

Gas-Discharge Displays: The State of the Art

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Abstract—The physics of the cold-cathode gas discharge is reviewed, with emphasis on such display-related aspects as the visible light output and the use of priming as a method of moving the light-emitting site through the display. Displays used for numerics, alphanumeric characters, and computer graphics are described, with attention being given both to commercially available units and to those which are still in the laboratory. Attempts to produce gas-discharge TV displays are reviewed. Such related problems as drive circuitry and overall system cost are discussed, with emphasis on considering the entire display system, including all the required power supplies and drive-circuit components.

I. INTRODUCTION

IN SURVEYING the state of the gas-discharge display art, I shall describe currently available devices and summarize research which may lead to new devices. This kind of survey requires attention to the interactions among the display devices themselves, their driving circuitry, and the end uses for the equipment. Because of the intimate relations among these three elements, it is necessary to consider them together rather than separately; in general, we must be concerned with display systems rather than just display devices.

Most display research and development is market oriented; managements see little point in funding work on devices for which there is not likely to be a demand. With this in mind, the survey mixes an account of the technology with a limited assessment of the competitive situation, not only among types of gas-discharge displays but also among the other types of displays that vie with gas discharges in the marketplace.

We begin with a review of the physics of the gas discharge, and then go on to describe displays used for numerals, alphanumeric characters in general, and graphic and image displays. There is some discussion of research on TV displays, which are the most difficult display problem because of the great technical difficulties and the severe cost constraints.

II. REVIEW OF THE PHYSICS OF THE DISCHARGE

In all of the devices discussed here, the electrodes are cold (except for the possible effects of electron or ion bombardment); thermionic emission plays no part. Electrons are released from the cathode (see Fig. 1) by positive-ion and UV-photon bombardment. Once the discharge has built up, there is a sheath of positive ions near the cathode. Electrons are accelerated across the gap between this sheath and the cathode by a potential that is typically

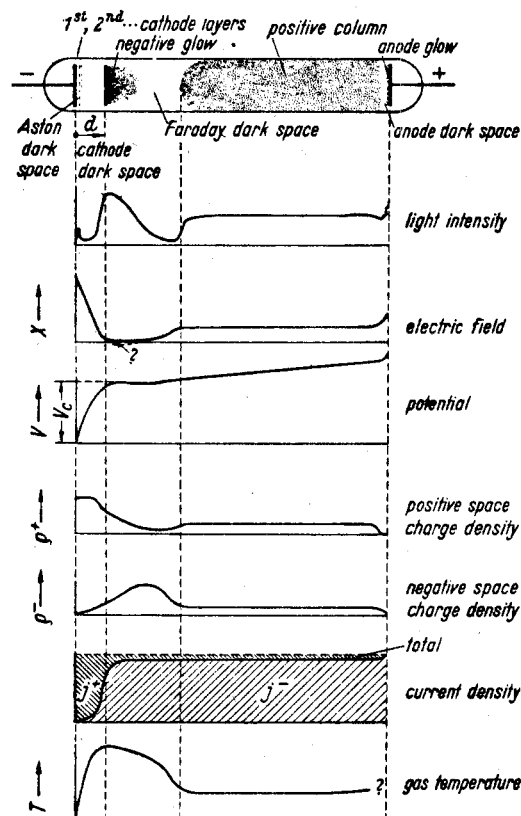


Fig. 1. The morphology of the discharge. In most display applications, the cathode dark space is very small and the various cathode layers indistinguishable. It is possible to have a self-sustaining discharge without a positive column; in fact, the anode may even be located in the Faraday dark space, although this gives rise to some unusual effects [1].

about 150 V. They thus acquire enough energy to ionize gas molecules. This ionization produces the cathode glow—a region in the immediate vicinity of the cathode where light and more ions are produced. The cathode glow is the visible output for a number of devices, including the well-known “Nixie” and most of the 7-segment numeric displays like the Burroughs “Panaplex” and the Beckman “Screened Image Displays.”

At the end of the cathode glow there is a relatively dark volume, the Faraday dark space, which is succeeded by the positive column. The column may be almost indefinitely long, and the additional voltage required per additional column length is small. However, the positive column may be vestigial or nonexistent if the anode is located in or near the Faraday dark space; 7-segment numeric displays are usually built this way. The positive column is an essentially neutral, lightly ionized plasma. Since electrons are much more mobile than ions, they are responsible for most of the

current. There is ionization and recombination throughout the region, with electrons and ions being lost to the walls and replaced by more charged particles produced by ionization.

The positive column can be used to produce light efficiently, as in the fluorescent lamp. The most efficient gas-discharge displays yet described have used the positive column in mercury to produce UV which excites phosphors. However, these displays have important disadvantages, including high voltage and high operating temperatures, and so far there are no commercial positive-column displays.

Because the electric field in the positive column is much lower than it is in the cathode glow, different states can be excited and the visible colors produced in the two regions can be quite different. Both regions are sources of both UV and visible light.

Several review articles and a book covering the physics of the discharge are listed in the bibliography [1]–[6].

A. General Types of Displays

In so-called dc gas discharges, the electrodes are immersed in the gas and are generally supplied with unidirectional pulses. Once a cell or display element is fired, that is, a self-sustaining discharge is produced, the impedance between cathode and anode becomes low or even negative. It is therefore necessary to limit the current, usually by means of a series resistor for each cathode or anode. DC matrix arrays can be operated in a memory mode, in which a dc voltage lower than the firing voltage is applied to all elements and individual elements are either fired or extinguished by suitable pulses superimposed on this [7]. This type of operation requires a limiting resistor for each element, and these are expensive and difficult to fabricate [8], [9]. An alternative is to make the cathodes of graphite; this changes the cell operation so that its ON resistance is positive and external limiting resistance is not needed [10]. Still another alternative is a pulsed operation in which the applied pulses are too short for a self-sustaining discharge to become stable [11], [12]. Neither of these alternatives has yet reached the stage of commercial application.

In ac discharges, the electrodes are usually insulated from the gas by thin dielectric films and the electrode configuration is symmetrical, whereas in dc displays the cathodes and anodes may be quite different. Charge is stored in the capacitances formed by these dielectric films and the resulting voltage aids in the reignition of the discharge on each half cycle of the applied voltage. The discharge current and the resulting light occur in short pulses for the gas mixtures used in ac panels with memory. At a typical operating frequency of 50 kHz, the cumulative effect of many pulses can be an average luminance of the order of 30 fL. A complete discharge forms in each half cycle. The stored charge also gives the display memory: The entire matrix array is supplied with a repetitive pulse voltage (the sustaining voltage) below that required to start the discharge. An additional pulse across a selected intersection in the matrix starts the discharge at that intersection, and the discharge sequence is sustained by the

repeated pulses with the aid of the charge stored in the series capacitance at each firing. The local firing is extinguished when the stored charge is reduced by supplying another, smaller "erase" pulse which causes firing at too low an amplitude to recharge the series capacitances [13]–[18].

AC panels can also be operated in a nonmemory mode in which an element emits light only as long as it is supplied with drive pulses [19], [20]. This kind of operation is tolerant of a much wider range of applied voltages and of such panel parameters as gas fill and interelectrode spacing.

In either memory or nonmemory modes, the series capacitance provides the isolation and current limiting needed for parallel operation of a number of cells. This capacitance equalizes the current density in different parts of large-area cells, thus keeping the luminance uniform over the entire area.

B. Firing, Priming, and Scanning

The firing voltage is a function of the gas, its pressure, and the geometry of the device. Uniformity of electrode size and spacing is necessary to secure uniform firing voltage among all the elements of a display; this can generally be achieved with reasonable mechanical tolerances. Most display elements that use the visible glow from the discharge (as distinguished from those that use the UV output or the electrons) are filled with a Penning mixture to reduce the firing voltage. Typically, this consists of neon plus about 0.5 percent argon.

The voltage across a self-sustaining discharge is usually significantly lower than the voltage required to initiate the discharge, and this voltage difference or breakback is one of the ingredients of memory in ac panels. It can also be used, in conjunction with appropriate circuit arrangements, to provide memory in dc displays. While the firing voltage for a typical cathode-glow display may be 170 V, a swing of only 60 V or less is needed to turn the discharge on and off, so that relatively low-voltage devices can be used to control the display.

The discharge does not begin immediately when the firing voltage is applied. There must be at least one electron or ion in the gap, to be accelerated and to produce the first of the ionizing or electron-emitting events necessary for breakdown. This requirement for initiating particles leads to a statistical time lag in breakdown. In addition, there is a formative time lag, usually a few microseconds, during which the breakdown process proceeds to the self-sustaining state. These delays can be reduced by increasing the applied voltage. Their existence imposes a minimum pulse-width, below which the statistical time lag and the resulting fluctuation in light output are intolerably large fractions of the overall light-pulse length and the light output, respectively. In ac discharges, this initial time lag is important in the initial firing, but once an element is fired, the sustain-pulse discharges recur with very low jitter.

The required electrons or ions can be introduced to the gap between electrodes from a nearby discharge. This is called priming, and it can reduce both the firing voltage

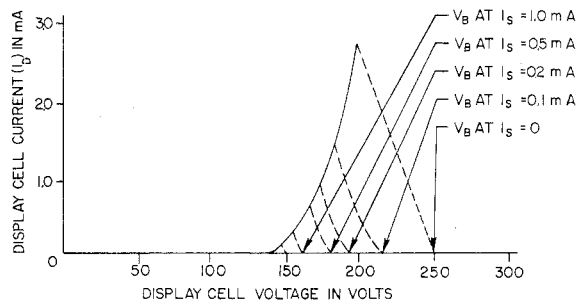


Fig. 2. E versus I characteristics of a primed cell as a function of the current i_p in the priming cell [21].

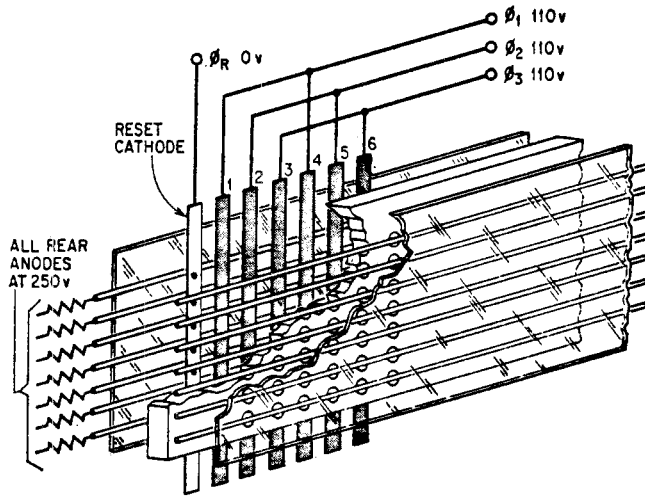


Fig. 3. The use of priming to effect scanning with only three drivers in the Burroughs "Self-Scan" display. First step: A discharge is established between the reset cathode and the rear anodes.

(see Fig. 2) and the time lag. If the priming is sufficiently intense, the firing voltage can be almost the same as the maintaining voltage and the firing delay drastically reduced [21].

Priming can also be used to effect scanning by insuring that only the nearest neighbor of an existing discharge will fire when voltage is applied to a number of electrodes simultaneously [22]–[23]. Figs. 3–6 show how this technique is used in the Burroughs "Self-Scan" dc display. The technique makes possible the scanning of several hundred electrodes with only three driving transistors at a great saving in drive-circuitry costs.

Priming is used in ac displays to make the firing voltage lower and more uniform [24]. It can also be used to move information from display element to display element [25]–[27], as in some reported versions of memory ac panels and in the alphanumeric "Plasmac" displays [19], [29].

This ability to use one discharge to affect a neighboring site and thus manipulate the position of the discharge or reduce the number of drive transistors is unique to gas-discharge displays, and is one of their major advantages.

Once the voltage has been removed from an anode-cathode pair, the cloud of electrons and ions between them takes some time to dissipate by recombination in the space and at the walls and electrodes. During this deionization

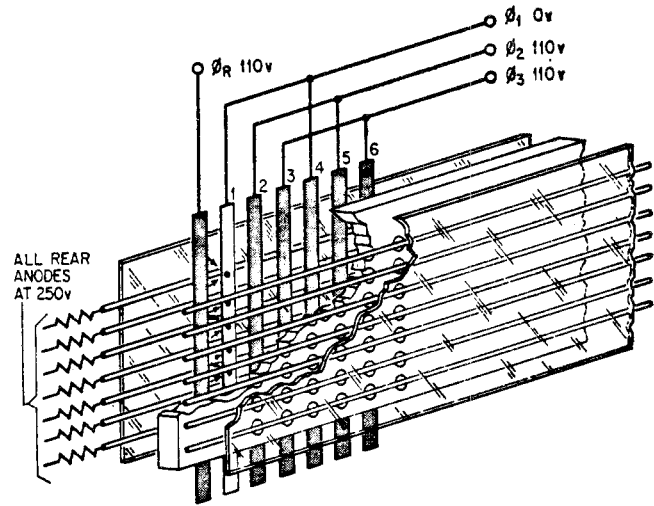


Fig. 4. The cathodes of phase 1 are dropped to 0 V, while the reset cathode is raised to 110 V. The discharge transfers to the first cathode. The other cathodes of ϕ_1 are too far away to be primed by the discharge at the reset cathode.

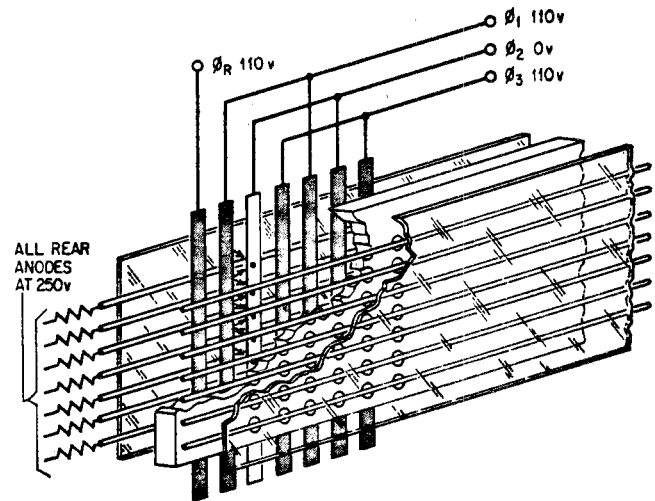


Fig. 5. ϕ_2 is dropped to 0 V, while ϕ_1 is raised to 110 V. Again, the discharge transfers to the nearest low cathode.

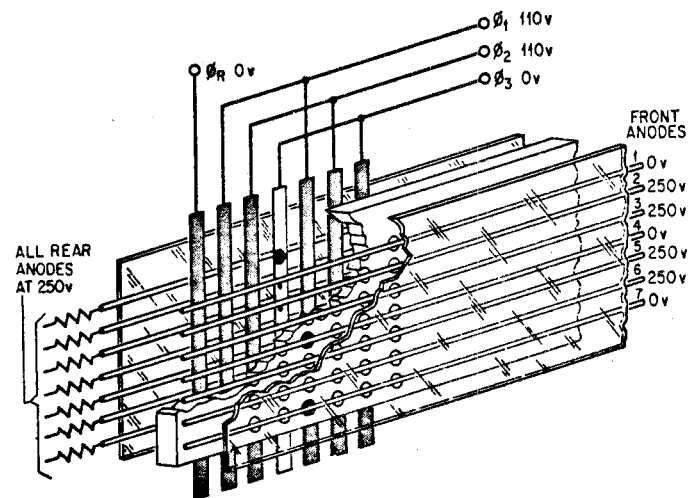


Fig. 6. By the same process, the discharge is transferred to the nearest cathode of ϕ_3 . A glow appears in front only in those cells in which the front anode is high and there is an active discharge in the rear; in other words, only in those front cells which are primed. Figs. 3–6 reprinted from [22]; copyright © McGraw-Hill, Inc., 1970.

time, if voltage is reapplied, the breakdown voltage will be less than in a cell which has not been fired recently. The deionization time may be hundreds of microseconds, depending on gas, pressure, geometry, and the effects of voltages below firing potential on the electrodes in "sweeping out" the charged particles. The lowered voltage is a limitation in matrix operation; one must be sure that the half-select voltage is lower than will cause a recently extinguished cell to re-fire. In self-scanning, it limits the scanning rate, but this can be circumvented by using more phases than the three that are shown in Figs. 3-6. For example, in television applications, with a vertical scan period of about 62 μ s/scanned electrode, Burroughs "Self-Scan" panels have been operated with seven scan phases.

III. NUMERIC DISPLAYS

There is a variety of these on the market, usually 7-segment numerics (with decimal points or colons associated with some or all of the numbers) with 2-10 digits in the same envelope. They are operated on dc, are usually multiplexed, that is, connected with the cathode segments as the columns of a matrix and the anodes (one per digit) as the rows, and operated one digit at a time, at frame rates of from 60/s to a few hundred/s. The digit segments are cathodes, and the cathode glow is in close proximity to the segments. Usually, the gas is the neon-argon Penning mixture previously mentioned, with a small amount of mercury added to reduce sputtering of the cathode. In some displays, notably those now made by Beckman (and formerly by Sperry), the pressure is reduced from some 100 to about 60 torr, causing the glow to spread and cover the gaps between segments, thus giving continuous-line numbers. Displays of this general type are available with formed cathodes to give more complex messages, or large cathode blocks that can be used to illuminate masks for the same effect. The cost of special tooling is low, so that customized displays for special applications are readily available.

Thick-film construction techniques have reduced the cost of these devices. The numbers are bright, easy to read, and are available in sizes up to an inch or more high. Even though IC's are readily available to drive them and the actual voltage swings are low, the fact that a 150-200-V dc supply is needed has caused them to lose ground to LED's and vacuum-fluorescent devices, especially in calculator displays. However, for applications where the quantities are less than a few hundred thousand digits per year, gas-discharge numbers are still competitive, more so as the digit size is made larger.

Large (as high as 6 in) ac-operated numeric displays have been built by National Electronics.¹ It appears easier to build large-area, uniformly illuminated devices for ac operation than for dc. National also builds ac-operated multi-digit numeric displays which include the ability to illuminate special messages, a feature of particular utility

in cash registers and other point-of-sale devices [20]. The multi-digit numbers use a kind of self-scanning, thus reducing the number of drivers well below what would be required for straight matrix addressing. Operation is in a nonmemory mode, which relieves tolerances on the applied voltages. However, the drive-voltage requirements are beyond the range of integrated circuits, and this has tended to raise system cost. Furthermore, at present there is only a single source for these displays, which has tended to make equipment manufacturers cautious about designing them into products.

Developments in the near future will probably include further work on low-cost fabrication techniques, as well as methods that enable a manufacturer to respond quickly to a customer's need for small quantities of special units. Gas-discharge and liquid-crystal manufacturers can do this more readily than can LED or vacuum-fluorescent suppliers. There will probably be more work on reducing the voltages required [30]. If ac numeric displays are to flourish, there should be development work on packaging the circuitry, so that a user can simply buy this rather than having to build it himself.

There has not been a great push for higher luminance, since the available luminance, in conjunction with simple contrast-enhancement methods such as colored light filters, has given adequate contrast for most applications. There may well be more work directed towards providing a choice of colors, and perhaps multiple colors within a single display, since the LED competitors are moving strongly in this direction.

IV. MESSAGES AND COMPUTER GRAPHICS

A. DC Devices

These are usually in dot-matrix format, which requires a large number of individual dots. As an example, a 16-character display in one line is typically organized as 95 columns and 7 rows, for a total of 665 dots. (If the inter-character columns need never be lit, then 15 columns \times 7 rows = 105 lamps can be saved.) A display like this can be much less expensive in gas-discharge than in LED technology, especially if some variant of self-scanning is used. In that case, if the horizontal scanning is done as in the Burroughs "Self-Scan" (see Figs. 3-6), only 3 scan drivers and 7 row drivers are required. An LED, EL, or a matrixed LCD display would require $95 + 7 = 102$ drive circuits.

In "Self-Scan" displays there is no internal memory, so the display must be continuously regenerated and the information stored in an external memory. Neither of these requirements is particularly burdensome, and the information in the external memory is easily edited and otherwise manipulated.

Displays of this type are available with as many as 12 lines of characters, with each line 40 characters wide. (If all the dots on such a panel are functional, this would be 25 334 elements.) There is no fundamental limitation on the number of horizontal lines, but there is a limitation on the number of vertical columns. Since the duty factor for

¹ This technology has recently been purchased by NCR Corporation.

each column is inversely proportional to the number of columns and the maximum luminance is determined by the maximum safe current, the average luminance is inversely proportional to the number of columns. Furthermore, the scan cannot be indefinitely fast, since, as we have seen, there is a minimum pulsewidth per cell below which operation will be too erratic to be satisfactory. In practice, it appears that some 200 scanned columns is the useful maximum.

There is no reason, in principle, that displays of this type cannot be used for graphics as well as for alphanumeric displays, but this has not been done much. One reason is that for graphic display, every display element must be represented in the external memory, whereas the memory for alphanumeric data need only contain a coded representation of the data. The code is translated into display-actuating signals by a ROM during each refresh cycle. The 8-bit ASCII code can represent 35–63 (5×7 to 7×9) elements on the panel, a substantial saving over a full bit map.

A choice of colors can be realized, using either the UV from the gas or the low-voltage electrons available to excite phosphors. However, the choice of colors is limited, and so far no selective-color displays have been announced. Luminance is about 50 fL and luminous efficiency is low, but this has not been a problem in most applications so far. New construction techniques should make these devices less expensive, and a larger choice of sizes can be anticipated in the future if there is a demand for them.

There has also been some development of non-self-scanning dc-matrix displays, but none of these have yet been truly commercially successful. Panels operated in a memory mode require a current-limiting resistor at each display element, and this is difficult and costly. (The graphite-cathode device mentioned earlier has not yet been marketed.) One device, which used a combination of "three-dimensional" addressing to reduce the number of drivers and the pulsed-dc memory technique, has apparently been abandoned for both cost and patent reasons [31].

B. AC Devices

Memory ac panels, such as the well-known "Digivue" (made by Owens-Illinois) are not limited in size by the minimum required luminance. In principle, an ac panel with memory could be made in any size, at least as far as luminance is concerned. In fact, Owens-Illinois sells 512×512 -element panels with about $8\frac{1}{2} \times 8\frac{1}{2}$ in of display area, and has made and sold 1024×1024 -element panels having four times this area [32], [33]. These panels have been used both for alphanumeric displays and for computer graphics. In many applications, it is an advantage that the panel is essentially transparent, so that it can be used as an overlay or information can be projected on it from the rear.

Average luminance is generally in the area of 20 fL and luminous efficiency is a few tenths of lumen per watt, both numbers adequate for most current applications. Color has

been demonstrated using an UV-emitting gas to excite phosphors [34]. Gray scale, which is easy to achieve in dc panels, is much harder in ac panels, but some schemes have been demonstrated [35]–[38].

Memory on the panel is not an unmixed blessing. Although it is responsible for the luminance and the fact that periodic refreshing of the display is not needed (the latter is particularly useful when the link between display and information source is of limited bandwidth), it is difficult to edit or manipulate data stored in this memory. Several schemes have been demonstrated for electrically reading out the information stored in the panel [39], and other schemes have been demonstrated for using a light pen to determine what data on the panel are to be accessed [40]–[43], but none of these techniques has yet become commercial, and we must assume that further developmental work will be required.

Another problem has been the provision of movable cursors, which can be done easily with scanned displays, both CRT's and scanned dc displays, but which is more difficult with memory panels [44].

AC panels need sustain voltages of the order of 130 V, although the write and erase pulses that are superimposed on this are much smaller. Furthermore, there is a driver for every row and every column. Since there are so many drivers, the cost of drive circuitry is of great importance, and many ingenious techniques have been devised to simplify the circuitry and reduce its cost [45]–[47]. This work has included the design of IC's and discrete circuits, techniques for mounting IC's directly on the panel, thus reducing the number of external connections [50], and continuing work on reducing the operating voltages by changing the panel construction [51], [52]. The use of low-work-function coatings and continuing work on improving dielectric quality and reducing dielectric thickness has been important in this context [53], [54].

Self-scan-like techniques have been demonstrated that provide for the moving of data across the display by using priming to control the ignition or extinction of neighboring elements [25]–[27], [55]. Such techniques could be used to reduce the number of drivers; information would be read in on a few lines and then moved to the final location, so that only a few lines would need write and erase circuits. However, these techniques have not yet reached commercial practice. One important reason for this is that the information density on the panel is reduced, since two or three electrodes per display element are needed to perform the scanning function. The resulting lowered density of illuminated dots gives a less satisfactory appearance, too.

The dominant construction technique is that employed by Owens-Illinois: two plane glass plates, each coated on the interior surfaces with metallic electrodes that are isolated from the gas by thin layers of dielectric, and that dielectric in turn coated with low-work-function, sputter-resistant material such as MgO [18], [56]. Spacing is maintained by a few glass spheres or rods, but these tend to perturb the write and erase voltages in their immediate

neighborhoods and so reduce the panel's tolerance to supply-voltage deviations. Other constructions have been reported; Control Data Corporation's method, in which the gas is contained within capillary tubes, with electrodes on the outside, is well-suited to displays several feet across [57]. There have also been proposals to put all the electrodes on one of the two glass sheets, so that the spacing between enclosing glass plates would no longer affect the operating parameters [58], [59]. Another advantage of this approach is higher luminance, since there are no opaque electrodes between the discharge and the observer. However, these schemes appear too expensive at present.

It is important to recognize that the ac plasma panel is the only current real competitor to the CRT for computer graphics or dense computer displays. It is still an expensive competitor, but the number of units in service continues to increase. As more manufacturers enter the field, and as its advantages in particular applications become important, it may continue to expand. However, its memory property will become less important (except as it affects light output) as the cost of semiconductor memory continues to decrease.

Nonmemory ac panels have also been built. In addition to the National Electronics-NCR panels mentioned earlier, larger displays, up to 8 lines of 32 characters each, are manufactured by Nippon Electric Company [20].

V. IMAGE DISPLAY

This is the most difficult application for displays. In alphanumeric and computer graphics, contrast is required; in image display, we need enough light that gray-scale steps can be clearly distinguished. Hence more output is required, and this makes luminous efficiency more important. Full-color capability is also more desirable; in many monochrome applications, white is a preferable color to red.

A. Cathode Glow

Gray scale is easy to achieve in dc devices, since modulation, either by duty factor or current, is usually straightforward. However, in cathode-glow devices, the luminance is limited and the efficiency low. Color displays have used UV from the cathode glow to excite phosphors.

An early attempt to make a gas-discharge TV display was described by Philips Research Laboratories in 1938 [60]. This was a straightforward dc matrix, operated a line at a time. An ingenious ingredient was the use of an anodized aluminum center sheet. This served to space and insulate the electrode wires and was easily fabricated.

Both Zenith and Bell Laboratories used essentially standard-construction Burroughs "Self-Scan" panels to display TV pictures; a photograph and the display parameters are shown in Figs. 7 and 8 [61]–[63]. Both displays showed TV pictures in real time; the Bell Laboratories display worked on "Picturephone" standards, while the Zenith display operated on U.S. broadcast standards. This

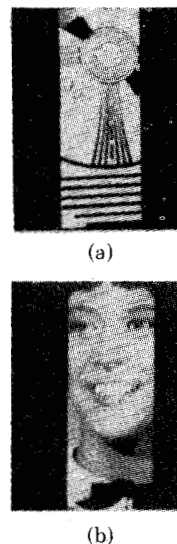


Fig. 7. Specimen pictures from the display with the specifications of Fig. 8 [62].

80 columns \times 212 rows
 2.4-in wide by 6.3-in high by 0.63-in deep
 Cell spacing: 0.030 in center-to-center
 Color: orange-red
 Voltage: 300 V peak-to-peak
 Current: 2 mA maximum per cell
 Addressing: line-at-a-time
 Gray scale: continuous
 Interlace: standard TV 2:1
 Percentage of TV picture shown: vertical, 43 percent; horizontal, 12 percent
 Video bandwidth: 3.3 MHz
 Horizontal resolution: 260 lines
 Vertical resolution: 350 lines
 Peak luminance: 8 fL
 Luminous efficiency: 0.1 lm/W
 Contrast ratio with no ambient light: 40:1

Fig. 8. Performance of a gas-discharge TV display based on the Burroughs "Self-Scan" panel, operating in real time [62]. Photographs of this display are in Fig. 7.

work demonstrated that gas-discharge panels could operate at these information rates and that picture intelligibility could be excellent, but they also showed that substantial improvement would be needed in luminance, luminous efficiency, and cost before even industrial or commercial uses could be tackled successfully. Consumer TV, with its requirement for 100 fL over large picture areas, is even more difficult.

Hitachi devised a design in which the cathode glow is well coupled to phosphor dots (Figs. 9 and 10) [64], [65]. This also makes provision for self-scanning in the vertical direction (in TV applications, self-scanning has been used in the relatively slow vertical direction, rather than in the horizontal direction more usual for alphanumeric displays). Although the pictures were of good quality, luminance and efficiency were low, and there was also a significant problem with life, since the phosphors became coated with material sputtered from the nearby cathodes.

Workers at Sony have also produced color TV pictures [66], [67]. Their design is much simpler (Figs. 11 and 12) and has the further advantage that it is built up of thick-

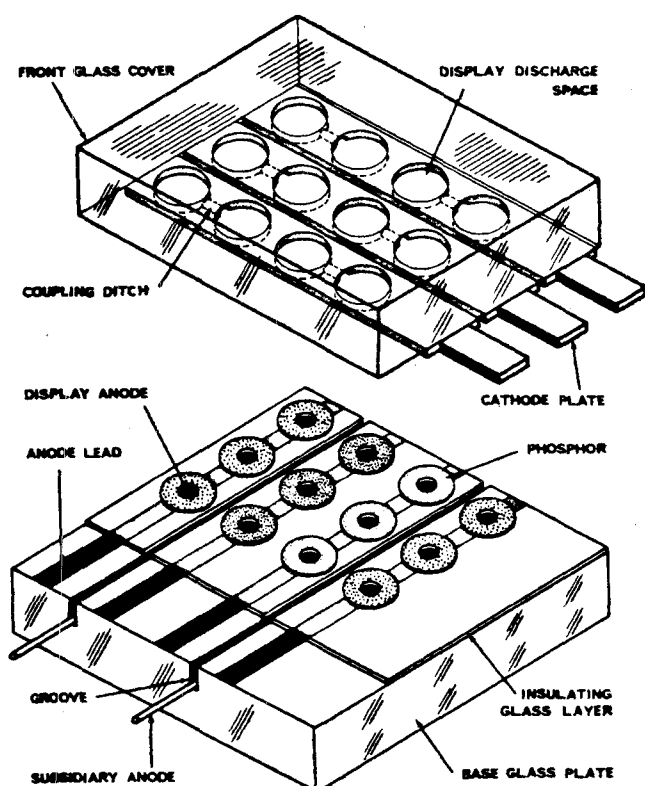


Fig. 9. Schematic of Hitachi's self-scanning display. The phosphor is well coupled to the cathode glow [64], [65].

panel size:	120 x 160 mm ²
resolution:	1 mm
areal luminance, B (white):	5 fL
peak luminance (red):	2700 fL
" (green):	11000 fL
" (blue):	1400 fL
power consumption (panel):	14 W
efficiency (white):	0.05 lm/W
contrast ratio (B _{max} /B _{min}):	8:1
" (B _{max} /B _{bg}):	over 300:1
gray scale (circuitry):	64
" (visual):	8
chromaticity coordinates,	
(red):	x=0.56, y=0.31
(green):	x=0.22, y=0.68
(blue):	x=0.17, y=0.14

Fig. 10. Performance of the Hitachi display [64], [65].

film layers, which should eventually be less expensive than the more complicated etched or machined structures of Burroughs and Hitachi. The Sony display also makes use of combined amplitude and pulsewidth modulation to permit the use of entirely digital drive electronics. However, one price for the simple panel construction has been the loss of the self-scanning feature, so a driver is needed for each row and each column. In a full-resolution color-TV display this would require some 1500 column drivers and 500 row drivers [68].

Like the dc alphanumeric displays described earlier, all of these displays operate line-at-a-time, that is, the TV signal is stored in a register containing as many "bins" as there are columns. Each bin then drives a column for an entire line time while another store is loaded with the next

incoming line of video. The format of the signals driving an alphanumeric display can be readily tailored to this requirement, but a TV signal must pass through a high-speed sample-and-hold circuit before being stored. Furthermore, in the image-display application, nonuniformity of the columns is much more objectionable than in alphanumeric or graphics applications. Most workers are now convinced that the only way to achieve satisfactory uniformity among the large number of column drivers needed for image displays is to make this circuitry digital, which in turn requires analog-to-digital converters capable of operating at TV rates. Such circuits are being developed in IC form [69], [70].

B. Positive Column

A promising approach to higher luminance and efficiency is the use of the positive column as a source of UV to excite phosphors, and this work has been pursued by Philips [71]–[73], General Telephone & Electronics [74], [75], and Zenith [76], [77]. The Zenith geometry is shown in Fig. 13. It includes self-scanning. The column is in the plane of the display, so that radiation from the phosphor is used efficiently. High efficiency—3.4 lm/W at 360-fL green spot luminance and TV duty factor—is promoted by restricting the cross section of the positive column and choosing gas pressures to increase the rate at which electrons are lost to the walls. The result is to raise the electron temperature and thus the rate of ionization in the positive column. The working gas is mercury, with helium as a buffer gas; to get a sufficiently high mercury pressure, the panel must be operated at about 80°C, which presents some obvious problems in a commercial device. Operating voltages are also higher than is convenient, but this is a more tractable problem than the temperature.

At Hitachi there has been work on several variations of positive-column geometry. A recent publication [78] describes a cell in which Xe radiation excites phosphors to give high spot luminances (1750 fL at unity duty factor) but with only 0.87-lm/W efficiency. With the use of a cathode resistor and appropriate voltages, the discharge can be switched between priming and display cells by a pulse; the cell has memory, but modulation at adequate light output requires on-times of a substantial fraction of a frame time, so it appears that the external circuitry would be complex and expensive.

These workers have also introduced a constriction into the positive column to increase the output [79], [80]. With this arrangement, luminous efficiency greater than 1 lm/W for green has been reported.

C. Constricted Glow

Workers at Toshiba have described a different approach, in which a glow discharge is constricted (Fig. 14) by an aperture in an insulator [81], [82]. The luminance from such a constriction can be high, and the discharge can be moved from electrode to electrode (Fig. 15) at rates that may eventually approach those needed for TV. It is not yet clear what the limitations of this approach are; small TV

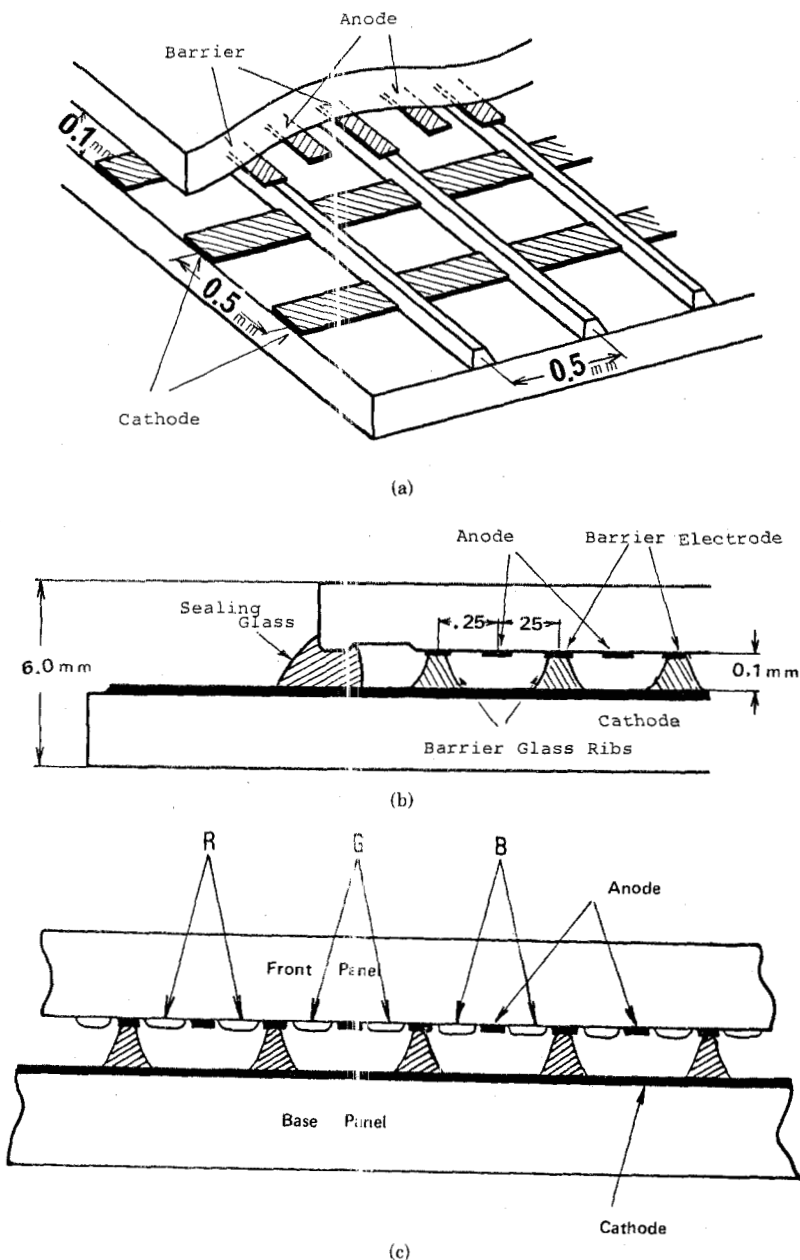


Fig. 11. Schematics of the Sony TV display. The barrier electrodes are biased to a lower potential than the anodes to prevent the discharge from jumping the thick-film ribs to produce crosstalk [67]. (a) Panel construction. (b) Cross section of the monochrome panel. (c) Cross section of the color panel.

	MONOCHROME	COLOR
PICTURE ELEMENTS	60,000 (212x282)	60,000 (20,000 EACH COLOR)
CELL SPACING	0.5mm	0.5mm (1.5mm EACH COLOR)
GRAY SCALE	32	48 (16 EACH COLOR)
OPERATING VOLTAGE	160 V	230 V
POWER CONSUMPTION	10W (PANEL&DRIVERS)	15W (PANEL&DRIVERS)
	80W (OTHER CIRCUITS)	200W (OTHER CIRCUITS)
PEAK LUMINANCE	25 FL	6 FL
CONTRAST RATIO	40:1	20:1

Fig. 12. Performance of the Sony display [67].

pictures have been made, but at element dwell times that were a factor of 60 greater than those required for broadcast TV.

D. Electron-Excited Phosphors

Since there is a large supply of electrons in all regions of the discharge, it is tempting to use these to excite phosphors by cathodoluminescence. Perhaps the earliest attempt along these lines was by Kazan [83]. Later, workers at Bell Laboratories used essentially the geometry of the Burroughs "Self-Scan" with the faceplate coated with a low-voltage blue-emitting phosphor [84]. Electrons were accelerated by the rise in electric field at the anode, the so-called "anode fall" (see Fig. 1), and the combination of the blue light from the phosphor and the red light of the neon cathode glow gave a white output, but at lower efficiency and luminance than the cathode glow alone. There has been other work on using the electrons in the discharge,

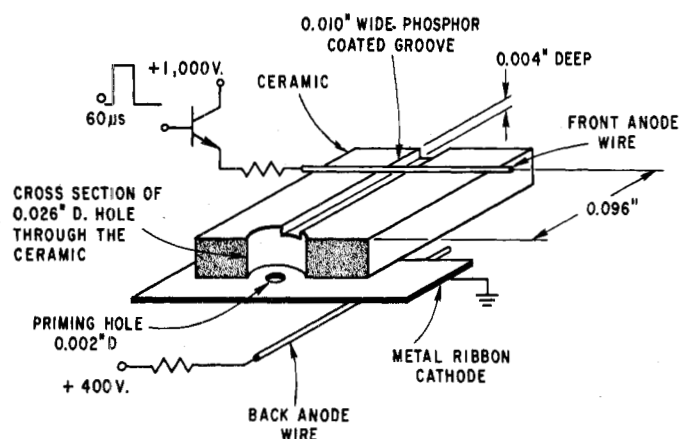


Fig. 13. Schematic of a phosphor-coated, UV-excited, helium-plus-mercury, positive-column discharge cell. The cell size is approximately correct for a 50-in-diagonal thin-screen color TV. To pulse the cell at TV rates, the gas is primed with starting particles and photons. The starting particles are continuously made by a dc discharge behind the cathode ribbon. They enter the groove via a small hole in the cathode. A 60- μ s current pulse is discharged through the groove once every 33.3 ms. This produces a positive column in the groove. Ultraviolet radiation from the positive column excites the phosphor coating the groove. Fluorescent light passes through the positive column and the clear glass to the viewer [76].

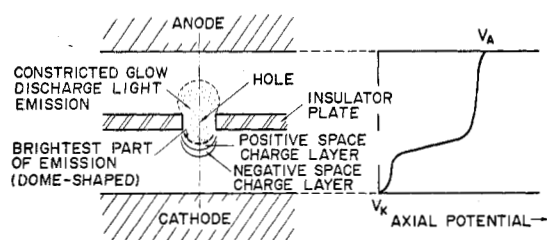


Fig. 14. Schematic of the constricted-glow device reported by Toshiba. The light is viewed through the transparent anode [82].

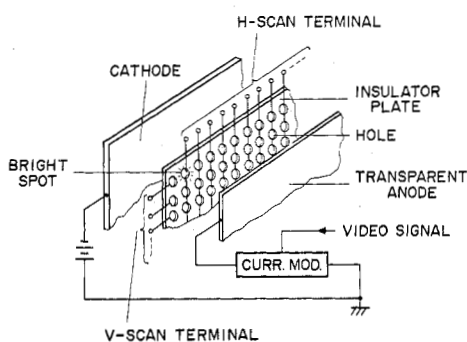


Fig. 15. Scanning of the Toshiba device [82]. The discharge is started at the left (V-scan terminal) and moved from hole to hole in the insulator by pulsing the electrode surrounding the next hole up and the electrode where the discharge is now, down. Because the hole on the same horizontal line is primed more strongly than holes on adjacent rows, the discharge travels in the same row. Self-scanning, like that shown in Figs. 3-6, can be employed in this device.

notably at the laboratories of the Japanese Broadcasting System (NHK) [85]. In their work, the product of pressure and distance between electrodes was low, the gas was helium, and they think that at least some of the electrons reaching the phosphor were electrons emitted from the cathode, with energies of about 150 eV.

So far, the work with electron excitation has been hampered by the fact that the electrons available are of low energy—10–20 eV (except for the small fraction of electrons with cathode-fall energies that may reach the anode). There is only one phosphor, ZnO, which operates at such low energies, and it gives only blue-green light. While this can be satisfactory for numeric displays, as indicated by the substantial commercial success of vacuum-fluorescent devices, it is not completely satisfactory for image displays. Overall efficiencies have been less than 0.1 lm/W in the work so far reported.

E. AC Panels

There have been two general approaches to the use of ac panels for image display. In the first, the memory property is used directly, and modulation is effected either by changing the duty factor or changing the density of illuminated elements on the panel [35], [86], [87]. Changing the duty factor requires the use of an external memory to determine when in the frame each picture element shall be turned on or off. Ingenious techniques have been devised to minimize the amount of external circuitry required, but it is still substantial.

Varying the density of illuminated elements on the panel means, in effect, that a single picture element will comprise several elements of the display, and so the information density of the panel must be reduced. Using a scheme called ordered dither, Judice and his co-workers at Bell Laboratories have worked out an ingenious compromise between information density on the panel and gray-scale range [88]–[92]. This general approach is not dependent on the repetition period of the TV signal, and so gray-scale images can be produced with the picture information remaining static for hours or varying at TV rates. The memory capability of the ac panel provides the storage. This should provide a significant augmentation to the usefulness of the ac panel, especially since no changes are required in otherwise standard panels; all the picture processing is done in external circuitry.

A number of techniques for modulating the light intensity from ac panels by changing the discharge parameters have been tried; work by Nolan at Owens-Illinois looks promising [36]–[38]. The approach is simple in principle: the sustain voltage is held at a value too low to give full regeneration of the charge stored in the series capacitance. Hence, after a write pulse, there is a train of discharges that get more and more feeble as less charge is transferred with each firing until finally the discharge sequence terminates (see Fig. 16). The number of firing cycles is a function of the amplitude of the write pulse, so this scheme translates the amplitude of the write pulse into the duty factor of the resulting pulse train. Slottow's analysis [16] can be used to visualize the operation of this scheme. The approach requires tailoring the characteristics of the gas in the panel to favor the operation, and while gray-scale rendition is good, the luminance and luminous efficiency are both still low. Picture uniformity requires both uniform panel characteristics and uniform drive electronics; cf.

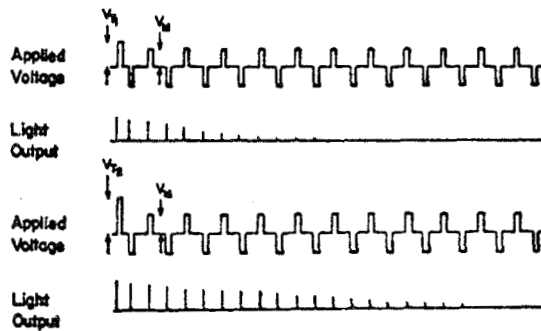


Fig. 16. Direct modulation of an ac panel with memory. The maintaining-voltage amplitude V_M is below that necessary to give memory. The charge deposited in the wall capacitances on the first (trigger) pulse is a function of the amplitude V_T of that pulse. This charge determines the number of maintain-voltage cycles for which the cell will fire and light be produced. The drawing shows pulse and light waveforms for two different trigger voltages [38].

Section V-A. The approach could provide a simple means for producing real-time TV pictures.

All of these approaches must contend with the limited luminance and luminous efficiency of ac panels. While there are many applications for which these will be adequate, it appears that major improvements will be needed before the performance of the CRT is seriously challenged in imaging applications. The single-sided panel construction mentioned earlier may help. However, dc approaches seem to be ahead at this writing.

VI. THE COMPETITIVE SITUATION

Displays compete with other types of displays, and this competitive situation is a function of the devices themselves, the associated circuitry, and the applications. The competition is a fluid one and the status changes almost monthly.

A. Seven-Segment Numeric Displays

This is a market which opened up rapidly with the advent of small calculators. In its early stages, gas-discharge displays were of great importance, but they were rapidly challenged by LED's, vacuum fluorescents, and liquid crystals. At present, gas-discharge numerics are used only in large calculators. Vacuum fluorescents have become increasingly important; LED's are used in very inexpensive and very expensive calculators, but less in intermediate models. Liquid crystals have been making only slow inroads, although their penetration is beginning to accelerate.

The principal reasons for this situation appear to be the necessity of supplying about 200 V for gas-discharge devices, plus the requirement for interface circuitry which is more expensive than that required for competing devices. The additional power-supply and interface components raise the system cost, even though the display device itself may cost less than its competitors. This illustrates the point that the cost of a display system must be considered as the *system* cost: the device itself and all the

components, including the power supply, required to make the display function and interface it with the rest of the system.

For numeric displays larger than about $\frac{3}{4}$ in high, the lower cost of gas-discharge devices tends to override the associated circuit costs, and gas-discharge numerics still have a significant market position. In particular, cash-register and other point-of-sale applications are being well served by gas-discharge displays, although there are also many 7-segment incandescent displays in service. While there should be a potential for liquid crystals in these applications, they have not yet appeared in quantity in commercial devices.

Improved construction techniques, schemes for lower switching voltages, and less-expensive drive circuits should continue to keep gas-discharge devices competitive, even as LED prices move lower.

Some of the newer technologies, like electrophoretic displays, may well make their first market appearance in this set of applications.

B. Multi-Digit Dot-Matrix Alphanumeric Displays

In these applications, where more than a hundred individual lamps may be required, gas-discharge devices have a substantial edge. The availability of self-scanning reduces the system cost a great deal, as indicated in Section IV-A, and the device cost itself will generally be less than that of competing technologies.

For multiline character displays, the competition is between gas-discharge displays and CRT's, other technologies are not yet on the market. The CRT is a mature and formidable competitor, but it is bulky. For one or two lines of characters, the gas-discharge devices should have a significant advantage; for displays of more lines than this, the competition is harder, especially where space considerations are not important.

Both ac and dc devices are being used in these applications, and on a significant scale: there are probably more than 40 000 multiline gas-discharge dot-matrix displays in service. Two substantial computer manufacturers, Burroughs and IBM, are installing dc and ac devices, respectively, in terminals of their manufacture. Burroughs sells its "Self-Scan" displays to other manufacturers as well. Other major suppliers of ac dot-matrix displays are Owens-Illinois, whose "Digivue" is probably the best known and most widely used device of this type, Fujitsu, and Nippon Electric Company.

All of these devices are expensive to build, and there is continuing work on reducing manufacturing cost as well as circuit cost. The geometry of dc self-scanning devices looks more complicated than that of ac panels, but the difficulties of holding the electrode, dielectric, and low-work-function coatings within acceptable tolerances appear to be such that ac panels are not necessarily less expensive than dc devices of the same size, while the peripheral circuitry is more expensive for ac than for dc. Recent advances in dc "Self-Scan" display geometry may give this device an advantage [93].

C. Computer Graphics and Image Display

The same devices that are used for large numbers of alphanumeric characters can, in principle, be used for computer graphics. In practice, though, there has been very little use of any displays other than ac panels with memory, like the "Digivue," in this application. In computer graphics one would like resolution approaching that of commercial TV, and while it is possible to build nonmemory panels with this many columns, the luminance decreases as the number of columns increases (assuming the display is scanned column by column), and some 200 columns appears to be the present practical limit. Memory devices do not have this limitation.

As was pointed out in Section IV-A, far less memory is needed for a nonmemory display of characters than for full graphics capability. Nevertheless, as the cost of semiconductor memory continues to decrease, we can assume that the provision of satisfactory contrast and luminance will become more important than the presence or absence of on-panel memory in deciding what device to use. Then memory will be important mainly as a means of achieving luminance and reducing flicker.

For interfacing with a computer, the digital access to gas-discharge displays is more convenient than is the analog access of the CRT, and it is claimed that gas-discharge displays are easier to use for long periods of time because there is less flicker and less small-scale image motion. Coupled with the flat packaging and the absence of well-regulated high-voltage supplies, the gas-discharge devices have several advantages to offset their higher cost and lower luminance.

The problems in image display are more difficult. Higher luminance is required, since it is necessary to display gray scale, and even the low-luminance parts of the picture must have adequate contrast. The provision of gray scale is itself a major problem. Eventually, it is desirable to match or surpass the performance of color-TV displays. The major impetus for work towards this goal is from consumer-TV manufacturers, who can foresee market volumes that can repay the research-and-development effort required. There is not nearly that much incentive in military, industrial, or commercial applications; hence, it is likely that these latter will await the successful development of consumer devices.

Since it is difficult to make really small individual gas-discharge elements, it is probable that the first gas-discharge TV displays will be larger than CRT displays. The size and the thin package should give them a good market position if costs can be kept within the consumer-TV range. Progress in this area will require substantial effort towards IC's for drive circuitry, and will probably be dependent on new IC packaging techniques, since the number of leads between drivers and panel must be very large. This is perhaps a major opportunity for thin-film transistors.

I should stress that while the facts I have collected here have been generated by many workers, the assessment of their relative significance and importance is mine, and is by no means a matter of universal agreement.

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