Bismuth and Yttrium Metals Under Extreme Conditions of Pressure and Temperature

Skyler J. Hanson, University of Wisconsin-Eau Claire
Christopher S. Perreault, and Yogesh K. Vohra
Department of Physics, University of Alabama at Birmingham, Birmingham, AL 35294

THE UNIVERSITY OF ALABAMA AT BIRMINGHAM

Abstract

The goal of this summer research project is to study phase transitions in materials at both extremes of low and high temperatures under high pressures. The high pressures were generated using a pair of single-crystal diamonds in a diamond anvil cell device. The first component of project dealt with high-pressures up to 20 GPa and low-temperatures of 15 K in a cryostat and electrical resistance measurements were performed on bismuth metal. Four probe electrical resistance measurements on bismuth indicate three phase transitions that were detected below 10 GPa. These phase transitions are distinct and marked by discontinuities in electrical resistance data as a function of pressure at room temperature. The diamond anvil cell was then cooled down to 15 K and these phase transitions were monitored at high pressures and low temperatures. The second component of project dealt with high pressures up to 70 GPa and high temperatures up to 2500 K. The high-pressure high-temperature studies were carried out at the double-sided laser heating facility for diamond anvil cells at the High Pressure Collaborative Access Team (HPCAT) beamline 16-ID-B, Advanced Photon Source, Argonne National Laboratory. In the high-pressure high-temperature studies in diamond anvil cell, rare-earth metal Yttrium was studied and high pressure phase transitions were followed to high temperatures. The present studies show the versatility of diamond anvil cell devices to explore a vast Pressure-Temperature (P-T) space to study phase transitions and synthesize novel materials under extreme conditions.

Introduction

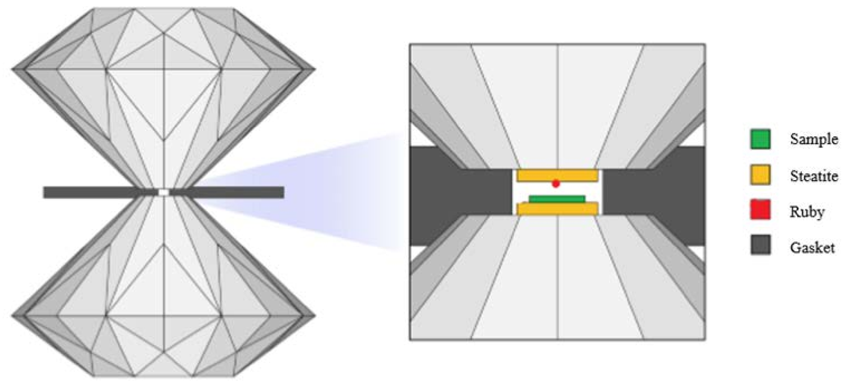

Figure 1: schematic of loaded diamond anvil cell

Diamond Anvil Cells (DAC) are used for high-pressure experiments because of their shear strength and transparency to a variety of electromagnetic radiation.

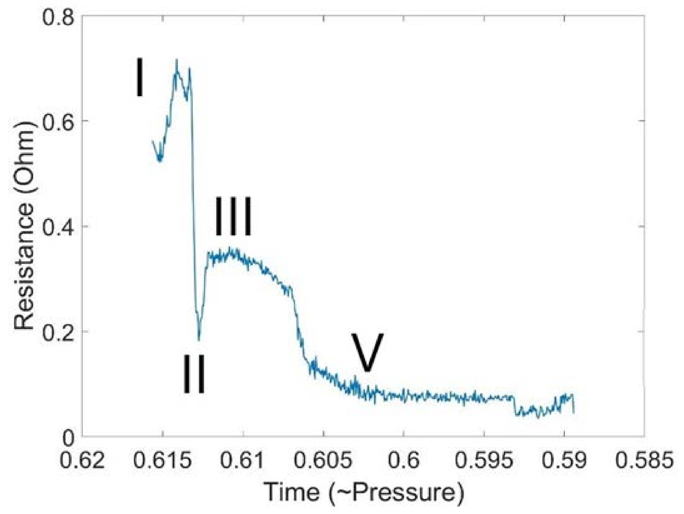

Figure 2: room temperature decompression of bismuth showing three phase transitions

Bismuth (Bi) is a semimetal that has been well-studied at high pressure for its unique electronic character and its many pressure-induced phase transitions. At room temperature, the generally accepted sequence of phase transitions are I→II→III→V (Hai-Yan, 1). The corresponding pressures for these transitions are ~2.6 GPa, 2.8 GPa, and 7.7 GPa.

Yttrium (Y) is a rare earth transition metal. The rare earth crystal structure sequence hexagonal close packed (hcp) → samarium type (Sm type) → double hexagonal close packed (dhcp) → mixed (dhcp + fcc) → distorted face centered cubic (dfcc) is observed in yttrium below 50 GPa.

Methods

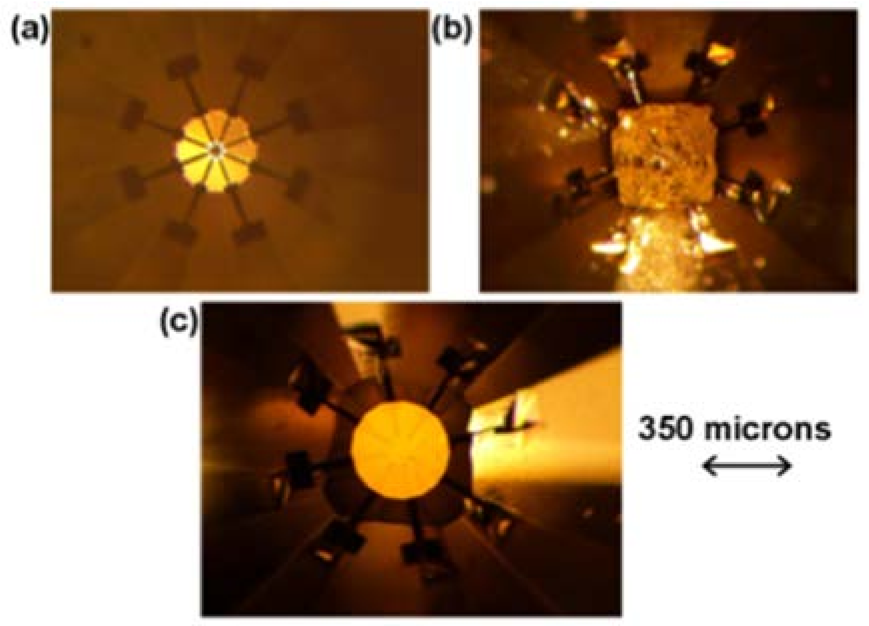

Figure 3: (a) electrical probes lithographed onto the diamond anvil cell. (b) diamond deposited through CVD on top of pattern. (c) finished designer-diamond anvil cell with culet 370 microns and probe diameter 85 microns. (Samudrala, 3)

Electrical and magnetic data can be measured by putting specially-fabricated metal leads atop the diamond culet through a process called Microwave Plasma Chemical Vapor Deposition (MPCVD). The cell used in the bismuth run was a single-crystalline designer diamond anvil with an 8-probe electrical pattern of tungsten metal made through the process of chemical-vapor deposition at the University of Alabama at Birmingham. The culet size was 300 microns with no bevel.

The cell was cooled to 15K in a cryostat at 0, 2.0, and 4.0 Bar. Resistance and temperature data were recorded through a LabView program. Ruby was used to calibrate pressure through a laser spectroscopy system, due to the pressure-dependent spectral shift in fluorescence of ruby

During the yttrium run, angle dispersive x-ray diffraction (ADXRD) was used for the determination of crystal structure. Because of the small sample size (< 100 micron) a narrow beam of high intensity is needed. high-energy X-rays are necessary to penetrate the diamond anvils and to obtain enough diffraction lines because the opening of the DAC is limited (usually $2\theta < 15°$) (Porsch, 1). The High-Pressure Collaborative Access Team (HPCAT) beamline 16-ID-B, Advanced Photon Source, Argonne National Laboratory provided x-rays with sufficient energy (λ= 0.40663Å) to analyze the crystalline structure of our sample size.

Yttrium was heated to temperatures of 2500K on an ID-B Laser Heating Table. In a laser-heated DAC, a sample is heated by absorbing the IR laser radiation (1064 nm). Yttrium cell was thermally insulated with MgO powder.

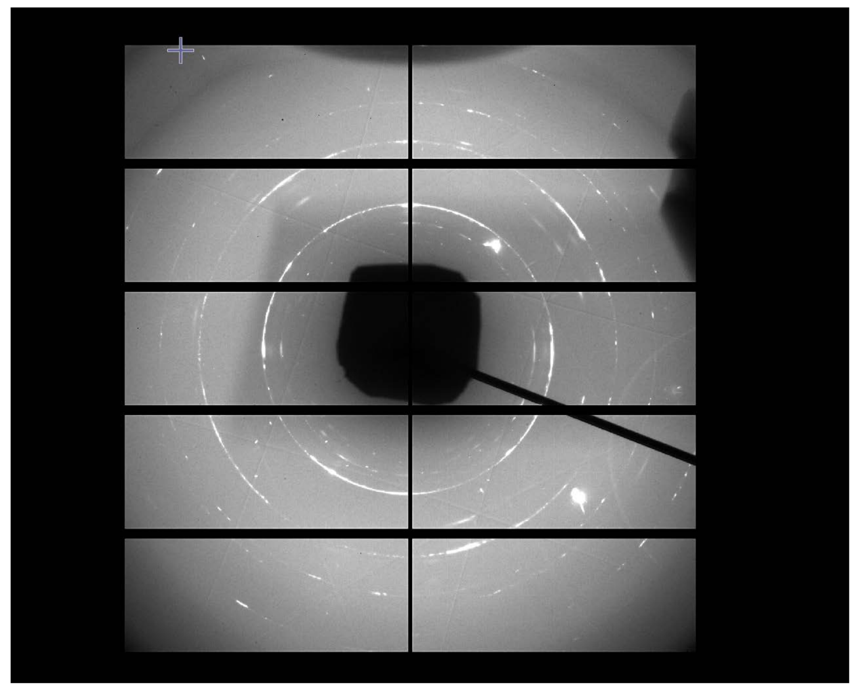

Figure 4: ADXRD pattern taken at Argonne National laboratory. Yttrium and MgO at 70GPa, ~1500K

Results on Bismuth

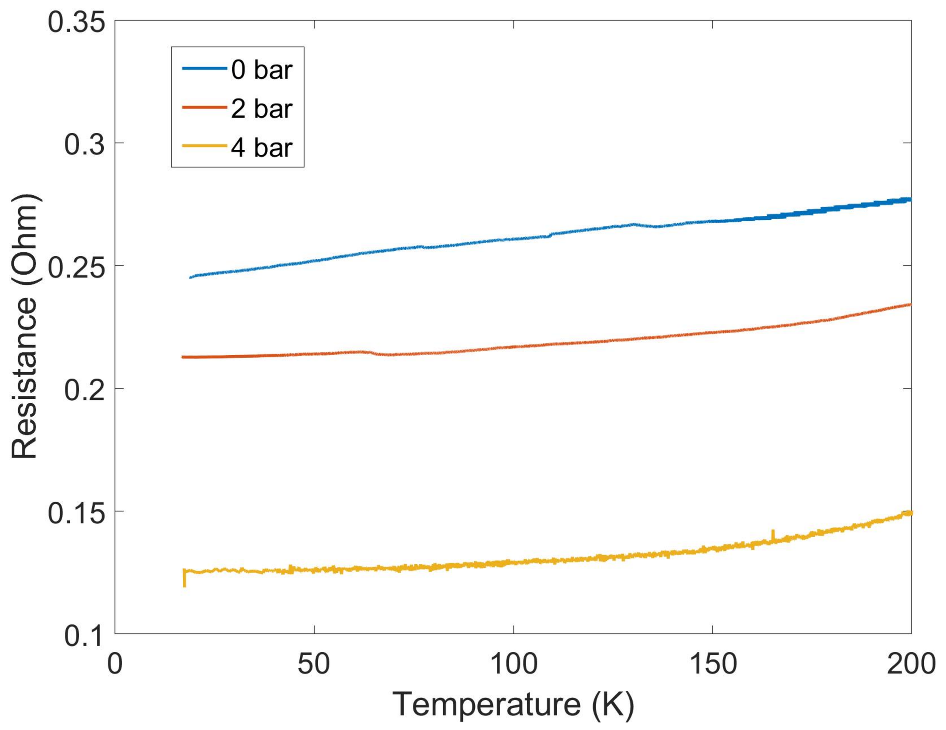

Figure 5: Graph comparing warming data of bismuth at 0, 2.0, 4.0 Bar. Minimum temperature 15K.

- At 0 Bar, The maximum pressure in the cell was ~6.0 GPa achieved at lowest temperature (~15K). Minimum resistance was ~.25 Ohms.
- At 2.0 Bar, the maximum pressure in the cell was ~8.0 GPa. Minimum resistance was ~.23 Ohms
- At 4.0 Bar, The maximum pressure in the cell was ~10.0 GPa. Minimum resistance was ~.13 Ohms.

Figure 5 compares the resistance of the sample at 0, 2.0, 4.0 Bar in relation to temperature.

Results on Yttrium

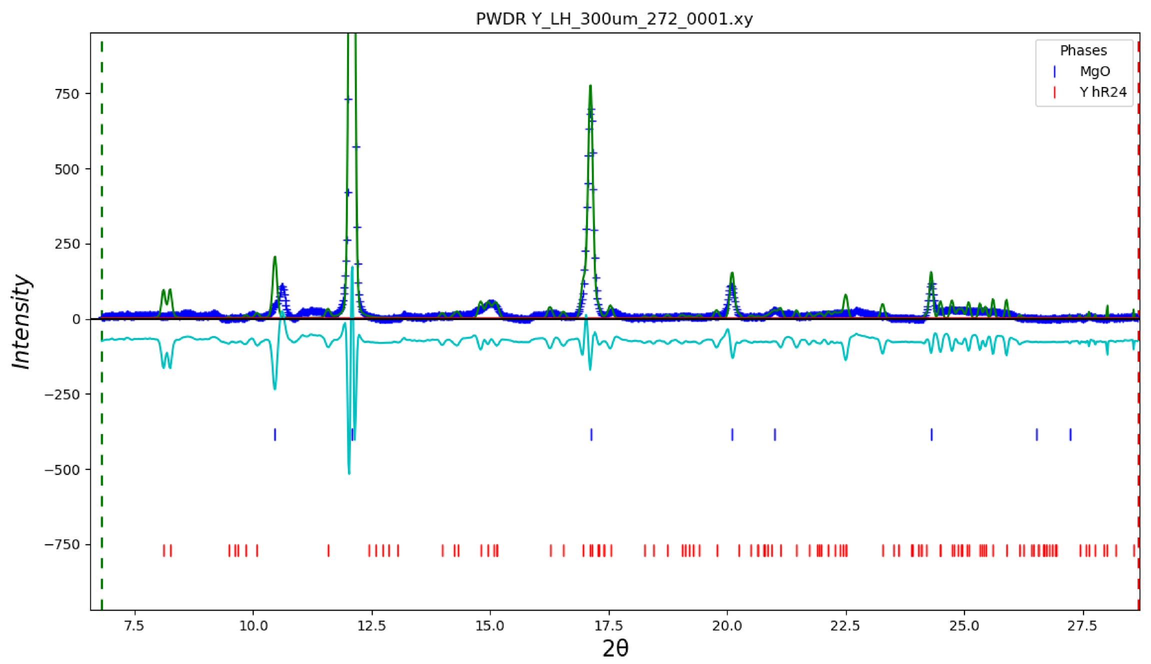

Figure 6: refinement of XRD pattern of yttrium and MgO at 70 GPa and 1500K

Figure 6 shows the refinement of the XRD pattern for yttrium and MgO at 70 GPa and 1500K. The refinement of this data can give the crystalline structure of yttrium.
The lattice parameter for MgO is a = 3.862±0.001 Å and for yttrium they are a = 5.654±0.001 Å and c = 14.213±0.002 Å. MgO has a cubic structure and yttrium's structure is distorted face-centered cubic (dfcc).

Conclusion

The Bismuth data shows that resistance of the material decreases as temperature decreases to 15K under high-pressures to 10GPa. Bismuth becomes a better conductor in high-pressure low-temperature experiments. However, this study did not conclude that bismuth is a superconducting material at the conditions tested.

The refinement of yttrium at 70 GPa and 1500K shows the spacing and structure of the material. However, more data must be refined in order to come to a conclusion on the behavior of yttrium under high-pressure high-temperature.

References

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WHERE DISCOVERIES BEGIN

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