Photodiode Development for fluorescence spectroscopy applications

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***Abstract*-- Two photodiode architectures were designed, built, and tested for comparison for implementation into a fluorescence spectroscopy, or fluorometric, system. All devices were fabricated on 4-inch, N-type silicon substrates. The photodiodes presented were tested for responsivity and response time, two main factors judging effective incorporation in fluorometric applications. The planar photodiode excels in responsivity due to the device's large active-area; however, high junction capacitance greatly hinders the response time. The lateral photodiode had much lower junction capacitance than the planar, but exhibited lesser responsivity due to the decreased active area size. The lateral photodiode was chosen as a candidate for time-resolved measurement due to the fast response of the device. Due to the responsiveness to low-light, the planar photodiode is chosen as the candidate for incorporation in fluorometric systems relying on irradiance measurement for operation.**

Keywords: Photodiode, Fluorescence Spectroscopy, Fluorometry, Silicon, Responsivity, Response Time

I. Introduction

Fluorescence spectroscopy is a lucrative technique used heavily in medical, industrial, and environmental applications. [1] Oxygen sensing via fluorescence spectroscopy, currently being developed by the author and the RIT Electrical Engineering Department, requires the use of oxygen quenching fluorophores, fluorescent materials sensitive to oxygen concentration, as well as excitation and recording devices to induce and measure the fluorescence. Photomultiplier tubes (PMTs) are commonly used as recording devices in fluorescence spectroscopy; however, PMTs, historically, are expensive and require large external power-supplies to operate, making the sensor unavailable to the average consumer. The use of low-cost, silicon photodiodes provides an excellent approach to decreasing the value of fluorescent oxygen sensors and expanding the use to a wider client base. Two silicon photodiode architectures are presented in hopes of maximizing sensor responsivity while minimizing junction capacitance and dark current.

Silicon photodetectors historically exhibit maximum responsivity at roughly 900nm due to the photonic absorption properties of the silicon lattice. The photocurrent generated through the conversion of photonic energy to electric current is amplified using a current-to-voltage, or transimpedance, amplifier. This amplifier operates on the feedback response of the photocurrent when combined with an operational amplifier in order to simulate normal operating conditions of a photodiode circuit. Response time is extracted from a transimpedance setup; however, the resistance used in the amplifier can be detrimental to response time.

II. Theory

A. Fluorescence Spectroscopy

Optical analysis is a powerful tool for the characterization of materials. Fluorescence Spectroscopy describes a method in which an *analyte* is studied based on the fluorescent emission exhibited by UV-light-excitation of the analyte, or a separate material sensitive to the analyte.

Fluorescence quenching operates on the principle of energy exchange between fluorescing particles and non-fluorescing particles. The oxygen sensor currently in development in conjunction with the RIT EE Department utilizes *Tris(2-2'bipyridal)dichlororuthenium(II)* as an oxygen indicator. In the absence of oxygen, the fluorescing of ruthenium-particles is un-impeded, leading to maximum fluorescent output. In the presence of oxygen, vibrational-induced fluorescence energy is transferred to the oxygen atom which halts, or "quenches," the fluorescence phenomenon. This reaction is shown in Fig. 1. The quenching effect of fluorescent materials also affects the lifetime of the fluorescent signal. Like intensity quenching, the lifetime will decrease with higher oxygen concentrations.

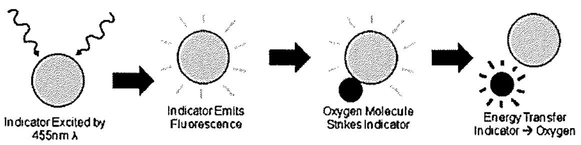

Fig. 1. Dynamic fluorescent quenching by oxygen atom through collisional energy transfer

The light power resulting from fluorescence spectroscopy is often low due to the un-equal conversion between absorption and emission. [3] The device receiving the fluorescent signal must be able to record low- intensity light (high responsivity), as well as short lifetimes (fast response time), given the specific application requirements.

B. Photodiode Design and Operation

Photodiodes operate as a PN-junction diode. When a photon of light enters the silicon lattice, the energy involved can cause an electron to be ejected, leaving an electron-less charge, or hole, behind. Fig. 2 depicts the generation of electron-hole pairs in silicon. Once the electron and hole are freed, they will travel to respective contacts, electrons to the anode and holes to the cathode; this movement generates the *photocurrent* of the device.

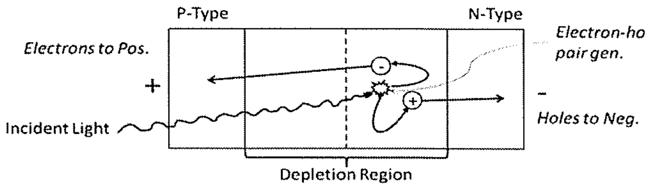

Fig. 2. Photon absorption and photocurrent generation

Electron-hole generation is the driving force behind photodiode operation. As more photons enter the silicon lattice, more electron-hole pairs are generated, leading to larger photocurrents and more-pronounced signals.

The region created at the junction of P+ and N+ dopants is known as the *depletion region*. The depletion region is an area of neutral charge and high electric-field which greatly accelerates electron-hole charges generated inside the region. Photons absorbed in the depletion region will generate a much larger signal than photons not absorbed in the region.

Responsivity of a photodiode is defined in terms of *photocurrent resulting from a specific wavelength of light.* Wavelength directly corresponds to the penetration depth of the photon in silicon, with longer wavelengths penetrating deeper. It is possible, given the correct architecture, to tailor the depletion region of the device to a specific wavelength – greatly increasing the responsivity of the photodiode to that energy, as shown in Fig. 3.

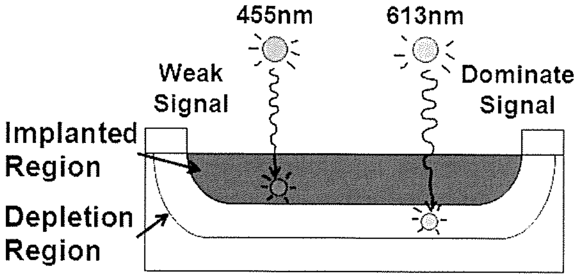

Fig. 3. Photonic absorption of silicon and tailoring of depletion region depth to match wavelength

Junction Capacitance is proportional to the size of the depletion region but inversely-proportional to the electric field inside the region. As junction capacitance increases, the time from photon absorption to signal output increases. For a fast response time, the junction capacitance of the device must be kept at a minimum.

C. Photodiode Architectures and Performance

Lateral photodiodes are built by generating alternating wells of P+ and N+ doped silicon, leaving small gaps between each well to form the depletion region. Fig. 4 displays the cross-section representation of the lateral photodiode.

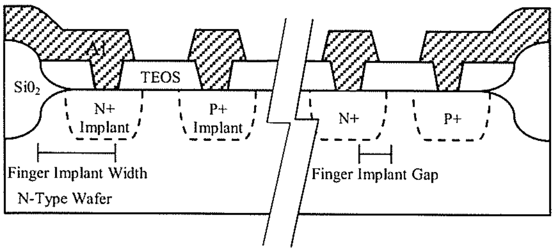

Fig. 4. Lateral photodiode cross-section with metrics

Since the depletion region is formed on the surface of the device, wavelength selectability is not possible for the lateral architecture.

Planar photodiodes are built from a bulk-implanted region in silicon. The active area is large, increasing the photoactive surface area, but also increasing the junction capacitance. Fig. 5 displays the cross-section of the planar photodiode.

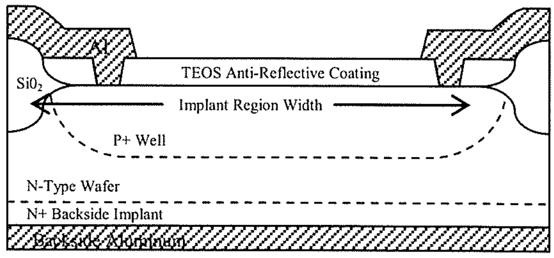

Fig. 5. Planar photodiode cross-section with metrics

The depth of the active-well implant can be tuned to modify the depth at which the depletion region is formed. This provides the planar photodiode with wavelength selectability which will result in a much higher responsivity for the wavelength energy corresponding to the junction depth.

TABLE I
COMPARISON OF PHOTODIODE ARCHITECTURES

Architecture	*Advantages*	*Disadvant*
Lateral	- Small Junction Capacitance - Fast Response Time	- No inherent λ - selectability - Low responsivit
Planar	- Tunable Depletion Depth - High Responsivity	- Large Junc Capacitance - Slow Resp Time

Table 1 provides a comparison between photodiode architectures in terms of responsivity and response time – two valuable factors in fluorescence spectroscopy.

III. PROCESS

All devices are constructed on 4-inch, n-type silicon substrates. The substrates are cleaned through the RCA-clean process at fabrication start and before each thermal stage. This practice reduces contamination of the tools and promotes defect reduction on-wafer through substrate cleanliness.

A designed experiment is created to test device performance across a variety of design changes. Table 2 provides the designed experiment for each device.

TABLE II
DESIGNED EXPERIMENT FOR PHOTODIODE FABRICATION

Architecture	Design Changes	# of Devices
Lateral	- Finger Implant Width* - 30 , 50 µm - Finger Implant Gap* - 50 , 100 µm	4
Planar	- Implant Region Width** - 1.0 , 1.5 mm	2

* Specifications shown in Fig. 4
** Specifications shown in Fig. 5

Each device was created on a single die, so both architectures could be fabricated at the same time.

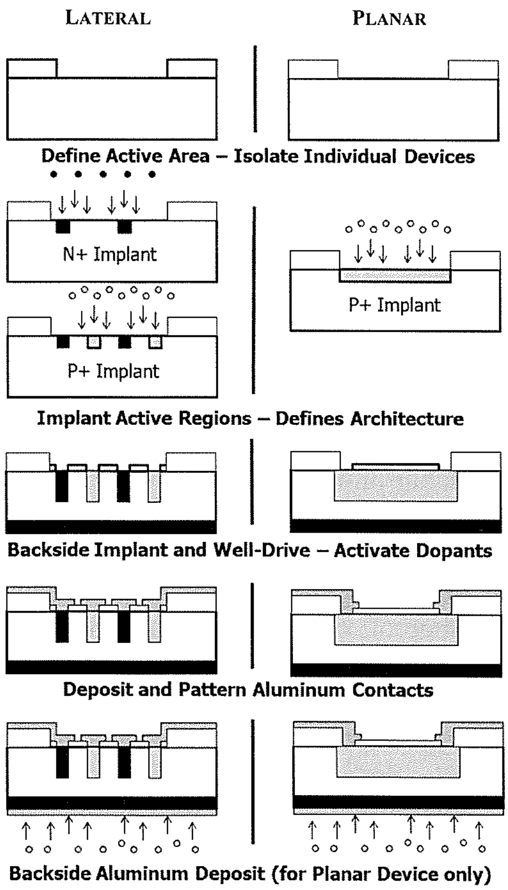

Fig. 6. Fabrication process flow for photodiodes

The fabrication process for the lateral and planar photodiodes is shown in Fig. 6. A 0.5 µm thick oxide was used to separate each device. Blanket implants are performed using the Varian 350D Ion Implanter at a dose of $5x10^{15}$ cm^{-2} for phosphorus and $4x10^{14}$ cm^{-2} for boron, respectively. Before dopant activation, a 100 nm TEOS (*Tetra-Ethyl Ortho-Silicate*) film is deposited to serve as an anti-reflective coating for the devices. A high temperature thermal step is performed to both anneal the TEOS film and activate the implanted dopants. Using a metal evaporator, aluminum is deposited on the top and bottom of the substrate and patterned for form contacts for the devices. A final anneal is performed to sinter the aluminum and finalize the fabrication process.

Testing of the photodiodes are performed in the RIT Device Test and Characterization Lab. Table 3 explains the tests performed to characterize the devices on-wafer.

TABLE III
LIST OF TESTS PERFORMED TO CHARACTERIZE PHOTODIODES

Test Performed	*Tool*
I-V Characterization	HP4145 Parameter Analyzer
Responsivity	OL-750S Spectroradiometer
C-V Characterization	MDC C-V Test Station

From the tests described in Table 3, both architectures are characterized for responsivity and response time (through capacitance-voltage). The ideality factor of each device is calculated from the results of the I-V characterization.

IV. RESULTS AND DISCUSSION

Both photodiode architectures were fabricated successfully following the processing sequence shown in Fig. 6. The I-V characteristics and subsequent ideality factors of each device is shown in Fig. 8 and Table 4, respectively.

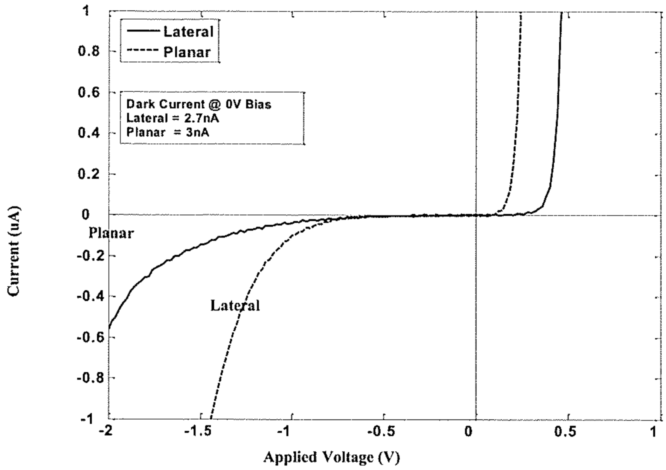

Fig. 8. I-V characteristics of lateral and planar photodiodes

The ideality factor determines the source of photocurrent in the device.

TABLE IV
IDEALITY FACTORS OF INDIVIDUAL DEVICES

Architecture	*Device Specifications*	*Ideality Factor*
	Width: 30 µm, Gap: 50 µm	1.10
Lateral	Width: 30 µm, Gap: 100 µm	1.09
	Width: 50 µm, Gap: 50 µm	~ 1
	Width: 50 µm, Gap: 100 µm	~ 1
Planar	Implant Region Width: 1.0 mm	2.01
	Implant Region Width: 1.5 mm	2.06

Table 4 explains that lateral photodiodes, with ideality factors close to 1, are mainly dominated by diffusion current, while the planar photodiodes, with ideality factors close to 2, are dominated by recombination current.

Fig. 9 shows the result of spectral-responsivity testing on the planar and lateral devices. The planar responsivity is twice the magnitude of the lateral, directly echoing the theory and making the device suitable for low-light applications.

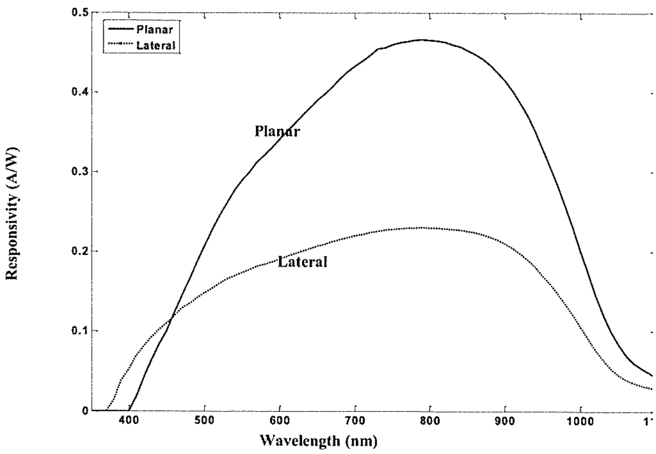

Fig. 9. Responsivity of lateral and planar photodiodes

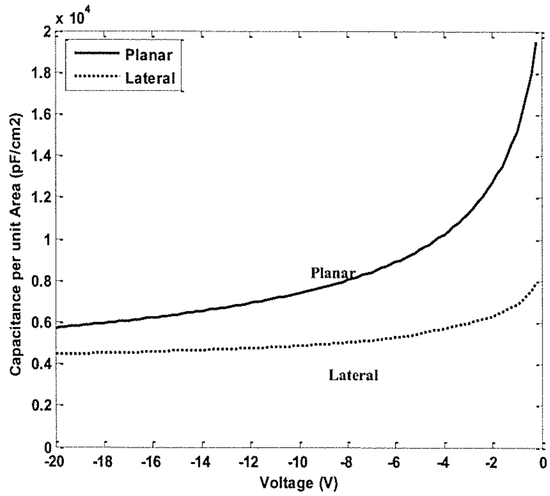

Fig. 10. C-V characteristics of lateral and planar photodiodes

Fig. 10 gives the current-voltage characterization of the two architectures. As shown, the lateral photodiode has lower inherent capacitance due to the smaller active area created between the interdigitated implants. A smaller capacitance reduces the response time of the device. Therefore, the lateral photodiode responds faster than the more-responsive planar.

For use in low-light applications, the planar photodiode is the obvious decision. However, for applications that require a time-resolved measurement of fluorescence, a lateral photodiode would be needed.

VI. CONCLUSION

Two photodiode architectures were designed and fabricated to determine applicability for use in a fluorescence spectroscopy system. The planar architecture had greatly increased responsivity due to the tuned depth of the depletion region and larger-area implant, making it the prime candidate for low-light applications. The smaller depletion regions in the lateral photodiode greatly decreased junction capacitance and response time. Time-resolved fluorometry would benefit from using the lateral photodiode.

Through designing, building, and testing two photodiode architectures, the performance of each can be molded to fit both measurement methods of fluorescence spectroscopy.

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ABOUT THE AUTHOR

Jeremy Goodman came to the Microelectronic Engineering Department in 2004. He worked for Eastman Kodak Company, Intel Corporation, and the CDC pursuing both semiconductor and biomedical engineering.

Jeremy hopes to pursue a career in medicine and looks forward to applying his semiconductor knowledge to the field.