Reduction of defects and improvement in the performance of blue phosphor for thick-dielectric electroluminescent displays using Color-by-Blue

Hisashi Abe Isao Yoshida Hiroki Hamada Derek Luke Yongbao Xin Yue Xu Rong Yang Eiric Johnstone Joe Acchione Paul Balmforth **Abstract** — Defect-free large-area inorganic thick-dielectric EL (TDEL) displays using Color by Blue (CBB) technology have been successfully developed. We have achieved the world's highest blue-phosphor luminance of 900 cd/m² for a single-pixel device by using CBB and by optimizing the e-beam gun configuration and the flow rate of H₂S in the vacuum chamber. By analyzing the defects on panels with triple-pattern phosphors and CBB panels, we also found that the number of defects on CBB panels can be drastically reduced compared with those on triple-pattern panels. The defect-free 17-in. VGA CBB panels show better characteristics, a high peak luminance of 600 cd/m² and a high contrast ratio of 1000:1, compared with those of triple-pattern panels.

Keywords — $BaAl_2S_4$, blue phosphor, Color-by-Blue, electroluminescence, flat-panel displays, thick-film hybrid.

TABLE 1 — Current state of flat-panel displays.

1 Introduction

Recently, flat-panel-display television has entered the TV marketplace. Although liquid-crystal displays (LCDs) and plasma-display panels (PDPs) are the dominant flat-panel technologies in the today's marketplace, they still have technological problems as shown in Table 1. Recently, many researchers and engineers have been developing new flat-panel-display technologies such as field-emission displays (FEDs),¹ organic light-emitting-diode (OLEDs) displays,² and inorganic electroluminescent displays (IELDs)³ in order to realize a hang-on-the-wall TV. We have developed the world's first full-color thick-dielectric EL (TDEL) displays⁴ and progress in developing large-sized TDEL displays has been made. Among the new flat-panel displays, TDEL is the leading candidate for the realization of hang-on-the-wall TV because of its advantage of light weight.

The development of inorganic EL technology began with the discovery of high-field electroluminescence in 1936.⁵ Then various technologies were invented, such as luminescence from molecular centers, LUMOCEN⁶; highluminance and long-lifetime ac thin-film EL displays⁷; multicolor emission from CaS- and SrS-based thin-film EL⁸; *etc.* However, high-luminance full-color EL did not appear until quite recently because high-luminance blue phosphors for EL had not yet been developed. Miura *et al.* have developed a new blue phosphor, europium-doped barium thioaluminate (BaAl₂S₄:Eu).⁹ This phosphor has the potential to produce a practical inorganic EL display. More recently, iFire Technology reported a high-luminance blue phosphor, Mg_xBa_{1-x}Al₂S₄: Eu,¹⁰ which has almost the same potential

Features	TDEL	PDP	LCD	FED
All Solid State	0	×	×	×
Rapid Video Response Speed	0	0	Δ	0
Unrestricted Viewing Angle	0	0	Δ	0
Power Consumption	Δ		0	0
Contrast (under bright room)	0	\bigtriangleup	0	\bigtriangleup
Luminance	0		0	0
Weight / Thickness	0		Δ	Δ
Resistant to Temperature Variation	0	0		0

as BaAl₂S₄:Eu. The addition of Mg enables the process temperature to be reduced. A full-color display requires three colors: red, green, and blue. "Triple-patterned phosphor" technology, which emits three colors in a pixel, and "Colorby-White" technology, which changes white light into three colors by the use of a color filter, can be used to obtain a full-color display. But they have some problems; for example, the process is complex and the efficiency is bad, respectively. Recently, we have developed CBB technology¹¹ by applying the principle of color conversion technology, which changes the blue color into red and green colors through color-changing materials. And we have shown that CBB technology has some advantages: a simpler process, less

telephone +81-72-841-1446, fax -1447, e-mail: h_abe@rd.sanyo.co.jp.

Revised version of a paper presented at the 10th International Displays Workshop (IDW '03) held December 3–5, 2003 in Fukuoka, Japan. H. Abe, I. Yoshida, and H. Hamada are with SANYO Electric Co., Ltd., 1-18-13, Hashirdani, Hirakata-City, Osaka, Japan;

Y. Xin, J. Acchione, Y. Xu, P. Balmforth, E. Johnstone, and R. Yang are with iFire Technology, Inc., 15 City View Drive, Toronto, Ontario, Canada M9W 5A5.

D. Luke is with Idealzon, Inc., 3100 Steels Ave. West, Suite 401, Vaughan, Ontario, Canada L4K 3R1.

[©] Copyright 2004 Society for Information Display 1071-0922/04/1203-0275\$1.00



FIGURE 1 — Electron-beam evaporation system.

expensive, and higher yield. Brighter blue-phosphor materials are needed in order to make CBB technology practicable.

We also investigated the defects of TDEL panels in order to improve the display quality, and we have reported that TDEL panels are tolerant of particle-related defects introduced during the fabrication processes.¹²

In this paper, we report on the improvement of the blue-phosphor performance needed to realize CBB technology, and present a detailed analysis of the defects of TDEL panels and the characteristics of high-quality 17-in. VGA TDEL display panels.

2 Improvement in blue-phosphor performance

It is necessary to develop a blue phosphor with a higher luminance in order to realize TV application. We have developed a high-luminous blue phosphor based on europium-doped barium thioaluminate, "G2" blue.¹³ This enabled the achievement of a blue luminance on a 17-in. panel which was sufficient when combined with the color-conversion materials, resulting in a white luminance of 600 cd/m².

Figure 1 shows a schematic of the electron-beam (EB) evaporation system. The luminance of the blue phosphor was increased by using an improved system as described below.

The thickness and composition uniformity of the bluephosphor film was improved by increasing the number of



FIGURE 2 — Uniformity of Al/Ba ratio and thickness of the blue phosphor films (four guns vs. two guns).



 $\ensuremath{\text{FIGURE 3}}\xspace - \ensuremath{\text{PL}}\xspace$ intensity of blue-phosphor films with different flow rates of $\ensuremath{\text{H}}\xspace_2 \ensuremath{\text{S}}\xspace$ gas.

EB guns to four from two; two guns for aluminum sulfide and two for europium-doped barium sulfide. Figure 2 shows the thickness and composition uniformity resulting from a number of two- and four-gun runs. The variations compared with an average value were derived from a panel (410×305) mm) and silicon monitor wafers. The evaporation rate was about 0.6 nm/sec. The average thickness and Al/Ba ratio were 400 nm and 3.3, respectively. The improved thickness and composition uniformity was achieved through the use of a simpler shadow-mask design made possible by a four-gun configuration as well as by a higher deposition rate for the phosphor film on the panel substrate that reduced the concentration of the contaminant species from the deposition atmosphere. The reduction in defect density and the contaminant species in the phosphor film was achieved by improving the deposition from the source material handling to the unloading of panels from the deposition apparatus.

A further improvement in the phosphor-film characteristics was also achieved by increasing the flow rate of H_2S gas in the vacuum chamber during the phosphor-deposition process to help ensure that the phosphor material was fully saturated with sulfur. The photoluminescence (PL) intensities for different flow rates of H_2S gas are shown in Fig. 3. The X-Y plane view shows a 17-in. panel. The variation in the PL intensity in a 17-in. panel was decreased from 45%



FIGURE 4 — L–V curves with different flow rates of H_2S gas.



FIGURE 5 — Structure of the TDEL panels using triple pattern technology and CBB technology.

to 20% by using a four-gun configuration with a higher flow rate of the H_2S gas. The use of a higher flow rate for H_2S gas also improved the quality of the G2 blue phosphor film. We think that the vacancies of the G2 blue phosphor film were compensated by the sulfur atoms in H_2S gas. The data from the x-ray diffraction (XRD), energy dispersive x-ray (EDX), and electron spectroscopy for the chemical analysis (ESCA) supports our estimate. The XRD data showed improvement in the crystallinity. The EDX and ESCA data showed a small reduction in the oxygen content in the phosphor film. We think that H_2S gas also prevented contamination by oxygen and H_2O in the evaporation chamber.

Figure 4 shows the luminance–voltage characteristics of typical samples for different flow rates of H_2S gas during phosphor deposition. The maximum luminance of the blue phosphor with a higher flow rate of H_2S gas is as high as 900 cd/m² and it is nearly twice that of the low flow rate of H_2S gas. The driving source is a 240-Hz pulse drive. Table 2 shows that the resulting CIEx, CIEy, and wavelength of both films are same for each condition.

3 Defects reduction

Figure 5 shows the structure of our TDEL panels for the combination of conventional triple-pattern technology and CBB technology. The panels consist of the substrate, printed row electrode, screen-printed thick-dielectric, phosphors, upper insulator, ITO, metal column electrode, and color filters or color-conversion materials (CCM). They are simple structures and we can produce panels cheaper than other flat-panel displays because they do not require a fine structure like that for a TFT-LCD.

TABLE 2 — Characteristics of blue phosphors with different flow rates of H_2S gas.

_	4 Guns		
H ₂ S Flow rate	H ₂ S: 28sccm	H ₂ S: 43sccm	
Luminance (L60) (cd/m^2)	401	718	
Vth (V)	186	178	
CIEx	0.14	0.14	
CIEy	0.10	0.10	
Wavelength (nm)	472	472	

(Measured at 240 Hz, 60 V above threshold)



FIGURE 6 — Distribution of different defects on a triple pattern panel.

Several strategies were employed to detect defects incorporated into the display structure during fabrication. Fully processed 17-in. triple-pattern test panels were inspected at various stages of the process to determine the types of defects and the spatial distribution of defects at each stage of the fabrication process, as shown in Fig. 6. We categorized the defects as "particle," "dark spot," and "fiber." Particle means a particle-related defect, dark spot means a defect without an alien substance, and fiber means a fiberrelated defect, respectively. Only defects greater than $30 \,\mu\text{m}$ were considered because the space between the ITO lines was 40 µm. Once a defect was located, it was photographed and the XY location was recorded. This resulted in a visual record of how a defect changed in appearance as the panels were processed through the fabrication process. The impact of each defect found was thus assessed after full process fabrication was complete. Scanning electron microscopy (SEM), focused ion bean (FIB), energy dispersive x-ray (EDX), and Auger electron spectroscopy (AES) were used to investigate a representative sample of each defect category.



FIGURE 7 — Distribution of open/short defects on a triple pattern panel.



FIGURE 8 — Process flows of a triple pattern panel and a CBB panel.

Figure 7 shows the open/short map of the image artifact for a triple-pattern panel after all processes. Many defects, such as particles, fiber dark spots, *etc.* discovered during the "inline defect assessment" were seldom found to affect display image quality. We think that the performance and image quality of TDEL displays is insensitive to inline defects introduced during the fabrication process.

Moreover, we produced defect-free panels using CBB technology¹¹ because the CBB technology has fewer process steps than traditional triple pattern technology¹⁴ as shown in Fig. 8. The CBB process eliminates two EB or sputter depositions and three patterning processes. These are replaced by two simple thick-film print processes. Figure 9 shows the total number of defects and open/shorts for the triple-pattern panel and CBB panel after all the processes. Fewer process steps for the CBB technology reduced the number of defects. From these results, CBB technology will give us a higher yield during the mass-production stage.

4 Panel performance

The features of the fabricated TDEL panels, both for the triple-pattern panel and the CBB panel, are summarized in



FIGURE 9 — Total number of defects on a triple pattern panel and a CBB panel.



FIGURE 10 — Image of a 17-in. VGA panel using CBB technology.

Table 3. The characteristics of the CBB panel are superior to those of the triple-pattern panel. Specifically, the defects in the CBB panel are very few because the CBB technology has fewer process steps than the triple-pattern technology. The improvement of the blue-phosphor deposition process made the peak luminance and the average contrast ratio of the CBB panel higher. We believe that the CBB panel will facilitate the realization of a higher yield and lower cost in the mass-production stage.

Figure 10 shows a photograph of a CBB panel. Few defects after all the processes were completed were repaired. Both good image quality and a defect-free panel was achieved by using CBB technology.

5 Conclusion

Defect-free 17-in. VGA TDEL displays have been successfully developed by using Color by Blue (CBB) technology. The world's highest blue-phosphor luminance of about 900 cd/m² for a 240-Hz pulse drive in a single-pixel device has

TABLE 3 — Characteristics of Typical TDEL Panels.

	Triple pattern panel	CBB panel
Diagonal size	17-inch	17-inch
Format	640*480*3	640*480*3
Number of colors	16.77 million	16.77 million
Peak luminance (cd/m ²)	350	600
Uniformity	70 %	70 %
Average contrast ratio (under dark room)	250:1	1000:1
White CIEx	0.30	0.27
White CIEy	0.32	0.29
White CIE range	0.05	0.01
Defects	10	0
Thickness (mm)	30	30

been achieved by optimizing the EB gun configuration and the flow rate of H_2S in the vacuum chamber. We have developed a CBB process which has fewer process steps than that for the triple pattern process. The number of defects on CBB panels is fewer than that for triple-pattern panels. We found that characteristics of a CBB panel, such as luminance and contrast ratio, are superior to those of triple-pattern panels.

References

- 1 S Uemura, J Yotani, T Nagasaka, H Kurachi, H Yamada, T Ezaki, T Maesoba, T Nakano, Y Saito, and M Yumura, "Large-Sized CNT-FED," *Proc IDW* '02, 1025 (2002).
- 2 K Mameno, R Nishikawa, K Suzuki, S Matsumoto, T Yamaguchi, K Yoneda, Y Hamada, H Kanno, Y Nishio, H Matsuoka, Y Saito, S Oima, N Mori, G Rajeswaran, S Mizukoshi, and T K Hotwar, "Development of 2.2-in. Full-Color AMOLED Display for Mobile Applications," *Proc IDW* '02, 235 (2002).
- 3 J Hirabayashi, Y Yano, M Susukida, and K Nagano, "Filtered and Filter-Less Full-Color Inorganic EL Displays," SID Symposium Digest 34, 1106 (2003).
- 4 D Seale and X Wu, "Full-Color Solid-State EL Display," *Proc IDW* '99, 861 (1999).
- 5 G Destriau, "Recherches sur les scintillations de zinc aux rayons," J Chim Physique **33**, 587 (1936).
- 6 D Kahng, "Electroluminescence of Rare-Earth and Transition-Metal Molecules in II-VI Compounds via Impact Excitation," Appl Phys Lett 13, 210 (1968).
- 7 T Inoguchi, M Takeda, Y Kakihara, Y Nakata, and M Yoshida, "Stable High-Brightness Thin-Film Electroluminescent Panels," *SID Symposium Digest* **5**, 84 (1974).
- 8 S Tanaka, V Shanker, M Shiiki, H Deguchi, and H Kobayashi, "Multi-Color Electroluminescence in Alkaline-Earth-Sulfide Thin-Film Devices," *SID Symposium Digest* 15, 218 (1985).
- 9 N Miura, "BaAl₂S₄:Eu Phosphors for Full-Color EL Displays," Proc Asia Display/IDW '01, 1059 (2001).
- 10 D Cheong, A Nakua, and P D B Pelluz, "Mg_xBa_{1-x}Al₂S₄:Eu Blue Phosphor in Thick-Dielectric EL," SID Symposium Digest 33, 105 (2002).
- 11 X.Wu, A Nakua, and D Cheong, "Full-Color Inorganic EL Displays by Color Conversion," *Proc IDW* '03, 1109 (2003).
- 12 D Luke, R Yang, D Briglio, H Abe, I Yoshida, and H Hamada, "Optical and Electrical Characterization of Particle-Related Defects in Large-Area Inorganic Thick-Dielectric Electroluminescent Displays," *SID Symposium Digest* 34, 1114 (2003).
- 13 X Wu, "The Quest for the Ideal Inorganic EL Phosphors," Proc Asia Display/IDW '01, 1055 (2001).
- D Seal, L Rodriques, C Werner, and D Irvine, "Self-Aligned Phosphor Patterning Techniques for Inorganic EL Displays," SID Symposium Digest, 109 (2002).



Hisashi Abe received his B.S. degree in physics from Kobe University, Japan, in 1981. He joined SANYO Electric Co. Ltd., Osaka, Japan, where he worked on the development of semiconductor lasers and LCDs. Since 2002, he has been working on the development of Inorganic EL displays. He is a member of the Society for Information Display and the Japan Society of Applied Physics.



Isao Yoshida received his B.E. degree in industrial chemistry from Kobe University, Japan, in 1983 and M. E. degree in molecular engineering from Kyoto University, Japan, in 1985. In 1985, he joined SANYO Electric Co., Ltd., and was engaged in compound semiconductor superlattices, High-Tc oxide superconductor thin films, and its electronics devices. He received his Ph.D. from Kobe University in 1996. He has worked on the development of inorganic EL displays since 2002. He is

a member of the Society for Information Display, the Chemical Society of Japan, the Japan Society of Applied Physics, and the Institute of Electronics, Information, and Communication Engineers.



Hiroki Hamada received his B.S., M.E., and Ph.D. degrees in electronic engineering from Kinki University, Japan in 1975, 1977, and 1980, respectively. In 1980, he joined SANYO Electric Co. Ltd., Osaka, Japan, where he was engaged in the research and development of semiconductor laser for compact disk (CD) and digital video disk (DVD). In 1992–2002, he was engaged in the research and development of low-and high-temperature-processed poly-Si TFT-LCDs and active-

matrix OLEDs. Since 2002, he has been working on the development of inorganic EL displays. He is currently a senior manager of the Material and Devices Development Center Business Unit. He received the best paper award in 2003 from the IEICE for the development of HD-LCD light valves using poly-Si TFTs. He served as a program committee member of AMLCD '96 through AMLCD '01, the program chair of AMLCD '02, a program committee member of the workshop on Active-Matrix Displays at IDW '97-'99 and IDW '02-'03, chair of the workshop on Active-Matrix Displays at IDW '00-'01, chair of AMLCD '04, program committee member of the workshop on Active-Matrix Display at IDW '04, and as an editor of the IEICE. He is an author or co-author of over 100 technical papers and conference papers, and an author of two books chapters on low-temperature-processed poly-Si TFT-LCDs. He has applied for over 100 foreign and domestic patents. He is a senior member of the IEEE LEOS & ED, and a member of the Society for Information Display, the Japan Society of Applied Physics, the Laser Society of Japan, and the Institute of Electronics, Information, and Communication Engineers of Japan.



Yongbao Xin received his B.Sc. degree in physics from Lanzhou University, China, in 1983, and his M.Sc. degree in physics from Shandong University, China, in 1990. He obtained his Ph.D. degree in physics from the Chinese University of Hong Kong in 1996, and then worked as a postdoctoral fellow at Georgia Institute of Technology, Atlanta, GA, U.S.A. In 1999, he joined iFire Technology, Inc., in Toronto, Canada, as a Research Scientist, working on the research and development of new

phosphor materials and processes. He holds several patents and has authored numerous technical papers related to new phosphor materials. He is a member of the Society for Information Display.



Yue Xu received her B.Eng. in electrical and electronic engineering from HuaZhong University of Science and Technology, WuHan, China, in 1982 and in 1994, respectively, and obtained her Ph.D degree from the Laboratory of thin-film materials for microelectronics at the University of Bordeaux in France. She jointed iFire Technology, Inc., in Toronto, Canada, in 1999 and has been engaged in the development of thin-film materials and processes for TDEL display technology.



Rong Yang received her B.Sc. degree in the physics and chemistry of semiconductors from the Shanghai University of Science and Technology, China, in 1988. She has been working at Chartered Semiconductor Manufacturing, Ltd., in Singapore, and National Semiconductor, Motorola in China. Mainly she has working experience as a process engineer, quality assurance engineer, etc. In 2001, she joined iFire Technology, Inc., in Toronto Canada, as an engineer in the integration

group, working on the defect reduction for EL displays.



Eiric Johnstone, Applications Manager, is a seasoned member of the iFire engineering team and has been responsible for various panel assembly, testing, design, and development projects. He joined iFire in 1997 as an electronics engineer, working on the development of panel control and driving systems. He was later advanced to lead the applications team, where he has been involved in several panel evaluation and testing programs. His current accountabilities include defining

iFire[™] panel specifications, product planning, as well as providing technical expertise and support for business development. He holds a B.Sc. degree with Honors from the University of Alberta and a B.Eng. in electrical engineering from the University of Alberta. He is a member of the Society for Information Display.



Joe Acchione received his Electronic Technologist Diploma form Humber College in Toronto, Canada, in 1982 and his B.Sc. degree from Lakehead University, Canada, in 1986. He has acquired almost 20 years of experience in manufacturing and has worked for various companies such as Motorola Information Systems in Toronto, Canada. In 1986, he joined Litton Systems in Toronto, Canada, where he worked in several fields including ring laser gyro inertial navigation systems

manufacturing and LCD manufacturing for military avionics application. During his career at Litton Systems Canada, he held various positions including Director of the product services organization. In 2000, he joined iFire Technology, Inc., in Toronto Canada as a Manager of the Thin Film section working on developing new materials, processes, and equipment for manufacturing TDEL displays. He is a member of the Society for Information Display.



Paul Balmforth received his B.Sc. (Hons) degree in physics from Lancaster University, U.K., in 1979. He immediately joined the microelectronics industry starting with General Instruments as a process engineer, moving on through the next 20 years to INMOS, National Semiconductor, and Seagate Microelectronics, working in various manufacturing, development, and integration engineering roles up to and including the Director level. In 1999, he joined iFire Technology, Inc., in Toronto,

Canada, as a research manager, building and managing a team of scientists and engineers to accelerate the development of the iFire TDEL technology. In 2002, he assumed the role of Baseline and Integration Manager, concentrating on scaling materials and process advancements to large-panel applications. He is a member of the Society for Information Display.



Derek Luke has an undergraduate degree in physics from Strathclyde University and a post-graduate degree in applied statistics from Napier University. He is currently the Vice President of Research & Development and Manufacturing for Ideazon Inc., a start-up company designing innovative and interchangeable gaming and other custom keyboards. He is responsible for windows driver development, hardware and electronics design, system integration and offshore manufac-

turing. Prior to Ideazon, he held various technical and operations positions at iFire Technology, Inc., was a Director of Product Development at Seagate, and has also held technical positions in Digital Equipment Corp. and Motorola.