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OPTICALLY POWERED ENERGY SOURCE IN A STANDARD CMOS PROCESS FOR INTEGRATION IN SMART DUST APPLICATIONS

AMIT KUMAR SINGH[1]

ECE Department, Bheemanna Khandre Institute of Technology Bhalki, Karnataka, India

ABSTRACT

Sensors are available in the form of micro size. In order to miniaturize NANO-power sensor nodes or smart dust, an industrial development power saving is one of the most important task so, in this paper enhancement of optically powered energy source is developed to replace traditional batteries or solar cells. This energy source consists of two photodiodes, which are P-well/DN-well and N-well/P-sub. The two photodiodes with an area of 1.5mm2 were fabricated using the UMC 0.25µm CMOS process and tested using an 830nm laser. Measurement results show that the energy source is able to generate a voltage from 0.5V to 0.8V with a 3.5% conversion efficiency. The proposed energy source was made using a standard CMOS process and therefore can to be integrated with the smart dust circuit on a single chip. This paper present the standard CMOS process for integration of smart dust and its industrial application.

KEYWORDS: Smartdust,CMOSProcess,NANO-powersensornodes

The new trend in the development of sensor nodes for wireless sensor networks is towards ultra-low power design, size reduction, and the ability of scavenging power. As a result some sensors and communication circuits have been realized consuming NANO-watts. When a node integrates self-contained sensing and communication system into a cubic-millimeter mote, it is called “Smart Dust”. Smart dust normally obtains energy from batteries or solar cells, which occupy a significant volume. To reduce the size of smart dust and scavenge power, the energy source can be implemented using photodiodes integrated on to the same CMOS chip as the smart dust circuits and supply the power to support the circuit’s operation. Photodiodes in the standard CMOS process have various applications. Image sensors are usually made from shallow p-n junctions, which can realize a linear response or a logarithmic response. The optical short-distance interconnects, such as board-to-board and chip-to-chip communications, use avalanche photodiodes for high speed data transmission, which are implemented by deep p-n junctions. Two previous papers have described photodiodes used to create an on-chip power source. One of these power sources consisted of two stages. The first stage includes a few P+/N-well photodiodes connected in parallel and then they are series connected to one P+/N-well photodiode in the second stage [17]. This consumes a large chip-area and a low energy conversion efficiency of 3% is obtained. In simulation results show that a two-diode voltage can be achieved by series connections of three desired p-n junctions located along a vertical line. However, the total available current of the source is small for long wavelength light illumination because it is limited by the shallow junction quantum efficiency. This paper presents an optically powered energy source in a standard CMOS process that is specifically designed to generate power from long wavelength light and is organized as follows.

CONFIGURATION OF ENERGY SOURCE

Optical wireless communications often use invisible near infrared wavelengths and an 830nm laser was therefore selected as the wavelength for communication to a smart dust node. In addition to receiving the optical signal the smart dust has been designed to generate power from the laser illumination. When a photodiode is under illumination, the voltage difference across the photodiode terminals is given by equation (1).

$$V_{Photodiode} = V_T\left(\frac{I_{ph}-I_l}{I_T}+1\right) \quad (1)$$

Where IT is the reverse saturation current of the diode, VT is thermal voltage which is approximately 25.9mV at 300 K, Iph is the generated photocurrent and IL is the load current. The photocurrent for a particular optical power is then a function of quantum efficiency of the photodiode.

QE(λ)=*(Nelectrons/Nphotons)=(hcIph/λqPop)(2)*

[1]**Corresponding author**

Where h is the Plank's constant, c is the speed of light, λ is the wavelength of the beam, Popt is the optical power received by the power photodiode and q is the electron charge. The absorption of light, and hence the quantum efficiency of a photodiode, then depends on the photon absorption coefficient of silicon and the thickness of the material. The number of absorbed photons Fabs(λ) is given by

$$_{abs}(\lambda) = F_0(\lambda)\,(1 - R(\lambda))\left(1 - e^{-\alpha(\lambda)x}\right) \quad (3)$$

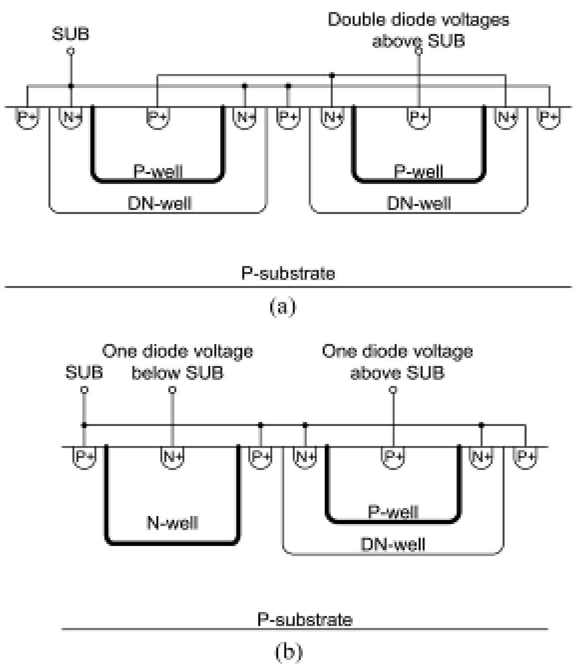

Figure 1: (a) 2 P-well/DN-wells. (b) N-well/P-sub and P-well/DN-well. All the bold lines in the figure represent the active junctions we use

where $F_0(\lambda)$ is the number of photons incident on the surface, $R(\lambda)$ is the fraction of photons reflected from the surface and (1- $R(\lambda)$) is the fraction of photons entering the photodiode, α(λ) is the photon absorption coefficient, x is the depth into the photodiode. The absorption coefficient is large for short wavelength and small for long wavelength [19]. This means that short wavelength light is absorbed near the silicon surface and the longer wavelength light is absorbed deeper in the material. Therefore, for the 830nm light, deep junction diodes are expected to generate larger photocurrents than shallow junctions.

A P-N junction photodiode under illumination could generate a voltage of approximately 0.3V - 0.45V and this voltage is too low to power the smart dust system. Therefore, two P-N junction photodiodes should be connected in series in order to achieve a useful voltage. This needs a triple-well CMOS process and the UMC 0.25µm CMOS process has been chosen for the design. There are six different P-N junctions available in this process; these are the N+/P-sub, P+/N-well, P+/DN-well (DN-well is deep N-well, which sits in the P-substrate and encloses a P-well.), N-well/P-sub, DN-well/P-sub and P-well/DN-well junctions.

The first three junctions in this list are shallow junctions and the last three are deeper junctions. All the Combinations including N+/P-sub, P+/DN-well or P+/N-well were rejected, because the shallow junctions have lower quantum efficiencies at 830nm wavelength. A cross section of the Connection of two P-well/DN-well is shown in Fig. 1(a).

The P side of the photodiode has a higher potential than the N side under illumination. Therefore the DN-well of one diode, shown on the left hand-side of Fig. 1(a), has to be connected to the substrate so that the P-well in this DN-well is one diode voltage above the substrate. This P-well is then connected to the DN-well of the other, right-hand diode, so that the P-well in the right diode can be two diode voltages above the substrate. Alternatively, both of N-well/P-sub and DN-well/P-sub diodes can be used in combination with P-well/DN-well. For example, the N-well on the left of Fig. 1(b) can be one diode voltage below the substrate. The DN-well on the right is connected to the substrate so that the P-well in this DN-well can generate a voltage that is one diode voltage above the substrate. Again a voltage difference of two diode voltages can be achieved.

MEASUREMENT AND DISCUSSION

Measurement Setup

The response of these photodiodes was then tested using a Newport 5005 laser driver to drive a 830nm laser diode. A metal shield with a 2.5mm diameter aperture in its centre was placed in front of the laser diode, to create a point light source. Two lenses were then used to collimate the laser beam and focus the light. The focused beam is directed to the chip by a beam splitter. The photodiode terminal voltage was measured using an Agilent 4155B when the current drawn from the diode was varied.

Single Photodiodes

The load line of single P-well/DN-well was measured and the quantum efficiency was found to be 7.45%. This is lower than expected and the possible reason is that the absorption depth of 830nm light is deeper than the P-well/DN-well junction. Therefore the DN-well/P-sub junction below the P-well/DN-well absorbs most of the photon-generated electrons. The load lines of N-well/P-sub, DN-well/P-sub and N+/P-sub were measured and the quantum efficiencies of them was found to be 64.64%, 70.46% and 1.68% respectively. As expected, the shallow junction N+/P-sub has the smallest quantum efficiency and is therefore a worse power source.

Cascaded P-WELL/DN-WELL

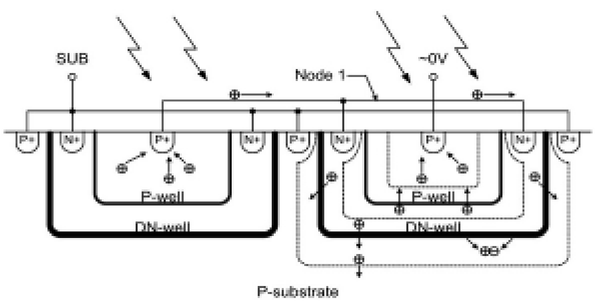

Figure 2: Illustration of the failure of two P-well/DN-well photodiodes in series. Dashed line represents depletion region

In order to attempt to obtain higher voltages, two P-well/DN-well or three P well/DN-well photodiodes were connected in series. However, measurement results show that the cascaded photodiode terminal voltage is approximately 0V. A possible explanation for this failure is illustrated in the Fig.2.

For the purpose of understanding, holes are used to show the movement of carriers in the photodiodes. Since the DN-well/P-sub junction absorbs more photons, only a small number of photon-generated holes move out of the left diode to the Node 1 and flow into the DN-well of the diode on the right. Most of the photon-generated carriers in the right diode are in the depletion region of DN-well/P-sub and these outnumber the holes from the left diode entering at Node 1. These holes are swept to the P-substrate by the internal field of this depletion region. Hence, the holes from the left diode are neutralized in the DN-well of the right diode.

Energy Source

The P-well/DN-well and N-well/P-sub were selected to be the energy source. The measurement results show the DN-well/P-sub has a higher quantum efficiency than N-well/P-sub.

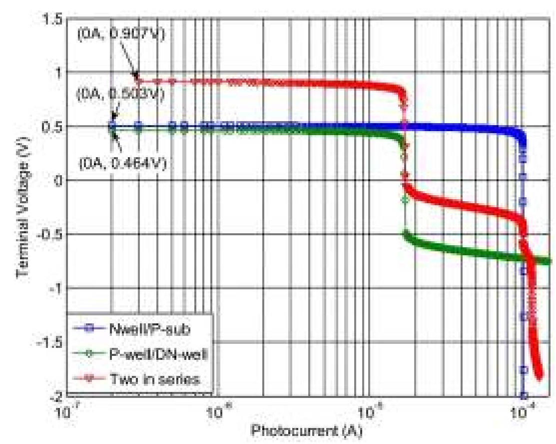

Figure 3: Load lines of N-well/P-sub, P-well/DN-well and two in series

However, if it is used to form the energy source with an P-well/DN-well photodiode, the two DN-wells may short. When these two photodiodes are connected in series, the terminal voltage of the two photodiodes in series is slightly smaller than the sum of the individual voltage of the two photodiodes, as shown in Fig. 4. This can be explained from the energy band diagrams in Fig. 4. When an open-circuit p-n junction is under illumination, photo generated minority carriers flow across the depletion region and the electrochemical potential of electrons is higher in the n-type region than in the p-type region by an amount of qV_{oc}, as shown in Fig. 4(a). When the proposed energy source in Fig. 1(b) is under illumination, the P-sub and DN-well are short circuited and this means they have the same Fermi level, as shown in Fig. 4(b).

The two photodiodes of the energy source are placed next to each other on the chip. This means that the photo-generated minority carriers in the P-sub and DN-well can diffuse in both directions and some photo-generated electrons in the P-sub recombine with the photo-generated holes in the DN-well. Therefore a slightly smaller open circuited voltage is achieved.

It can be seen that the maximum photocurrent to power the smart dust is limited by the P-well/DN-well photodiode due to its smaller quantum efficiency. Therefore the two photodiodes were resized with 0.2mm2 N-well/P-sub and 1.3mm2 P-well/DN-well. Another chip has been fabricated and its picture is shown in Fig. 6.

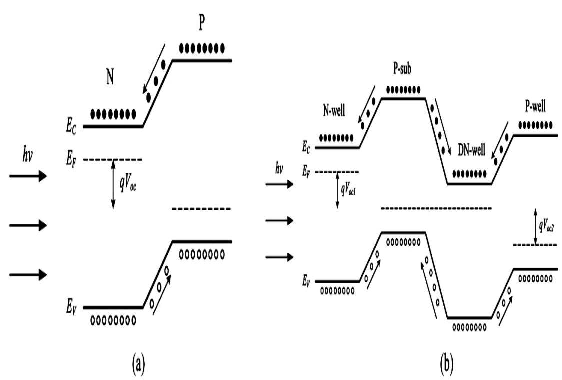

Figure 4: Energy band diagrams of open-circuit photodiodes under illumination.(a) Single p-n junction. (b) Proposed energy source, *q* is electron charge and *Voc* is open-circuit voltage

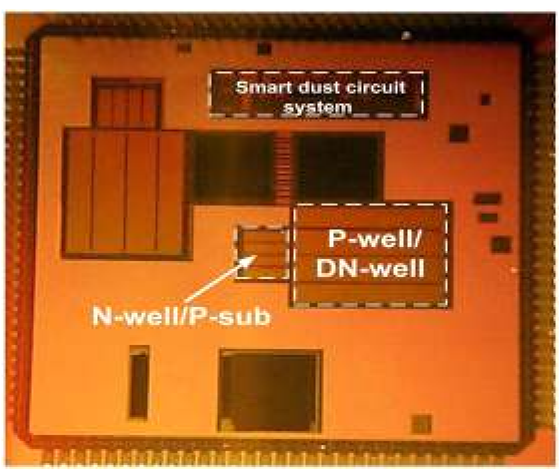

Figure 5: Second chip with resized photodiodes fabricated using UMC0.25µm CMOS process. N-well/P-sub is 0.2mm2 and P-well/DN-well is 1.3mm2

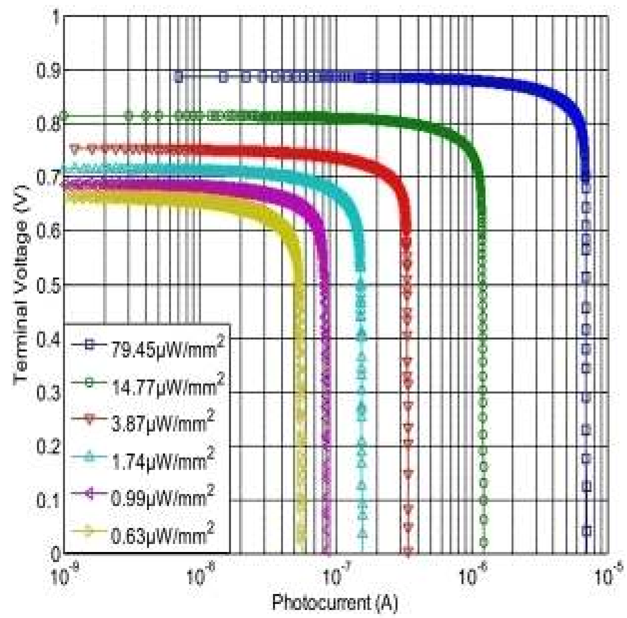

Figure 6: Measured load lines of the resized photodiodes in the second chip under a few different illumination intensities

Available voltages and currents at the max **TABLE**. power points.

Illumination intensity (µW/mm^2)	79.45	14.77	3.87	1.74	0.99	0.63
Voltage (V)	0.8	0.7	0.65	0.6	0.55	0.5
Current (nA)	6240	1140	315	145	81	53

The resized photodiodes are measured with a few different illumination intensities and the load lines are shown in Fig. 6. Eye safety restrictions mean that, the maximum illumination intensity from a 830nm laser is 79.45µW/mm^2. The generated voltages and available currents of the photodiodes at the maximum power points are summarized in Table 1. The optically powered energy source can supply a voltage from 0.5V to 0.8V and a current from Nano-amperes to microamperes at its maximum power point. The efficiency of the energy source is approximately 3.5% when illuminated by light with a wavelength of 830nm.

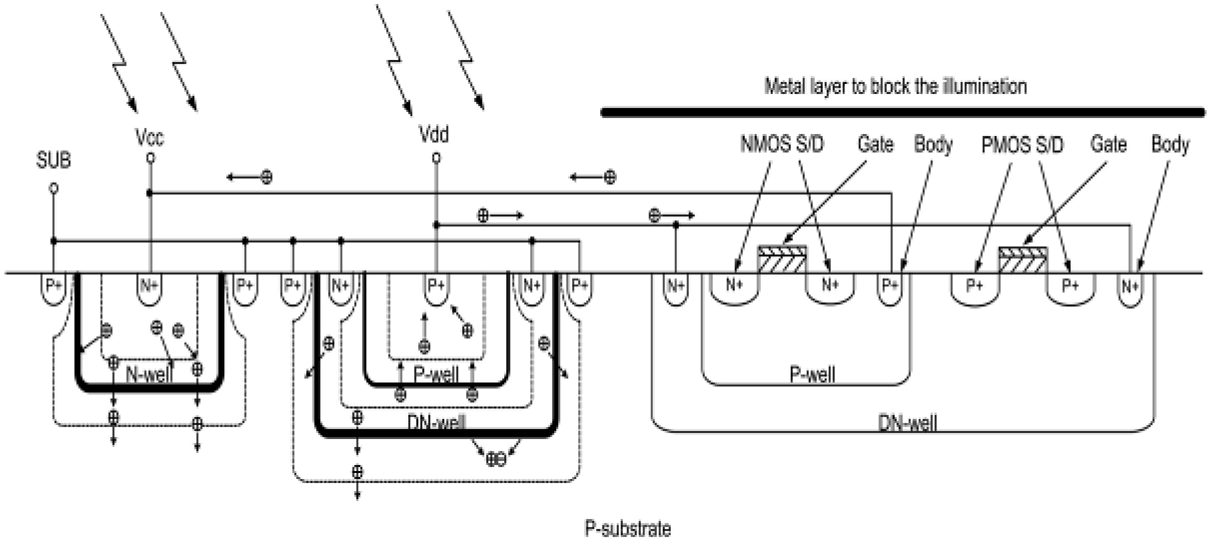

Figure 7: Connections of the proposed energy source to CMOS circuits

In order to power the circuit on the same chip using the photodiodes, connections of the energy source are shown in Fig. 7. All the CMOS circuits should sit in a DN-well connected to the P-well terminal of P-well/DN-well photodiode to isolate them from the substrate and the circuits should be covered by a metal layer to block the illumination. The ground of the circuit is then connected to the N-well terminal of N-well/P-sub photodiode. A smart dust circuit system was also fabricated on the second chip marked in Fig. 4. The proposed energy source can successfully power the smart dust requiring the voltage input in the range of 0.5V to 0.85V under illuminations. This smart dust system contains a photo detector, data recovery circuit, instruction e circuit and passive optical transmitter driving circuit and this system works as a communication platform for the optical wireless sensor networks.

PHOTODIODES

A photodiode is a semiconductor device that convert light into current. The current is generated when photons are absorbed in the photodiode a small amount of current is also produced when no light is present. Photodiodes may contain optical filters, built in lenses and may have large or small surface areas. Photodiodes usually have a slower response time as their surface area increases. The common traditional solar cell used to generate electric solar power is a large area photodiodes.

Photodiodes are similar to regular semiconductor diodes except that they may be either exposed or packaged with a window or optical fibre connection to allow light to reach the sensitive part of the device. Many photodiodes designed to for use specifically as a photodiode use a PIN junction rather than a p-n junction, to increase the speed of response.

An avalanche photodiode (APD) is a highly sensitive semiconductor electronic device that exploits the photoelectric effect to convert light to electricity. Avalanche photodiodes can be thought of as photo detectors that provide a built-n first stage of gain through avalanche multiplication. From a functional standpoint, they can be regarded as the semiconductor analog to photomultiplier. Avalanche photodiodes are more sensitive compared to other semiconductor photodiodes.

A typical application for avalanche photodiodes is a laser rangefinders and long range fiber optic telecommunication.

SENSOR NODES

A sensor node, also known as a mote, is a node in a sensor network that is capable of performing some processing, gathering sensory information and communicating with other connect nodes in the network. A mote is a node but a node is not always a mote.

A wireless sensor network continues to drive the need for ultra low power system design. Wireless sensors can enable a variety of applications including interactive environments for medicine, environmental monitoring networks, military target tracking, and detection of chemical and biological weapons. In many of these wireless systems, the power source is a bottleneck that limits system lifetime and performance, adds manufacturing cost, and increases system volume and maintenance expenditures. Delivering power to wireless sensor network nodes is a significant system design challenge. Solar energy harvesting has been proposed to extend the lifetime of these networks beyond the limitations which have been previously imposed by batteries.

SMARTDUST

When a node integrates self contained sensing and communication system into a cubic-millimeter mote, it is called smart dust. Smart dust normally obtains energy from batteries or solar cells, which occupy a significant volume.

Smart dust consists of series of circuit and micro-electro-mechanical systems (MEMS) designs to cast those functions into custom silicon. Micro-electro-mechanical systems (MEMS) consist of extremely tiny mechanical elements, often integrated together with electronic-circuitry.

The first Smart Dust implementation was a battery-powered MCM featuring a MEMS corner cube reflector for optical communications as shown in fig 8. Smart dust requires mainly revolutionary advances in miniaturization, integration & energy management. Hence designers have used MEMS technology to build small sensors, optical communication components, and power supplies .Micro-electro-mechanical systems consists of extremely tiny mechanical elements, often integrated together with electronic circuitry. They are measured in micrometers, that is millions of a meter. They are made in a similar fashion as computer chips. The advantage of this manufacturing process is not simply that small structures can be achieved but also that thousands or even millions of system elements can be fabricated simultaneously. This allows systems to be both highly complex and extremely low-cost. Micro-Electro-Mechanical Systems (MEMS) is the integration of mechanical elements, sensors, actuators, and electronics on a common silicon substrate through micro fabrication technology. While the electronics are fabricated using integrated circuit (IC) process sequences (e.g., CMOS, Bipolar processes), the micromechanical components are fabricated using compatible "micromachining" processes that selectively etch away parts of the silicon wafer or add new structural layers to form the mechanical and electromechanical devices.

APPLICATIONS

Photodiode

P-n photodiodes are used in similar applications to other photo detectors, such as photoconductors, charge coupled device, Photomultiplier tubes. They may be used generate an output which is depend upon the illumination or to change the state of circuitry.

Photodiodes are used in consumer electronics devices such as compact disc player, smoke detectors, and the receivers for infrared remote device used to control equipment from televisions to air conditioners.

Photodiodes are used for light measurement intensity in science and industry. They generally have a more linear response than photoconductors.

Smart dust

- Environmental science: Using motes, scientists learn more about soil contaminants, water flow, ocean cycles, invasive species, reasons why volcanoes erupt, endangered species, and the mating habits of different species. Also, since smart dust detects changes in heat and temperature, they can be used to monitor forests and prevent fires.
- Inventory control: A wireless network could be able to detect when certain products are out of stoke and send the signal to another computer that could reorder the goods, also, organizations could be able to track the location of their shipment 24/7 with smart dust which is useful when the product are expensive.
- Urban areas: A system motes can be placed within a city to determine the congestion of traffic areas or to indicate the location of an accident. This technology also has the potential to evaluate the structural soundness of different buildings by

incorporating and then checking for vibration heat etc…

- Army: This technology is being used by the military as an improved perimeter security system. Because the system can detect vibrations, temperature and sound, this emerging technology is perfect for detecting hostile or abnormal activity.

CONCLUSION

The traditional energy source component occupies a significant fraction of the volume of smart dust nodes. This paper introduced an optically powered energy source which can be integrated on the same IC chip as the smart dust circuits. Based on the standard UMC CMOS process, all the possible combinations of two P-N junctions in series were analysed. From the measurement results, only the P-well/DN-well and N-well/P-sub connected in series can generate a voltage different from 0.5V to 0.8V, which is capable of driving circuits. Although the conversion efficiency is approximately 3.5% at 830nm, enough power was available to power an example NANO-power sensor node. In many circumstances additional power can be obtained from ambient light.

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