Low-Temperature Polysilicon Thin-Film Transistor Driving with Integrated Driver for High-Resolution Light Emitting Polymer Display

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***Abstract*—A high-resolution low-temperature polysilicon thin-film transistor driven light emitting polymer display (LT p-Si TFT LEPD) with integrated drivers has been developed. We adopted conductance control of the TFT and optimized design and voltage in order to achieve good gray scale and simple pixel circuit. A p-channel TFT is used in order to guarantee reliability in dc bias. An inter-layer reduces parasitic capacitance of bus lines. Because of the combination of the LT p-Si TFT and LEP, the display is thin, compact, and lightweight, as well as having low power consumption, wide viewing angle, and fast response.**

I. Introduction

LOW-TEMPERATURE polysilicon thin-film transistors (LT p-Si TFT's) have been utilized to drive liquid crystal displays (LCD's) [1]–[3]. There are many candidates for active matrix devices, i.e., single-crystal Si MOS FET, amorphous Si TFT, high-temperature p-Si TFT, LT p-Si TFT, other semiconductor devices, etc. Among the candidates, only the LT p-Si TFT has performance high enough to compose integrated driver circuits and the capability of being fabricated on a large transparent substrate simultaneously. Additionally, it has already been reported that the LT p-Si TFT can also be fabricated on a plastic substrate [4]. These advantages of the LT p-Si TFT allow the present great successes to come true in LCD's, not only in research and development, but also in the market. However, the LT p-Si TFT is not only for LCD's. The LT p-Si TFT's have great potential even for other displays which have integrated driver circuits and are large sizes [5].

On the other hand, light emitting polymers (LEP's) [6]–[8] promise to achieve thin, compact, lightweight, and inexpensive displays. Moreover, the display can have low power consumption, wide viewing angle, and fast response. Until now, for LEP displays (LEPD's), mainly static and passive matrix driving methods have been utilized. However, for high-resolution displays consisting of many pixels, needless to say, the static method cannot drive the LEP. The passive matrix method cannot drive the LEP, either [9], because the high-resolution display demands high voltage in the short scanning period in order to achieve the required average brightness, and this high voltage results in a lower power efficiency of the light emitting. Accordingly, instead of the static or passive matrix driving method, an active matrix driving method is better for high-resolution display as the pixels may be driven close to their best power efficiency point.

Since the LEPD is not a cell structure, i.e., liquid layer and two sandwiching substrates, it does not need the second substrate. Moreover, the LEPD does not need a backlight, light guide, polarizer, diffuser, etc., which are used in the LCD. Therefore, the display consists of one substrate, peripheral drivers, and many contacts between them. The next target is to eliminate the peripheral drivers and contacts. If the peripheral drivers are replaced by monolithic drivers integrated on the substrate, not only can the peripheral drivers be eliminated, but the number of contacts can also be decreased. The display is dramatically reduced to only one substrate. As a result, the display will be exceedingly thin, compact, lightweight, and inexpensive.

Because of the advantage of the wide viewing angle, the LEPD is suitable for direct view applications. Most applications such as these are large size displays. In the case of the current LEPD structure, since the polymers and cathode metal are serially stacked on the substrate and light emits through the substrate, the substrate must be transparent. Therefore, for the device to drive the LEPD, the capability of fabrication on a large transparent, i.e., glass or plastic, substrate is needed.

In conclusion, in order to drive the high-resolution LEPD, the active matrix device is needed and it must have enough performance to compose integrated drivers and have the capability to be fabricated on the large transparent substrate, simultaneously. Only the LT p-Si TFT can satisfy these demands.

Therefore, the objective of our development in this paper is to confirm how the LT p-Si TFT is suitable to drive the high-resolution LEPD. A high-resolution LT p-Si TFT LEPD with integrated drivers is designed, fabricated, and evaluated [10]. We adopted conductance control of the TFT and optimized design and voltage in order to achieve good gray scale and simple pixel circuit. A p-channel TFT is used in order to guarantee reliability in dc bias. An inter-layer reduces

Manuscript received October 1, 1998; revised June 1, 1999. The review of this paper was arranged by Editor J. Hynecek.

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Publisher Item Identifier S 0018-9383(99)09015-2.

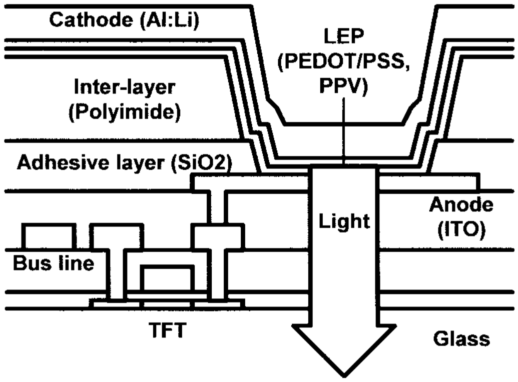


Fig. 1. Cross-sectional view of the LT p-Si TFT LEPD. LT p-Si TFT's are fabricated the same as the TFT-LCD. Light comes through the glass substrate. Since the TFT-LEPD needs only some thin films on one substrate, very thin, compact, lightweight, and inexpensive displays can be achieved. The function of the inter-layer is to distance the cathode and to reduce parasitic capacitance of bus lines.

parasitic capacitance of bus lines. The display is thin, compact, lightweight, low power consumption, wide viewing angle, and fast response.

II. Structure

A cross-sectional view of the TFT-LEPD is shown in Fig. 1. First, on a glass substrate, LT p-Si TFT's, bus lines, and pixel electrode are fabricated the same as they are in the TFT-LCD [1], [2]. A 50-nm a-Si is formed by LPCVD of Si_2H_6 at 425 °C. It is crystallized by multiple irradiation of 245 mJ/cm^2 KrF excimer laser. Phosphorous ions for n-channel TFT's and boron ions for p-channel TFT's are implemented with a dose of the 10^{15} cm^{-2} order at an energy of several ten keV. These impurities are activated at 300 °C–400 °C for 4 h. The TFT characteristics are shown in Fig. 2. Mobility for n-channel TFT and p-channel TFT is 120 cm^2/V · s and 40 cm^2/V · s, respectively. In the case of the LCD, the ITO pixel electrode is used in order to apply voltage to the liquid crystal. On the other hand, in the case of the LEPD, the ITO pixel electrode is used as an anode in order to supply current to the LEP.

Next, an adhesive layer, inter-layer are fabricated. The function of the SiO_2 adhesion layer is to improve adhesion between ITO and polyimide. The function of the polyimide inter-layer will be written in the following section. After the fabrication of the both layers, O_2 plasma surface operation is done in order to improve the wettability of the surface of the polyimide and ITO.

After that, LEP layer consisting of a conductive polymer and a light emission layer, and a cathode metal are fabricated in succession [8]. First, polyethylene dioxythiophene/polystylene sulphonate (PEDOT/PSS) are dispersed in water and spin-coated. Since the surface of the substrate is wettable by O_2 plasma operation mentioned above, the spin-coated layer can be very uniform. Then, the spin-coated layer is baked in order to remove solvent and make a thin film. Next, precursor of poly (p-phenylene vinylene) (PPV) is deposited by spin-coating with a water/methanol mixture as solvent. Thermal conversion forms the precursor to the conjugated polymer, PPV. The

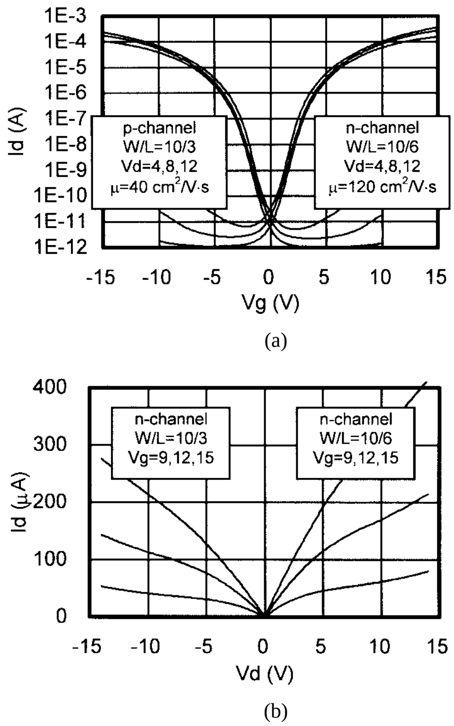


Fig. 2. TFT characteristics. (a) Transfer characteristics and (b) output characteristics are shown. Mobility for n- and p-channel TFT is 120 cm^2/V · s and 40 cm^2/V · s, respectively. A TFT model is extracted from these characteristics.

PEDOT/PSS and PPV are used as a conductive polymer and a light emission layer, respectively. After that, the aluminum with lithium is sputtered and used as a cathode for the LEPD.

Finally, a wire to supply current to the cathode is attached by pasting. The whole cathode is encapsulated by epoxy resin in order to avoid the degradation of the LEP and the cathode. A flexible tape is heat-sealed to the contacts on the substrate.

In the case of the TFT-LCD, an alignment layer, liquid crystal, and opposite substrate are needed on the TFT array substrate. On the opposite substrate, a black matrix, alignment layer, and opposite electrode are necessary. Moreover, a backlight, light guide, polarizer, diffuser, and other optical parts must be attached. On the other hand, in the case of the TFT-LEPD, whose structure is mentioned above, only some thin films on one substrate are needed. Therefore, very thin, compact, lightweight, and inexpensive displays can be achieved.

III. Novel Technologies

A. Conductance Control

We utilized conductance dependence of the driving TFT in order to control gray scale. A pixel equivalent circuit is shown in Fig. 3. A pixel is composed of two kinds of TFT, i.e., a switching and driving TFT, a storage capacitor, and an LEP diode. Actually, the switching TFT consists of three TFT's connected in series in order to decrease off current and reduce degradation caused by high electric fields around the drain edges of their channels [11]. The driving TFT consists of three TFT's connected in parallel in order to be cooled easily

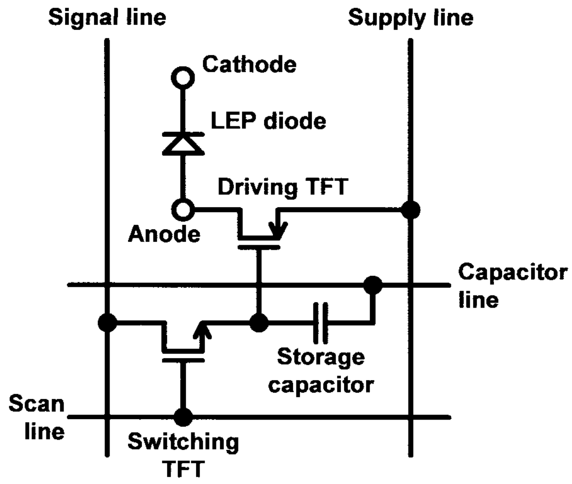


Fig. 3. Pixel circuit of the TFT-LEPD. A pixel is composed of a switching and driving TFT, a storage capacitor, and an LEP diode. Conductance dependence of the driving TFT is used in order to control gray scale. By this method, the pixel circuit can be simple.

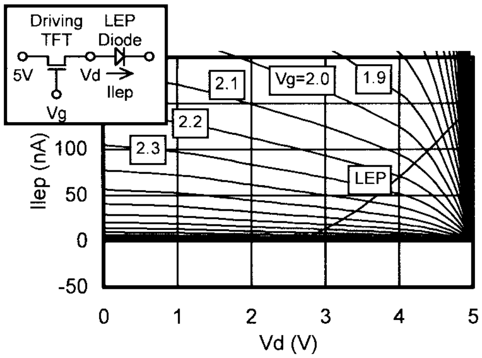


Fig. 4. Operation point analysis of the driving TFT and LEP diode. Horizontal and vertical axis are voltage of the terminal between the driving TFT and the LEP diode and current through the driving TFT and the LEP diode. The characteristics of the driving TFT corresponding to each gate voltage and the characteristic of the LEP diode are overlapped. The cross points of the characteristics mean operational points of the pixel equivalent circuit.

and reduce degradation caused by self-heating [12], [13]. The scan and signal drivers are integrated around the image area on the substrate and their workings are the same as those used in TFT-LCD's.

The mechanism for scanning, i.e., for transferring each signal voltage to the corresponding storage capacitor, is similar to that used in TFT-LCD's. The only difference is that the signal voltage stored in the capacitor does not have to be ac, but can be dc, because the LEP diode is driven by dc current and the driving TFT should control the LEP diode by dc voltage. Therefore, it is possible to reduce the amplitude of the signal voltage and scan voltage.

The signal voltage stored in the capacitor is also applied to the gate terminal of the driving TFT. The gate voltage controls conductance of the driving TFT and anode voltage depends on the relationship between the resistance of the driving TFT and LEP diode. That is, by varying signal voltage, current through the LEP from the supply line via the anode to the cathode and light emission can be modulated.

In the bright state, since the resistance of the driving TFT is negligible compared to that of the LEP diode, there is little voltage drop and wasted power consumption in the driving TFT. The power reduction in the bright state is very meaningful because the current is larger than other states.

There are only two TFT's in a pixel. This structure is conventional for current consuming devices, such as the LEP diode, and there are some disadvantages, for example, nonuniformity caused by variation of the characteristic between the driving TFT's. However, we chose this structure because the simplicity is very practical when we avoid the yield rate problem in mass production.

Next, the design and voltage were optimized. The driving TFT cannot work in the saturation region for all the gate voltages even if its design parameter is varied. There are two reasons. The first reason is low drain voltage. In order to reduce the power consumed in the driving TFT in the bright state, the resistance of the driving TFT should be negligible compared to the resistance of the LEP diode. This means that the voltage drop between the drain and the source terminal, i.e., drain voltage, is rather small. In addition, since the efficiency of the light emission from the LEP becomes very high and its threshold voltage becomes very low, recently, only about 5 V must be applied to the LEP diode for sufficient light emission. The second reason is that, as shown in Fig. 2, the LT p-Si TFT has no saturation region defined clearly, i.e., a flat characteristic which is independent of the drain voltage, because of many defects in the channel [14].

If a TFT worked in the saturation region, it would be easy to calculate the current because the current would mainly depend only on the gate voltage. However, since the TFT works in the nonsaturation region, it is very difficult to calculate the current by analytical calculation. The reason is as follows. The current depends on not only the gate voltage but also the drain voltage. The drain voltage is decided by the relationship of the resistance between the driving TFT and the LEP diode. This relationship is not decided until the current is decided because both the TFT and the LEP diode are nonlinear electric devices for applied voltages. Because of such a complicated mechanism, operational point analysis or circuit simulation by a computer is needed to perform the design.

Fig. 4 shows operational point analysis of the pixel equivalent circuit to achieve gray scale. The horizontal axis is voltage of the terminal between the driving TFT and the LEP diode, which is drain voltage of the driving TFT and anode voltage of the LEP diode, simultaneously. The vertical axis is drain current of the driving TFT, which is same as the current through the LEP diode. The characteristics of the driving TFT corresponding to each gate voltage, which is the signal voltage stored in the storage capacitor, are overlapped. The characteristic of the LEP diode is also overlapped. The cross points of the characteristics of the driving TFT and the LEP diode mean operational points of the pixel equivalent circuit for each gate voltage.

Circuit simulation with a TFT and LEP model [15] was done in order to design the driving TFT and LEP diode circuit including gray scale. These models are extracted from the measured data. Fig. 5 shows a simulated current–voltage

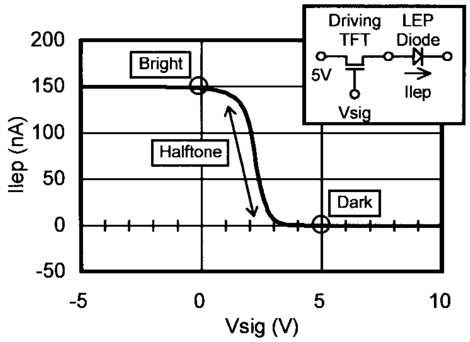


Fig. 5. Simulated current–voltage ($I-V$) characteristic of the driving TFT and LEP diode. Horizontal and vertical axis are signal voltage and current through the LEP diode, respectively. Gray scale can be acquired by optimizing all the design parameters. Signal voltage can be adjusted within a range of less than 5 V.

TABLE I
SPECIFICATIONS AND DESIGN PARAMETERS OF THE TFT-LEPD. DESIGN PARAMETERS WERE OPTIMIZED BY CIRCUIT SIMULATIONS. A HIGH-RESOLUTION LT p-Si TFT LEPD WITH INTEGRATED DRIVERS HAS BEEN FABRICATED

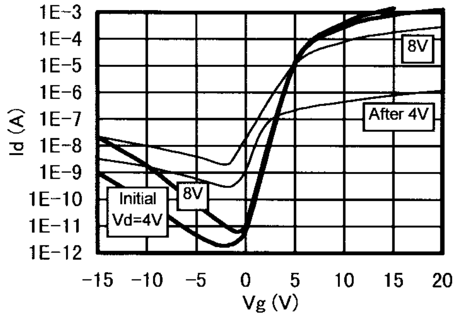
Image area size	Diagonal 4.4 cm
Pixel number	708 x 185
Pixel pitch	52 x 133 μm
Switching TFT	W / L = 9 / 12 μm
Driving TFT	W / L = 60 / 6 μm
Storage capacitor	0.27 pF
Open aperture ratio	12 %
Weight	15 g
Thickness	2.5 mm
Display outward size	4.5 x 3.7 cm

($I-V$) characteristic of the equivalent circuit consisting of the driving TFT and LEP diode. The horizontal axis is signal voltage, which is applied to the gate terminal of the driving TFT. The vertical axis is current through the driving TFT and LEP diode. Gray scale from the bright state via the halftone state to the dark state can be acquired.

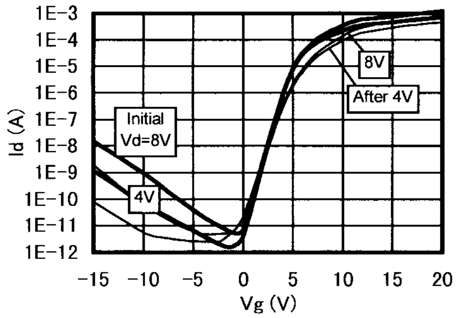
By such analyses and simulations, for the given area of the LEP, the design of the driving TFT, i.e., width and length, is optimized. Signal voltage can be adjusted within a range of less than 5 V, which may achieve very low power consumed in video signal circuit in the peripheral controller. After that, the entire design of the TFT-LEPD, i.e., the switching TFT, storage capacitor, etc., is decided. All the optimized design parameters and specifications of the TFT-LEPD are shown in Table I.

B. P-Channel TFT for Reliability in DC

In order to ensure the reliability of the driving TFT even when dc voltage is applied, a p-channel TFT is used. Fig. 6 shows a comparison of the reliability by measurement between an n-channel and p-channel TFT. Initial transfer characteristics and those after dc stress, i.e., gate voltage 20 V, drain voltage 0 V, temperature 70 °C, bias time 600 h, are overlaid. In this stress condition, gate voltage and temperature is higher than real working conditions in the TFT-LEPD. This was done to accelerate testing. It is clear that the p-channel TFT is much more reliable in dc bias than the n-channel TFT. The reason



(a)



(b)

Fig. 6. Comparison of reliability between an (a) n-channel and (b) p-channel TFT. Initial transfer characteristics and those after dc stress, i.e., Vg 20 V, Vd 0 V, temperature 70 °C, bias time 600 h, are overlaid. The TFT's have W/L of 100/12 μm. It is clear that the p-channel TFT is much more reliable in dc bias. Thus, a p-channel TFT is used for the driving TFT.

is not understandable now but we will research this important phenomena from now on.

C. Inter-Layer to Reduce Parasitic Capacitance

As we can see in Fig. 1, an inter-layer made of insulator covers all areas except for the light emission area in the anode. The function of the inter-layer is to exist on the signal lines, to distance the cathode, and to reduce parasitic capacitance of the signal lines. The thickness of the inter-layer was decided to be 1.0 μm, while that of SiO_2 adhesive layer, which exists between the inter-layer and the anode, is 0.1 μm. From these values, capacitance between the signal line and cathode is 3.1 pF. By adding other capacitance, total capacitance of the signal line is 10.5 pF. Resistance of the signal line itself is 330 Ω and the equivalent resistance of an LT p-Si TFT analog switch on the edge of the signal line is on the order of 1 kΩ at most. Therefore, the time constant of the signal line is on the order of 10 ns. This panel is designed for the point-at-time driving scheme [16], which means that during application of scan voltage, each signal voltage is applied sequentially. The selecting time for one signal line is 240 ns. Since the time constant is enough smaller than the selecting time, correct signal can be applied to the signal line.

D. Others

The LEP layer, i.e., the conductive layer and the light emitting layer, is not patterned. However, crosstalk of light emission between pixels does not occur. The reason is as

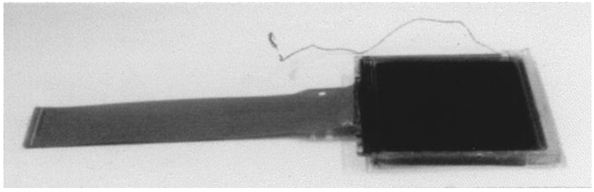


Fig. 7. View overlooking the TFT-LEPD. Because of no backlight, light guide, polarizer, diffuser, peripheral drivers, etc., the TFT-LEPD can be lightweight, thin, and compact.

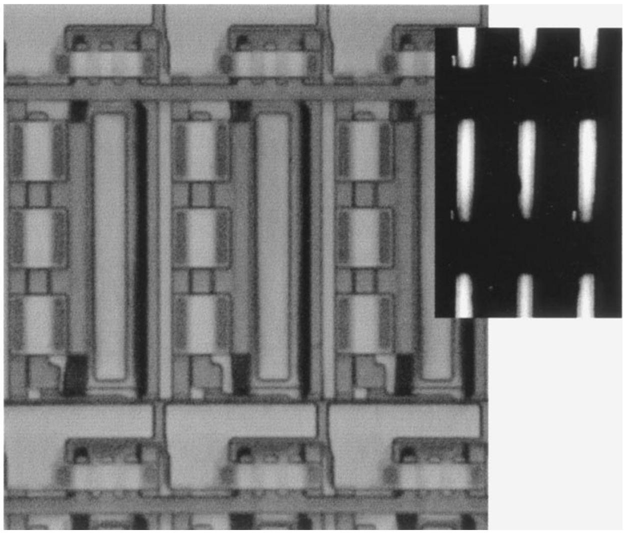


Fig. 8. Photographs of pixels and electroluminescence from the pixels. Since the light emission area ratio is at most 12%, reflection from cathode metal is reduced and contrast can be improved if the rest of the pixel is covered with a light shield layer.

follows. Since the electric resistivity of the conductive layer is about 1 k$\Omega \cdot$cm and its thickness is very thin (10 nm), its sheet resistance is 1.0×10^9 Ω/sq and its resistance between pixels is 6.0×10^8 Ω. The resistance is much higher than the LEP diode resistance, the order of 1.0×10^7 Ω. Moreover, the electric resistivity of the light emitting layer between pixels is still higher than that of the conductive layer. As a result, the LEP diode can be supposed to be electrically separated between each pixel.

IV. Results

A high-resolution LT p-Si TFT LEPD with a scan and signal integrated driver has been fabricated. The specifications have already been shown in Table I. A view overlooking the TFT-LEPD is shown in Fig. 7. No backlight, light guide, polarizer, diffuser, and peripheral drivers are needed. The number of contacts between the peripheral controller and the panel is reduced to only 27. Twenty-six of the contacts are through a flexible tape and one contact is through a wire pasted on the cathode. Consequently, the TFT-LEPD can be exceedingly lightweight, thin, and compact, as shown in Table I. Here, the second glass substrate is used only for encapsulation of the LEP and supporter, which can be eliminated easily in the near future.

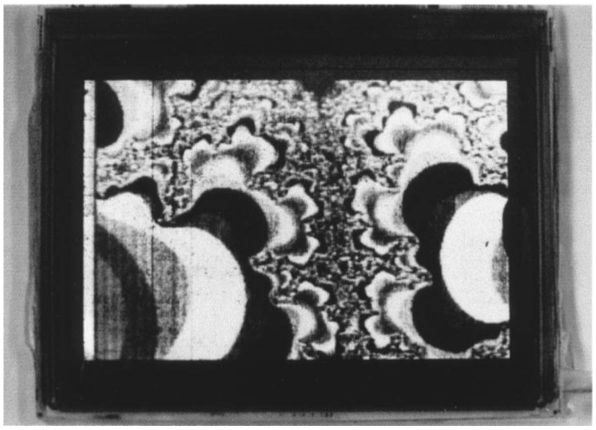


Fig. 9. Display image of the TFT-LEPD. Green monochrome display image is acquired. Neither nonuniformity nor crosstalk occurs.

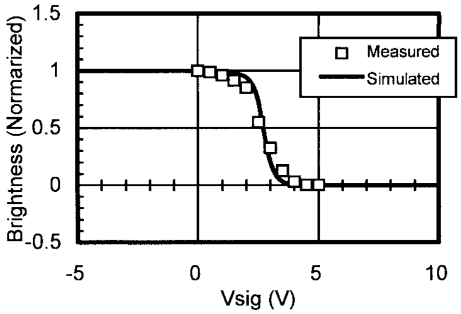


Fig. 10. Measured and simulated gray scale. Brightness is normalized by the maximum value. The measured gray scale is similar to the simulated one. It is found that good gray scale from the bright state via the halftone state to the dark state can be acquired.

Photographs of pixels and electroluminescence from the pixels are shown in Fig. 8. The light emission area ratio, i.e., the ratio between light emission area and whole area in a pixel, is at most 12%. In spite of the small ratio, there is no serious problem because all light comes from the light emission area, no light loss occurs, and power is not wasted. On the contrary, the small ratio can reduce reflection from cathode metal. If the rest of the pixel is covered with a light shield layer, all reflection from the display can be reduced and contrast can be improved.

A display image of the TFT-LEPD is shown in Fig. 9. Here, a green monochrome display is acquired. Neither nonuniformity caused by the parasitic capacitance of the bus lines nor crosstalk between pixels occurs. Measured and simulated gray scale is shown in Fig. 10. Here, brightness is normalized by the maximum value. The measured gray scale is similar to the simulated one. It is found that good gray scale from the bright state via the halftone state to the dark state can be acquired.

The achieved power consumption with the voltage and current are listed in Table II. The power consumed in the integrated driver is 20 mW. In order to achieve brightness of 100 Cd/m^2 from the whole panel, only 5 V is needed to be applied to the driving TFT and LEP, which leads to less than the current of 20 mA through the LEP and the power consumption of 100 mW. Therefore, total power consumption of the TFT-OELD is 120 mW at most. When the displayed

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