Phosphor selection constraints in application of gated field-emission microcathodes to flat panel displays

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The major issues and tradeoffs surrounding phosphor selection for field-emission flat panel displays are identified. The two main classes of commercially available phosphors applicable to flat panel displays are contrasted, and the major physical, electrical, chemical and optical factors effecting phosphor selection are discussed. The implications of screen layering designs and cathode materials are described as they relate to phosphor characteristics. Resolution requirements for displays severely limits the maximum anode voltage, which in turn forces specific phosphor choices. Possible solutions to these limitations are explored.

I. INTRODUCTION

Vacuum microelectronic field emitter arrays, fabricated using integrated circuit technology, show promise as cold cathodes in low-power, high-image quality flat-panel cathodoluminescent displays. Prototype displays based on field-emission devices have been demonstrated.[1] Electron emission is controlled by a gate (grid) electrode near the field emission cathode and the electrons are accelerated by the anode potential to a phosphor screen. Among the large variety of currently manufactured phosphors, only a few monochromatic and red–green–blue (RGB) triplet phosphors are viable for use in computer and television displays.[2] These are broadly classified as high-voltage (e.g., keV energy range) or low-voltage phosphors ($\leq$300 V acceleration potential). Conventional cathode ray tubes (CRTs) operate at anode potentials from about 9 to 35 kV. Color displays typically use minor variations of the P22 triplet. (Here and throughout the text, the World Wide Type Designation System[3] is used for phosphor names.) This set of red, green, and blue phosphors reliably allow a full range of colors to be reproduced with acceptable efficiency. Monochromatic displays employ a somewhat more diverse selection of phosphors; however, most of these are derivatives of the two component (blue and yellow) P4 phosphor when white luminescence is desired. Though high-voltage phosphors have all the characteristics necessary for wide commercial acceptance in CRT applications, they are neither efficient nor long-lived when operated at the low acceleration voltages and higher current densities of vacuum fluorescent and field-emission displays.

Vacuum fluorescent displays (VFDs) have found growing success as small character displays for automobile and consumer electronic applications. Typically, VFDs have approximately 10 V anode potential and use P15, a bluish–green phosphor with good low-voltage efficiency. VFD technology has not yet proven to be scalable to larger displays with high information content such as needed for computers or television. Consequently, little has been done to develop compatible red, green and blue low-voltage phosphor combinations. Field-emission displays (FEDs) can operate at higher anode voltages; however, current designs are limited by maximum cathode-to-screen spacing constraints from being able to use the several kV anode potentials needed for the CRT phosphors described above.[4-6] Progress in FED technology has renewed interest in low-voltage phosphor chemistry[7] in order that viable triplets can be found for full color displays. An alternative solution is to design FEDs in which it is possible to raise the acceleration potential to a level at which conventional CRT phosphors can be used. This approach has the additional benefit of lower peak-to-peak gate voltage swings, but has been generally disregarded because of fabrication complexities associated with the display design.[8] Table I summarizes the relevant characteristics of the current commercial high and low-voltage phosphors for CRT, VFD, and FED applications.

The phosphors which are suitable for full color displays are sulfides (normally of zinc or zinc compounds that form II–VI semiconductor hosts). Various dopants are used as luminescent activators. The high-voltage phosphors have high luminescent efficiency and acceptable decay times. They are low-cost, well-known, and highly reliable. The low-voltage phosphors listed in Table I are significantly less efficient, more expensive and not as well understood. They tend to be operated at higher current densities, which may contribute to shorter life and more rapid chemical degradation. The spectral response of low-voltage phosphors is also generally less monochromatic than what is obtained in commercial CRT materials. Indium oxide is often added for low-voltage applications to increase electrical conductivity. Fluorescent decay times of less than about 30 ms are acceptable for television displays and all of these phosphors are expected to comply.

II. PHOSPHOR SELECTION CONSTRAINTS

The selection of any specific phosphor for application to FEDs has important ramifications in (1) design of the screen type, (2) the power consumption in the display system, (3) the long-term reliability of the screen, and (4) the optical performance of the display. These particular issues are now addressed.

A. Phosphor screen design

High-voltage CRT phosphors are normally coated with a thin layer of aluminum ("aluminized") after deposition on the display screen. This procedure provides both a high conductivity path for the beam electrons as well as reflection

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TABLE I. Commercially available low-voltage and high-voltage phosphors potentially applicable to field-emission color (P22, LDP) or monochrome (P15) flat panel displays. (P15 is not suitable for full-color displays because of its pale bluish–green luminescence).

Type[a]	Material	Color	Decay time (μs)	Relative efficiency	Excitation energy
P22-Bl (a,b,c)	ZnS:Ag	Blue	30–50	21%	10–30 kV
P22-Gn (a,b,c)	ZnS:Cu,Al	Green	30–50	17%–23%	10–30 kV
P22-Re (a,b,c)	Y_2O_2S:Eu	Red	~200	13%	10–30 kV
P15 (a,b,d)	ZnO:Zn	Bluish–green	8	10%	10–1000 V
LDP-B3 (a)	ZnS:Zn+ In_2O_3	Blue	···	1%	10–1000 V
LDP-G1 (a)	ZnS:Cu, Al +In_2O_3	Green	250	3%	10–1000 V
LDP-R2 (a)	(ZnCd)S:Ag+ In_2O_3	Red	150–300	4%	10–1000 V

[a]Sources: a—Kasei Optonix Ltd., Japan; b—Riedel-de Haën, Germany; c—Sylvania GTE, USA; d—Aron Vecht and Associates, England.

back towards the viewer of the pixel radiation which shines *into* the tube. Electrons decelerate several keV in penetrating this aluminum layer[9] and yet must retain sufficient energy to excite the phosphor efficiently. A gap of several millimeters is required between the anode and cathode in order to support the required several-kV anode potential and yet avoid electrical breakdown within the vacuum. The cost-effective fabrication of spacers between the FED anode-cathode substrates at such a distance, which introduce no visual artifacts in the displayed images, is a major challenge–and *the* major reason that display designers presently prefer the use of low-voltage phosphors for FEDs despite the disadvantages in luminescent life, efficiency, and chromaticity.

Phosphor screens can be operated in one of several ways. The earliest method was to use uncoated, nonconductive phosphors in close proximity to the conductive anode which collects secondary electrons and maintains the phosphor potential. This method is practical for anode voltages less than approximately 10 kV, where the secondary electron yield of most materials is greater than unity. This method has not recently been applied to flat-panel displays, but further investigations may be worthwhile since it offers some possibility of using P22 phosphors at moderate voltages. Current practice in CRTs is to aluminize phosphors [Fig. 1(a)]. Such a technique makes higher anode voltages (and hence luminescent efficiencies) more practical. The aluminum also helps prevent negative ions from damaging the phosphor layer;[9] it may also help to chemically isolate the phosphors from the rest of the display.

Field-emission displays to date do not use the high acceleration potentials required for aluminized phosphor screens. This is due partly to the complication of making suitable standoffs. Consequently, phosphor screen design for FEDs consists of a structure such as in Fig. 1(b) where the phosphor is deposited onto a conductive, transparent indium–tin–oxide (ITO) layer. Alternatively, a very thin metal film can be used in place of the ITO is some light loss is tolerable; however, such a display will have inferior performance and greater cost. The evident advantage of depositing the phosphor over a transparent conductor is that low acceleration voltages can be used. A drawback of this approach is that the phosphor layer is exposed to the vacuum. In such a situation, the phosphors more readily contaminate the cathodes and the electron beams are more likely to degrade the phosphors. Attempts to improve phosphor stability in this case have

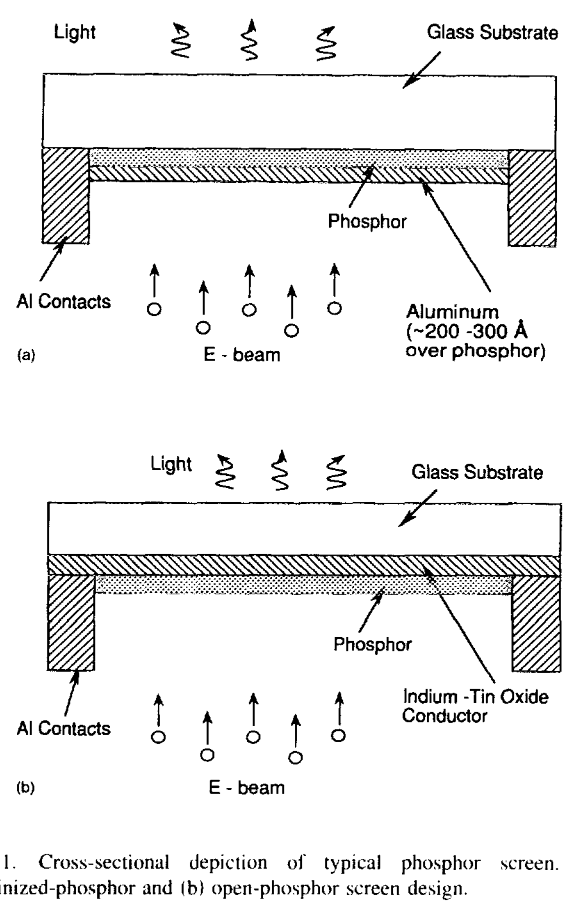

FIG. 1. Cross-sectional depiction of typical phosphor screen. (a) Aluminized-phosphor and (b) open-phosphor screen design.

been reported by encapsulating the individual phosphor grains.[10] Another possibility for providing suitable conductivity in the screen is to mix the phosphors with conductive materials. This is the approach used for the low-voltage color phosphors listed in Table I. There is, however, a loss in phosphor efficiency resultant of using this technique.

B. Power consumption

The cost and complexity of the cathode drive circuitry is also related to phosphor choice. Low anode voltage displays, as compared to high-voltage designs, require higher total electron currents to achieve comparable anode power density. This problem is compounded by the substantially lower efficiency of low-voltage phosphors. The result is a display which has higher net power consumption. The higher cathode currents required are obtained by increasing the peak-to-peak voltage of either the cathode or the gate drive waveforms. The consequence is that higher power integrated circuits, which tend to cost more, need to be used in the row and column drivers. FEDs demonstrated thus far, using low-voltage phosphors, require 30–50 V of peak-to-peak gate swing. Although this is considerably lower than the requirements of electroluminescent and plasma flat panel displays (100–250 V), it is not as low as liquid crystal displays (5–20 V). Techniques to increase the gain of field emission microcathodes, including reducing physical dimensions, sharpening cathode tips, using low work function coatings, and even using quantum well surface layers are being investigated; however, none of these techniques is likely to reduce the power requirements to the levels which can be realized if high-energy phosphors can be used.

C. Long-term screen reliability

Long phosphor life is necessary for most displays. Under ideal vacuum conditions, the light conversion efficiency of phosphors decreases as a function of electron current density and operating time. In a practical display, phosphor life can also be affected by the presence of residual gases (i.e., gases not removed in the display evacuation step) or outgassing products from other materials in the display. The phosphors themselves can also be the cause of vacuum contamination. Such outgassing may also cause cathode poisoning. It has been demonstrated that the ambient gas atmosphere effects the emission level and noise of Spindt cathodes.[11,12] Gaseous sulfides released from some color VFD phosphors are known to have deleterious effects both on the thermionic cathodes, as well as the phosphor itself.[13] The corresponding effects in FEDs are not yet well understood and likely depend on the cathode surface material. Cathode work function and even surface morphology may be affected by such adsorbed contaminants. Silicon cathodes can potentially experience changes in the surface doping as a result. These contaminants from the phosphor may consist of constituent materials (dissociated over time), trace elements or binders. The degree of influence from any of these factors depends on the fabrication processes used to make and/or deposit the phosphors. Therefore it is likely to have an enormous number of possible material combinations and interactions which may affect display life. The result of virtually any of these contaminations will be a corresponding drift in the cathode emission properties as well as a chemical change in the phosphor with time; the consequence of both of these phenomena is a variation in the luminescent emission.

D. Optical performance

The optical aspects of display performance are tightly related to the phosphor choice. The quality of moving images is partly dependent on phosphor persistence, which is a measure of how long phosphorescence continues after excitation is removed. Video rate displays require phosphors with suitably short persistence so that moving images do not leave visible trails on the screen. Persistence of less than about 30 ms is usually desired for personal computer and television displays. In some special situations, the screen is refreshed at a very low rate and longer persistence is desirable to minimize visible flicker. The full range of displayable colors (the "color space") of a particular screen depends on the specific color of each of the component phosphors. For example, by mixing the red, green, and blue emission of the P22 phosphors, commercial television displays can reproduce most of the colors occurring in natural scenes. Candidate low-energy phosphors for field emission displays must be able to fill a comparably good color space, otherwise the displays will never meet the expectation of consumers. The phosphor choice also affects display resolution. Scattering of emitted light in the phosphor layer causes an optical spot to be greater than the electron beam that excites it. Phosphor grain diameter should be about one tenth that of the electron beam for maximum resolution.

The general standards concerning number of individual picture elements ("pixels") and screen size for commercial television and computer displays, as summarized in Table II,[14] must be adhered to in flat-panel design. Display addressability is the linear density of pixels. In conventional color CRTs, the display resolution, which is the maximum density at which individual pixels can be visually resolved, can be less than the addressability because a shadow mask prevents electrons intended for one color of phosphor from hitting any other color. In current designs for FEDs, however, the resolution must exceed the addressability. In such a case, a smaller electron beam spot at the anode is required. Both the proximity focused[15] and multiplexed anode[16] design approaches require a small gap (less than about two tenths of a millimeter) between the anode and cathode substrates to meet the resolution requirements of television and computers. This small gap in turn limits the maximum anode voltage to less than a kilovolt. With this constraint, the use of aluminized phosphors is not possible.

A likely approach to control spot size such that resolution requirements can be met in a system with "large" cathode–anode spacing (e.g., such as needed if high-voltage phosphors are to be used) is to include a secondary aperture above the gate to form an electrostatic lens which actively controls the spot size, as shown in Fig. 2. This approach has been verified by simulation to be capable of collimating the beam and therefore achieving extremely high resolutions, as

TABLE II. Standard TV and computer resolution requirements (Ref. 14).

Characteristics	1000-line monitor	VGA monitor	HDTV	Large direct-view TV set
Pixels	1280	640	1920	440
Lines	1024	480	1035	485
Size (in.)	19 diagonal	13 diagonal	34 diagonal	27 diagonal
Addressability	~90 lines/in.	~60 lines/in.	50–70 lines/in.	~25 lines/in.
	~3.5 lines/mm	~2.5 lines/mm	~2–3 lines/mm	~1 line/mm

we have described elsewhere.[8] Fabrication complexity has not yet allowed experimental confirmation of this method.

III. EXPERIMENTAL EFFORT

Preliminary experimental work is focusing on the assessment of phosphor contamination of field-emission cathodes and concurrent degradation of phosphors by the incident electron beam. Data is extracted in a dry-pumped 10^{-7} Torr multiport vacuum system. Measurements can be made over the 100–360 K temperature range, using automated extraction software capable of making complete ac and dc analysis as well as noise and lifetime measurements. We are examining both two and three terminal devices. Our devices use silicon emission tips. Our investigation extends to the examination of polysilicon emitters in particular. In comparison to single crystal silicon, which is limited to practical commercial substrate sizes (8 in. diam), polysilicon can be deposited uniformly on substrates of arbitrary size and shape, producing potentially low-cost, large-area cathode arrays.

Open phosphor screens, analogous to the configuration of Fig. 1(b) have been fabricated using the monochrome P15 phosphor. Preliminary results have been obtained using these screens in a diode configuration with single-crystal cathodes, analogous to our previous technique.[17] The anode–cathode distance in these measurements ranges between 2 and 4 mm; the applied bias ranges from 0 to 1950 V. Analysis of these data will be published with the followup experiments including RGB triplets for FEDs. We are investigating the effects of outgassing of high vapor–pressure components as well as the effects of varying the configuration of the screen or cathode structure. The emission characteristics including current–voltage behavior, lifetime, noise, and contamination effects of these materials are being studied and compared to

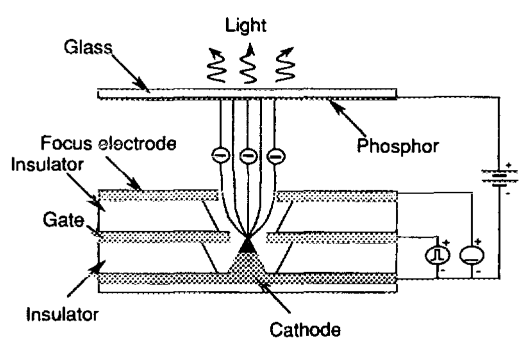

FIG. 2. Aperture-focusing field-emission cathode design for flat-panel displays, with vertical electrode arrangement.

the characteristics of single crystal emitters. Fabrication of several types of cathodes including various designs of focusing electrodes are being investigated.

IV. SUMMARY

Among the wide range of phosphors currently available, there are only two classes, high-, and low-voltage, feasible for field-emission flat panel displays. High-voltage phosphors are very attractive because complete RGB triplets are immediately available and have been demonstrated in CRTs to possess the color performance expected in the majority of modern displays. For flat-panel display applications, however, the use of high-voltage phosphors will require focused electron beams and a sophisticated anode–cathode separation technique. Both of these constraints, at present, are important unsolved engineering problems.

Low-voltage phosphors, which are lower in efficiency and have a higher spectral spread, may possibly also be used in flat-panel displays if contamination and phosphor lifetime issues can be resolved. There still exists the problem that low-voltage phosphors may not provide fully satisfactory visual performance due to the poorer color saturation. The higher power consumption required may make the resultant FED inferior to other technologies, such as active-matrix LCD flat-panel displays. As a result, we contend that, at the present, development of high-performance FEDs using high-voltage phosphors represents the lesser immediate technical challenge. With the development of new low-voltage phosphors (such as through the new ARPA-directed Phosphor Center for Excellence), it is likely that high-performance displays using low-energy phosphors will also become practical.

Research pertaining to constraints on flat-panel display design and to the performance of field emitters is continuing. Emphasis is being given to the study of the effects of the various types of phosphor screens on basic device characteristics, the determination of appropriate field-emission cathode-phosphor screen combinations, and the development of a corresponding practical, reliable display design.

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[1]A. Ghis, R. Meyer, Rh. Rambaud, F. Levy, and Th. Leroux, IEEE Trans. Electron Devices **ED-38**, 2320 (1991).
[2]K. Compton, Inf. Display **5**, 20 (1989).
[3]Electrical Industries Association, Publication No. TEP116-C.
[4]C. Curtin, *International Display Research Conference Technical Digest* (Society for Information Display, Playa del Rey, CA, 1991), p. 12.
[5]R. Meyer, *Fourth International Vacuum Microelectronics Conference Technical Digest* (Japan Society of Applied Physics, Tokyo, 1991), p. 6.
[6]F. Levy and R. Meyer, in Ref. 4, p. 20.
[7]A. Vecht, D. W. Smith, and S. S. Chadha, *Sixth International Vacuum Microelectronics Conference Technical Digest* (IEEE, New York, 1993), p. 143.
[8]W. D. Kesling and C. E. Hunt, *SID International Symposium, Digest of Technical Papers* (Society for Information Display, Playa del Rey, CA, 1993) Vol. 24, p. 599.
[9]P. A. Keller, *The Cathode Ray Tube* (Palisades, New York, 1991).
[10]F. Takahashi, K. Yoneshima, and K. Kojima, *SID International Symposium Digest of Technical Papers* (Society for Information Display, Playa del Rey, CA, 1992), Vol. 23, p. 166.
[11]S. Itoh, T. Niiyama, and M. Yokoyama, J. Vac. Sci. Technol. B **11**, 647 (1992).
[12]I. Brodie and C. A. Spindt, Adv. Electron. Electron Phys. **83**, 1 (1992).
[13]S. Itoh, T. Kimizuka, and T. Tonegava, J. Electrochem. Soc. **136**, 1819 (1989).
[14]D. Eccels, G. Romans, and J. Held, Inf. Display **9**, 16 (1993).
[15]C. A. Spindt *et al.*, IEEE Trans. Electron Devices **ED-36**, 225 (1989).
[16]T. Leroux, A. Ghis, R. Meyer, and D. Sarraasin, *SID International Symposium, Digest of Technical Papers* (Society for Information Display, Playa del Rey, CA, 1991), Vol. 22, p. 437.
[17]C. E. Hunt, J. T. Trujillo, and W. J. Orvis, IEEE Trans. Electron Devices **ED-38**, 2309 (1991).