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論 文 内 容 要 旨

Sensing technology using image sensors is expected as a fundamental technology for the IoT and Big Data era in various fields such as healthcare, agriculture, environment, automotive, and industrial applications for a safe, secure, and sustainable society. These applications require a wide dynamic range (WDR) performance that can image subjects with severe differences in brightness, a high signal-to-noise ratio (SNR) performance that enables high-precision analysis in 2-dimensional image, which has not yet been tackled, and a high sensitivity performance in a wide spectral response that can image various light-absorbing and light-emitting objects. An CIS achieving all requirements mentioned above leads to the realization of unprecedented functions in image sensors. In addition, high-precision absorption imaging will contribute to the creation of novel measurement technologies and play important roles in variety of fields. In view of this background, the purpose of this dissertation is to establish CMOS image sensor (CIS) technology with high SNR, WDR, and wide spectral response, and to demonstrate its sensing applications. This dissertation is structured as follows with five chapters.

Chapter 1 is the introduction. The role of CIS and key parameters for sensing applications were briefly introduced including basic architecture and operation of CIS, high SNR requirement, WDR requirement, wide spectral response requirement, relationship between absorption ratio and SNR of photo detector, and relating approaches and issues for those requirements. In conventional absorption analysis, single photodiodes or linear array sensors with 70-80 dB maximum SNR have been used as photodetectors. However, it is difficult to adapt current CIS for absorption analysis because of its low SNR of 30-40 dB. A CIS with over 70 dB SNR and spatial resolution is expected to dramatically improve the functions and performance of the photodetection part of imaging, measurement, and analysis equipment, and contributes to a safer and more secure society. WDR is required for applications capturing targets with strong light contrast, such as machine vision, automotive, and security cameras. In those applications, over 120 dB dynamic range is highly required with linear response, single exposure, single photodiode (PD). As previously reported WDR techniques, multiple exposures, multiple PDs, dual conversion gain (DCG), single-stage LOFIC have been introduced. This study focused on LOFIC because sensitivity and saturation can be designed independently. A single-stage LOFIC CIS that achieved a WDR of 100 dB and 32 dB SNR at the signal switching point has been reported, however, there is a challenge that the SNR at the signal switching point decreases when the WDR is further extended. These backgrounds have led the purpose of this study to develop a CIS technology with a high full well capacity (FWC), high SNR, WDR and wide spectral response, and its sensing applications. In specific terms, the goal was set to develop a CIS with high quantum efficiency (QE) over a wide range of ultraviolet (UV) to near-infrared (NIR) light wavelengths, maximum SNR of over 70 dB and WDR performance of over 120 dB, and adaptable to high precision absorption analysis requiring to detect microscopic light intensity changes under high light condition.

Chapter 2 discussed key technologies for simultaneously achieving high saturation, WDR, and wide optical waveband performances, including wide dynamic range pixel architecture with two-stage lateral overflow storage, low leakage and high capacitance density capacitors using Si trench structure for high saturation, and wide spectral response. For high SNR and WDR, high capacitance density in-pixel Si trench capacitor and two-stage LOFIC are proposed. A Si trench capacitor with high capacitance density and low leakage current that can be used as a charge storage capacitor of LOFIC is discussed. In addition, the fabrication of the Si trench capacitors on a low impurity concentration p-type Si substrate for improving NIR sensitivity was also discussed. As high SNR and WDR technologies, two-stage LOFIC architecture and operation were proposed. For high-precision absorption imaging, dual VR readout operation enlarging the gradation of slight absorbance and reading out with high gain was proposed. For high sensitivity in NIR waveband, low impurity concentration p-type Si substrate was proposed. The design flow of two-stage LOFIC to achieve the widest dynamic range based on the minimum floating diffusion (FD) capacitance as well as to achieve the highest SNR for absorption imaging target was also proposed.

In Chapter 3, design, fabrication, and measurement of a high FWC WDR wide spectral response CIS with key technologies described in Chapter 2 was discussed. In the design section, the overall circuit structure, LOFIC capacitance design, and pixel layout are discussed. Figure 1 shows the circuit block diagram. The capacitance of FD, LOFIC1, and LOFIC2 are 2.1 fF, 67 fF, and 1.5 pF were chosen based on the design flow, respectively. In the manufacturing section, the fabricating process, Si substrate and the specification of the designed CIS are shown. Figure 2 shows the chip micrograph. The effective pixels are $128^{H}\times128^{V}$, pixel size is $16\mu m^{H}\times16\mu m^{V}$, and fill factor is 52.8 %. In the measurement section, a method for adjusting the off level of the in-pixel transistors to form the overflow path of the two-stage LOFIC was described. In this section, the usefulness of the developed CIS with proposed key technologies were demonstrated by measurement data. In addition, as a future perspective, the pixel scaling was also discussed. The developed CIS achieved the maximum SNR of 70 dB, 122 dB of DR, and a high QE from 200-1100 nm. The SNR at signal switching points were 35 dB at S1/S2 switching point and 47 dB at S2/S3 signal switching points. In dual VR operation, the fixed pattern noise was reduced from 12.3 mV_{rms} in high SNR mode to 38.7 μV_{rms} by canceling the threshold voltage variation of the pixel source follower. The depletion layer was extended from about 1.3 μm to over 30 μm due to the change of wafers from an n-type substrate and a p-type epitaxial layer of 20-μm thickness with an acceptor concentration of 1.3×10^{15} cm^{-3} to a very low dopant concentration Si substrate in the order of 10^{12} cm^{-3}. Due to this, the improvement of PD QE was clearly confirmed; from 25.8%, 13.1%, and 1.94% to 89.7%, 78.2%, and 26.7% at 860 nm, 940 nm, and 1050 nm, respectively, for the perpendicular incidence. The performance summary and bench marking are shown in Table 1 and Figure 3, respectively. The pixel pitch can be scaled while maintaining its high spatial efficiency of FWC thanks to the high-density capacitor used for LOFIC. Several high capacitance density technologies have been reported to be useful for CIS pixels. By combining these capacitors with 3D stacking technology, it is highly possible to achieve a dynamic range of over 120 dB even for a few microns' pixel pitch using the proposed two-stage LOFIC architecture.

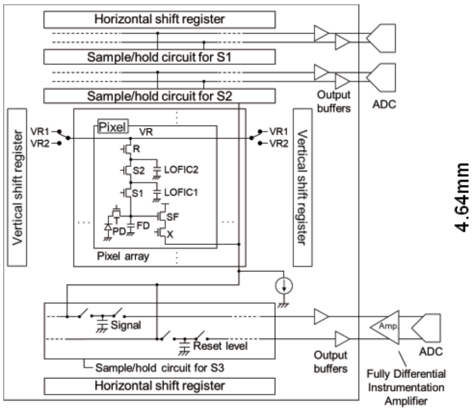


Figure 1 Block circuit diagram.

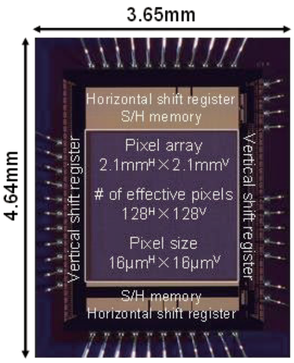
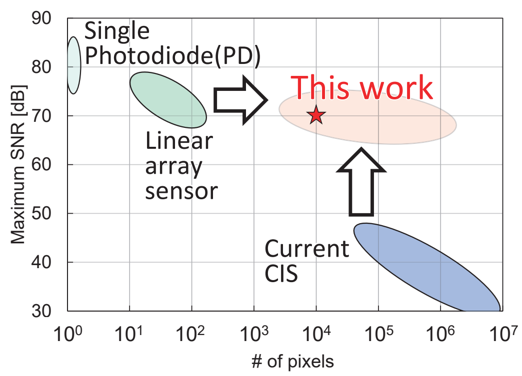


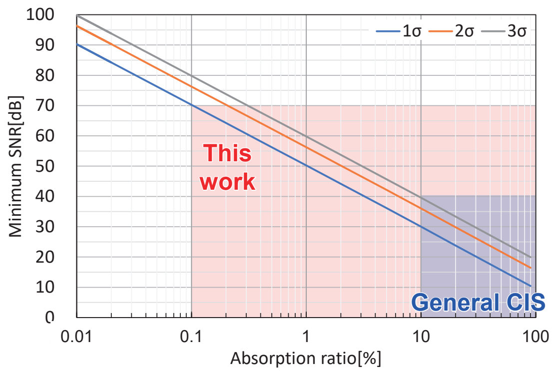
Figure 2 Chip micrograph.

Table 1 Performance summary.

Process technology		0.18μm 1-poly-Si 5-Metal CMOS with pinned PD
Power supply voltage		3.3V
Die size		3.65mm^H × 4.64mm^V
# of effective pixels		128^H × 128^V
Pixel size		16μm^H × 16μm^V
Fill factor		52.8%
Maximum Frame rate		685fps @ 20MHz
Capacitance	FD	2.1fF
	LOFIC1	67fF
	LOFIC2	1.5pF
FWC	High sensitivity S1	17.8ke$^-$
	High saturation S2	50.9ke$^-$
	High saturation S3	11.4Me$^-$ (WDR mode)
		24.3Me$^-$ (Dual VR mode)
SNR	S1/S2 switching point	35dB
	S2/S3 switching point	47dB
	Maximum S3	70dB
Dynamic range		>120dB
Spectral sensitivity range		200nm-1100nm



(a)



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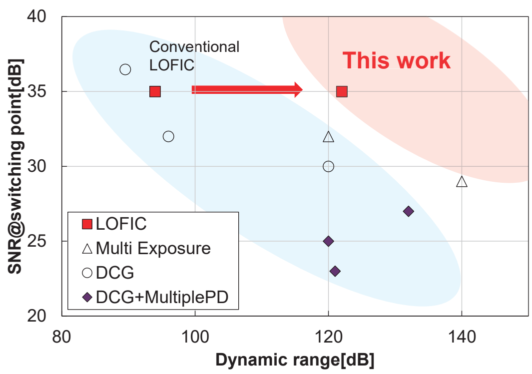

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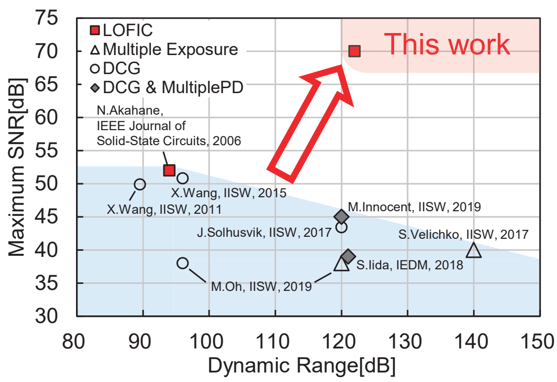

(d)

Figure 3 (a-d) Bench marking.

In Chapter 4, spectral imaging technology and sensing applications using the CIS fabricated in Chapter 3 were discussed. Two spectroscopic techniques were demonstrated. Time-sharing illumination of LEDs consisting of a light-switching system with eight LED wavelengths and an achromatic lens without chromatic aberration was developed in order to demonstrate spectral imaging in a wide range of wavelengths from UV to NIR. An electrically tunable liquid crystal bandpass filter was also discussed for use in environments with background light. As example applications, the UV absorption imaging of acetone and ozone aqueous dropped into water and the near-infrared absorption imaging of glucose for non-invasive measurement of blood glucose levels were demonstrated. Figure 4 shows the captured images of 5mg/dl glucose dropped into physiological saline solution visualized at 1050 nm wavelength captured with maximum SNR of 70dB. In this chapter, the spectral imaging system consisting of developed CIS and spectroscopic techniques and the high adaptation of the developed CIS to absorption imaging applications were studied and demonstrated. By using CIS with high spatial resolution instead of the one-dimension photodetectors, it was demonstrated that the measurement accuracy was improved by measuring substance distribution, concentration distribution and narrowing down the measurement target area. A step toward non-destructive and non-invasive absorption imaging was successfully demonstrated.

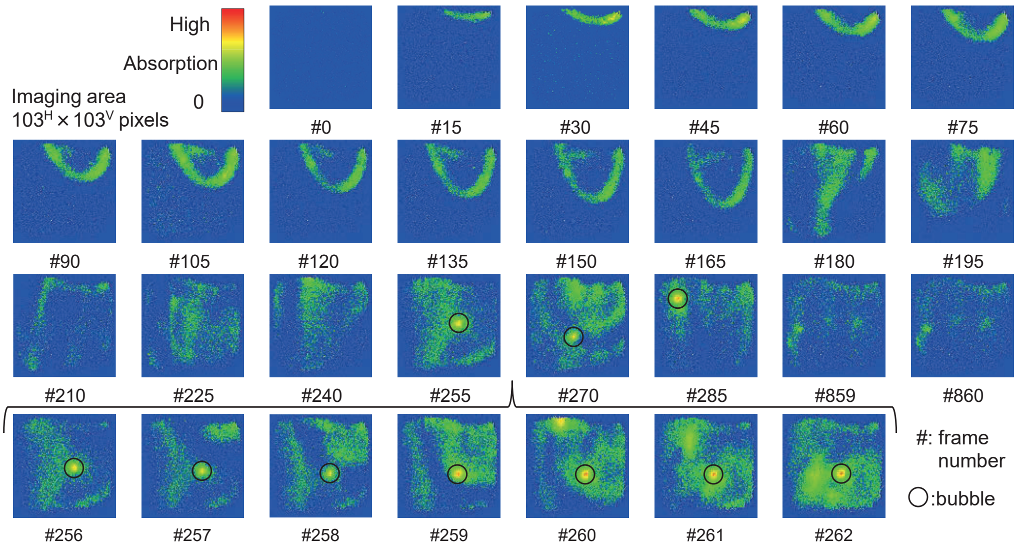

Figure 4 Diffusion of 5mg/dl glucose in physiological saline solution visualized at 1050nm wavelength captured with maximum SNR of 70dB.

Chapter 5 is the conclusion. In summary, this dissertation established a high saturation, WDR, and wide spectral response CIS technology that can be applied to various image sensing applications for the realization of a safe and secure society, by integrating advanced pixel architecture, materials, devices, and circuit technology. This dissertation summarized the results of demonstrating the usefulness of the CIS technology through high-precision, real-time, non-invasive and non-destructive sensing applications. The author would like to conclude this dissertation with the expectation that CIS with its unprecedentedly high SNR will lead to the realization of high-precision absorption analysis as a two-dimensional imaging technique and will be a fundamental technology for the creation of new industries.

論文審査結果の要旨

イメージセンサを用いたセンシング技術はヘルスケア、農業、環境、車載、産業用途等、様々な分野における安心・安全で持続可能な社会実現を目指した IoT・ビッグデータ時代の基盤技術として発展が期待されている。これらの用途では、激しい明暗差の被写体を撮像することのできる広ダイナミックレンジ性能や、分析装置並みの高精度分析を可能とする高い信号対雑音比（SNR）性能、さらには様々な吸光・発光対象を撮像することのできる広い光波長帯域における高感度性能等が必要とされる。しかしながら、従来の技術では、ダイナミックレンジと信号応答の高い線形性、動体歪みの少ない動画撮像性能、高い SNR 性能を並立できていないという課題が残存しており、特に高飽和・高 SNR 性能が必要とされる高精度な吸光イメージセンシング応用は、未開拓な領域となっていた。本論文ではこうした背景に鑑み、高飽和・広ダイナミックレンジ・広光波長帯域を兼備した CMOS イメージセンサ技術の確立とセンシング応用の実証を目的とし、その研究内容と成果をまとめたものであり、全文 5 章からなる。

第 1 章は序論である。

第 2 章では高飽和・広ダイナミックレンジ・広光波長帯域の性能を同時に実現するための要素技術について論じている。2 段型の横型オーバーフロー蓄積容量を搭載した広ダイナミックレンジ画素アーキテクチャ、高飽和化のための Si トレンチ構造を用いた低リーク・高容量密度キャパシタ、広光波長帯域化のための低不純物濃度 p 型 Si 基板を用いたフォトダイオード構造、高照度環境下における微小光量変化の高精度検出に資する信号読み出し方法からなる要素技術を提案し、これらを集積化するための製造技術と共に用途毎に応じた目標性能を満たす最適回路パラメータを導出する設計フローを明らかにしている。これは重要な成果である。

第 3 章では、前章で論じた要素技術を集積した CMOS イメージセンサを設計・試作しその性能を測定した結果を論じている。最小加工寸法 0.18μm の CMOS イメージセンサ製造プロセス技術に提案要素技術を導入して試作した 16μm 角の画素を有するプロトタイプイメージセンサにおいて、2430 万電子の飽和電荷数と 70dB 超の最高 SNR、単一露光で 120dB 超のダイナミックレンジ、光波長帯域 190〜1100nm における高量子効率を実証している。これは、きわめて有用な成果である。

第 4 章では、前章で試作した CMOS イメージセンサを用いた分光イメージング技術とセンシング応用について論じている。LED 光源、ないしはバンドパスフィルタと液晶セルとを組み合わせた小型チューナブルフィルタを用いた分光イメージングシステムを構築し、紫外吸光イメージングにより、食品・工業分野で多用されるオゾン水濃度のモニタリングに資する、サブ ppm オーダー濃度のオゾン水が拡散・対流する様をリアルタイムで撮像することに成功している。また、近赤外吸光イメージングにより、非侵襲血糖値検出器創出に資する 5mg/dl のグルコース溶液の拡散・対流する様をリアルタイムで明瞭に捉えると共に、2 次元画像取得に基づく非侵襲血管吸光イメージングへ向けたセンシングシステム創出の展望を明らかにしている。これらは、きわめて重要かつ有用な成果である。

第 5 章は結論である。

以上要するに本論文は、安心・安全な社会実現を目指した種々のイメージセンシング用途に適用可能な高飽和・広ダイナミックレンジ・広光波長帯域 CMOS イメージセンサ技術を、先進的な画素アーキテクチャ・材料・デバイス・回路技術を融合して確立し、その有用性を高精度・リアルタイムな非侵襲・非破壊センシング応用事例によって実証した成果をまとめたものであり、画像電子工学およびセンシング工学に寄与するところが少なくない。

よって、本論文は博士（工学）の学位論文として合格と認める。