TFEL Color by White

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Abstract

This paper overviews the "color by white" approach to make color Thin Film Electroluminescent (TFEL) displays. The performance of the SrS:Ce/ZnS:Mn phosphor is discussed in light of recent improvements of the SrS:Ce TFEL phosphor. The status of both direct view "color by white" TFEL color displays and miniature active matrix "color by white" TFEL displays for head mounted displays is briefly mentioned.

Introduction

Almost ten years ago Tanaka and coworkers proposed "color by white" for making color TFEL displays [1]. The simplicity of a TFEL color device structure without patterned phosphors was indeed attractive. In reality the lack of an efficient white TFEL color phosphor imposed a severe limitation at that time. Today "color by white" is the dominant approach to make color TFEL displays. There are several reasons for this evolution and at least the following two should be mentioned:

- the efficiency and the stability of the SrS:Ce TFEL phosphor have drastically improved during the last ten years. As a result of this development SrS:Ce fills the gap that was earlier perceived for the blue color in particular,
- patterned color filters have been developed for LCDs. The same color filter technology can be used for "color by white" TFEL displays.

The device structure in "color by white" color displays is shown in figure 1. It relies on an EL phosphor with a light emission spectrum covering the whole visible range. The most efficient phosphor for this purpose is the stacked SrS:Ce/ZnS:Mn phosphor.

Like in monochrome TFEL displays there is one dielectric film on either side of the light emitting phosphor film, but the processing order of the two electrodes is reversed. That is, the transparent electrodes are placed on top of the light emitting thin film structure. This "inverted" TFEL structure allows the color filters to be placed in close vicinity to the light emitting structure - a necessity in order to avoid parallax. The color filters can either be deposited directly on top of the TFEL film stack or on a separate color filter plate. Because the ambient light is highly absorbed in the color filters in the front, "color by white" TFEL displays have inherently a very good contrast even in high illumination.

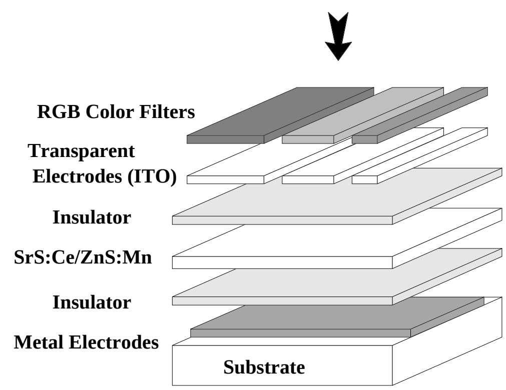

Figure 1. Cross-section view of the "color by white" display based on the inverted TFEL structure, the broad emission band SrS:Ce/ZnS:Mn phosphor film and color filters at the front.

One of the great advantages with the "color by white" TFEL display is the simple device structure. The manufacturing process is almost identical to the one used for monochrome displays with two patterning processes and three pump-downs. Therefore only minor capital investments are needed to add a color line to an existing monochrome TFEL production line.

Another advantage is that the substrate need not be glass. Opaque ceramic substrates can be used, which makes it possible to implement high temperature annealing in order to improve the efficiency of the phosphors. Another very interesting option is to use a silicon wafer substrate. This has opened up a new application for TFEL in head mounted displays, where an active matrix driving circuitry is integrated on a silicon wafer on top of which miniature color displays are made by using "color by white" TFEL see figure 2.

The key advantage of this display concept is that extremely high resolutions can be realized with the AMEL display structure.

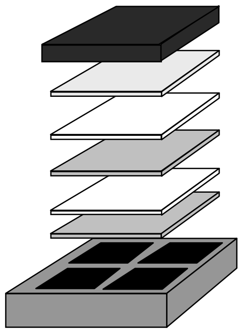

Figure 2. Cross-section view of the AMEL Display

<u>The SrS:Ce/ZnS:Mn phosphor</u>

The stacked SrS:Ce/ZnS:Mn phosphor is today by far the most suitable EL phosphor for “color by white”. ZnS:Mn is well-known from all yellow emitting monochrome TFEL displays. It is the most efficient EL phosphor with a rather wide emission spectrum ranging from the green to the red.

The SrS:Ce phosphor is in many regards different from the ZnS:Mn. The valence of the cerium dopant, which resides on a Sr^{2+} site, is +3. This implies that charge compensation must be present. The average threshold field for the onset of the emission is much lower, typically about $1*10^8$ V/m. It is therefore possible to stack the SrS:Ce on top of (or below) the ZnS:Mn film without increasing the voltage too much.

Continuous improvement of the SrS:Ce efficiency and stability has been achieved by the group at Heinrich-Hertz-Institut in Berlin using an MBE type of equipment, in which a $CeCl_3$ source is used for the cerium doping. Efficiency was first improved by adding atomic sulfur from a ZnS source [2]. Later the improvement was rather attributed to the incorporation of Zn at Sr vacancies [3]. Still better results were obtained with Mn, which similarly to Zn has a higher surface mobility than Sr, but which is easier to incorporate at the substrate temperature above 600 °C. As a result of these findings the luminous efficiency doubled and an appreciable improvement in the luminance stability was achieved as shown in figure 3.

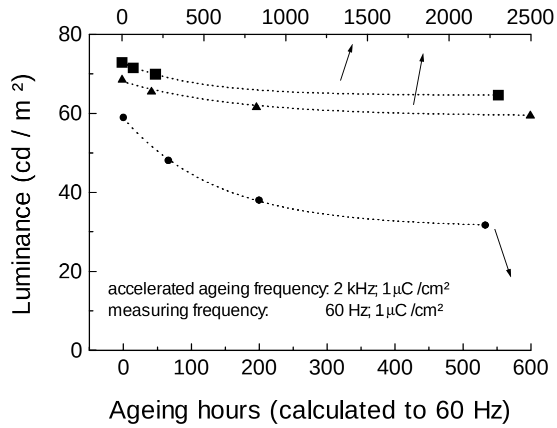

Figure 3. Aging characteristics of SrS:Ce,Cl (●), SrS:Ce,Zn,Cl ( ), and SrS:Ce,Mn, Cl (■) EL devices observed under accelerated aging conditions (from ref. [3]. Permission for Reprint, courtesy Society for Information Display).

Along similar lines the group att Tottori University has found that codoping with Zn improves the crystallinity and slows down the decrease in the luminance with time in EB evaporated SrS:Ce [4].

After the improvement of the SrS matrix the group at the Heinrich-Hertz-Institut has focused on the local environment of the Ce^{3+} center [5,6,7]. Comparisons to high quality SrS:Ce,Na powders clearly indicate that defects are induced in the vicinity of the Ce^{3+} when the cerium concentration is increased. By using a proprietary codopant the green shift associated with higher cerium concentration was considerably reduced [8]. As a result the critical blue emission has been increased by some 40 % [9]. Furthermore very good stability has been achieved. Under 2 kHz driving frequency the L_{50} luminance decreased 23 % in 700 hours [9]. Since time scales approximately with the driving frequency, this corresponds to more than 9,000 hours at 150 Hz. This fulfils phosphor stability requirements for a display product.

Excellent stability for the SrS:Ce/ZnS:Mn TFEL phosphor has also been reported by Mikami and coworkers [10].

SrS:Ce TFEL films have successfully been grown with ALE by using $Sr(thd)_2$, $Ce(thd)_4$ and H_2S albeit codoping e.g. with halides has turned out to be difficult. The efficiency and stability of these films is comparable to best evaporated and sputtered SrS:Ce films with the exception of the MBE grown SrS:Ce,Cl,Mn,"X" films just mentioned.

Similar performance has also been obtained with sputtered SrS:Ce,F,Ga films [11]. Excellent crystallinity is achieved in these films after RTA at some 800 °C.

The performance of state-of-the-art SrS:Ce TFEL films is summarized in TABLE 1. The measurement results were reported to the author by those having made the samples. For this reason the comparison is rather qualitative than quantitative. The samples had a reflecting aluminum back electrode and the frequency of the excitation voltage was 60 Hz. The unfiltered luminance was 1 cd/m^2 at the threshold voltage.

TABLE 1

Deposition method:	MBE [12]	EBE [13]	ALE [14]	Sputtr.[15]
U_{th} + 50 V	160 V	220 V	170 V	150 V
L_{50}(cd/m^2)	140	55	130	100
η_{50} (lm/W)	1.2	0.80	0.92	0.83
CIE(x; y)	(0.26; 0.48)	(0.21; 0.40)	(0.30; 0.54)	(0.30; 0.52)
L_{50},blue$^{*)}$	14	9.0	7.9	7.4
η_{50},blue$^{*)}$	0.12	0.12	0.06	0.06
CIE(x; y)$^{*)}$	(0.10; 0.16)	(0.13; 0.15)	(0.08; 0.20)	(0.09; 0.18)
$d_{SrS:Ce}$(nm)	700	750	900	720
Codopants	Cl,Mn,"X"	Zn	none	F,Ga

$^{*)}$ as calculated from the measured spectrum using a fictitious color filter with T = 100 % ; $\lambda \leq 500$ nm and T = 0 ; $\lambda > 500$nm. Same voltage as for the unfiltered emission.

The lower luminance in the EB evaporated SrS:Ce is mostly due to a lower cerium concentration, which was used to maximize the emission in the blue spectral region.

In addition to the efficiency of the SrS:Ce phosphor film, the thicknesses of the SrS:Ce and ZnS:Mn films determine highly the shape of the spectrum of the SrS:Ce/ZnS:Mn "white" phosphor. The optimal choice of the thickness of the two phosphor films depends eventually on the desired color hues and color balance of the display taking into account that different fill-factors can be given to the different colors. Because the maximum driving voltage forms a constraint, the impact on operating voltage with increasing phosphor thickness must simultaneously be considered. Typically the SrS:Ce is at least twice as thick as the ZnS:Mn film. The electron injection in the two phosphor films and thus the efficiency of the "white" phosphor can be improved by separating the SrS:Ce and ZnS:Mn films with an intermediate insulating layer. Furthermore attention has to be paid to the optical properties of the dielectric layers in the film stack.

The luminance performance of state-of-the-art SrS:Ce/ZnS:Mn grown with ALE is summarized in TABLE 2. The data is obtained from a sample with an reflecting aluminum electrode using commercial color filters. The frequency of the excitation voltage was 60 Hz and the threshold voltage (194 V) was chosen so that the green luminance was equal to 1 cd/m^2.

TABLE 2

	Red	Green	Blue
L_{50}	97 cd/m^2	220 cd/m^2	11 cd/m^2
η_{50}	0.44 lm/W	0.99 lm/W	0.05 lm/W
CIE (x; y)	(0.62;0.37)	(0.42;0.54)	(0.13; 0.36)

There are very significant trade-offs between the luminance and the color hues of the green and the blue colors because of the shape of the SrS:Ce/ZnS:Mn spectrum, shown e.g in ref. [16]. The intensity of the SrS:Ce spectrum decreases rapidly in the deep blue region. For this reason significantly higher luminance is achieved if a deep blue color is not attempted. Similarly the green luminance is considerably enhanced by taking advantage of the intense ZnS:Mn emission spectrum. A yellowish green color gives much higher luminance than a deeper green color.

The situation is somewhat different when driving the SrS:Ce/Zns:Mn phosphor at a very high frequency as is the case in the head mounted AMEL display. Because of the saturation of the ZnS:Mn emission the relative intensity of the SrS:Ce emission increases for driving frequencies above 1 kHz. This gives a more balanced SrS:Ce/ZnS:Mn emission spectrum and as a consequence better color purity for the blue color and the green color, as can be seen in TABLE 3. The ALE grown SrS:Ce/ZnS:Mn phosphor was driven at 4.5 kHz voltage. An LC shutter color filter, similar to the one used in the AMEL display [17], was used in front of the dot sample.

TABLE 3

	Red	Green	Blue
L_{40}	110 cd/m^2	410 cd/m^2	35 cd/m^2
CIE (x; y)	(0.63; 0.36)	(0.29; 0.68)	(0.12; 0.20)

Status of TFEL Color by White Displays

A 0.7” diagonal full color VGA AMEL display with 256 colors has recently been developed [17]. A much larger color gamut was obtained by using a field-sequential fast nematic LC color shutter instead of patterned color filters. This also simplified the manufacturing process considerably.

A 5” diagonal color by white QVGA direct view display has also been developed [16]. A luminance of 70 cd/m^2 and a contrast ratio above 2:1 at 50,000 lx have been achieved. The color gamut is adequate for applications where the three primary colors must be present, but where full color is not needed.

Conclusions

Color by white TFEL gives several advantages in fabricating high resolution miniature color displays for head mounted applications and direct view displays with wide viewing angle, large temperature range and very good contrast.

The improvements in the luminous efficiency and the luminance stability of the SrS:Ce during the last few years indicate that the “white” SrS:Ce/ZnS:Mn phosphor can be deposited with the perfomance needed for “color by white” TFEL display applications.

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