Cornell Center for Materials Research

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Project "Solid State Physics Elective Course"

Applications: elective courses with a strong emphasis on laboratory research in material science directed to learning physics and chemistry of solid state of matter

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Overview

This project was developed during Research Education for Teacher program in summer of 2006. The RET-II is funded by National Science Foundation through Cornell Center for Material Research (CCMR). The goal of this program is to submerge science teachers real-world research conducted in one of the CCMR facilities and gain first-hand experience. This project was developed in Prof. Rüdiger Dieckmann laboratory in Bard Hall.

Goals of the Project

The goals of this newly developed elective course for high school students are 1) to engage them in basic scientific research in the filed of Solid State Physics; 2) to expand and deepen their knowledge about fundamental physics laws; 3) to familiarize students with modern laboratory techniques and safety requirements; 4) to encourage young people to pursue careers in material research and related fields of physical sciences.

Equipment and Materials

1. Tube furnace – 3 items;
2. Thermocouples – 10 items;
3. IR-thermometer (pyrometer) – 3 items;
4. Isostatic press – 1 item;
5. Vacuum pump – 1 item;
6. Metal dies of various diameters;
7. Precision Mini X-Ray Diffractometer (optional)
8. Chemicals: Y_2O_3, CuO, CaO, or $CaCO_3$, SrO or $SrCO_3$, BaO or $BaCO_3$ etc, and various salts;
9. High temperature resistant wafers;
10. Mortars and pestles – 4 sets;
11. Chemical glassware;
12. Top heater;
13. Masks, gloves, filter paper as needed;
14. Analytical scales;
15. Electric wires, Nichrome wire as needed;
16. Rubber or plastic tubing;
17. Glycerol other press liquid according to the requirements;
18. Dewar vessel with screw top;
19. Other miscellaneous materials as needed.

<u>ATTENTION:</u> All lab procedure will be closely supervised by the teacher and, in some occasion, by a second adult, who can be another teacher or a lab specialist. No visitors will be allowed when experiments are performed. However, student will have a small assignment to develop and conduct a lab tour closer to the end of the course. This lab tours will target broader student population as well as parents, other teachers, and visitors.

<u>SAFETY:</u> All the students will have permission dated and signed by their caregivers. All students must strictly follow safety rules discussed in the beginning of the course. Any immature behavior in the lab will not be tolerated and such a student may face a temporary suspension or be permanently barred from this course.

Part-I Making tablets and rods

Initially, students will work in groups to come up with the procedure of making stable tables and rod out of thoroughly mixed portions of chemicals. Students will learn to use analytical scales and apply simple error calculation techniques. They will also be utilizing significant figures concept based on real data taken from the analytical scales.

In this part, class will learn how to use hydraulic isostatic press and dies for tablet and rob preparation. They will have to pass the prerequisite, **Formal test** on how to safely operate the press. Without passing it a student will not be allowed to operate it or participate in the group that is operating it.

Students will have to maintain a lab log and document all the procedures. The final document shall be a technical report on how to successfully prepare a tablet or rod of the given size that would not fall to pieces and maintain its shape during heat treatments.

Students will be given a rubric (created by using resources at http://rubistar.4teachers.org/index.php) that will help them develop a highly organized and easy to follow technical documentation that specifies masses, sizes, pressures, timescale, and any other necessary details of making tables or rods.

After the documentation is completed, groups will be rearranged and asked to follow the technical documentation and prepare from 3 to 6 samples depending on the time. Successful completion of this task will indicate that procedure developed by the students can be followed and the results are reproducible.

In case of mixed results, students will have to modify the technical documentation as they will have to follow it later many times for sample preparation. After this point, any modification to the technical documentation shall be minimal and only if required by the following experimentation.

This Part-I experience will also broaden the students' view on scientific method, which is usually delivered in high schools as something rigid that should be blindly followed and not modified. Usually, students react to any changes of the procedure in standard physics labs as "cheating", which only indicated very limited exposure of the students to real-life science research atmosphere. I believe this part of the Solid State Physics course will strongly address this issue and raise students' understanding of modern routes of research in Material sciences.

Part-II Baking High-Temperature Superconductors (HTSC)*

High-Temperature Superconductors are called so because they demonstrate zero electric resistance at temperatures significantly higher than liquid Helium (4.2K), and namely at temperatures near or above liquid Nitrogen (77K or higher)

In this part, students will learn how to operate high-temperature tube furnaces. The temperatures of the furnaces shall not exceed 1000 °C except, may be, a few cases. Operation of the furnaces will include several steps:

1. Measuring temperature profile of the furnaces.
    a) For this experiment, students are expected to lean different ways of measuring temperature. A **Formal lecture** will be given to briefly introduce modern thermometry. Then, the student will study in groups using various resources. This part of the experiment will be assessed by giving a test/quiz.
    b) In the experimental part, student will use thermocouples to measure temperature in the furnace tube at various distances. Then they will create a Temperature map of each furnace that was studied.
    c) Additionally, pyrometer or IR-thermometer will be utilized to monitor the temperature parallel to thermocouple measurements. This should give the idea that IR-thermometry may not always be a source of accurate information and that it should only be used as an estimating tool.
    d) Each experimental part will be followed by error analysis and plotting graph that may be useful later.

2. By this time, the class shall have sufficient number of tablet necessary for this experiment. Students will have to come up with ideas of measuring temperature of the tablet inside the furnace. In this particular part, they will be introduced to controlled and independent variables. The Fig. 1 below explain some details of the experiment:
    Two wafers W_1 and W_2 are placed as close as possible to ensure similar conditions for controlled and independent voltages measure by thermocouples TC_1 and TC_2. Students may also perform test

measurements on top of the sample; however, chemical purity may be affected as metals are introduced into the tablet. In any case, this will be a valuable experience for the class as they will learn to consciously choose between the value of the information and possible perishing of the sample.

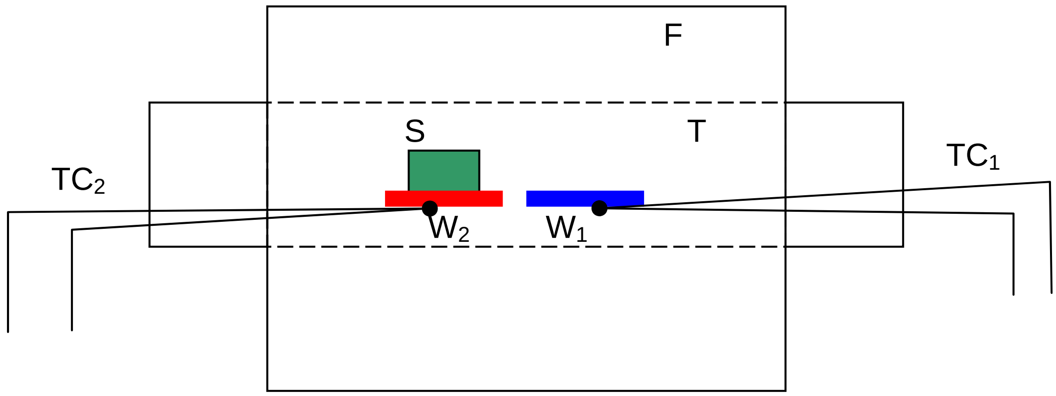
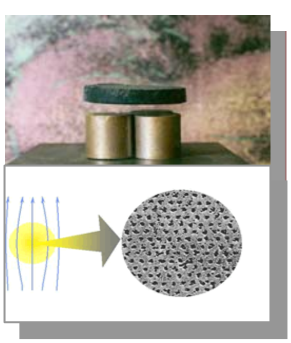


Fig.1: Schematics of temperature measurements. F – Tube Furnace, T – tube, where sample S are placed and heated, S – sample, W_1 and W_2 are controlled and independent wafers, respectively, TC_1 and TC_2 – are controlled and independent thermocouples.

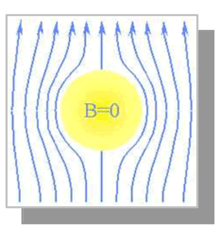
<u>Formal assessment</u> will be given as to how to measure temperatures at various ranges, pros and cons of each method, and how to choose the proper method depending on the experiment conditions. The latter will be assessed in form of problems, which may include multiple-choice and open-end questions.

3. As the class learned about thermometry and measured and created temperature profiles of each furnace, it is time to “bake” something cool! For this part, using try-and error method, each group will raise the temperature of the oven at a given rate. Increasing temperature of a sample may affect solid state reactions. And students will be asked to search literature on this topic and make a small group report on their finding. This will be **<u>formally assessed</u>** on pass-no pass basis. Samples then will be heated at the same temperature for the same amount of time.

   Cooling of all the samples shall be done really slowly as this part of experiment will be a controlled one. We may choose to control temperature drop electronically as it may require long hours. Each tablet is to be gone though a simple test: the Meissner Effect. Cooled by liquid nitrogen, each sample will be placed on a magnet to see if it “levitates”. Time of levitation will generally indicate quality of the HTSC samples. We can reserve some of the samples for follow-up measurements to more precisely assess the quality of superconductivity and possibly measure critical temperature T_c. In Fig.2, there is photo of the Meissner effect demonstration.



Type II usually HTSC (ceramics)



Type I usually metals and alloys

Fig.2: the photo shows a levitating superconductor above magnets. This phenomenon is explained by partial extortion of the external magnetic field from the ceramic HTSC. HTSC are superconductor of type II, which is different from type one. In type I superconductor, which are traditionally metals and alloys, magnetic field is completely pushed out of the bulk of material. Unlike type I, type II superconductors are essentially a mix of conducting and superconducting phases.

Additionally, a quick measurement of the density will be performed. At the end, the best temperature ramping will be selected keeping an open eye on other possibilities.

4. It must be noted that cooling down ramp will also be investigated. For this part of experiment, a heating ramp will be maintained the same for all the samples, and only cooling ramp will be different for different samples. Time of heating at constant “baking” temperature shall be the same for all the samples.

By the end of Part-II, students shall be able to develop a technological “roadmap” with best possible regimes for getting the longest levitation time. Certainly levitation test shall be calibrated for the mass as well as the density of the samples. And as this test just serves the purpose of separating wheat from chaff, it is not the final word describing the results of HTSC “baking”.

The coolest part is working with liquid Nitrogen and seeing the samples float. I think that when girls and boys will see the marvelous results of their work they will be thrilled and become strongly motivated to continue research, dig deeper, and look further. This will also let them prove that science, the real one can be done by regular guys like them, that it is fun, and that it empowers and inspires.

Part-III Theory of Solids

This part of the course goes along with the Part-II. Here student will utilize time while sample are “baking” to learn more about theory of solids. Students will be exposed to phases of matter; solids, liquids, gases, plasma. They will also learn subtle terminology of solid state physics. For example, word “phase” may have different meaning depending on the context. It may mean the crystallinity and specific configuration of crystals for solids. In another occasion, it may indicate stoichiometry of the compound. Yet in another, it may simply indicate solid or liquid phase.

Additionally, this course will teach about different crystal structures and orientations of planes. Simple concepts of X-ray powder spectrometry will be introduced. Materials accumulated during the RET-I (2005) and RET-II (2006) will be used as examples. Laue back scattering X-ray spectrometry will follow the powder XRD section. Excellent simulations available on-line will be used by student to study crystals of their interest[1, 2, 3]. If funding is sufficient, table-top powder X-ray Diffractometer may be used to study crystalline structure of various materials and the produced samples.

Students will also learn about various types of crystals and how and why their shapes are affected by the chemistry and stoichiometry. They may also be introduced to electron structure of atoms and learn more about different s-p hybridizations and how electron clouds overlap in various regular shapes. As a small hands-on project students will build one of the models using Styrofoam balls, sticks and color them with acrylic paints. These models should reflect known crystal structure as precisely as possible so that they can be used later as models in the future classes. Essentially, the idea is instead of buying a few expensive molecular models and being afraid that they eventually break, it is far better when students build those models and if they break them, so be it. By breaking many of them apart they will learn more than from a few static models getting dusty on the shelf and occasionally used by a teacher.

The end products should be crystal models with the brief description of the type of the crystal, and demonstration of a few planes. Student will have the project rubric that will be used to evaluate the work.

Part-IV Crowing Crystals

As it is not entirely impossible to grow crystals of HTSC in the school lab, it is more practical to grow other types of crystals from various solutions. Crystals of $CuSO_4{\bullet}5H_2O$, NaCl, $CaCl_2$, $MgCl_2$, and $AlCl_3$ etc. can be grown from purified solutions. Salts of other metals can be also considered for variations in colors. Some of the crystals may be a challenge to grow.

Two ways of growing crystals will be tested: 1) spontaneous growth from a random seed suspended in the saturated solution; 2) controlled growth, where a seed is suspended on the electrically controlled handle that can lift the seed at the set velocity.

These crystals then will be described and analyzed in terms of anisotropy. Students will be able to understand and explain why certain crystals are harder in given direction and less so in a different one. They will also learn about the mechanism of charge transfer in solid ionic crystals and attempt to experimentally measure it with various samples.

By the end of this part, students will write a one page concise and accurate description of one crystal that will include the class of the mineral, type of primitive crystals cell, type of symmetry in the crystal, anisotropic properties, and explain why the crystal demonstrates anisotropic properties.

Conclusion:

At the end of the course, the final exam will be given to assess students' knowledge of the factual material and conceptual understanding. Exam will include multiple-choice questions and open end questions. Student will also have a well organized and completed portfolio on Solid State physics that will give them "jump-start" should they decide to pursue education in material science. They will also develop communicative skills such as oral presentations, written scientific reports, and ability to discuss and develop tactical and strategic decisions. Students who have successfully completed this course will also have broader understanding of how real science is done and share that discovery with their peers from other classes as well as their parents and other adults.

The value that this course may add to the educational process is immeasurable: the lab experience of one of a kind, exploration and discovery of unusual properties of HTSC, magnetic levitation, and all that available and doable right in the school lab. Applications of physics laws will further strengthen students' understanding of solid state concepts, and their interconnection.

References:

XRD simulation and tutorials:

1. http://www.uni-wuerzburg.de/mineralogie/crystal/teaching/teaching.html;
2. http://pros.orange.fr/carine.crystallography/index.html

Laue

3. http://jcrystal.com/steffenweber/JAVA/jlaue/jlaue.html

Links:

1. Presses: B-10 Dake Bench Utility H-Frame Press at http://www1.mscdirect.com
2. Furnaces: http://www.sentrotech.com/tube.php
3. Precision Mini X-Ray Diffractometer (optional) and vacuum pump: http://www.mtixtl.com/

Acknowledgments

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