

A Bioelectronic P-I-N Diode Chip for Improved Efficiency Using Magnetosomes of Magnetotactic Bacteria

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Abstract—This research proposes the integration of conventional silicon electronics with bioelectronics for an improved responsivity and quantum efficiency in a photodetector. Introducing isolated magnetosomes of Magnetotactic Bacteria (MTB) in the active region of a p-i-n diode chip increases the photogenerated carriers drift velocity that improves the composite efficiency of the device. Basically, by tuning the magnetic field through the inbuilt electric field, the lifetime of the generated carriers can be extended and thereby eliminating the annihilation of generated excitons in the device. This research utilizes the unique effects of the wide range of phenomena offered by Magnetotactic bacteria considered as a nanomanipulator to improve the functions of the intrinsic region of the p-i-n diode. A responsivity of 0.89 $\mu\text{A}/\mu\text{W}$ at 850 nm was achieved. The speedy transportation of the generated carriers also improved the temperature stability of the device. Other projected advantages of this device include a very negligible package parasitic effect, negligible contact resistance, and an inductance of the order of 0.01 nH.

Index Terms—Bioelectronics, Magnetotactic-Bacteria, Nano-manipulators, PIN-Diode, scattering

1.0 INTRODUCTION

THERE is a growing demand for photo-detectors with improved efficiencies and functionalities for optical communication and remote sensing. The most predominant is the pn photodiodes developed in 1940 which are inexpensive, easy to use, are easily miniaturized and can be implemented in arrays. But a conventional pn junction photodiode suffers two major drawbacks: its junction or depletion layer capacitance is not sufficiently small to allow photo-detection at high modulation frequencies. Secondly, its depletion layer is at most a few microns; consequently, at long wavelengths where the penetration depth is greater than the depletion layer width. Majority of the photons are absorbed outside the depletion layer where there is no field to dissociate the excitons and drift them [1]. This led to the development of the p-i-n photodiode with a larger active region by Junichi Nishizawa in 1950. The p-i-n photodiode structure was designed such that photon absorption occurs over the intrinsic (i) layer. The photo-generated excitons in the i-layer are then dissociated by the field 'E' and drifted towards the n^+ and p^+ sides respectively. During the operation of the p-i-n diode, the response time of the device is determined by the transit times of the photo-generated carriers across the width (w) of the i-layer. Increasing 'w' allows more photons to be absorbed which increases the quantum efficiency but it slows down the speed of response as carrier transit times

becomes longer [2]. This tradeoff between quantum efficiency and responsivity is a major challenge in the fabrication of p-i-n diodes making it not ideal to produce a general purpose one. In order to improve on responsivity of a photo-detector, the photomultiplier tube (PMT) and avalanche photodiode (APD) was developed in which there is multiplication of carriers leading to a gain [3]. This gain improves the responsivity of the device but the device efficiency is adversely affected by the amplified noise alongside the input and the ionization noise. Also the APD operates with reverse biased voltage so it requires higher voltage for its operation. The high operating voltages, the non-linearity of the output signal, the need for complicated supporting circuitry, and higher cost due to the difficulty in fabricating the device limits the application of the APD. Other photo-detectors developed to achieve either improved quantum efficiency or responsivity such as the phototransistors still suffers major limitations associated with the amplified noise and temperature instability [4].

The focus of this research work is to improve both the efficiency and responsivity of a p-i-n photodiode by enhancing the carrier transport mechanism in the i-layer using the isolated magnetosomes of MTB. The improved carrier transport system in the i-layer will create opportunity for a wider active region within the p-i-n photodiode with extended carrier lifetime without facing exciton annihilation due to longer carrier path.

The quantity of the stored charge Q in the i-layer depends on the recombination time ' t ', and the forward bias current ' I_F ' as described in equation 1:

$$Q(\text{Coulombs}) = I_F t \quad (1)$$

The resistance of the intrinsic region under forward bias R_F is described in equation 2 below:

$$R_F(\text{Ohms}) = \left(\frac{w^2}{(\mu_N + \mu_P)} \right) \quad (2)$$

where w is the intrinsic region width

μ_N is electron mobility, and μ_P is hole mobility.

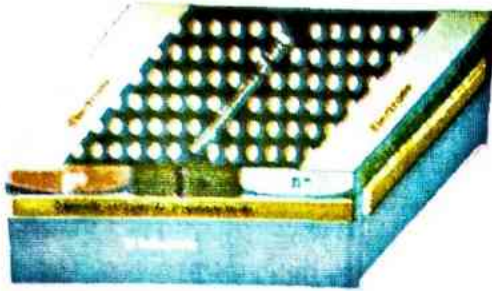


Figure 1. The Bioelectronic p-i-n diode structure

The transit time or drift time t_{drift} of such photo-generated carrier is expressed as:

$$t_{\text{drift}} = \frac{w}{V_d} \quad (3)$$

where V_d is the drift velocity and w is the width of the i-layer. Reducing the drift time increases the speed of response. Increase in the drift velocity V_d occurs by increasing the applied field ' E '. However, it has been observed that at high fields, V_d does not follow the ideal values of drift velocity equivalent to drift mobility times Electric field potential ($\mu_d E$), where μ_d is the drift mobility. Instead it tends to saturate at V_{sat} which is of the order of 10^5 ms^{-1} at fields greater than 10^6 Vm^{-1} on the case of silicon [5]. The $V_d = \mu_d E$ behavior is only observed at low electric fields. At high electric fields both the drift velocity and drift mobility saturate. The speed of the conventional p-i-n photodiodes is limited by the transit time of the photo-generated carriers across the i-layer [6] [7] [8].

In order to achieve high performance parameters in the design of a p-i-n diode, two basic conditions are of utmost importance. The first condition is that the total absorption of radiation inside the active region of photodiode must occur. The second factor is that conditions of low thermal generation of carriers must be created. The first condition depends on the active region which is the intrinsic region (i-region). The active region is limited by diffusion lengths of minority carriers on both sides of the junction. To achieve high quantum efficiency, the diffusion length

of minority carriers must be much longer than the radiation penetration depth. One approach is to elongate the diffusion length by broadening the energy bandgap, but this causes reduction in the absorption coefficient. This means that the achievement of the quantum efficiency close to unity is practically impossible. Another major challenge is the noise coming from the parasitic impedance and preamplifier which in long-wavelengths and high temperatures can be higher than the signal itself considering the Signal to Noise Ratio (SNR). The generated carriers transport properties are analyzed as follows:

Phenomenological transport equations for electrons and holes -

$$J_h = -qD_h \frac{dp}{dx} - q\mu_h p \frac{d\psi}{dx} \quad (4)$$

$$J_e = -qD_e \frac{dn}{dx} - q\mu_e n \frac{d\psi}{dx} \quad (5)$$

Two continuity equations -

$$\frac{dJ_e}{dx} + q(G - R) = 0 \quad (6)$$

$$\frac{dJ_h}{dx} + q(G - R) = 0 \quad (7)$$

The Poisson's equation

$$\frac{d^2\psi}{dx^2} = \frac{q}{\epsilon_s \epsilon_0} (N_D - N_A + p - n) \quad (8)$$

where n , D_e , μ_e , and J_e are the electron concentration, diffusion coefficient, mobility and current density, respectively; p , D_h , μ_h , and J_h are the same quantities for holes; q is the electron charge, G and R are the generation and recombination rates, respectively; ψ is the electric potential; N_D and N_A are the donor and acceptor concentrations, respectively; ϵ_s is the static dielectric function; and ϵ_0 is the permittivity of free space.

In this work, the generated excitons in the active region of the p-i-n photodiode were coupled to the magnetosomes of MTB considered as a nanomanipulator and used to accelerate the carriers to the donor-acceptor interface (see figure 1).

A. Magnetotactic Bacteria (MTB)

MTB belong to a polyphyletic group of bacteria discovered by Richard P. Blakemore in 1975. Their characteristic property of exhibiting magneto-taxis movement positions them to a wide range of applications. MTB orients along the magnetic field lines of Earth's magnetic field. They possess organelles called magnetosomes that contain magnetic crystals as magnetite (Fe_3O_4) or greigite (Fe_3S_4) [9] [10] [11] [12]. The sensitivity of magnetotactic bacteria to the Earth's magnetic field arises from the fact that they precipitate chains of crystals of magnetic

minerals within their cells. Magnetite-producing magnetotactic bacteria are usually found in an oxic-anoxic transition zone. The zone refers to the transition zone between oxygen-rich and oxygen starved water or sediment. The MTB magnetosome envelope allows for easy couplings of bioactive substances to its surface. Several different morphologies of MTB exist, differing in number, layout and pattern of the bacterial magnetic particles (BMPs) they contain. The diversity of MTB is reflected by the high number of different morphotypes found in environmental samples of water or sediment. Commonly observed morphotypes include spherical or ovoid cells (cocci), rod-shaped (bacilli), and spiral bacteria of various dimensions. One of the more distinctive morphotypes is an apparently multicellular bacterium referred to as the many-celled magnetotactic prokaryote (MMP). All MTB studied so far are motile by means of flagella are Gram-negative bacteria of various phyla [13]. Majority of known species are proteobacteria for example *Magnetospirillum magnetum* (see figure 2) an alphaproteobacterium, members of various phyla possess the magnetosome gene cluster such as *Candidatus Magnetobacterium bavaricum* a Nitrospira. The arrangement of flagella differs and can be polar, bipolar, or in tufts [14].



Figure 2. The *Magnetospirillum magnetum* (*Magnetotacticum* Strain MS-1)

2.0 Research Methodology

2.1 Culture of MTB and Isolation of the Magnetosomes

Samples of MTB were collected from freshwater site that has soft muddy sediment layer at the foot of the lagoon at University of Lagos, Akoka campus. The MTB was cultured using Magnetic Spirillum Growth Medium (MSGM). The preparation of the culture was made following the protocol of the ATCC medium: 1653 revised magnetic spirillum growth medium [15]. A thorough description of how the magnetosomes of the MTB were isolated is explained by [16]. The nanoparticles of Fe_3O_4 are characterized through Selected Area Electron Diffraction patterns. The Gold nanoparticles used have unique optical properties which make it suitable for photosensitive detectors [17] [18] [19]. Through ionic interaction, nanoparticles are integrated into a silicon substrate.

The characterization of the nanoparticles was achieved through various techniques namely Transmission Electron Microscopy (TEM), Zeta potential, Dynamic Light Scattering (DLS), Solution pH, and Ultra Violet Visible Spectroscopy. In order to generate large even photocurrent, nanoparticles of gold were deposited on the substrate to achieve light trapping and avalanche multiplication by forming a wavelength - scale texture on the substrate [20] [21]. Greater light absorption was also achieved through the use of scattering from gold nanoparticles excited at their surface plasmon resonance [22] [23].

2.2 The Coupling of the MTB Magnetosomes to the Generated Excitons in the I-layer

The isolated magnetosomes of MTB of grain size 30 – 40nm were incorporated into the channels created by the gold nanoparticles in the i-layer where they maintain electrostatic interactions with the generated carriers. The magnetosomes of MTB contains single crystals of Fe_3O_4 (magnetite). The single crystals have dimensions that range from 30 to 120nm and they are encapsulated by lipid membranes. These single crystals are monodomain-ferrimagnets. Here exists a system with a spinel structure Fe^{2+} and Fe^{3+} which occurs in the ratio 1:2. In the ordered state the spin - $\frac{5}{2}$ moments of Fe^{3+} order antiferromagnetically and the spin- 2 moments of Fe^{2+} order ferromagnetically creating a moment of $4\mu\text{B}$ per formula unit. Considering the spin wave theory for quantum antiferromagnetism as well as Bose condensation of spin reversals at finite wave vector Q in momentum space $(S+Q) \neq 0$ [24]. The excitons are coupled by Bose condensation finite geometries in the magnetosomes of MTB. In this system, the excitons are hard core Bose system in a finite one-dimensional system with a periodic boundary condition. Furthermore, we can map this condition onto the 1d spin - $\frac{1}{2}$ XXZ model in a uniform magnetic field, about which we have a wealth of information from Bethe ansatz solution as well as fermionization and bosonization background. In the fermionization approach, the hard core boson is converted into interacting fermions, by a Jordan – Wigner transformation and the condition becomes a Luttinger liquid on a finite chain.

2.3 Theory Calculations

The responsivity R of the photodetector shows the relationship of the electric current I_p flowing in the device circuit to the optical power P incident on it (equation 9).

$$I_p = \eta e \phi \frac{\eta P}{h\nu} \equiv RP \quad (9)$$

where η = quantum efficiency; $\hbar$ = reduced planks constant (Dirac constant); ν = frequency of the photon; and ϕ = mean photon flux.

The choice of gold nanoparticles was based on the principles that Raman scattering can be increased by orders of magnitude through the use of metal nanostructures[25] [26] [27]. Previous reports have shown that by applying silver nanoparticles on the surface of a 170nm thick silicon-on-insulator photo-detector at a wavelength of 850nm, the photocurrent increased by a factor of 20[28] while the use of gold nanoparticles has been reported to achieve plasmonic enhancement of 80% at similar conditions [29].

The tunable photo-physical attributes of metal nanoparticles is illustrated with a point dipole model describing the absorption and scattering of light as follows:

$$C_{\text{scattering}} = \frac{1}{6\pi} \left(\frac{2\pi}{\lambda} \right)^4 |\alpha|^2 \quad (10)$$

$$C_{\text{absorption}} = \frac{2\pi}{\lambda} I_m [\alpha] \quad (11)$$

where α is the polarizability of the particle given by:

$$\alpha = 3V \left[\frac{\epsilon_p / \epsilon_m - 1}{\epsilon_p / \epsilon_m + 2} \right] \quad (12)$$

where V is the particle volume

ϵ_m is the dielectric formation of the embedded medium.

ϵ_p is the dielectric function of the particle

A point of large particle polarizability, referred to as Surface Plasmon Resonance is given by:

$$\epsilon_p = -2\epsilon_m \quad (13)$$

Smaller nanoparticles offer light absorption without any scattering losses, whereas larger nanoparticles offer strong light scattering along with absorption. Au nanoparticles offer the desired properties.

3.0 Results and Analysis

The electrical and optical parameters measured during the fabrication of the device were recorded and presented in Table 1. The responsivity for the Advanced Bioelectronic diode chip as presented shows a remarkable improvement from the usual 0.65 $\mu\text{A}/\mu\text{W}$ at 850 nm to 0.89 $\mu\text{A}/\mu\text{W}$ at 850 nm attributed to the use of MTB. Conventional p-i-n diode Current-Voltage characteristics were matched with the bioelectronics p-i-n chip as shown in Figures 3 and 4. A comparison of the Current-Voltage characteristics

reveals a superior performance of the bioelectronics p-i-n diode chip.

Also, the effect of Capacitance against bias Voltage for conventional p-i-n Diodes with different diameters was presented in Figure 5. The device capacitance per unit area measured at -5V bias was shown to vary from 7.5 μFcm^{-2} to 9.9 μFcm^{-2} for diameters between 500 μm to 60 μm . This buttresses the defects of a conventional PIN diode. The dark current density at -5V bias is much lower for the Bioelectronic p-i-n diode. The fabricated device was also subjected to high temperature and high humidity and the dark current density remained approximately the same. The magnetosomes of the MTB remained viable at pH 7.04 and under atmospheric temperature and pressure.

Furthermore, the photoluminescence intensity of Au nanoparticles were also sampled as shown in Figures 6 and 7, and observed that the large photoluminescence enhancement is due to the localized enhancement of semiconductor optical absorption through the excitation of surface Plasmon resonances in proximate metal nanoparticles.

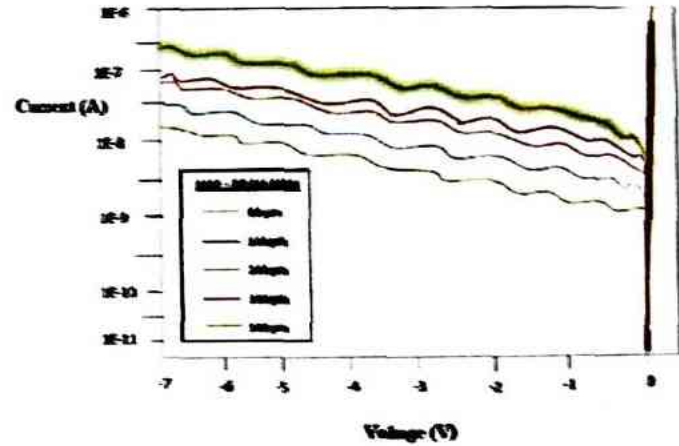


Figure 3. Current-Voltage Characteristics for PIN Photodiode

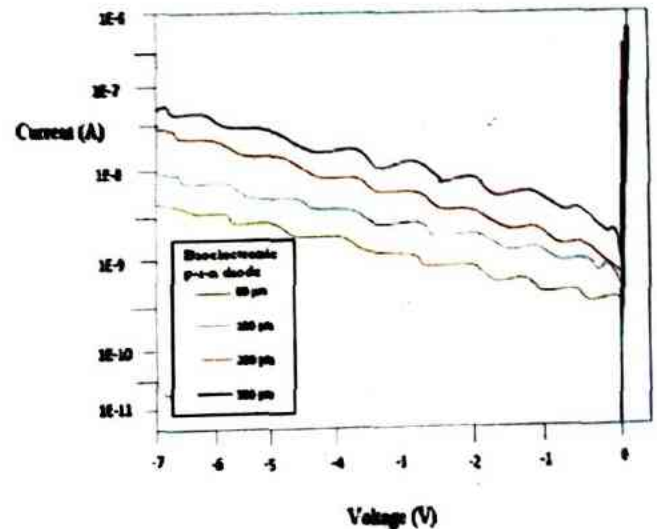


Figure 4. Current-Voltage Characteristics for Bioelectronic p-i-n diode chip

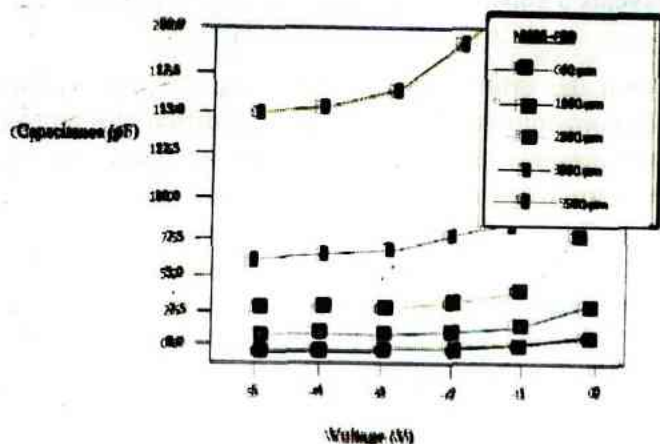


Figure 5. Capacitance (pF) versus Bias Voltage for PIN Photodiode

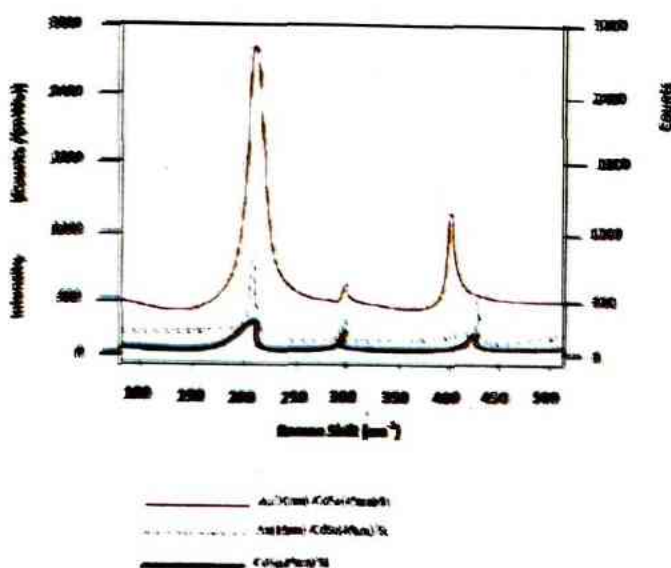


Figure 6. Effect of Raman Shift showing Au nanoparticles with strong surface enhanced Raman intensity at 30nm

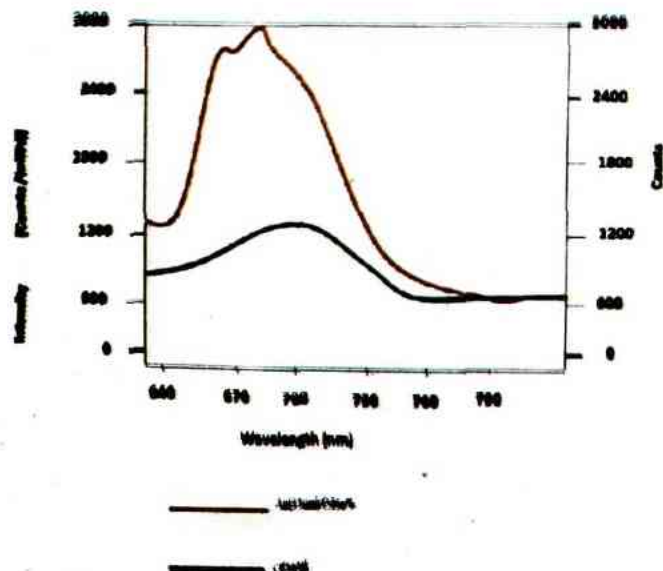


Figure 7. Photoluminescence Spectra of the nanoparticles on silicon embedded medium at room temperature

Table 1. The properties of the Bioelectronic p-i-n Diode chip.

Spectral response	700 – 2000nm
Peak response	0.55 A/W @ 1200nm
Rise/fall time	0.0001 ns
Diode capacitance	0.2 pF (typical)
NEP @ 1200 nm	$1.0 \times 10^{15} \text{ W}/\sqrt{\text{Hz}}$
Dark current	0.5nA (typical) 1.0nA (maximum)
PD Active diameter	0.1 mm
Bandwidth	1 GHz (minimum)
Damage threshold	100 mW Continuous Wave
Bias (reverse)	12V battery
Coupling lens	0.8" diameter
Coupling efficiency	98% (typical) from both single and multimode fibers over full spectral response.

4.0 Conclusion

A photodiode that uses a novel carrier transport mechanism aided by magnetosomes of Magnetotactic bacteria is proposed. The limitations associated with the geometries and functionalities of the p-i-n diode which affects its responsivity and quantum efficiency necessitated the proposal of the Bioelectronic P-I-N Diode chip. The major feature of the bioelectronics pin diode performance includes its ability to sense lower limits of signal detection, the resolution, and the speed of the device. Technically lower limits of signal detection are achieved by a combination of excellent gain, noise equivalent power, quantum efficiency, detectivity and dark current. Also the high resolution is attributed to the responsivity and response time. Other derived benefits of the bioelectronics p-i-n diode are its compact size, low power, low cost, and ease of production in mass. The Bioelectronic P-I-N photodiode achieves a responsivity of 0.89A/W at $\lambda = 1.55\mu\text{m}$ while still maintaining a high bandwidth of 50GHz. The device with 0.145mm^2 active area achieved 680MHz for cutoff frequency at 10V bias with 830nm radiation. Based on the work performed by other investigators on silicon devices, carrier lifetime has been found to increase with increasing temperature [30]. Accordingly, the variation of stored charge in the active region with temperature is a good

predictor of temperature dependence of the p-i-n diode resistance. The speedy transportation of the generated carriers in the Bioelectronic p-i-n diode achieved temperature stability of the device.

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