Development of uniaxial pressure cell with a foil-like manganin manometer

Hu Jin
2012 Summer GREAT Program
Mentor: Miles Frampton; Advisor: Rena Zieve

September 4, 2012

Abstract

We have developed a uniaxial pressure cell adjusted to the Physical Property Measurement System (PPMS) for resistance measurements on detwinned crystals. We have also developed a manganin manometer to monitor pressure during the experiment. In the reversibility test of manganin foil at room temperature, we find that the first time we apply some specific pressure to the foil, the resistance does not come back to the initial value when we take off the pressure. After that, for pressures lower (enough) than the pre-press pressure, resistance change is reversible. By pre-pressing the manganin foil, we can guarantee reversibility of the foil below 3.5kbar. We calibrate the manganin foil manometer on a cryostat which allows us to apply uniaxial pressure measured by a piezoelectric pressure gauge. The resistance of manganin foil as a function of temperature and uniaxial pressure is obtained. We have also designed a varnish-free sample holder for resistance measurement under uniaxial pressure on the cryostat.

1 Introduction

After the well-known BCS theory, which successfully explained the mechanism of conventional superconductors based on electron-phonon interaction, various kinds of unconventional superconductors were discovered, where a theory beyond the conventional BCS theory is needed. Although different kinds of unconventional superconductors have different properties, there are significant similarities among these materials, which might suggest that a unified theory for superconductivity exists.

Most importantly, various kinds of unconventional superconductors, such as cuprates, heavy fermion materials and iron-based superconductors, share a common property that the parent compounds are usually antiferromagnetic or ferromagnetic at low temperature, and superconductivity emerges when the magnetic order is suppressed by doping, pressure or other tuning methods. In some of the materials, superconductivity and magnetic order coexist in a specific domain of the phase diagram, which is strictly forbidden in conventional BCS theory. Thus, electron-electron interaction, and most likely, spin fluctuation, seems to play a crucial role in the pairing mechanism[1].

Another similarity among unconventional superconductors is related to their crystal structure. Most of them have a layer structure. In iron-based superconductors, the iron arsenic (or phosphorus, selenium, tellurium) layer is the instigator of superconductivity.

For iron-based superconductors, it is interesting that the magnetic property and the structural property are entangled with each other. The magnetic transition is either accompanied or preceded by a C_4 symmetry breaking structural transition from a tetragonal structure to an orthorhombic structure[2]. As the materials undergo the structural transiton, a large in-plane electronic anisotropy is developed in some 122 iron-arsenide superconductors[2]. The origin of the structural transition and the in-plane anisotropy is not yet clear.

H.Z.Arham et al.[3] use point-contact spectroscopy (PCS) to study iron pnictides and chalcogenides. They observe that the enhancement of zero-bias conductance only exists at those dopings and temperature where an in-plane electronic anisotropy has been detected. They argue that the conductance enhancement is a consequence of orbital fluctuations. And considering the related observation of conductance enhancement and in-plane electronic anisotropy, they concludes that the in-plane electronic anisotropy is also caused by orbital fluctuations. They also predict in-plane electronic anisotropy of $Fe_{1+y}Te$ both below and above the structural transition temperature (For y=0.13, $T_N \approx T_S \sim 59K$), which has not been tested yet, since they observe conductance enhancement below T_{onset}=75K. This prediction motivates us to study the property of $Fe_{1+y}Te$ at low temperature.

Detecting the in-plane electronic anisotropy below the structural transition temperature is not easy. Since the tetragonal structure has equivalent a- and b- axes, when the material undergoes a structural transition from the tetragonal structure to the orthorhombic structure, it tends to form structural twins[2]. The mixture of differently oriented twin domains obscures the measurement of in-plane electronic anisotropy. Uniaxial pressure has been widely used

to detwin the crystals *in situ*. By applying pressure along one of the orthorhombic b-axes, a preferable orientation of the orthorhombic structure is chosen so that there will be no (or less) twin domains below the transition.

The material $Fe_{1+y}Te$ is even special. The Neel temperatures for y=0.03 and y=0.13, which are close to their structural transition temperatures, are 67K and 59K respectively. These temperatures are below 77K, the temperature of liquid nitrogen, but much higher than the temperature of liquid helium. So it is not a reasonable choice to do the measurements in liquid helium. The best choice in our department is to use PPMS, which is more economical. Also PPMS could provide a more accurate temperature control in the temperature range of several tens of Kelvin.

Our goal of this summer is to develop a uniaxial pressure cell adjusted to PPMS for further resistance measurements on $Fe_{1+y}Te$ crystals. We expect the pressure cell to meet the following requirements.

- Adjusted to PPMS for resistance measurements.

- Allow uniaxial pressure up to at least 10kbar applied to $Fe_{1+y}Te$ sample along the orthorhombic b-axis .

- Allow monitoring pressure during the experiment.

2 Pressure measurement

For pressure measurement, our idea is to use manganin foil. Manganin is a kind of alloy of typically 86% copper, 12% manganese and 2% nickel[4]. The resistance behavior of manganin coils under hydrostatic pressure has been thoroughly studied[5][6][7] since P.W.Bridgman developed resistance pressure gauge in 1911[8]. Measurements of the resistance of manganin wire under high static pressure produced in a solid medium show that a linear relation exists between resistance and pressure with pressure up to 180kbar at room temperature[7]. The temperature dependence of manganin resistance is parabolic with a maximum around 304K[5]. Also, reference[9] shows that for manganin coil under hydrostatic pressure, the pressure coefficient of resistance increases linearly as the temperature increases in the range from 273K to 343K. On the contrary, reference[10] shows that the pressure coefficient of resistance of a manganin wire gauge is independent of temperature over the range 0≤T≤300K. The different results might be due to the fact that this effect is really small.

We first calibrate the manganin pressure gauge on a cryostat with a piezo and a bellow, which provides uniaxial pressure with helium gas, to determine the resistance as a function of uniaxial pressure and temperature R(p,T). After that, when we do experiments on PPMS, we measure the resistance of manganin gauge and temperature. With the knowledge of the function R(p,T), we will get the value of the uniaxial pressure. Liquid nitrogen allows us to cool the manometer down to 77K. (With an open dewar, it is actually difficult to reach 90K.) For lower temperature calibration, we are going to pump on liquid nitrogen, which might allow us to get to 65K, since the temperature

of the triple point of nitrogen is about 63.15K. This is still not low enough for the structural transition temperature of $Fe_{1.13}Te$. We need to do a little extrapolation for even lower temperatures.

2.1 Calibration and pressure measurement test of manganin wire: test of the idea

We fist use manganin wire to test our idea, simply because it is easily available in our lab. The diameter of the wire is 0.0057". Uniaxial pressure is applied to the wire by directly filling the bellow with helium gas or with the assistance of a finger for higher pressure. A piezoelectric pressure gauge is used to measure the pressure. Temperature is measured with a Cernox. We use liquid nitrogen to cool down the wire. Resistance is measured with a traditional four-wire method.
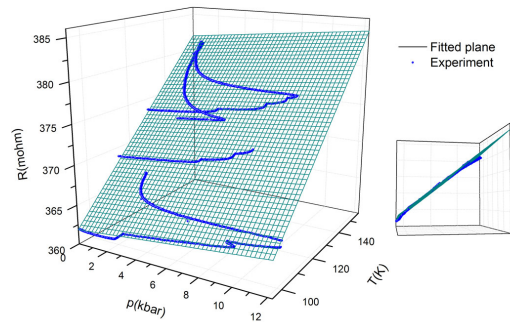

Figure 1: The resistance of the manganin wire as a function of uniaxial pressure and temperature. The inset shows that the data points are approximately on the same plane.

Three times of measurements are conducted in different ranges of temperature. In Figure 1 we plot the resistance of the manganin wire as a function of pressure and temperature. From the inset of Figure 1 we can see that the data points are approximately on the same plane. Thus for simplicity and a rough preliminary glance of the idea, we fit the data points into a plane, which is also shown in Figure 1. The function of the fitted plane is $R(m\Omega) = 331.62035 + 0.20487 \times p(kbar) + 0.31942 \times T(K)$. The pressure coefficient of resistance $\frac{1}{R_0}\frac{\partial R}{\partial p}$, where R_0 is the resistance at zero pressure, is about $6 \times 10^{-4} kbar^{-1}$. The pressure coefficient of resistance of manganin wire in literature varies from $1.447 \times 10^{-3} kbar^{-1}$ to $2.322 \times 10^{-3} kbar^{-1}$[7][9][11]. If we take a medium value $1.85 \times 10^{-3} kbar^{-1}$, the result of our measurement is about one-third of this value. Since in our experiment, only part of the wire is under pressure, the measured resistance is the resistance under pressure plus the resistance without any pressure. So our result is reasonable.

For further test of the calibration of manganin wire, we treat the data of the first two times of measurements as calibration data and fit them into a plane. And we treat the third time of measurement as an actual pressure measurement test and compare the pressure measured by piezo with that measured by the manganin wire. Figure 2 shows this comparison. Blue points are pressures measured by piezo. The fitted plane we get from the first two times of measurements is $R(m\Omega) = 331.70668 + 0.20203 \times p(kbar) + 0.3186 \times T(K)$, which can be transformed to $p(kbar) = (R(m\Omega) - 331.70668 - 0.3186 \times T(K))/0.20203$. Cyan points are pressures calculated from this function. We can see that the two groups of points are consistent with each other, especially at higher pressures.
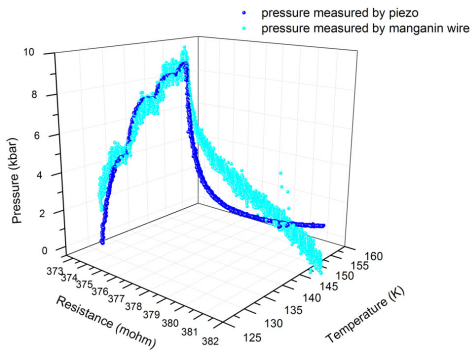

Figure 2: Blue points are pressures measured by piezo. Cyan points are pressures calculated from $p(kbar) = (R(m\Omega) - 331.70668 - 0.3186 \times T(K))/0.20203$

The rough calibration of manganin wire gives us confidence of our idea of pressure measurement. To get a more accurate function R(p,T) of manganin wire requires more careful experiments as well as better fit of experimental data, which we are not going to do, because we decide to use manganin foil instead for further experiments based on the following considerations.

- Manganin foil has a larger area, which means that for a specific pressure on the $Fe_{1+y}Te$ sample, a lower pressure is needed on the manganin gauge. At first we worried about irreversible deformation of manganin under high pressure. Thus we wanted to keep the manganin within its yield strength, which is about 1.72kbar for the manganin foil we are using. But after we discovered the pre-press property of manganin foil, which will be discussed in the next subsection, this consideration seems not that important.

- For our pressure cell (We will discuss it later), if we use manganin wire, spacers will be easily tilted and in contact with each other so that the pressure is not completely applied to the wire, which is terrible for both calibration and actual pressure measurements using the manganin gauge.

2.2 Reversibility test of manganin foil

Before calibrating the manganin foil, we conducted a reversibility test of it. We require that the function R(p,T) of manganin foil does not change after thermal or pressurizing treatments. Otherwise the function R(p,T) obtained in calibration experiments will not be applicable in real pressure measurements. We are more worried about its reversibility of pressure dependence of resistance. A simple test of this reversibility is to see whether the resistance will come back to the initial value when we take off the pressure. In the experiment, we fist apply some specific pressure to the manganin foil, and then take it off. We call this process a pressure treatment. We conduct this kind of pressure treatments at room temperature and different pressures for many times. And at the same time, we monitor the resistance.

The results are disappointing at first. In Figure 3 we can see that even for a pressure lower than 0.2kbar, the resistance is not reversible after the pressure treatment described above.
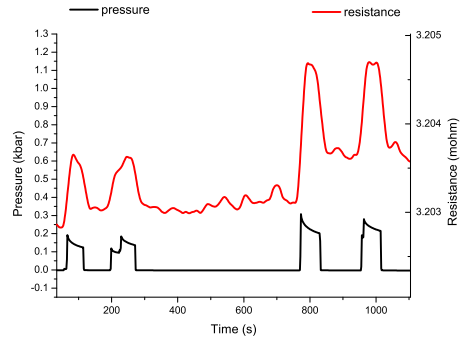

Figure 3: Reversibility test of manganin foil. Black line stands for pressure while red line stands for resistance. Even for a pressure lower than 0.2kbar, the resistance of manganin foil is not reversible after the pressure treatment.

However, we observed an interesting property of manganin foil as shown in Figure 4. If the pressure is so large that the manganin foil has never experienced it, the resistance is not reversible after the pressure treatment. But as long as we have pre-pressed the foil to some specific pressure, then we are safe for pressures lower than that. More careful experiments show that an irreversible region exists below the pre-press pressure. This means that if we want to guarantee the reversibility of the manganin foil, we cannot go all the way up to the pre-press pressure. In the last pressure treatment of Figure 4, the pressure is about 1.7bar which is lower than the pre-press pressure 2kbar, and the resistance is already irreversible. So it seems that the manganin foil can memorize the highest pressure it has ever experienced, but there is a small memory loss.
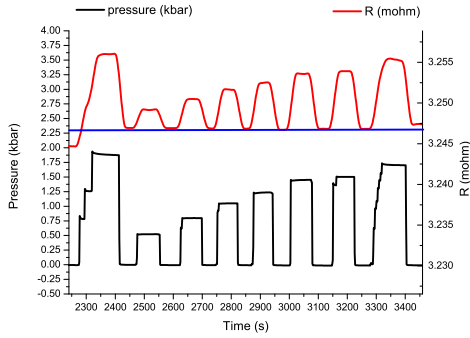
Figure 4: Reversibility test of manganin foil. Black line stands for pressure while red line stands for resistance. We first conduct a pressure treatment up to about 2kbar, which is a "new" high pressure for the foil. We can see the resistance does not come back to the initial value after that. For the six subsequent pressure treatments at pressures lower than the pre-press pressure 2kbar, the resistance is reversible. For the last pressure treatment, the resistance is irreversible because the pressure is so close to the pre-press pressure that it has entered the irreversible region. The blue line is for comparison.

This interesting property is crucial to our pressure measurement. It tells us that we need to pre-press the manganin foil before calibrating it. And after that, we can only apply pressures lower enough (not exceeding the threshold of irreversible region) to the foil in both calibration experiments and real pressure measurements.
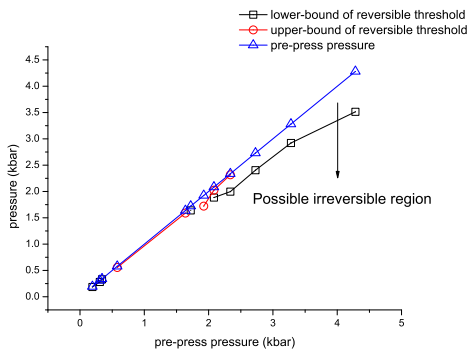

Figure 5: Irreversible region of the manganin foil. For details, see the text.

To determine the irreversible region for different pre-press pressures, we sweep the pressure in steps. This sweep is similar to the process shown in Figure 4. After the pre-press treatment, we conduct a series of pressure treatments from lower pressures to higher pressures until the resistance becomes irreversible. The pressure step where the resistance becomes irreversible for the first time is the upper-bound of the irreversible threshold. And the pressure step previous to that must be the lower-bound of the irreversible threshold. For example, for the sweep in figure 4, the upper-bound will be about 1.7kbar and the lower-bound will be about 1.5kbar. A rough result is shown in Figure 5, which cannot be treated seriously. More careful experiments are needed to get an accurate result. For our purpose of pressure measurement, we do not need an accurate result. We can guarantee the reversibility at pressures lower than 3.5kbar if we pre-press the manganin foil to about 4.3kbar, which is enough for us. We didn't test higher pressures.

Also, the pressure sensitivity of the manganin foil does not decrease after pre-press treatment. For pre-press treatment of 4.3kbar, the resistance still has an obvious response to pressure as low as 0.05kbar.

It is worthwhile to mention that in the case of manganin wire, the pre-press treatment was actually conducted unintentionally before the calibration. This is why the data points of different pressure treatments are approximately on the same plane.

It will be interesting to figure out the reason of this behavior of manganin foil. My explanation is that, when we apply some pressure to the manganin foil for the first time, no matter how small it is, there will be an irreversible deformation of the foil, which reduces the sectional area and hence enhances resistance. After that, for pressures lower enough than the pre-press pressure, the foil only undergoes reversible deformation, leading to a reversible behavior of resistance. I have no idea about why the deformation will be reversible after the pre-press. There also might be reasons related to the crystal structure of manganin. Miles suggests that the defects of crystal structure play a role in this behavior.

The test discussed above only guarantees that at room temperature the resistance will come back to the initial value when we take off the pressure. It says nothing about the reversibility of pressure-dependence or temperature-dependence of the resistance. Given that our ultimate requirement is that the function R(p,T) does not change after thermal or pressurizing treatments, the above test is not enough.

2.3 Calibration and pressure measurement test of manganin foil

A piece of manganin foil of dimensions 0.0200"×0.0478"×0.2345" is used for calibration. The foil is pre-pressed to about 2.2kbar at room temperature before calibration, which guarantees reversibility below about 1.8kbar. Five times of measurements are conducted in different ranges of temperature. In Figure 6 we plot the resistance of manganin foil as a function of uniaxial pressure and temperature. From the inset of Figure 6, we can see that the data points are also on a same plane approximately. For comparison, we fit the data points into a plane just like what we do to the manganin wire. The function of the plane is $R(m\Omega) =$

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$3.36344+0.00262708\times p(kbar)+0.00111267\times T(K)$. The pressure coefficient of resistance $\frac{1}{R_0}\frac{\partial R}{\partial p}$ is about $0.7\times 10^{-3}kbar^{-1}$. Considering the fact that the measured resistance is the resistance under pressure plus the resistance without pressure, this value is about the same as that of the manganin wire. So replacing manganin wire by manganin foil will not enhance the pressure coefficient of resistance notably. This suggests that the pressure coefficient of resistance is an intrinsic property of manganin. Or at least intrinsic effects dominate in this coefficient.
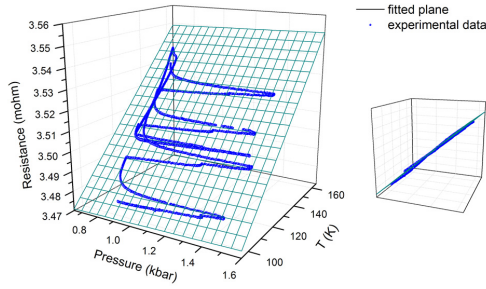

Figure 6: The resistance of the manganin foil as a function of uniaxial pressure and temperature. The inset shows that the data points are approximately on the same plane.
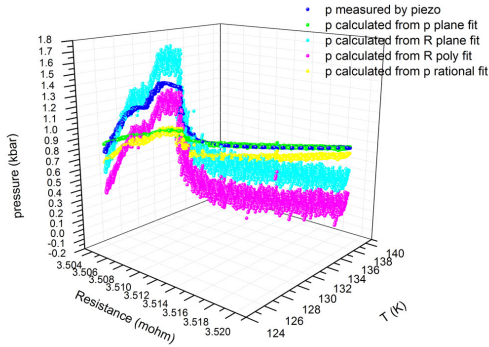

Figure 7: Comparison of pressures measured by piezo with those measured by the manganin foil. For details of the different groups of points, see the text.

We also conduct a measurement test of manganin foil, where we treat four out of the five times of measurements as calibration, and the other one as an actual pressure measurement. We fit data points from the four times of calibration measurements into a plane. The function is $R(m\Omega) = 3.36366+0.00237087\times p(kbar)+0.00111302\times T(K)$, which can be transformed to $p(kbar) = (R(m\Omega) - 3.36366-0.00111302\times T(K))/0.00237087$. We use this function to calculate the pressures from the measured da-

ta of resistance and temperature, which are shown as cyan points in Figure 7. Pressures measured by piezo are shown as blue points in Figure 7. The result is not very good. So we try some other methods of fitting, expecting to improve the result.

Totally four methods of fitting are used, the results of which are all shown in Figure 7. We have already explained the cyan points, which are called "p calculated from R plane fit" in Figure 7. Then we try to use polynomial function to fit the data, which is called "p calculated from R poly fit" in Figure 7. Based on the observations in reference[5] and [9], we try the function

$$R = R_0 + ap + bT + cT^2 + dpT.$$
$$Units : R : m\Omega; p : kbar; T : K. \tag{1}$$

The parameters we obtained (Fitting is completed using gnuplot.) are

R_0	a	b
3.29432	0.00990903	0.00214781
c	d	
-3.82173×10^{-6}	-5.66103×10^{-5}	

Then we transform the function to

$$p = \frac{R - R_0 - bT - cT^2}{a + dT}.$$
$$Units : R : m\Omega; p : kbar; T : K. \tag{2}$$

In Figure 7, magenta points are calculated from this function.

Then we realize that the errors in the fitting might be enlarged when we transform the function R(p,T) to p(R,T). So we decide to directly use the function p(R,T) to fit the data. We first conduct a plane fitting and obtain the function $p(kbar) = -231.86 + 69.3044R(m\Omega) - 0.0811904T(K)$. In Figure 7, green points are calculated from this function, which are called "p calculated from p plane fit".

The final trial is to directly use Equation 2 to fit the data. The parameters we obtained are

R_0	a	b
3.32448	-0.0155643	0.00180383
c	d	
-3.22715×10^{-6}	0.000179924	

And the pressures calculated from this function are shown as yellow points in Figure 7, which are called "p calculated from p rational fit".

We can see from Figure 7 that the two results (cyan and magenta) calculated from R(p,T) fiting behave better in the increasing process of pressure, while the two results (green and yellow) calculated from p(R,T) fitting behave better in the decreasing part of pressure. This might suggest that the drift effect of piezo plays an important role in the calibration.

For further comparison of the four methods of fitting, we define a standard deviation as follows.

$$\sigma = \sqrt{\frac{1}{N} \sum (\frac{p_{manganin} - p_{piezo}}{p_{piezo}})^2} \qquad (3)$$

N is the total number of data points. $p_{manganin}$ is the pressure measured by manganin gauge and p_{piezo} is the pressure measured by piezo. The standard deviation obtained from results of the four methods of fitting are

R plane fit	R poly fit	p plane fit	p rational fit
0.248	0.543	0.128	0.185

We can see that polynomial fitting or rational fitting fail to improve the result. And for both plane fitting and polynomial (or equivalently, rational) fitting, p(R,T) fittings are better than R(p,T) fittings.

We can also calculate the standard deviation of the previous results of manganin wire, which is 0.808. (In this calculation, we deleted the points of extremely large $(p_{manganin} - p_{piezo})/p_{piezo}$ values.) If we compare with the standard deviation from the results of R(p,T) plane fitting of manganin foil 0.248, manganin foil is indeed an improvement. (However this improvement is not supposed to be caused by replacing wire by foil. More possible reason is that the number of data points of manganin foil is much larger than that of the manganin wire.)

2.4 Discussion of data analysis

From the previous subsection we can see that the results for manganin foil is not good enough for actual pressure measurements. We'd like to give some discussions here for further improvement.

- We need more data. One reason is that the fitting function is only applicable in the region covered by the calibration data points. When we go beyond this region, the result gets bad. It is better to get enough data to cover the whole range of temperature and pressure we are interested in. Another reason is that more data will help us better determine the best form of fitting function. We are not sure about the actual form of the function R(p,T) or p(R,T). According to previous papers, Equation 1 or Equation 2 are supposed to work better than a simple plane. But it turns out that a plane works better. Also, the parameter a of p(R,T) rational fitting is a negative value, which is not physical. This means that there must be some problem with this method of fitting.

- The drift effect of piezo should be considered seriously. In our experiments, it usually takes only a short time to increase pressure on the manganin foil. Hence the drift could be neglected for this period. But we need to wait for a relatively long time until the pressure comes back to the initial value so that

we can conduct another measurement. In this relatively long period, the effect of drift is not clear. Actually we can only know for sure about the relative change of pressure during the pressure increasing process from the read-out of piezo. Because the base pressure for every single measurement might have been changed due to the drift. A possible solution is to measure the resistance of manganin foil as a function of temperature at zero pressure. This will help us determine the base pressure of every measurement.

- One of the most important tasks is to determine the form of fitting function. It will be helpful to reduce the 3D relationship to 2D relationships. So we could measure the resistance as a function of temperature at zero pressure so that we will know the temperature dependence of resistance. And then measure the resistance as a function of pressure at constant temperature (In the cryostat we are using, only room temperature and 77K can be kept constant for a long time.) so that we will know the pressure dependence of resistance. Then we may know the form of function R(p,T).
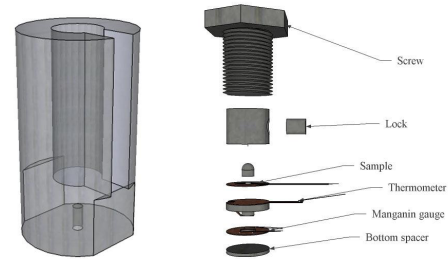

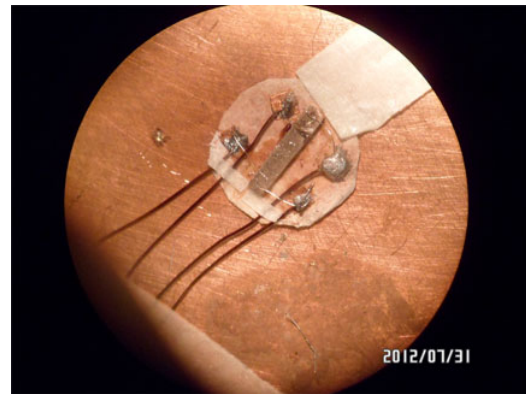Figure 8: Structure of the uniaxial pressure cell. For reference, diameter of the bottom spacer is 0.342"

Figure 9: A picture of the manganin foil manometer mounted on the bottom spacer.

3 Uniaxial pressure cell

3.1 The cell

Structure of the uniaxial pressure cell is shown in Figure 8. Uniaxial pressure is applied to the manganin foil manometer and the $Fe_{1+y}Te$ sample at the same time by a screw. Copper foil is used for thermal contact among manomter, thermometer and the sample. A lock is used to prevent the spacer from rotating, which might damage the sample.

Figure 9 is a picture of the manganin foil manometer mounted on the bottom spacer.

3.2 Varnish-free sample holder for the cryostat of dilution refrigerator

Conventional method of mounting the sample onto a spacer is to use varnish. But varnish has two problems. First, it is not hard enough to secure the sample when we apply pressure to it. Thus the sample is easily to fall during the experiment. Second, the solvent of varnish might degrade the sample slowly. Therefore, we decided to design a sample holder which allows us to secure the sample without varnish. Figure 10 shows a design for the cryostat of dilution refrigerator, where two adjustable horizontal spacers are used to make the sample stand on the holder.
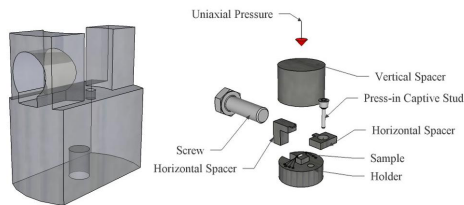

Figure 10: Varnish-free sample holder for the cryostat of dilution refrigerator. For reference, diameter of the vertical spacer is 0.4".

We have not tried this idea yet. It might also have some problems. Because of the horizontal spacers, a pressure along c-axis of the sample is applied. We are not sure whether this pressure will matter. We could use some soft materials such as rubber on the tips of the horizontal spacers to make this pressure as small as possible. Another solution is that the horizontal spacers are only used to guarantee the sample stands vertically before applying pressure. When uniaxial pressure is already applied to the sample, we expect the sample to be secure enough so that we can loosen the horizontal spacers. Also, it is very difficult to realize this idea in the uniaxial pressure cell described in the previous subsection, simply because it is very hard to make it even smaller to fit in the cell. Instead, we can try a simple slot on the holder and make the sample stand in the slot.

4 Future work

- Detailed reversibility test, especially thermal reversibility test. We should make sure that the function R(p,T) of manganin does not change after thermal and pressurizing treatments, at least after several times of treatments.

- Figure out how to fit the calibration data and get a reasonable extrapolation to lower temperatures. (Further study on previous papers is needed.)

- Figure out how to deal with the drift of piezo and how to distinguish between drift and real signal, especially the pressure change due to thermal contractions of the cryostat.

- Finally, resistance measurements of $Fe_{1+y}Te$ sample on PPMS.

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Appendices

A Instructions of making a foil-like manganin manometer

1. Determine the shape and dimension of the manganin foil. Here we actually care about the area of the manganin foil, which will be determined by the pressure we want to apply to the $Fe_{1+y}Te$ sample and the area of it. We expect a pressure up to 10kbar along the orthorhombic b-axis. Area of the sample is about $0.005" \times 0.12" = 6 \times 10^{-4} in^2$. If we pre-press the manganin foil to about 2.2kbar, then the irreversible threshold might be about 1.8kbar. So the area of the manganin foil is at least $6 \times 10^{-4} \times \frac{10kbar}{1.8kbar} in^2 = 3.3 \times 10^{-3} in^2$. If it is a circle, then the diameter will be 0.03". Because of machining considerations, we make the foil a rectangular of dimension $0.05" \times 0.25"$. The actual area under pressure is determined by the dimension 0.05" and the diameter of spacer, which is 0.1239". If we want to go to even higher pressures in future, we can change the shape of the foil to a circle so that we can make full use of the area of the spacer.

2. Cut the foil. I asked David from the machine shop for help. He punched on the foil and made a small rectangular of it.

3. Plane the foil as shown in Figure 11 and Figure 12 and measure the dimensions of it.

Figure 11: Plane the foil.

Figure 12: Plane the foil.

4. Cut a piece of copper foil of the shape shown in Figure 13 and make it flat. The dimension of the circle should be the same as that of the bottom spacer. The long strip should be narrow enough. It is a good idea to test it first in the pressure cell to make sure it fit in as shown in Figure 14.

Figure 13: Copper foil.

Figure 14: Test the copper foil in the pressure cell.

5. Varnish two pieces of cigarette paper on the copper foil as shown in Figure 15. Then use scissors to cut them into a circle. Test them together in the pressure cell again.

Figure 15: Varnish two pieces of cigarette paper.

6. Varnish the copper foil with cigarette paper onto the bottom spacer as shown in Figure 16. Test in the pressure cell again to make sure it fit in.

Figure 16: Varnish the copper foil onto the bottom spacer.

7. While waiting for the varnish drying, we can connect four pieces of Pt wire to the manganin foil using a point melter as shown in Figure 17. The voltage of the point melter is about 20%.
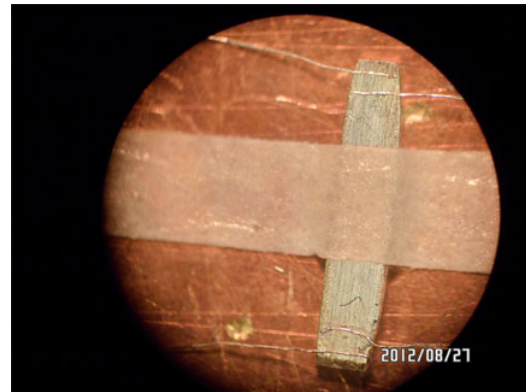
Figure 17: Connect Pt wire.

8. Varnish four small pieces of copper foil onto the cigarette paper on the bottom spacer. See Figure 18.

Figure 18: Varnish four small pieces of copper foil.

9. Solder four copper leads on the four small pieces of copper foil respectively. See Figure 19. My experience is to first put a little rosin flux on the copper foil.

Figure 19: Solder copper leads.

10. Varnish the manganin foil onto the cigarette paper on the bottom spacer. Make sure it is at the center. See Figure 20.

Figure 20: Varnish the manganin foil.
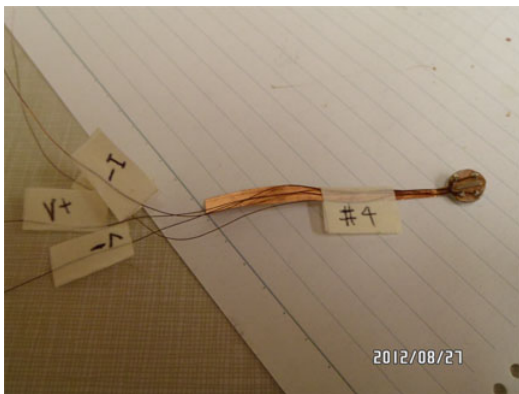
11. Make some labels. See Figure 21.

Figure 21: Make some labels.

12. Use the point melter to connect Pt wire to the soldering points. See Figure 22 and Figure 23. The voltage of the point melter is about 40%.

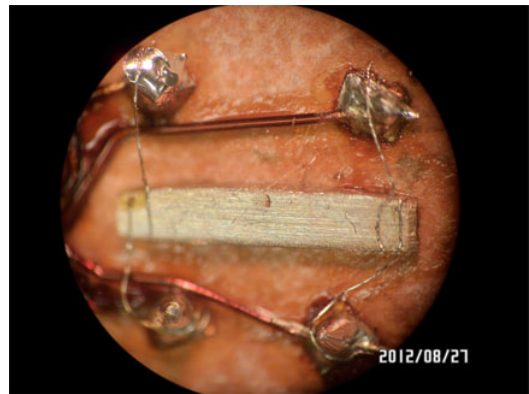Figure 22: Connect Pt wire to the soldering points.

Figure 23: Connect Pt wire to the soldering points.

13. Varnish two pieces of cigarette paper onto the upper spacer and varnish them on the manganin foil. See Figure 24 and Figure 25. My experience is to put nothing on them to press. Just leave them there and wait for the varnish drying.

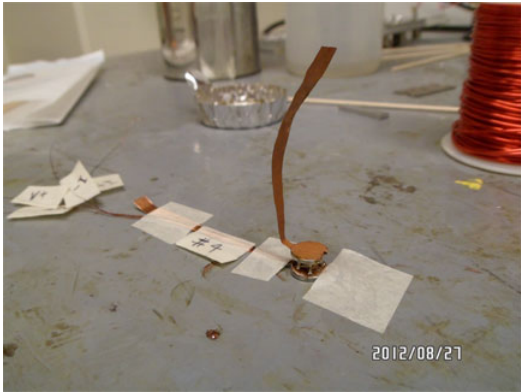Figure 24: Varnish two pieces of cigarette paper.
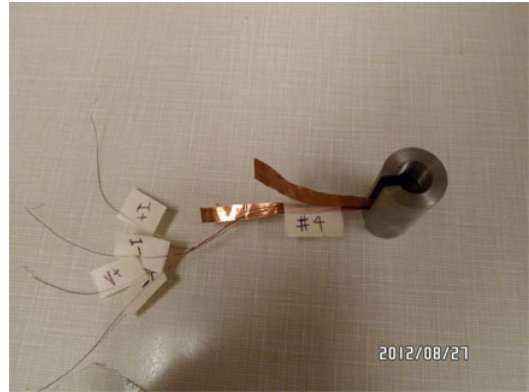
Figure 25: Varnish them together.

Figure 26: Test the whole manometer in the pressure cell.

14. Finally, test the whole manometer in the pressure cell to make sure it fit in. See Figure 26.