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Fabrication of Infrared Filters for Three-Dimensional CMOS Image Sensor Applications

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Infrared (IR) filters were developed to implement integrated three-dimensional (3D) image sensors that are capable of obtaining both color image and depth information at the same time. The combination of light filters applicable to the 3D image sensor is composed of a modified IR cut filter mounted on the objective lens module and on-chip filters such as IR pass filters and color filters. The IR cut filters were fabricated by inorganic SiO_2/TiO_2 multilayered thin-film deposition using RF magnetron sputtering. On-chip IR pass filters were synthetized by dissolving various pigments and dyes in organic solvents and by subsequent patterning with photolithography. The fabrication process of the filters is fairly compatible with the complementary metal oxide semiconductor (CMOS) process. Thus, the IR cut filter and IR pass filter combined with conventional color filters are considered successfully applicable to 3D image sensors.

Keywords : 3D image sensor, Depth sensor, Color filter, Infrared filter, Thin-film multilayer

1. INTRODUCTION

A CMOS image sensor is a device that detects and transmits the information that constitutes an optical image and converts the image data into an electrical signal [1]. Conventional CMOS image sensors provide two-dimensional color image information, whereas depth sensors provide three-dimensional information, or distance information to the object. Because the depth sensor uses an IR light as the light source, the depth sensor provides only black-and-white image information [2]. A 3D color image sensor has been proposed that can provide color image and depth information simultaneously within one chip [3]. The 3D sensor is composed of color sensor pixels and IR sensor pixels, which detect color image and depth information, respectively. Light filters integrated with the color pixels and IR pixels are indispensible for implementing one-chip 3D image sensors. However, they have not yet been studied extensively. The red, green, and blue (RGB) color filters on color pixels are selectively transparent to visible light, and the IR filters on the depth pixel are selectively transparent to IR light having wavelengths greater than 700 nm. Furthermore, an IR cut filter selectively transparent to both visible and near-infrared (NIR) light relative to far-infrared light must be mounted above the chip.

The 3D image sensor can be used for future consumer applications such as mobile-phone cameras and compact digital cameras capable of capturing 3D still and video images, permitting gesture control of certain functions. We demonstrate a novel filter consisting of IR pass filters combined with conventional color filters and integrated on a single chip, as well as an IR cut filter mounted over an objective lens module. The material preparation and fabrication process of the filters is described in detail in this paper.

2. EXPERIMENTS

2.1 Optical design and fabrication of the IR cut filters

Multilayered films composed of two dielectric oxide materials with different refractive indexes have been used conventionally as IR cut filters in CMOS image sensors [4,5]. We used the Essential Macleod program to simulate the number of layers and the thickness of the alternating layers of SiO_2 and TiO_2 films in order to obtain

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the intended optical spectrum of the modified IR cut filter. The two dielectric oxides, SiO_2 and TiO_2, thin film layers were prepared by RF magnetron sputtering. The gas flow rates were 20 sccm Ar and 5 sccm O_2, and the working pressure was 5 mTorr. The RF sputter power was 250 W. Sputter targets of SiO_2 and TiO_2 with a purity of 99.998% and 100 mm diameter were used. The target-substrate distance was fixed at 12 cm. The films were deposited on a glass wafer, the substrate temperature of which was fixed at 200℃. The substrates were rotated at 10 RPM to achieve uniform deposition across the whole area of the wafer.

2.2 Fabrication methods of the IR pass filters

The IR pass filter materials were synthetized by dissolving several color pigments and dyes into a solvent together with a binder resin, a photopolymerizable compound, a photoinitiator, and an additive material. IR pass filter patterning was tested on a bare glass wafer. First, the photoresist material of the IR pass filter was spin-coated on the wafer. Then, we defined the depth pixel pattern by i-line UV photolithography. We tested the integration of the IR pass filter on a wafer with a CMOS image sensor fabricated according to the process as described in Section 3.1.

2.3 Characterization of the filters

The surface morphology and cross-sectional shape of the multilayer films were observed by a field-emission scanning electron microscope (Hitachi, S-4700). The crystalline structure, including the crystal orientation and phases of the single-layer film and multilayer films, were observed by an X-ray diffractometer (XRD; Mac Science, MXP3). The transmission spectra for the multilayer films were measured using a UV/visible spectrophotometer (Shimadzu UV1800) over a wavelength range of 400~1,100 nm.

3. RESULTS AND DISCUSSION

3.1 Optical spectrum characteristics of the filters

Figure 1 shows the concept of our 3D image sensor integrated with IR filters and color filters. The 3D image sensor chip was fabricated by a 130 nm front-side illumination CMOS image sensor process. The sensor was modified from a 1,920(H)×1,080(V) 2M pixel array of standard 2.5T pixel RGBG Bayer-type color pixels with 2.25 μm pitch and a total of 1.55 Mpixels [3]. Figure 2 shows a schematic diagram of the targeted optical spectrum characteristics of the filters for our 3D image sensor. The optical spectra of the filters include those of a modified IR cut filter mounted on objective lens module, RGB color filters integrated on the image sensor pixels, and IR pass filters integrated on the depth sensor pixels. By employing these filter spectra characteristics together with the spatial arrangement as shown in Fig. 1, we can irradiate visible light onto the RGB color pixels only and IR light onto the depth pixels only to prevent the crosstalk of each signal.

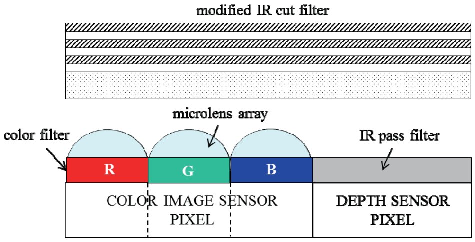

Fig. 1. Concept of the 3D sensor with a modified IR cut filter and integrated on-chip color filters and infrared pass filters.

An objective lens module was used to focus the incident light onto the photodiode region of the sensor. The IR cut filter plate was conventionally mounted on the objective lens module to reject light having a wavelength longer than approximately 700 nm, because intermixed IR light causes fogging of the color image. However, in our case, we need to transmit a narrow wavelength range of NIR light together with the visible light, because the time-of-flight (TOF) 3D sensor detects the distance to an object by illuminating a beam of IR light and receiving the light reflected from objects within the sensor's range. To detect the distance to an object, the scene is illuminated with a NIR LED of λ= 850 nm modulated at 20 MHz. Therefore, we employed a modified IR cut filter instead of the conventional one. Incident light having a wavelength shorter than approximately 700 nm and having wavelength from 830 nm to 850 nm transmits through the modified IR cut filter. Thus, our modified IR cut filter acts as a dual bandpass filter. Then, the RGB color filters transmit visible light only having a wavelength range of corresponding colors, and the IR pass filter transmits light having a wavelength range of 830~870 nm. The color image sensor and depth sensor convert the visible light and the NIR light, respectively, into electrical signals. Each sensor includes a photodiode that generates photocharge in response to the incident light.

We can control the optical spectrum of transmittance of the modified IR cut filter by selecting the kind of material of each film and structure of the layer. Figure 3 shows the variation of the optical constants such as refractive indices and extinction coefficients of SiO_2 and TiO_2 single film with wavelengths that were calculated by ellipsometry measurement. The measured values of the optical constants were higher at shorter wavelengths and gradually decreased or remained constant with increasing wavelength. The optical constants were slightly different from the theoretical values in a wavelength range of 400~1,100 nm [6]. These values were processed by the Essential Macleod program to simulate the optical transmittance with wavelength. The multilayer structures were

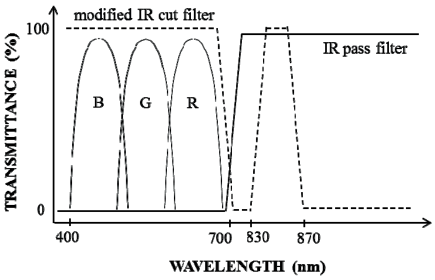

Fig. 2. Schematic diagram of targeted optical transmittance spectra of the color and IR filters.

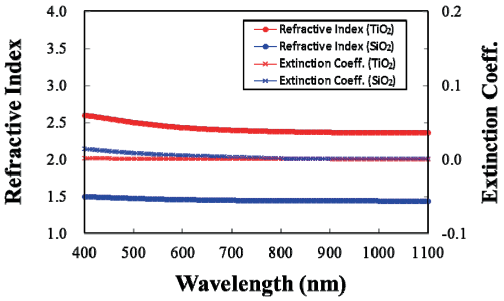

Fig. 3. Variation of refractive index and extinction coefficient of TiO_2 and SiO_2 thin film with wavelength.

designed and simulated with various parameters such as wavelength range, thickness, and layers of the structure. Finally, the effect of various structural parameters on the optical properties was analyzed to optimize the multilayered film structure. As the total thickness and number of layers increase, the transmittance of the multilayer structure increases in the visible light range and a wavelength range of 830~870 nm. However, too thick film and too many layers decrease the transmittance; therefore, there is an optimum range in the thickness and number of layers.

3.2 Fabrication and evaluation of the filters

The SiO_2/TiO_2 multilayered film for the modified IR cut filter was deposited by RF magnetron sputtering according to the simulation results. Figure 4 shows the scanning electron microscope (SEM) images of the surface and cross section of the SiO_2/TiO_2 multilayered film deposited on a glass wafer. The total thickness of the multilayered film was 3,920 nm in a total of 36 layers. The SEM image shows that the surface morphology was flat and smooth, composed of tiny grains of 10~20 nm, without significant particle formation. This structure is considered favorable for IR cut filter applications in terms of durability and reliability, because a film with large crystalline grains tends to exhibit higher internal stresses, leading to cracks and delamination. The cross-sectional SEM image shows the uniform formation of the multilayered films over a large area. Crystalline structures of the SiO_2 and TiO_2 single film and the SiO_2/TiO_2 multilayer film were analyzed by XRD. Significant peaks in the XRD curve were not observed, suggesting our single and multilayer films had an amorphous structure.

Figure 5 shows the simulated and measured optical spectra of the modified IR cut filter whose surface morphology and cross-sectional shape are shown in Fig. 4. The measured spectrum matches well with the simulated one, which means the film thickness and chemical composition of the films are consistent with the optical design. The measured spectrum characteristic of the modified IR cut filter showed more than 90% transmittance for light with wavelengths of 400~700 nm and of approximately 830~880 nm, and showed transmittance less than approximately 20% for light with wavelengths of 720~800 nm and longer than approximately 900 nm. The light transmittance of the filter in the selected wavelength range is based on light interference phenomena and is extensively employed in thin-film optics such as high-reflection, anti-reflection, and bandpass filters in the optical, optoelectronic, and solar-energy industries [7–11].

IR pass filters were formed on a 3D sensor wafer by a photolithography process. We confirmed that resolution as low as 2 μm, which is smaller than the 2.25 μm pitch of the 3D sensor chip, could be obtained by i-line UV photolithography. Conventional RGB color filters can be combined with our IR pass filter to obtain the integrated 3D sensor. The photoresist material for the IR pass filter included a binder resin, a photopolymerizable compound, a photoinitiator, a solvent, and an additive together with several color pigments and dyes.

The binder resin is dissolved in the solvent, reacts with light or heat, and serves as a binding agent for coloring. The binder resin includes an acrylic copolymer that is dissolved in an alkaline developing solution. The acrylic copolymer includes a monomer element having a hydrophobic radical. The photopolymerizable compound includes a monofunctional monomer, a difunctional monomer, and a multifunctional monomer. The photoinitiator may include at least one of the acetophenone family compounds. The photoinitiator may be used with a photoactivated radical generating agent and a photosensitizer. The solvent includes various types of organic solvents that are used for colored photosensitive resin compositions. The additive includes a cross-linking agent, an adhesion accelerator, a dispersing agent, and a surfactant. A compound of pigments, such as a mixture of red, green, and blue pigments for displaying black color, can be used as the pigments of the IR pass filter. The optical transmittance of the IR pass filter can be varied according to colors, amounts, and ratio of the pigments and dyes included in the photoresist.

Figure 6 shows the optical transmittance spectrum of the IR filter material applied to our 3D image sensor. The material characteristics exhibit transmittance more than approximately 80% for light having a wavelength longer than approximately 800 nm, and exhibits transmittance of approximately 20% for light having a wavelength of approximately 750 nm. An average transmittance of the material is

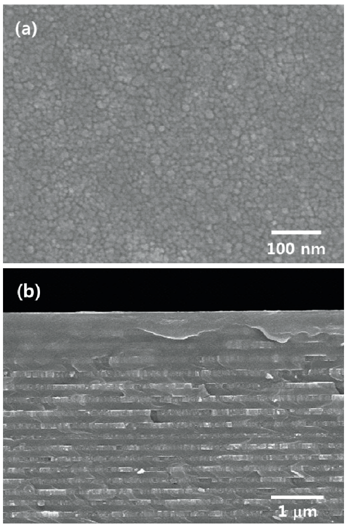

Fig. 4. SEM images showing (a) surface morphology and (b) cross-sectional shape of the SiO_2/TiO_2 multilayered film fabricated by RF magnetron sputtering.

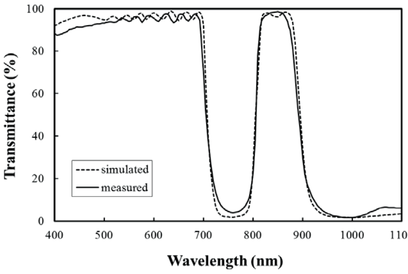

Fig. 5. Optical transmittance spectra of the modified IR cut filter mounted on a lens module fabricated by alternate deposition of SiO_2/TiO_2 multilayer films.

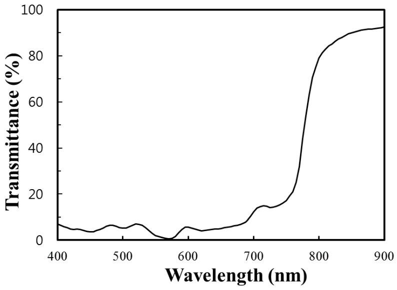

Fig. 6. Optical transmittance spectra of a typical IR pass filter integrated on depth sensor pixels.

less than 5% for light having a wavelength shorter than approximately 700 nm. Thus, the material can be applied to the IR pass filter for our 3D image sensor.

4. CONCLUSIONS

We developed novel IR filters for one-chip 3D image sensors composed of color and depth pixels that can capture both color images and depth information, respectively. In order to detect a beam of IR light, which is illuminated from an 850 nm LED and reflected from surrounding objects, we employed a new scheme of light filters. First, a modified IR cut filter that can transmit light with a wavelength of approximately 850 nm as well as visible light was designed and fabricated. Second, we developed new IR pass filters to integrate with conventional RGB color filters as on-chip filters. The optical transmission spectra characteristics of the IR cut and IR pass filters were satisfactory enough to be applicable to our 3D image sensor. Furthermore, the fabrication technologies of the IR filters are fairly compatible with the CMOS process. Thus, it can be said that our scheme of filters is suitable for 3D image sensors.

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REFERENCES

[1] S. K. Mendis, S. E. Kemeny, R. C. Gee, B. Pain, C. O. Staller, Q. Kim, and E. R. Fossum, *IEEE J. Solid-State Circuits*, **32**, 187 (1997). [DOI: https://doi.org/10.1109/4.551910]

[2] D. Stoppa, N. Massari, L. Pancheri, M. Malfatti, M. Perenzoni, and L. Gonzo, *IEEE J. Solid-State Circuits*, **46**, 248 (2011). [DOI: https://doi.org/10.1109/JSSC.2010.2085870]

[3] W. Kim, Y. Wang, I. Ovsiannikov, S. H. Lee, Y. Park, C. Chung, and E. Fossum, *Proc. 2012 IEEE International Solid-State Circuits Conference* (IEEE, San Francisco, USA, 2012) p. 392. [DOI: https://doi.org/10.1109/ISSCC.2012.6177061]

[4] X. Wang, H. Masumoto, Y. Someno, and T. Hirai, *Appl. Phys. Lett.*, **72**, 3264 (1998). [DOI: https://doi.org/10.1063/1.121618]

[5] J. H. Lee and G. E. Jang, *J. Cer. Proc. Res.*, **13**, s219 (2012).

[6] H. A. Macleod, *Thin Film Optical Filters*, Third Edition (Institute of Physics, Bristol and Philadelphia, 2001).

[7] A. Dakka, J. Lafait, M. Abd-Lefdil, and C. Sella, *M. J. Condensed Matter*, **2**, 153 (1999).

[8] S. Bauer, L. Klippe, U. Rothhaar, and M. Kuhr, *Thin Solid Films*, **442**, 189 (2003). [DOI: https://doi.org/10.1016/S0040-6090(03)00981-7]

[9] D. S. Hinczewski, M. Hinczewski, F. Z. Tepehan, and G. G. Tepehan, *Sol. Energy Mater. Sol. Cells*, **87**, 181 (2005). [DOI: https://doi.org/10.1016/j.solmat.2004.07.022]

[10] M. Asghar, M. Shoaib, F. Placido, and S. Naseem, *Cent. Eur. J. Phys.*, **6**, 853 (2008). [DOI: https://doi.org/10.2478/s11534-008-0104-3]

[11] M. Mazur, D. Wojcieszak, J. Domaradzki, D. Kaczmarek, S. Song, and F. Placido, *Opto–Electron. Rev.*, **21**, 233 (2013). [DOI: https://doi.org/10.2478/s11772–013–0085–7]