D-1 Semiconductor Physics and the Hall Effect

From Physics 191r

Hall Effect Word version File:D1Hall 10.doc

Hall Effect PDF version File:D1Hall 10.pdf

author: Bob Westervelt (1992)

First experiment: yes

Contents

LEARNING GOALS

- Measure the concentration and mobility of charge carriers in a semiconductor
- Determine the band gap in Germanium
- Learn to use a cryostat and cold finger cooled with liquid nitrogen
- Use and understand a lockin amplifier
- Handle cryogenic liquids safely

INTRODUCTION

The Hall (http://en.wikipedia.org/wiki/Edwin_Hall) effect is used very commonly to characterize semiconductor samples and to investigate new phenomena, because it allows one to separately determine (along with measurements of the resistance) the carrier concentration, the sign of the carrier charge, and the scattering time of carriers. Resistance measurements alone only determine the product of the carrier concentration and scattering time. The temperature dependence of these quantities provides even more information, and can be used to deduce the energy bandgap of the semiconductor and the characteristics of electrically active impurities: donor or acceptor, dopant concentration, and binding energy.

In this experiment you will investigate the temperature dependence of the carrier concentration and mobility in a sample of lightly doped p-type Ge. The sample is a single crystal of Ge doped with acceptors in a concentration $N_A \approx 4 \times 10^{11} \mathrm{cm}^{-3}$. At room temperature the sample is intrinsic: the concentrations n and p of electrons and holes are equal and determined by the generation of electron-hole pairs across the band gap. At lower temperatures the carrier concentration decreases exponentially in an activated fashion, until it approaches the acceptor concentration. At lower temperatures the sample is extrinsic and p-type. The concentration of holes is much greater than electrons and relatively temperature independent $p = N_A$. The mobility of electrons and holes is also temperature dependent throughout this range.

The geometry of the sample is a square with soldered indium contacts on each corner. Using the van der Pauw technique of exchanging leads and averaging resistance and Hall measurements, one can obtain accurate measurements of the resistivity and Hall constant even for non-ideal geometries such as this. The sample is heat sunk to a copper cold finger near a diode thermometer, which is read out on the LakeShore temperature controller.

APPARATUS

- Liquid nitrogen cryostat with copper cold finger
- LakeShore Cryotronics temperature controller
- Vacuum pump and gauge
- Ge sample - leads brought out to connection box
- Electromagnet and power supply
- Gaussmeter
- Lockin amplifier with built-in oscillator
- WaveTek function generator
- Series resistors in Pomona boxes
- Oscilloscope
- Multimeter

PROCEDURE

Before you start, check that the sample is mounted in the cryostat. Ask the staff for help to open the cryostat. Remount the cryostat on its stand and pump out the vacuum jacket to about 10 micrometers on the thermocouple vacuum gauge. Valve off the pump and fill the cryostat with liquid nitrogen. The sample will cool with a time constant of about one half hour. As the sample cools, you can control the temperature using the LakeShore temperature controller. A power supply can also be used to heat the cold finger manually. The lowest temperature achievable with liquid nitrogen is about 85 K. It is possible to fill the precooled cryostat with liquid helium to cool to about 20 K. Consult the staff if you would like to do this.

Make electrical measurements using the sinusoidal voltage source at the back of the lockin amplifier, which has a frequency of 1 kHz and a switchable value of 1 V_{rms} to 0.01 V_{rms}. Connect the reference out on the back panel to the reference input on the front panel. Alternatively, use the Wavetek function generator, connecting its

SYNC output to the lock-in reference. Measure the voltage source using a multimeter, and convert it to a current source using a large series resistor in a Pomona box of typically 100 kΩ to 1 MΩ. The value of this resistor should be much larger than the resistance of the sample, which is strongly temperature dependent. Connect the Pomona box to one current lead, and complete the circuit at the other current lead using a shorting cap or the equivalent. The voltage is measured differentially using both inputs of the lockin amplifier. To do the van der Pauw technique, you will need to switch leads at the sample connector box. Adjust the phase of the lockin and verify that everything is working correctly by monitoring the signal at the monitor output connector on the front panel.

The electromagnet is powered by a large d.c. power supply. Never disconnect the leads when current is flowing, or you will generate a large, dangerous and destructive voltage, just as you do for the spark plugs in your car. The magnetic field at the sample is the sum of that due to the coils and due to the magnetization of the iron core, which creates a small hysteresis as one sweeps the current up and down. To accurately determine the magnetic field use a gaussmeter.

First measure the magnetoresistance and Hall resistance vs. magnetic field (both polarities) at the lowest and highest temperatures, about 77 K and 300 K. The magnetoresistance is even in the applied field and the Hall effect is odd, but nominal measurements are usually a combination of both. One can separate the two effects using their symmetry i.e. the Hall resistance is antisymmetric as one reverses the magnetic field, while the magnetoresistance is symmetric. Your Hall measurements should be taken at as low a magnetic field as possible without losing too much signal so that $\omega_c \tau \ll 1$.

Once you have determined the best magnetic field range, measure the resistivity and Hall constant vs. temperature, and use this data to determine both the carrier concentration and mobility vs. temperature. Actually compute and plot your results as you take the data; this saves much grief later if you make any mistakes. Note that at room temperature the number of electrons and holes is equal and one might think that the Hall resistance is zero (is it?). You can find a correct treatment of this case in the references.

EXPERIMENT

Determine the carrier concentration and mobility vs temperature. Use these to determine the energy bandgap for Ge, the intrinsic carrier concentration at 300 K, the type and concentration of impurities, and the mechanism, which limits the mobility.

NOTES

REFERENCES

Articles

- D.K. de Vries and A.D. Wieck, "Potential distribution in the van der Pauw technique (http://www.fas.harvard.edu/~phys191r/References/d1/deVries1995.pdf) ," Am. J. Phys. **63** (12), December 1995.

- L.J. van der Pauw, "A Method of Measuring the Resistivity and Hall Coefficient of Lamellae of Arbitrary Shape (http://www.fas.harvard.edu/~phys191r/References/d1/vanderpauw1958.pdf) ," Philips Technical Review, **20**, 220, 1958.

Books

- R.B. Adler, A.C. Smith, and R.L. Longini, *Introduction to Semiconductor Physics*, (John Wiley & Sons, N.Y., 1964).
- R.A. Smith, *Semiconductors*, (Cambridge Univ. Press, Cambridge, 1978).
- D.A. Fraser, *The Physics of Semiconductor Devices*, (Clarendon Press, Oxford, 1979).
- R.A. Greiner, *Semiconductor Devices and Applications*, (McGraw Hill, N.Y., 1961).
- D.C. Look, "Electrical Characterization of GaAs Materials and Devices (http://www.fas.harvard.edu/~phys191r/References/d1/Look_GaAs.pdf) ," (John Wiley and Sons, 1988).
- J. Seymour, *Electronic Devices and Components*, (John Wiley & Sons, N.Y., 1981).
- N.W. Ashcroft and N.D. Mermin, *Introduction to Solid State Physics*, (Holt, Rinehart & Winston, N.Y., 1976).
- R.K. Willardson and A.C. Beer, editors, *Semiconductors and Semimetals*, Vol 15 - Contacts, Junctions, Emitters, (Academic Press, N.Y., 1981).
- K. Seeger, *Semiconductor Physics: An Introduction*, Springer Series in Solid-State Sciences, v.40, (Springer-Verlag, Berlin, 1991).

Appendix: Notes on Hall Effect with both Holes and Electrons

author: M. Tinkham (2004)

Simple Hall Effect

In a material with a single type of carrier with mass m and charge q, and a carrier density of n per unit volume, the Hall effect is simply derived, as follows: With a current density $J = nqv$, the carrier velocity is $v = J/nq$. In a magnetic field perpendicular to the motion, there is a Lorentz force $F = qvB$ tending to deflect the carrier velocity to the side. Such a deflection is physically impossible because the boundaries on the sample prevent a current in that direction. To prevent this deflection, a transverse electric field E is established by a surface charge. Equating the electric force qE to the Lorentz force so that they cancel, the electric field must be $E = vB = (J/nq)B = JB/nq = R_H JB$. This defines the Hall coefficent R_H. In an actual experiment, one measures the current I, and Hall voltage V, from which J and E can be determined by taking account of the sample dimensions in a simple rectangular sample. Physically, this inverse dependence on n can be understood by noting that for a given current density, the carrier velocity must be inversely proportional to carrier density, and the magnetic force is proportional to velocity.

Hall Effect with Two Types of Carriers

If there is an appreciable carrier density of both holes in the valence band and electrons in the conduction band, this simple analysis breaks down, but the principle remains the same. That is, we need to find the transverse electric field that will lead to zero *net* electric current in the transverse direction. This is not so simple to work through, because the two types of carriers in general will have different *mobilities*, $\mu = q\tau/m$, since they have different effective masses and scattering times, as well as opposite charges $\pm e$. When I worked through this, I found that the Hall coefficient should be given by

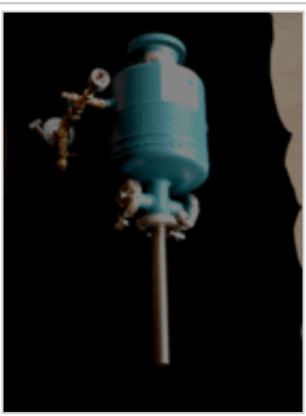
$$R_H = \frac{n_h \mu_h^2 - n_e \mu_e^2}{(n_h \mu_h + n_e \mu_e)^2} \left(\frac{1}{e}\right)$$

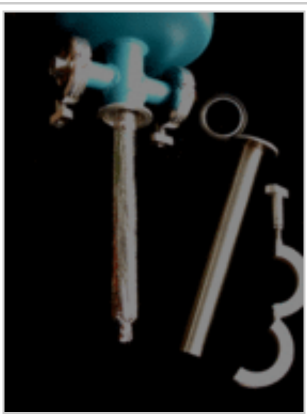
See K. Seeger, *Semiconductor Physics*, section 4.2 for a full derivation. (Or you may wish to check it yourself!) At least it reduces properly to $-1/n_e e$ and $+1/n_h e$ for the limits in which electrons or holes, respectively, are dominant, so that the minority carrier can be ignored. This is, in fact, usually the case, since the carrier concentrations can easily vary over many orders of magnitude, so are seldom nearly equal in a doped semiconductor. In an intrinsic semiconductor, n_e and n_h are equal, but there can still be a Hall effect, with the sign determined by the carrier with the higher mobility.

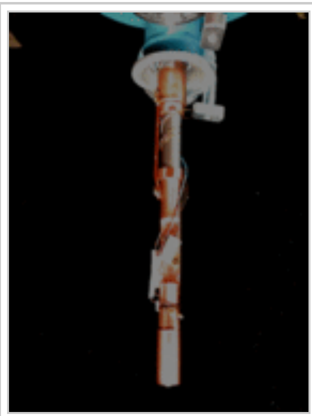
BENCH NOTES

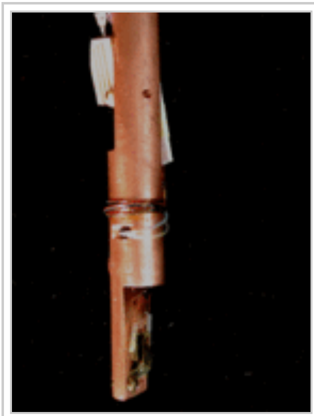
- Sample Info (http://www.fas.harvard.edu/~phys191r/Bench_Notes/D1/Sampleinfo.pdf)
- Sample Connections at BNC breakout box viewed from sample top: BNC1 ~ top left, BNC2 ~ bottom left, BNC3 ~ bottom right, BNC4 ~ top right.
- Wavetek 132 Function Generator (http://www.fas.harvard.edu/~phys191r/Bench_Notes/D1/wavetek132.pdf)
- Lakeshore 805 Temperature Controller (http://www.fas.harvard.edu/~phys191r/Bench_Notes/Tempcontroller.pdf)
- SR510 Lockin Amplifier (http://www.fas.harvard.edu/~phys191r/Bench_Notes/SR510.pdf)
- Bell 615 Gaussmeter (http://www.fas.harvard.edu/~phys191r/Bench_Notes/bell615.pdf)
- Kepco KS 60-10M Magnet Power Supply (http://www.fas.harvard.edu/~phys191r/Bench_Notes/D1/MagnetPowerSupply.pdf)
- Hall Effect Measurements (NIST) (http://www.eeel.nist.gov/812/intr.htm)

PHOTOS


Cryostat


Cryostat with cap removed, showing superinsulation


Cold finger


Sample

Sample closeup