A Study on CMOS Image Sensor with Optical Filter-less UV-selective Capability Using Differential Spectral Response Method

著者	SIPAUBA CARVALHO DA SILVA YHANG RICARDO
学位授与機関	Tohoku University
学位授与番号	11301甲第19303号
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シパウバ　カルバリオ　ダ　シルバ　イアンギ　リカルド
氏　　　　　　名　SIPAUBA CARVALHO DA SILVA YHANG RICARDO
研究科，専攻の名称　東北大学大学院工学研究科（博士課程）技術社会システム専攻
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論 文 審 査 委 員　主査　東北大学教授　須川　成利　東北大学教授　中村　健二
東北大学教授　石田　修一　東北大学准教授　黒田　理人

論文内容要約

In recent years, the pursuit of a safer, more secure and sustainable society has led to intensive research in the fields of industrial process automation – especially for the dirty, dangerous and dull jobs – security authentication, smart infrastructures, contaminant and pollutants detection, and so on. The research for technologies suitable to those new applications have driven the development of several fields, in special image sensing, for improved data acquisition and analysis. Image sensors are receiving particular attention due to the quick development in the field, and also because the new machine-based applications have different requirements than the current standard applications of imaging for human viewing and entertainment, meaning that there are several unexplored opportunities and possibilities in the imaging sensing field for machine-based applications. This research explores one of those unexplored areas, the imaging of ultraviolet light (UV: 200 – 400 nm), while conventional charge coupled devices (CCD) and complementary metal oxide semiconductor (CMOS) image sensors are optimized for imaging in the visible light waveband (400 – 700 nm). This research objective is to develop a CMOS image sensor (CIS) technology capable of capturing UV-selective images and visible light selective images simultaneously in a single exposure, with a simple setup that doesn't require optical filters or specialized light sources, and only conventional silicon integration technology and processes, for low cost manufacturing. The proposed and developed technology applies the novel concept of differential spectral response in order to extract both waveband information from high and low UV sensitivity pixels, being is highly suitable for UV imaging applications. This dissertation is organized into four chapters.

The introduction in Chapter 1 describes the current technology used for UV sensing and for UV imaging, as well as the current methods employ to achieve multispectral imaging, i.e., the simultaneous imaging of two or more wavebands. Current sensors with high UV sensitivity usually employ one of the following technologies: wide bandgap semiconductors, SOI, delta-doping CCD, CIS with highly UV sensitive photodiode and with high robustness to UV light exposure, and CIS with a high UV sensitivity organic thin film used as the pixel photodiode. Among those technologies, wide bandgap semiconductors have the best selectivity of UV sensitivity, since no residual sensitivity for the non-UV waveband can be achieved with some materials, but it has poor integrability with external circuits and are, therefore, not suitable for image sensors application. SOI sensor have improved integrability, but still have difficult integration and higher cost than common silicon processes. The CCD and CMOS image sensors reported, on the other hand, have UV light sensitivity but also achieve high sensitivity to visible and even to NIR wavebands, therefore they need to be combined with optical filters, or with specialized light sources in an environment free of background light for selective UV imaging. This necessity adds complication and cost for UV imaging applications. Also, not only UV-selective imaging, also performing simultaneous visible light selective imaging has the advantage of capturing the background visible light image information, extending the data analysis possibilities.

Multispectral imaging is a field have received special attention recently due to its possibilities. The thesis discusses about several methods used nowadays for multispectral imaging, such as by using external band-pass filters or on-chip filter arrays, or by using vertical stacking of several photodiodes by leveraging the relationship of the light penetration depth with the wavelength, or by using time-shared illumination. Those approaches, however, have several drawbacks when applied for UV-selective and visible light selective imaging, that are: the low UV light transmittance of UV bandpass filters and necessity of multiple image sensors, in the external filters approach, the difficulty of obtaining UV bandpass filters suitable for pixelwise integration, in the filter array approach, the difficult of extracting the UV signal directly from a surface thin layer, in the vertical stack approach, and the necessity of specialized light sources capable of synchronizing with the image sensor application, in an environment free of background light and only for absorption or reflective imaging, in the time-shared approach.

Considering those drawbacks and difficulties for simultaneous UV selective and visible light selective imaging, this thesis presents the new concept of differential spectral response, in order to achieve simultaneous UV and visible light spectral imaging, with a single image sensor and a simple optical structure that doesn't require optical filters, controlled background light or specialized light sources synchronized with the image sensor operation. The objective is to achieve 1) high selectivity of sensitivity for the UV and visible light wavebands, 2) easy manufacturing process, using only conventional silicon integration processes 3) easy setup, without requirements regarding to the light source or optical filters, and 4) maintenance of the high standards of the CMOS image sensor characteristics.

Chapter 2 proposes the differential spectral method, shown in Figure 1, for UV-selective detection using only silicon photodiodes, and presents a single-point UV sensor developed and manufactured by using the proposed method, for the principle confirmation. In the differential spectral response, two photodiode types, one with high sensitivity for the UV and visible light wavebands, and another with high sensitivity only to the visible light waveband are developed, and the UV-selective signal is obtained by extracting the differential signal of both photodiode types, while the visible light signal is simultaneously obtained by the photodiodes with high sensitivity only to visible light. The spectral sensitivities of both photodiode types are obtained by designing and optimizing the photodiode photomasks and the ion implantations in order to obtain internal potentials adjusted to form potential barriers at specific depths, according to the relationship between the light wavelength and the penetration depth in silicon. This approach has the advantage of being highly suitable for monolithic integration between both photodiode types, and also with external circuits, therefore it is applicable to CIS. Details about the differential spectral response method, the photodiode structures and theoretical calculations, as well as simulation results are shown and discussed.

Also, a single point UV photodetector composed by 8x6 photodiode units of each high or low UV sensitivity type was designed, manufactured and evaluated, in order to test the proposed differential spectral response method. The photodiodes were monolithically integrated in one single chip, and the differentiation between the photodiodes were achieved by only a few additional ion implantation steps. The measurement results have shown that, by extracting the differential spectral response between both pixel types, a high internal quantum efficiency (int. QE) of over 90% to UV light with a residual int. QE of less than 5% to wavelengths longer than 500 nm, and less than 0.6% for NIR light was successfully obtained, characterizing a high selectivity of sensitivity to the UV waveband, without using optical filters. The developed sensor has shown high robustness to continuous UV light exposure, with no sensitivity degradation after exposure, therefore it is highly suitable for UV sensing applications. To reduce the residual sensitivity, especially in the 400 nm to 500 nm region, an interference interlayer composed by several silicon oxide and silicon nitride layers deposited consecutively over the silicon substrate was developed, in order to reduce light transmittance in the 400 to 500 nm waveband by light interreference. The developed interlayer is highly suitable for on-chip deposition.

In Chapter 3, discussions about the applicability to CIS of the differential spectral response method presented and successfully accomplished in a single photodetector level in Chapter 2 are introduced. Detailed information about the design, layout, process, device and optical simulation are presented, as well as details about the chip manufacturing process and ion implantation conditions employed. Finally, a CIS with differential spectral response pixels was manufactured and evaluated, and the results are discussed. Simultaneous UV-selective and visible light selective imaging was successfully achieved, with a simple setup that doesn't require optical filters or specialized light sources. Compared with the single-point detectors, such as the UV sensor presented in Chapter 2, CIS applications require the photodiode structure to be optimized for pinned photodiode with complete charge transfer from the photodiode to the floating diffusion, and with a high full well capacity when the transfer gate is turned off.

Chapter 3 presents detailed information about the process and device simulations carried out to achieve the requirements necessary for CIS implementation of the differential spectral response pixels, that are: 1) depletion conditions in each layer, analyzed from the donor, acceptor, electron and holes concentrations in each photodiode layer; 2) complete charge transfer from the photodiode region to the floating diffusion, analyzed by calculating the potential shape from the photodiode to the transfer gate and floating diffusion, in order to check for possible potential pockets that traps the charges inside the photodiode; 3) full well capacity of the photodiode, and 4) spectral sensitivity. Details about the simulation setup, calculation methods and results are presented, as well as discussions about the results obtained for several ion implantation conditions and the relationship and trade-off between those characteristics when changing the implant doses.

A CIS prototype chip with 648^{H}x488^{H} resolution (640^{H}x480^{H} effective) and 5.6μm pixel pitch, containing differential spectral response pixels was designed, manufactured and evaluated for the photoelectron conversion characteristics, photon transfer curve, SNR characteristics and external QE. From the photon transfer curve, the conversion gain, full well capacity and dynamic range were calculated. The manufactured sensor achieved a high conversion gain of 172 μV/e⁻ and a high full well capacity of 131 ke⁻ in a single exposure, due the employment of the lateral overflow integration capacitor (LOFIC) technology, therefore a wide dynamic range of 92.3 dB was achieved. The image quality obtained from the sensor UV-selective image (differential signal) and the visible light image – i.e., the image obtained from the pixels with only high visible light sensitivity – were evaluated for a UV-C germicidal lamp and for a white-led light source, by calculating the signal amplitude and SNR of the captured images. Discussion about the results are also presented. Finally, several sample images demonstrating UV-selective and visible-selective imaging simultaneously and without bandpass filter are shown. The developed sensor successfully captured UV-selective and visible light selective images simultaneously by employing the differential spectral response method, without optical filters or specialized light sources.

In Chapter 4, the conclusion of this research is summarized.

In this research, the differential spectral response method was proposed and successfully applied to CMOS image sensor, and simultaneous UV-selective and visible light selective imaging was successfully achieved. When compared with conventional CIS, the developed technology requires only one added photomask and a few additional ion implantations, therefore it maintains the low cost and easy manufacturing currently found in conventional CIS, turning this technology is promising for various sensing applications that require UV light imaging under strong or variable background light and applications that require UV sensing and background recognition simultaneously.

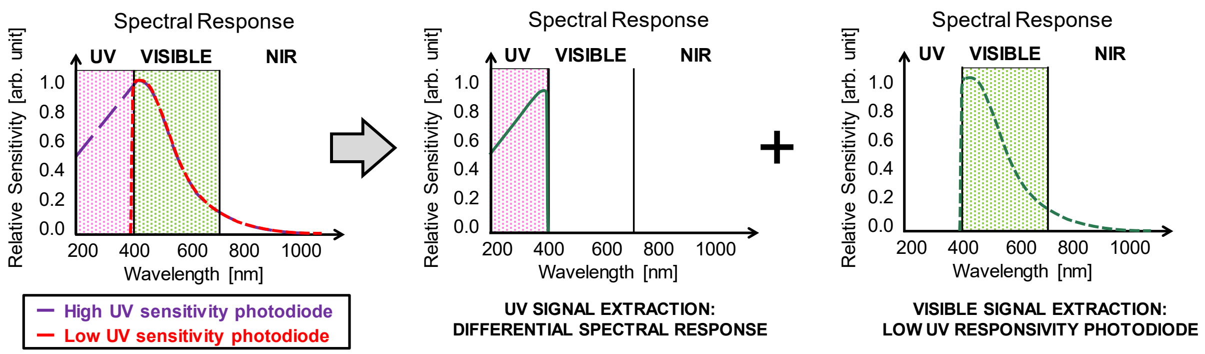

Figure 1 : Conceptual diagram of the differential spectral response method proposed and developed in this work, in order to achieve simultaneous detection of UV-selective signal and visible light selective signal. Two types of photodiodes, one with high UV and visible light sensitivity, and another with high sensitivity only to visible light are used. By matching the sensitivity in the visible and NIR wavebands, the UV-selective signal is extracted by the differential signal between the two photodiode types, and the visible light selective signal is simultaneously obtained from the high visible light sensitivity photodiodes.