ELSEVIER

Materials Chemistry and Physics 51 (1997) 107–113

MATERIALS CHEMISTRY AND PHYSICS

CRTs are forever as video display devices

Lyuji Ozawa [1]

L.L. Technology, Hopewell Junction, NY 12533, USA

Received 19 February 1997; revised 22 April 1997; accepted 22 April 1997

Abstract

The cathode ray tube (CRT) has a great advantage as a display device over flat panel displays such liquid crystal displays, plasma display devices (PDP) and electroluminescence (EL), although the CRT has disadvantages such as its bulky size and heavy weight. The image quality on the present screen in CRTs may further improve to print quality on sheets of paper by handling of phosphor screens under irradiation of electrons, realizing a paperless society. The disadvantage of CRTs may be traded off against the image quality on a paperless working desk. The production cost of monitor CRTs may also decrease to that for TV sets. Then, it can be said that CRTs are forever as video display devices. © 1997 Elsevier Science S.A.

Keywords: CRTs; Display devices; Monitors; Phosphor screen

1. Introduction

Cathode ray tubes (CRTs) dominate the display market. The production volume of color and monochrome CRTs in the World is still growing each year, and had reached nearly 200 million in 1995, contrary to forecasts by the Japanese producers of display devices in the early 1990s, and current publicity in the display community of the USA [1]. The forecast is that liquid crystal displays (LCDs) will take over the display market, and that CRTs diminish in the display market. Recently, the Japanese forecasts of the LCD market [2] have been lowered but LCDs still hold a potential in the display market. By the year 2000, the demand for color thin film transistor (TFT) LCDs will reach that for CRT monitors, owing to a reduction in the production cost close to that of CRT monitors (e.g. 1.2 times that of a CRT). The forecast is based on the hypothesis that CRT production technologies are well developed, with no room for further improvement. The reality differs from the Japanese forecast. Table 1 shows the statistics of production of color display devices for present desktop PCs in 1995, and the prediction for 2002 [4]. In 2002, 77.5% (=99.2/128) of desktop displays for PC (i.e. monitors) will be by CRTs, and LCDs will be only 22.5% (=28.8/128). 71% of total displays are CRTs; and 29% LCDs, mainly portable devices. The portable LCDs may be of the reflection type, rather than the backlight type, because of the power consumption.

Table 1
Statistics and projection of CRTs and LCDs (unit: million)

	1995			2002		
	Total	CRTs	LCDs	Total	CRTs	LCDs
Camcorder	8.8	5.8	3.0	19.9	8	11.4
Portable TV	2.7	0.2	2.5	4.8	0	4.8
Auto/navigation	3.9	0.1	3.9	16.1	0	16.1
Mobile	1.8	0	1.8	9.6	0	9.6
Notebook PC	11.4	0	11.4	37.7	0	37.7
Desktop PC	48.3	48.3	0	128.0	99.2	28.8
Others	78.9	70.9	8.0	218.1	201.2	16.9
Total	155.8	125.3	30.5	434.2	308.9	125.3
(%)	100	80	19	100	71	29

Source: quotation from Ref. [3].

The statistics indicate that the present CRTs are widely accepted by users of display devices, for reasons of (1) a high legibility of images on screen, (2) low production cost, and (3) less fatigue of the eyes. High legibility of images on screens results in less fatigue of the eyes. The high legibility of images on screens is determined by (4) a high instantaneous luminance, (5) resolution, (6) contrast, (7) response time, and (8) wide viewing angles.

I would like to say that the technologies involved in the present CRT production process have been optimized for color TV sets, but not for monitor applications. By optimi-

---

[1] Address for correspondence: Industrial Technology Research Institute, Vacuum Microelectronics Development Department, Building 15, D000, ERSO, Chutung, Hsinchu, ROC.

PII S0254-0584(97)01975-5

zation of the image quality of CRTs, an ultimate phosphor screen in CRTs may display the images similar to printed letters on sheets of paper or images similar to photographs. The production cost of the CRTs will fall to that for TV sets (about 1/5 of that of the present monitor CRT). Thus, the CRTs hold a strong competitive power over flat panel displays (FPDs).

The optimization of CRTs may be carried out with a better understanding of (a) the phosphor screens, (b) the collection of secondary electrons emitted from the phosphor particles, and (c) a high vacuum sealing technology. For an optimization of CRTs in future, a brief story of the past improvements is given below.

2. Improvement of screen luminance of color CRTs for TV sets

For a display device, a most important concern is screen luminance. The screen luminance of color CRTs in the 1960s was around 30 cd m^{-2}, which allowed us to watch color TV images in a dark room, as in a movie theater. In order to get acceptance of color TV sets by users, TV sets should be capable of being viewed in illuminated rooms. Because of the urgent requirements for spreading color TV sets to family rooms, efforts were concentrated on improvement of the screen luminance, rather than the image quality on phosphor screens. The screen luminance of present color CRTs for TV sets is around 300 cd m^{-2} (or 100 ft-L) with a white balance (9700 K ± 100 MPC). A screen luminance of 300 cd m^{-2} is bright enough to watch color TV images in illuminated rooms. A further increase in the screen luminance adversely affects the eyes of observers of TV images.

Fig. 1 shows the stepwise improvements, rather than gradual improvement, of the screen luminance before 1975 [5]. This is because the luminance improvements have been carried out by the conceptual changes (i.e., scientific improvement) in the usage of phosphor screens, rather than engineering improvement (e.g., a few %). Details are as follows.

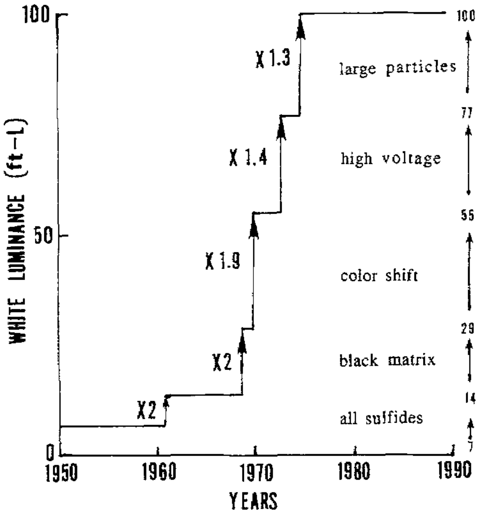

Fig. 1. Stepwise improvements of screen luminance of color CRTs for TV application before 1975.

Under irradiation of an electron beam in CRTs, the phosphor screens generate light that gives the screen luminance. The phosphor screen acts merely as an energy converter from the energy of invisible electrons to that of photons of visible lights. The intrinsic energy conversion efficiency of phosphor powders has remained at constant levels for the last 50 years, e.g. around 20% for the blue and green sulfide phosphors, and around 10% for the rare earth red phosphor. Therefore, the improvements in the screen luminance have been carried out by the usage of phosphor screens, with a better understanding of (a) colorimetry of cathodoluminescence (CL) of phosphor powder [5], (b) construction of powdered phosphor screens [6], and (c) handling phosphor properties [7].

In the 1960s, the screen luminance of color CRTs was limited by the luminance of the red phosphor. Study of the colorimetry led us an increase in the red lumen weight by factor of 2, if the color coordinates of the red phosphor shifts to $x = 0.64$, $y = 0.35$ from $x = 0.67$, $y = 0.33$ (NTSC) [8]. The color shift on the color diagram is small, but the change in the lumen weight is large (almost double) in the red color. The lumen weights, rather than the screen luminance, are important concerns for a white luminance by the color mixing.

The screen luminance is also increased (2 times) with enlargement of the phosphor pixels, by application of a black matrix [5]. The screen luminance should be linear with the energy of the electrons incident on the phosphor screen. The energy of the irradiated electrons can be changed with either electron beam densities or accelerating voltages. The screen luminance deviates from linearity with the electron beam density [5], but is linear with accelerating voltages. By an increase in accelerating voltage to 30 kV from 20 kV, the screen luminance is increased with 40%. Then, the attention shifted to the individual phosphor particles. The screen luminance of the blue and green phosphors increases to 35%, if the mean particle sizes of the phosphor powder are enlarged to 4.5 μm from 2 μm by microscope, with the availability of activator ions in particles [7]. Thus, we have the screen luminance of 300 cd m^{-2} of color CRTs for TV use. The improvement of the screen luminance of color CRT to 300 cd cm^{-2} was achieved before 1975. Since then, the screen luminance of color CRTs has not changed stepwise.

3. Advantages of present CRTs

The present CRTs have distinct advantages over FPDs. They are (1) a high instantaneous luminance, (2) wide dynamic range of luminance (e.g., gray scale), (3) viewing angles, (4) resolution of images, (5) response times, and (6) production cost.

3.1. Instantaneous luminance and screen luminance

The images on phosphor screen are illustrated with the scanning light spots, which are generated under the scanning electron beam on phosphor pixels. The eyes receive the scanning light spot, and the brain perceives the images with afterimage effect in the brain. For perception of the images on display devices, one should consider the instantaneous luminance of the scanning light spot (i.e., pixel), rather than the screen luminance that is averaged over the screen area and time. The instantaneous luminance of the phosphor pixels is an important concern for evaluation of the image quality on the screens.

In a CRT, scanning light spot is generated with a scanning electron beam focused to a diameter of less than 1 mm. In TV applications, the scanning conditions of the electron beam are determined by broadcasting system. For NTSC (National Television System Committee, USA) conditions, the images on the phosphor screen are illustrated with 30 frames s^{-1} with interlace. One image frame is composed with 525 horizontal lines, with video signals of 4.2 MHz. The time for one horizontal scanning line is 63.5 μs, independent of screen sizes. The electron beam current is around 1.0 mA, and is accelerated by 30 kV. If the spot size of the electron beam is 0.3 mm diameter, the phosphor screen of 0.3 mm diameter (i.e., phosphor pixel) is irradiated with an electron beam at 30 W $(0.3\ mm)^{-2}$ for 15 ns with a 20 in screen. The phosphor pixels convert the electron energy of 30 W to photons of visible light. Therefore, each phosphor pixel instantaneously emits cathodoluminescence (CL) of intensity proportional to the irradiated energy of electron beam. We can measure the equivalent instantaneous luminance. It is 400 000 cd $(0.3\ mm)^{-2}$ [9]. The screen luminance is given by the luminance averaged with time and screen area, that is 300 cd m^{-2}. The screen luminance of 300 cd m^{-2} is correlated with the instantaneous luminance of 400 000 cd $(0.3\ mm)^{-2}$ [9]. The high instantaneous luminance of the phosphor pixels in CRTs is a great advantage over the luminance of FPDs.

The high instantaneous luminance of pixels gives a high legibility of images on phosphor screens in CRTs. In order to compete with the screen luminance of color CRTs, FPDs such as LCD, PDP, EL and others should have the instantaneous luminance of 400 000 cd $(0.3\ mm)^{-2}$.

3.2. Wide dynamic range of luminance of color CRTs

The above calculation shows another advantage of CRTs, that is a linearity of the luminance over an extremely wide range [9] from 0 to 400 000 cd $(0.3\ mm)^{-2}$. Because the light perception is made with the instantaneous spot luminance, the gray scale should be determined by the instantaneous spot luminance, instead of the screen luminance. The phosphor screens in a CRT can display images with different light intensities (i.e., gray scale) of 400 000 steps by modifying the electron beam currents. FPDs do not have such a high gray scale.

3.3. Viewing angles

Viewing angles of images on screens are also an important consideration for choosing display devices. Phosphor screens in CRTs are made of tiny phosphor particles with sizes from 1 to 8 μm as observed in a microscope. Practical phosphor particles are inorganic crystals which lack a center of symmetry. The luminescence centers occupy lattice sites giving rise to the lack of a center of symmetry. An extremely strong electronic transition, which is forbidden in the symmetry environment, is allowed for the luminescent centers. This is why practical phosphor powders have a high luminance. Inorganic crystals (particles) which lack a center of symmetry have a high dielectric constant ε. The refractive index n of the crystals correlates with the dielectric constant, i.e. $n^2 = \varepsilon$. Hence, practical phosphor particles have a high refractive index n.

Because of the high refractive index of phosphor particles, the large amount of the emitted light in the particles reflects at internal walls of the particles (i.e., internal reflection), and a small amount of the light crosses the boundary to escape from the particle. The light reflected at the internal wall reflects again at other internal walls. Since the particle has no absorption band for the emitted light, the emitted light in the particle emerges from the particle after experiencing multireflection in the particles. Consequently, the direction of CL light generated in the particle is well randomized in the particle. The randomly oriented light emerges from the particles in all directions (i.e. a Lambertian light source). Each emitting particle in the phosphor screen in CRTs is indeed a Lambertian light source.

Since the images are formed with the Lambertian CL light from the particles in the screen, the image on the phosphor screen in CRTs has a wide viewing angle.

3.4. Resolution of images on phosphor screens

Although each phosphor particle is a Lambertian light source in the phosphor screen, the particle sizes are very small (around 0.005 mm) compared with the size of electron beam (more than 0.25 mm). The resolution of images on monochrome phosphor screens is determined by the sizes of electron beam. The sharpness of the images on a monochrome screen depends on the construction of particles in the screen. A sharp image is obtained with a screen constructed with 1.5 layers of phosphor particles.

In color CRTs, the resolution of images is determined by the sizes of the electron beam and the dot sizes (or stripe widths) of phosphor screens. The color phosphor screen is usually designed such that the dot sizes d are smaller than the size ϕ_e of electron beam to avoid flickering of images [5], i.e. $\phi_e > 8d$. The dot sizes depend strongly on the screening quality of color phosphor powders. If the commercial phosphor powder is screened on the face plate of CRTs, the minimum dot sizes of color phosphor screens are limited to 0.1 mm owing to poor quality of phosphor powders. To obtain a phosphor screen with small dots, phosphor powders should be improved to a suitable quality. This subject of phosphor powders remains for future study by the phosphor production industry.

3.5. *Respond time to signals*

The respond time of CL of a phosphor screen to the electron beam is very fast, i.e. a few ns. There is no problem with the response time of a CRT. One can clearly watch fast moving images on phosphor screens in CRTs.

4. Further improvement of CRTs

When the features of current CRTs are compared with those of FPDs, the great advantages of CRTs over FPDs are apparent, as described above. It is said that the production technologies of CRTs are state of the art. However, the production technologies of CRTs have not yet been optimized scientifically. The image quality on a phosphor screen in CRTs can be further improved, the ultimate target being that the phosphor screens in CRTs should display images equivalent to printed images on sheets of paper and photographs. The limitation of the image quality on phosphor screens comes mainly from (a) the structure of phosphor screens, and (b) flickering of images on phosphor screens.

4.1. *Screen luminance of phosphor screens*

As mentioned in the Section 3.4, the optimal phosphor screens should be constructed with phosphor particles in 1.5 layers, if the particles are distributes with a log–normal distribution [10]. The color phosphor screens in current CRTs are in practice constructed with around 3 layers, because of the difficulty of screening of the PVA phosphor slurries in thin layers [11]. With a reduction of one layer of phosphor particles, the screen luminance increases by 28% (i.e. 28% per layer) [12]. If phosphor screens with 1.5 layers are made with commercial phosphor powders, the screens have many holes through them which are not covered with the phosphor particles. Fig. 2 shows a micrograph of a color phosphor screen which was obtained with an optical microscope in transmission mode (original magnification, 100×). The through holes are caused with the aggregation of the phosphor particles in PVA phosphor slurry [11]. The phosphor particles disperse perfectly in a PVA phosphor slurry on application of an aging process [5]. Then, the PVA phosphor slurry may be screened on a face plate with 1.5 layers of particles without through holes. Consequently, the screen luminance will increase by more than 30%.

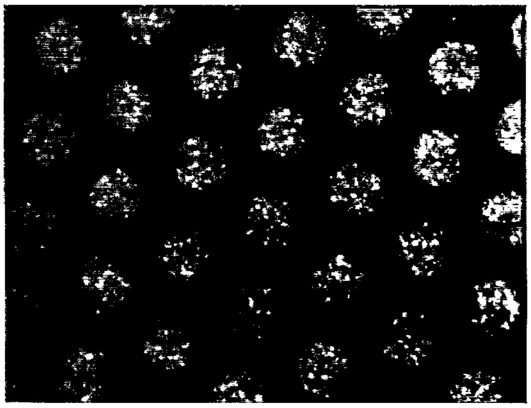

Fig. 2. Micrograph of thin color phosphor screen in transmission mode (original magnification, 100×).

4.2. *Flickering of images on phosphor screens*

A serious problem of images on phosphor screen in CRTs is flickering of small images. If images on screen are observed at a distance of more than 3 times the screen diagonal, as with TV images in a living room, one does not perceive serious flickering of images. If images are observed at a distance of the screen diagonal, or shorter, one perceives flickering of images. Removal of flicker of images on the screens in CRTs is urgently required for introduction of monitor (and internet) displays into the living room.

There are two kinds of flickering of light; one is caused purely by fluctuation of light intensities with time at the same place (i.e. $f(t)$), and other is caused by displacement of lighting position with time (i.e. $f(d,t)$), where t is time and d is displacement distance. The light spot on phosphor screens in CRTs is produced with CL, so that the fluctuation of CL intensities with time at the given place should first be discussed as a flickering source. The fluctuation of CL intensities at the given place relates with the repetition cycles of CL, that are correlated with the rise time and decay of CL.

The scientific study of the flickering of light intensities at a given place is made with measurements of the modulation transfer function (MFT), $G(t)$. The MTF values of the eyes are a constant (i.e. $G(t) = 1.0$) up to 30 Hz modulation frequencies, and decreases sharply with modulation frequencies above 30 Hz. In the frequency range that the MTF obtained with CL spots has a constant ($G(t)$ = constant, the magnitude of the CL intensities on the phosphor screens are not influenced by the irradiation cycles. The magnitude of the CL intensities are decreased for modulation frequencies in the region that $G(t)$ is less than 1.0. Hence, if the phosphor screens have constant $G(t)$ up to MTF frequencies higher than 30 Hz, the given phosphor pixels in the screens will surely exhibit flicker with frame cycles less than 30 Hz, but will not show flicker with frame cycles above 30 Hz, because of the afterimage effect of the brain. If the phosphor screens have a small value of $G(t)$ at 30 Hz, the screens may exhibit less flicker to the eyes, but the CL intensities have a high constant level and the modulated CL intensities become small

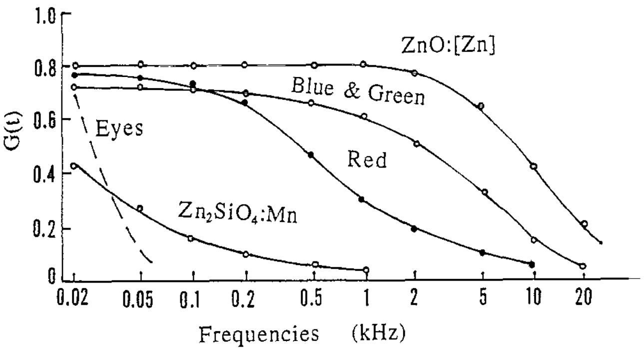

Fig. 3. Measurement results of MTF, $G(t)$, of phosphors having various decay times.

in magnitude. This means that the images on the screen are surely smeared with the decrease in the magnitude of CL intensities. To display a clear image on phosphor screens, the screen should be made with the phosphor powders having $G(t) = 1.0$ at frequencies higher than the frame cycles.

The MTFs of CL are obtained with irradiation of the electron beam modified with the frequencies on the phosphor screen. The rise time of CL of phosphors is very short (ns order), and the contribution of the rise time to the MTF is negligible. Hence, the MTF of CL depends solely on the decay time of CL. Fig. 3 shows the measurement results of MTF (i.e. $f(t)$) of several phosphor screens, which have different decay times. The study reveals that MTF curves of Zn_2SiO_4:Mn (and Zn_2SiO_4:Mn:As) are low at 30 Hz. Therefore, with Zn_2SiO_4:Mn phosphors (long decay), one may perceive less flicker of images constructed with the CL light under frame cycles greater than 30 Hz. However, moving images on the screens have a long tail, and the images on the phosphor screens in CRTs are smeared with a small contrast ratio, resulting in a poor image quality. To obtain a high image quality, the phosphor screen must be made with short decay phosphors. The blue and green sulfide phosphors and red phosphor for color CRTs (P22 phosphors) have short decay times (less than 500 μs at 1/e of initial intensity).

The small images on CRT screen for color TV sets flicker markedly under ordinary TV operation conditions. This kind of flicker is not related to the decay time of CL, but is caused by the displacement of the CL light spots with time (i.e. $f(d,t)$). The displacement of the CL light spots during the repetition of the frame cycles are caused by mislanding of the electron beam on the phosphor screens. The mislanding of the electron beam is not due to the targeting accuracy of the electron beam by DY (diffraction york) on CRTs. It is caused by the phosphor screens, as proved below.

Using a given CRT, the flicker of the images on the phosphor screens is significantly reduced by means of (a) an increase in the frame cycles, and (b) a decrease in the electron beam current. The results positively indicate that the flicker on phosphor screens is not caused with targeting accuracy of the electron beam by DY. Then, one finds practically the frame frequencies for monitor CRTs. Fig. 4 shows the frame cycles applied to various 17 in CRT monitors; SVGA (800×600), SVGA (1024×768), and XVGA (1280×1024). The minimum frame cycles for the perception of flicker are empirically determined. It is a constant scanning time for a line, that is 14 μs for a 17 in CRT, giving a constant irradiation time for a given phosphor particle. The above results definitely indicate that the flicker of images on phosphor screens is related to the irradiation time on a specified phosphor particle. The irradiation time on the phosphor particle is determined by the scanning speed of the electron beam, which is given by (horizontal length)/(scanning time of one horizontal time). It is 2.43×10^6 cm s^{-1} for a 17 in monitor CRT. Therefore, irradiation time on a 5 μm particle observed by microscope is 0.2 ns. Under TV operation conditions, the irradiation time on the same phosphor particle is 1 ns. The irradiation of an electron beam of 300 μA on a phosphor particle for 0.2 ns does not generate flicker, but the irradiation of the same particles for 1 ns generates appreciable flicker of the images. Thus, the flickering by $f(d,t)$ of CL is clearly related to the irradiation time of the electron beam on phosphor particles.

The displacement (flickering) of CL lights on phosphor screens can be accurately measured for commercial MTF devices. The threshold of irradiation time of electron beam on phosphor screen, which generate the flicker, has been studied for commercial MTF devices. The threshold time of flicker changes with electron beam density on the phosphor particles. The threshold time shortens with a high electron beam density. Under given irradiation conditions of the electron beam on a phosphor screen, the threshold time is strongly influenced by contamination of the surface of phosphor particles. The threshold time is markedly shortened by contamination with insulators, such as pigments, SiO_2 etc.

The flicker caused by $f(d,t)$ on a phosphor screen is related to the emission and correction of secondary electrons from the phosphor screens [5]. If the phosphor screens efficiently collect the secondary electrons, the flicker caused by $f(d,t)$ will be suppressed. If the phosphor screens do not have flicker due to $f(d,t)$, the spot size of the electron beam can reduce to the dot size (or stripe width) of a phosphor screen, resulting in a high resolution of the images on phosphor screen. A scientific study of the flicker of images on phosphor screens

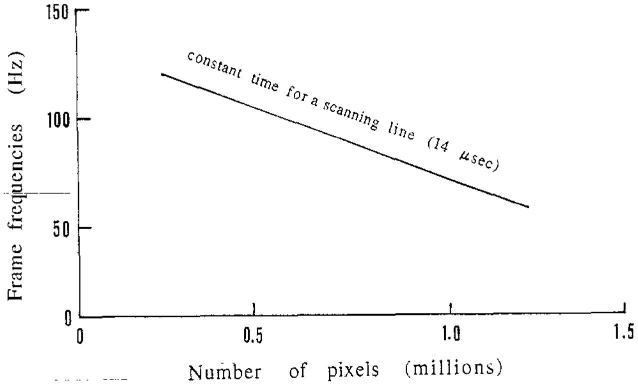

Fig. 4. Frame cycles of 17 in monitor CRTs in different information densities.

in CRTs remains for the future. This may be a good subject for material science.

4.3. Operation life of CRTs

The operation life of CRTs ends when the cathode terminates emission of thermoelectrons. Phosphor screens are slightly colored yellowish brown, but the screens do not end the generation of CL. The cathodes in CRTs are oxide cathodes. There is no material like oxide cathodes which have a low work function for emission of thermoelectrons.

Absorption of water seriously affects the formation of the oxide cathodes. After formation of the oxide cathodes, there are two reasons for damage to thermoelectron emission in vacuum. One is evaporation of Ba from the cathodes (intrinsic life), and another is absorption of residual gases (extrinsic life). Evaporation of Ba is accelerated with heating of the cathodes. The cathodes should be operated at as low a temperature as possible for a long life of the oxide cathodes; preferably below 700°C. Impregnate (i) cathodes and cavity reservoir cathodes have a short life for the emission of thermoelectrons, because of heating to a high temperature above 1000°C.

In practical CRTs, the oxide cathodes are heated to 800°C, to avoid absorption of the residual gases [13]. The oxide cathodes encounter the problem of ion bombardment. Ion bombardment spatters Ba from the surface of the cathodes. To avoid ion bombardment, the vacuum pressure of sealed CRT should be below 10^{-9} Torr. The vacuum of the freshly sealed CRTs is about 10^{-4} Torr, independent of the pumping facilities applied [13]. The sealing process and activation of the cathodes and getters in sealed CRTs markedly increase the vacuum pressure. Development of the sealing technology of CRTs may significantly extend the operation life of CRTs.

It should be noted that the published life curves do not follow the scientific method. The life curves should be plotted on semi-logarithmic graph paper, instead of ordinary graph paper. The reason is as follows: the life of the oxide cathodes is given by statistical results, which follow a holding time. The holding time is expressed with a Bernoulli probability $P(\lambda)$:

$$P(\lambda) = \lambda \exp(-\lambda t) \qquad (1)$$

Therefore, the life curve should be plotted as the logarithm of survivors against time on ordinary scale (semi-logarithmic graph paper). The life curve should consist of straight lines. The intrinsic life of the materials is given by a flat line. The inflection point of the straight lines, shorter than the intrinsic life, gives the end of the extrinsic factors (as with sickness in human life) to the life. By analysis of the curves, one may obtain much scientific information on the life. Fig. 5 shows a life curve that is replotted from the published data [14]. The initial decrease line is due to absorption (and bombardment) of the residual gases, and a constant line shows the intrinsic life of the oxide cathodes. The intrinsic life will suddenly end (not shown in the figure).

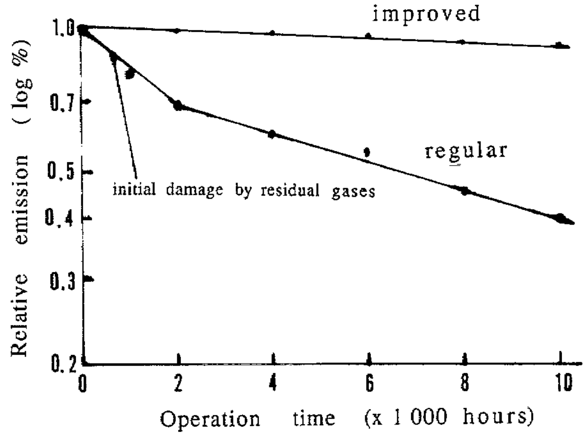

Fig. 5. Life curve of oxide cathodes replotted from Ref. [14].

4.4. Ultimate resolution of color CRTs

The resolution of color and monochrome CRTs should be discussed separately. The resolution of current color phosphor screens is predominantly determined by the stripe widths (or dot sizes) of the phosphor screen. The strip widths of current phosphor screens are limited by the screening of the phosphor powder. Commercial phosphor powders are aggregated in PVA phosphor slurry. The ideal phosphor powders are formed from (1) round particles with a rough surface, and (2) containing no microcrystals, (3) small particles less than 1.5 μm, (4) aggregated particles, and (5) residual fluxes [15]. Unfortunately, the quality of the commercial phosphor powders is far from that of an ideal phosphor powder.

If the ideal phosphor powder available one may screen color phosphor powders in any size with a fine stripe width, even with 12 μm width [15]. The screening technology allows three color phosphor stripes plus three black matrixes on a hair (about 70 μm). If the phosphor screens do not exhibit flickering of images, the screen sizes and stripe widths are no longer a limitation to the improvement of resolution of the images on phosphor screen in color CRTs. The resolution of images on the phosphor screens is surely determined by the design of the electron gun.

It is known that the size of an electron beam changes with the electron beam current. An electron beam spreads with an increase in the beam current. The spreading of the electron beam is explained by repulsion of electrons in the beam. However, repulsion of electrons seems to occur. Although electron beams from different electron guns are overlapped on the phosphor screen [5], the electron beam never spreads. We get the same diameter of emission spot. A new concept, rather than the established theory of electron optics, is needed for the design of an electron gun to improve the quality of images on phosphor screens in CRTs.

The resolution of phosphor screens in monochrome CRTs is determined by the design of the electron gun and the arrangement of particles on the screens. The ultimate monochrome phosphor screen is defect free with the arrangement of phosphor particles in 1.5 layers. With a combination of this screen and a developed electron gun, images of 60 lines mm^{-1} resolution (higher than printing resolution, 10 lines mm^{-1}) may be displayed on a monochrome phosphor screen [16].

4.5. Color combination of letters and background

For reading of letters for a long time, a better matching of letter and background color is requested. The combination has been determined historically. It is found in books. The combination of black letters on a slightly yellowish white background is probably a suitable combination for lengthy reading of images. All of the stimuli of the eyes are equally irradiated with the yellowish white background light. On the other hand, temporary information should be displayed in full color, as with books for children. We need both of them in our life.

4.6. Production cost

The production cost of color monitor CRTs should fall to that of the color CRTs for TV application. A major problem is the production yield of the color monitor CRTs, owing to arc discharge. The arc discharge in vacuum devices has been believed to be due to contamination by dust. However, the level of the arc discharge does not change with contamination by dust deliberately added to CRTs. If the arc discharge problem is solved in production, the production cost will fall by 30%. Another cost reduction may come with improvement of the screening technology of the phosphor powders. Then, a cost reduction of 1/5 may be expected in the near future.

5. Concluding remarks

The advantages of CRTs have been briefly described. If one compares the feature of current CRTs with those of developing FPDs, one may easily reach a conclusion that CRTs are forever as display devices in our life. However, this is not final. Further improvement of the image quality of CRTs is possible. The goal in the development of an ultimate CRT is CRTs that display images comparable with printed letters and images on sheets of paper. Then, a paperless society will be realized. This may require a scientific study of phosphor screens in CRTs at research laboratories, rather than empirical skills on the production side. This is a challenging subject for materials scientists.

References

[1] Information Display, 12 (July 1996) 10.
[2] T. Ishibashi, Nikkei Microwaves, (Dec. 1996) 131 (in Japanese).
[3] LCD Intelligence Update, K&T Institute, Tokyo, Japan; Information Display, 12 (July 1996) 34.
[4] Report on LCD Market, K&T Institute, Tokyo, Japan, 1996.
[5] L. Ozawa, Application of Cathodoluminescence to Display Devices, Kodansha, Japan, 1994, p 24.
[6] L. Ozawa and H.N. Hersh, J. Electrochem. Soc., 121 (1974) 894.
[7] L. Ozawa and H.N. Hersh, J. Electrochem. Soc., 124 (1977) 420.
[8] L. Ozawa and H. Torii, Joint Meeting of 4 Societies of Jpn. Electr. Eng., 1961, Abstract 1226 (in Japanese).
[9] L. Ozawa, Imaging and Display, 5 (1997) 151 (in Japanese).
[10] L. Ozawa, Cathodoluminescence, Kodansha, Japan, 1990.
[11] K. Oki, L. Ozawa and S. Lee, to be published.
[12] L. Ozawa, Jpn. Inst. Electr. Eng., 82 (1962) 109.
[13] L. Ozawa, Imaging and Display, 5 (1996) 59 (in Japanese).
[14] J.S. Choi, K.S. Choi, K.N. Joo, and S.S. Lee, Int. Display Workshop, Kobe, Japan, 1996, Abstract CRT2-5.
[15] L. Ozawa, Display and Imaging, 4 (1996) 111 (in Japanese).
[16] K. Oki and L. Ozawa, J. Soc. Inf. Displays, 3 (2) (1995) 51.