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Three-Dimensional CMOS Image Sensors Integrated with On-Chip Infrared Filters and Color Filters

[1]Ho-Pyo Hong and [2]Myung Bok Lee
[1]Department of Business Administration,
[2]Department of Industrial Technology Management, Gwangju University, 277 Hyodeok-ro, Nam-gu, 61743 Gwangju, Korea

Abstract: Infrared (IR) and color filters were integrated on one-chip CMOS image sensors to implement 3-Dimensional (3D) image sensors which are capable of capturing color image and depth information simultaneously. The combination of light filters applied for the 3D image sensor consists of an IR cut filter mounted over the objective lens module and on-chip filters such as IR pass filters and color filters. The IR cut filters were designed by the Essential Macleod program and fabricated by inorganic thin film deposition with RF magnetron sputtering. On-chip IR pass filters and color filters were fabricated by photolithography. The IR cut filter was formed by alternately stacking a SiO_2 layer and a TiO_2 layer to form multilayers with a total thickness of about 1930 nm. The spectrum characteristic of the IR cut filter showed a transmittance more than 90% for light with a wavelength ranging from about 400 nm to about 850 nm and showed a transmittance less than about 10% for light with a wavelength longer than about 900 nm. The spectrum characteristic of the IR pass filter showed a transmittance more than about 90% for light with a wavelength longer than about 850 nm and a low enough transmittance for visible light. The fabrication process of the filters is fairly CMOS compatible. Thus, the IR cut filter and IR pass filter together with the color filter are considered to be successfully applicable to the 3D image sensor. The 3D sensor adopting the new filters can be used for various imaging device applications which require conventional color image and distance information to an object at the same time.

Key words: Image sensor, 3D sensor, depth sensor, color filter, infrared filter, light transmittance

INTRODUCTION

CMOS image sensor is a semiconductor device which detects and conveys the information that constitutes an optical image and converts the image data into an electric signal (Mendis *et al*., 1997). Conventional CMOS image sensors provide two-dimensional color image information while depth sensors provide 3-dimensional information or depth information. Since, the depth sensor uses an IR light as a light source, the depth sensor provides only black-and-white image information (Oggier, 2009; Stoppa *et al*., 2011; Kim *et al*., 2011; Lee and Jang, 2012). We propose a 3D color image sensor which can provide color image information and depth information simultaneously within a single chip. Figure 1 shows the concept of our 3D image sensor integrated with on-chip color and IR filters. The Red, Green, Blue (RGB) color filters on color sensor pixel is selectively transparent to visible lights and the IR filter on the depth sensor pixel is selectively transparent to IR light having wavelengths >700 nm. We also mount an IR cut filter above the chip. This IR cut filter is selectively transparent to visible and Near-Infrared (NIR) light relative to far-infrared light.

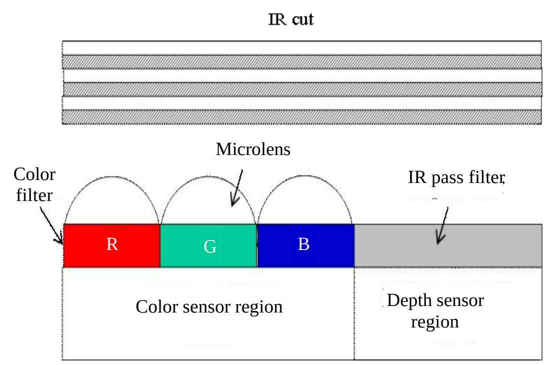

Fig. 1: Concept of the 3D sensor integrated with on-chip color filters and infrared pass filters

The 3D sensor can be used for various applications such as gesture recognition for game machine, web

Corresponding Author: Myung Bok Lee, Department of Industrial Technology Management, Gwangju University, 277 Hyodeok-ro, Nam-gu, 61743 Gwangju, Korea

camera and virtual reality and augmented reality devices. To implement a 3D color image sensor, only visible light should be incident on the color sensor region and only IR light should be incident on the depth region to prevent the crosstalk of each signal. We demonstrate a novel filter consisting of color filters and IR pass filters prepared on a single chip as well as IR cut filter mounted over a objective lens module. Material design and fabrication process of the filters will be described in detail.

MATERIALS AND METHODS

Optical design and deposition of the IR cut filters: As an IR cut filter, usually multilayered films are used composed of two dielectric oxide material with different refractive index (Wang *et al*., 1998; Lee and Jang, 2012). We can control the optical spectrum of transmittance of the filter according to the wavelength variation by selecting the kind of material of each layer and structure of the layer. We used the Essential Macleod program to simulate number of layers and each thickness of alternating layers of TiO_2 and SiO_2 films in order to obtain the intended optical spectrum of the IR cut filter. Two dielectric oxide TiO_2 and SiO_2 thin film layers were prepared by RF magnetron sputtering under a base pressure of 10 mTorr. Sputter targets of TiO_2 and SiO_2 with a purity of 99.99% and 5 cm as diameter was used. The target-substrate distance was fixed at 7 cm. The films were deposited on a glass wafer, substrate temperature of which was fixed at 100°C. The substrates were rotated at 30 rpm to achieve uniform deposition across the whole area.

Fabrication method of the 3D image sensors: The 3D image sensor was fabricated by a 0.13 μm front-side illumination CMOS image sensor process. In the sensor, color (RGB) and depth (Z) pixels are disposed across the image plane. The sensor is modified from a 1920 (H)×1080 (V) 2M pixel array of standard 2.5T pixel RGBG color pixels with 2.25 μm pitch and has total 1.55 M pixels (Kim *et al*., 2012). Each depth pixel is a pinned photodiode with two transfer gates and two output ports. Column signal lines are separate for color and range pixels. The signal processing is performed off-chip.

Fabrication method of the on-chip filters: The IR cut filter mounted on the objective lens module was fabricated by alternate deposition of SiO_2 and TiO_2 films on a glass substrate with RF magnetron sputtering according to the film structure design. On-chip IR pass filters and color filters were fabricated by photolithography. First, IR pass raw material composed of a photoresist including pigments of black color was spin-coated on the substrate of a CMOS image sensor fabricated as above process. Then we defined the depth pixel region by i-line UV photolithography. Second, green color photoresist material including pigments of green color was spin-coated on the substrate and green pixel region was defined by by i-line UV photolithography. Blue and red pixels were defined successively according to the same process as green pixels.

RESULTS AND DISCUSSION

Optical spectrum characteristics of the filters: Figure 2 shows the schematic diagram of targeted optical transmission spectrum characteristics of the filters for our 3D image sensor. The spectrum characteristics of filters include those of an IR cut filter mounted on lens module, RGB color filters integrated on image sensor pixels and IR pass filters integrated on depth sensor pixels. By employing these spectrum characteristics of filters together with spatial arrangement as Fig. 1, we can achieve our original purpose of irradiating visible lights onto the RGB color pixels and NIR LED light onto the depth pixels.

An objective lens module is used to focus the incident light onto the photodiode region of the sensor. The IR cut filter plate is mounted over the objective lens module to reject a light conventionally having a wavelength longer than about 700 nm because the intermixed IR light will lead to fogging the image. However, we need to transmit a narrow range of wavelength of IR light together with the visible light. It is because the TOF (Time-of-Flight) 3D sensor detects the distance to an object by project illuminating a beam of IR light and receive the returning reflection from objects within the sensor's range. To detect the distance, the scene is illuminated with a NIR LED of 850 nm wavelength modulated at 20 MHz. Thus, we employed a modified IR cut filter compared to the conventional one. Incident light

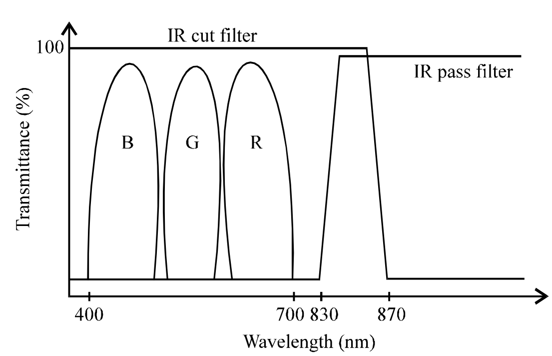

Fig. 2: Schematic diagram of targeted optical transmittance spectra of the color and IR filters

having wavelength shorter than about 870 nm transmits through the modified IR cut filter. Then the RGB color filters transmit visible light having a wavelength range of corresponding colors and the IR pass filter transmits light having a wavelength longer than about 830 nm. The color image sensor and depth sensor convert the visible light and the IR light, respectively into an electrical signal. Each sensor includes a photodiode that generates photocharge in response to the incident light.

To simulate the variation of optical transmittance with wavelength Essential Macleod was applied. Optical constants such as refractive index and extinction coefficient of TiO_2 and SiO_2 which were calculated by ellipsometry measurement were input in the program. The multilayer structures were designed and simulated with various parameters such as wavelength ranges, thickness and layers of structure. Finally, analysis on the parameter effect was performed with system modification for optical properties for the optimum simulation.

Fabrication and evaluation of the filters: The SiO_2/TiO_2 multilayered film for the IR cut filter was deposited by RF magnetron sputtering according to the simulation result. The surface of the multilayered film deposited on glass wafer was observed under different magnification by a high-resolution Scanning Electron Microscope (SEM). The SEM image shows that the structure is flat and smooth without significant particle formation. Grain morphology on the surface is not observed and the film seems to be in amorphous structure. This structure is considered to be favorable for IR cut filter application in terms of durability and reliability because a film composed of large crystallite grains is tend to be in a state of higher internal stress leading to crack, breakage and delamination phenomena. For further evaluation of the film structure, X-Ray Diffraction (XRD) analysis for the samples was also carried out in 2θ range of 10-90° to see if there is any crystalline grain formed in the film. No peaks in the XRD pattern were observed for the films.

Figure 3 shows the optical transmittance spectra of the modified IR cut filter fabricated by alternate deposition of SiO_2 and TiO_2 films by RF magnetron sputtering. The transmission spectra for all the samples were measured using Shimadzu UV1800 UV/vis spectrophotometer over a 400-1100 nm range. The total thickness of the film was 1930 nm and total 31 layers were deposited. The thicknesses of the stacked SiO_2 and TiO_2 layers in order to obtain the spectra shown in Fig. 3 are described in Table 1.

The spectrum characteristic of the modified IR cut filter showed a transmittance more than 90% for light with a wavelength of 400-850 nm and showed a transmittance

Table 1: The thicknesses of the stacked SiO_2/TiO_2 multilayer for the IR cut filter

Layers	Materials	Thickness (nm)	Layers	Materials	Thickness (nm)
1	SiO_2	72	17	SiO_2	17
2	TiO_2	20	18	TiO_2	19
3	SiO_2	5	19	SiO_2	164
4	TiO_2	69	20	TiO_2	88
5	SiO_2	24	21	SiO_2	14
6	TiO_2	13	22	TiO_2	16
7	SiO_2	132	23	SiO_2	159
8	TiO_2	9	24	TiO_2	19
9	SiO_2	27	25	SiO_2	5
10	TiO_2	65	26	TiO_2	75
11	SiO_2	10	27	SiO_2	23
12	TiO_2	23	28	TiO_2	8
13	SiO_2	156	29	SiO_2	154
14	TiO_2	13	30	TiO_2	19
15	SiO_2	16	31	SiO_2	19
16	TiO_2	74			

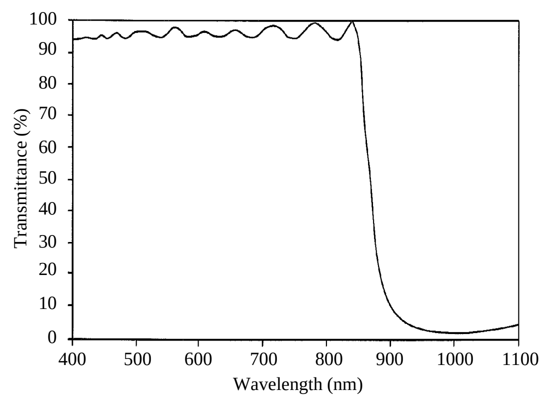

Fig. 3: Optical transmittance spectra of modified IR cut filter mounted on lens module fabricated by alternate deposition of SiO_2/TiO_2 multilayer films

less than about 10% for light with a wavelength longer than about 900 nm. The light transmittance of the filter in the selected wavelength range is based on light interference phenomena and extensively employed in thin film optics such as anti-reflection, high reflection and band-pass filter in the development of optical, electronic and solar energy industries (Hinczewski *et al*., 2005; Asghar *et al*., 2008; Mazur *et al*., 2013). The optical spectrum of the filter can be controlled by depositing dielectric multilayers with high and low refractive indexes with adjusting the thickness and the number of layers.

RGB color filters and IR pass filters were formed on a 3D sensor by four successive photolithography processes. Red, green, blue color photoresists for the respective color filters contain pigments of each color. Each color photoresists includes a binder resin, a photopolymerizable compound, a photoinitiator, an additive and a solvent, etc. The additive includes a cross-linking agent, an adhesion accelerator, a dispersing agent and a surfactant, etc. The binder resin is dissolved

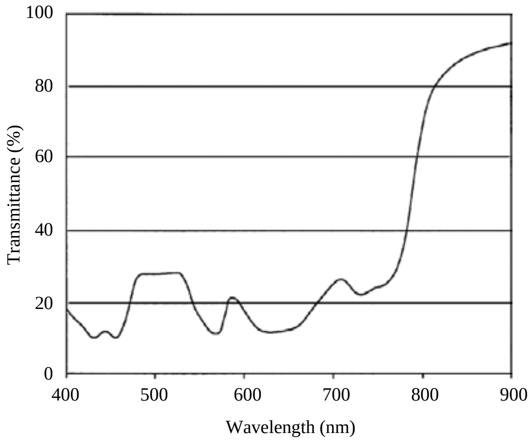

Fig. 4: Optical transmittance spectra of typical IR pass filter integrated on depth sensor pixels

in the solvent, reacts with light or heat and serves as a bind agent for coloring. The binder resin includes an acrylic copolymer that is dissolved in an alkaline developing solution. The acrylic copolymer includes a monomer having a hydrophobic radical. The photopolymerizable compound includes a monofunctional monomer, a difunctional monomer, a multifunctional monomer, etc. The photoinitiator may include at least one of acetophenone family compounds. The photoinitiator may be used with a photoactivated radical generating agent, a photosensitizer, etc. The solvent includes various types of organic solvents which are used for colored photosensitive resin compositions. Each pigment included may be processed, for example, by a surface treatment using a pigment derivative where an acidic group or a basic group is introduced, a graft treatment for a surface of the pigment by a polymer compound, a refinement treatment, a washing treatment by organic solvent and water to eliminate impurities, an eliminating treatment by ion exchange to eliminate ionic impurities, etc. The photoresist material for the IR pass filter includes also includes a binder resin, a photopolymerizable compound, a photoinitiator, an additive and a solvent, etc., together with corresponding color pigments. A compound of pigments such as mixture of red, green and blue pigments, showing black color can be used for pigment of the IR pass filter. The transmittance of the IR pass filter can be determined according to colors, amounts and ratio of the pigments included in the photoresist. Colored photoresists for RGB color filter and IR pass filter were successively spin-coated on the substrate and each pixel region was defined by i-line UV exposure followed by develop, rinse and drying.

Figure 4 shows the optical transmittance spectrum of the IR pass filter applied to the IR filter material. The material characteristics has a transmittance more than about 90% for light having a wavelength longer than about 850 nm and has a transmittance of about 28% for light having a wavelength of about 700 nm. An average transmittance of the material is about 16% for light having a wavelength shorter than about 700 nm. Thus, the material can be applied to the IR pass filter for our 3D image sensor.

CONCLUSION

We proposed a novel concept of 3D image sensors composed of color pixel and depth pixel which can capture both color image and depth information. In order to detect a beam of IR light which is project illuminated from 850 nm LED and receive returns back after reflection from surrounding objects, we employed new scheme of light filters. Firstly, a modified IR cut filter which can reflect light having a wavelength more than about 870 nm has been employed. By designing the SiO_2/TiO_2 multilayer film structure, we successfully demonstrated the IR cut filter with a fine optical spectrum characteristics showing a transmittance more than 90% for light of 400-850 nm wavelength and a transmittance less than about 10% for light of 900 nm wavelength or more. Second, we employed newly developed IR pass filters together with conventional RGB color filters as on-chip filters to obtain the color image and the distance information, respectively. Optical transmission spectrum characteristics of the infrared pass filter was satisfactory enough to be applicable to our sensor.

RECOMMENDATIONS

Furthermore, the fabrication technologies of the IR cut filter and the IR pass filters are similar to those frequently used in current semiconductor fabrication and can be said to be CMOS compatible. Thus, it can be said that our novel scheme of light filters can be employed for 3D color image sensor.

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