

Standard CMOS Process Integrated Silicon-Based Ultraviolet-Infrared Complementary Sensor

Takaya Sugiura , Member, IEEE, Hiroki Miura , and Nobuhiko Nakano , Member, IEEE

Abstract—This study proposes a new ultraviolet-infrared (UV-Ir) compatible sensor fabricated using the standard CMOS process. The concept is verified through a numerical simulation, wherein the standard CMOS process parameters used are evaluated. The proposed sensor is an extension of a previously proposed RGB sensor designed on the standard CMOS process, and calculating the current ratio enables the detection of UV with high sensitivity. In addition, the use of current rectification eliminates the short to middle wavelength region and leaves only the Ir region which is used for detection. High dynamic ranges of 160 dB are ensured for all UV, Ir and RGB which they are excellent for color sensing. Consequently, combined with the previously proposed RGB sensing, the new RGB+UV+Ir sensor is realized without any filters.

Index Terms—CMOS, device simulation, infrared, ultraviolet.

I. INTRODUCTION

ULTRAVIOLET (UV) detection is an interesting topic and several approaches have been proposed for its realization [1]–[4]. In general, UV detection is performed using a photodiode, which detects the light illumination and generates a photo-current. In most situations the illumination has a spectrum, including the visible lights and infrared (Ir) light along with the UV light. Silicon with band gap energy $E_g = 1.12$ eV reacts to visible lights; therefore, the filter that cuts them is necessary. The use of filter may be eliminated through the use of the wide-band gap (WBG) materials, such as silicon carbide (SiC) and gallium nitride (GaN) of $E_g \sim 3$ eV. However, the drawbacks of this approach include high costs and difficulty in integration. Recently, the Si-based filter-less UV detector was developed, wherein two photodiodes with different sensitivity to the UV light [6], [7] were used and realized as a discrete package. This implies that there is still considerable research required to realize the integration of UV sensors into LSI systems.

In addition to UV detection, Ir sensing is another interesting research topic in optical sensing because of its wide applications, such as telecommunication [8], food industries [9], and wood

science [10]. A region near Ir has larger energy than that of silicon's E_g of 1.12 eV; therefore, it can be detected using the silicon-based technology. Recently, Si-based Ir sensor employing organic materials was proposed [11], which implies that Ir sensing with silicon-only technology without any filters remains challenging.

A previous study proposed an RGB sensor designed using the standard CMOS process without any filters [12]. The concept of the sensor was based on utilizing the integration into an LSI block that provided several electronics devices with the same substrate. The fundamental concept applied here was the phenomenon of shorter wavelength light being absorbed near the surface. Subsequently, calculating the current difference enabled the detection of RGB. The elimination of the Ir region, realized by the Ir filter in previous works, has been realized by current rectification using a diode or MOSFET.

In this study, the standard CMOS process integrated filter-less UV-Ir complementary sensor was proposed by extending the concept of the previous RGB sensor. UV detection was realized by calculating the current ratio of the near-surface to deeper-depth absorbed photo-currents. Furthermore, Ir detection was realized by reversing the current rectification used in the previous RGB sensor to emphasize the Ir response. Consequently, combining these concepts with the RGB sensing, filter-less RGB+UV+Ir sensing was realized using the standard CMOS process that offered advantages of low-cost, mass-production, and system integration.

II. CONCEPT OF PROPOSED SENSOR

A. Fundamental Phenomenon

The fundamental phenomenon of the proposed sensor is the wavelength-dependent absorbed depth. The absorption coefficient α is expressed by the imaginary part k of the complex refractive index as [13]

$$\alpha = \frac{4\pi k}{\lambda}. \quad (1)$$

The most dominant part is the wavelength λ ; therefore, the short wavelength light is absorbed at the surface region. For silicon, the UV light up to 400 nm wavelength is absorbed till a depth of x μm .

The standard CMOS process provides several doping layers with different diffusion depth; therefore, it facilitates the formation of multiple pn-junctions to the depth direction. By contacting each layer of pn-junctions, different light responses

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The authors are with the Department of Electronics and Electrical Engineering, Keio University, Yokohama, Kanagawa 223-8522, Japan (e-mail: takaya_sugiura@nak.elec.keio.ac.jp; hmiura@nak.elec.keio.ac.jp; nak@elec.keio.ac.jp).

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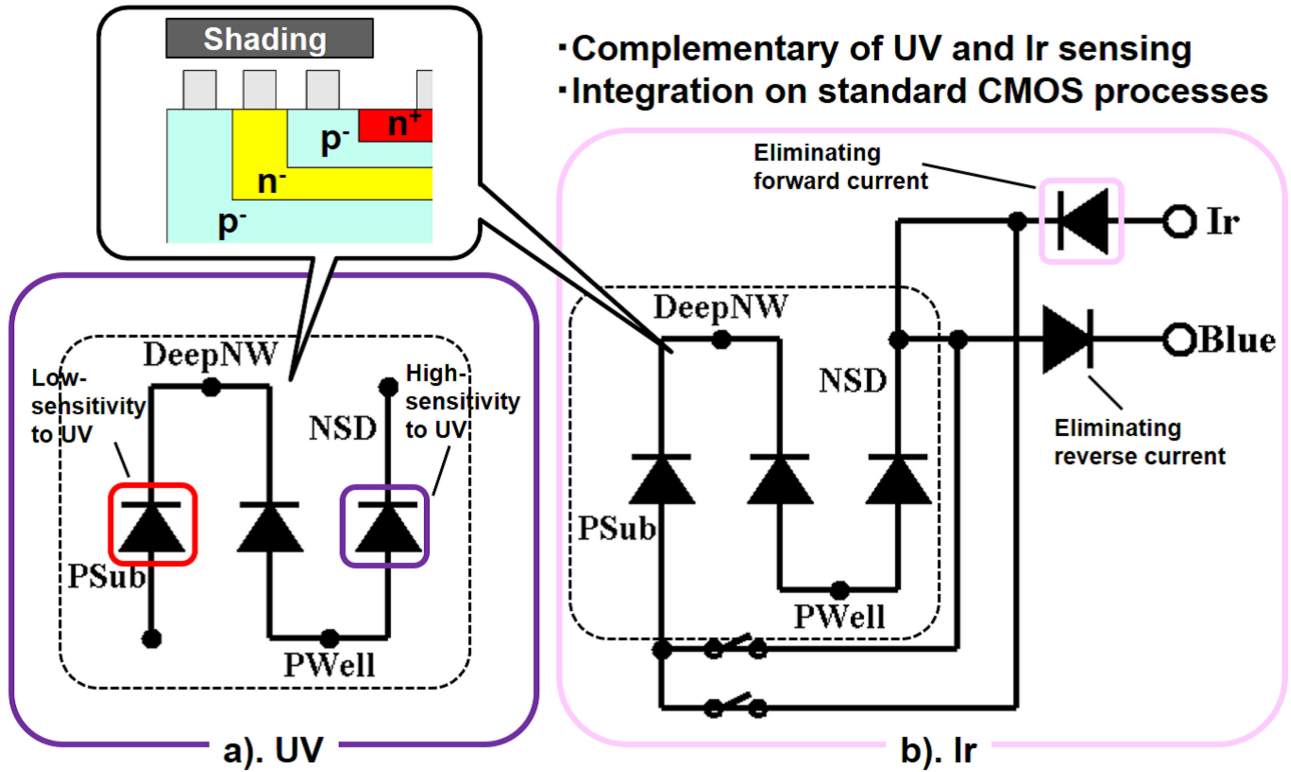


Fig. 1. Concept of UV and Ir sensing.

can be obtained. In addition, the surface layer provides short wavelength including UV and the deeper layers response to the long wavelength light. Consequently, calculating the current difference can eliminate the part of the wavelength response that provides the color detecting function. However, the difficulty in fitting process parameters can hinder the proper use of the sensor.

Our previous study focused on only RGB sensing, which is the most attractive part in optical sensor; however, it can still be expanded to the UV and Ir regions. The concept of the proposed sensing schemes are illustrated in Fig. 1. The following sections present a detailed discussion of each of UV and Ir sensing methods. Standard CMOS process integrability enables to easier control of sensor operations of RGB or UV or Ir detections by the CMOS technology.

B. UV Sensing

Calculating the current ratio instead of the current difference can emphasize the light response; essentially, enlarging the response of certain region and minimizing other parts. This phenomenon is particularly useful for the UV region because only the surface layer responds to it, whereas other parts output approximately zero photo-currents.

In the standard CMOS process, the top doping layer is NSD (or PSD); subsequently, to form the pn-junction, PWell (or NWell) should be formed. Further, there is an option to provide deeper doping region, referred to as DeepNW (or DeepPW), which is used for element separation primarily for mixed-signal integration. Therefore, four terminals of NSD, PWell, DeepNW,

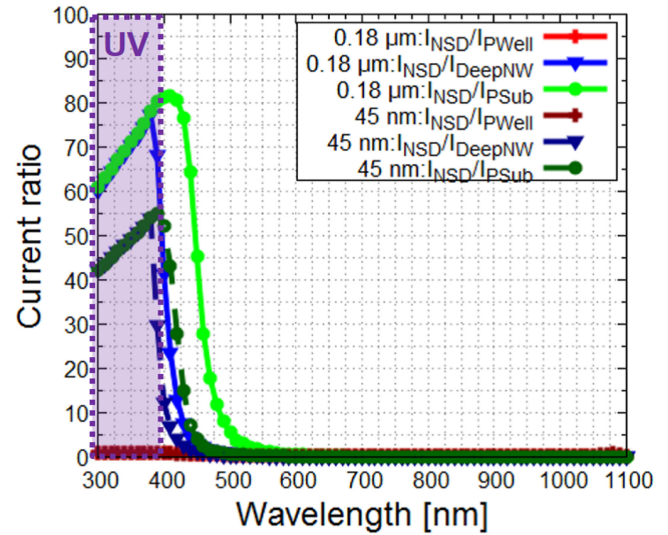
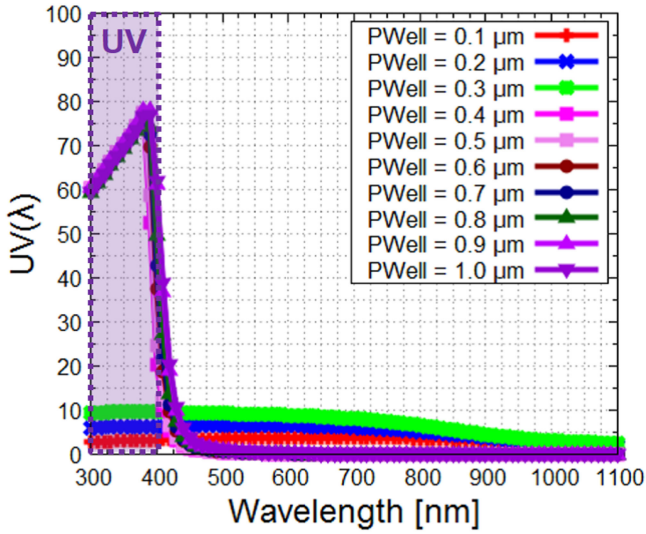
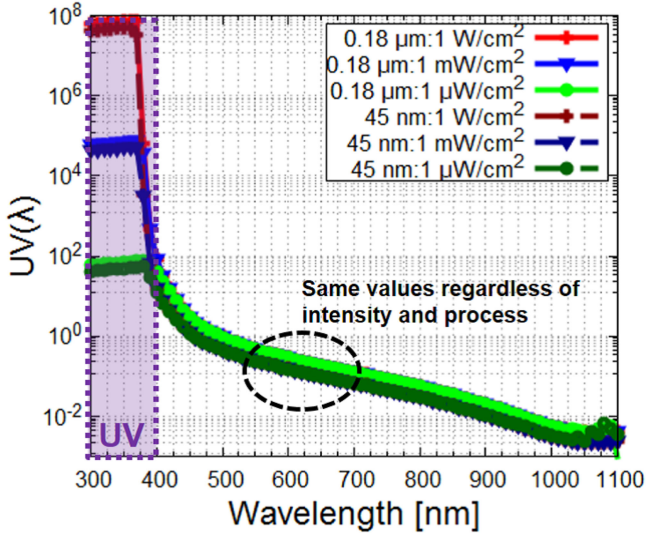


Fig. 2. Current ratios of each standard CMOS process of $0.18 \mu\text{m}$ or 45 nm .

and PSub (for p-type substrate process) are available along with consideration of the current ratio to NSD for the other three terminals.

C. Ir Sensing

The previously proposed RGB sensor was based on current rectification exploiting the advantage of the standard CMOS process and integration of diodes to eliminate the Ir region; it

Fig. 3. $UV(\lambda)$ of different PWell thickness values.Fig. 4. Intensity-dependent $UV(\lambda)$ of each standard CMOS process.

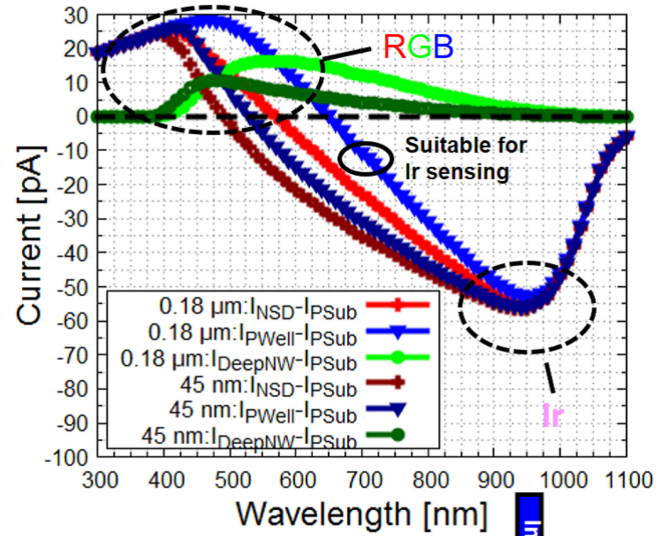
reversed the polarity of diodes, which enabled the elimination of Ir region. In addition, the complex calculation and integration with other semiconductor devices are the unique advantages of standard CMOS process fabrications.

III. RESULTS AND DISCUSSION

This study used Sentaurus Technology-Computer-Aided-Design (TCAD) software [14]. Further, modelling similar to that of the previous RGB sensor study was applied in this evaluation.

A. UV Sensing

Fig. 2 shows the evaluation of current ratio schemes with two standard CMOS processes of transistor length $0.18 \mu\text{m}$ and 45 nm . Through the calculation of the current ratio to NSD current I_{NSD} , the currents of DeepNW I_{DeepNW} and PSub

Fig. 5. Current differences of each standard CMOS process of $0.18 \mu\text{m}$ and 45 nm expanded to reverse current region and reversed current for Ir sensing.

I_{PSub} yielded high peaks in the UV region. Both processes worked well; using I_{DeepNW} is preferable to restrict the peaks within UV region. Therefore, the evaluation function $UV(\lambda)$ is determined as:

$$UV(\lambda) = I_{NSD}/I_{DeepNW}. \quad (2)$$

Here, $UV(\lambda)$ is the dimension-less.

The previous study on RGB sensor revealed that the connection of the depletion-regions can disable the functioning of the sensor. Therefore, the process parameter effect was evaluated by changing PWell thickness (the process parameters are based on those of $0.18 \mu\text{m}$ process), as shown in Fig. 3. However, an excessively thin PWell that connects depletion-regions of PWell and DeepNW is not suitable for UV sensing, similar to the case of RGB sensing. Hence, although sufficient PWell thickness enables UV sensing, UV light is absorbed in the top regions; therefore, PWell thickness can affect $UV(\lambda)$ more than the situations of RGB sensing.

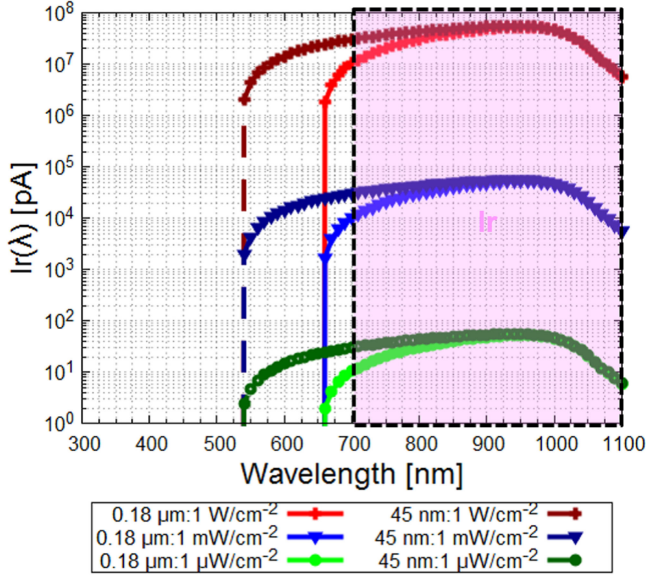


Fig. 6. Intensity-dependent $I_r(\lambda)$ of each standard CMOS process.

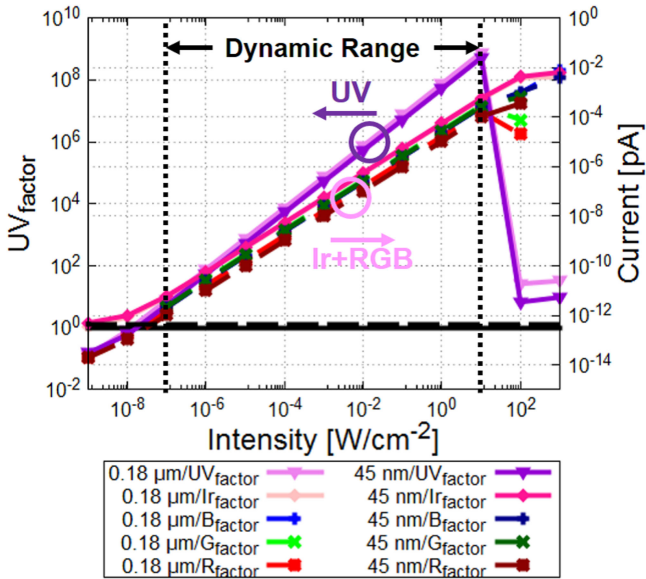


Fig. 7. Dynamic ranges of colors for each standard CMOS process.

Fig. 4 shows the intensity-dependent $UV(\lambda)$ evaluation on both $0.18 \mu\text{m}$ and 45 nm standard CMOS processes. As evident, the $UV(\lambda)$ can include the intensity information in the UV region. However, outside the UV region $UV(\lambda)$ becomes almost equal regardless of the intensity. Consequently, it is less likely to be a malfunction owing to the intensity effect.

B. Ir Sensing

The Ir sensing is based on RGB sensing scheme and eliminating the visible light response. Fig. 5 shows the wavelength responses of current differences with $0.18 \mu\text{m}$ and 45 nm CMOS processes with the expansion of the reverse current region from the study on RGB sensor [12]. Considering the reverse current,

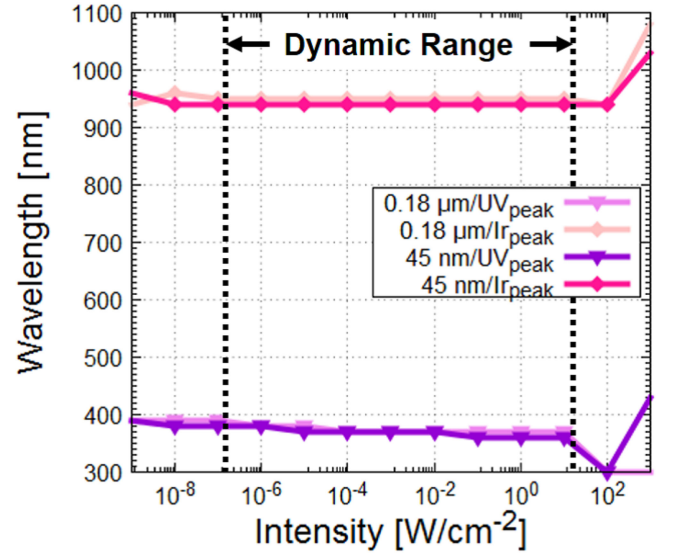


Fig. 8. Peak wavelengths corresponding to dynamic ranges for each standard CMOS process.

the peaks moved to the Ir region, approximately $900\text{--}1,000 \text{ nm}$ region, that is suitable for Ir sensing. Further, to eliminate the visible light response, the longer wavelength the contact current became smaller than that of PSub, and the use of PWell current was the best option among the three contacts. Therefore, the evaluation function $I_r(\lambda)$ is determined as

$$I_r(\lambda) = I_{PSub} - I_{PWell}. \quad (3)$$

Here, $I_r(\lambda)$ is the unit of A and becomes zero when $I_r(\lambda) < 0$. As explained in the concept level, this can easily be realized by using the diode to connect for passing the reverse current.

Regarding the $0.18 \mu\text{m}$ CMOS process, the wavelength shorter than 650 nm could be cut, and consequently, a peak at 950 nm was obtained. Comparing the peak values of the forward currents, Ir sensing exhibited a larger value among them, and better sensitivity was expected.

Fig. 6 shows the intensity-dependent $I_r(\lambda)$ for two processes and three intensities. The peak values are proportional to the intensity for two processes; therefore, the information of the wavelength and the intensity of the Ir light were appropriately sensed.

C. Sensor Designs

As we discussed in the previous work of RGB sensing [12], the sensor design must ensure the carrier separations by the multi-well structure. Too thin well thicknesses or too light doping induce the penetration of the depletion regions and generated carriers will pass through to the substrate region which this brings the malfunction.

The dynamic range is the important factor in sensing, and Fig. 7 shows every five colors of UV, Ir and RGB (from the previous work [12]) for each $0.18 \mu\text{m}$ and 45 nm CMOS process, respectively. The same high dynamic ranges of 160 dB are ensured both to UV and Ir which provide the high performances

for sensing. The corresponding peak wavelengths of both UV and Ir are shown in Fig. 8. Within the dynamic range regions, almost the constant corresponding wavelengths are ensured and avoids for confusing to other colors of RGB.

The proposed sensor is designed on standard CMOS processes, and the resolution of the sensing will be dependent on the process technologies. Here, for improving the resolution our sensor can be free from the limitation of formation of the color filters that are used on the previous sensor designs; the conventional RGB sensor uses tiled color filter patterns that needs the larger area for one element on the contrary our sensor can concentrate all the RGB, UV and Ir sensor to one vertical structure (and some nanometer-scale transistors, which they are much small compared to the sensor itself). In summary, our proposed sensor design not only enhances the applications of devices but also increases the resolution of optical sensing.

IV. CONCLUSION

This study proposed a concept for UV and Ir sensing using the standard CMOS process. It involved considering the current ratio for UV and using a rectifier, such as diode, to eliminate the visible light for Ir. Moreover, the detections were realized without any filters that pass a certain wavelength. Consequently, combining a previously proposed method for RGB sensing, RGB+UV+Ir sensing without any filters using the standard CMOS process could be achieved. High dynamic ranges of 160 dB are ensured for all five colors of UV, Ir and RGB which they provide the high performances of color sensing.

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