Electroluminescent displays

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Abstract — This paper will review the electrical and optical properties of both monochrome and color electroluminescent (EL) displays. A simple electrical model for thin-film-electroluminescent (TFEL) device operation will be presented and used to describe the luminance and power consumption of TFEL devices. The basic material characteristics that are desirable for EL phosphors will be described. Progress in the development of multicolor and full-color EL displays will be presented including device structures and phosphor advancements.

Keywords — *Color electroluminescence, electroluminescence, electroluminescent devices, TFEL.*

1 Introduction

The phenomenon of electroluminescence (EL) is the non-thermal conversion of electrical energy into luminous energy. There are two classes of EL devices. In the familiar light-emitting-diode (LED) devices, light is generated by electron-hole pair recombination near a *pn* junction. This paper, however, will focus on the second type of EL device in which the light is generated by impact excitation of a light-emitting center (called the activator) by high-energy electrons. The electrons gain their high energy from an electric field, and thus this type of EL is often called *high-field electroluminescence*. This review will focus only on the latter devices and will use the acronym EL to refer to these high-field devices in which the behavior of the majority carriers (the electrons) predominantly determine the device physics.

1.1 Device structure

EL devices for display applications can be fabricated with either thin-film or powder technology. This review will focus on thin-film devices. Figure 1 shows the device structure for a thin-film EL (TFEL) device.[1] First let us discuss the function of the individual layers of the TFEL device. The central layer is the thin-film phosphor which emits light when a large enough electric field is applied across it. The required field level is on the order of 1.5 MV/cm. Because of this high field level, any imperfection in the thin-film stack which produces a short circuit would cause a destructive amount of energy to be dissipated if the phosphor were directly connected to the electrodes. Therefore, current-limiting layers (the insulators) are needed on either side of the phosphor layer to form a reliable device structure. The insulators limit the maximum current to the capacitive charging and discharging displacement-current level. As we shall see later, the insulator layers also store charge which "amplifies" the internal electric field and significantly increases the luminous efficacy of TFEL devices. Finally, electrodes on the top and bottom of the device complete a basic capacitive structure. At least one set of these electrodes should be transparent to permit viewing of the emitted light.

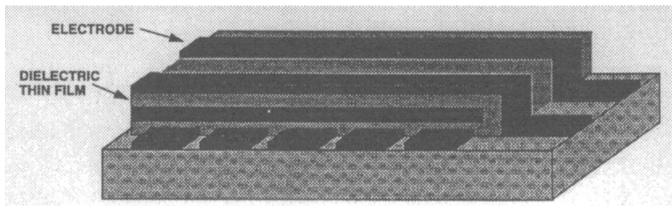

FIGURE 1 — TFEL structure.

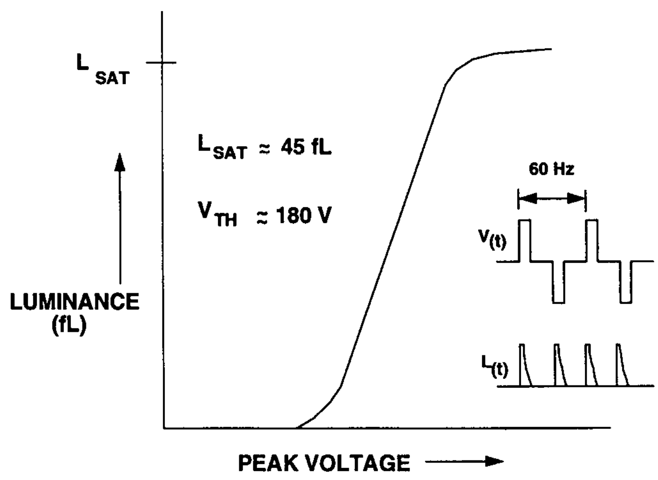

FIGURE 2 — Luminance *vs.* voltage characteristic.

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2.2 Operating characteristics

The luminance–voltage characteristics of a typical TFEL device are shown in Fig. 2. This curve features a threshold voltage below which little light is emitted, a steeply rising characteristic above threshold, and finally a saturation region. This highly non-linear characteristic provides the device with the capability to be electrically addressed at a very high multiplexing ratio while maintaining excellent contrast. This is just what is required for the matrix addressing of high-information-content (HIC) flat-panel displays (FPDs). The typical performance level achievable in the 640 × 480 TFEL display units now on the market is a luminance of 30 fL and contrast ratios of 15:1 in a 500-lux ambient. Because these displays have wide viewing angles (>160°) and operate at video rates, EL technology has all the characteristics required to produce HIC FPDs with the image quality of a cathode-ray tube (CRT). The solid-state nature of EL displays makes them extremely rugged, which is often a desirable characteristic for a FPD when used in portable applications.

2 Devices physics

2.1 Model for a TFEL device

Alt[2] has proposed that the simple model shown in Fig. 3 contains the essential device physics of a TFEL device and in practice this model has been found to model accurately the most significant characteristics of a TFEL device. This model treats the insulator layers of the device as perfect capacitors. The thin-film phosphor also behaves as a capacitor below a threshold voltage as represented by the Zener breakdown voltage of the back-to-back diodes. When the internal phosphor voltage is above threshold, real current flows in the phosphor layer and excites the light-emission centers.[3] The luminance of the device is proportional to power consumed in the real-current branch of the circuit with the proportionality constant being the experimentally determined efficacy, η, which has units of lumens per watt.

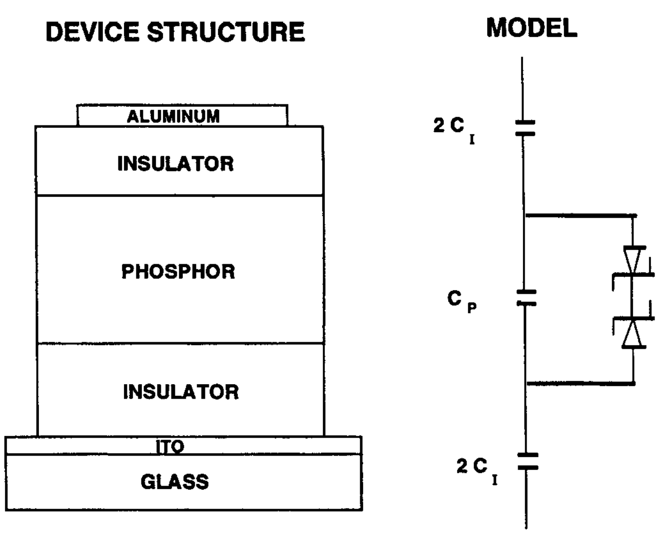

FIGURE 3 — TFEL circuit model.

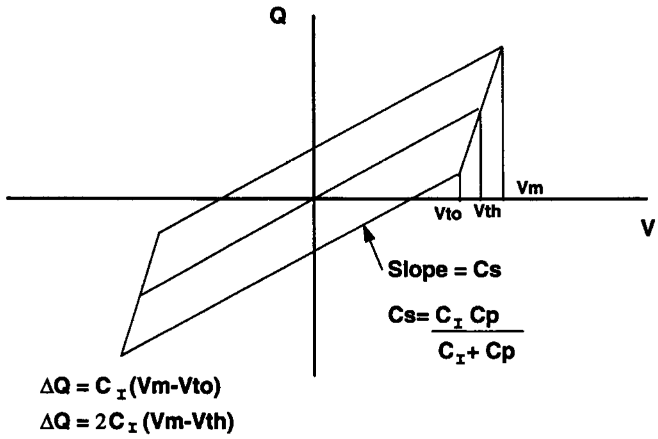

FIGURE 4 — *Q–V* characteristic of an EL device.

Figure 4 shows a charge–voltage (*Q–V*) diagram for the device model of Fig. 3. For voltages below the threshold voltage, the *Q–V* diagram is a straight line; the slope of the straight line is the capacitance of the series combination of the insulator and phosphor layers. Above threshold, the diodes begin to conduct and the slope of the *Q–V* diagram now increases to the capacitance of the insulator layers alone, since the capacitance of the phosphor layer is now shorted out. The charge transported across the phosphor layer is stored at the phosphor/insulator interface and creates an internal polarization field that opposes the field generated by the externally applied voltage. The charge at the interface continues to build up until the voltage across the diode drops below threshold at which time the charge transport is terminated. When the external voltage is reduced, the voltage across the diodes remains below threshold, and thus the charge transported remains at the interface and the magnitude of this charge is represented by value of Q for $V = 0$. The non-zero value of Q for $V = 0$ leads to a *Q–V* curve that "opens up" into a parallelogram for voltages above threshold. The area inside this parallelogram represents the power dissipated in generating the light from the EL device. The power is given by

$$P = 2fC_iV_{mod}V_{dth}, \tag{1}$$

where f is the light-pulse frequency, C_i is the insulator capacitance, V_{mod} is the voltage above the external threshold voltage, and V_{dth} is the internal diode threshold voltage.

For a typical commercial TFEL display, the values of these parameters are as follows: f = 60 Hz, C_i = 18 nF/cm^2, V_{mod} = 40 V, and V_{dth} = 90 V.

Substituting these values into Eq. (1) gives

$$P = 8 \text{ mW/cm}^2. \tag{2}$$

This result shows that the power required to generate the light from a TFEL display is quite low. Figure 5 shows that even for a 10-in.-diagonal VGA display with a pixel lumi-

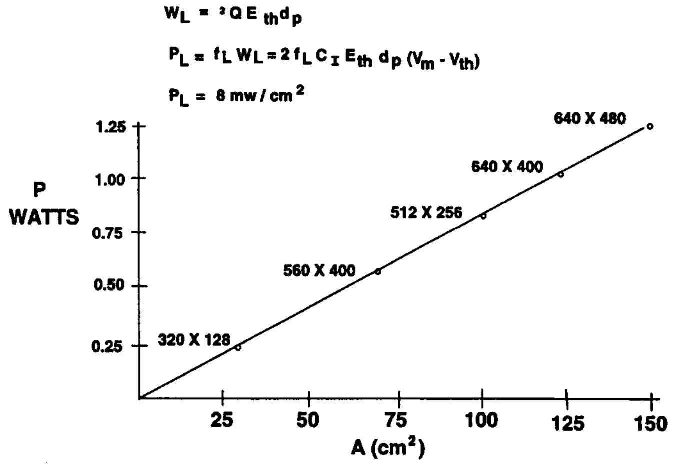

FIGURE 5 — Light-generation power consumption for a pixel luminance of 30 fL.

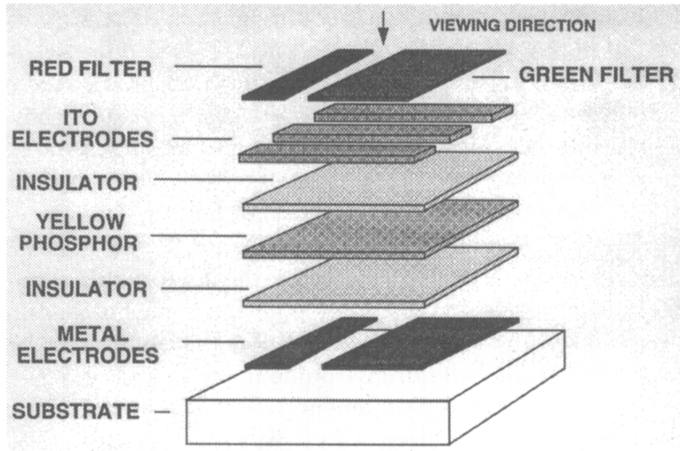

FIGURE 7 — Inverted multicolor display.

nance of 30 fL, the light-power dissipation is just over 1 W! One of the reasons for the low light-power dissipation of the capacitive structure of TFEL devices is that the charge stored at the interface actually lowers the external device turn-on voltage (V_{TO}) below the threshold voltage. This can be seen in Fig. 4 where the corner of the Q–V parallelogram is at a lower voltage than the threshold voltage where charge transport is first initiated. Physically, this is the result of the internal polarization field adding to the externally applied field when the polarity of the driving waveform is reversed.

The light emission from a TFEL device is found to be proportional to the power given in Eq. (1) and is given by

$$L = \eta P = 2\eta f C_i V_{mod} V_{dth}, \tag{3}$$

where L is the light emission in lumens and η is the efficacy in lumens per watt. The conversion to calculate the luminance of the display, B, in foot-lamberts, is given by

$$B = 929 \frac{\mathrm{cm}^2}{\mathrm{ft}^2} L. \tag{4}$$

By using the data for the typical luminance of a commercial TFEL display (45 fL) and for the power dissipation (8 mW/cm^2) in Eq. (4), and then solving for the efficacy, η, one obtains the result that

$$\eta = 6\ \mathrm{lm/W}. \tag{5}$$

This rather high luminous efficacy makes TFEL displays one of the most efficient solid-state light-producing devices.

2.2 EL phosphor materials

In general, phosphors, whether being used for EL or CRTs, consist of a host material doped with an activator which is the light-emission center. The classical EL phosphor consists of a ZnS host lattice doped with Mn atoms for the light emission centers. To be a phosphor host lattice, a material must satisfy the basic requirement of having a band gap large enough to emit visible light without absorption. This limits the class of possible materials to large-band-gap semiconductors ($E_g > 2.5$ eV) and insulators. The classical CRT phosphor host materials are the II-VI compounds and the rare-earth oxides and oxysulfides.

A priori, these same materials could be good hosts for EL devices. However, EL host materials have the additional

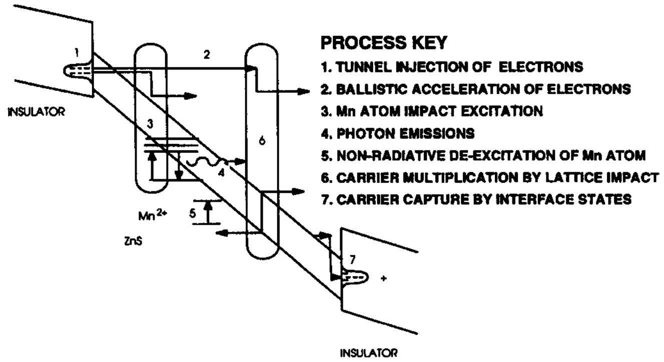

FIGURE 6 — Energy-band diagram for EL mechanism.

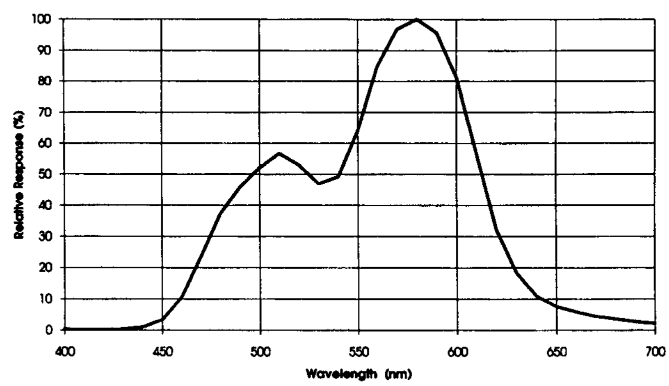

FIGURE 8 — White EL emission spectrum (Ref. 14).

requirement of providing a medium for the efficient transport of high-energy (>2 eV) electrons. To date, only the II-VI materials (for example ZnS, SrS, and CaS) have demonstrated this capability. Empirically, the oxide phosphors with their larger band gaps (>4.5 eV) do not seem to have the capability to transport significant current densities of hot electrons. Thus, the EL phosphor host materials used in today's devices have band gaps in the range of 3–4.5 eV.

To be an efficient EL phosphor, the light-emitting center must have a large cross section for the impact excitation mechanism shown in Fig. 6. In addition, the center must be stable in the high-field environment associated with the electroluminescence phenomenon. Because of this latter requirement, certain classic CRT light-emission centers perform very poorly when used in an EL device. The best example of this is the poor EL performance of the donor-acceptor center associated with the copper doping of ZnS, whereas the same center is the activator in P2, the efficient green CRT phosphor. Williams[3] has suggested that the shallow donor and acceptor levels are unstable in high fields because electrons can tunnel out of these levels. On the other hand, the Mn levels are very deep. In fact, it has been shown that the electron never leaves the Mn atom[4]. Useful EL dopants found to date include: Mn (yellow), Tb (green), Eu (red), Ce (blue), and Pr (white).

3 Color TFEL displays

In this section we will discuss the status of both multicolor and full-color TFEL displays. Color TFEL technology has the potential to produce a high-performance color flat FPD without the complexity of the TFT color liquid-crystal-display (LCD) approach. The technology for multicolor (red/green/yellow) TFEL displays has now matured to the point where the first commercial products have been introduced. Significant progress in the development of full-color (red/green/blue) TFEL displays has been made in the research laboratories in the last few years and, recently, the first full-color prototypes have been demonstrated.

3.1 Multicolor displays

Perhaps the simplest structure for achieving a multicolor display is shown in Fig. 7. This structure takes advantage of the rather broad-band emission characteristics of the standard ZnS:Mn phosphor in the green-to-red part of the spectrum and uses a filter to produce the primary red and green colors. In order to avoid parallax, it is necessary for the filter to be located in close proximity to the EL film stack, and thus an "inverted"[5] structure is used in which the electrode on the glass substrate is opaque and the electrode on top of the thin-film stack is transparent. The filter is placed directly on the film stack and the display is viewed through the filter. Because the filter is added at the end of the fabrication process, a low-temperature organic filter may be used. This structure has several advantages. From a performance point of view, perhaps its best attribute is the very good contrast that is achieved without the use of the traditional circular polarizer. Contrast ratios of 14:1 in an ambient of 500 lux are typical results. The areal luminance levels of these displays are in the 25-cd/m^2 range. From a manufacturing point of view, the fabrication of the active thin-film stack can be done with the same equipment line that is now used to fabricate monochrome TFEL devices with very good yields.

3.2 Full-color displays

3.2.1 Color EL phosphors

The development of efficient EL phosphor materials for the primary red, green, and blue colors has been the basic challenge for the realization of a practical full-color TFEL display technology. There have been two parallel avenues explored for color EL: (1) the development of an efficient white or broad-band phosphor that can be filtered to produce an RGB display or (2) the development of efficient red, green, and blue primary color EL phosphors. An efficient red (1 lm/W) has now been achieved with the combination of the standard ZnS:Mn yellow phosphor and a red filter.[6] The green ZnS:Tb phosphor also has an efficacy near 1 lm/W.[7,8] The best "blue" phosphor available until just recently was SrS:Ce[9] which, although efficient (0.8 lm/W), actually has a blue-green chromaticity (x = 0.19, y = 0.38). Thus, to achieve a true blue chromaticity this material had to be filtered, which resulted in a factor of 6 reduction in blue luminance.

Interestingly, the host material SrS is also the basis for the present "white" phosphor research. Below, the details of the most recent work done on developing efficient white and blue EL phosphors will be reviewed.

3.2.2 White phosphors

There have been several approaches to achieve an efficient "white" EL phosphor including SrS:Ce,Eu,[10] SrS:Ce/SrS:Eu,[10] SrS:Ce/CaS:Eu,[11] ZnS/SrS:Ce,[12] and ZnS:Mn/SrSeCe.[13] However, most of the recent work has focused on a layered phosphor material of either SrS:Ce/ZnS or SrS:Ce/ZnS:Mn. The group at Komatsu[14] showed that the combination of SrS:Ce and ZnS:Mn extends the blue-green emission of the SrS:Ce phosphor to the yellow-red portion of the spectrum (see Fig. 8) and then by using filters, reasonable pixel luminance could be achieved for the red (23 cd/m^2), green (37 cd/m^2), and blue (6 cd/m^2).

A further optimization of the performance of the basic SrS:Ce/ZnS phosphor has been reported by the groups at Tottori University and the University of Stuttgart. They have found that multilayer thin-film structures of these materials result in a higher "white brightness." The structures that these groups build have as many as nine alternating layers of SrS and ZnS. The optimum thickness of the ZnS layer was 150 nm and that of the SrS was 200 nm. These groups hypothesized that the multiple interfaces result in enhanced luminescence when the electric field reverses.

However, more recent results indicate that efficient SrS:Ce/ZnS:Mn TFEL phosphors can be obtained with only a single layer of SrS:Ce sandwiched by ZnS:Mn layers on the top and bottom. The group at Planar International[15] reports achieving a brightness of 220 cd/m^2 @ 60 Hz using an atomic layer epitaxy (ALE) process to deposit SrS:Ce/ZnS:Mn films. Mauch and co-workers have reported an efficacy of 1.6 lm/W by mixing ZnS into SrS:Ce during the deposition.[16]

3.2.3 Blue phosphors

The primary focus had been on achieving an EL phosphor with sufficient blue luminance. The first material to show promise for the blue EL phosphor was SrS:Ce, which was first studied by Planar Systems for TFEL applications.[9] However, the broad-band blue-green emission of SrS:Ce requires filtering in order to achieve a true blue primary color. In terms of reducing the number of process steps, it is desirable to develop a blue phosphor that does not need a blue filter.

A significant breakthrough was reported in 1993[17] when it was shown that a group of ternary sulfides were efficient host materials for the blue EL phosphor. These materials have the general chemical formula MGa_2S_4 (where M is Ca, Sr, or Ba) and when activated with Ce are relatively efficient blue phosphors. These materials had previously been investigated by Peters and Baglio for their cathodoluminescent[18] properties and they had found that the Ce emission occurred at a shorter wavelength than that of the corresponding alkaline earth sulfide and that these ternary sulfides were also more chemically stable than the alkaline earth sulfides.

Table 1 lists the emission characteristics of these materials when incorporated into a EL device and compares the chromaticity to that of SrS:Ce.

The data in Table 1 clearly show that the ternary thiogallates provide a much deeper blue emission than the SrS:Ce phosphor. The CIE coordinates of the $SrGa_2S_4$:Ce phosphor has the lowest CIE y value and would provide a color gamut close to that of the standard CRT display. However, the eye response for the $SrGa_2S_4$:Ce phosphor emission is nearly a factor of 2 less than that of the $CaGa_2S_4$:Ce emission. Thus, for equivalent energy efficiency, the cerium-activated calcium thiogallate phosphate would

TABLE 1 — EL emission results for MGa_2S_4:Ce phosphors

Phosphor	Peak wavelength (nm)	CIE coordinates x	CIE coordinates y
$CaGa_2S_4$:Ce (1 at. %)	459	0.15	0.19
$SrGa_2S_4$Ce (1 at. %)	445	0.15	0.10
$BaGa_2S_4$Ce (0.5 at. %)	452	0.15	0.15
SrS:Ce	480	0.19	0.38

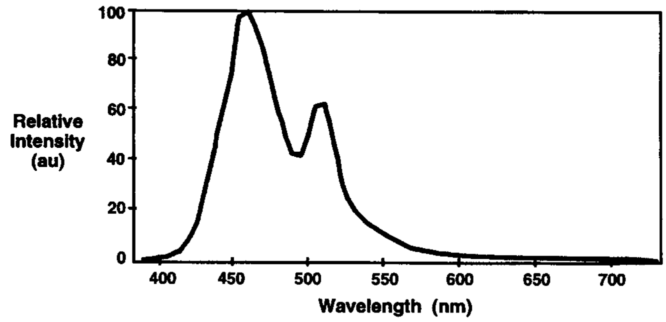

FIGURE 9 — EL emission spectrum for $CaGa_2S_4$:Ce (1 at.%) film.

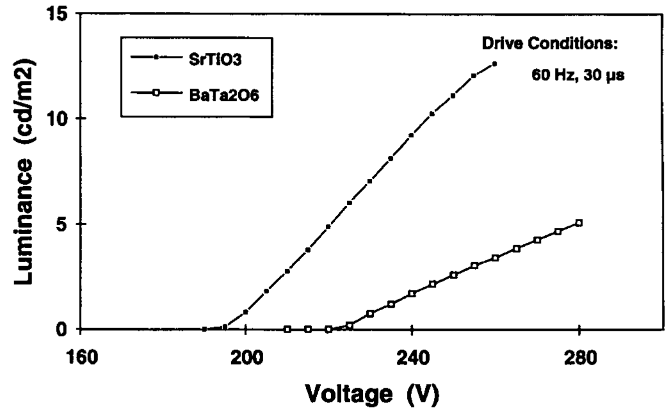

FIGURE 10 — Luminance *vs.* voltage for $CaGa_2S_4$:Ce (1 at.%) devices using $SrTiO_3$ and $BaTa_2O_6$ lower insulators.

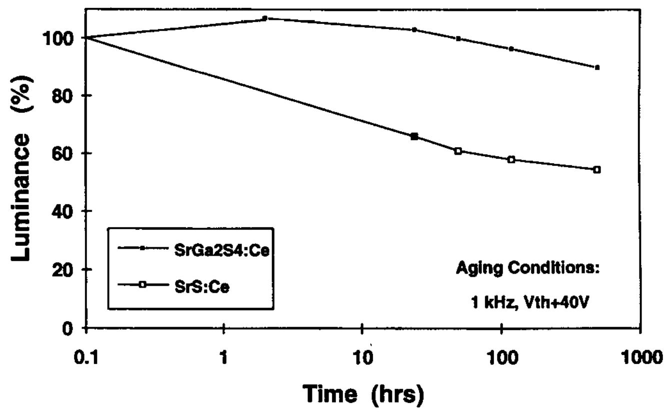

FIGURE 11 — Luminance *vs.* aging time at 1 kHz, V_{th} + 40 V for sputtered $SrGa_2S_4$:Ce TFEL device compared with e-beam-evaporated SrS:Ce device.

achieve twice the photopic luminance of the strontium based host. Figure 9 shows a typical emission spectrum for a $CaGa_2S_4$:Ce EL device. Figure 10 shows the luminance–voltage curves for a Ca_2S_4:Ce device.

The best luminance achieved to date is 10 cd/m^2 at 60 Hz. Figure 11 shows that the stability of the phosphor is very good, in agreement with the results obtained for this material when used as a CRT phosphor. Thus, for the first time the thiogallate blue EL phosphors demonstrate sufficient

TABLE 2 — EL phosphor performance data

Phosphor material	Emission color	CIE x	CIE y	L (cd/m^2) @ 60 Hz
ZnS:Mn	Yellow	0.50	0.50	300
CaS:Eu	Red	0.68	0.31	12
ZnS:Mn/filter	Red	0.65	0.35	65
ZnS:Tb	Green	0.30	0.60	100
SrS:Ce	Blue Green	0.19	0.38	130
$SrGa_2S_4$:Ce	Blue	0.15	0.10	5
$CaGa_2S_4$:Ce	Blue	0.15	0.19	10
ZnS:Mn/SrS:Ce	"White"	0.44	0.48	220

stability, luminance, and blue chromaticity to build a full-color TFEL display.

3.2.4 EL phosphor summary

Table 2 gives a representative list of the reported EL phosphor performance data.

3.2.5 Full-color device structures: Filtered broadband phosphor approach for color TFEL displays

One of the two primary device structures being developed for full-color TFEL displays is the combination of a broadband "white" phosphor with a patterned color filter. This device structure is shown in Fig. 12. This structure has the advantage of maintaining the simple device-fabrication sequence of a monochrome TFEL display (*i.e.*, no patterning of the thin-film phosphor or insulator layers) and achieving color by laminating a patterned color filter to the EL device at the end of the process. Using this approach, the group at Planar International has built a 9-in.-diagonal 512(×3) × 256 RGB display based on the broad emission from the SrS:Ce/ZnS:Mn phosphor. Using a frame frequency of 180 Hz, the display achieves a white luminance of 25 cd/m^2.[19] Table 3 lists the areal luminance and CIE coordinates for this display.

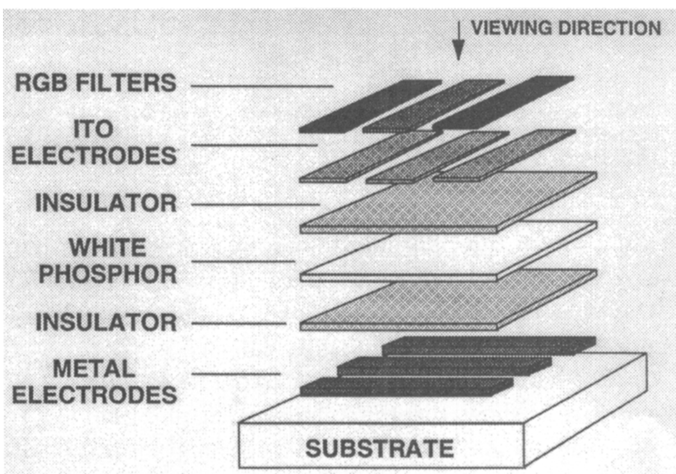

FIGURE 12 — Color-filter TFEL structure.

TABLE 3 — Performance of the 9-in.RGB display

Color	Luminance (cd/m^2)	CIE (x, y)
Red	8	(0.62; 0.37)
Green	14	(0.38; 0.58)
Blue	3	(0.24; 0.35)
White	25	(0.45; 0.44)

Further improvement in these characteristics is expected. In particular, a deeper blue chromaticity is desired.

3.2.6 Dual-substrate full-color EL display panel structure

Figure 13 shows a cross-sectional view of a dual-substrate full-color TFEL structure that has been developed at Planar. This structure has been referred to previously as a hybrid of stacked and patterned phosphor layers.[20] In the present implementation, the front (top) substrate consists of patterned red and green phosphors. The red color is obtained by filtering the ZnS:Mn emission as described previously.[6] An ALE-deposited ZnS:Tb phosphor film is used for the green emitter.[8] The red/green substrate employs the conventional EL layer structure with the exception that the rear row electrode is a transparent ITO layer instead of aluminum. Narrow aluminum bus bars are added in parallel with the row electrodes on both substrates to enhance conductivity. The rear substrate is a monochrome blue-emitting EL panel with transparent top and bottom electrodes. The new cerium-activated calcium thiogallate phosphor film is used as the blue emitter. A black layer was applied to the back of the rear substrate in order to achieve high contrast without

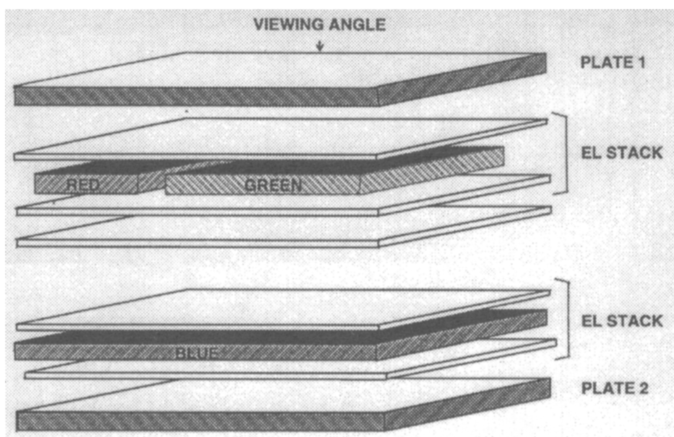

FIGURE 13 — Dual-substrate color display.

TABLE 4 — RGB TFEL phosphor performance

Color	Brightness capability (cd/m^2)	CIE chromaticity x	y
Red	65	0.65	0.34
Green	100	0.31	0.60
Blue	10	0.15	0.19

the need for a circular polarizing filter. The red and green substrates are aligned and sealed together in close proximity in color to achieve a wide viewing angle with no parallax.

3.2.7 Panel performance

The luminance and color capabilities of the red and green TFEL phosphors are listed together with those measured for the new blue $CaGa_2S_4$:Ce phosphor in Table 4. These values were measured at 60 Hz and 40 V over threshold on individual phosphor test devices. As shown by the table, the ratio of the red, green, and blue luminance capabilities is 6.7:10:1. If equal-size RGB subpixels are employed in the full-color panel, the blue luminance would need to be further enhanced to balance the maximum capabilities for the other two primaries in order to achieve the desired 3:6:1 RGB ratio. The dual-substrate panel structure, however, allows the blue subpixel to be nearly the same size as the sum of the red and green subpixel areas while maintaining a high fill factor for the red and green.

The dual-panel structure also allows the drive electronics to be independently optimized for each substrate. The threshold voltage of the blue phosphor, therefore, need not match that established for the red and green phosphors. By splitting the columns on the blue substrate a higher refresh frequency can be used, yielding increased blue luminance. A further advantage of the dual-substrate structure is that each of the red/green and blue substrates can be processed and tested separately before they are sealed, which is expected to produce higher manufacturing yields.

Planar has built a quarter-VGA panel using the dual-substrate structure. With a frame frequency of 180 Hz, the display achieves a white luminance of 35 cd/m^2. The performance of the quarter-VGA full-color panel is given in Table 5.

The CIE chromaticity diagram in Fig. 14 shows the color range that can be achieved by the dual-substrate full-color TFEL compared with that for the color CRT. The EL red and green primaries are more saturated than those for the color CRT while the blue EL CIE coordinates approach those of the CRT.

TABLE 5 — Quarter-VGA dual-substrate color-panel performance

Color	Luminance (cd/m^2)	CIE (x; y)
Red	10	(0.63; 0.36)
Green	20	(0.31; 0.60)
Blue	5	(0.17; 0.22)
White	35	(0.36; 0.40)

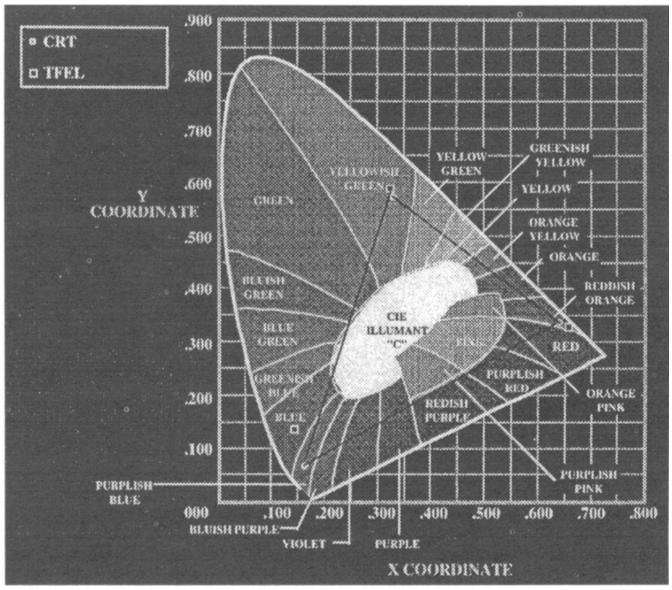

FIGURE 14 — TFEL panel chromaticity.

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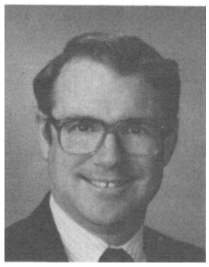

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