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ELECTROLUMINESCENT DISPLAY TECHNOLOGY.

Technical report

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device capabilities. A survey of future prospects will cover improvements in efficiency, multicolor displays and various device configurations.

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ELECTROLUMINESCENT DISPLAY TECHNOLOGY

INTRODUCTION

When electroluminescent (EL) devices caused a flurry of activity in the early 60's, the problems that proved to be most critical were those of lifetime and "brightness". The powdered phosphors being used at that time suffered from a rather short (~ 2000 hrs) luminance half-life. This kind of problem is serious for lighting applications but even more disastrous for display applications. In a display, the statistics of picture element duty cycle are not uniform. Those elements that are used most heavily will decay most rapidly and display uniformity will be impossible to maintain.

Powder phosphors with longer lifetime have subsequently been developed which can be used to make acceptable devices but with very limited applications. The real solution to this problem however, lies in the development of the thin-film EL (TFEL) phosphor which, after a brief burn-in period, in certain cases has demonstrated absolutely constant brightness characteristics up to 30,000 hours. The thin-film phosphor has the added advantage that it is transparent, which allows a high contrast structure to be made by placing a black, light absorbing layer immediately behind the transparent display medium. This results in good legibility in sunlight ambience at luminance levels as low as 15-20 footlamberts (fL). This legibility is therefore achieved without the disadvantages associated with high "brightness", (e.g., high power dissipation, and short life.)

DEVICE STRUCTURE AND COMPOSITION

The structure of this type of device, shown in Figure 1, can be fabricated entirely by vacuum deposition. The transparent front electrode of tin oxide, indium oxide or thin metallic films can be sputtered or thermally evaporated. In the case of tin oxide it is commonly applied by a pyrolytic process. The insulating layers are generally sputtered or e-beam evaporated yttrium oxide or aluminum oxide or in some cases, chemically vapor-deposited silicon nitride. The electroluminescent layer of zinc sulfide doped with manganese can be sputtered or thermally evaporated from a doped source or by co-evaporating zinc sulfide and manganese. Various compositions and processes are being used to produce black layers but these are generally proprietary. The difficulties associated with incorporating this black layer into the display structure stem from the fact that most materials that are sufficiently black (less than 0.25% diffuse reflectivity) tend to be electronically semiconductive. Some attempts to put the black layer inside the insulator-phosphor sandwich have been successful while others report degradation of the phosphor light output and efficiency as a result of incorporating the black layer. Another approach, that of applying the black layer outside of the ZnS/insulator structure, requires that the material must have a low conductivity to avoid leakage between the rear electrodes. This has been tried with some degree of success.

The materials and process controls necessary to fabricate devices with this structure reliably and repeatedly appear to be understood and a number

of companies are now quite close to the point of having a product of this sort commercially available.

MULTIPLEXING REQUIREMENTS

A piece of glass bearing a light emitter and hundreds of electrodes is not yet a display. To be a display, it requires some method of driving individual picture elements with the information to be displayed, just as a cathode ray tube does not become a display until high voltage drive, brightness control and deflection circuitry are applied to it. The device shown in Figure 1 is depicted with a matrix of row and column electrodes. If such a device has M columns and N rows then the $M \times N$ elements are accessible through $M + N$ electrodes and we must be able to multiplex the drive signals to the panel. The ability to do this depends primarily on the threshold characteristics of the luminance voltage response of the electroluminescent film. The usual way of multiplexing such a matrix is to apply positive and negative half-voltages to one row and to those columns in which we wish to light up the elements in that row. It must be kept in mind that this explanation is somewhat simplified and the actual drive signals must be alternating current (ac) with a fair degree of symmetry. As all of the rows of the matrix are scanned, the "on" elements will see full voltage for a time proportional to $1/N$. However, depending on the information being displayed, many of the "off" elements may see a half-voltage all or nearly all of the time. In order to achieve an acceptable contrast between the "on" and "off" elements, the display medium must therefore have a discrimination ratio that is much greater than N where the discrimination ratio is defined as the luminance at full voltage divided by the luminance at half-voltage. TFEL has a discrimination ratio on the order of 10^4 to 10^5 which has been demonstrated as being adequate to allow multiplexing of hundreds of lines. Actual contrast and crosstalk between lines will also be affected by factors such as phosphor persistence and driving voltage waveform but the discrimination ratio is the primary determining factor. The next important factor in operating a matrix display is the fact that there is a relatively large capacitive coupling between all of the lines on the panel. This is taken into account by the half-voltage addressing scheme but puts severe constraints on the types of drive circuits that can be used. Essentially, it requires active pull-up and pull-down in both directions on each lead.

The capacitive nature of the panel also affects the choice of driving waveform in terms of power efficiency. Although there would be reasons such as circuit simplicity, to use square pulse waveforms, this would prove to be very inefficient. The square wave of voltage, V, would store an amount of energy equal to CV^2 on the device capacitance and then dump it to ground dissipating the total energy with each half-cycle. If a sinusoidal drive waveform is used, the power dissipated in light generation and losses represents less than 5 percent of the $V \times I$ product, since the phase difference between the current and voltage is very nearly 90° . Therefore, a resonant drive system in which an inductor is used in conjunction with the panel capacitance should be used to obtain the low power consumption that is possible with the TFEL display. Drive circuitry capable of multiplexing data into a matrix EL display compatible with an ac resonant drive waveform,

is being designed and evaluated at our laboratory and elsewhere.

Many of the problems of multiplexing a matrix display, such as limited luminance and efficiency can be circumvented by the use of local storage at each picture element. There are currently two ways being investigated to do this. One makes use of a hysteresis effect that has been observed in specially prepared electroluminescent films. A sustaining voltage signal is applied at a level below that necessary to turn the panel on. Pulses are superimposed to turn on elements which then are maintained in the "on" condition by the sustaining voltage. Although there have been a number of reports of experimental observations of this memory phenomenon, actual electrically addressed display devices have not yet been demonstrated using this approach.

The other approach to providing local memory on the display is the use of a thin-film transistor circuit array deposited directly on the display substrate such as that shown schematically in Figure 2. This is significantly more complex to fabricate but has been successfully demonstrated by a number of researchers. This approach puts fewer demands on the display materials and structures, provides high luminance by allowing a nearly 100 percent duty cycle for an "on" element and is entirely compatible with an efficient resonant drive system. The feasibility of the thin-film transistor/TFEL structure has been proven and the fabrication processes involved should be quite cost effective when actual producibility is finally achieved.

OPERATING CHARACTERISTICS

The general operating characteristics of an electroluminescent film can be ascertained from Figures 3 and 4. Figure 3 shows the voltage and current waveforms at 5 kilohertz (kHz) of a lighted EL film with an area of about $\frac{1}{2}$ inch squared. The higher curve is the voltage and at 100 volt/division (V/div) shows a 230 V peak. The current curve is measured at 50 milliamperes/div (mA/div) and is very nearly 90° out of phase with the voltage showing the almost purely capacitive reactance. The light generating portion of this waveform is too small to be seen in this curve. In order to measure this critical component of the current, an equivalent capacitor is put in parallel with the film and the two currents are measured differentially. The results of this measurement are shown in Figure 4. The voltage is the same as in the previous figure but the current is measured at 1 mA/div. The 2 mA current pulse seen here coincides very closely with the output of light by the film, and can be seen to occur just before the peak voltage. The power dissipation obtained from integrating the product of these voltage and current curves yields efficiency figures between 1 and 4 lumens per watt (lm/W.) This relatively high luminous efficiency (an order of a magnitude greater than that of light emitting diodes (LEDs) or conventional plasma display panels), in conjunction with the high contrast achieved at low luminance levels, results in a sunlight legible display with very low power dissipations. Specifically, assuming a one lm/W efficiency, including line drivers, and an active area fill-factor of 50 percent, a 1 square foot panel, will dissipate 10 watts in

achieving a sunlight legible 20 fL luminance over the entire panel. If the panel is filled with alphanumeric characters, the total power dissipation will be 3 watts. For a 6 inch by 3 inch panel filled with alphanumeric characters, the power dissipation becomes 0.375 watt. A summary of present and expected operating characteristics is shown in Table 1.

SYSTEM APPLICATIONS

The operational characteristics of thin-film electroluminescent displays such as sunlight legibility, low power consumption, low volume, lightweight and ability to withstand a broad range of environmental conditions make this technology ideally suited for a variety of portable display applications. In our Laboratory, we are working on the design of a hand-held computer data entry terminal. Using the TFEL display with a transparent touch-keyboard overlay, one can build full capabilities of an alphanumeric and graphics data terminal into a battery-operated hand-held device. In addition to devices of this sort, EL displays are planned for use in aircraft cockpits because of their sunlight legibility, uniform dimmability to very low levels, and the inherent gray scale capability making them suitable for video displays as well. The emergence of display technology at this point in time when microprocessors and related devices are expanding our data processing capabilities so rapidly, provides the possibility for many exciting new applications concepts.

In the military marketplace, the TFEL capabilities make such a display suitable for a wide range of tactical applications. The hand-held application for a forward observer or for personal communications is obvious because of the high contrast/low power capabilities; however, equipment in the man-portable or vehicular mounted category can also find significant advantage in utilizing TFEL displays, because of the same, aforementioned features. Equipment in this category includes automated test equipment, unit level switching, modular record traffic terminals, operation and fire direction terminals, radio communications equipment, radars, and signal intelligence equipment as well as a variety of airborne displays.

At the present time the following specific TFEL display configurations are being developed for the aforementioned applications:

- Numeric readout modules consisting of 2-digit packages which include drive and decode circuitry that are end-butable. In addition to airborne use, such numerics are for gun-mounted fire direction, radio, and other types of digital instrumentation.

- Matrix-addressed panels vary in size from 2 inches to 6 inches on a side and vary in resolution from 30 lpi to 50 lpi. Such panels could be used in hand-held or small-space alphanumeric or graphic applications, with or without a touch panel overlay for convenient user interaction.

- A 5½ inch by 7 inch, 100 lpi panel having a total 512 by 640-line resolution; this panel can be used in a 512 by 512 mode for vector/graphics

and a 480 by 640 mode for live television. Such operation would be, in general, superior to that found in most television receivers under U.S. broadcast standards because of the guaranteed complete field interlace which is a consequence of the digital addressing.

Electroluminescent technology isn't limited to these applications. Future plans call for expansion to add capabilities for multi-color displays and map overlay displays.

Taking advantage of the transparency of the TFEL structure, one can, in principle, deposit a double or triple layer phosphor structure with corresponding matrix addressing electrodes for each layer. By properly addressing the different color phosphor layers, a multi-color display will result without a loss in resolution, very much as in penetration color CRTs. However, in this case, 3 phosphor layers could be used and addressed independently, thereby giving rise to a full spectrum.

Going to a simpler structure, one can, in principle, make the back metallic electrodes transparent and eliminate the black layer, resulting in a completely transparent display. This may be used in a map overlay mode, or superimposed over any other hard copy. For the military, the low power, small size features of such a display could put important accurate map correlative capabilities in the hands of low echelon troops, since expensive and bulky map digitization equipment would not be needed.

CONCLUSIONS

The high luminous efficiency and high contrast of thin-film electroluminescent displays, coupled with their apparent long life and environmental ruggedness, make this technology particularly attractive for alphanumeric, graphics and video applications where display system size is critical. Although this technology has not yet reached the stage of product availability, efforts in Japan and growing efforts in the United States indicate that relatively off-the-shelf products should start to become available in the near future.

Future potential in multi-color and map overlay capabilities adds to the attractiveness of this technology. Since TFEL represents a "new" display technology, marketing should not concentrate on the "replacement market" but on new product types with sophisticated display capabilities heretofore unavailable. The hand-held computer graphics terminal is a good example of this.

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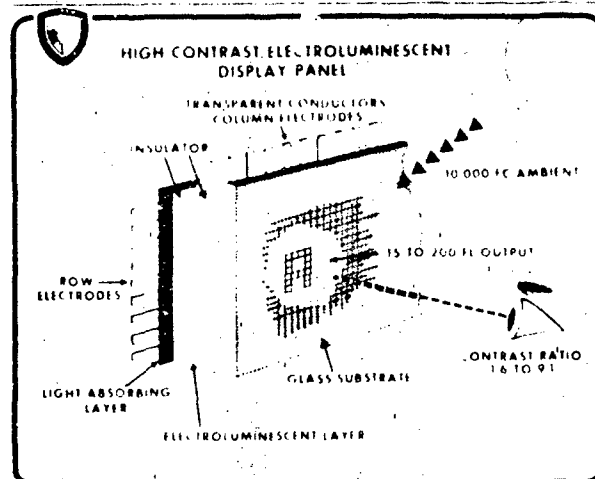


Figure 1. High Contrast Electroluminescent Display Panel

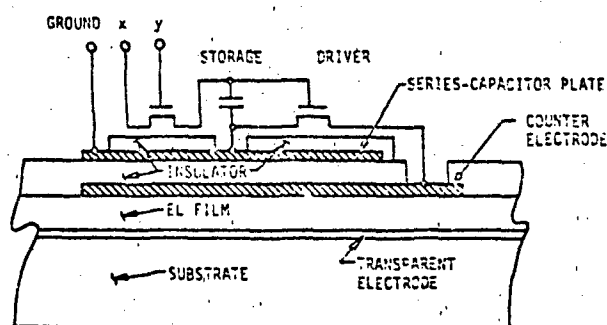


Figure 2.

Figure 2. Thin-Film Transistor Structure

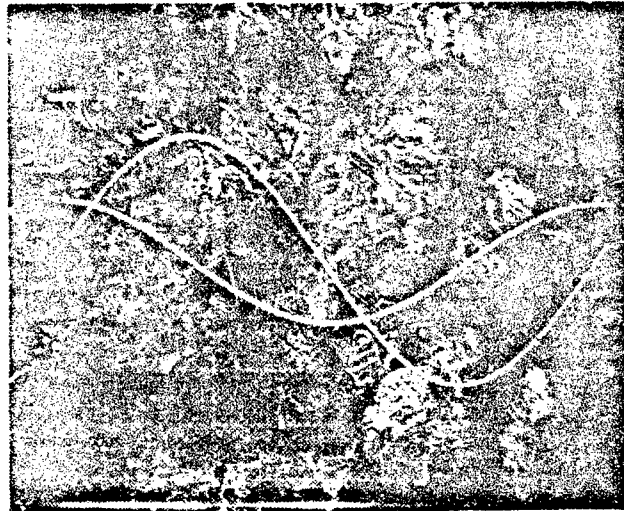


Figure 3. Voltage-Current Waveforms

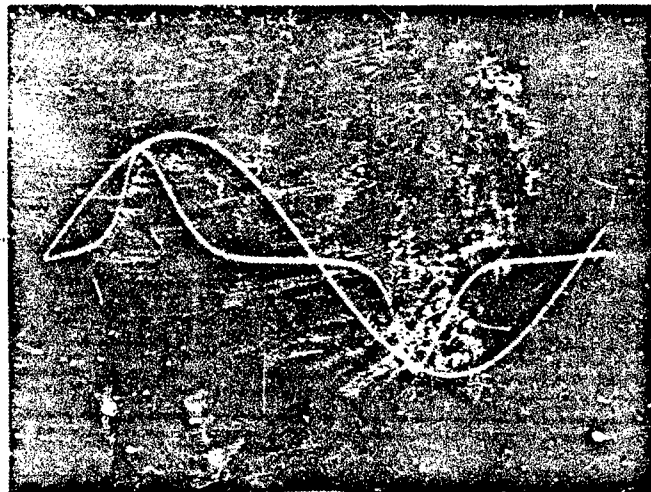


Figure 4. Waveforms of Voltage and Current
with Capacitive Component Removed

TABLE 1
ELECTROLUMINESCENT DISPLAY CHARACTERISTICS

PARAMETER	CURRENT	NEAR-TERM	FUTURE
RESOLUTION	70 LPI	100 LPI	500 LPI
LUMINANCE	30 FL	60 FL	200 FL
CONTRAST	LEGIBLE IN BRIGHT ROOM LIGHTING	SUNLIGHT LEGIBLE	SUNLIGHT LEGIBLE
POWER EFFICIENCY	4 LUMENS/WATT 1 LUMEN/WATT WITH DRIVERS	1.5 LUMEN/WATT WITH DRIVERS	4 LUMENS/WATT WITH DRIVERS
OPERATING VOLTAGE	200 VRMS	100 VRMS	75 VRMS
POWER CONSUMPTION	3.2 WATTS FOR 8" X 10"	2 WATTS	1 WATT
MULTIPLEXING CAPABILITY	240 LINES	500 LINES	WITH 1FTS THOUSAND LINES
OPERATING TEMPERATURE	0°C TO 70°C LIMITED ONLY BY PACKAGE SEAL	-55°C TO +125°C	-55°C TO +125°C
SIZE	6" DIAGONAL	10" DIAGONAL	LIMITED ONLY BY SIZE OF THIN-FILM DEPOSITION EQPT.
COLOR	YELLOW	YELLOW & GREEN AVAILABLE	FULL COLOR