

Materials: An interdisciplinary integrative approach

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ABSTRACT

A full-year survey-of-materials-science course as offered at Bowling Green State University for the past 5 years is described. The course has several unique features, including a modular, team-taught approach with a laboratory component. The laboratory segment is the most demanding portion of the course to set up, and alternatives are discussed in adapting equipment on hand to the course. The feasibility of offering a course in materials science in a non-engineering setting is discussed and some problems associated with offering the course in the "arts and sciences" context are examined.

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Introduction

Many people, especially science policy makers, have recognized the field of materials science as comprising one of the key developmental areas in physical science in the 21st Century. The National Research Council (NRC) has published a comprehensive review¹ of the status of the field and its manpower needs, and, apart from the expected suggestions about graduate education, has also made some interesting observations regarding materials education at the undergraduate level. In the report, the NRC promotes a wider preparation of practitioners in the field to recruit other professionals into it. Clearly, a career in materials is a viable option for a physics major with an interest in applied physics, especially in times when employment opportunities are otherwise limited.

The first point that must be considered is that materials science is an *integrative* discipline, in that advances in a variety of other disciplines as well as physics contribute to progress in the field. Second, the so-called materials-designated departments (e.g., Materials Science and Engineering Departments) number only on the order of 100 units throughout the country, and, as the example title implies, are usually associated with an engineering school or division.

Although widely recognized as an essential component of an engineering undergraduate education for over a quarter of a century, undergraduate courses in materials are only just now making their

appearance as a part of the undergraduate curriculum in physics and other basic science departments. Of course, almost every undergraduate physics curriculum contains an "Introduction to Solid State Physics" course that typically follows the rubric laid down decades ago in textbooks such as *Introduction to Solid State Physics*, by Charles Kittel². A simple comparison of this text with those that are typically used in introductory materials science courses in materials-designated departments³⁻⁵ quickly reveals both similarities and differences. The similarities lie in the commonality of a good fraction of the subject matter. Where the physics text classifies topics more or less according the physical properties being studied and is pitched at a higher mathematical level, the materials text classifies topics according the type of materials being studied and typically contains more empirical data. In some cases, the two approaches arrive at the same categorization; in others, they are widely disparate.

An important distinction between the two types of course is clear in the pedagogical approach. The solid state physics course follows the usual cumulative approach common to most all physics courses. The main emphasis is on crystalline materials and the many important successful theoretical treatments of thermal, electronic, optical and magnetic properties of this class of materials, but especially how they all can be relatively well understood from first principles. Dislocations, diffusion and amorphous substances are treated as obvious "add-ons". This

approach is only natural for a field that cut its teeth on the spectacular success of semiconductor and metals physics over the last four decades.

On the other hand, a brief perusal of the currently available materials texts reveals a different emphasis. Materials are viewed from an applied perspective; e.g., the important property of steel or any structural alloy is mechanical strength, while for the glass used in fiber optics, it is the refractive index and the optical absorption that dictate the utility of the material. The needed physical (or chemical) principles underlying these properties and how the materials are produced and characterized are important, but are not the overriding feature of emphasis; rather it is the application and the possible enhancement of the properties to fill a practical need that is of utmost importance.

The upshot is that rather than trying to completely understand a simple model system, it is more appropriate in materials science to only partially understand a complex system that happens to have direct application. The latter contrast is also underscored in a greater emphasis on the empirical approach, and the need to characterize the system through empirical observations. For this reason, the instruments used for characterizing various properties of materials, especially on the microscopic level, are prominently featured. Thus, Scanning and Transmission Electron Microscopes, X-ray Diffraction, Atomic Probe Microscopes, and many other diagnostic techniques are regarded as tools

that the student should become familiar with. This requirement argues strongly for a laboratory/demonstration experience to be included as an important component of a materials science survey course. By contrast, the attachment of a laboratory to the typical undergraduate solid state physics course is a rare occurrence, although innovative laboratory-based materials courses have been described^{6,7} that focus on serving physics majors alone.

In this Department, we have also concluded that some acquaintance with the materials science approach is a valuable asset for the undergraduate physics major, both from a general knowledge standpoint and from a career standpoint. The inclusion of a survey course in materials science as a technical elective can be a valuable experience for those physics students who intend to pursue a career in applied physics.

An Integrated Course

At Bowling Green State University, there is no engineering division. The perceived need for a materials science curriculum originated from among the physics and chemistry faculty. The ability to provide a survey course in materials is by definition, beyond the capability of a single science department. Although we in physics feel competent to instruct on mechanical, electrical, magnetic and optical properties, we would be hard pressed to adequately cover such topics as polymer synthesis, tribology

and corrosion. In addition, the types of laboratory and demonstration apparatus that are necessary to provide the appropriate experience for the students are hardly ever contained in a single department. Although many physics faculties are amazingly versatile in their ability to tackle courses on a wide variety of topics, there is a limit to how far the renaissance ethic can be pushed. The decision to offer a materials curriculum here that would serve students from a variety of science departments was at least bi-disciplinary from the outset.

When the planners sat down and began to develop the details of such a curriculum, it was agreed that the first offering should be a yearlong survey-of-materials-science course. The original intention was to merrily follow along one of the standard materials science and engineering texts. The strong consensus that such a course must have a laboratory component led to a serious evaluation of the type and suitability of the available equipment. The only modern electron microscopes here are housed in the Biology Department. The only modern X-ray diffraction equipment is housed in the Geology Department, and the only metallurgical preparation and testing equipment is housed in the Technology Systems Department. The Physics & Astronomy Department houses all of the electrical, magnetic and optical equipment that would be used. One could almost immediately envision a veritable disciplinary Tower of Babel in trying to integrate the various "traditional"

departmental units into providing service for this single course. The task at hand was to develop a coherent course offering that utilizes the facilities of five departments and the expertise of the faculty from six of them.

Course Structure

The typical 15-week semester-long course was broken into segments or "modules", in which a given topic is taught by an instructor who is knowledgeable in the field. For example, the first course in the sequence is subdivided into the following modules: 1.) crystals-growth and analysis, 2.) dislocations, 3.) diffusion, 4.) elastic properties, 5.) phase diagrams and alloy metallurgy, 6.) ceramics, 7.) polymers, and 8.) corrosion. The second course consists of modules covering 1.) conductive materials, 2.) magnetic materials, 3.) semiconductors, 4.) superconductors, 5.) optical materials, 7.) surface science and 8.) tribology. The course is offered for three credit hours, and is arranged with two lecture/recitation hours and one 3-hour laboratory each week, for a total of 5 contact hours per week. Each module therefore is covered in a period of approximately 2 weeks. Use is made of a standard introductory materials science textbook⁴, although some of the assigned problems are sometimes augmented and expanded upon.

Logistics dictates that one person be placed in charge as the coordinator each semester. It is the coordinator's job to ensure that the

transition from one module to the next is a smooth one. It is his job to marshal test questions from the various module instructors to produce exams that are unified in format and coverage. It is his job to complete arrangements for the laboratory experiences by lining up adequate space and supplies. In addition, it has been our goal to offer a "field trip" to the students each term. This trip is typically a visit to some materials-based industry or laboratory in the local area. To date, we have visited a local semiconductor fabrication plant, a small "compact" steel mill, a tire manufacturing plant, a refractory ceramics plant, and a hazardous metal (Be) fabrication plant. It has been our experience that the industrial hosts are more than happy to lead a one or two hour tour of their facilities.

Laboratory sequence

The laboratory schedule for the first semester of the course is listed in Appendix I, along with a general description of the equipment and the exercise that the students perform, usually in pairs. In some cases the experience could be more correctly termed a participatory demonstration rather than a totally hands-on exercise. Even though this part of the course represents only one-third of the credits, our view is that it is the most important component of the whole. The pedagogical idea that is applied in designing the laboratory exercises is to emphasize characterization techniques. Thus, in the first semester, we begin with

visible and x-ray diffraction to introduce periodic crystal structures. The powder method is used to identify unknown substances. The Laue method of crystal orientation- confirmation is applied to single crystals that the students grow themselves in acrylic molds using gallium metal. This particular material is quite instructive for this purpose because it melts at just above room temperature, and can be readily supercooled if obtained in a sufficiently pure state. These several laboratory exercises are thus keyed to the lecture discussion of crystal structures and bonding.

The next general characterization topic is microscopy, beginning with the use of the optical microscope to observe and measure defect structures in a number of materials. Electron microscopy is covered next, with the scanning electron microscope (SEM) and the standard X-ray fluorescence spectroscopy attachment for elemental analysis. At this stage, the students are encouraged to bring in their own specimens for examination, an approach that is very popular. The transmission electron microscope (TEM) is demonstrated with an introduction to the various methods of sample preparation. The corresponding lecture segment covers vacancies, dislocations and diffusion.

The next group of characterization methods studied in the first semester are the standard suite of mechanical tests used for metals, including stress-strain measurements, hardness, and toughness indicators. These are carried over into the study of polymeric materials, where their

variation with changing composition is studied. At this point in the course, the lecture material emphasizes phase diagrams, elasticity and other measures of mechanical characterization. A final module on corrosion mechanisms in different types of materials is included to correlate with simple electrochemical experiments.

Appendix II summarizes the topics covered in the second semester of the course. The first materials synthesis technique studied is vacuum evaporation. A thin metal film is evaporated on a glass substrate, and the thickness is gauged using a piezoelectric thickness monitor. In the module on electrical properties, the resistance of the film is measured by means of the conventional four-terminal technique, and the thickness deduced by assuming the bulk value for the electrical resistivity of the material. A third measurement of the film thickness is carried out using the SEM or by means of optical interference. In either case, the student is faced with the problem of reconciling the three sets of measurements. A short module on superconductivity is next covered using high T_c superconductors for determination of the critical temperature and the critical current. These four laboratory exercises are undertaken while electrical resistance and other transport properties are treated in the lecture portion. An alternative would be to discuss thermoelectricity at this point and to have students perform an experiment with a thermocouple.

Magnetic materials are studied by starting with ferromagnets,

hysteresis, and examining the domain structure that they present. Various decoration methods are employed, including Ferrofluid[®] 8. This method allows the student to bring in his own samples (e.g. floppy or hard disks, recording tape) and examine them. The SEM/XAFS facility is used to study the elemental structure of a series of thin film ferromagnetic alloys and correlation of magnetic properties with composition deduced. The lecture covers magnetism and the application of magnetic materials at the same time.

Optical materials are studied beginning with basic infrared absorption and reflection properties on through electro-optics and non-linear optical properties and their applications. The essential material properties necessary for second harmonic generation, for instance, are compared among different materials. In the lecture portion, some basic optical principles are introduced and direct applications in electro-optics, optical data transmission, and non-linear optics are covered.

Finally, a brief introduction to surface science, mainly from the materials characterization standpoint is presented. As a simple applied example, some of the quite recent advances in tribology and the study of friction are covered. By using these laboratory experiences, the standard order of lecture topics as is usually covered in the materials science survey course can be presented in a way that enhances student interest.

Student Performance and Faculty Response

The above course has been offered in complete form at Bowling Green University for each of the last 5 years. It is coordinated through the Center for Materials Science. The enrollment has ranged from 4 to 13 per semester, with students in several science and technology major programs evincing an interest in materials science by taking it as an elective. The course typically entails two midterm examinations and a comprehensive final examination each semester. The students are required to submit standard formal laboratory reports on the experiments that they perform each week. In the case of demonstration experiences, no reports are submitted. A variation of the course is also offered to graduate students for graduate credit. To obtain graduate credit, students are required to submit a term paper detailing some aspect of the research on or applications of materials in the modern world. These reports require a demonstrated acquaintance with the literature in the field with appropriate references.

Although several physics majors have taken the course, the mathematical level is somewhat lower than what they would encounter in a typical upper level physics course in order to accommodate the varied mathematical backgrounds of students in other majors. As instructors we have learned to strike a compromise between mathematical rigor and a more descriptive approach. The students have discovered that in a sense

they also must change somewhat: physics and chemistry students adapt to more descriptive learning, and geology, biology and technology students adapt to more mathematical rigor. In at least two cases, the excellent experience that the course provides has prompted students to enroll in graduate-level materials science programs as they continue their formal education in pursuit of a materials-based career. In this sense, the integrated course has begun to fulfill the desire of the National Research Council.

The faculty involved in the course are still quite enthusiastic about their participation, even after 5 years of experience. At the present time, many of the module instructors are teaching the course as an overload, so there is clearly an enthusiastic sense of mission involved.

Conclusion

The maturation of materials science as a component of the curriculum for physical science students can only take place when it becomes a common offering even in those institutions where there is no engineering division. The experimental survey course that has been offered at Bowling Green State University has been successful by providing a yearlong technical elective course in materials science for science and technology majors. The course syllabus follows a fairly thorough survey of most all the areas of materials science, and can easily be adapted to fit

the curriculum of any four-year undergraduate institution provided that some basic apparatus is available. Our experience indicates that an essential component of the course is the laboratory/demonstration portion. The topics covered in the laboratory exercises can be quite flexible and adjusted to accommodate the local equipment complement. In the case where such equipment is not available, it is possible and highly advisable to utilize some of the materials science digital media resources^{9,10} that have become available in recent years, so that some connection with real-world experiments and processes can be made. Judging from our experience and student evaluations, it is the laboratory experience that attracts and involves the students in the course.

References

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4. *Materials Science and Engineering - an Introduction*, by William D. Callister, Jr. , 4th edition, (New York: Wiley, 1997).
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6. F. Millstein, P. W. Smith, Jr., *Materials science undergraduate course laboratory in which students perform original research*, Am. J. Phys.**43**, 793-798 (1975).
7. H. Jaeger, M. J. Pechan, D. K. Lottis, *Material physics: A new contemporary undergraduate laboratory*, Am. J. Phys. **66**, 724-730 (1998).
8. Ferrofluidics Corp., 40 Simon St., Nashua, NH 03061.
9. An excellent example is *Visualizations in Materials Science*, at North Carolina State University at <http://vims.ncsu.edu>

10. *Material Science-A Multimedia Approach*, by John C. Russ (Brooks-Cole, Boston, 1996);
<http://www.brookscole.com/engineering/ge/matsci.html>
11. Spectra Physics, 1335 Terra Bella Ave., Mountain View, CA 94043
12. Philips Analytical Inc., 12 Michigan Dr., Natick, MA 01760
13. Alfa Aesar, 30 Bond St., Ward Hill, MA 01835
14. Polaroid Corp., 784 Memorial Dr., Cambridge, MA 02139
15. Esselte Leitz GmbH & Co KG, Siemensstraße 64 · D-70469 Stuttgart, Germany
16. Leica Microsystems Inc., 2345 Waukegan Rd., Bannockburn, IL 60015
17. Nissei Sangyo America, Ltd., 755 Ravendale Dr., Mountain View, CA 94043
18. This company is not in the electron microscope business at this time.
For an alternative source see reference 17.
19. Tinius Olsen Testing Machine Co. Inc., Easton Road P.O. Box 429, Willow Grove, PA 19090
20. Pasco Scientific, 10101 Foothills Blvd., Roseville, CA 95747
21. Vernier Software & Technology, 13979 SW Millikan Way, OR 97005
22. This company is not in business any more. An alternative source is:
Flexbar Machine Corp., 250 Gibbs Rd., Islandia, NY 11722-2697
23. now Perkin Elmer Instruments, Inc., 801 S. Illinois Ave., Oak Ridge, TN 37831-0895

24. Varian Vacuum Technologies, 121 Hartwell Ave., Lexington, MA 02421
25. Sargent-Welch, P.O. Box 5229, Buffalo Grove, IL 60089
26. Inficon, Two Technology Place, East Syracuse, New York 13057
27. Keithley Instruments, Inc., 28775 Aurora Rd., Cleveland, OH 44139
28. Colorado Superconductor, Inc., P.O. Box 8223, Ft. Collins, CO 80526
29. This company is not in the microscope business at this time. For an alternate source, see reference 16.
30. Axiom Analytical, Inc., 17751 Sky Park Cir. Units A-C., Irvine, CA 92714

Appendix I

Week-by-week schedule of laboratory exercises-first semester

1. Optical diffraction using lasers

Equipment: Spectra Physics¹¹ model 155 He-Ne laser with TEM grids. Series of 2-D lattice types on 35 mm slide.

Student Activity: This exercise is intended to provide an introduction to crystal structures and the techniques for measuring them. Students determine grid spacing using its optical diffraction pattern. The wire diameter is obtained using this information along with the mesh size. Lattice symmetries are identified in reciprocal space from diffraction pattern through 2-D lattice samples.

2. X-ray diffraction

Equipment: Philips¹² model PW1830 X-ray system with model PN3550 diffractometer.

Student Activity: Students use diffraction pattern and Bragg's law to determine crystal structure of a cubic crystal and the lattice spacing. This exercise is repeated for several oxide materials and the number of atoms per unit cell determined. The atomic radius of the cation is determined using the unit cell spacing and the given atomic radius for oxygen.

3. Crystal growth and orientation

Equipment: In-house constructed 4-piece Plexiglas[®] molds (3 in by 4 in-plans available) are filled with supercooled ultrapure (7-9's +) gallium from Alfa Aesar¹³, Philips¹² model PW1830 X-ray system with Polaroid¹⁴ XR-7 Laue X-ray camera.

Student Activity: Students fill molds with supercooled metal and initiate growth with a seed crystal. Growth fronts are observed and measured. Crystals are X-rayed using Laue back-reflection method. Offset of crystal axis orientation from seeded direction is determined by students using Laue prints.

4. Optical microscopy examination of defect structures

Equipment: Leitz¹⁵ Pollux and Leica¹⁶ DMP/SP (polarizing) microscopes

Student Activity: Students examine etched and/or decorated samples of CaCO_3 , SiO_2 , Mg_2SiO_4 , and PbS and identify various defect structures. Sample crystallite aggregate images are provided and students use the linear intercept method to determine the average grain size.

5. SEM

Equipment: Hitachi¹⁷ model 2700 Scanning Electron Microscope with X-ray Fluorescence Spectroscopy attachment.

Student Activity: This is a demonstration of the operation and the uses of the SEM. Students bring in various samples of materials to examine under the SEM, either for morphology or elemental analysis. Some examples are: compact disk, magnetic stripe, magnetic tape, hologram on credit card, etc.

6. TEM

Equipment: Zeiss¹⁸ model S-10 Transmission Electron Microscope

Student Activity: This is a demonstration of the operation and the uses of the TEM. The importance of sample preparation is covered, including the microtome.

7. Crystal deformation and stress analysis

Equipment: Leitz¹⁵ Pollux and Leica¹⁶ DMP/SP polarizing microscopes, glass slide.

Student Activity: Students melt a quantity of *p-dichlorobenzene* (mothballs) on a microscope slide with a small "lever arm" inserted. As the lever is gently rotated, deformation takes place. Students record descriptions of the deformation features. Polarized light is used to examine the stress patterns in previously prepared samples and to plot the isochromatics that are observed. Results are compared to predictions of Griffith's theory of cracking.

8. Metals: elastic properties

Equipment: Tinius-Olsen¹⁹ model Super L universal tensile testing machine, steel test specimens.

Student Activity: Students observe tensile test run and use a plot of stress vs. elongation data to obtain: elastic modulus, yield stress (0.2%), ultimate tensile strength, percent elongation at fracture, and percent reduction in cross-section at fracture.

9. Elastic Properties

Equipment: Pasco²⁰ model 003-06268 photogate, Vernier²¹ ULI interface with micro-computer. Samples consist of 1/8 in diameter X 24 in long rods of: brass, steel, wood, glass, copper, aluminum, and Plexiglas[®].

Student Activity: Each rod is weighted by about 100 g in the center and then set into oscillation. The photogate is used to measure the frequency for about 100 swings. From the data, the students can obtain the elastic modulus for the variety of materials studied, and compare the values. A URL for this experiment is available at:

<http://feynman.bgsu.edu/physics/rm133/expt.1.22-youngs.mod./Expt.1.22-Main.html>

10. Metals: hardness testing

Equipment: Wilson Industries²² model 30VRPL, Rockwell Surface Hardness Testing Machine with steel alloy samples, including samples with spatial hardness variation.

Student Activity: Students examine hardness variation along the surface of a steel disk using the testing machine. Comparison of the hardness of various alloys is made.

11. Polymers

Equipment: Various readily available polymer materials (from plastic bags, plastic containers) with polymer type numbers imprinted on them, bungee cord, rubber band. Also requires a centimeter ruler, micrometer, small metal pail (with handle) and about 50 steel 1/4 in bolts.

Student Activity: Students cut a strip of one of the polymer materials (about 2 cm wide) and suspend it. The cup is attached at the other end. As bolts are added to the cup, the elongation of the strip is measured. Students plot the number of washers vs. elongation and can measure elastic modulus, elastic limit and observe plastic deformation region.

12. Corrosion-Polarization Curves

Equipment: Princeton Applied Research²³ potentiostat, potential cell, iron, stainless steel electrodes

Student Activity: Students measure the rest potential using the potentiostat in both cathodic and anodic directions to obtain polarization curve. Extrapolation is made to determine i_{corr} , and from this the rate of corrosion.

Appendix II

Week-by-week schedule of laboratory exercises-second semester

1. Vacuum Evaporation System–Introduction to Vacuum pumps and Gauges

Equipment: In-house-built vacuum evaporation system with Varian²⁴ model M-2 diffusion pump, water-cooled baffle, and Sargent-Welch²⁵ model 1402 backing pump. System includes Inficon²⁶ model XTM/2 film thickness monitor.

Student Activity: This exercise is a directed activity with students observing. Fundamentals of vacuum evaporation are reviewed along with an introduction to vacuum pumps and pressure gauges.

2. Thin Film Evaporation

Equipment: Same system as above. Resistance evaporation is carried out using stranded tungsten filament.

Student Activity: A glass slide coated with an aluminum film (100 to 400 Å) is prepared for each pair of students. The thickness indicated by the thickness monitor is recorded.

3. Film Resistance

Equipment: Keithley²⁷ model 177 DMM (2). In-house-built constant current source with adjustable output. Silver paint, #38 AWG insulated copper wire, and vernier calipers.

Student Activity: Students connect four copper leads to the previously prepared aluminum thin film using silver paint. A four-terminal dc measurement of the resistance of the film is made. The thickness of the film is calculated by measuring the width, probe distance, and by assuming a reasonable value for the resistivity of aluminum (size effects may become important).

4. SEM

Equipment: Scanning electron microscope as in week 5 of Appendix I.

Student Activity: Glass slides with aluminum films prepared previously are viewed edge-on (after fracture) with SEM to determine film thickness. All three film thickness measurements are compared in a final report.

5. Superconductivity

Equipment: High T_c superconductivity kits available from Colorado Superconductor, Inc²⁸. Keithley²⁷ model 177 DMM (2), in-house-built low-current power supply, Pasco²⁰ model SF-9584 low voltage (high-current) power supply, and liquid nitrogen.

Student Activity: Students determine critical temperature by measuring resistance using four-terminal dc method. Critical temperature is measured as a function of increasing the sample current to extrapolate to the critical current.

6. Hysteresis

Equipment: Oscilloscope and in-house-built non-ferrous transformer with accessible core to be filled by ferromagnetic material (a Rowland ring can also be used). Various ferromagnetic materials of hard and soft variety, such as steel wire, transformer iron, nails, etc.

Student Activity: Curves of secondary voltage vs. primary current are plotted for the various magnetic materials available. These quantities are proportional to B and H respectively. This exercise is used solely as a qualitative means of comparing ferromagnetic materials so that the student understands the categorization and the applications of magnetically hard and soft materials.

7. Domains

Equipment: Bausch and Lomb²⁹ binocular zoom microscope, Ferrofluid⁸, and various magnetic materials used in everyday life.

Student Activity: Students bring in various magnetic materials, such as floppy disks, audio tape, old credit cards, etc. These objects are painted with Ferrofluid⁸ to reveal magnetic domains when viewed under the microscope. Quantitative calculations of such things as bit density on the floppy disk are included.

8. Magnetic Thin Films

Equipment: Scanning electron microscope as in week 5 of Appendix I.

Student Activity: This exercise is a demonstration using the EXAFS elemental analysis capability of the SEM. A series of nickel-iron films of varying alloy concentration are examined and the composition deduced. The ferromagnetic properties are correlated with composition.

9. Reflection/Absorption-Infrared Properties

Equipment: Analect³⁰ model ATC-650 FTIR Spectrophotometer

Student Activity: The IR spectra of several materials, including mica, glass and crystalline substances including semiconductors are obtained. Students use the output to identify characteristic features of the spectra.

10. Optoelectronics

Equipment: Any relatively high-power He-Ne laser. Harmonic generation materials such as: KDP and lithium niobate.

Student Activity: This exercise is a demonstration of second harmonic generation using the above-listed crystalline materials. It relies specifically on a specialized in-house equipment complement. It is suggested that any other experiment using lasers (solid state or otherwise) could be offered that entails observing the effects on various materials.

11. Surface Science

Equipment: In-house built photoelectron microscope is used to demonstrate various real-time surface reaction morphologies, such as step formation. Magnetic domains can also be observed. This is a specialized piece of equipment and could be replaced with any other type of surface characterization equipment on hand, such as an Auger analyzer, etc.

12. Tribology

Equipment: Adjustable incline with slider cart. Both surfaces can be interchanged to aluminum, wood and Plexiglas[®]. Three glass tubes (5 cm diameter X 1 m long), ball bearings of assorted diameter, motor oil, glycerol, shampoo, micrometer, balance, and graduated cylinder.

Student Activity: Students determine terminal velocity of ball bearings in different fluids and use Stokes' law to calculate the liquid viscosity. The coefficient of static friction for the three combinations of dry surfaces are measured.