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Laboratory Teaching Modules on Organic Electronics and Liquid Crystal Displays for Undergraduate and Graduate Education

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ABSTRACT

We have developed of a sequence of laboratory teaching modules that offer hands-on experience with organic semiconductor devices and liquid crystal display technologies**.** This paper provides an overview of four such modules: a single-pixel liquid crystal display (LCD), a polymer light-emitting diode (pLED), an organic photovoltaic (OPV) solar cell, and a polymer field-effect transistor (pFET, aka organic thin-film transistor, OTFT). Through these modules, we aim to expand on traditional semiconductor device education to address key concepts pertinent to organic devices, including thin-film fabrication methods, electrical/optical characterization, charge injection/transport in organic materials, self-assembly, light emission/ absorption/polarization, and basic molecular orbitals energy concepts. A comprehensive set of laboratory procedures has been prepared and the entire project has been designed with a low-cost approach so as to be implemented by virtually any university or similar institution. All lab modules and set-up instructions are available at: http://www.ece.ncsu.edu/oleg/wiki/NSF_Lab_Modules.

INTRODUCTION

"Soft" organic materials are at the leading edge of current research and comprise the core technology of an increasing number of commercially available consumer products including displays, lighting, flexible electronics, and renewable energy devices [1,2]. These are arguably some of the most compelling topics for advanced electrical engineering (EE) students, and their fabrication—in comparison to more traditional inorganic solid-state devices—is simpler, cheaper, and faster. However, precious little comprehensive instruction exists at the undergraduate and graduate levels that provides the opportunity for hands-on learning in soft matter physics and devices in the teaching laboratory context. It is our aim to seize this educational opportunity by creating coherent instructional materials that offer the experience of building and characterizing soft electronic devices with minimal investment of time and capital.

Our slate of laboratory modules includes the following: a single-pixel liquid crystal display (LCD), a polymer light-emitting diode (pLED), an organic photovoltaic (OPV) solar cell, and a polymer field-effect transistor (pFET, aka organic thin-film transistor, OTFT). Within the modules, we have devised a method of layering cathodes without vacuum deposition and have developed procedures and infrastructure that ensures both safety and function without requiring dedicated environmental chambers. What follows is an overview of each module's fabrication process, the academic value of each as a stand-alone experiment, and their educational contribution to a companion undergraduate course. Finally, we provide our analysis of the modules' effectiveness, including actual student feedback.

DISCUSSION : LAB MODULE OVERVIEWS

Module One: LCD Pixel

Liquid crystal (LC) devices are ubiquitous in modern times [3]. Large, flat-screen televisions and computer monitors are becoming household staples and it is de rigueur to carry compact, high-resolution, do-it-all mobile gadgets. Understanding the science behind these devices provides useful technical insight into our ever-advancing world. In order to highlight the fundamental principles of operation relevant to these applications, our first lab module directs the student to fabricate his or her own single-pixel liquid crystal display.

Liquid crystal materials are mesophases that constitute a genuine state of matter whose molecular properties share characteristics of both crystals and ordinary liquids. Like crystalline solids, liquid crystals have anisotropic physical properties, i.e. they exhibit orientational order and limited positional order. Such “partial order” is seldom taught in an (EE) curriculum heavy with inorganic solid-state physics. Additionally, this module introduces the student to the various flavors of partial order, basic liquid crystal chemistry, polarization of light and polarizers, optical transmittance principles, and the twisted nematic LCD mode [3].

In addition to fabricating a single-pixel LCD, this lab enables the student to explain how a particular liquid crystal would respond to an applied electric field, calculate and measure the transmittance of polarized and unpolarized light through a polarizer, calculate and measure the threshold voltage of a particular LCD, and employ a spectrometer and photodetector for photonic characterization.

Partial order is not limited to liquid crystal materials. Figure 1(a) is an image of kayak racers jammed into a river exhibiting some degree of orientational order. A cross section of the device to be constructed is presented in Figure 1(b), the chemical structure of a common liquid crystal material (5CB) is shown in Figure 1(c), and an example of the transmittance vs. voltage data taken by the students from an LCD pixel is Figure 1(d).

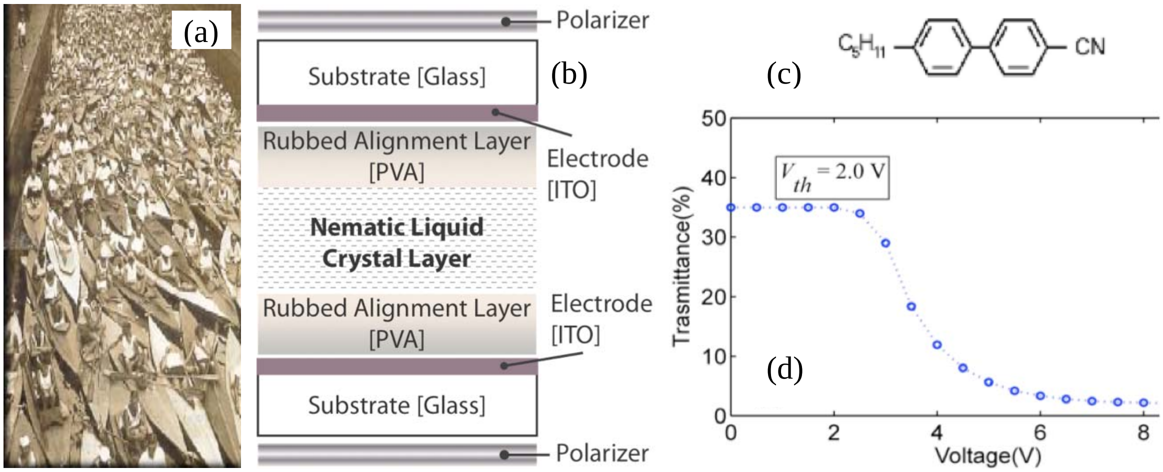

Figure 1. (a) Kayaks on a river displaying partial order [source unknown]; (b) LCD pixel cross-section; (c) Chemical structure of a common liquid crystal molecule, 5CB; (d) Transmittance of an LCD pixel as a function of applied voltage, where threshold voltage is 2.0 V.

Module Two: Polymer LED

Polymer light-emitting diodes (pLED) fall into the general category of organic LEDs, or OLEDs. Early devices were very inefficient, yielding only a few percent external quantum efficiency. Improvements in OLED technology and discovery of better materials in the past two decades have seen this efficiency rise to rival both incandescent lamps and inorganic LEDs [4]. Much excitement has surrounded OLEDs as of late due to several cutting-edge applications such as flexible displays, roll-to-roll processing, and inexpensive lighting. It would certainly behoove the up-and-coming electrical engineer to be familiar with the science of OLEDs. Unfortunately, the typical EE curriculum is heavy on inorganic devices and light on soft electronics.

In module two, the student is exposed to polymer science, photonics, and electro-optics [5]. Additionally, the student will come away from the lab with several new skills including identification of electroluminescence and photoluminescence spectra, knowledge of lifetime and why it is a crucial parameter in soft electronics, and being able to measure such photonic parameters as radiance and luminance. As was the case in module one, the student will also learn new techniques such as properly using optical power meters and applying optical adhesive.

The primary portion of this module is the fabrication of a pLED as shown in Figure 2(a). In the course of construction, the student will spin-cast two polymer layers: poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS), the hole transport layer, and poly[2-methoxy-5-(2'-ethyl-hexyloxy)—1,4-phenylene vinylene] (MEH-PPV), the light-emitting layer, onto glass coated with indium tin oxide (ITO). The polymer structures are drawn in Figure 2(b). Operation (Figure 2(c)) occurs as follows: when a threshold voltage is applied, the PEDOT:PSS layer eases hole injection from the anode to the light-emitting MEH-PPV layer and the cathode (gallium-indium (GaIn) eutectic) supplies electrons. Recombination occurs and light is emitted in the red-orange region as seen in the electroluminescence curve of Figure 2(d).

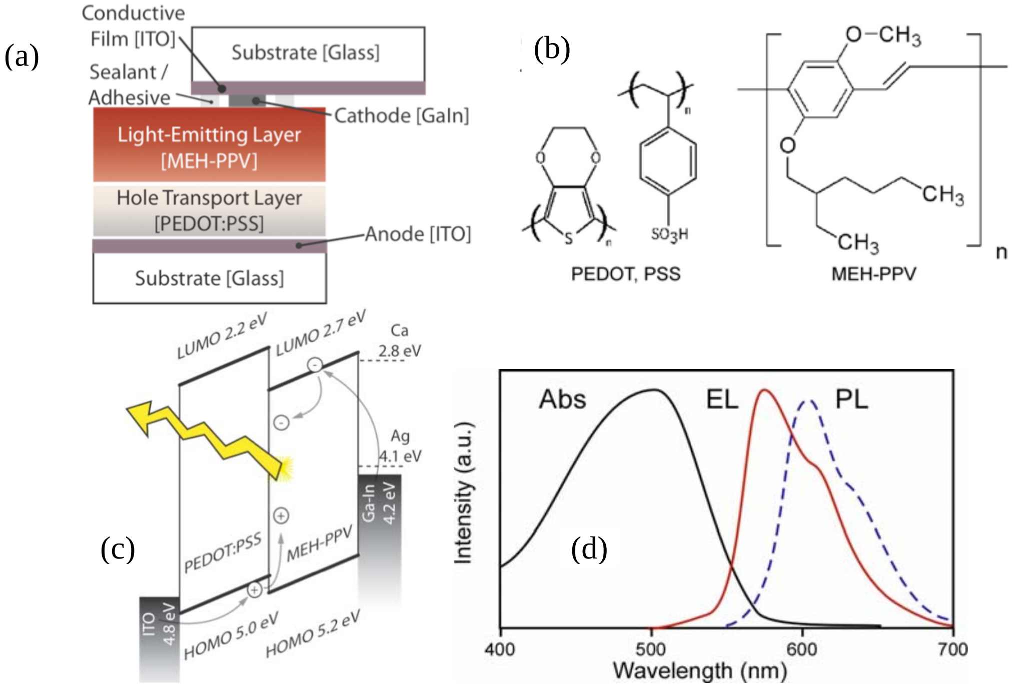

Figure 2. (a) pLED cross-section; (b) Chemical structures of PEDOT:PSS and MEH-PPV; (c) Energy band diagram showing basic pLED device operation; (d) Spectra of MEH-PPV—Absorption (Abs), Electroluminescence (EL), and Photoluminescence (PL).

Module Three: Organic Photovoltaic Solar Cell

With significant annual growth over the past five years, solar cells (inorganic, and increasingly those of the organic variety) are becoming one of the strongest contenders for cheap, scalable, and efficient renewable energies [6]. Current OPV technologies include flexible substrates, continuous printing processes, and easy integration into other commercial devices. Competition, however, is strong among technologies looking to take a big share in the renewable energies market making this an ideal time for students to be jumping into the game.

In this module, the student is exposed to electrical engineering concepts with which they are likely familiar including power generation and charge transport [7]. However, due to the difficulty and expense in fabricating inorganic materials, these same students may have only been given examples in a book from which to learn these concepts. This module affords an opportunity to fabricate a working solar cell and to physically measure its power density and efficiencies all while learning more about polymer science and photonics.

The cross-section of the OPV in question is presented in Figure 3(a). Fabrication will include spin-casting a PEDOT:PSS layer onto an ITO-coated glass substrate and spin-casting a layer containing both the conjugated polymer poly[2-methoxy-5-(3',7'-dimethyloctyloxy)-p-phenylene vinylene] (MDMO-PPV) and methano[60]fullerene [6,6]-phenyl C_{61} butyric acid methyl ester (PCBM), a fullerene-based polymer, as the photon-absorbing layer. The chemical structures of MDMO-PPV and PCBM may be found in Figure 3(b). The operation of the OPV cell is explained in the form of an energy band diagram in Figure 3(c) and an example of the data measured by the students—a power density curve—is presented in Figure 3(d).

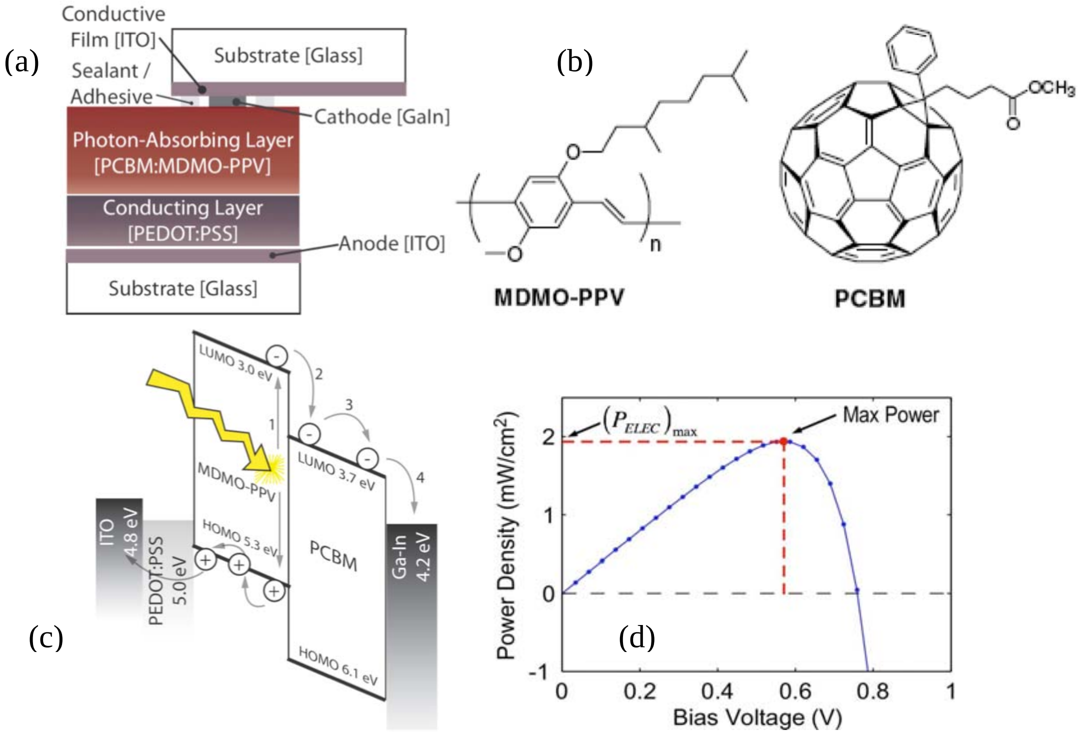

Figure 3. (a) OPV cross-section; (b) Chemical structures of MDMO-PPV and PCBM; (c) Energy band diagram showing bi-layer OPV device operation: (1) optical excitation, (2) exciton relaxation, (3) exciton dissociation by charge transfer, (4) charge collection; (d) Output power density data for an OPV device.

Module Four: Organic Thin Film Transistor

In the past decade, organic thin-film transistor (OTFT) research has seen a surge due to a rising consumer demand for smaller, cheaper, and more portable electronics [8]. Applications such as electronic-paper, flexible displays, and large-area transistor printing have promised to meet such demands. The first OTFTs could not match the mobility of inorganic thin film transistors produced from amorphous silicon. In a span of fewer than fifteen years, however, discovery of better materials and device structures have brought OTFT devices into direct competition with their inorganic brethren [4]. With consumers unlikely to request bulkier or less portable electronic devices anytime soon, this is a perfect time for resourceful engineers to be familiar with OTFTs.

In this module, the student is again exposed to more familiar EE concepts such as transistor device physics, charge transport, and carrier mobility. Like the previous modules, however, new ideas will be presented including polymer science and the operation of organic transistor devices—decidedly different from that of the traditional solid-state. Unlike a metal-insulator-semiconductor field-effect transistor (MISFET), an OTFT does not contain p-n junctions or even a bulk region. This will require introducing the student to charge injection and its important role in OTFT operation.

The cross-section of the OTFT is presented in Figure 4(a). New to the student will likely be the concept of interdigitated source and drain electrodes, a pattern of which is shown in Figure 4(b). Such a pattern will be photolithographically etched onto ITO-coated glass substrates. Onto these the student will spin-cast the organic semiconductor regioregular poly(3-hexylthiophene) (P3HT), whose chemical structure is drawn in Figure 4(c), followed by a polymer insulator, polyvinyl alcohol (PVA). Finally, a gate structure consisting of GaIn, optical adhesive, and ITO-coated glass will be sealed onto the top of the structure, finalizing the three-terminal device. The student will characterize the device by monitoring the drain current while modulating gate voltage, effectively measuring current-voltage data as in inorganic devices.

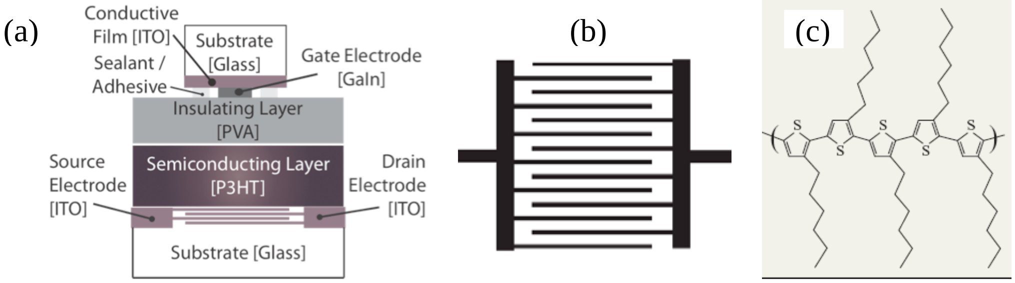

Figure 4. (a) OTFT cross-section; (b) Interdigitated pattern etched into ITO-coated glass for source and drain electrodes; (c) Chemical structure of P3HT.

CONCLUSIONS

Our goal with this project has been to develop a series of laboratory modules that give hands-on experience with organic electronic materials and LCD technology, i.e. soft electronics. The modules have been developed in a fashion that allows them to stand alone on their academic merit or to accompany a one-semester course on soft electronics. In either case, the target students are advanced undergraduates (and graduates) within EE, materials science, or physics.

On the whole, the objectives of these modules include the following: learning fundamental knowledge of electrons, photons, transport, and fluorescence; gaining hands-on knowledge of device behavior, fabrication techniques, and characterization skills; and finding inspiration to conduct research in a graduate school or industrial setting.

An additional aim of this project was for the entire set of laboratory modules to be implemented at a cost accessible by practically any institution. In addition to finding all lab documents freely available online (given in Abstract), interested parties will find a bill of materials for preparing their own soft electronics laboratory. The total capital investment is less than US$9000 for those willing to find a few surplus or discounted parts.

While success can be difficult to measure, especially among students, we have found from direct feedback that the slate of modules is a valuable learning aid. Table I highlights responses by students to a recent anonymous survey. Overall, the response has been tremendous and the students convey very positive experiences. A survey of a companion soft electronics course included the following comment: "The labs made the course very valuable, and probably one of my favorite courses in my seven years of taking [EE] courses. Actually building these devices imparts knowledge and understanding that can only be gained by hands on activities."

Table I. Responses to an anonymous survey of 27 students regarding the lab modules.

Prompt	**Composite Score** (0 – 5)
Lab sessions contributed to mastery of course concepts	4.73
Lab facilities, equipment, supplies, etc. where adequate	4.69
The degree of lab difficulty was appropriate	4.66
Overall, the labs were effective learning experiences	4.70

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