Development of Organic Imaging Device
- Novel Image Sensor with Organic Photoconductive Films

We have been studying the photoconductive properties of organic films that are sensitive to only red, green, or blue light in an effort to develop high-resolution compact color cameras without color separation optical systems. In this paper, we describe photoconductive films whose organic molecules are sensitive to a single primary color component, image pickup using a camera tube that incorporates such organic film, and the operation of a CMOS readout circuit overlaid with this organic film. These results show the great potential for the development of high-resolution prism-less color cameras.

1. Introduction
Meeting the demands of the ever diversifying field of program production with enhanced mobility for the reporting of disasters, incidents, and accidents, along with new video expression methods, is requiring smaller, yet higher performance Hi-Vision (HDTV) color camera systems.

The authors of this paper have been advancing research on a high-performance color image sensor using organic photoconductive films. This image sensor will realize a super-compact color camera with no color separation prism and with excellent imaging characteristics, including a sensitivity and picture quality that are equivalent to that of regular color broadcasting cameras with three image sensors. This paper will describe the advantages of organic material application to imaging devices such as television broadcasting cameras. This will be followed by a report on an operational experiment using a camera tube that incorporates an organic film, and on the wavelength selectivity of organic films. It will also introduce a readout technology using a Complementary Metal-Oxide Semiconductor (CMOS) circuit, which is being developed as a fundamental experiment with the goal of constructing a future color imaging device.

2. Present TV Camera Imaging Scheme and a New Imaging Scheme Using Organic Material
The main imaging scheme employed in television camera systems used for broadcasting is a three image sensors system that uses a color separation prism to separate incident light entering the camera into red, green, and blue light, which is then detected by three separate imaging sensors, one for each color. The inserted Figure 1 (a) describes a configuration model for the three image sensors scheme. While this scheme has a high resolution and is capable of utilizing nearly all the incident light, its structure, including its lens, make drastic camera size reduction difficult. In the case of consumer model video cameras and digital cameras, their mainstream imaging system is a single plate color device consisting of three or four colored filters pasted over an image sensor like a mosaic. Although this scheme has the advantage of having only one imaging sensor with no prism, resulting in a compact, lightweight camera system, its low resolution and poor light use efficiency in comparison to that of a broadcast camera with three image sensors fall short for broadcasting use. If an image sensor can be fabricated that is similar to photographic film with a function to separate the three primary colors in the depth direction of its film (Figure 1 (b)), it will...
eliminate the need for a prism, realizing the construction of a palm-sized super-compact television camera with high picture quality. There are stacked imaging devices that employ the property of the depth difference for light in the primary colors approaching the inside of a silicon substrate. However, attainment of color separation characteristics equivalent to that of three image sensors through this scheme is considered difficult. The fabrication of a stacked imaging device with high picture quality for broadcasting requires the stack of individual films, each with high wavelength selectivity for only one primary color. Organic materials show superior characteristics, such as good absorption of visible light, and the absorption of light in a specific wavelength. Considering that the incorporation of organic films in a camera’s photoconductor will increase its fill factor to nearly 100%, we believe that a highly-sensitive, high-resolution single image sensor with good color separation capability can be fabricated through the selection of appropriate organic materials for stacking films, to readout the charge from each layer.

3. Wavelength Selectivity for Organic Films

With the aim of verifying the superior wavelength selectivity of organic materials as photoconductive material, a sandwich cell using organic film for its photoconductor was constructed to examine its light response characteristics.

3.1 Selection of organic material with sensitivity for three primary colors and the cell structure

The realization of a stacked imaging device similar to that shown in Figure 1 (b) requires the selection of organic material that absorbs only one of the three primary color wavelengths but allows penetration by the other colors. The color of the material itself will be a complementary color for the absorbing color. Since the complimentary color for blue is yellow, with magenta for green and cyan for red, the first choices for the organic material would be final film colors of yellow, magenta, and cyan. This is the basis for our selecting coumarin 6 (C6) as the blue absorbing organic material, rhodamine 6G (R6G) as the green absorbing organic material, and zinc phthalocyanine (ZnPc) as the red absorbing organic material.

Utilizing the nature that C6 and R6G are easily soluble in an organic solvent, a film was fabricated using a spin-coating method by adding them to a kind of conductive polymer, polysilane. Polysilane is a transparent material that does not absorb visible wavelength light, making it a very suitable polymer for dispersing C6 or R6G. The structure of this prototype cell is illustrated in Figure 2. It consists of a polysilane layer containing C6 or R6G placed between a transparent electrode (indium tin oxide: ITO) and an aluminum electrode, with light radiated from the ITO electrode side. This prototype film was fabricated through an instillation of chloroform solution containing polysilane with 5% C6 or R6G added to it, over a glass substrate with an ITO electrode. The glass substrate was then spun to form a 1μm-thick film. This was followed by placing an 80nm-thick aluminum electrode as its opposing electrode using the vacuum deposition method.

On the other hand, ZnPc is added using the vacuum deposition method, since it is not easily soluble in an organic solvent. The inserted Figure 3 shows the structure of this prototype film. In a vacuum vessel with a pressure of approximately 1.0×10⁻⁵Pa, 100nm-thick ZnPc was deposited over a glass substrate with an ITO electrode. Utilizing the nature that ZnPc is a hole transport material, we performed successive 100nm deposition of Tris-8-hydroxyquinoline aluminum (Alq₃), which is frequently used as an electron transport layer in organic electroluminescent (EL), over ZnPc, and finally formed a 80nm-thick aluminum electrode as the opposing electrode.
3.2 Wavelength selectivity
The inserted Figure 4 (a) describes the photoabsorption spectrum for the three types of organic film that we fabricated. It shows the peak photoabsorption for the C6-doped polysilane film in the blue color region, the peak for the R6G-doped polysilane film in the green color region, and the ZnPc/Alq3 double layer in the red color region, each corresponding to the photoabsorption spectrum of C6, R6G, and ZnPc, respectively. Figure 4 (b) indicates the spectral sensitivity characteristics for these devices with an applied electrical field of $5.0 \times 10^5 \text{V/cm}$. It reveals that all the films generated photocurrent corresponding to the three respective primary colors, which originated from the photoabsorption characteristics of the organic materials used. Although these prototypes did not reach a degree of color separation equivalent to the prism in a color camera system, because we selected relatively easily-obtainable materials to employ in them, it is believed that the future fabrication of materials from their molecular design will improve color separation characteristics. These results indicated the prospect of realizing a single image sensor through the stack of photoconductive films using organic material.

4. Image pickup from Organic Photoconductive Film
As described above, the experiment using a sandwich cell clarified that the selection of organic material will enable the construction of photoconductive film with a wavelength selectivity capability, which is indispensable for a single image sensor. This chapter reports the results of an operation experiment using a camera tube that incorporates the organic film, with the purpose of understanding the properties of organic film as an imaging device. We employed the camera tube in order to easily evaluate the application possibility of organic film for an imaging device.

4.1 Prototype camera tube construction
The external appearance of the prototype camera tube is shown in Figure 5. It is a vacuum-tight cylindrical glass tube that contains a target using organic film and an electron gun. The structure of organic film and the operational principle of this camera tube are illustrated in the inserted Figure 6. The reduction of dark current was attempted by the selection of ZnPc for a photoconductive material, used in a layered structure with a hole-blocking material, BCP, placed between an ITO transparent electrode and a ZnPc film. The BCP film and ZnPc film were fabricated successively using the vacuum deposition method. The electron gun for an HDTV system was incorporated into an MM-type (electromagnetic focusing/deflection) camera tube that performs the focusing and deflection of the electron beam at an external coil. The transparent electrode for signal readout is impressed with a target voltage $V_t$. We can obtain a video output signal through scanning the electron beam that generates, at $R_L$, a current that corresponds to the photoproduction charge accumulated within the film.

Figure 4: (a) Light absorption property and (b) spectral sensitivity for the three prototype films

Figure 5: Appearance of prototype camera tube
4.2 Resolution characteristics and quantum efficiency

The picture in Figure 7 is an image shot with an HDTV monochrome camera that incorporates the prototype camera tube. It was taken with a target voltage of 33V, with white incident light. The image shows that organic film has a good resolution. A shooting experiment with a test chart also confirmed that this prototype tube is capable of a resolution of 800 TV lines or higher. The resolution of a camera tube is determined by both the resolution of the photoconductive film itself, and the electron beam diameter. While inadequate resolution of the film sometimes reduces the resolution due to accumulated charge flows in the horizontal direction of the film, the resolution of the prototype tube was maintained at the same level even while adjusting the target voltage. This indicates a further resolution improvement possibility when using an electron beam with a smaller diameter for focusing, since the prototype tube resolution is restricted by the electron beam diameter. The above mentioned results indicate that a resolution that is high enough for HDTV application can be obtained without the need for pixel segmentation, revealing the prospect for the construction of a high-definition, organic imaging device with a 100% fill factor.

The inserted Figure 8 describes the quantum efficiency (output electron number/radiated photon number). Its target voltage was 48V, with a radiated optical power of 0.3μW/cm². The quantum efficiency when radiated with light at the 620nm wavelength was approximately 15%. The chart also includes the photoabsorption spectrum for the film, showing a close match between the quantum efficiency shape and the photoabsorption spectrum shape, which successfully verified the wavelength selective capability in the operation of the prototype camera tube, that had previously been confirmed using the cell.

Figure 6: Structure and operation principle of target using organic films

Figure 7: HDTV imaging example using prototype tube

Figure 8: Quantum efficiency and Photoabsorption spectrum for the prototype tube
5. Examinations on Future Solid-state Fabrication Using CMOS Readout Circuit

The realization of a future super-compact organic imaging device will require the combination of organic films with a solid-state readout circuit. As a fundamental experiment for this future application, organic films were fabricated over a CMOS readout circuit for characteristic evaluation.

5.1 Configuration

This prototype CMOS readout circuit for organic film had an effective area of 1.34 x 1.34 mm², with an effective pixel number of 128 horizontally x 128 vertically. We deposited Alq₃ as an electron transport layer over this CMOS circuit, followed by the deposition of ZnPc as its photoconductive layer. Both the Alq₃ and ZnPc films had a film thickness of 100 nm. The device was constructed with the deposition of a 15 nm semi-transparent gold electrode to apply a voltage over the organic film.

A cross-sectional view of a pixel is illustrated in the inserted Figure 9. When light enters from the gold electrode side, electrons and holes are generated within the organic film, accumulating electrons at the pixel electrode due to the electrical field applied to the film. As the row selective line is set to turn on the MOS transistor, current flows over the output circuit for output as a video signal.

5.2 Output signal characteristics

The signal output voltage-film application voltage characteristics for the prototype device are described in Figure 10. With the use of a red color transmitting filter, only red light, which the ZnPc is sensitive to, was radiated. A clear signal output voltage was observed when a voltage over -9 V was applied, showing an increase in signal output voltage up to -14 V where the output voltage at a dark period begins to rise. The successful readout of the photoelectric charge occurring within an organic film using the CMOS circuit moved us a step closer to the realization of a highly-sensitive, high-resolution single image sensor based on organic films.

5.3 Future organic imaging device

Figure 11 illustrates a conceptual image of an advanced organic imaging device, which the authors are currently considering. It has a structure of layered organic films, each of which is sensitive to only blue, green, or red light and is equipped with a transparent circuit that can readout a color signal. As described in this paper, it has been verified that it is feasible to have organic films that are exclusively sensitive to only one of the three primary colors in light, with signal readout from a solid-state circuit. It has also been verified that a resolution high enough for HDTV system application can be obtained without the segmentation of pixels in the film. Future work in this research will involve the further advancement of studies to readout a color signal from each of the layered organic films, together with the engineering of a transparent readout circuit, with...
a view toward the early implementation of a single image sensor using organic films.

6. Conclusion
With the aim of constructing an advanced, high picture-quality, super-compact color camera system, examinations were made on photoconductive film using organic materials with wavelength selectivity. Prototype photoconductive films were fabricated based on coumarin 6 (C6) for blue, rhodamine 6G (R6G) for green, and zinc phthalocyanine (ZnPc) for red, with which we confirmed that optical photocurrent that closely corresponds to the three primary colors in light could be obtained. Operational experiments with a camera tube incorporating the organic films verified a resolution that is high enough for HDTV system application. It was also shown that it is very feasible to apply the organic material to the photoconductor of a stacked single image sensor, through the observation of a clear output signal voltage at the characteristic evaluation using organic film fabricated over a COMS readout circuit.

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