Magnetophonon Experiment

Physics 450

August 14, 2008

Contents

1 Introduction

In this experiment the magnetophonon resonance effect in Indium Antimonide is investigated. A resonant interaction between electrons in cyclotron motion and optical phonons occurs when a certain criterion is fulfilled. When the interaction takes place, small oscillations in the ρ versus B curve arise [1]. It will be theses oscillations that will be observed and measured.

2 Background

When a magnetic field is applied to a metal or semiconductor the free electron states collapse from particle in a box states onto Landau levels. For refreshment in this field refer to 343 notes or a solid state physics textbook, for example [2]. The electrons themselves perform cyclotron orbits in the X-Y plane or spirals along the field in the Z direction. At fixed k_z, the energy difference between the Landau levels is given by:

$$\Delta E = \hbar\omega_c = \frac{\hbar e B}{m^*} \tag{1}$$

where m^* is the effective, or band mass of the free electrons. In a semiconductor there is a strong elastic interaction between the intrinsic or extrinsic electron and the lattice (Bragg reflection), which often results in a very low effective mass ($m^* \approx 0.1 m_e$).

The conductivity of a pure metal or semiconductor (intrinsic or extrinsic) is limited by scattering of the carriers by atomic vibrations (Deybe acoustic phonons) at room temperature. As the temperature is decreased, so is the acoustic phonon density, so that scattering by impurities dominates.

In a III-V or II-VI semiconductor, there are optical phonon modes. These are modes in which neighboring atoms move out-of-phase. The analogue is the anti-symmetric mode of the two-coupled oscillator system. The III-V bond is to some extent ionic; that is the III atom picks up electronic charge from the V atom as in the fully ionic alkali-halide crystals. Therefore an electric field will induce relative motion of atoms. For this reason the optic phonon modes can be excited by an electromagnetic wave of the correct frequency. This is in the optical part of the spectrum and hence the name.

In a III-V or II-VI semiconductor, when the cyclotron frequency of the free electron is equal to the optical phonon frequency there is a resonant interaction which induces electron transitions between Landau levels and the generation or annihilation of optical phonons. This will occur whenever

$$n\hbar\omega_c = \hbar\omega_{opt} \tag{2}$$

where n is an integer. This resonant interaction will also increase the electrical resistance of the semiconductor. This was predicted in 1961 by Gurevitch and Firsov [3].

The resistance of the semiconductor is a linear function of the magnetic field and the resonance peaks are a small effect on top of that linear dependence. A clever procedure, which makes use of a phase sensitive detector, is used to measure dρ/dB, which eliminates the linear term in ρ. (The constant dρ/dB background can be reduced to zero with a reverse voltage). The resonance peaks can then be clearly observed [4, 5].

3 Equipment

A diagram indicating how to hook up the equipment for this experiment is shown in figure 1.

The sample is inserted into the end of a nitrogen vapor transfer line. The rate at which cold vapor passes the sample is governed by a heater in the liquid nitrogen storage dewar. The sample is also positioned between the pole-faces of a 0-1.2 T iron core, copper-coil electromagnet and a small auxiliary electromagnet. The main magnet generates a slowly ramped magnetic field. The smaller electromagnet is driven by an AC current from an audio amplifier and generates an auxiliary alternating field.

A four terminal method with a constant current is used to measure the resistance of the sample. The voltage is measured with a phase sensitive detector. If the field is given by:

$$B = B_0 + b\cos\omega_0 t \tag{3}$$

then

$$V = V(B_0) + \left(\frac{dV}{dB}\right) b\cos\omega_0 t \tag{4}$$

or

$$\rho = \rho(B_0) + \left(\frac{d\rho}{dB}\right) b\cos\omega_0 t. \tag{5}$$

The phase sensitive detector measures only the dρ/dB term.

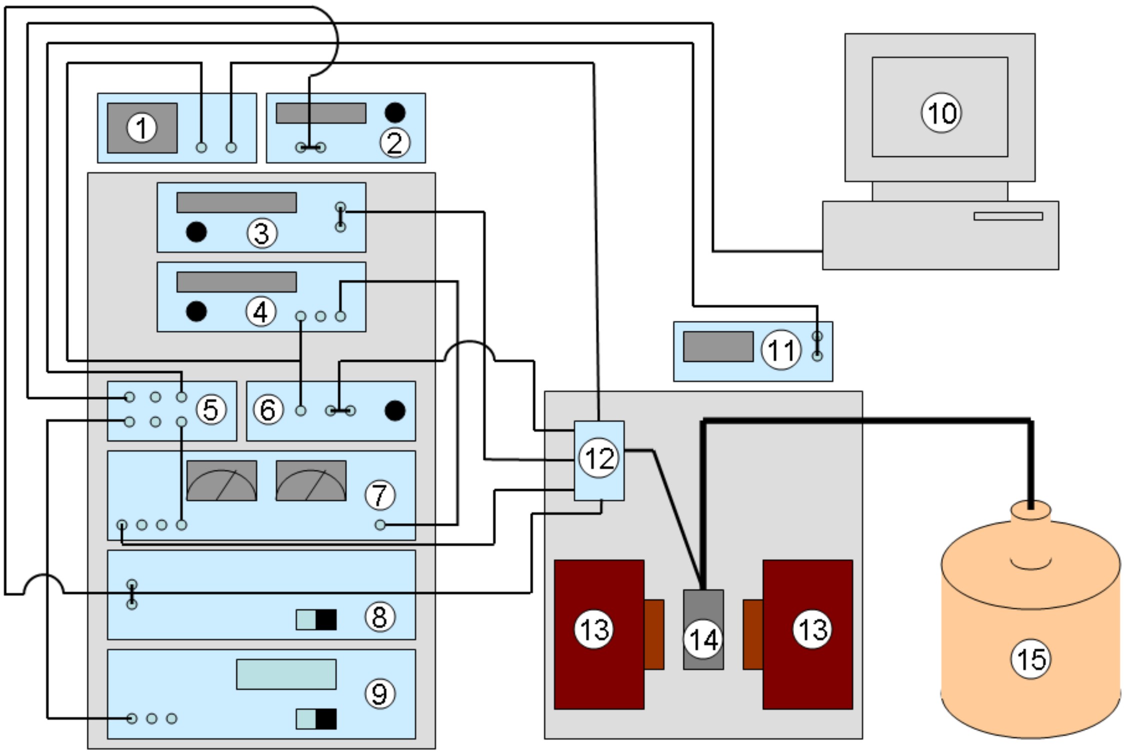

Figure 1: Schematic diagram of the experimental setup.

1.	Oscilloscope	9.	Xantrex AC Controller
2.	Keithley 160 DMM	10.	Computer
3.	Keithley 177 DMM	11.	RFL Gaussmeter
4.	Function Generator	12.	Source Box
5.	Sample Box	13.	Electromagnet
6.	Bogen Audio Amplifier	14.	Sample
7.	SRS Lock-In Amplifier	15.	Dewar
8.	10V Reference Supply		

Table 1: Equipment list.

4 Experiment

First, check all of the wiring and make sure that you understand the components and their function. Next, set the sample current and the modulation (auxiliary) magnetic field. Determine that you are getting a signal from the phase sensitive detector. Then start the vapor transfer, measure the sample temperature, and at 100 K, make a field sweep. Repeat the experiment at a series of temperatures. Use the Gaussmeter to calibrate the field axis on the computer plot.

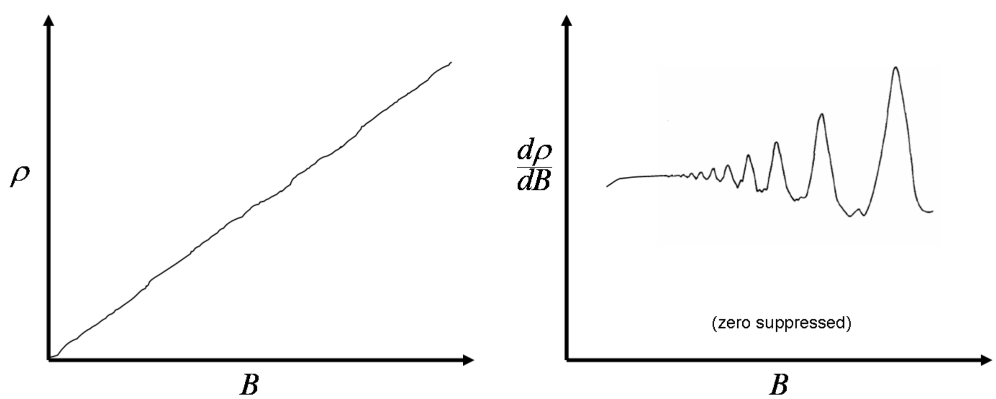

Figure 2: Sample Plots [6].

5 Analysis

For each sweep determine the fields corresponding to the separate resonance numbers n. The basic equation is:

$$\frac{neB}{m^*} = \omega_{opt}. \tag{6}$$

This shows that a plot of 1/B versus n should give a straight line of slope $e/m^*\omega_{opt}$. When combined with the longitudinal optic mode frequency of InSb, the effective mass can be determined.

6 Appendix A: Supplementary Information

The sample is a single crystal of Indium Antimonide about 2 mm square in cross-section and about 1.5 cm long. Electrical connections are soldered at each end and a thermocouple junction is in close proximity.

Measure the resistance of the sample circuit (sample + wires). You want to put constant current through the sample and measure changes in voltage (resistance) as a measure of change in resistivity and hence scattering. To get sufficient sensitivity, 20 mA is a good current to use (avoid high power to not heat the sample). Use a voltage supply with a series resistance large compared to the sample resistance for an effective constant current supply.

Cool the sample to about 120 K by evaporating liquid nitrogen with the heater in the dewar. For safety, check that the dewar is electrically grounded with the clamp.

Take the voltage leads initially to the Y-axis of an X-Y recorder and the output of a Hall-Probe Gaussmeter to the X-axis. Sweep the magnetic field and note the change in resistivity of the sample. This is called magnetoresistance. Sweeping the field can be accomplished by ramping the magnet power supply up or down using the programmable power supply and Labview controlling software. Check that the position of the Gaussmeter probe gives a true indication of the field at the sample position.

Due to the resonance with the optical phonons, there are small perturbations in the plot of ρ vs. B. In order to see them clearly, you will need to use the trick of AC modulation of the ramping magnetic field, using the wire coils surrounding the sample, with a phase sensitive detector on the voltage output leads. Drive the modulating coil by a sinewave generator with a power amplifier to deliver sufficient modulation current to the coils. Measure the resistance of the coils; it is low enough that an amplifier may be overloaded driving them directly, so a series resistor or 2.2 ohms is inserted. Monitor the voltage across the modulating coils with an oscilloscope; it should be a few volts peak-to-peak, undistorted. Can you estimate the modulating field? The modulating frequency should not be too low (lock-in amplifiers are often limited to 10 or 100 Hz) and not too high (to avoid serious phase shifts from coil inductance), avoid a multiple of 60 Hz line frequency.

Connect the output of the lock-in amplifier to the Y-axis of the X-Y recorder, and optimize lock-in settings for filters, phases, etc.

Some supplementary apparatus comprehension diagrams are included below.

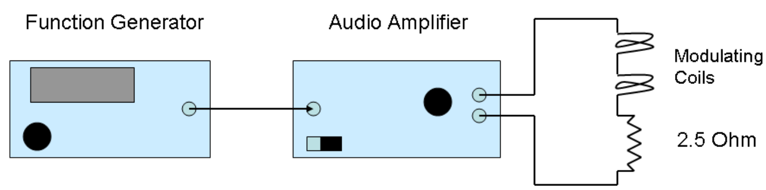

Figure 3: Modulating coil circuit.

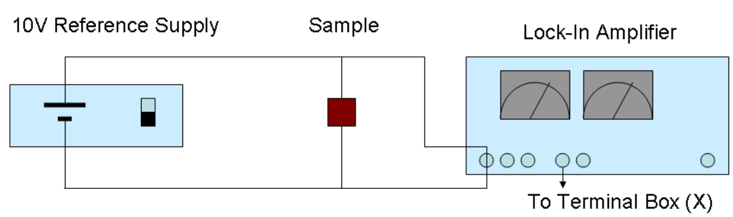

Figure 4: Sample circuit.

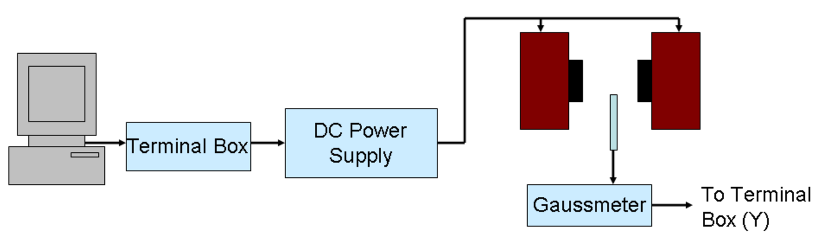

Figure 5: Electromagnet circuit.

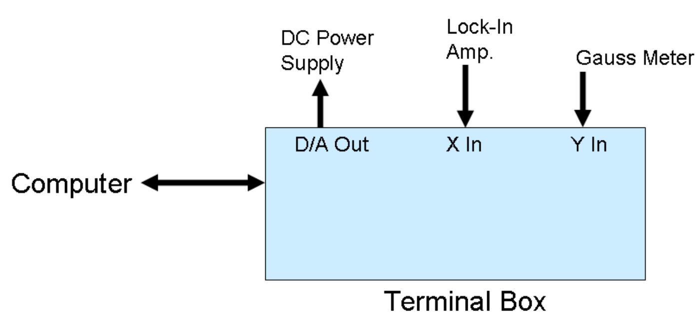

Figure 6: Terminal box.

7 Appendix B: Thermocouple Calibration

Chromel-alumel thermocouple calibration sheet:

$^{\circ}C$	0	1	2	3	4	5	6	7	8	9 (mV)
-190	-5.6	-5.62	-5.63	-5.65	-5.67	-5.68	-5.7	-5.71	-5.73	-5.74
-180	-5.43	-5.45	-5.46	-5.48	-5.5	-5.52	-5.53	-5.55	-5.57	-5.58
-170	-5.24	-5.26	-5.28	-5.3	-5.32	-5.34	-5.35	-5.37	-5.39	-5.41
-160	-5.03	-5.05	-5.08	-5.1	-5.12	-5.14	-5.16	-5.18	-5.2	-5.22
-150	-4.81	-4.84	-4.86	-4.88	-4.9	-4.92	-4.95	-4.97	-4.99	-5.01
-140	-4.58	-4.6	-4.62	-4.65	-4.67	-4.7	-4.72	-4.74	-4.77	-4.79
-130	-4.32	-4.35	-4.37	-4.4	-4.42	-4.45	-4.48	-4.5	-4.52	-4.55
-120	-4.06	-4.08	-4.11	-4.14	-4.16	-4.19	-4.22	-4.24	-4.27	-4.3
-110	-3.78	-3.81	-3.84	-3.86	-3.89	-3.92	-3.95	-3.98	-4.0	-4.03
-100	-3.49	-3.52	-3.55	-3.58	-3.61	-3.64	-3.66	-3.69	-3.72	-3.75
-90	-3.19	-3.22	-3.25	-3.28	-3.31	-3.34	-3.37	-3.4	-3.43	-3.46
-80	-2.87	-2.9	-2.93	-2.96	-3.0	-3.03	-3.06	-3.09	-3.12	-3.16
-70	-2.54	-2.57	-2.61	-2.64	-2.67	-2.71	-2.74	-2.77	-2.8	-2.84
-60	-2.29	-2.24	-2.27	-2.3	-2.34	-2.37	-2.41	-2.33	-2.47	-2.51
-50	-1.86	-1.89	-1.93	-1.96	-2.0	-2.03	-2.07	-2.1	-2.13	-2.17
-40	-1.5	-1.54	-1.57	-1.61	-1.64	-1.68	-1.72	-1.75	-1.79	-1.82
-30	-1.14	-1.17	-1.21	-1.25	-1.28	-1.32	-1.36	-1.39	-1.43	-1.37
-20	-0.77	-0.8	-0.84	-0.88	-0.92	-0.95	-0.99	-1.03	-1.06	-1.1
-10	-0.39	-0.42	-0.46	-0.5	-0.54	-0.58	-0.62	-0.66	-0.69	-0.73
-0	0	-0.04	-0.08	-0.12	-0.16	-0.19	-0.23	-0.27	-0.31	-0.35
+0	0	0.04	0.08	0.12	0.16	0.2	0.24	0.28	0.32	0.36
10	0.4	0.44	0.48	0.52	0.56	0.6	0.64	0.68	0.72	0.76
20	0.8	0.84	0.88	0.92	0.96	1.0	1.04	1.08	1.12	1.16
30	1.2	1.24	1.28	1.32	1.36	1.4	1.44	1.49	1.53	1.57

Table 2: Electromotive Force in Absolture Millvolts, Temperatures in $^{\circ}C$ (Int. 1948) Reference Junctions at $0^{\circ}C$.

References

[1] Stradling, R. A. and Wood, R. A. *Journal of Physics Part C: Solid State Physics* **1**, 1711 (1968).

[2] Blackmore, J. S. *Solid State Physics*. Saunders, (1974).

[3] Gurevitch, V. L. and Firsov, Y. A. *Soviet Physics JETP-USSR* **13**(1), 137–146 (1961).

[4] Parfenev, R. V., Shalyt, S. S., and Muzhdaba, V. M. *Soviet Physics JETP-USSR* **20**(2), 294 (1965).

[5] Haas, M. and Henvis, W. *Journal of Physics and Chemistry of Solids* **23**, 1099 (1962).

[6] Nicholas, R. J. *Progress in Quantum Electronics* **10**, 1–75 (1985).