A Senior Level Polymer Electronics Course: Unique Instruction or Just Low Cost?

David Braun, California Polytechnic State University, San Luis Obispo

Abstract

After progressing from research laboratories to factories to the market, semiconducting polymers now appear in commercial products and offer educational opportunities. Semiconducting polymers are excellent materials with which to teach semiconductor device fabrication principles, device testing, optical and electronic properties, polymer synthesis, polymer film preparation, and structure-property relationships. Previous publications have emphasized multidisciplinary course modules based on semiconducting polymers.[1] This work emphasizes how the use of semiconducting polymers in an undergraduate polymer electronics course benefits electrical engineering and computer engineering students.

Introduction

This article reasons that semiconducting polymers improve student learning by making normally obscure semiconductor concepts more tangible in a relatively inexpensive laboratory environment. We describe primarily experiences resulting from teaching Cal Poly's Polymer Electronics Lab course (EE 422) since 2000. Course modules cover the sequence of operations and analysis required to fabricate and test light-emitting diodes (LEDs) based on semiconducting polymers.[2] As a result of building and testing the polymer LEDs, students gain hands-on experience with core concepts in semiconductor devices and opto-electronic device characterization.

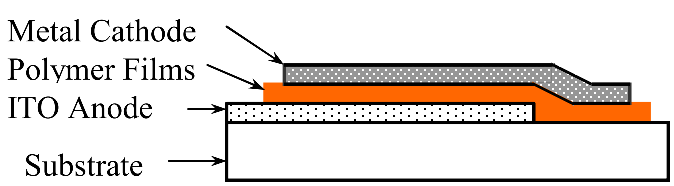

Figure 1 – Polymer LED Geometry

A polymer LED consists essentially of a plastic sandwich. Figure 1 illustrates the device geometry. Applying a positive voltage to the anode relative to the cathode causes current to flow through the polymer film and light emission from the polymer film through the transparent bottom electrode and substrate. Since this article does not provide a complete introduction to polymer LEDs, an interested reader might wish to consult a wide body of polymer LED literature that exists.[1,3] The polymer LED represents a relatively simple vehicle with which to achieve several learning objectives.

Learning Objectives

The Polymer Electronics Lab course aims to achieve the following learning objectives.[4]

1. Apply knowledge of solid state device fabrication and characterization to build and analyze the performance of a solid state device based on a semiconducting polymer.
2. Gain practice with the mental dexterity necessary to operate complex laboratory equipment successfully and the manual dexterity necessary to manipulate fragile samples precisely.
3. Perform the following laboratory procedures:
    - Substrate Preparation Techniques
    - Polymer Film Preparation
    - Vacuum Evaporation
    - Device Characterization
4. Exercise cognitive skills in order to complete each procedure correctly and produce a working device.
5. Apply factual information and problem solving skills obtained from previous math, science and engineering courses to perform each procedure.
6. Successfully operate the unique technology in the lab by functioning cooperatively in respectful, thoughtful, and knowledgeable teams.
7. Practice excellent oral and written communication skills.

Consider the above learning objectives in more detail. The key aim of the course (objective 1) could apply to several different devices based on semiconducting polymers, including LEDs, transistors, and solar cells, all devices undergoing various stages of research and development as they mature toward commercial applications. We prefer to use the polymer LED in class, because it is an optoelectronic device that combines electronic and optical features, because it is the most established technically and because it does not require fine patterning. With appropriate adjustments to the course, instructors could use polymer solar cells or transistors, instead. Using the semiconducting polymers provides the additional benefit relative to inorganic LEDs of not requiring relatively expensive and more complex fabrication techniques such as molecular beam epitaxy or chemical vapor deposition.

The course is a laboratory course that provides students with practical fabrication experiences (objective 2). The decision to offer the course as a stand-alone laboratory course with no significant lecture component stems from two considerations. First, such a laboratory course is intrinsically compatible with Cal Poly's "Learn By Doing" philosophy. The course places a greater emphasis on device fabrication, characterization, and documentation than on analysis and theory. The process of manipulating fragile glass substrates with thin polymer and metal films through the appropriate laboratory equipment places a strong emphasis on performance and psychomotor outcomes.[5] The lack of lecture sessions significantly decreases the course's theoretical emphasis. One lecture session on the first day of class and mini-lectures and discussions during subsequent lab sessions provide sufficient support for the laboratory activities, but only contain essential supporting theoretical concepts. Second, offering the course as a one-unit class that meets for one three-hour lab session each week of a ten week quarter makes the course more appealing to some students. A tension exists as more units compress into the undergraduate curriculum, and this one unit course is a relatively small investment of time for students who feel pressured by having to take many units of coursework. Students who the course excites to further study may proceed to a full microelectronics fabrication experience. Other students may receive a meaningful introduction with less time investment on their part compared to a more extensive integrated circuits fabrication course.

Figure 2 – Polymer Electronics Laboratory

1) Prepare pre-patterned ITO coated glass substrate in dust-free work area under the HEPA filter unit.
2) Spin coat polymer anode, if desired, then transfer substrate into nitrogen glove box.
3) Spin-coat electroluminescent polymer film from solution.
4) Transfer coated substrate into nitrogen glove box with low oxygen and moisture content.
5) Deposit top calcium metal electrodes in vacuum evaporator using a shadow mask to define pixels.
6) Characterize performance of polymer LED pixels by measuring current, brightness, and efficiency as a function of bias voltage.

Objectives 3, 4 and 5 capture the bulk of the course content as measured by time on task as the students complete each step involved in fabricating a substrate with several polymer LED pixels. In successive lab sessions, each student builds the device pictured in Figure 1 from bottom to top. Figure 2 illustrates where each step in the fabrication sequence takes place in the Polymer Electronics Lab. Samples proceed from the front right to the left rear of the fabrication and test facility. Several steps in the fabrication process occur inside nitrogen gloveboxes. Working in the inert atmosphere gloveboxes serves at least three purposes:

1) The inert atmosphere reduces corrosion of the reactive calcium cathode,
2) Filtering dust out of the inert gas maintains a relatively dust free volume that avoids the need for a full cleanroom, and
3) Performing procedures inside the glovebox, behind lexan windows using 15 mil rubber gloves provides a rigorous degree of safety protection for the students for the steps that involve organic solvents or metal evaporation in the vacuum system.

The lab web site provides more information about semiconducting polymers, lab projects, course modules and the course lab manual.[2]

Objective 6 expresses the desire that the course could teach teamwork skills. Unfortunately, recent implementations of the course haven't quite addressed this goal successfully. Certainly, the students work in groups as they complete various lab procedures. However, instructors have not taught students to organize their teams or perform specific roles in their team. Reflecting the intrinsically interdisciplinary nature of the field of semiconducting polymers, students from the majors of chemistry, physics, materials science, computer engineering and electrical engineering have taken the Polymer Electronics Lab course in the last few years. Students from the different majors do gain the opportunity to interact, discuss, and learn from each other during the lab.

The course does emphasize the communication skills both written and oral (objective 7) required when people work in a technically advanced workspace that requires well coordinated actions among participants. The physical and scheduling constraints imposed by a three workstation glove box layout necessitate clear communication among students to complete lab sessions in a harmonious manner that results in well performing polymer LEDs and no harm to delicate lab equipment.

Discussion

During EE 422, the Polymer Electronics Laboratory course, students apply their knowledge of solid state device fabrication and characterization to build and analyze the performance of a solid state device based on a semiconducting polymer. Students interested in semiconductor electronics learn how to characterize semiconductor devices such as diodes and transistors. In theory, the students should also learn how these devices operate internally. Such comprehension is crucial for later course-work, but the concepts are relatively sophisticated. Consider an inorganic light-emitting diode. It is possible to observe under a microscope that tiny wires connect to a semiconductor crystal and that light emerges from the crystal. Nevertheless, the process may remain somewhat mysterious, for at least two reasons above and beyond the semiconductor device physics. First, the fabrication of an inorganic light-emitting diode requires sophisticated and expensive fabrication techniques such as molecular beam epitaxy (MBE) and chemical vapor deposition (CVD), which few undergraduates have access to. Second, the components of most inorganic LED devices have microscopic dimensions, with entire devices occupying less than one cubic millimeter, excluding packaging and lenses. Semiconducting polymers enable students to make and test devices large enough to be visible to the naked eye and do so using the simple and inexpensive fabrication techniques outlined in the previous section.

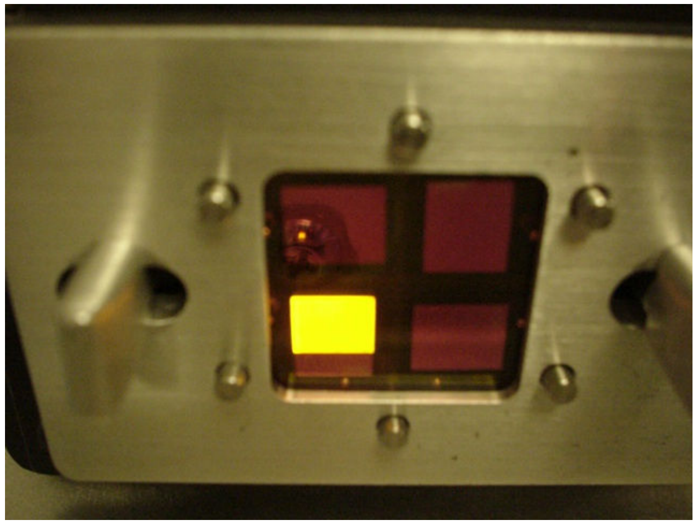

Figure 3 – Polymer LEDs in Test Jig[2]

After completing the fabrication process, the student can operate the device by applying a voltage between the electrodes and observe light emission. Figure 3 is a photograph of a polymer LED substrate with four pixels loaded in the test jig, with the lower left LED under test and emitting light. The picture is approximately to scale. Interesting thought processes begin with the realization that the device emits light when positive and negative charge carriers recombine in the conducting polymer. Students gain a vivid illustration of charge injection into a semiconductor, charge transport, and the process of light emission from a semiconductor. Measuring the electrical characteristics and intensity of light emitted by various devices can spark a variety of creative experiments and lead to refinements in the above model.

Depending on students' personal interests, the instructor can include discussions of polymer chemistry, engineering design, semiconductor physics, and/or materials science. Questions typically arise during the course as students observe the polymer material make transitions from chunks of solid sitting in a jar to a material dissolved in a liquid to a thin solid film that operates as the active semiconductor in a LED. Throughout this sequence, the polymer retains its semiconducting properties. For sufficiently motivated students who are unsatisfied with simplified energy band diagrams, the available research and patent literature on semiconducting polymers provides some answers and more questions. At least 10 of the 60 students who have taken the course since 2000 have completed senior projects that grew out of their experience in the Polymer Electronics Lab course. Senior project topics include materials experiments in polymer LEDs and solar cells, optimization of device fabrication, and automated device testing.

Conclusion

The Polymer electronics permits device fabrication, while requiring less infrastructure than a fully equipped cleanroom. In fact, dramatically less expensive options exist than those used in the laboratory described above.[6] This work describes an educational approach intermediate between a tabletop LED construction project and a complete multiple mask integrated circuit fabrication sequence. The simpler approach[6] suffices to demonstrate physics, chemistry, and materials' properties. The present approach allows students to gain hands-on experience with integrated circuit fabrication techniques and process equipment. Use of the relatively low volume dust free work spaces and gloveboxes in the lab provides some economic savings relative to a cleanroom facility. Not including the initial cost of the empty room provided by the university to house the lab, laboratory construction, equipment, and materials cost less than $250,000. In spite of its relatively low cost, the resulting facility contains several key fabrication features of factories used to produce organic electroluminescent (OLED) displays on a large volume. The EE 422 Polymer Electronics Lab course operates at an intermediate scale in terms of the time required of students, the cost of the facilities, and the procedural complexity. The course provides students with access to learning objectives and activities typical of integrated circuit fabrication as well as the unique features of semiconducting polymers.

Acknowledgements

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David Braun is a Professor in the Electrical Engineering Department at Cal Poly in San Luis Obispo. He worked at Philips Research Labs in Eindhoven, the Netherlands from 1992 to 1996, after completing the Ph.D. in Electrical Engineering at U.C. Santa Barbara. Please see **www.ee.calpoly.edu/~dbraun/** for information about his courses, teaching interests, and research.