CMOS Image Sensor with Organic Photoconductive Layer Having Narrow Absorption Band and Proposal of Stack Type Solid-State Image Sensor

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Abstract

Digital still cameras overtook film cameras in Japanese market in 2000 in terms of sales volume owing to their versatile functions. However, the image-capturing capabilities such as sensitivity and latitude of color films are still superior to those of digital image sensors. In this paper, we attribute the cause for the high performance of color films to their multi-layered structure, and propose the solid-state image sensors with stacked organic photoconductive layers having narrow absorption bands on CMOS read-out circuits.

Introduction

This study has been undertaken to analyze the reason why the image-capturing ability of traditional analog photography with silver halides as sensors is still superior to that of digital photography with full use of the most advanced semiconductor technologies, and to propose a new concept for a solid-state image sensor having photoconductive and carrier-transporting layers separately by applying the result of the above-stated analysis to the latest semiconductor devices.

Structure of Solid-State Image Sensor and Their Limit

CCD and CMOS are now competing with each other in capability as image sensors. While there are differences between them in the structures for the transfer and read-out of signal charges, the structures of photodiodes, which capture images, are essentially the same between them. Namely, mosaic color filters as arranged according to Bayer pattern are installed in regularly arranged pixels in an image sensor so that the light of one of the three primary colors is absorbed by each of the pixels. It is therefore obvious that the lights of the other two primary colors are absorbed by each filter, and are therefore wasted without contributing to image formation. In addition, an optical low pass filter, which is necessary to eliminate the appearance of moiré owing to regularly and two-dimensionally arranged mosaic color filters, brings about the reduction of the resolution of a digital still camera.

Three-Dimensional Structure of Color Films

At the 29th International Congress of Imaging Science in Tokyo in 2002 (ICIS'02), M. Uchida and S. Takada reported that both sensitivity and latitude of a color negative film were superior to those of a digital still camera on the basis of the result of the comparison between them in terms of their total capabilities including sensitivity, granularity, sharpness, saturation of colors, gradation, and fidelity in color reproduction of the images, which were captured by color films and digital still cameras for consumers, and were digitally printed [1].

A color negative film with wide dynamic range for exposure is composed of three major layers, which are sensitive to blue, green, and red lights and coated one on another from top to bottom, while each major layer is furthermore composed of three sub-layers with high, medium, and low sensitivities. Although a color negative film contains many fine silver iodobromide grains, it is sensitive to light owing to the light absorption, not necessarily by silver halide grains by themselves, but by self-organized J-aggregates of sensitizing dyes. Then, light-excited sensitizing dye molecules inject electrons into silver halide grains and render them developable for image formation. The multi-layered structures of color sensitive photographic materials are made practical by the technology named simultaneous multi-layer coating, by which all the layers in a material are coated simultaneously, and makes it possible to achieve color-sensitive photographic materials with high sensitivity and wide dynamic range.

Application of Multi-layered Structure Technology to Solid-State image Sensor

Since the light absorption by silicon widely extends from blue to near-infrared lights, three kinds of color filters, each of which transmits the light of one of the three primary colors, are needed to make each pixel exclusively sensitive to the light of one of the three primary colors by absorbing the lights of the other two primary colors and preventing them from contributing to image formation. In order to escape from this dilemma, it is necessary to develop photoconductive layers, which exclusively absorb the light of one of the three primary colors and transmit the lights of the other two primary colors, and combine them with circuits to read-out signal charges generated by the photoconductive layers [2]. This idea is described in details in US Patent Application applied by Fuji Photo Film Co., Ltd [3]. Figure 1 illustrates the cross section of the proposed stack type solid-state image sensor composed of three photoconductive layers, a silicon device to read-out signal charges, and vertical electric circuits to combine among them. In this case, it is possible from theoretical viewpoint to design an image sensor in such a way the fraction of an area of each image-capturing layer in a pixel area is nearly 100 %.

Trial Product of an Image Sensor with an Organic Photoconductive Layer and a CMOS Read-Out Circuit

While the present authors are planning to develop a solid-state color image sensor with vertically stacked layers, they have experimentally produced a CMOS image sensor with an organic photoconductive layer, and proved that it actually works well as a monochromatic image sensor. Figure 2 illustrates the cross section of the photoconductive layer indicative of its structure, and the read-out circuit installed in a CMOS substrate (experimentally manufactured by TSMC). Thus, incident light meets for the first time a transparent counter electrode composed of ITO, then an electron blocking layer, an organic photoconductive layer composed of quinacridone, and finally a pixel electrode composed of ITO. Figure 3 shows the absorption spectrum of a thin layer of quinacridone with a sharp absorption band in green region. The signal charges generated in the photoconductive layer is transferred through a via plug to a storage diode installed in a CMOS substrate, stored there, and read out to reproduce an image by a 3Tr CMOS read-out circuit.

The specifications of the image sensor are 120×160 in pixel number, 20 μm×20 μm in pixel size, and 30 field/sec in read-out speed. Figure 4 shows the pictures reproduced by the circuit for the evaluation of the image-capturing ability of an image sensor. The figure (a) shows the picture of the Japanese doll. The figure (b), which shows the picture of the EIAJ resolution chart, indicates that the image sensor could exhibit the limit of the resolution (i.e., 120TV lines) as predicted by the number of vertical pixels in the image sensor. Figure 5 shows the dependence of the photocurrent on the amount of exposure. The photocurrent was nearly proportional to the amount of exposure. We could confirm the fundamental operation of the image sensor.

Conclusion

The analysis of a color film has revealed that the cause for its high performance to capture an image is attributed to its unique structure with multi-layers of photosensitive materials arranged vertical to incident light. It has been concluded that the multi-layered structure works well owing to the facts that silver halide grains are nearly transparent in visible region, and that incident light is mostly absorbed by organic sensitizing dyes, which absorb only the light of one of the three primary colors and transmit the lights of the other two primary colors. In this study, we have developed photoconductive layers, which absorb only the light of one of the three primary colors and transmit the lights of the other two primary colors, and proposed the solid-state image sensor with vertically stacked photoconductive layers on a CMOS read-out circuit. In addition, we experimentally produced a monochromatic CMOS image sensor with a photoconductive layer, and succeeded in capturing images by it and in evaluating its fundamental operation.

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Author Biography

Shunji Takada is a Fellow of Fuji Photo Film Co., Ltd. He received his M.S. in physics from Tohoku University and joined Fujifilm in 1971. He received his doctorial degree from Tokyo Institute of Technology in 2000. Since then, he has been a visiting associate professor of Department of Electronics and Applied Physics. He was selected as a Fellow of IS&T in 2004.*

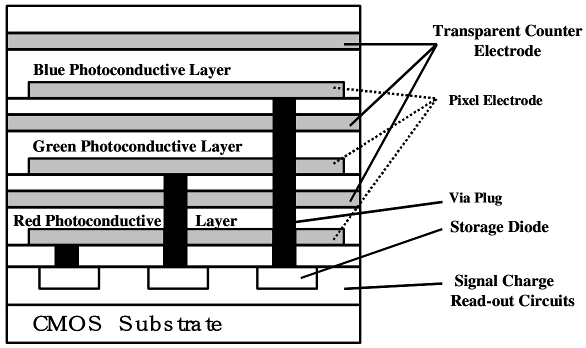

***Figure 1**. An illustration showing the cross section of the proposed stack type solid-state image sensor composed of three photoconductive layers and a silicon device to read-out signal charges.*

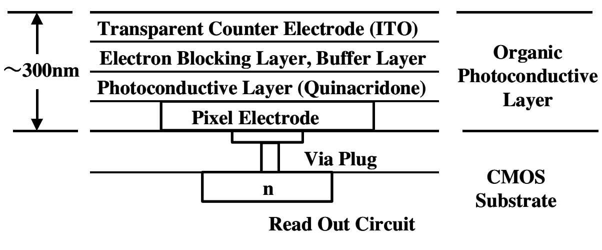

***Figure 2**. Schematic diagram of the monochromatic CMOS image sensor with an organic photoconductive layer and a signal charge read-out circuit.*

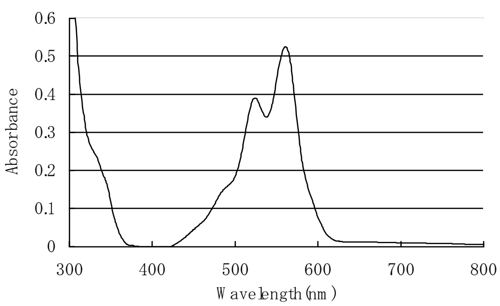

***Figure 3**. Absorption spectrum of a thin layer of quinacridone.*

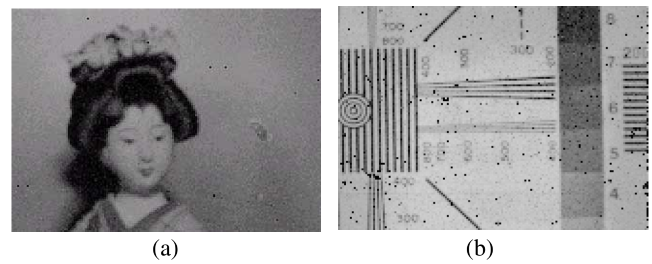

***Figure 4**. Pictures of the Japanese doll and the EIJA resolution chart which were taken by the image sensor experimentally produced in this study.*

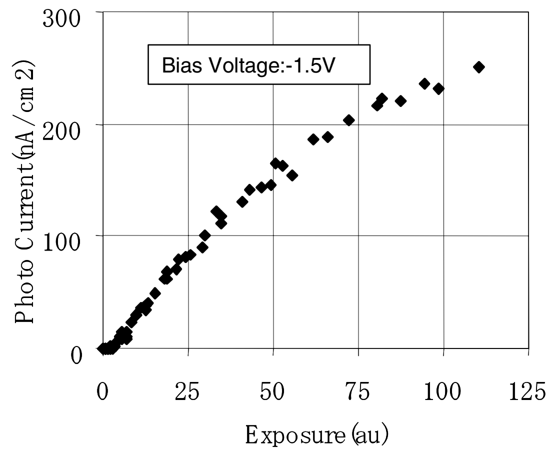

***Figure 5**. The dependence of the photocurrent on the amount of exposure.*