Elgraphy: A New High-Resolution Image Capturing System

H. Kamiyama, M. Utsumi, S. Hikosaka, M. Akada, T. Toida, M. Matsuo, and E. Inoue

Central Research Institute, Dainippon Printing Co., Ltd., Chiba-Ken, Japan

Image capturing systems generally fall into two broad categories: silver halide photography and digital imaging equipment. Each has advantages and disadvantages; a user must select the method that best suits his needs. The authors of this article are conducting research and development into a new image capturing method called Elgraphy that combines electrophotography and liquid crystal technology. It has the advantages of being a dry system, and having a high resolution and high sensitivity. Efforts are being made to establish a new imaging technology that exploits the characteristics of Elgraphy.[1–4] This article provides an overview of the new image capturing technology; details will appear in subsequent articles.

Journal of Imaging Science and Technology 44: 45–50 (2000)

Introduction

The remarkable advances in digital image processing technology in recent years have utilized many types of high-performance recording materials. Data is digitally processed and sent to a high-resolution output device, such as a dye-sublimation, laser or inkjet printer. Image capturing systems, on the other hand, fall into two types: digital cameras and silver halide photography. Although the former has the merit of being a dry method and provides very quick access and processing, its resolution is limited by the number of pixels in the CCD devices. In contrast, the latter provides very high resolution, but access is slow because of the wet processing.

To overcome the disadvantages of existing technologies, the authors have been working assiduously on developing a new dry method of capturing images. It employs an intermediate recording medium (image receptor), a camera, and a controller. Visual information is first stored on the intermediate medium, and is immediately ready for conversion to digital data and subsequent viewing on a display or as printed output. The authors have named the new technology Elgraphy because it is based on a combination of electrophotography and liquid crystal technology. This article provides an overview of Elgraphy; the details of many aspects will be described in later articles.

Image Acquisition Process

The Elgraphy system consists of four subprocesses: image capture, scanning, image processing, and output. The four steps are schematically shown in Fig. 1.

Original manuscript received November 19, 1998

Color plate 1 is printed in the color plate section of this issue, page 80.

Image Capture. Visual information is acquired by a camera that has been newly developed especially for Elgraphy. In addition to ordinary lenses and a shutter, it contains a device, e.g., a prism, that decomposes light

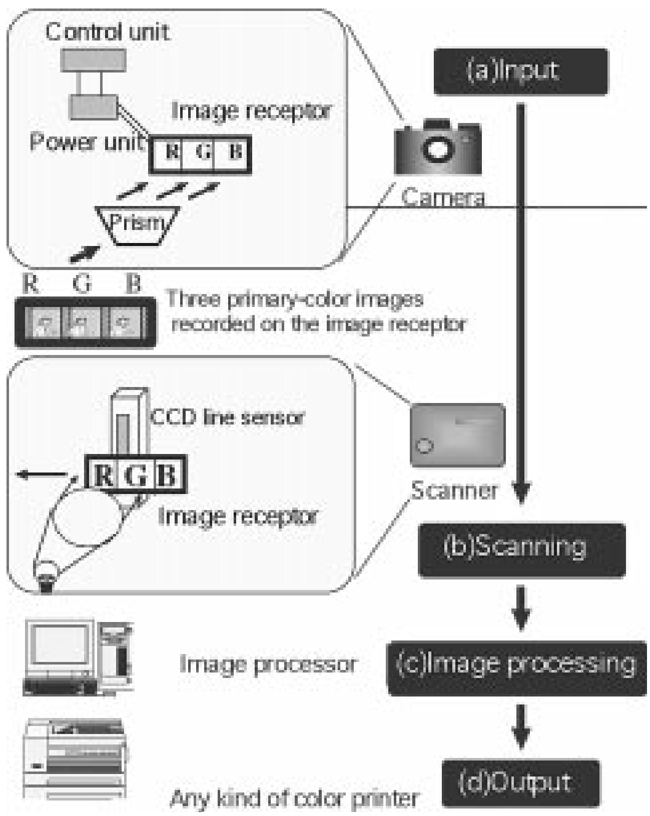


Figure 1. Components and processes of Elgraphy

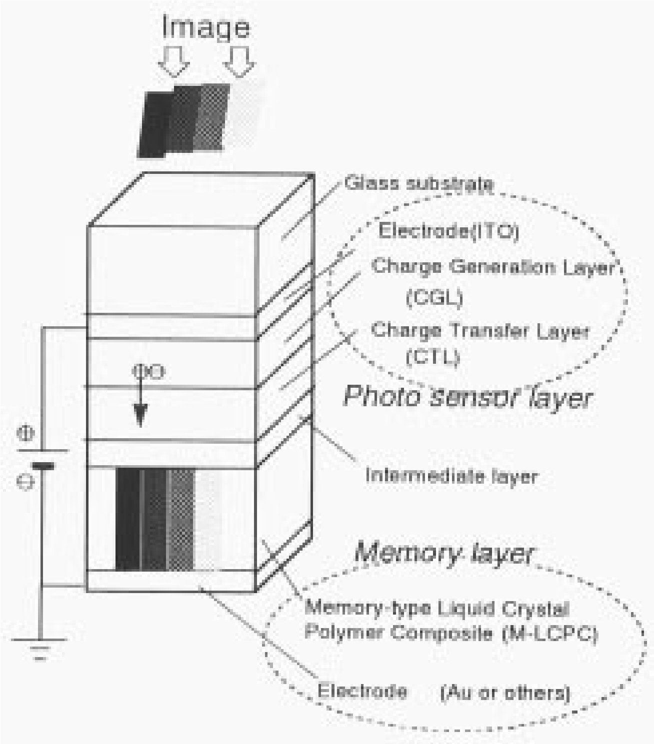


Figure 2. Structure and configuration of the image receptor.

into the three primary colors (RGB), a high-voltage source, and a control unit. In the camera, light from an input image is broken down into the RGB colors that illuminate the image receptor. In this state, the RGB image is formed on the image receptor under application of a suitable voltage for a proper duration.

Scanning. The image receptor containing the RGB images is detached from the camera, and the analog images are converted to digital data by scanning the images with a dedicated CCD line scanner (5000 pixels, 7 μm/pixel).

Image Processing. The digital data produced by the scanner is processed on a computer, and a color image can easily be reproduced by combining the RGB component data.

Output. The resulting high-quality color image can either be viewed on a monitor or be printed out on a color printer.

Image Storage in Image Receptor

Structure of Image Receptor. The image receptor (Fig. 2) primarily consists of two functional components: a photosensor layer and a memory layer. The photosensor layer is comprised of an ITO electrode on the bottom, followed by a charge generation layer (CGL) and a charge transport layer (CTL).

The memory layer is stacked on top of that, with an intermediate layer (insulating resin) inserted in between. Finally, either a transparent electrode (e.g. ITO) or a translucent electrode (e.g. gold) is formed on the memory layer. The memory layer is made of a memory type liquid crystal polymer composite (M-LCPC).

Mechanism of Image Formation. An image forms in the image receptor when it is exposed to light while a voltage is being applied to it so as to bias the photosensor layer positively and the memory layer negatively. Photocurrent flows in the illuminated regions, and a dark, or base, current flows in the other regions. The photoinduced current is defined to be the difference between the photocurrent and the base current. It is proportional to the intensity of the light illuminating the photosensor layer. The current induced in this layer generates an electric field inside the memory layer, and the total accumulated charge due to the base current and photoinduced current causes the M-LCPC molecules in the memory layer to become spatially aligned.

Before anything is recorded, the molecules of liquid crystal are randomly oriented and scatter light to produce a milky-white color. The liquid crystal changes from translucent to transparent as the molecules become more and more aligned due to the electric field arising from the electric current in the photosensor layer. The M-LCPC is a smectic-A type that exhibits a high degree of ordering and retains the ordering at room temperature after removal of the field, thus enabling an image to be stored. The degree of ordering depends on the light intensity, which means that the image receptor stores the light intensity as analog information.

Exposure is usually carried out under the following conditions: a camera-to-object distance of around 1.5 m; illumination with a 6300-K strobe flashing at a shutter speed of 1/250 s (ISO 10); and a voltage of 400 V applied for 1/25 s. Elgraphy has roughly the same exposure latitude as conventional digital photography.

Photosensor Layer

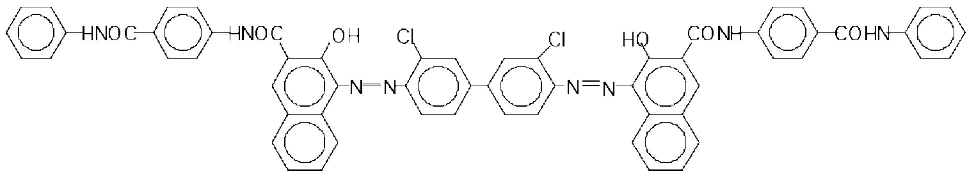
Structure of Photosensor Layer. The photosensor layer consists of a CGL and a CTL on an ITO glass substrate. When exposed to light while a voltage is being applied, the photoinduced carriers (holes) generated in the CGL are injected into the CTL, and migrate toward the memory layer. This flow constitutes a photocurrent.

The CGL is a mixture of a charge-generation material (bis-azo pigment, Dainichiseika Color & Chemicals MFG. Co., Ltd.) dispersed in polyvinyl formaldehyde resin (3:1 by weight), and is formed into a sheet 0.3 μm thick. The CTL is made by dispersing an charge transport material (bis-dimethyl-phenyl-dipropyl aminophenyl benzene, Takasago International Corporation) in polycarbonate resin (3:1 by weight), and has a thickness of 10 μm.

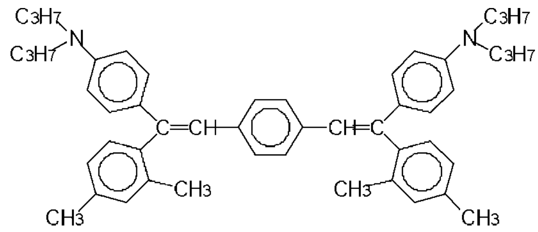
To examine the effect of current injected from the ITO electrode, a SiO_2 blocking layer with a thickness of 0.1 μm was sputtered onto the ITO electrode, and a photosensor with the same configuration as the one described previously was made on the SiO_2.

Amplification of Photoinduced Current in Photosensor Layer. The photoconductivity of the photosensor was measured by the following method: A sandwich cell (4 mm × 4 mm) was formed by evaporating a gold electrode onto the CTL. A DC voltage of 15 V/μm that biased the ITO electrode positively and the gold electrode negatively was applied across the photosensor, and the photocurrent generated by exposure to light was measured (Fig. 3). The light source was a halogen lamp, and mono-chromatic pulses (560 nm, 33 ms) were generated by a monochromator and an electric shutter. All measurements were conducted at room temperature.

Figure 4 shows the photo and dark current response of the Elgraphic photosensor and a photosensor with a blocking (SiO_2) layer, to pulsed illumination. The dark



Charge Generation Material(CGM)



Charge Transport Material(CTM)

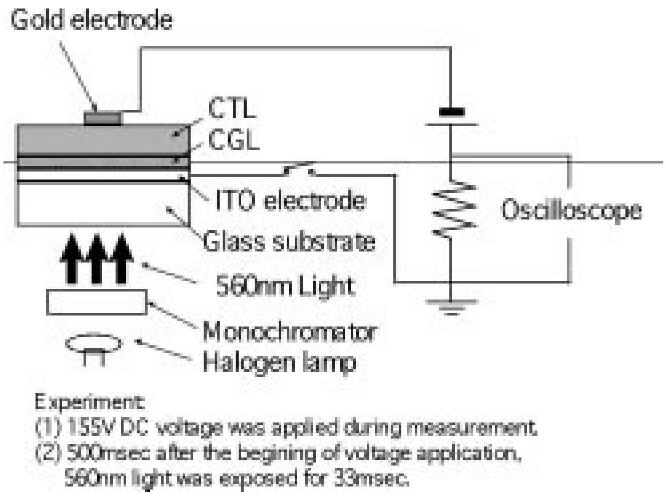


Figure 3. Setup for measuring I–V characteristics showing circuit diagram and structure of modified photosensor.

current of the blocking-type photosensor is smaller, and has a value of only less than 0.01 μA/cm^2. The photocurrent of the blocking-type photosensor rose over several milliseconds, remained steady while illumination continued, and then dropped sharply after the light was cut off. The generation of the photocurrent can be ascribed to photocarriers generated in the photoconductive layer by the illumination; the calculated quantum yield was 0.29.

In contrast, the dark current of the Elgraphic photosensor exhibited a much larger value of around 3 μA/cm^2; and the photocurrent continued to increase while it was being illuminated. The photocurrent continued to flow and decreased only gradually after the light was cut off. There are three inflection points (A, B, and C) in the photocurrent profile, as can be seen in Fig. 4.

In the region between 0 and (A), the photocurrent exhibited the same characteristics as that of the blocking-type sensor. Assuming that the current at (A) continues to flow during illumination, the calculated quantum yield is then 0.31. The photocurrent observed in this region can be ascribed to photocarriers generated in the photoconductive layer by the illumination.

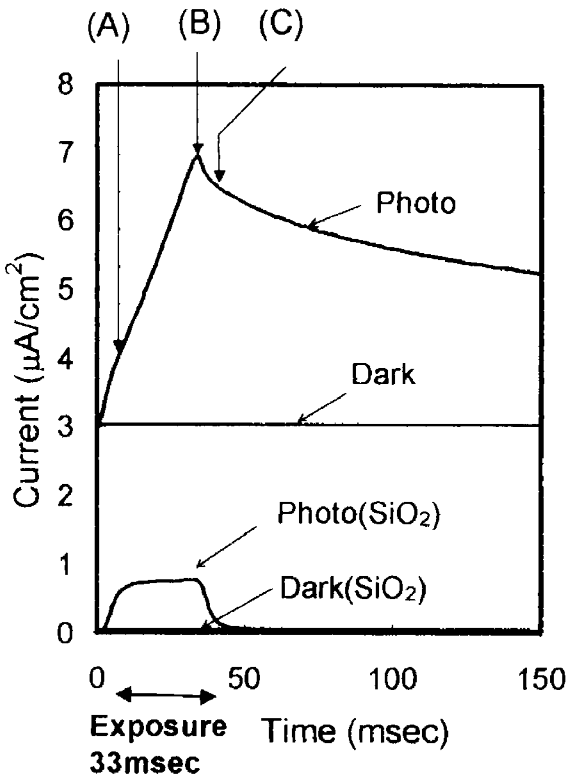


Figure 4. Characteristics of photo and dark current when light pulse was exposed. The light pulse was 560 nm, 3.0 μW/cm^2 for 33 ms. Applied voltage was DC-120V.

In the region between (A) and (B), the photocurrent exhibited markedly different behavior in that it increased continuously during illumination. In addition to the photocarriers, holes injected from the ITO electrode may contribute to the increase in current.

In the region between (B) and (C), the current dropped off rapidly when the light was cut off. The magnitude of the drop is equal to the magnitude of the increase in the region from 0 to (A), indicating that the drop is due to the quenching of photocarriers.

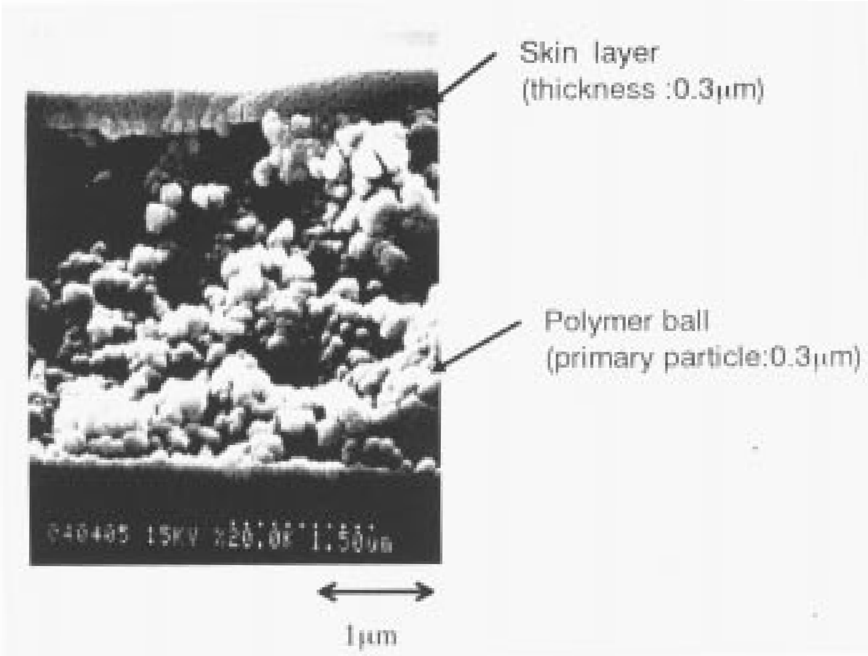


Figure 5. A micrographic cross-sectional view of the M-LCPC extracted liquid crystal by hot methanol.

In the region from (C) and beyond, the current continued to flow and decreased only gradually, even though the light had been cut off. The photosensor clearly exhibited a memory effect, suggesting that space charges generated by the illumination were trapped in the layer.

In contrast to the blocking-type sample, the Elgraphy photosensor is designed to provide a larger darkcurrent. The M-LCPC requires a large excess charge (darkcurrent), regardless of whether there is any exposure information or not, because a stronger electric field (threshold electric field) is needed to align the molecules. The figure shows that the photocurrent steadily increases during exposure. After illumination ceases, current continues to flow and falls off only gradually. The number of electrons that cause the photoinduced current is larger than the number of photons absorbed by the photosensor, i.e., the apparent quantum yield exceeds unity.[5,6] A detailed discussion of this amplified photoinduced current will be presented in a subsequent article.

Intermediate Layer

To avoid the mixing of the CTM in the photosensor layer and the liquid crystal in the memory layer, an intermediate layer is placed between the two layers. It consists of a coat of polyvinyl-alcohol resin with a thickness of 0.5–1.0 μm.

Memory Layer (M-LCPC)

Structure of M-LCPC. M-LCPC is prepared by mixing a smectic-A liquid crystal (cyan biphenyl alkyl derivative, MERCK) and a UV-curable acrylic monomer (di-pentaerythrithol hexacrylate, Nippon Kayaku Co., Ltd.) in a ratio of three to two by weight. Crosslinking is brought about by UV irradiation. The structural features of M-LCPC are described below.

Figure 5 shows a cross sectional view of M-LCPC. An ITO electrode is covered with memory-type smectic-A liquid crystal with submicron spheres of polymer (polymer balls) dispersed throughout, producing two distinct phases. In ordinary polymer-dispersed liquid crystal (PDLC) materials, the liquid crystal forms domains and it is the disorder among the domains that causes light to scatter. However, in M-LCPC liquid crystal fills the microscopic gaps between the polymer balls; so the orientation of the molecules (rather than domains) of liquid crystal is the main factor determining the transparency. The higher image resolution of M-LCPC is attributable to this fact.

In addition, the surface of M-LCPC is covered with a skin, which prevents the liquid crystal molecules from escaping. The skin layer is produced by the crosslinking of the UV-curable acrylic monomer. The M-LCPC layer is 6 μm thick.

Transmittance-Voltage Characteristics of M-LCPC. The change in transmittance due to an applied voltage was measured with the setup shown in Fig. 6. An ITO glass substrate was coated with M-LCPC, and a gold electrode was evaporated on top to form a cell. A sawtooth bias (0-500 V, 10 kHz) was applied across the cell, and the change in transmittance upon exposure to light from a xenon lamp that passed through a 488-nm monochromatic filter was recorded with a CCD device.

The transmittance-voltage characteristics of M-LCPC are shown in Fig. 7. The transmittance begins to increase when the applied voltage exceeds the threshold value of 200 V, and reaches a maximum (100%) at about 300V. Voltages between 250 and 300 V are utilized for image recording. The optimum threshold and voltage range for recording depend on the thickness of the M-LCPC layer, the liquid crystal material, and the fabrication conditions. This will be reported on in a subsequent article.

Image Resolution of M-LCPC. The photosensor layer and the M-LCPC layer are stuck together with a 9 μm-thick spacer in between. The M-LCPC was illuminated through a chromium mask with line-and-space patterns (width: 2, 3, 6, 12, and 20 μm) to determine its resolution. The luminance on the surface was set to 20 lux by adjusting the brightness of a halogen lamp, and 700 V voltage pulses with a width of 1/25 s. were applied. The experiment revealed that lines and spaces as narrow as 6 μm could be resolved. However, when an image is re-

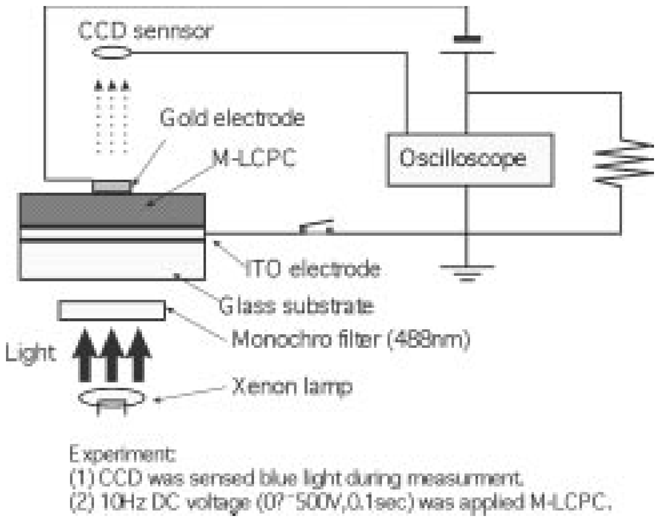


Figure 6. Setup for measuring V-T characteristics showing circuit diagram and structure of modified M-LCPC.

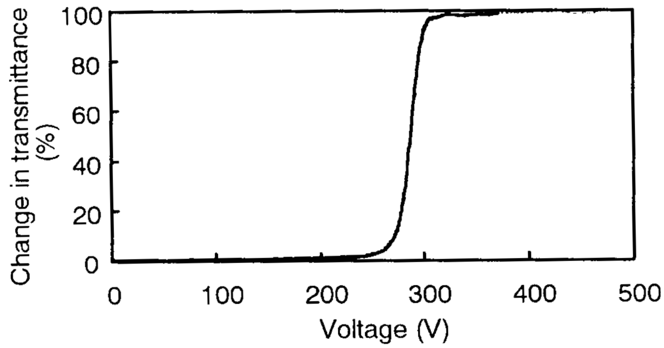


Figure 7. Change in transmittance of memory layer versus applied voltage at room temperature.

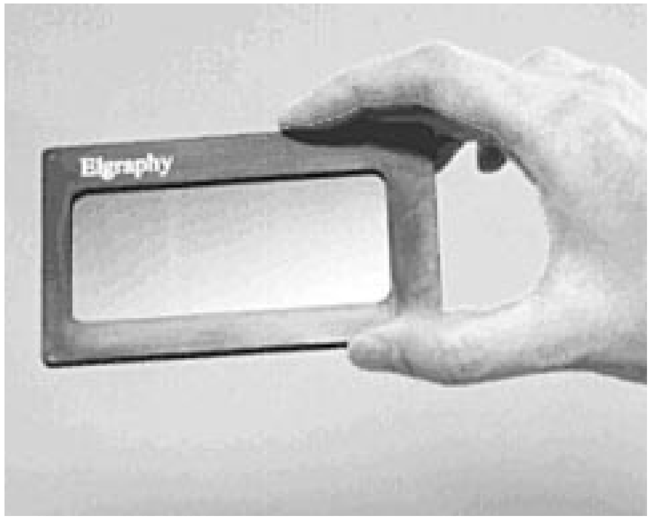


Figure 8. Photograph of view of the plastic cased image receptor.

corded using a camera, the resolving power of the lens and scanner limit the overall resolution, and a 6 μm resolution has not yet been attained.

Characteristics of Whole System

Table I compares the characteristics of the Elgraphy image capturing system to those of conventional silver halide photography and a digital camera. The sensitivity of silver halide film and commercially available digital cameras were taken from product catalogs.

Processing and Access Time. All of the image formation processes in Elgraphy are dry. So the time needed for the wet processing required in silver halide photography is totally eliminated. Moreover, unlike digital photography which requires interpolation calculations to fill in the gaps between pixels, Elgraphy requires only the simple superimposition of analog RGB images, which means that it can process a larger number of images in the same amount of time. Around ten minutes are required from image capture to image output.

Sensitivity and its Enhancement. The photosensor, the M-LCPC, and the image processing in Elgraphy each exhibit their own amplification effects. The photosensor amplifies the photoinduced current; the quantum yield suggests an amplification factor of around 10. In the M-LCPC, around 1.8×10^{17} liquid crystal mol/cm^2 must become spatially aligned to produce a unit difference in photographic density. This requires a charge of 1.0×10^{-7} C/cm^2(6.3×10^{11} electrons/cm^2). Calculation of the number of liquid crystal molecules aligned by a single electric charge indicates an amplification factor of around 10^5–10^6.

Although the optical density of M-LCPC is unity, the value for an output image after image processing and the output process is 2, which translates into a ten-fold amplification through density conversion. The combination of the above effects provides Elgraphy with an amplification of around 10^8, and the sensitivity is roughly equivalent to ISO 10-50 for silver halide film. (Table II)

Number of Pixels. Figure 8 shows a photograph of an image receptor unit. This unit has R, G, and B images, each of which is the size of one frame of 35 mm film. The unit contains about 50 million pixels.

Latitude. An image receptor was exposed to white light from a halogen lamp. The light first passed through a 3-level gray-scale filter and was adjusted so that the luminance on the surface was 50 lux. Gray-scale images were recorded by applying 680 V voltage pulses with a width of 1/20 s. The images were scanned with a CCD device employing 450 nm monochromatic light, and the transmittance was determined. Figure 9 shows the change in the density of the liquid crystal layer versus the intensity of light adjusted with the gray-scale filter. The vertical axis indicates the dispersion and the transmittance in steps from 0 to 255. The second Y-axis is transmittance. The applied voltage was such that the dark current produced a transmittance of 10% in unexposed M-LCPC. That is, the gray-scale background image was recorded while the M-LCPC was in a semitransparent state. The exposure intensity where photocurrent started to increase the transmittance of the M-LCPC was 0.08 lux-s, and the exposure latitude was in two orders of magnitude.

In Elgraphy, the characteristics of the curve shown in Fig. 9 can be modified by adjusting the voltage and exposure conditions; and the image characteristics, such as latitude and contrast, can also be freely controlled. The details will be provided in a future article.

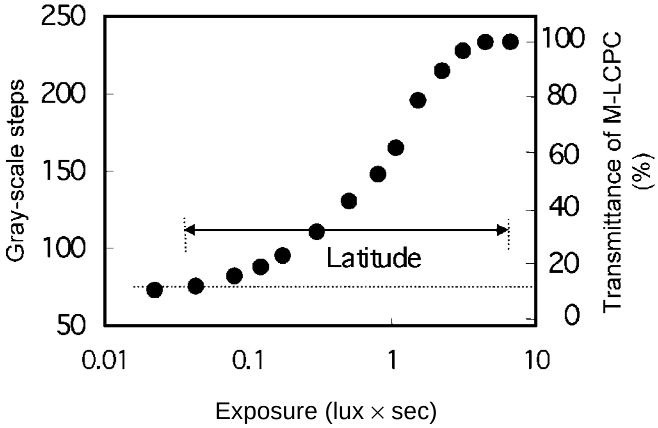


Figure 9. Latitude of Elgraphy.

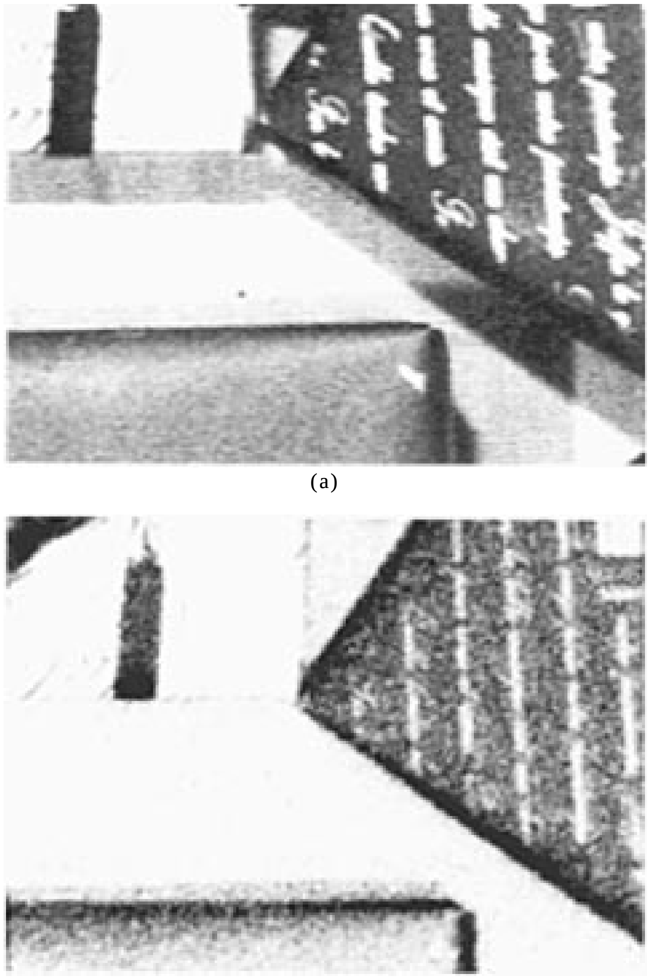
TABLE I. Main Characteristics of Image Capturing Systems

Factors	Silver halide photography*	Digital camera**	Elgraphy
Access time	several hours order	minute order	minute order
Process	wet	dry	dry
Sensitivity	ISO 100	ISO 80	ISO 10-50
Number of pixel	18 million	6 million	50 million
Latitude	3	2	2
Granularity	Fine	—	Fine

* Fuji color FUJICHROME PROVIA 100 4 × 5
** Canon EOS DCS1

TABLE II. Amplification of Recording System

Recording system	Amplification	Sensitivity (ISO)
Electrophotography	10^6–10^7	1-10
Elgraphy (total)	10^7–10^8	10-100
(Photosensor)	(1–10)	
(M-LCPC)	(10^5–10^6)	
(Output process)	(10)	
Silver Halide	10^7–10^9	30-3000



(a)

(b)

Figure 10. Comparison of output image quality of Elgraphy and silver halide. Both images are enlarged 60 times to see the difference.

Granularity. Figure 10 shows an image on silver halide film (FUJI color G100) and an Elgraphy image scanned by the scanner, as described above. Both images have been enlarged by the same amount. As can be seen, the Elgraphy image is very fine-grained.

Conclusion

The authors have developed a novel photo-electronic imaging system called Elgraphy. This system has four component subprocesses: image capture, scanning, image processing, and output. The sensitivity of the system corresponds to ISO 10-50, and the image receptor is capable of 6 μm resolution. Research and development are now being carried out to put the technique to practical use. Plate 1 (p. 80) shows representative Elgraphy output images.

Acknowledgement. The authors would like to thank Mr. Yasuo Yamaji and Mr. Kuniaki Kamei for their encouragement and support throughout this study.

References

1. M. Utsumi, M. Akada and E. Inoue, *IS&T's 48th Annual Conference Proceedings*, IS&T, Springfield, VA, 1995, p. 499.
2. M. Akada, D. Aoki, H. Kamiyama, and E. Inoue *IS&T's 49th Annual Conference Proceedings*, IS&T, Springfield, VA, 1996, p. 290.
3. M. Akada, D. Aoki, H. Kamiyama, and E. Inoue, *IS&T's 5th Int'l. Congress on Advances in Non-Impact Printing Technologies*, IS&T, Springfield, VA, 1996, p. 333.
4. H. Kamiyama, D. Aoki, S. Hikosaka, and E. Inoue, paper presented at Japan Hardcopy Fall Meeting (1996)
5. D. Aoki, S. Sakano, M. Okabe, O. Shimizu, M. Utsumi, M. Akada, and E. Inoue, Ref. 1, p. 502.
6. D. Aoki, M. Kashiwabara, T. Idehara, H. Kamiyama, M. Akada, and E. Inoue. *Extended Abstracts*, (*43rd Spring Meeting, 1996*), No. 3, Japan Society of Applied Physics and Related Societies, Tokyo, 1996, p. 1321.

(a) a portrait

(b) a still life

Plate 1. Output imaegs of Elgraphy (H. Kamiyama, et al., pp. 45- 50).