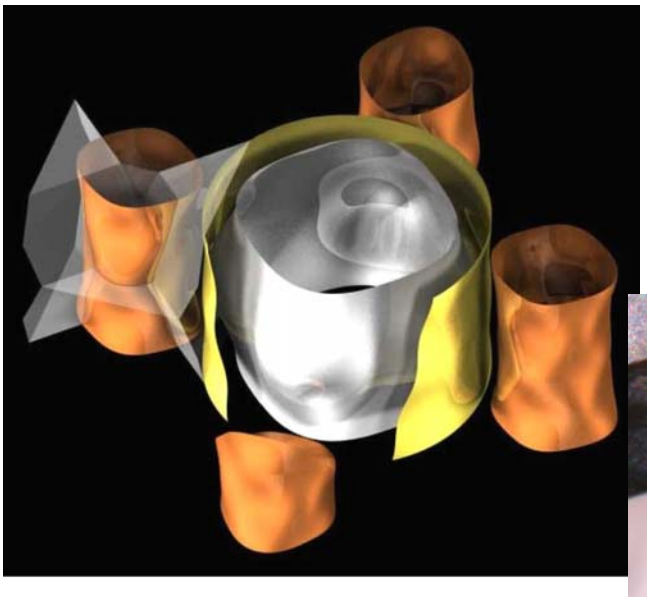
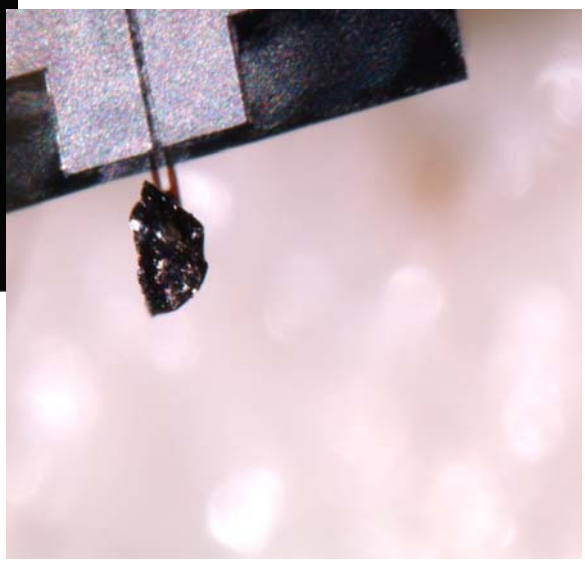
Sensitive Technique Used To Measure Fermi Surfaces





By: Alexander S. Graffeo

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Introduction

When performing experiments that require taking magnetic measurements under conditions of high magnetic fields, many types of equipment, such as SQUID, which has a sensitivity of approximately 10^{-7}emu and is expensive, are prone to damage or are cost prohibitive. However, there is a method available that measures to greater levels of sensitivity. By utilizing simple electronic circuits such as the Wheatstone bridge and an extremely sensitive measuring device called the micropiezolever, it may be possible to measure to a greater level of sensitivity (on the order of 10^{-11}emu), at a very low cost (approximately $100). This sensitive measurement method should yield results similar to those of a capacitance bridge, but with much less sophistication and cost.

Fermi Energy and Surface

Before we begin, let us first discuss a Fermi surface. Imagine there are several electrons in a box at T=0K as in figure1.

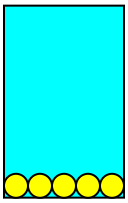


Figure 1 – Several electrons in a box

In accordance with the Pauli exclusion principle, a maximum of two electrons may occupy each quantum energy level. The energy of the last filled level at T=0K is the Fermi energy (see figure 2)[1].

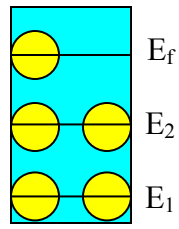


Figure 2 – Electrons distributed into energy levels. The energy of the electron in the last layer is the Fermi energy E_f.

These electrons exhibit wave-like properties. Frequently electrons may be described by a wave vector, k, which consists of kx, ky, and kz, components [3].

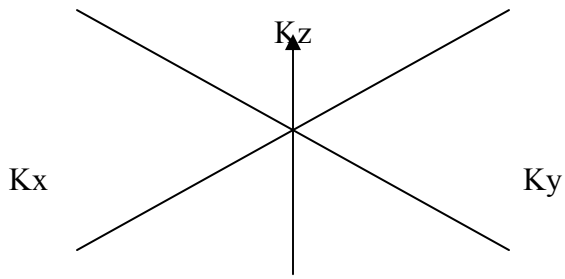


Figure 3 – 3-dimensional K-space

If the individual electrons are described in k-space, it is possible to see how the electrons are distributed (in K-space)[3]. By connecting the points in k-space where energy of the wave vectors is equal to Fermi energy, the contours will form a Fermi surface [3].

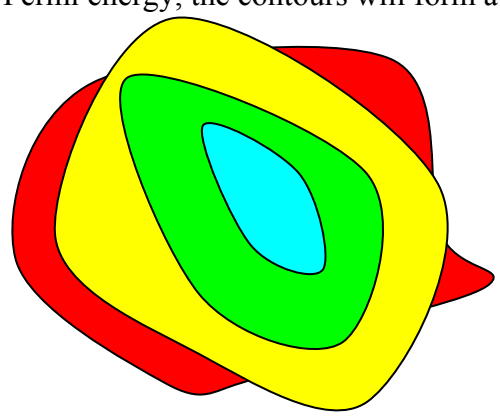


Figure 4 – An example of Fermi surface contours.

The ability to measure a Fermi surface plays an extremely important role in determining various properties of a sample, such as electrical, magnetic, thermal, and optical properties. The Pauli exclusion principal states that only one electron may occupy each quantum energy level. Therefore, electrons at lower energy quantum states are not easily excited into unoccupied higher energy levels. As a result, the small fraction of electrons close to the Fermi energy, determine the overall properties of a metal [5].

The de Haas – Van Alphen effect

The de Haas – Van Alphen effect is probably the most common and powerful technique used to measure a Fermi surface. In 1930 de Haas and Van Alphen performed an experiment that has become well known among physicists. While measuring the magnetization M of a sample of Bismuth as a function of magnetic field intensity in high fields at 14.2K, they noticed oscillations in M/H (see figure 1) [5]. Since 1952, when Onsager pointed out the usefulness of this effect many experiments have been performed, which display the oscillatory field dependence on magnetic susceptibility, $\chi = \partial M/\partial H$. When the susceptibility is plotted against inverse field, the oscillations display regularity, showing that χ has a periodic dependence on 1/H [5] . Typical data (of a metal) may be seen in figure 5 [9].

It is now known that similar oscillating behavior occurs in the conductivity (Shubnikok-de Haas effect), magnetostriction (dependence of sample size on magnetic field strength), and many other quantities [5].

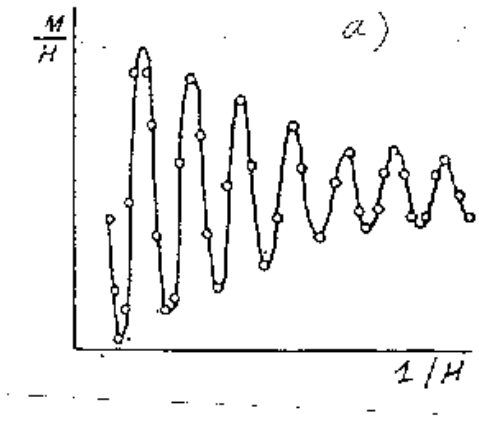


Figure 5 – The de Haas – Van Alphen effect [6].

Using the de Haas – Van Alphen Effect to measure Fermi-surfaces

In 1930, while de Haas and Van Alphen were observing oscillations, another scientist, Landau, without knowledge of de Haas and Van Alphen's experiment, predicted the oscillations as a direct consequence of the quantization of electronic orbits in a magnetic field. In 1952, Onsanger discovered that the change in 1/H through a single period of oscillation, $\Delta(1/H)$, was determined by the relation:

$$\Delta(1/H) = (2\pi e/hc)(1/A_e)$$

Where A_e = any extremal cross-sectional area of the Fermi surface in a plane normal to the magnetic field [5].

By utilizing the above relationship, it is possible to alter the direction of the magnetic field in order to measure different extremal areas. If an adequate number of extremal areas are

measured, it is possible to map an entire Fermi surface. An example of a mapped Fermi surface is shown in figure 6 [5].

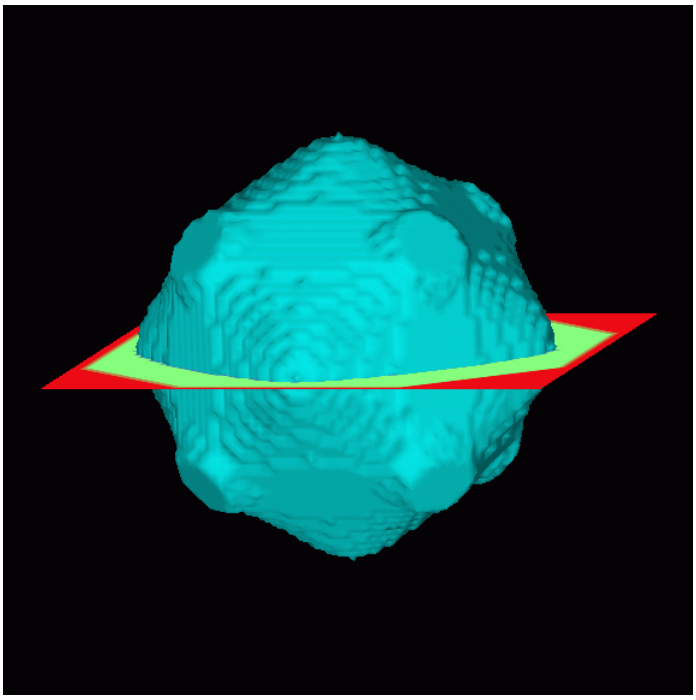
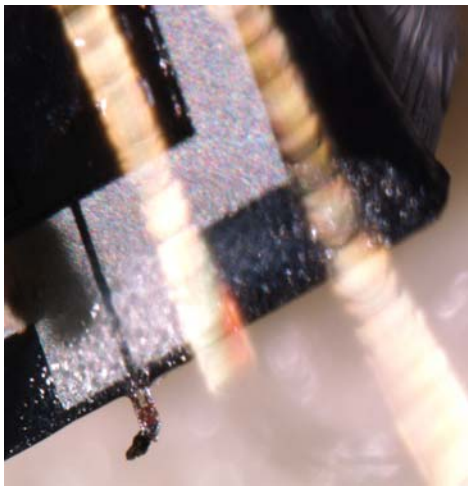


Figure 6 – A mapped Fermi surface of copper [4].

In order to utilize the relationship previously pointed out by Onsager, it is first necessary to measure the oscillations. In our experimentation, it is possible to utilize the fact that in a field, a magnetized sample experiences a torque proportional to its magnetic moment. The method used, is to place a sample on an extremely sensitive lever attached to a small electric circuit, also called a micropiezolever (see figures 8-10).

Figure 8 – A sample of Sr_2RuO_4 mounted on a Micropiezolever.



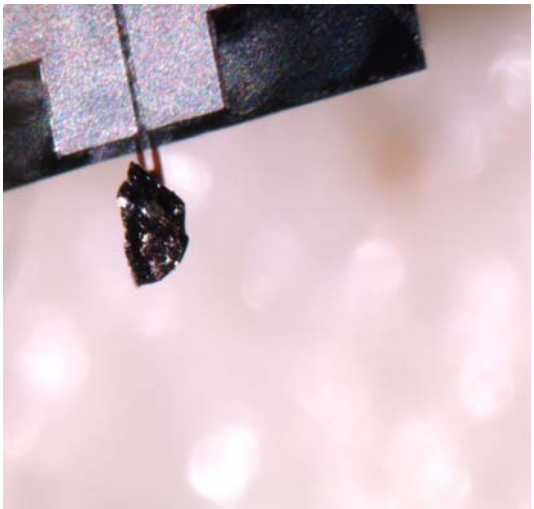


Figure 9 – A larger sample of Sr_2RuO_4 mounted on a Micropiezolever.

Figure 10 – A sample of Sr_2RuO_4 mounted on a micropiezolever circuit.

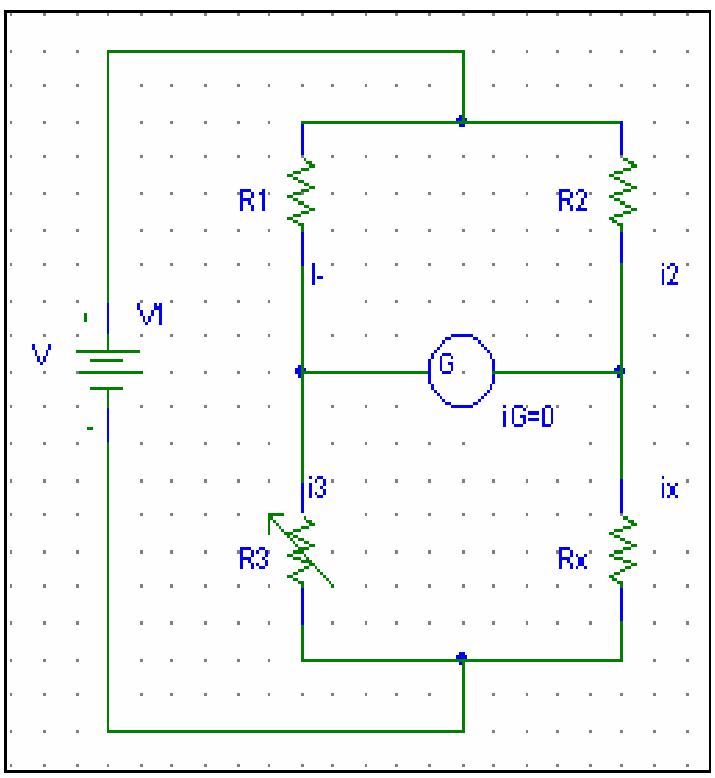
The micropiezolever and sample are then placed on a probe, which is equipped with a rotator to allow the angle between the sample and magnetic field to be varied. The sample is then ~~placed in a high magnetic field, at low temperature (below 4K). The chang~~ing torque

causes a change in force on the micropiezolever. Due to the force on the lever, the micropiezolever bends, thereby changing the resistance of the lever. By utilizing a Wheatstone bridge circuit, it is possible to measure the very sensitive changes in resistance, which correlates to the oscillations of magnetization and susceptibility. It is now possible to compare the inverse field and oscillations and calculate various extremal areas. These different extremal areas may then be used to map a Fermi surface.

The Wheatstone Bridge

In situations requiring the precise measurement of resistance, it is often useful to use a Wheatstone bridge circuit. The circuit shown in figure 11 is an example of a Wheatstone bridge circuit [2].

Figure 11 – A typical Wheatstone bridge circuit



To measure the unknown resistance, connect as shown in figure 11. Next, adjust R_3 until there is no current through G. Now, by applying KCL at the center node, it is found that

$$I_1 = I_3 \quad (1)$$

and

$$I_2 = Ix \quad (2)$$

Since $I_G = 0$, KVL requires that

$$I_1 R_1 = I_2 R_2 \quad (3)$$

And

$$I_3 R_3 = IxRx \quad (4)$$

By dividing the equations and substituting ($I_1 = I_3$ and $I_2 = Ix$) it is seen that

$$\frac{R_1}{R_3} = \frac{R_2}{Rx} \quad (5)$$

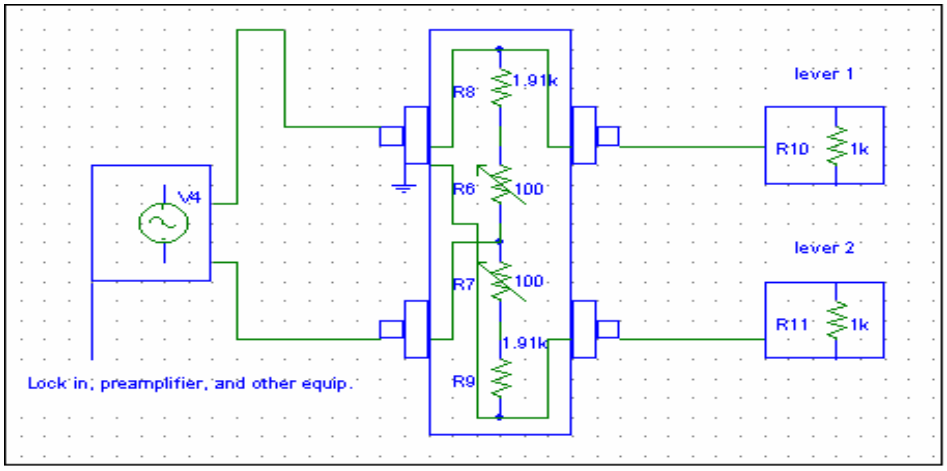
Therefore,

$$Rx = \frac{R_3(R_2)}{R_1} \quad (6)$$

By using this relationship, unknown resistances may be used as the heart of many different types of gauges by if properly calibrated.

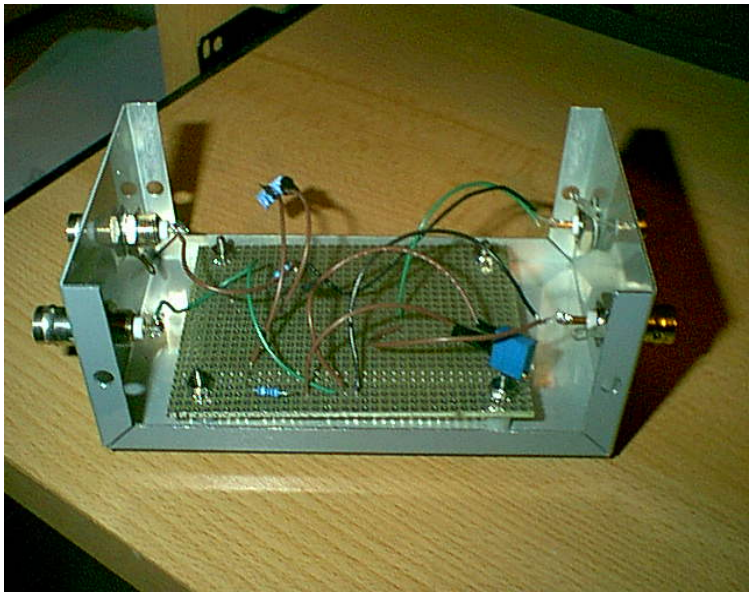
Actual Design of Bridge Boxes

In the actual design of the first bridge box, 1.91KΩ resistors were placed in series with 12-turn 100Ω trimmer potentiometers. The co-axial connections went to an excitation the lock-in, and one each for the two sections of the micropiezolever circuit. Because of faulty connections and a lack of precision in the potentiometers, the bridge proved difficult to adjust.



(a)

(b)



(c)

Figure 12 – The first bridge box

The second bridge box utilized more sensitive 25-turn 100Ω potentiometers. This circuit proved to be much easier to adjust. Also, due to improved wiring, there was less noise present.

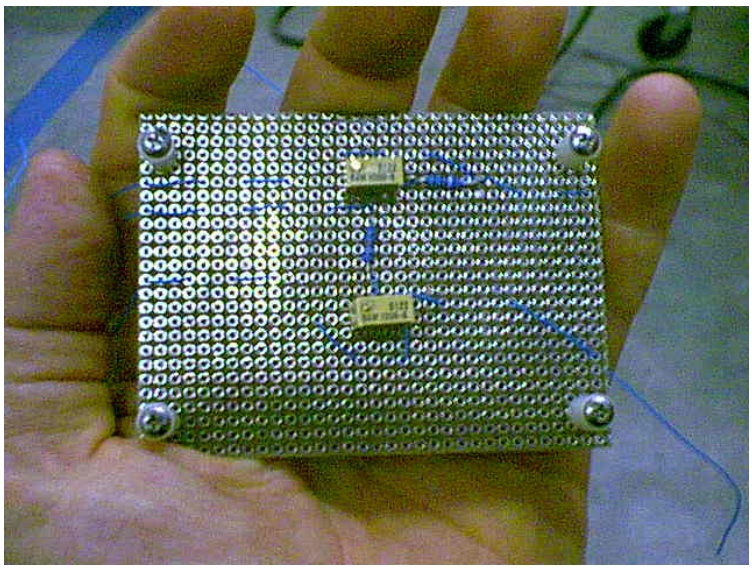
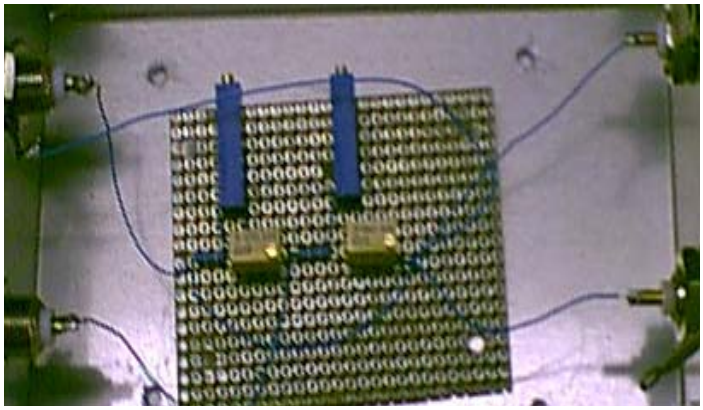


Figure 13 – Bridge circuit #2 proved to be a much more efficient circuit.

In order to compensate for expected changes in resistance at cryogenic temperatures, a third bridge was built utilizing two potentiometers in series, a 25-turn 100Ω potentiometer and a 12-turn 500Ω potentiometer. This third bridge will be tested in August 2002, at which time the micropiezolever will be placed in liquid Helium.

Figure 14 – Bridge circuit #3 will be tested at a later date.



Experimental Results

During the period from July 15 – 20, 2002, tests using a similar Wheatstone bridge circuit were performed in cell 9 at the NHMFL in Tallahassee, Florida. The data was acquired in an effort to map the Fermi surface of MgB_2. Figure 15 shows the elegant display of the pronounced de Haas – Van Alphen effect.

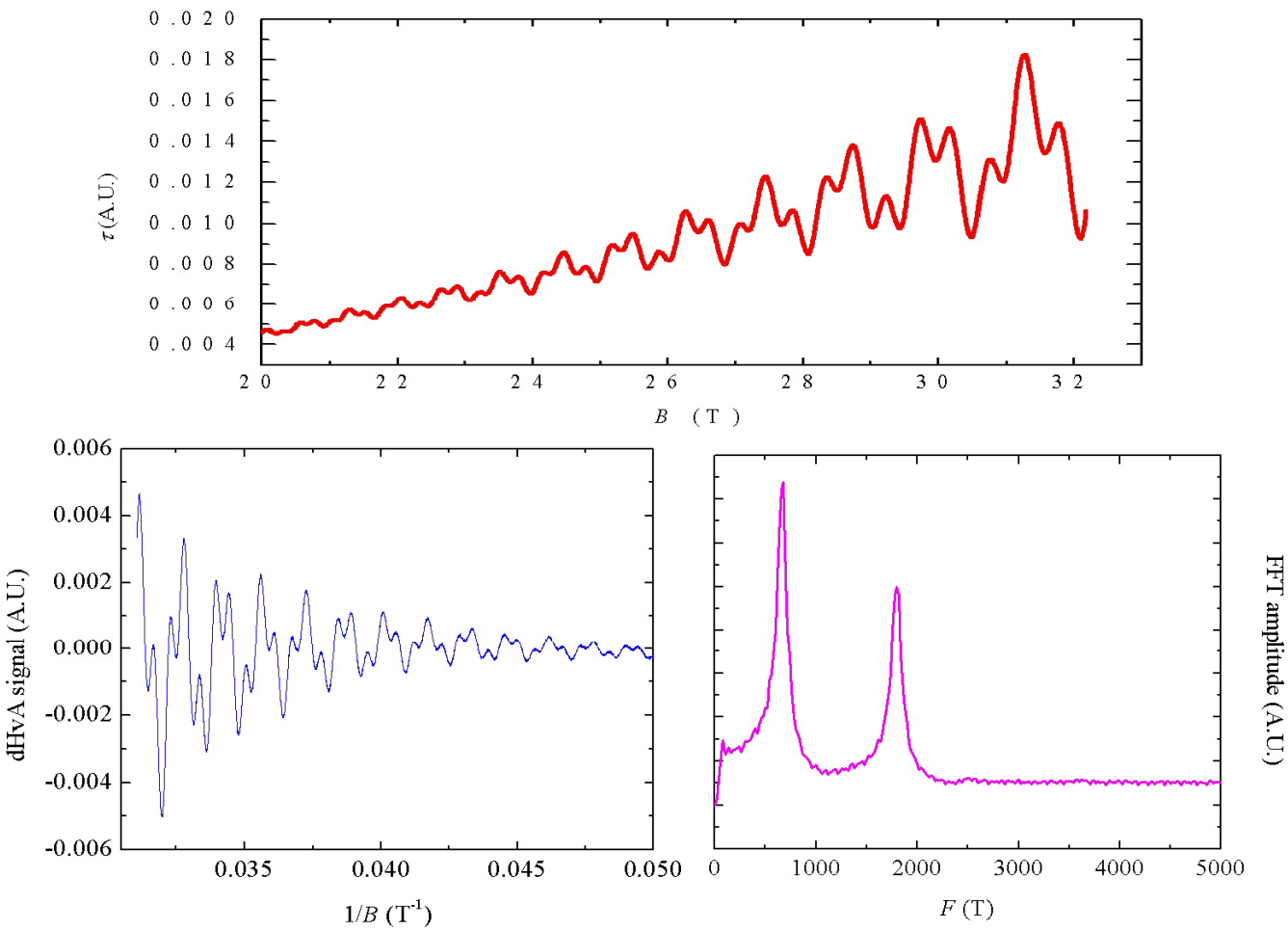


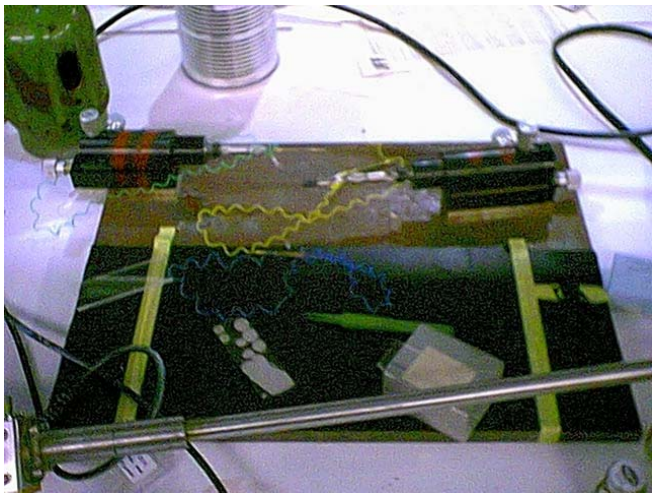
Figure 15 – Data taken on MgB_2. Notice the periodic oscillations.

In August 2002, the bridge boxes, which have never before been used for this purpose, will be tested on a sample of Sr2RuO4. When considering the experimental process, there were many questions that had to be considered. A few major considerations are as follows:

- Could the sample be successfully mounted without causing the micropiezolever to fail?
- Would the weight of the sample cause the catastrophic failure of the micropiezolever?
- Would the electronic circuit work?
- If the electronic circuit does work, will it achieve the expected sensitivity of 10^{-11} emu?

As shown previously in figures 8-10, the sample mounting process was successful. A great deal of care was taken to ensure survival of both the sample and micropiezolever. In order to handle the precision maneuvering that was required, micromanipulators (see figure 16) were used.

Figure 16 – micro-manipulators used for sample mounting



The strength of the micropiezolever also seems to be sufficient for the sample. In order to ensure the integrity of the experimental results, samples of two different sizes will be tested.

When connected to the lock-in, bridge#1 lacked the desired level of sensitivity. Also, due to loose wiring, the level of noise present was exceedingly high. Bridge #2, which utilized 25-turn potentiometers (as opposed to 12-turns in bridge #1), performed to a much higher standard. The level of noise was also greatly reduced. The bridge will undergo further testing at cryogenic temperatures (in liquid Helium) in August 2002. The third bridge utilizing dual potentiometers (see figure 14) will also be tested in August 2002.

In order to best test the effect of cryogenic temperatures on the micropiezolevers, a custom probe featuring a rotator is currently under construction (see figure 17).

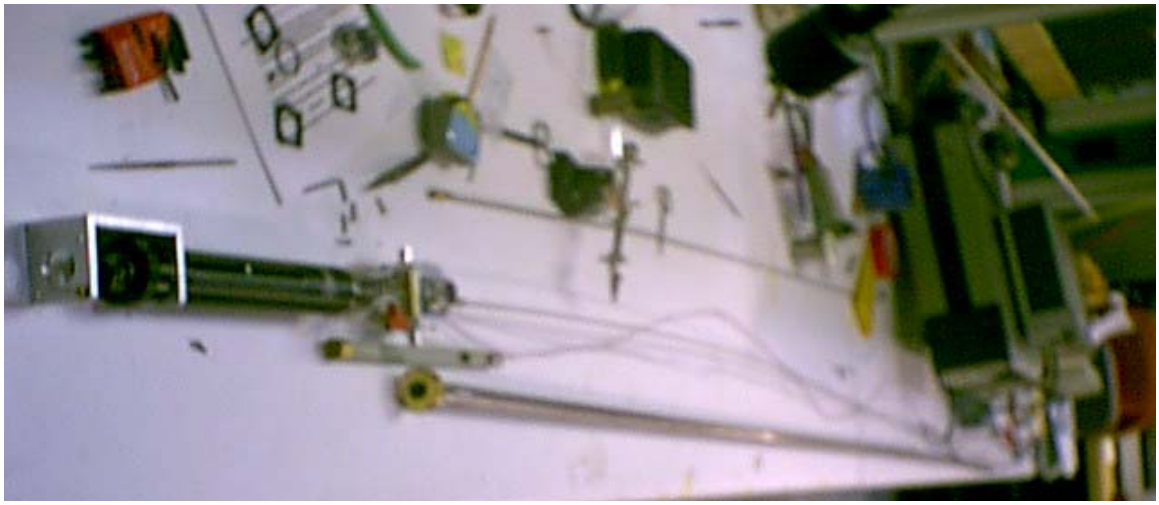


Figure 17 – Probe under construction

Further testing will commence upon completion of the probe (expected in August 2002).

The sample of Sr_2RuO_4 is expected to possess oscillations similar to those shown below in figure 16.

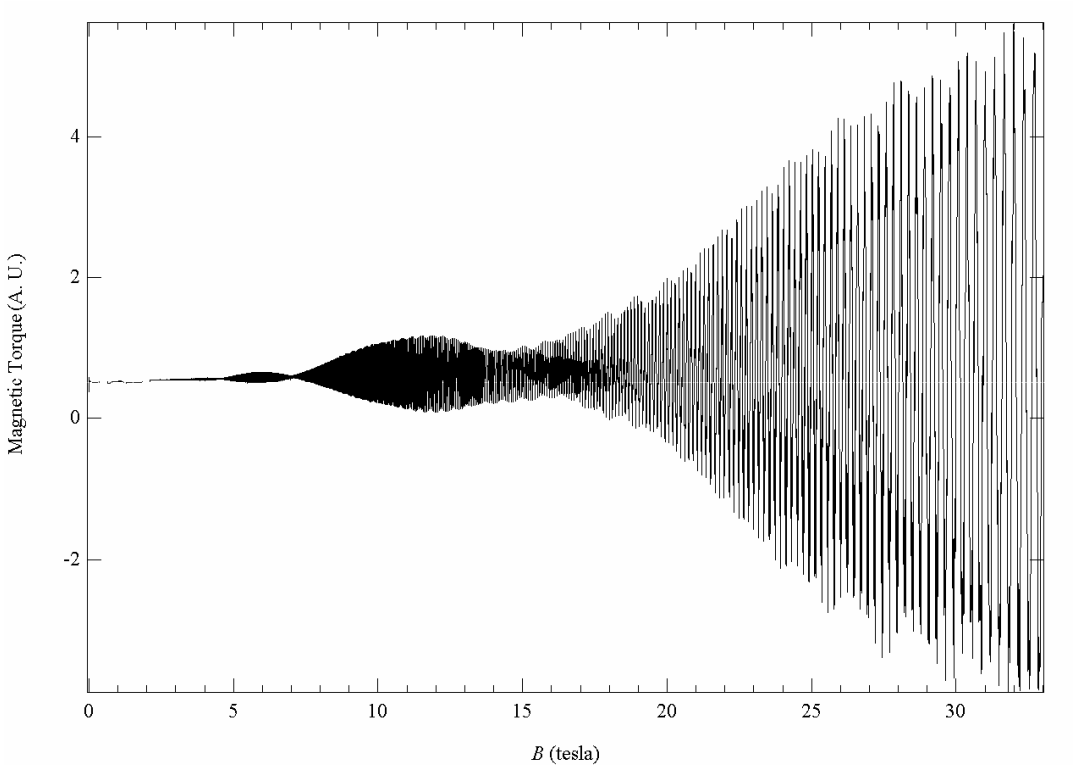


Figure 16 – The de Haas – Van Alphen effect in Sr_2RuO_4.

It will then be possible to map the Feri surface, which is shown in figure 17.

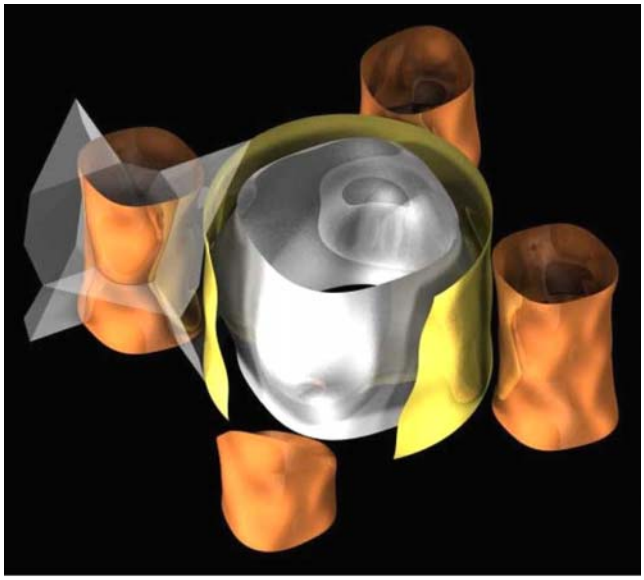


Figure 17 – The Fermi surface of Sr_2RuO_4 [7,8].

By comparing the data measured by the micropiezolevers with the known characteristics of Sr_2RuO_4, it will be possible to check the accuracy of the measurements. If the bridge boxes prove to work correctly, they will allow users to accurately measure the de Haas – Van Alphen effect. This information will then be used to precisely map the fermi surface of various materials.

Conclusion

In concluding, it has been shown that the possibility exists, that the use of micropiezolevers used in conjunction with a Wheatstone bridge circuit, may provide an increase in the sensitivity of measurements taken in high magnetic fields, at cryogenic temperatures. The use of micropiezlevers will allow this added sensitivity for approximately $100.00. This is a small fraction of the cost of measuring techniques that yield comparable results.

While the use of the micropiezolevers has yet to be attempted in the manner that is proposed, similar (but different) procedures run on MgB2 (Phil Meesan, July 15-20, 2002: Cell9 NHMFL Tallahassee, FL) suggest that the sensitivity of measurements may be increased by their use.

To date, such hurdles as sensitive sample mounting of Sr_2RuO_4, reduction of noise in the Wheatstone bridge, and increasing the sensitivity of potentiometers, have been successful. Upon completion of probe construction in early August 2002, the sample will be tested in liquid Helium. The de Haas effect is well known for this sample, and accuracy of the measurements will be easily checked. Provided the test results are satisfactory, the micropiezolever may eventually allow increased sensitivity of measurement at a minimal cost.

References

1. Tipler, Paul A., (1999). Physics for Scientists and Engineers (Vol. 1). New York, NY: W.H. Freeman and Company.

2. Irwin, David J., Wu, Dhwan-Hwa, (1999). Basic Engineering Circuit Analysis (6th ed.). NY, NY: John Wiley & Sons, Inc.

3. Wasserman, J., (2002). Quick and Dirty Preview of Solid State Physics. http://pha.jhu.edu/~jeffwass/2ndYrSem/slide17.html.

4. Anonymous, Fermi surface of Copper. http://www-theorie.physit.uni-bremen.de/~ischnell/fermi/.

5. Ashcroft, Niel W., Mermin, David N., Solid State Physics. (1976). NY, NY: Harcourt Brace College Publishers.

6. Magniel (1999). Physics Lecture Notes. http://magniel.com/hmtj/education/lecture/v20.html#v24.

7. A. P. Mackenzie et. al. PRL, 76, 3786 (1996)

8. C. bergman et. al. PRL, 84, 2662 (2000)