A Spectral Imaging System with an Over 70dB SNR CMOS Image Sensor and Electrically Tunable 10nm FWHM Multi-Bandpass Filter

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ABSTRACT

This paper presents a new spectral imaging system utilizing an unprecedentedly high signal to noise ratio (SNR) wide spectral response CMOS image sensor (CIS) and an electrically tunable multi-bandpass optical filter with narrow full width at half maximum (FWHM) of transmitted waveband. The developed CIS exhibits 71dB SNR, $1.5\times10^7e^-$ full well capacity (FWC), 190-1100nm spectral sensitivity, with very high quantum efficiency (QE) in near infrared (NIR) waveband using low impurity concentration Si wafer ($\sim10^{12}cm^{-3}$). By the developed multi-bandpass filter, four wavebands: 630nm, 800nm, 960nm and 1050nm are electrically tuned exclusively with the 10nm FWHM. Using the developed spectral imaging system, a diffusion of 5mg/dl glucose into physiological saline solution was successfully visualized under 960nm and 1050nm wavebands, at which absorptions of water molecules and glucose appear within UV to NIR waveband, respectively.

INTRODUCTION

Spectral imaging has been utilized in many application fields including scientific instrumentation, medical, agricultural and so on with variety sets of light wavelength from UV to NIR. Several spectral imaging technologies have been reported so far, such as using on-chip Fabry-Perot filters [1], filter wheels, liquid crystal (LC) tunable filters [3], a time-sharing illumination of LEDs [4], and so on. In general, a designated set of several wavebands for spectral analysis is determined by each spectral imaging application such as monitoring of growing condition of crops, contamination detection, and health condition monitoring. A small-size spectroscopic method that can select required wavebands stably with narrow FWHM while not degrading spatial and temporal resolutions of image sensor is highly desired. Yet, these features have not been achieved simultaneously by the conventional technologies.

Spectral imaging can be roughly divided into emission/reflection based analysis and absorption based analysis. High sensitivity and high SNR are required in these analyses, respectively. Here, an absorption analysis is used to identify and measure concentration of chemical substances of an object by measuring the attenuation of light intensity that pass through it. The Beer-Lambert law that describes the principle of absorption analysis is given by the equation 1,

$$C = -\frac{1}{\alpha L}\log_{10}\frac{I_1}{I_0} = \frac{A_\lambda}{\alpha L} \qquad (1)$$

where, C is concentration [mol/m^3], α is absorption coefficient [m^2/mol], L is optical path length [m], I_0 is incident light, I_1 is transmitted light and A_λ is absorbance.

Measurement accuracy of absorption analysis is in general determined by the detection accuracy of microscopic change of light intensity under strong light irradiation, and thus the SNR of detectors. The SNR is given by the equation 2,

$$SNR = 20\log_{10}\left(\frac{N_{sig}}{\sqrt{\sqrt{N_{sig}}^2 + n_{sys}^2}}\right) \approx 20\log_{10}\sqrt{N_{sig}} \qquad (2)$$

where, N_{sig} is the number of signal electrons and n_{sys} is the input referred number of system noise in electrons. The maximum SNR is determined by the number of signal electrons equal to FWC of CIS when the photon shot noise is dominant. Single point detectors such as single photodiode (PD) or linear array sensor with 70~80dB SNR have been utilized in current absorption spectrometry. Two-dimensional absorption imaging has some potential advantages; by using images, component and concentration distribution can be measured and by selecting target region, measurement accuracy will be improved.

For CIS to be utilized in spectral imaging including absorption imaging, over 70dB high SNR corresponding to about 140dB dynamic range, linear response to light intensity and wide spectral response are required. In order to achieve 70dB SNR, 10Me$^-$ FWC is required according to the equation 2. A previously reported high FWC CIS has 2Me$^-$ FWC [5]. Though there are logarithmic response CIS capable of capturing images under high light intensity, linear response CIS is suitable for absorption imaging. A wide spectral response is effective to develop a highly adoptive spectral imaging system. Furthermore, high QE is required for such a high FWC CIS in order to achieve high framerate or lower light illumination level of the absorption imaging system. For improving sensitivity to UV waveband, a PD technology achieving high sensitivity and high light resistance to UV-light has been reported [6-7]. However, in NIR waveband, the QE needs to be improved for life scientific, medical and agricultural applications. A CIS that meets these required specifications has not been reported.

The goal of this work is to develop a new spectral imaging system utilizing a linear response CIS with over 10Me$^-$ FWC which is equivalent to 70dB SNR and high QE from UV to NIR, and an electrically tunable narrow FWHM multi-bandpass optical filter with stable peak wavelength, synchronized waveband switching capability with the CIS operation and no resolution degradation.

As an example of absorption imaging application, glucose diffusion into physiological saline solution aiming at non-invasive blood glucose measurement was experimented.

DESIGNE AND PERFORMANCES OF DEVELOPED CMOS IMAGE SENSOR

The developed CMOS image sensor was fabricated using a 0.18μm 1-poly-Si 5-metal CMOS image sensor process technology with buried pinned PD. The power supply voltage is 3.3V and the chip size is $3.01mm^H\times3.69mm^V$. The pixel pitch and the number of effective pixels are 16μm and $128^H\times128^V$, respectively. The circuit architecture and the

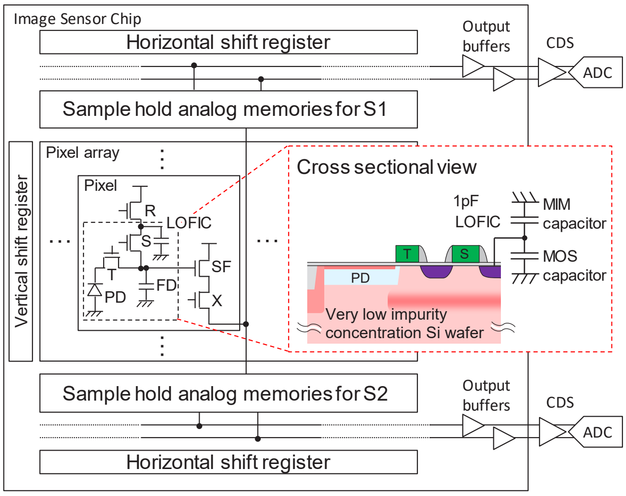

Fig. 1. Circuit architecture. In pixel, high light resistance wide spectral response PD and 1pF LOFIC are implemented. LOFIC consists of stacked MOS and MIM capacitors.

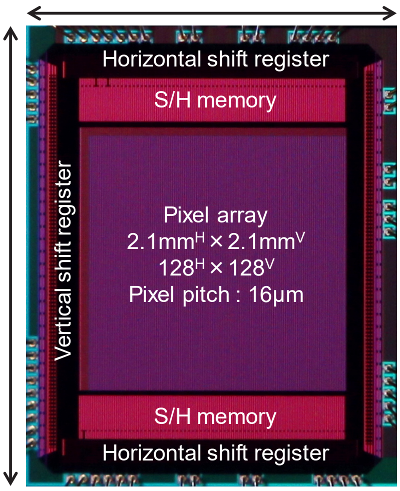

Fig. 2. Developed CMOS image sensor chip.

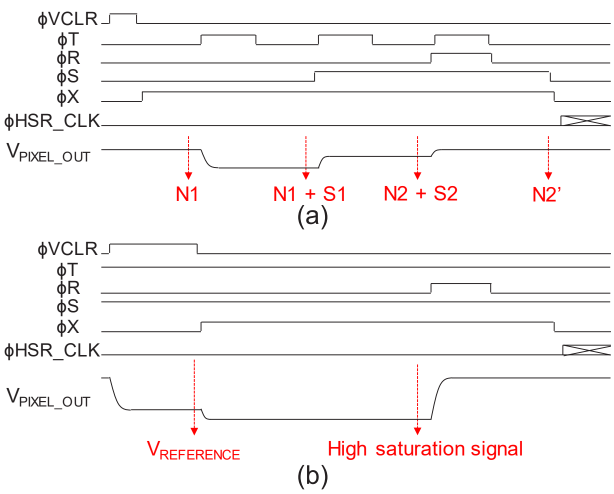

Fig. 3. Timing diagrams in H blanking period of (a) the wide dynamic range LOFIC operation mode and (b) the high SNR absorption imaging operation, respectively.

micrograph of the developed CIS chip are shown in Fig.1 and Fig.2, respectively.

In order to achieve 10Me$^-$ FWC, the lateral overflow integration capacitor (LOFIC) technology [8-9] was introduced and a high capacitance density stacked MOS and MIM capacitors were employed in pixels.

The developed CIS has two operation modes: a wide dynamic range LOFIC operation and an over 70dB high SNR operation. In the former mode, a high sensitivity photo-signal due to high conversion gain with the small capacitance floating diffusion (FD) and a high FWC photo-signal due to the large capacitance composed by LOFIC and FD are simultaneously obtained. The FWC is determined by LOFIC and FD. In the high SNR operation mode, the PD capacitance is added to LOFIC and FD with a high signal voltage range to achieve a higher FWC. The high SNR signal is obtained by the difference value of reference voltage and pixel output signal in the column level. By setting the reference voltage near the saturation value, microscopic signal change such as due to absorption is accurately detected. The timing diagrams are shown in Fig.3. The conceptual illustration of photo-electron conversion characteristic is shown in Fig.4. The measured photon transfer curve in the high SNR operation mode is shown in Fig.5. A high QE performance for a wide light waveband of 190-1100nm was obtained by following features. In the UV waveband, a PD technology achieving the high QE and high light resistance to UV-light by forming a high concentration surface p$^+$ layer with steep dopant concentration profile [6-7] was employed to the developed CIS. In order to achieve high QE in NIR waveband, a very low impurity concentration Si wafer (~10^{12}cm^{-3}) was employed. Since the penetration depth

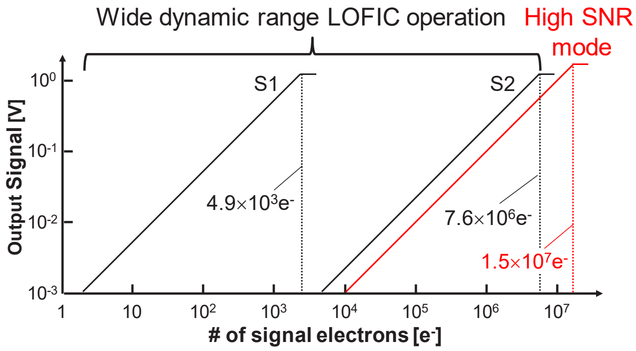

Fig. 4. Conceptual illustration of photo-electric conversion characteristic. Black lines show wide dynamic range LOFIC operation mode (S1, S2) and red line shows high SNR mode.

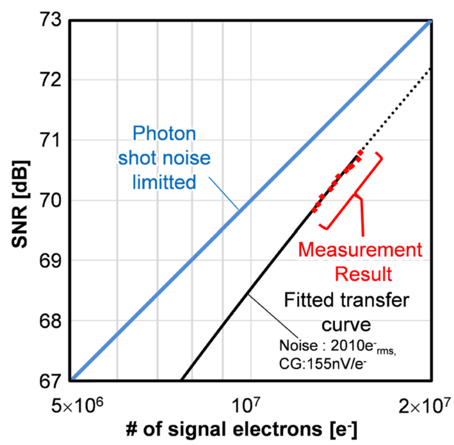

Fig. 5. Measured SNR as a function of signal electrons in high SNR mode.

of NIR light is much deeper than visible light, extending the depletion layer of PD is effective. By using the Si wafer, the depletion layer width is extended drastically. Fig.6 shows the measured spectral sensitivity of the developed CIS. Here the beats of QE characteristics are caused by interference of light due to the inter-metal dielectric film on the PD. The high QE characteristic for a wide waveband was successfully obtained, such as 40% at 250nm, 68% at 500nm, 62% at 900nm and 15% at 1050nm. Summary of the developed CIS performance is shown in Table 1. The developed CIS exhibited 71dB SNR, $1.5\times10^7e^-$ FWC, 190-1100nm spectral sensitivity, 1120fps and high robustness to UV-light irradiation.

DEVELOPED SPECTRAL IMAGING SYSTEM AND RESULTS

The concept of the developed spectral imaging system utilizing the developed CIS, electrically tunable multi-bandpass optical filter and achromatic lens is shown in Fig.7. As the optical lens to capture spectroscopic images from the wide range of waveband, an achromatic lens system consisting of two infinite conjugate lenses placed back-to-back was introduced. It suppresses the chromatic aberration due to focal length errors of different wavelengths. The structure of developed optical filter is shown in Fig.8. It is composed of the three liquid crystal (LC) layers, polarizers, wave plates and a narrow FWHM bandpass filter (BPF) with four peak transmission wavelengths. The peak wavelengths of the developed BPF are 630nm, 800nm, 960nm and 1050nm, and the FWHM of each waveband is less than 10nm. The set of wavebands of the developed optical filter is changeable by replacing the BPF. At this time it was selected to account for several spectral imaging applications including blood glucose sensing as explained later. By applying a set of bias voltages to the three LCs to tune their transmittance, desired one waveband out of the four is selected. In Fig.8, a characteristic of the developed filter tuned at 1050nm light wavelength is shown. The filter picture is shown in Fig.9. The filer size is T 5.2mm × W 25mm × L 25mm. The measured transmittance of the developed filter is shown in Fig.10.

As a preliminary experiment for non-invasive blood glucose measurement, a diffusion of glucose into physiological saline solution was experimented. Non-invasive blood glucose measurement has been desired by 422 million diabetic patients and hypoglycemia patients in the world [10], because the monitoring methods today puts heavy mental and physical burdens on them. The measurement accuracy of 5mg/dl is required to detect low glucose level of hypoglycemia patients accurately. It is known that glucose dissolved in physiological saline solution has absorption peaks at 960nm and 1050nm among UV to NIR waveband, where 960nm and 1050nm correspond to an absorption peak due to water molecules and glucose molecules, respectively. Fig.11. shows a setup of glucose absorption imaging. A glucose aqueous solution was dropped into about 3ml physiological saline solution in a cell. The optical path length of the cell was 10mm. In this setup, the light passes through a diffuser, target cell and developed electrically tunable multi-bandpass optical filter, and reaches the developed CIS. Fig. 12 shows absorption

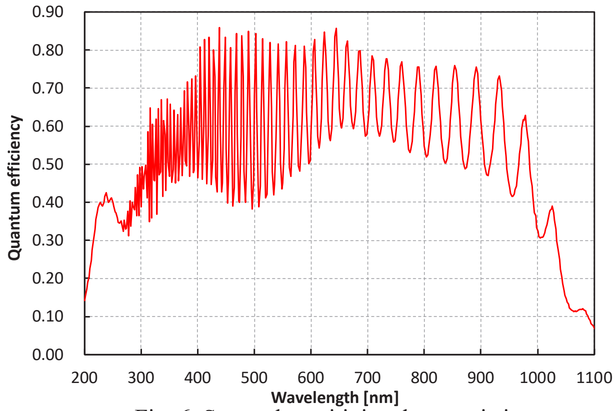

Fig. 6. Spectral sensitivity characteristic.

Table. 1. Summary of developed CIS performance.

Process technology	1-Poly 5-Metal CMOS with pinned PD
Power supply voltage	3.3V
Die size	$3009\mu m^H \times 3687\mu m^V$
# of effective pixels (Total)	$128^H \times 128^V (134^H \times 132^V)$
Pixel size	$16\mu m^H \times 16\mu m^V$
Maximum Frame Rate	1120fps
Capacitance of FD	0.66fF
Capacitance of LOFIC	0.956pF (MOS:781.4fF, MIM:174.2fF)
Capacitance of PD	85fF
Full well capacity (FD)	$4.9\times10^3e^-$
Full well capacity (FD + LOFIC)	$7.6\times10^6e^-$
Full well capacity (FD + LOFIC + PD)	$1.5\times10^7e^-$
SNR	~71dB
Spectral sensitivity range	190nm - 1100nm

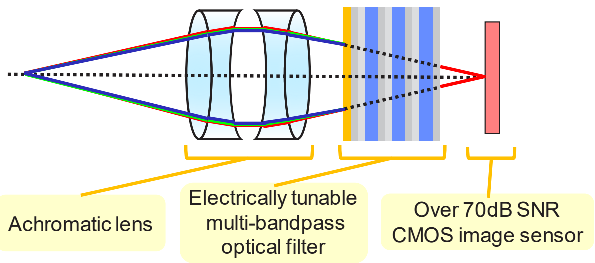

Fig. 7. Developed spectral imaging system.

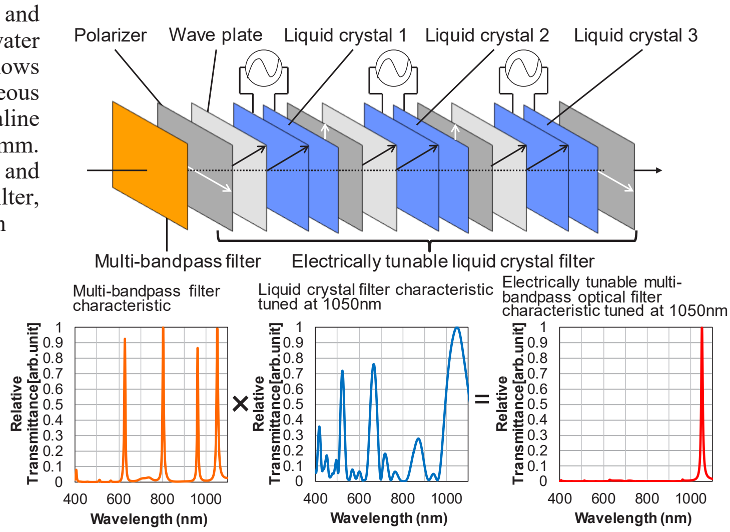

Fig. 8. Structure of electrically tunable multi-bandpass optical filter.

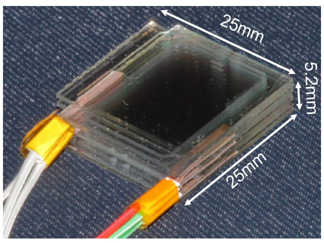

Fig. 9. The picture of tunable filter.

images of 5mg/dl glucose diffusion into physiological saline solution cropped to 29 × 79 pixels under both 960nm and 1050nm light wavelengths captured at the over 70dB high SNR operation mode. Here, the absorption images were visualized by following steps: first, an image of physiological saline solution was captured as incident light I_0 in the equation 1 before dropping glucose; second, absorption frames were captured during glucose dropping as transmitted light I_1 in the equation 1; lastly, absorption frames were colored by the differential signal values between I_0 and I_1. It should be noted that at 960nm wavelength, I_1 becomes larger than I_0 at higher glucose concentration level, because the light absorption due to water molecules become smaller. Red and green colors show the regions with about 5mg/dl and 3.5mg/dl glucose concentrations, respectively. From these visualized results, it can be said that the developed spectral imaging system has measurement accuracy of less than 5mg/dl glucose concentration due to the 70dB SNR imaging at 960nm and 1050nm. 80dB SNR is achievable by improving the developed spectral imaging system.

CONCLUSION

A new CMOS image sensor has been designed, fabricated and evaluated. It achieved over 70dB SNR, $1.5\times10^7e^-$ FWC, 190-1100nm spectral sensitivity with high QE in NIR, and high robustness to UV-light irradiation. A spectral imaging system was developed by using the CIS and the electrically tunable narrow FWHM multi-bandpass optical filter. By using the developed system, diffusion of 5mg/dl glucose into physiological saline solution was successfully visualized. The developed spectral imaging system is highly adoptive to not only conventional but also new spectral imaging applications.

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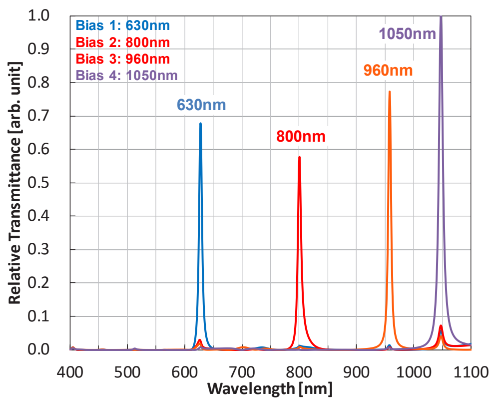

Fig. 10. Transmittance of the developed electrically tunable multi-bandpass optical filter.

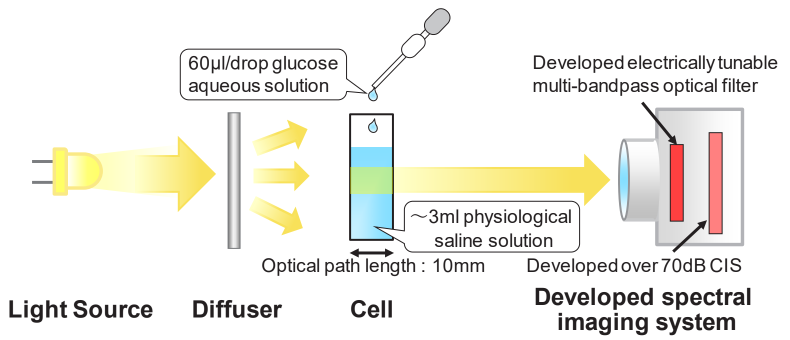

Fig. 11. Set up of glucose absorption imaging.

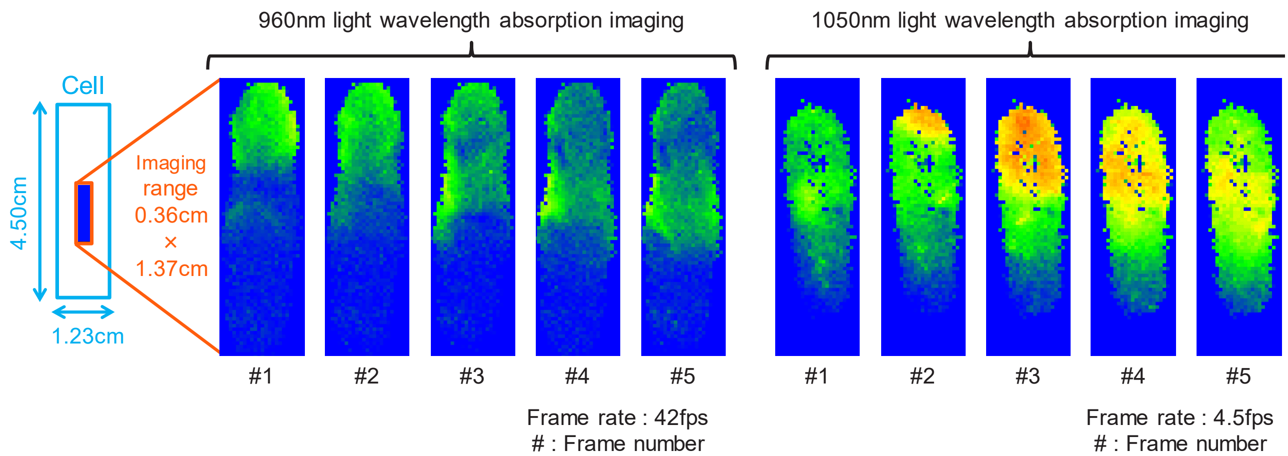

Fig. 12. Diffusion of 5mg/dl glucose visualized by 960nm and 1050nm light wavelength absorption imaging.