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CMOS-integrated optical power transfer for an ultra-small wireless implantable devices

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Abstract

We developed a CMOS optical power receiver chip with integrated photovoltaic cells. The chip was designed to drive an InGaN blue LED for optogenetic stimulation. To realize a high-voltage PV current generation, we used Bosch process to separate the integrated PV cells on the CMOS chip. We confirmed the expected functionality of the CMOS-based power receiver, and realized the ultra-small implantable optogenetic stimulator. Then we designed a next-generation CMOS chip with regulated LED current for well-controlled operation.

1. Introduction

Optogenetics is a set of bioscientific and engineering technologies in which photosensitive proteins are introduced into biological cells by means of genetics. It gives new types of neural stimulation strategies using light. In optogenetics, not only genetic methodology, but also technologies for optical stimulation technology plays essential roles.

In the first stage of the optogenetics, light delivery using fiber-optics was used to demonstrate the concept. Then, to overcome the limitations such as low resolution or an external fiber-tethering, various kinds of wireless optical stimulation systems have been proposed and demonstrated.

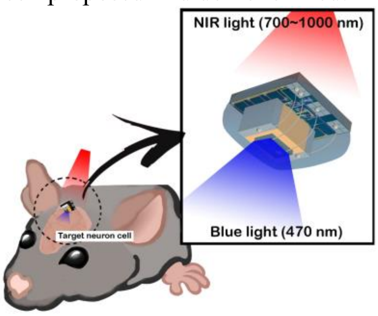


Fig. 1 Concept of the ultra-small, optically-driven implantable optogenetic stimulator.

In previous work, we have proposed and demonstrated a CMOS-based optical energy harvesting with multiple small photovoltaic (PV) cells [1]. In this work, we integrated the PV cells onto the CMOS chip and realized a small optical power receiver chip. The optical power receiver chip has a capability of driving an InGaN blue light-emitting diode (LED). The target application of the CMOS chip is a ultra-small (~1 mm dimensions), fully-wireless implantable optogenetic stimulator. Figure 1 shows the concept of the proposed wireless optogenetic stimulator. This device is expected to be used in various optogenetic experiments using animals in free-moving situations.

In this paper, we present the design of the CMOS chip, device packaging and a functional demonstration. We also present a next-generation CMOS chip with improved functionality.

2. Device design and fabrication

Basic concept of CMOS-integrated on-chip PV cells for optical wireless power transfer

In this study, to realize an ultra-small implantable optogenetic stimulator shown in Fig. 1, we integrated the PV cells onto the CMOS chip. We used a 0.35 μm standard CMOS process for this work. In this CMOS process, pn junction with the largest PV efficiency is Nwell – Psub structure. However, the p-sub is a chip-wide common structure and inevitably shorted, as shown in Fig. 2 (a). In this work, we introduced a post-CMOS Bosch process to separate the on-chip PV cells (Fig. 2(b)).

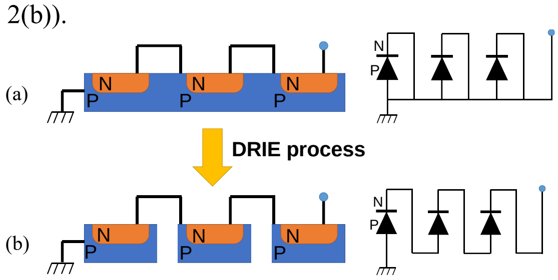


Fig. 2 Cross-sectional structures of the CMOS chip, (a) as-fabricated and (b) after the Bosch process.

Design of the CMOS optical power receiver chip

Figure 3 a shows block diagram of the CMOS optical power receiver chip with the integrated PV cells [2]. The CMOS chip consists of a self-powered voltage detector and a CMOS switch and the integrated PV cells. We configured 10-series on-chip PV cells to obtain the operating power of the system, and 7-series cells to obtain bias voltages for the CMOS control circuit.

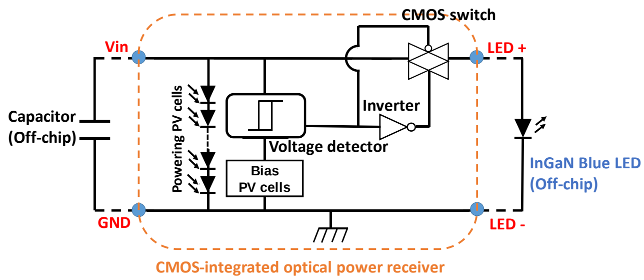
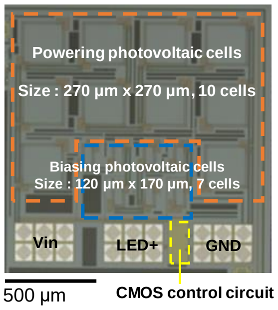
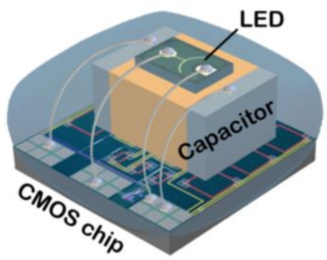


Fig. 3 Block diagram of the proposed optically-powered, implantable optogenetic stimulator.

An operation of the circuit starts with charging an external capacitor with the current generated by the integrated PV cells until the voltage of the capacitor reaches V_{TH}. Then, voltage detector turns on a CMOS switch and supplies power to the target circuit (an InGaN blue LED in this work). After that, when voltage of the capacitor drops to V_{TL}, voltage detector turns off the CMOS switch and stops to supply power to the target circuit. Figure 4 shows a layout of the CMOS chip, and Table 1 shows specifications of the chip.





(Left) Fig. 4 Layout of the CMOS optical power receiver.
(Right) Fig. 5 The structure of the device

Table 1 Specification of the CMOS chip

Technology	0.35 µm 2-poly 4-metal std, CMOS process
Chip size	1.25 mm × 1.25 mm
Photodiodes	Nwell-Psub
Operating voltage	3.0～4.0 V
Number of pads	3
Terminals	Vin, GND, LED+

Device structure and packaging process

We set the target protein of the optogenetic stimulation as ChR2, which is one of the commonly used in optogenetics. We chose an InGaN LED with an emission peak around 470 nm. The device consists of 3 components. Figure 5 shows the structure of the device. The components were bonded using epoxy resin, and connected with Al wire. Finally, the whole device was molded by epoxy or acryl resin. Figure 6 shows the photographs of the assembled device.

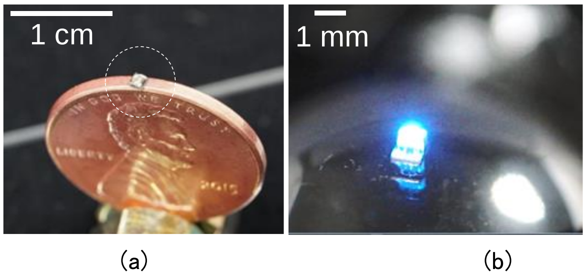


Fig. 6 (a) The assembled device placed on edge of US one cent coin, and (b) the device in operation.

3. Functional evaluation and improved CMOS design

Functional demonstration

We operated the system shown in Fig, 3 in both bench-top and assembled (Figs. 5, 6) conditions [2]. We successfully operated the blue LED with capacitances in a range between 1 and 10 µF. We confirmed the device can be operated by 860 nm infrared (IR) light with illumination less than 1 mW/mm^2. The peak emission intensity exceeds 10 mW/mm^2 which is typically required in optogenetic stimulations. These results prove the concept of the optical power transfer with the CMOS-integrated PV cells.

CMOS chip with improved functionality

In the present CMOS design, no current-regulating function is integrated in the CMOS control circuit. It leads to a high-intensity, very-short pulse. The pulse duration is as short as 1 ms or less. To use the energy charged in the capacitor efficiently, we integrated the current-regulating function on the CMOS chip.

Figure 7 shows block diagram and layout of the next-generation CMOS chip. The current-limitation was realized by introducing NMOS current source at the cathodic side of the LED. We configured four LED- terminals with preset currents of 200µA, 500 µA, 1mA, and 2mA. We can choose one of the LED- pad in the packaging phase.

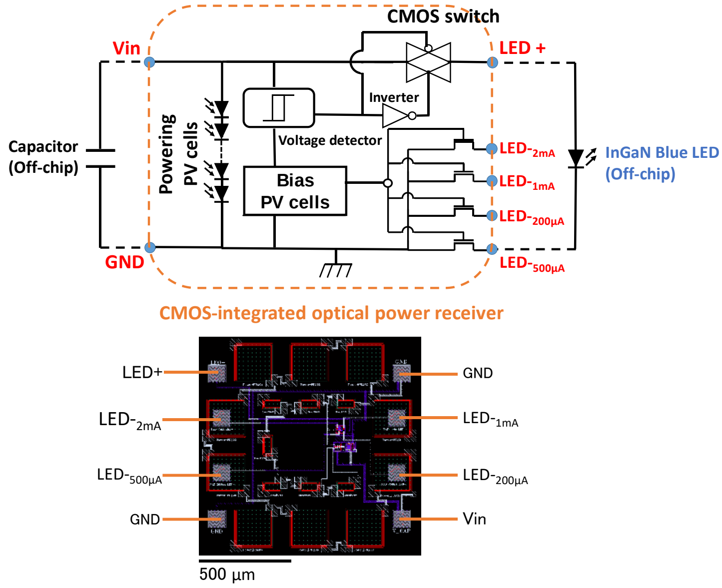


Fig. 7 A Block diagram and layout of the CMOS chip with LED current regulation

4. Conclusion

We proposed and realized a CMOS-based optical power receiver with on-chip integrated PV cells. The technology is suitable for ultra-small wireless electronics such as implantable devices. We realized an ultra-small implantable optogenetic stimulator that can be wirelessly operated by IR light.

After demonstrating the device functionality, we designed an improved CMOS chip with regulated LED current, which gives well-defined emission power and pulse duration.

Acknowledgements

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