A Multi Spectral Imaging System with a 71dB SNR 190-1100 nm CMOS Image Sensor and an Electrically Tunable Multi Bandpass Filter

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Abstract This paper demonstrates a multi spectral imaging system utilizing a linear response, high signal to noise ratio (SNR) and 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 achieved 71dB SNR, $1.5 \times 10^7 \text{e}^{-}$ full well capacity (FWC), 190-1100nm spectral response with very high quantum efficiency (QE) in near infrared (NIR) waveband using low impurity concentration Si wafer ($\sim 10^{12} \text{cm}^{-3}$). With the developed CIS, diffusion of 5mg/dl glucose into physiological saline solution, as a preliminary experiment for non-invasive blood glucose measurement, was successfully visualized under 960nm and 1050nm wavelengths, at which absorptions of water molecules and glucose appear among UV to NIR waveband, respectively.

Keywords: multi spectral imaging, FWC, SNR, CMOS image sensor, bandpass filter, absorption analysis.

1. Introduction

Spectral imaging is an analysis method that obtains spatial information of spectrum by combining spectroscopy and optical imaging. In spectroscopy, wavelength information of light emission, absorption, refraction or scattering is obtained to analyze material characteristics, such as composition, concentration and so on. By obtaining spatial information altogether, it is possible to perform component and concentration distribution measurement. Also, by narrowing down the analysis target area, the accuracy is to be improved in comparison with a single point detector. For this reason, spectral imaging has been extensively researched and is expected to be applied to many fields including scientific instrumentation, medical, agricultural and so on. Several applications have already been reported, such as environmental monitoring, food inspection, biomedical analysis and so on with a variety of light waveband sets from UV to NIR. In general, a designated set of several wavebands for spectral analysis is required by each spectral imaging application.

Spectral imaging can be roughly divided into emission based imaging and absorption based imaging. 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 a target object by measuring the attenuation of light intensity that pass through it. The Beer-Lambert law describes the principle of absorption analysis as expressed by the following equation.

$$C = \frac{1}{\alpha d} \log \frac{I_0}{I_1} = \frac{A_d}{\alpha d}$$  \hspace{1cm} (1)

Here, $C$ is concentration [mol/m$^3$], $\alpha$ is absorption coefficient [m$^2$/mol], $L$ is optical path length [m], $I_0$ is incident light intensity, $I_1$ is transmitted light intensity and $A_d$ is absorbance, respectively.

Measurement accuracy of absorption analysis is in general determined by the detection accuracy of microscopic change of light intensity under strong light irradiation, where the SNR is given by the equation (2),
Here, $N_{\text{sig}}$ is the number of signal electrons and $n_{\text{sys}}$ is the input referred system noise in electrons. The maximum SNR is determined by the number of signal electrons equal to FWC of CIS when photon shot noise is dominant. Since CISs have a relatively small FWC when compared with single photodiodes (PDs) due to the small pixel size, they have lower maximum SNR. Conventional CISs have an SNR of 30-40dB, while single point detectors such as single PDs or linear array sensors employed in current absorption spectrometry have an SNR in the range of 70-80dB\(^9\). For spectral absorption imaging applications, it is necessary to develop a CIS with at least 70dB SNR with a sufficient resolution. In order to achieve 70dB SNR, 10Me– FWC is required according to the equation (2). Though there are logarithmic response CISs\(^{10}\) capable of capturing images under high light intensity, linear response CISs are suitable for absorption imaging for ease of image analysis.

Furthermore, a wide spectral response from UV to NIR is necessary for applying the system to a wide range of fields, for instance, environmental pollutants imaging under UV light\(^{11}\) and biomedical imaging under NIR\(^{7,8}\). Also, high QE is required for such a high FWC CIS in order to achieve higher framerate and to enable absorption imaging under lower light illumination. For the UV waveband, a PD technology achieving high sensitivity and high light resistance to UV-light has been reported\(^{12}\). However, for spectral imaging in life science, medical and agricultural applications, NIR QE also needs to be improved.

A previously reported CIS for spectral imaging\(^{13}\) has 190-1000nm wide spectral response, high QE and high robustness for UV light. It achieved 200ke– FWC with the lateral overflow integration capacitor (LOFIC) technology\(^{14,15}\) and a relatively high QE for NIR waveband with 20µm thick p-epitaxial layer on n-type Si substrate. Further improvements of FWC and NIR QE are needed for spectral absorption imaging fields.

Regarding spectroscopic techniques, the conventional spectroscopic methods can be classified in the following four categories: on-chip band-pass filters\(^{16}\), filter wheels\(^{1}\), liquid crystal (LC) tunable filters\(^{17-19}\), and a time-sharing illumination of LEDs\(^{11,20,21}\). The on-chip band-pass filters method achieves narrow FWHM. Since there is a trade-off relationship between the number of wavebands and the resolution, a high resolution CIS is needed. A set of wavebands needs to be predetermined because it is difficult to change the wavebands after CIS manufacturing. The filter wheels method also achieves narrow FWHM and the set of wavebands can be easily changed. Since mechanical sliding parts are utilized, obtaining a high speed waveband tuning capability is a challenge. And a system size tends to be relatively large. The LC tunable filters method can tune the filter transmission waveband by applying bias voltages without resolution degradation. There is a trade-off relationship between FWHM and transmittance. In order to obtain a narrower FWHM, more LC layers are needed which decreases transmittance\(^{15}\). The transition time tends to be determined by LC response. The time-sharing illumination of LEDs method allows an user to select the desired wavelengths by choosing the LEDs without degrading resolution. It is used when the background light can be controlled. FWHM is determined by LED characteristics.

A real-time spectroscopic method capable of selecting the required wavebands with narrow and stable FWHM, fast waveband switching capability which is to be synchronized with the CIS operation and no resolution degradation is highly desired. Yet, these features have not been achieved simultaneously by the conventional technologies.

The objective of this work is to develop a multi 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 multi bandpass optical filter with narrow and stable FWHM, fast waveband switching capability which is to be synchronized with the CIS operation and no resolution degradation. This paper is the extended version of the recent conference report\(^{22}\), and more detailed design information, experiment results are newly added. As an example of absorption imaging application using the CIS, imaging of glucose diffusion into physiological saline solution aiming at non-invasive blood glucose measurement is demonstrated.

### 2. Design and performances of developed CMOS image sensor

The objective of the developed CIS is to achieve high FWC with a large LOFIC and high NIR QE by utilizing a low impurity concentration p-type Si wafer\(^{22}\). The LOFIC capacitance required to achieve a FWC of 10Me– is calculated by the equation (3).
Here, \( V_{\text{sat}} \) is the maximum signal range at FD and is restricted by linearity of the signal readout circuit. In this sensor, a relatively high voltage of 1.6V is selected for improving FWC.

The 1pF LOFIC was formed with a high capacitance density stacked MOS and MIM capacitor. Considering a good balance between sensitivity and crosstalk in the NIR waveband, pixel pitch was set to 16µm. The required resolution varies depending on the application. In this work, the number of effective pixels was designed to be \( 128^H \times 128^V \) for achieving a high frame rate and a sufficient resolution as a prototype chip characterization. The high frame rate performance is suitable when combining the developed CIS and a time-sharing spectral imaging method.

The developed CIS was fabricated using a 0.18µm 1-poly-Si 5-metal CIS process technology with buried pinned PD. The chip size is 3.01mm\( ^H \times 3.69\text{mm}^V \) and the effective pixel array size is 2.05mm\( ^H \times 2.05\text{mm}^V \). A 3.3V power supply voltage is employed. The circuit architecture and the micrograph of the fabricated CIS chip are shown in Fig.1 and Fig.2, respectively.

The developed CIS has two operation modes: a wide dynamic range LOFIC operation and a high SNR operation with over 70dB SNR. The timing diagrams are shown in Fig.3. In the former mode, a high sensitivity photo-signal due to high conversion gain obtained by 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 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 by a linear response.

The measured photo-electric conversion characteristic is shown in Fig.4. In both operation modes, linear response to light intensity was achieved. The measured photon transfer curve in high SNR operation is shown in Fig.5. \( 1.5 \times 10^7 \) e– FWC and 71dB SNR are achieved. Fig.6 shows the measured spectral sensitivity of the developed
CIS fabricated on the low impurity concentration Si wafer (~10^{12} cm^{-3}) and the previously reported CIS fabricated on 20µm thick p-epitaxial layer (~10^{15} cm^{-3}) on n-type Si. A high QE for a wide light waveband of 190-1100nm was successfully obtained by the implementation of the following technologies. In the UV waveband, UV-light is converted to photoelectrons only within a few nanometer region of the PD surface. Fixed charges are generated in the dielectric film above the PD surface by UV-light irradiation, that causes potential change near the PD surface. Therefore, achieving high sensitivity and high light resistance to UV-light simultaneously is difficult with the conventional technology. In this sensor, these characteristics were simultaneously achieved by forming a high concentration surface p+ layer with a steep dopant concentration profile. Due to the introduced dopant concentration profile, an electric field that drifts photo-electrons is formed uniformly toward the near Si surface and the potential change due to the generated fixed charges is suppressed. In the NIR waveband, high QE was achieved by employing a very low impurity concentration Si wafer (~10^{12} cm^{-3}). Since the penetration depth of NIR light is much deeper than visible light in silicon, extending the PD depletion layer is effective to improve NIR QE. By using the low impurity concentration Si wafer, the depletion layer width is extended significantly. Here, the beats in the 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 achieved, such as 40% at 250nm, 68% at 500nm, 62% at 900nm and 15% at 1050nm. Compared to the previous work, three times higher QE at 900nm and ten times higher QE at 1050nm was obtained. The performance summary of the developed CIS is shown in Table 1. The developed CIS translated from Japanese.
exhibited 71dB SNR, $1.5 \times 10^7$ e– FWC, 190-1100nm spectral sensitivity, 1120fps and high robustness to UV-light irradiation.

3. Developed spectral imaging system and results

The objective of the developed multi spectral imaging system is to achieve narrow FWHM, no resolution degradation, real-time operation, and the ability to easily replace a set of wavebands simultaneously.

The components of the developed spectral imaging system are shown in Fig. 7. The developed CIS, and electrically tunable multi bandpass optical filter, and an achromatic lens were employed. The achromatic lens system, consisting of two infinite conjugate lenses placed back-to-back, was introduced in order to capture spectroscopic images from the wide waveband range. It suppresses the chromatic aberration due to focal length errors of different wavelengths.

The structure of the developed optical filter 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 measured transmittance of the developed BPF is shown in Fig. 8 and the wavebands and FWHM of each waveband is shown in Table. 2. The wavebands of the developed BPF are 630nm, 800nm, 960nm and 1050nm with less than 10nm FWHM of each waveband. The set of wavebands of the developed optical filter is changeable by replacing the BPF. At this time, it was selected for several spectral imaging applications including blood glucose sensing as explained later. In order to tune their transmittance, a set of bias voltages are applied to the three LCs. The light of four wavebands pass through the BPF and non-selected three wavelengths are blocked by the LC unit by controlling phase retardation of the three LCs with the set of bias voltages. Therefore, the desired one waveband out of the four is selected. The picture of LC unit of the tunable filter is shown in Fig. 9.

Fig. 10 (a) shows the set-up of the system composed by four LEDs, the developed electrically tunable multi bandpass optical filter, a lens and the developed CIS in order to check the operation and confirm the ability to capture multispectral images. Fig. 10 (b) shows the emission spectrum of the LEDs used in this experiment having peak wavelengths of 635nm, 840nm, 957nm, and 1022nm and the FWHM of 13nm, 48nm, 46nm, 76nm, respectively. Fig. 11. shows the captured images of LEDs tuned for each peak waveband.

As a preliminary experiment for non-invasive blood glucose measurement, diffusion of glucose into physiological saline solution was experimented. Non-invasive blood glucose measurement has been desired by 422 million diabetic and hypoglycemia patients in the world, because the currently used monitoring methods put heavy mental and physical burdens on them.
order to detect low glucose level of hypoglycemia patients accurately, a measurement accuracy of 5mg/dl is required. It is known that glucose dissolved in physiological saline solution has absorption peaks at 960nm and 1050nm among UV to NIR waveband due to water molecules and glucose molecules, respectively. Fig. 12. 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 bandpass filter, and reaches the developed CIS. Fig. 13. shows absorption 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 high SNR operation. These pictures were taken by the same pixel area. The visualized glucose areas of two wavelengths are different due to variation of irradiation area of LEDs.

Here, the absorption images were visualized by the following steps: first, an image of physiological saline solution was captured before dropping glucose, as incident light $I_0$ in the equation (1); 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 levels, because the light absorption due to water molecules become smaller. Red and green colors show the regions with glucose concentrations of approximately 5mg/dl and 3.5mg/dl, respectively. The blue pixels surrounded by green or red pixels in 1050nm wavelength pointed by arrow in Fig.13 are saturated because of the variation of light intensity. 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.

4. Conclusion

A high SNR wide spectral response CMOS image sensor has been designed, fabricated and measured. It achieved over 70dB SNR, 1.5×10^5e– 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 developed CIS and the electrically tunable multi bandpass optical filter. By using the developed CIS, 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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References

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