We believe that the boron implantation causes some damage inside the oxide and creates weak spots near the poly-Si/SiO$_2$ interface. For substrate injection, the location of the weak spot is remote from the cathode and it gives a low critical electric field, and large $Q_{bd}(+)$. For gate injection, these generated weak spots are close to the cathode, the high critical electric field and small $Q_{bd}(-)$ can be obtained. The apparent differences between $Q_{bd}(-)$ and $Q_{bd}(+)$ are due to the location of the trapped charge near the poly-Si/SiO$_2$ interface. Meanwhile, the location of the generated weak spots is related to the dose and energy of the boron implantation. In this paper, the polysilicon-dose dependence of Q_{bd} can be fully explained.

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Thin Film Energy-Controlled Variable Color Cathodoluminescent Screens

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ABSTRACT

A new technique for obtaining energy-variable multicolor cathodoluminescent display screens is presented. This technique employs radio frequency ion plasma sputtering of one thin-film phosphor material over a dissimilar phosphor substrate. The technique employed differs from the old "Penetron" screen in that the substrate and the secondary phosphor layer are single-crystal materials. This results in higher resolution and allows the use of lower energy beam excitation. The experiments presented use Y_2O_3:Eu (red) deposited on a $Y_3Al_5O_{12}$-Tb,Ce (green) substrate with excitation in the low killovolt range. The method demonstrated, however, is extendable to a full red-green-blue triplet composed of a wide variety of materials. The screens are particularly applicable to small, low-power formats, such as avionics and instrumentation displays.

Introduction

Voltage-sensitive screens with variable output color based on beam penetration phosphor mechanism (known as Penetron screens) were commercially manufactured from late 1960s until mid-1980s for avionics and radar application due to higher resolution compared to conventional cathode ray tubes (CRTs). Widely used CRT screens have two major features limiting the resolution: first, the spot size is limited by the shadow mask; second, each color pixel occupies an area three times larger than the area required for a single color phosphor dot. In the Penetron cathodoluminescent screen (CLS) different colors are displayed within the same area of the screen. Due to this fact, and also thanks to the absence of the shadow-mask, the resolution of the Penetron screens is inherently limited only by the beam spot and, to a lesser degree, by phosphor grain size.[1] The conventional Penetron screens consisted of two different "onion-skin" layers made of transparent phosphors separated by a dielectric barrier layer. The principle of color variation is illustrated in Fig. 1: at low accelerating voltages, the electron beam is totally absorbed in the phosphor layer closest to the electron gun thus producing one output color (usually red); at higher voltages the beam penetrates through the first phosphor layer and excites the second (green) layer closest to the viewer. Certain configurations of phosphor layers allowed display of intervening colors (yellow or orange) at intermediate acceleration voltages. Although it is technically difficult to extend the Penetron approach to a display with a full-color gamut by using multiple layers of color phosphors, the high resolution makes the Penetron idea quite attractive for special applications requiring very high readability and color contrast. The same approach, multiple phosphor layers excited by different energy electron beam, could also be used for applications requiring high dynamic contrast by using two phosphors with different decay times.

In this work, an improved approach to the formation of the penetration-type of color screens is presented. In order to further refine the resolution of the screen, the construction of a double-layer thin-film-on-single-crystal cathodoluminescent screen is suggested. These screens consist of a thin layer of yttrium or lanthanum oxide or oxysulfide activated by rare earth elements deposited on top of a single-crystal phosphor substrate. For example in the data presented, a red luminescent Y_2O_3:Eu thin film is deposited on top of a green luminescent $Y_3Al_5O_{12}$-Tb,Ce substrate. Since neither cathodoluminescent layer possesses a grain structure, the resolution of these screens should be limited only by electron beam spot size.

Thin Film Manufacturing

The first part of the work consists of optimization of various manufacturing methods applicable to the fabrication of thin film phosphor layers. Commercially available phosphors of suitable color of luminance obtained from industrial manufacturers were used as a source for the thin films grown. Films were deposited using 4 in. targets fabricated by pressing powder phosphors of appropriate composition. (See for example Ref. 2.)

Several growth were examined including sputtering, methods of thin films evaporation electron beam, radio frequency (RF) ion-plasma magnetron sputtering, and RF ion-plasma diode sputtering. The films manufactured using electron beam evaporation did not have sufficient stability and degenerated during the measurements. The RF magnetron sputtering produced films with brightness of the order of 1 to 3 candelas per square meter (cd m^{-2}) under excitation by a 10 kV electron beam with a current density of 2 μA cm^{-2}. However the adhesion of the film to the single-crystal substrate was found to be insufficient. The best results were achieved by using the RF ion-plasma diode sputtering method: the mechanical properties of the films were the most stable, and the average brightness of the films exceeded 50 cd $\cdot$ m^2 at 12 kV and 2 μA cm^{-2}.

Table I. Brightness of cathodoluminescent layers with different colors of luminescence (electron beam excitation at $U{:}J = 8$ kV:μA cm^{-2}).

Screen composition	L (cd/m^2)	Color of luminescence
Y_2O_3-Eu	36	Red
La_2O_2S-Eu	5.2	Red
Y_2O_2S-Eu	78	Red
$Y_2O_2S,Gd_{20}O_2S$-Tb	26	Blue
Y_2O_2S-Tb	24	Blue
La_2O_2S-Tb	40	Green
La_2O_2S-Nd	1.2	Blue-violet

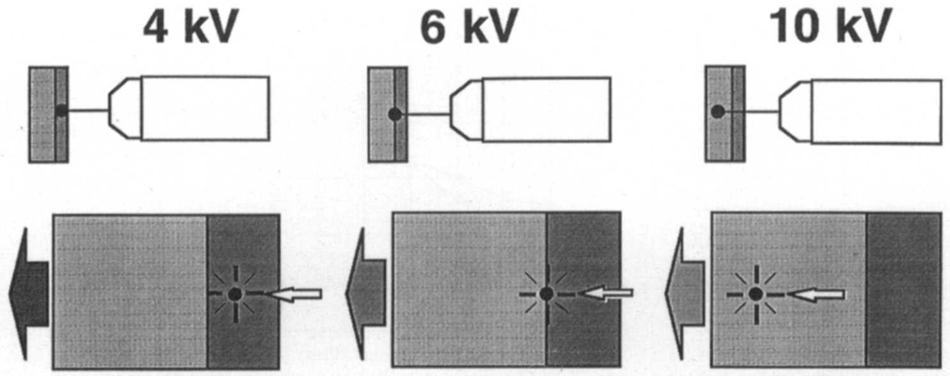
Further optimization of the fabrication technology for luminescent Y_2O_3-Eu films included study the following parameters in how affected the thin film structure: reactive gas composition, RF plasma parameters, deposition chamber geometry, substrate temperature, and the thermal treatment and environment. It was found that the best results are achieved through RF ion-plasma diode sputtering at 13.56 MHz using plasma compression obtained with a magnetic field generated by external solenoids. In order to maintain the film stoichiometry, deposition was done in a reactive atmosphere. In the case of Y_2O_3:Eu, the atmosphere was Ar/O_2 and the optimal percentage of oxygen in the mixture was 25%.[3] For oxysulfide deposition, the sputtering atmosphere was Ar/H_2S as reported elsewhere.[4] After deposition, a thermal anneal at 1200 to 1300 K increased both thin-film grain size and luminescent brightness.

Results and Discussion

Thin film characterization.—Using RF ion-plasma diode sputtering technology, 0.1 to 1 μm thick layers of different materials have been fabricated for the red, green, and blue spectral regions (see Table I).

Experimental study of the cathodoluminesce of the thin films was performed using an electron gun with a thermionic emitter and acceleration variable voltage from 2 to 20 kV. Initially, thin films were characterized on transparent sapphire substrates, with a metallic mesh to drain off the current and to prevent charging effects. Preliminary characterization of the fabricated films showed that the most promising for flat panel display applications is Y_2O_3:Eu. Its emission is localized in one narrow spectral band, and thermal quenching of its luminescence thermal quenching begins at temperatures above 450 K. Fabrication of Y_2O_3-Eu_3thin films is simple and safe. The brightness of these films varied between 11 cd m^{-2} at 6 kV and 50 cd m^{-2} at 12 kV.

The dependence of cathodoluminescent brightness (L) of the Y_2O_3-Eu thin film on sapphire on electron beam current density (j) (lux-ampere characteristics, LAC) is shown in Fig. 1. That LAC can be described by a power law $L = j^{\alpha}$. Transition from a linear function (exponent $\alpha = 1$) at low levels of excitation (below 50 μA cm^{-2}) to sublinear



A - RED B - ORANGE C - GREEN

Fig. 1. Voltage sensitive screens: principle of color variation using different acceleration voltages.

(α = 0.3) at high excitation density is found. It indicates the presence of both radiative and nonradiative recombination centers in the Y_2O_3-Eu films. The behavior is explained by an increase in non-radiative recombination as the incident electron density increases.

The optical experiments show that the brightness is very high for the Y_2O_3-Eu thin film cathodoluminescent screens on sapphire. Furthermore, greater than 90% of this radiation is concentrated in a narrow luminescence band of at 612 nm with a half-width $\Delta\lambda$ = 3 nm. The band corresponds to the $^5D_0 \rightarrow {}^7F_2$ transition in Eu^{3+}.

Double-layer variable color screens.—To produce variable color screens, the Y_2O_3:Eu thin film described above was deposited on top of a green luminescent single crystal $Y_3Al_5O_{12}$-Tb,Ce substrate.

Figure 2 demonstrates the principle of color variation. The output color change is achieved through changing the electron penetration depth by modifying the electron beam energy. At accelerating voltages below 4 to 5 kV, the electron beam is totally absorbed in the surface thin film phosphor layer closest to the electron gun (Fig. 1a.), thus producing a red output color. As the voltage increases above 7 to 8 kV, the beam penetrates through the thin film and excites the single-crystal (green) substrate closest to the viewer (Fig. 1c). Intervening colors (peach or orange) can be displayed at intermediate acceleration voltages (Fig. 1b).

Output light spectra produced by excitation using the variable voltage electron gun are shown in Fig. 3. Plot A taken at 5 kV shows the red luminance peak at 612 nm. At 10 kV, the beam penetrates into the substrate and thus the displayed color changes from red to green (Fig. 3, plot B) with the peak maximum at 540 nm. A portion of electron beam, however, activates the red thin film layer while penetrating through it. As a result, the 612 nm peak still shows up in the plot. Nevertheless, the eye perceives the color as green.

In order to study luminance of the variable color screens, the transport through the thin film and into the single crystal substrate was investigated by varying the thickness of the film from 0.1 to 0.5 μm. The $Y_3Al_5O_{12}$-Tb,Ce substrate was approximately 1.5 μm thick, so electrons do not fully traverse it. The output color was measured using two different optical color filters: blue-green and orange. Figure 4 shows an example of such measurements. For the optimal performance of the screen it is necessary that the relative intensity of red light at voltages below 6 kV to be greater than the intensity in the green part of spectrum by at least a factor of two. The optimal thickness for the Y_2O_3:Eu thin-film layer, determined from

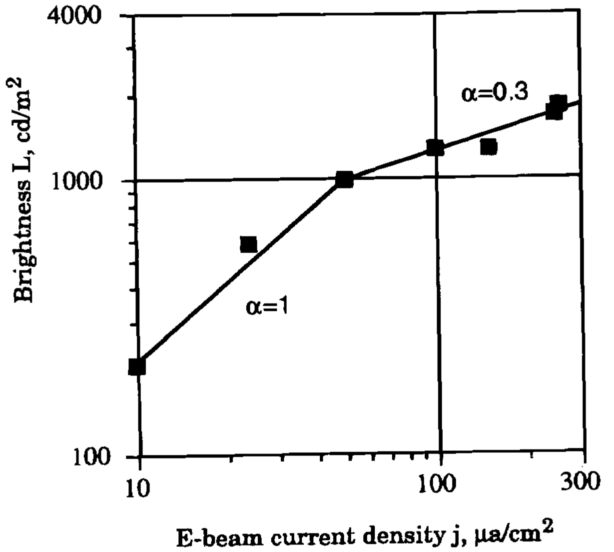


Fig. 2. Logarithmic dependence of luminescence brightness of Y_2O_3-Eu thin films on sapphire substrate vs. electron beam current density.

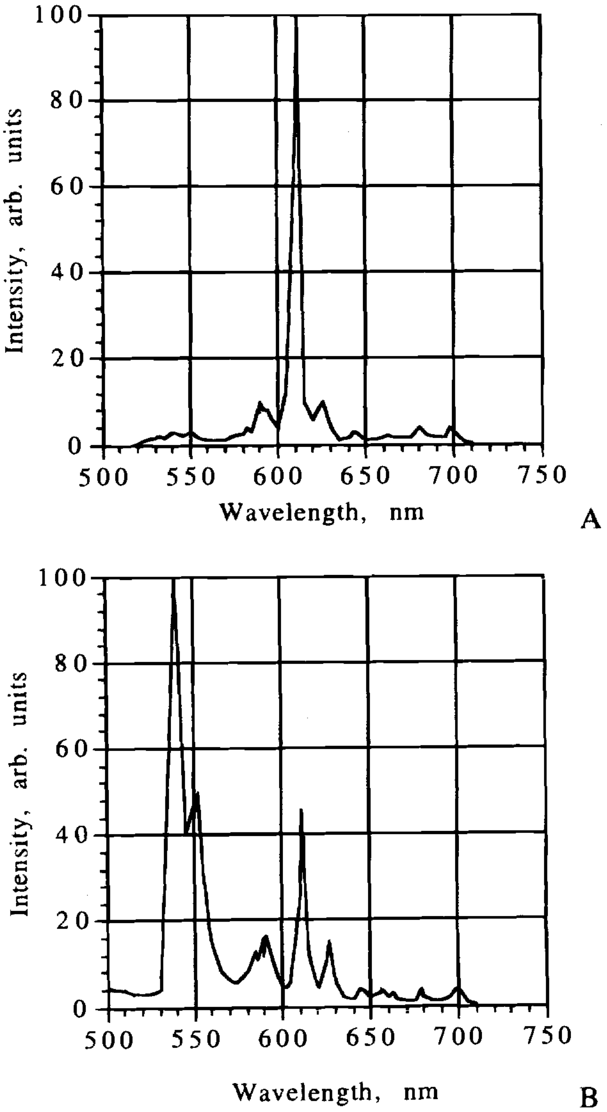


Fig. 3. Spectra of cathodoluminescence of Y_2O_3-Eu/$Y_3Al_5O_{12}$-Tb,Ce thin film on single-crystal CLS at electron excitation energies of 5 (A) and 10 keV (B).

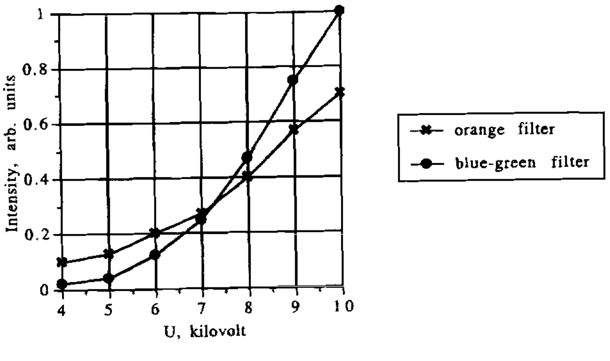


Fig. 4. Dependence of luminescence intensity in red (orange filter) (×) and green (blue-green filter) (●) spectral regions for Y_2O_3-Eu/$Y_3Al_5O_{12}$-Tb,Ce thin film on single-crystal CLS on electron excitation energy.

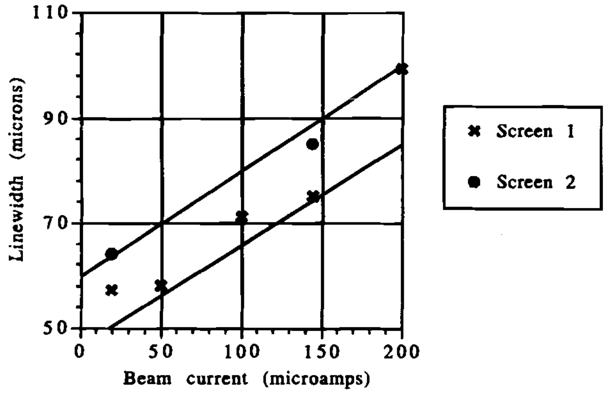


Fig. 5. Dependence of the image linewidth on electron beam excitation density. Data collected using two Y_2O_3-Eu thin film CLS on sapphire substrates.

the measurements of color intensity in the red and green regions, was found to be in the range of 0.15 to 0.20 μm.

Several variable-color screens were tested giving the following characteristics: (*i*) red/green luminescence color switching voltages, 5/10 kV; (*ii*) output light efficiency in red 0.17 to 0.35 cd/W; (*iii*) output light efficiency in green 1.5 to 2 cd/W; and (*iv*) color coordinates of red $x = 0.629$, $y = 0.345$ and of green: $x = 0.340$, $y = 0.471$.

In order to estimate the resolution of the thin film screens, the dependence of image linewidth on electron excitation density has been measured. For powder grain screens, the image linewidth is limited by the size of grain and by the intergranular nonuniformity which also leads to spatial noise. For thin film screens, the image linewidth is determined not by grain size but by the electron beam density (Fig. 5). Data were collected using two Y_2O_3:Eu thin film catholominescent screens (CLS) on sapphire substrates; the linewidth values lie within the area delimited by two parallel lines as shown in the figure. The linewidth of the better screen was found to be less than 60 μm for 25 μA of beam current, which is approximately two times smaller than that of the small grain powder screens (110 to 120 μm). Since no account of the beam size has been made, the true resolution of the thin film screen could actually be even better.

Conclusion

Various methods for deposition of luminese thin-film oxides and oxysulfides with rare earth elements have been investigated and optimized. Variable-color thin film on single-crystal substrate cathodoluminescent screens have been developed. Variation of luminescence output color by variation of the electron beam excitation energy has been demonstrated. These screens are shown to achieve higher resolution than CRT screens and thus can lead to applications in correlation systems or image processing systems with high information density.

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