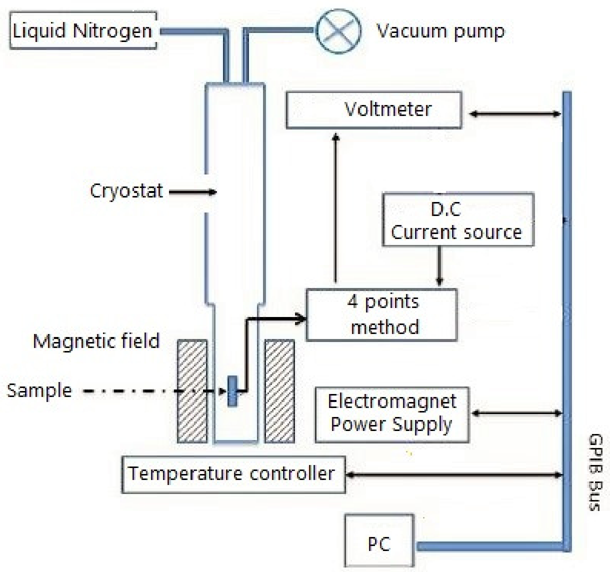

Figure 1 Experimental Setup

With this system, we can measure both the resistance and the Hall Effect[7–12]. This can be done using two different configurations: a Hall bar and the Van der Pauw sample arrangement[13–15], as shown in Fig. 2. In the Van der Pauw arrangement, the electrical contacts are connected to the boundaries of a square sample and the Hall voltage is measured diagonally. In a Hall bar, the current flows through an elongated plate and the Hall voltage is measured at the cross section. In both cases, the voltage is measured perpendicular to the current, and the voltage and current contacts are separated. Such configurations are called "four-point probes". Measurements of resistance effects in these configurations are only related to the properties of sample, not to the measurement circuit.

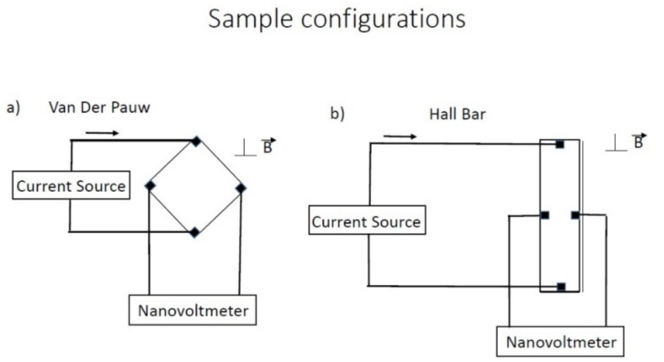

Figure 2 Hall measurement configurations

The sample is attached to a special holder with connected wires. The plane of the holder is perpendicular to the axis of the magnetic coils and can rotate 180 degrees. The holder is inserted into the evacuation area of the cryostat. This allows us to hold the sample either in vacuum or at a low constant gas pressure. The gas delivered to this region is pure helium. The outer walls of the cryostat are cooled by liquid nitrogen. The inside cools to 77 Kelvin, so the helium remains gaseous at a pressure of a few millibars. The temperature of the area containing the sample can be adjusted from 77K to 300K. This control is achieved by cooling the gas or adjusting the heater with the help of a CERNOX temperature sensor and a controller from Lakeshore Cryotronics. This control system stabilizes the sample area to a temperature constant within 0.1 K. Measurements of the Hall voltage are performed under a constant magnetic field. The field can be adjusted from 0 to 0.8 Tesla, in both directions.

The sample that we use is the HSP-T Hall Sensor of the Cryomagnetic. The sample type is a Hall bar with one voltage output. The sample is completely isolated from the external environment in the evacuation chamber of the cryostat, which makes it possible to avoid oxidation. Although we do not know the material of the sample or its exact thickness, the manufacturer provides the dependence of the Hall voltage on the magnetic field. Hence, we can compare our measurements with those of the manufacturer. According to the theory, the Hall voltage depends on the magnetic field, the current, the charge of the carriers, the population density of the charge carriers, and the thickness of the sample.

$$V_{hall} = \frac{BI}{nqt} \qquad (1)$$

Changes to the measured Hall voltage can only occur because the magnetic field B or electric current I change. All other factors are constant for the sample.

As described in the Introduction, our innovation is to use a power source with very low noise. We use a 9V battery as the source of voltage, and disconnect the measurement circuit completely from the external network. The load on the source should be no more than 9V, and ideally much less to reduce noise. To create a constant current through the sample, we use an operational amplifier. If the voltage load is not large and its changes are not great, then the noise in the current is very small.

Experimental Results

The Hall bar calibration sample has a linear Hall effect when the magnetic field is perpendicular to the current passing through the sample. The manufacturer provides the ratio of the Hall voltage to the magnitude of the magnetic field for a current of 100 mA. In order to test our system and learn its sensitivity, we measured the Hall voltage as a function of the external field using our four-point probe. Due to our assumption that the density of carriers does not depend on the current, we can measure this relation for different currents and check whether it is proportional to the manufacturer's value.

We measured the Hall effect under two currents: 100 µA and 10 µA. The results are shown in Figure 3.

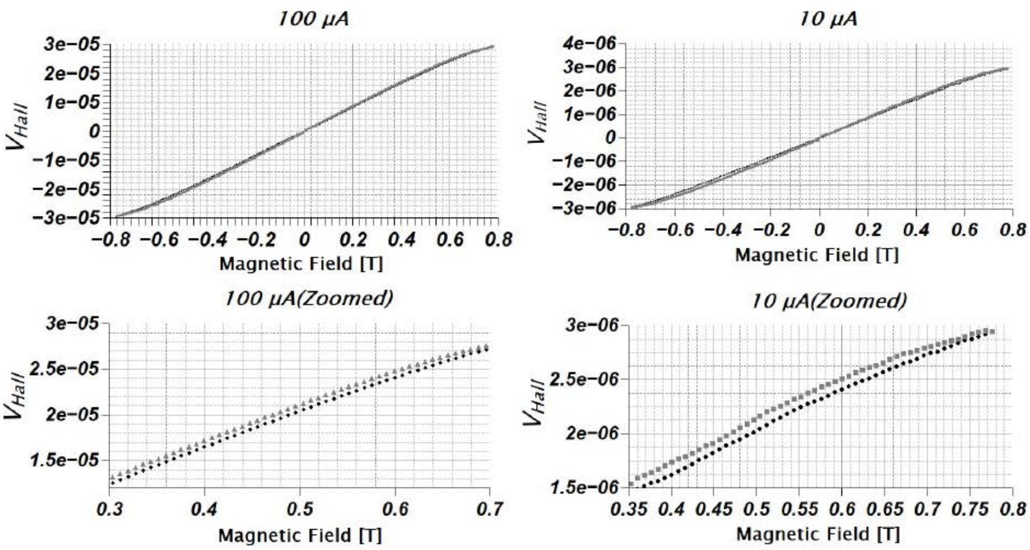

Figure 3 Full (upper plots) and zoomed (bottom plots) Hall effect responces to magnetic field at 100 and 10 µA

In this figure, the dependence of the Hall voltage on the magnetic field is linear for both current values. In Table 1 we compare the slopes of the Hall effect measured for 100 µA and 10 µA to that provided by the manufacturer an in addition comparing hysteresis deviation in to curves.

Table 1 Hall Coeficients

100 mA (Manufacturer)	100 µA	10 µA	Current
38.93 mV/T	39.85 µV/T	3.955 µV/T	Hall Voltage/Magnetic Field
200m%	205m%	164 m%	Linearity Error
Not defined	0.6 µV	0.1 µV	Hysteresis Deviation

First of all, the slopes of the two graphs differ by a factor of 9.98, which is consistent with the factor of 10 between the two currents and matches our expectation from equation 1. Secondly, both series of measurements have a relative error in the approximate range 230-240 m%. In order to decrease the relative error, we focus on the regions where the Hall voltage is linear.

Conclusion

In conclusion, we see that our solution can improve the sensitivity of known transport measurement systems with a relatively simple setup. In order to improve this system is necessary to improve temperature stability. It can be done by better control over temperature conductivity. In addition, better control over magnetization can be achieved if automatic switch of magnetic field will be installed in the system. For our estimations these things will lead to reduce the noise in Hall effect measurements much below 160 m%. In addition we have measured hysteresis deviations for these measurements.

References

1. Wolf, S. A. *et al.* Spintronics: a spin-based electronics vision for the future. *Science (80-.).* **294,** 1488–1495 (2001).
2. Vélez, S. *et al.* Hanle magnetoresistance in thin metal films with strong spin-orbit coupling. *Phys. Rev. Lett.* **116,** 16603 (2016).
3. Tainosho, T. *et al.* Spin Hall magnetoresistance at the interface between platinum and cobalt ferrite thin films with large magnetic anisotropy. *AIP Adv.* **7,** 55936 (2017).
4. Althammer, M. *et al.* Pure spin current transport in gallium doped zinc oxide. *Appl. Phys. Lett.* **110,** 52403 (2017).
5. Kisslinger, F. *et al.* Linear magnetoresistance in mosaic-like bilayer graphene. *Nat. Phys.* **11,** 650–653 (2015).
6. Nakayama, H. *et al.* Rashba-Edelstein Magnetoresistance in Metallic Heterostructures. *Phys. Rev. Lett.* **117,** 116602 (2016).

7. Chen, Y., Yi, H. T. & Podzorov, V. High-resolution ac measurements of the Hall effect in organic field-effect transistors. *Phys. Rev. Appl.* **5,** 34008 (2016).

8. Hurd, C. *The Hall Effect in Metals and Alloys*. (Springer US, 2012). at <https://books.google.co.il/books?id=ZKruoAEACAAJ>

9. Nifa, I. *et al.* Characterization of 2DEG in AlGaN/GaN heterostructure by Hall effect. *Microelectron. Eng.* **178,** 128–131 (2017).

10. Secula, E. Hall Effect Measurements. (2008).

11. van der PAUYV, L. J. A method of measuring specific resistivity and Hall effect of discs of arbitrary shape. *Philips Res. Rep.* **13,** 1–9 (1958).

12. Blanchard, H., De Montmollin, F., Hubin, J. & Popovic, R. S. Highly sensitive Hall sensor in CMOS technology. *Sensors Actuators A Phys.* **82,** 144–148 (2000).

13. Borup, K. A., Fischer, K. F. F., Brown, D. R., Snyder, G. J. & Iversen, B. B. Measuring anisotropic resistivity of single crystals using the van der Pauw technique. *Phys. Rev. B* **92,** 45210 (2015).

14. Castro, H., Galvis, J. & Castro, S. Automated Setup for Van Der Pauw Hall Measurements. *Instrum. Meas. IEEE Trans.* **60,** 198–205 (2011).

15. Schumacher, B. *et al.* DC conductivity measurements in the Van der Pauw geometry. *IEEE Trans. Instrum. Meas. 52* (2017).