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Pressure Dependence of the Metal-Insulator Transition in FeSi1-xA1x

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Abstract

In the same manner that Si can be doped with B, the insulator FeSi can be doped with Al to create a metal. By applying a force to a doped Si sample at low temperature, the carrier density can be altered and the sample driven through its metal-insulator transition. We have attempted to do the same with FeSi. However, for the pressures we were able to obtain (~2kbar) no significant changes in the conductivity resulted.

Introduction

My research has focused on the metal-insulator transition in $FeSi_{1-x}Al_x$. Previous research[1] has shown that sufficiently doping the insulator FeSi with AL at the Si site will produce metallic conduction. The material has been studied with concentrations of Al substitution ranging from 0% to 8%. Lattice constant, thermoelectric effect, Hall effect, electrical conductivity, magnetic susceptibility, specific heat, and magnetoresistance have all been measured and show a systematic variation with the concentration of Al. The results have shown that the transition from low temperature insulator to low temperature metal occurs between 0.5% Al and 1% Al

$FeSi_{1-x}Al_x$ becomes a metal when the concentration of Al is made high enough to create the necessary carrier density. To achieve more precise control over the carrier densities (thereby allowing us to study the sample very near the transition point), we have used samples with fixed levels of Al doping. A given sample has a fixed level of impurities, but by applying a force to the sample the carrier density can be altered. In the case of $FeSi_{1-x}Al_x$ pressure decreases the carrier density since it is a hole-doped semiconductor. Sufficiently high pressures should be able to drive a single metallic sample of $FeSi_{1-x}Al_x$ through the metal-insulator transition, enabling us to study the sample very close to the transition. By using the same sample for an entire set of data on both sides of the transition point, we will be able to maintain better control over extraneous variables and avoid problems due to the variations in individual samples.

Experimental Equipment

I. Pressure Cell:

The pressure cell, shown in figure 1, is the component that allows the sample to be put under a constant applied pressure. The cell is pressurized through the He line. This exerts a force on the membrane, which in turn exerts a force on the sample. The force on the sample can be measured using the capacitor plates. For a parallel plate capacitor, such as the one in the pressure cell, the capacitance is given by the equation

$$C = \kappa\ (A/d)$$

where κ is the dielectric constant of the material between the plates, A is the area of the plates, and d is the distance between the plates. From this equation, 1/C should decrease linearly as the distance between the plates decreases.

II. Cryostat:

The main function of the cryostat is to keep the sample in a controlled environment at low temperature. A simple diagram of the cryostat is shown in figure 2. The valves allow access to the vacuum can and the 1K pot. The ports at the top of the cryostat are used to attach experimental wiring and similar items. The tapered seal is designed to maintain a vacuum in the vacuum can while allowing easy access to the experimental stages of the cryostat. The heat sinks dissipate any heat conducted into the vacuum can by the wiring. The 1K pot is used to cool the experimental stage to below 4.2K by evaporating He from inside it.

III. Dewar:

The dewar contains the liquid helium used to cool the cryostat. It also contains a 5T superconducting magnet, which allows for studies at high magnetic fields. Figure 3 is a diagram of the dewar.

IV. Instrumentation:

The external instrumentation used in this experiment included a Hewlett Packard 3457A multimeter to monitor the thermometers, a EG&G 7260 lockin amplifier to measure the sample resistances, a EG&G 5209 lockin amplifier to regulate the temperature, and a Hewlett Packard 6651A DC power supply to run the superconducting magnet.

V. Software:

The external instrumentation was controlled almost entirely using the LabView software package and GPIB interface. The software allowed for greater precision and efficiency in data gathering and also allowed multiple instruments to be run simultaneously.

Experimental Procedure

I. Capacitor Calibration:

The first step in my work was the assembly of the pressure cell and the calibration of the capacitor within. Using only the lower section of the pressure cell (the sample bracket and the capacitor below) I applied a known force to the sample bracket and measured the capacitance using a capacitance bridge. A few plots of the data I gathered are shown in figure 4. I found that the inverse capacitance did fall linearly with the applied force at room temperature and at liquid nitrogen temperature (77K). The actual value of the capacitance varied depending on the initial setup of the pressure cell (sample positioning, tightness of the bolts, etc.) but that the change in capacitance was constant regardless of starting point.

II. Sample Preparation and Mounting:

To prepare a sample to be mounted in the pressure cell, I first had to cut the sample using a wire saw to the appropriate dimensions for the bracket, approximately 1mm X 1mm on end and 5-7mm long. Once cut, the four sample leads were attached using silver paste and fine platinum wire. These wires were run to a four-lead connector on the outside of the bracket to allow measurements. The sample I studied was FeSi with 1% Al doping.

III. Cryostat Assembly:

The next step was assembling the cryostat. All the parts of the cryostat had to be fitted together and checked to ensure a leak free system. Once the system was leak tight, wiring was added to monitor the experiment. From the 26-pin connector at the top of the cryostat, I ran four pair of copper leads for monitoring the sample itself and nine pair of resistive leads to run the heater and thermometers. I also attached a pair of small diameter coaxial wires to measure the capacitance in the pressure cell and stainless steel tubing to pressurize the cell.

IV. Heat Sinking:

Once the wiring and tubing was in place, I began to put the heat sinks in place. Each path for heat had to be cooled to keep the experimental stage at the desired temperature. A diagram of the inside of the vacuum can with the heat sinks in place is shown in figure 5. All wiring and tubing was firmly anchored at the upper heat sink (at 4.2K from the liquid helium

bath) and again at the lower (isolated from the bath, below the 1K pot).

Heat loads repeatedly presented a problem in this experiment. After initially setting up the cryostat and finding that the temperature was not reaching the desired levels, I removed the potential heat loads from the cryostat and began to systematically replace them in hope of locating the source of the heat load. Using this method, and also by replacing some of the leads with smaller diameter wire, I was able to substantially reduce the heat load on the system and achieve much lower experimental temperatures.

V. Cool Down:

Once the cryostat was tested, I was able to cool down and begin the actual experimental runs. A typical cool down procedure is as follows. First, the cryostat (with sample in place) is closed and the vacuum can is pumped out. Then, both the cryostat and the superconducting magnet are pre-cooled to liquid nitrogen temperature. A small amount of helium gas is added to the vacuum can to speed up the cooling. Once the pre-cooling is complete, the magnet is remounted in the dewar and the cryostat is inserted. Then liquid helium is transferred into the dewar. Using the thermometers on the experimental stage, the temperature can be monitored. After the temperature stabilizes at 4.2K, the exchange gas in the vacuum can is pumped out and the 1K pot can be pressurized if necessary. Once pressurized, the 1K pot will be filled with liquid helium, which can be pumped out of the pot to lower the temperature inside the vacuum can below 4.2K to as low as 1.7K.

VI. Data Collection:

Using the software and instrumentation, data can be taken on the sample as it cools initially. Once cool, the temperature can be controlled using a heater mounted on the experimental stage. One of the software programs can perform PID calculations to equilibrate the temperature. The pressure applied to the sample is controlled externally by a pressure regulator, and is generally set at a constant value for a particular data set. The resistance of the sample is measured using the lockin amplifier and a four-lead measurement to reduce the effects of both noise and the lead resistances.

Results

Data was taken on the FeSi 1%Al sample at two different applied pressures, 0 psi and 150 psi. 150 psi applied to the 0.27 in^2 pressure cell produces 40.5 lbs or 180 N of force on the sample itself. The 150 psi of pressure produced approximately a 0.7 pF increase in the capacitance of the pressure cell. The value of the capacitance varied from run to run, but was always about 29 pF at 0 applied pressure. From the calibration data (like that shown in figure 4) this change in capacitance is consistent with a force of 180 N on the sample. This 180 N force on the 1.07 mm^2 area of the sample produces a pressure of 1.7 kbar.

A plot of the resistivity data is shown in figure 6, a plot of the conductivity in figure 7. Figure 7 shows an unusual linear $\sigma(T)$, matching the results of previous work[1] with $FeSi_{1-x}Al_x$. At 4.2K, the conductivity was 455 $(\Omega\ cm)^{-1}$. From the line fits on the conductivity plot, $d\sigma/dT$ is approximately 2 $(\Omega\ cm\ K)^{-1}$. These values of σ and $d\sigma/dT$ correspond well with previously measured values[1].

Conclusion

As seen in figures 6 and 7, the application of 150 psi of pressure seemed to have no measurable effect on the sample studied. Figure 8 shows the behavior of phosphorous doped Si in a similar experiment[2]. Even at 4.2K, there was a noticeable change in the conductivity. The carrier density of doped Si is on the order of $10^{18}/cm^3$ while the carrier density of the doped FeSi is $10^{20}/cm^3$. Because of this increased carrier density needed to enter the metallic phase, higher pressures may be required to produce the same level of effect in the sample.

Further work on this experiment is required. The same samples, under higher pressure, may reach the required carrier density. Additionally, by using lower doped samples closer to the metal-insulator transition, the pressures we used may be sufficient for transition. Magnetic field studies of the samples could also provide more insight into the nature of the transition.

References

[1]J.F. DiTusa et al, Phys. Rev. B, 58, 10288 (1998).
[2]T.F. Rosenbaum et al, Phys. Rev. B, 27, 7509 (1983).

Figures

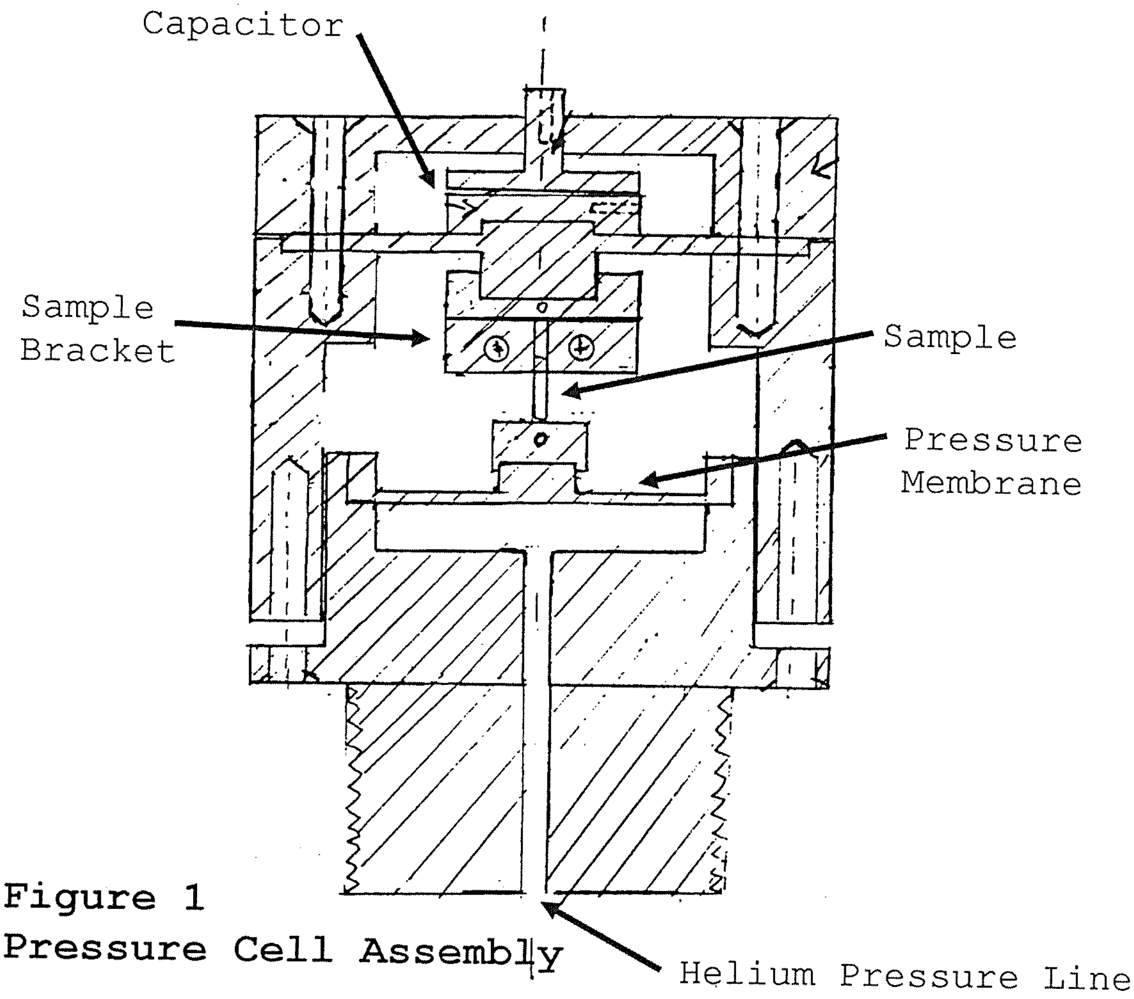

Figure 1
Pressure Cell Assembly

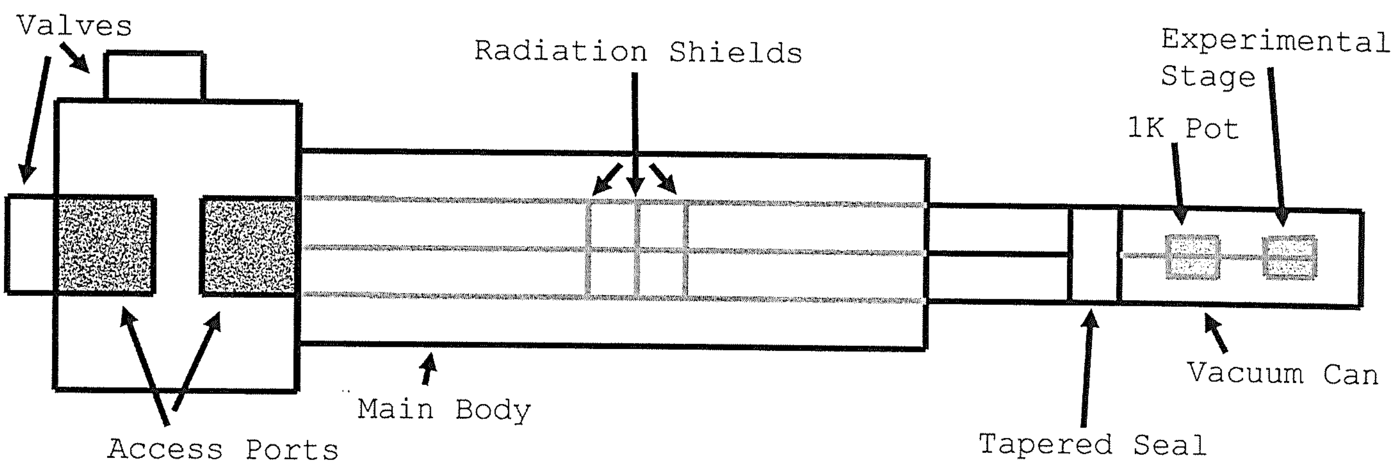

Figure 2: Cryostat
(not to scale)

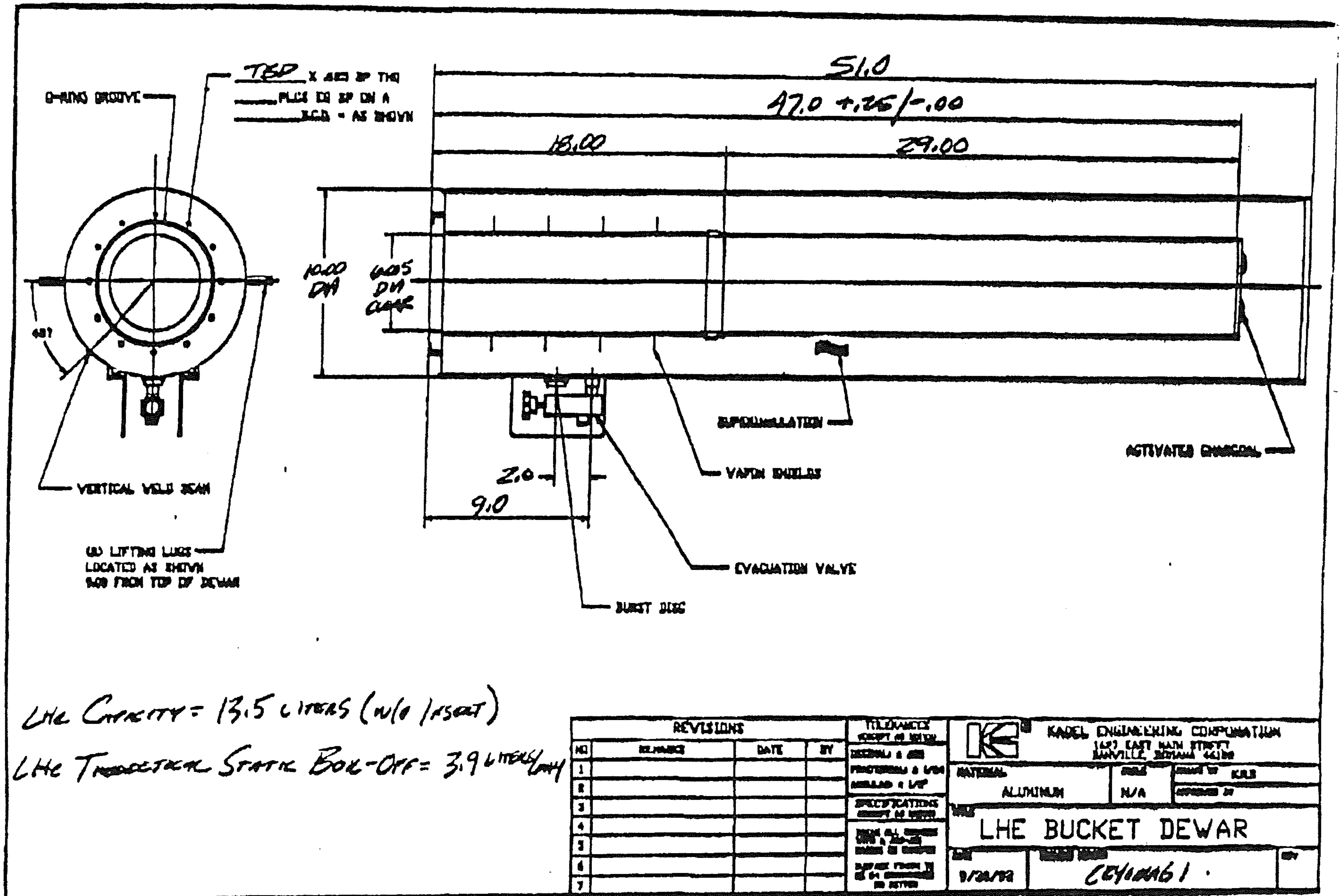

Figure 3: Helium Dewar

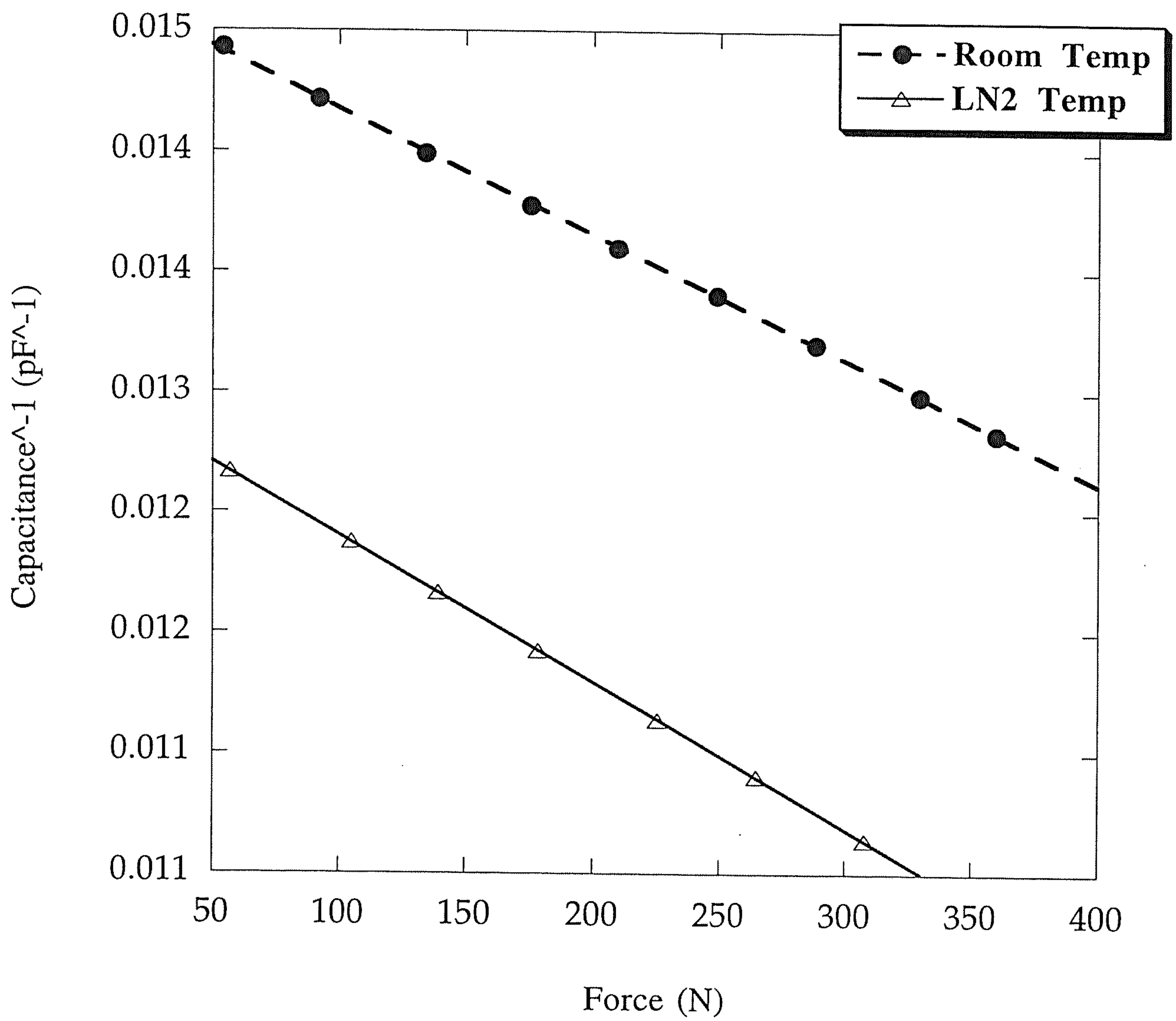

Figure 4: Capacitor Calibration Data

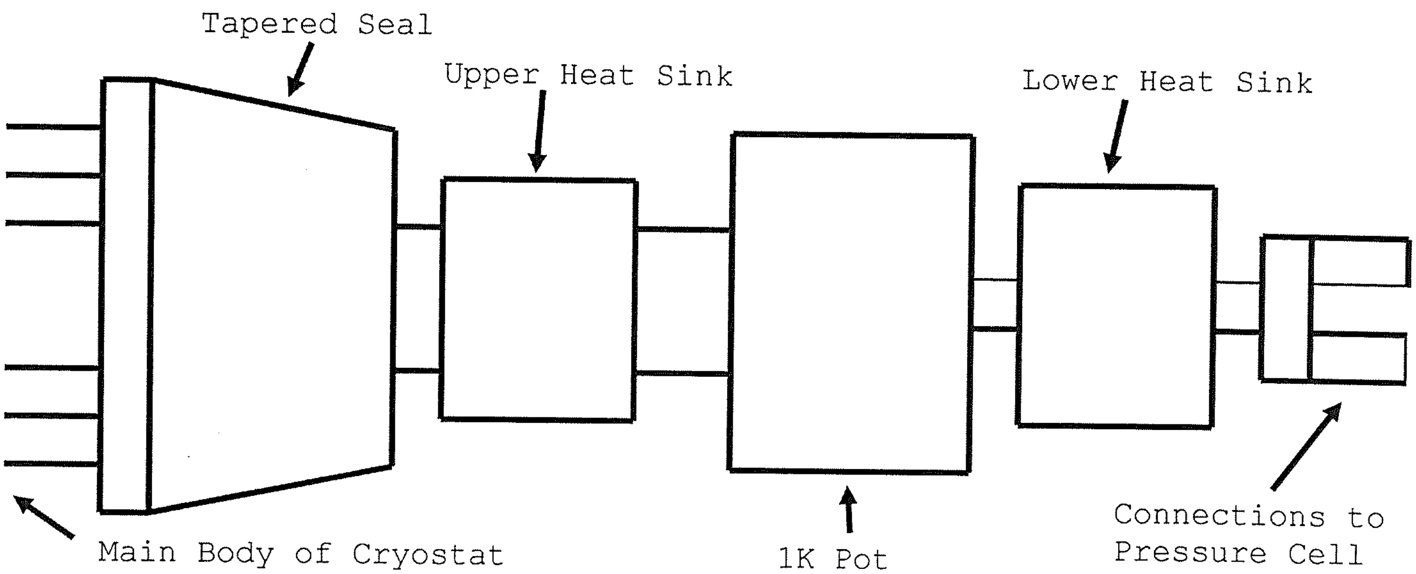

Figure 5: Heat Sinks and Interior of Vacuum Can

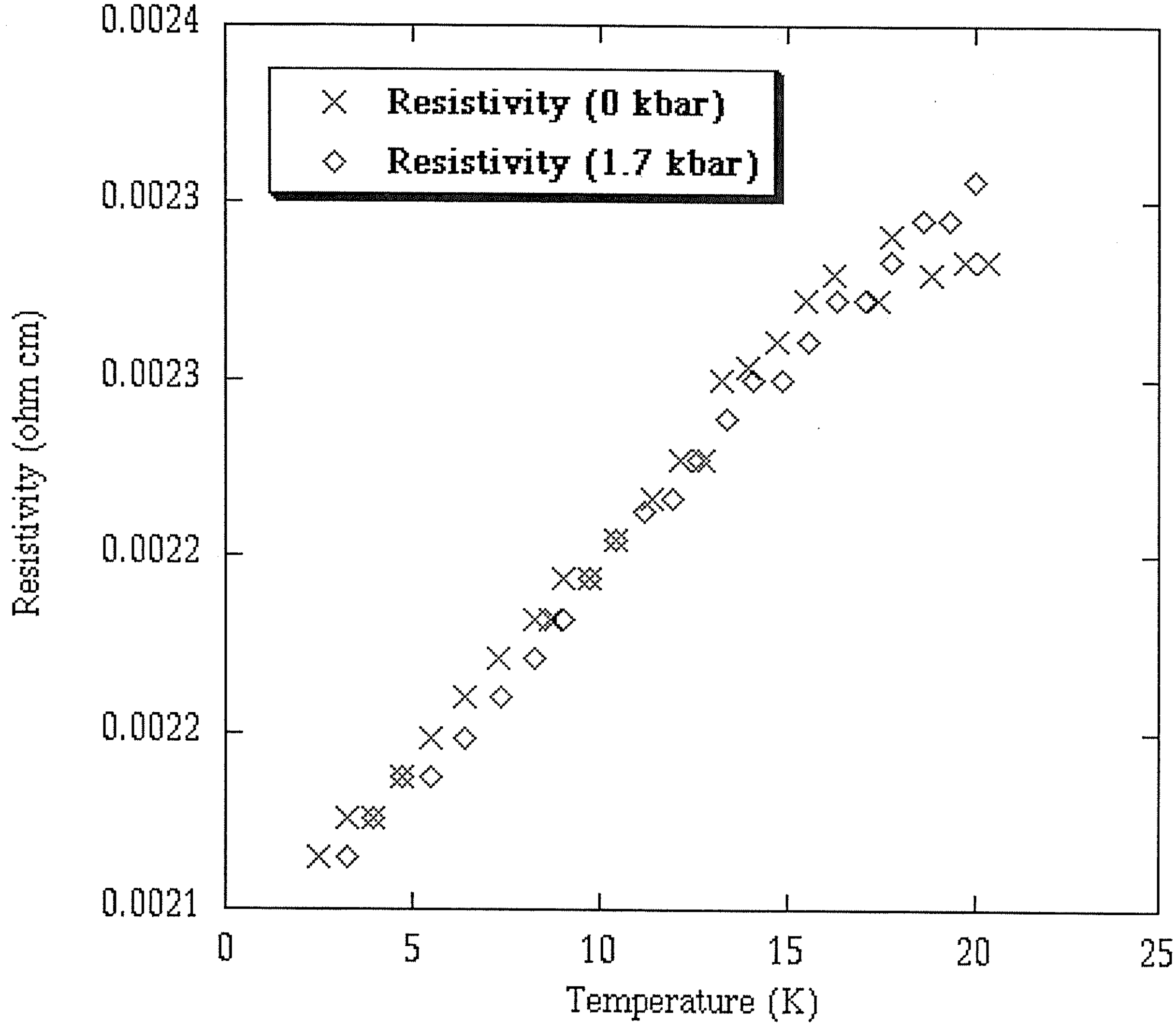

Figure 6: Resistivity vs Temperature for FeSi 1%Al

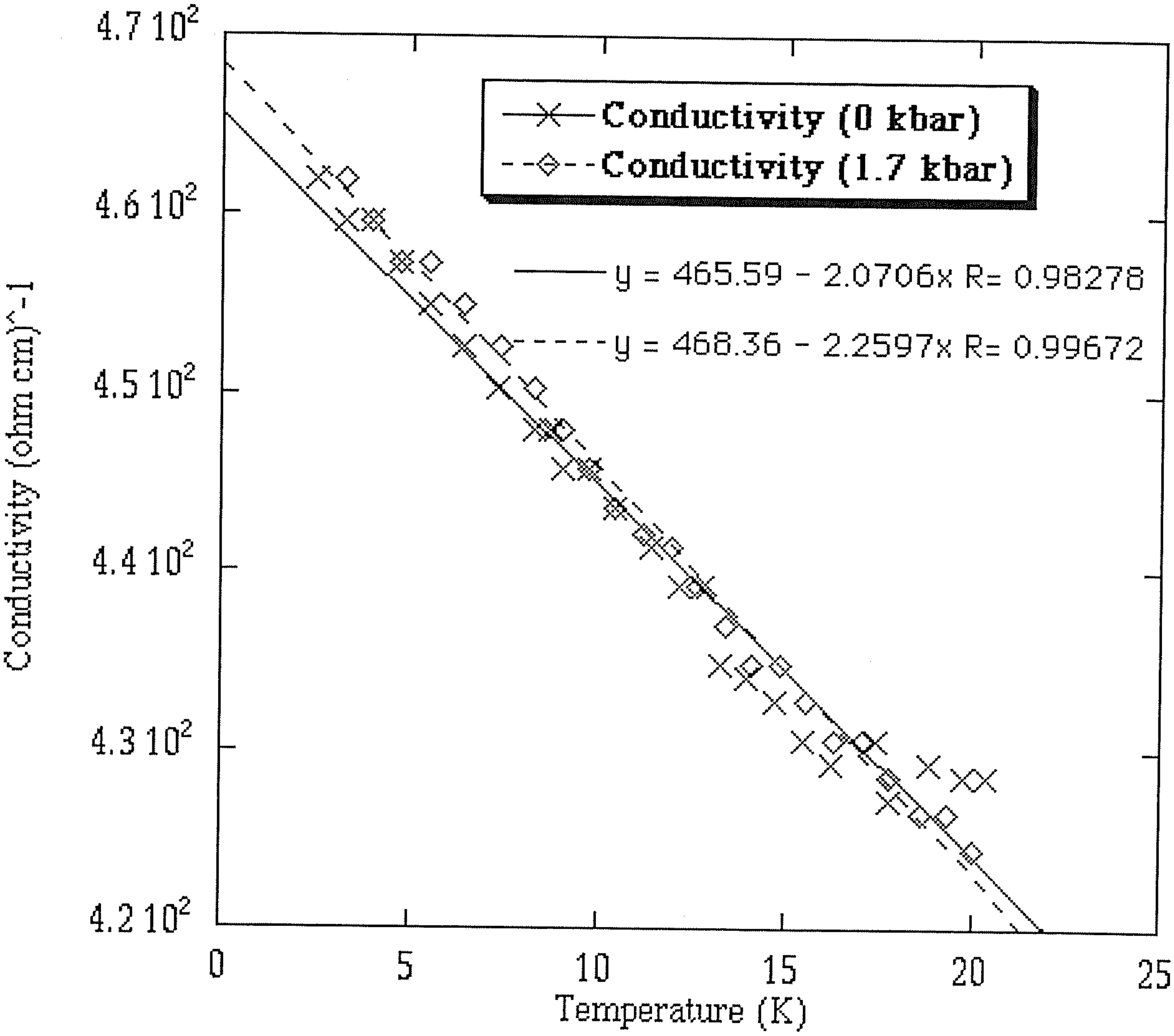

Figure 7: Conductivity vs Temperature for FeSi 1%Al

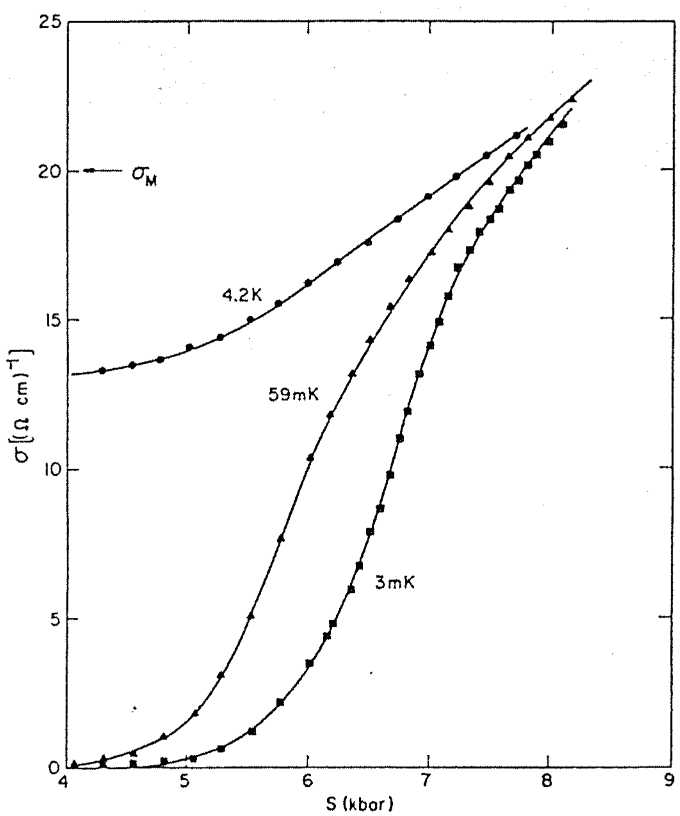

Figure 8:
Conductivity vs Uniaxial Stress in Phosphorous doped Si