

# EL Displays Based on ALE Grown Phosphors and Insulator Thin Films

A. Pakkala

Planar International Ltd., Espoo, Finland

## Abstract

The development and current performance status of electroluminescent (EL) displays based on Atomic Layer Epitaxy (ALE) grown phosphor and insulator thin films is reviewed in this paper. The performance of ZnS:Mn based monochrome and multicolor EL display products is discussed, as well as the development status of new phosphors for full color EL displays. The importance of high quality insulators is emphasized also.

## Introduction

Monochrome and multicolor EL displays are today widely used in industrial, medical electronics, instrumentation and transportation, as well as in special office applications. Excellent picture quality with wide viewing angle, fast response time and very wide operating temperature range, as well as a compact and reliable structure and very long lifetime, are the main characteristics of these displays. Over 250,000 EL displays are produced annually worldwide and the accumulated number of EL display installed in various end-user equipment is over one million.

Monochrome EL displays are based on a simple insulator-phosphor-insulator thin film structure, as shown in Figure 1 [1].

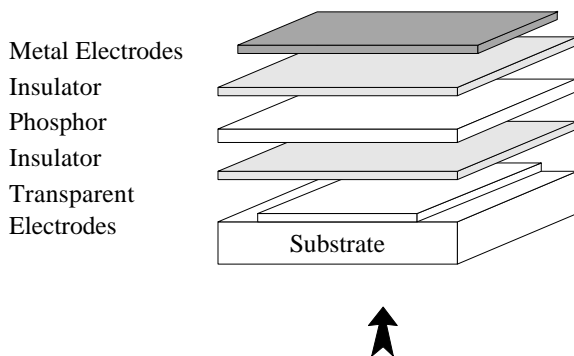


Figure 1. Monochrome EL display structure.

EL displays are built on transparent glass substrates. The ZnS:Mn phosphor layer which emits light under high electric field is the core of the structure. This phosphor layer is sandwiched between two current limiting insulating layers which are essential for the reliability and long lifetime of the device. Electrodes on top and bottom of the device complete the

capacitive thin film stack. At least one set of the electrodes is transparent for viewing of the emitted light. Finally this solid state thin film structure is encapsulated with a cover glass. EL displays based on this insulator-phosphor-insulator structure are made with a simple two photostep manufacturing process.

The non-linear luminance-voltage characteristics of the EL display, as shown in Figure 2, provide the device with the capability to be addressed at a high multiplexing ratio while maintaining excellent contrast over the whole viewing angle. This feature makes the EL devices suitable for high information content applications. These displays have also very wide viewing angles ( $> 160$  degrees both horizontally and vertically) and fast response, suitable for video rates.

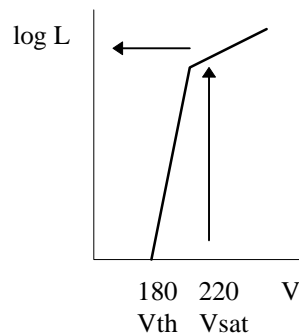


Fig. 2. Luminance-voltage characteristics of an EL device

The color EL displays are based on a filtered structure with a broad-band light emitting phosphor, the "Color by White" concept [2], [3], as shown in Figure 3.

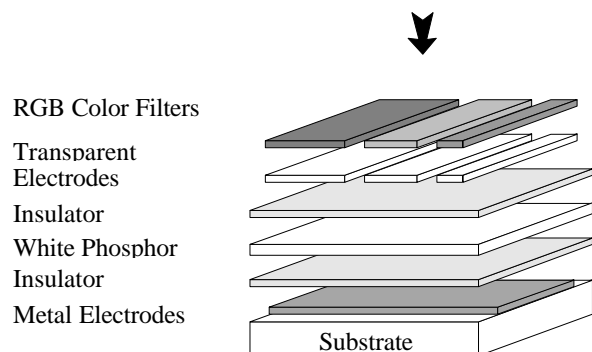


Figure 3. Color EL display structure.

The multicolor display products are based on the broad-band red-green emitting ZnS:Mn phosphor. A broad-band white light emitting ZnS:Mn/SrS:Ce phosphor is widely used in full color EL display prototypes. Also the “Color by White” EL display structures are made with a simple, two photostep, manufacturing process.

### Deposition Techniques for EL Displays

ALE technology is one of the deposition techniques used to produce phosphor and insulator thin film layers for EL display products. High vacuum evaporation is also widely used for phosphor deposition combined with sputtering processes to produce the insulator layers. In general the monochrome EL display products made with any of these deposition techniques have comparable performance characteristics.

Color EL phosphors are also grown with ALE technology. Other thin film deposition techniques used for color EL phosphor development are high vacuum evaporation, sputtering and various conventional CVD and MOCVD methods. The best color EL phosphor results have been achieved until now with UHV reactive evaporation [4] and reasonably good performance has also been achieved with ALE techniques [5].

### Development of the ALE Deposition Method

ALE is a method for producing thin film layers one atomic layer at a time by utilizing a self-control based on saturating surface reactions. ALE was originally developed to meet the needs of improved ZnS and insulator thin films for EL display devices [6], [7], [8], [9]. This goal was met and it led to commercial production of EL displays.

ALE method is based on separate surface reactions between the growing surface and each of the components of the compound, one at a time. The reactants are supplied to the growing surface in vapor phase, either as elemental vapors or as inorganic or organic volatile compounds of the elements. The general principle of the ALE process is described in Figures 4 and 5. Two options for the growth of ZnS are used as examples. In each reaction there are sites for only one monolayer to make a bond with the original surface. A basic condition for ALE growth is that the bond energy of a monolayer chemisorbed on a surface is higher than the bond strength of subsequent layers on top of the formed monolayer. The temperature of the substrate is used as the primary controlling parameter. The selection of the precursors is also important to achieve a practical process

window. The greater the difference between the bond energy of a monolayer and the bond energies of the subsequent layers, the better the self-controlling characteristics of the process are.

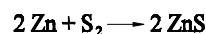
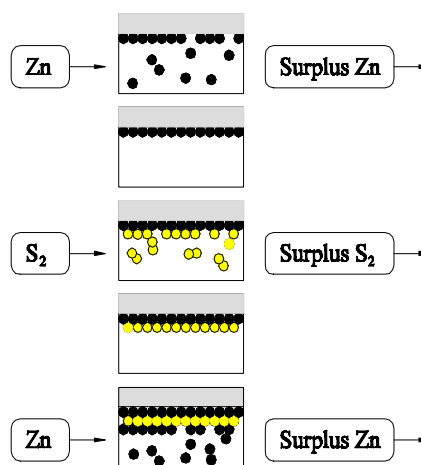


Figure 4. ZnS ALE process with Zn and S<sub>2</sub> as reactants.

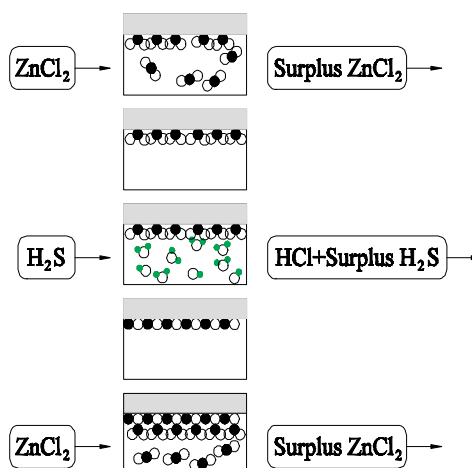


Figure 5. ZnS ALE process with ZnCl<sub>2</sub> and H<sub>2</sub>S as reactants.

The ALE process was demonstrated for the first time in 1974 in a high vacuum system with a rotating substrate holder for the sequencing, Figure 6. Mechanical tolerances between the substrate holder and the sources were extremely tight to minimize the leak of the source chemicals to the surrounding vacuum. Elemental zinc and sulphur were used to grow ZnS.

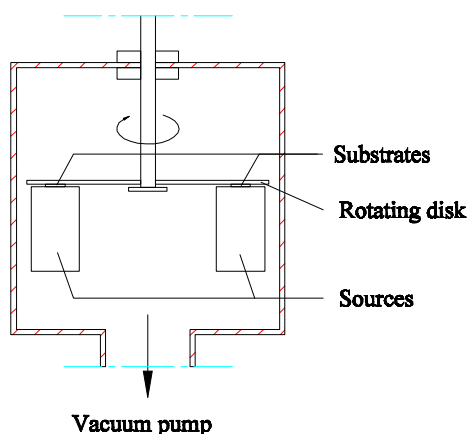


Figure 6. ALE reactor used in the first demonstration of the ALE process [6].

A carrier gas flow system is used in commercial production of EL display devices, Figure 7.  $ZnCl_2$ ,  $MnCl_2$  and  $H_2S$  are used as the reactants to grow  $ZnS:Mn$ . The carrier gas flow system utilizes effectively the saturation mechanism of a monolayer formation obtained in the ALE growth. Reactants with a reasonable vapor pressure, stability and reactivity are needed to grow thin films with ALE method in a carrier gas flow system, as the front end of the substrates receive a higher flux density than the downstream end of the substrate.

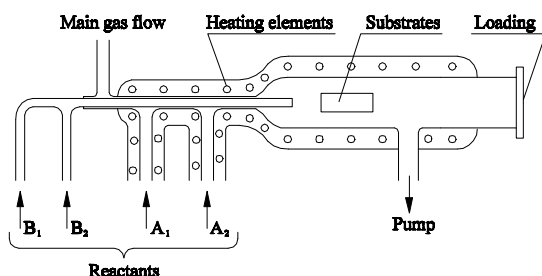


Figure 7. A carrier gas flow based ALE reactor [6].

### ZnS:Mn Based Device Structures for EL Displays

$ZnCl_2$ ,  $MnCl_2$  and  $H_2S$  are used as the reactants to grow  $ZnS:Mn$  to produce monochrome and multicolor, red-green-yellow, EL display products. The insulator-phosphor-insulator thin film stack is deposited on soda lime glass substrates in one single pumpdown in an automated batch process at a process temperature of 500C. Substrate sizes from 10" to 14" have been used. Typical phosphor performance values of the structures are shown in Table 1.

Recently  $ZnS:Mn$  based EL structures have been grown also by using organic reactants for Zn and Mn

[11], [12]. Diethyl zinc (DEZ),  $Mn(thd)_3$  and  $H_2S$  have been used as reactants. A lower deposition temperature below 400C is possible because of the higher vapor pressure of these organic compounds. The performance values of these structures are summarized in Table 1.

Table 1. ALE grown  $ZnS:Mn$  phosphor performance ( $L_{40}$  at 60 Hz, Al back electrode) [10], [11].

ALE process	Test dot luminance ( $cd/m^2$ )	Color coordinates (x, y)
$ZnCl_2$ , $MnCl_2$ , $H_2S$	440	0.52, 0.48
DEZ, $Mn(thd)_3$ , $H_2S$	430	0.54, 0.46

Examples of the performance of ALE  $ZnS:Mn$  based high contrast ICEBrite™ [13] monochrome and multicolor red-green displays are shown in Table 2.

Table 2. Performance of ALE based high contrast ICEBrite™ monochrome and multicolor red-green displays with a high contrast black background [12].

Display type	Frame rate (Hz)	Typical areal luminance ( $cd/m^2$ )
Monochrome 10.4" VGA	120	60
Monochrome 5.5" QVGA	240	120
Multicolor 10.4" VGA	120	25
Multicolor 5.5" QVGA	240	50

Due to its surface-controlled nature the ALE process is effective in step coverage and conformal coating of surfaces with micro-structures. This leads to the growth of pinhole-free thin films with a high breakdown strength. This feature is utilized also in the use of ALE grown insulator-phosphor-insulator films for miniature high resolution active-matrix electroluminescent (AMEL) displays [14].

### Phosphors for Color EL Displays

$ZnS:Mn/SrS:Ce$  based color EL phosphors have been developed using the ALE technique.  $ZnS:Mn$  is grown by using the organic reactants for Zn and Mn as described above.  $SrS:Ce$  is grown from  $Sr(thd)_2$ ,  $Ce(thd)_4$  and  $H_2S$  [10], [15]. Similar insulator are used as in the monochrome EL display devices. Table 3 summarizes the phosphor performance values. Examples of other color phosphor materials grown by ALE are  $ZnS:Tb$  for green [16] and  $ZnS:Sm$  and  $CaS:Eu$  for red [17].

Table 3. ALE grown ZnS:Mn/SrS:Ce phosphor performance ( $L_{50}$  at 60 Hz, Al back electrode) [12], [18]

Color	Test dot luminance (cd/m <sup>2</sup> )	Color coordinates (x, y)
“White”	480	0.49, 0.48
Red	97	0.62, 0.37
Green	220	0.42, 0.54
Blue	11	0.13, 0.36

### **ALE Grown Insulators for EL Devices**

The most widely used ALE grown insulator for EL devices is a mixed  $Al_2O_3/TiO_2$  structure with very good breakdown characteristics.  $AlCl_3$ ,  $TiCl_4$  and  $H_2O$  are used as reactants. Examples of other insulator materials grown by ALE are  $Ta_2O_5$  [17],  $ZrO_2$ ,  $HfO_2$  and  $Y_2O_3$  [18]. Excellent results have also been achieved with ALE grown mixed structures of  $Al_2O_3/Ta_2O_5$ ,  $Al_2O_3/ZrO_2$  and  $Al_2O_3/HfO_2$  [19].

### **Summary**

Monochrome EL displays have established an important position in the fast growing flat panel display markets. Excellent picture quality with wide viewing angle, fast response time and wide operating temperature range, as well as a compact and reliable structure, are the main characteristics of the displays. EL devices have also a simple structure which forms the basis for the high manufacturing yields. The future development of ALE processes for EL display applications is focused on further enhanced performance of monochrome and multicolor displays for high ambient light application and on the development of phosphors for the first full color EL display products.

### **Acknowledgments**

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