National Conference on Innovative Paradigms in Engineering & Technology (NCIPET-2013)
Proceedings published by International Journal of Computer Applications® (IJCA)

Fractal based Photodiode for On-Chip Energy Harvesting

Apurva A. Pathak
Dept. of Electronics Engg.
S.B.Jain Collage of Engg.

Smita T. Bedarkar
Department of ETC
Priyadarshini College of Engg.

Poonam T. Bedarkar
Dept.of Electronics Engg
KITS Ramtek

ABSTRACT

This paper presents the design and test of a photodiode with improved conversion efficiency for on-chip solar energy harvesting applications. The improved efficiency is achieved by exploiting the lateral photo response of the photodiode through the usage of diodes with fractal geometries. The fractal diodes have a large perimeter-to-area ratio which translates into more collected charges due to lateral photo response. An approximation of the quadric Koch island fractal has been designed and fabricated in a 0.5μm CMOS process along with a rectangular photodiode of equal area but different perimeter that serves as the control. Measurements of the fabricated chip show improvements in the charge collection of the fractal-based photodiode of up to 6% with respect to the rectangular control photodiode.

INTRODUCTION

CMOS system provides a low-cost, high accuracy, and parallel measurement solution for biosensor detection and quantificationCMOS technology have enabled the fabrication of on-chip sensory systems that integrate transducers, computational and communication circuits. These sensors have to often operate unattended for extended periods of time. Thus, it is critical that battery life is extended as much as possible by reducing power consumption or the duty cycle of the sensor. An approach that has the potential to enable nearly perpetual operation is to harvest ambient energy to power up the sensor or to recharge its batteries. Ambient energy can be in the form of vibrations, heat, electromagnetic and solar. Additionally, the integration of an energy harvesting device on the same chip with the sensor is appealing because it can reduce fabrication costs and the overall size of the sensor. In this work we focus on improving the efficiency of on-chip solar energy harvesting devices through the usage of fractal-shaped photodiodes.

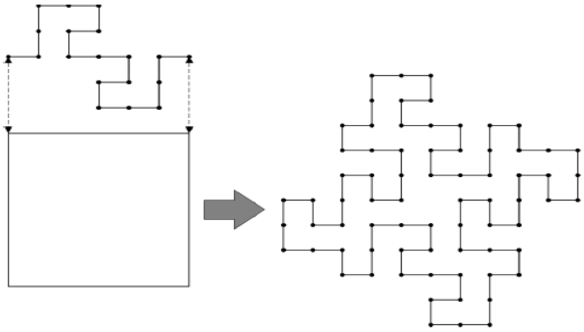
Integrating photodiodes with logic and exploiting on-die interconnect capacitance for energy storage can enable new, low-cost energy harvesting wireless systems. To further explore the tradeoffs between optical efficiency and capacitive energy storage for integrated photodiodes, an array of photovoltaics with various diffractive storage capacitors was designed in TSMC's 90 nm CMOS technology. Transient effects from interfacing the photodiodes with switching regulators were examined. A quantitative comparison between 90 nm and 0.35 μm CMOS logic processes for energy harvesting capabilities was carried out. Measurements show an increase in power generation for the newer CMOS technology, however at the cost of reduced output voltage.

An attempt at improving the efficiency of photodiodes for on-chip solar energy harvesting is presented in [4] and employs p-diff/n-well finger-like photodiodes with vertical optical diffraction gratings. The goal of the vertical diffraction gratings was to reflect light back and forth until it reaches the photodiodes at the bottom. It also creates a vertical parallel plate storage capacitance that can be used to store the harvested energy. Diffraction gratings with variable groove heights and variable grating periods ranging from 100 nm to 10 μm are fabricated in a one-step deposition process. Gratings fabricated with this technique have potential applications in integrated photonic devices. The motivation for using a fractal shape is that an increase in perimeter will lead to an increase in the photodiode's peripheral response. The peripheral response is a mechanism by which photo-generated carriers are collected by the lateral depletion regions This mechanism leads to a photoactive area that may be much larger than the original p-n junction area [5]. In applications such as imaging, the peripheral response gives rise to lateral crosstalk which degrades the contrast of an image [6]. However, for energy collection it is a desirable feature. Fractal-based geometries have been applied to the design of other devices such as integrated capacitors that exploit the lateral flux resulting in a 2.3 increase in the capacitance per unit area

1. Fractal

A *fractal* is a concept introduced by Benoit B. Mandelbrot that denotes a large class of objects that have the basic property of self-similarity and scale invariance. Fractals can be constructed by the repeated application of a rule to an initial geometrical shape or seed or can also be created from mathematical formulas. Many natural objects like mountains, the coastline of an island or a fern can be described with the help of fractals. The complexity of nature's shapes differs in kind, not merely degree, from that of the shapes of ordinary geometry, the geometry of fractal shapes

The photodiode design presented in this work is based on the quadric Koch island fractal. The *quadratic Koch island* can simply be called the *Koch island*. it requires only right angle corners which makes easier the design of the corresponding layout and because its area remains constant as the fractal is generated. To construct the quadric Koch island fractal we start with an initial square. This initial shape is called the *initiator*. A *generator* is then applied to each side of the initiator and the process is repeated on each side of the resulting curve. From figure 1 it can be observed that the resulting shape has the same area as the initial square, however its perimeter is three times longer.



segment size (6 in this case). For the quadric Koch island fractal the dimension is

$$\log 18/\log 6 = 1.61.$$

An additional feature of the quadric Koch island that is useful in the intended application is that the area remains the same while the perimeter increases.

2. EXPERIMENT SETUP METHODOLOGY AND MEASUREMENT RESULTS

The experimental setup is shown.

The laser source is tuned to a particular wavelength and its output power is measured with the power meter. The fabricated chip was mounted on a support and then moved in front of the laser to be illuminated. The I-V curve for each diode was acquired using the source meter. The diode junction voltage was swept by the source meter from -0.3 V to 0.5 V with 4 mV steps and the resulting diode current was measured. To minimize noise, 200 sweeps were performed and averaged to obtain a cleaner I-V curve. This procedure was repeated for both diodes and for the following wavelengths: 488 nm, 514 nm, 520 nm, 568 nm and 647 nm.

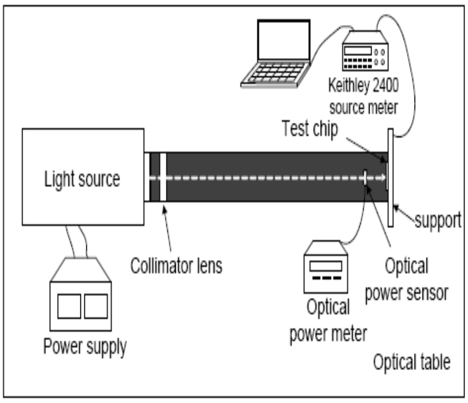
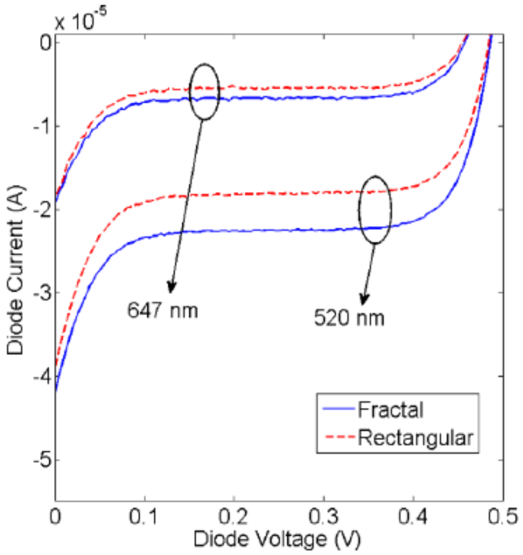


Fig. 3

Measurement Results

shows the I-V curves for the 520 nm and 647 nm laser wavelengths.



The measured laser output power at these wavelengths is 3.07 mW and 1.57 mW correspondingly. From the I-V curves we observe that the fractal photodiode consistently collects a larger photo-current than the rectangular diode. The negative sign of the current indicates that it flows from the cathode to the anode showing that the diode behaves as a solar cell generating power. In the figures the voltage range of interest when the photodiode works as a solar cell is shown. Beyond 0.5 V we observe the exponential behavior typical of a forward-biased diode. For negative bias voltages the photodiode still outperforms the rectangular one.

The conversion efficiency of both diodes was also computed and compared. To this end, the photon flux, , for each wavelength was calculated using the following E_{ph} is the photon energy at a particular wavelength. is given by:

Finally, the conversion efficiency was estimated using:

$$\eta = \frac{I_{diode}}{qA_{diode}F_0} \times 100\%$$

where : q is the electron charge, A_{diode} is the area of the diode and is the diode current in the region of interest (the current is fairly constant in this region).

Figure 6 shows he computed conversion efficiency of both diodes for the five wavelengths at which measurements were taken. At 514 nm the proposed fractal photodiode is up 10% more efficient than the rectangular one. A spectral response of both diodes is also observed that is consistent with the theoretical efficiency calculations of silicon diodes [12].

The I-V curves for both diodes were also measured under sunny outdoor conditions to simulate a practical energy-harvesting scenario. These I-V curves are shown in Fig. 7. The incident light power was measured with a broadband optical power meter (Scientech 361) to be 100 mW. The detector area of this meter is 6.157×10-4 m2. The photon flux was then calculated using equation (4) and found to be 4.536×1020 photons/m2·s. In this calculation we employed λ=555 nm which is the standard for white light photometry. The efficiency for the rectangular photodiode turned out to be 35% and the efficiency of the fractal photodiode 41%. Thus a 6% overall improvement was achieved by the designed fractal diode. Larger improvements in efficiency can still be achieved if a second or third iteration of the chosen fractal is employed to further increase the diode perimeter. To appreciate the potential improvement in efficiency that this would yield,

Since the areas of both diodes are the same, the extra current in the fractal diode, , must be due to the difference in perimeters. Thus, we can write:

fractal. Recall that each iteration of this fractal increases the perimeter by three, thus, for the first iteration we have: $\Delta_L = 2L_{rect}$ where L_{rect} is the perimeter of the rectangular diode. For the second iteration we would $\Delta_L = 8L_{rect}$ and for the third iteration:. $\Delta_L = 26L_{rect}$. The increase in the perimeter difference is exponential (as predicted from equation (2)). Thus, we can expect larger efficiencies for the fractal as we increase the level of detail of the fractal geometries employed.

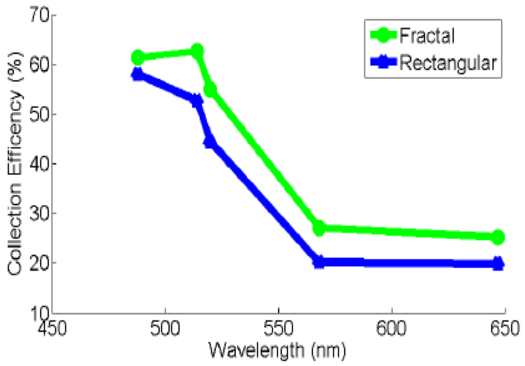


Fig. 6

3. CONCLUSIONS AND FUTURE WORK

A photodiode design based on fractal geometry for on-chip energy harvesting applications was presented. The motivation for using a fractal-shape diode was to take advantage of the diode’s lateral photo response by increasing its perimeter. A longer perimeter would mean that more laterally generated charges could be collected. The fractals of interest for this application would have the same area as their initiator and a larger fractal dimension. A fractal that satisfies these properties is the quadric Koch island.

As a proof of concept, the first iteration of this fractal was fabricated on a 0.5 µm CMOS process along with a rectangular control diode of the same area but different perimeter. Measurements validate the approach and show a 6% increase in efficiency in sunny outdoor conditions. Future work includes the test of geometries with more fractal iterations and other fractals such as the quadratic Koch island, the Peano and the Sierpinski curves.

REFERENCES

[1] N. Guilar, Chen, A., Kleeburg, T., Amirtharajah, R., "Integrated Solar Energy Harvesting and Storage," *International Symposium on Low Power Electronics and Design,* pp. 20-24, 2006.

[2] A. Fish, Hamami, S., Yadid-Pecht, O., "CMOS image sensors with self-powered generation capability," *IEEE Trans. Circuits and Systems - II,* vol. 53, pp. 1210-1214, 2006.

[3] C. Wang, Devos, F., "Design and implementation of electrical-supply-free VLSI circuits," *IEE Proc. Circuits, Devices and Systems,* vol. 152, pp. 272-278, 2005.

[4] N. J. Guilar, Fong, E. G., Kleeburg, T., Yankelevich, D. R., Amirtharajah, R., "Energy harvesting photodiodes with integrated 2D diffractive storage capacitance," *International Symposium on Low Power Electronics and Design,* pp. 63-68, 2008.

[5] H. Holloway, Brailsford, A. D., "Peripheral photoresponse of a p-n junction," *Journal of Applied Physics,* vol. 54, pp. 4641-4656.

[6]S. Kleinfelder, Chen, Y., Koohi, A., "Distributed and fractal pixel sensors," *Proceedings of the SPIE,* vol. 5678, pp. 144-155, 2005

[7] B. B. Mandelbrot, *The fractal geometry of nature*. New York: Freeman, 1983. [12] A. Moini, *Vision Chips*. Boston: Kluwer.