Phosphor challenge for field-emission flat-panel displays

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(Received 25 August 1996; accepted 4 November 1996)

The requirements of low-energy excitation combined with practical constraints of commercial supply and other issues, mandate the use of readily available commercial CRT phosphors, such as ZnS and Y_2O_3-based P22, for first-generation field-emission flat-panel displays. The use of these phosphors at low (e.g., $\leqslant$2–4 kV) excitation energies places considerable problems with brightness, efficacy, spectral response, long-term reliability, screen manufacture and materials synthesis, surface conditioning and outgassing protection, and low-cost manufacturing. The tradeoffs imposed by using phosphors designed for optimum performance in the 15–30 kV range at the low voltages employed by field-emission displays are presented and discussed. © *1997 American Vacuum Society.* [S0734-211X(97)01202-X]

I. BACKGROUND

The use of field-emission cathodes to illuminate cathodoluminescent phosphors in a flat-panel display has been proposed for decades; however, this was not experimentally demonstrated until recently[1] and extended to full color, using red-green-blue (RGB) phosphor ''triplets'' since that time.[2] The fact that RGB phosphor triplets for color television and CRTs have been commercially available for over 30 years does not assure that these are applicable to the field-emission display (FED). In fact, the architecture of the FED is such that commercial CRT phosphors are not optimum, and consequently there are challenges to overcome in using RGB triplets in this new display configuration.[3] Specifically, (a) CRT phosphors are operated at very high acceleration voltages, typically 13–30 kV, and such high voltages require significant anode-cathode spacing (e.g., $>$1 cm) to prevent vacuum breakdown, arcing and associated destructive consequences such as field ionization of the surfaces. (b) Operation of FEDs with closer anode-cathode spacing, such as 1 mm, can be achieved at lower voltages, such as 2–4 kV; however, this spacing is still problematic. Making invisible ''spacers'' which separate anode and cathode uniformly, is complex and potentially expensive. Also, the field-emission beams need to be aperture focused or co-planar focused[4] (if resolution, such as 100 lines/in., as found in SVGA displays, is to be obtained) and standard CRT phosphors do not perform well at such voltages. To overcome the focusing constraint, anode-cathode spacings need to be quite close, such as in the 10–200 μm range, and acceleration voltages need to be well less than 1 kV. Some of the focusing requirements can be eased by switching the anode potential between selected colors in the RGB triplet, such as done in the LETI prototype color display;[2] however, because of the potential arcing between grounded and charged phosphors on the anode plate, the magnitude of the anode potential still must be kept low. Finally, (c) the close proximity between anode and cathode create a low conductance vacuum condition within the system, requiring complex gettering techniques if the high-vacuum routinely obtained in CRTs is to be obtained. This vacuum requirement is especially important with field-emission devices which are well documented to be susceptible to poisoning, microplasma generation, and pressure-dependent noise phenomena.

Phosphor triplets operating optimally at $<$1 kV are not commercially available at present. Research in this topic is the focus of several groups, including the ARPA-funded consortium of American Universities, National Labs and Industries known as the Phosphor Technology Center Of Excellence (PTCOE). Even if an optimum triplet is discovered in the near future, there are significant supply problems to be surmounted: whereas CRT phosphors are based on ZnS, In_2O_3, and other commonplace elements, the new phosphors being explored employ rare-earth elements and other materials which may present a challenge to phosphor manufacturers which must supply enormous quantities to the display industry. Until such time as a breakthrough in low-energy phosphors for FEDs occurs, the only viable option is to use focused field-emission beams with mm-scale anode-cathode spacings and to operate with commercially available phosphors at low kV (e.g., lower than optimal) acceleration. This overview discusses the technical challenges of such an approach.

II. EXCITATION ENERGY, PENETRATION DEPTH, AND EFFICIENCY

The maximum brightness required of a CRT is typically 70 $\mathrm{Cd\,m^{-2}}$ (or ''nit''), in use as a monitor, and above 300 $\mathrm{Cd\,m^{-2}}$ if used for television. This end-user requirement dictates the acceleration energy necessary given the current limits of the cathode array and the output from any specific phosphor screen type. Using the PTCOE reference standard, the P-22 RGB triplet,[5] regardless of the screen deposition method, these brightness requirements cannot be met with less than approximately 2 kV acceleration voltage. This can be considered a practical lower limit for viable use of commercial CRT phosphors in FEDs.

There are several possible dominant mechanisms which limit the low-energy brightness. Because the penetration

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depth is low, the emission is typically a surface-dominated phenomenon. One possible limitation is the low number of excitation centers, or dopant ‘‘activators’’ which exist in the volume of phosphor which is penetrated and subsequently excited by either primary or secondary electrons within the anode screen; this number of centers has been modeled and it is projected there are simply insufficient carrier transitions to provide the required brightness.[6] The second, and more material-specific problem, is that surface recombination events, or possibly nonradiative events in the surface layers, may limit otherwise efficient bulk phosphors from acceptable luminescence when operating in a surface-dominated mode. It is possible that H_2 passivation or some other surface treatment technique will improve performance, but no definitive data has been published yet supporting these methods.

The efficacy of a phosphor is an important figure of merit of its operation within a system. The standard ‘‘efficiency’’ unit is Lumens/Watt (1 Footlambert flux over 1 square foot consuming 1 W); however, the efficiency, measured with radiometric detectors, which have flat response over the visible spectrum, is not equivalent to the efficacy, which is a measure of human response. The reason for this inequivalence is due to the variable response of the human eye over the color spectrum. As a consequence, phosphors in a display system are generally not optimally equal in efficiency, but should be nearly equivalent in efficacy. There is some confusion in analyzing published efficiency data because some spectrophotometers are corrected for human response and are actually measuring efficacy.

Phosphor triplets are virtually never equivalent in efficacy and the most efficient of the three primary colors not only varies with chemical composition but also with excitation energy. For example, at 4 kV the P22 green phosphor has been recorded as high as 43 Lumens/Watt (23% relative efficiency), P22 red is 8 Lumens/Watt and the P22 blue is correspondingly 4.5 Lumens/Watt.[5] The reduction in efficiency at 0.5 kV is nonlinear: green is 7, red is 0.8, and blue is 0.5 Lumens/Watt. The human eye, normalized to the green, its most sensitive color, requires about 7% greater red brightness and almost 80% greater blue brightness for average equivalent response. It is evident that the color the human eye is least sensitive to (blue) is also the color for which our available phosphors are least efficient. Furthermore, the relative efficiencies of the RGB triplet are mismatched with the relative brightness needs in human response. Consequently, a display system must compensate for these mismatches by under/overdriving each pixel according to its color, attenuating overbright colors with gray filtering, or damping the brightest colors by either depositing smaller or thinner phosphor spots. Therefore, performance is virtually certain to be compromised either in electronics or in luminescent efficiency.

III. SPECTRAL RESPONSE

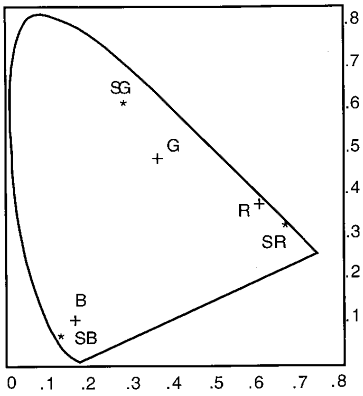

FIG. 1. CIE 1931 chromaticity diagram showing the color coordinates of (a) the RGB triplet P22 standard phosphors used as a reference by the ARPA-PTCOE, marked with *, and (b) the ‘‘low-voltage’’ YAG:Eu (red), YAG:Tb (green), and Y_2SiO_5:Ce (blue) phosphors studied (Ref. 7) as a possible FED replacement, marked with a +.

The relative color space of RGB triplets are essentially never equivalent. Figure 1 shows the 1931 CIE relative color space of the P22 CRT phosphors and the relative color space of a ‘‘low-voltage’’ triplet of YAG:Eu, YAG:Tb, and Y_2SiO_5:Ce which we are investigating.[7] The inequivalence does not result in an inapplicability of one or the other triplet to a full-color display; but it does require different primary color mixing to obtain faithful rendering of color images. Furthermore, certain triplets which do not sufficiently separate the primaries in color space may produce some unsatisfactory mixed colors. The selection of a triplet becomes a judgment of what comprises a least offensive compromise in overall color performance.

A similar tradeoff exists in low-voltage spectral output. Figure 2 demonstrates an RGB triplet with the relative spectral output. It is clear that the phosphors which produce either doublets or broad band output will give indistinct, muddy or white appearance on a screen. For best performance in a display, it will be necessary to have distinct monochromaticity in each primary of the triplet.

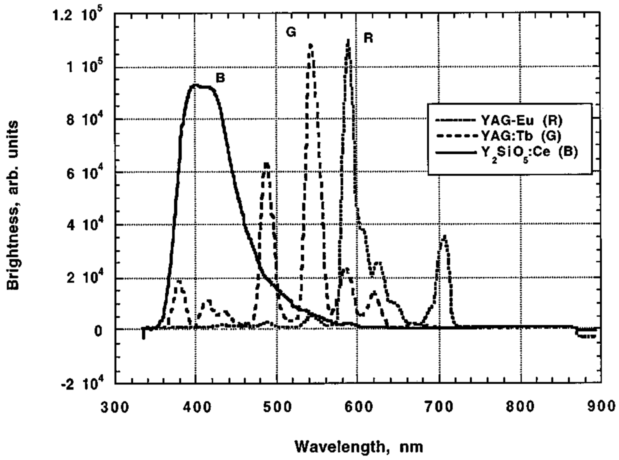

FIG. 2. Brightness vs wavelength of typical ‘‘low-voltage’’ phosphors earmarked for FED applications. The evident satellite intensities (R and G) result in poor color saturation, especially in green. Broadband emission, often seen (such as B here) in this class of phosphors, gives an unpleasant ‘‘muddy’’ appearance.

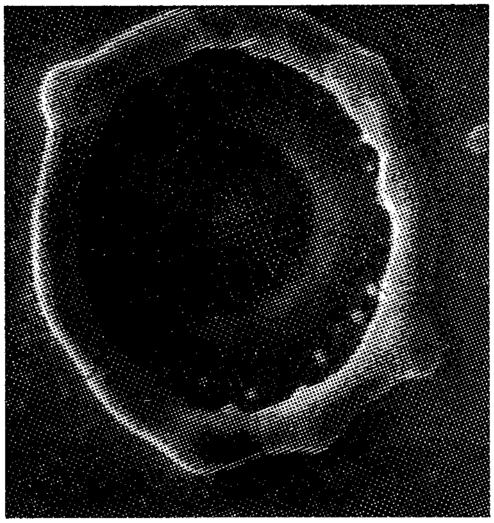

FIG. 3. Failed field-emission cathode with stoichiometric phosphor residue on the rim of the damaged gate. Trace phosphor desorbed from the anode ionizes and is electrostatically attracted and deposited on the gate metal during operation in a display with a nonaluminized screen.

IV. SCREEN DESIGN, RELIABILITY, ALUMINIZATION, AND ELECTROSTIMULATED DESORPTION

The use of lower energy with phosphors introduces the need to re-examine the screen fabrication methods. Traditional silk screening or printing of powder phosphors may be unsatisfactory because the inferior surface condition and the dielectric nature of the phosphor grains. Superior methods for low-energy surface-activated cathodoluminescence will likely incorporate thin-film rf sputter,[8] or possibly electrophoretic, deposition of the phosphor[9] onto a transparent conductor such as indium-tin oxide (ITO). Furthermore, the traditional techniques of grinding bulk phosphors into powders with appropriate grain size for low-energy operation may introduce excessive defect density to the materials such that the efficiency of the phosphor is further degraded. This may require the use of novel fabrication technology for obtaining the phosphor grains, such as combustion synthesis[10] which can decrease the defect density sufficiently. The need to use these various techniques will increase the complexity and cost of the display system.

It is well known that the electron beam can have deleterious effects on the anode screen. The momentum transfer can physically damage and dissociate phosphor materials. If these dissociated materials are ionized by the beam, they are attracted to the field emitters and can contaminate the gate regions. Figure 3 is an electron micrograph showing dislodged phosphor materials which have deposited over time on the periphery of the gate of the field emitter and likely caused the eventual failure of the emitter. Auger microprobe analysis has confirmed that this deposit is the stoichiometric phosphor material.

The stability of the screen can be improved by coating the anode screen with a thin aluminum layer. This has the triple benefit of (a) modest (although imperfect) encapsulation of the phosphor, (b) providing a simple, low-cost ground path for the beam electrons coming out of the phosphors, and (c) reflection of the rearward-directed light back forward to the viewer, giving an ‘‘effective’’ improvement in phosphor efficiency. The solution requires extra acceleration energy to allow the primary electrons to penetrate the aluminization layer; correspondingly, there is an increased spacing needed between the cathodes and anode. This increased spacing requirement, and the resulting beam focusing requirements, may be significant since the energy loss in an minimal aluminization layer is about 2 kV: e.g., comparable to the excitation energy desired for the phosphor.

Regardless of whether the anode screen is aluminized or not, the electron beam will cause immediate and continuous electro-stimulated desorption of materials off the anode surface. At first, these are primarily trace amounts of H_2O, CO, and O_2 which reach stable rates of desorption after several hours of initial operation.[11] With time, however, the desorption of metalization and/or phosphor constituents becomes the dominant outgas product. It very likely increases the need for sophisticated gettering methods which allow the cathodes to operate reliably at low pressure. Depending on the phosphor chosen, the screen material will ‘‘age’’ and the brightness will drop.[12] This does not likely lead to chromatic shifts; however, this aging process varies with each phosphor material. The balance between the three primary colors will shift with time and will result in changing color mixing.

V. SUMMARY AND CONCLUSIONS

Because of manufacturing and other practical constraints, the near-term use of commercial CRT phosphors, at reduced acceleration energy, such as 2–4 kV, in FEDs is assured. This has serious tradeoff concerns with respect to efficiency, spectral response, long-term reliability and stability, surface passivation, desorption, screening, and synthesis methods. The solution for each issue discussed incurs compromises impacting other performance criteria of the display system.

We contend that the performance of the first-generation commercial field-emission flat-panel displays will rely heavily on the selection of appropriate CRT phosphors and how they are incorporated within the system. The successful application of low-energy RGB phosphor triplets, with a corresponding measurable improvement in color performance and efficiency, is unlikely to be realized until new materials and ensuing new manufacturing capabilities are found; because of this, only more distant generations of flat-panel displays will employ such phosphors.

ACKNOWLEDGMENTS

The authors acknowledge and thank Dr. Tom Felter, Dr. Mike Malinowski, and Dr. Alec Talin of Sandia National Laboratory-California for their numerous contributions in this study.

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