Simple assembling of organic light-emitting diodes for teaching purposes in undergraduate labs

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Electroluminescent organic molecules and polymers have emerged as advanced materials used to fabricate organic light-emitting diodes (OLEDs) whose unique technological features could revolutionize the industry of flat-panel displays. Although in many cases these novel organic materials combine low cost and ease of processing, OLEDs fabrication for educational purposes has rarely been reported. In this work, we report a simple and inexpensive method to fabricate organic electroluminescent devices intended for educational purposes at the undergraduate level of physics, chemistry and material sciences. For ease of fabrication the cathode in the diode structure was formed by either an alloy of Bi-Pb-Cd-Sn or by a Ga-In alloy in the liquid phase, or simply by silver paint, whereas we used ITO (Indium Tin Oxide) deposited on glass substrates as the anode. Substrates of flexible plastic were also used. The OLEDs were fabricated using the spin-coating technique with solutions of the fluorescent materials Alq_3 and MEH:PPV, as well as the phosphor complex $Ru(bpy)_3$. We report measurement data on current-voltage curves, luminescence, and efficiencies obtained by students fabricating and testing the devices under normal room conditions.

Keywords: OLED; organic materials; education.

Recientemente los polímeros y moléculas orgánicas electroluminescentes han surgido como una nueva generación de materiales avanzados que tienen un gran potencial tecnológico; muestra de ello es el desarrollo de OLEDs (diodos orgánicos emisores de luz, por sus siglas en inglés) que podrían revolucionar la industria de pantallas planas (flat-panel displays). Aunque estos nuevos materiales son de bajo costo y fácil procesamiento, su potencial como herramientas de enseñanza ha sido poco aprovechado y por tanto existen pocos reportes al respecto en la literatura. En este trabajo presentamos un método económico para fabricar y caracterizar diodos orgánicos emisores de luz bajo la perspectiva de la enseñanza a niveles universitarios en áreas de la física, química o ciencia de materiales. Para una fabricación sencilla usamos como cátodos las aleaciones de Bi-Pb-Cd-Sn y Ga-In, esta última en forma líquida; de manera similar, usamos pintura de plata para tal propósito, en tanto que como ánodo se utilizó ITO (oxido de estaño indio) depositado sobre sustratos de vidrio. Sustratos flexibles de plástico fueron también utilizados. Los OLEDs se fabricaron empleando la técnica de deposición por centrifugación a partir de soluciones de las moléculas fluorescentes Alq_3 y MEH:PPV, así como del material fosforescente complejo de $Ru(bpy)_3$. Se reportan datos de luminiscencia, curvas de corriente-voltaje y cálculos de eficiencia obtenidos por estudiantes que fabricaron y caracterizaron estos dispositivos bajo condiciones normales de presión, temperatura y humedad.

Descriptores: OLED; materiales orgánicos; enseñanza y educación.

PACS: 78.60.Fi; 42.70.Jk; 01.40.-d; 01.50.Pa

1. Introduction

Electroluminescence (EL) is the physical process by which electricity is directly converted to light using non-incandescent materials. This phenomenon, first discovered in the early 20th century [1], is behind the operation of light-emitting diodes (LEDs), which are found in applications such as: on/off indicators in all sorts of electronic equipment, remote controls for TV's/DVD's, flashlights, traffic lights, toys, alphanumeric displays, image displays, and so on. To date, the spreading use of LED technology in our daily life is based on the construction of devices utilizing exclusively inorganic semiconductors. Very recently, however, a new generation of EL semiconductors, namely, organic semiconductors (small organic molecules and polymers), has been developed to assemble organic light-emitting diodes (OLEDs) (for reviews on the history and development of OLEDs see Ref. 2 to 5). During the last decade or so these novel materials have been studied intensively by many research groups, in both academia and industry, owing to their promising applications in flat-panel displays which could in the near future replace image displays made of inorganic LEDs, cathode ray tubes and liquid crystal displays. The advantages of OLEDs for display applications are: brighter colors and higher contrast, lower cost, wider viewing angles (based on their Lambertian emission), lower power consumption and mechanical flexibility (exceptional applications such as flexible displays that could be rolled up are possible).

OLED devices are still an emerging technology but one that is quickly reaching maturity. For instance, the state-of-the-art is such that OLEDs have typical turn-on voltages between 3 and 5 V and produce luminance values $\gg 100$ candelas per square meter (the luminance generated by a computer screen) driven by current densities in the mA/cm^2 range [5]. In regard to efficiency, the organic devices can easily reach between 25 and 100% of internal quantum efficiency (defined as the ratio of the number of emitted light quanta to the number of injected carriers), while for external quantum efficiency (the ratio of the number of light quanta coupled out of the device to the number of injected carriers) typical values between 5 and 15% are observed [2]. It is worth mentioning that these values for the device operation are ideal for passive as well as active display applications; consequently, leader companies in the industry of display technology project a mass production of full-color OLED displays [6].

Organic semiconductors have the property of being, in many cases, low-cost, easy-to-process materials so that their use is ideal for educational purposes. Despite this, however, few reports exist with this orientation; for instance, the fabrication of organic electrochromic devices [7], hybrid (organic-inorganic) solar cells[8,9] and photorefractive-based polymer holograms has been reported [10]. OLEDs fabrication has also been reported by Sevian *et al.* where a simple recipe of fabrication was provided, but its actual potential was not fully described since the characterization of their devices was not performed [11]. Motivated by this, we present here a simple fabrication method and complete characterization of OLEDs. For the sake of illustration, we report on OLEDs assembled with different kinds of organic EL materials and by using different cathodes, such as woods metal (Bi-Pb-Cd-Sn), Ga-In alloy or silver paint, which, in addition to their easy processability, reduce the cost of the devices thus making them more affordable for undergraduate labs. The approach we followed is so versatile that we have adapted it from experiments performed by students during two or three laboratory classes for basic OLED preparation and characterization which consist in the turn-on of devices and acquisition of current-voltage curves, or during one-month summer internships which include more complex sample characterization, *i.e.*, calculation of photometric quantities and determination of quantum efficiency and luminous efficiency. In this way, undergraduate students learn or review various topics such as the EL effect, basics of organic semiconductors, exciton formation and radiative decay, concepts of radiometry and photometry and thin-film preparation, to mention only a few, and at the same time learn about the current research on material science and its technological implications. The data presented are the result of the experimental experience of physics students working from this teaching perspective. Nevertheless, as this topic includes many aspects of chemistry and material science, it can be conveniently adapted for students with that background, placing special emphasis on chemical synthesis and material processing.

2. Basic Theory of OLEDs

The process of EL in OLEDs is based on the injection of holes and electrons from electrodes into organic layers, after which they recombine to form excitons that radiatively decay to produce light. The OLED structure used in the present work consisted of four layers: two organic layers and two electrode layers (the anode and cathode, respectively). The OLED structure and the EL process are depicted in Fig. 1. The hole injector layer (HIL) is an organic film that performs the function of assisting the injection of holes from the anode and transporting them to the boundaries between the two organic layers. The emissive layer (EML) is another organic film where electrons are injected from the metal cathode and are transported through in order to recombine with holes on the interface of the two organic layers. The charge injection and transport into these layers takes place according to the energy levels depicted in Fig. 1b. As charge injection is a limiting factor in determining the luminance and operating voltage in OLEDs, it follows from this figure that low work function and high work function materials are preferred for cathode and anode, respectively. This can be seen from the fact that, by reducing the injection barriers in the electrode-organic material interfaces, the charges can be injected effortlessly through thermionic injection, thus reducing the device working voltage. In more detail, we can describe the electronic structure of the emissive layer using the ionization potential (*Ip*) and the electron affinity (*A*). *Ip* and *A* are related to the charge injection phenomena since for electrons the injection barrier is given by *Wc-A*, and for holes by *Ip-Wa*, where *Wa* and *Wc* are the work functions of anode and cathode, respectively. Note that in the EML, the electron and the hole-conducting levels will be typically between 2-3 eV and 5-6 eV below the vacuum level, respectively, corresponding to the electron affinity and the ionization potential of the material. On the other hand, organic electroluminescent emission is required to be in the visible range with photon energies 3 eV. For EL organic molecules, the energy of the photon emitted is a function of the energy difference between the electron and hole-conducting levels, or in terms of organic semiconductor theory, between the highest occupied molecular orbital (HOMO) and the lowest unoccupied molecular orbital (LUMO) levels (HOMO and LUMO levels are analogous to valence and conduction bands in an inorganic semiconductor, and these levels correlate with *Ip* and *A*, respectively). In this way, the emission color can be tuned over a wide range by an appropriate choice of organic materials, either a small conjugated molecule or a polymer.

After electrons and holes are injected into the organic material, they are transported within it by an electric field. This charge transport is another important factor in determining the performance of OLEDs. The ability of a material to transport charges is called mobility and is measured in units of charge speed per unit of electric field. Sophisticated hopping theory based on the disorder formalism [12] proposes that a quantum jump of electrons is the essential transport mechanism through the localized states in amorphous organic materials. These localized states are known as π-conjugated states. The energy needed to jump through the states is provided by the electric field applied or by thermal energy. In general, organic materials transport preferentially either holes or electrons, with typical mobilities of between 10^{-3} and 10^{-9} cm^2/Vs. Thus, after charge injection and transport process, the holes and electrons meet in the emissive layer (*i.e.*, in the frontier between the EML and HIL) to form a bounded state called an exciton, which eventually decays, giving rise to light emission (see Fig. 1c). An exciton is an electron-hole pair which is strongly bounded by a coulomb force.

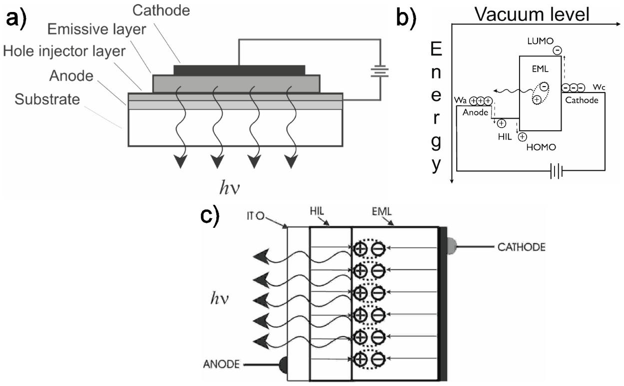

FIGURE 1. a) OLED configuration used in this work; b) energy level scheme representing the work functions of the anode, hole injector layer (HIL) and cathode; the molecular orbitals HOMO and LUMO of the electroluminescent molecule are also shown; c) exciton formation.

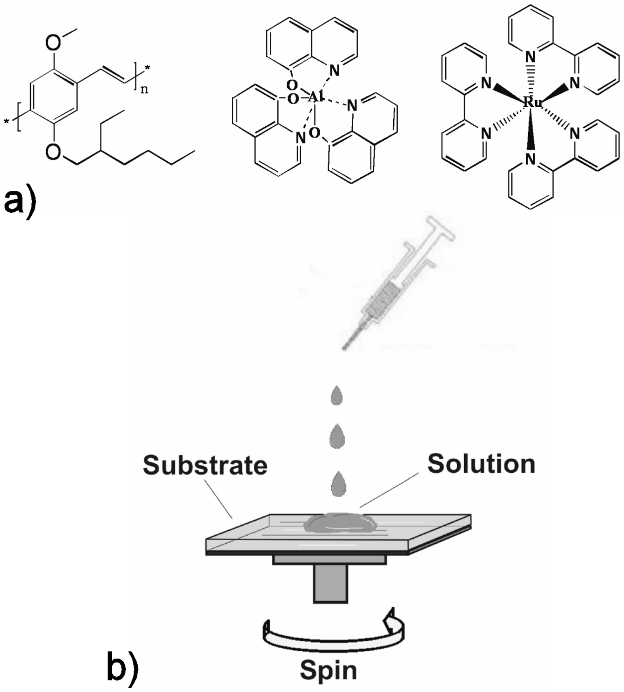

FIGURE 2. a) Molecular structure of organic molecules used in this work. From left to right: MEH:PPV polymer, Alq_3 molecule and Ruthenium Complex. b) Scheme of spin-coating technique to deposit thin films of organic molecules.

3. OLEDs fabrication

3.1. Electroluminescent and charge transport materials

To fabricate OLEDs, we used as electroluminescent materials both small molecules and polymers. By doing this, students learn the advantages and limitations of fabrication in each case. Figure 2a shows the chemical structure of the conjugated polymer MEH:PPV [Poly[2-methoxy-5-(2'-ethyl-hexyloxy)-1,4-phenylenevinylene]] and the small molecules Alq_3 [Tris-(8-hydroxyquinoline) Aluminum salt], and $Ru(bpy)_3$ [Tris(2,2Õ-bipyridine)ruthenium(II) Tetrafluoroborate complex ion]. MEH:PPV and Alq_3 are commercially available materials, while $Ru(bpy)_3$ was synthesized by students according to the procedure reported in the literature [11,13]. As hole injector material we used the polymer PEDOT:PSS [Poly(3,4-ethylene dioxythiophene)/poly(styrenesulfonate)]. All the materials used in this work were acquired from Aldrich (Mexico) and processed as received.

3.2. Spin-coating method

To create the OLED structure, we deposited thin layers of organic materials onto substrates by using the spin-coating technique. Briefly, this technique consists in dissolving the organic materials in solvents so that an amount of the solution is placed on a substrate, which is then rotated at high speed in order to spread the liquid by centrifugal force. This procedure quickly evaporates the solvent and creates a uniform solid film. Figure 2b is an illustrative sketch of the process. By using this method, and depending mainly on the speed rotation, solution viscosity and time of rotation, typical film thicknesses of between 50 and 1000 nm are obtained.

3.3. Organic solutions

MEH:PPV was dissolved in chloroform ($CHCl_3$). Students followed two approaches for solution preparation and both of these made the OLEDs work adequately. In the first approach, low concentration solutions of 0.5% wt (*i.e.*, a solution with 99.5% weight of solvent and 0.5% weight of polymer) were prepared. With these solutions EML layers were fabricated by the consecutive deposition of thin films (this method is described in Sec. 3.5). In the second approach, high-concentration solutions were prepared by dissolving 30 mg of MEH:PPV in 10 m*l* of chloroform; then the solutions were allowed to rest for a while until 50% of the solvent was evaporated. In this case only a single-film deposition was necessary to fabricate an EML. Students should observe that at high concentrations, MEH:PPV do not dissolve immediately, so it is advisable to allow the solution to mix overnight before deposition (a stir bar and magnetic stir plate were used to dissolve the materials). In regard to Alq_3 and $Ru(bpy)_3$, which are small molecules, we dissolved them using the guest-host approach (small molecules tend to crystallize easily and disperse unevenly when deposited by the spin-coating technique, precluding the formation of good films). So, by using an inert polymer (host), it is possible to create films of good optical quality in which small molecules (guest) are dispersed. The inert polymers Polyvinyl alcohol (PVA) and polystyrene (PS) were used as host materials. Ruthenium complex was combined with PVA in a proportion of 1:2.5 (by weight) and the mixture PVA:Ru(bpy)$_3$ was dissolved in water or Methylene chloride at 1% wt. Similarly, Alq$_3$ was dissolved in chloroform at 0.2% wt and then PS was added so that Alq$_3$ and PS were in a 3:1 proportion. As these solutions were of very low concentration, consecutive spin-coating deposition was required for the EML layer fabrication (at least five depositions). An EML with only one film deposition was possible in the case of Ru(bpy)$_3$ by preparing solutions with a higher concentration, but in the case of Alq$_3$ this was not possible since it has very low solubility.

3.4. Substrate preparation

An Indium Tin Oxide (ITO) layer was used as the anode. ITO has a work function of 4.7*e*V and exhibits a high optical transmittance $> 83\%$ (it is from this electrode that the emitted light is coupled out from the OLED, as shown in Fig. 1). Glass substrates coated with ITO film (film thickness 200 nm) of low resistance (4-12 ohms) were acquired from Delta Technologies Ltd (USA) and then cut into pieces measuring 2cm$\times$2cm. The ITO was cleaned by immersion in different solvents: water and soap, distilled water, and ethanol. Alternatively, students used for the cleaning process acetone, toluene and isopropanol, obtaining similar results. If an ultrasonic bath is available, it is advisable to use this equipment for 20 minutes for each solvent. The cleaning process is very important for good OLEDs operation since dust particles present in the air could reach the ITO surface and cause a short circuit; this is because the dust particles are usually bigger than the thickness of the deposited organic film. For drying the ITO, its substrate can be placed in an oven or on a hot plate for several minutes at 80°C.

3.5. Layer deposition

After the solutions were prepared, the organic layers were deposited over ITO film by using a commercial spin coater. Although this equipment is not always present in undergraduate labs, students can assemble a homemade spin-coater with the use of a motor with high revolutions > 500 rpm (*i.e.*, the cooling fan for a computer CPU). The substrates can be held, during deposition, to the homemade spin-coater by using double-face tape to reproduce the scheme shown in Fig. 2b; here the coating fluid is dispensed onto the substrate by using a syringe. The first layer to be deposited onto the ITO is the hole injector material (very thin films of HIL must be deposited in this step of the OLED assembly). After this the EML layer is deposited. We recommend drying the films after each deposition with the same procedure mentioned above for drying the cleaned ITO. Note that the primary reason for OLEDs failure is insufficient drying of the organic layer before adding the cathode layer. This procedure also helps to cure the films in order to deposit a new film over a previously deposited film, thereby obtaining thicker films.

The last layer to be deposited is the cathode. For the assembly of our OLEDs we looked for cathode metals that satisfied the criteria of easy deposition and easy acquisition (*i.e.*, commercially available at low cost). Thus, a Bi-Pb-Cd-Sn alloy (Woods metal), Ga-In eutectic alloy and silver paint were selected as cathode metals. Woods metal is composed of 50% Bi, 25% Pb, 12.5% Cd and 12.5% Sn; Ga-In eutectic consists of 24.5% Indium and 75.5% Gallium. These alloys have low melting points of 75°C and 15.7°C, respectively. In the case of silver paint, this is available commercially in many hardware and electronics stores. Then, by means of these metals in the liquid phase it was very simple to deposit the cathode layer onto the OLED structure. In the case of Ga-In, for instance, the material is liquid at room temperature and easily adheres to the EML by just smearing it on with a cotton swab (good adhesion to the EML increases charge injection and favors high efficiency values). For the case of Woods metal, the material must be melted 10°C above its melting point ($>$75°C) and then dropped over the organic surface; this metal quickly solidifies. In regard to silver paint (a liquid solution), the deposition is similar to Ga-In. Note, however, that silver paint contains some solvents that dissolve the organic films to some extent. Nevertheless, it is a good option for educational purposes as it is very cheap and easy to obtain.

In the procedure described above, the area of OLED emission can be the same as the substrate area. For basic OLED characterization, however, it is recommendable to pattern small areas for light emission; this is because with big areas the probability of having a film defect increases, thus generating short circuits or inhomogeneous emission. We followed a straightforward procedure to do this: prior to cathode deposition, masking tape was used to cover the EML; this tape was patterned with small circular apertures typically between 2.5 and 4 mm which defined the area of emission.

4. OLED Characterization

4.1. Results and discussion

The simplest characterization to be performed on an OLED is the measurement of current-voltage ($I - V$) curves. To do this, we used a variable DC voltage source that fed the devices while $I - V$ data was acquired with the aid of two multi-testers. To avoid quick sample degradation due to film imperfections, a resistor in series can be used to limit the current (more than 100 mA easily destroyed the samples). The patterned emission regions in the OLEDs allowed us to compute current densities ($J = I$/area), as shown in Fig. 3. These plots summarize various facts. First, the devices started emitting light between 3 and 15 volts; these turn-on voltages are clearly observed in $J - V$ curves as those points where the current rises very rapidly in the diode behavior shown in the inset of Fig. 3. On the other hand, we observed that the Ruthenium complex Ru(bpy)$_3$ and MEH:PPV worked satisfactorily with both alloys Bi-Pb-Cd-Sn (Woods metal) and Ga-In, though the former was more efficient and degraded more slowly; Alq$_3$, on the other hand, showed a poor performance. Silver paint also made the OLEDs work, but not as well as the other two cathodes.

In general, the OLEDs performance was strongly affected by layer quality and thickness; due to this, the good performance exhibited by MEH:PPV was explained in part by its good mechanical properties as the polymer that permitted the best deposition of organic layers. These factors in combination with the energy levels of active materials determined the balancing of carrier densities and the carrier mobilities which directly affects the probability of exciton formation. We can refer to the LUMO and HOMO energy levels involved in the EL process (see Fig. 2). For our materials these values are: 2.9 and 5.04 eV for MEH:PPV, respectively; 3.65 and 5.63 eV for Ru(bpy)$_3$; and 2.4 and 5.4 eV for Alq$_3$. On the other hand, the work functions for ITO, HIL and Ga-In are 4.7, 5.1 and 4.2 eV, respectively (to the best of our knowledge the Woods metal work function has not been reported). Hence, Ru(bpy)$_3$, MEH:PPV and Alq$_3$ had in that order increasing barriers for electron injection when a Ga-In cathode was used; the hole injection barrier increased successively for MEH:PPV, Alq$_3$ and Ru(bpy)$_3$.

The second characterization curve that can be obtained is light intensity versus voltage. Relative light intensities (in arbitrary units) were obtained by measuring the electrical signals generated by OLED emission in a photodiode. For this experiment, the photodiode can be connected to a simple amplifier whose output voltage is measured with a voltmeter.

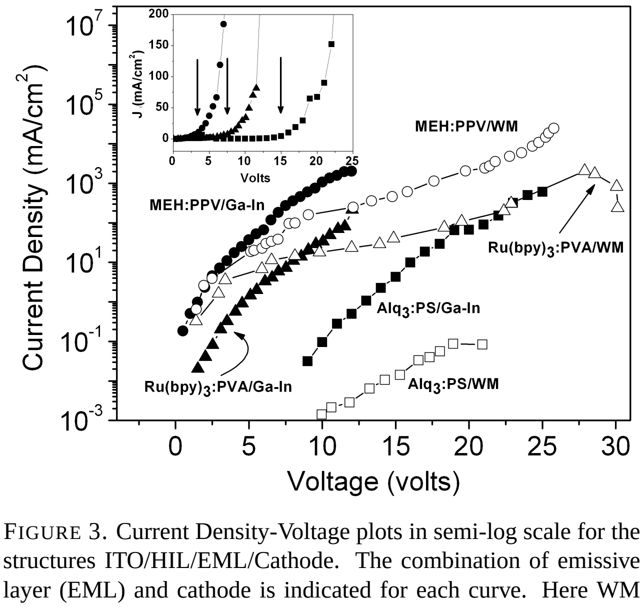

FIGURE 3. Current Density-Voltage plots in semi-log scale for the structures ITO/HIL/EML/Cathode. The combination of emissive layer (EML) and cathode is indicated for each curve. Here WM stands for Woods metal (Bi-Pb-Cd-Sn). Inset: Current Density-Voltage plots (without log scale). The arrows depict the turn-on voltage for OLEDs.

This is a straightforward measurement that students carried out without major difficulties, obtaining curves of light intensity versus voltage and corroborating the turn-on behavior at voltage values that coincide with those observed for the $J - V$ curves. Likewise, the high intensity of emitted light also allowed students to detect the EL spectrum with the help of an optical fiber and a spectrometer. The optical fiber is very convenient as it can guide the light to the spectrometer input. In our case, a hand-held spectrometer (Ocean Optics S2000) was used to do this. Figure 4 shows the normalized electroluminescence spectra corresponding to red emission for MEH:PPV and Ru(bpy)$_3$ and green for Alq$_3$. Another way to measure these spectra is with the use of a monochromator (frequently available in undergraduate labs) and any kind of available photodetector (*i.e.*, simple silicon photodiode) or photomultiplier tube.

Once the EL spectra are available, the OLEDs characterization can be further completed. For instance, it is possible to determine the amount of emitted light in terms of photometric measurements such as luminance in units of candelas/area (cd/m^2 = lumens/ m^2 sr). This photometric quantity is equivalent to the radiometric quantity of radiance (W/m^2 sr). Luminance is used in display technology to consider only the visible light in units that are weighted according to the sensitivity of the human eye (photopic response) [14]. Although these measurements were a bit more challenging to carry out than those presented in Figs. 2 and 3, they turned out to be very valuable experiences since they allowed the students to assimilate radiometric and photometric concepts.

To calculate the luminance, let us refer to Fig. 5. The OLED has a luminance L (in units of candelas per square meter) and we consider it to be a Lambertian source (its radiance is uniform across its entire surface). It follows that the power P_{in} detected by a photodetector located at a distance s_{sd} is given by [14]:

$$P_{in} = \frac{L}{C_v} \iint \frac{\cos\theta_s \cos\theta_d}{s_{sd}^2} dA_s dA_d \tag{1}$$

where C_v is the photopic response, θ is the angle between the light ray and the line normal to the surfaces area A, with the s and d subscripts denoting source and detector, respectively. As the OLED's emission is non-monochromatic, the photopic response must be weighted as

$$C_v = K_m \int\limits_{380}^{770} \Phi(\lambda) V(\lambda) d\lambda \tag{2}$$

where $\Phi(\lambda)$ is the OLED emission spectrum normalized with its area, K_m (=683 lm/W) is the conversion factor from watts to lumens and $V(\lambda)$ is the spectral efficiency for photopic vision (with nonzero values of between 380 and 780 nm corresponding to the wavelength range of human eye sensitivity). The values for $V(\lambda)$ can be found tabulated in many references, such as [[14]]. Finally, to compute the luminance we make an approximation: we assumed that $\cos\theta_{s,d} \approx 1$ owing to the fact that $s_{sd}^2 \gg dA_s, dA_d$. Therefore:

$$L \approx P_{in}\frac{C_v s_{sd}^2}{A_d A_s} = \frac{V_{out} C_v s_{sd}^2}{R A_d A_s} \tag{3}$$

where V_{out} and R are the photodetector's output voltage and responsivity (volts/W), respectively. The value of R is provided by the photodetector manufacturer and is usually not a constant but depends on the wavelength, so that an average value can be used or a weighted R value can be obtained (*i.e.*, $R \approx \int_0^\infty \Phi(\lambda)R(\lambda)d\lambda$). To corroborate the correct calibration in our experimental setup, we substituted the OLED with an inorganic LED. By knowing the optical (photometric) behavior of the LED, a comparison between the measured luminance (with our photodetector) and that reported by the manufacturer can be made (LED data-sheets report the luminous intensity for a specific forward current). Figure 6 presents the luminance measured with a large area (8 mm of diameter) silicon detector, located at 8 cm from the OLEDs, that was calibrated according to the Eq. (3). Here we see that the highest luminance is achieved with MEH:PPV. The values of luminance that we measured were relatively high: ≈3000 cd/m^2.

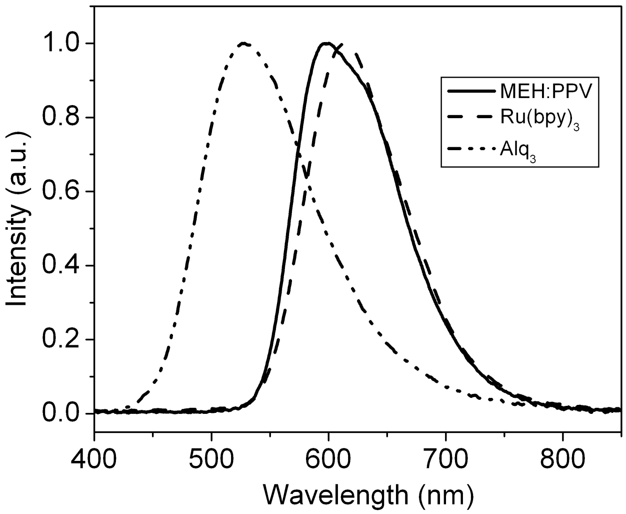

FIGURE 4. Normalized electroluminescence spectra of OLEDs with different active materials (EML).

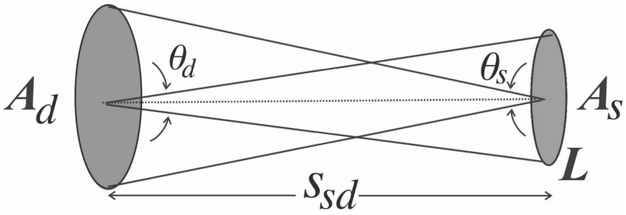

FIGURE 5. Scheme representing the areas of emission (*As*) for the OLED and detection (*Ad*) for the photodetector and the parameters involved to performed photometric calculations of luminance.

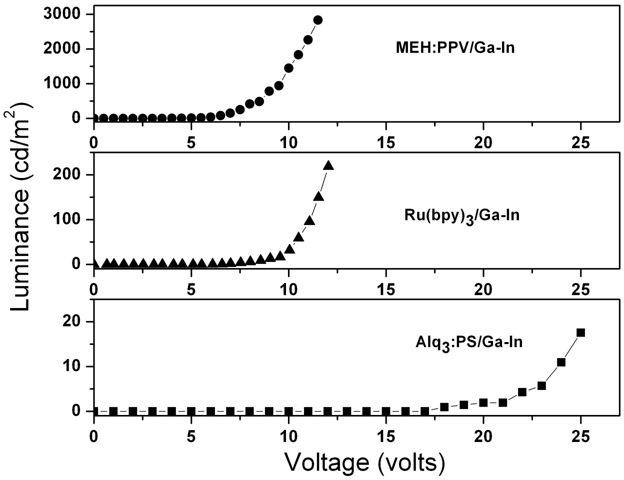

FIGURE 6. Luminance-Voltage Curves for OLED's with different EL materials. The combination of emissive layer (EML) and cathode is indicated for each curve.

Despite the high luminance values obtained in our OLEDs, it must be observed that they were obtained with very high current ($\sim$ 2030 mA/cm^2) and voltage (12 volts) values. In the literature there are various ways to estimate the OLED efficiency. To take advantage of the parameters we obtained previously, we computed the luminous efficiency η_p (expressed in lumens/Watt) which is the ratio of the optical flux to the electrical input given by:

$$\eta_p = \frac{L\pi}{JV} \tag{4}$$

From $J-V$ and $L-V$ plots it turned out that maximum luminous efficiencies were about 0.05 lm/W for the cases of MEH:PPV and Ru(bpy)$_3$ and 0.007 lm/W for the case of Alq$_3$. The larger of these two values is between one and two orders of magnitude lower than values reported in the literature for the state of the art in OLEDs [2]. These relatively low efficiencies are the payoff for simple and rudimentary OLED fabrication and testing in environments rich in oxygen and moisture (in organic materials the EL effect is seriously weakened by these two factors). In addition to this, it is worth mentioning that we preferred to use thick active layers (approximately in the range of 0.3 - 0.7 μm for the EML) in order to avoid a quick sample degradation because this thickness acted as an encapsulation for the device; in fact, our approach resulted in an optimization between luminance and layer thickness. The advantage of using thick EMLs was particularly evident for the case of Ru(bpy)$_3$. In research laboratories, however, the devices are fabricated and encapsulated in inert environments so that very thin layers (<100 nm) are deposited, thus offering reduced electrical resistance with high charge transport at low electrical bias voltage, which in turn favors high device efficiencies.

Finally, besides the basic electrical and optical characterization performed on OLEDs, it is also possible to fabricate these devices to demonstrate one of their major advantages: the EL effect in large active areas. Figure 7 presents the pic-

FIGURE 7. a) CIO logo, b) OLED with the anode layer (ITO coated glass slide) patterned with the CIO logo (2 cm $\times$ 0.7 cm). In this case Ru(bpy)$_3$ and Ga-In were used as the EML and cathode, respectively.

ture for OLEDs with the logo of our institution with dimensions of about 2 cm$\times$0.7 cm. This logo was patterned directly in the ITO layer by etching it with traditional techniques used for printed electronic circuits. Here Ru(bpy)$_3$ and Ga-In were used as the EML and cathode, respectively. Similarly, it was possible to make OLEDs fabricated over flexible substrates; to do this, optical grade PET film coated with In$_2$O$_3$/Au/Ag was utilized as the anode.

5. Conclusions

We demonstrated simple OLEDs fabrication by using metal cathodes processed from liquids, *i.e.*, alloys with a low melting point or silver paint. Although these metals are not viable for commercial OLEDs, we conclude that they are an economical approach that can be conveniently used in combination with organic solutions to produce bright OLEDs: Luminances up to 3000 cd/m^2 can be achieved for small areas of emission. These metal cathodes are convenient substitutes for evaporated aluminum or other metals. Evaporation technique is expensive, time consuming, and it is not accessible for undergraduate labs. With this, students can carry out easily basic characterization as $J-V$ curves and fabricate large-area and flexible devices; in addition, and depending on the apparatus available in undergraduate labs, more advanced characterization as electroluminance spectra, $L-V$ plots and luminous efficiency can also be performed. We consider that this method for fabricating and characterizing OLEDs is illustrative and motivational for students, and it is a good example of how the teaching of some general principles of physics, chemistry or material science, at the university level, can explain to students, and introduce them to, contemporary fundamental and applied research.

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