Electroluminescence of doped organic thin films

C. W. Tang, S. A. VanSlyke, and C. H. Chen
Corporate Research Laboratories, Eastman Kodak Company, Rochester, New York 14650-02122

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Electroluminescent (EL) devices are constructed using multilayer organic thin films. The basic structure consists of a hole-transport layer and a luminescent layer. The hole-transport layer is an amorphous diamine film in which the only mobile carrier is the hole. The luminescent layer consists of a host material, 8-hydroxyquinoline aluminum (Alq), which predominantly transports electrons. High radiance has been achieved at an operating voltage of less than 10 V. By doping the Alq layer with highly fluorescent molecules, the EL efficiency has been improved by about a factor of 2 in comparison with the undoped cell. Representative dopants are coumarins and DCMs. The EL quantum efficiency of the doped system is about 2.5%, photon/electron. The EL colors can be readily tuned from the blue-green to orange-red by a suitable choice of dopants as well as by changing the concentration of the dopant. In the doped system the electron-hole recombination and emission zones can be confined to about 50 Å near the hole-transport interface. In the undoped Alq, the EL emission zone is considerably larger due to exciton diffusion. The multilayer doped EL structure offers a simple means for the direct determination of exciton diffusion length.

I. INTRODUCTION

In our previous paper[1] we described a highly efficient electroluminescent (EL) device using two-layer, organic thin films as the emitting elements. More recently, organic EL cells with a three-layer, thin-film structure have also been reported to give bright electroluminescence.[2,3] The objective is to construct a device with the necessary attributes for display applications. The primary advantage of using organic materials as the EL emitters is the availability of highly luminescent organic molecules throughout the entire visible region, making possible the fabrication of a full-color display panel. Most of the earlier work in organic EL[4] was focused upon the blue-emitting aromatic hydrocarbons, partly because there are few blue inorganic phosphors suitable for making EL devices. Development in the field of organic EL has been limited due to the lack of operational stability and, in most instances, the need for a high-voltage drive which compromises the EL operational efficiency.[5]

Our previous work[1] was the first to demonstrate that efficient and bright EL devices can be made using a new organic EL material. A luminance greater than 1000 cd/m^2 has been achieved at a voltage below 10 V. The EL quantum yield is about 1% (0.01 photon/electon). This yield is limited, in part, by the relatively low fluorescence quantum efficiency of the emitter material, 8-hydroxyquinoline aluminum (Alq). For the evaporated Alq film used in the EL device, this fluorescence yield is 8%.[6] In a dilute solution, it is on the order of a few percent, depending on the solvent.[7] Therefore, with Alq as the emitter, the EL efficiency would have an upper limit of only about 2% when the spin-conserved electron-hole recombination statistics are taken into consideration.[8]

In order to increase the EL efficiency, an obvious choice is to search for an emitter more fluorescent than Alq. The difficulty is, however, in finding an organic material with the necessary EL properties, such as the ability to transport charge carriers. An alternative is to find some means to increase the Alq luminescence efficiency. To this end, the well-known scheme of sensitized luminescence in an organic guest–host system is useful.[9] The method has been used in previous organic EL systems, such as anthracene doped with tetracene, primarily as a way to shift the emission spectra.[10] In the Alq system, substantial gain in both fluorescent and EL efficiencies can be realized with a suitable choice of dopants, as will be shown in this paper. We will describe this improved organic EL device, and we will show that the combination of multilayer cell structure and a doped emitter offers a convenient probe for the mechanism of organic electroluminescence.

II. EXPERIMENT

The fabrication of the organic EL cell has been described briefly.[1] The cell has a multilayer structure. Figure 1 shows the two structures used in this work. Common between them is a diamine hole-transporting layer, typically 750 Å, which is on top of the indium-tin-oxide (ITO) conducting glass. The difference between the two structures is in the emitter layer. In structure A, the doped or undoped Alq

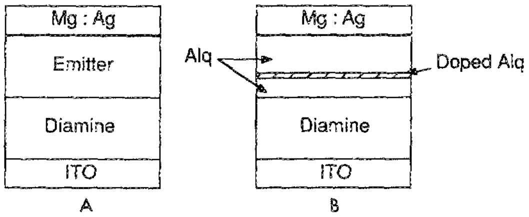

FIG. 1. Configurations of multilayer organic EL cells: (a) ITO/diamine/doped or undoped Alq/Mg:Ag, (b) ITO/ diamine/Alq/doped Alq/Alq/Mg:Ag.

layer constitutes the entire emitter. In structure B, the emitter layer consists of a doped layer located within the pure Alq layer. This doped layer can be adjacent to the hole-transport layer. The area of the EL cell is typically 0.1 cm^2.

The substrate is ITO glass supplied by PPG Industries or Balzers Optical Group. The thickness of the ITO layer is about 1200 Å and the sheet resistance is 10–20 Ω/□. The cleanliness of the substrates was found to be important in the performance of the organic EL cells. The routine cleaning procedure included sonication in a detergent, rinsing in deionized water and isopropyl alcohol, vapor degreasing in toluene, and finally irradiation in a UV-ozone chamber. An uncleaned substrate often resulted in an EL cell requiring a higher-voltage drive and in irregular stability behavior.

Organic materials were obtained from several sources. Alq was synthesized according to published procedures. Coumarin 540 and DCM1 were obtained from Exciton or Eastman Chemicals.

The EL cells were prepared by conventional vapor deposition. The source organic materials were evaporated from quartz crucibles onto ITO-coated glass kept at ambient temperature. The rate of deposition was typically 2–4 Å/s for the diamine and Alq layers. The deposition rate for the dopant was much lower, typically less than 0.1 Å/s. This rate can be maintained during deposition by controlling the temperature of the crucible to within 1 °C. The deposition rates were monitored independently by thickness/rate monitors (Sloan Omni III). For the dopant deposition, the monitor was placed close to the source, about 3 in., in order to provide adequate thickness registration. The source-substrate distance was usually 16 in. Using multiple shadow masks and shutters, EL cells of different configurations and/or compositions were made in one pumpdown.

The top electrode is a Mg:Ag (10:1) mixed film about 2000 Å thick. It was vapor deposited from the two metal sources and independently controlled by separate monitors. The deposition rate for Mg was typically 10 Å/s, and for Ag, 1 Å/s. The EL cells are usually encapsulated or stored in a dry argon chamber after fabrication to protect the Mg:Ag cathode from atmospheric corrosion.

The light (brightness)-current-voltage characteristics were measured using an EGG-555 radiometer and Keithley digital voltmeters (model 195). The photometric measurements were done using a Minolta photometer. The photoluminescence measurements were obtained from a Perkin–Elmer LS-5 fluorimeter and the EL emission spectra from a PAR OMA-III optical channel anaylzer fitted with a $\frac{1}{4}$-m monochromator.

III. RESULTS AND DISCUSSION

A. Organic materials

Figure 2 lists the molecular structures of the organic materials used in the EL cells. They belong to three classes: the diamine for the hole-tranport layer; Alq as the host emitter layer; and coumarin 540, DCM1, and DCM2 as representative dopants.

The diamine belongs to a class of aromatic amines that have been extensively studied in connection with their applications in electrophotography.[11,12] They are generally characterized by their ability to transport holes but not electrons. The hole mobility in a pure, binderless amine film is on the order of 10^{-2} to 10^{-4} cm^2 V^{-1} s^{-1} at about 10^5 V/cm. The hole mobility of the evaporated diamine film used in the present EL cells has been found to be 7×10^{-3} cm^2 V^{-1} s^{-1} by the time-of-flight method.[13] In solution the diamine can be reversibly oxidized at a potential of + 0.84 V. It is the ease of formation and the stability of the radical cations that is responsible for the hole-transporting property. This particular diamine is also chosen because of its good film-forming property, which permits the growth of pinhole-free thin films. For instance, a 750-Å-thick film, used routinely for EL cells, is optically smooth, and appears to be amorphous when examined under a transmission electron microscope. It is the dimeric structure of the diamine which lowers the molecular symmetry and thus inhibits the formation of a crystalline film.

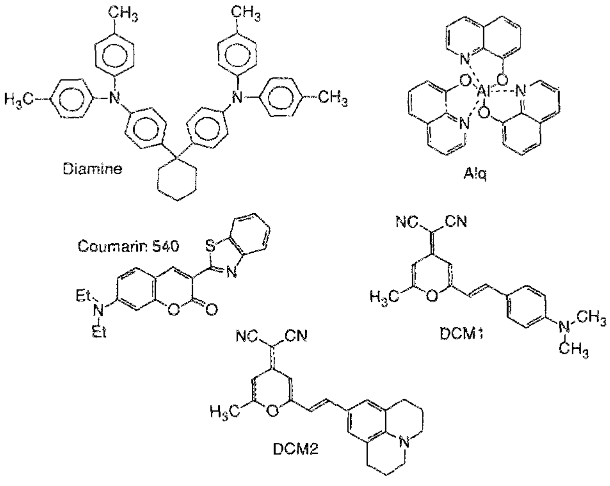

FIG. 2. Molecular structures of (1) diamine, (2) Alq, and (3) C540, DCM1, and DCM2.

The host emitter, Alq, belongs to a well-known class of metal chelates.[14] The stability and fluorescence properties of these materials have been studied extensively.[15,16] Alq is one of the most fluorescent and stable molecules in this class and also has the ability to form smooth thin films. An evaporated Alq film appears to be microcrystalline with grain size smaller than 500 Å. The transport properties of Alq are virtually unknown. Our results from EL experiments indicate that Alq is capable of transporting electrons, but the hole range appears to be limited. The carrier mobilities have not been determined.

Numerous organic fluorescent molecules have been found to be useful as dopants in Alq. Coumarins and DCMs were chosen to illustrate their common properties as acceptors in the energy transfer from Alq. The coumarins as a class emit in the blue-green region and the DCMs emit in the orange-red. They are both highly fluorescent in dilute solution with quantum efficiencies on the order of 50%–100%.[17] In concentrated solution and in the solid state, however, their fluorescence is much reduced. For instance, a pure DCM1 film prepared by vapor deposition was found to be almost nonfluorescent, and a coumarin film was only weakly fluorescent.

B. Fluorescence of doped films

Depending on concentration, the dopant molecules may retain their high fluorescence efficiency in the Alq matrix. This is clearly seen in the DCM1/Alq and coumarin 540/Alq systems as shown in Figs. 3 and 4, respectively. These fluorescence spectra wera obtained by exciting into the Alq absorption peak at 390 nm where the optical density is 0.14. At this wavelength, there is minimal absorption due to the dopants. As the concentration of the guest molecules increases, the fluorescence intensity first increases rapidly, and then decreases. Figure 5 plots the integrated area of the fluorescence bands as a function of guest concentrations. At the optimal concentration, the doped Alq films yield three to five times more total fluorescence emission than the undoped Alq film. This means that the optimally doped emitter will have a fluorescence efficiency as high as 40% as compared with only 8% in the undoped Alq emitter.

The optimal guest concentration for fluorescence enhancement differs for the two systems. For DCM1, it is about 0.25–0.5 mol %, and for C540 about 0.5–1 mol %. This difference is most likely related to the different degree of interdopant interaction in the Alq matrix. The fact that the pure DCM1 film is almost nonfluorescent suggests that the onset of fluorescence quenching in the DCM/Alq system occurs at a lower dopant concentration than in the C540/Alq system. Along with the decrease in fluorescence intensity with higher concentration, a gradual red shift in the peak fluorescence occurs. This shift is perhaps attributable to the excimer fluorescence of the dopant. It is again in the DCM1/Alq system that the shift is the largest, indicating that the interdopant interaction in the Alq matrix is stronger in DCM1 than in the coumarin 540.

The fluorescence lifetime of Alq in solution (toluene) and in thin film has been measured. The single-exponential lifetime is 16 ns in both solution and thin film. When the Alq film is doped, such as with C540 (2.0 mol %), the fluorescence decay curve is best fit with two lifetimes: 2.5 ns (85% of the emitting molecules) and 7.2 ns (15%). The short lifetime is perhaps characteristic of the C540, which is 2.2 ns in toluene solution and the long lifetime component may be attributed to the perturbed Alq molecules.

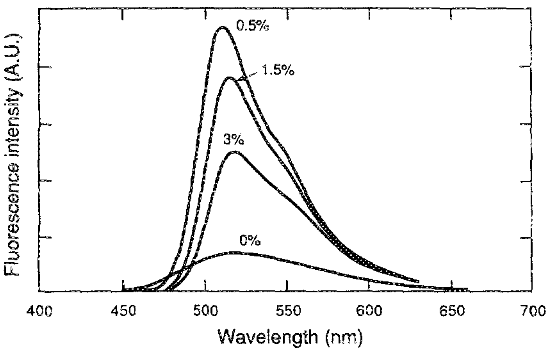

FIG. 4. Fluorescence spectra of C540/Alq (600 Å) as a function of C540 concentration.

From the EL point of view, the fluorescence lifetime represents the shortest possible response of the EL device. The EL response measured for the present device is, however, of the order of 10^{-6} s. It is dependent on the cell's capacitance, which is about 20 nF/cm^2, and on the series resistance. The latter is related, in part, to the low mobility of the organic materials.

C. Electroluminescence

1. Light-current-voltage characteristics

The light-current-voltage curves for an undoped and a doped cell are shown in Figs. 6 and 7, respectively. The common cell configuration is:

ITO/Diamine (750 Å)/Emitter (600 Å)/

Mg:Ag (10:1, 2000 Å).

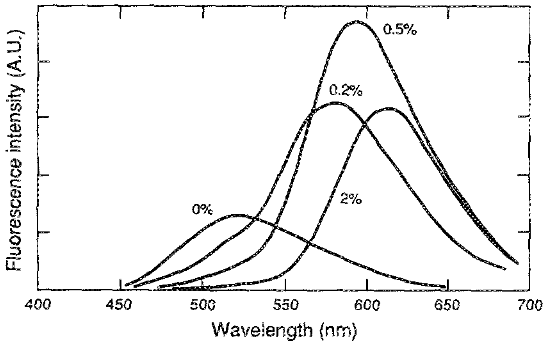

FIG. 3. Fluorescence spectra of DCM1/Alq (600 Å) as a function of DCM1 concentration.

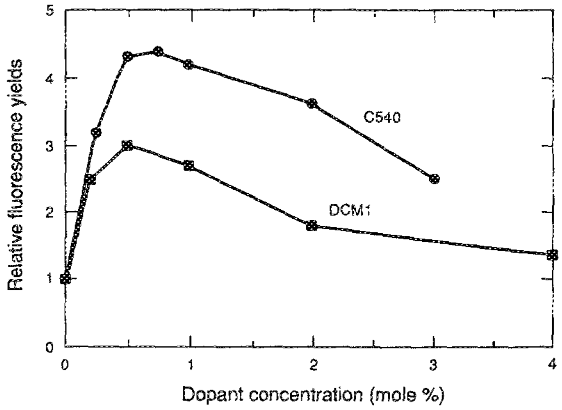

FIG. 5. Fluorescence gain as a function of concentration: (1) DCM1 and (2) C540 in Alq.

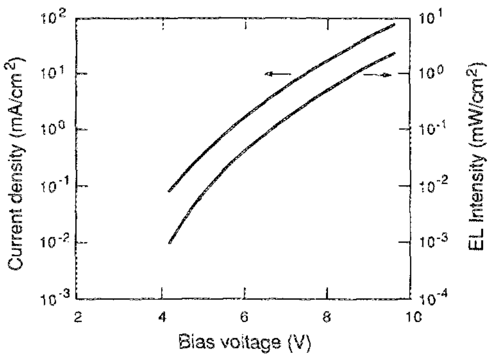

FIG. 6. Light-current-voltage characteristics for a undoped cell: ITO/diamine (750 Å)/Alq (600 Å)/Mg:Ag.

The emitter layer for the doped cell is C540/Alq (0.5 mol % C540). The EL light output is plotted in radiance units, mW/cm^2. At 0.05 mW/cm^2 for both cells, the EL emission is clearly visible in ambient room light. For this light level output the equivalent brightness in photometric units is 50 cd/m^2 for the undoped cell. In general, at the optimal level of doping for EL operation, the current-voltage characteristics are not significantly different between the doped and the undoped cell. At much higher dopant levels, the current-voltage curves will noticeably shift to a higher voltage, indicating that the dopant can influence the carrier transport properties. This is particularly so for the DCMs, where the voltage shift is as much as 2–5 V at concentrations above 2%.

The voltage required to drive the doped or undoped EL cells is quite low, usually 6–7 V to achieve the 0.05-mW/cm^2 radiance. As shown in Figs. 6 and 7, these cells can be driven to very high radiance levels using a voltage below 10 V. The drive voltage can be either dc or ac. When operated in the ac mode, light emission is seen only in the forward bias cycle corresponding to a positive potential on the ITO electrode.

The average electric field on the cell is actually rather high for EL operation, on the order of 5×10^5 V/cm for a 6-V bias across the organic layers, which are typically 1300 Å thick. This high field is apparently needed for the injection of electrons from the Mg:Ag cathode where a barrier is found to exist. The Mg:Ag cathode was found to provide efficient electron injection relative to other metals, such as In, due to the low work-function Mg component. The Ag component was added to improve the sticking coefficient of Mg on the Alq film and was found to retard the atmospheric corrosion of the Mg component. The hole injection from the ITO electrode is ohmic.

The higher EL efficiency of the doped cells in comparison with the undoped cell is clearly seen in the light-current characteristics. Figure 8 shows the EL light output versus injected current for a number of optimally doped and undoped cells. For the undoped cell, the light output is directly proportional to the injected current for the entire current range. For the doped cells, the dependence is linear at the low current range below 10 mA/cm^2, but becomes slightly nonlinear at higher current densities. The slopes of the plots measure the EL efficiencies (W/A). They are listed in Table I together with the EL quantum efficiencies (photons/electron) and the peak emission wavelengths. It can be seen that the C540-, DCM1-, and DCM2-doped cells are about a factor of 1.5–2 times more efficient than the undoped Alq cell.

The issue of stability of the doped and undoped EL cells is complicated and will be discussed in more detail in a future publication. We have tested both the doped and undoped cells under constant current excitation and found that continuous light output above 0.05 mW/cm^2 can be maintained over a few hundred hours. The doped cells live longer than the undoped cells partly because of their higher efficiency and levels of light output.

2. EL spectra

For an undoped two-layer cell, the EL emission spectrum is identical to the fluorescence spectrum of Alq, indicating that the Alq layer is the emitter.[18] For a doped, two-layer cell where the entire Alq layer is uniformly doped with guest molecules [Fig. 1(a)], the EL spectrum is again essentially identical to the fluorescence of the doped Alq layer. Figure 9 shows the normalized EL spectra for the undoped Alq, C540/Alq (1%) and DCM1/Alq (0.25%) cells. The EL spectra have a dependence on the dopant concentration similar to that of the fluorescence spectra shown in Figs. 3

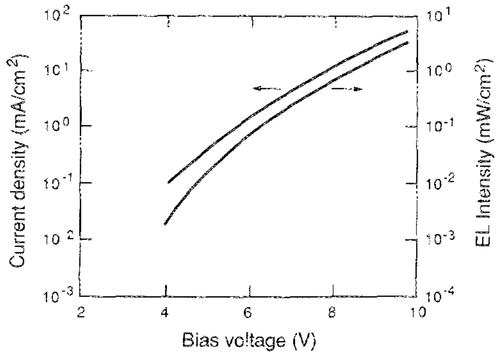

FIG. 7. Light-current-voltage characteristics for a C540 doped cell: ITO/diamine (750 Å)/Alq + C540 (600 Å)/Mg:Ag.

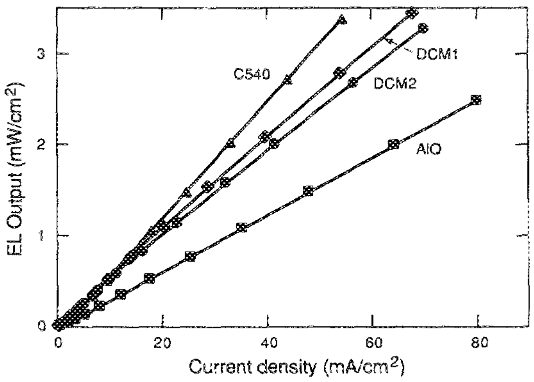

FIG. 8. Light-current characteristics for doped and undoped EL cells.

TABLE I. Efficiencies of organic electroluminiscent cells.

Emitter	Alq	C540/Alq	DCMl/Alq	DCM2/Alq
Emission wavelength (nm)	540	510	570–620[a]	610–650[a]
EL efficiency (W/A)	0.031	0.061[b]	0.052[b]	0.049[b]
EL quantum efficiency (photon/electron)	0.013	0.025[b]	0.023[b]	0.023[b]

[a] Concentration dependent.

[b] Optimally doped (see text).

and 4. At low concentration, the EL spectrum is a composite of the Alq and dopant emission. The guest emission becomes predominant at higher concentration. Thus, the color of the EL cell can be easily tuned by choosing a suitable dopant or by changing the concentration. Between the coumarin and DCM classes of dopants, the color of the doped Alq cell can range from blue-green to orange-red, that is, from 500 to 650 nm. The short wavelength limit is imposed by the fluorescence of the host Alq.

Figure 10 plots the relative EL efficiencies as a function of the dopant concentration. In the C540/Alq system, the optimal concentration is about 0.5%–1.0% for both EL and fluorescence yields. The decrease in EL yield with increasing dopant concentration is directly related to the decrease in the fluorescence yield, as in the case of the C540/Alq cells. In the DCM1/Alq cells, the optimal concentration is about 0.1%–0.5%. The EL yield, however, falls off more rapidly than the fluorescence yield with increasing dopant concentration.

Another important difference in the concentration dependence of the EL and fluorescence yields is the enhancement factor, which is the ratio of the quantum efficiencies of emissions with and without the dopant. At the optimal concentration, the maximum EL enhancement factor is 2–2.5 in both C540/Alq and DCM/Alq, whereas the maximum fluorescence enhancement factor is about 4.5 for the C540/Alq and about 3 for the DCM/Alq. The reason for this lower enhancement in the EL mode is not clearly understood. It could be attributed to the fact that in the EL mode the entire emission is derived from a narrow zone near the diamine/Alq interface (as will be shown later), whereas the photoexcited fluorescence is from the bulk of the 600-Å doped thin films. It is possible that the dopant in this narrow zone is less fluorescent due to its proximity to the diamine, which may form a donor-acceptor complex or exciplex with the dopant.

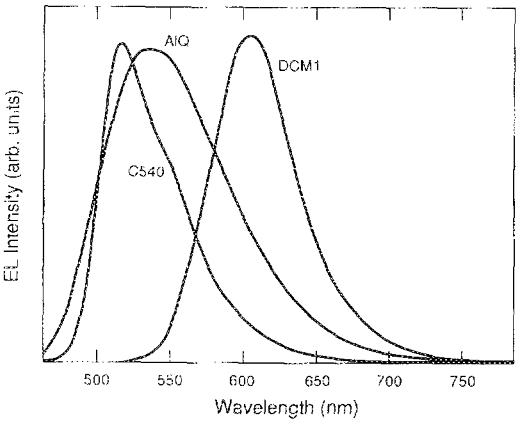

FIG. 9. EL emission spectra: (1) undoped Alq, (2) C540/Alq, and (3) DCM1/Alq.

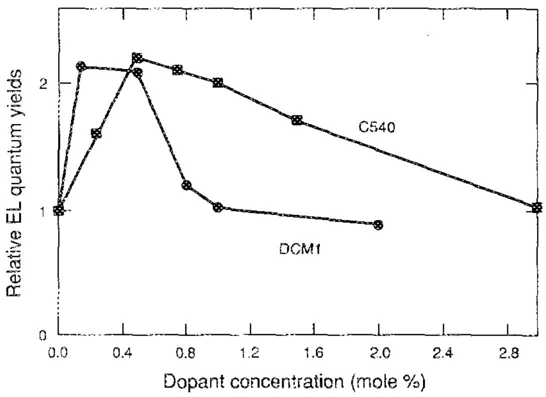

FIG. 10. Relative EL quantum efficiencies as a function of dopant concentration in Alq.

3. Recombination and emission zone

As mentioned earlier, the only mobile carriers in the diamine layer are holes. This layer effectively prohibits any significant transport of electrons and therefore confines the electron-hole recombination within the Alq emitter layer. Depending on the relative injection efficiencies and mobilities of the electrons and holes in the Alq, the location of the recombination zone will reside either near the hole-transport/emitter interface or the cathode/emitter interface. The emission zone from which the EL originates may be different from the recombination zone, depending on the events subsequent to the electron-hole recombination. In any case, the emission zone width represents the upper limit for the electron hole recombination zone. The multilayer doped emitter EL structure, as will be seen, is useful in probing these important EL parameters.

The emission zone is relatively simple to locate in a doped system. In one experiment, the emitter layer was subdivided into two layers according to Fig. 1(b). The C540-doped Alq layer was sandwiched between the diamine layer and the undoped Alq layer. The thickness of the doped layer was varied from 50 to 600 Å and the undoped layer was adjusted to maintain a total thickness of 600 Å for the composite emitter. The concentration of the dopant, about 1 mol %, is sufficient for complete energy transfer from Alq to C540. Figure 11 shows the EL yields as a function of the thickness of the doped layer. Since the EL yield of the doped layer is larger than the undoped Alq by about a factor of 2, one would expect a variation of EL efficiencies in this series

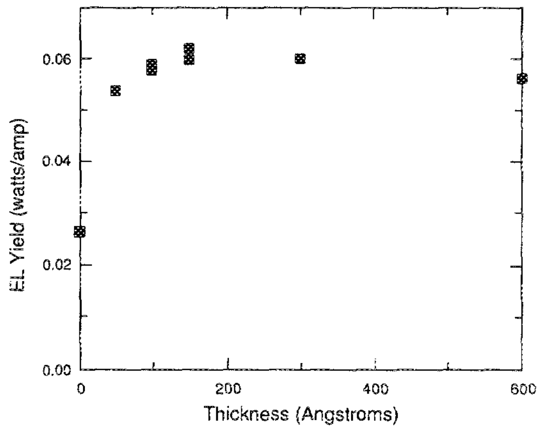

FIG. 11. EL quantum yields as a function of the thickness of the C540-doped emitter layer.

of cells if both doped and undoped layers were to contribute to the emission zone. Except for the falloff at about 50 Å, the EL yield is relatively independent of the thickness of the doped layer. One concludes that the EL emissions are entirely from the doped layer, provided its thickness is greater than about 50 Å. The EL spectra of these cells are also found to be identical to each other and are characteristic of the C540 molecules, indicating that the EL emission is from the doped layer. These results indicate the following: (1) The emission zone is located within about 50 Å of the doped Alq layer adjacent to the hole-transport layer. The recombination zone, by implication, is also located in this region. (2) The electron, once injected into the emitter layer, has to be drawn close to the hole-transport/emitter interface to recombine with the hole. Therefore, its range is at least the thickness of the Alq layer. In fact, the electron range was found to be at least 2000 Å at 5×10^5 V/cm from EL experiments employing thick Alq films.

The emission and recombination zones established here are for the doped Alq emitter layer. For the undoped Alq cell, these zones might be quite different. The emission zone of the undoped Alq cell can be determined quite readily using a doped layer in a slightly different configuration. Within an undoped Alq layer (600 Å), a 40-Å doped layer (0.5%) was inserted [Fig. 1(b)]. DCM2 was chosen as the dopant because it emits in the red and is therefore readily distinguishable from the Alq emission. This doped layer thus acts as a spacial sensing layer. The location of this layer was varied from near the hole-transport layer to near the cathode and the corresponding EL emission spectra were recorded. Figure 12 shows a series of EL emission spectra as a function of the location of the sensing layer at a distance of q angstroms from the diamine/emitter interface. When the sensing layer is placed adjacent to the hole-transport layer, the EL spectrum largely resembles the emission of the dopant. When it is separated by as little as 50 Å from the hole-transport layer, the EL spectrum is a composite of the Alq and DCM2 emissions. At larger distances the doped layer's contribution to the EL emission diminishes and becomes insignificant when its distance is greater than about 400 Å. This distance, therefore, approximates the dimension of the emission zone in the undoped Alq layer.

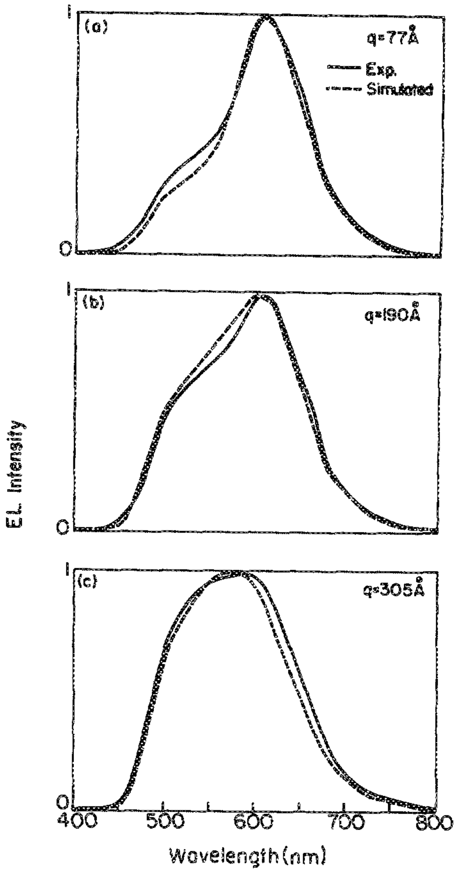

FIG. 12. Experimental and simulated EL spectra as a function of the location of the sensing layer. q is the distance of the sensing layer from the diamine/Alq interface. The simulated spectra were obtained assuming an exciton diffusion length of 200 Å.

4. Exciton diffusion in Alq

The observation that the width of the EL emission zones varies in the doped Alq systems just described suggests that exciton formation and migration are involved in the EL processes. The initial electron-hole recombination presumably occurs in the host Alq within a narrow zone adjacent to the diamine layer. Following recombination, a sheet of excitons is created which undergoes a one-dimensional diffusion towards the cathode. The emission zone is therefore governed by the exciton diffusion coefficient and its lifetime in the emitter layer. The determination of the location of this emission zone using the doped EL sensing layer enables one to evaluate the exciton diffusion parameters. The method is an adaptation of the surface photoluminescence quenching used originally by Simpson.[19] In electroluminescence, the method has an advantage in that the location of the exciton source is well defined by the recombination zone.

Using this method, the sensing layer is placed at a distance, q, from the hole-transport/emitter interface in an Alq film of thickness d. Under constant current excitation, the steady-state density distribution of Alq excitons, $\rho(x)$, is assumed to be an exponential function:

$$\rho(x) = \rho(0)\exp(-x/L), \quad (1)$$

where x is the distance measured from the hole-transport interface, $\rho(0)$ is the exciton density at the interface, and L is the exciton diffusion length which is related to the exciton diffusion coefficient, D, and the lifetime, τ, by

$$L = \sqrt{(D\tau)}. \quad (2)$$

The total emission at a given wavelength, $I_{\rm EL}(\lambda)$, is found by integrating the contribution from the undoped Alq layer, $x < q$, and the doped Alq layer, $x > q$. The thin doped layer traps all the excitons arriving at its surface, an assumption based on the experimental fact that a 50-Å doped layer adjacent to the hole-transport layer is the entire emission zone. Therefore,

$$I_{\rm EL}(\lambda) \propto \phi_{\rm Alq}(\lambda)(1 - e^{-q/L}) + \phi_{\rm DCM2}(\lambda)(e^{-q/L}), \quad (3)$$

where $\phi_{\rm Alq}(\lambda)$ and $\phi_{\rm DCM2}(\lambda)$ are the relative EL quantum efficiencies of pure Alq and doped Alq cells.

Using Eq. (3) and the known EL emission spectra of the undoped and doped cells, EL spectra for different q can be simulated using L as the adjustable parameter. This has been done for the series of EL cells described in Fig. 12. The best fit for all three spectra is found for $L = 200$ Å. This value seems reasonable as it falls within the range measured for a variety of aromatic organic crystals using different methods.[20] From the measured radiative lifetime of 16 ns for the Alq film, a diffusion coefficient of 7.6×10^{-4} cm^2 s^{-1} for the Alq exciton is obtained using Eq. (2).

The model for exciton diffusion assumes that the excitons originate from a narrow electron-hole recombination zone at the diamine/Alq interface. If this recombination zone is, in fact, quite extended, then the estimate for the exciton diffusion would be incorrect. In an extreme case, the result of the sensing layer experiment can be explained by a short exciton diffusion length and an extended recombination zone width which is only limited by the hole carrier range. This alternative model is correct only if the dopants are themselves efficient hole traps in Alq. We do not have independent experiments to show this is the case.

IV. CONCLUSIONS

The multilayer thin-film organic EL cell has been shown to be an efficient light-emitting device. The importance of the multilayer structure is that it provides a configuration where the organic materials in each layer can be independently optimized for the EL processes. We have shown that by utilizing a hole-transport layer and an emitter layer, the electron-hole recombination zone can be confined in the emitter layer, removed from the electrodes. This would have been more difficult to achieve in the conventional organic EL cell using only a single layer of organic material. The very thin-film structure of the EL cell also enables its operation at a low voltage.

We have demonstrated that the EL efficiency of the host emitter, Alq, can be improved by about a factor of 2 by doping the Alq host with C540, DCM1, or DCM2. EL emissions with a range of colors from blue-green to orange-red can be readily produced using these dopants.

The multilayer structure was found to be useful in elucidating the mechanism of electroluminescence in organic materials. The recombination zone in the multilayer EL cell was found to be small, on the order of 50 Å. The EL emission zone in undoped Alq, however, is considerably larger due to the diffusion of excitons. In a doped system, these excitons are effectively trapped by the dopants, thus narrowing the emission zone. The exciton diffusion length for Alq has been determined to be about 200 Å.

ACKNOWLEDGMENT

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