Vacuum fluorescent displays: from single digits to colour TV

K. KIYOZUMI, T. NAKAMURA

Physical principles and operational characteristics of various vacuum fluorescent displays are outlined. A VFD history and details of construction are also given. Displays of various resolutions for different applications are described up to a 256 x 256 dot matrix unit. Uniform brightness and precise switching operation are realized using improved anode and grid electrode construction, anode baseplate processing, and grid configuration and its fixing processes. A scrolling VFD and a MOS FET switching array VFD are introduced. The latter uses an integrated circuit of 241 x 246 elements to produce a picture 23 x 23 mm. Prospects for the development of VFDs are given in conclusion.

Keywords: display devices (computers); vacuum fluorescent displays; graphic displays; Japan.

The vacuum fluorescent display tube, based on the combined concept of a triode and a cathode ray tube, was first produced by Ise Electronics Corporation in 1967. Three stages of development have followed since then. The first was the single digital tube using a tubular glass envelope. The second was the multi-digital glass envelope tube capable of displaying six to 13 digits. Both of these make use of ceramic substrates upon which electrodes are constructed. Material cost of these however called for a third generation which could survive competition in the market, which in those days was clearly characterized by two overwhelming needs, for cost competitiveness and for a planar or flat display configuration. The third generation of VFD dispenses with the ceramic substrate which its predecessors depended upon and achieves the required planar configuration. It makes use of one side of the flat glass vacuum envelope as the substrate, upon which a wiring layer, insulating layer, anode electrodes, phosphor layers, grid mesh, and the rest are mounted by various deposition processes. Another glass plate, the faceplate, over which a set of linear filamentary cathodes is mounted, is sealed to the substrate or the base glass plate leaving a little space between the two.

CONSTRUCTION

The VFD is essentially a three-element vacuum tube[1], part of which is made of transparent material. The envelope encloses a direct heated filament cathode, metallic mesh grids and phosphor-coated anode segments (Fig. 1).

The wiring layer, insulating layer and the phosphor-coated anodes are processed by thick film printing. The wiring layer edge protrudes from the envelope, facilitating connections of internal electrodes to external circuits. As the dimensions of the dot anode and dot pitch decrease, a high density of wiring becomes necessary. The only way for thick film printing to cope with this high density of wiring is in stacking up the wiring into a multi-layer structure. Increased processing costs and augmentation of interelectrode capacitance are inevitable with this technique.

These difficulties are overcome using a composite technique on the glass substrate. Here, thin films of fine aluminium wiring are added to the thick film printing[2]. The composite glass substrate is shown in Fig. 2[3]. The grid is constructed by photo-etching a stainless foil into a lattice structure or into sheets with hexagonal pores. The cathode is an extremely fine pure tungsten filament coated with alkaline earth carbonates. Activation of the cathode during processing is carried out in the same manner as for conventional electron tubes:

$$(\mathrm{Ba, Sr, Ca})\,\mathrm{CO_3} = \mathrm{CO_2} + (\mathrm{Ba, Sr, Ca})\,\mathrm{O}.$$

Until 1981, the face glass was mostly formed and processed from plate glass. However, in recent years pieces of glass cut from plate glass which are then joined by fritting to form the desired shapes for face glasses have become prevalent.

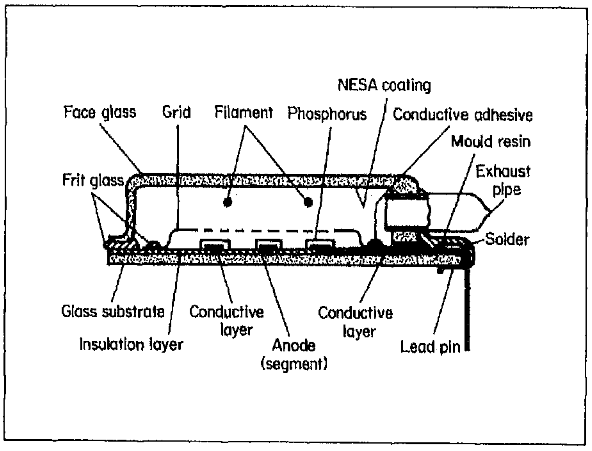


Fig. 1 Cross section through a vacuum fluorescent display

The authors are at the Ise Electronics Corporation, 700 Aza Wada, Ueno-cho, Ise City, Mie, Japan.

0141–9382/83/040213–08 $03.00

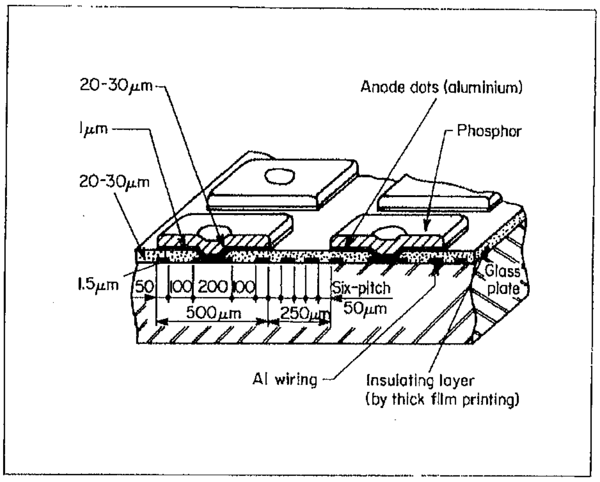


Fig. 2 Cross section showing detail of the composite glass substrate (dimensions not defined are in µm)

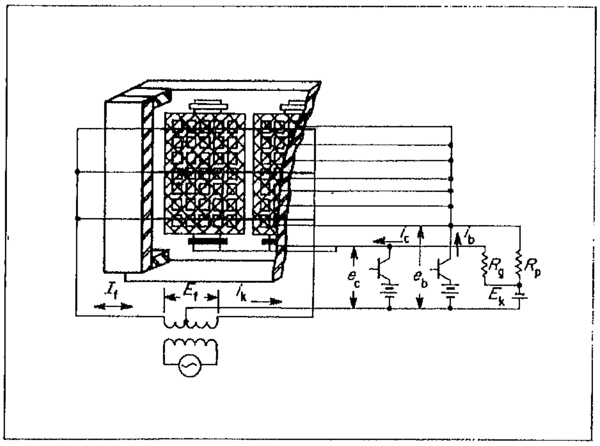


Fig. 3 VFD operation

OPERATION

The principle of operation of VFDs is shown in Fig. 3. By application of prescribed voltages to each of the electrodes, the cathode will emit electrons at 650°C. The grid located between the cathode and the anode controls the electron flow from the cathode to the anode. The correct positive potential on the grid accelerates as well as diffuses the electrons from the cathode to the anode; the correct negative potential cuts off the electrons to the anode. Since the grid is made of metallic mesh, some of the electrons that strike it are captured. This gives rise to the grid current. Those electrons that pass through the grid mesh arrive at the anode and, by virtue of their kinetic energy, excite the phosphor to emit light, thus causing the anode current to flow. Here, the anode must also have applied to it the correct positive potential, ie the grid and anode should be simultaneously positively charged for the emission of light.

CHARACTERISTICS

As stated before, the VFD is basically a triode, and is characterized by a variety of properties. These will be described for a typical dot character VFD (DC405A2).

Cathode start-up characteristics

Figure 4 shows the change in filament current I_f, brightness L, anode current i_b and grid current I_c against filament voltage E_f. Each parameter increases as E_f is raised. In the case shown, L, i_b and i_c exhibit saturation beyond $E_f = 8$ V. If E_f is fixed at a value lower than 8 V, a variation of brightness results from the fluctuation of the power source. If E_f is fixed at an excessive voltage, it is evident that substantial filament power is wasted which is not only ineffective in raising the brightness, but also deteriorates the filament life by unnecessarily raising the temperature. It is most desirable to set E_f at the lowest possible value in the saturation region. The standard rating of filament voltage of the DC405A2 is 8.9 V.

Anode and grid voltage

The anode voltage e_b and the grid voltage e_c have a great effect on the brightness L. Effective use of the VFD depends to a large extent on the best choice of e_b and e_c values. Except in rare special cases, e_b and e_c are assigned equal voltages.

As shown in Fig. 5, L, i_b and i_c do not exhibit saturation with respect to the increase of e_{bc}. Brightness L apparently exhibits a good increase, but the cathode current i_k, which is the sum of i_b and i_c, also increases. This makes it likely to

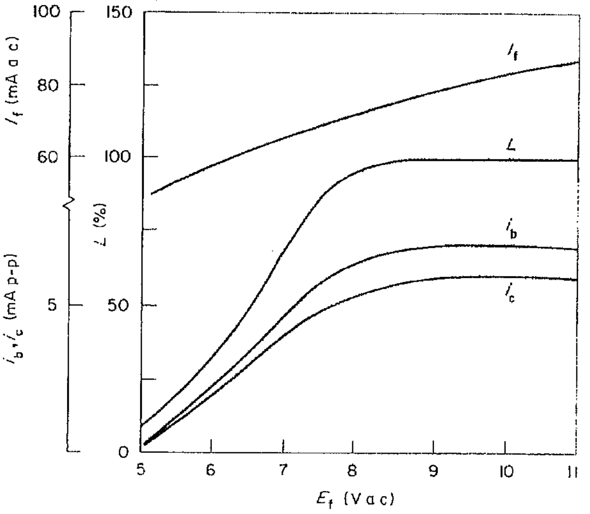


Fig. 4 Cathode start-up characteristics ($e_b = e_c$ 45 V p-p; duty ratio 1/50)

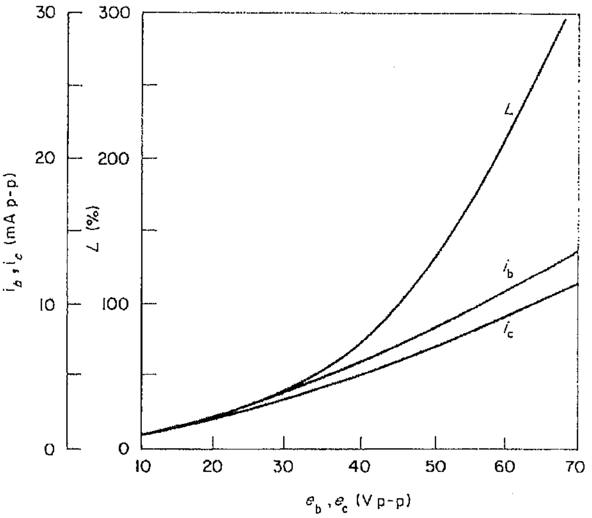


Fig. 5 Voltage characteristics ($E_f = 8.9$ V a c; duty ratio 1/50)

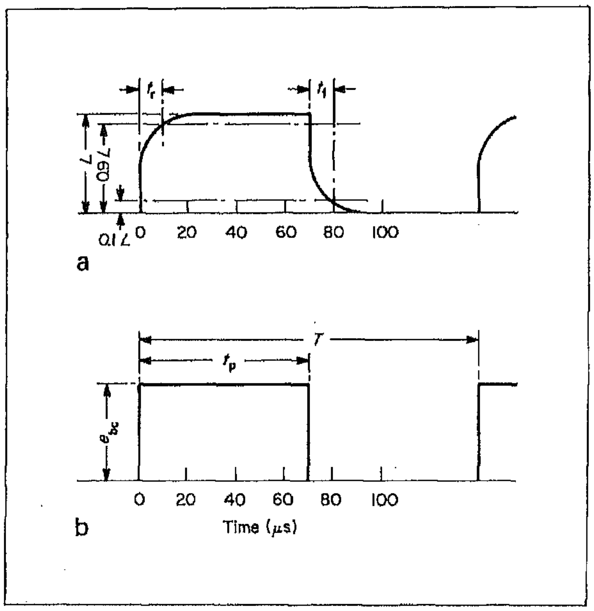


Fig. 6 ZnO:Zn phosphor light response: (a) for a square input voltage waveform on the anode and grid (b)

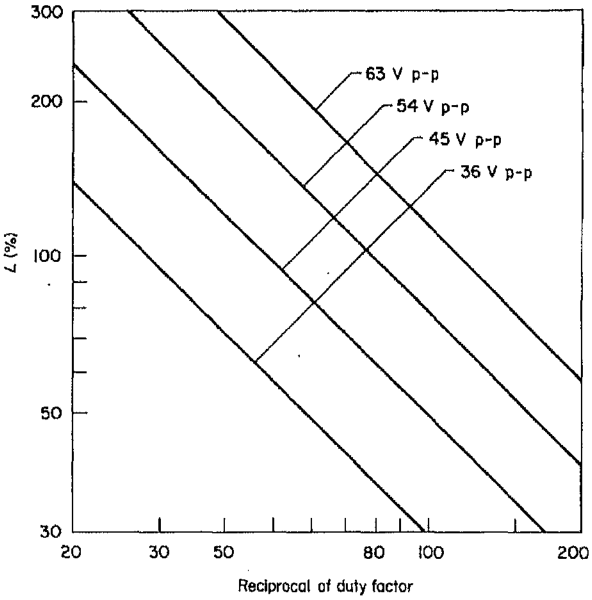


Fig. 7 Brightness against duty factor for various values of $e_b = e_c$ shown (E_f = 8.9 V a c)

exceed the limit for stable electron emission heating, which may result in damage to the cathode. The standard rating of e_b and e_c of DC405A2 is set at 45 Vp-p.

Duty factor

In a dynamically driven VFD, duty factor (DF) is considered one of the factors that governs the brightness and quality of the display. The duty factor depends upon the number of digits of the VFD and the blanking time.

Figure 6 shows the pulse activation response of a ZnO:Zn phosphor which gives out blue-green light. The rise and fall times, t_r and t_f, are both about 10 µs. As shown in Fig. 7, L is proportional to DF, which is expressed as

$$DF = t_p/T$$

The pulse length t_p and period of repetition T are shown in Fig. 6. Figures 4 and 5 show results of measurements performed at $DF = 1/50$ and $t_p = 100$ µs.

Cut-off

In practice, a VFD must extinguish the light by placing negative potentials on the grid and anode. Figures 8 and 9 show the cut-off characteristics of the grid and anode. Referring to Fig. 3, a voltage E_k is placed on each of the grids or the dot anodes as the cut-off voltage through resistors R_g and R_p.

DOT CHARACTER VFDs

The ability to increase the size of the displayed information is important for a display device. In the newly developed types of VFDs of 5 x 7 elements, 5 x 7 elements with cursor, 5 x 12 elements, JIS and ASCII bases exist which render possible displays of five letters comprised of upper and lower case alphabets, Katakana and special symbols.

Dot character displays have been developed with one line with 6 to 80 characters up to two to 12 lines with 40 characters per line at various character heights. Currently, 480 is the largest number of characters on a VFD (Fig. 10). Since it has a large number of lead terminals, this VFD is mounted on a special printed circuit board which is designed to be able to be connected to a conventional printed circuit connector. An example of a block diagram of a drive circuit is shown in Fig. 11[5].

DOT MATRIX VFDs

Since both segment and dot character displays are partitioned between the digits restriction on the quantity and

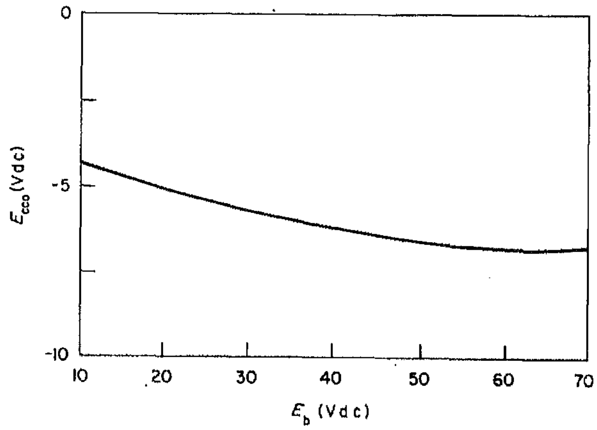


Fig. 8 Grid cut-off characteristics (E_f = 8.9 V a c)

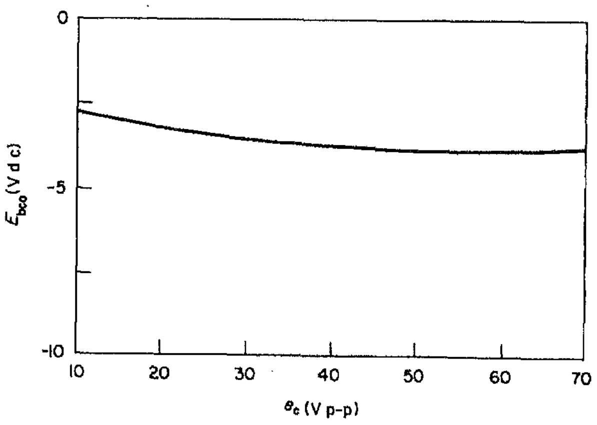


Fig. 9 Anode cut-off characteristics (E_f = 8.9 V a c; duty ratio 1/50)

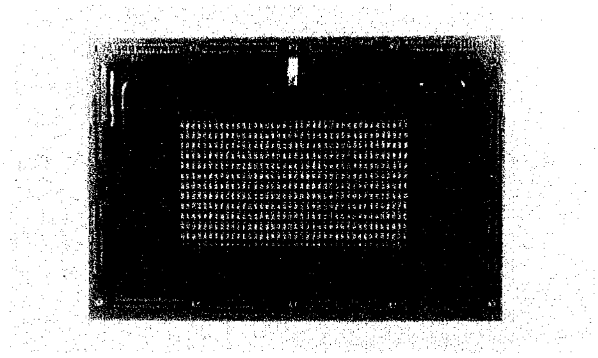


Fig. 10 480-character display with cursor

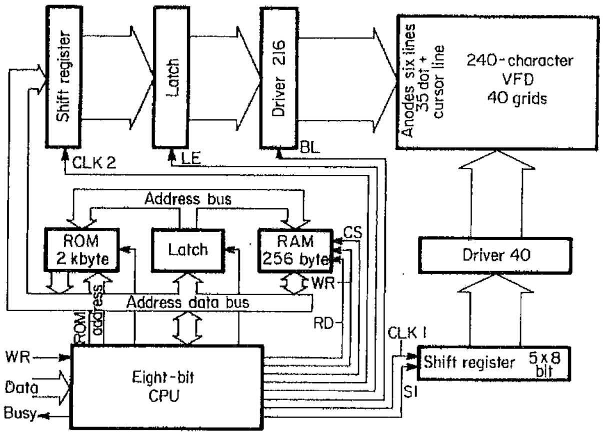


Fig. 11 Example of a VFD driver block diagram

variety of display is inevitable^{6}. An array of picture elements at equal spacings along the vertical and horizontal directions overcomes this limitation. This enables displays of Hiragana, Kanji and other complex letters in addition to the simple alphabets already catered for using small dot matrix VFDs. Drawings, graphs, graphics and TV images^{7} may now also be displayed. Figure 12 is an example of an image display on 128 x 128 element screen.

The dot matrix display has a construction basically similar to that of the element shown in Fig. 1. However, connection of the element anodes and the arrangement of the grids are such as to form a matrix. Driving conditions are also devised to match the anode and grid conditions. Driving voltages on the anodes and grids give rise to light emission at the intersection point when the same positive potential is applied to each.

The anode elements must be made small to realize high resolution, which necessitates a thinning down of the grid width. This in turn leads to insufficient control of electron flow from the cathode to the anode which allows the effect of the neighbouring negatively biased grid to extinguish the light on the anode. It is thus necessary to focus as many electrons as possible to the single anode which is supposed to be activated^{6}.

Figure 13 shows examples of the connection of the anodes in a dot matrix display. In the first case, which is a single matrix arrangement, neither end of the anode luminesces as mentioned above. In the case of the double matrix however, the anodes are alternately wired in two groups, and the two neighbouring grids that face the dot anode have a positive driving voltage together with the dot anode. This enables the dot anode to luminesce over its whole area at the required brightness. A half-pitch shift of the grid with regard to the anode dots and simultaneous application of a driving voltage to two neighbouring grids result in an overall luminescence of the dot anode (Fig. 14). The arrangement of the dot anodes and grids is shown in Fig. 15.

A graphic display using this scheme with 256 x 256 elements is shown in Fig. 16. This is a VFD with dots 0.2 mm square. The elements are arranged in the x and y directions at a pitch of 0.4 mm. A block diagram of a 128-element square image display system is shownin Fig. 17. Figure 12 is an example of a displayed picture with 15 gradations of grey scale.

SCROLL VFDs

The scroll VFD is a dot matrix display with many more elements in the x direction. A unit shift when the display

Fig. 12 Example of an image displayed on a 128 X128 element VFD

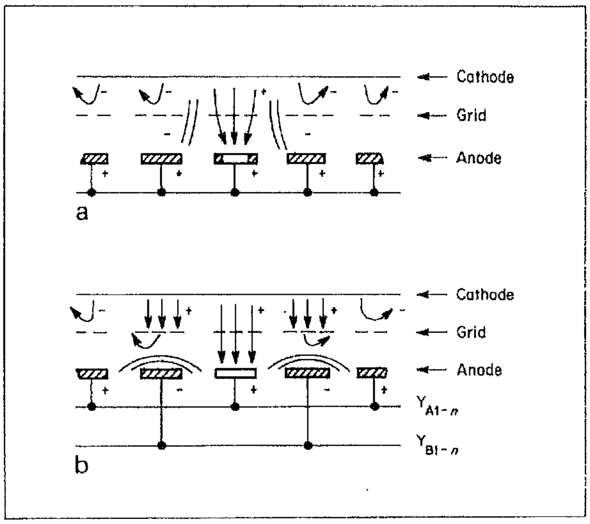


Fig. 13 Connection of dot anodes of a dot matrix display

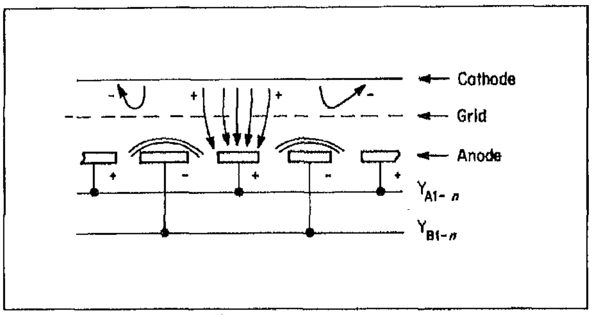


Fig. 14 Connection of dot anodes of an improved dot matrix display

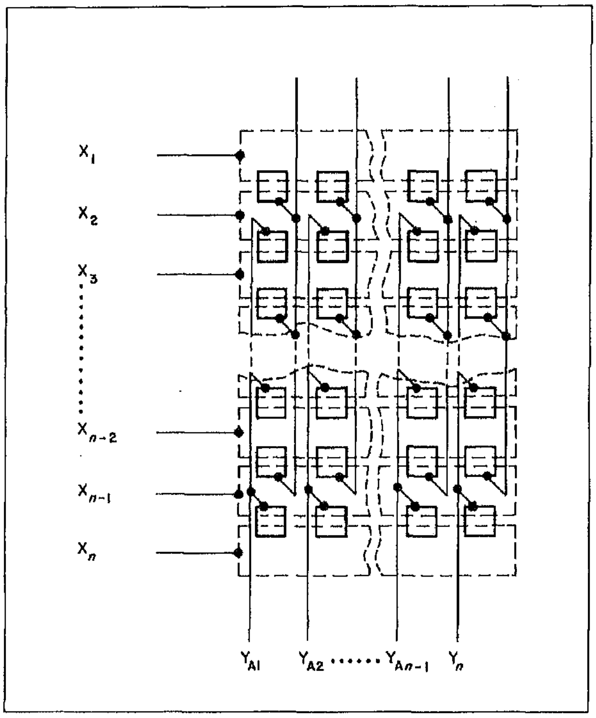
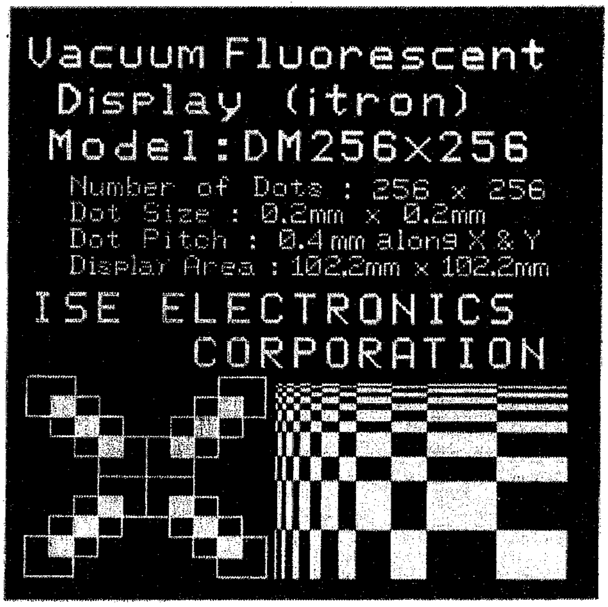


Fig. 15 Arrangement of dot anodes and grids



Vacuum Fluorescent
Display (itron)
Model:DM256x256
Number of Dots : 256 x 256
Dot Size : 0.2mm x 0.2mm
Dot Pitch : 0.4mm along X & Y
Display Area : 102.2mm x 102.2mm
ISE ELECTRONICS
CORPORATION

Fig. 16 Example of a graphic display on a 256 X256 element VFD

pattern is scrolled corresponds to a displacement of a unit pitch of the dot. Repetition of the shift at a constant rate causes the displayed pattern to move from the left to the right. This scrolling display also uses the double matrix, giving a better quality of display.

Figure 18 shows a single matrix in which a supposedly active dot anode is seen to illuminate only partially, affected by the potential of the neighbouring grid, while a supposedly inactive anode is seen to illuminate partially, degrading the quality of display performance. With the double matrix arrangement, however, combined with improvements in the driving system, the whole area of just the active dots luminesces. A bright, high quality display results. Figure 19 shows the dot anode connection and grid arrangement of a scrolling display.

Figure 20 shows a section of an animated picture displayed on a 256 x 64 dot matrix display (pitch – 0.65 mm; dot size – 0.4 mm square). The driver circuit for the display is shown in the block diagram of Fig. 21. Figure 22 shows another display, this one 256 x 26 elements. Its character

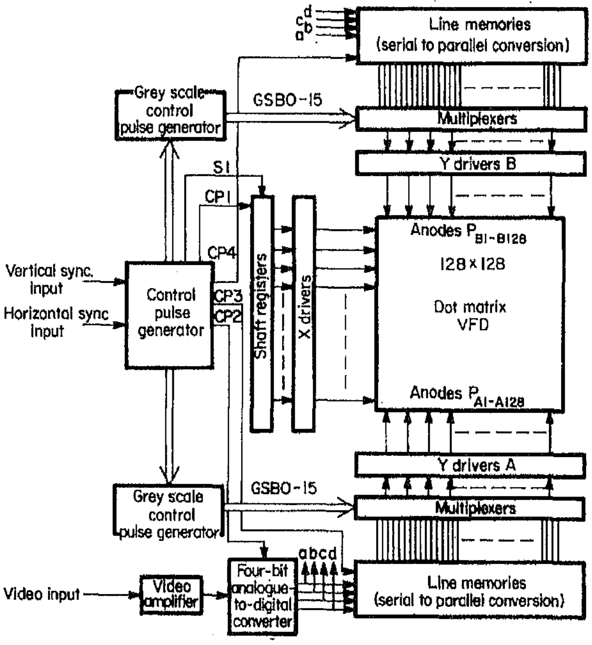


Fig. 17 Drive circuit to picture display

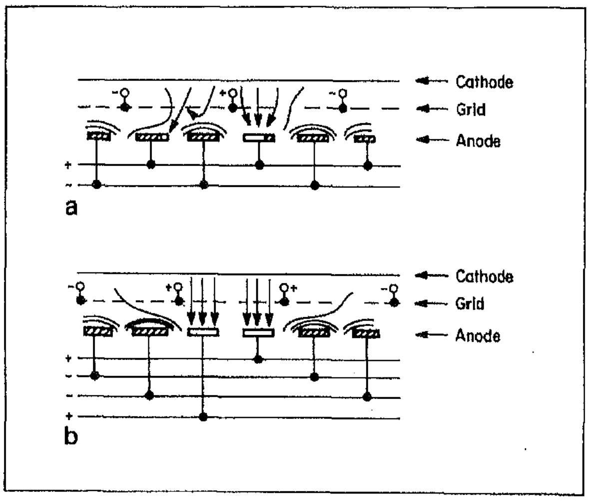


Fig. 18 Connection of dot anodes of a scroll display

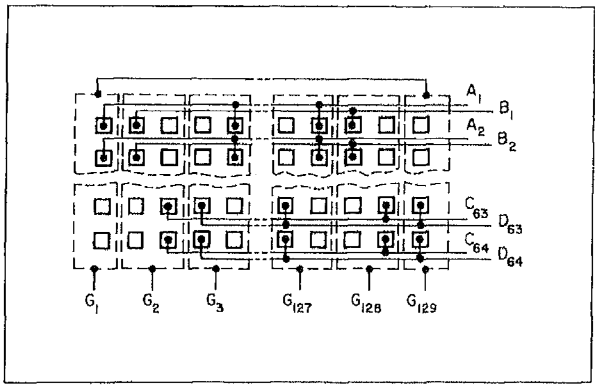


Fig. 19 Arrangement of dot anodes and grids on a scroll display

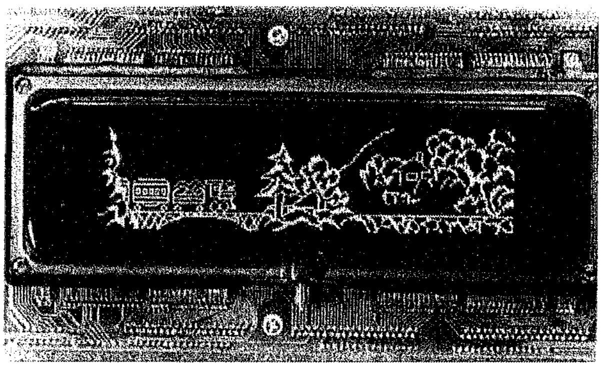


Fig. 20 Example of an animation display on a 256 ×64 element VFD

display of 24 x 24 dots is more than sufficient to delineate the Ming Dynasty Kanji characters shown. In fact a 16 x 16 display proves adequate for practically acceptable Kanji characters.

The relatively large number of lead terminals in dot matrix scroll display panels is accommodated by mounting the panels on specially designed printed circuit boards, which may accept conventional connectors.

ACTIVE MATRIX VFDs

The number of pixels available on VFDs has increased sufficiently for TV images now to be displayble. However, TV displays depend upon the grid scanning system which

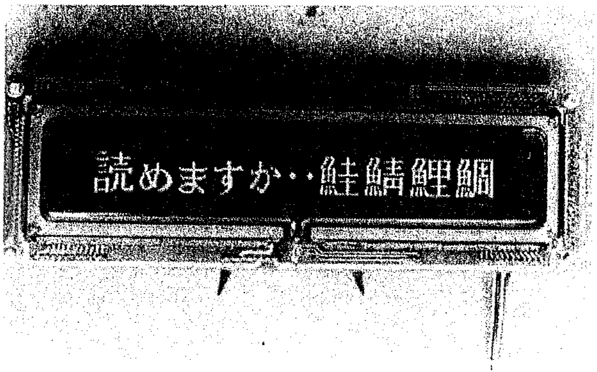


Fig. 22 Examples of Kanji and Hiragana characters displayed on a 256 ×26 element VFD

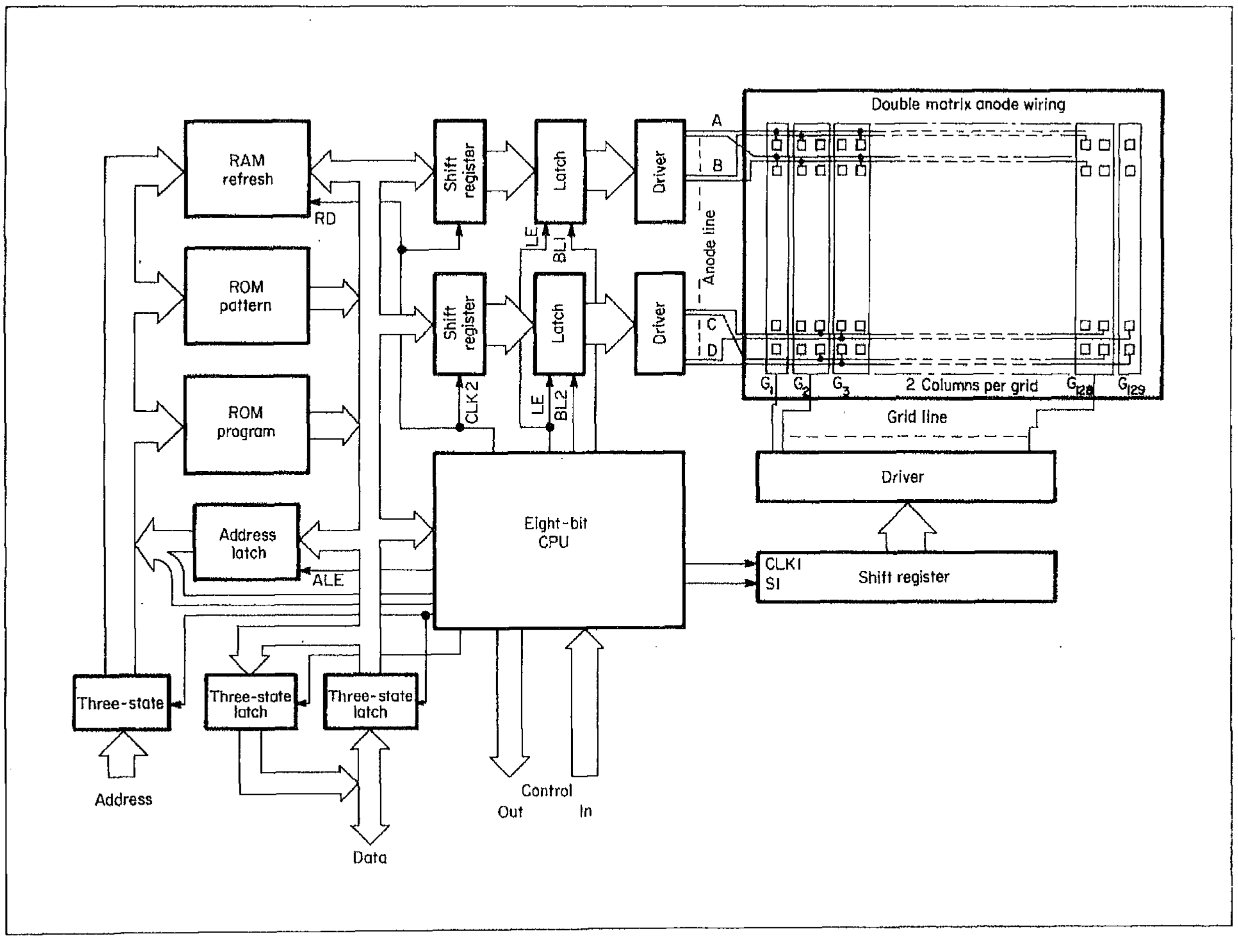


Fig. 21 256 ×64 element VFD driver block diagram

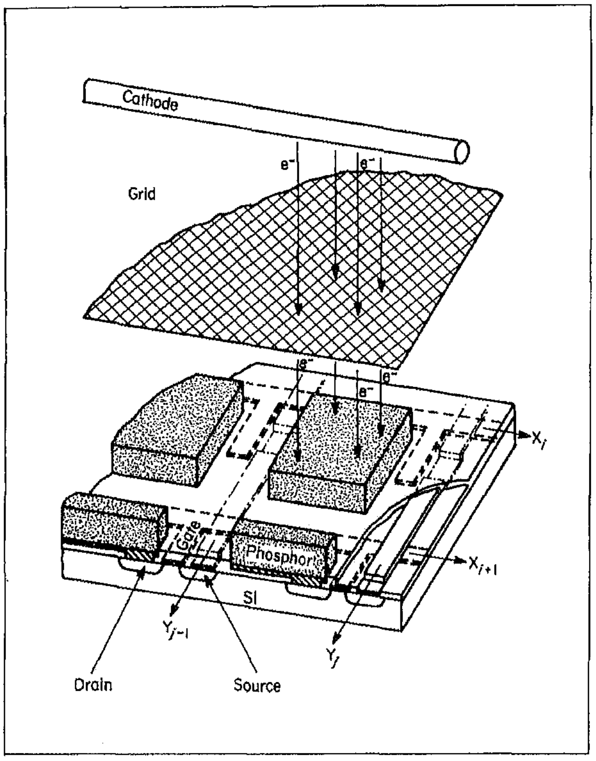


Fig. 23 Active matrix display operation

limits the pixel density and requires a low driving voltage. One possibility for a breakthrough in this area is to use silicon MOS FETs as switching elements[9,10].

Figure 23 illustrates the basic principle of the switching element. Each pixel consists of a MOS FET processed on a silicon wafer and a phosphor dot deposited on the drain electrode of the FET (in the p channel case). By applying an appropriate combination of voltages to the gate and source electrodes, the conductivity of the FET is increased, allowing the positive source voltage to be applied to the phosphor, thereby illuminating it. An array of cathode filaments acts as a source of electrons, together with a single grid electrode extending across the display to draw the electrons from the cathode and cause uniform flooding of the phosphor elements. The semiconductor substrate allows memory and driver functions to be built in. This enables a brightness of about 1 000 cd m^{-2} to be produced at voltages in the range 15 to 20 V.

The driving voltage and current appear to satisfy most of the conditions required for the various potential applications. This proved most effective in reducing the number of connecting terminals which had necessarily increased greatly with the increase of the number of pixels in the grid dynamic driving system. The improved scheme also enhances reliability and cuts the cost of the display module. Furthermore, it lends itself well to microprocessing technology for the realization of extremely high density pixel displays. Experiments have shown that pixels with a pitch of 20 to 30 μm are realizable.

Characteristics of an experimental tube example are listed in Table 1. Except for the driving voltage and number of pixels, values are approximate. No memory or driving circuit was included internally in the experimental tube.

Table 1. Experimental tube characteristics

Tube thickness	10 mm
Chip size	23 x 23 mm
Number of pixels	241 x 246
Pixel pitch	90 μm
Luminous area	45 μm diameter
Power	1 W (60 Hz; duty factor: 1/300)
Driving voltage (V_s)	30 V
Maximum brightness	30 cd m^{-2} (60 Hz; duty factor: 1/300)

While the monolithic substrate is a must, restrictions imposed upon the display area associated by use of the silicon chip may cause problems. Nevertheless, in applications where a large scale monolithic substrate is not necessary, it is possible to construct a silicon chip having a desired area by patchwork of a number of small area silicon chips as in the case of a hybrid integrated circuit.

Colour display on any new type of display (ie not the CRT) harbours difficulties. However, of these the VFD appears to be closest to providing a practical colour display. In particular, in the case of the present active matrix scheme, realization of an effective duty cycle of 100 per cent is always possible regardless of the duty cycle of the input signal. This should prove extremely advantageous in exciting phosphors of low luminous efficiency – the blue and red. With these features, applications are anticipated in displays of high density, ultra-fine picture images, in complex character displays, such as those for Kanji, and other complex displays.

VFD PROSPECTS

Since VFDs have been applied as dot matrix character displays, their growth in size has become apparent. The need for increased quantities of displayed information calls for the development and establishment of processing and constructing materials, components and the manufacturing technologies necessary in assembling these into a composite display device.

For dot matrix displays, improving the resolution remains the most important problem. This calls for a reduction of the dot pitch and size for the availability of the number of dots within a unit area. This relates closely to the grid structure and to the tube fabrication technology which includes the way in which the dot anodes are connected. Problems also remain in the wiring, connection with external circuits, and also in the further development of the driving circuit chips which demand high levels of cooperation with the semiconductor industry. Finally, the development of multi-colour matrix displays promises a vast expansion of VFD applications.

References

1 **Kiyozumi, K., Masuda, M., Nakamura, T.** 'Flat panel multi-digit fluorescent display' *Soc Inf Disp Dig* (1976) 130

2 **Morikawa, M., Hattori, M., Shimojo, T.** 'Fabrication of substrate glass for VFD deposited with aluminium thin film' *Ise Electronics Tech Rep* 3 10

3 **Kasano, K., Masuda, M., Shimojo, T., Kiyozumi, K.** 'A 240-character vacuum fluorescent display and its drive circuitry' *Proc Soc Inf Disp* **21** 2 (1980) 107

4 **Nakamura, T., Kiyozumi, K., Mito, S.** 'Vacuum fluorescent display' in 'Advances in image pickup and display, Volume 5' edited by B. Kazam (Academic, 1983) 199

5 **Iwade, M., Kasano, K.** 'A 240-character vacuum fluorescent display and its drive circuitry' *Ise Electronics Tech Rep* 3 30

6 'Ise Electronics comes out with novel VFD capable of Kanji displays' *Electron Mater Mag* (Japan) (1979) 19

7 **Iwade, M., Kasano, K., Masuda, M., Nakamura, T.** 'Vacuum fluorescent display for TV video image' *Soc Inf Disp Dig* (1981) 136

8 'Ise Develops a 128 ×128 pixels graphic display VFD' *Nikkei Electron Rep* (25 December 1978) 60

9 **Uemura, S., Kiyozumi, K.** 'Flat VFD TV display incorporating MOS FET switching array' *IEEE Trans Electron Devices* **ED-28** 6 (1981) 749

10 **Uemura, S., Kiyozumi, K.** 'Flat VFD TV display incorporating MOS FET switching array' *J Inst TV Eng Japan* **ED-477** (1979) IPD 46