

Current heating in polymer light emitting diodes

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We present an investigation of current-induced heating in polymer light emitting diodes. Using short electrical pulse measurements, we were able to quantify the temperature rise in the active region. We consider that heating effects play a major role in limiting the maximum efficiency of devices and in initiating degradation mechanisms. Heating and heat sinking are also discussed in the context of electrically pumped polymer lasers. © 1998 American Institute of Physics.
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Organic light-emitting diodes (LEDs) have reached the point where their efficiency and stability are now suitable for commercial display applications. Recent reports of optically pumped lasing in organic based cavities¹⁻⁵ have raised the bar even higher with the new application in mind being the electrically pumped laser. Although we have recently reported⁶ high values of sustainable peak currents (1 kA cm⁻²) and light output (5 mW or 5 × 10⁶ cd m⁻²) for a 1–2 mm² LED, positive gain has not yet been measured⁶ in electrically driven devices. While there are many differences between optically and electrically pumped devices, the most obvious one is the existence of current and the unavoidable voltage drop associated with it. In other words, electrically pumped devices are more susceptible to Joule heating problems. In this letter we examine the issue of current (and voltage) induced heating and its role in determining the characteristics of polymer LEDs. We find that, under continuous wave operation, the temperature in the recombination zone may be elevated by at least 60 °C and that it limits the maximum external and internal efficiencies attainable in devices.

The device structure used is shown in the inset to Fig. 1. It consisted of bottom contact of indium–tin–oxide (ITO) (on glass) on top of which Al stripes were deposited to reduce voltage drop associated with the ITO. The Al stripes were then covered by Al₂O₃ stripes which defined the bottom contact area. This was followed by polymer layers and a top electrode which consisted of Ca (200 nm), Al (250 nm), and Au (60 nm). The area of the top electrode was 1 × 4 mm² and the active region was 1 × 1 mm². The top electrode was made thick, so as to absorb heat efficiently from the polymer, and served as a first-stage heat sinking for the device. When tested, the top electrode was placed in direct contact (by pressure) with a heat sink of a larger heat capacity (second stage heat sink). All measurements were done under vacuum of 10⁻⁵–10⁻⁶ mbar. The possible role of current heating is shown in Fig. 1 for an LED with a polymer layer consisting of standard poly(*p*-phenylenevinylene) (PPV)⁷ which was spin-coated and converted to yield a ~140 nm thick layer. This figure shows the LED efficiency as a function of applied voltage for two distinct experimental conditions. The bottom line shows a continuous wave (cw) measurement in which the second-stage heat sink was removed. As is known for this type of device, the device efficiency rises and levels

off at a certain voltage (9 V here). The maximum efficiency measured under cw conditions was 0.125 cd/A (~0.1% internal quantum efficiency). The top measurement was performed using pulses of 500 ns duration at 500 Hz repetition rate (second-stage heat sink in place). This low repetition rate and the setup sensitivity, limited the measurement to the relatively higher voltage regime. We note that in the pulsed case the efficiency continues to rise and reaches a value which is about four times higher than that of the cw case. This behavior suggests that Joule heating may be important in this type of polymer LED.

A common way of characterizing the temperature inside a light emitting device (at the recombination zone) is to use the temperature dependence of the emission properties as an internal thermometer. The most frequently used features relate to the emission spectrum: the spectral position, which reflects the temperature dependent band gap, and the spectral shape which reflects the temperature dependence of the energy distribution of the emitting species.⁸ Sometimes, the absolute value of the emitted power may prove useful as well.⁹ When the emission properties are used, the actual temperature measured is that of the emitting species. Since the emitters and the lattice come into equilibrium within a few ps,^{10,11} in most cases the emission properties can be used to deduce the lattice (device) temperature as well. For the temperature characterizations we used a polymer layer configuration that was found to be more stable and efficient⁶ than the

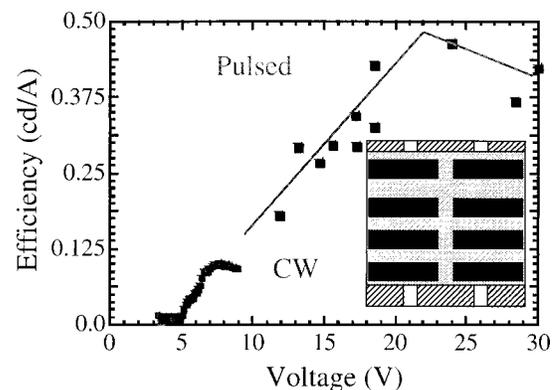


FIG. 1. Device efficiency as a function of applied voltage. The bottom line was measured under cw conditions and the square markers under short pulse, low duty cycle, conditions. The line is a guide to the eye. The inset shows the LED configuration from bottom up: ITO, Al covered by Al₂O₃, polymer layers, contact layers.

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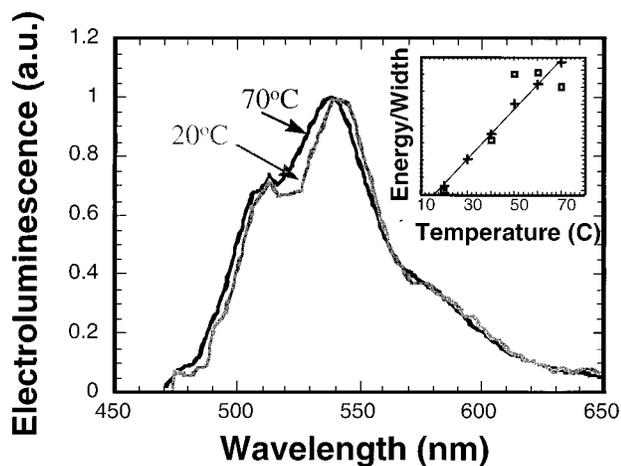


FIG. 2. Average emission spectra measured at two heat-sink temperatures (20 and 70 °C). The inset shows the change of peak energy and width as a function of temperature.

configuration used in Fig. 1 (maximum efficiency under cw operation of 3.75 cd/A at 11 V) which consisted of a thin layer of conducting polymer, a 70 nm of standard PPV,⁷ and 80 nm of PPV co-polymer.¹² Figure 2 shows the emission spectrum measured using 400 ns long 15 V pulses for two different heat-sink temperatures. When the temperature is elevated from room temperature (20 °C) to 70 °C the emission peak shifts to the blue and broadens. The emission spectrum was measured at 10 °C intervals and the inset to Fig. 2 shows the temperature dependence of the main emission peak position and width. In order to obtain these values the spectra were plotted as a function of energy (eV) and the main peak was fitted with a Gaussian function. In this small temperature range we find that the temperature dependence can be linearly fitted, as shown by the line in the inset. Once the temperature dependence of the main peak (shift of $0.015 \mu\text{m}^{-1}$ for 50°) is obtained, it can be used as a calibrated thermometer for other measurements.

In order to characterize the heating in a working device we measured the emission spectrum for different pulse widths while keeping the repetition rate constant (6 kHz). Figure 3 shows a sample of measured emission spectra for an applied voltage of 15 V and a corresponding current of 25

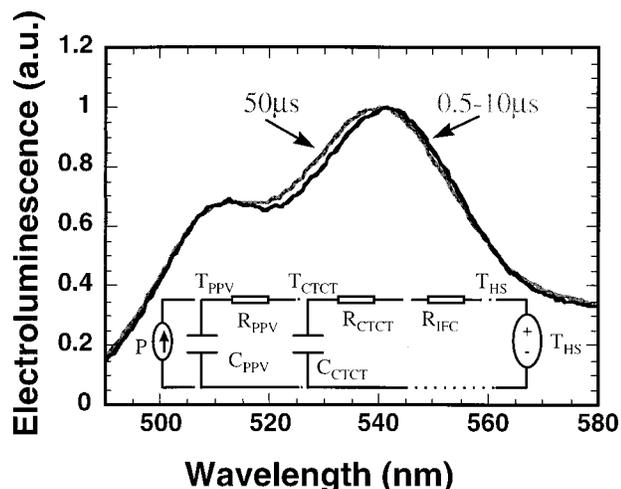


FIG. 3. Average emission spectra taken with pulses of differing duration. The inset shows the device equivalent circuit.

mA. We note that at up to 10 μs (5% duty cycle) there is no apparent shift, suggesting the device has good heat-sinking properties. Beyond 10 μs there is a clear indication of heating as the main peak shifts and broadens. We found that the rise in temperature is approximately linear with the pulse width and reaches a value of 20 °C at a duty cycle of 30% (50 μs pulse). In order to explain the above results we constructed and equivalent heat circuit, shown in the inset to Fig. 3. Using literature data^{13,14} we calculated the PPV film heat capacitance (C_{PPV}) to be 5.6×10^{-8} J/K and its resistance (R_{PPV}) to be 375×10^{-3} K/W. The contact parameters are $C_{\text{CTCT}} = 380 \times 10^{-8}$ J/K and $R_{\text{CTCT}} = 2.4 \times 10^{-3}$ K/W. The heat resistance associated with the interface between the metallic contact and the heat sink is represented by R_{IFC} . P is the drive power ($P = I \times V$) and T_{HS} is the heat-sink (thermal bath) temperature. The above values show that the main LED heat resistance is associated with the PPV film and that the main heat capacitance is associated with the thick electrode. The heat capacity of the electrodes is such that the energy produced by a 10 μs pulse of 15 V and 25 mA will raise the temperature by only 1 K. This is in good agreement with the very small spectral change found for 0.5–10 μs pulses (Fig. 3). The temperature rise of 20 K at 30% duty cycle is clearly too high for the calculated heat capacity. This result suggests that the heat does not dissipate between the pulses but it rather accumulates due to the interface heat resistance. Using a temperature rise of 20 K at 30% duty cycle we find that $R_{\text{IFC}} = 160$ K/W. This relatively high resistance is behind the temperature rise at the high duty-cycle regime and is caused by the moderate pressure used to join the LED with the heat sink, in order to avoid deformation of the soft PPV film. In our simple resistance capacitance (RC) circuit we have neglected the role of the glass substrate since it was not in contact with the heat sink. For completeness we state the heat resistance of 1 mm³ glass which is 110 K/W. Despite the relatively high resistance at the interfaces, at duty cycles below 5% the thick electrode is sufficient to dissipate the heat from the polymer film.

In organic LEDs the emission spectrum is sometimes found to be bias dependent. This is often attributed to a shift in the location of the recombination zone within the device and varying interference effects. We found that when short pulses at low repetition rate were used, the emission spectrum, its polarization, and its angular dependence, did not change. Namely, when heating effects are excluded no appreciable spectral change is observed in the present devices.

To conclude, we have shown that temperature effects play an important role in the operation of polymer LEDs. We have presented results using an improved device design and mounting procedure⁶ which was aimed at reducing temperature effects. We note that our mounting scheme resulted in a temperature rise which is the equivalent of 60° at cw operation. At an average output level of 100 cd m⁻² the average temperature rise of this device configuration (with the heat sink) will be less than 1°. For display application however, the instantaneous temperature rise depends on the peak power which is determined by the number of pixels and the drive scheme. Device configurations which do not address the heating issue may result in a significant temperature rise.

Although we have not presented evidence for the direct re-

lation between current heating and degradation, we found that devices made with thinner top electrodes tend to degrade significantly faster. In the context of the possible realization of electrically pumped polymer lasers in which high current densities (drive voltage) will be required, we note that any device configuration will have to account for heat flow within the device.

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