Si image sensors with wide spectral response and high robustness to ultraviolet light exposure

Rihito Kuroda\textsuperscript{a)} and Shigetoshi Sugawa

Graduate School of Engineering, Tohoku University,
6–6–11 Aza Aoba, Aramaki, Aoba-ku, Sendai, Miyagi 980–8579, Japan
\textsuperscript{a)} kuroda@fff.niche.tohoku.ac.jp

Abstract: Si image sensors with a wide spectral response range and a high robustness to ultraviolet light exposure based on flattened Si surface are described in this paper. A photodiode (PD) fabrication technology is developed to form a thin surface high concentration layer with steep dopant profile on flattened Si surface. Due to this, PDs with a wide spectral response ranging from 200 to 1000 nm is achieved with almost 100\% internal quantum efficiency to ultraviolet light (UV-light) waveband. In addition, high robustness of light sensitivity and dark current toward UV-light exposure is obtained. The developed technology is applied to in-pixel buried PDs of photodiode arrays and a CMOS image sensor. The advanced performances of fabricated sensors are verified with experimental results.

Keywords: CMOS image sensor, photodiode array, photodiode, ultraviolet light, Si surface

Classification: Electron devices, circuits, and systems

References

1 Introduction

For both scientific and consumer applications, R&D efforts are continuously being paid in order to improve basic characteristics of image sensors such as signal to noise ratio (S/N), dynamic range, spatial resolution, frame rate,
power consumption and so on. A spectral response is one of these basic characteristics of an image sensor. Photodiode (PD) light sensors, PD arrays (PDAs) and area image sensors with a spectral response to ultraviolet light (UV-light), visible and near infrared (NIR) light wavebands are employed in various types of analytical instruments and detectors as well as imaging instruments. These include absorption and emission spectrometers, flame detectors, surface defect detectors, satellite cameras, surveillance cameras and so on [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14]. These instruments are used in a variety of scientific and engineering fields: chemical, life scientific and medical analyses, material science and semiconductor manufacturing, factory automation, environmental assessment and space vision [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14]. Image sensors used in these fields are required to have high sensitivity through 200 to 1000 nm or selected waveband of these. Also, a high robustness of light sensitivity and dark current is required toward strong light irradiation, especially to UV-light with high photon energy. It is because these image sensors are continuously irradiated by UV-light or sometimes irradiated by strong incident light. For the image sensor development, an improvement of UV-light sensitivity and an improvement of sensitivity robustness to UV-light exposure have been challenges [15, 16, 17, 18]. Fig. 1 shows the depth from Si surface where the integrated amount of incident light decreases to 90% and 37% due to the absorption as a function of the wavelength and photon energy. For the Si detector case, the UV-light penetration depth is only 4–6 nm, photo-generated carriers generated within top few atomic layers of Si must be collected to achieve a high UV-light sensitivity. For this reason, an atomic scale control of the dopant profile of the Si surface region is necessary. It is to form a drift field for photo-generated carriers to be detected [12, 17, 18]. Also, to increase sensitivity to NIR-light photo-generated carriers generated several tens of micron meters from Si surface must be collected. In addition, due to the high photon energy of UV-light, fixed charges in the insulator film above Si and interface states at the insulator/Si interface are generated. These cause a change in the surface potential of PD and an increase of generation/recombination rate at the surface, thus, leading to degradations of light sensitivity and dark current [15, 16].

![Fig. 1.](image-url)
Fig. 2 shows a typical atomic force microscopy image of (100) oriented Si surface after modified RCA cleaning [19]. The peak-to-valley of about 1 nm appears for the measured window of 1 µm². The buried photodiode structure shown in Fig. 3(a) is widely adopted in CCD and CMOS image sensors to suppress dark current due to carrier generation through the interface states. When forming a thin surface high concentration layer to generate a drift field on such a conventional rough Si surface, a depletion layer edge would reach localized spots of SiO₂/Si interface. These become a sensitivity loss and dark current generation spots if interface states exist as shown in Fig. 3(b).

Several approaches have been reported to increase UV-light sensitivity of image sensors, such as a backside illuminated (BSI)-CCD and a BSI-CMOS image sensor with additional backside surface treatment processes to form thin high dopant concentration layers, and detector-on-Si type CMOS imagers with UV-light sensitive materials such as AlGaN as detector [12, 13, 14]. We have focused on improving Si PD performances. By doing so, a cost effective and widely applicable monolithic image sensing system will be obtained. In this paper, the developed PD technology is described which is based on an atomically flattened Si surface for the formation of the thin surface high concentration layer with a steep dopant profile in order to generate a drift field for photo-generated carriers near Si surface. And its applications to in-pixel buried PDs for emission and absorption PDAs as well as a CMOS image sensor are described. In the next section, the concept and
the characteristics of the developed PD technology is described. In section 3, two types of PDAs specially designed for absorption and emission spectrometers as well as a 5.6 µm pixel pitch CMOS image sensor using the developed PD technology are demonstrated.

2 Highly UV-light sensitive and highly robust PD technology

2.1 PD concept

Figs. 4 and 5 summarize the targeted PD structure and its dopant profile near the Si surface. A thin surface high concentration layer with steep dopant profile is formed uniformly on atomically flattened Si surface. A high concentration surface neutral region is formed in the top few nanometer region to passivate the interface states to suppress the sensitivity loss and dark current generation due to recombination and generation processes [17, 18]. Here, the concentration of neutral region is designed to be high enough to suppress the potential change at the surface due to the generation of fixed charges due to UV-light exposure. The steep dopant profile of the surface high concentration layer is to form an electric field to drift photo-generated carriers to the buried layer. Here, the electric field of this surface high concentration layer is induced

![Diagram of PD structure](image)

Fig. 4. (a) Schematic illustration of the targeted PD structure for the photoelectron detection case and (b) AFM image of atomically flat Si surface formed by ultra-pure Ar ambient annealing process.

![Diagram of dopant profile](image)

Fig. 5. (a) Key features and the dopant profile of the developed PD.
by space charges of depletion layer and gradient of the carrier concentration of top neutral region. Also, dopant concentration at the pn junction between the surface high concentration layer and the buried layer is set relatively low to reduce the electric field for the suppression of the dark current. In addition, the junction depth \( x_j \) and dopant concentration profile are designed so that the depletion layer does not reach the Si surface. Atomic scale flatness of SiO\(_2\)/Si interface is required so as to form the above mentioned thin and steep dopant profile uniformly. And a small trap density insulator film should be formed above the PD for suppressing the fixed charge generation due to trapping of the carriers excited by high photon energy UV-light. Here, the atomically flat Si surface is formed by annealing a bare Si surface wafer at around 800 °C or above in an ultra-pure Ar ambient with a residue H\(_2\)O concentration of 30 ppb or less [20, 21, 22]. By this process, a flat Si surface formed by atomic terrace and mono-atomic layer steps are obtained [20]. In addition, by an alkali-free wet cleaning process in dark ambient condition for bare Si wafer to suppress the local Si etching and by an oxygen radical oxidation process with isotropic oxidation reaction, the atomic flatness level is maintained through the device fabrication process [20, 21].

### 2.2 Fabricated PD characteristics

Based on the PD concept, \( n^+p_n \) and \( p^+n_p \) PDs were fabricated. Fig. 6 and 7 show the process flow and cross sectional view of the fabricated PDs. The Si surface flattening process was employed at the beginning of the process flow and the flatness level was maintained for the PD formation process. The implantation process for the surface high concentration layer was carried out

![Fig. 6.](image-url)  (a) Process flow of the fabricated PDs.

![Fig. 7.](image-url)  (a) Cross sectional view of the fabricated PDs.
through 7 nm thick oxide film. In this process, projected range is designed in the through implantation oxide film so as to form a steep dopant profile in Si. A rapid thermal annealing process was carried out to suppress the diffusion of dopant atoms while activating them with a small thermal budget. Fig. 8 shows the As and B dopant depth profile of the surface high concentration layer of fabricated n^+pn and p^+np PDs. They were measured by secondary ion mass spectrometer. The thin and steep dopant profiles were formed for both types of the PDs.

Fig. 9 shows the quantum efficiency (QE) of the developed PDs as a function of wavelength. The dotted lines show the transmittance of the SiO2 films formed above the PDs. A wide spectral response from 200 to 1000 nm is successfully obtained for both n^+pn and p^+np types. Especially at around 200 to 320 nm, the QE characteristics reach the transmittance curves, i.e., almost 100% internal QE in Si PD is achieved. This shows that the photo-generated carriers in Si surface region are successfully collected. An UV-light exposure acceleration stress was carried out for the fabricated PDs to evaluate their stability for a long time use. A super high pressure mercury lamp was employed for the UV-light exposure stress. The spectral distribution of the employed UV-light source is shown elsewhere [17]. Fig. 10(a–b) shows the QE at 250 nm and dark current as functions of UV-light irradiation stress time. The degradations of light sensitivity and dark current were both very small,
showing that the fabricated PDs have high stability to strong UV-light exposure.

For some application fields such as multi spectral imaging [23], a high sensitivity to a selected waveband is preferred. A high transmittance band pass filter composed of multilayer stack of SiN and SiO₂ is deposited right above the PD [24]. Here, SiN film deposition conditions were specially tuned in order to achieve the high transmittance to UV-light waveband. Fig. 11 shows the QE as a function of wavelength. A very high QE of 80% is achieved at the wavelength of 260 nm. By tuning the thickness and layer condition of the filter, the peak sensitivity wavelength is able to be optimized [24].

3 Application to PDAs and CMOS image sensors

3.1 Integration of PD technology to in-pixel PDs of image sensors

In this section, applications of the developed PD technology to PDAs and a CMOS image sensor are described. As mentioned previously, the developed
PD technology requires special processes such as shallow ion implantation and rapid activation annealing. The developed PD technology was integrated into a standard 0.18 µm 1-poly-Si and 3-metal CMOS image sensor process. In order to integrate the developed PD technology the image sensor process with various types of active and passive components such as MOS transistors, registers and capacitors, the process flow and conditions regarding to the thermal budget and ion implantations were optimized. For the formation of thin and steep p+ layer, process conditions related to the Si surface flatness, ion implantation for PD and activation anneal were tuned; the SiO₂/Si interface flatness was maintained at the same level as the gate oxide/Si interface, the shallow BF₂⁺ implantation was carried out through a thin oxide film, and a rapid thermal annealing process equivalent to the activation process of the S/D high concentration region was applied as the dopant activation anneal for the surface high concentration layer of PD [25, 26]. For the following fabrication of image sensors, Si wafers with 20 µm thick low dopant concentration p-type epitaxial layer was employed in order to increase NIR-light sensitivity.

### 3.2 Application to PDAs for absorption and emission spectrometers

A principle of the measurement of spectrometers is to measure the intensity of light with a wide spectral waveband from UV-light to NIR-light which transmitted through, reflected or emitted from a target sample by a PDA. A diffraction grating is employed to disperse the wavelength of incident light. Fig. 12 shows a spectroscopy system with a PDA sensor of which multiple numbers of PDs are placed in a line. The dispersed light is simultaneously measured. In addition to the high stability of sensor performances for a long time use, there is especially required performance in each field of absorption and emission spectroscopy. In the absorption spectroscopy, the PDA is normally irradiated by strong light, and observes a small change in light intensity due to light absorption by a sample. A full well capacity (FWC): the amount of charge that a pixel can hold before the saturation is required to be high for the PD. This is to increase S/N during the measurement. Here, S/N increases in proportion to the square root of light intensity when the photon shot noise is the main noise source. On the other hand, in the emission

![Fig. 12. Schematic diagram of a spectrometry system with a grating and a PDA.](image-url)
spectroscopy, the PDA detects low levels of light emitted from a sample. A high sensitivity is required to obtain large signal amplitude from weak emitted light. Fig. 13(a–b) shows a circuit block diagram and a cross section of PD of a general structure of PDA. In general, for signal reading out, the photo-electrons are integrated and converted as voltage signal by an external charge amplifier. In this general PDA structure, because the PD is long rectangle, photo-carriers generated near the far side of the select switch takes a long time to be readout. That is, the RC delay by resistance and capacitance of the PD limits the signal readout time.

Figs. 14–15 show circuit block diagrams and cross sectional viewgraph of one pixel each of the developed PDAs [27]. Three types of PDAs including two types of developed structures were fabricated. The developed structures were

![Fig. 13.](image)

(a) Circuit block diagram of a general PDA and (b) pixel cross sectional view.

![Fig. 14.](image)

(a) Circuit block diagram and (b) pixel cross sectional view of the developed PDA type 1 for an absorption spectrometer.

![Fig. 15.](image)

(a) Circuit block diagram and (b) pixel cross sectional view of the developed PDA type 2 for an emission spectrometer.
specially designed for absorption spectroscopy with a high FWC (type 1 as shown in Fig. 14) and for emission spectroscopy with a high sensitivity (type 2 as shown in Fig. 15). In both types, the developed highly UV-light sensitive and highly reliable PD technology was employed. A general structure PDA (type 3 as shown in Fig. 13) was also fabricated and measured as a reference. About the developed PDAs, multiple readout paths were placed along the long side of the rectangle PD as shown in Fig. 14(a) and Fig. 15(a) in order to achieve fast readout speed. Metal wires are placed as signal readout paths on the isolation regions in between PDs. Based on the structure, the RC time constant of PD is drastically reduced, and realizes a fast readout speed. PDs in the developed PDAs were independently optimized depending on their signal readout structures. The PDA type 1 has partially depleted buried PDs of which charge integration layer has a relatively high concentration in order to achieve a high FWC for absorption spectroscopy. The PDA type 2 has buried pinned PDs for the full charge transfer to the in-pixel floating diffusion (FD) node in order to achieve a high sensitivity for emission spectroscopy. In the PDA type 2, a source follower amplifier was embedded in each pixel, and the photo-charges are converted as voltage signal at the FD to be readout. Compared with the general PDA readout structure, it is expected that the PDA type 1 exhibits an increased FWC because of the additional capacitance between the surface p+ layer and charge integrating n layer for a same n layer dopant concentration. The reference PDA type 3 has PDs that consist of the np junction of the surface charge integrating n layer and the p-type epitaxial layer as shown in Fig. 13(b). Fig. 16 represents the chip micrograph of the developed PDAs. The circuit consists of a pixel array, output line and digital circuit block in all types. The die size is 28.6 mmH × 3.3 mmV. The pixel size is 25 µmH × 2500 µmV. The pixel pitch is 25 µm. The effective pixel number is 1024 (total is 1028). The supply voltage is 3.3 V.

Fig. 17 shows the photo-electric conversion characteristics for the fabricated three types of PDAs [27]. Here, the vertical and horizontal axes are the output voltage and the light exposure which is the product of light intensity and integration time. All three types have good linearity. From the result, the FWC was 9 pC for the PDA type 3 with the conventional np junction type PD. The FWC values were 68 pC for the PDA types 1 with the p+np junction type PD. It was confirmed that introduced surface highly concentration p+ layer increase the FWC. Also, the PDA type 2 exhibited a high sensitivity which is about six times higher than that of type 1 and 3. The FWC of the PDA type 2 is limited by the FD capacitance and it was 5 pC in the fabricated PDA. Fig. 18(a–c) shows the QE before and after the UV light exposure.

![Fig. 16. (a) Chip micrograph of the developed PDA.](image-url)
stress as a function of wavelength [27]. The same UV-light source as explained in the previous section was employed for this experiment. For (a) type 1 and (b) type 2, the initial sensitivities are both high, and almost no sensitivity degradation was observed even after 10,000 min UV irradiation. On the other hand, for (c) type 3 the initial sensitivity is lower than type 1 and 2 from UV-light to NIR-light waveband, and the sensitivity degradations at wavelength less than 400 nm were clearly observed after UV exposure stress. Fig. 18(d) shows the QE at the wavelength of 250 nm. The vertical axis is normalized by the initial QE value of each type. The sensitivity degradation occurred after 100 min irradiation in the PDA type 3 with a general PD dopant profile. After 10,000 min irradiation, the sensitivity was decreased to less than 40% of the

Fig. 17. Photo-electric conversion characteristics of the fabricated three types of PDAs.

Fig. 18. Spectral QE for (a) type 1, (b) type 2 and (c) type 3, respectively. (d) QE normalized by the initial values at 250 nm of types 1, 2 and 3 as a function of the UV light irradiation time.
initial value in the type 3. In contrast, for the PDA types 1 and 2, there was almost no degradation until 1,000 min, and the degradations were the only 10% at 10,000 min.

Furthermore, the signal readout speed was evaluated and it was confirmed that the developed PDAs types 1 and 2 exhibit more than 150 times faster readout time than that of a general type due to the multiple readout paths along the long side of the rectangle PD [27]. The improvements of the speed as well as the sensitivity robustness were successfully confirmed for the developed PDAs.

### 3.3 Application to CMOS image sensor

A 5.6 µm pixel pitch front-side-illuminated (FSI) CMOS image sensor with buried pinned-PD having the surface photo-generated electron drift layer explained in the previous section was fabricated. The lateral overflow integration capacitor (LOFIC) pixel architecture was employed for a high conversion gain (CG) and a high FWC performance [28, 29]. A wide dynamic range and high sensitivity linear response imaging are achieved with a single exposure by CMOS image sensor with LOFIC [28, 29]. The image sensor chip was fabricated using the same process technology as the PDAs explained in the previous sub-section. Fig. 19 shows the chip micrograph and the design specification of the developed CMOS image sensor, respectively.

From the measured photoelectric conversion and the S/N characteristics, the CG, the dark random noise, and the FWC were 110 µV/e−, 2.1 e−, and 1.6 × 10⁵ e−, respectively. The dynamic range was 97 dB. Due to the small floating diffusion (FD) capacitance and a large LOFIC capacitance, high CG and FWC were simultaneously obtained. The PD dark current at 60 °C was 6.4 e−/sec-µm² which is normalized by the pixel area, and no increase of dark current was detected due to the UV-light exposure stress explained next. The fabricated chip was exposed to the UV-light stress to evaluate the sensitivity and dark current stabilities. The same UV-light source explained in the previous section was also employed for this experiment. Spectral response and dark current were measured before and after the UV-light exposure. Fig. 20 shows the spectral response of the fabricated CMOS image sensor measured before and after the UV-light irradiation for 1,000 min. For both

<table>
<thead>
<tr>
<th>Process technology</th>
<th>0.18 µm 1P3M CMOS with buried pinned PD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply voltage</td>
<td>3.3 V</td>
</tr>
<tr>
<td>Die size</td>
<td>9.5H × 9.5V mm²</td>
</tr>
<tr>
<td>Pixel size</td>
<td>5.6H × 5.6V µm²</td>
</tr>
<tr>
<td>Number of pixels</td>
<td>Total 1312H × 968V</td>
</tr>
<tr>
<td></td>
<td>Effective 1280H × 960V</td>
</tr>
<tr>
<td>Fill factor</td>
<td>26%</td>
</tr>
</tbody>
</table>

Fig. 19. (a) Chip micrograph and (b) design specification of the fabricated CMOS image sensor.
cases, the high photo-sensitivity was obtained for a wide light waveband of 200–1000 nm. In addition, it was confirmed that almost no degradation of spectral response occurred for the fabricated chip [25, 26, 30]. Fig. 21 shows the sample images under various conditions [30]. The captured area was separated into two sections. On the left side section there were a stuffed doll, a paprika and a mountain landscape on the background picture under NIR

![Spectral Response of the Fabricated CMOS Image Sensor Chip](image)

**Fig. 20.** Spectral response of the fabricated CMOS image sensor chip measured before and after the UV-light irradiation for 1,000 min.

![Sample Images](image)

**Fig. 21.** Sample images. Upper left figure shows the schematic drawing of the object. Upper right, image taken with UV-light (254 nm) source and a narrow UV-light band transmission lens filter. Lower left, image taken with IR-cut lens filter. Lower right, image taken without optical filters. “Musubimarubu” shown in upper left image is copyrighted material of Sendai Miyagi tourist campaign promotion Council (approval number: 26029).
light (700–1100 nm) irradiation. And on the right side section there were a stuffed doll, a light bulb and a white paper with a picture drawn by a sun block cream containing UV-light absorbent under visible light. The light conditions were the same except for the upper right image where the right side section was additionally exposed by UV-light from a germicidal lamp. During capturing images, an UV-light transmission lens: Pentax B2528UV was employed. Three pictures were taken with an UV-light transmission filter having a narrow distribution around 254 nm (upper right image), with IR cut filter (lower left image) and without optical filters (lower right image). For the upper right image, the picture on the white paper was clearly observed when the germicidal lamp was irradiated. For the lower left image, the light bulb and the dark place were observed simultaneously. The left side under NIR-light could not be seen. For the lower right image, the objects under the NIR-light were observed clearly. Therefore the developed CMOS image sensor successfully captured the UV-light, visible-light, and NIR-light with a wide DR performance.

4 Conclusion

In this paper, key features and the process technologies of PD to achieve a wide spectral response ranging from 200 to 1000 nm and a high stability of light sensitivity and dark current to strong UV-light exposure were summarized. Both n^+pn and p^+np PDs with the structure having thin surface high concentration layers formed on atomically flattened Si surface exhibit superior characteristics on light sensitivity and its stability to UV-light exposure. The developed PD process technology was applied to PDAs specially designed for absorption and emission spectrometers and a wide dynamic range CMOS image sensor. A wide spectral sensitivity of 200–1000 nm as well as a high stability of light sensitivity were successfully achieved. The developed image sensors are expected to be utilized for various applications that require wide waveband light detection and imaging.

Acknowledgments

This work was supported by JST SENTAN-project. Authors would like to acknowledge Shimadzu Corp. and LAPIS Semiconductor Miyagi Co., Ltd. for their cooperation.

Rihito Kuroda
received the B.S. degree in electronic engineering and the M.S. and Ph.D. degrees in management science and technology from Tohoku University, Sendai, Japan, in 2005, 2007, and 2010, respectively. He was a Research Fellow of the Japan Society for the Promotion of Science Research from 2007 to 2010. From 2010, he has been an Assistant Professor with the Graduate School of Engineering, Tohoku University, where he is currently an Associate Professor from 2014.
Shigetoshi Sugawa received the M.S. degree in physics from the Tokyo Institute of Technology, Tokyo, Japan, in 1982 and the Ph.D. degree in electrical engineering from Tohoku University, Sendai, Japan, in 1996. In 1982–1999, he was with Canon Inc. In 1999, he moved to Tohoku University, where he is currently a Professor with the Graduate School of Engineering, also with the New Industry Creation Hatchery Center.