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A Conceptual Investigation at the Interface between Wireless Power Devices and CMOS Neuron IC for Retinal Image Acquisition

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Abstract: In this paper, a conceptual investigation of the interface between wireless power devices and a retina complementary metal oxide semiconductor (CMOS) neuron integrated circuit (IC) have been presented. The proposed investigation consists of three designs: design-I, design-II, and design-III. Design-I involves a slotted loop monopole antenna as per American National Standards Institute (ANSI) guidelines, which achieve an ultra-wide band ranging from 3.1 GHz to 10.6 GHz. The biocompatible antenna is made on silicon-nitride substrate using on-wafer packaging technology and it is used as a receiver device. The performance of antenna provides a wideband, sufficient power to receive, and low losses due to the avoidance of printed circuit board (PCB) fabrication. A CMOS based multi-stack power harvesting circuit achieves the output power ranging from 4 mW to 2.7 W and corresponds from the selected Radio Frequency (RF) bands of loop antenna is exhibited in design-II. The power efficiency of 40% to 82%, with respect to output powers of 4 mW to 2.7 W, is achieved. Design-III includes a CMOS based retina neuron circuit that employs a dynamic feedback technique and support to achieve the number of read-out spikes. At the end of the interface between wireless power devices and a CMOS retina neuron IC, 50 mV read-out spikes are achieved, with varying light intensity, from 0 mW/cm² to 2 mW/cm². The proposed design-II and design-III are implemented and fabricated using commercial CMOS 0.065 μ m, Samsung process. The antenna and RF power harvesting IC could be placed on a contact lens platform while retina neuron IC can be implanted after ganglions cells inside the eye. The antenna and harvesting IC are physically connected to the retina circuit in the form of light. This conceptual investigation could support medical professionals in achieving an interfacing approach to restore the image visualization.

Keywords: integrated circuit (IC); CMOS (complementary metal oxide semiconductor); image acquisition; retina neuron; wireless power devices; on-wafer antenna; RF power harvesting

1. Introduction

A recent survey about the retinal prosthesis has shown a great interest towards wireless power devices, such as RF antenna and RF harvester IC to restore the image vision for blind people. However, once these wireless power devices are placed on transparent contact lens they could enable the implanted neuron ICs through wireless approach without any cost of external power or battery. The image vision depends upon interior functions of the retina, which respond through light from photoreceptors to the ganglion cells. There are several retina diseases, such as retinal degenerative (RD), retinitis pigmentosa (RP), and age-related macular degeneration (AMD), which are leading

causes of blindness, affecting millions worldwide [1]. In order to guard clear vision of blind people, recent technologies required to integrate biological sensors and telemetry. Moreover, an active lens could be used to provide a new tool/methods for research studies without the need for lab chemistry or needles [2]. Figure 1 shows the conceptual layout of wireless interfacing between RF power devices and CMOS neuron IC. The fact is that a contact lens placed exterior to eye could capture image information from the RF wireless video camera, which can pass through the antenna and the RF power harvester IC. The harvested power penetrates into contact lens in the form of light, which passes through photoreceptors to the ganglion cells inside the human eye where retina neuron IC provides appropriate magnitude of read-out spikes for biological image acquisition. The dashed marked figure shows signal flow process from photoreceptors to the brain [3].

Figure 1. A conceptual layout at the interface between wireless power devices and complementary metal oxide semiconductor (CMOS) retina neuron integrated circuit (IC) for image acquisition.

A wireless power from external sources has been utilized for stimulation implant in [4–6]. However, some more reported works have shown interest for various applications, such as retinal prosthesis, neural stimulation, and neural recording. For that purpose, they used inductive coupling coil technique for delivering power and telemetry where data rate and size were not suitable for implantation. From [7–18], a fully integrated retinal stimulator has been implemented. It enables the new techniques for retinal prosthetic device by adopting the mixed-voltage design, empowering the flexible stimulation patterns, and enhancing the stimulation channels. Moreover, recent technologies offer smart and transparent contact vision lens that fast replaces the bulky inductive coils and the non-scalable implant sizes. In order to build a better display, newly developed contact lens could be used as a platform where devices can be remotely powered, communicate with cell phone, and continuously provide the user with appropriate information. In [19–21], active lens has initially focused on medical monitoring application by developing an embedded sensor on a contact lens. Moreover, to the best of the authors' knowledge, a fully autonomous integrated system on the retina vision using interfacing approach has not been developed yet. For example, Leonardiet al. [19] have demonstrated an embedded Micro-Electro-Mechanical Systems (MEMS) strain gauge sensor on a contact lens for measuring intraocular pressure. However, the device does not incorporate a telemetry chip and the sensor readout interface involves wired connection to the lens. In [20], the single chip intraocular pressure sensor implanted in the eye's lens had been powered using a 13.56 MHz inductive link with the external unit embedded in spectacle frame. Inductive links offer a relatively short range of operation and the external reader unit needs to be mounted close to the eye. In [21], authors have developed a capacitive pressure sensor on lens but could not implement a read-out circuitry.

This paper reports an empirical and conceptual investigation at the interface between wireless power transfer and CMOS neuron IC for retinal image acquisition for the first time. The proposed implementation includes a wireless antenna, RF power harvester, and retina neuron circuit. The on-wafer antenna and RF power harvester IC could be placed on contact lens, which delivers light source to the photoreceptor into retinal circuit. The work is organized as follows: Section 2 involves concepts of integration strategy, design, and performance evaluation of on-wafer antenna, RF power harvester circuit, and retina neuron IC. The result and discussion of CMOS neuron IC is given in Section 3, followed by conclusion in Section 4.

2. Design and Implementation

A typical block strategy of wireless power transfer and CMOS neuron IC that provides interested interfacing are shown in Figure 2. The antenna, RF power harvesting, and retina neuron circuit are interfacing between them through wireless power transfer. The full integration structure provides exterior part (outside the contact lens) and interior part (after ganglion cell inside the eye) for retinal image processing. The antenna receives RF signals from video camera and sends to the power harvester circuit for appropriate Direct Current (DC) power. Finally, CMOS neuron retina provides read-out spikes with respect to intensity of light.

Figure 2. Proposed block diagram at the interface between wireless power devices and CMOS neuron IC.

The transmission method of power and data transfer between devices on contact lens and implant device inside eye mainly depend upon light, which carries a packet of information for image acquisition by retina. In order to maintain safety standards, RF telemetry has been employed on contact lens where antenna delivers the RF power to harvest circuit. The harvesting circuit provides DC power to custom micro-light-emitting diode (μ -LED). The μ -LED is mainly responsible for light production and transmission. Once light passes through ganglion, amacrine, bipolar, horizontal cells, and photoreceptors, it eventually stimulates the photoreceptors that convert it into electrical signals. These photoreceptors generate signals that are transmitted through an intermediate layer of neurons to the ganglion cells. Finally, they would propagate the information to the optic nerve and then to the brain in form of action potentials. These action potentials in form of output spikes are generated by neuron retina circuit. Section 2.1 provides antenna design and its performance evaluation, while analysis and implementation of RF power harvesting circuit is discussed in Section 2.2. A retina neuron circuit that provides event matrix of read-out spikes will be discussed in Section 2.3.

2.1. Antenna Design-I with Performance Evaluation

A small electrical loop microstrip antenna is one of the excellent choices to fix on contact lens platform for receiving RF image without implant inside the human eye. As per ANSI guidelines, any device implantation has a frequency limit, beyond that it is harmless for human tissues. The Federal Communications Commission (FCC) approved an ultra-wide band (UWB) frequency range from 3.1 GHz to 10.6 GHz. UWB antenna design offers various advantages over narrowband systems,

such as small size, low power consumption, higher bit rates, and highly integrated systems [22–24]. Here, one important point is that the designed small loop antenna could be placed on a glass contact lens instead of an implanted one. Meanwhile, this work designed a small loop antenna by following ANSI and FCC medical guidelines. Two major issues are concerned when medical professionals need to adopt technology and advancement for retinal prosthesis. First, the size of device should be at least half of the standard contact lens of the human eye. Second, the device should be biocompatible because it needs to be worn for a longer time. With concern of the first point, antenna design has to be chosen as a slotted loop monopole antenna with operating frequency of 3.5 GHz. The reason for considering the operating frequency of 3.5 GHz is to achieve maximum radiation efficiency at lower band of operation. The antenna is fabricated using on-wafer packaging technology to achieve an adequate size in place of using printed circuit board (PCB) substrate. Silicon-nitride wafer in 5 mm diameter is taken to design the antenna because of biocompatibility. The primary challenge for designing a small antenna relies on achieving sufficient antenna efficiency. However, the efficiency will drop if antenna size is smaller than electromagnetic wave length. Therefore, a high frequency is considered in order to achieve sufficient efficiency from the small loop antenna. The proposed three-dimensional (3D) isometric view of the small electrically antenna is shown in Figure 3a, while its fabrication view is shown in Figure 3b. The antenna design consists of cross shape slot on the loop patch while monopole (or defected) on the ground plane. The antenna design is implemented on the silicon nitride wafer having (dielectric constant (ϵ_o) of 5.6, loss tangent ($\tan\rho$) of 0.0028 and thickness of 200 μm) at 3.5 GHz, respectively. The dimension of the on-wafer antenna is 4 mm $\times$ 3.7 mm, which is less when compared to PCB-fabricated UWB antennas. The fabrication of antenna uses high-resistivity silicon nitride (HRSiN) substrate based on wafer-level packaging technology (WLP). The proposed antenna consists of 50 mm HRSiN on-chip layer, one solder layer, and one 45 mm HRSiN substrate carrying patch layer and feeding structure with WLP technology. An antenna is excited using microstrip feed whose dimensions are measured from edge of the patch and the ground. The full wave simulation of proposed antenna is carried out on Advanced Design System (ADS) v. 2019 using a microwave momentum electromagnetic field (EM) package. The characterization of the antenna design commences with its wideband performance, which is evaluated on the basis of electromagnetic field (EM) analysis, and can be seen in Figure 4. The simulated and measured return loss variation, with respect to frequency, is shown in Figure 4a where wideband performance is achieved from 3.1 GHz to 10.7 GHz with multi-resonating frequencies.

Figure 3. Proposed slotted small loop antenna with its (a) isometric view and (b) fabricated view.

(a)

(b)

(c)

(d)

Figure 4. The performance of the proposed antenna with its (a) return loss versus frequency, (b) antenna received power, (c) antenna efficiency, and (d) tilt angle of receiver antenna.

The reported literature based on slotted patch antenna has observed that lower and higher frequency bands are affected when slot elements are embedded on the antenna geometry because of disturbance in surface current directions on the patch and the ground plane. Figure 4b shows the plot of received antenna power from wireless video camera. Here, we have considered video camera as RF wireless device, which can transmit a power of 242 mW towards the antenna while maximum received antenna power of 29 mW is achieved at the desired frequency of operation. The received power of the antenna is measured using video camera (Canon High-definition (HD) RF GHz wireless, Ōta, Tokyo, Japan), power meter (N8262A P-series), and vector network analyzer (VNA) (Keysight Technologies, 8722ES, Santa Rosa, CA, United States) hardware set-ups. The simulated and measured antenna power are made good correlation with each other. The antenna efficiency variation with respect to frequency is illustrated in Figure 4c. The maximum antenna efficiency of 70% is observed within ultra-wide band of performance. The most important tilt angle of receiving antenna is plotting in Figure 4d. The title angle shows an equal radiated power from -90° to 90° in both direction (top and bottom). The measurement is done by using Keysight Technologies' vector network analyzer (VNA) (Keysight Technologies, 8722ES, Santa Rosa, CA, USA) with proper calibration. Tilt angle is measured by using small anechoic chamber under the environmental conditions.

2.2. RF Power Harvesting Design-II

This subsection investigates the power harvesting method from the wireless radio frequency (RF) wideband of operations. It is well known that RF wireless power harvesting holds vast potential for replacing batteries or increasing life spans. Therefore, this research work introduces a CMOS based RF power harvesting circuit; the schematic is shown in Figure 5a. The architecture of CMOS IC consists of power harvesting stages, storage capacitors, and filtering network. The corresponding noise power is achieved at the output when frequency bands are considered in division stages and they are varied at the input of power harvester circuit stages. Finally, smooth and regulated DC output powers are obtained at the output of T-shape filtering network ranging from mW to Watt. An efficient rectifier, on-chip capacitor, and robust power are essential for RF power harvesting system. In order to avoid the junction and oxide breakdown of the transistors in previous metal oxide semiconductor (MOS) technologies, we employ the new rectifier scheme as shown in Figure 5a.

Figure 5. Cont.

Figure 5. Proposed RF power harvesting circuit with its (a) schematic and (b) die microchip photograph (including on-chip antenna).

To enhance the rectifier sensitivity, using CMOS process provides a lower threshold operation for the diodes that are realized using P-type metal oxide semiconductor (PMOS) transistors, where the body terminal tied to the source in order to eliminate the body effect. The considered threshold voltage operation of the PMOS transistor in forward bias can be expressed as in (1) [25].

$$V_{thp} = V_{th0p} - \gamma \left(\sqrt{|2\phi_F - V_{sb}|} - \sqrt{|2\phi_F|} \right) \quad (1)$$

where V_{th0p} is zero threshold voltage when substrate voltage (V_{sb}) is zero, γ is the body effect coefficient, and $2\phi_F$ is the surface potential. The considered drain current operation for PMOS transistors for calculating power at each stage can be expressed as in (2).

$$I_{ds} = I_B \left(\frac{W}{L} \right) \left(e^{\left(\frac{V_d}{n\phi_t} \right)} - e^{\left(-\frac{(n-1)V_d}{n\phi_t} \right)} \right) \quad (2)$$

where V_d is drain voltage I_{ds} is the current through channel of the transistor with its negative direction from drain to source, W is the channel width, L is the channel length, ϕ_t is the thermal voltage and equals to 26 mV at room temperature and n is the slope factor, respectively. The proposed schematic consists of stacked power harvesting stages because it avoids additional DC power losses and provides a power combining technique. Here, it is noted that the reason for choosing a two stage stacked techniques is to maintain a design trade-off between output power and impedance matching. In power harvesting circuit, each stage consists of four diode-connected transistors named as M1 to M4 and M1' to M4', respectively. The coupling capacitors C1 to C4 pass the RF signals that correspond to each stage to provide an unregulated DC signals. The T-network employed for filter operation corresponds to unregulated DC signals and obtains the regulated output DC power ranging from milliWatt to Watt. A schematic of power harvesting circuit is analyzed and implemented using commercial CMOS process design kit on Advanced Design RF Simulator (ADS), which can be seen in Figure 5a. While the microchip photograph of the power harvester circuit along with on-chip antenna in single platform IC is shown in Figure 5b where on-chip filtering network takes only 12% area of the whole chip. The chip fabrication is done by using commercial 65 nm Samsung CMOS process. The fabrication of metal-insulator-metal layer is employed for the passive components. The area of the on-chip antenna and power harvesting IC are calculated as $1.4 \times 2.3 \text{ mm}^2$. The chip measurement is done using Agilent power meter where output powers are measured with respect to frequency bands ranging from 3 GHz to 5.5 GHz, 5.5 GHz to 7.5 GHz and 7.5 GHz to 10.5 GHz, respectively. Therefore, the corresponding output powers of 4 mW to 7.5 mW, 7 mW to 0.1 mW, and 0 mW to 2.7 W are achieved when input power is considered as 0dBm. The measured and simulated results of output powers are shown in

Figure 6a–c respectively. In addition, the plot of harvested efficiency is shown in Figure 7. The output powers ranging from 4 mW to 2.7 W corresponds to power efficiency of 40% to 82%. The interesting point is that efficiency linearly increases with the increase of output power from millimeter watt-to-watt range. The reason for that is due to multi-stacking technique of harvesting circuit, which reduces the power losses and diminishes the parasitic interconnects. The dimension values of each component used in power harvesting circuit are shown in Table 1.

Figure 6. Plot of output power with respect to frequency ranging from (a) 3 GHz to 5.5 GHz, (b) 5.5 GHz to 7.5 GHz, and (c) 7.5 GHz to 10.5 GHz.

Figure 7. Variation of efficiency with respect to output power.

Table 1. The dimensions values of each component in power harvester IC.

Component	Dimension
M1	40/0.18 μm
M2	23.5/0.18 μm
M3	112/0.18 μm
M4	58/0.18 μm
M1'	38/0.18 μm
M2'	23.5/0.18 μm
M3'	10/0.18 μm
M4'	28/0.18 μm
C1	46 pF
C2	10 pF
C3	12 pF
C4	80 pF
C5	20 fF
L1	0.5 nH
L2	0.267 nH
C'	112 fF

2.3. CMOS Retina Neuron IC: Design-III

This subsection demonstrates the empirical and experimental demonstration of CMOS retina circuit for retinal image acquisition. The analysis of CMOS retina circuit consists of current event generator, current mirror, and dynamic feedback stage that can be seen in Figure 8a. The CMOS based neuron retina circuit employs a photosensitive element as photodiode. Basically, an image address-event representation (AER) is employed for biological image acquisition. In AER, a sequence of pulses or spikes is formed at the output by information where analog value of the data being transmitted is encoded by spike frequency or intervals. The data is encoded in form of digital pulses using step-forward encoding method (SW), which is immune to noise. SW encoding is easy to optimize and effective method compared to other methods such as threshold-based and moving-window [26]. The requirement of retina neuron for high resolution of image acquisition, which could be accomplished by using a technique as employed here into retina circuit. A conceptual investigation after wireless power transfer is discussed here. In fact, the contact lens ICs can receive RF based signal information for image visualization. This image-based information could reach to the interior of human eye where CMOS neuron IC can read number of read-out spikes as image in the form of light. The theoretical approach of current mirror block neuron circuit provides an output as read-out spikes. It is observed that amplitude of read-out spikes depends on two parameters: (1) light intensity, which applies to the photodiode. Here it is produced by using a custom off-chip $\mu\text{-LED}$. The custom $\mu\text{-LED}$ is a power hungry device, which receives the power from harvesting IC. The power is extracted from the RF harvesting circuit that varies from 4 mW to 2.7 W. This large variation of power when applied to the $\mu\text{-LED}$ produces light. The light intensity of 0 W/cm² to 2.7 W/cm² given to the photodiode of neuron circuit, achieves reduction in the amplitude of read-out spikes that are about to be 60.9% as compared to the existing one, and (2) control voltage, which introduces a controlled pole for promoting the amplitude tuning mechanism. It is observed that variation in control voltage gives indirect impact on the threshold voltage of M9 transistor that can be expressed as in Equation (3).

$$V_{T9} = V_{T90} + \gamma \left(\sqrt{2\phi_F - V_0} - \sqrt{2\phi_F} \right) \quad (3)$$

where V_{T90} is the zero-bias threshold voltage of M9, γ is body coefficient whose expression $\left(\gamma = \frac{\sqrt{2q\epsilon_{\text{substrate}}P_{\text{substrate}}}}{C_{\text{ox}}} \right)$, ϕ_F is the fermi potential and V_0 is the inverter output, respectively. This variation of threshold voltage increases the threshold current of all transistors from M9 to

M11. Due to this, amplitude of read-out spikes can be tuned. The tuned amplitude basically depends upon transfer function $h(s)$ of the closed loop M8 and M9, and which can be expressed in Equation (4).

$$h(s) = \frac{A(s)}{1 + A(s)\beta(s)} \quad (4)$$

where

$$\beta(s) = \left(\frac{g_{m,M9}}{g_{m,M11}} \right) \left(\frac{Y_A}{Y_A + Y_B} \right) \quad (5)$$

$g_{m,M9}$ and $g_{m,M11}$ are the transconductance of M9 and M11 while $\left(\frac{Y_A}{Y_A + Y_B} \right)$ term is fractional admittance of dynamic feedback stage. The ratio of $\left(\frac{g_{m,M9}}{g_{m,M11}} \right)$ plays an important role for controlled pole, which provides an amplitude tuning mechanism in the read-out spikes. This amplitude tuning mechanism could provide better retinal image acquisition by selection of appropriate voltage. The layout and fabricated chip photograph of retina neuron IC are shown in Figure 8b,c, respectively. The chip area of retina circuit is calculated as $1.1 \times 2.1 \text{ mm}^2$.

Figure 8. Cont.

Figure 8. CMOS retina neuron IC with its (a) schematic, (b) layout, and (c) microchip photograph.

3. Results and Discussion

This section includes results and discussion of CMOS retina neuron IC that supports photoreceptors for retinal image acquisition. The four main challenges incur when slotted loop antenna, RF power harvesting IC, and retina circuit are inducted in an integration manner as well as interfacing approach: (1) to choose appropriate antenna, which can receive RF signals in the desired direction; (2) RF power harvester circuit should meet the biocompatibility requirements for retina neuron IC; (3) it is important to deliver sufficient energy to the photodiode of neuron circuit for appropriate selection in magnitude of read-out spikes; and (4) optimized process for heterogeneous integration of components. It is important to note that the area of slotted antenna and RF power harvester IC are obtained according to general dimensions of contact lens. Generally, the area of standard contact lens is about 1 cm^2 with total thickness of about $200 \text{ }\mu\text{m}$. The calculated area of small electrical antenna is about 4 mm^2 with thickness of 0.12 mm , while the area of power harvester IC is 1.2 mm^2 . The measurement set-up of interfacing between the wireless power devices and the CMOS neuron IC is shown in Figure 9a where performance of antenna is measured using Agilent vector network analyzer with port 1 and achieves wide band performance from 3.1 GHz to 10.7 GHz . Another port 2 of the network analyzer is used for input selection of the power harvesting circuit where we choose resonating frequencies for each band at the input port of the RF harvester chip. The harvested power measured from the power meter using channel A and B are delivered to the neuron circuit IC via off-chip $\mu\text{-LED}$ that provides light to the photodiode. The neuron retina chip provides read-out spikes varied according to light intensity is controlled by the control voltage. The measured read-out spikes is shown in Figure 9b where 50 mV of amplitude is an appropriate choice for better resolution of image acquisition while the power or light intensity is varied from 0 W/cm^2 to 2 W/cm^2 , respectively. The considered image is aligned along XY plane that shows the alphabetical letters. It is observed that better resolution of letters has been received by retina when 50 mV amplitude of read-out spikes is tuned, otherwise it would provide low resolution if other amplitude is selected. For example, low resolution of image can be seen in Figure 9c when 110 mV of amplitude is taken. Consequently, it is clear at the observation point that selection of amplitudes of read-out spikes is very important parameter for retinal image acquisition. Moreover, the power consumption of retina neuron IC is illustrated in Figure 9d. The lowest value of power consumption 110 nW has been achieved, which made good agreement with simulated one. The performance comparison of current works with other reported ones are shown in Table 2.

Figure 9. (a) Experimental investigation at the interface between wireless power devices and CMOS neuron IC, (b) retinal image acquisition where magnitude of read-out spikes is 50 mV, (c) retinal image acquisition where magnitude of read-out spikes is 110 mV, and (d) power consumption.

4. Conclusions

This work investigated conceptual and empirical interfacing between wireless power devices and CMOS neuron IC for retinal image processing. The proposed work involved three different architectures, i.e., slotted antenna, RF power harvesting, and retina neuron circuit, all of them work out to be for retinal image visualization. The slotted antenna achieved an ultra-wideband performance ranging from 3.1 GHz to 10.7 GHz while RF power harvesting circuit acts as a rectifier that yields output power using wideband of operation. Finally, the harvested power delivered to the neuron retina circuit provides a read-out spike voltage. The retinal image acquisition using proposed interfacing achieved an improvement of about 60.9%. In the future, we plan to implant our proposed system to the patient by stimulating the ganglion cell through implantation of multi-electrode arrays.

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